

Structure, circulation, and breakdown of the
Congo Air Boundary



Charles Knight
Keble College
University of Oxford

A thesis submitted for the degree of
Doctor of Philosophy

Hilary Term 2026

Abstract

The onset of the austral summer rains across subtropical southern Africa marks a critical transition in the regional hydroclimate that is of major socio-economic importance. Yet the dynamical processes controlling rainfall onset remain poorly understood, hindering seasonal predictability and undermining confidence in projections of delayed rainfall onset under future warming. Resolving this requires an improved understanding of the regional circulation features that modulate the southward migration of the tropical rain belt toward southern Africa from August to December.

A key feature in this transition is the Congo Air Boundary (CAB), a synoptic-scale dryline and convergence zone that is commonly interpreted as marking the southern edge of the tropical rain belt. Variability in the location and persistence of the CAB is a first-order control on August–December rainfall across subtropical southern Africa (10–25°S) from intraseasonal to climate-change timescales. However, fundamental aspects of the CAB remain poorly understood. A deficit of *in situ* observations means that the structure and circulation of the atmosphere across the CAB is known only from models and reanalyses, the fidelity of which is uncertain at the data-sparse southern African tropical edge. This hinders understanding of the processes governing CAB maintenance and breakdown, and by extension the mechanisms shaping rain belt seasonality and its response to future warming.

This thesis addresses these gaps by drawing on novel observations from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (2021–2025), which has collected the first detailed *in situ* measurements of the thermodynamic and kinematic structure of the atmosphere at the CAB. These observations are used to diagnose the structure and circulation across the CAB and to explore the processes governing its maintenance. The CAB is shown to feature a

sharp moisture discontinuity of up to 12.0 g kg^{-1} per 100 km, forming at the interface of a dry regime characterised by a near dry-adiabatic ($9.6 \text{ }^{\circ}\text{C km}^{-1}$) afternoon boundary layer, and a moist regime characterised by mid-afternoon convective available potential energy exceeding 1400 J kg^{-1} . A conceptual model of the atmosphere across the CAB is developed, revealing its intricate mesoscale structure, circulation, and modulation through the diurnal cycle. This demonstrates a tight coupling between the CAB, the southern African heat low, and the southern African easterly jet, and identifies a shallow overturning circulation on the moist side of the dryline.

Theory developed on the maintenance of the CAB is complemented by an analysis of the large-scale processes leading to its breakdown, revealing that approximately 70% of breakdown events are associated with midlatitude disturbances. These disturbances modify large-scale subsidence, low-level moisture transport, and mid-level moisture-flux divergence to erode the CAB. Synthesising insights on the maintenance and breakdown of the CAB, the thesis argues for a revised conceptualisation of the CAB as poleward displaced from the tropical rain belt but intimately tied to its location and seasonality. This coupling arises through the equatorward advection of dry mid-level air at the CAB by shallow overturning, in a mechanism observed in other tropical rainfall regimes adjacent to heat lows and consistent with global monsoon theory.

The ability of three reanalysis products to reproduce the CAB and its associated features during the DRY-CAB field campaign is also evaluated. This reveals that reanalyses poorly represent key mesoscale aspects of the CAB, with biases exceeding $\pm 25\%$ in dryline strength and large errors in its diurnal modulation related to the misrepresentation of moisture transport on the moist side of the dryline. These findings highlight the limitations of reanalyses for representing the mesoscale processes important to rainfall onset at the southern African tropical edge.

Acknowledgements

The foremost thanks in these acknowledgements must go to Richard Washington. It was Richard who first suggested I consider southern African climate dynamics as a research focus – a suggestion that grew into an undergraduate dissertation, two months in the field in north-west Zambia, and ultimately this thesis. His clear scientific vision has shaped both the conceptual foundations of this work and the field observations on which it is based. The existence of this research, and much of my development and outlook as an independent scientist, are owed to his guidance and support.

Callum Munday has also played an instrumental role in the development of this work and in shaping my broader scientific perspective. His encyclopaedic knowledge of the literature, measured perspective and ability to see the big picture have been invaluable throughout the completion of this work. From day one in an Oxford party shop hunting for helium, Callum has been a fantastic mentor and a constant source of guidance, insight, and good humour.

This thesis is deeply reliant on the DRY-CAB project and the unique observational datasets it generated. I am greatly indebted to the many people who contributed, in ways both large and small, to its design and execution. Working with the field data collected during the 2022 campaign has been a privilege, made all the more meaningful by a first-hand appreciation of the substantial effort, collaboration, logistical complexity, financial commitment and 01:45 alarms that underpin the collection of every individual data point. Many of these contributors are acknowledged explicitly in Chapters 3 and 4. I also thank those who have worked to develop and maintain the wider range of meteorological and climate datasets on which this thesis draws, and gratefully acknowledge the financial support provided by the Keble College Bigg Scholarship in African Climate Science, without which this work would not

have been possible.

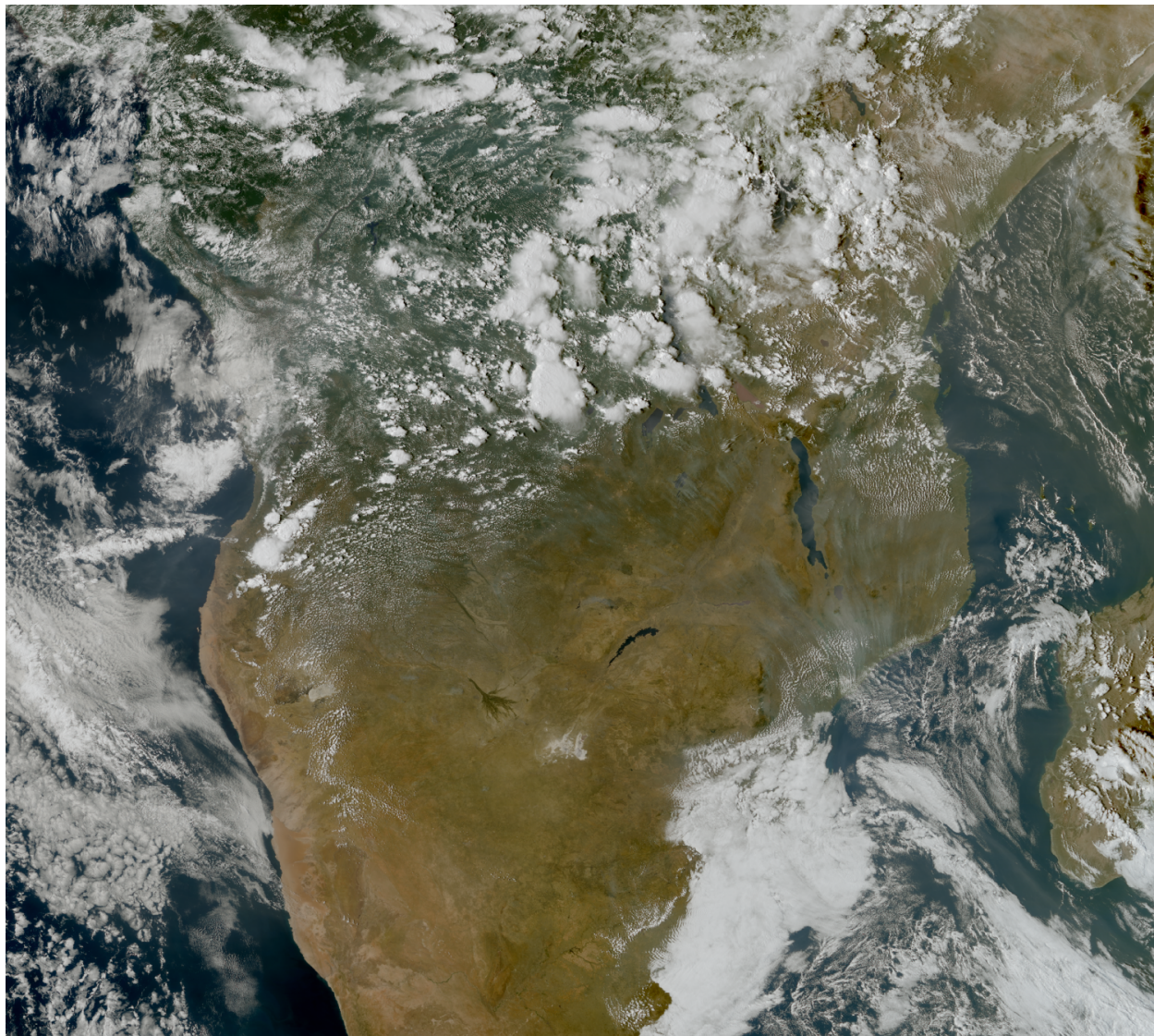
The extended list of people I would like to thank is far too long to include in full. A notable mention must go to Sebastian Engelstaedter, who introduced me to coding and climate computation, and David Ford and the wider IT team for their hard work ensuring server uptime. I also thank Neil Hart, Richard Jones, and Matt Hawcroft for the time and care they devoted to my Transfer and Confirmation of Status, as well as for many other helpful discussions over the last $3\frac{1}{2}$ years.

My fellow climate PhDs have made the process of completing this thesis a genuine pleasure. Kitty Attwood deserves first mention as a true friend and as both a scientific and creative adviser, alongside Alex Henry, Alice Jardine, and Kate Maddern. I wish you the very best in your own work and long may our friendships last. The wider Climate Lab has been the most amazing family over the past three and a half years. Sebastian, Marcia, Fran, Jerry, Zeyao, and Rebecca – thanks for making it feel like home.

My family have supported and encouraged me from the very beginning, and I am deeply grateful to them. Alice Marks has also been a rock, providing unwavering support through both the highs and the lows.

This thesis, and my wider scientific outlook, has been shaped and greatly enhanced by my involvement in a number of projects, large and small, including DRY-CAB, KAPEX, KAPEX2, and MASIKA. Through these projects, I have met and worked with a huge number of inspiring people – far too many to give due credit to here. These friendships and memories will stay with me long after this thesis.

Lastly, I would like to acknowledge The Inklings Group Community Interest Company (CIC) and Yattendon Brewing Company, trading as Renegade Brewery, without whom this thesis may never have been completed, or equally may have been completed six months earlier.



MTG-I1 Flexible Combined Imager True Colour image of central southern Africa at 11:50 UTC on 3 October 2025, with the Congo Air Boundary in place. Data courtesy of EUMETSAT.

Table of Contents

Abstract	i
Acknowledgements	iii
Table of Contents	xi
List of Figures	xii
List of Tables	xxiv
List of Acronyms	xxvi
1 Introduction	1
1.1 Motivation and rationale	2
1.2 Climate of the southern African tropical edge	8
1.2.1 Definition and study area	8
1.2.2 Rainfall climatology	10
1.2.2.1 Seasonal cycle	10
1.2.2.2 Rainfall onset	13
1.2.3 The Congo Air Boundary	13
1.2.4 The September-November (pre-rainfall onset) mean-state cir- culation	16
1.2.4.1 Heat lows	18
1.2.4.2 Botswana high	19
1.2.4.3 African Easterly Jet South	20
1.2.4.4 Subtropical easterlies	20
1.2.4.5 Congo north-westerlies	21
1.2.4.6 Subtropical highs	21
1.2.4.7 Midlatitude westerlies	22
1.2.4.8 Rainfall-producing systems	23
1.2.5 The January-February (post-rainfall onset) mean-state cir- culation	23
1.2.5.1 Circulation features lost	23
1.2.5.2 Circulation features modified	24
1.2.5.3 Circulation features gained	24
1.2.5.4 Rainfall producing systems	25
1.2.6 Rainfall variability	26
1.2.7 Observed and projected change	28

1.3	Observations of the atmosphere	29
1.3.1	Routine observations	30
1.3.2	Field campaigns	31
1.4	Models and reanalyses	34
1.4.1	Modelling challenges	35
1.4.2	Reanalyses	35
1.5	Thesis aims	37
1.6	Thesis outline	39
1.6.1	Thesis format	40
1.6.2	A note on manuscript order of inclusion	41
1.7	Authorship declaration	42
2	Data and methods	44
2.1	Data	45
2.1.1	DRY-CAB field campaign	45
2.1.1.1	Summary	45
2.1.1.2	Field site selection	46
2.1.1.3	Sampling strategy	47
2.1.1.4	Instrumentation	52
2.1.1.5	Data quality control	54
2.1.1.6	Division into meteorological phases	55
2.1.2	Satellite data	57
2.1.3	Gridded precipitation products	57
2.1.4	Reanalyses	58
2.1.4.1	ERA5 (ECMWF)	59
2.1.4.2	MERRA-2 (NASA)	59
2.1.4.3	JRA-3Q (JMA)	60
2.2	Methods	60
2.2.1	Composite analysis	60
2.2.2	Canny-edge detection	61
2.2.3	Process-based evaluation	62
2.2.4	Comparison of point observations to gridded datasets	63
3	Observations of the atmosphere across the Congo Air Boundary	66
3.1	Foreword to Chapter 3	68
3.2	Introduction	69
3.3	Background	73
3.4	Data and methods	74
3.4.1	Field observations	74

3.4.2	Meteorological phases	75
3.4.3	Meteorological setting	78
3.5	Results	80
3.5.1	How do the thermodynamics of the atmosphere vary across the CAB?	80
3.5.2	How does the circulation of the atmosphere vary across the CAB?	85
3.5.3	How is the CAB modified by the diurnal cycle?	89
3.6	Discussion	94
3.6.1	Conceptual model	94
3.6.2	The CAB and the heat low	95
3.6.3	The CAB and shallow overturning	96
3.6.4	The CAB and the African Easterly Jet South	97
3.6.5	The CAB and the Botswana High	98
3.6.6	Comparison with other drylines	98
3.6.7	CAB breakdown	100
3.6.8	Generalisability	100
3.7	Conclusion	102
3.8	Acknowledgments	103
3.9	Afterword to Chapter 3	105
4	Evaluation of the Congo Air Boundary in reanalyses during the 2022 DRY-CAB field campaign	106
4.1	Foreword to Chapter 4	108
4.2	Introduction	109
4.3	Methods	111
4.3.1	Reanalysis evaluation	111
4.3.2	Data	114
4.3.2.1	Field observations	114
4.3.2.2	Reanalyses	116
4.3.3	Comparison considerations	117
4.4	Results	119
4.4.1	How well do reanalyses reproduce the key thermodynamic and circulation features that comprise the Congo Air Boundary?	119
4.4.1.1	CAB dryline & convergence zone	119
4.4.1.2	North-westerly (moist) low-level jet	121
4.4.1.3	Easterly (dry) low-level jet	123
4.4.1.4	African Easterly Jet South	126
4.4.1.5	Dry-convective mixing	126

4.4.1.6	Mid-level stability	129
4.4.2	How do diagnosed differences between reanalyses and observations influence convective environments?	131
4.4.3	How do diagnosed differences between reanalyses and observations influence rainfall onset meteorology?	132
4.5	Summary and conclusions	136
4.5.1	Representation of the CAB	138
4.5.2	Upscale implications	139
4.5.3	Broader implications and outlook	140
4.6	Acknowledgments	141
4.7	Appendix	142
4.7.1	Appendix A: Comparison considerations	142
4.7.1.1	CAB location	142
4.7.1.2	Spatial comparison considerations	142
4.7.1.3	Vertical comparison considerations	146
4.7.2	Appendix B: Supplementary diagnostics	146
4.8	Afterword to Chapter 4	149
5	Remote midlatitude control of rainfall onset at the southern African tropical edge	150
5.1	Foreword to Chapter 5	152
5.1.1	Rationale for the use of reanalyses	153
5.1.2	CAB breakdown in 2022	155
5.2	Introduction	159
5.3	Background	161
5.3.1	Onset predictability	161
5.3.2	The Congo Air Boundary	162
5.3.3	Midlatitude influence on the (sub)tropics	164
5.4	Data and methods	168
5.4.1	Data	168
5.4.2	Breakdown detection	169
5.4.3	Compositing	170
5.5	Results	170
5.5.1	Congo Air Boundary breakdown	170
5.5.2	What proportion of breakdowns are associated with the mid-latitudes?	174
5.5.2.1	Strong trough identification	174
5.5.2.2	Rossby wave breaking identification	175
5.5.2.3	Association with breakdown	176

5.5.3	What Rossby waves cause breakdown?	178
5.5.3.1	Wavenumbers	180
5.5.3.2	Wave trains	181
5.5.3.3	Wave sources	182
5.5.4	How do Rossby waves contribute to breakdown?	184
5.5.4.1	Vertical velocity	184
5.5.4.2	Wind field modification	187
5.5.4.3	Summary	190
5.6	Discussion	193
5.6.1	Low latitude rainfall and upper-level troughs	193
5.6.2	Implications for onset prediction	194
5.6.3	Future change	195
5.7	Conclusion	196
5.8	Acknowledgments	197
5.9	Afterword to Chapter 5	199
5.9.1	Mid-level moisture-flux divergence and the AEJ-S	199
5.9.2	Summary	201
6	Conclusions	204
6.1	Introduction	205
6.2	Fulfilment of thesis goals and aims	206
6.2.1	Aim 1: Diagnose the structure and circulation of the Congo Air Boundary using <i>in situ</i> observations	207
6.2.2	Aim 2: Evaluate the representation of the CAB in reanalyses	209
6.2.3	Aim 3: Characterise the large-scale mechanisms associated with the breakdown of the CAB	211
6.3	Discussion	212
6.3.1	The CAB and the tropical rain belt	213
6.3.2	Predictability of rainfall onset	217
6.3.3	Are reanalyses <i>fit for purpose</i> at the tropical edge?	219
6.3.4	Open questions and avenues for future research	221
6.3.4.1	Generalisability of DRY-CAB observations	221
6.3.4.2	Representation of the CAB in numerical models	223
6.3.4.3	The role of moist-convective processes in CAB break- down	226
6.3.4.4	Controls on Congo north-westerlies	227
6.3.4.5	Maintenance of the AEJ-S	228
6.3.4.6	Extension of the CAB into East Africa	229
6.3.4.7	Reformation of the CAB	230

6.4 Concluding remarks	231
References	234

List of Figures

1.1	A schematic of the lower-level (surface to 600 hPa) pre-onset (August to October) circulation at the southern African tropical edge. The Congo Air Boundary (CAB; Howard and Washington, 2019) is shown as a solid blue line separating moist tropical air (blue shading) from dry subtropical air (red shading). The southern African Heat Low is a large area of intense surface heating, characterised by an unstable boundary layer (red hatched; Attwood et al., 2024). Embedded in this heat low are dry cyclonic circulations, which form preferentially at the locations indicated by red cyclonic symbols (Howard and Washington, 2018). Other major features of the regional circulation include the African Easterly Jet South (purple arrow; Kuethe et al., 2020), subtropical easterlies (green arrows) and low-level Congo Basin north-westerlies (blue arrows; Pokam et al., 2014).	4
1.2	The odds ratio of a rainy day (defined as $> 1 \text{ mm day}^{-1}$) in October and November given the absence of the CAB, calculated in CHIRPSv2 daily data from 1981–2018. Contours show the per-gridcell October–November CAB dryline frequency of occurrence [% of days], based on the Howard and Washington (2019) detection algorithm applied to 1979–2018 ERA5 2 m specific humidity; contours are drawn at 0.5–4.5% in 1% intervals. The tropical edge, typically defined as spanning 10–20°S, is hatched.	11
1.3	Annual cycle of precipitation [mm day^{-1}] by latitude (starting 1 July) for the period 1981–2018. Precipitation is from the CHIRPS v2 dataset. Green contours denote ERA5 specific humidity at 850 hPa, plotted at 1 g kg^{-1} intervals from 8 to 12 g kg^{-1} . Red contours indicate ERA5 horizontal convergence at 850 hPa, plotted at $0.3 \times 10^{-5} \text{ s}^{-1}$ intervals for values $> 0.5 \times 10^{-5} \text{ s}^{-1}$. The solar declination angle is shown by the orange dashed line. All fields are averaged zonally over 18–28°E.	12
1.4	A monthly climatology (1979–2018) of the CAB a–e) dryline and f–j) convergence line spatial distribution in ERA5. CAB dryline (convergence line) grid cells are detected by applying the canny-edge detection algorithm of Howard and Washington (2019) to ERA5 2m specific humidity (100m zonal and meridional winds). Units are frequency per grid cell per month, with the convergence-line colourbar scaled identically to the dryline colourbar.	16
1.5	Schematic of key circulation features over southern Africa. The left column (a,c) shows a schematic latitudinal cross section at 20°E, the right column (b,d) shows a latitudinal cross section at 30°E. The top row (a,b) is for before tropical-edge rainfall onset (October–November), and the bottom row is for after tropical-edge rainfall onset (January–February). AL: Angola Low, BH: Botswana High, CCO: Congo Convective Outflow, HL: Heat Low, WJ: westerly jet. Reproduced from Munday et al. (2025).	17

1.6	a) Time series of the number of automatic weather stations reporting 2-m air temperature to the Global Telecommunication System (GTS) with >50% data uptime across the southern African tropical edge 5–25°S from 1984 to 2022. Bars are coloured by country. b) Spatial distribution of station coverage across the southern African tropical edge (5–25°S), with size and colour indicating the percentage of days between 2013 and 2022 with available temperature observations. Data is from the Met Office Integrated Data Archive System (MIDAS).	32
1.7	a) Time series of the number of radiosonde soundings across the southern African tropical edge (5–25°S) from 1970 to 2024, with bars coloured by country. b) Spatial distribution of radiosonde station coverage across the southern African tropical edge (5–25°S), with marker size and colour indicating the percentage of days between 2015 and 2024 with radiosonde soundings. A red cross marks the location of a radiosonde station that is no longer active. Data is from the Integrated Global Radiosonde Archive (IGRA), with pilot balloon ascents excluded.	33
2.1	A monthly climatology (1979–2018) of the CAB a-e) dryline and f-j) convergence zone spatial distribution in ERA5. CAB dryline (convergence zone) grid cells are detected by applying the canny-edge detection algorithm of Howard and Washington (2019) to ERA5 2m specific humidity (100m zonal and meridional winds). Units are frequency per grid cell per month, with the convergence-line colourbar scaled identically to the dryline colourbar. A transect between Ikelele and Solwezi is plotted in red. In the bottom right of each subplot, the average number of days per month the CAB intersects the transect is reported.	47
2.2	Location of the DRY-CAB project field sites. Green cross; automatic weather station (AWS) only sites; blue circle: Nchila radiosonde site with AWS and LiDAR; red circle: Solwezi radiosonde site with AWS and LiDAR. Surface elevation from the Global Multi-resolution Terrain Elevation Data 2010 is shaded.	50
2.3	Schematic map of the DRY-CAB field campaign sites and instrumentation. Measurement sites are indicated by red crosses, while the instrumentation deployed at each site is denoted by icons of a red balloon (radiosondes), an automatic weather station and a LiDAR. Background features (roads, waterways, waterbodies and forested areas) are from OpenStreetMap (© OpenStreetMap contributors). . . .	50
2.4	Timeline of DRY-CAB field campaign instrumentation deployment at each field site. Instrumentation is denoted by icons of red balloons (radiosondes), automatic weather stations (AWS) and a LiDAR. The project’s 44-day IOP, with a full suite of instrumentation and 8-daily radiosondes from Nchila and Solwezi, is indicated by hatching. . . .	51

2.5	Hovmöller plot of MSE [kJ kg^{-1}] at Nchila and Solwezi during the DRY-CAB field campaign. The project IOP, from 1 October to 13 November and characterised by 8-daily radiosonde ascents from both sites, is indicated by a red bar.	52
2.6	a) Phase-space plot of the 5 meteorological phases of the field campaign IOP. The y-axis indicates the daily maximum surface MSE at the Nchila field site [kJ kg^{-1}] and the x-axis the difference to the equivalent value at Solwezi. Daily values within each phase are plotted as diamonds while the phase mean is marked by a cross. b) A timeseries of daily maximum surface MSE [kJ kg^{-1}] at the Nchila and Solwezi field sites.	56
2.7	Graphical illustration of four potential methods for comparing field site observations (red cross) to gridded model data a) nearest neighbour, b) average of the four nearest grid points, c) distance-weighted average of the four nearest grid points, and d) weighted average over an assigned 30 x 30 km grid square.	65
3.1	A schematic of the lower level (surface–600hPa) pre-onset (August to October) circulation at the southern African tropical edge. The Congo Air Boundary (CAB; Howard and Washington, 2019) is shown as a solid blue line separating moist tropical air (blue shading) from dry subtropical air (red shading). The southern African Heat Low is a large area of intense surface heating, characterised by an unstable boundary layer (red hatched; Attwood et al., 2024). Embedded in this heat low are dry cyclonic circulations, which form preferentially at the locations indicated by red cyclonic symbols (Howard and Washington, 2018). Other major features of the regional circulation include the African Easterly Jet South (purple arrow; Kuete et al., 2020), subtropical easterlies (green arrows), and low-level Congo Basin north-westerlies (blue arrows; Pokam et al., 2014).	70
3.2	Location of the DRY-CAB project field sites. Red cross: Automatic weather station (AWS) only sites; green triangles: radiosonde sites with AWS and LiDAR. In a), large blue triangles denote active radiosonde stations, defined as those conducting soundings on more than 15% of days between 2015-2024 (Luanda, Dar es Salaam, Windhoek, and Pretoria). Small blue triangles show stations with soundings on fewer than 15% of days during the same period (Harare, Luena, Lubango, and Walvis Bay). Radiosonde data are from the Integrated Global Radiosonde Archive (IGRA) v2.2. The black dotted line outlines the circumscribed circle of active radiosonde sites, with a radius of approximately 1,542 km. Surface elevation [m] from the Global Multi-resolution Terrain Elevation Data 2010 dataset is shaded in purple.	76

3.3	Phase-space plot of the five meteorological phases of the field campaign. The y-axis indicates the maximum surface MSE [kJ kg^{-1}] at the Nchila field site and the x-axis the difference to the equivalent value at Solwezi. Daily values within each phase are plotted as diamonds while the phase mean is marked by a cross.	77
3.4	Mean brightness temperature [K] in the a) $10.8 \mu\text{m}$ and b) $6.25 \mu\text{m}$ channels from the Meteosat-10 (MSG-3) Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument, and c) 12:00 LT mean land surface temperature [$^{\circ}\text{C}$] from the Land Surface Analysis Satellite Applications Facility (LSA SAF) SEVIRI MLST (Land Surface Temperature) product, for Phases 1 and 3 of the field campaign (1–5 and 16–22 October). The Nchila and Solwezi field sites are indicated by blue and red circles respectively, while the difference between values at the two field sites (Nchila – Solwezi) is reported bottom right.	79
3.5	A timeseries of station specific humidity [g kg^{-1}] at Nchila (dashed) and Mwinilunga (dotted) on the 5th October 2022. A solid line plots the specific humidity gradient (∇q) [$\text{g kg}^{-1} / 100 \text{ km}$] between the two sites (right-hand y-axis). Wind barbs indicate the 20-minute surface mean winds, coloured by specific humidity and with half-, full-, and flag-barbs denoting 0.25 , 0.5 , and 2 m s^{-1} respectively	81
3.6	Mean 14:00 LT DSE and MSE profiles [kJ kg^{-1}] stratified by CAB location for the (a) Nchila and (b) Solwezi field sites. Nchila sampled a dry regime during Phase 2 and a moist regime during Phases 1, 3 and 4 (Table 5.1). Solwezi sampled a dry regime during Phases 1, 2 and 3, and a moist regime during Phase 4. c) plots simultaneous cross-CAB profiles from Phases 1 & 3, during which Solwezi sampled the dry regime and Nchila the moist regime.	83
3.7	Violin plot of inversion midpoint pressure [hPa] from radiosondes stratified by CAB location for the a) Nchila and b) Solwezi field sites. Inversions are identified in 1 hPa resolution radiosonde profiles as layers where temperature is stable or increases with height between successive levels. Nchila sampled a dry regime during Phase 2 and a moist regime during Phases 1, 3 and 4. Solwezi sampled a dry regime during Phases 1, 2 and 3, and a moist regime during Phase 4 (Table 3.1). c) shows simultaneous cross-CAB inversions from Phases 1 and 3, during which Solwezi was on the dry side and Nchila on the moist side. Surface and near-surface inversions, defined as beginning below 800 hPa, are excluded. Violin width indicates the distribution of inversion midpoint pressure, while a black vertical line spans the interquartile range. Horizontal black marks indicate the lower quartile, median, and upper quartile, while an ‘x’ marks the mean. Colour indicates mean inversion strength [$^{\circ}\text{C}$], defined as the temperature difference between the top and bottom of the inversion layer.	84

3.8	The diurnal cycle of wind speed [m s^{-1}] at a) Nchila (moist regime) and b) Solwezi (dry regime) during Phase 1 & 3 of the field campaign. Wind barbs indicate wind direction and speed (with north to the top of the plot). Isentropes are plotted at 2 K intervals in red. c) shows the magnitude (colours) and vector (arrows) differences in wind speed [m s^{-1}] between the two sites, with arrows shown only where wind speed differences between the sites are statistically significant ($p < 0.05$). Panels (d–g) present hodographs of the diurnal cycle of low-level (d: 850 hPa, f: 800 hPa) and mid-level (e, g: 650 hPa) winds at each field site. Sunrise, sunset, and solar noon are indicated by half and full circles respectively.	87
3.9	The component of the a) wind divergence [s^{-1}] and b) moisture flux divergence [$\text{g kg}^{-1} \text{s}^{-1}$] that is parallel to the bearing between the two field sites during field campaign Phase 1 & 3. Contours plot the magnitude of the difference in this component of the wind or moisture flux between the two field sites. Sunrise/sunset and solar noon are indicated by half and full circles respectively.	88
3.10	The diurnal cycle of a) the diurnal Nchila specific humidity perturbation (q') [g kg^{-1}] at the Nchila field site (moist side of the CAB) and b) the difference in specific humidity between Nchila and Solwezi [g kg^{-1}], both during field campaign Phase 1 & 3. Overlaid are contours of the component of moisture flux divergence parallel to the bearing between the two sites. Sunrise/sunset and solar noon are indicated by half and full circles respectively.	91
3.11	The diurnal cycle of MSG-3 SEVIRI $10.8 \mu\text{m}$ channel brightness temperature [K] by distance from the CAB during field campaign Phases 1 & 3. The location of the CAB is approximated as half way between the Nchila and Solwezi field sites with a bearing of 80° determined from SEVIRI $6.25 \mu\text{m}$ channel brightness temperatures (Figure 3.3). A black line plots the amplitude of the diurnal cycle by distance from the CAB. Red points show the hour of the brightness temperature maximum and blue points the minimum. Sunrise/sunset and solar noon are indicated by half and full circles respectively.	93
3.12	Schematic illustrating atmospheric processes across the Congo Air Boundary (CAB) a) during the day and b) at night.	94
4.1	Day-mean near-surface (850 hPa) specific humidity [g kg^{-1}] and vector winds [m s^{-1}] over subtropical southern Africa on 5 October 2022, when Knight et al. (2026) report that the CAB was located between the Nchila (green) and Solwezi (red) field sites and associated with a specific humidity gradient of 12.0 g kg^{-1} per 100 km. The reanalyses are a) ERA5, b) MERRA-2 and c) JRA-3Q. The location of the Nchila and Solwezi field sites are marked with green and red circles respectively. The CAB dryline, as detected by the canny-edge method of Howard and Washington (2019) (after interpolation to a $0.25^\circ \times 0.25^\circ$ grid) is plotted in purple.	111

4.2	Schematic from Knight et al. (2026), derived from DRY-CAB observations, illustrating the key thermodynamic and circulation features that comprise the CAB a) at night and b) during the day. The six defining features are (1) a dryline and convergence zone, (2) the north-westerly moist low-level jet, (3) the easterly dry low-level jet, (4) the African Easterly Jet South (AEJ-S), (5) dry-convective mixing, and (6) mid-level stability associated with the Botswana High.	113
4.3	850 hPa specific humidity (q) at a) Nchila and b) Solwezi, and c) dry-line intensity calculated as the specific humidity difference between Nchila and Solwezi in observations (black) and reanalyses (ERA5; green, MERRA2; orange, JRA-3Q; blue). The sampling base is "cross-CAB" (Table 4.1). An 'x' denotes where the reanalysis mean is significantly different from observations at $p < 0.05$	120
4.4	a-d) The component of the moisture flux divergence (∇qv) [$\text{g kg}^{-1} \text{s}^{-1}$] that is parallel to the bearing between the two field sites in a) observations and reanalyses: b) ERA5, c) MERRA-2, and d) JRA-3Q. The sampling base is "cross-CAB" (Table 4.1). A black line plots moisture fluxes by pressure integrated across the diurnal cycle [$\text{g kg}^{-1} \text{hPa}^{-1}$]. P_0 denotes the vertical level associated with a switch from diurnally integrated moisture accumulation to export. The ratio of vertically and diurnally integrated moisture accumulation below P_0 to export above P_0 is shown in the upper right of each panel. Values near unity indicate that low-level moisture convergence is largely compensated by divergence aloft, values greater than one indicate net moisture accumulation, and values less than one indicate net moisture export. Sunrise/sunset and solar noon are indicated by half and full circles respectively.	122
4.5	Diurnal cycle and vertical structure of the north-westerly (moist) LLJ in observations and reanalyses. The sampling base is "moist side" (Table 4.1). a) Hour-pressure evolution of observed north-westerly moisture fluxes (qv_{nw} ; shading) [$\text{g kg}^{-1} \text{m s}^{-1}$] together with the north-westerly LLJ index (lines) [$\text{g kg}^{-1} \text{m s}^{-1}$] defined as the 825-hPa north-westerly moisture flux in observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). North-westerly flow is defined as positive. b-d) Reanalysis bias (reanalysis minus observations) in north-westerly moisture flux as a function of pressure and hour for b) ERA5, c) MERRA-2, and d) JRA-3Q. Hatching indicates the 825-hPa level used to define the LLJ index. An 'x' marks hours where the LLJ index differs significantly from observations at the 0.05 level. Sunrise/sunset and solar noon are indicated by half and full circles respectively.	124

- 4.6 Diurnal cycle of the easterly (dry) LLJ in observations and reanalyses. The sampling base is "dry side" (Table 4.1). a) Hour-pressure evolution of zonal wind (shading) [m s^{-1}] together with the LLJ index (lines) [m s^{-1}] defined as the 800 hPa zonal wind in observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Easterly (along-jet) flow is defined as positive. b-d) Reanalysis error (reanalysis minus observations) as a function of pressure and hour for b) ERA5, c) MERRA-2 and d) JRA-3Q. In a), an 'x' marks where the LLJ index differs significantly from observations at the 0.05 significance level. Sunrise/sunset and solar noon are indicated by half and full circles respectively. 125
- 4.7 Diurnal cycle of the African Easterly Jet South (AEJ-S) in observations and reanalyses. The sampling base is "moist side" (Table 4.1). a) Hour-pressure evolution of easterly winds (shading) [m s^{-1}] together with the AEJ-S index (lines) [m s^{-1}] defined as the zonal wind at 650 hPa in observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Easterly (along-jet) flow is defined as positive. b-d) Reanalysis error (reanalysis minus observations) as a function of pressure and hour for b) ERA5, c) MERRA-2 and d) JRA-3Q. In a), an 'x' marks where the AEJ-S index differs significantly from observations at the 0.05 significance level. Sunrise/-sunset and solar noon are indicated by half and full circles respectively. 127
- 4.8 The diurnal cycle of the diurnal specific humidity perturbation (q') [g kg^{-1}] in a) observations and reanalyses: b) ERA5, c) MERRA-2, and d) JRA-3Q. The sampling base is "moist side" (Table 4.1). A black line plots the pressure level of the median maximum q' for each hour. Sunrise/sunset and solar noon are indicated by half and full circles respectively. 129
- 4.9 Mid-level stability, defined as the potential temperature lapse rate between 500 and 600 hPa [$K 100 \text{ hPa}^{-1}$], for observations and reanalyses on a) the "dry side" and b) the "moist side" of the CAB (Table 4.1). Higher values indicate greater mid-level stability. The distributions are shown as violin plots for observations, ERA5, MERRA-2, and JRA-55. Violin width indicates the distribution density, while a black vertical line spans the interquartile range. Horizontal black marks indicate the lower quartile, median, and upper quartile, while an 'x' marks the mean. 130
- 4.10 a-c) Quantile-quantile plots of observed and reanalysis 14:00 LT surface CAPE [J kg^{-1}] by reanalysis: a) ERA5, b) MERRA-2, c) JRA-3Q. d-f) quantile-quantile plots of observed and reanalysis 850–600 hPa bulk shear [m s^{-1}] by reanalysis: a) ERA5, b) MERRA-2, c) JRA-3Q. Colours indicate regime according to Table 4.1, with "dry side" in red, "moist side" in green, and "breakdown" in blue. 133

4.11	Mean 14:00 LT surface CAPE values [J kg^{-1}] calculated from surface parcels in observations ($CAPE_{obs}$), reanalyses ($CAPE_{re}$) and three substitution scenarios ($CAPE_{re} T_{obs}$, $CAPE_{re} D_{obs}$ and $CAPE_{re} E_{obs}$). Results are presented for a) ERA5, b) MERRA-2, and c) JRA-3Q, with values shown for the dry side of CAB, the moist side of CAB and post CAB breakdown. The three substitution scenarios are as follows: $CAPE_{re} T_{obs}$ is reanalysis CAPE with observed 2m temperature substituted for reanalysis 2m temperature, $CAPE_{re} D_{obs}$ is reanalysis CAPE with observed 2m dew point temperature substituted for reanalysis 2m temperature, and $CAPE_{re} E_{obs}$ is reanalysis CAPE with the observed environmental temperature profile substituted for the reanalysis environmental temperature profile. Colours indicate the percentage difference to $CAPE_{obs}$	134
4.12	a-d) Scatterplots of Solwezi daily maximum surface MSE [kJ kg^{-1}] versus Nchila daily maximum surface MSE [kJ kg^{-1}] from a) observations, b) ERA5, c) MERRA-2, and d) JRA-3Q during the field campaign IOP. Diamonds plot daily values within each phase while squares indicate the phase mean. Black arrows trace the sequential evolution of the five meteorological phases. In b-d), reanalysis mean values are marked with an 'x' where they differ significantly from observations at either Nchila or Solwezi, based on paired t-tests with Holm correction for each phase. e-g) Phase mean daily maximum 850 hPa MSE at Nchila and Solwezi as a percentile [%] of the tropical ($20^\circ\text{N} - 20^\circ\text{S}$) land 850 hPa MSE distribution. Dashed lines indicate respective percentiles when observed MSE is substituted into reanalysis MSE distributions.	137
4.13	850 hPa specific humidity [g kg^{-1}] as a function of distance along an extended Nchila-Solwezi transect, measured relative to the Nchila field site. Reanalysis specific humidity (ERA5: green; MERRA-2: orange; JRA-3Q: blue) is linearly interpolated onto the transect, with shading indicating the interquartile range of the 3-hourly (ERA5, MERRA-2) and 6-hourly (JRA-3Q) data within each phase. Panels show a) Phases 1 and 3, when the CAB lay between the two field sites; b) Phase 2, when both sites sampled a dry regime; and c) Phase 4, when both sites sampled a moist regime.	143
4.14	The location of the nearest reanalysis grid cell (MERRA-2: orange, JRA-3Q: blue, ERA5: green) to the Nchila (red square) and Solwezi (red triangle) field sites.	144

4.15	Correlation coefficient (r) and root-mean-square error ($RMSE$) by variable (a,d: specific humidity [g kg^{-1}]; b,e: u-wind [m s^{-1}]; c,f: v-wind [m s^{-1}]) and field site (a–c: Nchila; d–f: Solwezi) for four observation-reanalysis comparison methods. For each reanalysis (ERA5, MERRA-2, JRA-3Q), r (solid bars) and $RMSE$ (hatched bars) are plotted for the following four comparison methods: M1 – nearest neighbour; M2 – average of the four nearest grid points; M3 – distance-weighted average of the four nearest grid points; M4 – weighted average over an assigned 30x30km grid square.	145
4.16	Diurnal evolution of the vertically integrated near-surface (850–800 hPa) moisture tendency ($\partial Q/\partial t$) [$\text{kg m}^2 \text{s}^{-1}$], calculated as a 6-hour centred finite difference, from radiosonde observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Sampling base: "moist side".	147
4.17	Diurnal cycle of the median near-surface (850–800 hPa) bulk Richardson number (Ri_b) in radiosonde observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Sampling base: "moist side".	147
5.1	Rainfall by latitude from 1st September to 30th November 2022. Rainfall is averaged from 20–35° east. Rainfall data is CHIRPS v2. Overlaid are the meteorological phases of the field campaign (Phases 1 through 5) and the location of the CAB in the three atmospheric reanalyses (ERA5; MERRA-2, JRA-3Q), objectively identified with the canny-edge detection algorithm of Howard and Washington (2019) following interpolation to a common 0.25° grid. Circle diameter is proportional to the number of grid cells detected.	155
5.2	Effect of (a) spatial averaging and (b) temporal averaging on normalised inter-reanalysis spread for a suite of atmospheric variables at the Nchila field site. To investigate spatial averaging sensitivity, reanalysis data at 6-hourly resolution is averaged across various spatial scales. To investigate temporal averaging sensitivity, reanalysis data at 0.5° resolution is averaged across various temporal scales. The inter-reanalysis spread is calculated as $(\text{max} - \text{min})/2$ and normalised to the spread at a) 0.5° or b) 6-hourly resolution. Results are shown for specific humidity (Q), zonal wind (U), meridional wind (V), and temperature (T) at 850, 500, and 200 hPa.	156
5.3	Daily evolution of ERA5 850 hPa specific humidity (shading, g kg^{-1}) and moisture flux vectors ($\mathbf{q} = q \cdot \mathbf{v}$, arrows) over southern Africa from 29 October to 3 November 2022. White contours denote 500 hPa geopotential height [gpm], and thick black lines indicate the 330 K potential temperature contour on the -2 PVU surface (the dynamical tropopause). Regions of strong moisture-flux convergence ($< -0.2 \times 10^{-4} \text{s}^{-1}$) are hatched. Coloured grid cell markers highlight CAB regions identified by ERA5 (red), MERRA-2 (blue), and JRA-3Q (green).	158

5.4	Odds ratio of a rainy day ($> 0.1 \text{ mm day}^{-1}$) in October or November given the presence or absence of the Congo Air Boundary (CAB). The colourmap is scaled exponentially. Rainfall data is from the CHIRPS V2 precipitation dataset while daily CAB detection follows the canny edge method of Howard and Washington (2019) (fully detailed in methods). The odds ratio is calculated from a 1981-2018 climatology, with 816 CAB present days and 1502 CAB absent days. Stippling indicates the regions where October November CAB frequency at the day-scale is positively associated with ERA5 rainfall onset date (following the method of Liebmann et al. (2012)) at the 95% significance level in a 1979–2018 climatology.	160
5.5	(a) A 40-year (1979–2018) climatology of daily Congo Air Boundary (CAB) frequency from 1 September to 1 December. CAB detection follows the canny-edge method of Howard and Washington (2019). (b,c) Composite plots of ERA5 climatological (1979–2018) 850 hPa specific humidity [g kg^{-1}] and CAPE [J kg^{-1}] for the last 7 calendar days of September ('A') where CAB frequency is 80% and (d,e) the first 7 calendar days of November ('B') where CAB frequency is 32%.	165
5.6	A schematic of key southern African regional circulation features with (a) the CAB present and (b) absent. Features are as given in the legend and are not to scale. Locations are approximate. Gold stars mark the September-November hotspots of anticyclonic Rossby wave breaking identified by Ndarana and Waugh (2011). CAB breakdown represents the transition of the regional circulation from a CAB-present state (left panel) to a CAB-absent state (right panel) over timescales of 2-5 days. Tropical temperature troughs here are indicative of a variety of midlatitude precipitation mechanisms.	166
5.7	Lead (D-3, D-2, D-1) and lagged (D=0, D+1, D+2) daily composite vertical profiles of specific humidity [g kg^{-1}] by latitude for 1979–2018 CAB breakdown events (n=85) averaged across 20-30°E. The day of CAB breakdown is designated D=0 for each of the 85 included breakdown events.	171
5.8	Lead (D-1) and lagged (D=0, D+1, D+2) composite day-mean 850 hPa specific humidity [g kg^{-1}] (left column, a-d), 2m temperature anomaly [$^{\circ}\text{C}$] (centre column, e-h), and 250 hPa streamfunction anomaly (against an October climatology) [$\times 10^6 \text{ m}^2 \text{ s}^{-1}$] (right column, i-l) for all 1979–2018 CAB breakdown events (n=85) from D-1 to D+2. A [$-9 \times 10^{-5} \text{ s}^{-1}$] absolute vorticity contour at 250hPa is plotted over streamfunction anomalies (right column). Positive streamfunction anomalies are cyclonic. Stippling indicates where anomalies are significantly different from the October climatology or zero at the 0.05 level.	172

5.9	Lead (D-1) and lagged (D=0, D+1, D+2) composite day-mean 250 hPa absolute vorticity [$\times 10^{-5} \text{ s}^{-1}$] (left column, a-d), 850 hPa specific humidity anomaly [g kg^{-1}] (centre column, e-h) and 12:00 UTC CAPE [J kg^{-1}] (right column, i-l) for all CAB breakdown events related to midlatitude Rossby waves (both RWB and TR event sets, n=60). For RWB breakdowns D=0 is defined as the first day of overturning, while for TR breakdowns D=0 is defined as the day of maximum ‘TP’ index values. Stippling indicates where values are significantly different from the October climatology or zero at the 0.05 level.	179
5.10	Composite 5-day change in 850 hPa specific humidity [g kg^{-1}] and pentad precipitation change (difference in total rainfall between the previous and following 5 days) [mm] for all CAB breakdowns (ALL) and each of the RWB, TR and CF event sets. The RWB event set is a subset of ALL where breakdown is associated with Rossby wave breaking, while TR is a subset of ALL where breakdown is associated with troughs. RWB and TR trigger large-scale responses over southern Africa. The CF event set is a counterfactual of trough events that do not trigger a large-scale response over the domain.	180
5.11	Composite day-mean 250 hPa geopotential height anomaly [gpm] for D=0 of the RWB (a), TR (b) and CF (c) event sets. A solid black contour plots [$-9 \times 10^{-5} \text{ s}^{-1}$] absolute vorticity at 250hPa. Dashed black closed contours plot OLR anomaly [W m^{-2}] for the 5 days previous to the event shown at an interval of -4 W m^{-2} . Stippling indicates where geopotential height anomalies are significantly different from zero at the 0.05 level.	183
5.12	Lead (D-1) and lagged (D=0, D+1, D+2) composite latitudinal profiles (20-30°E) of vertical velocity [Pa s^{-1}] for each of the RWB (a-d), TR (e-h) and CF (i-l) event sets. Topography is shaded black. A solid black contour plots 7 g kg^{-1} specific humidity. Stippling indicates where vertical velocity is significantly different from the October climatology at the 0.05 level. Streamlines show vertical velocity and the northward wind component, with vertical velocity scaled by 1000.	188
5.13	Lead (D-1) and lagged (D=0, D+1, D+2) composite 500 hPa vertical velocity [Pa s^{-1}] and OLR anomaly [W m^{-2}] (against an October climatology) each of the RWB (a-d), TR (e-h) and CF (i-l) event sets. A solid black contour plots [$-9 \times 10^{-5} \text{ s}^{-1}$] absolute vorticity at 250 hPa. Stippling indicates where vertical velocity is significantly different from the October climatology at the 0.05 level.	189

5.14	Lead (D-1) and lagged (D=0, D+1, D+2) composite 850 hPa moisture fluxes (vectors) and anomaly of the moisture fluxes (shaded, against an October climatology) [$\text{g kg}^{-1} \cdot \text{m s}^{-1}$] for each of the RWB (a-d), TR (e-h) and CF (i-l) event sets. Black contours plot 850 hPa geopotential height contours at 10 m intervals from 1520-1580 m. Moisture flux vectors are plotted where the u or v component of the moisture flux anomaly is significantly different from the October climatology at the 0.05 level.	191
5.15	Lead (D - 2) and lagged (D = 0, D - 2) composite 650 hPa moisture flux divergence (shaded; $\times 10^{-7} \text{ s}^{-1}$) and zonal wind (contours $< -5 \text{ m s}^{-1}$ in 1 m s^{-1} intervals) for (a) all CAB breakdown events, (b) the RWB breakdown subset, (c) the TR breakdown subset, and (d) the counter-factual CF event set. Stippling indicates where moisture flux divergence is significantly different from D-2 at the 0.01 level.	202
6.1	A schematic of the large-scale meridional circulation of central Africa about the September equinox, when the solar zenith is overhead the equator. The blue line (bottom plot) indicates rainfall rates by latitude, with the rainbelt latitude range shaded. CAB; Congo Air Boundary. ITD; Intertropical discontinuity. EQ; equator. HL; Heat low. Q-conv; moisture flux convergence. Q-div; moisture flux divergence. AEJ; African Easterly Jet. TEJ; Tropical Easterly Jet.	217
6.2	850 hPa specific humidity (q) at a) Nchila and b) Solwezi, and c) the cross-CAB dryline intensity calculated as the specific humidity difference between Nchila and Solwezi. An 'x' denotes where reanalysis and model means are significantly different from observations at $p < 0.05$. The Unified Model can be considered a pseudo-reanalysis, as 48-hour simulations do not provide significant opportunity for the simulation to diverge from its driving forecast model. The first 24 hours are excluded to account for model spin-up.	225
6.3	MSE [kJ kg^{-1}] in Solwezi radiosonde ascents from 7 November to 9 December during the DRY-CAB field campaign.	231

List of Tables

1.1	A summary of climate literature published on the CAB. Data sources include reanalyses (ERA-Interim and ERA5 from the European Centre for Medium-Range Weather Forecasts, NCEP2; National Centers for Environmental Prediction Reanalysis 2, JRA-55: Japanese 55-year Reanalysis), satellite observations (TRMM; Tropical Rainfall Measuring Mission, CHIRPS: Climate Hazards Group Infrared Precipitation with Stations), and in situ observations (SASSCAL; Southern African Science Service Centre for Climate Change and Adaptive Land Management). Additional abbreviations: ITCZ; Intertropical Convergence Zone, GCM; General Circulation Model, CMIP; Coupled Model Intercomparison Project.	6
2.1	Schedule of observations during the DRY-CAB field campaign.	48
2.2	Radiosonde ascent summary statistics during the field campaign IOP. Median ascent time and horizontal drift distance are reported as a function of elevation above the surface, with first and third quartiles also indicated. A boundary layer depth of ≈ 3.6 km corresponds to the approximate mean mid-afternoon ($\approx 14:00$ LT) mixed-layer depth.	51
2.3	Dates and durations of the five meteorological phases of the 44-day field campaign IOP. For each phase, the thermodynamic regime sampled at the Nchila and Solwezi field sites is indicated as "Moist", "Dry" or "No CAB". "Moist" ("dry") denotes that the site lay on the moist (dry) side of the CAB. "No CAB" is assigned to Phase 5 as reanalysis diagnostics indicate the CAB did not form during this period.	56
2.4	Reanalyses used in this thesis.	59
3.1	Dates and durations of the five meteorological phases of the 44-day field campaign IOP. For each phase, the thermodynamic regime sampled at the Nchila and Solwezi field sites is indicated. Moist (dry) denotes that the site lay on the moist (dry) side of the CAB. Data from Phase 5, during which the CAB does not form, is not used in this study.	76
3.2	Simultaneously sampled cross-CAB values of thermodynamic variables at Nchila (moist regime) and Solwezi (dry regime) during field campaign Phases 1 & 3. Means and standard deviations are reported.	84
4.1	Dates and durations of the five meteorological phases of the 44-day field campaign IOP. Each field site is assigned "Moist", "Dry" or "Breakdown" for each phase depending on the location of the CAB. During Phase 5 ("Breakdown") the CAB did not form. Sampling was "Cross-CAB" in Phase 1 & 3.	115
4.2	Reanalysis products used in this study.	117

4.3	Decomposition of 05:00 LT north-westerly moisture flux (qv_{nw}) at 825 hPa [$\text{g kg}^{-1} \text{ m s}^{-1}$] into specific humidity (q) [g kg^{-1}] and north-westerly wind (v_{nw}) [m s^{-1}] components in observations and reanalyses. Bold font denotes values that differ significantly from observations at the 0.05 significance level. Sampling base: "moist side". . . .	148
4.4	North-west to south-east aligned 14:00 LT gradients of thermodynamic and surface flux variables from ERA5, MERRA-2, and JRA-3Q. Gradients are estimated as the finite difference of two $3^\circ \times 3^\circ$ latitude-longitude boxes with the field site at their shared corner. The pressure-gradient force (PGF) is computed as $-\partial\Phi/\partial x$ and evaluated along with the geopotential height gradient (∇z) at 850 hPa. L and S denote latent and sensible heat fluxes, respectively, $L + S$ the total turbulent surface heat flux, and EF the evaporative fraction defined as $\text{EF} = L/(L + S)$. The sensible heat flux gradient (∇S) is decomposed into contributions associated with gradients in the total turbulent flux (∇S from $\nabla(L + S)$) and in evaporative fraction (∇S from ∇EF). Sampling base: "moist side".	148
5.1	Monthly proportion of 1979–2018 CAB breakdown events related to midlatitude Rossby waves. Breakdowns are associated if occurring within two days of RWB or strong trough events.	177
5.2	Mean position and standard deviation of the Julian Day of CAB breakdown events in the annual cycle for ALL, RWB, TR and CF. The 'ALL' event set is centred on the day of detected CAB breakdown, while the RWB event set is centred on the first day of detected overturning and the TR and CF sets are centred on the day of maximum 'TP' index values.	178
5.3	Amplitude and variance of the first 10 harmonics of composite 250 hPa geopotential height anomaly between 180° – 180°E at 40°S for each of the RWB, TR and CF cases. Harmonics with the largest explanatory variance are highlighted in bold.	181

List of Acronyms

AEJ	African Easterly Jet
AEJ-N	African Easterly Jet – North
AEJ-S	African Easterly Jet – South
AWS	Automatic weather station
CAB	Congo Air Boundary
CAPE	Convective available potential energy
CAT	Central African Time
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMIP	Coupled Model Intercomparison Project
COL	Cut-off low
DRC	Democratic Republic of Congo
DRY-CAB	Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary
DSE	Dry static energy
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño–Southern Oscillation
EUMETSAT	European Organisation for the Exploitation of Meteorological Satel- lites
GCM	General circulation models
GMAO	Global Modelling and Assimilation Office
GNSS	Global Navigation Satellite System
GTS	Global Telecommunication System
IFS	Integrated Forecast System
IGRA	Integrated Global Radiosonde Archive
IOP	Intensive observational period

ITCZ	Intertropical Convergence Zone
JMA	Japanese Meteorological Agency
LLJ	Low-level jet
LT	Local time
MCS	Mesoscale convective system
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications version 2
MIDAS	Met Office Integrated Data Archive System
MSE	Moist static energy
NERC	Natural Environment Research Council
OLR	Outgoing longwave radiation
PV	Potential vorticity
RCP	Representative Concentration Pathway
RMSE	Root mean square error
RWB	Rossby wave breaking
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SEVIRI	Spinning Enhanced Visible and Infrared Imager
TTT	Tropical Temperature Trough
UTC	Coordinated Universal Time

1 | Introduction



Driving north on the Mwinilunga – Ikelenge highway (T5), North-West Province, Zambia. 24 September 2022.

1.1 Motivation and rationale

The onset of the summer rains over subtropical southern Africa, which typically occurs from October to December, marks a major transition in the regional hydro-climate that is of profound socio-economic importance. The timely arrival of rainfall is crucial to rain-fed agricultural systems (Reason et al., 2005; Kniveton et al., 2009), crop yields (Tadross et al., 2005; Nhamo et al., 2019), electricity generation (Conway et al., 2017; Falchetta et al., 2019) and potable water supply (Burls et al., 2019).

Substantial interannual variability in rainfall onset therefore presents a major regional challenge. Onset date standard deviations exceed 30 days across parts of the southern African tropical edge (Hachigonta et al., 2008; Mupangwa et al., 2011; Dunning et al., 2016; Byakatonda et al., 2018; Manhique et al., 2023), and such variability has historically translated into large socio-economic impacts. Failed rains caused a 7-9% GDP drop in Malawi and Zambia in 1992 (Thurlow et al., 2012; Conway et al., 2015) and were associated with widespread crop failure in the 2025 growing season (World Food Programme, 2025).

Understanding the processes that govern the onset of the summer rains has therefore long been a goal of both climate research and operational forecasters (Phakula et al., 2018; Ratnam et al., 2018). However, the basic dynamics of the southern African climate system pre-rainfall onset (September-November), and the transition to a post-rainfall onset (December-February) mean state, remain an active area of research (Nicholson, 2018). In particular, there is limited understanding of the circulation features that modulate the southward progression of the tropical rain belt toward southern Africa.

Against this backdrop, projections of future change are particularly concerning. Successive generations of climate models indicate a delay in rainfall onset of approximately two weeks by 2080 – 2100 under a business-as-usual emissions scenario

compared to the present day (Dunning et al., 2018). These projections are consistent with emerging observational evidence of early-summer rainfall declines (Munday et al., 2025) and pronounced warming during October at rates of up to four times the global mean (MacKellar et al., 2014; Engelbrecht et al., 2015; Engdaw et al., 2022; Munday et al., 2025). For a region so dependent on the timely arrival of the summer rains, the risk to livelihoods, development, and future prosperity is substantial.

At the continental scale, it is the southward movement of the tropical rain belt that brings rainfall onset to subtropical southern Africa. This is to the first order thermodynamically driven by the seasonal cycle of solar insolation (Giannini et al., 2008; Hart et al., 2019) and the requirement for energy export away from the summer hemisphere (e.g., Schneider et al., 2014; Biasutti et al., 2018). As the rain belt migrates southward from its August position north of the equator, its southern edge is thought to be demarcated by the Congo Air Boundary (CAB; Figure 1.1), a pronounced meridional gradient in low-level moisture co-located with a maximum in near-surface convergence (Howard and Washington, 2019).

The CAB is typically defined as the synoptic-scale convergence zone and dryline that occurs where near-saturated low-level north-westerlies originating from the equatorial east Atlantic and Congo Basin meet dry easterly trade winds from the tropical southwest Indian Ocean (Hills, 1979; Torrance, 1979; Nicholson, 1996; Levin et al., 2009; Tierney et al., 2011; Dezfuli, 2017; Howard and Washington, 2019). The CAB forms preferentially on the slope from the Congo Basin to the Katanga Plateau ($8 - 12^{\circ}\text{S}$) with a south-west to north-east orientation, and is most common in August and September (present on $> 95\%$ days), declining in frequency through to December (present on $< 10\%$ of days) (Howard and Washington, 2019). The CAB forms at the interface of a dry (subtropical) and moist (tropical) regime, and its seasonal migration is closely linked to that of the tropical rain belt, with the CAB migrating southward from August to November at an average rate of approximately

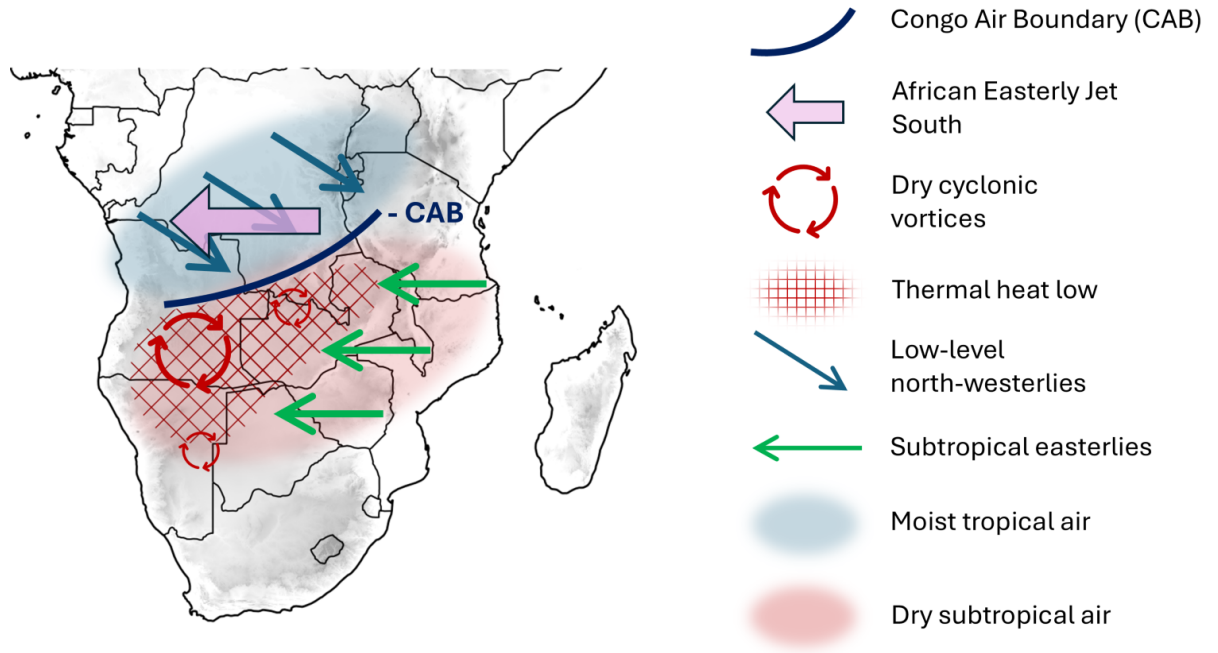


Figure 1.1: A schematic of the lower-level (surface to 600 hPa) pre-onset (August to October) circulation at the southern African tropical edge. The Congo Air Boundary (CAB; Howard and Washington, 2019) is shown as a solid blue line separating moist tropical air (blue shading) from dry subtropical air (red shading). The southern African Heat Low is a large area of intense surface heating, characterised by an unstable boundary layer (red hatched; Attwood et al., 2024). Embedded in this heat low are dry cyclonic circulations, which form preferentially at the locations indicated by red cyclonic symbols (Howard and Washington, 2018). Other major features of the regional circulation include the African Easterly Jet South (purple arrow; Kuete et al., 2020), subtropical easterlies (green arrows) and low-level Congo Basin north-westerlies (blue arrows; Pokam et al., 2014).

2° per month (Howard and Washington, 2019). For this reason, the CAB is commonly thought to demarcate the southern edge of the tropical rain belt, although the actual nature of this relationship remains uncertain.

The CAB does not form south of approximately 15°S, implying that its breakdown is a necessary condition for tropical rainfall south of that latitude (Howard and Washington, 2019, 2020). Consistent with this, rainfall from 15–25°S is strongly anticorrelated with CAB frequency in October, November, and December ($r \leq -0.58$), and CAB breakdown date is closely related to the rainfall onset date (Howard and Washington, 2019; 2020). This same relationship underpins the mechanism by which climate models project future drying and delayed rainfall onset over southern Africa: Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathway 8.5 (RCP8.5) simulations show a 13% increase in CAB frequency from October–December and a two-week delay in the climatological CAB breakdown date by the end of the twenty-first century (Howard and Washington, 2020). The CAB is therefore central to both present early-summer rainfall variability and to projections of future change.

While the term "Congo Air Boundary" or "Zaire Air Boundary" was coined as early as the 1950s by regional forecasters and has since featured widely in descriptions of the regional climate (e.g., Nicholson, 1996; Dezfuli, 2017), the CAB itself has received relatively little attention in scientific literature. This means that many aspects of the feature are poorly understood. Table 1.1 summarises published work on the CAB to date. Collectively, this literature establishes the CAB as a key feature of the regional hydroclimate, outlines a climatology, and demonstrates its importance to both rainfall seasonality and projections of future change. However, it points to substantial knowledge gaps, particularly regarding the structure and circulation of the atmosphere at the CAB, its relationship to the rain belt, and the processes that govern its maintenance and breakdown.

Table 1.1: A summary of climate literature published on the CAB. Data sources include reanalyses (ERA-Interim and ERA5 from the European Centre for Medium-Range Weather Forecasts, NCEP2; National Centers for Environmental Prediction Reanalysis 2, JRA-55: Japanese 55-year Reanalysis), satellite observations (TRMM; Tropical Rainfall Measuring Mission, CHIRPS: Climate Hazards Group Infrared Precipitation with Stations), and in situ observations (SASSCAL; Southern African Science Service Centre for Climate Change and Adaptive Land Management). Additional abbreviations: ITCZ; Intertropical Convergence Zone, GCM; General Circulation Model, CMIP; Coupled Model Intercomparison Project.

Reference	Contributions	Data
Hills, 1979	Descriptive climatology.	Pilot balloons, weather stations
Torrance, 1979	Descriptive climatology.	Pilot balloons, weather stations
Levin et al., 2009	Demonstrate that the CAB separates Indian Ocean moisture from continental transpired moisture.	Isotopic analysis
Nicholson, 2018	Argue that the CAB is distinct from the ITCZ.	ERA-Interim
Howard and Washington, 2019	Reanalysis-based climatology; hypothesise role of the heat low in CAB maintenance.	ERA5, SASSCAL weather stations
Howard and Washington, 2020	Show that GCMs reproduce the seasonal cycle of CAB and that future drying over southern Africa is linked to delay in CAB breakdown.	CMIP5
Longandjo and Rouault, 2020	Suggest CAB in East Africa is located at the foot of the rising branch of zonal overturning in the Congo Basin.	ERA-Interim, NCEP2 and JRA-55
Moses et al., 2023	Relate annual cycle of southern African dry spells to Botswana High and CAB; demonstrate CAB is associated with north-west to south-east gradient in dry spell and hot day frequency.	ERA5, CHIRPSv2, drought and vegetation indices
Worden and Fu, 2025	Investigate seasonal rainfall characteristics north of the CAB.	ERA-5, TRMM

A major contributing factor to these knowledge gaps is a lack of *in situ* observational data. The early descriptive climatologies of Hills (1979) and Torrance (1979) used a small number of pilot balloon observations across central and southern Africa to diagnose the presence of a discontinuity between low-level north-westerlies and easterlies in the southern Congo ($\sim 10^\circ\text{S}$) from August to November. However, until very recently, no radiosondes had been released in proximity to the CAB, and the present-day surface station network in the region is extremely sparse. Recent studies have therefore typically relied on modelled data and reanalyses, but there is a large degree of uncertainty as to whether these datasets can accurately resolve the atmosphere at the southern African tropical edge. This hinders the development of theory not only about the CAB itself, but also of broader questions concerning rain belt seasonality and future change.

The Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (2021–2025) has recently established the first detailed *in situ* measurements of the CAB. Through a field campaign comprising dual-site, high-temporal-resolution upper-air soundings, LiDAR observations, and a network of automatic weather stations, the DRY-CAB project sampled surface conditions and vertical atmospheric profiles in proximity to, and across, the CAB dryline and convergence zone. These observations constitute the first direct sampling of the thermodynamic and kinematic structure of the atmosphere at the CAB, detailing aspects of the feature that have previously only been inferred from models and reanalyses.

These novel observations form the foundation of this thesis, which draws on data from the DRY-CAB field campaign to characterise, for the first time, the vertical structure and circulation of the atmosphere at the CAB. In doing so, the thesis seeks to identify the processes that maintain the CAB and then to use these insights to investigate the large-scale mechanisms governing its breakdown. The thesis additionally aims to evaluate how faithfully the CAB is represented in reanalysis datasets,

providing clarity on the adequacy of reanalyses at the southern African tropical edge through austral spring. Together, this analysis seeks to provide a more complete basis for understanding a key feature of the tropical-edge atmosphere and to clarify its relationship to the tropical rain belt from August to November.

In the following section (Section 1.2) the CAB is placed within the context of the seasonal cycle of rainfall and the mean-state circulation of southern Africa. Subsequently, the main data sources used to investigate the southern African climate system are reviewed, namely atmospheric observations (Section 1.3) and models and reanalyses (Section 1.4). Limitations and challenges associated with these data sources are discussed, highlighting the unique opportunity provided by field observations from DRY-CAB. The aims of the thesis are subsequently outlined in Section 1.5, followed by a description of the thesis structure and organisation in Section 1.6.

1.2 Climate of the southern African tropical edge

1.2.1 Definition and study area

Southern Africa is defined here as the continental region of Africa south of the Congo Basin (approximately 10°S), extending longitudinally from the Atlantic coast of Angola, Namibia, and South Africa ($\sim 10^{\circ}\text{E}$) to the Indian Ocean coast of Mozambique ($\sim 40^{\circ}\text{E}$). We omit Madagascar as the CAB, the focus of this thesis, is a continental circulation feature. Under this definition, southern Africa comprises South Africa, Lesotho, Eswatini, Namibia, Botswana, Mozambique, Zimbabwe, Angola, Zambia, Malawi, and the southern part of the Democratic Republic of Congo (DRC).

The climate of this region stretches from equatorial rainforest at its northern edge, through humid subtropical and semiarid climates in the south-west (Beck et al., 2018). A unifying characteristic is a unimodal rainfall regime with peak rainfall occurring during the austral summer from October to March, with the exception of

the Western Cape of South Africa, which experiences a winter rainfall regime.

Within southern Africa, this thesis focuses specifically on the tropical margin, or "tropical edge". This region receives some of the highest rainfall totals in southern Africa, with annual accumulated rainfall in excess of $1000 \text{ mm year}^{-1}$ (Munday et al., 2025). The tropical edge is conventionally defined as spanning latitudes between 10° and 20°S and includes Angola, Zambia, Malawi, northern Mozambique, northern Botswana, and northern Zimbabwe (Figure 1.2; hatched).

Since this thesis focuses on the CAB, the study area is further refined by considering both the climatological position of the CAB and the sensitivity of October–November rainfall to its presence or absence. We quantify rainfall sensitivity to the CAB through contrasting the odds of rainfall exceeding a 1 mm day^{-1} threshold when the CAB is absent versus when it is present (Figure 1.2). Rainfall that is independent of CAB occurrence yields an odds ratio approaching 1, with values significantly above 1 indicating a strong enhancement of rainfall likelihood in the absence of the CAB.

Figure 1.2 shows that the CAB preferentially forms during October and November across eastern Angola, north-western Zambia, and the southern DRC. A broad area southeast of this climatological position exhibits strong rainfall sensitivity to CAB presence: across much of central southern Africa, the likelihood of a rainy day during October and November is approximately 10 times higher when the CAB is absent. Regions exhibiting particularly strong sensitivity include south-eastern Angola, Zambia, Zimbabwe, northern Botswana, and central Mozambique. This sensitivity is largely confined to the 10° – 22°S latitudinal band and is zonally restricted between approximately 16° and 35°E . Rainfall in northern Mozambique ($> 35^\circ\text{E}$), north-eastern Angola ($< 16^\circ\text{E}$) and to the south of 22°S is not sensitive to CAB presence, with precipitation in these areas associated with rainfall-producing systems that occur independently of CAB presence.

The primary study area of this thesis therefore encompasses the southern African tropical edge between 10° – 22° S and 16° – 35° E. This includes both the region in which the CAB forms in October and November, and the area to its southeast where the CAB exerts a large control on early-summer rainfall. It is worth explicitly noting that, unlike some authors (e.g., Longandjo and Rouault, 2020; Worden and Fu, 2025), this thesis does not consider the extension of the CAB into East Africa, where the feature becomes more meridional in orientation.

1.2.2 Rainfall climatology

1.2.2.1 Seasonal cycle

The seasonal cycle of rainfall over the African continent is primarily modulated by the migration of the relatively zonally symmetric and meridionally confined tropical rain belt (Figure 1.3), a broad region of high column-integrated moisture and convective precipitation that migrates north and south across the continent following the annual migration of the solar zenith (orange dashed; Giannini et al., 2008; Dunning et al., 2016; Hart et al., 2019). This rain belt is analogous to, and is sometimes referred to as, the Intertropical Convergence Zone (ITCZ), although this is not strictly accurate over Africa as during austral summer the convergence of near-surface winds from the northern and southern hemispheres remains north of the equator (Leroux, 2001; Nicholson, 2018).

The migration of the tropical rain belt leads to distinct regional rainfall regimes across the African continent. Its northward displacement from June–August gives rise to the West African monsoon (Sultan and Janicot, 2003), while in Central and East Africa, the twice-yearly passage of the rain belt around the equinoxes results in a bimodal rainfall regime with maxima from September–November and March–May. The southward displacement of the rain belt from December–February accounts for the unimodal seasonal cycle of rainfall over southern Africa with an austral sum-

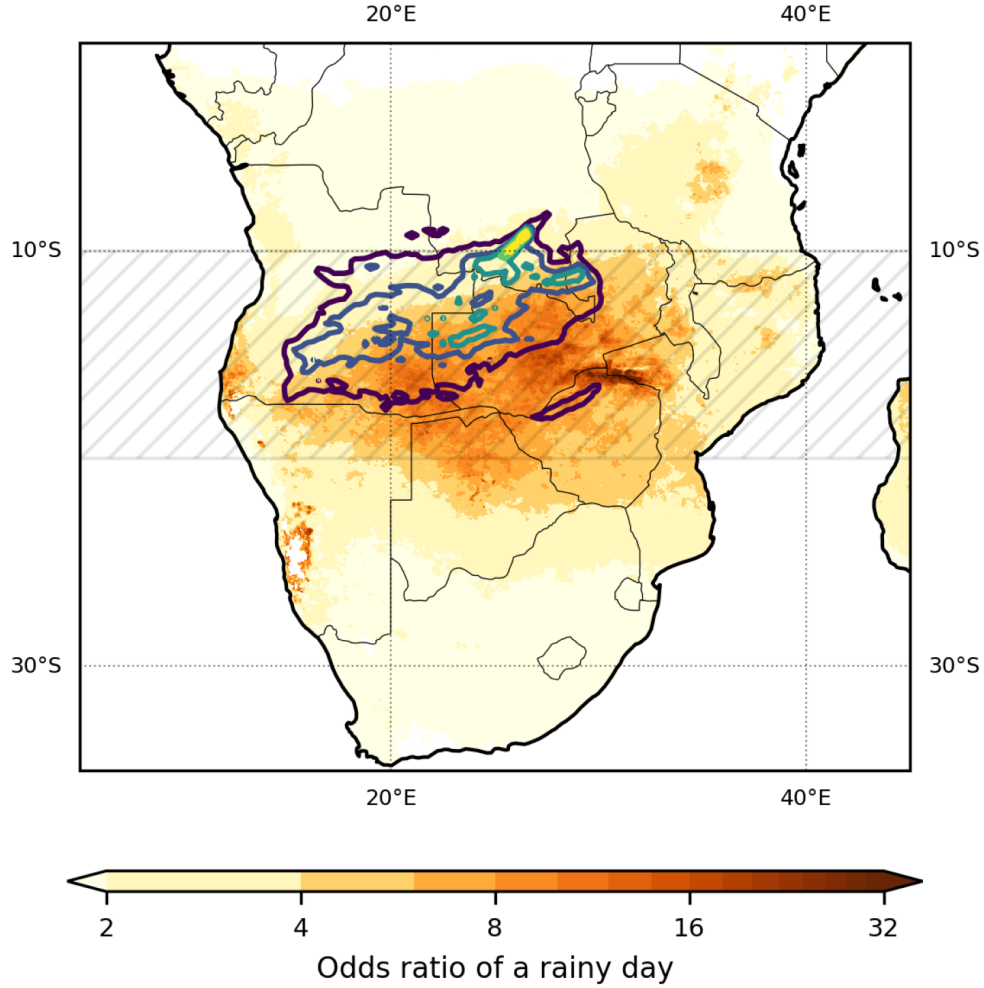


Figure 1.2: The odds ratio of a rainy day (defined as $> 1 \text{ mm day}^{-1}$) in October and November given the absence of the CAB, calculated in CHIRPSv2 daily data from 1981–2018. Contours show the per-gridcell October–November CAB dryline frequency of occurrence [% of days], based on the Howard and Washington (2019) detection algorithm applied to 1979–2018 ERA5 2 m specific humidity; contours are drawn at 0.5–4.5% in 1% intervals. The tropical edge, typically defined as spanning 10–20°S, is hatched.

mer rainfall maximum (Figure 1.3). The transition from a bimodal to a unimodal rainfall regime occurs at approximately 7°S near 20°E, shifting equatorward to approximately 4°S near 30°E (Dunning et al., 2016).

Across the African continent south of the equator, rainfall is highest in the bimodal regime of the southern Democratic Republic of the Congo (0°–7°S), where mean annual totals reach approximately 1550 mm year^{−1}. In the areas characterised by a single summer rainy season, the highest rainfall totals are found across the ‘tropical edge’ between 10° and 20°S (Angola, Zambia and northern Mozambique), where mean annual accumulations range from 1000 to 1100 mm year^{−1}. In contrast, the lowest rainfall totals occur in the Namib Desert, where mean annual precipitation is less than 100 mm year^{−1} (Munday et al., 2025).

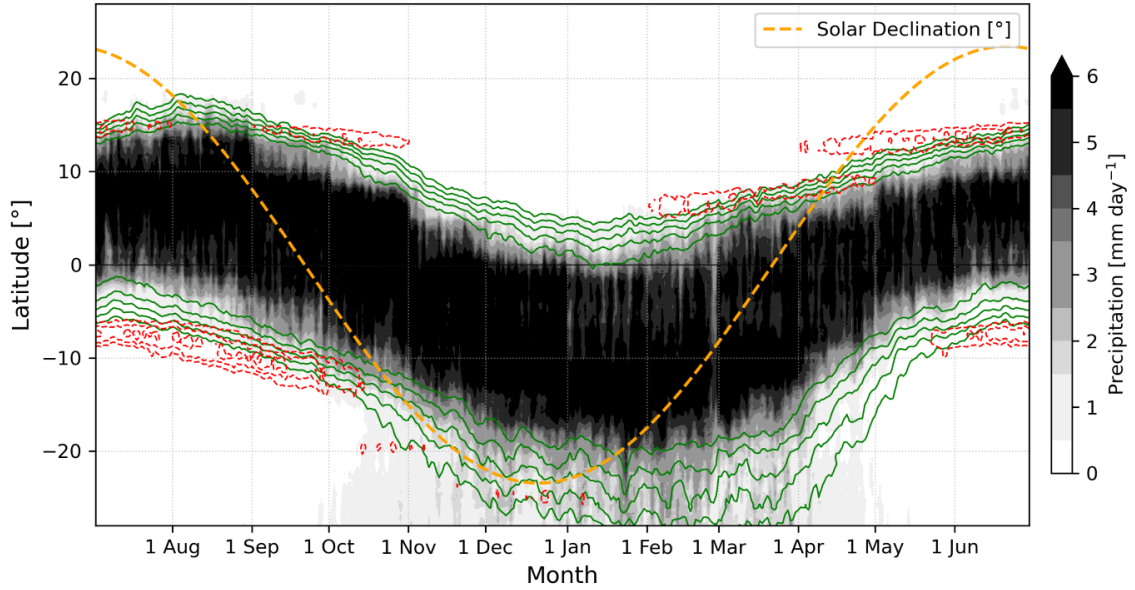


Figure 1.3: Annual cycle of precipitation [mm day^{−1}] by latitude (starting 1 July) for the period 1981–2018. Precipitation is from the CHIRPS v2 dataset. Green contours denote ERA5 specific humidity at 850 hPa, plotted at 1 g kg^{−1} intervals from 8 to 12 g kg^{−1}. Red contours indicate ERA5 horizontal convergence at 850 hPa, plotted at 0.3 × 10^{−5} s^{−1} intervals for values > 0.5 × 10^{−5} s^{−1}. The solar declination angle is shown by the orange dashed line. All fields are averaged zonally over 18–28°E.

1.2.2.2 Rainfall onset

The southward migration of the tropical rain belt from August to November gives rise to the onset of the summer rains over southern Africa. However, in contrast to the gradual climatological migration of the tropical rain belt implied by Figure 1.3, rainfall onset over southern Africa in any given year typically occurs abruptly. This is associated with the loss of a sharp meridional moisture gradient at the southern African tropical edge (the CAB), which is accompanied by a rapid southward shift in deep convection and the latitude of the rain belt.

The timing of this abrupt transition is highly variable year-to-year, with onset date standard deviations exceeding 30 days across parts of the tropical edge (Hachigonta et al., 2008; Mupangwa et al., 2011; Dunning et al., 2016; Byakatonda et al., 2018; Manhique et al., 2023). Such variability poses a major challenge for livelihoods and socio-economic viability across subtropical southern Africa, underscoring the importance of a comprehensive understanding of the dynamical processes governing the onset of the summer rains. Despite this, knowledge of the circulation features that modulate the southward progression of the tropical rain belt toward southern Africa between August and December remains limited. One such feature is the CAB (Figure 1.1).

1.2.3 The Congo Air Boundary

As the rain belt migrates southward from its August position north of the equator, its southern edge is thought to be demarcated by the Congo Air Boundary (CAB; Figure 1.1), a pronounced meridional gradient in low-level moisture, co-located with a maximum in near-surface convergence (Figure 1.3).

The CAB forms where near-saturated low-level north-westerlies originating from the equatorial eastern Atlantic and the Congo Basin converge with easterly trade winds from the tropical southwest Indian Ocean (Johnson, 1965; Hills, 1979; Torrance,

1979; Nicholson, 1996; Levin et al., 2009; Tierney et al., 2011; Dezfuli, 2017; Howard and Washington, 2019). As these easterlies traverse the heated continental interior, they dry substantially and are diluted by deep tropospheric subsidence (Howard and Washington, 2019). The resulting boundary is characterised by a sharp low-level moisture discontinuity that separates a moist, convectively active tropical regime to the north from a dry subtropical regime to the south (Torrance, 1979).

Early studies of the CAB were largely based on synoptic chart analysis and the accumulated forecasting experience of expert regional meteorologists in the pre-satellite era (e.g., Taljaard, 1953, 1972; Torrance, 1979; Hills, 1979). In this literature, the CAB was often identified through low-level convergence alone. Some authors have therefore described the CAB as persisting through austral summer and acting as a preferred corridor for the westward propagation of tropical lows (Taljaard, 1986; van Heerden and Taljaard, 1998). However, convergence at the tropical edge is substantially weaker and less coherent beyond November (Figure 1.3; Howard and Washington, 2019).

This thesis follows recent literature in defining the CAB using a more restrictive criterion, whereby the CAB is identified as a coherent synoptic-scale dryline and/or convergence feature present on daily (weather) timescales. Howard and Washington (2019) demonstrate that these conditions are met primarily during austral spring, consistent with Figure 1.3. This definition reflects the role of the CAB in separating moist tropical air from dry subtropical air between August and November, and underpins its common interpretation as demarcating the southern edge of the tropical rain belt. However, the precise nature of this relationship remains uncertain, with an open question as to whether the CAB is truly coincident with the southern margin of the rain belt (Torrance, 1979; Howard and Washington, 2019), or instead poleward-displaced as suggested by Leroux (2001).

The abrupt onset of the summer rains across subtropical southern Africa, described

in Section 1.2.2.2, is closely linked to the breakdown of the CAB, which occurs contemporaneously with the rapid southward advance of convection and the tropical rain belt. CAB breakdown heralds a reconfiguration of low-level moisture fluxes across southern Africa, whereby Congo north-westerlies penetrate further southward and subtropical easterlies are no longer dried by heating and subsidence, allowing the western Indian Ocean to act as a moisture source (D’Abreton and Lindesay, 1993; Rapolaki et al., 2020). While the CAB may reform following breakdown during early spring, this typically does not occur beyond November, marking the permanent transition to a post-onset summer rainfall regime characterised by widespread moist convection.

Recently, Howard and Washington (2019) established an objective climatology of the CAB dryline and convergence zone in ERA5 using a novel image processing algorithm. They showed that the CAB migrates southward from August to November at an average rate of approximately 2° of latitude per month, while its detection frequency decreases over the same period such that the feature is largely absent by December (Figure 1.4). They further demonstrated a strong statistical link between the CAB and rainfall variability, with interannual variability in CAB latitude and frequency explaining at least 55% of August–December rainfall variability over southern Africa between 15° and 25°S .

The characteristics and variability of the CAB are therefore closely associated with both rainfall onset and early-summer interannual variability across the southern African tropical edge. However, despite its importance, the CAB itself has received relatively little attention in scientific literature, leaving key unresolved questions regarding the CAB’s structure and circulation, the ability of models to faithfully reproduce the CAB, and the large-scale mechanisms associated with CAB breakdown. Addressing these questions is the primary focus of this thesis.

The remainder of Section 1.2 serves to place the CAB within the context of the

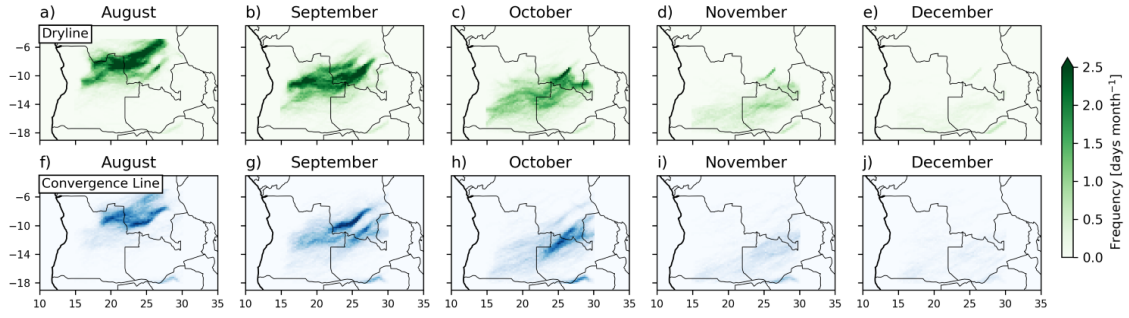


Figure 1.4: A monthly climatology (1979-2018) of the CAB a-e) dryline and f-j) convergence line spatial distribution in ERA5. CAB dryline (convergence line) grid cells are detected by applying the canny-edge detection algorithm of Howard and Washington (2019) to ERA5 2m specific humidity (100m zonal and meridional winds). Units are frequency per grid cell per month, with the convergence-line colourbar scaled identically to the dryline colourbar.

pre-onset (September-November; Section 1.2.4) and post-onset (December-February; Section 1.2.5) regional circulation, as well as in relation to tropical edge rainfall variability (Section 1.2.6), observed trends, and projections of future change (Section 1.2.7). In support of this, Figure 1.5 provides a schematic overview of the pre-onset and post-onset mean-state circulation of southern Africa.

Given the extensive literature describing the southern African climate system, emphasis here is placed on circulation features that are most relevant to later analysis – readers seeking a more comprehensive treatment are referred to the reviews of Tyson and Preston-Whyte (2000), Reason (2017), and Munday et al. (2025).

1.2.4 The September-November (pre-rainfall onset) mean-state circulation

This section describes the mean-state circulation of the tropical edge from September to November, prior to rainfall onset, documenting the background environment in which the CAB forms. Key circulation features including heat lows, mid-tropospheric anticyclones, low- and mid-level jets, and the midlatitude westerlies are reviewed.

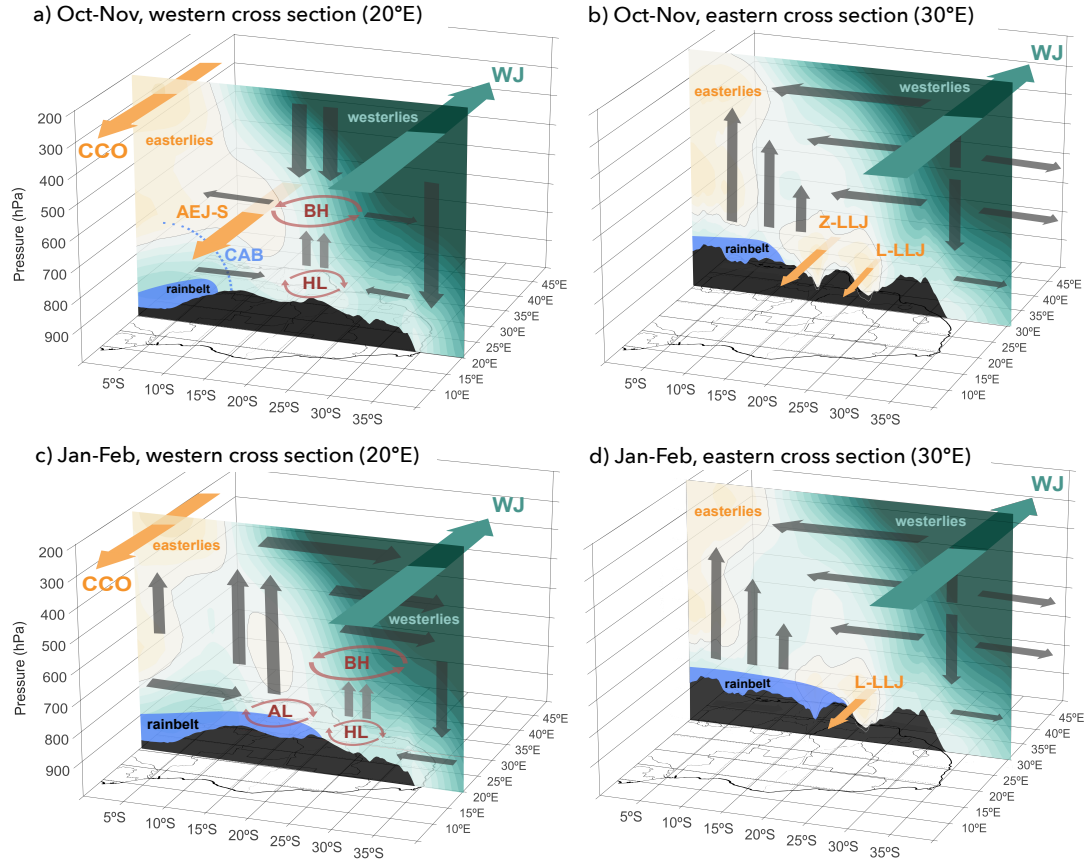


Figure 1.5: Schematic of key circulation features over southern Africa. The left column (a,c) shows a schematic latitudinal cross section at 20°E, the right column (b,d) shows a latitudinal cross section at 30°E. The top row (a,b) is for before tropical-edge rainfall onset (October-November), and the bottom row is for after tropical-edge rainfall onset (January-February). AL: Angola Low, BH: Botswana High, CCO: Congo Convective Outflow, HL: Heat Low, WJ: westerly jet. Reproduced from Munday et al. (2025).

1.2.4.1 Heat lows

The pre-onset circulation at the tropical edge is shaped by strong surface heating and large-scale subsidence, which gives rise to a heat low. Heat lows, also termed thermal lows (and indicated ‘HL’ in Figure 1.5), are regions of low pressure in the lower troposphere that develop in response to intense surface heating under large-scale subsidence and clear-sky conditions. They are associated with deep, dry convective boundary layers capped by a mid-level high and exhibit a pronounced diurnal cycle (Racz and Smith, 1999; Parker et al., 2005; Spengler and Smith, 2008; Attwood, 2024). During the day, heating establishes large-scale pressure gradients but low-level inflow is inhibited by strong turbulent mixing. At night, reduced boundary-layer turbulence and the development of a surface temperature inversion allows strong cyclonic inflow to develop toward the low-pressure centre.

Over southern Africa, a climatological heat low forms preferentially over southern Angola in September and October, extending eastwards across Zambia and the tropical edge and capped by the mid-level Botswana High (Figure 1.1; Attwood et al., 2024). At the daily scale, this climatological feature is composed of transient local pressure minima associated with strong cyclonic vortices (Howard and Washington, 2018). The heat low is therefore deeply embedded in the regional low-level circulation, establishing the pressure gradients that drive low-level flow across the subcontinent, including a west coast anabatic sea-breeze, nocturnal easterly low-level jets (Cook et al., 2004; Munday et al., 2021; Spavins-Hicks et al., 2021) and Congo north-westerlies. The strength and location of the heat low on weather timescales is likely to influence convergence at the southern edge of the tropical rain belt and, by extension, the location of the CAB, although the nature of the relationship between the two features on these scales is not fully understood.

Reanalysis-based diagnostics suggest that the heat low may contribute to maintaining the sharp moisture gradient at the CAB through nocturnal near-surface

moistening associated with cyclonic inflow toward the heat low followed by daytime near-surface drying associated with dry-convective mixing (Howard and Washington, 2019). This provides a potential mechanistic link between the location of the heat low, the Congo Air Boundary, and the tropical rain belt. However, the robustness of this hypothesis remains uncertain, as it relies on processes that are parameterised in reanalyses and occur in a region where lower-tropospheric observations are sparse.

1.2.4.2 Botswana high

The Botswana High, indicated ‘BH’ in Figure 1.5, is a semi-permanent mid-tropospheric anticyclone at approximately 500 hPa over subtropical southern Africa. It is associated with large-scale subsidence and caps a heat low-related dry convective boundary layer over the continental interior (Reason, 2016; Moses et al., 2023). The Botswana High is analogous to the Bolivian High over South America and the Bilybara High over Western Australia (Reason, 2016), arising in response to latent heat release associated with deep convection over tropical southern Africa to the northeast (Lenters and Cook, 1997). Moses et al. (2023) show that the Botswana high shifts southward with the CAB from August to November, alongside the CAB-associated north-west to south-east gradient in dry spell and hot day frequency.

In research to date, the Botswana High has primarily been characterised using monthly-mean fields, typically via indices based on spatially averaged 500 hPa geopotential height (e.g., Driver and Reason, 2017; Moses et al., 2023). This means that both its manifestation on daily timescales and its relationship to the CAB are both poorly understood. However, observational evidence from the SAFARI-1992 field campaign suggests that the feature is associated with persistent mid-level subsidence inversions near 500 hPa, which limit vertical turbulent mixing associated with the heat low to approximately 3-4 km above the surface (Garstang et al., 1996). This capping inversion plays a key role in maintaining hot, dry boundary layer conditions over the interior plateau of southern Africa pre-onset (Moses et al., 2023).

1.2.4.3 African Easterly Jet South

The African Easterly Jet-South (AEJ-S) is a mid-tropospheric easterly jet centred near 650 hPa that can be understood as the thermal-wind response to the meridional temperature gradient between a dry subtropical regime over southern Africa and a moist convective regime in the Congo Basin (Nicholson and Grist, 2003; Kuete et al., 2020). The jet is most prominent from August to November, peaking in frequency during September and October when it is present on approximately 56% of days (Adebiyi and Zuidema, 2016).

The AEJ-S is linked to the heat low and the Botswana high, with the AEJ-S forming on the northern flank of the Botswana high. A strong jet is associated with an enhanced meridional temperature gradient and negative rainfall anomalies in the southern Congo (Kuete et al., 2020). The AEJ-S additionally influences the offshore stratocumulus cloud deck through the transport of biomass-burning aerosols toward the South Atlantic (Adebiyi and Zuidema, 2016; Ryoo et al., 2022; Tatro and Zuidema, 2025). However, outstanding questions remain regarding the role of the AEJ-S in southern Congo rainfall and its spatial and temporal relationship with other elements of the tropical-edge circulation, including the CAB. In particular, a purely thermal-wind explanation of jet maintenance does not fully explain the spatial preference of the AEJ-S over northern Angola and the western Congo Basin, to the northwest of the CAB, rather than symmetrically across the tropical edge.

1.2.4.4 Subtropical easterlies

The low-level circulation across much of eastern southern Africa pre-rainfall onset is characterised by subtropical easterlies. This easterly flow, originating from the western Indian Ocean, reaches the tropical edge in a substantially dried state, in part due to strong heating of the continental surface and dilution by deep tropospheric subsidence. This maintains low near-surface specific humidity to the south

of the CAB. Through austral spring, easterlies are driven by the large-scale pressure gradient established by the heat low and modulated by synoptic features such as the Mozambique Channel Trough and ridging anticyclones (Barimalala et al., 2020, 2021; Spavins-Hicks et al., 2021; Jury, 2023).

The subtropical easterlies exhibit a pronounced diurnal cycle, with large-scale flow suppressed by boundary-layer turbulence during the day and accelerating at night to form low-level jets (LLJs). Regional topography further organises this flow, with distinct LLJs developing within the Limpopo and Zambezi river valleys, where easterly winds are topographically channelled and accelerated (Munday et al., 2021; Spavins-Hicks et al., 2021; Barimalala et al., 2021).

1.2.4.5 Congo north-westerlies

The low-level circulation over the southern Congo Basin is characterised by north-westerly flow, which can be understood as the combination of distinct zonal and meridional components. This north-westerly flow provides the primary moisture source on the northern side of the CAB, originating in the equatorial east Atlantic and enriched by high evapotranspiration in the Congo Basin (Pokam et al., 2014).

The westerly component is driven primarily by zonal land-sea thermal contrasts between the equatorial Atlantic and the African continent, establishing a Walker-type circulation that is strongest during the March-May and September-November seasons when solar heating is most intense (Pokam et al., 2014). The northerly component of the flow is associated with the meridional pressure gradient between the Congo Basin and southern Africa, and frequently manifests as cyclonic inflow toward the southern African heat low through austral spring (Attwood et al., 2024).

1.2.4.6 Subtropical highs

Subtropical highs are semi-permanent anticyclonic pressure systems located near 30° latitude in both hemispheres, associated with the descending branch of the Hadley

circulation (Rodwell and Hoskins, 2001; Marshall and Plumb, 2008). Over southern Africa, the subtropical highs of primary importance are those over the adjacent oceans: the South Atlantic High (also referred to as the St Helena High) and the Mascarene High in the southwest Indian Ocean.

While often represented as broad, coherent systems in climatological means, subtropical highs typically manifest on daily timescales as discrete high-pressure cells whose position and intensity are frequently modified by passing midlatitude disturbances. The subtropical highs play a key role in the low-level circulation, with easterly geostrophic flow along the northern flank of the Mascarene High constituting the trade winds of the southwest Indian Ocean (Jury and Nkosi, 2000). In contrast, low-level flow from the South Atlantic High recurves near 5°S under land-sea temperature gradients to become low-level westerlies in the Congo (Pokam et al., 2014).

1.2.4.7 Midlatitude westerlies

The upper-tropospheric circulation south of approximately 15°S is dominated by midlatitude westerlies. These westerlies are strongest just south of the southern African continent ($35\text{--}40^{\circ}\text{S}$), and variations in jet latitude and strength have important consequences for the regional climate, influencing the propagation of midlatitude disturbances, the occurrence of tropical-extratropical interactions and vertical shear (Lindesay, 1988; Hart, Washington and Reason, 2018).

Two upper-level westerly jets are typically identified: a subtropical jet associated with the poleward transport of angular momentum by the Hadley circulation, and a polar jet that is primarily eddy-driven through momentum flux convergence by transient baroclinic waves (Held, 1975; Held and Hou, 1980). The relative position and strength of these jets modulate the atmospheric waveguides along which Rossby waves propagate, influencing the likelihood of midlatitude disturbances interacting with the subtropics (Hoskins and Ambrizzi, 1993; Wirth et al., 2018; Hart, Wash-

ington and Reason, 2018). Compared to the Northern Hemisphere, the Southern Hemisphere flow is more zonally symmetric, with weaker stationary wave structures due to reduced land-sea contrasts (Mo, 1986; Trenberth, 1991; Robertson and Mechoso, 2003).

1.2.4.8 Rainfall-producing systems

With the CAB in place, rainfall-producing systems are largely absent from the tropical edge. However, several rainfall-producing systems are associated with rainfall north and south of the tropical edge region. To the north, rainfall in the Congo Basin is associated with mesoscale convective systems (MCSs) that may be modulated by tropical disturbances such as eastward propagating Kelvin waves (Nguyen and Duvel, 2008; Dong and Washington, 2025). To the south, rainfall is associated with midlatitude systems such as cut-off lows and ridging highs (Favre et al., 2013; Ndarana and Waugh, 2010).

1.2.5 The January-February (post-rainfall onset) mean-state circulation

The transition to a post-rainfall onset circulation regime is characterised by a fundamental reorganisation of the tropical-edge circulation following the breakdown of the CAB. Many of the defining features of the pre-onset circulation are lost or modified, while new circulation features and rainfall-producing systems emerge.

1.2.5.1 Circulation features lost

A defining feature of the transition from a pre-onset to post-onset circulation regime is the breakdown of the CAB. The loss of the CAB is associated with a reconfiguration of the regional circulation and the establishment of a moist convective regime over southern Africa as moisture limitation and subsidence inhibition to the south of the former CAB position is lost (Howard and Washington, 2019). The transition

to austral summer is also associated with the loss of the AEJ-S, which forms on fewer than 10% of days beyond December (Adebiyi and Zuidema, 2016).

1.2.5.2 Circulation features modified

Following rainfall onset, the heat low shifts south-westward from its October–November position across southern Angola and the tropical edge to the Kalahari Desert (Attwood et al., 2024). The Botswana High similarly shifts south-westward to remain south of the rain belt, expanding zonally to form part of a broader anticyclonic ridge extending from the South Atlantic across southern Africa to the western Indian Ocean (Driver and Reason, 2017; Moses et al., 2023).

The transition to a post-onset circulation regime is characterised by a reconfiguration of low-level moisture fluxes over southern Africa. As subsidence over southern Africa is replaced with ascent, moisture fluxes embedded within low-level easterlies increase markedly, enabling the southwest Indian Ocean to act as a major moisture source for the continental interior (D’Abreton and Lindesay, 1993; Vigaud et al., 2009; Munday and Washington, 2018). North-westerly flow from the Congo Basin provides another major moisture source for the southern African interior during austral summer (Vigaud et al., 2009), associated with cyclonic inflow toward moist low-pressure systems linked to tropical lows, which climatologically aggregate to form the Angola Low (Howard and Washington, 2018).

1.2.5.3 Circulation features gained

Post-onset, the tropical edge region, previously characterised by a heat low, becomes dominated by deep moist convection and the passage of tropical lows that typically track from east to west between approximately 12° and 20°S (Taljaard, 1953; Howard et al., 2019). Orographic influences, including the effects of an anabatic sea breeze along the Angolan coast, act to slow and stall these systems over Angola. This leads to the development of a climatological low-pressure system known as the Angola

Low, indicated ‘AL’ in Figure 1.5 (Zunckel et al., 1996; Mulenga, 1999; Munday and Washington, 2017; Howard and Washington, 2018).

The eastern edge of the heat low over the Kalahari marks the limit of moist easterly flow into the subcontinent (Taljaard, 1986; Tyson and Crimp, 1998), which leads to north-west to south-east orientated drylines to the east of the heat low. These drylines, referred to as the Kalahari Discontinuity, are present on over two-thirds of summer days (Howard and Washington, 2019; van Schalkwyk et al., 2022).

Austral summer is also characterised by the emergence of the South Indian Ocean Convergence Zone (SIOCZ), a diagonally oriented band of low-level convergence and enhanced precipitation extending from central southern Africa southeastward (Streten, 1975; Cook, 2000). The SIOCZ is analogous to the South Atlantic and South Pacific Convergence Zones, though it is generally weaker and more intermittent (Kodama, 1992; Cook, 2000). Synoptically, the SIOCZ is expressed through the preferential formation of tropical-extratropical cloud bands.

1.2.5.4 Rainfall producing systems

Post-onset, a range of rainfall-producing systems contribute to precipitation across the southern African tropical edge. These systems include cloud bands, tropical lows, mesoscale convective systems (MCSs), tropical cyclones, and midlatitude disturbances.

Cloud bands, sometimes referred to as tropical-temperate troughs (TTTs), are diagonally oriented cloud features linking tropical convection with midlatitude disturbances (Harrison, 1984; Hart et al., 2013). Cloud bands require upper-level forcing from the subtropical jet and sufficient low-level moisture, conditions that are met only once the CAB has broken down (Todd and Washington, 1999; Hart et al., 2010; Macron et al., 2014).

Tropical lows are cyclonic vortices that typically form over land in the tropical edge

region between approximately 12° and 20°S and propagate westward during the austral summer (Taljaard, 1953; Tyson and Preston-Whyte, 2000; Howard et al., 2019). They are most prevalent during December-February and contribute to between 30% and 70% of December-February tropical edge rainfall (Howard et al., 2019).

Other rainfall-producing systems include mesoscale convective systems (MCSs), tropical cyclones and midlatitude disturbances. MCSs are particularly important over the Congo Basin, Angola, Mozambique, and eastern South Africa where they contribute to intense rainfall and the mesoscale organisation of convection (Houze, 2004; Zipser et al., 2006; Blamey and Reason, 2012; Morake et al., 2021; Dong and Washington, 2025). Midlatitude influences, including ridging highs and cut-off lows, also contribute to austral summer rainfall toward the southern margin of the tropical edge (Favre et al., 2013; Ndarana and Waugh, 2010). Lastly, tropical cyclones originating over the southwest Indian Ocean only rarely penetrate inland, but can produce severe rainfall impacts when they do (Mavume et al., 2010).

1.2.6 Rainfall variability

Rainfall over the southern African tropical edge exhibits substantial variability on both high-frequency (sub-seasonal) and low-frequency (interannual) timescales. This variability is an important component of the regional climate system but is not a focus of this thesis, so it is summarised only briefly here to provide context.

On sub-seasonal timescales, austral-summer rainfall is modulated by a range of high-frequency modes of variability of both tropical and midlatitude origin. Tropical modes of variability include equatorial Kelvin waves, westward-propagating tropical lows and the Madden-Julian Oscillation (MJO; Madden and Julian, 1994), while midlatitude influences typically manifest as tropical-extratropical cloud bands. These modes influence the organisation and intensity of convection and contribute to variability in sub-seasonal rainfall totals (Liu et al., 2022).

On interannual timescales, rainfall variability at the tropical edge arises from interactions between large-scale climate modes and the regional circulation. The El Niño-Southern Oscillation (ENSO) represents the dominant source of interannual variability, with El Niño events typically associated with drier-than-average austral summers and La Niña events favouring wetter conditions (Lindesay, 1988; Maphugwi et al., 2025). These impacts are highly event-dependent and strongly modulated by regional circulation features such as the Angola Low and Botswana High (Reason and Jagadheesha, 2005; Blamey et al., 2018). Recent literature has additionally underscored the importance of both ENSO flavour (Blamey and Reason, 2023; Blamey et al., 2018) and event duration (Thoithi et al., 2025, 2026) on circulation, rainfall and temperature impacts across southern Africa. ENSO-rainfall relationships are strongest from December-February and weaker from September-November, with no documented link to the timing of rainfall onset (Nicholson and Kim, 1997; Reason and Jagadheesha, 2005; Moeletsi et al., 2011).

Additional sources of interannual variability arise from sea surface temperature anomalies in the Indian and Atlantic Oceans. The Indian Ocean Dipole (IOD) is associated with enhanced rainfall along the eastern coast of southern Africa through September-November, while positive phases of the Subtropical Indian Ocean Dipole (SIOD) are associated with enhanced moisture transport from the southwest Indian Ocean and increased summer rainfall totals (Behera and Yamagata, 2001; Reason and Mulenga, 1999; Reason, 2001, 2002). Extratropical variability also contributes, with key modes of variability including the Southern Annular Mode (SAM) and zonal stationary wave patterns. Many of these modes are interlinked; for example, certain midlatitude stationary wave patterns associated with ENSO influence the probability of tropical-extratropical interactions and therefore tropical-edge rainfall (Hart, Washington and Reason, 2018; Kim et al., 2024).

Overall, rainfall variability across the tropical edge reflects the combined influence

of tropical and extratropical climate modes acting across multiple timescales and mediated by regional circulation features. How these modes interact with the CAB, particularly in relation to its breakdown and the timing of rainfall onset, remains poorly understood.

1.2.7 Observed and projected change

Multiple studies report significant warming across the southern African tropical edge in austral spring, with rates accelerating in recent decades (Jury, 2013; MacKellar et al., 2014; Engelbrecht et al., 2015; Engdaw et al., 2022). Munday et al. (2025) identify a warming hotspot in October over Angola and Zambia where warming rates over the past four decades have reached up to $0.9 \text{ K decade}^{-1}$, approximately three to four times the global mean rate. Alongside this warming, there is an emerging signal of rainfall decline in October, with statistically significant rainfall decreases of up to $0.5 \text{ mm day}^{-1} \text{ decade}^{-1}$ across six rainfall datasets at the tropical edge (Munday et al., 2025). However, the robustness of a drying trend is impacted by strong interannual to interdecadal variability (Dieppois et al., 2016), differences among observational products and declines in rain-gauge coverage (Maidment et al., 2015).

These observed trends are consistent with projections of future change. Southern Africa is one of the few land regions globally for which climate models show consistent agreement on future declines in rainfall (He and Soden, 2017; Ranasinghe et al., 2023). This drying signal is strongest and most robust from October to December, and has persisted across successive generations of climate models from CMIP3 through CMIP6. Under high-emissions scenarios, CMIP6 ensemble projections indicate reductions in rainfall of up to approximately 11 mm month^{-1} by the end of the twenty-first century in October and November, with weaker declines in December (Munday et al., 2025). These projected changes are reproduced in regional climate models and convection-permitting simulations, indicating a robustness across mod-

elling frameworks (Engelbrecht et al., 2009; Pinto et al., 2016; Kendon et al., 2019; Kennedy-Asser et al., 2026).

Several studies link this early-summer drying to a delay in rainfall onset (Shongwe et al., 2009; Dunning et al., 2018), and Howard and Washington (2020) have shown that in CMIP5 models a delay to rainfall onset is associated with a northward shift in CAB latitude and a 13% increase in CAB frequency from October to December, leading to a two week delay to climatological CAB breakdown by the end of the 21st century in CMIP5 RCP8.5 simulations (Howard and Washington, 2020). A more persistent CAB inhibits the southward penetration of moisture-bearing northerlies from the Congo Basin and maintains dry subtropical easterlies, delaying the establishment of a moist convective regime over southern Africa and the start of the summer rains.

While climate change is not a focus of this thesis, the role of the CAB in projections of delayed rainfall onset, together with its proximity to (and possible involvement in) warming and (emerging) drying trends, provides strong motivation for investigating the processes governing its maintenance and breakdown.

1.3 Observations of the atmosphere

Observations of the atmosphere through both routine observations and dedicated field campaigns provide the empirical foundation for understanding the southern African climate system. In this section, the availability of observations at the southern African tropical edge is reviewed, with an emphasis on how observational scarcity constrains understanding of key features of the tropical edge atmosphere such as the CAB. This assessment highlights the unique opportunity afforded by observations from the DRY-CAB campaign to advance understanding of the regional climate.

1.3.1 Routine observations

A major constraint on climate research over southern Africa, and particularly the tropical edge, is the scarcity of routine atmospheric observations. Africa has the sparsest climate-observing system of any inhabited continent, reflecting a combination of long-standing political instability, logistical challenges associated with maintaining stations in remote regions, and limited institutional prioritisation of meteorological infrastructure (Washington et al., 2013; James et al., 2018).

Across subtropical southern Africa (5–25°S), the density of surface automatic weather stations (AWS) reporting to the Global Telecommunication System (GTS) over the past decade has averaged approximately one station per 38,000 km², with a highly uneven spatial distribution. AWS coverage is relatively dense in South Africa and Zimbabwe (Figure 1.6), but declines sharply northwest of the Zambia-Zimbabwe border. Across much of the tropical edge, surface observations are exceptionally sparse, and data availability is further reduced by station downtime, with many stations reporting on less than 30% of days. As a result, large contiguous regions remain effectively unmonitored. Notably, the total number of AWS reporting to GTS between 5°S and 25°S has remained essentially unchanged over the past four decades, with declines in several key tropical-edge countries, including Zambia and Angola (James et al., 2018; Harris et al., 2020).

Observations through the depth of the troposphere are even more limited (Figure 1.7). The number of radiosonde measurements from 5–25°S has declined markedly since 1990, with the Integrated Global Radiosonde Archive (IGRA) documenting a four-fold decrease in radiosonde observations from 1981-1990 to the most recent decade (2015-2024; Figure 1.7). Across the vast majority of the tropical edge, routine upper-air observations of winds, temperature, and humidity are entirely absent (Figure 1.7b).

This lack of routine observational data hinders the characterisation of key features

of the low-level circulation, including but not limited to the CAB. While Howard (2019) used the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) station network to examine the surface expression of the CAB using eight AWS across Angola and Zambia, the limited spatial coverage of these stations restricted analysis to only surface thermodynamic variables evaluated as a function of distance from the CAB. In combination with the complete lack of routine upper-air soundings in proximity to the CAB, existing routine observations are therefore unable to address major outstanding questions concerning the structure and circulation of the atmosphere at the CAB and the processes associated with its maintenance and breakdown.

1.3.2 Field campaigns

A second source of empirical data for understanding the climate system is intensive field campaigns, often targeted at key circulation features or regions. By concentrating intensive, coordinated observations over limited regions and time periods, such campaigns enable direct investigation of atmospheric processes that cannot be captured by sparse networks of routine observations.

Across Africa, such campaigns have delivered significant advances in understanding of regional climate processes. In West Africa, for example, projects including HAPEX (Goutorbe et al., 1994), JET2000 (Thorncroft et al., 2003), AMMA (Redelsperger et al., 2006), and DACCWA (Knippertz et al., 2015) have transformed understanding of monsoon dynamics. Similarly, the FENNEC campaign provided new insight into Saharan boundary-layer processes and dust-atmosphere interactions (Marshall et al., 2013; Todd et al., 2013). Targeted observations have also proven critical for resolving the structure and maintenance of other subtropical drylines such as in the U.S. Great Plains (Rasmussen et al., 1994; Weckwerth et al., 2004).

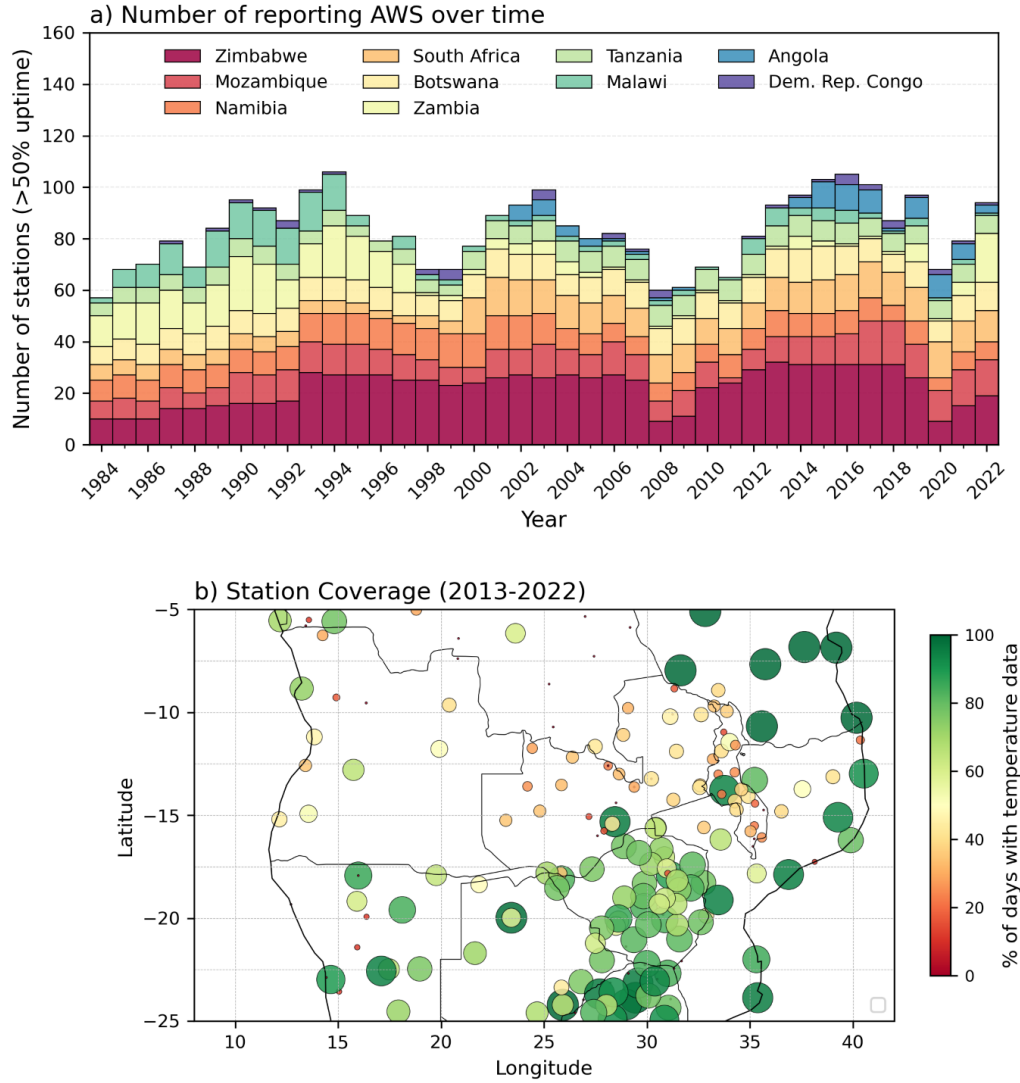


Figure 1.6: a) Time series of the number of automatic weather stations reporting 2-m air temperature to the Global Telecommunication System (GTS) with >50% data uptime across the southern African tropical edge 5–25°S from 1984 to 2022. Bars are coloured by country. b) Spatial distribution of station coverage across the southern African tropical edge (5–25°S), with size and colour indicating the percentage of days between 2013 and 2022 with available temperature observations. Data is from the Met Office Integrated Data Archive System (MIDAS).

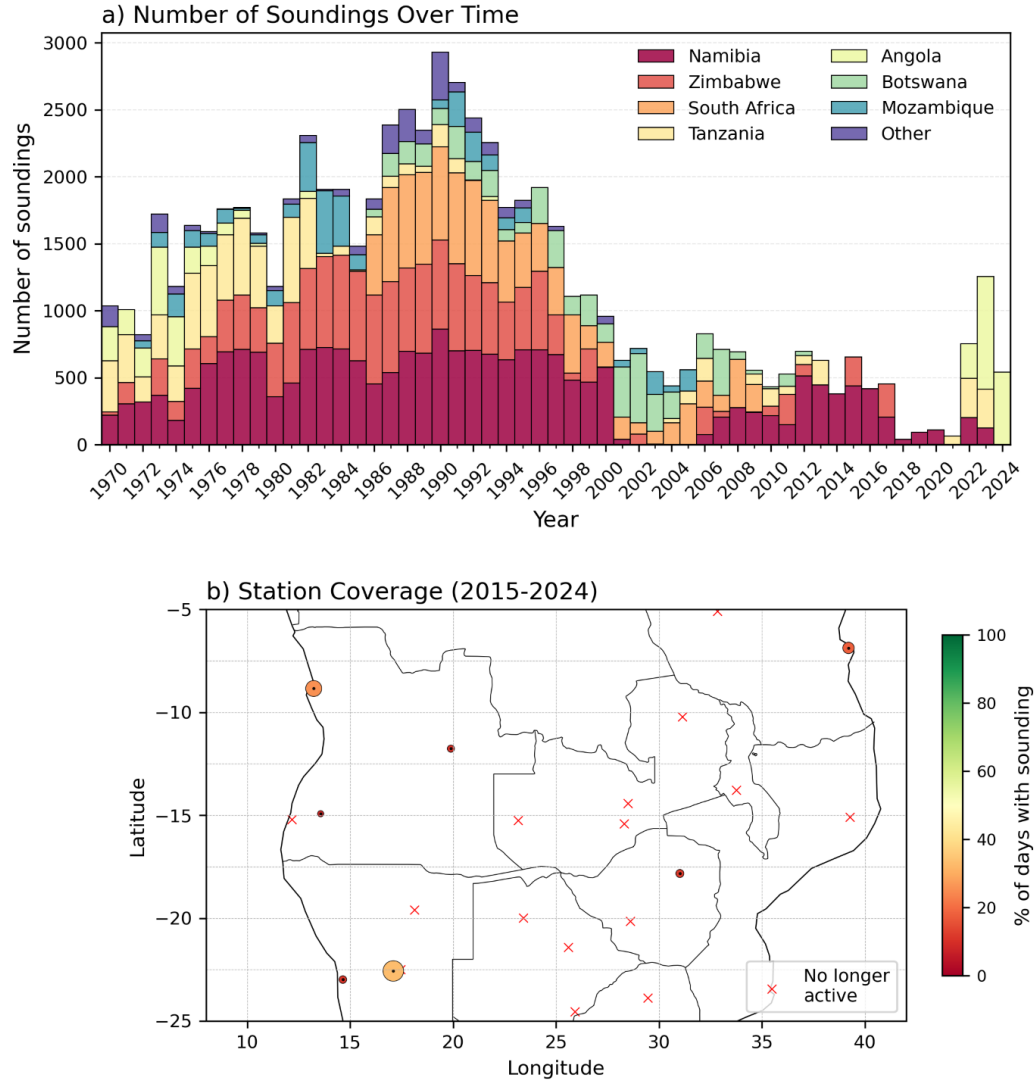


Figure 1.7: a) Time series of the number of radiosonde soundings across the southern African tropical edge (5–25°S) from 1970 to 2024, with bars coloured by country. b) Spatial distribution of radiosonde station coverage across the southern African tropical edge (5–25°S), with marker size and colour indicating the percentage of days between 2015 and 2024 with radiosonde soundings. A red cross marks the location of a radiosonde station that is no longer active. Data is from the Integrated Global Radiosonde Archive (IGRA), with pilot balloon ascents excluded.

In contrast, the few field campaigns to have taken place in southern Africa have largely focused on dry-season processes, particularly biomass burning and the west coast stratocumulus cloud deck. Major programmes such as SAFARI1992 (Lindesay et al., 1996) and SAFARI2000 (Swap et al., 2003), along with more recent campaigns including AEROCLO-SA (Formenti et al., 2019), CLARIFY (Haywood et al., 2021), and ORACLES (Ryoo et al., 2022) have yielded important insights into aerosol-cloud interactions and atmospheric composition but were not designed to investigate the regional circulation of the tropical-edge region.

The Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (2021–2025) has recently established the first *in situ* measurements of surface conditions and vertical atmospheric profiles in proximity to, and across, the CAB dryline and convergence zone as part of a targeted field campaign designed to capture CAB structure, circulation and diurnal evolution. These observations present a unique opportunity to address long-standing gaps in our understanding of the CAB. In particular, the high temporal resolution of the radiosonde and surface observations enables direct investigation of the diurnal modulation of the structure and circulation of the atmosphere across the CAB, providing a basis for investigating the mechanisms that maintain the dryline and govern its breakdown.

1.4 Models and reanalyses

Prior to the DRY-CAB campaign, the absence of routine upper-air observations and targeted field campaigns at the southern African tropical edge (Section 1.3) meant that numerical modelling and reanalyses provided the primary data source through which the CAB and the wider climate of the southern African tropical edge has been studied to date. Here, we review the uncertainties associated with the representation of the tropical edge atmosphere in these datasets.

1.4.1 Modelling challenges

The complex topography, circulation, and range of weather systems that characterise the tropical edge climate present a challenge for climate models. Accordingly, models exhibit variable skill in representing key features of the austral spring (September–November) circulation: the AEJ-S is systematically too weak (Adebiyi et al., 2023), and shallow convection associated with the heat low (Munday and Washington, 2018; Hart, Washington and Stratton, 2018) and low-level moisture fluxes in the Congo Basin (Creese and Washington, 2018, 2016) are poorly represented.

Although the climatological behaviour of the CAB is relatively well reproduced in climate models (Howard and Washington, 2020), there is a large degree of uncertainty regarding the mechanisms through which the CAB is produced, maintained, and broken down. Reanalysis-based diagnostics suggest that the maintenance of the CAB is tied to intricate mesoscale dynamics, including vertical turbulent moisture transport associated with dry convection in the heat low (Howard and Washington, 2019), but such processes are parameterised rather than explicitly resolved in models. Furthermore, some models exhibit little to no mid-tropospheric subsidence over southern Africa from September to November (Hart, Washington and Stratton, 2018), which has been suggested to be essential for the maintenance of dry conditions to the south of the CAB (Howard et al., 2019). This raises the possibility that essential processes bound up in the formation, maintenance and breakdown of the CAB in the real atmosphere may be absent or misrepresented. Without means to evaluate the representation of the CAB in models, confidence in CAB-associated outputs, such as projections of a delay to rainfall onset, are undermined.

1.4.2 Reanalyses

Given the limitations of free-running models, many studies have relied on reanalyses to investigate the tropical-edge climate. Reanalyses combine historical observations

with a fixed numerical weather prediction model and data assimilation system to produce temporally consistent, sub-daily estimates of the atmospheric state. They assimilate both conventional observations (e.g., surface stations, radiosondes, aircraft data) and satellite-derived datasets. Across the tropics, satellite data provides the dominant source of constraint, particularly microwave radiance measurements (Samrat et al., 2025).

In well-observed regions, or when considering large spatial and temporal scales, reanalyses are tightly constrained by assimilated observations. As a result, different products tend to agree closely in large-scale circulation fields despite differences in model physics, assimilation schemes, and assimilated observations. In contrast, in observation-sparse regions such as subtropical southern Africa (Section 1.3), reanalyses are weakly constrained, particularly in the lower troposphere. While satellite observations provide large-scale and upper-level constraints, reanalyses rely heavily on their modelled components near the surface (Podglajen et al., 2014; Roffe and van der Walt, 2023). This means their representation of low-level circulation features may be subject to similar errors as those in free-running models arising from modelling choices and parameterisation schemes. This is of particular concern for the CAB, where the mesoscale processes hypothesised to maintain the dryline are parameterised (Howard and Washington, 2019).

To manage these uncertainties, many studies adopt a multi-reanalysis approach, treating agreement between products as a proxy for fidelity. However, no study to date has systematically assessed the representation of the CAB across different reanalysis products. Moreover, similar resolutions and parameterisation choices mean that inter-product agreement is not necessarily a robust indicator of fidelity.

Observations from the DRY-CAB field campaign provide a unique opportunity to address these uncertainties for the first time. The DRY-CAB dataset comprises high-frequency, *in situ* measurements of the lower-tropospheric structure and circu-

lation at the CAB that are independent of the data assimilation process, thereby representing a robust out-of-sample test of reanalyses (Graham et al., 2019). These observations enable an evaluation of the representation of the CAB and its constituent features across multiple reanalysis products, addressing questions of their adequacy for climate research at the southern African tropical edge through austral spring.

1.5 Thesis aims

The Congo Air Boundary (CAB) is a key feature of the southern African tropical-edge atmosphere from August to November, associated with both present-day early-summer rainfall variability and future projections of drying. However, the preceding literature review has highlighted that the structure and circulation of the atmosphere at the CAB, its representation in reanalyses, and the large-scale mechanisms associated with its breakdown are poorly understood. This thesis addresses these knowledge gaps, drawing on novel *in situ* observations collected during the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (2021–2025), reanalyses and satellite datasets.

The DRY-CAB project has recently established the first detailed *in situ* measurements of the CAB, providing an opportunity to characterise the vertical structure and circulation of the atmosphere at the CAB in observations for the first time. This motivates the first aim of this thesis:

Aim 1. Diagnose the structure and circulation of the Congo Air Boundary using *in situ* observations.

This aim characterises the thermodynamic structure and circulation of the atmosphere at and across the CAB, including gradients in moisture and stability and the depth and diurnal evolution of moist Congo north-westerlies and dry subtropical

easterlies. Through this analysis, a conceptual model of the atmosphere at the CAB is developed.

Field observations from DRY-CAB, together with the conceptual model developed under Aim 1, provide an empirically grounded benchmark for assessing how faithfully the CAB is represented in reanalyses. This leads to the second aim of this thesis:

Aim 2. Evaluate the representation of the Congo Air Boundary in reanalyses.

Work under this aim evaluates the representation of key features of the atmosphere at the CAB in reanalyses during the DRY-CAB campaign, addressing uncertainty in reanalysis fidelity at the southern African tropical edge during austral spring.

With an improved understanding of the structure of the CAB and the processes that maintain it, a major outstanding question concerns the large-scale mechanisms associated with its breakdown. This motivates the third and final aim of the thesis:

Aim 3. Characterise the large-scale mechanisms associated with the breakdown of the Congo Air Boundary.

This aim diagnoses the large-scale mechanisms associated with the breakdown of the CAB, and the associated reorganisation of the tropical-edge atmosphere to a moist convective regime, complementing the understanding of CAB maintenance developed under Aim 1.

Together, these three aims provide a new, empirically grounded perspective on the structure and circulation of a defining feature of the tropical-edge atmosphere, its representation in reanalyses, and the processes governing its maintenance and breakdown.

Through this analysis, the thesis seeks to provide insight into the nature of the relationship between the CAB and the tropical rain belt, and the adequacy of reanalyses for investigating tropical edge climate dynamics through austral spring. It additionally seeks to highlight the value of targeted field campaigns for advancing

understanding of regional climate dynamics and their representation in numerical models.

1.6 Thesis outline

This thesis is presented as a thesis by publication. The main results take the form of research articles which have been submitted to peer-reviewed journals. Each paper is presented as a separate chapter, prefaced by a foreword and afterword which explain how each paper contributes to achieving the aims of this thesis. The discussion section synthesises results and the relationships between the separate manuscripts. The papers that comprise this thesis, their journals, and publication status at the time of submission are as follows:

Knight, C., Washington, R., Munday, C., Hart, N., Nkonde, E., Imbwae, F., Kasongo, W. (2025). Observations of the atmosphere across the Congo Air Boundary.

- Submitted to *Journal of Climate* on 28 January 2026.
- Comprises thesis Chapter 3.

Knight, C., Washington, R., Munday, C., Nkonde, E., Imbwae, F., and Kasongo, W. (2026). Evaluation of the Congo Air Boundary in reanalyses during the 2022 DRY-CAB field campaign.

- Submitted to *Journal of Climate* on 07 February 2026.
- Comprises thesis Chapter 4.

Knight, C., & Washington, R. (2024). Remote Midlatitude Control of Rainfall Onset at the Southern African Tropical Edge. *Journal of Climate*, 37(8), 2519–2539. <https://doi.org/10.1175/JCLI-D-23-0446.1>

- Published in *Journal of Climate* on 22 March 2024.
- Comprises thesis Chapter 5.

1.6.1 Thesis format

This section outlines how each of the following chapters contributes to the thesis.

Chapter 2 describes the datasets and methodological approaches that underpin the thesis. It introduces the DRY-CAB project, under which the observational data that underpins Chapters 3 and 4 and was collected. It also provides a high-level summary of the various techniques and methods employed throughout the thesis, including the objective detection of the CAB in reanalysis data, composite analysis, and process-based model evaluation.

Chapter 3 addresses the first aim of the thesis, drawing on upper-air and surface data from the DRY-CAB field campaign to provide the first observational characterisation of the structure and circulation of the atmosphere at the CAB. The chapter establishes the CAB as a sharp dryline and convergence zone forming at the interface of two air masses shaped by distinctive thermodynamic and circulation regimes, and reveals how this structure and circulation evolves through the diurnal cycle. The chapter synthesises these findings into a conceptual model which accounts for CAB structure, diurnal modulation, and maintenance. In doing so, it provides new insight into the mesoscale structure and circulation of the atmosphere at the data-scarce southern African tropical edge.

Chapter 4 addresses the second aim of this thesis by evaluating the representation of the CAB in three reanalyses. The chapter applies a process-based evaluation methodology, underpinned by the conceptual model built in Chapter 3, to evaluate whether reanalyses successfully reproduce the key features that comprise the CAB during the DRY-CAB field campaign. This reveals that reanalyses exhibit substantial errors in the CAB’s mesoscale structure and circulation, particularly to the north of the CAB where moisture availability and transport differ substantially between reanalyses. The chapter highlights reanalysis limitations across the southern African tropical edge and provides insight into model weaknesses and priorities

for future development.

Chapter 5 addresses Aim 3 of this thesis by investigating the large-scale mechanisms associated with the breakdown of the CAB. Breakdown is shown to occur over timescales of 3-5 days and to be frequently associated with disturbances originating in the midlatitudes. These disturbances reshape vertical motion, low-level flow, and mid-level moisture-flux divergence across the tropical edge, eroding the CAB and facilitating a transition to a moist convective regime. The chapter provides an explanation for CAB breakdown that is rooted in the synoptic-scale weather processes that bring the first rains to the tropical edge, with implications for the predictability of rainfall onset and theory linking the extratropics to the seasonal cycle of tropical rainfall.

Chapter 6 synthesises the findings of the thesis and reflects on the broader themes that emerge from the analysis. It begins by summarising the main results and evaluating how the aims set out in Chapter 1 have been fulfilled, before discussing their broader implications. In particular, the chapter reflects on the relationship between the CAB and the tropical rain belt, drawing on insights from across the thesis. The chapter develops a novel conceptual model of the large-scale circulation across central Africa when the CAB is present, and argues that the CAB should be conceptualised as poleward-displaced from the rain belt. The chapter also considers the implications of the results for the predictability of rainfall onset, the adequacy of reanalysis products at the southern African tropical edge, and identifies key open questions and priorities for future research. It concludes by drawing together the thesis's main contributions.

1.6.2 A note on manuscript order of inclusion

The order in which the manuscripts appear in this thesis differs from the sequence in which they were originally drafted and submitted. This is a deliberate choice made

to favour the structure and narrative of the thesis over the chronology of the research process. The thesis is organised to present a progression of ideas and analysis across scales: from the local-to-mesoscale features comprising the CAB through to the large-scale mechanisms associated with its breakdown.

In terms of publication chronology, the manuscript that comprises Chapter 5 was drafted and submitted first, followed by that comprising Chapter 3 and then Chapter 4. This means that while Chapters 3 and 4 build sequentially and have continuity of ideas and citations, Chapter 5 was written without knowledge of the results of the preceding two chapters. This unavoidably introduces discontinuity in ideas, emphasis, and citations. To address this, an afterword in Chapter 5 reflects on the chapter's results in light of the insights that emerged in Chapters 3 and 4. Chapter 6 provides a further opportunity for a synthesis of results that integrates the contributions of all three manuscripts. This ensures that the thesis forms a cohesive and logically connected body of work, despite being presented in an order that differs from the research process.

1.7 Authorship declaration

For all three manuscripts that constitute the thesis, I have conducted all the analysis and writing. Supervisors Richard Washington and Callum Munday discussed results, methodology and paper structure with me, and commented on the drafted manuscripts. They also discussed responses to reviewer comments through the peer review process on the manuscript that comprises Chapter 5. Edson Nkonde, Felix Imbwae and Wallace Kasongo were fundamental to the collection of field data during the DRY-CAB project and are accordingly acknowledged as co-authors in the manuscripts that underpins Chapter 3 and 4. Neil Hart commented on a draft of the manuscript that underpins Chapter 3 and made key contributions to the development and implementation of the DRY-CAB project, on which Chapters 3 and 4

of the thesis rely.

2 | Data and methods



Eland graze behind the Davis Vantage Pro2 automatic weather station installed at Nchila. 1 November 2022.

This chapter outlines the datasets and methodologies used in this thesis. The analysis presented in Chapters 3 and 4 draws on observational data from the DRY-CAB project, while Chapters 4 and 5 also incorporate data from reanalyses. Satellite observations and gridded rainfall products are used in support throughout. These datasets are described in Section 2.1.

The thesis also employs a combination of methodological approaches, including an image-processing algorithm to objectively detect the CAB (Howard and Washington, 2019), composite analysis, dynamical budgets, and process-based model evaluation. A high-level overview of these methods is provided in Section 2.2, with a more detailed description in the relevant chapters.

2.1 Data

2.1.1 DRY-CAB field campaign

2.1.1.1 Summary

The Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (2021–2025) has recently established the first detailed *in situ* observational dataset to date for the CAB. Here we describe this dataset, including details of field site selection, instrumentation, sampling strategy, and the division of the field data into meteorological phases. This complements the detailed overview of the project framework and rationale presented in Washington et al. (2026, in preparation).

The DRY-CAB project was funded by the UK Natural Environment Research Council (NERC; grant NE/V011928/1) and consisted of three main components:

1. A pilot field campaign in October 2021,
2. A main field campaign from September to November 2022, and
3. A suite of numerical model experiments.

The pilot field campaign involved 3-hourly radiosonde launches from a single field site in north-western Zambia between 06 UTC on 29 October 2021 and 06 UTC on 13 November 2021. Data from the pilot campaign and the numerical model experiments are not used in this thesis and are therefore not described further.

2.1.1.2 Field site selection

Field site selection for the main DRY-CAB field campaign was guided by analysis of historical forecast data and monthly climatologies of CAB location derived from the ERA5 reanalysis. CAB dryline and convergence-line positions were identified using the Canny-edge detection algorithm of Howard and Washington (2019). Figure 2.1 is therefore illustrative of the diagnostic approach used to identify optimal field site locations.

Radiosonde site selection was motivated by two primary objectives. First, to maximise the likelihood of sampling air masses in close proximity to the CAB. Second, to maximise the likelihood of simultaneously sampling air masses on either side of the CAB dryline and convergence zone.

With respect to the first objective, Figure 2.1 shows that the CAB migrates southward from August to October, with both dryline and convergence-zone CABs forming regularly over north-western Zambia in October, and less frequently in September. CAB frequency declines from September through December, suggesting that earlier sampling may be preferable. However, during August and September the CAB is typically located over the southern Democratic Republic of the Congo, where logistical and geopolitical constraints make fieldwork challenging. This identified north-western Zambia as the optimal region for deployment.

The second objective required the selection of a pair of field sites that maximised the probability of simultaneous dry-side and moist-side sampling. Analysis of CAB frequency along multiple candidate transects indicated that a north-west to south-east

axis was most favourable. ERA5 diagnostics suggest that a Ikelenge–Solwezi transect (red line) has a high likelihood of intersecting the CAB during October, when a dryline CAB intersects this transect on an average of 7.0 days and a convergence-zone CAB on 8.1 days (Figure 2.1)

In summary, ERA5 diagnostics and historical forecast data indicated that radiosonde sites located in proximity to Ikelenge and Solwezi provided a high likelihood of sampling (i) air masses in close proximity to the CAB and (ii) air masses simultaneously across the CAB dryline and convergence zone. Logistical constraints further refined the site selection to Nchila Wildlife Reserve (11.249°S , 24.327°E) and Solwezi Airport (12.171°S , 26.364°E). To complement these upper-air measurements, additional AWS were deployed along an approximate Ikelenge–Solwezi transect to capture finer-scale variations in surface meteorological conditions.

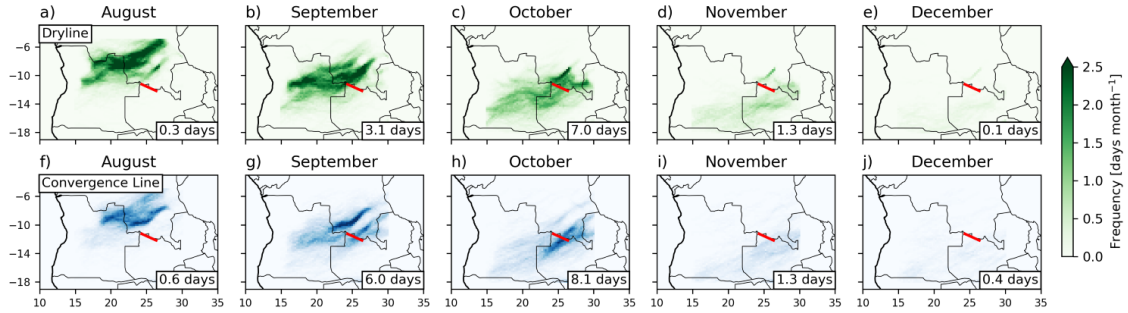


Figure 2.1: A monthly climatology (1979–2018) of the CAB a-e) dryline and f-j) convergence zone spatial distribution in ERA5. CAB dryline (convergence zone) grid cells are detected by applying the canny-edge detection algorithm of Howard and Washington (2019) to ERA5 2m specific humidity (100m zonal and meridional winds). Units are frequency per grid cell per month, with the convergence-line colourbar scaled identically to the dryline colourbar. A transect between Ikelenge and Solwezi is plotted in red. In the bottom right of each subplot, the average number of days per month the CAB intersects the transect is reported.

2.1.1.3 Sampling strategy

The main DRY-CAB field campaign comprised intensive radiosonde and surface observations from two sites in north-west Zambia through austral spring 2022.

Radiosonde supersites, equipped with radiosondes, an automatic weather station (AWS) and a Doppler LiDAR, were located at Nchila (11.249°S, 24.327°E) and Solwezi (12.171°S, 26.364°E) and supported by three additional AWS (Table 2.1). The Nchila and Solwezi supersites were located on the Katanga Plateau at an altitude of 1400 m ($\approx$ 859 hPa) and 1393 m ($\approx$ 861 hPa) respectively, with Solwezi 244.2 km to the east-southeast of Nchila. The locations of the field sites are shown in Figure 2.2 and Figure 2.3, with the latter also providing an overview of the instrumentation deployed at each site.

The schedule of observations through the field campaign is summarised in Table 2.1 and Figure 2.4. The first weather station was installed on 13 August 2022, with radiosonde sampling conducted between 22 September and 9 December 2022. The campaign featured a 44-day intensive observation period (IOP) from 1 October to 13 November 2022, during which radiosondes were released every three hours (eight launches daily) at 00, 03, 06, 09, 12, 15, 18, and 21 UTC from both Nchila and Solwezi. Throughout the IOP, all AWS and both LiDAR systems were operational.

Table 2.1: Schedule of observations during the DRY-CAB field campaign.

Instrument	Location	Date and time (UTC)	Temporal resolution	Notes
Radiosonde	Nchila 24.327°E 11.249°S	2022-09-22 12:00 – 2022-09-25 12:00	12-hourly	
		2022-09-25 18:00 – 2022-10-01 00:00	6-hourly	
		2022-10-01 03:00 – 2022-11-13 03:00	3-hourly	Extra: 2022-10-22 16:30
	Solwezi 26.368°E 12.171°S	2022-09-27 00:00 – 2022-09-30 00:00	12-hourly	
		2022-09-30 06:00 – 2022-10-01 00:00	6-hourly	
		2022-10-01 03:00 –	3-hourly	Missing:

Continued on next page

Table 2.1 – continued from previous page

Instrument	Location	Date and time (UTC)	Temporal resolution	Notes
		2022-11-15 06:00		2022-10-14 15:00, 2022-10-23 21:00, 2022-10-24 00:00, 2022-10-24 03:00, 2022-11-04 03:00, 2022-11-04 06:00, 2022-11-10 03:00, 2022-11-14 12:00, 2022-11-14 18:00
		2022-11-15 12:00 – 2022-11-21 18:00	6-hourly	
		2022-11-22 12:00 – 2022-12-09 12:00	Daily	
Automatic weather station	Nchila 24.327°E 11.249°S	2022-09-22 08:28 – 2022-11-12 08:17	1-minute	
	Solwezi 26.368°E 12.171°S	2022-08-13 10:50 – 2022-11-14 06:00	10-minute	Downtime > 6 hours: 2022-08-22 14:40 – 2022-08-23 01:00, 2022-09-27 15:00 – 2022-09-27 23:30
	Mwinilunga 24.432°E 11.734°S	2022-08-23 07:40 – 2022-11-13 08:10	10-minute	Downtime > 6 hours: 2022-08-24 09:30 – 2022-08-29 16:00, 2022-09-20 14:10 – 2022-09-26 21:00
	Zengamina 24.193°E 11.124°S	2022-09-27 12:40 – 2022-11-13 14:10	10-minute	
	Deovolente 25.902°E 12.340°S	2022-09-30 12:40 – 2022-11-11 06:50	10-minute	
LiDAR	Nchila (Sakeji) 24.312°E 11.234°S	2022-09-17 10:53 – 2022-11-12 13:18	6-second vertical retrievals, 10-minute horizontal winds	Downtime > 6 hours: 2022-10-20 17:51 – 2022-10-23 16:43
	Solwezi 26.368°E 12.171°S	2022-09-13 14:15 – 2022-11-14 08:04	3-second vertical retrievals, 15-minute horizontal winds	Downtime > 24 hours: 2022-10-13 05:19 – 2022-10-26 14:51, 2022-10-31 13:25 – 2022-11-01 17:56

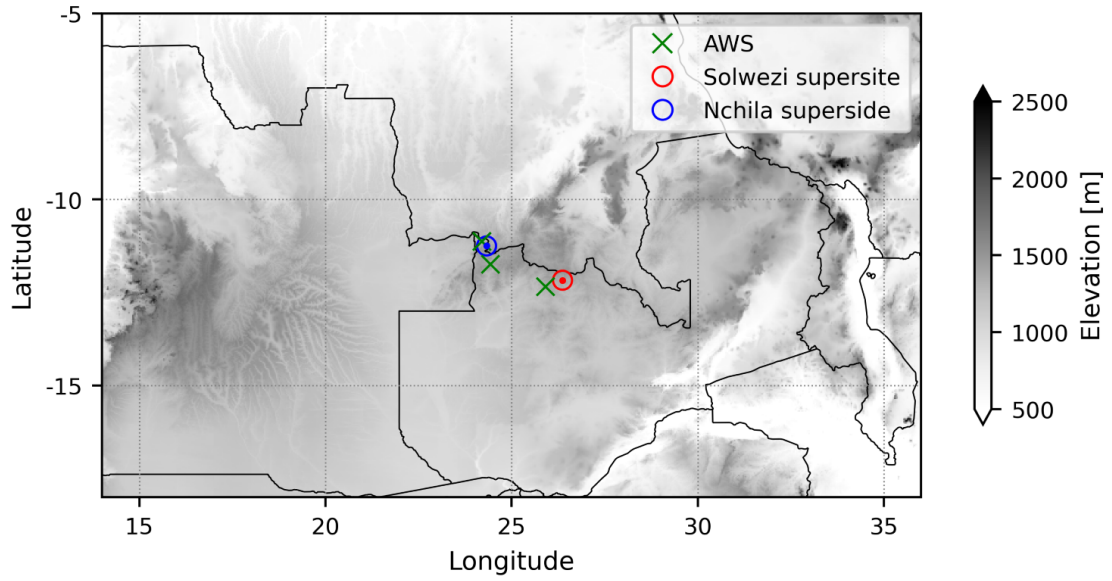


Figure 2.2: Location of the DRY-CAB project field sites. Green cross; automatic weather station (AWS) only sites; blue circle: Nchila radiosonde site with AWS and LiDAR; red circle: Solwezi radiosonde site with AWS and LiDAR. Surface elevation from the Global Multi-resolution Terrain Elevation Data 2010 is shaded.

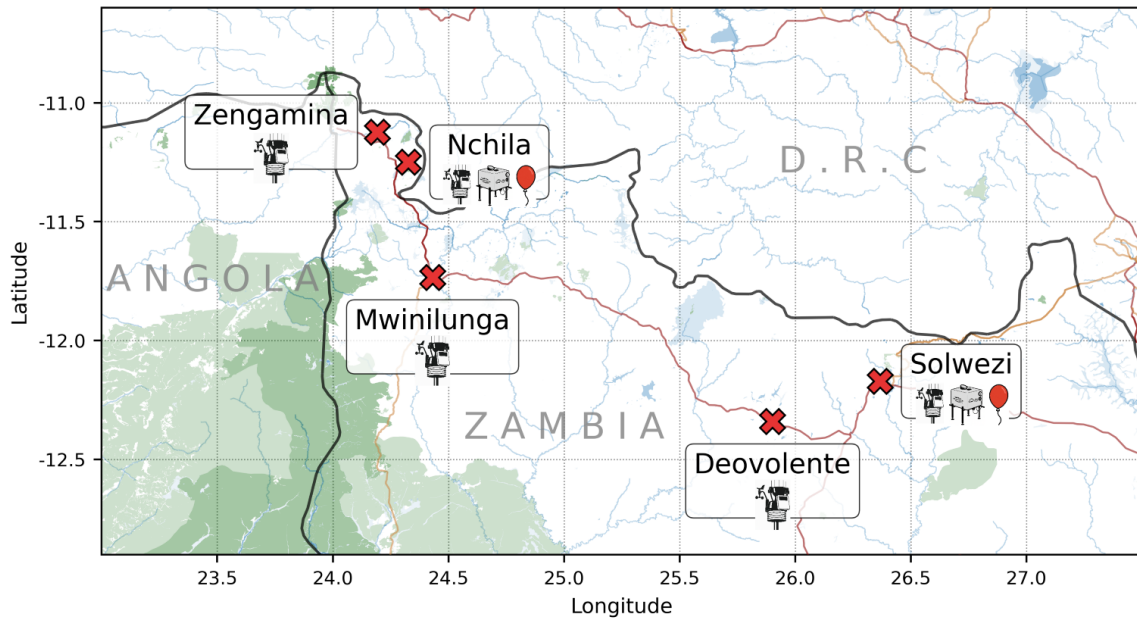


Figure 2.3: Schematic map of the DRY-CAB field campaign sites and instrumentation. Measurement sites are indicated by red crosses, while the instrumentation deployed at each site is denoted by icons of a red balloon (radiosondes), an automatic weather station and a LiDAR. Background features (roads, waterways, waterbodies and forested areas) are from OpenStreetMap (© OpenStreetMap contributors).

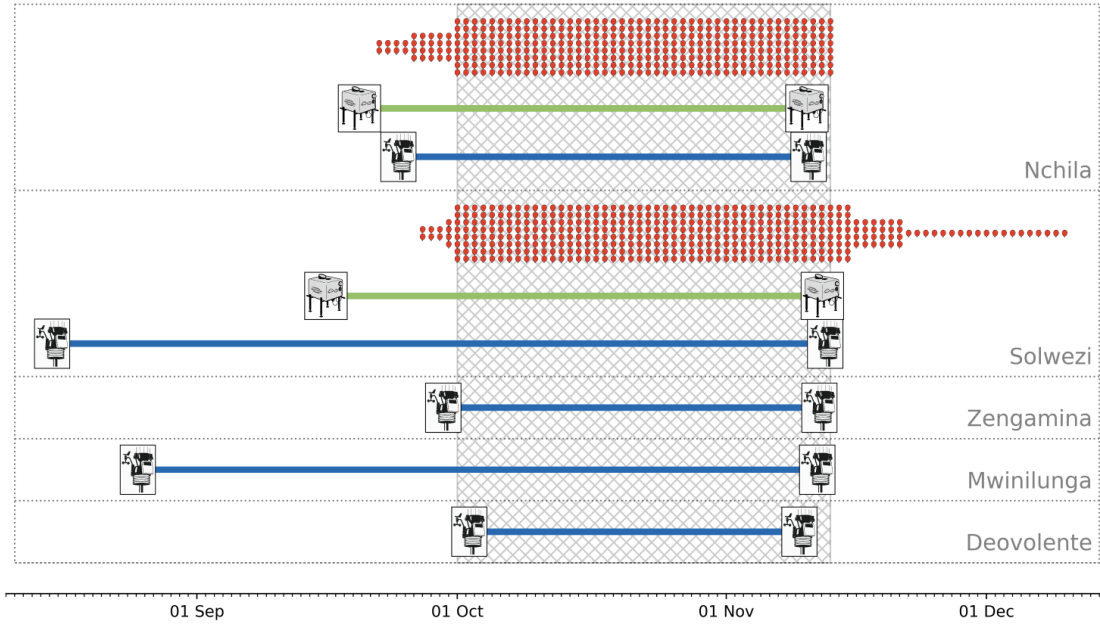


Figure 2.4: Timeline of DRY-CAB field campaign instrumentation deployment at each field site. Instrumentation is denoted by icons of red ballons (radiosondes), automatic weather stations (AWS) and a LiDAR. The project’s 44-day IOP, with a full suite of instrumentation and 8-daily radiosondes from Nchila and Solwezi, is indicated by hatching.

Table 2.2: Radiosonde ascent summary statistics during the field campaign IOP. Median ascent time and horizontal drift distance are reported as a function of elevation above the surface, with first and third quartiles also indicated. A boundary layer depth of ≈ 3.6 km corresponds to the approximate mean mid-afternoon ($\approx 14:00$ LT) mixed-layer depth.

Elevation above surface (km)	Time (min)			Distance (km)		
	Median	Q1	Q3	Median	Q1	Q3
1	5	5	6	1.4	0.9	2.3
3.6 (boundary layer)	18	16	20	5.9	4.2	7.7
5	25	23	27	7.4	5.1	10.0
10	49	46	53	8.5	4.8	13.4
15	73	68	79	14.3	9.5	20.2
16.7 (tropopause)	75	69	81	14.6	9.8	21.0

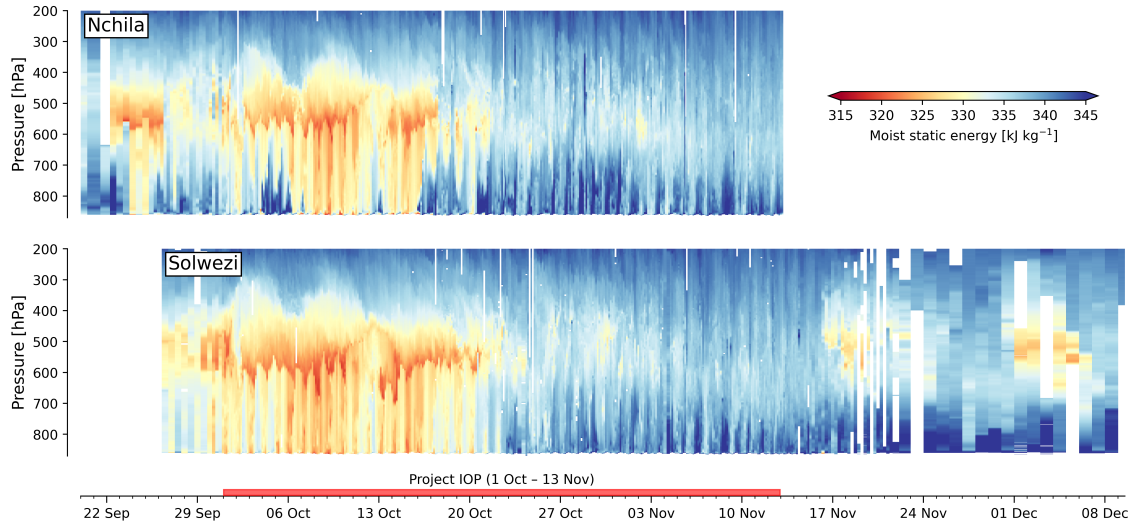


Figure 2.5: Hovmöller plot of MSE [kJ kg^{-1}] at Nchila and Solwezi during the DRY-CAB field campaign. The project IOP, from 1 October to 13 November and characterised by 8-daily radiosonde ascents from both sites, is indicated by a red bar.

2.1.1.4 Instrumentation

GRAW DFM-17 radiosonde

GRAW DFM-17 radiosondes were deployed at Nchila and Solwezi. The radiosondes measured temperature and humidity, and derived zonal and meridional wind components from Global Navigation Satellite System (GNSS) displacement. The pressure coordinate was modelled from GNSS elevation and AWS surface pressure.

The temperature sensor on a DFM-17 radiosonde is a heated resistive element designed to prevent icing and minimise time-lag, with a measurement range of -100 to $+60$ $^{\circ}\text{C}$, an accuracy of < 0.25 $^{\circ}\text{C}$, and a response time of < 0.6 s at 1000 hPa. Relative humidity is measured using a heated capacitive thin-film polymer sensor with $< 3\%$ uncertainty and a response time of 0.2 s at $+20$ $^{\circ}\text{C}$ (increasing to 10 s at -60 $^{\circ}\text{C}$). Winds are calculated from GNSS displacement, with the GNSS receiver providing horizontal position accuracy < 2.5 m, vertical accuracy < 10 m, and horizontal velocity accuracy < 0.1 m s^{-1} . The system transmits data at 1 Hz via a 400 – 406 MHz telemetry link.

Each radiosonde was attached to a helium-filled balloon inflated to a diameter of approximately 118 cm, suspended by a 30 m unwinder. Across the field campaign, average ascent time to the tropopause (≈ 16.7 km) was 75 minutes (interquartile range: 69 – 81 min), during which radiosondes exhibited a median horizontal drift of 14.6 km (9.8 – 21.0 km). The boundary layer (≈ 3.6 km) was sampled within the first 18 minutes of ascent. Further ascent statistics are summarised in Table 2.2.

Radiosonde data are used as output by the GrawMET software in the "*_Radiosonde-Data.txt*" report, in which ascent data is interpolated to 1 hPa vertical resolution. Data is subsequently quality controlled, but no further post-processing corrections or adjustments are applied. Radiosondes are known to exhibit a nighttime cold bias and daytime warm bias on the order ± 0.4 K due to radiation effects, which increases with altitude and solar elevation angle (Sun et al., 2013). We do not correct for this as our primary area of interest is the lower troposphere.

In addition, radiosonde temperature and humidity sensors can exhibit transient errors immediately after emerging from cloud due to "wet-bulb" effects associated with evaporation or sublimation of condensed water or ice on the sensor surface (Ingleby, 2017). This artefact is evident in some DRY-CAB radiosonde profiles as a brief, sharp decrease in temperature when the radiosonde exits regions of high relative humidity.

Davis Vantage Pro2 automatic weather station

Davis Vantage Pro2 automatic weather stations were deployed at the Nchila and Solwezi radiosonde sites and at three additional locations along an approximate Nchila-Solwezi transect (Zengamina, Mwinilunga and Deovolente; Figure 2.3). The AWS recorded at 10-minute resolution or greater and were installed at a height of approximately 1.5 m above ground level, preferably in open and exposed locations.

Each station continuously measured barometric pressure (accuracy ≈ 1 hPa), air temperature (PN-junction silicon diode; accuracy 0.3°C), relative humidity (film-

capacitor element; accuracy $\approx 2\%$), tipping-bucket rainfall (0.2 mm per tip), solar radiation, and wind speed and direction. Wind speed was obtained from a solid-state magnetic cup sensor (accuracy the greater of 0.9 m s^{-1} or 5%) and wind direction from a potentiometer wind vane reporting direction at 22.5° intervals. The radiation shield is passive (unaspirated), introducing a temperature error of $\approx 2^\circ\text{C}$ at solar noon under low wind conditions due to radiation effects, which we do not correct for (Davis Instruments, 2018).

Halophotonics Doppler LiDAR

Two Halophotonics Doppler LiDAR systems were deployed during the DRY-CAB project, with one installed at each radiosonde field site. The instruments provide continuous sensing of boundary-layer aerosol structure and wind by measuring aerosol backscatter and Doppler velocity from eye-safe laser pulses, enabling retrievals of vertical motion and horizontal wind components within the lower troposphere. This data is not used in this thesis.

2.1.1.5 Data quality control

For the radiosonde data, skew-T and altitude plots were manually inspected for each ascent. Clearly erroneous spikes in temperature and dewpoint profiles were identified, typically associated with weak signal reception between the radiosonde and the ground-station receiver. This issue particularly affected approximately one week of Nchila radiosonde launches, when strong upper-level westerlies meant line-of-sight signal transmission was disrupted in the latter half of ascents. In all such cases, affected data points were replaced with NaN values. A small number of ascents exhibited spurious wind measurements due to GPS errors, characterised by unrealistically high wind speeds or abrupt changes in wind speed with height. These instances were again manually identified and affected data points were replaced with NaN values.

In several Solwezi radiosonde ascents conducted after 14 November, the telemetry signal was intermittently lost and regained during ascent, causing the modelled elevation-pressure relationship in the GrawMET output to fail and resulting in incorrect pressure values being assigned to otherwise valid observations. In these cases, radiosonde elevation was converted to pressure using the IOP-mean elevation-pressure relationship.

AWS data required minimal quality control.

2.1.1.6 Division into meteorological phases

Figure 2.5 provides an overview of radiosonde observations from the Nchila and Solwezi field sites collected during the field campaign. The project IOP from 1 October to 13 November is indicated by a red bar. Significant changes to the thermodynamic structure of the atmosphere through time are evident. Substantial inter-site differences are also clear, particularly below 600 hPa.

To facilitate analysis of the field campaign data, the IOP has been divided into five distinct meteorological phases (Phases 1-5). These phases are defined according to the daily maximum in surface moist static energy (MSE) at Nchila and Solwezi. The use of daily maximum MSE follows theoretical and observational studies demonstrating that tropical convection is to first order governed by surface MSE (Neelin and Held, 1987; Nie et al., 2010). Additionally, Hart et al. (2019) have shown that near-surface MSE is a good diagnostic for identifying the location of deep convection over Africa.

The five phases are summarised in Table 2.3, and their distribution in MSE phase space (alongside a corresponding time series) is illustrated in Figure 2.6. Reanalyses indicate that the CAB is associated with sharp MSE gradients driven primarily by the latent component (Howard and Washington, 2019). Consequently, abrupt variations in near-surface MSE at the field sites are expected to reflect changes in

the position of the CAB relative to the field sites. This reasoning underpins the assignment of a "dry" or "moist" regime to each field site for Phases 1 through 4 (Table 2.3). The transition from Phase 4 to Phase 5 is distinguished by the date after which reanalyses indicate that CAB does not form. For Phase 5, "No CAB" is therefore assigned to each site.

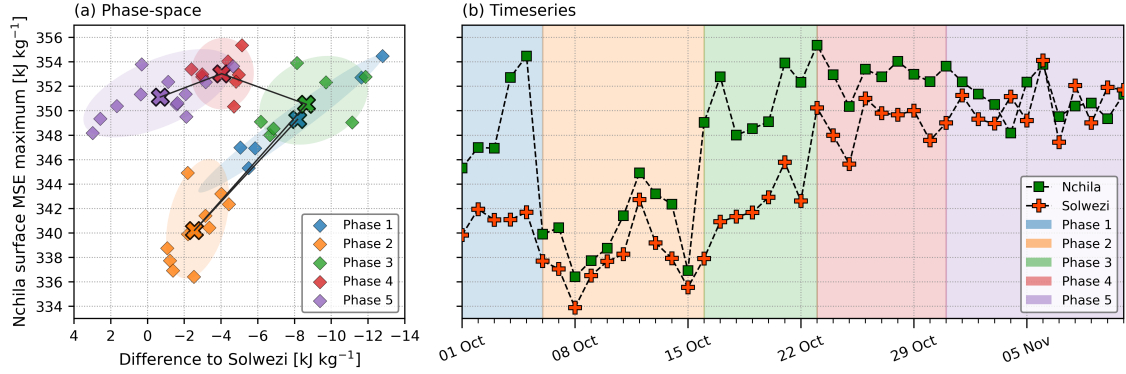


Figure 2.6: a) Phase-space plot of the 5 meteorological phases of the field campaign IOP. The y-axis indicates the daily maximum surface MSE at the Nchila field site [kJ kg^{-1}] and the x-axis the difference to the equivalent value at Solwezi. Daily values within each phase are plotted as diamonds while the phase mean is marked by a cross. b) A timeseries of daily maximum surface MSE [kJ kg^{-1}] at the Nchila and Solwezi field sites.

Table 2.3: Dates and durations of the five meteorological phases of the 44-day field campaign IOP. For each phase, the thermodynamic regime sampled at the Nchila and Solwezi field sites is indicated as "Moist", "Dry" or "No CAB". "Moist" ("dry") denotes that the site lay on the moist (dry) side of the CAB. "No CAB" is assigned to Phase 5 as reanalysis diagnostics indicate the CAB did not form during this period.

Phase	Start date	End date	Days	Regime at site	
				Nchila	Solwezi
Phase 1	2022-10-01	2022-10-05	5	Moist	Dry
Phase 2	2022-10-06	2022-10-15	10	Dry	Dry
Phase 3	2022-10-16	2022-10-22	7	Moist	Dry
Phase 4	2022-10-23	2022-10-30	8	Moist	Moist
Phase 5	2022-10-31	2022-11-13	14	No CAB	No CAB

2.1.2 Satellite data

Satellite data is used in Chapters 3 and 5. A primary source is the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on EUMETSAT’s MSG-10 satellite, positioned at 0° longitude. SEVIRI provides 12-channel imagery every 15 minutes, with 3 km resolution (1 km for the high-resolution visible channel). Eight channels capture thermal infrared radiance: channels particularly useful for CAB identification are the IR10.8 ‘clean’ channel and the water-vapour-sensitive IR6.2. Additionally, $1^\circ \times 1^\circ$ resolution daily outgoing longwave radiation (OLR) data from NOAA’s CDR v1.2 is used to detect anomalous large-scale convection over southern Africa in Chapter 5 from 1979 to 2018 (Lee, 2014).

2.1.3 Gridded precipitation products

In regions with sparse ground-based observations, gridded precipitation products offer a best-guess estimate of rainfall. This thesis uses the Climate Hazards Infrared Precipitation with Stations v2 (CHIRPS) dataset, which combines infrared satellite cold cloud duration (CCD) estimates with station data via machine learning (Funk et al., 2015). CHIRPS covers land areas between 50°N and 50°S at 0.05° resolution from 1981 to present. Daily rainfall is derived from CCD, scaled by a satellite-based monthly climatology, and bias-corrected using rain gauge data through inverse distance weighting.

Studies have shown that CHIRPS performs favourably across Africa and the southern African tropical edge, particularly in terms of monthly rainfall totals (Du et al., 2024; Maphugwi et al., 2024). Known limitations, including poor performance over complex terrain and difficulty in detecting high precipitation events, are not particularly relevant to our study or study area given a focus on large-area accumulated totals and the relatively homogenous topography of southern Africa. However, it is important to note that over subtropical southern Africa, station coverage is ex-

tremely limited. This means that estimates rely heavily on the CCD component and are poorly constrained by rain gauge data.

2.1.4 Reanalyses

Reanalysis datasets combine historical weather observations with a consistent forecast model and data assimilation system to provide estimates of the global atmospheric state at sub-daily resolution over an extended period. They assimilate both conventional observations (e.g., radiosondes, surface stations, aircraft reports) and satellite-based measurements (e.g., atmospheric motion vectors, microwave radiances) using either three-dimensional variational (3D-Var) or four-dimensional variational (4D-Var) techniques.

In this thesis, reanalysis data are used for three main purposes:

- to evaluate the representation of the CAB in reanalyses (Chapter 4);
- to identify CAB breakdown events (Chapter 5); and
- to explore the large-scale mechanisms associated with CAB breakdown (Chapter 5).

Three reanalyses are used: ERA5, MERRA-2, and JRA-3Q. These products are selected based on the following criteria:

- they are the latest reanalyses from their respective modelling centres;
- they are regularly used in present-day climate research, and
- they are updated in near-real time.

The key characteristics of each dataset are summarised in Table 2.4 and described below.

Table 2.4: Reanalyses used in this thesis.

Reanalysis	Time res.	Lon res.	Lat res.	Vert. levels	Assim. method
ERA5	1-hourly	0.25°	0.25°	137	4D-Var
MERRA-2	3-hourly	0.625°	0.5°	72	3D-Var
JRA-3Q	6-hourly	0.375°	0.375°	100	4D-Var

2.1.4.1 ERA5 (ECMWF)

The ECMWF’s ERA5 reanalysis (Hersbach et al., 2020) is a 4th-generation reanalysis using the Integrated Forecast System (IFS) model (Cy41r2) with 12-hourly 4D-Var assimilation, T639 resolution (≈ 31 km) and 137 vertical levels, released in 2017. Data is hourly, covering the time period of 1940 up to the present day. Uncertainty estimates are available by means of a 10-member ensemble at reduced resolution, although in this work only the high-resolution realisation is used. ERA5 is often considered the "gold standard" reanalysis dataset and has become one of the most widely used historical weather datasets in scientific research with $\approx 26,000$ citations at the time of submission. Leading machine-learning forecast models such as Pangu-Weather (Huawei), GraphCast (Google), AIFS (ECMWF) and Aurora (Microsoft) are trained on ERA5 data (Bi et al., 2023; Lam et al., 2023; Lang et al., 2024; Bodnar et al., 2025).

2.1.4.2 MERRA-2 (NASA)

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), is the latest reanalysis of the satellite era produced by NASA’s Global Modelling and Assimilation Office (GMAO) (Gelaro et al., 2017). Released in 2016, it is generated with version 5.12.4 of the GEOS atmospheric data assimilation system, which combines the GEOS-5 model physics (finite-volume cubed-sphere dynamical core) with a 3D-Var analysis scheme on a 6-hourly cycle. Resolution is $0.5^\circ \times 0.625^\circ$, with 72 vertical levels. Output variables are available at different

time resolutions depending on the variable: hourly for 2D diagnostic fields, 3 hourly for the 3D diagnostic fields, and 6 hourly for prognostic fields. Unlike ERA5 and JRA-3Q, it assimilates only clear-sky radiances, which limits the use of cloud- and rain-affected satellite data.

2.1.4.3 JRA-3Q (JMA)

The JRA-3Q reanalysis is a third-generation reanalysis product from the Japanese Meteorological Agency (JMA), released in 2023 and superseding the JRA-55 reanalysis product (Kosaka et al., 2024). JRA-3Q is produced with a low-resolution (TL479, ≈ 40 km) version of the JMA Global Spectral Model using 4D-var assimilation and 100 vertical levels. Pressure-level data are available at 6-hourly resolution.

2.2 Methods

2.2.1 Composite analysis

Composite analysis is a technique that is used throughout this thesis. It involves averaging multiple cases that meet one or more selection criteria in order to highlight consistent signals while reducing random variability (Yarnal, 1993). Composites may be constructed using simple or complex criteria, and multiple composite sets can be generated to enable comparison across different event types. In Chapters 3 and 4, composites are created on the meteorological phases of the DRY-CAB field campaign IOP, while Chapter 5 presents lead and lagged composites of objectively identified subsets of CAB breakdown events.

The key strength of composite analysis is its ability to suppress case-specific noise while retaining systematic signals. However, two limitations are important to consider. First, the composite mean may not accurately represent any individual member, either because a small number of cases disproportionately influence the average

or because superposed features produce an unrealistic "blended" structure that is not representative of any individual case (Yarnal, 1993). To address this, individual cases contributing to each composite are inspected alongside the composite mean.

A second limitation is that a difference in the composite mean does not necessarily entail a statistically significant difference in the composite mean. Therefore, where appropriate, statistical significance is assessed using Student's t-tests to ensure robust interpretation of results. However, caution is required when interpreting outcomes from a large number of statistical tests, as when many tests are performed across grid points some will appear significant purely by chance (Livezey and Chen, 1983). This can lead to an exaggerated impression of the robustness or spatial coherence of results (Wilks, 2016).

2.2.2 Canny-edge detection

This thesis uses the objective algorithm of Howard and Washington (2019) to identify the CAB in reanalysis datasets. The method applies Canny (1986) edge-detection techniques to surface humidity and low-level wind fields, followed by filtering based on segment length, orientation, latitude, and magnitude, to isolate drylines and convergence zones associated with the CAB. The implementation used here is identical to that of Howard and Washington (2019), with the corresponding code publicly available at <https://github.com/EmmaHoward/drylines>.

Objective CAB detection in reanalyses is used in this thesis to:

- Illustrate the (reanalysis) climatology of the CAB and show how this informed DRY-CAB field-site selection (Chapters 1 and 2);
- Provide synoptic-scale context for reanalysis evaluation (Chapter 4); and
- Objectively identify CAB breakdown events (Chapter 5).

The thesis primarily employs the dryline detection formulation over the convergence

zone detection formulation, as Howard and Washington (2019) found that the dry-line CAB was more reliable and easily detected than the convergence line CAB. The thresholds used for filtering CAB-associated drylines are identical to those in Howard and Washington (2019), which are optimised for CAB detection in the ERA5 reanalysis. To detect the CAB in the MERRA-2 and JRA-3Q reanalyses, they are first interpolated to ERA5’s $0.25^\circ \times 0.25^\circ$ resolution. This ensures that all filtering criteria (e.g., magnitude thresholds, minimum lengths) operate consistently across datasets and do not need to be rescaled for differing native grid sizes.

2.2.3 Process-based evaluation

James et al. (2018) suggest model evaluation can be conceptually divided into two main approaches: a) analysis of physical processes (i.e., process-based evaluation), and b) quantification of performance. A large proportion of climate model evaluation work falls into the latter category, relying on statistical comparisons between model output and observations or reanalyses across key variables (Flato et al., 2014). However, while such diagnostics might provide useful benchmarks of model skill, they can be misleading, and models may reproduce observations through compensating errors or processes that differ from those in the real world (e.g., Zhang et al., 2013). Furthermore, such statistics rarely reveal why a model is wrong, limiting their value in identifying model weaknesses and guiding model development.

To address these limitations, Chapter 4 adopts a ‘process based evaluation’ methodology. This approach places emphasis on the mechanisms and processes through which models generate their outputs, determining if they reflect those operating in the real atmosphere. Process-based evaluation has been widely applied to global circulation models, including the CMIP model ensembles (Dieppois et al., 2015; James et al., 2015; Creese and Washington, 2016; Bracegirdle et al., 2018; Cui et al., 2024), typically using reanalyses as a benchmark for the processes operating in the ‘real’ atmosphere. Such work has been crucial for assessing model credibility and the plau-

sibility of future projections. For example, James et al. (2015) showed that models projecting strong drying in West Africa inhibit rainfall in both the historical and future periods through a mechanism of anomalous upper-tropospheric subsidence that does not exist in the real (reanalysis) world, casting doubt on the plausibility of future drying.

In Chapter 4, we extend this method to the assessment of reanalyses. This builds on studies such as Podglajen et al. (2014) and Itterly et al. (2018), which demonstrate the value of evaluating not only whether reanalyses reproduce observed atmospheric states, but whether they correctly capture the processes that lead to those states. For example, Podglajen et al. (2014) show that reanalysis errors in the representation of horizontal winds in the equatorial lower stratosphere are related to an improper representation of large-scale equatorial Kelvin and Yanai wave packets, particularly in observationally sparse regions such as over the Indian Ocean and western Pacific. Similarly, Itterly et al. (2018) showed that biases in the Amazonian convective diurnal cycle are sustained and amplified by errors carried over from the previous day through cloud and radiative feedbacks. These studies illustrate how process-based evaluation can contextualise when and why reanalyses succeed or fail, aiding a more informed view of model weaknesses and priorities for future development.

2.2.4 Comparison of point observations to gridded datasets

In Chapter 4, *in situ* observations from DRY-CAB are compared to reanalysis datasets. A fundamental challenge in such comparisons is the issue of representativeness that arises when collocating point observations with gridded (e.g., model) data. In reanalyses, values represent the average state within a grid cell centred on fixed latitude-longitude coordinates, rather than a true point measurement. Observations, on the other hand, are representative of specific latitude-longitude coordinates. This complicates a direct comparison between the two.

A range of co-location techniques have been proposed in the literature to address this limitation, although no consensus has emerged regarding the optimal approach (Figure 2.7). Commonly used methods include: (a) nearest-neighbour comparison, whereby the observed value is compared with the reanalysis grid cell in which the observation lies; (b) averaging of the four nearest grid points surrounding the observation; (c) distance-weighted averaging of those four grid points; and (d) assigned-area or square-based averaging, in which all grid cells overlapping a predefined region centred on the observation (e.g., 15×15 km or 30×30 km) are averaged, weighted by their fractional overlap (Ruti et al., 2008; Mooney et al., 2011).

Mooney et al. (2011) quantified differences arising from these four co-location methods when comparing surface air temperature observations with multiple reanalyses across 11 synoptic stations in Ireland. They found that differences in correlation coefficients and root mean square error between methods were small (typically <0.01 in correlation) and not statistically significant at the 95% confidence level.

In this thesis, observations are compared with reanalysis data using a nearest-neighbour colocation approach. This choice is motivated by its simplicity, transparency, and widespread use in the literature, and is further supported by sensitivity testing presented in the Appendices of Chapter 4. This demonstrates that correlation coefficients and root mean square errors for several key variables are insensitive to the choice of colocation method, despite the presence of strong spatial gradients across the CAB.

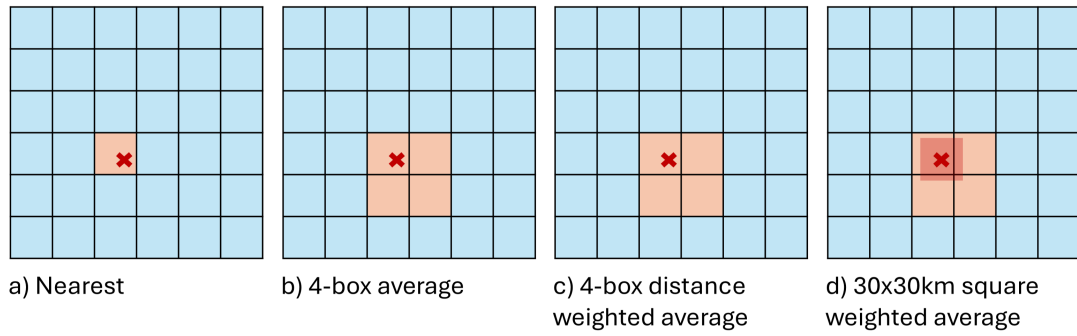


Figure 2.7: Graphical illustration of four potential methods for comparing field site observations (red cross) to gridded model data a) nearest neighbour, b) average of the four nearest grid points, c) distance-weighted average of the four nearest grid points, and d) weighted average over an assigned 30 x 30 km grid square.

3 | Observations of the atmosphere across the Congo Air Boundary



Dr Callum Munday releases the 14:00 LT radiosonde at Nchila on 10 October 2022.

The Congo Air Boundary (CAB) is a synoptic-scale dryline and convergence zone that is a defining feature of the southern African tropical-edge climate from August to November, playing a central role in both the timing of rainfall onset and projections of regional drying. Here we present the first detailed observations of the CAB using surface and upper-air data from the Decreasing Rainfall to Year 2100 - Role of the Congo Air Boundary (DRY-CAB) project. Based on observations between 1 October and 13 November 2022, the CAB is shown to feature a specific humidity gradient of up to 12.0 g kg^{-1} per 100km . On the dry side of the CAB, the afternoon boundary layer is near dry-adiabatic ($9.6 \text{ }^{\circ}\text{C km}^{-1}$) and capped by a midlevel inversion, while on the moist side the boundary layer is more stably stratified ($9.1 \text{ }^{\circ}\text{C km}^{-1}$) and mid-level inversions weaker. Low-level convergence at the CAB peaks at 05:00 local time and is accompanied by mid-level divergence, as a dry (7 g kg^{-1}), 15.0 m s^{-1} easterly low-level jet is lifted above a shallow ($\approx 600 \text{ m}$ deep) layer of moist (15 g kg^{-1}) north-westerlies. Observations evidence shallow overturning to the north of the CAB, comprising north-westerly low-level flow, ascent at the CAB, and a mid-level return flow, and suggest the CAB is not typically associated with deep convection. Results are synthesised in a conceptual model which illuminates the structure and maintenance of a feature not previously resolved in observations and establishes a baseline for model evaluation.

3.1 Foreword to Chapter 3

Chapter 3 addresses the first aim of this thesis by characterising the structure and circulation of the atmosphere across the CAB in observations. Using upper-air and surface observations from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project, the chapter resolves the intricate mesoscale workings of the atmosphere at the CAB, including gradients in moisture and stability and the depth and diurnal evolution of moist Congo northwesterlies and dry subtropical easterlies.

The chapter establishes the CAB as a sharp dryline and convergence zone separating two air masses with strongly contrasting circulation regimes and thermodynamic properties, and reveals how the structure of the CAB evolves through the day. On the basis of these results, the chapter develops a novel conceptual model of the atmosphere across the CAB. This model describes the structure, circulation, and diurnal modulation of the CAB and clarifies the processes responsible for its maintenance. Through doing so, the chapter fulfils Aim 1 of this thesis and provides new insight into the mesoscale structure of the atmosphere at the data-sparse southern African tropical edge.

Chapter 3 is presented in the form of a manuscript:

Knight, C., Washington, R., Munday, C., Hart, N., Nkonde, E., Imbwae, F., and Kasongo, W. (2026). Observations of the atmosphere across the Congo Air Boundary.

Submitted to *Journal of Climate* on 28 January 2026.

3.2 Introduction

The August–November pre-rainfall-onset circulation over tropical southern Africa is characterised by a distinguishing large-scale feature, the Congo Air Boundary (CAB). The CAB is a synoptic-scale convergence zone and dryline that occurs where near-saturated low-level north-westerlies originating from the equatorial east Atlantic and Congo Basin meet easterly trade winds from the tropical southwest Indian Ocean (Figure 3.1), which are dried by strong heating of the continental surface and diluted by deep tropospheric subsidence (Torrance, 1979; Hills, 1979; Tierney et al., 2011; Dezfuli and Nicholson, 2013; Nicholson, 2015; Howard and Washington, 2019). Like other drylines, the CAB is characterised by near-surface convergence and a sharp horizontal contrast in the low-level moisture field (Owen, 1966; Schaefer, 1974; Howard and Washington, 2019).

The CAB is a primary control on spring and early summer rainfall at the southern African tropical edge. Knight and Washington (2024) show that in September and October, rainy days are 8–16 times more likely over the core of the southern African subtropics when the CAB is absent. Similarly, Howard and Washington (2019) found that the frequency of the CAB in October, November and December is strongly anti-correlated ($r \leq -0.58$) with subtropical southern African rainfall between 15–25°E. The CAB also plays a central role in projections of future rainfall change: successive CMIP generations simulate delayed rainfall onset and early-summer drying under warming scenarios (Shongwe et al., 2009; Christenson et al., 2017; Dunning et al., 2018; Munday et al., 2025), associated with an increase in CAB frequency from October to December.

Given the significance of the CAB to both present-day rainfall variability and to future change, it is crucial we understand its structure and maintenance. Yet the CAB has been the subject of relatively little recent scholarship, all of which has

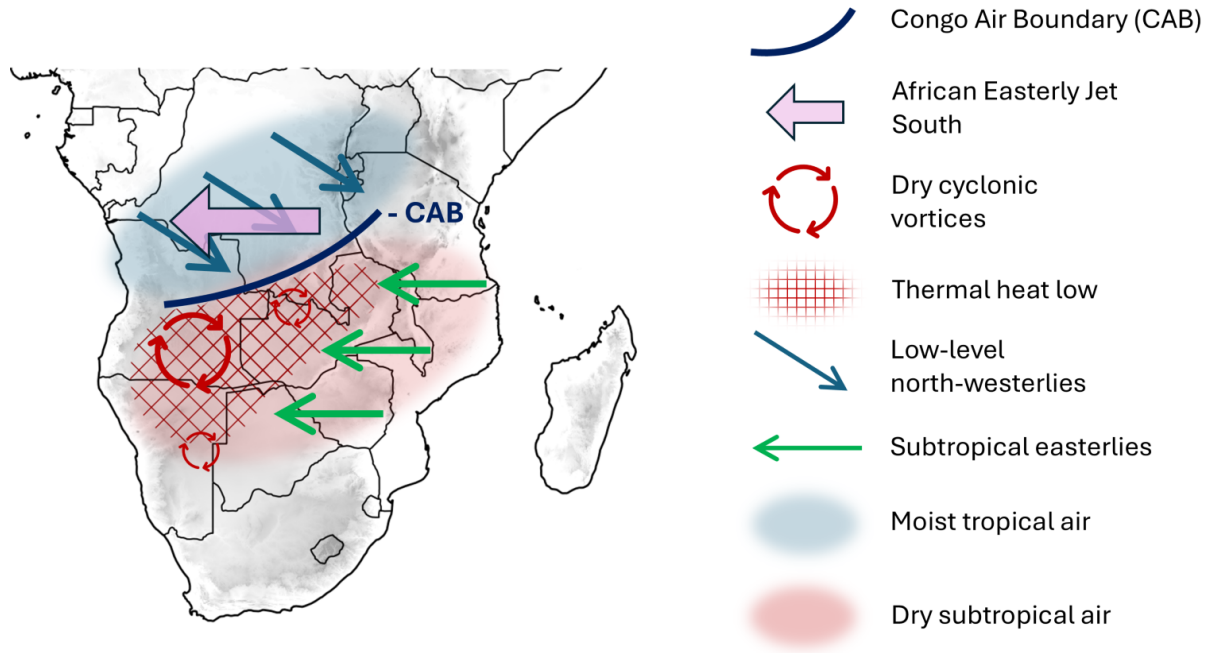


Figure 3.1: A schematic of the lower level (surface–600hPa) pre-onset (August to October) circulation at the southern African tropical edge. The Congo Air Boundary (CAB; Howard and Washington, 2019) is shown as a solid blue line separating moist tropical air (blue shading) from dry subtropical air (red shading). The southern African Heat Low is a large area of intense surface heating, characterised by an unstable boundary layer (red hatched; Attwood et al., 2024). Embedded in this heat low are dry cyclonic circulations, which form preferentially at the locations indicated by red cyclonic symbols (Howard and Washington, 2018). Other major features of the regional circulation include the African Easterly Jet South (purple arrow; Kuete et al., 2020), subtropical easterlies (green arrows), and low-level Congo Basin north-westerlies (blue arrows; Pokam et al., 2014).

been based on reanalysis or model data (Howard and Washington, 2019; Knight and Washington, 2024). As a result, our understanding of the feature is not grounded in direct observation of the atmosphere. This strongly contrasts to drylines elsewhere, such as the Great Plains, for which our understanding is underpinned by a breadth of observational studies (e.g., Schaefer, 1974; Ziegler and Hane, 1993; Atkins et al., 1998; Ziegler and Rasmussen, 1998; Miao and Geerts, 2007; Bergmaier et al., 2014). The scarcity of observational data in central southern Africa means it is reasonable to be sceptical of the accuracy of models and reanalyses. As of 2022, the operational (GTS-reporting) upper-air sounding stations of Luanda, Dar es Salaam, Windhoek, and Pretoria bound a vast region (circumradius >1500 km) within which there are no regularly reporting radiosonde stations (Figure 3.2a). As a result, reanalyses are not constrained in the lower troposphere and rely heavily on their modelled components, in which key dryline-associated mesoscale processes are parametrised. This raises uncertainty about the model-derived body of literature to date that describes the CAB.

One way to circumvent structural problems in observational coverage, and associated issues with numerical models, is through intensive observational periods targeted at important regions or features of the circulation. Fundamental new insights into the operation of regional climates have stemmed from such projects across Africa, such as the Africa Monsoon Multidisciplinary Analysis (AMMA; Redelsperger et al., 2006) and Dynamics-Aerosol-Chemistry-Cloud Interactions (DACCIIWA; Knippertz et al., 2015) projects in West Africa, and the Fennec campaign in the Sahara (Marshall et al., 2013; Todd et al., 2013). This approach has also proven useful for resolving the structure and maintenance of drylines elsewhere, including the drylines of the Great Plains (Rasmussen et al., 1994; Weckwerth et al., 2004).

In this paper, we use surface and upper-air (radiosonde) data from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project to

study the structure and dynamics of the atmosphere across the CAB (Washington et al., 2026 – in preparation). The DRY-CAB field campaign consisted of intensive sampling of surface conditions and vertical profiles of the atmosphere from two sites in north-west Zambia during austral spring (1 October – 13 November) 2022 (Figure 3.2). With this novel observational data, we aim to answer the following three research questions:

1. How do the thermodynamics of the atmosphere vary across the Congo Air Boundary?
2. How does the circulation of the atmosphere vary across the Congo Air Boundary?
3. How is the Congo Air Boundary modified by the diurnal cycle?

Our analysis yields insights into the structure and maintenance of the CAB, advancing understanding of atmospheric processes at the data-sparse southern African tropical edge. Through contrasting our observations with conceptual models of dry-lines elsewhere, we reveal key similarities and notable differences. Additionally, our results establish an observational baseline against which the ability of models to simulate the CAB can be tested.

The paper proceeds with an overview of our current understanding of the CAB in Section 3.3. An outline of the field campaign and this paper’s sampling strategy follows in Section 3.4. Section 3.5 reports our results, structured by the three research questions above. Section 3.6 discusses our results in the context of dryline literature and presents a novel schematic summarising the atmosphere at the CAB, while the final section presents our conclusions.

3.3 Background

The Congo Air Boundary (CAB; Figure 3.1) was heuristically conceptualised by weather forecasters in the 1950s and 1960s but until recently was a forgotten feature in the climate science literature. Recently, Howard and Washington (2019) applied a novel canny-edge detection algorithm to reanalysis data to derive a climatology. They showed that the CAB forms preferentially on the slope from the Congo Basin to the Katanga Plateau (8–12°S) with a diagonal (south-west to north-east) orientation, and that it is most common in austral spring (present on >95% of August and September days), declining in frequency through to the summer (present on <10% of December days). Additionally, Knight and Washington (2024) explored the process of CAB breakdown in reanalyses, showing that the breakdown of the CAB is coincident with a rapid southward shift in the latitude of the tropical rain belt and the replacement of a dry-convective regime with deep moist convection across southern Africa over a period of 3–5 days. The dynamics of the CAB are therefore tightly related to the seasonal evolution of summer rainfall and to the dynamics of the tropical rain belt as it migrates southward in the summer hemisphere.

Given the importance of the CAB to the seasonal cycle of southern African rainfall, understanding the features structure and maintenance is essential. However, substantial knowledge gaps remain owing to the scarcity of observations in the region. We do not know if the CAB, and atmospheric processes at the CAB, are plausibly reproduced by numerical models. This undermines confidence in forecasts of rainfall onset (Knight and Washington, 2024) and projections of future drying (Howard and Washington, 2020). Establishing the structure of the atmosphere across the CAB represents a critical first step toward addressing these issues.

Conceptual models of drylines elsewhere highlight the role of topography and the diurnal cycle of surface heating in organising dryline structure and evolution, and

similar mechanisms may operate at the CAB. Drylines elsewhere can also act as hotspots for convective initiation and severe weather (McCarthy and Koch, 1982; Bluestein and Parker, 1993; Ziegler and Rasmussen, 1998; Bergmaier and Geerts, 2015; Bai et al., 2019; van Schalkwyk et al., 2023). Establishing the extent to which the CAB shares these characteristics is valuable for understanding its dynamical distinctiveness and its role in the regional circulation.

It is important to clarify that this study does not aim to contrast observations of the CAB to its representation in reanalyses, nor does it seek to conduct a rigorous comparison between the CAB and drylines in other regions. Instead, by characterising the atmosphere across the CAB using novel observational data, we establish a foundation for future comparative analyses.

3.4 Data and methods

3.4.1 Field observations

We use surface and upper-air (radiosonde) observations from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (Washington et al., 2026, in preparation). The main field campaign comprised intensive radiosonde and surface observations from two sites in north-west Zambia through austral spring of 2022. Radiosonde supersites, equipped with radiosondes, an automatic weather station (AWS) and a Doppler LiDAR, were located at Nchila (11.249°S, 24.327°E) and Solwezi (12.171°S, 26.364°E) (Figure 3.2) and supported by three additional AWS. The Nchila and Solwezi supersites were located on the Katanga Plateau at an altitude of 1400 m ($\approx$ 859 hPa) and 1393 m ($\approx$ 861 hPa) respectively, with Solwezi 244.2 km to the east-southeast of Nchila. A full description of the DRY-CAB project, including justification of site selection and sampling strategy, is provided in Washington et al. (2026, in preparation).

During the field campaign intensive observational period (IOP), GRAW DFM-17 radiosondes were released at 3-hourly intervals from both radiosonde supersites for 44 days from 1 October to 13 November. The AWS deployed were Davis Vantage Pro weather stations that recorded data at 10-minute resolution or greater. Radiosonde release times were 00, 03, 06, 09, 12, 15, 18, and 21 UTC. The field site time zone is Central African Time (CAT; UTC+2), and we report all times in this study in local time, denoted ‘LT’ (e.g., 15:00 LT = 13:00 UTC).

3.4.2 Meteorological phases

The 44-day field campaign IOP from 1 October to 13 November may be divided into five distinct meteorological phases (Phase 1-5) defined by the daily maximum in field site surface moist static energy (MSE). Surface MSE is chosen as a diagnostic as both theory and observations indicate that tropical convection is, to the first order, controlled by the maximum in surface MSE (Neelin and Held, 1987; Nie et al., 2010), and Hart et al. (2019) show near-surface MSE is a good diagnostic for convection over Africa. The five meteorological phases are summarised in Table 3.1 and illustrated in the phase-space diagram of Figure 3.3.

Phase 1 of the field campaign is characterised by high surface MSE values at Nchila (349.1 kJ kg^{-1}) and large differences to Solwezi (-8.2 kJ kg^{-1}). As the CAB is expected to be the principal control of MSE, primarily through the latent component, we may infer that the dryline lies between the two sites with Nchila on the moist side of the CAB and Solwezi on the dry side. Phase 2 is characterised by lower MSE at both sites, indicating that both sites are located on the dry side of the CAB. Phase 3, like Phase 1, is characterised by high MSE at Nchila (350.5 kJ kg^{-1}) and a large difference to Solwezi (-8.6 kJ kg^{-1}), implying that the CAB again bisects the two sites. In Phase 4 and Phase 5, both sites are characterised by high MSE

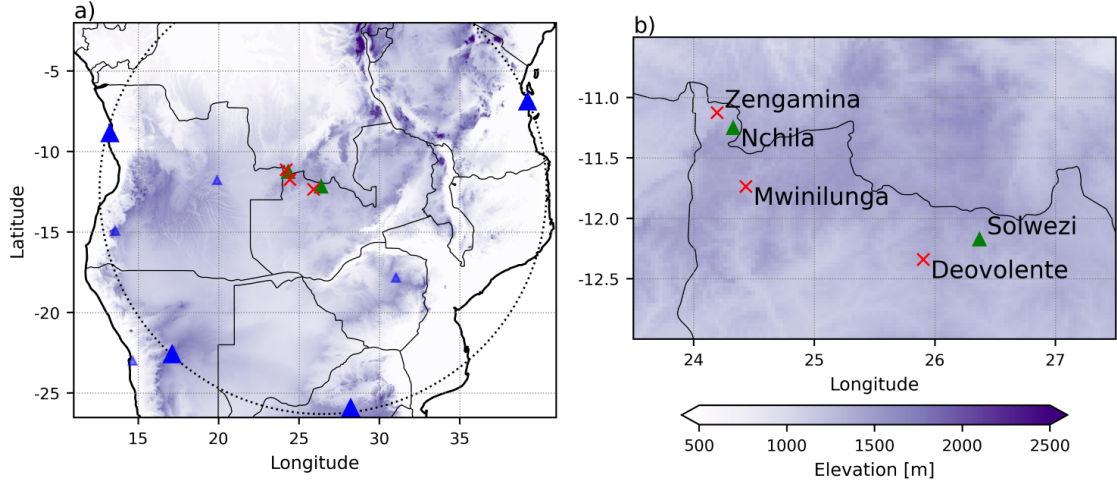


Figure 3.2: Location of the DRY-CAB project field sites. Red cross: Automatic weather station (AWS) only sites; green triangles: radiosonde sites with AWS and LiDAR. In a), large blue triangles denote active radiosonde stations, defined as those conducting soundings on more than 15% of days between 2015-2024 (Luanda, Dar es Salaam, Windhoek, and Pretoria). Small blue triangles show stations with soundings on fewer than 15% of days during the same period (Harare, Luena, Lubango, and Walvis Bay). Radiosonde data are from the Integrated Global Radiosonde Archive (IGRA) v2.2. The black dotted line outlines the circumscribed circle of active radiosonde sites, with a radius of approximately 1,542 km. Surface elevation [m] from the Global Multi-resolution Terrain Elevation Data 2010 dataset is shaded in purple.

Table 3.1: Dates and durations of the five meteorological phases of the 44-day field campaign IOP. For each phase, the thermodynamic regime sampled at the Nchila and Solwezi field sites is indicated. Moist (dry) denotes that the site lay on the moist (dry) side of the CAB. Data from Phase 5, during which the CAB does not form, is not used in this study.

Phase	Start date	End date	Days	Regime at site		Cross-CAB?
				Nchila	Solwezi	
Phase 1	2022-10-01	2022-10-05	5	Moist	Dry	Yes
Phase 2	2022-10-06	2022-10-15	10	Dry	Dry	No
Phase 3	2022-10-16	2022-10-22	7	Moist	Dry	Yes
Phase 4	2022-10-23	2022-10-30	8	Moist	Moist	No
Phase 5	2022-10-31	2022-11-13	14	No CAB	No CAB	-

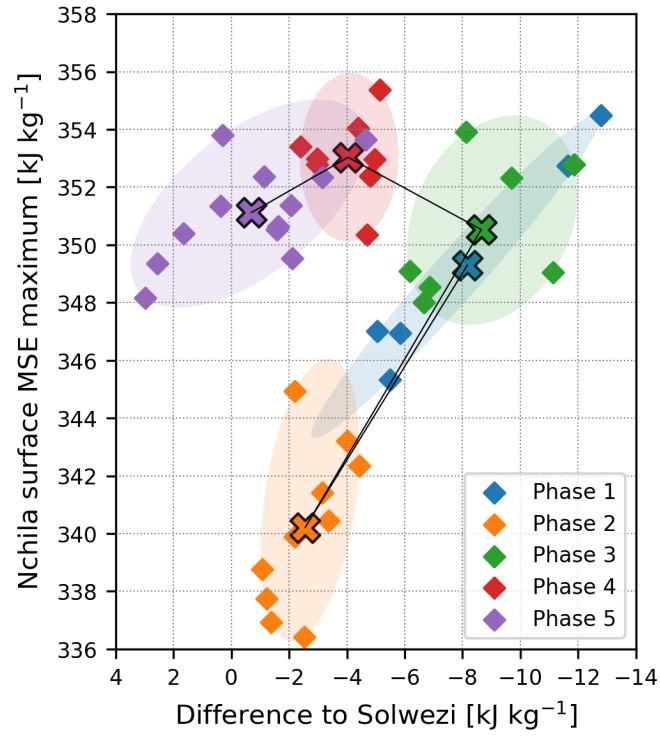


Figure 3.3: Phase-space plot of the five meteorological phases of the field campaign. The y-axis indicates the maximum surface MSE [kJ kg^{-1}] at the Nchila field site and the x-axis the difference to the equivalent value at Solwezi. Daily values within each phase are plotted as diamonds while the phase mean is marked by a cross.

($\approx 351 \text{ kJ kg}^{-1}$) and inter-site differences are small, suggesting both sites sample the moist side of the CAB. These phases are distinguished by the breakdown of the CAB, which does not form in Phase 5. Data from Phase 5 is therefore not used in this study.

As the aim of this work is to characterise the atmosphere across the CAB, we are particularly interested in the meteorology of the two phases during which the CAB appears to bisect the two field sites. Phases 1 and 3 represent 12 days from 1–5 and then 16–22 October (inclusive) where Nchila was characterised by a moist regime and Solwezi a dry regime. To confirm that this difference is enforced by the location of the CAB, we inspect data from the geostationary satellite Meteosat 10 (MSG–3; Figure 3.4). This confirms that Phases 1 and 3 are characterised by a canonical "CAB-in-place" synoptic setting. Low brightness temperatures in the $10.8 \mu\text{m}$ and $6.25 \mu\text{m}$ channels are observed over the Congo Basin and northeast Angola, while higher brightness temperatures dominate southern Angola and much of Zambia. The location of the CAB dryline is clearest in the $6.25 \mu\text{m}$ -centred radiation channel (Figure 3.4b), for which brightness temperatures are indicative of mid-level water vapour and the CAB is seen as a sharp south-west to north-east aligned discontinuity which cleanly bisects the two field sites. Gradients in land surface temperature and $10.8 \mu\text{m}$ brightness temperatures are similarly aligned but more complex and/or diffuse. This confirms that during Phases 1 and 3, radiosondes at Nchila sampled the moist side of the CAB and radiosondes at Solwezi the dry side. These "cross-CAB" observations form the core sampling base for this investigation.

3.4.3 Meteorological setting

In 2022 the CAB was present almost continuously from August through to its breakdown on 31 October. A brief breakdown occurred on 20 September, although this was short-lived and the CAB re-established within 2 days. Rainfall onset dates,

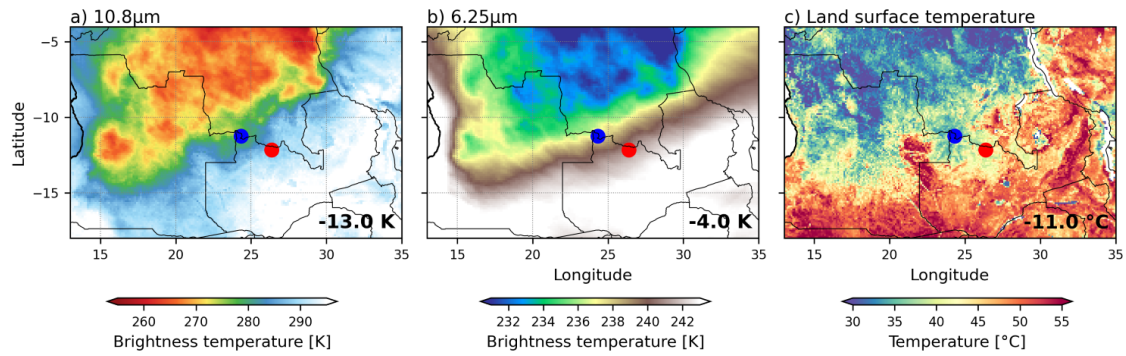


Figure 3.4: Mean brightness temperature [K] in the a) $10.8\ \mu\text{m}$ and b) $6.25\ \mu\text{m}$ channels from the Meteosat-10 (MSG-3) Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument, and c) 12:00 LT mean land surface temperature [$^{\circ}\text{C}$] from the Land Surface Analysis Satellite Applications Facility (LSA SAF) SEVIRI MLST (Land Surface Temperature) product, for Phases 1 and 3 of the field campaign (1–5 and 16–22 October). The Nchila and Solwezi field sites are indicated by blue and red circles respectively, while the difference between values at the two field sites (Nchila – Solwezi) is reported bottom right.

defined using the method of Liebmann et al. (2012) and applied to CHIRPS data, were largely similar to the climatology across much of the tropical edge. September–November CHIRPS rainfall totals were also largely as expected, suggesting austral spring 2022 was fairly typical. However, rainfall was particularly high ($>150\%$) across Zimbabwe and central Mozambique and particularly low ($<50\%$) across southern Tanzania and northern Mozambique. This rainfall dipole is often associated with La Niña conditions, linked to a displacement of the Southern Indian Ocean Convergence Zone (Chongue and Nishii, 2024). Indeed, the second half of 2022 was characterised by a La Niña event with a September–November mean Oceanic Niño Index of -0.97 , part of a rare multi-year "triple-dip" La Niña spanning 2020–2023 (Li et al., 2023; Thoithi et al., 2025, 2026). La Niña events are generally associated with enhanced summer rainfall totals over southern Africa (Lindesay, 1988), and triple-dip La Niña events typically exhibit greater circulation anomalies and rainfall and temperature impacts than single-year or "double-dip" events (Thoithi et al., 2025, 2026). However, these relationships are strongest in the core of the summer and there is no established connection to the CAB or to rainfall onset dates. Poten-

tial implications for the generalisability of our results are discussed in Section 3.6.8.

In terms of intraseasonal variability, the Madden-Julian Oscillation (MJO; Madden and Julian, 1994) was not active during September and early October as diagnosed by the Real-time Multivariate MJO (RMM) index (Wheeler and Hendon, 2004). During the latter half of October, the MJO was active in RMM phases 5 and 6, associated with enhanced convection over the Maritime Continent and suppressed convection over Africa, before progressing into RMM phase 7 in early November.

3.5 Results

This section presents observations of the Congo Air Boundary (CAB), structured around the three research questions introduced in Section 3.2. This includes the thermodynamic structure of the atmosphere across the CAB (Section 3.5.1), the circulation of the atmosphere across the CAB (Section 3.5.2), and modulation of the CAB through the diurnal cycle (Section 3.5.3).

3.5.1 How do the thermodynamics of the atmosphere vary across the CAB?

A first-order component of the thermodynamics of the atmosphere across the CAB is the strength of the CAB dryline. In studies of drylines in southern Africa and beyond, drylines are typically defined as surface moisture boundaries with a minimum specific humidity gradient of $3 \text{ g kg}^{-1} 100 \text{ km}^{-1}$ (Hoch and Markowski, 2005; Bergmaier and Geerts, 2015; Bechis et al., 2020; van Schalkwyk et al., 2022). While the reanalysis climatology of Howard and Washington (2019) employed a more stringent threshold of 3 g kg^{-1} per 0.25° grid cell ($\approx 31 \text{ km}$) when identifying the CAB, the magnitude of the moisture gradient across the CAB is not known.

Figure 3.5 plots the time evolution of the strongest inter-AWS specific humidity

gradient observed during the campaign, sampled between the Nchila and Mwinilunga AWS stations on 5 October during Phase 1. A maximum specific humidity gradient (∇q) of 12.0 g kg^{-1} per 100 km is recorded at 16:10 LT. Early in the day, specific humidity is high at both sites (15 g kg^{-1} at 09:00 LT), but subsequently diverges with decreasing Mwinilunga q concurrent with a wind regime shift from northerlies to easterlies. This evolution indicates a gradual transition of Mwinilunga from the moist side of the CAB (15 g kg^{-1}) to the dry side (7 g kg^{-1}) between 09:00 and 16:00 LT, occurring in the context of drying at both sites.

These observations confirm that the CAB dryline can meet and significantly exceed the canonical $3 \text{ g kg}^{-1} 100 \text{ km}^{-1}$ threshold and is comparable in strength to drylines elsewhere (Ziegler and Hane, 1993; Atkins et al., 1998; Ziegler and Rasmussen, 1998; Miao and Geerts, 2007). It is likely that the gradient we report is a conservative estimate, as the distance between AWS is 57 km and drylines often exhibit the sharpest moisture gradient over a distance of a few kilometres or less (Miao and Geerts, 2007).

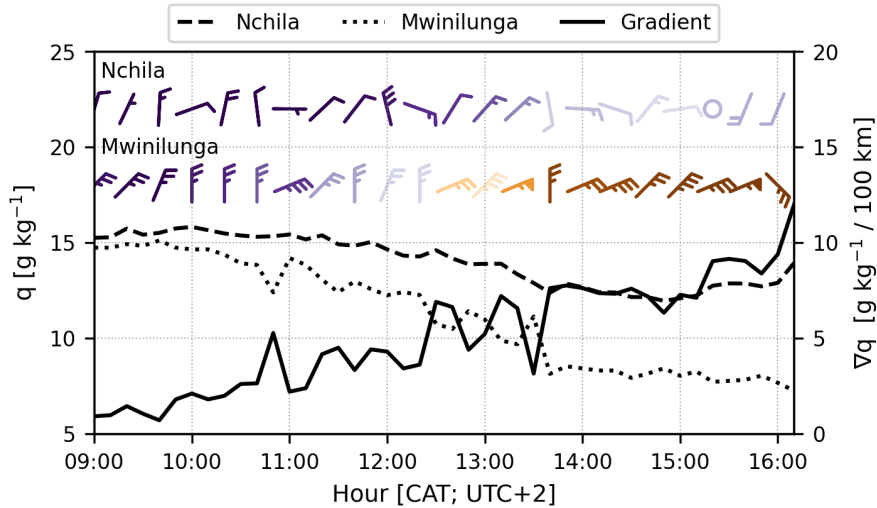


Figure 3.5: A timeseries of station specific humidity [g kg^{-1}] at Nchila (dashed) and Mwinilunga (dotted) on the 5th October 2022. A solid line plots the specific humidity gradient (∇q) [$\text{g kg}^{-1} / 100 \text{ km}$] between the two sites (right-hand y-axis). Wind barbs indicate the 20-minute surface mean winds, coloured by specific humidity and with half-, full-, and flag-barbs denoting 0.25 , 0.5 , and 2 m s^{-1} respectively

To examine thermodynamic gradients across the CAB extending above the surface, Figure 3.6 presents dry static energy (DSE) and moist static energy (MSE) profiles from 14:00 LT radiosonde ascents stratified by the location of the CAB. At both Nchila and Solwezi (Figure 3.6a,b), a dry regime (CAB to the north) is characterised by a dry-adiabatic boundary layer extending to approximately 650 hPa, whereas in the moist regime, boundary layer DSE is more stably stratified. Near-surface MSE is substantially higher in the moist regime, reflecting the contribution of near-surface moisture through the latent term ($L_v q$).

Figure 3.6c additionally shows mean DSE and MSE profiles from 14:00 LT radiosonde ascents during Phases 1 and 3 of the field campaign, when radiosondes simultaneously sampled the vertical structure of the atmosphere across the CAB. Thermodynamic profiles closely resemble those in Figure 3.6a,b, confirming that differences at Nchila and Solwezi arise from the location of the CAB rather than from the seasonal evolution of atmospheric profiles. Near-surface MSE is 6.3 kJ kg^{-1} higher at Nchila than at Solwezi, driven by $L_v q$, and the surface to mid-level MSE gradient, a metric of conditional instability, is 7.3 kJ kg^{-1} higher. This indicates substantially greater conditional instability on the moist side of the CAB. Interestingly, above 500 hPa $\text{DSE} \approx \text{MSE}$ at both sites, suggesting that the mid- to upper troposphere remains relatively dry in the moist regime despite the large degree of conditional instability. Table 3.2 offers further summary statistics, confirming that on the dry side of the CAB the boundary layer is approximately dry-adiabatic with an average 14:00 LT lapse rate of $9.6 \text{ }^\circ\text{C km}^{-1}$, compared to $9.1 \text{ }^\circ\text{C km}^{-1}$ on the moist side.

Differences in mid-level stability further distinguish the thermodynamic regimes on either side of the CAB (Figure 3.7). At Nchila, the mean inversion strength (defined as the temperature difference between the top and base of the inversion) is $1.03 \text{ }^\circ\text{C}$ on the dry side of the CAB, compared with $0.49 \text{ }^\circ\text{C}$ on the moist side; at Solwezi,

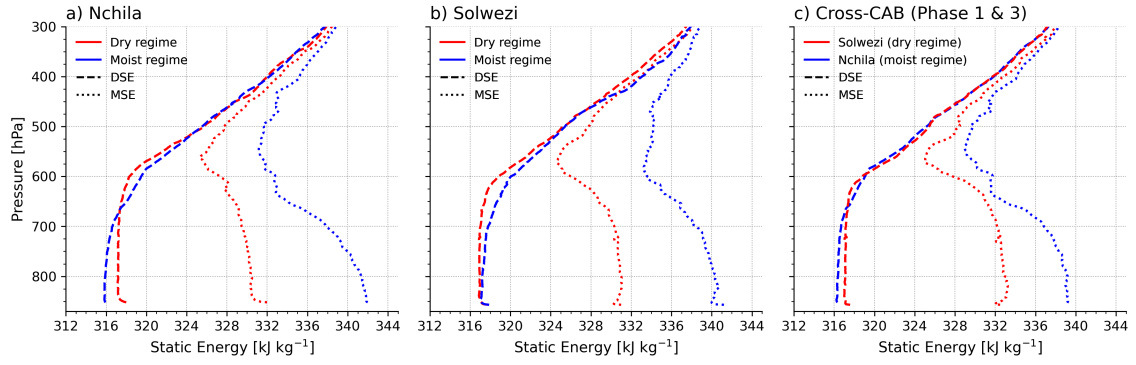


Figure 3.6: Mean 14:00 LT DSE and MSE profiles [kJ kg^{-1}] stratified by CAB location for the (a) Nchila and (b) Solwezi field sites. Nchila sampled a dry regime during Phase 2 and a moist regime during Phases 1, 3 and 4 (Table 5.1). Solwezi sampled a dry regime during Phases 1, 2 and 3, and a moist regime during Phase 4. c) plots simultaneous cross-CAB profiles from Phases 1 & 3, during which Solwezi sampled the dry regime and Nchila the moist regime.

a similar contrast is observed. At both sites, strong dry-side inversions form preferentially at 550 hPa, capping a dry-adiabatic boundary layer (Figure 3.6). During Phases 1 and 3, where sampling is simultaneous, we see that inversion contrasts persist but are reduced in magnitude ($0.70\text{ }^{\circ}\text{C}$ on the dry side versus $0.56\text{ }^{\circ}\text{C}$ on the moist side). This is also reflected in the bulk 600–500 hPa stability, with lapse rates of $5.19\text{ }^{\circ}\text{C km}^{-1}$ on the dry side and $5.56\text{ }^{\circ}\text{C km}^{-1}$ on the moist side. Together, this suggests that cross-CAB differences in mid-level stability are a feature of the atmosphere across the CAB, but that they occur within broader seasonal variations in large-scale subsidence.

In summary, observations diagnose the CAB as the interface of two sharply contrasting thermodynamic regimes. North of the dryline, the atmosphere is characterised by high near-surface moisture, weaker mid-level stability, and a large degree of conditional instability (mean 14:00 LT CAPE of 1480 J kg^{-1} ; Table 3.2). To the south, a heat low-like regime prevails, with low near-surface moisture and a deep dry-adiabatic boundary layer capped by a strong mid-level inversion.

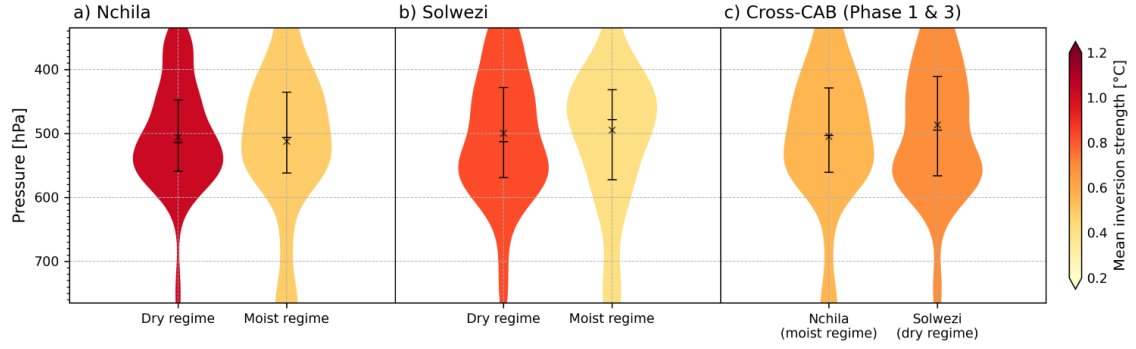


Figure 3.7: Violin plot of inversion midpoint pressure [hPa] from radiosondes stratified by CAB location for the a) Nchila and b) Solwezi field sites. Inversions are identified in 1 hPa resolution radiosonde profiles as layers where temperature is stable or increases with height between successive levels. Nchila sampled a dry regime during Phase 2 and a moist regime during Phases 1, 3 and 4. Solwezi sampled a dry regime during Phases 1, 2 and 3, and a moist regime during Phase 4 (Table 3.1). c) shows simultaneous cross-CAB inversions from Phases 1 and 3, during which Solwezi was on the dry side and Nchila on the moist side. Surface and near-surface inversions, defined as beginning below 800 hPa, are excluded. Violin width indicates the distribution of inversion midpoint pressure, while a black vertical line spans the interquartile range. Horizontal black marks indicate the lower quartile, median, and upper quartile, while an ‘x’ marks the mean. Colour indicates mean inversion strength [°C], defined as the temperature difference between the top and bottom of the inversion layer.

Table 3.2: Simultaneously sampled cross-CAB values of thermodynamic variables at Nchila (moist regime) and Solwezi (dry regime) during field campaign Phases 1 & 3. Means and standard deviations are reported.

Variable	Nchila		Solwezi	
	Mean	SD	Mean	SD
14:00 LT CAPE [J kg^{-1}]	1480	850	22	48
Total column water [mm]	25.0	4.6	17.5	4.1
2 m dewpoint [°C]	13.9	2.1	9.4	2.0
14:00 LT surface–500 hPa MSE gradient [kJ kg^{-1}]	20.8	4.5	13.5	2.0
Daily surface heating [10^6 J m^{-2}]	36.6	0.3	42.8	0.2
Daily max temperature [°C]	30.7	1.0	31.3	0.6
14:00 LT 850–600 hPa lapse rate [°C km^{-1}]	9.1	0.7	9.6	0.3
14:00 LT 600–500 hPa lapse rate [°C km^{-1}]	5.6	1.1	5.2	1.3
Daily max nocturnal surface inversion strength [°C]	5.4	3.8	4.9	2.7

3.5.2 How does the circulation of the atmosphere vary across the CAB?

Our second research question concerns how the circulation of the atmosphere varies across the CAB. Figure 3.4 shows that at Mwinilunga, the transition from a moist dry regime coincides with a wind regime shift in which moist northerlies are replaced by dry easterlies. This suggests that distinct wind regimes characterise the dry and moist sides of the CAB.

To further examine this, we plot the diurnal cycle of wind speed and direction by pressure at Nchila and Solwezi during field campaign Phases 1 & 3 (Figure 3.8). At Nchila (on the moist side), mid-level flow is dominated by persistent easterlies associated with the African Easterly Jet South (AEJ-S). These easterlies are strongest at night (up to 9.2 m s^{-1} at 650 hPa) and weaker during the day, when they extend to the surface. At night, these easterlies are undercut by shallow north-westerlies confined to below 800 hPa ($\approx 600\text{m}$ above the surface). Contoured isentropes indicate that these north-westerlies override a surface stable layer which forms and strengthens overnight following the cessation of surface heating, reaching a maximum inversion strength of 5.4°C at 05:00 LT. Interestingly, the shear zone between the low-level north-westerlies and overriding easterlies is not associated with a stable layer, suggesting the airmasses have similar thermal properties.

At Solwezi, daytime winds resemble those at Nchila, with weak easterlies extending from the surface to 500 hPa. At night, however, the lower troposphere is dominated by a strong (15.0 m s^{-1}) easterly low-level jet (LLJ) at 800 hPa. This LLJ also forms above a surface stable layer, though surface inversions are weaker than at Nchila (4.9°C vs. 5.4°C) and reach maximum strength earlier in the evening (23:00 LT), likely due to shear-induced turbulence beneath the jet. The diurnal cycle of the LLJ corresponds well to theory; following the cessation of surface heating, radiative cooling leads to the development of the stable surface layer which suppresses turbu-

lent mixing and reduces eddy viscosity. Surface winds readjust to a new balance of forces, producing an ageostrophic acceleration toward low pressure associated with the south-of-CAB potential temperature maximum (i.e., a heat low). The interaction of the Coriolis force with this ageostrophic acceleration produces an inertial oscillation of the jet (Blackadar, 1957; Shapiro and Fedorovich, 2010; Van De Wiel et al., 2010). Given a latitude of -12.1°S the inertial period for this oscillation is 57 hours, allowing the completion of about a quarter of the oscillation before sunrise. Accordingly, winds strengthen and deflect towards the south throughout the night, peaking at 08:00 LT (15.0 m s^{-1}) until surface heating re-establishes boundary-layer eddy viscosity and large-scale flow is re-inhibited (Figure 3.8f).

Figure 3.8c shows the magnitude and vector difference in wind speed between Nchila and Solwezi. Overnight, large zonal wind differences develop below 750 hPa, with an oppositely signed difference between 750 and 600 hPa. Given that Solwezi lies approximately 240 km east-southeast of Nchila, these vertically opposing zonal wind differences imply low-level (mid-level) convergence (divergence) between the two sites. To quantify this, we calculate the component of the divergence (Figure 3.9a) and moisture flux divergence (Figure 3.9b) that is parallel to the bearing between the two field sites. Low-level convergence is strongest at night in the 850–800 hPa layer, increasing from near zero at 17:00 LT to a maximum of $4.9 \times 10^{-5} \text{ s}^{-1}$ at 05:00 LT. Aloft, mid-level divergence in the 700–600 hPa layer follows a similar diurnal cycle, peaking at 05:00 LT ($2.6 \times 10^{-5} \text{ s}^{-1}$) and present at all timesteps but 14:00 LT. Moisture-flux divergence exhibits the same structure and diurnal cycle.

Although only one horizontal component of the divergence is resolved, these results demonstrate that convergence at the CAB is shallow, strongly diurnal, and coupled to divergence in the mid-levels. This arises because the nocturnal easterly LLJ characterising the dry regime is lifted above shallow north-westerlies at the CAB, transferring momentum upward into the mid-levels. This behaviour has interesting

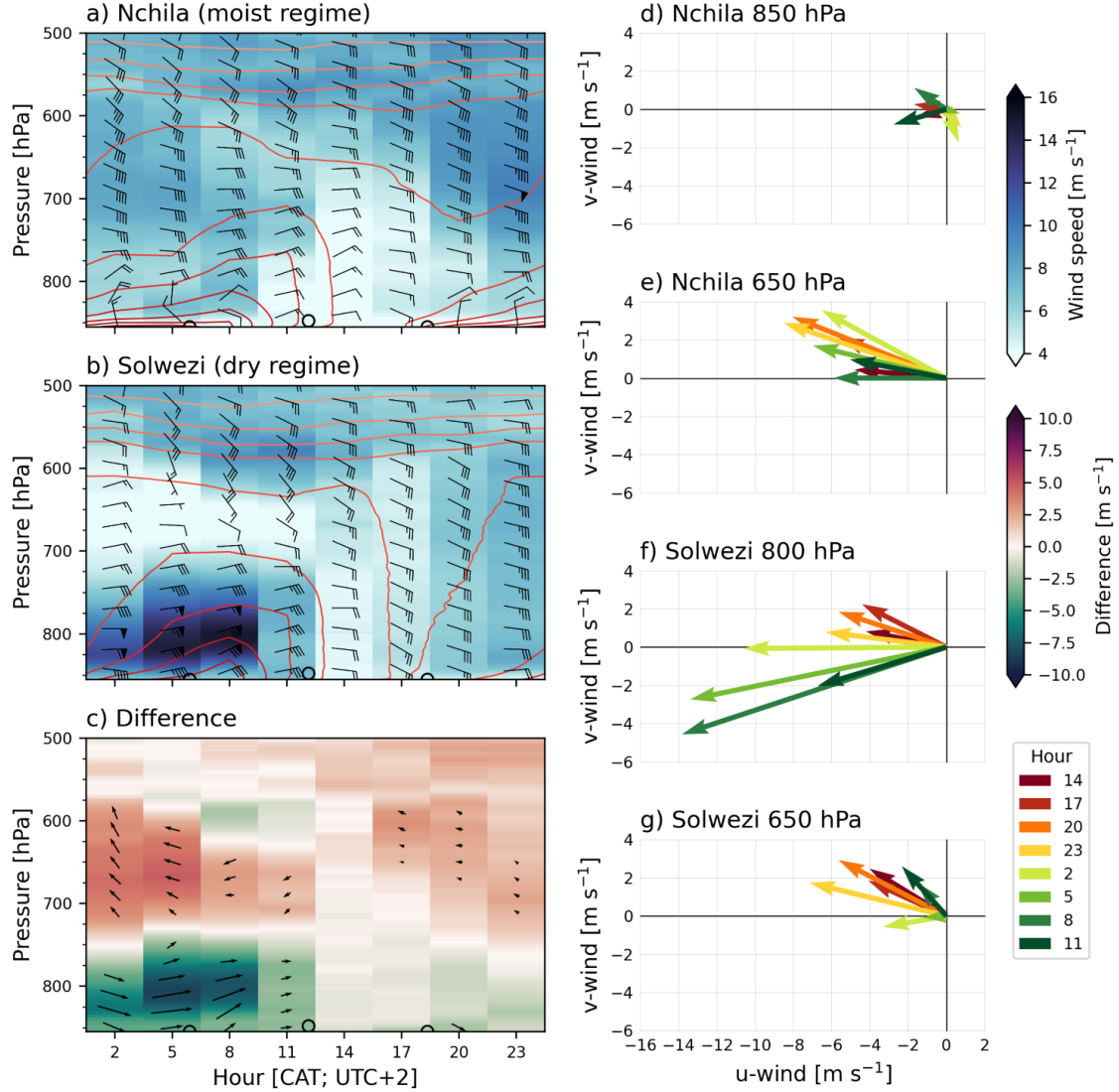


Figure 3.8: The diurnal cycle of wind speed [m s⁻¹] at a) Nchila (moist regime) and b) Solwezi (dry regime) during Phase 1 & 3 of the field campaign. Wind barbs indicate wind direction and speed (with north to the top of the plot). Isentropes are plotted at 2 K intervals in red. c) shows the magnitude (colours) and vector (arrows) differences in wind speed [m s⁻¹] between the two sites, with arrows shown only where wind speed differences between the sites are statistically significant ($p < 0.05$). Panels (d–g) present hodographs of the diurnal cycle of low-level (d: 850 hPa, f: 800 hPa) and mid-level (e, g: 650 hPa) winds at each field site. Sunrise, sunset, and solar noon are indicated by half and full circles respectively.

parallels with drylines elsewhere, discussed in Section 3.6, and suggests a possible but unexplored link to the maintenance of the mid-level AEJ-S through vertical momentum transfer.

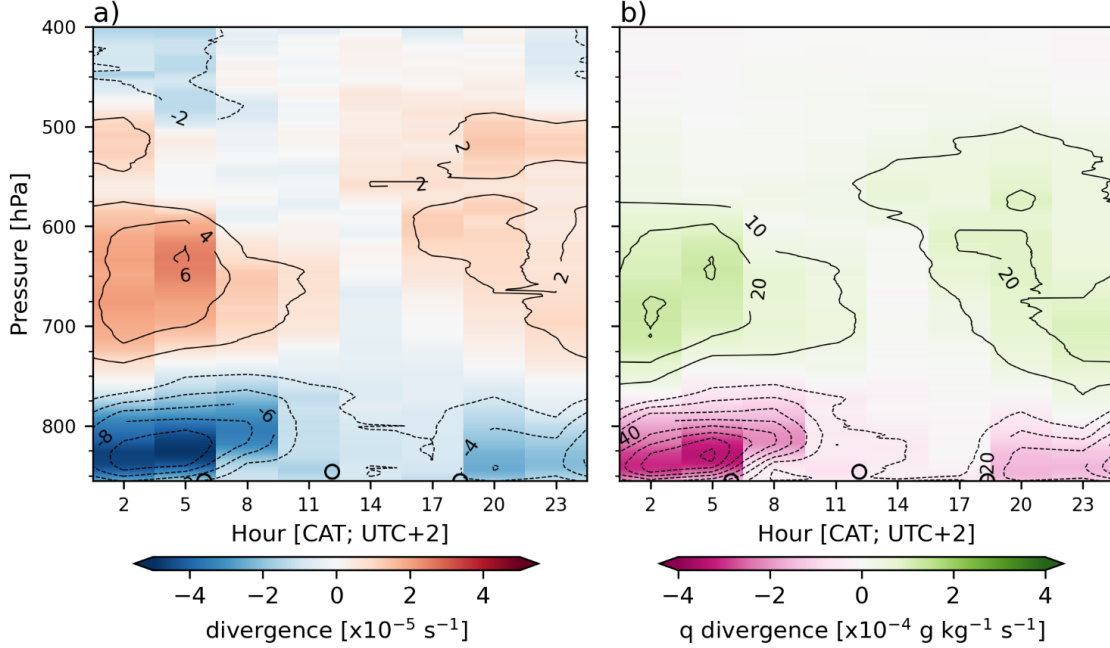


Figure 3.9: The component of the a) wind divergence [s^{-1}] and b) moisture flux divergence [$\text{g kg}^{-1} \text{s}^{-1}$] that is parallel to the bearing between the two field sites during field campaign Phase 1 & 3. Contours plot the magnitude of the difference in this component of the wind or moisture flux between the two field sites. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

In summary, this section has characterised strongly differing near-surface wind regimes across the CAB. These differences maximise at night, when weak near-surface north-westerlies on the moist side of the CAB converge with a strong (15.0 m s^{-1}) easterly LLJ on the dry side. The easterly LLJ strengthens overnight under an inertial oscillation, leading to a nocturnal maximum in convergence at the CAB at 05:00 LT. This is accompanied by mid-level divergence as the easterly LLJ is lifted above shallow north-westerlies.

3.5.3 How is the CAB modified by the diurnal cycle?

Our final research question concerns the modification of the CAB by the diurnal cycle. Drylines in other regions are strongly modified by the diurnal cycle of surface heating and the resulting reorganisation of the boundary layer, and results thus far suggest this is also true of the CAB.

We focus first on the moist side of the CAB (Nchila), as this is where diurnal variations in moisture are expected to be the largest. To diagnose changes in the vertical distribution of moisture, we analyse the specific humidity perturbation (q'), defined as the deviation of specific humidity (q) from its diurnal mean state ($\bar{q}$). Assuming that the mean moisture tendency is negligible over Phases 1 and 3, the evolution of q' through the diurnal cycle can be approximated by the perturbation moisture budget (Eq.1):

$$\frac{\partial q'}{\partial t} = E' - P' - \nabla \cdot (\mathbf{v}q)' \quad (3.1)$$

where E and P are the addition and removal of moisture from the atmosphere by evaporation and precipitation, respectively, and $-\nabla \cdot (\mathbf{v}q)$ represents the 3D moisture flux convergence.

In Section 3.5.2, we resolved a single horizontal component of $-\nabla \cdot (\mathbf{v}q)$ across the CAB. Figure 3.10a shows that the diurnal cycle of Nchila q' is well explained by a) this component of the moisture flux divergence (contoured) and b) vertical turbulent mixing. A shallow layer of near-surface moisture accumulates overnight under low-level moisture flux convergence. After sunrise, surface heating drives turbulent boundary-layer eddies that mix this near-surface moisture upward and dry air downward, redistributing moisture through the boundary layer. Then from 17:00 LT through to the next morning, moisture flux divergence between 750 hPa and 500 hPa exports moisture, leading to gradual mid-level drying. Over the full diurnal

cycle, the column-integrated moisture tendency approaches zero, as nocturnal low-level accumulation is balanced by mid-level export. These processes act to maintain moist conditions to the north of the CAB in a way that is consistent with that proposed by Howard and Washington (2019).

Diurnally varying moisture (q') on the moist side of the CAB directly modulates the strength and depth of the dryline. Figure 3.10b shows that the CAB is strongest (up to 7.9 g kg^{-1}) at 05:00 LT but also at its most shallow, with no cross-CAB moisture contrast above 750 hPa ($\approx 1 \text{ km}$ above the surface). During the day, strong turbulent mixing (Figure 3.10a) weakens but deepens the CAB such that by 17:00 LT it extends through the depth of the boundary layer ($\approx 3.5 \text{ km}$) but is characterised by a moisture gradient of just 2.0 g kg^{-1} . Comparison of q' at Nchila to that at Solwezi (not shown) indicates that changes in dryline strength are driven primarily by moisture perturbations on the moist side of the CAB, with much smaller variability on the dry side. The maintenance and modulation of the moisture gradient at the CAB can therefore be explained by the combined effects of (i) low-level moisture flux convergence, (ii) mid-level moisture flux divergence, and (iii) turbulent boundary-layer mixing. Interestingly, the diurnal cycle of CAB intensity is out of phase with that of drylines over the U.S. Great Plains, which typically strengthen during the afternoon and weaken overnight (Schaefer, 1974); this contrast is discussed further in the following section.

Strong diurnal modulation of the CAB would be expected to influence convection at and near the CAB. Drylines elsewhere often act as preferred locations for convective initiation (McCarthy and Koch, 1982; Bluestein and Parker, 1993; Ziegler and Rasmussen, 1998; Bergmaier and Geerts, 2015; Bai et al., 2019; van Schalkwyk et al., 2023), but the extent to which this applies to the CAB is not known. We therefore investigate the diurnal cycle of convection across the CAB in Figure 3.11 using $10.8 \text{ }\mu\text{m}$ brightness temperatures as a proxy: in the absence of warm rain

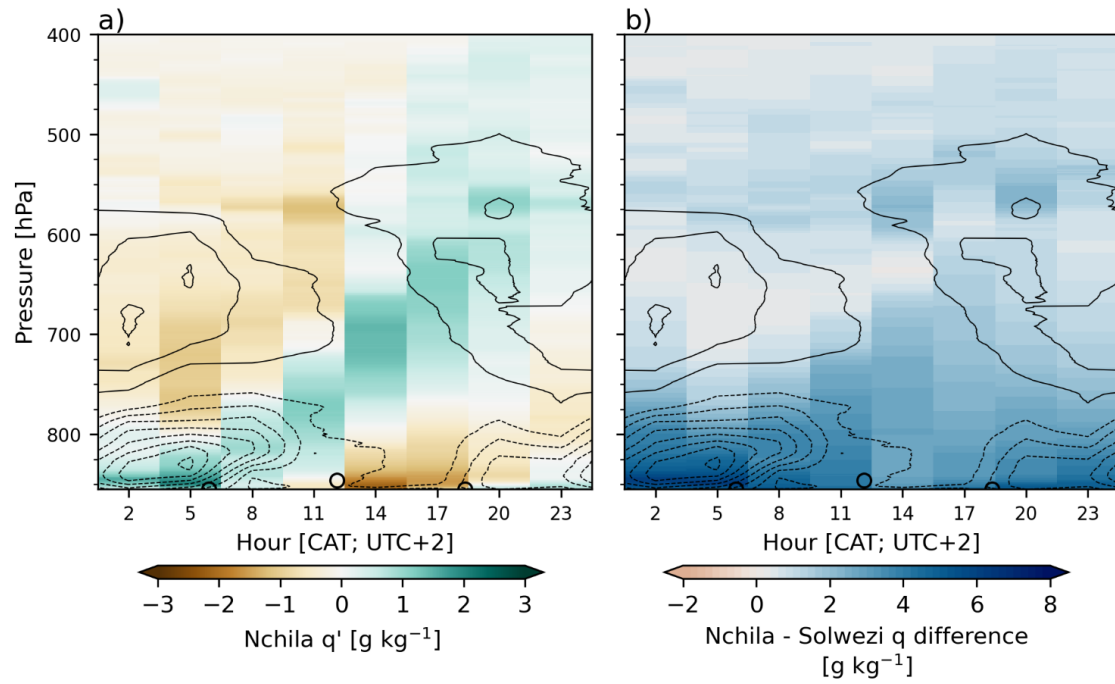


Figure 3.10: The diurnal cycle of a) the diurnal Nchila specific humidity perturbation (q') [g kg⁻¹] at the Nchila field site (moist side of the CAB) and b) the difference in specific humidity between Nchila and Solwezi [g kg⁻¹], both during field campaign Phase 1 & 3. Overlaid are contours of the component of moisture flux divergence parallel to the bearing between the two sites. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

processes, cloud-top brightness temperatures are a robust predictor of precipitation rates across equatorial Africa (Maidment et al., 2014; Funk et al., 2015; Andrews et al., 2025).

Figure 3.11 shows the diurnal cycle of $10.8\ \mu\text{m}$ brightness temperatures is relatively uniform across $\sim 700\ \text{km}$ to the south of CAB, with a maximum near local midday (12:00 LT) under strong shortwave heating and a minimum shortly before sunrise due to nocturnal longwave cooling. At and immediately northwest of the CAB, midday brightness temperatures are modestly reduced, consistent with the presence of scattered cumulus. The nocturnal brightness temperature minimum occurs earlier in the evening (21:00 LT) than to the south of the CAB, but does not reach values associated with deep convection. We hypothesise that this reflects the advection of anvils from convective systems located further to the northwest.

Further to the north-west, the nocturnal brightness temperature minimum becomes both earlier and colder, reaching $\approx 255\ \text{K}$ by 19:00 LT approximately $400\ \text{km}$ north-west of the CAB. This indicates that deep convection preferentially occurs well north of the CAB, rather than at the dryline itself. Beyond $400\ \text{km}$ convection is increasingly deep and/or frequent, and by $\approx 700\ \text{km}$ north the brightness temperature minimum shifts to the early morning (03:00 LT), potentially reflecting convective organisation deep in the Congo Basin (Dong and Washington, 2025).

A notable feature of Figure 3.11 is the large amplitude of the brightness-temperature diurnal cycle at and north of the CAB, indicating strong diurnal modulation of convection. We propose that this arises from dynamically forced nocturnal suppression of convection. North of the CAB, near-surface moisture is high, yielding substantial conditional instability ($1480\ \text{J kg}^{-1}$; Table 3.2). Shallow-to-congestus convection develops around the early-afternoon temperature maximum, leading to an early-evening minimum in brightness temperatures. After sunset, however, large-scale winds accelerate as frictional effects weaken. Low-level convergence at the

CAB intensifies and is accompanied by mid-level moisture-flux divergence, which extends into the Congo as moist air is replaced with drier air of subtropical origin. This divergence, and associated entrainment of dry air into existing convective systems, suppresses convection and inhibits mesoscale organisation, promoting relatively cloud-free mornings and efficient surface heating that reinforces the large diurnal amplitude. If correct, this mechanism implies that mesoscale dynamics at the CAB, and particularly mid-level moisture flux divergence, is key to regulating convection in the southern Congo Basin through austral spring.

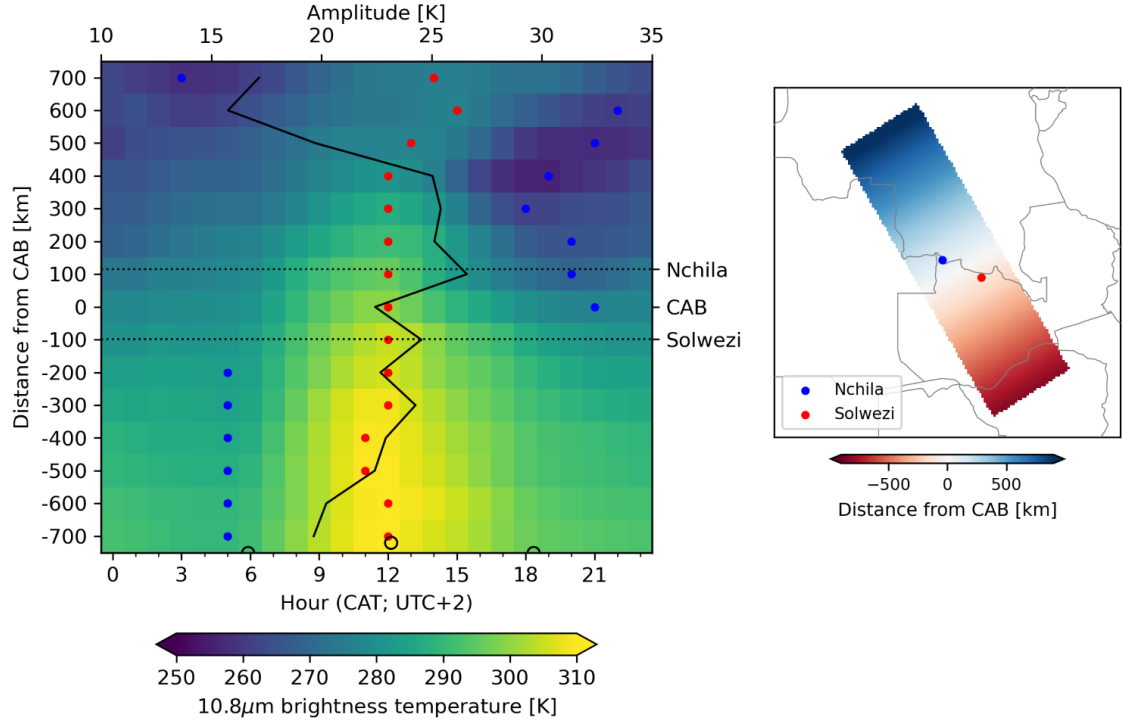


Figure 3.11: The diurnal cycle of MSG-3 SEVIRI 10.8 μm channel brightness temperature [K] by distance from the CAB during field campaign Phases 1 & 3. The location of the CAB is approximated as half way between the Nchila and Solwezi field sites with a bearing of 80° determined from SEVIRI 6.25 μm channel brightness temperatures (Figure 3.3). A black line plots the amplitude of the diurnal cycle by distance from the CAB. Red points show the hour of the brightness temperature maximum and blue points the minimum. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

3.6 Discussion

3.6.1 Conceptual model

The results presented here allow us to construct a conceptual model of the atmosphere across the Congo Air Boundary (CAB) that is grounded entirely in empirical observations (Figure 3.12). This synthesises key aspects of the structure of the CAB and its modulation through the diurnal cycle, with each element corresponding to components either resolved or implied by the observations presented in this study.

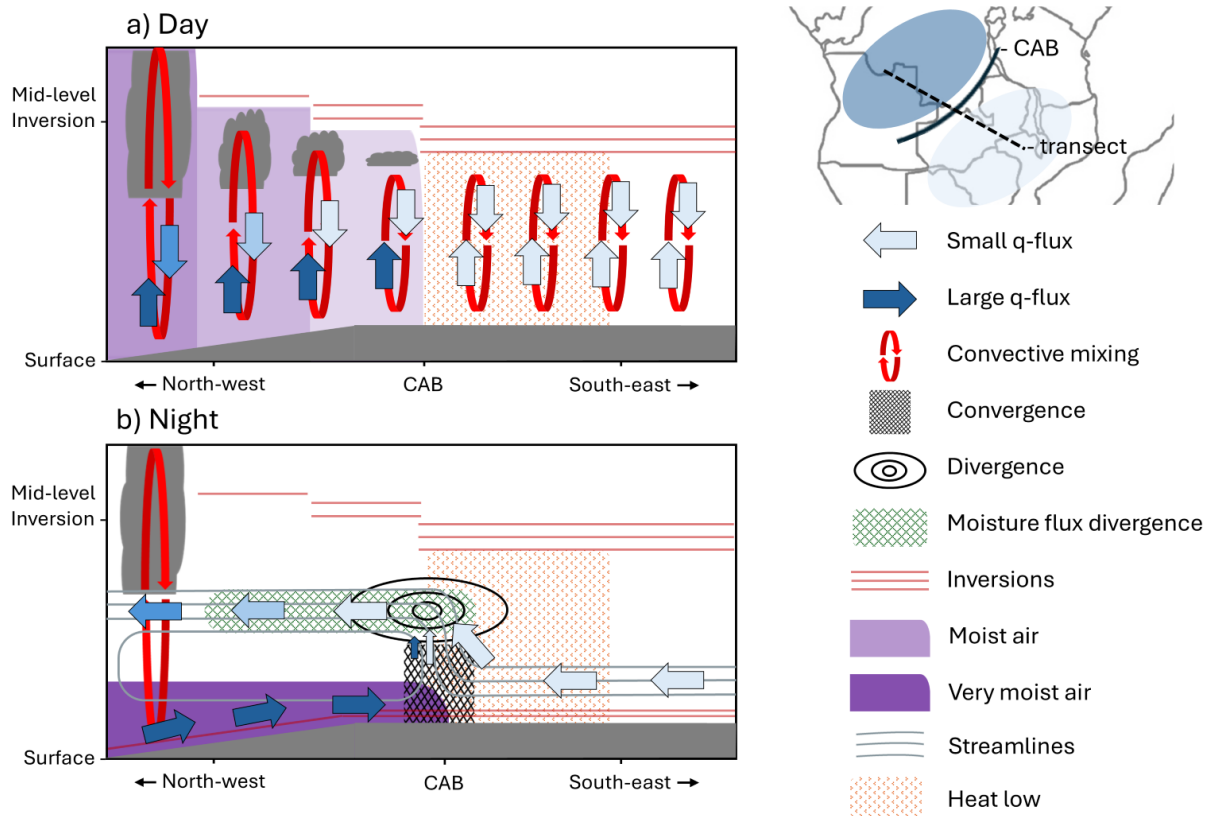


Figure 3.12: Schematic illustrating atmospheric processes across the Congo Air Boundary (CAB) a) during the day and b) at night.

During the day. On the moist side of the CAB, boundary-layer turbulence mixes (Congo) moisture upwards and dry(er) air of subtropical origin downward, drying the surface and weakening the cross-CAB moisture gradient. Moist convection is

shallow-to-congestus in nature, inhibited by midlevel stability which decreases into the Congo basin as distance from the CAB increases. On the dry side, the boundary layer is dominated by intense dry convection associated with the heat low and capped by a strong mid-level inversion.

At night. Following the cessation of surface heating, radiative cooling leads to the development of a stable surface layer and suppression of turbulent mixing. Surface winds adjust toward a new balance of forces, producing an ageostrophic acceleration toward low pressure associated with the heat low. At the CAB, strong low-level convergence develops between shallow moisture-laden north-westerlies and dry subtropical easterlies, sharpening the near-surface dryline. This is accompanied by mid-level moisture-flux divergence as easterlies are lifted above north-westerlies, inducing a drying tendency in the upper boundary layer. This nullifies the midlevel cross-CAB moisture gradient and contributes to the suppression of convection, meaning that only storms deep into Congo are able to organise and persist through the night.

3.6.2 The CAB and the heat low

Heat lows are regions of low surface pressure that develop under intense surface heating, large-scale subsidence, and clear-sky conditions (Racz and Smith, 1999; Attwood, 2024). Reanalysis-based studies show that in austral spring, a heat low forms preferentially over southern Angola and extends eastward across Zambia and the tropical edge (Howard and Washington, 2018; Attwood et al., 2024). Consistent with this, our observations evidence a heat low-like regime to the south of the CAB, where the afternoon boundary layer is near dry-adiabatic ($9.6\text{ }^{\circ}\text{C km}^{-1}$) to approximately 650 hPa and capped by a strong mid-level inversion. The elevated Katanga plateau enables efficient heating of a relatively shallow atmospheric column south of the CAB (Zangl and Chico, 2006; Smith and Spengler, 2011), providing a plausible mechanism for the nocturnal ageostrophic acceleration and subsequent convergence of winds at the CAB.

Howard and Washington (2019) hypothesised that the heat low contributes to CAB maintenance, whereby the atmosphere is moistened under nocturnal advection toward the heat low, followed by daytime drying associated with turbulent mixing. Results in Section 3.5.3 support this hypothesis and suggest a tight spatial and temporal relationship between the heat low, the CAB and moisture convergence at the tropical edge that warrants further investigation given documented trends in heat low intensity (Attwood et al., 2024).

3.6.3 The CAB and shallow overturning

Our results evidence a shallow overturning circulation on the moist side of the CAB, indicated by streamlines in the schematic of Figure 3.12. This circulation comprises north-westerly low-level flow towards the CAB, forced ascent associated with low-level convergence, and a mid-level return flow embedded within the AEJ-S. Two branches are directly resolved in observations: low-level north-westerlies and the mid-level return flow. A third, ascent at the CAB, is inferred from the convergence resolved in Section 3.5.2. Together, these features are consistent with shallow overturning in a vertical plane normal to the CAB, implying rotation about a horizontal axis broadly southwest–northeast (parallel to the CAB).

This shallow overturning circulation has implications for the thermodynamic environment of the southern Congo that help to explain the relationship between the CAB and convection. The mid-level return branch advects relatively warm, dry subtropical air into the southern Congo and is associated with mid-level moisture-flux divergence at the CAB. Analogous circulations inhibit convection in other monsoon regions including West Africa (Shekhar and Boos, 2017), India (Parker et al., 2016), and Australia (Xie et al., 2010), consistent with the well-established sensitivity of deep convection to mid-level humidity (Derbyshire et al., 2004; Sobel and Bellon, 2009; Holloway and Neelin, 2009).

This diagnosis may help to address longstanding uncertainty regarding the relationship between the CAB and the tropical rain belt, and specifically whether the CAB lies within the rain belt, marks its southern margin, or is displaced poleward of it (Howard and Washington, 2019). Our results suggest that low-level moisture convergence and high surface MSE at the CAB are not coupled to deep convection, which instead preferentially occurs further equatorward. In this sense, the CAB is displaced southward of the tropical rain belt.

3.6.4 The CAB and the African Easterly Jet South

The AEJ-S is a mid-tropospheric easterly jet to the north of the CAB, diagnosed in Section 3.5.2 as mid-level jet at 650 hPa on the moist side of the CAB, associated with wind speeds of up to 9.2 m s^{-1} overnight and 5.6 m s^{-1} during the day. To the author’s knowledge, this represents the first observations of the diurnal cycle of the AEJ-S.

The AEJ-S is traditionally interpreted as a thermal-wind response to the meridional temperature gradient between a dry subtropical regime over southern Africa and a moist convective regime in the Congo Basin (Nicholson and Grist, 2003; Kuete et al., 2020). However, this explanation appears incomplete, as it does not readily explain the observed diurnal cycle or the spatial preference of the jet immediately northwest of the CAB. Here, we hypothesise that the lifting of subtropical easterlies at the CAB is an additional, previously unrecognised maintenance mechanism through momentum transfer to the mid-levels. This may help to explain the relationship between a persistent CAB, a strong AEJ-S and low rainfall totals in the southern Congo (Jackson et al., 2009; Dezfuli and Nicholson, 2013; Kuete et al., 2020), and is interesting in the context of observed strengthening of the AEJ-S, particularly in October (Tatro and Zuidema, 2025).

3.6.5 The CAB and the Botswana High

The Botswana High is a semi-permanent mid-tropospheric anticyclone at approximately 500 hPa over subtropical southern Africa, associated with large-scale subsidence and capping a heat low-related dry-convective boundary layer over the continental interior (Reason, 2016; Moses et al., 2023). The feature is typically characterised using monthly-mean indices of 500 hPa geopotential height (e.g., Driver and Reason, 2017), and so its manifestation on daily timescales and relationship to the CAB are poorly understood.

Our radiosonde observations document persistent mid-level inversions near 550 hPa, with substantially greater strength on the dry side of the CAB (mean ~ 1.03 °C at Nchila) where they cap a deep dry-adiabatic boundary layer. We interpret these mid-level inversions as a result of subsidence associated with the Botswana High. This is consistent with observations from the SAFARI-1992 campaign, which identified persistent subsidence inversions near 500 hPa associated with the Botswana High that limited vertical turbulent mixing to approximately 3–4 km above the surface (Garstang et al., 1996). The pronounced cross-CAB gradients in both mid-level inversion strength and low-level lapse rates, over relatively short spatial scales, suggest that on daily timescales the CAB may delineate the equatorward extent of the Botswana High.

3.6.6 Comparison with other drylines

The CAB shares several dynamical features with drylines in other regions, raising a question over the extent to which the CAB is dynamically unusual. In many respects, our schematic compares well with conceptual models of drylines elsewhere. For example, Great Plains drylines are characterised by the lifting of dry (westerly) flow over moist (easterly) flow, a configuration also reported at the West African Intertropical Discontinuity (ITD; Pospichal et al., 2010) and for Argentinean drylines

(Bechis et al., 2020). Similar to the CAB, observations of the ITD from Nangatchori, Benin show nocturnal mid-level drying (i.e., moisture flux divergence), with turbulent eddies mixing near-surface moisture vertically before nocturnal north-easterlies export mid-level moisture and dry the upper boundary layer (Pospichal et al., 2010). Reanalysis-based moisture budget analyses of Argentinean drylines suggest a similar sequence of processes (Bechis et al., 2020, 2022). As at the CAB, the net effect is the tilting of the dryline toward the moist air at night, such that the dryline is deepest during the day and shallowest at night.

Some differences emerge in the comparison of our results to conceptual models of Great Plains drylines. Most notably, the diurnal cycle of dryline strength is antiphase. This has been attributed to a unique role of topography in the Great Plains, where sloping terrain prompts daytime sharpening of the dryline through differential boundary-layer growth and a downslope terrain effect on mixing (Schaefer, 1974; Arnup and Reeder, 2007, 2009). In contrast, the flatter topography of southern Africa allows for more uniform boundary-layer growth. A second distinction is vertical structure: conceptual models of drylines in the Great Plains feature a strong stable layer between low-level moist air and mid-level dry air. In contrast, at the CAB there is no evidence of a stable layer separating low-level moisture from drier air aloft (Figure 3.8a).

Finally, the CAB appears to belong to a class of drylines that are not typically associated with deep convection. Drylines elsewhere frequently act as preferred locations for convective initiation, often 15–25 km into the moist side (Bluestein and Parker, 1993; Ziegler and Rasmussen, 1998; Bergmaier and Geerts, 2015). In southern Africa, van Schalkwyk et al. (2023) show that 76% of Kalahari drylines are associated with deep convection during austral summer. In contrast, the CAB appears rarely associated with deep convection. We hypothesise this reflects convective inhibition by (i) large-scale subsidence and (ii) dynamically maintained

mid-level drying through the cross-CAB advection of dry air.

3.6.7 CAB breakdown

This work represents an observational case study of a canonical "CAB-in-place" synoptic setting, so it has not explored aspects of the atmosphere at the CAB during CAB breakdown, which Knight and Washington (2024) show is associated with a rapid convective regime transition over southern Africa on timescales of 3–5 days and the onset of the summer rains. Our results indicate that moist convection at and north of the CAB is suppressed by a combination of (i) subsidence-induced mid-level stability and (ii) mid-level moisture-flux divergence, with (iii) moisture limitation providing an additional constraint south of the CAB. This suggests possible pathways by which CAB breakdown might occur. In particular, changes in mid-level stability or the balance between low-level moisture convergence and mid-level moisture divergence associated with shallow overturning could permit moisture accumulation and the development of moist convection at the CAB, contributing to its breakdown. This has interesting parallels to the West African monsoon onset, which is similarly governed by the balance of low-level moisture convergence and mid-level moisture divergence associated with shallow overturning, with inertial instability developing when the former overwhelms the latter (Hagos and Cook, 2007; Cook, 2015). We suggest that a detailed exploration of the local to mesoscale atmospheric processes underpinning CAB breakdown is a priority for future work.

3.6.8 Generalisability

An assumption of this work is that results derived from radiosonde observations at two tropical-edge field sites are generalisable to (i) other years and (ii) other locations along the CAB dryline. Definitive assessment of this assumption would require further targeted observations. However, Figure 3.4 and the reanalysis-based climatology of Howard and Washington (2019) indicate that the CAB is a large-

scale and spatially coherent feature, lending confidence that the processes identified here will be broadly applicable along its length. Additionally, conceptual models of drylines elsewhere built from spatially and temporally limited observations (e.g. Ziegler and Hane, 1993) have been shown by further analysis to be robust and representative.

The field campaign took place during the second year of a rare three-year ("triple-dip") La Niña event spanning 2020–2023 (Li et al., 2023; Thoithi et al., 2025, 2026). Such events are associated with distinct large-scale circulation anomalies over southern Africa, including a strengthened Mascarene High, enhanced easterly moisture fluxes from the southwest Indian Ocean, and a positive phase of the Southern Annular Mode, influencing rainfall, temperature extremes, and dry spell characteristics (Thoithi et al., 2025, 2026). While these influences are strongest during austral summer (January–April), regional rainfall anomaly patterns during September–November 2022 are consistent with the radiosonde IOP taking place under a La Niña-modified (i.e., non-neutral) background state. Some aspects of the observed structure of the CAB (e.g., mid-level subsidence inversions and south-of-CAB moisture fluxes) may be sensitive to this large-scale influence. However, key processes governing low-level convergence and dryline strength operate at the mesoscale and are primarily controlled by the diurnal cycle of surface heating. This suggests that, while the magnitude of individual features may vary across different background states, the conceptual model of CAB structure and maintenance remains robust. An explicit test of this would require further observations across different locations, years and background states. Accordingly, we hope this manuscript serves to strengthen the case for greater investment in observational capacity across central southern Africa.

3.7 Conclusion

This paper has presented the first detailed observations of the Congo Air Boundary (CAB) using upper-air and surface data from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project. These observations provide new insight into the structure, circulation, and diurnal modulation of the CAB, advancing understanding of atmospheric dynamics and thermodynamics at the data-sparse southern African tropical edge. The key findings are synthesised schematically in Figure 3.12.

Based on field observations between 1 October and 13 November 2022, we show the CAB to be a dryline and convergence-line featuring a specific humidity gradient of up to 12.0 g kg^{-1} per 100 km. On the dry side of the CAB the afternoon boundary layer is near dry-adiabatic ($9.6 \text{ }^{\circ}\text{C km}^{-1}$) capped by a midlevel inversion with a mean strength of $1.14 \text{ }^{\circ}\text{C}$. On the moist side, the boundary layer is more stably stratified ($9.1 \text{ }^{\circ}\text{C km}^{-1}$) and inversions weaker ($0.38 \text{ }^{\circ}\text{C}$) and more vertically dispersed. Daily maximum surface MSE is 8.4 kJ kg^{-1} higher on the moist side of the CAB, driven by the latent component, resulting in pronounced cross-CAB contrasts in conditional instability, with mean 14:00 LT CAPE 1480 J kg^{-1} on the moist side compared with 22 J kg^{-1} on the dry side.

We diagnose strongly contrasting nocturnal circulation regimes across the CAB. North of the CAB, 9.2 m s^{-1} mid-level easterlies associated with the AEJ-S overly weak near-surface north-westerlies, while to the south the circulation is characterised by a strong (15.0 m s^{-1}) easterly LLJ. This LLJ strengthens overnight under an inertial oscillation, such that convergence at the CAB maximises at 05:00 LT with a magnitude of $4.9 \times 10^{-5} \text{ s}^{-1}$. Nocturnal convergence is accompanied by mid-level moisture divergence as the dry (7 g kg^{-1}) easterly LLJ is lifted above moist (15 g kg^{-1}) north-westerlies. The structure and strength of the CAB dryline is strongly

modulated by the diurnal cycle, such that the CAB is shallow ($\approx 1\text{km}$) but strong (7.9 g kg^{-1}) at night and weak (2.0 g kg^{-1}) but deep ($\approx 3.5\text{km}$) during the day.

Our observations provide evidence for a shallow overturning circulation on the moist side of the CAB, comprising low-level north-westerly flow toward the CAB, ascent associated with low-level convergence, and a mid-level return flow embedded within the AEJ-S. We hypothesise that this circulation suppresses deep convection at and north of the CAB as the mid-level return branch advects warm, dry subtropical air into the southern Congo Basin. As a result, only beyond approximately 400 km north of the CAB does convection appear to organise into mesoscale convective systems.

Our results, which are grounded in observations of the physical climate system, establish a baseline against which the ability of models to simulate the CAB can be tested. This lays the groundwork for further research establishing whether models used for forecasting and climate projection have the fidelity to simulate the CAB, and by extension the dynamical elements that control the progression of rainfall southwards in early summer. Such work is essential for establishing confidence in projections of future drying and advancing seasonal forecasting skill.

3.8 Acknowledgments

The first author is funded by the Keble College Bigg Scholarship in African Climate Science. The DRY-CAB project is funded by the NERC Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) grant (NE/V011928/1). Richard Washington was project PI, with Neil Hart and Steve Woolnough co-investigators and Chris Reason contributing. The project is deeply indebted to Edson Nkonde, Director of the Zambia Meteorological Department, and to Felix Imbwae and Col Rodney Mulenga. Wallace Kasongo and his team – Lawrence Chisengele, Sakuwaha Kalumbi, Fanold Moonga, Enock Moomba, Chinoya Chinoya,

Lucy Namonje, Kakuhu Mubanga, Ashili Mwila, Ireen Mwansa, Nathan Kaluwaji, Levy Zulu, Stanely Shakalima, Davies Kapya Langeni, Wilfred Kabwe Mwaba, Ray Nayunda, Enock Chisha, and Auster Mweene – led data collection at the Solwezi radiosonde station. The Nchila radiosonde station was supported by Sebastian Engelstaedter, Kitty Attwood, Alice Jardine and Chris Edmunds. We thank Mark Ronald and Doug Hanna at Sakeji School for invaluable practical assistance in the field and Pete and Lynne Fisher of Hillwood Farm for hosting us at Nchila.

3.9 Afterword to Chapter 3

Chapter 3 has fulfilled the first aim of this thesis by resolving the structure and circulation of the CAB in observations. Using detailed surface and upper-air measurements from the DRY-CAB field campaign, the chapter has characterised the structure, circulation, and diurnal modulation of the atmosphere across the CAB.

The analysis establishes the CAB as a sharp dryline and convergence zone separating two distinct thermodynamic and circulation regimes, and demonstrates that its structure and intensity are strongly modulated by the diurnal cycle of surface heating. By resolving the key thermodynamic and circulation elements of the atmosphere across the CAB and integrating them into an empirically grounded conceptual model, Chapter 3 directly addresses Aim 1 of this thesis. In doing so, it provides new insight into the structure and maintenance of the CAB and advances understanding of climate dynamics at the data-sparse southern African tropical edge.

The results of this chapter provide a benchmark against which reanalysis representation of the CAB will be evaluated in Chapter 4.

4 | Evaluation of the Congo Air Boundary in re-analyses during the 2022 DRY-CAB field campaign



Deep convective clouds over the Democratic Republic of the Congo are lit by the setting sun. 3 November 2022.

The Congo Air Boundary (CAB) is a synoptic-scale dryline and convergence zone that forms across southern Africa from August to November and plays a central role in both the timing of rainfall onset and projections of regional drying. Until recently, our understanding of the CAB has relied almost entirely on reanalysis and model data. However, the fidelity with which the CAB is reproduced in these datasets is not known. Using a new observational benchmark derived from the DRY-CAB field campaign, this study evaluates the ability of three reanalyses – ERA5, MERRA-2, and JRA-3Q – to reproduce the CAB. All three exhibit substantial errors in the CAB’s mesoscale structure and circulation: no product captures dryline strength (biases $\geq \pm 25\%$), and only ERA5 successfully reproduces its diurnal evolution. A process-based evaluation reveals that these errors stem from misrepresented moisture transport to the north of the CAB. North-westerly moisture fluxes that advect moisture to the CAB are of the wrong sign in MERRA-2 (-120% bias), exhibit an incorrect diurnal cycle in JRA-3Q (maximum at 20:00 rather than 02:00), and arise from compensating biases in ERA5. ERA5 and MERRA-2 additionally exhibit excessive 11:00 LT instability and daytime near-surface drying (biases 71–221%). We show that these errors propagate upscale to degrade a) reanalysis convective environments and b) the simulated seasonal evolution of the tropical-edge atmosphere through rainfall onset. Our findings demonstrate the importance of CAB representation to reanalysis fidelity at the southern African tropical-edge and highlight the inadequacy of reanalyses for studying mesoscale processes across the data-sparse region.

4.1 Foreword to Chapter 4

Chapter 4 addresses the second aim of this thesis by evaluating how well the CAB is reproduced in three reanalyses during the DRY-CAB campaign. This is motivated by the fact that we do not know whether key aspects of the CAB are absent or misrepresented in these datasets.

The chapter applies a process-based evaluation methodology, guided by the conceptual model developed in Chapter 3, to assess the performance of three recent reanalysis products: ERA5, MERRA-2, and JRA-3Q. The evaluation focuses on whether these products reproduce the key features that comprise the CAB during the DRY-CAB field campaign.

Analysis shows that while all three reanalyses reproduce a CAB at the synoptic scale, they exhibit substantial errors in its mesoscale structure and circulation. The most pronounced errors occur north of the CAB, where moisture availability and transport differ substantially between products. By examining how errors in the representation of the CAB relate to the representation of its key comprising features, Chapter 4 highlights reanalysis weaknesses at the tropical edge, informs priorities for model development, and underscores the need for caution when using reanalyses in tropical-edge research.

Chapter 4 is presented in the form of a manuscript:

Knight, C., Washington, R., Munday, C., Nkonde, E., Imbwae, F., and Kasongo, W. (2026). Evaluation of the Congo Air Boundary in reanalyses during the 2022 DRY-CAB field campaign.

Submitted to *Journal of Climate* on 07 February 2026.

4.2 Introduction

The August to November pre-rainfall onset circulation at the southern African tropical edge is characterised by a distinguishing large-scale circulation feature, the Congo Air Boundary (CAB). The CAB is defined as the synoptic-scale convergence zone and dryline that occurs where near-saturated low-level north-westerlies originating from the equatorial east Atlantic and Congo Basin meet easterly trade winds from the tropical southwest Indian Ocean, which are dried by strong heating of the continental surface and diluted by deep tropospheric subsidence (Torrance, 1979; Hills, 1979; Levin et al., 2009; Tierney et al., 2011; Dezfuli and Nicholson, 2013; Nicholson, 2015; Howard and Washington, 2019) (Figure 4.1).

The CAB is associated with a strong north-west to south-east gradient in rainfall, moisture and convective available potential energy (CAPE). To the north-west, the atmosphere is characterised by high boundary-layer moist static energy (MSE) and lapse rates approaching the saturated adiabatic lapse rate, while to the south-east the atmosphere is characterised by lower boundary-layer MSE and a stable mid-troposphere (Torrance, 1979; Howard and Washington, 2019; Knight et al., 2026). The breakdown of the CAB is therefore key to the southward seasonal migration of the tropical rain belt into southern Africa, and by extension rainfall onset (Knight and Washington, 2024). The feature is also central to rainfall projections under future warming scenarios, with early summer drying and a delay to rainfall onset across the tropical edge coupled to a delay to CAB breakdown in global circulation models (Howard and Washington, 2020).

Prior to Knight et al. (2026), our understanding of the CAB was based almost entirely on reanalysis and model data. However, there is uncertainty over whether reanalyses can accurately resolve processes at the southern African tropical edge, stemming from two core issues. First, the paucity of *in situ* observations – partic-

ularly station and radiosonde data – means that reanalyses are weakly constrained near the surface and rely heavily on their modelled components. Second, observational and reanalysis diagnostics point to intricate mesoscale dynamics at the CAB (Howard and Washington, 2019; Knight et al., 2026), but these are largely parameterised rather than explicitly resolved. Reanalyses clearly feature a CAB at the synoptic scale on 5 October 2022, when Knight et al. (2026) report a specific humidity gradient of 12.0 g kg^{-1} per 100km between automatic weather stations in north-west Zambia associated with the CAB (Figure 4.1). However, no work to date has evaluated reanalysis representation of the CAB against observations, meaning we do not know a) whether essential processes operating at the dryline are absent or misrepresented, or b) the extent to which the representation of the CAB differs between reanalyses.

Here we seek to address this knowledge gap through evaluating three reanalyses against observations from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project. Although limited in spatial and temporal extent, the DRY-CAB observations provide a detailed, unassimilated benchmark of the southern African tropical-edge atmosphere. To maximise insight from this targeted sampling, we adopt a "process-based" evaluation framework to assess whether reanalyses realistically simulate the key features that comprise the CAB as described by Knight et al. (2026). Specifically, we assess the extent to which reanalyses reproduce defining features of the CAB, such as dryline moisture gradients, horizontal and vertical moisture transport, low-level jets (LLJs) and mid-level stability. This approach allows biases to be interpreted in terms of underlying physical processes, providing greater guidance on model weaknesses and priorities for future development (Neelin et al., 2023).

In this work, we seek to address the following three research questions:

1. How well do reanalyses reproduce the key thermodynamic and circulation

features that comprise the Congo Air Boundary?

2. How do diagnosed differences between reanalyses and observations influence convective environments?
3. How do diagnosed differences between reanalyses and observations influence rainfall onset meteorology?

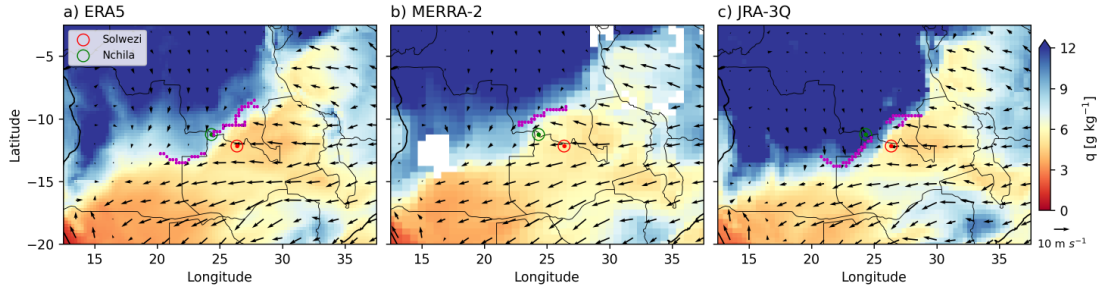


Figure 4.1: Day-mean near-surface (850 hPa) specific humidity [g kg^{-1}] and vector winds [m s^{-1}] over subtropical southern Africa on 5 October 2022, when Knight et al. (2026) report that the CAB was located between the Nchila (green) and Solwezi (red) field sites and associated with a specific humidity gradient of 12.0 g kg^{-1} per 100 km. The reanalyses are a) ERA5, b) MERRA-2 and c) JRA-3Q. The location of the Nchila and Solwezi field sites are marked with green and red circles respectively. The CAB dryline, as detected by the canny-edge method of Howard and Washington (2019) (after interpolation to a $0.25^\circ \times 0.25^\circ$ grid) is plotted in purple.

4.3 Methods

4.3.1 Reanalysis evaluation

It is not possible to know a priori which reanalyses provide the most faithful representation of the tropical edge atmosphere, meaning evaluation is required (Flato et al., 2014). Performance-based metrics such as correlation coefficients, root-mean-square error, or mean bias can provide useful benchmarks but may be misleading, as models may reproduce observations through compensating errors or processes that differ from those in the real world (e.g., Zhang et al., 2013). Furthermore,

such statistics rarely reveal why a model is wrong, limiting their value in identifying model weaknesses and guiding model development.

Process-based evaluation addresses these limitations through examining the mechanisms and processes through which models generate their outputs and assessing whether they reflect those operating in the real atmosphere (e.g., Podglajen et al., 2014; James et al., 2015; Itterly et al., 2018; Daron et al., 2019; Kenfack et al., 2023; Best et al., 2025). Data from field campaigns provide a crucial source of detailed, independent (unassimilated) observations for such analysis (e.g. Betts et al., 1996; Betts and Jakob, 2002; Duynkerke and Teixeira, 2001; Largeron et al., 2015; Itterly et al., 2018; Graham et al., 2019; Munday et al., 2024).

The DRY-CAB project has recently provided the first detailed *in situ* observations of the atmosphere in proximity to and across the CAB. From these observations, Knight et al. (2026) developed a schematic model of tropical-edge atmosphere associated with the CAB (Figure 4.2), identifying six defining features: (1) a dryline and convergence zone, (2) the north-westerly moist low-level jet, (3) the easterly dry low-level jet, (4) the African Easterly Jet South, (5) dry-convective mixing, and (6) mid-level stability associated with the Botswana High. This feature-level description of the CAB provides the basis for a process-based evaluation of reanalyses.

In this study, we use these six features as diagnostic benchmarks to evaluate the ability of three reanalyses to reproduce the CAB. This approach is particularly appropriate given the limited spatial and temporal sampling of the available observations. We aim to identify where and why differences arise between reanalyses and observations, as well as between reanalyses themselves. By interpreting these differences in terms of the underlying physical processes, our approach supports a more detailed assessment of model weaknesses and helps to inform priorities for future development (Neelin et al., 2023).

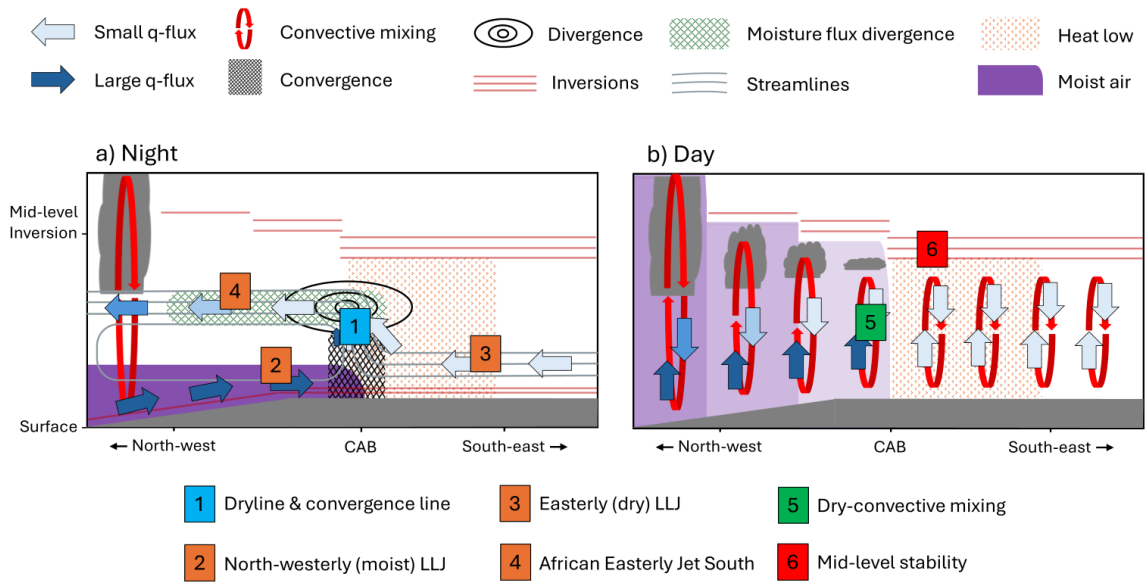


Figure 4.2: Schematic from Knight et al. (2026), derived from DRY-CAB observations, illustrating the key thermodynamic and circulation features that comprise the CAB a) at night and b) during the day. The six defining features are (1) a dryline and convergence zone, (2) the north-westerly moist low-level jet, (3) the easterly dry low-level jet, (4) the African Easterly Jet South (AEJ-S), (5) dry-convective mixing, and (6) mid-level stability associated with the Botswana High.

4.3.2 Data

4.3.2.1 Field observations

We use surface and upper-air (radiosonde) observations from the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project. The main field campaign comprised intensive radiosonde and surface observations from two sites in north-west Zambia through austral spring 2022. Radiosonde supersites, equipped with radiosondes, an automatic weather station (AWS) and a Doppler LiDAR, were located at Nchila (11.249°S, 24.327°E) and Solwezi (12.171°S, 26.364°E) and supported by three additional AWS (Figure 4.1). The Nchila and Solwezi radiosonde sites were located on the Katanga Plateau at an altitude of 1400 m ($\approx$ 859 hPa) and 1393 m ($\approx$ 861 hPa) respectively, with Solwezi 244.2 km to the east-southeast of Nchila. A full description of the DRY-CAB project, including justification of site selection and sampling strategy, is provided in Washington et al. (2026, in preparation).

During the field campaign intensive observational period (IOP), GRAW DFM-17 radiosondes were released at 3-hourly intervals from both radiosonde supersites for 44 days from 1 October – 13 November. Radiosonde release times were 00, 03, 06, 09, 12, 15, 18, and 21 UTC. The field site time zone is Central African Time (CAT; UTC+2), and we report all times in this study in local time, denoted ‘LT’ (e.g., 15:00 LT = 13:00 UTC).

The 44-day field campaign IOP from 1 October to 13 November may be divided into five distinct meteorological phases (Phase 1-5) defined by the daily maximum in field site surface MSE. Absolute MSE values and inter-site differences allow the CAB to be located during each phase – this is summarised in Table 4.1 and further described in Knight et al. (2026).

Table 4.1: Dates and durations of the five meteorological phases of the 44-day field campaign IOP. Each field site is assigned "Moist", "Dry" or "Breakdown" for each phase depending on the location of the CAB. During Phase 5 ("Breakdown") the CAB did not form. Sampling was "Cross-CAB" in Phase 1 & 3.

Phase	Start date	End date	Days	Regime at site	
				Nchila	Solwezi
Phase 1	2022-10-01	2022-10-05	5	Moist	Dry
Phase 2	2022-10-06	2022-10-15	10	Dry	Dry
Phase 3	2022-10-16	2022-10-22	7	Moist	Dry
Phase 4	2022-10-23	2022-10-30	8	Moist	Moist
Phase 5	2022-10-31	2022-11-13	14	Breakdown	Breakdown

The migration of the CAB through the five meteorological phases means the dataset includes periods where the CAB was between sites, and periods where both sites were subject to the same regime (Table 4.1). This variability gives rise to two possible sampling strategies.

A strict "cross-CAB" sampling strategy considers only Phases 1 and 3, during which the CAB bisected the two field sites. Under this approach, data from Nchila details the moist side, while data from Solwezi details the dry side. While Knight et al. (2026) adopted this approach, a disadvantage is the low number of days ($n=12$), which offers a less robust evaluation with a greater risk that reanalysis error is not representative of systematic deficiencies.

An alternative "by-regime" sampling strategy pools data from all phases and sites into three regimes ("dry", "moist", "breakdown") and then composites on each regime. Under this approach, moist-side features such as the north-westerly LLJ are resolved using data from both Nchila (Phases 1, 3, and 4) and Solwezi (Phase 4). This method substantially increases the sample size (dry = 32 days, moist = 28 days, breakdown = 28 days) by allowing for the inclusion of instances when both sites sample the same regime. A disadvantage of this approach is that dynamics may vary with distance from the CAB, potentially grouping distinct conditions.

However, Knight et al. (2026) show that such within-regime differences are small compared to the differences between regimes. This would also only impact absolute values, rather than the robustness of any comparison.

In this work, both sampling strategies are required, as certain CAB features such as dryline intensity and low-level convergence cannot be defined without simultaneous observations across the CAB. We favour the "by-regime" sampling strategy where possible because it provides a larger sample for a more robust comparison. In all cases, the sampling strategy used is clearly stated. As a sensitivity test, all figures were reproduced using only the cross-CAB sample and results were unchanged.

4.3.2.2 Reanalyses

Reanalyses combine historical weather observations with a numerical weather prediction model and data assimilation system to provide a dynamically consistent estimate of the global atmospheric state at sub-daily resolution. Reanalyses assimilate both conventional (e.g., radiosondes, surface stations, aircraft reports) and satellite-based (e.g., atmospheric motion vectors, microwave radiances) observations using either 3D-Var or 4D-Var techniques. In regions where conventional observations are sparse, such as subtropical southern Africa, reanalyses rely more heavily on their modelled components and are less constrained by data assimilation (Podglajen et al., 2014; Roffe and van der Walt, 2023).

In this analysis, we evaluate three reanalysis products: ERA5, MERRA-2 and JRA-3Q. We have selected these reanalyses on the following criteria: a) they are the latest reanalyses from their respective modelling centres, b) they are regularly used in present-day climate research, and c) they are updated in near real time (as of publication). Characteristics of these reanalyses are summarised in Table 4.2 and described below.

- ERA5 (Hersbach et al., 2020) is ECMWF's latest-generation reanalysis, pro-

duced using the Integrated Forecast System (Cy41r2) with 4D-Var data assimilation and released in 2017. Although ensemble-based uncertainty estimates are available, only the high-resolution deterministic realisation is used.

- The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), is the latest reanalysis produced by NASA’s Global Modelling and Assimilation Office (Gelaro et al., 2017), released in 2016. It uses version 5.12.4 of the GEOS atmospheric data assimilation system, which combines the GEOS-5 model physics with 3D-Var data assimilation on a 6-hourly cycle. Unlike ERA5 and JRA-3Q, it assimilates only clear-sky radiances.
- JRA-3Q (Kosaka et al., 2024) is the Japanese Meteorological Agency’s third-generation global reanalysis, released in 2023 and superseding JRA-55. It is produced using the JMA operational system as of December 2018 with 4D-Var assimilation.

Table 4.2: Reanalysis products used in this study.

Reanalysis	Time res.	Lon res.	Lat res.	Vert. levels	Assim. method
ERA5	1-hourly	0.25°	0.25°	137	4D-Var
MERRA-2	3-hourly	0.625°	0.5°	72	3D-Var
JRA-3Q	6-hourly	0.375°	0.375°	100	4D-Var

4.3.3 Comparison considerations

There are multiple approaches to comparing gridded model output with point observations, and no universally accepted best practice exists. Here, we provide a high-level overview of our choices and assumptions; a more detailed justification along with sensitivity testing is presented in Appendix A.

First, radiosondes are assumed to be Eulerian point measures valid for the release location and time. To collocate observations with gridded reanalysis fields, we adopt

a nearest-neighbour approach. Sensitivity tests using alternative spatial co-location methods indicate that comparison metrics are insensitive to colocation method (Figure 4.15).

Pressure-level reanalysis fields are used throughout, as these are the most widely available and are commonly employed in reanalysis-based studies. All reanalyses are interpolated to a common 25 hPa pressure grid. Single-level comparisons use only pressure levels common to both radiosonde and reanalysis data, while bulk layer quantities are derived by interpolating radiosonde profiles to the reanalysis grid. Differences in surface pressure between observations and reanalyses are small, and no adjustment for feature height relative to the surface is required.

Temporal matching is constrained by data availability. ERA5 and MERRA-2 provide a 3-hourly output for pressure-level variables, while data for JRA-3Q is only available at 6-hourly intervals. To maximise data use, we compare ERA5 and MERRA-2 with the 3-hourly observation dataset, and JRA-3Q with a reduced 6-hourly subset. This ensures a fair comparison while avoiding the need to discard half the radiosonde observations.

A requirement for this evaluation is that reanalyses place the CAB in the correct location relative to our two field sites, otherwise a CAB reproduced with perfect fidelity in the wrong place would appear erroneous. To confirm this, Figure 4.13 plots 850 hPa specific humidity along an extended Nchila-Solwezi transect. During Phases 1 and 3, all reanalyses place the moist-dry transition between the two field sites, although this transition is gradual in ERA5 and MERRA-2. During Phase 2, all reanalyses correctly locate both sites within a dry regime; and during Phase 4, all reanalyses correctly locate both sites within a moist regime, in agreement with the observational classification of Table 4.1. The correct placement of the CAB across reanalyses is likely attributable to constraint from satellite radiances, particularly microwave observations, despite the scarcity of conventional *in situ* data (Samrat

et al., 2025).

4.4 Results

4.4.1 How well do reanalyses reproduce the key thermodynamic and circulation features that comprise the Congo Air Boundary?

4.4.1.1 CAB dryline & convergence zone

We begin with two properties by which the CAB is most commonly defined: moisture gradients and low-level convergence, labelled "[1]" in the schematic of Figure 4.2. Because evaluating these features requires data sampled simultaneously across the CAB, we use the "cross-CAB" sampling base (Table 4.1).

The observed diurnal cycle of dryline strength (Figure 4.3c) is characterised by a strong 850 hPa moisture gradient overnight (maximum intensity 6.18 g kg^{-1} at 05:00 LT) and a weaker moisture gradient during the day. This diurnal cycle arises from large variations in moist-side specific humidity (Figure 4.3a).

- ERA5 underestimates the 850 hPa moisture gradient across the CAB at all times of day, with peak dryline intensity 36% weaker than observed. This bias stems from a mean moist-side moisture deficit of 2.32 g kg^{-1} , while the dry side is well reproduced. The diurnal cycle of moist-side specific humidity, and by extension dryline intensity, is successfully reproduced.
- MERRA-2 has an even weaker dryline than ERA5, underestimating maximum intensity by 64%. This again stems from a large mean moist-side moisture deficit (2.88 g kg^{-1}). Additionally, the diurnal cycle of dryline intensity is out of phase with observations and its amplitude is muted, with little modulation through the day.

- JRA-3Q overestimates the observed maximum dryline intensity by 25% and incorrectly places the maximum intensity in the early evening (20:00 LT), linked to a $+3.1 \text{ g kg}^{-1}$ moist-side moisture bias at that timestep.

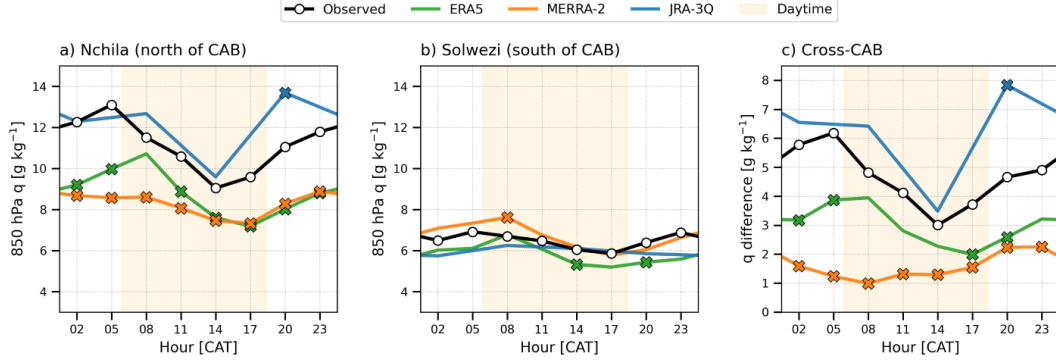


Figure 4.3: 850 hPa specific humidity (q) at a) Nchila and b) Solwezi, and c) dryline intensity calculated as the specific humidity difference between Nchila and Solwezi in observations (black) and reanalyses (ERA5; green, MERRA2; orange, JRA-3Q; blue). The sampling base is "cross-CAB" (Table 4.1). An 'x' denotes where the reanalysis mean is significantly different from observations at $p < 0.05$.

The observed diurnal cycle of moisture flux divergence (specifically, the component of the moisture flux divergence that is parallel to the bearing between the two field sites) is characterised by nocturnal low-level convergence and mid-level divergence, with a transition between the two regimes at 756hPa (Figure 4.4a). Maximum convergence occurs at 05:00 LT with a magnitude of $3.37 \times 10^{-4} \text{ g kg}^{-1} \text{ s}^{-1}$. The ratio of vertically and diurnally integrated moisture accumulation to export is 0.61, indicating that mid-level moisture export substantially exceeds low-level accumulation.

- ERA5 (Figure 4.4b) captures the amplitude and phase of the diurnal cycle well, with maximum convergence at 05:00 LT ($3.88 \times 10^{-4} \text{ g kg}^{-1} \text{ s}^{-1}$). However, convergence extends too deeply (by 39 hPa) and integrated mid-level moisture export is underestimated by 23%. As a result, moisture accumulation significantly exceeds export (at a ratio of 1.38), unlike observations.
- MERRA-2 (Figure 4.4c) underestimates convergence throughout the day, with the nocturnal maximum 35% weaker than observed ($2.19 \times 10^{-4} \text{ g kg}^{-1} \text{ s}^{-1}$).

However, convergence depth and the magnitude of mid-level integrated moisture export are closer to that observed, such that the ratio of moisture accumulation to export is similar to observations (0.66).

- JRA-3Q (Figure 4.4d) overestimates the nocturnal maximum in low-level convergence by 30% ($4.39 \times 10^{-4} \text{ g kg}^{-1} \text{ s}^{-1}$) and misrepresents the diurnal cycle, with a spurious early evening (20:00 LT) maximum (the diurnal cycle of mid-level divergence is similarly erroneous). Integrated moisture accumulation is approximately equal to export.

In summary, reanalyses differ to a large degree in their representation of moisture gradients and low-level convergence at the CAB. All three products exhibit statistically significant specific humidity biases on the moist side of the CAB, while the dry side is well reproduced. Only ERA5 successfully captures the observed diurnal cycle of dryline intensity and low-level convergence. However, this convergence extends too deeply, leading to significantly excessive moisture accumulation relative to export.

In both MERRA-2 and JRA-3Q, errors in dryline intensity appear to be closely linked to errors in moisture flux convergence. To examine this relationship further, we next assess how reanalyses represent the north-westerly LLJ that supplies moisture to the moist side of the dryline.

4.4.1.2 North-westerly (moist) low-level jet

The north-westerly LLJ (labelled "[2]" in Figure 4.2), is a key feature of the nocturnal circulation on the moist side of the CAB, forming below 800 hPa and advecting moist air from the Congo Basin toward the tropical edge (Pokam et al., 2014; Knight et al., 2026). As the LLJ is a feature of the atmosphere north of the CAB, we adopt a "moist-side" sampling base (Table 4.1).

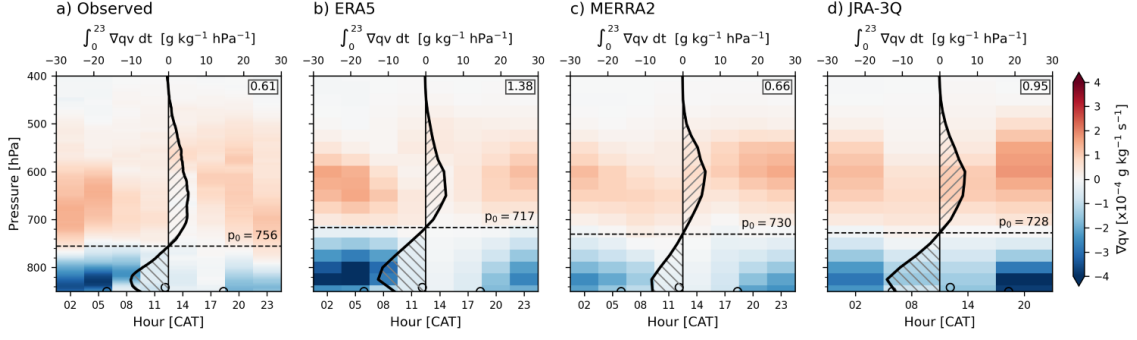


Figure 4.4: a-d) The component of the moisture flux divergence (∇qv) [$\text{g kg}^{-1} \text{s}^{-1}$] that is parallel to the bearing between the two field sites in a) observations and reanalyses: b) ERA5, c) MERRA-2, and d) JRA-3Q. The sampling base is "cross-CAB" (Table 4.1). A black line plots moisture fluxes by pressure integrated across the diurnal cycle [$\text{g kg}^{-1} \text{hPa}^{-1}$]. P_0 denotes the vertical level associated with a switch from diurnally integrated moisture accumulation to export. The ratio of vertically and diurnally integrated moisture accumulation below P_0 to export above P_0 is shown in the upper right of each panel. Values near unity indicate that low-level moisture convergence is largely compensated by divergence aloft, values greater than one indicate net moisture accumulation, and values less than one indicate net moisture export. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

In observations, the LLJ is expressed as a nocturnal maximum in north-westerly moisture flux below 800 hPa (Figure 4.5). We therefore define a jet index as the north-westerly moisture flux (qv_{nw}) at 825 hPa, with north-westerly flow as positive. Figure 4.5a shows the index diurnal cycle in observations and reanalyses, with Figure 4.5b-d additionally showing reanalysis qv_{nw} bias as a function of pressure. In observations, the index peaks at 02:00 LT ($28.8 \text{ g kg}^{-1} \text{m s}^{-1}$), with positive values overnight and negative values during the day.

- ERA5 successfully reproduces the phasing and amplitude of the index diurnal cycle, with magnitudes at 02:00 LT underestimated by just 6% (not statistically significant). However, a decomposition reveals that this agreement arises from compensating errors: q is underestimated on the moist side (as indicated in Figure 4.3) while v_{nw} is overestimated (both statistically significant; Table 4.3). Furthermore, Figure 4.5b shows that north-westerly moisture fluxes are excessively deep overnight.

- MERRA-2 performs poorly, with the index largely negative (south-easterly) throughout the diurnal cycle. At 02:00 LT, when observed fluxes peak at $28.8 \text{ g kg}^{-1} \text{ m s}^{-1}$, MERRA-2 simulates a qv_{nw} of $-5.5 \text{ g kg}^{-1} \text{ m s}^{-1}$.
- JRA-3Q reproduces the magnitude of the LLJ but not the diurnal cycle, with the index peaking in the evening (20:00 LT) instead of the early morning. At 20:00 LT, an index of $28.3 \text{ g kg}^{-1} \text{ m s}^{-1}$ overestimates observed values by $+27.1 \text{ g kg}^{-1} \text{ m s}^{-1}$ while at 02:00 LT, fluxes are underestimated by 35% ($p=0.35$).

In all three reanalyses, the representation of the north-westerly LLJ is closely related to biases in low-level convergence and dryline intensity (Section 4.4.1.1). In MERRA-2, the absence of a north-westerly LLJ component accounts for its weak dryline and convergence zone, while the spurious evening moisture advection in JRA-3Q explains its evening maximum in convergence and dryline strength. In ERA5, compensating errors in q and v_{nw} yield near-correct maximum moisture flux convergence magnitudes despite an underestimation of specific humidity north of the dryline. However, the excessively deep north-westerly moisture fluxes overnight lead to an overestimation of vertically integrated near-surface moisture convergence.

The spurious early-evening index maximum in JRA-3Q is associated with an exaggerated NW–SE (cross-CAB) geopotential height gradient relative to other reanalyses (Table 4.4). This, in turn, appears to be related to exaggerated positive (negative) cross-CAB gradients in sensible (latent) heat fluxes (Table 4.4), suggesting that the representation of land-atmosphere coupling may contribute to inter-reanalysis differences in the low-level circulation to the north of the CAB (e.g., Poll et al., 2022; Best et al., 2025).

4.4.1.3 Easterly (dry) low-level jet

Next, we evaluate the easterly LLJ. This jet, labelled "[3]" in Figure 4.2, is a key circulation feature on the dry side of the CAB, so we adopt a "dry-side" sampling

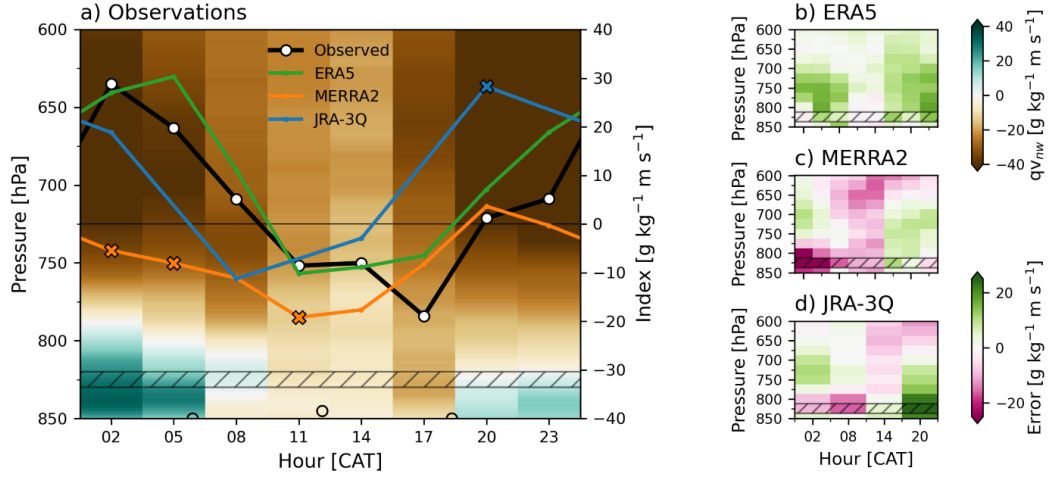


Figure 4.5: Diurnal cycle and vertical structure of the north-westerly (moist) LLJ in observations and reanalyses. The sampling base is "moist side" (Table 4.1). a) Hour-pressure evolution of observed north-westerly moisture fluxes (qv_{nw} ; shading) [$\text{g kg}^{-1} \text{ m s}^{-1}$] together with the north-westerly LLJ index (lines) [$\text{g kg}^{-1} \text{ m s}^{-1}$] defined as the 825-hPa north-westerly moisture flux in observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). North-westerly flow is defined as positive. b-d) Reanalysis bias (reanalysis minus observations) in north-westerly moisture flux as a function of pressure and hour for b) ERA5, c) MERRA-2, and d) JRA-3Q. Hatching indicates the 825-hPa level used to define the LLJ index. An 'x' marks hours where the LLJ index differs significantly from observations at the 0.05 level. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

base (Table 4.1). Knight et al. (2026) show that the easterly LLJ is characterised by strong easterly flow with a northerly component that increases overnight under an inertial oscillation, with maximum wind speeds occurring in the morning near 800 hPa. We therefore define a jet index as the zonal wind component at 800 hPa, with along-jet (easterly) flow as positive. Figure 4.6 shows the diurnal cycle of this jet index in observations and reanalyses, while Figure 4.6b-d additionally show reanalysis bias as a function of pressure.

In observations, the jet is weakest at 14:00 LT and strengthens overnight, peaking at 08:00 LT with a mean wind speed of 14.6 m s^{-1} . All three reanalyses reproduce the diurnal cycle of the jet index. However, all underestimate the 08:00 LT windspeed maximum. ERA5 is closest to observations (13.0 m s^{-1} , -11%) followed by MERRA-2 (12.0 m s^{-1} , -17%) and lastly JRA-3Q (11.0 m s^{-1} , -25%). Differences to MERRA-2 and JRA-3Q are significant at the 0.05 level.

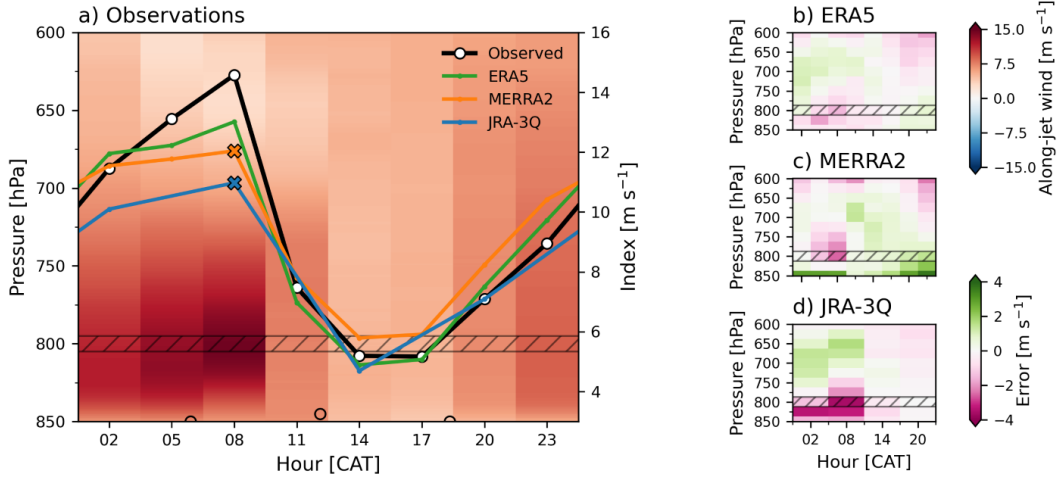


Figure 4.6: Diurnal cycle of the easterly (dry) LLJ in observations and reanalyses. The sampling base is "dry side" (Table 4.1). a) Hour-pressure evolution of zonal wind (shading) [m s^{-1}] together with the LLJ index (lines) [m s^{-1}] defined as the 800 hPa zonal wind in observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Easterly (along-jet) flow is defined as positive. b-d) Reanalysis error (reanalysis minus observations) as a function of pressure and hour for b) ERA5, c) MERRA-2 and d) JRA-3Q. In a), an 'x' marks where the LLJ index differs significantly from observations at the 0.05 significance level. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

4.4.1.4 African Easterly Jet South

The African Easterly Jet South (AEJ-S), labelled "[4]" in Figure 4.2, is an important mid-level circulation feature on the moist side of the CAB, with links to mid-level moisture flux divergence (Knight et al., 2026), rainfall in the southern Congo (Kueete et al., 2023) and aerosol transport to the south-east Atlantic (Adebiyi and Zuidema, 2016). We define an AEJ-S index as the zonal wind component at 650 hPa, with along-jet (easterly) flow as positive, using the "moist-side" sampling base (Table 4.1). Figure 4.7 shows the diurnal cycle of this jet index in observations and reanalyses, while Figure 4.7b-d additionally show reanalysis bias as a function of pressure.

All three reanalyses underestimate mean jet strength. Observed AEJ-S winds average 6.9 m s^{-1} across the diurnal cycle, compared to 6.5 m s^{-1} in ERA5 (-6%), 6.1 m s^{-1} in MERRA-2 (-11%), and 6.5 m s^{-1} in JRA-3Q (-6%), with differences to MERRA-2 and JRA-3Q are significant at the 0.05 level. ERA5 and JRA-3Q broadly reproduce the observed diurnal cycle of jet strength, with an overnight maximum and 14:00 LT minimum. In contrast, MERRA-2 fails to capture the diurnal cycle, and exhibits a spurious dual minimum at 05:00 and 17:00 LT.

4.4.1.5 Dry-convective mixing

We next examine dry-convective mixing on the moist side of the CAB (labelled "[5]" in Figure 4.2). Dry-convective mixing on the moist side of the CAB is central to the diurnal modulation of dryline structure, whereby daytime turbulent mixing redistributes moisture vertically, drying the surface layer and weakening the dryline (Mulenga, 1999; Mulenga et al., 2003; Munday and Washington, 2017; Howard and Washington, 2019; Attwood et al., 2024; Knight et al., 2026)

We evaluate this mechanism in reanalyses using the diurnal specific humidity perturbation (q') as a diagnostic, defined as the specific humidity (q) deviation from the

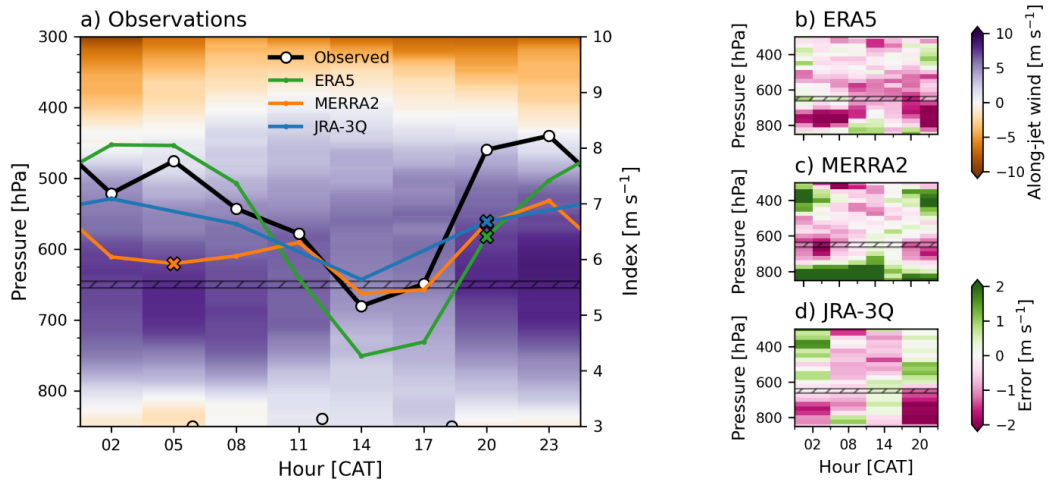


Figure 4.7: Diurnal cycle of the African Easterly Jet South (AEJ-S) in observations and reanalyses. The sampling base is "moist side" (Table 4.1). a) Hour-pressure evolution of easterly winds (shading) [m s^{-1}] together with the AEJ-S index (lines) [m s^{-1}] defined as the zonal wind at 650 hPa in observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Easterly (along-jet) flow is defined as positive. b-d) Reanalysis error (reanalysis minus observations) as a function of pressure and hour for b) ERA5, c) MERRA-2 and d) JRA-3Q. In a), an 'x' marks where the AEJ-S index differs significantly from observations at the 0.05 significance level. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

daily mean ($\bar{q}$) at each level (Figure 4.8). Observations show overnight accumulation of near-surface moisture, consistent with near-surface convergence (Figure 4.4a). After sunrise, turbulent fluxes mix moist air upwards and dry air downwards, drying the near-surface layer. All three reanalyses qualitatively reproduce this diurnal cycle, providing confidence in the ability of reanalysis parameterisations to represent the basic pattern of vertical turbulent moisture transport.

Despite this qualitative agreement, biases are evident. In ERA5, daytime near-surface drying appears excessive. Additionally, boundary-layer growth, approximated by the height of the q' maximum (Figure 4.8; black line), appears too rapid from 08:00 to 14:00 LT in both ERA5 and MERRA-2 and too gradual in JRA-3Q. Near-surface q' magnitudes are consistently small in MERRA-2, in line with its previously identified north-of-CAB dry bias, while in JRA-3Q there is a signature of evening moistening consistent with previously identified errors in north-of-CAB moisture advection.

Calculation of the vertically integrated near-surface (850–800 hPa) moisture tendency confirms that both ERA5 and MERRA-2 significantly overestimate the near-surface drying through the morning (Figure 4.16). At 11:00 LT, the observed drying tendency ($-1.4 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$) is exceeded by 221% in ERA5 and 71% in MERRA-2. Drying at this timestep is associated with the vertical turbulent transport of moisture (Figure 4.8). This suggests that the contribution of turbulent mixing to CAB maintenance may be smaller than inferred from earlier ERA5-based studies (e.g., Howard and Washington, 2019).

The excessive morning drying and apparent overly rapid boundary-layer growth in both ERA5 and MERRA-2 is associated with unrealistically strong daytime instability in the two reanalyses as diagnosed by the near-surface (850–800 hPa) bulk Richardson number (Ri_b). Through late morning and early afternoon (11:00–14:00 LT), both ERA5 and MERRA-2 simulate very strong instability ($Ri_b < -18$), in

stark contrast to observations ($Ri_b \geq -0.3$) and JRA-3Q ($Ri_b \approx -5$) which indicate only weakly unstable conditions (Figure 4.17). As the three reanalyses employ distinct turbulence formulations, we hypothesise that differences in the parameterisation of sub-grid vertical turbulent transport of heat and moisture contribute to their divergent representations of morning instability, boundary-layer growth, and vertical turbulent moisture transport, consistent with Best et al. (2025).

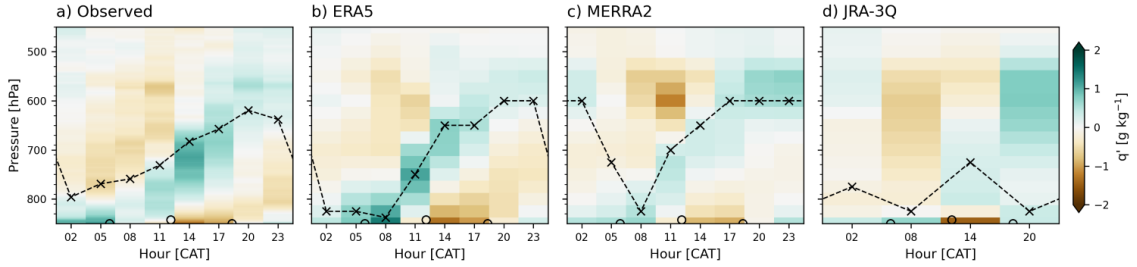


Figure 4.8: The diurnal cycle of the diurnal specific humidity perturbation (q') [g kg^{-1}] in a) observations and reanalyses: b) ERA5, c) MERRA-2, and d) JRA-3Q. The sampling base is "moist side" (Table 4.1). A black line plots the pressure level of the median maximum q' for each hour. Sunrise/sunset and solar noon are indicated by half and full circles respectively.

4.4.1.6 Mid-level stability

Finally, Figure 4.9 compares observed and reanalysis distributions of mid-level stability (Figure 4.2 "[6]") on the dry and moist sides of the CAB, using a lapse-rate index defined as the potential temperature lapse rate between 500 and 600 hPa.

On the dry side, the observed mean mid-level potential temperature lapse rate is 8.3 K per 100 hPa, with 32% of profiles exceeding 10 K per 100 hPa. Reanalyses reproduce the mean well (ERA5: 8.1 K per 100 hPa; MERRA-2: 8.8 K per 100 hPa; JRA-55: 8.3 K per 100 hPa), but all underestimate the frequency of highly stable profiles with only 23% of ERA5, 27% of MERRA-2, and 20% of JRA-55 profiles exceeding 10 K per 100 hPa.

On the moist side, the observed mean mid-level potential temperature lapse rate is

7.2 K per 100 hPa, with 27% of profiles less stable than 6 K per 100 hPa. All three reanalyses are biased toward higher stability (ERA5: 7.6 K per 100 hPa; MERRA-2: 7.8 K per 100 hPa; JRA-55: 7.9 K per 100 hPa) and strongly under-represent the frequency of lower-stability conditions, with only 5% of ERA5, 12% of MERRA-2, and 9% of JRA-55 profiles falling below 6 K per 100 hPa.

Reanalyses therefore struggle to represent the full distribution of mid-level stability; on the dry side, highly stable conditions are under-represented, while on the moist side, lower-stability conditions are under-represented.

Reanalyses therefore struggle to represent the full distribution of mid-level stability associated with Botswana High subsidence. On the dry side, highly stable conditions are under-represented, while on the moist side, lower-stability conditions are under-represented. This is consistent with (i) an underestimation of mid-tropospheric subsidence on the dry side of the CAB, and (ii) an equatorward overextension of subsidence and the influence of the Botswana High across the CAB.

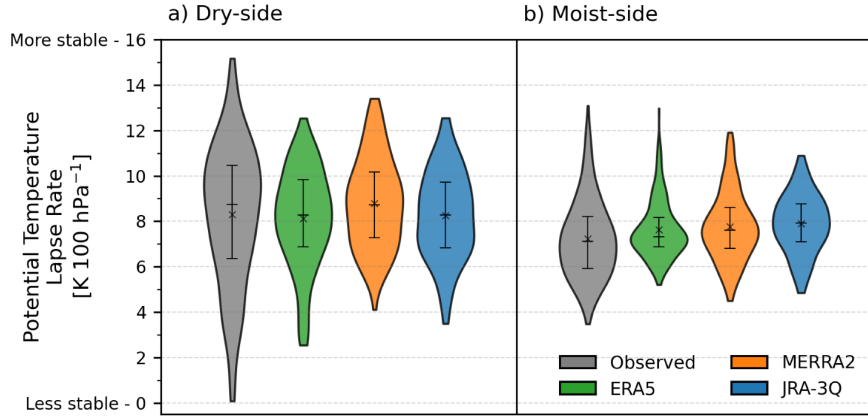


Figure 4.9: Mid-level stability, defined as the potential temperature lapse rate between 500 and 600 hPa [$K 100 hPa^{-1}$], for observations and reanalyses on a) the "dry side" and b) the "moist side" of the CAB (Table 4.1). Higher values indicate greater mid-level stability. The distributions are shown as violin plots for observations, ERA5, MERRA-2, and JRA-55. Violin width indicates the distribution density, while a black vertical line spans the interquartile range. Horizontal black marks indicate the lower quartile, median, and upper quartile, while an 'x' marks the mean.

4.4.2 How do diagnosed differences between reanalyses and observations influence convective environments?

Errors in the representation of the CAB diagnosed in Section 4.4.1 would be expected to affect convective environments at the southern African tropical edge. To quantify these impacts, we compare observed and reanalysis distributions of 14:00 LT surface CAPE and 850-600 hPa bulk shear in Figure 4.10. We use quantile-quantile plots to evaluate how well reanalyses reproduce the full distributions of conditional instability and shear; in a perfect match to observations, all points would fall along the 1:1 line (Figure 4.10; dashed). Capturing the upper quantiles is especially important if reanalyses are to represent the most convectively favourable environments important to severe weather. Surface-based CAPE is preferred to mixed-layer CAPE as it is less sensitive to errors in the low-level moisture field (Gensini et al., 2014). It is calculated using MetPy’s surface-based CAPE function, with observed or reanalysis surface pressure, 2m temperature and 2m dewpoint defining the parcel and vertical temperature and dewpoint profiles (at 25 hPa resolution) defining the environment.

Figure 4.10 shows that all three reanalyses struggle to reproduce CAB-adjacent (i.e., dry and moist side) convective environments. ERA5 underestimates dry- and moist-side mean CAPE by 82% and 65%, and MERRA-2 by 85% and 75%, respectively, with errors consistent across the entire distribution. JRA-3Q performs marginally better, with a mean bias of -41% and -38% across the dry and moist side distributions. All three products perform better following CAB breakdown, suggesting that CAPE errors are rooted in the misrepresentation of the CAB.

Errors in 850–600 hPa bulk shear are less systematic. In ERA5, mean dry- and moist-side shear is underestimated by 45% and 40%, respectively, while the post-breakdown distribution is better reproduced. In MERRA-2, mean breakdown and dry-side shear are underestimated by 46% and 34%, whereas the moist-side distribution is closer to observations. JRA-3Q performs best for CAB-adjacent (dry

and moist) shear distributions but underestimates breakdown shear by 45%. In sum, these results suggest that reanalyses have limited ability to capture the austral spring convective environments relevant to severe weather and rainfall onset.

To further diagnose the source of CAPE errors, we conduct a substitution experiment in which observed values of 2m temperature, 2m dewpoint, and environmental temperature profiles are inserted into the reanalysis CAPE calculation (Figure 4.11). This shows that errors in reanalysis CAPE are overwhelmingly attributable to surface moisture biases. Substituting observed 2m dewpoint, the mean (absolute) percent error is reduced from 50% to 20% across all reanalyses and regimes, with improvements in all but one case and especially large reductions across the moist regime (ERA5: 65% $\rightarrow$ 0%, MERRA-2: 76% $\rightarrow$ 12%, JRA-3Q: 38% $\rightarrow$ 2%). In contrast, substituting observed 2m temperature slightly increases the mean error (i.e., degrades reanalysis performance) while substituting environmental profiles has a negligible effect. This implicates reanalysis moisture transport errors associated with the representation of the CAB, identified under RQ1, as the cause of the poor representation of tropical-edge convective environments.

4.4.3 How do diagnosed differences between reanalyses and observations influence rainfall onset meteorology?

Sections 4.4.1 and 4.4.2 have shown that reanalyses misrepresent key aspects of the CAB, especially moist-side moisture transport (RQ1), and that these errors project onto reanalysis representation of convective environments (RQ2). Here, we examine how these biases propagate further upscale to influence the seasonal evolution of the tropical-edge atmosphere through rainfall onset.

We analyse phase-space plots of daily maximum surface MSE through the five meteorological phases of the field campaign (Figure 4.12). Tropical convection is, to

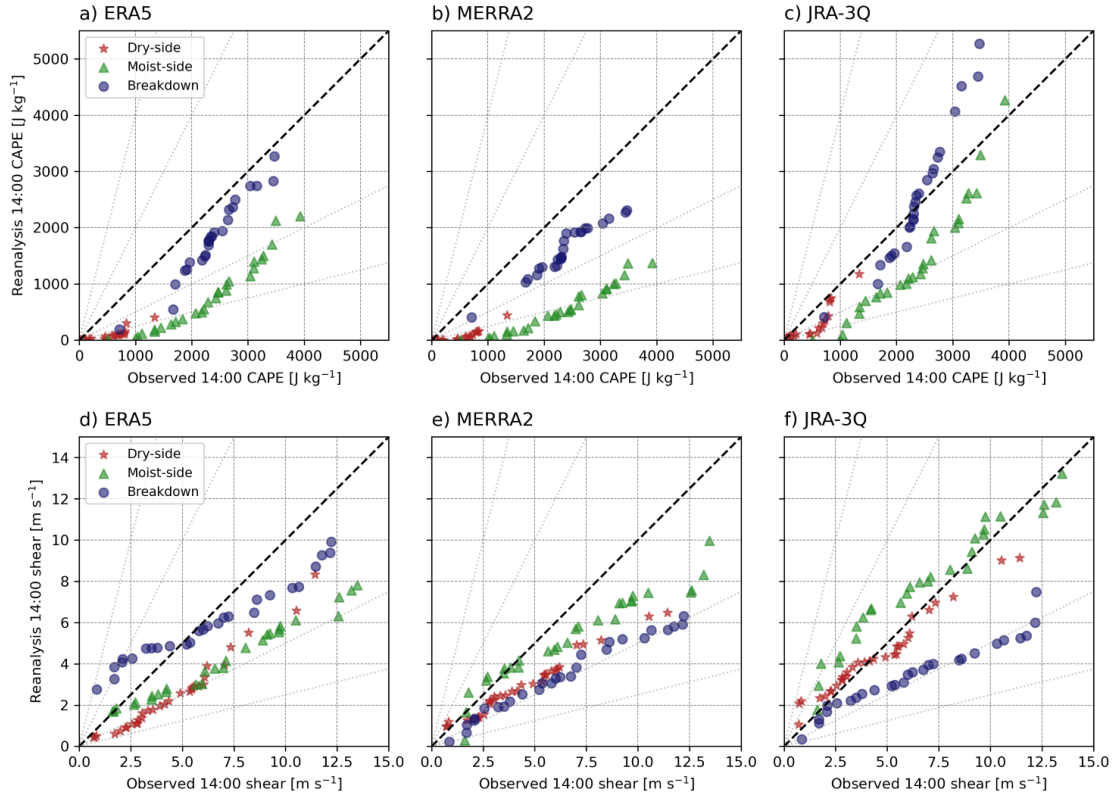


Figure 4.10: a-c) Quantile-quantile plots of observed and reanalysis 14:00 LT surface CAPE [J kg^{-1}] by reanalysis: a) ERA5, b) MERRA-2, c) JRA-3Q. d-f) quantile-quantile plots of observed and reanalysis 850–600 hPa bulk shear [m s^{-1}] by reanalysis: a) ERA5, b) MERRA-2, c) JRA-3Q. Colours indicate regime according to Table 4.1, with "dry side" in red, "moist side" in green, and "breakdown" in blue.

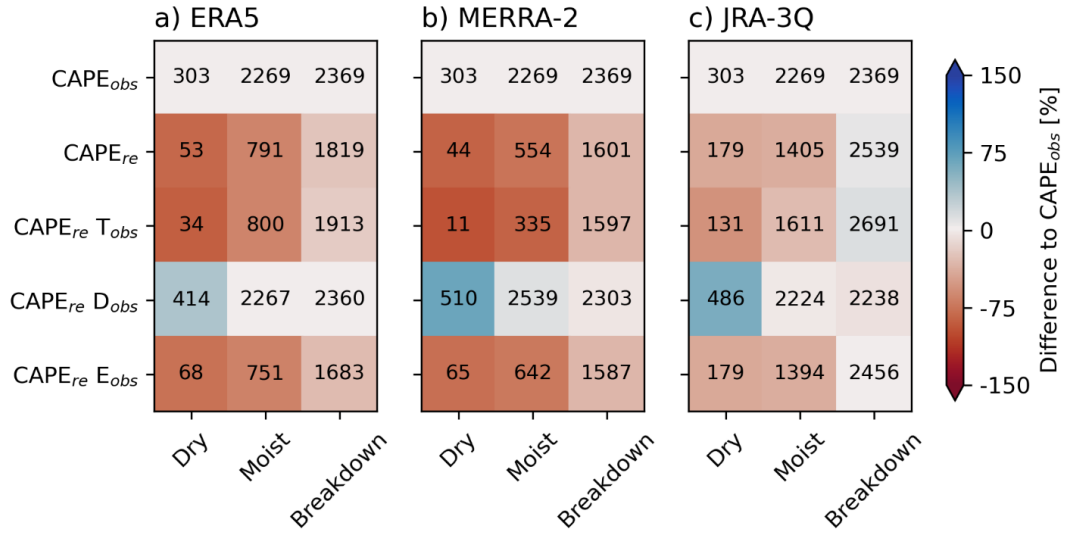


Figure 4.11: Mean 14:00 LT surface CAPE values [J kg⁻¹] calculated from surface parcels in observations ($CAPE_{obs}$), reanalyses ($CAPE_{re}$) and three substitution scenarios ($CAPE_{re} T_{obs}$, $CAPE_{re} D_{obs}$ and $CAPE_{re} E_{obs}$). Results are presented for a) ERA5, b) MERRA-2, and c) JRA-3Q, with values shown for the dry side of CAB, the moist side of CAB and post CAB breakdown. The three substitution scenarios are as follows: $CAPE_{re} T_{obs}$ is reanalysis CAPE with observed 2m temperature substituted for reanalysis 2m temperature, $CAPE_{re} D_{obs}$ is reanalysis CAPE with observed 2m dew point temperature substituted for reanalysis 2m temperature, and $CAPE_{re} E_{obs}$ is reanalysis CAPE with the observed environmental temperature profile substituted for the reanalysis environmental temperature profile. Colours indicate the percentage difference to $CAPE_{obs}$.

first order, controlled by maximum surface MSE (Neelin and Held, 1987; Nie et al., 2010), and Hart et al. (2019) show near-surface MSE is a good diagnostic for convection over Africa. MSE therefore provides a thermodynamic framework, independent of rainfall parameterisations, with which reanalysis behaviour through tropical-edge onset can be investigated.

The observed seasonal evolution of MSE (Figure 4.12a) is characterised by abrupt regime shifts, whereby changes in the position of the CAB produce step-like changes in MSE through the latent component. From Phase 1 to Phase 2, MSE decreases sharply at Nchila with little change at Solwezi, placing both sites on the dry side of the CAB; then from Phase 2 to Phase 3, this is reversed. From Phase 3 to Phase 4, MSE increases at Solwezi with little change at Nchila, placing both sites on the moist side of the CAB. Change from Phase 4 to Phase 5 (through CAB breakdown) is small as both sites are already in a moist regime to the north of the CAB.

In ERA5 and particularly MERRA-2, these sharp independent transitions are not captured (Figure 4.12b,c). Both products simulate a more gradual and near-concurrent moistening, and substantially underestimate observed inter-site MSE contrasts. JRA-3Q performs better in reproducing the observed step-like transitions. However, this apparent success must be treated cautiously: a correct representation of onset meteorology is reproduced for the wrong reasons, with moisture brought to the moist side of the CAB through a spurious circulation not observed in the real world (Section 4.4.1.2).

To place local instability in a wider tropical context, we additionally express field-site MSE as a percentile of the tropical (20°N-20°S) land MSE distribution (Figure 4.12e-g). Consistent with convective quasi-equilibrium, deep convection in the tropics preferentially occurs in regions with anomalously high moist instability and humidity relative to the background state. Expressing MSE in relative terms therefore provides a more relevant diagnostic of instability than absolute values. This

framing reinforces earlier results: ERA5 and particularly MERRA-2 depict a gradual, near-1:1 evolution in instability between the two sites, failing to place moist-side CAB environments near the upper tail of the tropical instability distribution. In contrast, JRA-3Q successfully characterises the moist side of the CAB as persistently near the 100th percentile of tropical instability.

In summary, ERA5 and MERRA-2 do not reproduce key aspects of observed rainfall onset meteorology through October and November 2022. While JRA-3Q more closely reproduces the observed step-like evolution of instability, this apparent agreement must be interpreted cautiously, as it arises from spurious north-of-CAB moisture advection rather than from a realistic representation of the underlying circulation. These results indicate that biases in the mesoscale representation of the CAB and associated moisture transport processes propagate upscale to influence reanalysis representation of the seasonal evolution of the tropical-edge atmosphere through rainfall onset. This limits the ability of reanalyses to diagnose onset mechanisms and variability in the region if processes at the mesoscale play a dominant role.

4.5 Summary and conclusions

The Congo Air Boundary (CAB) is a defining feature of the southern African tropical edge circulation from August to November, marking the transition between moist tropical and dry subtropical airmasses at the southern edge of the rain belt. Its dynamics underpin both the onset of the rainy season and projections of future drying across the region. Much of the literature on the CAB to date, and on the southern African tropical edge more broadly, has relied on reanalyses. However, the fidelity with which the CAB is reproduced in these datasets is not known.

Here, we have applied a process-based evaluation methodology to evaluate the representation of the CAB in three reanalyses (ERA5, MERRA-2, and JRA-3Q). Our

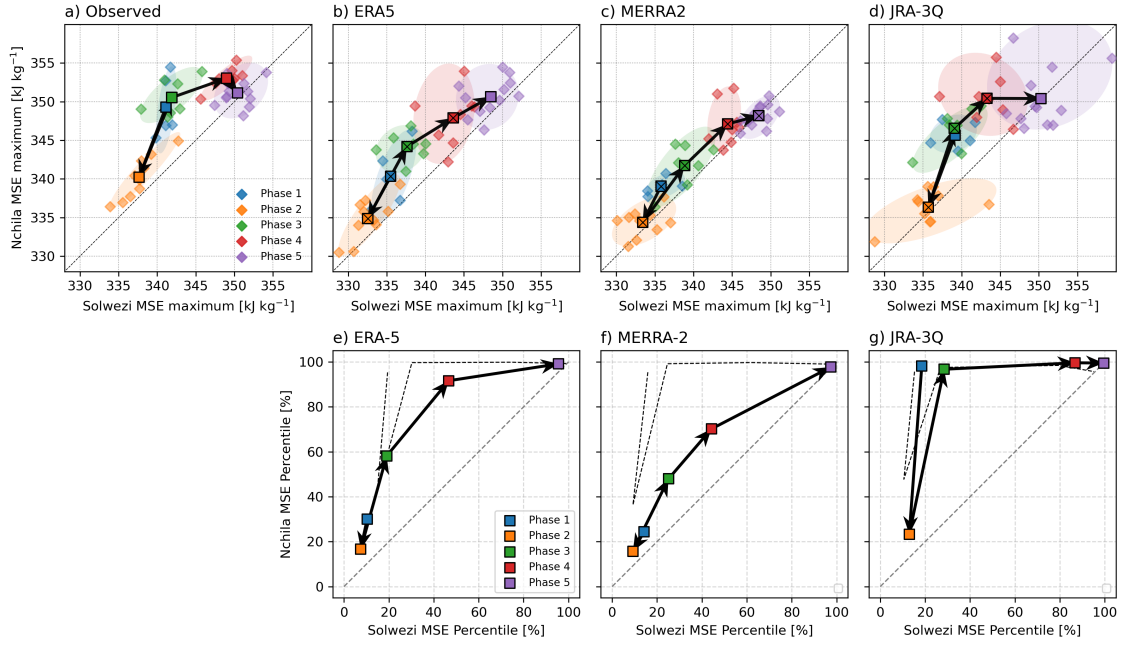


Figure 4.12: a-d) Scatterplots of Solwezi daily maximum surface MSE [kJ kg⁻¹] versus Nchila daily maximum surface MSE [kJ kg⁻¹] from a) observations, b) ERA5, c) MERRA-2, and d) JRA-3Q during the field campaign IOP. Diamonds plot daily values within each phase while squares indicate the phase mean. Black arrows trace the sequential evolution of the five meteorological phases. In b-d), reanalysis mean values are marked with an 'x' where they differ significantly from observations at either Nchila or Solwezi, based on paired t-tests with Holm correction for each phase. e-g) Phase mean daily maximum 850 hPa MSE at Nchila and Solwezi as a percentile [%] of the tropical (20°N – 20°S) land 850 hPa MSE distribution. Dashed lines indicate respective percentiles when observed MSE is substituted into reanalysis MSE distributions.

evaluation is guided by the observation-derived conceptual model of Knight et al. (2026) and uses independent, unassimilated observations from the DRY-CAB field campaign.

4.5.1 Representation of the CAB

All three reanalyses reproduce a CAB, defined as a dryline and convergence zone at the interface of a moist (tropical) and dry (subtropical) regime at the southern African tropical edge (Torrance, 1979; Howard and Washington, 2019; Knight et al., 2026). However, we find that all exhibit substantial errors in its thermodynamic structure and circulation. The largest errors arise from the representation of the atmosphere north of the CAB, while the dry regime to the south is comparatively well reproduced.

Among the reanalyses assessed, ERA5 performs best, successfully capturing the broad diurnal evolution of the atmosphere at the CAB. However, dryline intensity is underestimated by 36%, associated with a mean 2.3 g kg^{-1} specific humidity deficit and 221% overestimation of morning near-surface drying north of the dryline. The magnitude and diurnal cycle of 825 hPa north-westerly moisture fluxes to the north of the CAB are correctly reproduced, although this arises through compensating biases, with specific humidity underestimated and north-westerly wind speeds overestimated, and north-westerly flow is excessively deep.

We find that MERRA-2 performs poorly at the CAB, contrary to earlier studies suggesting strong climatological performance over central Africa (e.g., Hua et al., 2019). The north-westerly LLJ is frequently of the wrong sign through the diurnal cycle, leading to a weak CAB with little diurnal modulation. The maximum in dryline strength is underestimated by 64% while the nocturnal moisture convergence maximum is 35% weaker than observed. In addition, the strength of the AEJ-S is underestimated, and its diurnal cycle is not captured.

The representation of the CAB in JRA-3Q is dominated by a spurious diurnal circulation on the moist side of the dryline, hypothesised to be associated with errors in the cross-CAB partitioning of surface sensible and latent heat fluxes. This circulation advects moisture toward the CAB in the evening (20:00 LT) rather than early morning as observed, leading to large errors in the magnitude and diurnal cycle of the dryline moisture gradient, low-level moisture convergence and mid-level moisture divergence.

Across all three reanalyses, the largest errors are linked to the representation of horizontal and vertical moisture transport north of the CAB. North-westerly moisture fluxes that advect moisture to the CAB are of the wrong sign in MERRA-2 (-120% bias), exhibit an incorrect diurnal cycle in JRA-3Q (maximum at 20:00 rather than 02:00), and arise from compensating biases in ERA5. ERA5 and MERRA-2 additionally exhibit excessive 11:00 LT instability and daytime near-surface drying (biases 71–221%). Our results point to deficiencies in the representation of land-atmosphere coupling and sub-grid physics (e.g., boundary-layer turbulence) as likely sources of error and divergence between reanalysis products.

4.5.2 Upscale implications

Systematic errors in moist-side moisture transport propagate upscale to influence both convective environments and the seasonal evolution of the atmosphere through rainfall onset. All three reanalyses poorly represent convective environments either side of the CAB, with north-of-CAB CAPE underestimated by $>38\%$ in all cases due to near-surface moisture deficits. While bulk shear errors are less systematic, our results suggest that reanalyses have limited ability to capture the austral spring convective environments relevant to severe weather and rainfall onset.

Errors in moist-side moisture transport additionally impact the representation of tropical-edge rainfall onset meteorology. Observations show that onset is charac-

terised by sharp, site-specific regime shifts in daily maximum surface MSE as the CAB shifts position, reflecting abrupt changes in near-surface moisture. ERA5 and MERRA-2 fail to capture these transitions, instead simulating a smooth, near-simultaneous moistening of the two field sites. While JRA-3Q reproduces the observed step-like behaviour more closely, its apparent success is tied to spurious north-of-CAB moisture advection, rendering it "right for the wrong reasons". Collectively, these biases limit the ability of reanalyses to diagnose rainfall onset mechanisms and variability at the southern African tropical edge if processes at the mesoscale play a dominant role.

4.5.3 Broader implications and outlook

Our study demonstrates that while reanalyses reproduce a CAB at the synoptic scale, their fidelity in representing the mesoscale processes that comprise it, and particularly those that govern moisture transport on the moist side of the CAB, is limited. We show that biases propagate upscale to influence reanalysis convective environments and the seasonal evolution of the atmosphere through rainfall onset. This underscores a) the need for caution when using reanalyses to diagnose mesoscale processes and dynamics at the tropical edge, and b) the importance of CAB representation to the successful simulation of the tropical-edge atmosphere through austral spring.

A major contributing factor to reanalysis errors (and inter-reanalysis differences) is the lack of observational constraint in the lower troposphere over central and southern Africa. As a result, reanalyses behave largely as models, with atmospheric states strongly shaped by model physics and parameterisation choices. This allows substantial differences to arise between products, particularly for aspects of the climate strongly shaped by sub-grid physics (e.g., dry-convective mixing) and land-atmosphere coupling (Edwards et al., 2020; Poll et al., 2022; Best et al., 2025). Our analysis points to these modelled processes as a likely source of divergence between

reanalyses, so improving their parameterisation represents an important priority for future model development.

A significant challenge remains in translating results from process-based analyses such as this into operational model development (Neelin et al., 2023). In this context, convection-permitting experiments with the Met Office Unified Model conducted during the DRY-CAB campaign provide an opportunity to assess whether improved resolution and updated physics yield a more realistic representation of the CAB and tropical-edge onset dynamics.

Finally, our results highlight the value of spatially and temporally limited but high-quality observations for model evaluation. Carefully designed, targeted field campaigns such as DRY-CAB provide rare observations with which model behaviour can be interrogated, underpinning model evaluation frameworks that have the potential to improve both our understanding of, and ability to model, the climate system.

4.6 Acknowledgments

The first author is funded by the Keble College Bigg Scholarship in African Climate Science. The DRY-CAB project is funded by the NERC Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) grant (NE/V011928/1). Richard Washington was project PI, with Neil Hart and Steve Woolnough co-investigators and Chris Reason contributing. The project is deeply indebted to Edson Nkonde, Director of the Zambia Meteorological Department, and to Felix Imbwae and Col Rodney Mulenga for their contributions. Wallace Kasongo and his team – Lawrence Chisengele, Sakuwaha Kalumbi, Fanold Moonga, Enock Moomba, Chinoya Chinoya, Lucy Namonje, Kakuhu Mubanga, Ashili Mwila, Ireen Mwansa, Nathan Kaluwaji, Levy Zulu, Stanely Shakalima, Davies Kapya Langeni, Wilfred Kabwe Mwaba, Ray Nayunda, Enock Chisha, and Auster Mweene – led data collection at the Solwezi radiosonde station. The Nchila radiosonde station was supported

by Sebastian Engelstaedter, Kitty Attwood, Alice Jardine and Chris Edmunds. We additionally wish to thank Mark Ronald and Doug Hanna at Sakeji School for invaluable practical assistance in the field, and Pete and Lynne Fisher of Hillwood Farm.

4.7 Appendix

4.7.1 Appendix A: Comparison considerations

4.7.1.1 CAB location

A requirement for the evaluation presented in the main text is that reanalyses place the CAB in the correct location relative to the two field sites. Figure 4.13 demonstrates that all reanalyses correctly capture the location of the moist-dry transition relative to Nchila and Solwezi, and by extension the observed regime classification in Table 4.1.

4.7.1.2 Spatial comparison considerations

A radiosonde is neither strictly Eulerian nor Lagrangian, because while it moves in the air it does not follow the same parcel. In the DRY-CAB campaign, the average radiosonde ascent to the tropopause (16.7 km) lasted 75 minutes (IQR: 69–81), with a median horizontal drift of 14.6 km (IQR: 10–21). For the purposes of our analysis, we make the assumption that radiosondes are effectively Eulerian point measures valid for the release location and time. This assumption is justified because radiosonde drift is small relative to the size of the highest-resolution reanalysis grid box (<48%) and the lowest 3 km of the atmosphere – where diurnal changes are most rapid – are sampled within the first 15 minutes of ascent.

A further issue of representativeness arises when collocating point observations with

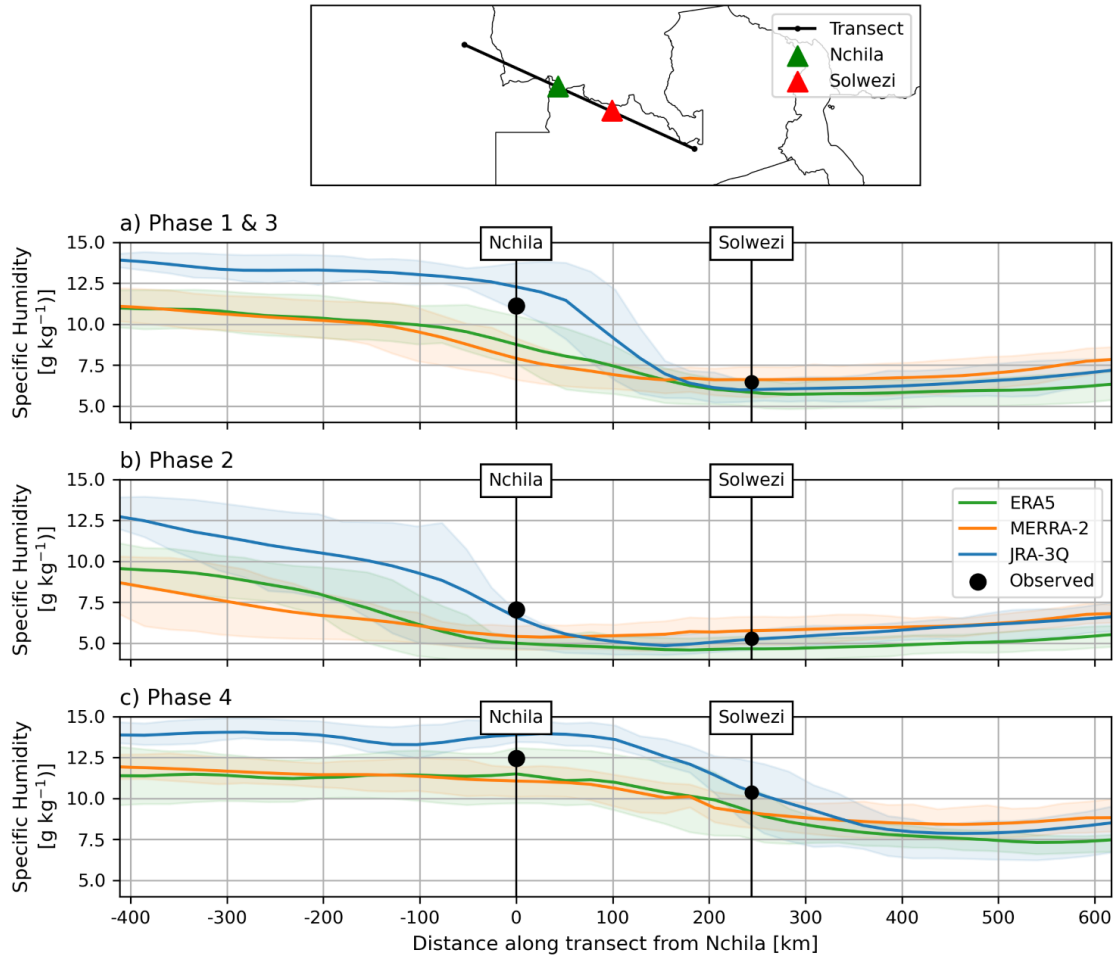


Figure 4.13: 850 hPa specific humidity [g kg⁻¹] as a function of distance along an extended Nchila-Solwezi transect, measured relative to the Nchila field site. Reanalysis specific humidity (ERA5: green; MERRA-2: orange; JRA-3Q: blue) is linearly interpolated onto the transect, with shading indicating the interquartile range of the 3-hourly (ERA5, MERRA-2) and 6-hourly (JRA-3Q) data within each phase. Panels show a) Phases 1 and 3, when the CAB lay between the two field sites; b) Phase 2, when both sites sampled a dry regime; and c) Phase 4, when both sites sampled a moist regime.

gridded model data. In reanalyses, values represent the average state within a grid cell centred on fixed latitude-longitude coordinates, rather than a true point measurement. This complicates direct comparison with observations. Additionally, differing spatial resolutions mean that a given location may fall at the centre of a grid box in one reanalysis and near the edge in another (Figure 4.14).

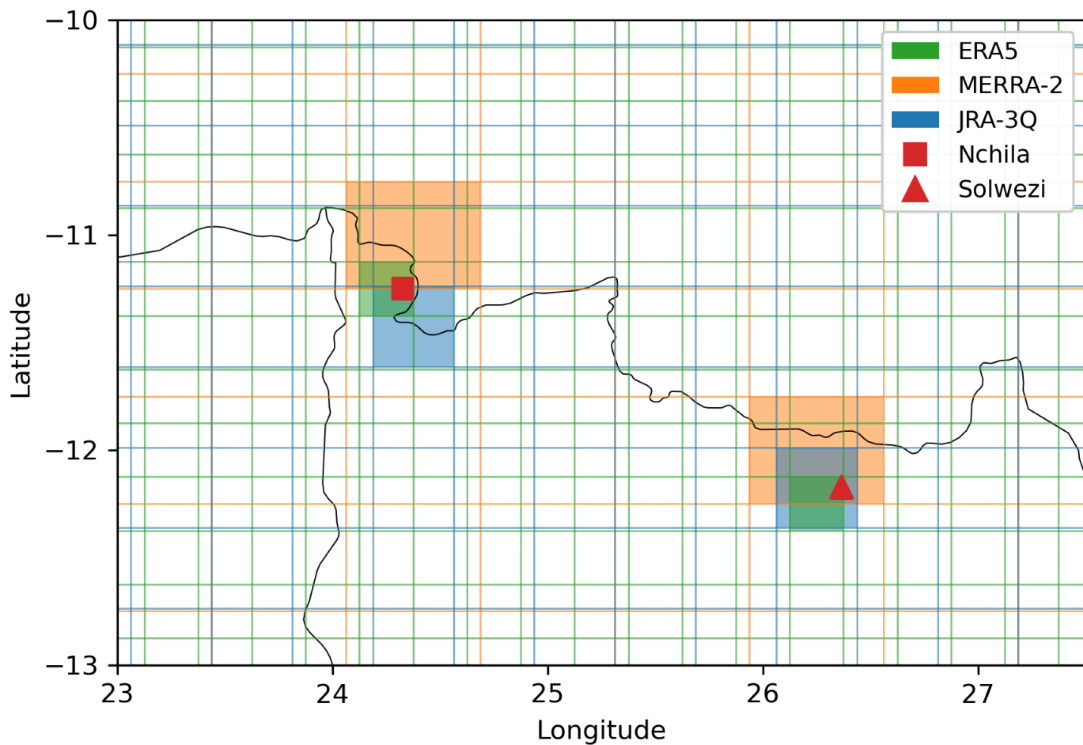


Figure 4.14: The location of the nearest reanalysis grid cell (MERRA-2: orange, JRA-3Q: blue, ERA5: green) to the Nchila (red square) and Solwezi (red triangle) field sites.

To address this, several station-grid co-location approaches are commonly used, including nearest-neighbour sampling (Figure 4.14), averaging of the four nearest grid points, distance-weighted averaging of the four nearest grid points, and area-weighted averaging over a fixed square region centred on the station (e.g., 30×30 km; Ruti et al., 2008; Mooney et al., 2011). The methods differ in how grid boxes

near the observation point in 2D space are weighted.

To test for sensitivity to the co-location method, we calculate root-mean-square error ($RMSE$) and correlation coefficient at each field site for the four described methods (Figure 4.15). Both metrics are insensitive to the choice of co-location technique for three lower-tropospheric variables that vary strongly across the CAB; the difference in $RMSE$ between sampling methods is typically an order of magnitude smaller than the $RMSE$ between reanalyses and observations. This result holds when the five meteorological phases of the field campaign are considered individually, providing confidence that diagnosed errors are not an artefact of the co-location method. Given these findings, we adopt a nearest-neighbour co-location technique (Figure 4.14).

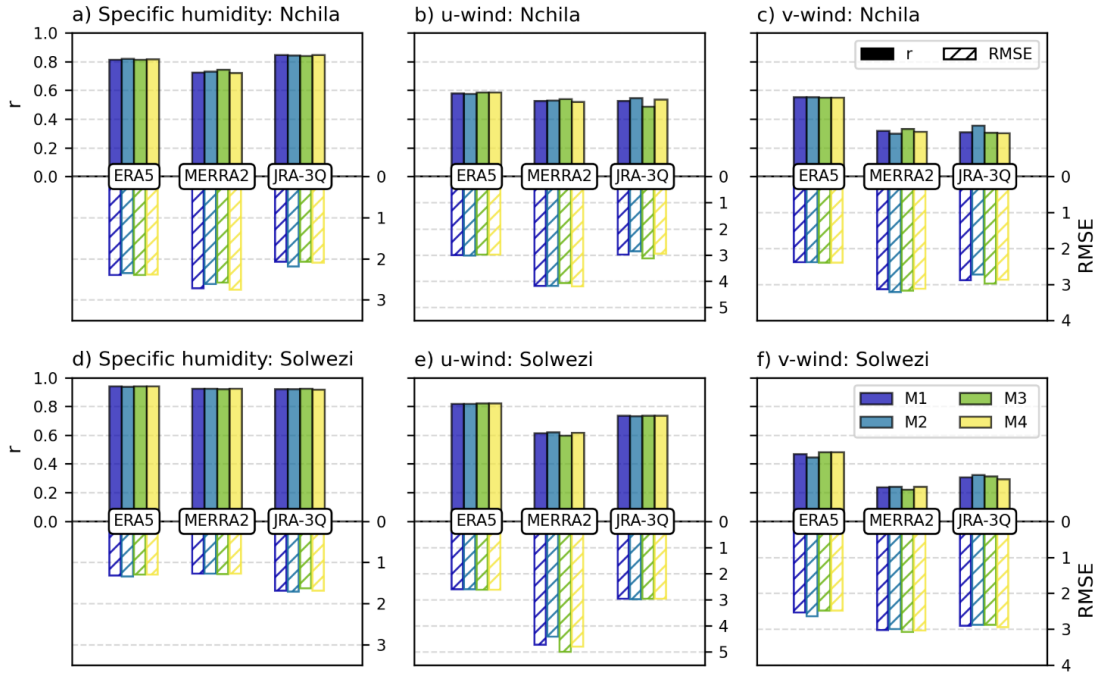


Figure 4.15: Correlation coefficient (r) and root-mean-square error ($RMSE$) by variable (a,d: specific humidity [g kg^{-1}]; b,e: u-wind [m s^{-1}]; c,f: v-wind [m s^{-1}]) and field site (a–c: Nchila; d–f: Solwezi) for four observation-reanalysis comparison methods. For each reanalysis (ERA5, MERRA-2, JRA-3Q), r (solid bars) and $RMSE$ (hatched bars) are plotted for the following four comparison methods: M1 – nearest neighbour; M2 – average of the four nearest grid points; M3 – distance-weighted average of the four nearest grid points; M4 – weighted average over an assigned 30x30km grid square.

4.7.1.3 Vertical comparison considerations

Radiosonde data from the DRY-CAB field campaign is at 1 hPa resolution, whereas reanalysis vertical resolution depends on the number of model levels and the subsequent interpolation to pressure coordinates. At their available pressure-level resolution, all three reanalyses share a lowest near-surface level at 850 hPa and use a vertical spacing of 25 hPa between 850 and 700 hPa and 50 hPa between 700 and 200 hPa. To establish a consistent vertical grid, all reanalyses are interpolated to a common 25 hPa pressure grid.

For single-level comparisons (e.g., zonal wind at 800 hPa), only pressure levels common to both the radiosonde observations and the reanalyses are used, avoiding the need for interpolation. For layer-mean or layer-integrated quantities (e.g., zonal wind averaged over 850-750 hPa) and bias evaluations as a function of pressure, the 1 hPa-resolution radiosonde data is linearly interpolated to 25 hPa to enable direct comparison with the reanalyses.

At the DRY-CAB field sites, observed mean surface pressure at Nchila was 859 hPa, and 861 hPa at Solwezi. Reanalysis surface pressure is generally close to observed: ERA5 slightly overestimates mean surface pressure at both sites (+5 and +3 hPa), MERRA-2 is notably high at Nchila (+12 hPa) but accurate at Solwezi, while JRA-3Q agrees well at both sites ($< \pm 1.5$ hPa). As biases are small, no adjustment is made for the height of features above the surface.

4.7.2 Appendix B: Supplementary diagnostics

The supplementary diagnostics provided here support the interpretation of Section 3.4.1.

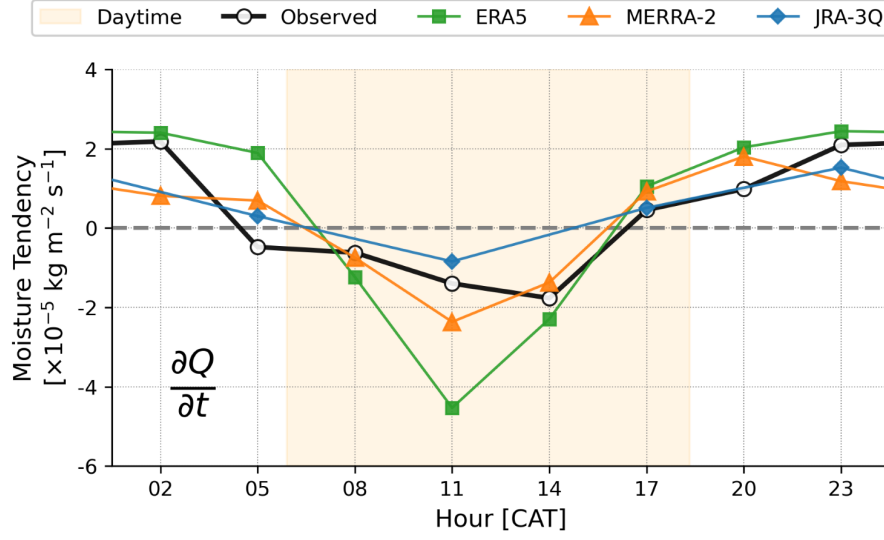


Figure 4.16: Diurnal evolution of the vertically integrated near-surface (850–800 hPa) moisture tendency ($\partial Q/\partial t$) [$\text{kg m}^{-2} \text{s}^{-1}$], calculated as a 6-hour centred finite difference, from radiosonde observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Sampling base: "moist side".

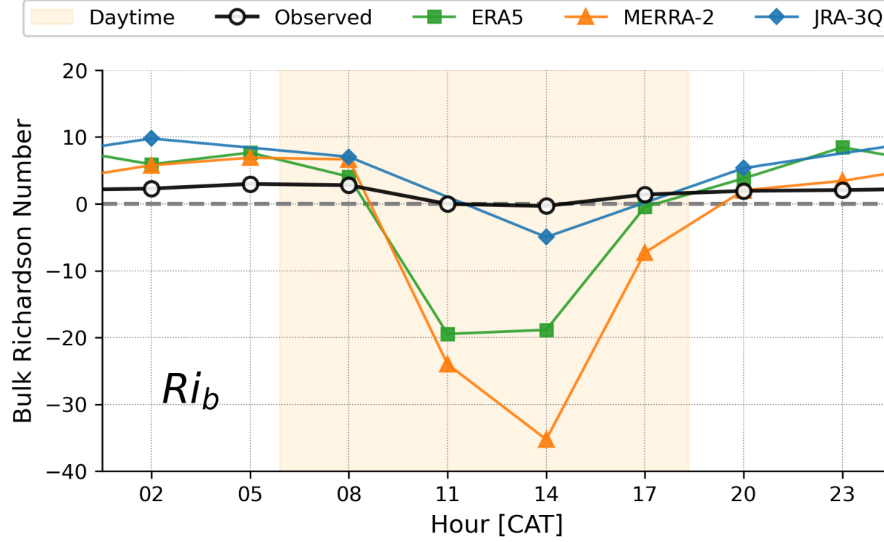


Figure 4.17: Diurnal cycle of the median near-surface (850–800 hPa) bulk Richardson number (Ri_b) in radiosonde observations (black) and reanalyses (ERA5: green; MERRA-2: orange; JRA-3Q: blue). Sampling base: "moist side".

Table 4.3: Decomposition of 05:00 LT north-westerly moisture flux (qv_{nw}) at 825 hPa [$\text{g kg}^{-1} \text{ m s}^{-1}$] into specific humidity (q) [g kg^{-1}] and north-westerly wind (v_{nw}) [m s^{-1}] components in observations and reanalyses. Bold font denotes values that differ significantly from observations at the 0.05 significance level. Sampling base: "moist side".

	qv_{nw} [$\text{g kg}^{-1} \text{ m s}^{-1}$]	q [g kg^{-1}]	v_{nw} [m s^{-1}]
Observed	28.8	10.5	2.2
ERA5	27.0	9.2	3.1
MERRA-2	-5.5	9.1	-1.2
JRA-3Q	18.8	10.5	1.8

Table 4.4: North-west to south-east aligned 14:00 LT gradients of thermodynamic and surface flux variables from ERA5, MERRA-2, and JRA-3Q. Gradients are estimated as the finite difference of two $3^\circ \times 3^\circ$ latitude-longitude boxes with the field site at their shared corner. The pressure-gradient force (PGF) is computed as $-\partial\Phi/\partial x$ and evaluated along with the geopotential height gradient (∇z) at 850 hPa. L and S denote latent and sensible heat fluxes, respectively, $L + S$ the total turbulent surface heat flux, and EF the evaporative fraction defined as $\text{EF} = L/(L + S)$. The sensible heat flux gradient (∇S) is decomposed into contributions associated with gradients in the total turbulent flux (∇S from $\nabla(L + S)$) and in evaporative fraction (∇S from ∇EF). Sampling base: "moist side".

Variable	Reanalysis		
	ERA5	MERRA-2	JRA-3Q
PGF [$\times 10^{-4} \text{ m s}^{-2}$]	0.93	1.23	2.14
∇z [$\times 10^{-5} \text{ m}^{-1}$]	-0.95	-1.25	-2.18
$\nabla(L + S)$ [$\times 10^{-4} \text{ W m}^{-3}$]	1.05	2.24	0.40
∇S [$\times 10^{-4} \text{ W m}^{-3}$]	2.8	4.4	6.6
∇L [$\times 10^{-4} \text{ W m}^{-3}$]	-1.8	-2.2	-6.2
∇EF [$\times 10^{-6} \text{ m}^{-1}$]	-0.44	-0.78	-1.29
∇S from $\nabla(L + S)$ [%]	23.7	38.1	3.6
∇S from ∇EF [%]	76.3	61.9	96.4

4.8 Afterword to Chapter 4

Chapter 4 has fulfilled the second aim of this thesis by evaluating how well three reanalyses represent the CAB, and the features that comprise it, during the DRY-CAB field campaign. This was achieved using a process-based evaluation methodology grounded in the conceptual model developed in Chapter 3.

The chapter demonstrates that while all three reanalyses successfully reproduce the CAB as a synoptic-scale dryline and convergence zone, they exhibit substantial errors in its mesoscale structure and circulation. The most pronounced errors occur north of the CAB, where moisture availability and both horizontal and vertical moisture transport differ markedly between reanalyses. In comparison, the dry subtropical regime to the south is comparatively well represented.

These biases are contextualised through considering the upscale impacts on CAB-adjacent convective environments and the seasonal evolution of the tropical-edge atmosphere through October and November. This demonstrates the importance of CAB representation to the successful simulation of the tropical-edge atmosphere through austral spring.

By establishing the ability of three reanalysis products to reproduce the CAB, Chapter 4 sheds light on the locations and scales at which reanalyses can be used with confidence and those under which caution is required. Despite errors in the CAB's mesoscale structure and circulation, all three products reproduce i) a CAB at the synoptic scale and ii) key aspects of the dry subtropical regime to the south. Provided large-scale fields remain sufficiently constrained by data assimilation, reanalyses are therefore still well placed to answer the question posed by Aim 3 on the large-scale mechanisms associated with the breakdown of the CAB. This is explored in the foreword to Chapter 5.

5 | Remote midlatitude control of rainfall onset at the southern African tropical edge



A large overhead storm forces the author from their tent. 28 October 2022.

Rainfall over the southern African tropical boundary is highly variable, particularly around the onset of the summer rains. However, understanding of the causes of variability in onset timing is poor. A lack of observational data in the region is compounded by the complexity of climate dynamics and variability at the interface of the tropics and the midlatitudes. Key to onset over the region is the Congo Air Boundary (CAB), a distinguishing circulation feature present in September and declining in frequency until November. The CAB is crucial to early-season rainfall; precipitation is broadly inhibited when the CAB is present, while its breakdown allows large-scale rainfall and onset over central southern Africa. This work identifies a remote midlatitude influence on the timing of CAB breakdown using the high-resolution reanalysis dataset ERA5. Propagating and (upstream) breaking low-wavenumber Rossby waves in the southern hemisphere westerly jet are shown to be related to >70% of breakdown events. Breakdown is forced by (a) the replacement of subsidence over eastern southern Africa with synoptically-forced ascent, (b) wind-field modification that leads to positive 850 hPa continental convergence anomalies and enhanced moisture advection from the Congo Basin and the southwest Indian Ocean, and (c) replacement of mid-level moisture flux divergence at the CAB with moisture flux convergence. Upper-level anticyclonic vorticity tendency induced by enhanced convection slows Rossby wave propagation aloft, contributing to wave breaking and the persistence of conditions favourable to convection. The identification of this midlatitude influence on CAB breakdown reveals new potential sources of predictability for onset and demonstrates the significant equatorward extent of midlatitude influences to the tropical edge.

5.1 Foreword to Chapter 5

Chapter 5 addresses the third and final aim of this thesis, investigating the large-scale meteorological conditions and mechanisms associated with the breakdown of the CAB. The chapter characterises the reorganisation of the atmosphere from a CAB-in-place to a CAB-absent state and identifies the large-scale mechanisms associated with this transition, complementing theory developed in Chapter 3 accounting for the maintenance of the CAB. This is motivated by the role of CAB breakdown in the onset of the summer rains over southern Africa, and by its relevance to projections of delayed onset under future warming scenarios (Howard and Washington, 2022).

Analysis shows that CAB breakdown typically occurs over timescales of 3–5 days and is frequently associated with disturbances originating in the midlatitudes. Tracing the mechanisms underpinning this association, the chapter demonstrates how extratropical disturbances reshape vertical motion, low-level flow and mid-level moisture flux divergence to erode the CAB and facilitate a transition to a moist convective regime. The results have implications for the predictability of rainfall onset over southern Africa, and more broadly for theory that accounts for extratropical influences on the seasonal migration of the tropical rain belt.

The manuscript comprising this chapter was written, submitted, and published prior to the analysis that has been presented in Chapters 3 and 4. As a result, there may be discontinuity in ideas, emphasis, and citations. To address this, an afterword to Chapter 5 reflects on the chapter’s results in light of the findings of preceding chapters. In particular, the role of mid-level moisture flux divergence, as proposed in Chapter 3, is discussed.

Chapter 5 is presented in the form of a manuscript:

Knight, C., & Washington, R. (2024). Remote Midlatitude Control of Rainfall Onset at the Southern African Tropical Edge. *Journal of Climate*, 37(8), 2519–

5.1.1 Rationale for the use of reanalyses

Chapter 4 has provided important context for interpreting reanalyses at the southern African tropical edge, highlighting the locations and scales at which they can be used with relative confidence and those for which caution is required. Although reanalyses exhibit substantial errors in the mesoscale structure and dynamics of the atmosphere north of the CAB, all reanalyses reproduce a synoptic-scale dryline and convergence zone at the tropical edge as well as key aspects of the dry subtropical regime to the south. This means that, provided large-scale fields remain constrained by data assimilation, reanalyses are still well suited to addressing the third aim of this thesis: identifying the large-scale mechanisms associated with CAB breakdown. Here we seek to further establish and justify the basis for this.

A requirement for reanalyses to be used to investigate the large-scale mechanisms associated with CAB breakdown is that they accurately capture the timing of CAB breakdown. A starting point for investigating this is to consider CAB breakdown in austral spring 2022, which underpins the analyses presented in Chapters 3 and 4. CAB breakdown is not directly resolved in the DRY-CAB observations: phase-space analysis of field site moist static energy does not reveal a distinct signature associated with the transition from a north-of-CAB to a CAB-absent state (Phase 4 to Phase 5). As a result, independent observations such as satellite outgoing longwave radiation or gridded satellite-gauge rainfall products (e.g., CHIRPS v2) must instead be used to validate reanalysis breakdown timing (Figure 5.1).

Figure 5.1 shows the evolution of CHIRPS rainfall by latitude through austral spring 2022. The meteorological phases of the field campaign, and the location of the CAB in three reanalyses (ERA5, MERRA-2, and JRA-3Q) detected with the algorithm of

Howard and Washington (2019), are overlaid. Despite substantial differences in their representation of the CAB, as documented in Chapter 4, Figure 5.1 shows strong agreement on the timing of CAB breakdown with all reanalyses indicating that the CAB ceases to form after 1 November (aside from a brief reappearance during a short dry spell). This is validated by a concurrent rapid southward shift in the tropical rain belt in an independent satellite-derived precipitation product (CHIRPS v2). The close agreement between reanalyses suggests that the timing of CAB breakdown is constrained by data assimilation, such that reanalyses have limited degrees of freedom in breakdown timing even when their mesoscale representation of the CAB differs.

This reflects a scale dependence of reanalysis agreement at the southern African tropical edge, illustrated in Figure 5.2. Reanalyses perform poorly in representing mesoscale processes at the CAB, particularly those governing low-level moisture transport on the moist side of the dryline (Chapter 4). These processes operate at spatial scales of a few degrees or less and evolve on sub-daily timescales, where observational constraints are weak and key aspects are parameterised (left side of plots). In contrast, CAB breakdown is a synoptic-scale phenomenon, evolving over several days and involving circulation anomalies spanning much of southern Africa (right side of plots). At these larger spatial and temporal scales, reanalyses are more strongly constrained by observations, particularly microwave satellite radiance observations and Global Navigation Satellite System radio occultation, which data denial experiments show are the largest constraint in the tropics and the Southern Hemisphere (Samrat et al., 2025). These observing systems anchor the large-scale structure of the atmosphere, particularly in the mid- to upper-levels, reducing reanalysis disagreement by a factor of 2–4 and ensuring consistency in the timing of CAB breakdown (Figure 5.2).

These considerations provide confidence in the fact that reanalyses successfully re-

produce the large-scale dynamics associated with CAB breakdown, despite their documented limitations in the previous chapter.

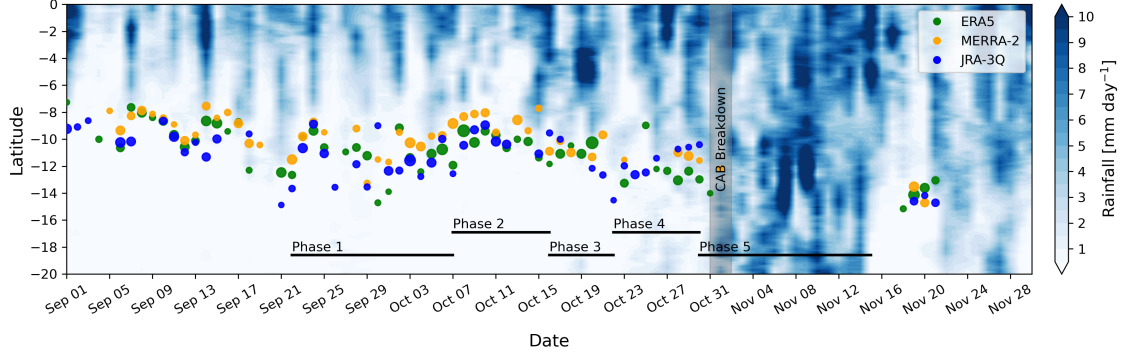


Figure 5.1: Rainfall by latitude from 1st September to 30th November 2022. Rainfall is averaged from 20-35° east. Rainfall data is CHIRPS v2. Overlaid are the meteorological phases of the field campaign (Phases 1 through 5) and the location of the CAB in the three atmospheric reanalyses (ERA5; MERRA-2, JRA-3Q), objectively identified with the canny-edge detection algorithm of Howard and Washington (2019) following interpolation to a common 0.25° grid. Circle diameter is proportional to the number of grid cells detected.

5.1.2 CAB breakdown in 2022

Given the focus of Chapters 3 and 4 on a case study of 2022, it is fitting to first address Aim 3 in the context of this season. As shown in Figure 5.1, the three reanalyses examined in Chapter 4 show close agreement on the timing of CAB breakdown. We therefore examine the associated large-scale dynamics, recognising the value of case studies as a hypothesis-generating tool rather than a basis for generalisation.

Figure 5.3 shows the evolution of near-surface (850 hPa) specific humidity, moisture fluxes, and convergence in the ERA5 reanalysis through CAB breakdown. CAB dryline grid cells from ERA5, MERRA-2 and JRA-3Q are additionally overlaid. The breakdown of the CAB occurs from 30 October to 2 November, accompanied by enhanced easterly moisture transport from the southwest Indian Ocean. These

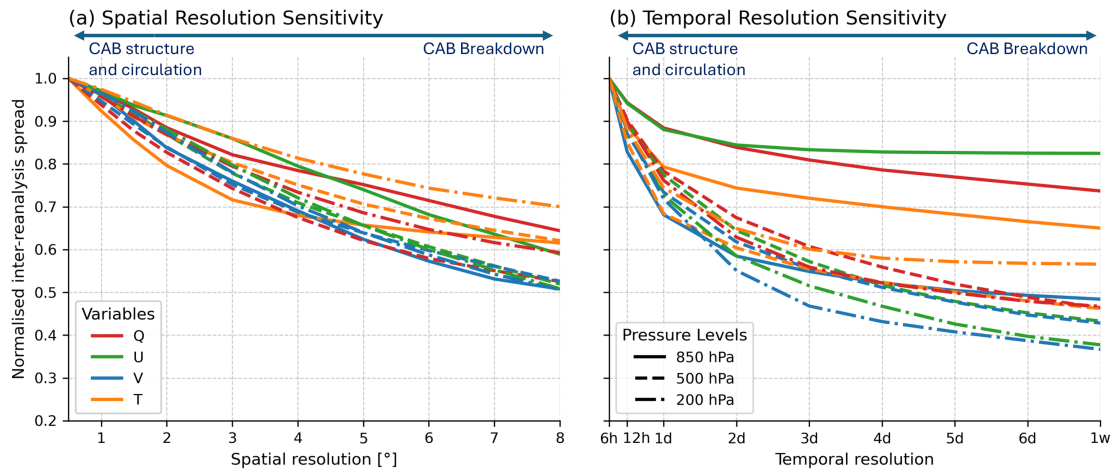


Figure 5.2: Effect of (a) spatial averaging and (b) temporal averaging on normalised inter-reanalysis spread for a suite of atmospheric variables at the Nchila field site. To investigate spatial averaging sensitivity, reanalysis data at 6-hourly resolution is averaged across various spatial scales. To investigate temporal averaging sensitivity, reanalysis data at 0.5° resolution is averaged across various temporal scales. The inter-reanalysis spread is calculated as $(\max - \min)/2$ and normalised to the spread at a) 0.5° or b) 6-hourly resolution. Results are shown for specific humidity (Q), zonal wind (U), meridional wind (V), and temperature (T) at 850, 500, and 200 hPa.

enhanced moisture fluxes are associated with the development of a cut-off low off the west coast of southern Africa, which is a favoured location for the formation of cut-off lows (Singleton and Reason, 2007). A distinct cold-cored low at 500 hPa is first evident on 1 November and subsequently strengthens and propagates eastward through 3 November. The formation of the cut-off low is associated with upper-level Rossby wave breaking.

This case study suggests that CAB breakdown can be associated with the formation of cut-off lows off the west coast of southern Africa, which modifies low-level moisture transport to break down the CAB. However, a single event is insufficient to characterise the mechanisms responsible for CAB breakdown more generally. The remainder of this chapter, presented as a manuscript, therefore extends analysis to a 40-year climatology of CAB breakdown events, enabling a systematic characterisation of CAB breakdown and associated large-scale mechanisms.

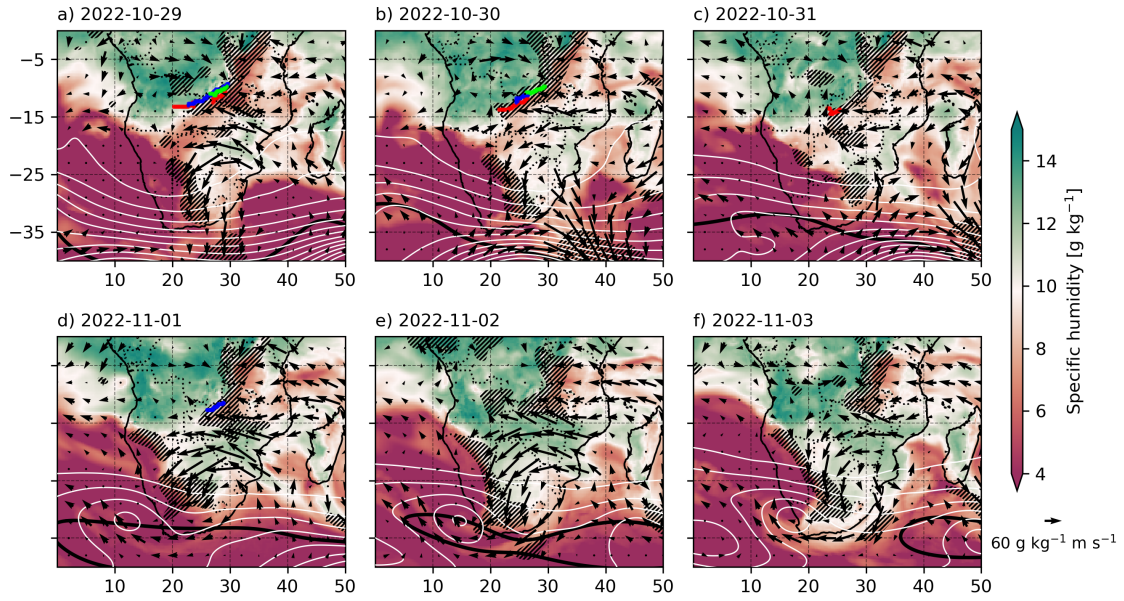


Figure 5.3: Daily evolution of ERA5 850 hPa specific humidity (shading, g kg^{-1}) and moisture flux vectors ($\mathbf{q} = q \cdot \mathbf{v}$, arrows) over southern Africa from 29 October to 3 November 2022. White contours denote 500 hPa geopotential height [gpm], and thick black lines indicate the 330 K potential temperature contour on the -2 PVU surface (the dynamical tropopause). Regions of strong moisture-flux convergence ($< -0.2 \times 10^{-4} \text{ s}^{-1}$) are hatched. Coloured grid cell markers highlight CAB regions identified by ERA5 (red), MERRA-2 (blue), and JRA-3Q (green).

5.2 Introduction

The timing of early summer rainfall onset over southern Africa exerts a profoundly important control on socio-economic viability from the community to the regional scale (Reason et al., 2005; Kniveton et al., 2009; Thurlow et al., 2012; Conway et al., 2015). Agricultural productivity (Kanemasu et al., 1990), food security (Tadross et al., 2005) and power generation (Conway et al., 2015) are all negatively impacted by variable or late rainfall onset, with the latter highly correlated with shorter growing season length (Reason et al., 2005). Accordingly, understanding the controls on rainfall onset and improving its predictability has long been a key goal for forecasters (Phakula et al., 2018; Ratnam et al., 2018).

The August-October pre-onset circulation over tropical southern Africa is characterised by a unique and distinguishing large-scale feature, the Congo Air Boundary (CAB). The CAB occurs at the interface of tropical deep convection in the southern Congo Basin and dry stable subtropical air to the south (Torrance, 1979). With the CAB in place, tropical convection is locked into the Congo basin to the north while the subtropics to the south are dominated by deep subsidence, low surface dewpoint temperatures and a dry regime (Howard and Washington, 2019). The breakdown of the CAB occurs contemporaneously with the southward advance of convection over the subcontinent as subsidence inhibition and moisture limitation is lost, facilitating broad rainfall over southern Africa.

The presence or absence of the CAB is a critical control of transition-season rainfall over the region. Figure 5.4 presents the odds ratios of a rainy day in October or November under CAB presence or absence. Rainy days are 8 times more likely over the core of the southern African subtropics (centred on southern Zambia, northern Zimbabwe, northern Botswana and S.E Namibia) in the absence of the CAB, with this increase locally as large as 40 times in the Zambezi river valley. Understand-

ing the dynamics of the CAB, and particularly the causes of CAB breakdown, is therefore integral to understanding onset at the southern African tropical edge.

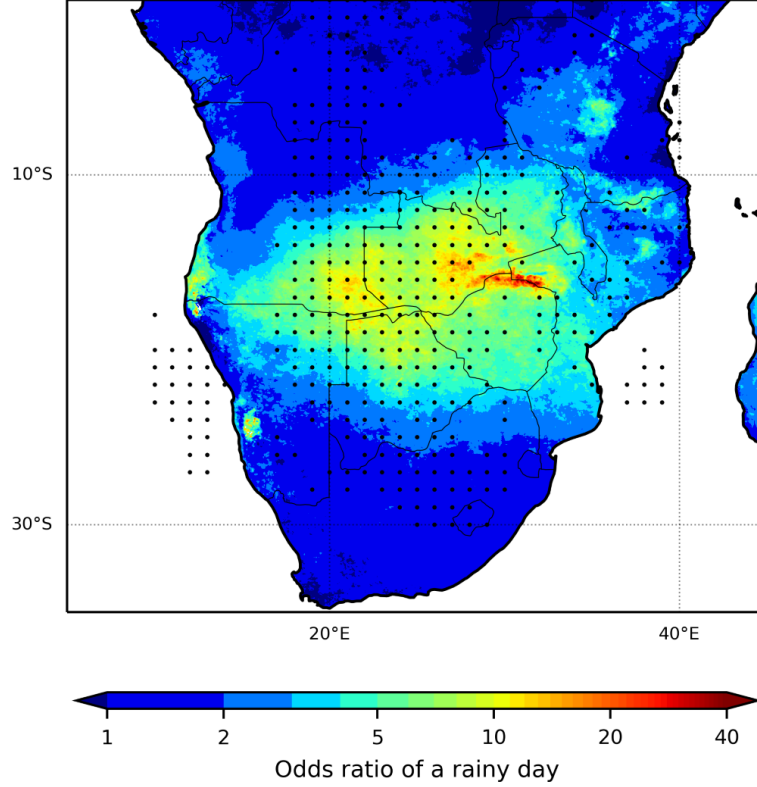


Figure 5.4: Odds ratio of a rainy day ($> 0.1 \text{ mm day}^{-1}$) in October or November given the presence or absence of the Congo Air Boundary (CAB). The colourmap is scaled exponentially. Rainfall data is from the CHIRPS V2 precipitation dataset while daily CAB detection follows the canny edge method of Howard and Washington (2019) (fully detailed in methods). The odds ratio is calculated from a 1981-2018 climatology, with 816 CAB present days and 1502 CAB absent days. Stippling indicates the regions where October November CAB frequency at the day-scale is positively associated with ERA5 rainfall onset date (following the method of Liebmann et al. (2012)) at the 95% significance level in a 1979–2018 climatology.

It is well established in the literature that midlatitude disturbances can be associated with precipitation extremes in subtropical and tropical regions (Knippertz, 2007; De Vries, 2021). As illustrative examples over Africa, Ward et al. (2021) show a remote influence of upper-level midlatitude troughs to Saharan warming and northern Congo rainfall, while Hart et al. (2010) link three summer rainfall extremes over south Africa to cloud bands and Rossby waves in the southern hemisphere west-

erly jet. Given these well-documented tropical-extratropical linkages, it is plausible that midlatitude disturbances play a role in the breakdown of the CAB and onset of the rains over tropical southern Africa. While literature addresses sub-seasonal modulation of rainfall over southern Africa by the midlatitudes, the contribution of Rossby wave dynamics to onset processes is unexplored. To address this research gap, this paper will first identify and characterise CAB breakdown events. Subsequently, it will investigate the causes of these breakdown events and the potential role of midlatitude disturbances in the breakdown process.

5.3 Background

5.3.1 Onset predictability

Predictive skill in the forecasting of southern African summer rains onset has remained elusive. While Ratnam et al. (2018) were able to produce onset forecasts with realistic spatial distributions over the subcontinent using a seasonal prediction model ensemble, root-mean-square error values were greater than 30 days over most of South Africa and southern Botswana, Zimbabwe and Mozambique. Similarly, Phakula et al. (2018) showed that while global coupled models had skill predicting 3-month seasonal rainfall totals over a similar domain, they struggled with forecasting rainfall totals for the onset months of October and November. Clearly, onset is a key period for which seasonal forecasting is lacking in skill. Underpinning this dearth in predictive skill is a poor understanding of the controlling dynamics of rainfall onset. This means that it is difficult to point to the particular deficiencies in numerical model simulations that require improvement to enhance forecasting skill.

5.3.2 The Congo Air Boundary

Forming during the pre-rainfall onset period, the Congo Air Boundary (CAB) is a distinct feature of the tropical edge. The CAB is defined as a convergence zone and dryline where near-saturated low-level westerlies originating from the equatorial east Atlantic and Congo Basin meet easterly trade winds from the southwest Indian Ocean, which are dried by strong heating of the continental surface and diluted by deep tropospheric subsidence south of the CAB (Howard and Washington, 2019). It represents the southern limit of the area of tropical deep moist convection, with a stable subtropical troposphere dominating to the south.

Figure 5.5 demonstrates the climatological importance of CAB dynamics to onset over southern Africa. From August to October, the CAB edges southward from the Congo basin, maintaining integrity but displacing dry conditions with moist convection. In October and November, spells of weather occur where the CAB breaks down and the strong meridional gradient in humidity is lost, allowing deep moist convection and significant rainfall over the central subtropics (Howard and Washington, 2019). In the last week of September (shown as ‘A’ in Figure 5.5), where the climatological daily CAB frequency is 80%, a strong dryline is clear in near-surface specific humidity and the high values of CAPE are contained in the Congo Basin north of 10°S. Conversely, by the first week of November (‘B’ in Figure 5.5), where CAB frequency is 32%, the CAB dryline is absent from the climatological specific humidity field and CAPE values $>250 \text{ J kg}^{-1}$ are prevalent over large parts of southern Africa. The CAB typically does not reform after the latter half of November, marking the full transition to a post-onset rainfall regime where widespread convection and rainfall occur through a variety of mechanisms such as cloud bands and tropical lows (Hart et al., 2013; Howard et al., 2019).

The CAB exercises an important control on rainfall over the core of the southern African subtropics (Figure 5.4). High odds ratio values centred on southern Zambia,

northern Zimbabwe, northern Botswana and S.E Namibia indicate that the CAB strongly controls precipitation over the region, with rainy days 5-40 times more likely when the CAB is absent. In the figure, the climatological location of the CAB is clear as the c.1000 km south-west north-east diagonal line around 10–12°S that demarcates the northern limit of the region of high odds ratios (Figure 5.4, Figure 5.5b). Odds ratios decline south of 22°S as midlatitude rainfall mechanisms such as tropical temperature troughs (TTTs), cut-off lows (COLs) and ridging highs become increasingly important. These contribute to rainfall over the far south of the subcontinent independent of CAB presence or absence. Midlatitude precipitation mechanisms may also contribute to rainfall over the central domain through tropical-extratropical interactions, but importantly this is only a) in the absence of the CAB or b) through causing its breakdown, hence the importance of the feature as a regional precipitation control.

Figure 5.6 presents a schematic of pre- and post- CAB breakdown regimes over southern Africa. Under the pre-breakdown regime, moist air is locked into the Congo basin to the north of the CAB, with dry air capped by subsidence and a strong Botswana high circulation to the south (Moses et al., 2023). The influence of midlatitude precipitation mechanisms is confined to the south of the subcontinent. Under the post breakdown regime, the CAB is absent. Moist air covers most of southern Africa with a new dryline forming over the Kalahari (Howard and Washington, 2019). The midlevel Botswana high is replaced by tropical convection through the depth of the troposphere and midlatitude influences may modulate precipitation over the entirety of the subcontinent under tropical-extratropical interactions. The transition from a pre- to post-breakdown regime occurs over timescales of 2–5 days and is what we term in this work "CAB breakdown". Given the importance of the CAB to early-summer rainfall over tropical southern Africa, considering the causes of this breakdown is a crucial step towards understanding the controlling dynamics of rainfall onset.

5.3.3 Midlatitude influence on the (sub)tropics

The midlatitudes influence the subtropics and tropics through baroclinic Rossby waves. These are long horizontal wavelength (>2000 km) oscillations in the midlatitude westerlies that predominantly occur in the upper troposphere and lower stratosphere. The propagation of these Rossby waves creates perturbations in the climatologically meridional stratification of potential vorticity (PV); upper-level ridges create poleward intrusions of high-PV air, while upper-level troughs create equatorward intrusions of low-PV air (in the southern hemisphere, PV is generally negative and decreases towards the poles). Troughs may be involved in Rossby wave breaking (RWB) where Rossby waves amplify and overturn such that the typical meridional gradient of PV becomes reversed (McIntyre and Palmer, 1983). Southern Africa is a particular Rossby wave breaking hotspot; wave breaking typically initiates in the southeast Atlantic, consolidates over the continent and dissipates in the southwest Indian Ocean (Postel and Hitchman, 1999). We include the upstream and downstream wave breaking hotspots for September-November identified in Ndarana and Waugh's (2011) southern Hemisphere wave breaking climatology in our Figure 5.6 schematic.

Numerous studies document the link between Rossby waves, Rossby wave breaking and subtropical extreme precipitation events (Knippertz, 2007). For example, Hart et al. (2010) link PV troughs with tropical-extratropical cloud bands (regionally known as TTTs) while Ndarana and Waugh (2010) show that Rossby wave breaking is associated with 89% of southern Hemisphere cut off lows (COLs), both of which are linked to extreme spring and summer precipitation events over southern Africa (Hart et al., 2010; Favre et al., 2013). Ridging highs, important in advecting moisture from the southwest Indian Ocean to the continental interior, also have a well-established relationship with RWB (Ivanciu et al., 2022). More broadly, De Vries (2021) link $>80\%$ of extreme subtropical precipitation events to Rossby wave

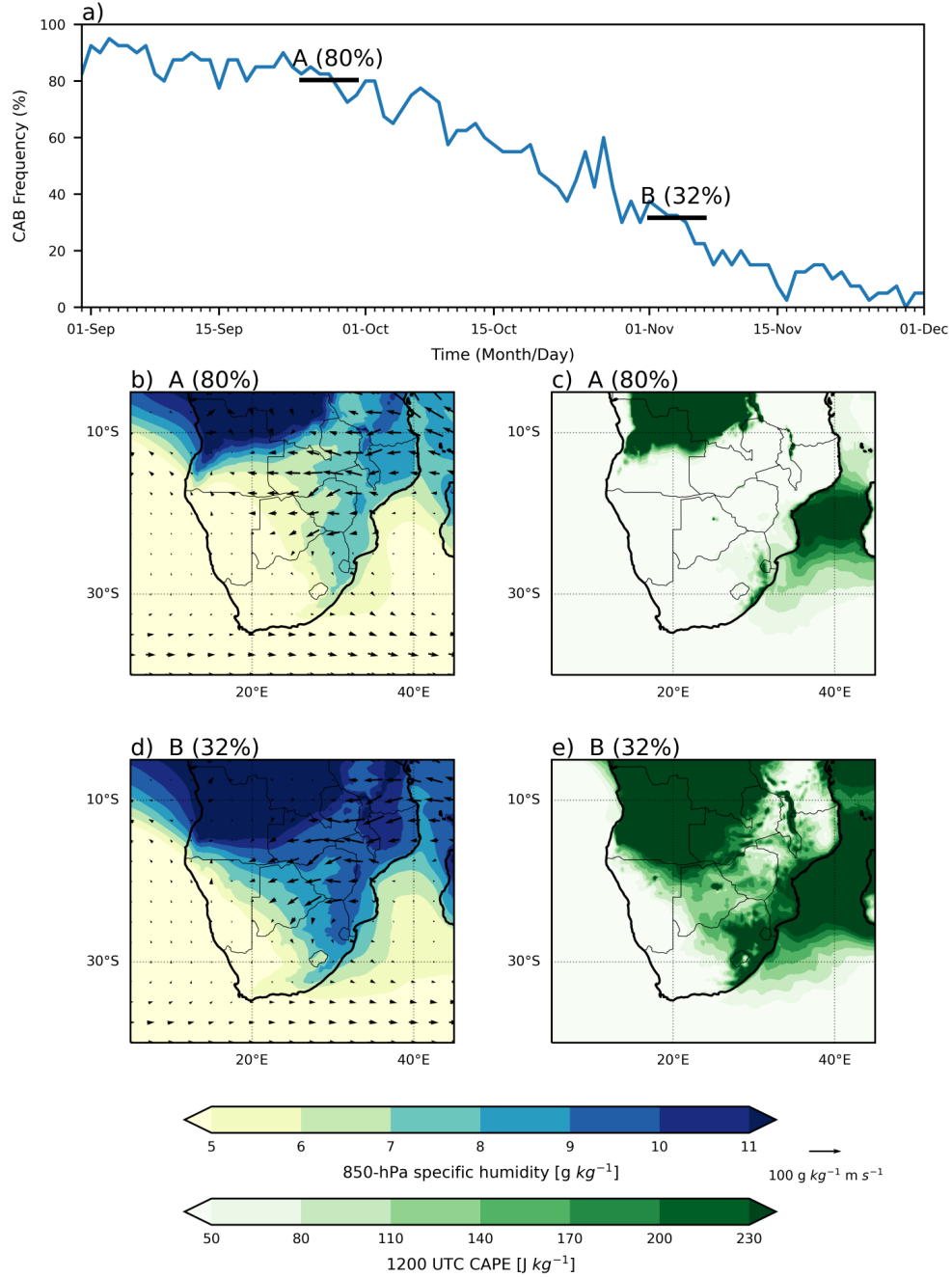


Figure 5.5: (a) A 40-year (1979–2018) climatology of daily Congo Air Boundary (CAB) frequency from 1 September to 1 December. CAB detection follows the canny-edge method of Howard and Washington (2019). (b,c) Composite plots of ERA5 climatological (1979–2018) 850 hPa specific humidity [g kg^{-1}] and CAPE [J kg^{-1}] for the last 7 calendar days of September ('A') where CAB frequency is 80% and (d,e) the first 7 calendar days of November ('B') where CAB frequency is 32%.

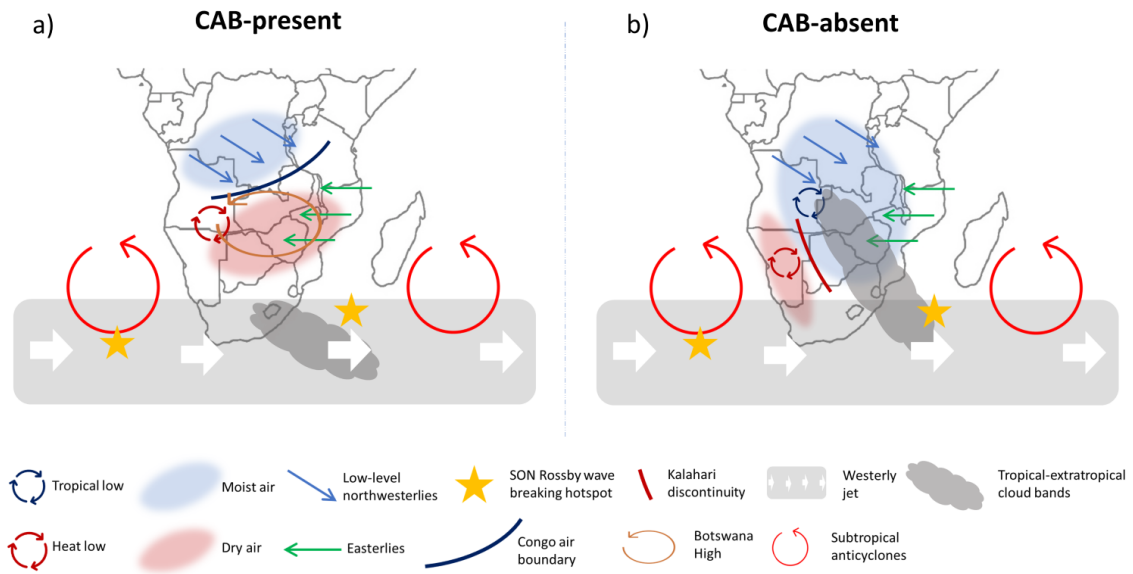


Figure 5.6: A schematic of key southern African regional circulation features with (a) the CAB present and (b) absent. Features are as given in the legend and are not to scale. Locations are approximate. Gold stars mark the September-November hotspots of anticyclonic Rossby wave breaking identified by Ndarana and Waugh (2011). CAB breakdown represents the transition of the regional circulation from a CAB-present state (left panel) to a CAB-absent state (right panel) over timescales of 2-5 days. Tropical temperature troughs here are indicative of a variety of midlatitude precipitation mechanisms.

breaking in a global review. These Rossby-wave-related precipitation extremes are typically concurrent with intense poleward moisture transport from (moist) tropical to (dry) subtropical regions. Qualitatively, this anomalous subtropical precipitation and poleward moisture transport is analogous to CAB breakdown. However, studies that address the extent to which baroclinic Rossby waves modify atmospheric stability and moisture fluxes over southern Africa have largely focused on the austral summer (Hart et al., 2010; Macron et al., 2014) and the southern regions of the continent which are known to receive rainfall of midlatitude origin (Ndarana et al., 2018; Reason and Rouault, 2005; Favre et al., 2013; Ndarana et al., 2021, 2022; Ivanciu et al., 2022). Less is known about the potential role of such midlatitude disturbances in onset dynamics over central southern Africa and the tropical edge.

While midlatitude disturbances are the key to transition-season rainfall over the south of the subcontinent, any role in rainfall onset at the tropical edge is mediated by the CAB. Midlatitude precipitation mechanisms cannot contribute to rainfall at the tropical edge when the CAB is present (Figure 5.4). Only when the CAB is absent, or through causing CAB breakdown, may they contribute to precipitation at the tropical edge and thus rainfall onset. In other words, CAB breakdown "unlocks" the possibility of tropical-extratropical interactions over southern Africa and allows midlatitude influences to modulate precipitation from the extra-tropics to the Congo Basin as is well established in the literature. Given this, it is plausible that midlatitude disturbances play a role in the timing of onset at the southern African tropical edge if midlatitude baroclinic disturbances are a cause of CAB breakdown. To investigate this, in the subsequent section we identify and characterise CAB breakdown events before investigating breakdown causes.

5.4 Data and methods

5.4.1 Data

This work uses hourly or daily mean surface and pressure-level reanalysis fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 product (Hersbach et al., 2020). The ECMWF ERA5 reanalysis is a detailed record of past climate from 1950-present, with a 31km grid spacing, 137 vertical levels and hourly output for a range of atmosphere, land and ocean variables. Only data subsequent to 1979 is used as routine satellite observations over the southern hemisphere began after this date (Tennant, 2004). ERA5 is favoured over other reanalyses due to its spatial resolution, record length and established verification. To ensure that results presented here are not sensitive to reanalysis product, we also use the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis, which is known to perform well in the Congo Basin (Hua et al., 2019). MERRA2 fields are omitted for brevity as MERRA2 and ERA5 were remarkably consistent in the evolution of dynamic and thermodynamic fields across breakdowns, likely due to the large spatial scales across which the processes of interest occur.

Outgoing longwave radiation (OLR) data from the OLR version 1.2 dataset provided by the National Oceanic and Atmospheric Administration (NOAA) Climate Data Record (CDR) at a $1^\circ \times 1^\circ$ resolution is used to identify anomalous convection over southern Africa (Lee, 2014).

Daily precipitation data is used to characterise rainfall location and intensity. Similar results were produced when using ERA5 precipitation and satellite-derived precipitation data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS v2) dataset. ERA5 precipitation is presented owing to data availability for the full period of OLR data (1979–2018) and consistency with the dynamical fields.

5.4.2 Breakdown detection

We identify the CAB on a daily timescale in the ERA5 reanalysis following Howard and Washington (2019) whereby a canny edge detection algorithm is applied to smoothed fields of surface specific humidity to identify strong gradients in the continental sector 5–18°S. Subsequent shape/orientation/length filtering removes non-significant segments and those not associated with the CAB. The canny edge detection algorithm of (Howard and Washington, 2019) is available publicly on GitHub.

To identify CAB breakdown events, a daily timeseries of total detected CAB grid cells was produced for August–December 1979–2018. This was smoothed with a 5-day running mean. CAB breakdown events were then defined as instances where the 5-day mean CAB grid cell count fell below 40 for 4 consecutive days [> 40 Day -1 , < 40 Day 0 to 3]. A total of 108 breakdown events were identified for the 1979–2018 period. Breakdown detection frequency increases with a greater grid cell threshold, with a threshold of 35 (45) leading to the detection of 96 (115) events.

To confirm CAB presence at D-2 and CAB absence at D+2, visual inspection of day-mean surface specific humidity was carried out. 23 cases were rejected on the grounds that the CAB was either absent at D-2 ($n=12$) or present at D+2 ($n=11$). We take this stringent approach to CAB breakdown identification as the objective of this work is to investigate only the large-scale breakdown events associated with significant increases in specific humidity over sub-tropical southern Africa, which are, by extension, the most important to early season rainfall. The total number of CAB breakdowns identified from 1979–2018 was 85, an average of 2.13 breakdown events per year. Breakdown was most frequent in October ($n=40$), followed by November ($n=24$), September ($n=17$), August ($n=3$) and December ($n=1$).

5.4.3 Compositing

We present in the following section composite means of the 85 1979–2018 breakdowns. All 85 breakdown events were brought into phase by assigning $D=0$ to the day on which breakdown was identified. Because of differences in the location, amplitude, and phase of various features of interest there will necessarily be some smearing and smoothing in both time and space within the composites. The logic of calculating a composite mean is that the signal-to-noise ratio will be enhanced.

5.5 Results

5.5.1 Congo Air Boundary breakdown

First, we characterise CAB breakdown events through composite analysis of the 85 breakdown events identified. Figure 5.7 shows that a key feature of CAB breakdown is the loss of a strong meridional specific humidity gradient and a southward advance of the area of high specific humidity. Initially ($D-3$) the CAB is present as a strong near-surface gradient at 12°S . From $D=0$, moist ($>10 \text{ g kg}^{-1}$) air advances southward and the CAB dryline is lost. The 7 g kg^{-1} specific humidity contour advances around 10° latitude (1100km) southward over 3 days.

Figure 5.8 plots the 4-day evolution of near-surface specific humidity anomaly, surface temperature anomaly and upper-level streamfunction anomaly around CAB breakdowns. We use the 250 hPa pressure level for "upper levels" through this work as this pressure surface is in close proximity to both the subtropical and midlatitude dynamical tropopause positions (Ndarana and Waugh, 2010). The specific humidity field shows a significant increase in moisture over much of southern Africa during breakdown, and particularly over southeast Angola, Zambia, Zimbabwe and Botswana. The region of increased moisture is strongly collocated with the region

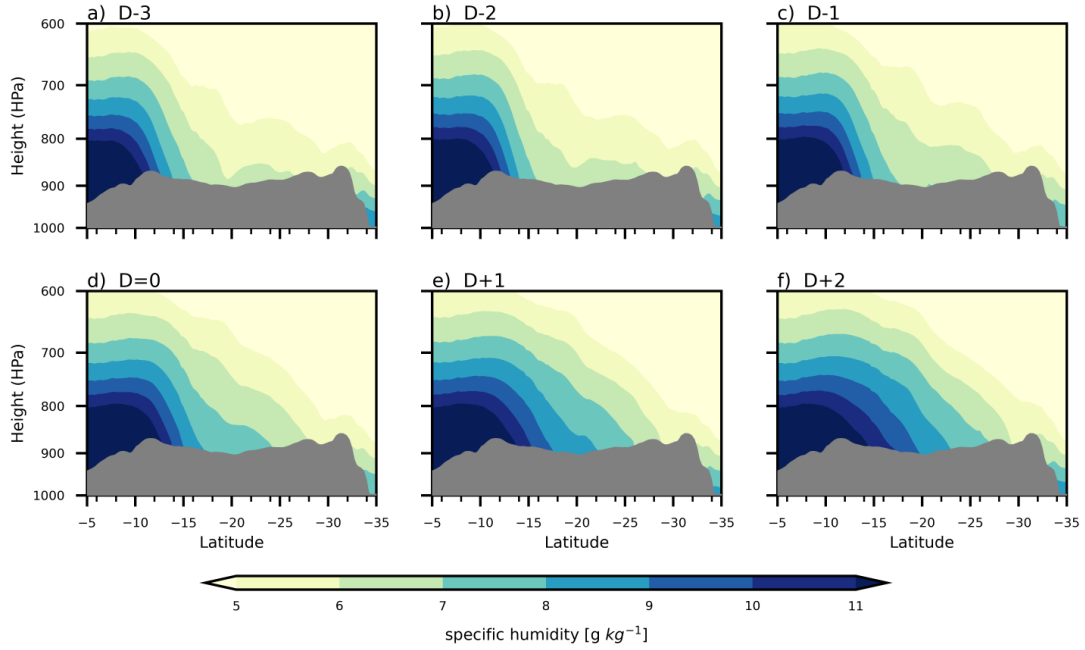


Figure 5.7: Lead (D-3, D-2, D-1) and lagged (D=0, D+1, D+2) daily composite vertical profiles of specific humidity [g kg^{-1}] by latitude for 1979–2018 CAB breakdown events ($n=85$) averaged across $20\text{--}30^\circ\text{E}$. The day of CAB breakdown is designated D=0 for each of the 85 included breakdown events.

of high rainfall sensitivity to the CAB identified in Figure 5.4, highlighting the importance of moisture limitation to the CAB-rainfall relationship. Concurrently, there is a transition through the sequence from broadly positive to broadly negative temperature anomalies over central southern Africa. Streamfunction at 250 hPa shows positive (cyclonic) anomalies over the subcontinent, which shift northward and increase in magnitude through the sequence. The region of maximum specific humidity change and the equatorward edge of positive streamfunction anomalies are strongly co-located.

Figure 5.8 suggests a coherent midlatitude signature during CAB breakdowns. Positive (cyclonic) streamfunction anomalies diagnose the presence of a stationary upper-level trough during the sequence. Troughs are cool events over southern Africa due to the influence of cold air advection and cloud shading (Kuwete et al., 2020), visible as the transient cool anomaly at the tip of the subcontinent from D-1 to D+1. This

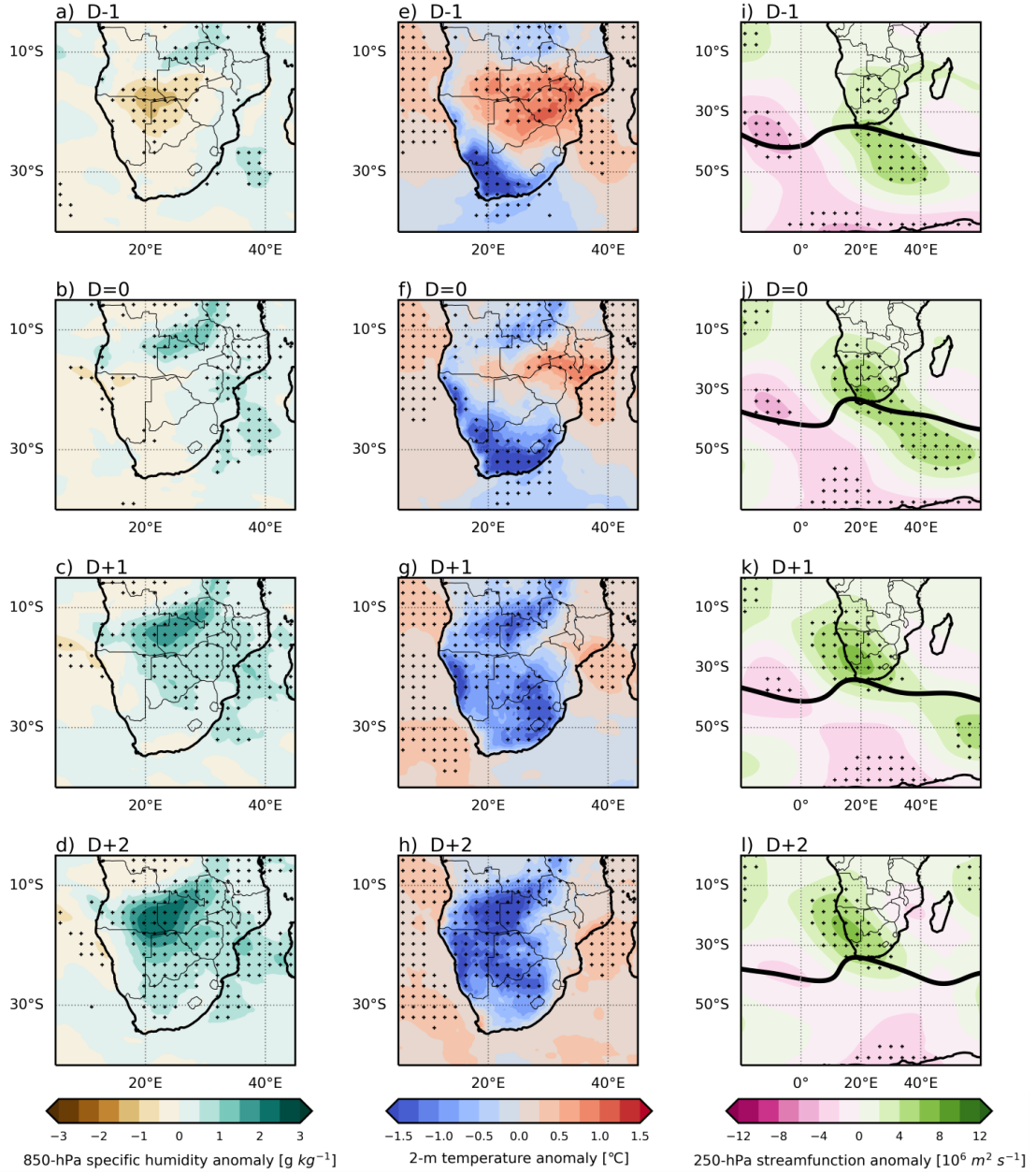


Figure 5.8: Lead (D-1) and lagged (D=0, D+1, D+2) composite day-mean 850 hPa specific humidity [g kg^{-1}] (left column, a-d), 2m temperature anomaly [$^{\circ}\text{C}$] (centre column, e-h), and 250 hPa streamfunction anomaly (against an October climatology) [$\times 10^6 \text{ m}^2 \text{ s}^{-1}$] (right column, i-l) for all 1979–2018 CAB breakdown events ($n=85$) from D-1 to D+2. A [$-9 \times 10^{-5} \text{ s}^{-1}$] absolute vorticity contour at 250hPa is plotted over streamfunction anomalies (right column). Positive streamfunction anomalies are cyclonic. Stippling indicates where anomalies are significantly different from the October climatology or zero at the 0.05 level.

signal is significant in a composite of all 1979–2018 breakdown events, suggesting that troughs may play an important role in forcing the cooling and moistening of southern Africa during CAB breakdown.

It is notable that cyclonic streamfunction anomalies persist and even intensify over southern Africa through the 4-day breakdown sequence. Typically, troughs propagate eastward with the zonal flow at a phase speed set by their wavenumber (Holton, 2012). Stationarity is possible in two ways; low wavenumber Rossby waves with zero phase speed, or Rossby wave breaking (RWB). Streamfunction anomalies associated with a low-wavenumber (high wavelength) Rossby wave would exhibit greater zonal separation between positive and negative anomalies, meaning RWB is the likely cause of the anomaly patterns of Figure 5.8. There is also evidence of a transient midlatitude disturbance in the west-east migration of the most southerly streamfunction and temperature anomalies through the sequence. The reviews of Knippertz (2007) and De Vries (2021) highlight the large body of work that links midlatitude troughs and RWB to enhanced tropical convection, providing a mechanism by which such disturbances may be causally related to CAB breakdown. The strength of signals emerging from Figure 5.8 are weak, however, as troughs may not occur with every breakdown.

In light of these results, we pose the following research questions:

- RQ1: What proportion of CAB breakdowns are related to the troughs in the midlatitudes?
- RQ2: What are the characteristics of Rossby waves that are related to breakdown?
- RQ3: How do Rossby waves contribute to breakdown?

5.5.2 What proportion of breakdowns are associated with the midlatitudes?

To determine the proportion of CAB breakdown events associated with the midlatitudes (RQ1), we begin by testing for the proportion of breakdown events that are immediately preceded by a) troughs or b) RWB. The methods to identify each are outlined below.

5.5.2.1 Strong trough identification

We identify upper-level troughs over southern Africa using a trough parameter (TP) index. Several previous studies have defined an index of upper-level midlatitude flow to explore co-varying climatic features (e.g., Jacobeit (1987), Knippertz (2007) and Ward et al. (2021)). A similar method to Ward et al. (2021) is used here. The trough parameter (TP) index is calculated as:

$$TP = \left(\frac{Z_1 + Z_3}{2} \right) - Z_2 \quad (5.1)$$

across a latitudinal domain of 35–45°S, where Z_2 is the mean geopotential height anomaly at 300 hPa for a 10° longitudinal domain centred on 25°E and Z_1 and Z_3 are average 300 hPa anomalies for the 12.5° zones to the west (Z_1) and east (Z_3) of Z_2 . The 300 hPa geopotential height anomaly is calculated against an October climatology, and TP index values computed at 6-hourly intervals for the study period of August–December 1979–2018. The method assumes a north-south axis and longitudinal trough extension of around 2000 km at 35°S, and we note that index values will decline for similar troughs with differing axis orientations or longitudinal extensions.

A strong trough is considered present on a given day if TP_{daymax} is greater than 1 standard deviation above the August–December mean ($TP_{daymax} > 1134$). This

threshold resulted in 15% of days from August to December 1979–2018 being classed as strong trough days. A threshold of 1200 (1000) flagged 14% (18%) of days as strong trough days. We consider one standard deviation above the mean an appropriate middle value that flags significant troughs but is not highly sensitive to assumptions of the index method about wavelength, location and orientation.

5.5.2.2 Rossby wave breaking identification

We identify Rossby wave breaking (RWB) within our southern African sector of interest [0–50°E, 20–70°S] by the overturning of 250 hPa absolute vorticity contours, following the method of Ndarana and Waugh (2010) and Barnes and Hartmann (2012). Absolute vorticity is computed from ERA5 pressure level data as:

$$\eta \equiv f + \zeta \quad (5.2)$$

where f is the Coriolis parameter and ζ pressure-level relative vorticity.

Daily relative vorticity (ζ) at $0.25^\circ \times 0.25^\circ$ resolution was obtained from ERA5 archives, summed with planetary vorticity (Coriolis parameter, f), and smoothed. Smoothing is achieved through conversion of globally gridded data to spectral data and then a truncation of spherical harmonics at T15. This ensured that the method only identifies large-scale overturning as a wave breaking event, rather than small-scale perturbations in the vorticity field. A RWB detection algorithm then searches for locations along select absolute vorticity contours [C] where a single meridian intersects C at least three times, and these intersection points are flagged as an overturning point. Where two or more overturning points are in longitudinal proximity (i.e., overturning spans two meridian lines) they are grouped together as a RWB event. Only RWB events for which the mean latitude and longitude of all overturning points falls within the sector of interest [0–50°E, 20–70°S] are retained, and small-scale events with $<20^\circ$ along the meridian between the most northern

and most southern intersection points are removed. RWB in the sector of interest was identified on 34% of days from August to December 1979–2018, including both anticyclonic and cyclonic wave breaking. Barnes and Hartmann (2012) show that RWB identification in pressure-level absolute vorticity is a robust method that produces a similar distribution to RWB identification using potential vorticity (PV) on isothermal surfaces. We prefer a pressure-level absolute vorticity metric for its simplicity and for consistency through this paper; the properties of PV (conservation, invertibility) that have made it such a key tool for unlocking midlatitude dynamics are not relevant to this work (Hoskins, 2015). Unless otherwise stated, for data visualisation purposes absolute vorticity is presented with a spherical truncation at T21 in plots to enhance signal to noise.

5.5.2.3 Association with breakdown

To determine Rossby wave association to breakdown, we test if breakdown is accompanied by RWB or a strong trough event in the time interval from two days prior to the day of detected breakdown. A RWB event set is constructed as a subset of the 85 identified breakdown events where RWB was detected 0–50°E and 20–70°S from two days prior to the day of detected breakdown, while a trough (TR) event set was constructed as a subset of the 85 identified breakdown events where a strong trough was detected in the same period. Breakdown events flagged by both the trough and RWB detection schemes were assigned only to the RWB category. To enhance the strength of signals in subsequent composite analyses and account for the differing dynamical evolution of each breakdown, the date of a RWB breakdown event ($D=0$) is defined as the first day of detected overturning of absolute vorticity. Dates of TR breakdown events ($D=0$) are defined as the day of maximum TP index values. Relative to CAB-gridcell detected breakdown dates, RWB or TR dates were either i) unchanged, ii) 1 day previous or ii) 2 days previous.

Overall, 53% (45/85) of 1979–2018 CAB breakdown events are associated with

Rossby wave breaking over southern Africa. A further 18% (15 of 85) are associated with troughs in the midlatitude westerly jet. In total, 60 (71%) of the 85 CAB breakdown events from 1979–2018 cooccur with troughs or RWB. The proportion of associated breakdowns decreases through the onset period from 100% in August (n=3) through to 46% in November (n=11), as shown in Table 5.1, suggesting a decreasing association of midlatitude Rossby waves and breakdown through the transition season.

Table 5.1: Monthly proportion of 1979–2018 CAB breakdown events related to midlatitude Rossby waves. Breakdowns are associated if occurring within two days of RWB or strong trough events.

Month	N. of Rossby wave associated breakdowns	N. of not associated breakdowns	Total	Proportion
August	3	0	3	100%
September	12	5	17	71%
October	34	6	40	85%
November	11	13	24	46%
December	0	1	1	0%

Figure 5.9 presents a composite of 250 hPa absolute vorticity, near-surface specific humidity anomaly and convective available potential energy (CAPE) for the 60 CAB breakdown events we relate to midlatitude Rossby waves. Upper-level absolute vorticity shows a westward-leaning trough at D-1, with a strong CAB in place, negative specific humidity anomalies over southern Africa and CAPE locked into the Congo Basin. At D=0, anticyclonic RWB is clear from the overturning of the upper-level absolute vorticity contours. Through D=0 and D+1, the strong meridional gradient of specific humidity and CAPE is eroded. By D+2, the RWB event has begun to dissipate but significant increases in specific humidity south of the CAB are clear, matched by higher 1200 UTC CAPE over a broad region of southern Africa. It is clear that RWB is contemporaneous with a large and spatially significant increase

in specific humidity and CAPE over subtropical southern Africa.

5.5.3 What Rossby waves cause breakdown?

Having demonstrated that RWB is contemporaneous with breakdown and large increases in specific humidity and CAPE over subtropical southern Africa, we next investigate the characteristics of the Rossby waves that are concurrent with breakdowns (RQ2). To aid this analysis, a counterfactual event set (CF) is constructed featuring 32 September–October–November strong trough events (TP threshold of > 1 std dev above mean) from 1979–2018 that did not lead to CAB breakdown. The distribution of these events in the annual cycle was broadly similar to that of the TR and RWB event sets (Table 5.2).

Figure 5.10 shows the composite 5-day change in 850 hPa specific humidity and pentad precipitation change for each event set. CAB breakdown, shown by significant increases in specific humidity south of the CAB’s preferred location, is clear in the ALL, RWB and TR event sets, with no significant change in CF. Rainfall is strongly co-located with increases in specific humidity; the three breakdown cases contribute significantly to precipitation over the subcontinent while the CF case remains dry.

Table 5.2: Mean position and standard deviation of the Julian Day of CAB breakdown events in the annual cycle for ALL, RWB, TR and CF. The ‘ALL’ event set is centred on the day of detected CAB breakdown, while the RWB event set is centred on the first day of detected overturning and the TR and CF sets are centred on the day of maximum ‘TP’ index values.

Event Set (n)	Julian Day Mean	Std Dev
ALL (85)	291	23.7
RWB (45)	283	20.9
TR (15)	301	18.4
CF (33)	281	8.6

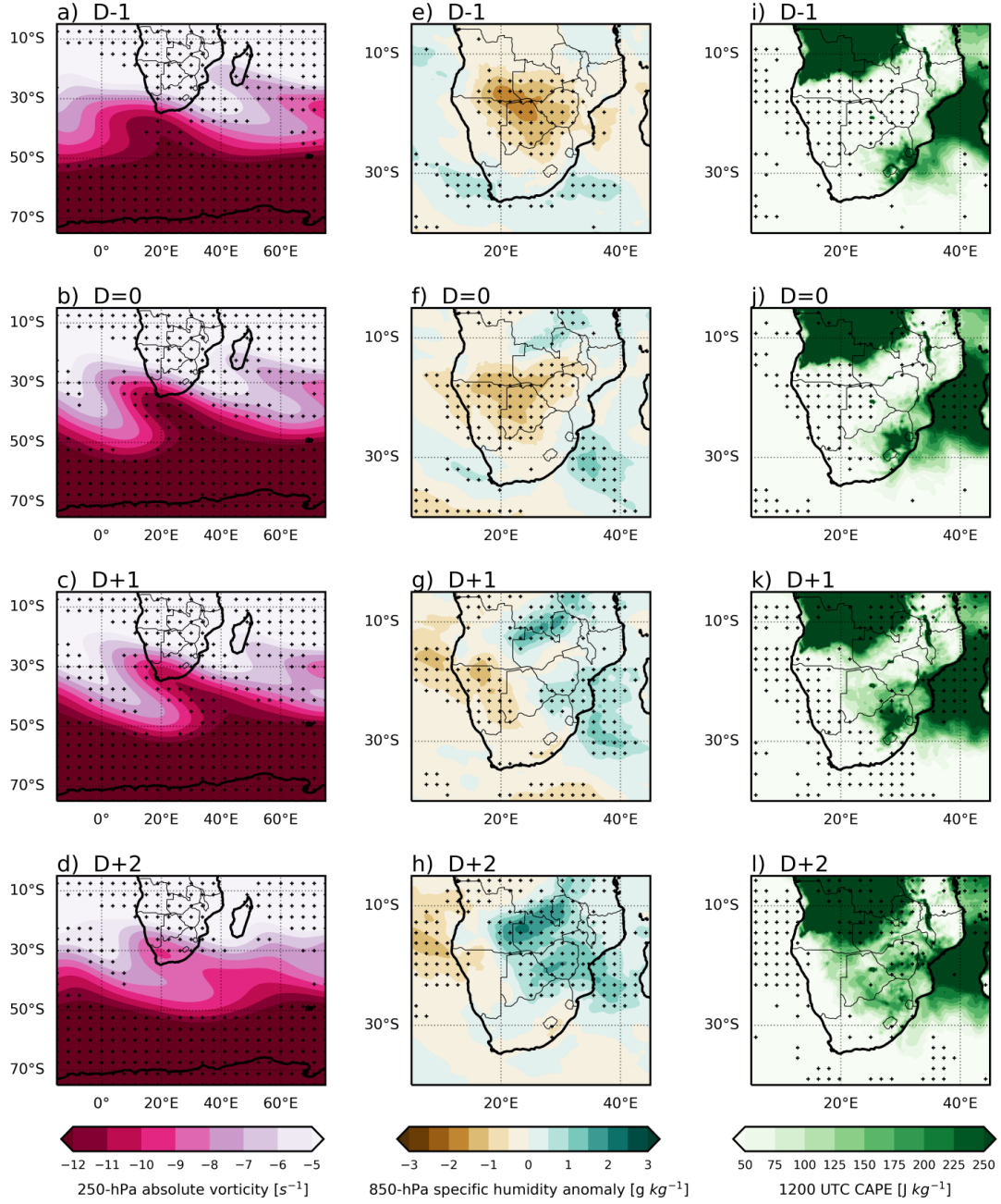


Figure 5.9: Lead (D-1) and lagged (D=0, D+1, D+2) composite day-mean 250 hPa absolute vorticity [$\times 10^{-5} \text{ s}^{-1}$] (left column, a-d), 850 hPa specific humidity anomaly [g kg^{-1}] (centre column, e-h) and 12:00 UTC CAPE [J kg^{-1}] (right column, i-l) for all CAB breakdown events related to midlatitude Rossby waves (both RWB and TR event sets, $n=60$). For RWB breakdowns D=0 is defined as the first day of overturning, while for TR breakdowns D=0 is defined as the day of maximum ‘TP’ index values. Stippling indicates where values are significantly different from the October climatology or zero at the 0.05 level.

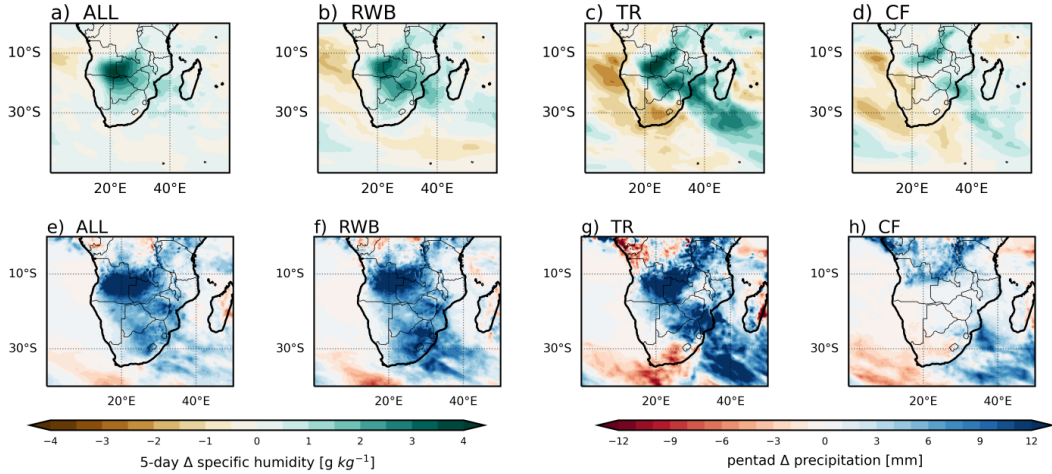


Figure 5.10: Composite 5-day change in 850 hPa specific humidity [g kg^{-1}] and pentad precipitation change (difference in total rainfall between the previous and following 5 days) [mm] for all CAB breakdowns (ALL) and each of the RWB, TR and CF event sets. The RWB event set is a subset of ALL where breakdown is associated with Rossby wave breaking, while TR is a subset of ALL where breakdown is associated with troughs. RWB and TR trigger large-scale responses over southern Africa. The CF event set is a counterfactual of trough events that do not trigger a large-scale response over the domain.

5.5.3.1 Wavenumbers

Here we analyse wavenumbers to determine the characteristics of the waves bound up with the RWB, TR and CF cases. Higher wavenumber waves propagate more rapidly eastward with the zonal flow while low-wavenumber planetary waves are stationary or retrogress (Holton, 2012). Table 5.3 details the amplitude and explanatory variance of the first 10 harmonics of 250 hPa geopotential height anomaly at 40°S for each of the three event sets. For the RWB case, the greatest explanatory variance is for wavenumbers 4 and 5, accounting for 18.4% and 20.4% of variance respectively. For the TR case, the greatest explanatory variance is for wavenumber 3, accounting for 26.7% of variance and with an amplitude of 45.3 gpm. And for the CF case, the greatest explanatory variance is for wavenumber 6, accounting for 25.0% of variance and with an amplitude of 38.1 gpm. The Rossby waves that are important to breakdown therefore appear to be characterised by much lower wavenumbers than those unrelated to breakdowns. Extending the analysis over further latitudinal

bands, the low wavenumber signals of the RWB and TR cases are dominant consistently through to 55°S, while the wavenumber 6 peak of the CF case holds dominant explanatory power only from 35°S–40°S. We interpret that the Rossby waves related to breakdown are latitudinally coherent low-wavenumber disturbances across both the polar and subtropical jet, while those unrelated to breakdown are weaker higher-wavenumber disturbances confined to only the subtropical jet.

Table 5.3: Amplitude and variance of the first 10 harmonics of composite 250 hPa geopotential height anomaly between 180–180°E at 40°S for each of the RWB, TR and CF cases. Harmonics with the largest explanatory variance are highlighted in bold.

	Harmonic									
	1	2	3	4	5	6	7	8	9	10
RWB										
Amplitude	8.7	27.9	26.9	29.9	31.5	10.6	9.4	4.1	0.5	1.4
Variance	1.6	16.1	14.9	18.4	20.4	2.3	1.8	0.4	0.0	0.0
TR										
Amplitude	29.0	12.4	45.3	40.6	36.7	21.5	29.3	4.3	6.1	3.9
Variance	10.9	2.0	26.7	21.4	17.6	6.0	11.2	0.2	0.5	0.2
CF										
Amplitude	30.6	31.5	15.0	22.0	22.1	38.1	20.1	11.3	6.5	4.3
Variance	16.1	17.2	3.9	8.4	8.4	25.0	7.0	2.2	0.7	0.3

5.5.3.2 Wave trains

Next, we consider the large-scale wave trains within which the vorticity anomalies of interest are embedded. Figure 5.11 plots southern hemisphere upper-level geopotential height anomalies for the RWB, TR and CF event sets. In all three cases, a negative geopotential height anomaly indicative of an upper-level trough overlies southern Africa. In the RWB case this negative anomaly is broad and somewhat zonally orientated, covering a large range of latitudes and longitudes, while for the TR and CF cases it is confined to the southern tip of the continent.

At the larger scale, the RWB case is characterised by a deeply extratropical trough-ridge structure in the south Atlantic, with associated geopotential height anomalies extending from 30–70°S (Table 5.3, Figure 5.11a). Anticyclonic Rossby wave breaking occurs on the downstream equatorward flank of this wave train.

The TR composite is characterised by a wavenumber-3 trough centred over southern Africa with ridges fore and aft (Table 5.3, Figure 5.11b). Compared to RWB, anomalies are weakly defined in the extratropical South Atlantic, but stronger over southern Africa. The extent to which RWB and TR differ is noteworthy; the two cases are products of very different wavetrains and RWB does not appear to be a dynamical extension of TR troughs where overturning occurs.

While structurally similar to TR, the geopotential height anomalies of the CF case are weaker and less meridionally extensive, with stippling generally confined to lower latitudes ($<50^\circ\text{S}$). We interpret this difference between TR and CF as further support that CF cases are weaker transient wavenumber-6 troughs confined to the subtropical jet, while TR cases are deeper low-wavenumber troughs involving superposition of the polar and subtropical jets (Table 5.3, Figure 5.11).

5.5.3.3 Wave sources

Finally, we consider potential sources of the Rossby waves related to CAB breakdown. Sardeshmukh and Hoskins (1988) show that regions with divergent winds, such as those occurring in areas with strong meridional gradients of zonal winds, can advect vorticity and act as a source of Rossby wave energy. As well as stationary influences such as orography, vortex stretching as a result of convection can enhance divergence and act as a Rossby wave source.

The dashed contours of Figure 5.11 plot the mean OLR anomaly for the 5 days preceding each event set to identify upstream regions of anomalous convection that may be a Rossby wave source. In the TR composite, anomalous convection in the

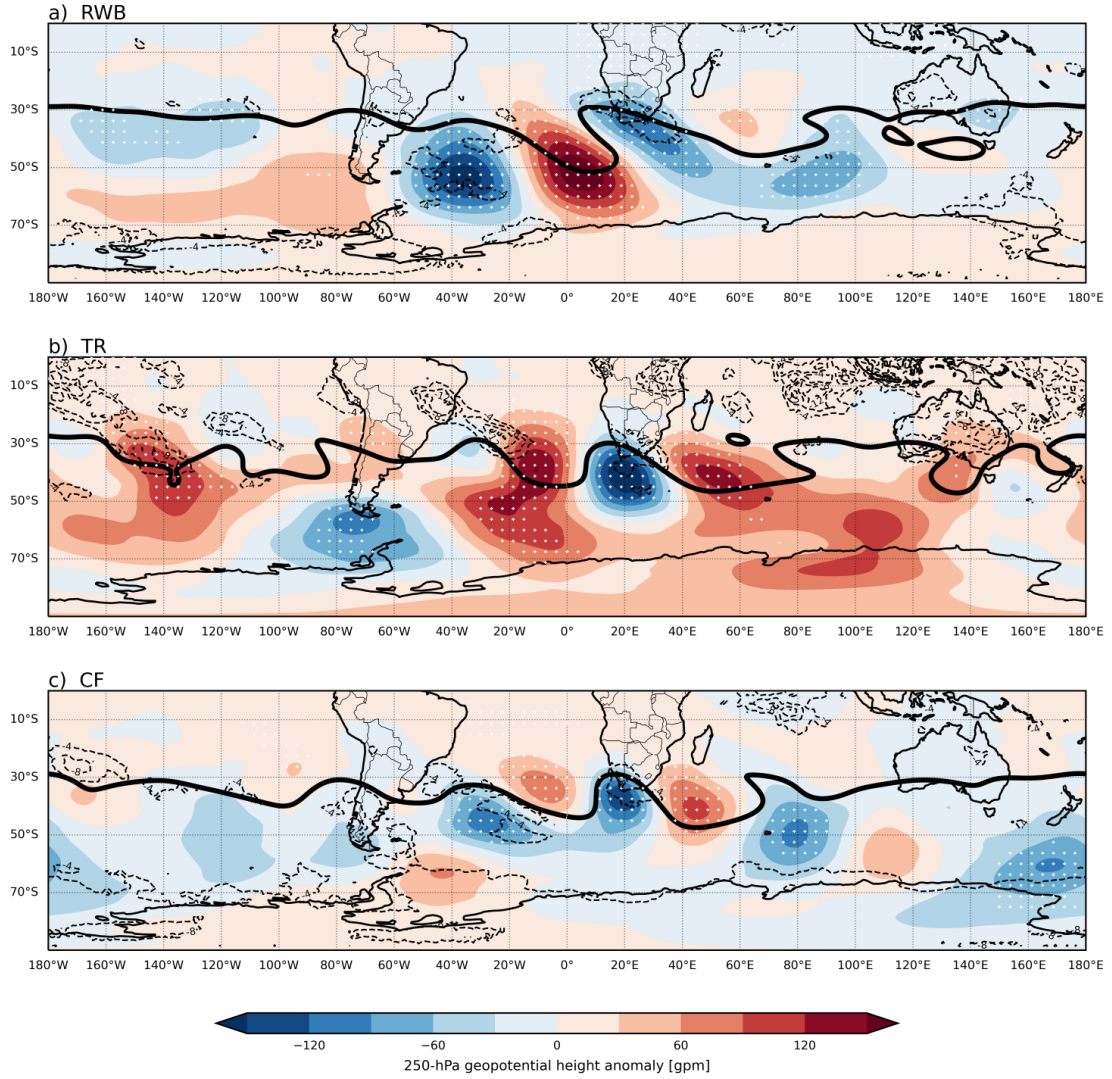


Figure 5.11: Composite day-mean 250 hPa geopotential height anomaly [gpm] for D=0 of the RWB (a), TR (b) and CF (c) event sets. A solid black contour plots $[-9 \times 10^{-5} \text{ s}^{-1}]$ absolute vorticity at 250hPa. Dashed black closed contours plot OLR anomaly $[\text{W m}^{-2}]$ for the 5 days previous to the event shown at an interval of -4 W m^{-2} . Stippling indicates where geopotential height anomalies are significantly different from zero at the 0.05 level.

South Atlantic Convergence Zone (SACZ) is clear. SACZ convection can excite Rossby waves that propagate downstream to cause rainfall in southern Africa. Indeed, Grimm and Reason (2015) document a 5-day lagged summer teleconnection between rainfall in South America and Southern Africa as a result of this wave excitation. Dynamically, upper-level anticyclonic vorticity tendency induced by enhanced convection stalls the upper-level flow, contributing to downstream divergence and exciting a Rossby wave that grows and propagates towards southern Africa. Subsequent wave superposition with an extratropical disturbance produces a deep and energetic trough that causes CAB breakdown. The RWB and CF cases lack such a clear upstream convective signal across a 5-day lead. A more detailed inspection of the evolution of daily geopotential and OLR anomalies at a 0 to 6 day lead indicates that RWB and CF are led by deeply extratropical disturbances in the South Atlantic off the eastern coast of South America. These OLR anomalies are transient and decrease in magnitude with an increasing lead time, suggesting that a coherent upstream convective signal is not a feature of these two cases. This is likely a result of the averaging of a diverse number of upstream evolutions. Only the TR composite is characterised by clear upstream convection in the SACZ across a 5-day lead.

5.5.4 How do Rossby waves contribute to breakdown?

In this section we consider the evolution of each of the RWB, TR and CF cases over southern Africa to investigate how Rossby waves dynamically contribute to CAB breakdown.

5.5.4.1 Vertical velocity

Figure 5.12 and 5.13 show lagged composite vertical velocity by latitude and at 500 hPa respectively for each of the three composite cases. In Figure 5.12, the 7 g kg^{-1} specific humidity contour identifies the tropical region of high humidity. At D-1 for all three event sets the CAB is clearly in place, with moist air locked into

the Congo Basin and a strong demarcation between deep tropospheric ascent in the Congo [0–10°S] and the mid-level subsidence of the subtropics to the south of the CAB. Initial (D-1) south-of-CAB subsidence is stronger in the CF case than others, possibly due to the earlier seasonal distribution of the CF events against an October climatology (Table 5.2). This south-of-CAB subsidence is key to the maintenance of a CAB-in-place, pre-onset state, diluting the easterly winds and forcing a highly stable atmospheric profile. D-1 streamlines indicate this subsidence is related to both the midlatitudes and local overturning. By the end of the breakdown sequence (D+2), there is a clear southward extension of the region of high humidity in the two CAB breakdown cases (RWB and TR), while the counterfactual (CF) remains unchanged. Mid-level subsidence is replaced by ascent in the two CAB breakdown cases but persists in CF.

Figure 5.13 shows that the latitudinal changes in vertical velocity identified in Figure 5.12 can be attributed to Rossby waves in the midlatitude westerly jet. A solid black contour plots $-9 \times 10^{-5} \text{ s}^{-1}$ absolute vorticity, showing wave breaking in the RWB case and transient troughs migrating eastward in the TR and CF cases. In all cases, patterns of ascent and subsidence are tightly coupled to upper-level vorticity anomalies with ascent leading and subsidence trailing.

In the RWB case, wave breaking leads to the establishment of semi-stationary ascent over the subcontinent and descent off the south-west coast. Through the sequence we see south-of-CAB subsidence eroded by this semi-stationary ascent, so that by the end of the sequence ascent dominates through the depth of the troposphere and large negative OLR anomalies establish over the majority of subtropical southern Africa (Figure 5.12, 5.13). The dynamical impact of wave breaking here tightly reflects that demonstrated by Funatsu and Waugh (2008) in the tropical Pacific, whereby upper-level PV anomalies promote convection through destabilising the lower troposphere and causing upward motion ahead of the vorticity anomaly. We

view the location of wave breaking here as key; wave breaking must be upstream of southern Africa and vorticity anomalies located over the western seaboard for this ascent to consolidate over the continental interior and promote CAB breakdown. Wave breaking at this location is identified as a hotspot in Ndarana and Waugh’s (2011) southern Hemisphere wave breaking climatology, but is less common than wave breaking downstream of southern Africa.

In the TR case, we see vertical velocity patterns associated with the transient trough migrate eastward. Strong ascent is associated with the trough’s divergent leading edge and subsidence associated with the convergent trailing edge. A cloud-band structure of negative OLR anomalies, tightly coupled to the region of maximum vertical ascent, displaces south-of-CAB subsidence and leads to region-wide negative OLR anomalies by D+2.

The CF case is structurally similar to TR. However, the northward extension of perturbed vertical velocity is less and no permanent change to the dominant south-of-CAB subsidence occurs through the sequence. A weak cloud-band OLR signature is seen over the southwestern Indian Ocean, but it does not have any continental extension. A key distinction between TR and CF is that we see the TR case instigate a tropical-extratropical interaction over southern Africa that displaces south-of-CAB subsidence with region-wide ascent. In contrast, the CF case is insufficient to force this and south-of-CAB subsidence remains in place.

In all three cases, negative OLR anomalies lead the upper-level vorticity anomaly. Latent heating associated with this convection introduces an upper-level anticyclonic vorticity tendency which counteracts the cyclonic circulation around the vorticity anomaly, slowing wave propagation by stalling the leading edge of the trough. This contributes to wave amplitude growth and increases the probability of overturning (wave breaking). We observe this effect in all three cases as the disturbances transit southern Africa; wave propagation totally stalls in RWB while we see minor over-

turning of absolute vorticity in TR and an increasing wave amplitude and westward tilt in CF. This is not a surprising result; Ndarana and Waugh (2011) show a clear wave breaking hotspot downstream of southern Africa. In the RWB case, this feedback facilitates the persistence of synoptic ascent and further promotes breakdown. This is to a certain extent also true of the TR case, as although the trough remains transient we see wave amplitude growth and eastward propagation is slowed. In the CF case, convection in the Mozambique channel slows wave propagation and contributes to RWB, a strong ridging high and enhanced south-of-CAB subsidence (Ivanciu et al., 2022). This adds dry upper-level air to the southern African domain and acts to reinforce a CAB-present state (Figure 5.12k,l).

5.5.4.2 Wind field modification

Figure 5.14 plots moisture fluxes to investigate near-surface wind field modification during breakdowns. All three cases exhibit a D=0 reduction in easterly moisture fluxes where they would be convergent with the low-level Congo westerlies around the CAB. This is an apparent common feature of midlatitude troughs over southern Africa; transient lows force an eastward displacement of the Mascarene anticyclone, weakening geopotential gradients around the Mozambique channel and slackening the easterlies across Mozambique and Zambia. At the same time, and likely related to the loss of convergence at the CAB, we see enhanced north-westerly moisture fluxes in the Congo. This leads to a southward advance of the region of moist air from the Congo Basin in all cases.

In the latter stages of the sequence, ridging of the South Atlantic high is also clear in all three cases. The importance of ridging highs in advecting moisture from the Mozambique channel to the continental interior is well established in the literature, and we see evidence of enhanced moisture fluxes along this axis in all three cases (Ndarana et al., 2021, 2022; Ivanciu et al., 2022). In the RWB and TR cases,

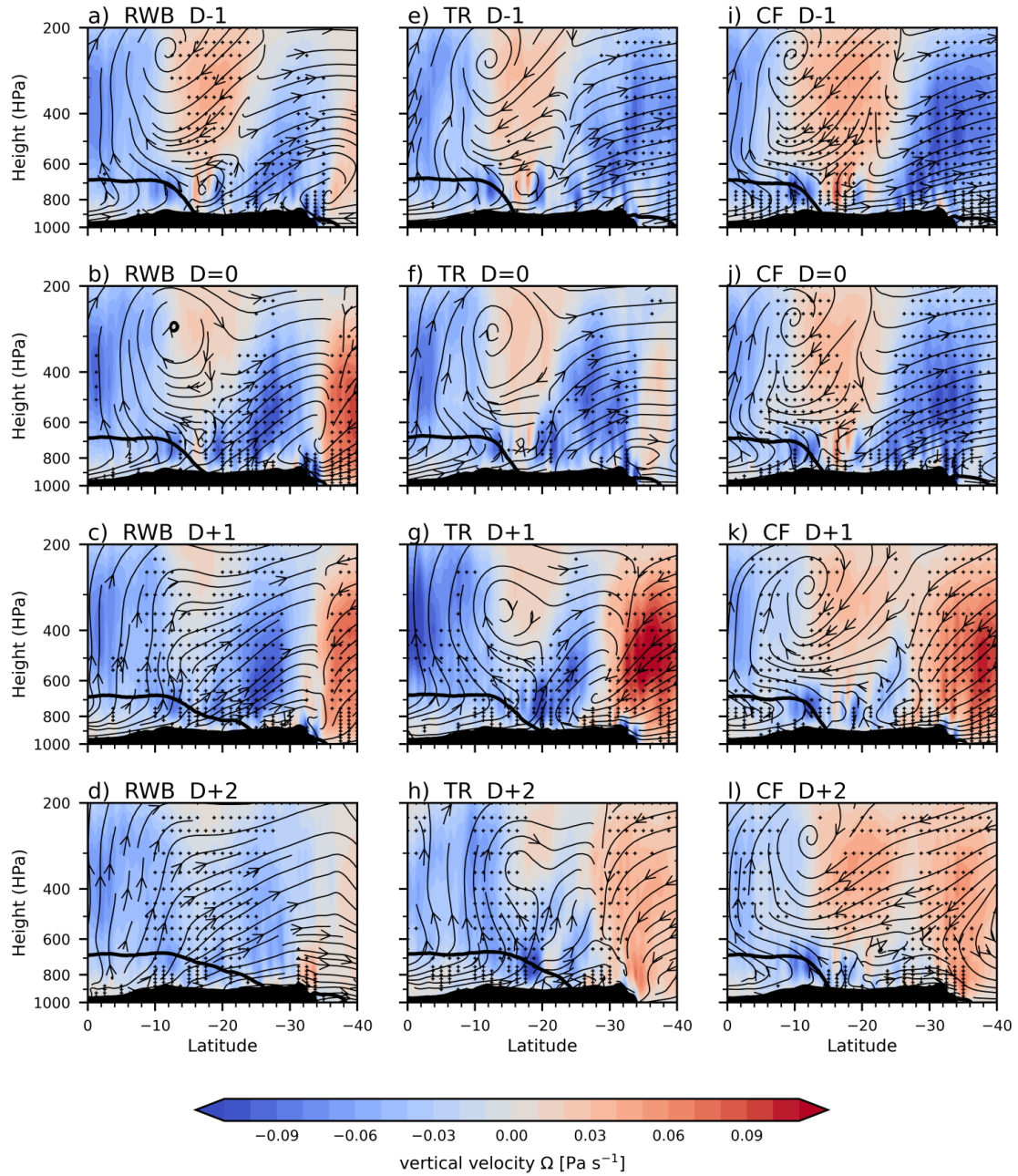


Figure 5.12: Lead (D-1) and lagged (D=0, D+1, D+2) composite latitudinal profiles (20-30°E) of vertical velocity [Pa s⁻¹] for each of the RWB (a-d), TR (e-h) and CF (i-l) event sets. Topography is shaded black. A solid black contour plots 7 g kg⁻¹ specific humidity. Stippling indicates where vertical velocity is significantly different from the October climatology at the 0.05 level. Streamlines show vertical velocity and the northward wind component, with vertical velocity scaled by 1000.

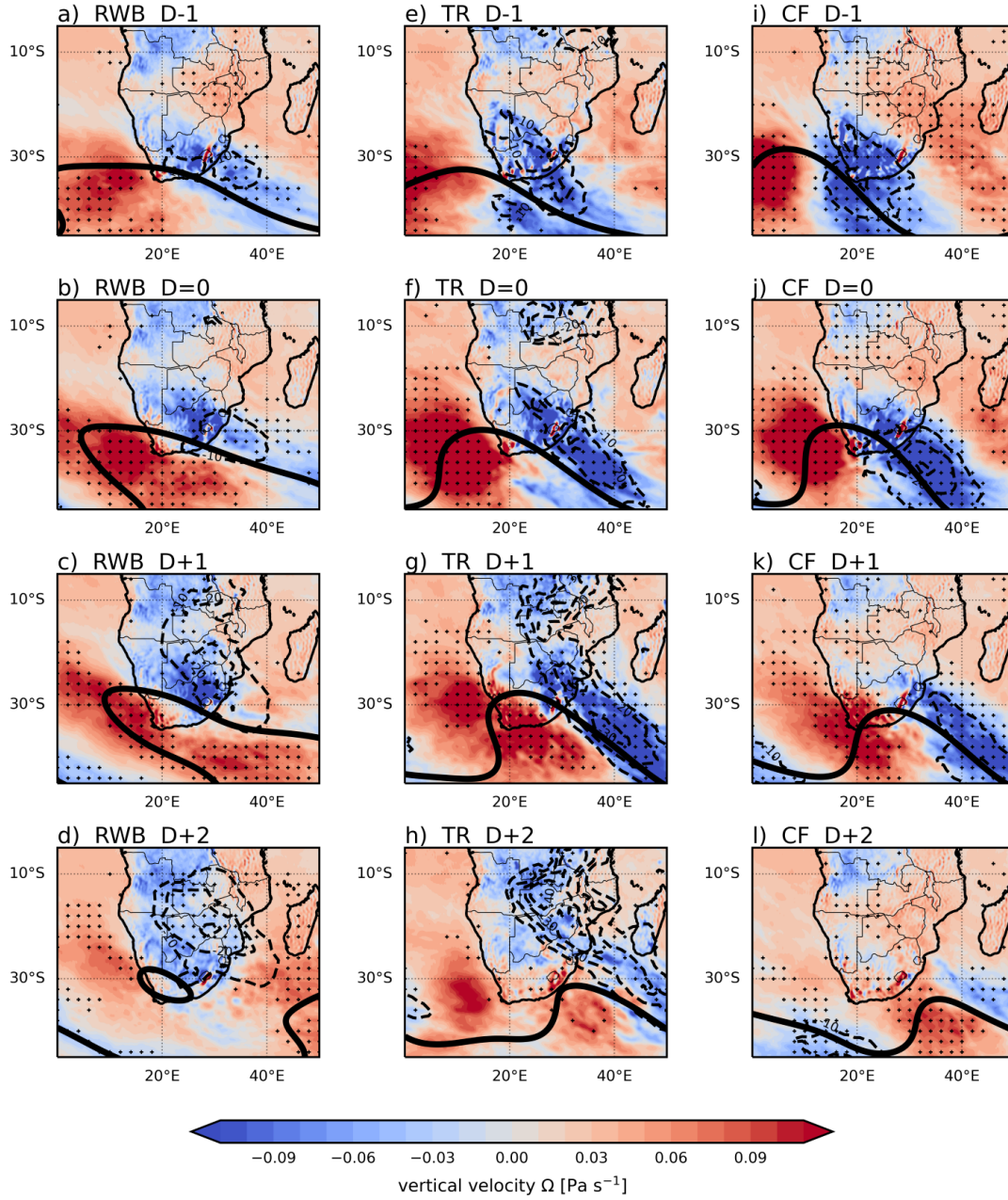


Figure 5.13: Lead (D-1) and lagged (D=0, D+1, D+2) composite 500 hPa vertical velocity [Pa s^{-1}] and OLR anomaly [W m^{-2}] (against an October climatology) each of the RWB (a-d), TR (e-h) and CF (i-l) event sets. A solid black contour plots [$-9 \times 10^{-5} \text{ s}^{-1}$] absolute vorticity at 250 hPa. Stippling indicates where vertical velocity is significantly different from the October climatology at the 0.05 level.

anomalous positive moisture fluxes are seen in the Limpopo and Zambezi low level jet regions, particularly in the TR case at D+2. This is largely driven geostrophically by a ridging high-pressure system in RWB, whereas for TR the moisture flux appears dominantly ageostrophic. In the CF case, these moisture fluxes are generally weaker. Low level jets act as ‘atmospheric rivers’ for the inflow of moisture from the southwestern Indian Ocean into the subcontinent, which is then available for precipitation, providing fuel for the breakdown event (Munday et al., 2021; Spavins-Hicks et al., 2021; Barimalala et al., 2021). Where this is combined with a mechanism of synoptic ascent, such as RWB or cloud bands, breakdown may lead to significant rainfall over southern Africa.

It is interesting to note that in general, Figure 5.14 is characterised by negative moisture flux anomalies over central southern Africa associated with weaker moisture fluxes embedded in the subtropical easterlies. The resulting loss of CAB convergence appears key to allowing moisture-laden Congo air to advance southward and fuel convection over subtropical southern Africa. Moisture fluxes of the CF case look broadly similar to TR and RWB (but with reduced intensity and shorter-lived anomalies), underscoring the controlling importance of vorticity-forced changes in static stability to breakdown.

5.5.4.3 Summary

This section has identified two primary mechanisms that summarise the contribution of midlatitude troughs to CAB breakdown. These are:

1. The replacement of south-of-CAB tropospheric subsidence with Rossby-wave associated synoptic ascent.
2. Modification of the climatological wind field that leads to (a) southward moisture transport from the Congo Basin and (b) anomalous moisture fluxes from the southwestern Indian Ocean into the continental interior by ridging highs.

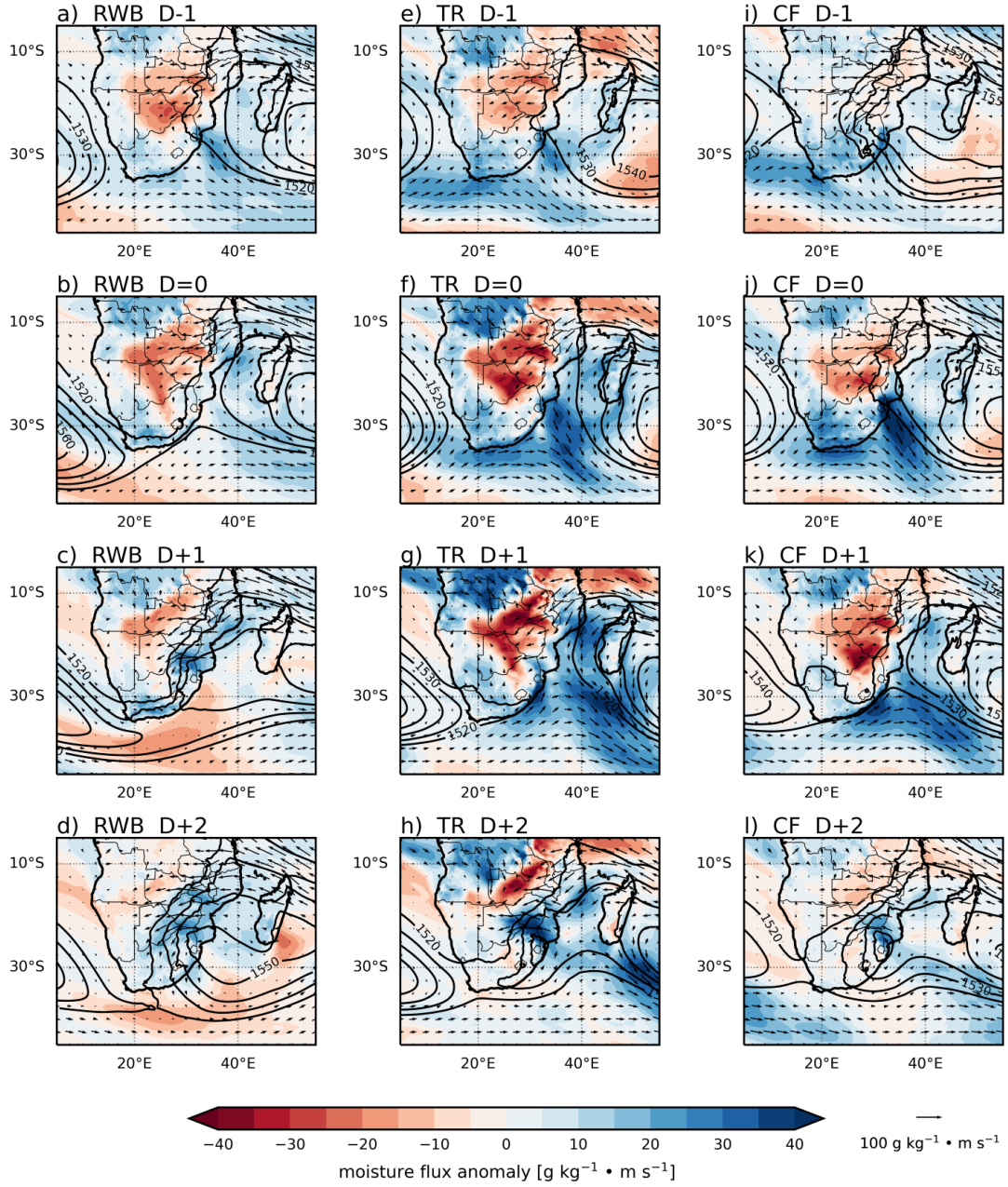


Figure 5.14: Lead (D-1) and lagged (D=0, D+1, D+2) composite 850 hPa moisture fluxes (vectors) and anomaly of the moisture fluxes (shaded, against an October climatology) [$\text{g kg}^{-1} \cdot \text{m s}^{-1}$] for each of the RWB (a-d), TR (e-h) and CF (i-l) event sets. Black contours plot 850 hPa geopotential height contours at 10 m intervals from 1520-1580 m. Moisture flux vectors are plotted where the u or v component of the moisture flux anomaly is significantly different from the October climatology at the 0.05 level.

To ensure results presented here are not sensitive to reanalysis product, we reproduced key figures using the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis, known to perform well in the Congo Basin (Hua et al., 2019)). An analysis of specific humidity, vertical velocity, upper level absolute vorticity and u- and v- wind fields yields remarkably consistent dynamic and thermodynamic evolutions as those we have identified in ERA5, giving confidence the mechanisms identified here are not sensitive to reanalysis product.

Both mechanisms (1) and (2) are complementary in their contributions to CAB breakdown and the switch from a dry-subtropical to moist-tropical regime over southern Africa. The starkest differences against the counterfactual are seen in the vertical velocity fields, where breakdown leads to a total removal of south-of-CAB subsidence. The loss of south-of-CAB subsidence facilitates both a) convection through reduced atmospheric stability and b) enhanced moisture fluxes from the Mozambique channel. If subsidence remains, modified moisture fluxes are insufficient to force breakdown.

The importance of Rossby wave breaking to CAB breakdown is mediated by the location of wave breaking (i.e., the location of upper-level vorticity anomalies). 53% of 1979–2018 CAB breakdowns were associated with wave breaking upstream of southern Africa on the equatorward flank of an extratropical trough-ridge in the south Atlantic. Upstream wave breaking promotes semi-stationary ascent over the continental interior, eroding south-of-CAB subsidence and promoting breakdown. While we only searched for wave breaking as far as 50°E, we found no evidence of association with downstream wave breaking despite this being more common in September October and November (Ndarana and Waugh, 2010).

Similarly, it appears that the importance of transient troughs to CAB breakdown is mediated by trough energetics (i.e., the magnitude of upper-level vorticity anomalies). We view the TR cases, accounting for 15% of 1979–2018 CAB breakdowns,

as a subset of the most energetic transition season troughs over southern Africa, and show that this is related to upstream Rossby wave source activity in the SACZ. This convection excites a Rossby wave that propagates downstream and superposes with an extratropical wave to create a highly energetic trough that causes CAB breakdown.

5.6 Discussion

5.6.1 Low latitude rainfall and upper-level troughs

The Congo Air Boundary (CAB) is a distinct feature of the tropical edge, marking the southern limit of the tropical rain belt at around 10-15°S. The demonstration of a midlatitude control on CAB breakdown highlights the significant equatorward extent of midlatitude influences and shows midlatitude control of transition-season rainfall across a significant geographical area well north of the traditionally defined latitudes of midlatitude precipitation (Figure 5.4).

The review of Knippertz (2007) outlines how penetration of upper-level troughs into the tropics is frequently associated with enhanced convection, with the climatology of De Vries (2021) building on this further by providing a global perspective on the importance of Rossby wave breaking to subtropical precipitation extremes. Here we demonstrate the importance of PV troughs and Rossby wave breaking to not only anomalous subtropical precipitation but also to the seasonal cycle of rainfall and onset timing over central southern Africa. Extratropical disturbances are associated with patterns of weather where CAB breakdown occurs over a timescale of a few days, facilitating a transition from a dry subtropical to wet tropical regime over the region and unlocking the possibility of further tropical-extratropical interactions.

An outstanding question raised by Knippertz (2007) is the extent to which such anomalous low-latitude precipitation is a direct causal result of extratropical upper-

level troughs. Put differently, in the instances of PV-trough related CAB breakdowns, does wave amplification and breaking directly cause convection and rainfall, or does convection and latent heating cause wave amplification and breaking? This is an area that requires further investigation. Idealized dry simulations similar to that of Matthews and Kiladis (2000) in the tropical pacific and Davidson et al. (2007) over the Australian monsoon region may be fruitful in teasing apart the relative roles of dry wave dynamics and diabatic heating associated with convection in the synoptic-scale processes important to CAB breakdown.

5.6.2 Implications for onset prediction

The results of this work have implications for the sub-seasonal prediction of onset over southern Africa and our understanding of the limits to that predictability. The midlatitudes are often considered a stochastic influence on the extra-tropics; although dynamics are represented well under quasi-geostrophic theory, they are generally predictable only for short lead times. The chaotic nature of the atmosphere means inevitable initial condition errors go on to influence all scales of motion in a finite time, so that explicit determination at the synoptic scale is not possible beyond a threshold of about two weeks (Lorenz, 1963, 1984). Given the implication of midlatitude Rossby waves in a significant proportion of breakdown events, the prediction of onset at long lead times may be challenging.

Seasonal and sub-seasonal prediction typically relies on the fact that certain circulation types have intrinsically longer predictability times than individual synoptic weather patterns, and that predictable longer-term variability influences the probability of certain modes of atmospheric circulation and the probabilistic distribution of possible outcomes (Palmer and Anderson, 1994). This may be true of the midlatitude circulations important to breakdown. The Southern Annular Mode is a control on mean jet latitude, whilst La Niña has been shown to increase the occurrence of a distinct subtropical jet over the region compared to El Niño (Gillett et al., 2006;

Hart, Washington and Reason, 2018). The breakdown of the stratospheric polar vortex is predictable at longer lead times and is associated with a well-documented shift towards a negative Southern Annular Mode (Shen et al., 2020). If a relationship between these modes of variability and the probability of occurrence of the Rossby waves identified in Section 4c can be shown, there is potential for the derivation of probabilistic predictability statements related to breakdown and onset.

5.6.3 Future change

Coupled Model Intercomparison Project (CMIP) Phase 3, 5 and 6 models simulate a statistically robust rainfall decline over southern Africa in the 21st century as a response to rising global temperatures, with models dynamically forcing this drying trend through a later average CAB breakdown date (Shongwe et al., 2009; He and Soden, 2017; Howard and Washington, 2020). The implication of the midlatitudes in CAB breakdown raises novel questions about this future drying.

A number of studies have outlined an expected poleward shift in the midlatitude westerly jets under climate change, with Barnes and Hartmann (2012) showing that this poleward shift of the Southern Hemisphere midlatitude jet is accompanied by a poleward shift in anticyclonic wave breaking in all GCMs across multiple climate forcing scenarios. Such a trend has been identified in the northern Hemisphere historical record by Jing and Banerjee’s (2018) study of changes in RWB from 1981–2015 in the MERRA2 reanalysis. It is plausible that a poleward shift in the westerly jets and consequently RWB may lead to a reduced role of midlatitude breakdown processes in the future, contributing to a later mean CAB breakdown and rainy season onset over southern Africa. This is particularly true given the importance of the location of wave breaking in determining impact on CAB breakdown. A minor change in jet dynamics could impact the frequency of wave breaking upstream of southern Africa and consequently have large impacts on RWB-related CAB breakdowns. Some of the regional rainfall impacts of a poleward shift in RWB have been

considered by Ivanciu et al. (2022), who modelled the impact of poleward shifting RWB on southern African ridging highs and found both a decreasing frequency and southward shift in the area of associated rainfall. The contribution of midlatitude future change to CAB breakdown dynamics therefore represents an exciting area for further study.

5.7 Conclusion

This work has diagnosed a midlatitude influence on CAB breakdown and rainfall onset over the core of the southern African subtropics. Specifically, it has shown that propagating and breaking low-wavenumber Rossby waves in the southern hemisphere westerly jet can force CAB breakdown and a transition from a dry pre-onset regime to one characterised by broad precipitation over southern Africa. This demonstration of a remote midlatitude influence on CAB breakdown is novel and has important implications for how rainfall onset is considered at the tropical edge.

Analysis showed that that $>70\%$ of large-scale CAB breakdown events from 1979–2018 were related to midlatitude Rossby waves, cooccurring with strong troughs (18%) or RWB (53%) (RQ1). The proportion of midlatitude associated breakdowns decreases through the onset period from 100% in August ($n=3$) through to 46% in November ($n=11$), suggesting a decreasing seasonal importance of the midlatitudes to breakdown as tropical influences become more important.

The types of Rossby waves important to breakdown include energetic large amplitude low wavenumber troughs, and troughs exhibiting anticyclonic Rossby wave breaking (RQ2). The former appear to be related to anomalous SACZ convection, while the latter is associated with a deeply extratropical ridge-trough structure in the South Atlantic.

Midlatitude dynamics contribute to breakdown through (a) the replacement of broad

south-of-CAB tropospheric subsidence with synoptic ascent from either RWB or cloud bands and (b) modification of the climatological wind field leading to a reduction in convergence at the CAB and its southward advance, along with greater moisture flux from the southwestern Indian Ocean from ridging highs and convergence in the continental interior (RQ3). Our results suggest that importance of Rossby wave breaking to CAB breakdown is mediated by the location of wave breaking, while the importance of transient troughs to CAB breakdown is mediated by trough energetics.

The demonstration of a midlatitude influence on the CAB has implications for global understandings of the general circulation, highlighting the significant equatorward extent of dynamical midlatitude influences and precipitation control. The novel demonstration of a remote midlatitude influence on onset timing over southern Africa adds to the body of evidence for midlatitude precipitation control at the tropical edge.

Multiple sub-tropical regions, such as southern Africa, are highly vulnerable to current and future rainfall variability. It is clear that an integrated consideration of both tropical and midlatitude influence and future change is essential for rigorous understandings of present-day and future precipitation variability.

5.8 Acknowledgments

The first author is funded by the Keble College Bigg Scholarship in African Climate Science. Professor Richard Washington is partly funded by the NERC Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) grant (NE/V011928/1). The authors would like to thank Kitty Attwood, Dr Callum Munday, Dr Emma Howard, Dr Neil Hart and Dr Sebastian Engelstaeder for helpful discussions. They would also like to thank the three reviewers of this manuscript for a number of thought-provoking comments and their suggestions for improving

manuscript presentation and clarity.

5.9 Afterword to Chapter 5

Chapter 5 has addressed the third aim of this thesis by investigating the large-scale mechanisms associated with the breakdown of the CAB. However, because the analysis presented in Chapter 5 was conducted prior to that in Chapters 3 and 4, insights that have emerged from the preceding chapters are not fully reflected in the manuscript. In particular, findings from Chapter 3 concerning CAB maintenance and the role of mid-level moisture flux divergence are not yet reconciled with the large-scale mechanisms that break down the CAB.

In this afterword, the results of Chapter 5 are revisited in light of these earlier findings. Particular emphasis is given to mid-level moisture flux divergence, which Chapter 3 hypothesised is important to both CAB maintenance and the inhibition of convection to its north.

5.9.1 Mid-level moisture-flux divergence and the AEJ-S

The results of Chapter 3 indicate that a CAB-in-place state is associated with three mechanisms which act to suppress convection across the tropical edge:

- i) moisture limitation south of the CAB,
- ii) subsidence inhibition south of, at, and north of the CAB, and
- iii) mid-level moisture-flux divergence at and north of the CAB.

The preceding analysis has accounted for modification to both (i) moisture limitation and (ii) subsidence inhibition through CAB breakdown, whereby midlatitude disturbances reconfigure low-level moisture fluxes and modify subsidence with forced (quasi-geostrophic) ascent. However, the evolution of (iii) mid-level moisture-flux divergence was not examined, as this mechanism had not yet been identified at the time the analysis was conducted. To update the analysis in light of these earlier re-

sults and complete the CAB breakdown story, we therefore consider how mid-level moisture-flux divergence evolves through CAB breakdown.

Figure 5.15 shows the evolution of mid-level (650 hPa) moisture-flux divergence across the CAB breakdown event sets analysed in this chapter, alongside a counterfactual case in which no breakdown occurs. Two days prior to breakdown (D-2), moisture-flux divergence surrounds the Congo Basin in a broad arc extending from south-western Angola to East Africa. Divergence is tightly co-located with the southern margin and entrance region of the African Easterly Jet South (AEJ-S), which is strong ($> 8 \text{ m s}^{-1}$) and well defined at D-2 in all cases.

Through CAB breakdown (Figure 5.15a-c), moisture-flux divergence over Angola and western Zambia is replaced by moisture-flux convergence. Concurrently, the AEJ-S weakens substantially and becomes poorly defined, although easterly flow persists over the eastern Congo Basin. In contrast, in the counterfactual case where the CAB does not break down (Figure 5.15d), the arc of mid-level moisture-flux divergence is maintained throughout the sequence and the AEJ-S remains strong. The weakening of the AEJ-S during breakdown is consistent with both a loss of vertical momentum transfer at the CAB, as hypothesised in Chapter 3, and a weakening of the thermal wind balance associated with a reduced meridional temperature gradient between the Congo Basin and southern Africa (Figure 5.8e-h; Kuete et al., 2020).

The loss of mid-level moisture-flux divergence at the CAB during breakdown therefore emerges as a key missing component of the CAB breakdown story presented in Chapter 5. Once this mid-level moisture export pathway is removed, moisture can accumulate in the lower-mid troposphere, conditioning the environment to be more favourable for deep convection. This highlights the role of mid-level moisture convergence in controlling the location of tropical convection across central Africa, as argued by Jackson et al. (2009), Longandjo and Rouault (2020, 2024) and Dong

and Washington (2025) amongst others.

5.9.2 Summary

This chapter has addressed the third aim of this thesis by investigating the large-scale meteorological conditions and mechanisms associated with the breakdown of the CAB. It has characterised the reorganisation of the atmosphere from a CAB-in-place to a CAB-absent state and identified the mechanisms through which the dryline is eroded, complementing theory developed in Chapter 3 accounting for the maintenance of the CAB.

Through a composite analysis of objectively identified CAB breakdown events, the chapter has shown that CAB breakdown typically occurs over timescales of 3–5 days and is frequently associated with disturbances originating in the midlatitudes, with propagating and upstream-breaking Rossby waves implicated in more than 70% of events.

By tracing the mechanisms underpinning this association, Chapter 5 has demonstrated how extratropical disturbances reshape vertical motion, the low-level circulation and mid-level moisture-flux divergence over southern Africa to break down the CAB. In particular, the three processes that inhibit convection at the tropical edge while the CAB is in place (moisture limitation, subsidence inhibition, and mid-level moisture-flux divergence) are removed, facilitating a transition to a moist convective regime.

Chapter 5 therefore provides an explanation for CAB breakdown and rainfall onset over subtropical southern Africa that is rooted in the synoptic-scale weather processes that bring the first rains to the tropical edge. In identifying the dominant driver of breakdown and the associated large-scale mechanisms through which the CAB is eroded, Chapter 5 directly fulfils Aim 3 of this thesis. These results

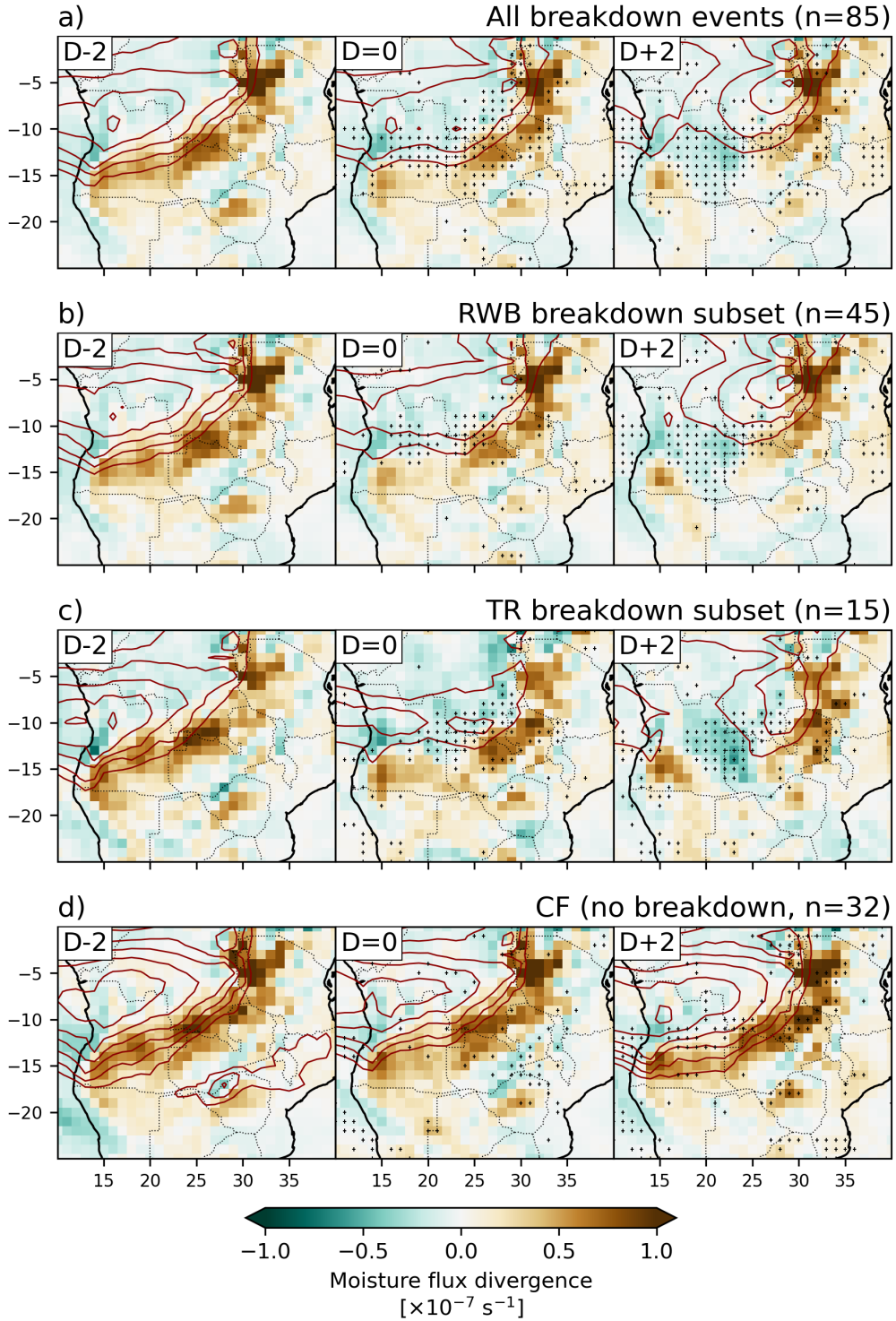


Figure 5.15: Lead (D - 2) and lagged (D = 0, D - 2) composite 650 hPa moisture flux divergence (shaded; $\times 10^{-7} \text{ s}^{-1}$) and zonal wind (contours $< -5 \text{ m s}^{-1}$ in 1 m s^{-1} intervals) for (a) all CAB breakdown events, (b) the RWB breakdown subset, (c) the TR breakdown subset, and (d) the counter-factual CF event set. Stippling indicates where moisture flux divergence is significantly different from D-2 at the 0.01 level.

have implications for the predictability of rainfall onset over southern Africa and for broader theory that accounts for the influence of the extratropics on tropical rain belt seasonality.

6 | Conclusions



A deep red sunset over Angola from camp at Nchila. 8 October 2022.

6.1 Introduction

The onset of the summer rains over subtropical southern Africa is of major socio-economic importance, with far-reaching implications for agriculture, energy generation and water security. Yet many parts of the fundamental dynamics of the southern African tropical edge climate system pre-rainfall onset and the transition to a post-onset (austral summer) mean state remain poorly understood. In particular, a more comprehensive understanding of the circulation features that modulate the southward migration of the tropical rain belt toward southern Africa is required.

A key feature in this transition is the Congo Air Boundary (CAB), a synoptic-scale dryline and convergence zone that is often conceptualised as demarcating the southern edge of the tropical rain belt from August to November (Howard and Washington, 2019). Variability in the CAB’s location and persistence is a first-order control on August–December rainfall across subtropical southern Africa (10–25°S), and an increased persistence of the CAB from October to December has been implicated in projections of delayed rainfall onset across the region.

Despite the importance of the CAB to tropical-edge rainfall, the feature has received relatively little attention in the literature. A lack of *in situ* observations means that the structure and circulation of the atmosphere at the CAB is poorly constrained, limiting understanding of the processes governing its maintenance and breakdown. Addressing these research gaps is made difficult by uncertainty over the ability of models and reanalyses to reproduce the CAB.

This thesis has addressed these knowledge gaps by drawing on novel *in situ* observations collected by the Decreasing Rainfall to Year 2100 – Role of the Congo Air Boundary (DRY-CAB) project (2021–2025), together with reanalyses and satellite datasets. In doing so, it has provided a new, empirically grounded perspective on the structure and circulation of a defining feature of the tropical-edge atmosphere,

the processes governing its maintenance and breakdown and its representation in reanalyses. This final chapter synthesises these results, drawing together key insights from across the thesis to reflect on their broader implications.

The chapter proceeds as follows. Section 6.2 revisits the original aims of the thesis, describing how they were achieved and summarising key findings. Broader themes emerging across the chapters are then discussed in Section 6.3, with particular emphasis on what the results reveal about the spatial and temporal relationship between the CAB and the tropical rain belt. Directions for future research are outlined before the chapter concludes with a reflection on the wider significance of the findings for climate science (Section 6.4).

6.2 Fulfilment of thesis goals and aims

This thesis set out to address key knowledge gaps regarding the structure and circulation of the atmosphere at the CAB, its representation in models, and the large-scale mechanisms associated with its breakdown. To achieve this goal, three specific aims were defined:

Aim 1. Diagnose the structure and circulation of the Congo Air Boundary using *in situ* observations.

Aim 2. Evaluate the representation of the Congo Air Boundary in reanalyses.

Aim 3. Characterise the large-scale mechanisms associated with the breakdown of the Congo Air Boundary.

The following section revisits each of these aims in turn, describing how the thesis has fulfilled each aim and summarising the key results.

6.2.1 Aim 1: Diagnose the structure and circulation of the Congo Air Boundary using *in situ* observations

The first aim of this thesis sought to resolve the structure and circulation of the CAB using *in situ* observations, including the modulation of these aspects through the diurnal cycle. This aim was motivated by the long-standing absence of direct observations of the atmosphere at the CAB, and resulting reliance on reanalysis and model datasets – the fidelity of which is uncertain at the southern African tropical edge.

Aim 1 is addressed in Chapter 3, which characterises the structure and circulation of the atmosphere across the CAB, drawing on the first *in situ* upper-air and surface measurements of the CAB collected during the DRY-CAB field campaign. The analysis particularly focuses on 12 days from 1–5 and 16–22 October 2022 (inclusive), during which the CAB bisected the two DRY-CAB field sites, allowing simultaneous sampling across the CAB dryline and convergence line.

Surface data and vertical (radiosonde) profiles are used to diagnose the thermodynamic structure of the atmosphere at and across the CAB. This reveals that the CAB is characterised by a sharp specific humidity gradient of up to 12.0 g kg^{-1} per 100 km, separating two strongly contrasting thermodynamic regimes. On the dry side, the afternoon boundary layer is near dry-adiabatic ($9.6 \text{ }^{\circ}\text{C km}^{-1}$) and capped by a strong mid-level inversion, consistent with intense surface heating and dry-convective mixing associated with the southern African heat low and a mid-level inversion maintained by subsidence associated with the Botswana High. In contrast, the moist side of the CAB exhibits a more stably stratified boundary layer, weaker and more vertically diffuse inversions, and substantially higher near-surface moist static energy (MSE).

Surface data and vertical profiles are also used to diagnose the circulation of the

atmosphere at and across the CAB. This analysis diagnoses two strongly contrasting circulation regimes across the CAB, with differences particularly stark at night. North of the CAB, 9.2 m s^{-1} mid-level easterlies associated with the AEJ-S overlies a shallow ($\approx 600 \text{ m}$ deep) layer of weak, moisture-laden north-westerlies, while to the south the nocturnal circulation is dominated by a dry easterly low-level jet (LLJ). This LLJ strengthens to approximately 15 m s^{-1} overnight under an inertial oscillation, such that low-level convergence at the CAB peaks around 05:00 local time. Nocturnal convergence is accompanied by mid-level moisture-flux divergence as dry easterlies are lifted above moist north-westerlies.

Lastly, the modulation of the CAB through the diurnal cycle is investigated. The intensity of the CAB is shown to be strongly modulated through the diurnal cycle, with the near-surface moisture gradient approximately four times stronger at night (7.9 g kg^{-1}) than during the day (2.0 g kg^{-1}). This behaviour reflects the competing influences of daytime dry-convective mixing, which vertically redistributes moisture and weakens the surface gradient, and nocturnal low-level convergence, which sharpens the dryline. These findings support the hypothesis of Howard and Washington (2019) that the heat low contributes to CAB maintenance through a combination of horizontal moisture transport associated with cyclonic inflow and vertical redistribution by dry-convective mixing.

Insights from this analysis are synthesised into a novel, empirically derived conceptual model of the tropical-edge atmosphere that describes the structure, circulation, and diurnal modulation of the CAB, thereby directly addressing Aim 1. This model identifies shallow overturning on the moist side of the CAB, comprising low-level north-westerly flow toward the CAB, ascent associated with low-level convergence, and a mid-level return flow embedded within the AEJ-S. This shallow overturning advects warm, dry subtropical air into the southern Congo Basin and is hypothesised to inhibit deep convection at and north of the CAB. This represents the first

observational evidence of a rainfall-inhibiting circulation in the southern Congo that is also present in other heat-low-adjacent monsoon regions (Nie et al., 2010).

Overall, analysis under Aim 1 makes three principal contributions to the wider literature. First, it resolves the mesoscale structure and circulation of the atmosphere at the CAB from observations for the first time, advancing understanding of atmospheric dynamics at the data-sparse southern African tropical edge. Second, it situates the CAB within a broader class of subtropical dryline features and assesses the CAB’s dynamical distinctiveness. Finally, it develops an observation-based conceptual model that provides a foundation for future evaluation of CAB representation in models and reanalyses.

6.2.2 Aim 2: Evaluate the representation of the CAB in reanalyses

The second aim of this thesis was to evaluate how well reanalyses represent the CAB and the features that comprise it. This aim was motivated by the fact that we do not know whether key aspects of the CAB are absent or misrepresented in reanalyses.

This aim is addressed in Chapter 4, which applies a process-based evaluation framework to evaluate the representation of the CAB in three recent reanalysis products (ERA5, MERRA-2, and JRA-3Q) during the DRY-CAB field campaign. The chapter uses six defining features of the CAB, identified in the conceptual model developed under Aim 1, as diagnostic benchmarks. These six features are (1) a dryline and convergence zone, (2) the north-westerly moist low-level jet, (3) the easterly dry low-level jet, (4) the African Easterly Jet South (AEJ-S), (5) dry-convective mixing, and (6) mid-level stability.

This analysis demonstrates that all three reanalyses exhibit substantial errors in the mesoscale structure and circulation of the CAB. A key finding is that reanalysis

errors, and inter-reanalysis differences, primarily stem from deficiencies in the representation of horizontal and vertical moisture transport to the north of the CAB. North-westerly moisture fluxes that advect moisture to the CAB are of the wrong sign in MERRA-2 (-120% bias), exhibit an incorrect diurnal cycle in JRA-3Q (maximum at 20:00 rather than 02:00), and arise from compensating biases in ERA5. ERA5 and MERRA-2 additionally exhibit excessive 11:00 LT instability and day-time near-surface drying (biases $\geq 71\%$). In comparison, the dry subtropical regime to the south of the CAB is relatively well reproduced. Our analysis points to deficiencies in parameterised aspects of the climate system, including land–atmosphere coupling and vertical turbulent moisture transport, as likely sources of error and divergence between reanalysis products. This identifies the representation of these processes as a priority for future model development.

Chapter 4 contextualises these errors by examining their upscale impacts on convective environments and rainfall-onset meteorology. This demonstrates that all three reanalyses underestimate north-of-CAB CAPE by more than 38%, principally due to near-surface moisture deficits associated with north-of-CAB moisture transport. While errors in vertical wind shear are less systematic, this limits the ability of reanalyses to represent the convective environments most relevant to severe weather and rainfall onset at the southern African tropical edge.

Using an MSE framework, the analysis in Chapter 4 additionally shows that ERA5 and MERRA-2 fail to capture the sharp, site-specific regime transitions that characterise the observed seasonal evolution through October and November, instead simulating a smooth, near-simultaneous moistening of the atmosphere. Although JRA-3Q reproduces this evolution more closely, it does so for incorrect reasons, associated with spurious moisture advection north of the CAB. This demonstrates the importance of CAB representation to the successful simulation of the seasonal evolution of the tropical-edge atmosphere through austral spring. Findings under

Aim 2 therefore have important implications for efforts to model the tropical-edge climate across timescales ranging from sub-seasonal forecasting to climate-change projections.

6.2.3 Aim 3: Characterise the large-scale mechanisms associated with the breakdown of the CAB

The third and final aim of this thesis was to characterise the large-scale mechanisms associated with the breakdown of the CAB. This aim was motivated by the role of CAB breakdown in rainfall onset and projections of future drying (Howard and Washington, 2020).

Aim 3 is addressed in Chapter 5, which investigates the meteorology of CAB breakdown through a 40-year reanalysis climatology. An objective method for identifying CAB breakdown events is first developed, building on the CAB canny-edge detection algorithm of Howard and Washington (2019). Lead-lag composites of these events are then used to characterise the evolution of the atmosphere through CAB breakdown and to diagnose the associated large-scale mechanisms by which the CAB is broken down.

This analysis reveals that CAB breakdown represents a large-scale convective regime shift over central southern Africa, in which a subtropical dry-convective regime is replaced by a tropical moist-convective regime over timescales of approximately 3–5 days. This provides a dynamical explanation for the spatial coherence in rainfall-onset timing previously identified statistically over southern Africa (Bombardi et al., 2020).

A remote midlatitude control on the timing of CAB breakdown is identified, with approximately 70% of breakdown events associated with propagating or upstream-breaking low-wavenumber Rossby waves in the Southern Hemisphere westerly jet. Chapter 5 explores the mechanisms that underpin this relationship, revealing how ex-

tratsropical disturbances reshape vertical motion, low-level circulation, and mid-level moisture-flux divergence to break down the CAB. The replacement of subsidence with ascent permits substantial increases in moisture fluxes embedded within the subtropical easterlies, while modified pressure gradients enhance northerly moisture transport from the Congo Basin and mid-level moisture-flux divergence at the tropical edge is lost. Together, these processes promote the breakdown of the CAB and a rapid transition to a moist-convective regime.

This analysis provides an explanation of CAB breakdown and tropical-edge rainfall onset that is rooted in the synoptic-scale weather processes that bring the first rains, directly addressing Aim 3 of this thesis. This indicates that the timing of CAB breakdown is typically dictated by extratropical dynamics, placing a fundamental constraint on onset predictability linked to the intrinsic predictability limits of midlatitude Rossby waves. More broadly, the findings demonstrate the deep equatorward reach of midlatitude influences and the role of midlatitude wave dynamics in governing the seasonal migration of the tropical rain belt.

6.3 Discussion

While the preceding three chapters were written as self-contained studies, Section 6.2 demonstrates that they have achieved the primary aims of this thesis. In doing so, the thesis has provided a new, empirically grounded perspective on the structure and circulation of a defining feature of the tropical-edge atmosphere, its representation in reanalysis products, and the processes governing its maintenance and breakdown.

Building on this synthesis, this section discusses the broader themes that emerge across the thesis. It first considers the implications of these findings for the conceptualisation of the CAB within the southern African climate system and for its relationship to the tropical rain belt. It then reflects on the implications of results for the predictability of rainfall onset and the extent to which reanalyses can be

considered *fit for purpose* at the tropical edge. Finally, remaining uncertainties are identified, and priorities for future research are established.

6.3.1 The CAB and the tropical rain belt

There is longstanding ambiguity as to whether the CAB should be conceptualised as embedded within the tropical rain belt, marking its southern edge, or displaced poleward of it (Hills, 1979). A substantial portion of this ambiguity arises from contrasting definitions of the CAB. For example, Longandjo and Rouault (2020) describe the CAB as a convectively active feature forming at the base of zonal overturning in central Africa; however, this interpretation follows from defining the CAB as a climatological region of meridional-mean zonal wind convergence. Similarly, the convectively active CAB associated with westward-propagating tropical lows described by van Heerden and Taljaard (1998) likely corresponds to late-summer conditions, when convergence at the tropical edge is weaker, less spatially coherent, and not associated with a moisture discontinuity.

In the literature that defines the CAB in the same way as this thesis, the prevailing view is that the CAB demarcates the southern edge of the tropical rain belt. Leroux (2001) and Torrance (1979), for example, emphasise the dry character of the air immediately south of the CAB and interpret the feature as marking the southern limit of deep convection. The climatology of Howard and Washington (2019) similarly shows a close spatial relationship between the CAB and the rain belt’s southern edge from August to November. However, the precise nature of this relationship remains uncertain. It is not clear whether the CAB is truly coincident with the southern margin of the rain belt (Torrance, 1979; Howard and Washington, 2019), or instead displaced poleward, as suggested by Leroux (2001) who argues that dry mid-level winds suppress rainfall to the north of the CAB. Clarifying this relationship is central to understanding how the CAB should be conceptualised within the southern African climate system during austral spring.

In this regard, a key advance made in this thesis is the identification in Chapter 3 of a shallow overturning circulation on the moist side of the CAB. As summarised schematically in Figure 6.1 and discussed below, the presence of this circulation implies that the CAB should be conceptualised as displaced poleward from the tropical rain belt, as suggested by Leroux (2001), while remaining tightly coupled to its southward migration toward southern Africa from August to November.

Chapter 3 provides the first observational evidence for shallow overturning north of the CAB, comprising low-level north-westerly flow toward the CAB, ascent associated with low-level convergence, and a mid-level return flow embedded within the AEJ-S. The mid-level return branch associated with the circulation advects warm, dry subtropical air equatorward into the southern Congo Basin, resulting in persistent mid-level moisture-flux divergence at and north of the CAB (Figure 6.1). This suppresses deep convection in the southern Congo, enforcing a spatial separation between the CAB and the main region of tropical precipitation to its north.

The importance of mid-level moisture-flux divergence becomes especially clear when contrasted against near-surface thermodynamic forcing. Chapter 3 shows that at and north of the CAB, low-level moisture is convergent, surface MSE is high, and CAPE frequently exceeds 3000 J kg^{-1} (Figure 4.10). Yet deep convection is largely absent, contrary to expectations from both convective quasi-equilibrium and moisture-convergence frameworks for rain belt location. This apparent contradiction can be explained by the observed equatorward advection of dry air at mid-levels, which offsets the favourable near-surface thermodynamic conditions to result in the suppression of deep convection north of the CAB.

This mechanism is not unique to southern Africa. Shallow overturning circulations that inhibit convection through mid-level drying have been identified in other monsoon regions, including West Africa (Shekhar and Boos, 2017), north Africa (Longandjo and Rouault, 2024), India (Parker et al., 2016), and Australia (Xie et al.,

2010). This is consistent with the well-established sensitivity of deep convection to mid-level humidity (Derbyshire et al., 2004; Sobel and Bellon, 2009; Holloway and Neelin, 2009), and with broader monsoon theory which emphasises the controlling importance of mid-level dry air advection in tropical regions adjacent to heat lows (e.g., Nie et al., 2010; Shekhar and Boos, 2016). The results of this thesis suggest the southern Congo (from August to November) is an additional regime in which mid-level dry air plays a central (and previously under-recognised) role in setting the location of tropical convection relative to surface thermodynamic forcing.

From a large-scale circulation perspective, the CAB appears to form the poleward foot of a "bottom-heavy" or "mixed-type" Hadley circulation over the southern Congo (Figure 6.1), in which a shallow dry overturning circulation is superimposed on a deeper moist overturning circulation (Nie et al., 2010). In this configuration, the rising branch of the Hadley cell (and tropical precipitation maximum) is located significantly equatorward of the surface convergence maximum at the CAB, associated with mid-level moisture convergence on the equatorward flank of the shallow overturning circulation (Figure 6.1). A similar structure has been identified in the northern Congo (Longandjo and Rouault, 2024), suggesting that when the CAB is present, the large-scale meridional circulation over central Africa is approximately symmetric about the equator.

The results of Chapter 5 fit well with this revised conceptualisation of the CAB. CAB breakdown is shown to be accompanied by a rapid southward shift of tropical convection over Africa on timescales of 3–5 days. This transition coincides with the loss of mid-level moisture-flux divergence associated with the shallow overturning, allowing moisture to accumulate through the lower to mid-troposphere at the tropical edge. The resulting environment becomes rapidly more conducive to deep convection, facilitating an abrupt southward displacement of the rain belt. The loss of shallow overturning therefore provides a plausible mechanism for both the rapid

breakdown of the CAB and the associated abrupt southward displacement of the tropical rain belt. Establishing the intensity, seasonality, and climatological prevalence of this overturning circulation, and its role in CAB breakdown, represents a promising direction for future research.

Chapter 4 demonstrates that reanalyses are not well suited for this work, as they poorly reproduce key aspects of the shallow overturning circulation. Observed low-level moisture transport embedded within the north-westerlies is not reproduced in MERRA-2, has an incorrect diurnal cycle in JRA-3Q, and exhibits compensating errors in wind speed and moisture in ERA5. Consequently, low-level convergence and implied ascent at the CAB are underestimated in MERRA-2 and mistimed in JRA-3Q, while the AEJ-S is also too weak in both reanalyses. Surface CAPE to the north of the CAB is also significantly underestimated in all three reanalyses, associated with north-of-CAB moisture transport errors. This limits the ability of reanalyses to diagnose how shallow overturning modulates convective environments north of the CAB, and by extension, how the loss of shallow overturning may contribute to CAB breakdown and rainfall onset.

In summary, the results of this thesis suggest that previous conceptual models of the mean-state climate of central Africa during the September–November transition season were incomplete, as they did not account for shallow overturning in the southern Congo and associated equatorward (cross-CAB) advection of dry mid-level air. The presence of this circulation implies that the CAB should be conceptualised as lying poleward of the southern edge of the tropical rain belt, analogous to the relationship between the intertropical discontinuity and West African monsoon rainfall (Nicholson, 2009). It also helps to situate the distribution of tropical precipitation over central and southern Africa within global monsoon theory, and emphasises the role of mid-level moisture convergence and divergence in setting the location of the tropical precipitation maximum, as previously argued by Jackson et al. (2009),

Longandjo and Rouault (2020, 2024) and Dong and Washington (2025).

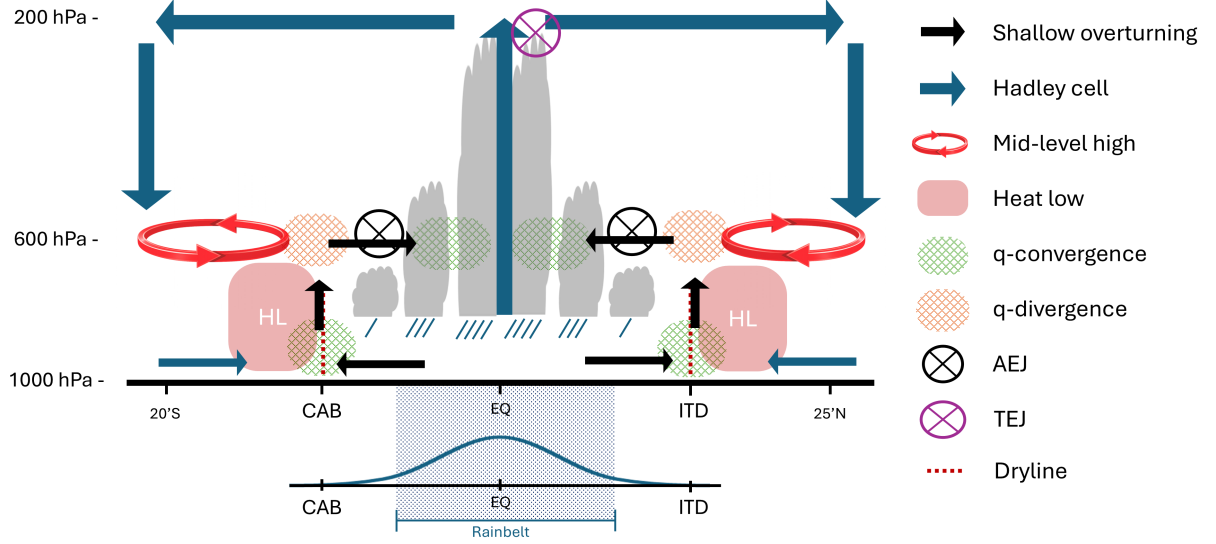


Figure 6.1: A schematic of the large-scale meridional circulation of central Africa about the September equinox, when the solar zenith is overhead the equator. The blue line (bottom plot) indicates rainfall rates by latitude, with the rainbelt latitude range shaded. CAB; Congo Air Boundary. ITD; Intertropical discontinuity. EQ; equator. HL; Heat low. Q-conv; moisture flux convergence. Q-div; moisture flux divergence. AEJ; African Easterly Jet. TEJ; Tropical Easterly Jet.

6.3.2 Predictability of rainfall onset

The timing of rainfall onset over southern Africa is of major socioeconomic importance, influencing agricultural productivity, food security, and power generation (Kanemasu et al., 1990; Reason et al., 2005; Tadross et al., 2005; Conway et al., 2015). This has made improved onset predictability a longstanding objective of seasonal forecasting (Meza et al., 2008). However, model skill has proved elusive; while seasonal prediction systems reproduce the broad spatial structure of onset timing, onset date errors commonly exceed 30 days across much of southern Africa (Ratnam et al., 2018).

Results presented in this thesis suggest that this limited predictability has a dynamical origin. Chapter 5 has demonstrated that the timing of CAB breakdown

is fundamentally controlled by disturbances originating in the midlatitudes, with propagating and upstream-breaking Rossby waves implicated in more than 70% of CAB breakdown events. The predictability of rainfall onset is therefore constrained by the intrinsic predictability limits of midlatitude dynamics.

This constraint extends beyond rainfall onset. Extratropical influences dominate high-frequency rainfall variability throughout the southern African summer rainfall season (Liu et al., 2022), contributing to southern Africa having the lowest sub-seasonal prediction skill of any global monsoon region. Correlations at 2-4-week lead times are weak (≈ 0.13), with little statistically significant skill beyond forecast day 10, consistent with the present-day practical predictability limit of midlatitude weather (Zhang et al., 2019).

Although extratropical dynamics are often treated as a stochastic influence on the tropics and subtropics, longer-lead skill may exist if particular circulation regimes possess enhanced predictability or if slowly varying boundary conditions modulate the likelihood of key atmospheric states (Palmer and Anderson, 1994). To date, no such relationships have been established, but they warrant further investigation. Reforecast pooling approaches, such as the UNprecedented Simulated Extreme ENsemble (UNSEEN; Thompson et al., 2017), offer a means of overcoming limited sample sizes and could enable systematic assessment of whether large-scale climate modes such as ENSO influence the probability or timing of CAB breakdown and associated midlatitude wave dynamics.

However, the results of this thesis suggest that a more promising avenue for future progress may lie in reframing onset forecasting objectives, rather than attempting to improve deterministic ‘onset date’ predictions. Forecast quantities that integrate across multiple weather events, or that reflect changes in the probability of rainfall-favourable circulation regimes, are less constrained by the intrinsic predictability limits of individual midlatitude disturbances. Metrics such as early-season mean

rainfall, dry-spell frequency, or the probability of occurrence of rainfall-producing circulation regimes may therefore offer greater potential for both forecast skill and decision relevance, even if the precise timing of individual onset-triggering events remains unpredictable at longer lead times.

6.3.3 Are reanalyses *fit for purpose* at the tropical edge?

Through an evaluation of the CAB in reanalyses during the DRY-CAB field campaign (Chapter 4), this thesis has sought to assess whether reanalyses are *fit for purpose* at the southern African tropical edge. Here, we reflect further on their suitability for studying the tropical-edge atmosphere through austral spring, framed by Parker’s (2020) *adequacy-for-purpose* principle, which states that models should be evaluated in relation to the specific scientific questions they are used to address.

Reanalyses are widely used as pseudo-observations (Parker, 2016) across a broad range of applications, including climate analysis, machine-learning forecasting (Bi et al., 2023; Lam et al., 2023; Lang et al., 2024; Bodnar et al., 2025), and the process-based evaluation of general circulation models (GCMs) (Dieppois et al., 2015; James et al., 2015; Creese and Washington, 2016; Bracegirdle et al., 2018; Cui et al., 2024). The results of Chapter 4 indicate that this practice is problematic when the phenomena of interest are strongly influenced by processes at the mesoscale. Although all three reanalyses examined (ERA5, MERRA-2, JRA-3Q) reproduce a CAB at the synoptic scale, they exhibit substantial errors in its mesoscale structure and circulation. These errors propagate upscale and degrade representations of convective environments and rainfall-onset meteorology. This indicates that reanalyses are not adequate for addressing scientific questions that depend on the detailed mesoscale structure and evolution of the CAB.

With respect to Parker’s (2020) *adequacy-for-purpose* principle, a central scientific question motivating this thesis, and much research on the southern African tropi-

cal edge, concerns the controlling dynamics of rainfall onset. Chapter 5 has shown that the timing of CAB breakdown, and by extension tropical-edge rainfall onset, is fundamentally controlled by large-scale dynamics associated with midlatitude disturbances. These are spatial scales that reanalyses reproduce well, as they are tightly constrained by the data assimilation process and have little ability to diverge (Section 5.1). This means that reanalyses are suitable for developing a first-order understanding of the large-scale dynamical controls on rainfall onset.

However, Chapter 3 demonstrates that many of the processes relevant to the maintenance of the CAB operate at the mesoscale, and further hypothesises that mesoscale moist-convective processes play an important role in accounting for the rapidity of CAB breakdown. Sections 6.3.1 and 6.3.4.3 raise additional questions regarding the role of shallow overturning and local-to-mesoscale moist-convective processes in CAB breakdown and rainfall onset. These processes operate at a spatial scale which, on the basis of the results of Chapter 4, we argue reanalyses should not be considered *fit for purpose*. This means reanalyses are inadequate for studying the mesoscale dynamics that this thesis hypothesises are important to explaining the rapidity of CAB breakdown.

These findings are likely symptomatic of a broader limitation in reanalysis representations of mesoscale processes across the data-sparse tropics. For example, Itterly et al. (2018) show that biases in the Amazonian convective diurnal cycle are sustained and amplified by errors in the atmospheric state carried over from the previous day through cloud and radiative feedbacks, with those errors originating in the parameterisation of tropical deep convection. Similarly, the analysis of Chapter 4 points toward deficiencies in other parameterised and poorly constrained aspects of the climate system, such as land-atmosphere coupling and the sub-grid vertical turbulent transport of heat and moisture. In regions with limited observational constraint, such parameterisation errors can persist and amplify, leading to

systematic biases in the representation of key aspects of the climate system. These findings underscore the need for caution when using reanalyses in tropical-edge climate research, and highlight the importance of explicitly considering the spatial and temporal scales at which reanalyses can (and cannot) be regarded as adequate across the data-sparse tropics.

6.3.4 Open questions and avenues for future research

6.3.4.1 Generalisability of DRY-CAB observations

The analyses presented in Chapters 3 and 4 are underpinned by 44 days of intensive radiosonde and surface observations from two tropical-edge field sites during the DRY-CAB campaign. This has enabled a uniquely detailed, process-oriented characterisation of the mesoscale structure and circulation of the atmosphere at the CAB and has led to a new view of CAB maintenance involving shallow overturning on the moist side of the boundary. The same observations have also demonstrated the inadequacy of reanalyses in representing these mesoscale dynamics. The DRY-CAB observations have therefore provided a rare window into atmospheric dynamics that would otherwise have remained uncertain.

An open question is the extent to which the structure and circulation of the atmosphere diagnosed during DRY-CAB is generalisable a) along the length of the CAB and b) across different years. The field campaign took place during the second year of a rare three-year ("triple-dip") La Niña event spanning 2020–2023 (Li et al., 2023; Thoithi et al., 2025, 2026). Thoithi et al. (2025, 2026) show that such prolonged La Niña events are associated with distinct large-scale circulation anomalies over southern Africa, including a strengthened Mascarene High, enhanced easterly moisture fluxes from the southwest Indian Ocean, and a positive phase of the Southern Annular Mode, influencing rainfall, temperature extremes, and dry spell characteristics through austral summer (January–April). While ENSO teleconnections are weaker

in austral spring, regional rainfall anomaly patterns from September–November 2022 are consistent with a La Niña associated south-west displacement of the Southern Indian Ocean Convergence Zone (Chongue and Nishii, 2024), indicating that the radiosonde intensive observation period occurred under a La Niña-modified (i.e., non-neutral) background state.

Some aspects of the structure and circulation of the atmosphere at the CAB resolved in Chapter 3, including the strength and persistence of mid-level subsidence inversions associated with the Botswana High and the strength and moisture content of south-of-CAB subtropical easterlies, may be modified by this large-scale setting. However, key processes at the CAB modulating the diurnal cycle of convergence and dryline strength primarily operate at the mesoscale, governed by the diurnal cycle of surface heating. This gives confidence in the fact that, while the magnitude of individual features may vary across different background states, the underlying processes identified in Chapter 3 and summarised in the conceptual model are robust. Importantly, this also does not affect the validity of comparisons between observations and reanalyses presented in Chapter 4.

Further confidence in the spatial and temporal generalisability of our results arises from the large-scale coherence of the CAB and its associated circulation in reanalysis data. Howard and Washington (2019) show that the CAB is a spatially extensive and relatively homogeneous feature in ERA5, and the key characteristics of the observed CAB are broadly consistent with their 40-year climatology, which does not include 2022. Moreover, the use of careful case studies to infer dryline structure and dynamics from limited field data has a strong track record (e.g., Ziegler and Hane, 1993).

Nevertheless, given the demonstrated limitations of reanalyses at the scales of interest and the possible impact of the La Niña background state, the most robust means of testing the generalisability of our results is through additional observations. Only

limited aspects of the shallow overturning circulation north of the CAB have been directly resolved in this thesis, and over a relatively few number of days. The equatorward extent of mid-level dry-air advection, its impact on convective environments in the southern Congo, and the extent to which subsidence over the southern Congo completes the overturning circulation is not known. Nor is the climatological presence or seasonality of the circulation and the extent of its modification by large-scale modes of variability such as ENSO.

A major challenge in addressing these questions is the scarcity of routine atmospheric observations across subtropical southern Africa, as outlined in Section 1.3.1. Routine radiosonde measurements between 5 and 25°S have declined markedly since 1990, with the Integrated Global Radiosonde Archive documenting an approximately four-fold decrease in observations from the 1980s to the most recent decade, and across much of the tropical edge, routine upper-air observations of winds, temperature, and humidity are entirely absent. This means existing operational observing networks are not able to address these outstanding questions.

While this remains the case, short-duration but intensive field campaigns such as DRY-CAB represent the most viable means of directly observing the mesoscale dynamics of the tropical-edge atmosphere and advancing understanding of climate dynamics in the region. While such campaigns cannot by themselves establish climatological behaviour, further targeted observations would provide critical constraints on the mesoscale processes this thesis hypothesises are important to a) the spatial distribution of convection and b) the rapidity of tropical edge rainfall onset. They would also help to establish the broader applicability of insights derived from the DRY-CAB campaign.

6.3.4.2 Representation of the CAB in numerical models

This thesis has highlighted the need to better understand how the representation of the CAB depends on model formulation and resolution. The analysis presented in

Chapter 4 considered only a limited range of model resolutions (0.25° – 0.625°) within a single modelling framework (reanalyses). A more systematic investigation across a broader hierarchy of model types and resolutions would help to clarify which aspects of CAB structure and maintenance are sensitive to model formulation and resolution, and which model frameworks offer the best representation of the atmosphere at the CAB.

At the high-resolution end of this hierarchy, the Met Office convection-permitting simulations conducted alongside the DRY-CAB field campaign provide a valuable testbed for examining the impact of explicitly resolved convection on the representation of the CAB. These simulations consist of limited-area, 48-hour integrations of the Unified Model at 4 km horizontal resolution, run daily throughout the campaign period. Figure 6.2 presents an initial exploration of the diurnal cycle of the CAB dryline in these simulations, reproducing Figure 4.3 from Chapter 4 with the addition of the Unified Model results. Interestingly, a substantial moisture deficit persists on the moist side of the CAB, and there is no clear improvement in the diurnal cycle of dryline intensity. Further analysis of the structure and circulation of the CAB in these simulations would help to determine the added value of convection-permitting simulations for representing the CAB and related tropical-edge dynamics.

At the other end of the model resolution hierarchy are coarse-resolution GCMs. Previous work suggests that the climatology of the CAB is generally well reproduced in this class of models, with many CMIP5 models exhibiting CAB frequencies, latitudinal positions, and seasonal evolution broadly consistent with reanalyses (Howard and Washington, 2020). However, there is uncertainty regarding the physical mechanisms through which the CAB is maintained and broken down in these simulations. A process-based evaluation of the CAB in GCMs, analogous to the analysis in Chapter 4, would help address this uncertainty. Specifically, two key tests emerge from the results of this thesis.

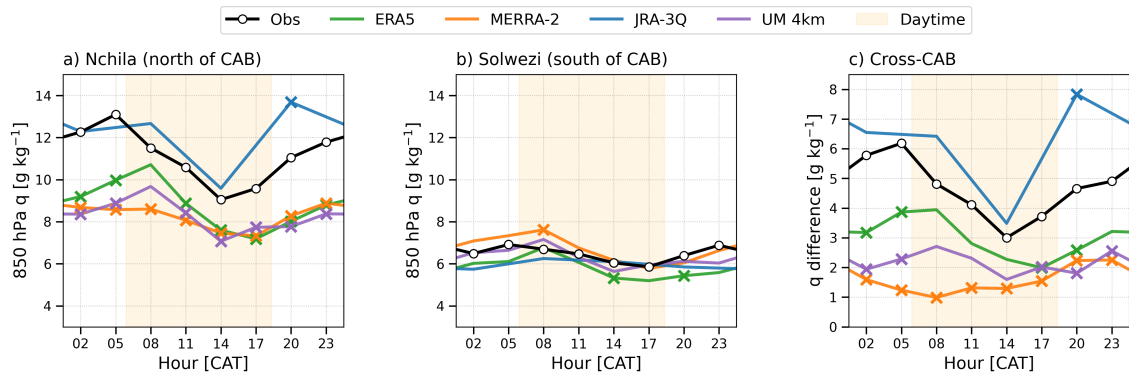


Figure 6.2: 850 hPa specific humidity (q) at a) Nchila and b) Solwezi, and c) the cross-CAB dryline intensity calculated as the specific humidity difference between Nchila and Solwezi. An ‘x’ denotes where reanalysis and model means are significantly different from observations at $p < 0.05$. The Unified Model can be considered a pseudo-reanalysis, as 48-hour simulations do not provide significant opportunity for the simulation to diverge from its driving forecast model. The first 24 hours are excluded to account for model spin-up.

The first test concerns the maintenance of the CAB. Some GCMs that sustain a CAB exhibit little to no mid-tropospheric subsidence over southern Africa in October and November (Hart, Washington and Stratton, 2018). This raises concerns regarding the processes by which models maintain the CAB, as a lack of subsidence is difficult to reconcile with the mid-level inversions observed north and south of the CAB in Chapter 3 and with theory that suggests subsidence is key to the maintenance of dry conditions to the south of the CAB (Howard and Washington, 2019).

The second test concerns how models break down the CAB. Chapter 5 demonstrates that breakdown is frequently instigated by extratropical disturbances and associated tropical-extratropical interactions. However, CMIP5 models exhibit systematic biases in the midlatitude mean state, including errors in jet structure and Rossby wave propagation and refraction over southern Africa (James et al., 2020). If models fail to plausibly reproduce the core mechanism by which the CAB is broken down, then confidence in the simulated delay to climatological CAB breakdown under future climate change is undermined.

A failure to satisfy either of these tests would call into question the realism of pro-

jected changes in CAB behaviour and, by extension, projections of early-summer drying across central southern Africa. This concern is amplified by the results of Chapter 4, which show that errors in CAB representation can exert significant up-scale impacts on the simulated seasonal evolution of the tropical-edge atmosphere. Establishing whether GCMs plausibly represent the CAB and its breakdown is therefore an important step toward establishing confidence in future projections of rainfall and circulation change.

6.3.4.3 The role of moist-convective processes in CAB breakdown

The results of Chapters 3 and 5 suggest that moist-convective processes may influence both the timing of breakdown and the rapidity of the transition from a CAB-in-place to a CAB-absent state. With respect to breakdown timing, Chapter 5 did not account for 30% of CAB breakdown events. It is plausible that in these cases moist-convective processes, and particularly organised modes of tropical convection such as equatorial Kelvin waves, westward-propagating tropical lows, and the Madden-Julian Oscillation (MJO; Madden and Julian, 1994)(MJO; Madden and Julian, 1994) play a role in the breakdown of the CAB. If so, this would be consistent with established links between organised tropical convection and rainfall onset in other regions (e.g., Hendon and Liebmann, 1990; Hung and Yanai, 2004; Tong et al., 2009; Zhou and Murtugudde, 2014; Grimm, 2019).

Moist convection may also play a key role during CAB breakdown itself, acting as a feedback that helps to explain the observed rapidity of the transition to a moist convective regime as suggested in Section 6.3.1. A useful analogue in this regard may be provided by the West African monsoon jump, in which a rapid poleward shift of the rain belt occurs once low-level moisture convergence overwhelms mid-level moisture export associated with shallow overturning. In that system, the resulting moistening of the lower-mid troposphere enables shallow-to-congestus convection, with diabatic heating strengthening pressure gradients and establishing inertial in-

stability that accelerates the transition from shallow overturning to deep convection across the Sahel (Hagos and Cook, 2007; Cook, 2015).

Chapters 3 and 5 suggest that an analogous balance operates at the CAB. In particular, the competition between low-level moisture convergence and mid-level drying associated with shallow overturning appears central to both the maintenance of the CAB and its breakdown. The loss of mid-level drying through CAB breakdown allows moisture to accumulate, and associated diabatic heating from shallow-to-congestus convection provides a plausible positive feedback that could reinforce pressure gradients, increase low-level moisture convergence, and accelerate CAB breakdown. Further investigation of these moist-convective feedbacks would help to clarify aspects of both the timing and rapidity of CAB breakdown, complementing the large-scale mechanisms identified in this thesis.

6.3.4.4 Controls on Congo north-westerlies

Chapters 3 and 4 demonstrate that moisture fluxes embedded within low-level Congo north-westerlies are central to both the maintenance of the CAB and its accurate representation in numerical models, while Chapter 5 shows that enhanced northerly moisture transport in the southern Congo Basin is a key feature of CAB breakdown. However, there is limited understanding of the processes that drive these winds and control their strength and variability.

Previous studies have primarily attributed low-level flow in the southern Congo to zonal land-sea thermal contrasts between the equatorial east Atlantic and the African continent, which establish low-level westerlies and a Walker-type circulation (Pokam et al., 2014). However, this does not account for the northerly component of the low-level flow responsible for advecting moisture toward the tropical edge and supplying moisture to southern Africa during CAB breakdown.

Results from Chapter 3 point to the southern African heat low as an important

control, with observed low-level flow consistent with inflow toward the heat low centre (Attwood et al., 2024). However, it is unclear how sensitive the strength and direction of low-level moisture fluxes in the southern Congo Basin are to variations in heat-low intensity and spatial extent. Chapter 5 additionally suggests that enhanced north-westerly moisture fluxes are a feature of some CAB breakdown events, raising the possibility that the extratropics provide an additional control.

A useful framework for this investigation may be to consider moisture fluxes in the southern Congo Basin within the constraints imposed by topography. In particular, the Katanga Plateau may serve a dual role: (1) acting as a barrier that northerly moisture transport from the Congo Basin must surmount, and (2) functioning as an elevated heat source that promotes the development of a heat low and thereby enhances northerly flow. Future research should aim to disentangle the relative contributions of the heat low, extratropical forcing, topography, and other as-yet unrecognised processes in controlling northerly flow in the southern Congo Basin.

6.3.4.5 Maintenance of the AEJ-S

The results of this thesis highlight the need to better understand the mechanisms that maintain the African Easterly Jet-South (AEJ-S), and in particular to quantify the relative importance of (i) thermal wind balance and (ii) vertical momentum transfer in the vicinity of the CAB. Kuete et al. (2020) propose that AEJ-S maintenance is primarily associated with geostrophic flow around the mid-level Botswana High. However, this framework does not readily explain the observed spatial preference of the AEJ-S over northern Angola and the western Congo Basin, immediately northwest of the CAB, nor its diurnal cycle, with a nighttime maximum and daytime minimum diagnosed in Chapters 3 and 4.

Chapter 3 hypothesised that vertical momentum transfer at the CAB provides an additional maintenance mechanism for the AEJ-S. This is consistent with the close spatial and temporal relationship between the CAB and the AEJ-S identified in

Chapters 3 and 5, and offers a potential explanation for the jet’s observed diurnal cycle. Quantifying the relative contributions of these mechanisms could be achieved through analysis of the zonal momentum budget, which explicitly separates the roles of advection, pressure-gradient forcing, Coriolis acceleration, and unresolved processes.

Understanding AEJ-S maintenance is particularly important in the context of observed and projected change at the southern African tropical edge. Tatro and Zuidema (2025) document a strengthening of the AEJ-S since the early 2000s, whereas coupled climate models show highly model-dependent projections of future change (Creese et al., 2019). If vertical momentum transfer at the CAB is a key maintenance mechanism, it is likely to be poorly represented in coarse-resolution coupled models, potentially explaining model underestimation of jet strength (Adebiyi et al., 2023) and the discrepancy between observed trends and future projections.

6.3.4.6 Extension of the CAB into East Africa

The extension of the CAB into East Africa was not addressed in this thesis and remains poorly understood. Some literature implies that the CAB in East Africa may play a fundamentally different role in the regional circulation from that identified over southern Africa. This has contributed to divergent views on the seasonality of the CAB and its relationship with tropical convection (e.g., Taljaard, 1953, 1972; Nicholson, 2018; Longandjo and Rouault, 2020; Akinsanola et al., 2025; Worden and Fu, 2025).

A key outstanding question is whether these differences arise primarily from inconsistent definitions of the CAB, or from genuine physical differences. Definitional differences may stem from the fact that in this thesis and in southern African literature, the CAB is defined by the dual requirement of a dryline and a convergence line, whereas studies focusing on East Africa have typically identified the CAB using convergence alone (Hills, 1979; Nicholson, 1996; Levin et al., 2009; Dezfuli, 2017;

Longandjo and Rouault, 2020). In addition, the CAB as defined here is considered a synoptic-scale weather feature while the CAB in East Africa has primarily been considered in a climatological sense (Hills, 1979; Nicholson, 2018; Longandjo and Rouault, 2020). On the other hand, physical differences may arise from the complex topography of East Africa, which provides a markedly different setting from the gently sloping plateau of southern Africa. Resolving these issues would clarify whether the CAB extends into East Africa or instead represents a distinct circulation feature in that region.

6.3.4.7 Reformation of the CAB

A missing component of the CAB life cycle concerns how, and under what conditions, the CAB reforms following breakdown. The reformation of the CAB is important for early-summer dry spells and rainfall variability, which is particularly critical for crop planting decisions across southern Africa (Reason et al., 2005; Kniveton et al., 2009).

During the DRY-CAB field campaign, two instances of CAB reformation were documented, associated with broad dry spells over southern Africa (Figure 6.3). These events provide an entry point for investigating the processes that lead to the reformation of the CAB. In both cases, reformation was associated with mid-level dry air, observed in Solwezi radiosondes as a MSE minima on 18 November and 2 December 2022 (Figure 6.3). Near-surface MSE remains high during these periods, suggesting that the CAB reformed to the south of Solwezi.

An immediate question concerns the origin of the mid-level dry air: is it generated locally through subsidence, or advected into the region? Analogues from other monsoon systems suggest that dry-air intrusions can suppress convection and organise dry spells, with origins often tied to extratropical wave trains embedded in the subtropical jet (e.g., Mapes and Zuidema, 1996; Parker et al., 2016; Aslam et al., 2024). Whether similar mechanisms operate during CAB reformation remains an

open question. An additional question concerns whether reformation involves the same set of processes that maintain a true CAB, or whether it instead reflects transient dryline events associated with episodic mid-level dry-air intrusions.

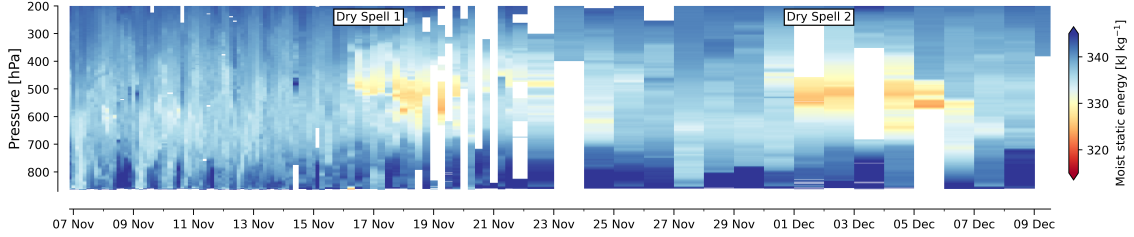


Figure 6.3: MSE [kJ kg^{-1}] in Solwezi radiosonde ascents from 7 November to 9 December during the DRY-CAB field campaign.

6.4 Concluding remarks

This thesis has drawn on novel *in situ* observations from the DRY-CAB field campaign, reanalyses and satellite data to develop a new perspective on the structure and circulation of the CAB, the processes governing its maintenance and breakdown, and its representation in reanalyses. This has been achieved through three complementary strands of analysis: an observational characterisation of the CAB using DRY-CAB measurements, an investigation of the large-scale mechanisms associated with CAB breakdown, and a process-based evaluation of how well reanalyses represent the CAB and its comprising features.

The central contribution of this thesis is an improved understanding of the controls on the location and seasonality of tropical convection across central and southern Africa. A key finding in this regard is the identification of cross-CAB advection of mid-level dry (subtropical) air, associated with a previously undocumented shallow overturning circulation on the moist side of the CAB. The presence of this circulation implies that the CAB is displaced poleward of the tropical rain belt: while the CAB is characterised by strong low-level moisture-flux convergence and elevated

MSE on its moist side, divergence of moisture in the mid-troposphere suppresses deep convection by reducing mid-level humidity. A revised conceptual model of the large-scale CAB-in-place meridional circulation, summarised schematically in Section 6.3.1, is consistent with broader monsoon theory that emphasises the role of mid-tropospheric dry air in regulating the location and seasonality of deep tropical convection (e.g., Nie et al., 2010; Shekhar and Boos, 2016). It also raises interesting hypotheses regarding the role of mesoscale moist-convective processes in accelerating the breakdown of the CAB.

A second major contribution of this thesis is the demonstration that errors in the representation of the CAB exert significant upscale impacts on the simulated tropical-edge atmosphere. Chapter 4 shows that three reanalyses exhibit errors in key elements comprising the CAB, which propagate upscale to degrade the representation of CAB-adjacent convective environments and the seasonal evolution of the tropical-edge atmosphere through rainfall onset. These results highlight persistent challenges in modelling the tropical-edge atmosphere that arise from an inadequate representation of the CAB, even in observationally constrained reanalyses. In free-running simulations, errors in CAB structure and circulation may project onto larger-scale aspects of the tropical-edge climate, including the location of tropical convection, the ability of the CAB to break down, and the seasonal migration of the tropical rain belt toward southern Africa. Such upscale impacts are likely to affect model skill across timescales ranging from the sub-seasonal to climate change, the full extent of which remains poorly understood.

A third major contribution of this thesis is the identification of a midlatitude control on the breakdown of the CAB and, by extension, the onset of the summer rains over southern Africa. This result has important implications for rainfall-onset predictability, highlighting a fundamental constraint imposed by the intrinsic predictability limits of midlatitude wave dynamics. More broadly, it demonstrates the

deep equatorward reach of extratropical influences and establishes a clear dynamical pathway through which midlatitude variability modulates the seasonal migration of the tropical rain belt over Africa. These results also raise important questions regarding climate-model projections of delayed CAB breakdown under future warming. James et al. (2020) show that CMIP5 models exhibit systematic biases in the midlatitude mean state over southern Africa, including biases in jet structure and Rossby wave refractive properties that directly affect modelled tropical-extratropical interactions. Given the central role of Rossby wave dynamics in CAB breakdown identified here, such biases call into question the mechanisms underlying the simulated delay in CAB breakdown and underscore the need for further investigation.

A final contribution of this thesis is that it highlights the value of targeted field observations in advancing understanding of regional climate dynamics. Key aspects of this thesis are grounded in observational data collected during the DRY-CAB field campaign, comprising approximately 788 radiosonde launches from two tropical-edge sites between 1 October and 13 November 2022, together with 321 station-days of surface observations. These measurements have enabled the development of an empirically derived conceptual model of the atmosphere across the CAB, revealing previously unrecognised aspects of the regional circulation and providing a basis for the evaluation of reanalyses and comparison to other drylines. In doing so, this thesis shows how carefully designed field campaigns in sparsely observed regions can illuminate the dynamics of key circulation features, underpinning observational analyses and model-evaluation frameworks that improve both understanding of, and ability to model, the climate system.

References

- Adebiyi, A. A., Akinsanola, A. A. and Ajoku, O. F. (2023), ‘The Misrepresentation of the Southern African Easterly Jet in Models and Its Implications for Aerosol, Clouds, and Precipitation Distributions’, *Journal of Climate* **36**(22), 7785–7809.
- Adebiyi, A. A. and Zuidema, P. (2016), ‘The role of the southern African easterly jet in modifying the southeast Atlantic aerosol and cloud environments’, *Quarterly Journal of the Royal Meteorological Society* **142**(697), 1574–1589.
- Akinsanola, A. A., Wenhaji, C. N., Barimalala, R., Monerie, P.-A., Dixon, R. D., Tamoffo, A. T., Adeniyi, M. O., Ongoma, V., Diallo, I., Gudoshava, M., Wainwright, C. M., James, R., Silverio, K. C., Faye, A., Nangombe, S. S., Pokam, M. W., Vondou, D. A., Hart, N. C. G., Pinto, I., Kilavi, M., Hagos, S., Rajagopal, E. N., Kolli, R. K. and Joseph, S. (2025), ‘Modeling of Precipitation over Africa: Progress, Challenges, and Prospects’, *Advances in Atmospheric Sciences* **43**(1), 59–86.
- Andrews, P. C., Cook, K. H. and Vizzy, E. K. (2025), ‘Cloud-top brightness temperature inconsistent indicator of extreme surface rainfall in western and central equatorial Africa’, *Climate Dynamics* **63**(5), 207.
- Arnup, S. J. and Reeder, M. J. (2007), ‘The Diurnal and Seasonal Variation of the Northern Australian Dryline’, *Monthly Weather Review* **135**(8), 2995–3008.
- Arnup, S. and Reeder, M. (2009), ‘The structure and evolution of the northern Australian dryline’, *Australian Meteorological and Oceanographic Journal* **58**(04), 215–231.
- Aslam, A. A., Schwendike, J., Peatman, S. C., Birch, C. E., Bollasina, M. A. and Barrett, P. (2024), ‘Mid-level dry air intrusions over the southern Maritime Continent’, *Quarterly Journal of the Royal Meteorological Society* **150**(759), 727–745.
- Atkins, N. T., Wakimoto, R. M. and Ziegler, C. L. (1998), ‘Observations of the Finescale Structure of a Dryline during VORTEX 95’, *Monthly Weather Review* **126**(3), 525–550.
- Attwood, K. (2024), Heat Lows, in ‘Earth Systems and Environmental Sciences’, Elsevier.
- Attwood, K., Washington, R. and Munday, C. (2024), ‘The Southern African Heat Low: Structure, Seasonal and Diurnal Variability, and Climatological Trends’, *Journal of Climate* **37**(10), 3037–3053.
- Bai, L., Meng, Z., Huang, Y., Zhang, Y., Niu, S. and Su, T. (2019), ‘Convection Initiation Resulting From the Interaction Between a Quasi-Stationary Dryline and Intersecting Gust Fronts: A Case Study’, *Journal of Geophysical Research: Atmospheres* **124**(5), 2379–2396.
- Barimalala, R., Blamey, R. C., Desbiolles, F. and Reason, C. J. C. (2020), ‘Variability in the Mozambique Channel Trough and Impacts on Southeast African Rainfall’, *Journal of Climate* **33**(2), 749–765.

- Barimalala, R., Blamey, R. C., Desbiolles, F. and Reason, C. J. C. (2021), ‘The influence of southeastern African river valley jets on regional rainfall’, *Climate Dynamics* **57**(9-10), 2905–2920.
- Barnes, E. A. and Hartmann, D. L. (2012), ‘Detection of Rossby wave breaking and its response to shifts of the midlatitude jet with climate change’, *Journal of Geophysical Research: Atmospheres* **117**(D9).
- Bechis, H., Ruiz, J., Salio, P., Cancelada, M. and Alvarez Imaz, M. (2022), ‘Mesoscale influences on the development of a dryline in Argentina: A modelling case study’, *Atmospheric Research* **265**.
- Bechis, H., Salio, P. and Ruiz, J. J. (2020), ‘Drylines in Argentina: Synoptic Climatology and Processes Leading to Their Genesis’, *Monthly Weather Review* **148**(1), 111–129.
- Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A. and Wood, E. F. (2018), ‘Present and future Koppen-Geiger climate classification maps at 1-km resolution’, *Scientific Data* **5**(1), 180–214.
- Behera, S. K. and Yamagata, T. (2001), ‘Subtropical SST dipole events in the southern Indian Ocean’, *Geophysical Research Letters* **28**(2), 327–330.
- Bergmaier, P. T. and Geerts, B. (2015), ‘Characteristics and Synoptic Environment of Drylines Occurring over the Higher Terrain of Southeastern Wyoming’, *Weather and Forecasting* **30**(6), 1733–1748.
- Bergmaier, P. T., Geerts, B., Wang, Z., Liu, B. and Campbell, P. C. (2014), ‘A Dryline in Southeast Wyoming. Part II: Airborne In Situ and Raman Lidar Observations’, *Monthly Weather Review* **142**(8), 2961–2977.
- Best, M. J., Lock, A. P., Balsamo, G., Bazile, E., Beau, I., Cuxart, J., Ek, M. B., Findell, K., Fridlind, A., Holtslag, A. A. M., Huang, W., Jiménez, M. A., Kumar, S., Lawrence, D., Malyshev, S., Le Moigne, P., Puma, M., Ronda, R., Santanello, J. A., Sandu, I., Shen, X., Steeneveld, G.-J., Svensson, G., Vaillancourt, P. A., Wang, W., Zadra, A. and Zheng, W. (2025), ‘Rolling DICE to advance knowledge of land–atmosphere interactions’, *Quarterly Journal of the Royal Meteorological Society* **151**(769).
- Betts, A. K., Hong, S.-Y. and Pan, H.-L. (1996), ‘Comparison of NCEP-NCAR Reanalysis with 1987 FIFE Data’, *Monthly Weather Review* **124**(7), 1480–1498.
- Betts, A. K. and Jakob, C. (2002), ‘Evaluation of the diurnal cycle of precipitation, surface thermodynamics, and surface fluxes in the ECMWF model using LBA data’, *Journal of Geophysical Research: Atmospheres* **107**(D20).
- Bi, K., Xie, L., Zhang, H., Chen, X., Gu, X. and Tian, Q. (2023), ‘Accurate medium-range global weather forecasting with 3D neural networks’, *Nature* **619**(7970), 533–538.
- Biasutti, M., Voigt, A., Boos, W. R., Braconnot, P., Hargreaves, J. C., Harrison, S. P., Kang, S. M., Mapes, B. E., Scheff, J., Schumacher, C., Sobel, A. H. and

- Xie, S.-P. (2018), ‘Global energetics and local physics as drivers of past, present and future monsoons’, *Nature Geoscience* **11**(6), 392–400.
- Blackadar, A. K. (1957), ‘Boundary Layer Wind Maxima and Their Significance for the Growth of Nocturnal Inversions’, *Bulletin of the American Meteorological Society* **38**(5), 283–290.
- Blamey, R. C., Kolusu, S. R., Mahlalela, P., Todd, M. C. and Reason, C. J. C. (2018), ‘The role of regional circulation features in regulating El Niño climate impacts over southern Africa: A comparison of the 2015/2016 drought with previous events’, *International Journal of Climatology* **38**(11), 4276–4295.
- Blamey, R. C. and Reason, C. J. C. (2012), ‘Mesoscale Convective Complexes over Southern Africa’, *Journal of Climate* **25**(2), 753–766.
- Blamey, R. C. and Reason, C. J. C. (2023), ‘Diversity and Ranking of ENSO Impacts along the Eastern Seaboard of Subtropical Southern Africa’, *Atmosphere* **14**(6), 1042.
- Bluestein, H. B. and Parker, S. S. (1993), ‘Modes of Isolated, Severe Convective Storm Formation along the Dryline’, *Monthly Weather Review* **121**(5), 1354–1372.
- Bodnar, C., Bruinsma, W. P., Lucic, A., Stanley, M., Allen, A., Brandstetter, J., Garvan, P., Riechert, M., Weyn, J. A., Dong, H., Gupta, J. K., Thambiratnam, K., Archibald, A. T., Wu, C.-C., Heider, E., Welling, M., Turner, R. E. and Perdikaris, P. (2025), ‘A foundation model for the Earth system’, *Nature* **641**(8065), 1180–1187.
- Bombardi, R. J., Moron, V. and Goodnight, J. S. (2020), ‘Detection, variability, and predictability of monsoon onset and withdrawal dates: A review’, *International Journal of Climatology* **40**(2), 641–667.
- Bracegirdle, T. J., Lu, H., Eade, R. and Woollings, T. (2018), ‘Do CMIP5 Models Reproduce Observed Low-Frequency North Atlantic Jet Variability?’, *Geophysical Research Letters* **45**(14), 7204–7212.
- Burls, N. J., Blamey, R. C., Cash, B. A., Swenson, E. T., al Fahad, A., Bopape, M.-J. M., Straus, D. M. and Reason, C. J. C. (2019), ‘The Cape Town “Day Zero” drought and Hadley cell expansion’, *npj Climate and Atmospheric Science* **2**(1), 27.
- Byakatonda, J., Parida, B., Kenabatho, P. K. and Moalafhi, D. (2018), ‘Influence of climate variability and length of rainy season on crop yields in semiarid Botswana’, *Agricultural and Forest Meteorology* **248**, 130–144.
- Canny, J. (1986), ‘A Computational Approach to Edge Detection’, *IEEE Transactions on Pattern Analysis and Machine Intelligence* **PAMI-8**(6), 679–698.
- Chongue, L. A. and Nishii, K. (2024), ‘The influence of tropical and subtropical modes of climate variability on precipitation in Mozambique’, *International Journal of Climatology* **44**(9), 2993–3005.

- Christenson, C. E., Martin, J. E. and Handlos, Z. J. (2017), ‘A Synoptic Climatology of Northern Hemisphere, Cold Season Polar and Subtropical Jet Superposition Events’, *Journal of Climate* **30**(18), 7231–7246.
- Conway, D., Dalin, C., Landman, W. A. and Osborn, T. J. (2017), ‘Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption’, *Nature Energy* **2**(12), 946–953.
- Conway, D., van Garderen, E. A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., Thurlow, J., Zhu, T. and Dalin, C. (2015), ‘Climate and southern Africa’s water–energy–food nexus’, *Nature Climate Change* **5**(9), 837–846.
- Cook, C., Reason, C. and Hewitson, B. (2004), ‘Wet and dry spells within particularly wet and dry summers in the South African summer rainfall region’, *Climate Research* **26**, 17–31.
- Cook, K. H. (2000), ‘The South Indian Convergence Zone and Interannual Rainfall Variability over Southern Africa’, *Journal of Climate* **13**(21), 3789–3804.
- Cook, K. H. (2015), ‘Role of inertial instability in the West African monsoon jump’, *Journal of Geophysical Research: Atmospheres* **120**(8), 3085–3102.
- Creese, A. and Washington, R. (2016), ‘Using qflux to constrain modeled Congo Basin rainfall in the CMIP5 ensemble’, *Journal of Geophysical Research: Atmospheres* **121**(22), 13,415–13,442.
- Creese, A. and Washington, R. (2018), ‘A Process-Based Assessment of CMIP5 Rainfall in the Congo Basin: The September–November Rainy Season’, *Journal of Climate* **31**(18), 7417–7439.
- Creese, A., Washington, R. and Munday, C. (2019), ‘The Plausibility of September–November Congo Basin Rainfall Change in Coupled Climate Models’, *Journal of Geophysical Research: Atmospheres* **124**(11), 5822–5846.
- Cui, J., DeMott, C., Dellaripa, E. R. and Maloney, E. (2024), ‘Process-Based Evaluation of Intraseasonal Oceanic Kelvin Waves in the Pacific Ocean in CMIP6 Models’, *Journal of Climate* **37**(23), 6435–6452.
- D’Abreton, P. C. and Lindesay, J. A. (1993), ‘Water vapour transport over Southern Africa during wet and dry early and late summer months’, *International Journal of Climatology* **13**(2), 151–170.
- Daron, J., Burgin, L., Janes, T., Jones, R. G. and Jack, C. (2019), ‘Climate process chains: Examples from southern Africa’, *International Journal of Climatology* **39**(12), 4784–4797.
- Davidson, N. E., Tory, K. J., Reeder, M. J. and Drosowsky, W. L. (2007), ‘Extratropical–Tropical Interaction during Onset of the Australian Monsoon: Reanalysis Diagnostics and Idealized Dry Simulations’, *Journal of the Atmospheric Sciences* **64**(10), 3475–3498.

- Davis Instruments (2018), ‘Vantage Pro2 Spec Sheets’, <https://support.davisinstruments.com/category/esfbscicgu-vantage-pro-2>.
- De Vries (2021), ‘A global climatological perspective on the importance of Rossby wave breaking and intense moisture transport for extreme precipitation events’, *Weather and Climate Dynamics* **2**(1), 129–161.
- Derbyshire, S. H., Beau, I., Bechtold, P., Grandpeix, J.-Y., Piriou, J.-M., Redelsperger, J.-L. and Soares, P. M. M. (2004), ‘Sensitivity of moist convection to environmental humidity’, *Quarterly Journal of the Royal Meteorological Society* **130**(604), 3055–3079.
- Dezfuli, A. (2017), Climate of Western and Central Equatorial Africa, in ‘Oxford Research Encyclopedia of Climate Science’, Oxford University Press.
- Dezfuli, A. K. and Nicholson, S. E. (2013), ‘The Relationship of Rainfall Variability in Western Equatorial Africa to the Tropical Oceans and Atmospheric Circulation. Part II: The Boreal Autumn’, *Journal of Climate* **26**(1), 66–84.
- Dieppois, B., Pohl, B., Rouault, M., New, M., Lawler, D. and Keenlyside, N. (2016), ‘Interannual to interdecadal variability of winter and summer southern African rainfall, and their teleconnections’, *Journal of Geophysical Research: Atmospheres* **121**(11), 6215–6239.
- Dieppois, B., Rouault, M. and New, M. (2015), ‘The impact of ENSO on Southern African rainfall in CMIP5 ocean atmosphere coupled climate models’, *Climate Dynamics* **45**(9), 2425–2442.
- Dong, Z. and Washington, R. (2025), ‘Evolution and Characteristics of Mesoscale Convective Systems over the Congo Basin’, *Journal of Climate* **38**(24), 7333–7350.
- Driver, P. and Reason, C. J. C. (2017), ‘Variability in the Botswana High and its relationships with rainfall and temperature characteristics over southern Africa’, *International Journal of Climatology* **37**(S1), 570–581.
- Du, H., Tan, M. L., Zhang, F., Chun, K. P., Li, L. and Kabir, M. H. (2024), ‘Evaluating the effectiveness of CHIRPS data for hydroclimatic studies’, *Theoretical and Applied Climatology* **155**(3), 1519–1539.
- Dunning, C. M., Black, E. and Allan, R. P. (2018), ‘Later Wet Seasons with More Intense Rainfall over Africa under Future Climate Change’, *Journal of Climate* **31**(23), 9719–9738.
- Dunning, C. M., Black, E. C. L. and Allan, R. P. (2016), ‘The onset and cessation of seasonal rainfall over Africa: ONSET AND CESSATION OF AFRICAN RAINFALL’, *Journal of Geophysical Research: Atmospheres* **121**(19), 11,405–11,424.
- Duykerke, P. G. and Teixeira, J. (2001), ‘Comparison of the ECMWF Reanalysis with FIRE I Observations: Diurnal Variation of Marine Stratocumulus’, *Journal of Climate* **14**(7), 1466–1478.
- Edwards, J. M., Beljaars, A. C. M., Holtslag, A. A. M. and Lock, A. P. (2020),

- ‘Representation of Boundary-Layer Processes in Numerical Weather Prediction and Climate Models’, *Boundary-Layer Meteorology* **177**(2), 511–539.
- Engdaw, M. M., Ballinger, A. P., Hegerl, G. C. and Steiner, A. K. (2022), ‘Changes in temperature and heat waves over Africa using observational and reanalysis data sets’, *International Journal of Climatology* **42**(2), 1165–1180.
- Engelbrecht, F. A., McGregor, J. L. and Engelbrecht, C. J. (2009), ‘Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa’, *International Journal of Climatology* **29**(7), 1013–1033.
- Engelbrecht, F., Adegoke, J., Bopape, M.-J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. and Gatebe, C. (2015), ‘Projections of rapidly rising surface temperatures over Africa under low mitigation’, *Environmental Research Letters* **10**(8).
- Falchetta, G., Gernaat, D. E. H. J., Hunt, J. and Sterl, S. (2019), ‘Hydropower dependency and climate change in sub-Saharan Africa: A nexus framework and evidence-based review’, *Journal of Cleaner Production* **231**, 1399–1417.
- Favre, A., Hewitson, B., Lennard, C., Cerezo-Mota, R. and Tadross, M. (2013), ‘Cut-off Lows in the South Africa region and their contribution to precipitation’, *Climate Dynamics* **41**(9), 2331–2351.
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Rummukainen, M. and more (2014), Evaluation of climate models, in ‘Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change’, Cambridge University Press, pp. 741–866.
- Formenti, P., D’Anna, B., Flamant, C., Mallet, M., Piketh, S. J., Schepanski, K., Waquet, F., Auriol, F., Brogniez, G., Burnet, F., Chaboureau, J.-P., Chauvigné, A., Chazette, P., Denjean, C., Desboeufs, K., Doussin, J.-F., Elguindi, N., Feuerstein, S., Gaetani, M., Giorio, C., Klopfer, D., Mallet, M. D., Nabat, P., Monod, A., Solmon, F., Namwoonde, A., Chikwililwa, C., Mushi, R., Welton, E. J. and Holben, B. (2019), ‘The Aerosols, Radiation and Clouds in Southern Africa Field Campaign in Namibia: Overview, Illustrative Observations, and Way Forward’, *Bulletin of the American Meteorological Society* **100**(7), 1277–1298.
- Funatsu, B. M. and Waugh, D. W. (2008), ‘Connections between Potential Vorticity Intrusions and Convection in the Eastern Tropical Pacific’, *Journal of the Atmospheric Sciences* **65**(3), 987–1002.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. and Michaelsen, J. (2015), ‘The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes’, *Scientific Data* **2**(1).
- Garstang, M., Tyson, P. D., Swap, R., Edwards, M., Källberg, P. and Lindesay, J. A.

- (1996), ‘Horizontal and vertical transport of air over southern Africa’, *Journal of Geophysical Research: Atmospheres* **101**(D19), 23721–23736.
- Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Parityka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M. and Zhao, B. (2017), ‘The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)’, *Journal of Climate* **30**(14), 5419–5454.
- Gensini, V. A., Mote, T. L. and Brooks, H. E. (2014), ‘Severe-Thunderstorm Reanalysis Environments and Collocated Radiosonde Observations’, *Journal of Applied Meteorology and Climatology* **53**(3), 742–751.
- Giannini, A., Biasutti, M., Held, I. M. and Sobel, A. H. (2008), ‘A global perspective on African climate’, *Climatic Change* **90**(4), 359–383.
- Gillett, N. P., Kell, T. D. and Jones, P. D. (2006), ‘Regional climate impacts of the Southern Annular Mode’, *Geophysical Research Letters* **33**(23).
- Goutorbe, J.-P., Lebel, T., Tinga, A., Bessemoulin, P., Brouwer, J., Dolman, A. J., Engman, E. T., Gash, J. H. C., Hoepffner, M., Kabat, P., Kerr, Y. H., Monteny, B., Prince, S., Said, F., Sellers, P. and Wallace, J. S. (1994), ‘HAPEX-Sahel: A large-scale study of land-atmosphere interactions in the semi-arid tropics’, *Annales Geophysicae* **12**(1), 53–64.
- Graham, R. M., Cohen, L., Ritzhaupt, N., Segger, B., Graversen, R. G., Rinke, A., Walden, V. P., Granskog, M. A. and Hudson, S. R. (2019), ‘Evaluation of Six Atmospheric Reanalyses over Arctic Sea Ice from Winter to Early Summer’, *Journal of Climate* **32**(14), 4121–4143.
- Grimm, A. M. (2019), ‘Madden–Julian Oscillation impacts on South American summer monsoon season: Precipitation anomalies, extreme events, teleconnections, and role in the MJO cycle’, *Climate Dynamics* **53**(1), 907–932.
- Grimm, A. M. and Reason, C. J. C. (2015), ‘Intraseasonal Teleconnections between South America and South Africa’, *Journal of Climate* **28**(23), 9489–9497.
- Hachigonta, S., Reason, C. J. C. and Tadross, M. (2008), ‘An analysis of onset date and rainy season duration over Zambia’, *Theoretical and Applied Climatology* **91**(1-4), 229–243.
- Hagos, S. M. and Cook, K. H. (2007), ‘Dynamics of the West African Monsoon Jump’, *Journal of Climate* **20**(21), 5264–5284.
- Harris, I., Osborn, T. J., Jones, P. and Lister, D. (2020), ‘Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset’, *Scientific Data* **7**(1), 109.
- Harrison, M. S. J. (1984), ‘A generalized classification of South African summer rain-bearing synoptic systems’, *Journal of Climatology* **4**(5), 547–560.

- Hart, N. C. G., Reason, C. J. C. and Fauchereau, N. (2010), ‘Tropical–Extratropical Interactions over Southern Africa: Three Cases of Heavy Summer Season Rainfall’, *Monthly Weather Review* **138**(7), 2608–2623.
- Hart, N. C. G., Reason, C. J. C. and Fauchereau, N. (2013), ‘Cloud bands over southern Africa: Seasonality, contribution to rainfall variability and modulation by the MJO’, *Climate Dynamics* **41**(5), 1199–1212.
- Hart, N. C. G., Washington, R. and Maidment, R. I. (2019), ‘Deep Convection over Africa: Annual Cycle, ENSO, and Trends in the Hotspots’, *Journal of Climate* **32**(24), 8791–8811.
- Hart, N. C. G., Washington, R. and Reason, C. J. C. (2018), ‘On the Likelihood of Tropical–Extratropical Cloud Bands in the South Indian Convergence Zone during ENSO Events’, *Journal of Climate* **31**(7), 2797–2817.
- Hart, N. C. G., Washington, R. and Stratton, R. A. (2018), ‘Stronger Local Overturning in Convective-Permitting Regional Climate Model Improves Simulation of the Subtropical Annual Cycle’, *Geophysical Research Letters* **45**(20).
- Haywood, J. M., Abel, S. J., Barrett, P. A., Bellouin, N., Blyth, A., Bower, K. N., Brooks, M., Carslaw, K., Che, H., Coe, H., Cotterell, M. I., Crawford, I., Cui, Z., Davies, N., Dingley, B., Field, P., Formenti, P., Gordon, H., de Graaf, M., Herbert, R., Johnson, B., Jones, A. C., Langridge, J. M., Malavelle, F., Partridge, D. G., Peers, F., Redemann, J., Stier, P., Szpek, K., Taylor, J. W., Watson-Parris, D., Wood, R., Wu, H. and Zuidema, P. (2021), ‘The CLOUD–Aerosol–Radiation Interaction and Forcing: Year 2017 (CLARIFY-2017) measurement campaign’, *Atmospheric Chemistry and Physics* **21**(2), 1049–1084.
- He, J. and Soden, B. J. (2017), ‘A re-examination of the projected subtropical precipitation decline’, *Nature Climate Change* **7**(1), 53–57.
- Held, I. M. (1975), ‘Momentum Transport by Quasi-Geostrophic Eddies’, *Journal of the Atmospheric Sciences* **32**(7), 1494–1497.
- Held, I. M. and Hou, A. Y. (1980), ‘Nonlinear Axially Symmetric Circulations in a Nearly Inviscid Atmosphere’, *Journal of the Atmospheric Sciences* **37**(3), 515–533.
- Hendon, H. H. and Liebmann, B. (1990), ‘A Composite Study of Onset of the Australian Summer Monsoon’, *Journal of the Atmospheric Sciences* **47**(18), 2227–2240.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.-N. (2020), ‘The ERA5 global reanalysis’, *Quarterly Journal of the Royal Meteorological Society* **146**(730), 1999–2049.

- Hills, R. C. (1979), ‘The Structure of the Inter-Tropical Convergence Zone in Equatorial Africa and Its Relationship to East African Rainfall’, *Transactions of the Institute of British Geographers* **4**(3), 329–352.
- Hoch, J. and Markowski, P. (2005), ‘A Climatology of Springtime Dryline Position in the U.S. Great Plains Region’, *Journal of Climate* **18**(12).
- Holloway, C. E. and Neelin, J. D. (2009), ‘Moisture Vertical Structure, Column Water Vapor, and Tropical Deep Convection’, *Journal of the Atmospheric Sciences* **66**(6), 1665–1683.
- Holton, J. (2012), *An Introduction to Dynamic Meteorology*, Vol. 88, 5th revised edition edn, Academic Press, Amsterdam.
- Hoskins, B. (2015), ‘Potential vorticity and the PV perspective’, *Advances in Atmospheric Sciences* **32**(1), 2–9.
- Hoskins, B. J. and Ambrizzi, T. (1993), ‘Rossby Wave Propagation on a Realistic Longitudinally Varying Flow’, *Journal of the Atmospheric Sciences* **50**(12), 1661–1671.
- Houze, R. A. (2004), ‘Mesoscale convective systems’, *Reviews of Geophysics* **42**(4).
- Howard, E. (2019), Southern African Synoptic Climate Dynamics and Future Change: Tropical Lows and the Congo Air Boundary, <http://purl.org/dc/dcmitype/Text>, University of Oxford.
- Howard, E. and Washington, R. (2018), ‘Characterizing the Synoptic Expression of the Angola Low’, *Journal of Climate* **31**(17), 7147–7165.
- Howard, E. and Washington, R. (2019), ‘Drylines in Southern Africa: Rediscovering the Congo Air Boundary’, *Journal of Climate* **32**(23), 8223–8242.
- Howard, E. and Washington, R. (2020), ‘Tracing Future Spring and Summer Drying in Southern Africa to Tropical Lows and the Congo Air Boundary’, *Journal of Climate* **33**(14), 6205–6228.
- Howard, E., Washington, R. and Hodges, K. I. (2019), ‘Tropical Lows in Southern Africa: Tracks, Rainfall Contributions, and the Role of ENSO’, *Journal of Geophysical Research: Atmospheres* **124**(21), 11009–11032.
- Hua, W., Zhou, L., Nicholson, S. E., Chen, H. and Qin, M. (2019), ‘Assessing reanalysis data for understanding rainfall climatology and variability over Central Equatorial Africa’, *Climate Dynamics* **53**(1), 651–669.
- Hung, C.-W. and Yanai, M. (2004), ‘Factors contributing to the onset of the Australian summer monsoon’, *Quarterly Journal of the Royal Meteorological Society* **130**(597), 739–758.
- Ingleby, B. (2017), ‘An assessment of different radiosonde types 2015/2016’, *ECMWF Technical Memoranda*.
- Itterly, K. F., Taylor, P. C. and Dodson, J. B. (2018), ‘Sensitivity of the Amazonian

- Convective Diurnal Cycle to Its Environment in Observations and Reanalysis', *Journal of Geophysical Research: Atmospheres* **123**(22), 12,621–12,646.
- Ivanciu, I., Ndarana, T., Matthes, K. and Wahl, S. (2022), 'On the Ridging of the South Atlantic Anticyclone Over South Africa: The Impact of Rossby Wave Breaking and of Climate Change', *Geophysical Research Letters* **49**(20).
- Jackson, B., Nicholson, S. E. and Klotter, D. (2009), 'Mesoscale Convective Systems over Western Equatorial Africa and Their Relationship to Large-Scale Circulation', *Monthly Weather Review* **137**(4), 1272–1294.
- Jacobeit, J. (1987), 'Variations of trough positions and precipitation patterns in the mediterranean area', *Journal of Climatology* **7**(5), 453–476.
- James, R., Hart, N. C. G., Munday, C., Reason, C. J. C. and Washington, R. (2020), 'Coupled Climate Model Simulation of Tropical–Extratropical Cloud Bands over Southern Africa', *Journal of Climate* **33**(19), 8579–8602.
- James, R., Washington, R., Abiodun, B., Kay, G., Mutemi, J., Pokam, W., Hart, N., Artan, G. and Senior, C. (2018), 'Evaluating Climate Models with an African Lens', *Bulletin of the American Meteorological Society* **99**(2), 313–336.
- James, R., Washington, R. and Jones, R. (2015), 'Process-based assessment of an ensemble of climate projections for West Africa', *Journal of Geophysical Research: Atmospheres* **120**(4), 1221–1238.
- Jing, P. and Banerjee, S. (2018), 'Rossby Wave Breaking and Isentropic Stratosphere-Troposphere Exchange During 1981–2015 in the Northern Hemisphere', *Journal of Geophysical Research: Atmospheres* **123**(17), 9011–9025.
- Johnson, D. H. (1965), 'African synoptic meteorology', *Meteorology and the Desert Locust*.
- Jury, M. R. (2013), 'Climate trends in southern Africa (with erratum)', *South African Journal of Science* **109**(1/2), 111.
- Jury, M. R. (2023), 'Meteorology of 'ridging high' rainfall over the KwaZulu-Natal coastal plains', *International Journal of Climatology* **43**(16), 7516–7531.
- Jury, M. R. and Nkosi, S. E. (2000), 'Easterly flow in the tropical Indian Ocean and climate variability over south-east Africa', *Water South Africa* **26**(2).
- Kanemasu, E. T., Stewart, J. I., van Donk, S. J. and Virmani, S. M. (1990), Agroclimatic Approaches for Improving Agricultural Productivity in Semiarid Tropics, in R. P. Singh, J. F. Parr and B. A. Stewart, eds, 'Advances in Soil Science: Dryland Agriculture: Strategies for Sustainability Volume 13', Advances in Soil Science, Springer, New York, NY, pp. 273–309.
- Kendon, E. J., Stratton, R. A., Tucker, S., Marsham, J. H., Berthou, S., Rowell, D. P. and Senior, C. A. (2019), 'Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale', *Nature Communications* **10**(1), 1794.

- Kenfack, K., Tamoffo, A. T., Djiotang Tchotchou, L. A. and Vondou, D. A. (2023), ‘Assessment of uncertainties in reanalysis datasets in reproducing thermodynamic mechanisms in the moisture budget’s provision in the Congo Basin’, *Theoretical and Applied Climatology* **154**(1), 613–626.
- Kennedy-Asser, A. T., James, R. A., Daron, J., Craig, A., Jack, C. D., Wolski, P. and Jones, R. G. (2026), ‘Do climate models agree on seasonal rainfall patterns and future changes over Southern Africa?’, *Climatic Change* **179**(2), 22.
- Kim, D., Song, H., Chun, H.-Y., Yoo, C., Kang, M.-J. and Lee, H.-K. (2024), ‘Springtime Southern Hemisphere Quasi-Stationary Planetary Wave Activities Associated With ENSO/IOD’, *Journal of Geophysical Research: Atmospheres* **129**(2).
- Knight, C. and Washington, R. (2024), ‘Remote Midlatitude Control of Rainfall Onset at the Southern African Tropical Edge’, *Journal of Climate* **37**(8), 2519–2539.
- Knight, C., Washington, R., Munday, C., Hart, N., Nkonde, E., Imbwae, F. and Wallace Kasongo (2026), ‘Observations of the atmosphere across the Congo Air Boundary’, *Submitted to Journal of Climate*.
- Knippertz, P. (2007), ‘Tropical–extratropical interactions related to upper-level troughs at low latitudes’, *Dynamics of Atmospheres and Oceans* **43**(1-2), 36–62.
- Knippertz, P., Coe, H., Chiu, J. C., Evans, M. J., Fink, A. H., Kalthoff, N., Lioussé, C., Mari, C., Allan, R. P., Brooks, B., Danour, S., Flamant, C., Jegede, O. O., Lohou, F. and Marsham, J. H. (2015), ‘The DACCWA Project: Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa’, *Bulletin of the American Meteorological Society* **96**(9), 1451–1460.
- Kniveton, D. R., Layberry, R., Williams, C. J. R. and Peck, M. (2009), ‘Trends in the start of the wet season over Africa’, *International Journal of Climatology* **29**(9), 1216–1225.
- Kodama, Y. (1992), ‘Large-Scale Common Features of Subtropical Precipitation Zones (the Baiu Frontal Zone, the SPCZ, and the SACZ) Part I: Characteristics of Subtropical Frontal Zones’, *Journal of the Meteorological Society of Japan. Ser. II* **70**(4), 813–836.
- Kosaka, Y., Kobayashi, S., Harada, Y., Kobayashi, C., Naoe, H., Yoshimoto, K., Harada, M., Goto, N., Chiba, J., Miyaoka, K., Sekiguchi, R., Deushi, M., Kama-hori, H., Nakaegawa, T., Tanaka, T. Y., Tokuhito, T., Sato, Y., Matsushita, Y. and Onogi, K. (2024), ‘The JRA-3Q Reanalysis’, *Journal of the Meteorological Society of Japan. Ser. II* **102**(1), 49–109.
- Kuete, G., Mba, W. P., James, R., Dyer, E., Annor, T. and Washington, R. (2023), ‘How do coupled models represent the African Easterly Jets and their associated dynamics over Central Africa during the September–November rainy season?’, *Climate Dynamics* **60**(9), 2907–2929.

- Kuete, G., Mba, W. P. and Washington, R. (2020), ‘African Easterly Jet South: Control, maintenance mechanisms and link with Southern subtropical waves’, *Climate Dynamics* **54**(3), 1539–1552.
- Lam, R., Sanchez-Gonzalez, A., Willson, M., Wirnsberger, P., Fortunato, M., Alet, F., Ravuri, S., Ewalds, T., Eaton-Rosen, Z., Hu, W., Merosse, A., Hoyer, S., Holland, G., Vinyals, O., Stott, J., Pritzel, A., Mohamed, S. and Battaglia, P. (2023), ‘Learning skillful medium-range global weather forecasting’, *Science* **382**(6677), 1416–1421.
- Lang, S., Alexe, M., Chantry, M., Dramsch, J., Pinault, F., Raoult, B., Clare, M. C. A., Lessig, C., Maier-Gerber, M., Magnusson, L., Bouallègue, Z. B., Nemesio, A. P., Dueben, P. D., Brown, A., Pappenberger, F. and Rabier, F. (2024), ‘AIFS – ECMWF’s data-driven forecasting system’.
- Largerion, Y., Guichard, F., Bouniol, D., Couvreur, F., Kergoat, L. and Marticorena, B. (2015), ‘Can we use surface wind fields from meteorological reanalyses for Sahelian dust emission simulations?’, *Geophysical Research Letters* **42**(7), 2490–2499.
- Lee, H.-T. (2014), ‘NOAA Climate Data Record (CDR) of Daily Outgoing Longwave Radiation (OLR), Version 1.2’, <https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00875>.
- Lenters, J. D. and Cook, K. H. (1997), ‘On the Origin of the Bolivian High and Related Circulation Features of the South American Climate’, *Journal of the Atmospheric Sciences* **54**(5), 656–678.
- Leroux, M. (2001), *The Meteorology and Climate of Tropical Africa*, Springer Praxis Books in Environmental Sciences, Praxis Publ, Chichester, UK.
- Levin, N. E., Zipser, E. J. and Cerling, T. E. (2009), ‘Isotopic composition of waters from Ethiopia and Kenya: Insights into moisture sources for eastern Africa’, *Journal of Geophysical Research: Atmospheres* **114**(D23).
- Li, X., Hu, Z.-Z., McPhaden, M. J., Zhu, C. and Liu, Y. (2023), ‘Triple-Dip La Ninas in 1998–2001 and 2020–2023: Impact of Mean State Changes’, *Journal of Geophysical Research: Atmospheres* **128**(17).
- Liebmann, B., Bladé, I., Kiladis, G. N., Carvalho, L. M. V., Senay, G. B., Allured, D., Leroux, S. and Funk, C. (2012), ‘Seasonality of African Precipitation from 1996 to 2009’, *Journal of Climate* **25**(12), 4304–4322.
- Lindesay, J. A. (1988), ‘South African rainfall, the Southern Oscillation and a Southern Hemisphere semi-annual cycle’, *Journal of Climatology* **8**(1), 17–30.
- Lindesay, J. A., Andreae, M. O., Goldammer, J. G., Harris, G., Annegarn, H. J., Garstang, M., Scholes, R. J. and van Wilgen, B. W. (1996), ‘International geosphere-biosphere programme/international global atmospheric chemistry SAFARI-92 field experiment: Background and overview’, *Journal of Geophysical Research: Atmospheres* **101**(D19), 23521–23530.

- Liu, F., Wang, B., Ouyang, Y., Wang, H., Qiao, S., Chen, G. and Dong, W. (2022), ‘Intraseasonal variability of global land monsoon precipitation and its recent trend’, *npj Climate and Atmospheric Science* **5**(1), 30.
- Livezey, R. E. and Chen, W. Y. (1983), ‘Statistical Field Significance and its Determination by Monte Carlo Techniques’, *Monthly Weather Review* **111**(1), 46–59.
- Longandjo, G.-N. T. and Rouault, M. (2020), ‘On the Structure of the Regional-Scale Circulation over Central Africa: Seasonal Evolution, Variability, and Mechanisms’, *Journal of Climate* **33**(1), 145–162.
- Longandjo, G.-N. T. and Rouault, M. (2024), ‘Revisiting the Seasonal Cycle of Rainfall over Central Africa’, *Journal of Climate* **37**(3), 1015–1032.
- Lorenz, E. N. (1963), ‘Deterministic Nonperiodic Flow’, *Journal of the Atmospheric Sciences* **20**(2), 130–141.
- Lorenz, E. N. (1984), ‘Irregularity: A fundamental property of the atmosphere’, *Tellus A* **36A**(2), 98–110.
- MacKellar, N., New, M. and Jack, C. (2014), ‘Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010’, *South African Journal of Science* **110**(7/8), 13.
- Macron, C., Pohl, B., Richard, Y. and Bessafi, M. (2014), ‘How do Tropical Temperate Troughs Form and Develop over Southern Africa?’, *Journal of Climate* **27**(4), 1633–1647.
- Madden, R. A. and Julian, P. R. (1994), ‘Observations of the 40–50-Day Tropical Oscillation—A Review’, *Monthly Weather Review* **122**(5), 814–837.
- Maidment, R. I., Allan, R. P. and Black, E. (2015), ‘Recent observed and simulated changes in precipitation over Africa’, *Geophysical Research Letters* **42**(19), 8155–8164.
- Maidment, R. I., Grimes, D., Allan, R. P., Tarnavsky, E., Stringer, M., Hewison, T., Roebeling, R. and Black, E. (2014), ‘The 30 year TAMSAT African Rainfall Climatology And Time series (TARCAT) data set’, *Journal of Geophysical Research: Atmospheres* **119**(18), 10,619–10,644.
- Manhique, A. J., Reason, C. J. C. and Barimalala, R. (2023), ‘Rainfall onset and cessation over Mozambique and relationship with sea surface temperature and atmospheric patterns’, *International Journal of Climatology* **43**(11), 4849–4863.
- Mapes, B. E. and Zuidema, P. (1996), ‘Radiative-Dynamical Consequences of Dry Tongues in the Tropical Troposphere’, *Journal of the Atmospheric Sciences* **53**(4), 620–638.
- Maphugwi, M., Blamey, R. C. and Reason, C. J. C. (2024), ‘Rainfall characteristics over the Congo Air Boundary Region in southern Africa: A comparison of station and gridded rainfall products’, *Atmospheric Research* **311**.

- Maphugwi, M., Blamey, R. C. and Reason, C. J. C. (2025), ‘Rainfall variability over the eastern Congo Air Boundary Region of Southern Africa’, *Theoretical and Applied Climatology* **156**(6).
- Marshall, J. and Plumb, R. A., eds (2008), *Atmosphere, Ocean, and Climate Dynamics: An Introductory Text*, number v. 93 in ‘International Geophysics Series’, Elsevier Academic Press, Amsterdam Burlington, MA.
- Marsham, J. H., Hobby, M., Allen, C. J. T., Banks, J. R., Bart, M., Brooks, B. J., Cavazos-Guerra, C., Engelstaedter, S., Gascoyne, M., Lima, A. R., Martins, J. V., McQuaid, J. B., O’Leary, A., Ouchene, B., Ouladichir, A., Parker, D. J., Saci, A., Salah-Ferroudj, M., Todd, M. C. and Washington, R. (2013), ‘Meteorology and dust in the central Sahara: Observations from Fennec supersite-1 during the June 2011 Intensive Observation Period’, *Journal of Geophysical Research: Atmospheres* **118**(10), 4069–4089.
- Matthews, A. J. and Kiladis, G. N. (2000), ‘A Model of Rossby Waves Linked to Submonthly Convection over the Eastern Tropical Pacific’, *Journal of the Atmospheric Sciences* **57**(23), 3785–3798.
- Mavume, A., Rydberg, L., Rouault, M. and Lutjeharms, J. (2010), ‘Climatology and Landfall of Tropical Cyclones in the South- West Indian Ocean’, *Western Indian Ocean Journal of Marine Science* **8**(1).
- McCarthy, J. and Koch, S. E. (1982), ‘The Evolution of an Oklahoma Dryline. Part I: A Meso- and Subsynoptic-Scale Analysis’, *Journal of the Atmospheric Sciences* **39**(2), 225–236.
- McIntyre, M. E. and Palmer, T. N. (1983), ‘Breaking planetary waves in the stratosphere’, *Nature* **305**(5935), 593–600.
- Meza, F. J., Hansen, J. W. and Osgood, D. (2008), ‘Economic Value of Seasonal Climate Forecasts for Agriculture: Review of Ex-Ante Assessments and Recommendations for Future Research’, *Journal of Applied Meteorology and Climatology* **47**(5), 1269–1286.
- Miao, Q. and Geerts, B. (2007), ‘Finescale Vertical Structure and Dynamics of Some Dryline Boundaries Observed in IHOP’, *Monthly Weather Review* **135**(12), 4161–4184.
- Mo, K. C. (1986), ‘Quasi-Stationary States in the Southern Hemisphere’, *Monthly Weather Review* **114**(5), 808–823.
- Moeletsi, M. E., Walker, S. and Landman, W. A. (2011), ‘ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa’, *Physics and Chemistry of the Earth* **36**(14-15), 715–726.
- Mooney, P. A., Mulligan, F. J. and Fealy, R. (2011), ‘Comparison of ERA-40, ERA-Interim and NCEP/NCAR reanalysis data with observed surface air temperatures over Ireland’, *International Journal of Climatology* **31**(4), 545–557.

- Morake, D. M., Blamey, R. C. and Reason, C. J. C. (2021), ‘Long-Lived Mesoscale Convective Systems over Eastern South Africa’, *Journal of Climate* **34**(15), 6421–6439.
- Moses, O., Blamey, R. C. and Reason, C. J. C. (2023), ‘Drought metrics and temperature extremes over the Okavango River basin, southern Africa, and links with the Botswana high’, *International Journal of Climatology* **43**(14), 6463–6483.
- Mulenga, H. M. (1999), Southern African Climate Anomalies, Summer Rainfall and the Angola Low, PhD thesis, University of Cape Town.
- Mulenga, H., Rouault, M. and Reason, C. (2003), ‘Dry summers over northeastern South Africa and associated circulation anomalies’, *Climate Research* **25**, 29–41.
- Munday, C., Engelstaedter, S., Washington, R., Ogutu, G., Olago, D., Ouma, G., Warner, J., Ong’ech, D., Nkatha, R., Ogolla, C., Lees, T. and Wanguba, B. (2024), ‘The Turkana Jet Diurnal Cycle in Observations and Reanalysis’, *Journal of Climate* **37**(18), 4633–4645.
- Munday, C. and Washington, R. (2017), ‘Circulation controls on southern African precipitation in coupled models: The role of the Angola Low’, *Journal of Geophysical Research: Atmospheres* **122**(2), 861–877.
- Munday, C. and Washington, R. (2018), ‘Systematic Climate Model Rainfall Biases over Southern Africa: Links to Moisture Circulation and Topography’, *Journal of Climate* **31**(18), 7533–7548.
- Munday, C., Washington, R., Engelstaedter, S., Zilli, M., Harbord, S., Knight, C., Attwood, K. and Hart, N. (2025), ‘Southern African Climate Change: Processes, Models, and Projections’, *WIREs Climate Change* **16**(5).
- Munday, C., Washington, R. and Hart, N. (2021), ‘African Low-Level Jets and Their Importance for Water Vapor Transport and Rainfall’, *Geophysical Research Letters* **48**(1).
- Mupangwa, W., Walker, S. and Twomlow, S. (2011), ‘Start, end and dry spells of the growing season in semi-arid southern Zimbabwe’, *Journal of Arid Environments* **75**(11), 1097–1104.
- Ndarana, T., Bopape, M.-J., Waugh, D. and Dyson, L. (2018), ‘The Influence of the Lower Stratosphere on Ridging Atlantic Ocean Anticyclones over South Africa’, *Journal of Climate* **31**(15), 6175–6187.
- Ndarana, T., Mpati, S., Bopape, M.-J., Engelbrecht, F. and Chikoore, H. (2021), ‘The flow and moisture fluxes associated with ridging South Atlantic Ocean anticyclones during the subtropical southern African summer’, *International Journal of Climatology* **41**(S1), 1000–1017.
- Ndarana, T., Rammopo, T. S., Reason, C. J., Bopape, M.-J., Engelbrecht, F. and Chikoore, H. (2022), ‘Two types of ridging South Atlantic Ocean anticyclones over South Africa and the associated dynamical processes’, *Atmospheric Research* **265**.

- Ndarana, T. and Waugh, D. W. (2010), ‘The link between cut-off lows and Rossby wave breaking in the Southern Hemisphere’, *Quarterly Journal of the Royal Meteorological Society* **136**(649), 869–885.
- Ndarana, T. and Waugh, D. W. (2011), ‘A Climatology of Rossby Wave Breaking on the Southern Hemisphere Tropopause’, *Journal of the Atmospheric Sciences* **68**(4), 798–811.
- Neelin, J. D. and Held, I. M. (1987), ‘Modeling Tropical Convergence Based on the Moist Static Energy Budget’, *Monthly Weather Review* **115**(1), 3–12.
- Neelin, J. D., Krasting, J. P., Radhakrishnan, A., Liptak, J., Jackson, T., Ming, Y., Dong, W., Gettelman, A., Coleman, D. R., Maloney, E. D., Wing, A. A., Kuo, Y.-H., Ahmed, F., Ullrich, P., Bitz, C. M., Neale, R. B., Ordóñez, A. and Maroon, E. A. (2023), ‘Process-Oriented Diagnostics: Principles, Practice, Community Development, and Common Standards’, *Bulletin of the American Meteorological Society* **104**(8), 1452–1468.
- Nguyen, H. and Duvel, J.-P. (2008), ‘Synoptic Wave Perturbations and Convective Systems over Equatorial Africa’, *Journal of Climate* **21**(23), 6372–6388.
- Nhamo, L., Matchaya, G., Mabhaudhi, T., Nhlengethwa, S., Nhemachena, C. and Mpandeli, S. (2019), ‘Cereal Production Trends under Climate Change: Impacts and Adaptation Strategies in Southern Africa’, *Agriculture* **9**(2), 30.
- Nicholson, S. (1996), *A Review of Climate Dynamics and Climate Variability in Eastern Africa*, 1 edn, Routledge, pp. 25–56.
- Nicholson, S. E. (2009), ‘A revised picture of the structure of the “monsoon” and land ITCZ over West Africa’, *Climate Dynamics* **32**(7), 1155–1171.
- Nicholson, S. E. (2015), ‘Long-term variability of the East African ‘short rains’ and its links to large-scale factors’, *International Journal of Climatology* **35**(13), 3979–3990.
- Nicholson, S. E. (2018), ‘The ITCZ and the Seasonal Cycle over Equatorial Africa’, *Bulletin of the American Meteorological Society* **99**(2), 337–348.
- Nicholson, S. E. and Grist, J. P. (2003), ‘The Seasonal Evolution of the Atmospheric Circulation over West Africa and Equatorial Africa’, *Journal of Climate* **16**(7), 1013–1030.
- Nicholson, S. E. and Kim, J. (1997), ‘The Relationship of the El Niño–Southern Oscillation to African Rainfall’, *International Journal of Climatology* **17**(2), 117–135.
- Nie, J., Boos, W. R. and Kuang, Z. (2010), ‘Observational Evaluation of a Convective Quasi-Equilibrium View of Monsoons’, *Journal of Climate* **23**(16), 4416–4428.
- Owen, J. (1966), ‘A Study of Thunderstorm Formation Along Dry Lines’, *Journal of Applied Meteorology and Climatology* **5**(1), 58–63.

- Palmer, T. N. and Anderson, D. L. T. (1994), ‘The prospects for seasonal forecasting—A review paper’, *Quarterly Journal of the Royal Meteorological Society* **120**(518), 755–793.
- Parker, D. J., Burton, R. R., Diongue-Niang, A., Ellis, R. J., Felton, M., Taylor, C. M., Thorncroft, C. D., Bessemoulin, P. and Tompkins, A. M. (2005), ‘The diurnal cycle of the West African monsoon circulation’, *Quarterly Journal of the Royal Meteorological Society* **131**(611), 2839–2860.
- Parker, D. J., Willetts, P., Birch, C., Turner, A. G., Marsham, J. H., Taylor, C. M., Kolusu, S. and Martin, G. M. (2016), ‘The interaction of moist convection and mid-level dry air in the advance of the onset of the Indian monsoon’, *Quarterly Journal of the Royal Meteorological Society* **142**(699), 2256–2272.
- Parker, W. S. (2016), ‘Reanalyses and Observations: What’s the Difference?’, *Bulletin of the American Meteorological Society* **97**(9), 1565–1572.
- Parker, W. S. (2020), ‘Model Evaluation: An Adequacy-for-Purpose View’, *Philosophy of Science* **87**(3), 457–477.
- Phakula, S., Landman, W. A. and Beraki, A. F. (2018), ‘Forecasting seasonal rainfall characteristics and onset months over South Africa’, *International Journal of Climatology* **38**(S1), 889–900.
- Pinto, I., Lennard, C., Tadross, M., Hewitson, B., Dosio, A., Nikulin, G., Panitz, H.-J. and Shongwe, M. E. (2016), ‘Evaluation and projections of extreme precipitation over southern Africa from two CORDEX models’, *Climatic Change* **135**(3), 655–668.
- Podglajen, A., Hertzog, A., Plougonven, R. and Žagar, N. (2014), ‘Assessment of the accuracy of (re)analyses in the equatorial lower stratosphere’, *Journal of Geophysical Research: Atmospheres* **119**(19), 11,166–11,188.
- Pokam, W. M., Bain, C. L., Chadwick, R. S., Graham, R., Sonwa, D. J. and Kamga, F. M. (2014), ‘Identification of Processes Driving Low-Level Westerlies in West Equatorial Africa’, *Journal of Climate* **27**(11), 4245–4262.
- Poll, S., Shrestha, P. and Simmer, C. (2022), ‘Grid resolution dependency of land surface heterogeneity effects on boundary-layer structure’, *Quarterly Journal of the Royal Meteorological Society* **148**(742), 141–158.
- Pospichal, B., Karam, D., Crewell, S., Flamant, C., Hünnerbein, A., Bock, O. and Saïd, F. (2010), ‘Diurnal cycle of the intertropical discontinuity over West Africa analysed by remote sensing and mesoscale modelling’, *Quarterly Journal of the Royal Meteorological Society* **136**(S1), 92–106.
- Postel, G. A. and Hitchman, M. H. (1999), ‘A Climatology of Rossby Wave Breaking along the Subtropical Tropopause’, *Journal of the Atmospheric Sciences* **56**(3), 359–373.
- Racz, Z. and Smith, R. K. (1999), ‘The dynamics of heat lows’, *Quarterly Journal of the Royal Meteorological Society* **125**(553), 225–252.

- Ranasinghe, R., Ruane, A. and Vautard, R. (2023), Climate Change Information for Regional Impact and for Risk Assessment, *in* ‘Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change’, 1 edn, Cambridge University Press.
- Rapolaki, R. S., Blamey, R. C., Hermes, J. C. and Reason, C. J. C. (2020), ‘Moisture sources associated with heavy rainfall over the Limpopo River Basin, southern Africa’, *Climate Dynamics* **55**(5), 1473–1487.
- Rasmussen, E. N., Straka, J. M., Davies-Jones, R., Doswell, C. A., Carr, F. H., Eilts, M. D. and MacGorman, D. R. (1994), ‘Verification of the Origins of Rotation in Tornadoes Experiment: VORTEX’, *Bulletin of the American Meteorological Society* **75**(6), 995–1006.
- Ratnam, J. V., Doi, T., Landman, W. A. and Behera, S. K. (2018), ‘Seasonal Forecasting of Onset of Summer Rains over South Africa’, *Journal of Applied Meteorology and Climatology* **57**(12), 2697–2711.
- Reason, C. J. C. (2001), ‘Subtropical Indian Ocean SST dipole events and southern African rainfall’, *Geophysical Research Letters* **28**(11), 2225–2227.
- Reason, C. J. C. (2002), ‘Sensitivity of the southern African circulation to dipole sea-surface temperature patterns in the south Indian Ocean’, *International Journal of Climatology* **22**(4), 377–393.
- Reason, C. J. C. (2016), ‘The Bolivian, Botswana, and Bilybara Highs and Southern Hemisphere drought/floods’, *Geophysical Research Letters* **43**(3), 1280–1286.
- Reason, C. J. C. (2017), Climate of Southern Africa, *in* ‘Oxford Research Encyclopedia of Climate Science’, Oxford University Press.
- Reason, C. J. C., Hachigonta, S. and Phaladi, R. F. (2005), ‘Interannual variability in rainy season characteristics over the Limpopo region of southern Africa’, *International Journal of Climatology* **25**(14), 1835–1853.
- Reason, C. J. C. and Jagadheesha, D. (2005), ‘A model investigation of recent ENSO impacts over southern Africa’, *Meteorology and Atmospheric Physics* **89**(1), 181–205.
- Reason, C. J. C. and Rouault, M. (2005), ‘Links between the Antarctic Oscillation and winter rainfall over western South Africa’, *Geophysical Research Letters* **32**(7).
- Reason, C. and Mulenga, H. (1999), ‘Relationships between South African rainfall and SST anomalies in the Southwest Indian Ocean’, *International Journal of Climatology* **19**(15), 1651–1673.
- Redelsperger, J.-L., Thorncroft, C. D., Diedhiou, A., Lebel, T., Parker, D. J. and Polcher, J. (2006), ‘African Monsoon Multidisciplinary Analysis: An International Research Project and Field Campaign’, *Bulletin of the American Meteorological Society* **87**(12), 1739–1746.

- Robertson, A. W. and Mechoso, C. R. (2003), ‘Circulation Regimes and Low-Frequency Oscillations in the South Pacific Sector’, *Monthly Weather Review* **131**(8), 1566–1576.
- Rodwell, M. J. and Hoskins, B. J. (2001), ‘Subtropical Anticyclones and Summer Monsoons’, *Journal of Climate* **14**(15), 3192–3211.
- Roffe, S. J. and van der Walt, A. J. (2023), ‘Representation and evaluation of southern Africa’s seasonal mean and extreme temperatures in the ERA5-based reanalysis products’, *Atmospheric Research* **284**.
- Ruti, P. M., Marullo, S., D’Ortenzio, F. and Tremant, M. (2008), ‘Comparison of analyzed and measured wind speeds in the perspective of oceanic simulations over the Mediterranean basin: Analyses, QuikSCAT and buoy data’, *Journal of Marine Systems* **70**(1), 33–48.
- Ryoo, J.-M., Pfister, L., Ueyama, R., Zuidema, P., Wood, R., Chang, I. and Redemann, J. (2022), ‘A meteorological overview of the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) campaign over the southeastern Atlantic during 2016–2018: Part 2 – Daily and synoptic characteristics’, *Atmospheric Chemistry and Physics* **22**(21), 14209–14241.
- Samrat, N. H., Candy, B., Lewis, O., Cotton, J., Smith, F., Halloran, G., Harlow, C., Lawrence, H., Migliorini, S., Smith, A. and Thomas, C. (2025), ‘Observation impact evaluation through data denial experiments in the Met Office global numerical weather prediction system’, *Quarterly Journal of the Royal Meteorological Society* **151**(771).
- Sardeshmukh, P. D. and Hoskins, B. J. (1988), ‘The Generation of Global Rotational Flow by Steady Idealized Tropical Divergence’, *Journal of the Atmospheric Sciences* **45**(7), 1228–1251.
- Schaefer, J. T. (1974), ‘The Life Cycle of the Dryline’, *Journal of Applied Meteorology and Climatology* **13**(4), 444–449.
- Schneider, T., Bischoff, T. and Haug, G. H. (2014), ‘Migrations and dynamics of the intertropical convergence zone’, *Nature* **513**(7516), 45–53.
- Shapiro, A. and Fedorovich, E. (2010), ‘Analytical description of a nocturnal low-level jet’, *Quarterly Journal of the Royal Meteorological Society* **136**(650), 1255–1262.
- Shekhar, R. and Boos, W. R. (2016), ‘Improving Energy-Based Estimates of Monsoon Location in the Presence of Proximal Deserts’, *Journal of Climate* **29**(13), 4741–4761.
- Shekhar, R. and Boos, W. R. (2017), ‘Weakening and Shifting of the Saharan Shallow Meridional Circulation during Wet Years of the West African Monsoon’, *Journal of Climate* **30**(18), 7399–7422.
- Shen, X., Wang, L. and Osprey, S. (2020), ‘Tropospheric Forcing of the 2019 Antarctic Sudden Stratospheric Warming’, *Geophysical Research Letters* **47**(20).

- Shongwe, M. E., van Oldenborgh, G. J., van den Hurk, B. J. J. M., de Boer, B., Coelho, C. A. S. and van Aalst, M. K. (2009), ‘Projected Changes in Mean and Extreme Precipitation in Africa under Global Warming. Part I: Southern Africa’, *Journal of Climate* **22**(13), 3819–3837.
- Singleton, A. T. and Reason, C. J. C. (2007), ‘Variability in the characteristics of cut-off low pressure systems over subtropical southern Africa’, *International Journal of Climatology* **27**(3), 295–310.
- Smith, R. K. and Spengler, T. (2011), ‘The dynamics of heat lows over elevated terrain’, *Quarterly Journal of the Royal Meteorological Society* **137**(654), 250–263.
- Sobel, A. H. and Bellon, G. (2009), ‘The Effect of Imposed Drying on Parameterized Deep Convection’, *Journal of the Atmospheric Sciences* **66**(7), 2085–2096.
- Spavins-Hicks, Z. D., Washington, R. and Munday, C. (2021), ‘The Limpopo Low-Level Jet: Mean Climatology and Role in Water Vapor Transport’, *Journal of Geophysical Research: Atmospheres* **126**(16).
- Spengler, T. and Smith, R. K. (2008), ‘The dynamics of heat lows over flat terrain’, *Quarterly Journal of the Royal Meteorological Society* **134**(637), 2157–2172.
- Streten, N. A. (1975), ‘Satellite Derived Inferences to Some Characteristics of the South Pacific Atmospheric Circulation Associated with the Niño Event of 1972–73’, *Monthly Weather Review* **103**(11), 989–995.
- Sultan, B. and Janicot, S. (2003), ‘The West African Monsoon Dynamics. Part II: The “Preonset” and “Onset” of the Summer Monsoon’, *Journal of Climate* **16**(21), 3407–3427.
- Sun, B., Reale, A., Schroeder, S., Seidel, D. J. and Ballish, B. (2013), ‘Toward improved corrections for radiation-induced biases in radiosonde temperature observations’, *Journal of Geophysical Research: Atmospheres* **118**(10), 4231–4243.
- Swap, R. J., Annegarn, H. J., Suttles, J. T., King, M. D., Platnick, S., Privette, J. L. and Scholes, R. J. (2003), ‘Africa burning: A thematic analysis of the Southern African Regional Science Initiative (SAFARI 2000)’, *Journal of Geophysical Research: Atmospheres* **108**(D13).
- Tadross, M. A., Hewitson, B. C. and Usman, M. T. (2005), ‘The Interannual Variability of the Onset of the Maize Growing Season over South Africa and Zimbabwe’, *Journal of Climate* **18**(16), 3356–3372.
- Taljaard, J. J. (1953), ‘The Mean Circulation in the Lower Troposphere over Southern Africa’, *South African Geographical Journal* **35**(1), 33–45.
- Taljaard, J. J. (1972), Synoptic Meteorology of the Southern Hemisphere, *in* H. van Loon, J. J. Taljaard, T. Sasamori, J. London, D. V. Hoyt, K. Labitzke, C. W. Newton and C. W. Newton, eds, ‘Meteorology of the Southern Hemisphere’, American Meteorological Society, Boston, MA, pp. 139–213.

- Taljaard, J. J. (1986), ‘Change of rainfall distribution and circulation patterns over Southern Africa in summer’, *Journal of Climatology* **6**(6), 579–592.
- Tatro, T. and Zuidema, P. (2025), ‘More biomass burning aerosol is being advected westward over the southern tropical Atlantic since 2003’, *Science of The Total Environment* **965**.
- Tennant, W. (2004), ‘Considerations when using pre-1979 NCEP/NCAR reanalyses in the southern hemisphere’, *Geophysical Research Letters* **31**(11).
- Thoithi, W., Blamey, R. C. and Reason, C. J. C. (2025), ‘La Nina Impacts on Southeastern African Climate: The Influence of Event Duration’, *International Journal of Climatology* **45**(14).
- Thoithi, W., Blamey, R. C. and Reason, C. J. C. (2026), ‘Circulation anomalies associated with mid- to late summer rainfall differences during multiyear La Niña events over subtropical southeastern Africa’, *Climate Dynamics* **64**(3), 128.
- Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S. and Belcher, S. E. (2017), ‘High risk of unprecedented UK rainfall in the current climate’, *Nature Communications* **8**(1), 107.
- Thorncroft, C. D., Parker, D. J., Burton, R. R., Diop, M., Ayers, J. H., Barjat, H., Devereau, S., Diongue, A., Dumelow, R., Kindred, D. R., Price, N. M., Saloum, M., Taylor, C. M. and Tompkins, A. M. (2003), ‘The JET2000 Project: Aircraft Observations of the African Easterly Jet and African Easterly Waves: Aircraft Observations of the African Easterly Jet and African Easterly Waves’, *Bulletin of the American Meteorological Society* **84**(3), 337–352.
- Thurlow, J., Zhu, T. and Diao, X. (2012), ‘Current Climate Variability and Future Climate Change: Estimated Growth and Poverty Impacts for Zambia’, *Review of Development Economics* **16**(3), 394–411.
- Tierney, J. E., Lewis, S. C., Cook, B. I., LeGrande, A. N. and Schmidt, G. A. (2011), ‘Model, proxy and isotopic perspectives on the East African Humid Period’, *Earth and Planetary Science Letters* **307**(1), 103–112.
- Todd, M. C., Allen, C. J. T., Bart, M., Bechir, M., Bentefouet, J., Brooks, B. J., Cavazos-Guerra, C., Clovis, T., Deyane, S., Dieh, M., Engelstaedter, S., Flamant, C., Garcia-Carreras, L., Gandega, A., Gascoyne, M., Hobby, M., Kocha, C., Lavaysse, C., Marsham, J. H., Martins, J. V., McQuaid, J. B., Ngamini, J. B., Parker, D. J., Podvin, T., Rocha-Lima, A., Traore, S., Wang, Y. and Washington, R. (2013), ‘Meteorological and dust aerosol conditions over the western Saharan region observed at Fennec Supersite-2 during the intensive observation period in June 2011’, *Journal of Geophysical Research: Atmospheres* **118**(15), 8426–8447.
- Todd, M. and Washington, R. (1999), ‘Circulation anomalies associated with tropical-temperate troughs in southern Africa and the south west Indian Ocean’, *Climate Dynamics* **15**(12), 937–951.
- Tong, H. W., Chan, J. C. L. and Zhou, W. (2009), ‘The role of MJO and mid-

- latitude fronts in the South China Sea summer monsoon onset', *Climate Dynamics* **33**(6), 827–841.
- Torrance, J. D. (1979), 'Upper windflow patterns in relation to rainfall in south-east central africa', *Weather* **34**(3), 106–115.
- Trenberth, K. E. (1991), 'Storm Tracks in the Southern Hemisphere', *Journal of the Atmospheric Sciences* **48**(19), 2159–2178.
- Tyson, P. D. and Crimp, S. J. (1998), 'The Climate of the Kalahari Transect', *Transactions of the Royal Society of South Africa* **53**(2), 93–112.
- Tyson, P. D. and Preston-Whyte, R. A. (2000), *The Weather and Climate of Southern Africa*, 2nd ed edn, Oxford University Press, Cape Town.
- Van De Wiel, B. J. H., Moene, A. F., Steeneveld, G. J., Baas, P., Bosveld, F. C. and Holtslag, A. A. M. (2010), 'A Conceptual View on Inertial Oscillations and Nocturnal Low-Level Jets', *Journal of the Atmospheric Sciences* **67**(8), 2679–2689.
- van Heerden, J. and Taljaard, J. J. (1998), Africa and Surrounding Waters, *in* D. J. Karoly and D. G. Vincent, eds, 'Meteorology of the Southern Hemisphere', American Meteorological Society, Boston, MA, pp. 141–174.
- van Schalkwyk, L., Blamey, R. C., Dyson, L. L. and Reason, C. J. C. (2022), 'A Climatology of Drylines in the Interior of Subtropical Southern Africa', *Journal of Climate* **35**(19), 6411–6430.
- van Schalkwyk, L., Blamey, R. C., Gijben, M. and Reason, C. J. C. (2023), 'A Climatology of Dryline-Related Convection on the Western Plateau of Subtropical Southern Africa', *Journal of Geophysical Research: Atmospheres* **128**(18).
- Vigaud, N., Richard, Y., Rouault, M. and Fauchereau, N. (2009), 'Moisture transport between the South Atlantic Ocean and southern Africa: Relationships with summer rainfall and associated dynamics', *Climate Dynamics* **32**(1), 113–123.
- Ward, N., Fink, A. H., Keane, R. J., Guichard, F., Marsham, J. H., Parker, D. J. and Taylor, C. M. (2021), 'Synoptic timescale linkage between midlatitude winter troughs Sahara temperature patterns and northern Congo rainfall: A building block of regional climate variability', *International Journal of Climatology* **41**(5), 3153–3173.
- Washington, R., James, R., Pearce, H., Pokam, W. M. and Moufouma-Okia, W. (2013), 'Congo Basin rainfall climatology: Can we believe the climate models?', *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**(1625).
- Weckwerth, T. M., Parsons, D. B., Koch, S. E., Moore, J. A., LeMone, M. A., Demoz, B. B., Flamant, C., Geerts, B., Wang, J. and Feltz, W. F. (2004), 'An Overview of the International H2O Project (IHOP_2002) and Some Preliminary Highlights', *Bulletin of the American Meteorological Society* **85**(2), 253–278.
- Wheeler, M. C. and Hendon, H. H. (2004), 'An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction', *Monthly Weather Review* **132**(8), 1917–1932.

- Wilks, D. S. (2016), “‘The Stippling Shows Statistically Significant Grid Points’: How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It’, *Bulletin of the American Meteorological Society* **97**(12), 2263–2273.
- Wirth, V., Riemer, M., Chang, E. K. M. and Martius, O. (2018), ‘Rossby Wave Packets on the Midlatitude Waveguide—A Review’, *Monthly Weather Review* **146**(7), 1965–2001.
- Worden, S. and Fu, R. (2025), ‘On the mechanisms that control the rainy season transition period in the southern Congo Basin’, *Climate Dynamics* **63**(3), 157.
- World Food Programme (2025), ‘Southern Africa Drought | World Food Programme’, <https://www.wfp.org/emergencies/southern-africa-drought>.
- Xie, S., Hume, T., Jakob, C., Klein, S. A., McCoy, R. B. and Zhang, M. (2010), ‘Observed Large-Scale Structures and Diabatic Heating and Drying Profiles during TWP-ICE’, *Journal of Climate* **23**(1), 57–79.
- Yarnal, B. (1993), *Synoptic Climatology in Environmental Analysis: A Primer*, Studies in Climatology Series, Belhaven, London.
- Zangl, G. and Chico, S. G. (2006), ‘The Thermal Circulation of a Grand Plateau: Sensitivity to the Height, Width, and Shape of the Plateau’, *Monthly Weather Review* **134**(9), 2581–2600.
- Zhang, D.-L., Lin, Y., Zhao, P., Yu, X., Wang, S., Kang, H. and Ding, Y. (2013), ‘The Beijing extreme rainfall of 21 July 2012: “Right results” but for wrong reasons’, *Geophysical Research Letters* **40**(7), 1426–1431.
- Zhang, F., Sun, Y. Q., Magnusson, L., Buizza, R., Lin, S.-J., Chen, J.-H. and Emanuel, K. (2019), ‘What Is the Predictability Limit of Midlatitude Weather?’, *Journal of the Atmospheric Sciences* **76**(4), 1077–1091.
- Zhou, L. and Murtugudde, R. (2014), ‘Impact of Northward-Propagating Intraseasonal Variability on the Onset of Indian Summer Monsoon’, *Journal of Climate* **27**(1), 126–139.
- Ziegler, C. L. and Hane, C. E. (1993), ‘An Observational Study of the Dryline’, *Monthly Weather Review* **121**(4), 1134–1151.
- Ziegler, C. L. and Rasmussen, E. N. (1998), ‘The Initiation of Moist Convection at the Dryline: Forecasting Issues from a Case Study Perspective’, *Weather and Forecasting* **13**(4), 1106–1131.
- Zipser, E. J., Cecil, D. J., Liu, C., Nesbitt, S. W. and Yorty, D. P. (2006), ‘Where are the most intense thunderstorms on earth?’, *Bulletin of the American Meteorological Society* **87**(8), 1057–1072.
- Zunckel, M., Hong, Y., Brassel, K. and O’Beirne, S. (1996), ‘Characteristics of the nocturnal boundary layer: Okaukuejo, Namibia, during SAFARI-92’, *Journal of Geophysical Research: Atmospheres* **101**(D19), 23757–23766.