

Characterising the Synoptic Expression of the Angola Low

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ABSTRACT

7 The Angola Low is a key feature of the southern African wet season atmo-
8 sphere which influences precipitation across the continent. This paper uses
9 ERA-Interim reanalysis to show that the synoptic expression of the Angola
10 Low is a combination of dry heat lows and moist tropical low-pressure sys-
11 tems. Angola Heat Low and Angola Tropical Low composites are contrasted
12 against similar lows observed in other continental tropical regions and found
13 to be broadly comparable. The implications that the distinction between dry
14 and moist events has for the inter-annual relationship between the Angola
15 Low, precipitation and ENSO are examined. The tropical lows exhibit unusual
16 semi-stationary behaviour by lingering in the Angola region rather than trav-
17 elling offshore. This behaviour is proposed to be caused by an integrated sea
18 breeze-anabatic wind which enhances (inhibits) cyclonic vorticity stretching
19 and convection inland (near the coast). The combined effect of the heat lows
20 and the anchored tropical lows creates the Angola Low in the climatological
21 average. By elucidating the mechanisms of the Angola Low, this research im-
22 proves the foundation of process-based evaluation of southern African present
23 and future climate in CMIP and AMIP models.

24 1. Introduction

25 Precipitation underpins the lives of 150 million people in southern Africa¹. Shifts in rainfall
26 can undercut agricultural production, undermine water, food and energy security, and ultimately
27 threaten the economic viability of the region (Conway et al., 2015). In this region, rainfall is
28 strongly variable on a wide range of time-scales, from intraseasonal through to decadal (Reason
29 et al., 2006). The local climate dynamics driving precipitation variability are complex, and a com-
30 prehensive understanding of the processes which force the local climate remains elusive. With
31 approximately 60% of the region over 800 m above sea level (NOAA, 1988), and spanning over
32 20° of latitude from the tropics to the midlatitudes, southern Africa exists in the nexus of compet-
33 ing climatic features. One such feature, the Angola Low, is known to have a central influence over
34 wet season precipitation across the subcontinent (e.g. Reason and Jagadheesha (2005), Cook et al.
35 (2004)).

36 The Angola Low is a semi-permanent low-pressure system associated with cyclonic circulation.
37 It is easily identifiable in the December-January-February climatology of near-surface geopotential
38 height (e.g. Munday and Washington (2017)) as shown in Figure 1. The system is centred over
39 eastern Angola at about 13°S and extends into surrounding countries. It is associated with the
40 convergence of moisture flux originating from the western Indian and south east Atlantic Oceans,
41 and thus modulates moisture transport into the subcontinent (Rouault et al., 2003).

42 The Angola Low was first named as a distinct feature by Zunckel et al. (1996) although the first
43 comprehensive analysis of its meteorology was developed by Mulenga (1998). Perhaps because
44 of the dearth of circulation data over remote western Zambia and war-torn eastern Angola, the in-
45 tegrity of the closed Angola Low circulation had remained elusive to pioneers of southern African

¹Loosely defined here as mainland Africa south of 10° S.

climate who described the broad convergence zone in which the feature tends to develop as the Congo Air Boundary (Taljaard (1953) and (Taljaard, 1972)), and also as the Zaire Air Boundary.

a. Angola Low Significance

The development of climate models and reanalysis products has shone light on the vital role of the Angola Low in the dynamics of southern African climate. Cook et al. (2004) studied composites of wet and dry spells based on South African rain gauge data. They found that wet spells are associated with stronger Angola Low circulations in NCEP2 reanalysis data than dry spells. In addition to this, Munday and Washington (2017) have shown that in some regions of Southern Africa, 40-60% of the inter-model precipitation variability between historical CMIP5 models can be explained by the simulated depth of the Angola Low.

The dominant mode of inter-annual variability in southern African precipitation is the El Niño Southern Oscillation (ENSO) (e.g. Lindesay (1988)). Through the El Niño phase, ENSO is a key driver of some of the most severe recent droughts in the region. Based on an examination of the circulation over southern Africa in a well spread sample of 3 El Niño and 2 La Niña summers, Reason and Jagadheesha (2005) suggested that the Angola Low has a modulating influence of ENSO on southern African precipitation.

There is also evidence that the Angola Low may be a precursor to tropical-temperate cloud band (TTT) formation (Todd and Washington (1999) and Hart et al. (2010)), which provide a significant proportion of rainfall across the whole of the southern African region (Harrison, 1984). The Angola Low enables southward transport of atmospheric water vapour from the tropics, crucial to the development of TTTs. In an idealised model experiment, Cook (2000) found that an idealised thermal low similar to the Angola Low acts as a root zone for a land based convergence zone analogous to the South Indian Convergence Zone (SICZ), the time mean manifestation of TTTs.

69 Future changes in the Angola Low are likely to impact southern African precipitation. Vizzy
70 and Cook (2016) observe a recent strengthening of the Angola Low in multiple reanalysis datasets
71 from 1982 through to 2013, by examining trends in mean sea level pressure and surface winds.
72 They find that this is associated with sea surface temperature warming off the Angola Coast in
73 concert with a decrease in coastal upwelling in the eastern South Atlantic. Similarly, Vizzy et al.
74 (2015) studied a regional climate model representing projections of southern African climate into
75 the late 21st century. In their simulations, a shortening of the wet season over Malawi was linked to
76 a projected strengthening of the continental lows, including the Angola Low, in April, associated
77 with increased surface heating due to anthropogenic climate change.

78 Considering its importance to the regional climate, it is crucial that the mechanisms which drive
79 the Angola Low are well understood so as to increase confidence in future projections of southern
80 African precipitation. However at present, the dynamics of the Angola Low, particularly on a
81 synoptic time-scale, are not clear. Furthermore, a paucity of measurement data in tropical Africa
82 means that process-based evaluation of climate models is often more feasible than performance-
83 based evaluations (James et al., 2018). An understanding of the mechanisms of the Angola Low
84 will allow process-based evaluation of climate models to reduce the uncertainty around future
85 projections of regional precipitation changes.

86 *b. Angola Low Dynamics*

87 Traditionally, the Angola Low has been considered to be a dry thermal low, following the the-
88 oretical framework of (RÁCZ and Smith, 1999). The idealised work of Spengler et al. (2005) and
89 Reason (1996) predict that at tropical and subtropical latitudes, continental heat lows will form
90 on the western sides of continents due to the interaction of the background easterly flow with the
91 surface heating and topography. Many aspects of the Angola Low are consistent with this frame-

92 work. Mulenga (1998) found that the Angola Low could be formed in a quasi-geostrophic model
93 of southern Africa as a Matsuno-Gill response to surface heating, using a similar method to Leslie
94 (1980).

95 However, there is emerging evidence that moist convection may be as important to the Angola
96 Low as dry convection. Mulenga (1998) remarks that the Angola Low may act as an anchor
97 point for deep tropical convection. Further to this, Munday and Washington (2017) found that the
98 convection driving the Angola Low shifts from being shallow and dry to moist and deep at around
99 midsummer each year. Particularly notable instances of deep convection in the Angola region
100 have occurred when Indian Ocean tropical cyclones, including Eline in February 2000 (Reason
101 and Keibel, 2004) and Bonita in January 1996, (Mudenda and Mumba, 1996) have crossed onto
102 the African continent in Mozambique and traversed up the Zambezi River Basin to merge with
103 Angola Low.

104 *c. Paper Aims and Structure*

105 Despite its evident importance to southern African climate system on many time-scales, the
106 Angola Low is typically considered as a feature of the seasonal mean. Little attention has been
107 paid to its dynamics or synoptic expression. The focus of this paper is to perform a detailed
108 analysis of the Angola Low as modelled in the ERA-Interim reanalysis database.

109 We diagnose the Angola Low as a combination of early season heat low events and late season
110 transient tropical low events, which we denote the Angola Heat Low and the Angola Tropical
111 Low. We investigate the bearing this division has on the relationship between the Angola Low
112 and precipitation. Our findings indicate that the inter-annual variability of the tropical lows is cor-
113 related to inter-annual summer precipitation variability. In contrast, we find that the inter-annual
114 variability of the heat lows has no bearing on precipitation variability. While heat low events fit

115 nicely into the idealised theory described by Rácz and Smith (1999) and Spengler et al. (2005), the
116 tropical lows are dynamically similar to transient monsoon lows and depressions that have been
117 observed across India and northern Australia (Hunt et al., 2016). These southern African tropical
118 lows, which form within the tropical rain band, are semi-stationary and linger in the Angola Low
119 region, in contrast to those which form elsewhere. We find evidence suggesting this behaviour
120 may stem from the interactions of the west coast sea breeze with an anabatic wind associated with
121 the steep escarpment along the Angola-Namibia Coast. This integrated sea breeze-anabatic wind
122 will be referred to as an anabatic sea breeze for brevity.

123 The remainder of this paper proceeds as follows. Section 3 classifies the Angola Low as a series
124 of thermal lows (the Angola Heat Low) and tropical lows (the Angola Tropical Low). We then
125 examine the synoptic characteristics of each of the two phases. In section 4 we establish the influ-
126 ence of ENSO on the Angola Low, and then examine the different effects of the Angola Heat Low
127 and the Angola Tropical Low on precipitation. The paper then moves towards an understanding
128 of the local drivers of the Angola Low in section 5. The final section summarises the research
129 findings and discusses its implications.

130 **2. Data and Methods**

131 This study uses the ERA-Interim reanalysis dataset at native resolution (0.75 degrees), as de-
132 scribed by Dee et al. (2011). 37 Austral summers were analysed, starting in September 1979 and
133 ending in March 2016. Data is analysed on a daily time-scale unless otherwise indicated. The
134 primary region of interest is southern Angola and northern Namibia (11 - 19°S, 14 - 25°E). This
135 analysis was repeated using 3 hourly MERRA2 data, spanning from September 1980 through to
136 March 2016. The results of this analysis were qualitatively similar to those obtained from ERA-

137 Interim and led to the same conclusions. For brevity, only the ERA-Interim results are presented
138 in this paper.

139 To identify Angola Low events, we consider the daily mean vorticity within the region of interest
140 described above. For each day in the sample period, grid cells with vorticity at 800 hPa less than
141 $-4 \times 10^{-5} \text{ s}^{-1}$ were classified as Angola Low grid cells, and classified as a heat low or tropical
142 low. The choice of the vorticity threshold and the definition of classification system are described
143 in section 3a. The centre of an Angola low event at a point in that time is then calculated as the
144 centroid of a group of adjacent Angola Low grid cells of the same phase. This method allows
145 for multiple events to exist in the region of interest at a period of time, provided that none of
146 their constituent grid cells are adjacent. The average number of grid cells which were identified
147 in each cluster was 6.2, implying a radius of about 100 km. Each cluster represents the core of
148 a cyclonic system, and so the total radius of the cluster is often larger than this core. 90% of the
149 clusters contained less than 15 grid cells. However, the distribution of the cluster sizes was highly
150 skewed, and the largest cluster identified contained 57 grid cells. This cluster occurred on the 18th
151 of January 1996, when Mudenda and Mumba (1996) report that ex-Tropical Cyclone Bonita had
152 merged with the Angola Low. The sensitivity of all results to the relative vorticity threshold has
153 been tested using a threshold of $-3.5 \times 10^{-5} \text{ s}^{-1}$. This increased the number of Angola Low grid
154 cells flagged, but all other results were qualitatively unchanged and the statistical significance of
155 the results still held in all cases.

156 We have used composite analysis to study the structure of various atmospheric fields during An-
157 gola Low events. In order to remove the effect of the seasonal cycle, a 14 day running mean cli-
158 matology is subtracted from both the composite sample and the population before testing. A two-
159 tailed Welch's t-test is then applied to test the null hypothesis that the composite mean anomaly
160 is the same as that of the climatology. Autocorrelation within the composite samples has been

controlled for by assuming that the data follow a first order autoregressive process and calculating an effective sample size using the lag-1 autocorrelation coefficient. The false discovery rate is controlled by calculating a threshold level p_{FDR}^* based on an FDR control value of $\alpha_{FDR} = 0.05$ (Wilks, 2011). A combined value of p_{FDR}^* is calculated for each multi-panel figure and is presented in each figure caption. Despite the use of anomalies to calculate significance, we have elected to show the full fields in the composite plots. We found this displayed greater clarity of the overall results.

3. Synoptic Characteristics

In order to study the synoptic events which comprise the Angola Low, we generated a set of time and space coordinates in the study area which featured strong cyclonic relative vorticity. We then studied the phase space of various atmospheric variables at the identified coordinates. This revealed two clear clusters of synoptic events. In this section, we describe the method used to classify the two clusters, the synoptic characteristics of the two clusters of low-pressure systems, and finally the behaviour of the systems. Despite the low latitude of the study area, we find that geostrophic balance is still a useful approximation. Above the boundary layer, the overall magnitude of the ageostrophic component is about 33% of the overall magnitude of the geostrophic component.

a. Classification System

The distinction between the Angola Heat Low and the Angola Thermal Low on the daily time-scale has been characterised by considering the dry static stability of events with strong cyclonic vorticity. For each day in the study period, grid cells in the primary region of interest (11 - 19°S, 14 - 25°E) with daily mean relative vorticity at 800 hPa less than $-4 \times 10^{-5} \text{s}^{-1}$ have been identified.

183 A heat map of the static stability at 700 hPa against the 800 hPa relative vorticity is given in
 184 Figure 2. From this it can be seen that there are two distinct clusters of events, those with high
 185 static stability (above 0.0033 K/m and coloured blue) and those with low static stability (below
 186 0.0033 K/m and coloured red). The lower panel of Figure 2 shows a parameter space heat map
 187 of specific humidity against static stability. This demonstrates that the clustering is also present
 188 in specific humidity, with the more (less) statically stable events being wetter (drier). Here, the
 189 static stability is taken as the vertical derivative of potential temperature. Other parameters (not
 190 shown) including temperature and potential vorticity, also show this clear distinction between
 191 the two types of events. The vorticity threshold was chosen as the weakest threshold at which
 192 a bimodal distribution emerged in Figure 2 with minimal overlap between the clusters. As noted
 193 earlier, lowering the vorticity threshold to $-3.5 \times 10^{-5} \text{s}^{-1}$ does not change the results significantly,
 194 however we choose to use the stronger threshold to keep the clusters more distinct. Based on the
 195 results of Figure 2, each vertical profile in the region of interest and study period with 800 hPa
 196 relative vorticity less than $-4 \times 10^{-5} \text{s}^{-1}$ is classified as a heat low (tropical low) grid cell if its
 197 static stability at 700 hPa is less than (greater than) 0.0033 K/m.

198 The key differences between the dynamics and thermodynamics of the two phases of the An-
 199 gola Low are illustrated in Figure 3. This figure has been constructed by compositing vertical
 200 profiles of various atmospheric variables at the closest grid cell to the centroid of each heat low
 201 and tropical low event. It is evident that the heat lows are associated with cyclonic circulation
 202 capped at 700 hPa, hot surface temperatures, low surface humidity, and neutrally stratified static
 203 stability. This indicates that the heat lows in the Angola region feature shallow dry convection, as
 204 per the idealised heat lows studied by Rácz and Smith (1999). Conversely, the tropical lows are
 205 associated with cyclonic circulation up to 300-400 hPa and high surface humidity. While the dry

static stability profile is stable, the moist stability, indicated by the θ_e profile, is unstable. Thus the tropical lows feature deep moist convection, maintained by latent heat release.

Consistent with the finding of Munday and Washington (2017), a seasonal distinction between occurrences of the Angola Heat Low and the Angola Tropical Low is apparent. Figure 4 shows a 2D histogram map of where intense cyclonic circulation associated with dry and moist convection occur from October through to March. The method used to identify heat low and tropical low grid cells is as described above, however, the results are shown for southern Africa. Dry convection is strongly evident in Angola from October to November, and moist convection is present from December through to March. Also apparent is the moist convecting Mozambique Channel trough and the dry convecting Kalahari heat low, which are not the focus of this research. It is clear that the Angola Low presents as the Angola Heat Low from October through to November, and then transitions to the Angola Tropical Low during December when the wet season begins, and remains as the Angola Tropical Low until March. This leads us to investigate the synoptic structure of these two phases separately below.

220 *b. Angola Heat Low Dynamics*

Key diurnal characteristics of the Angola Heat Low for comparison to the literature surrounding idealised heat lows are presented in Figure 5. The figure shows diurnal vertical west-east cross-sections of winds and potential temperature during heat lows identified using the methodology described in section 3a, centred on the centroid of the heat low grid cells. These cross-sections are consistent with Figures 6 to 9 of Rácz and Smith (1999) and Figure 3 of Spengler and Smith (2008), which demonstrate vertical cross-sections of potential temperature and winds in idealised heat low experiments. The authors found that the radial wind inflow is strongest overnight and rotates into a geostrophic tangential wind in the early morning, and that the potential temperature

229 at the centre of the heat lows is unstable in the middle of the day. A mid-level anticyclone sits
230 above the heat low and is strongest in the morning.

231 The main difference between the idealised models and our ERA-Interim based analysis is that
232 the instability is weaker in the reanalysis. The weak instability may result from the averaging of
233 many heat lows in our composite. The westerly zonal inflow resembles a sea breeze, which will
234 be further discussed in section 5. We also find that the upper-level jet which caps the upper-level
235 anticyclone is significantly stronger during the heat low than in the climatology, despite the fact
236 that the climatological seasonal cycle was removed when statistical significance was calculated.
237 Overall there is satisfactory evidence that the Angola Heat Low is indeed a thermal low in the
238 traditional sense.

239 *c. Angola Tropical Low Dynamics*

240 As cold-cored synoptic-scale lows that track over a tropical landmass, the tropical lows in the
241 Angola region bear resemblance to tropical low-pressure systems, including monsoon depressions.
242 Monsoon depressions have been most intensively studied over the Indian Subcontinent (e.g. Hunt
243 et al. (2016), Godbole (1977)), but have also been studied over northern Australia (Berry et al.,
244 2012). Hurley and Boos (2015) conducted a comprehensive study of these features across low
245 latitude land masses and noted their similarities and differences across different regions of the
246 globe, including southern Africa.

247 The Angola Tropical Low consists of a deep column of potential vorticity, extending from the
248 surface to about 300 hPa (Figure 6). The panels in Figure 6 show daily vertical west-east cross-
249 sections of various atmospheric variables during tropical lows identified using the methodology
250 described in section 3a, centred on the centroid of the tropical low grid cells. The temperature
251 anomaly field features a dipole which is cool near the surface and warm in the upper-troposphere.

252 In contrast with the Angola Heat Low, the upper-level zonal winds during the Angola Tropical
253 Low are easterly, suggesting that the tropical lows are embedded in the tropical easterly jet. The
254 cyclonic circulation anomalies reach out from the centre of the system approximately 500 km,
255 giving the total system an average diameter of 1000 km. These observations are consistent with
256 the structures of the Indian and northern Australian monsoon lows and depressions observed by
257 Hunt et al. (2016), Berry et al. (2011) and Hurley and Boos (2015). This implies that the growth
258 and propagation mechanisms of these circulations may resemble those of the tropical lows in
259 Angola.

260 The implication that some low-pressure systems over southern Africa are dynamically similar
261 to monsoon depressions in Australia and India is not immediately reconcilable with the work of
262 Hurley and Boos (2015). The southern African composites of Hurley and Boos (2015) do not show
263 the characteristic temperature or PV structure of a typical monsoon low. However, their composite
264 sample contains data from December to February and is performed over an area which extends
265 down to 25° S. Hence the sample will contain Kalahari and Angola heat lows as well as tropical
266 lows, which would be expected to obscure the signal of the tropical depressions. Therefore we
267 conclude that the tropical lows in the Angola region are dynamically related to the monsoon lows
268 that have been observed over Australia and India. Hurley and Boos (2015) identified on average
269 12.5 low-pressure systems from November to February in southern Africa, in contrast to 25 over
270 the same period in Australia and 18 from May to August in India. Even before accounting for
271 the fact that some of these systems may be heat lows, tropical lows are less common in Southern
272 Africa than in these other regions.

273 *d. Movement of Synoptic Events*

274 Figure 7 shows the longitudes and timing of grid cells in seven selected years which meet the
275 threshold criteria of heat low and tropical low events. The years displayed in Figure 7 have been
276 chosen to represent a range of ENSO phases. In this instance, the domain has been extended to (11
277 - 19°S, 0 - 55°E) and the classification has been run over six hourly data. Heat lows, shown in red,
278 develop in two longitudinal bands centred on 18 and 22° E, which sometimes merge and rarely
279 move more than 5 degrees. The heat lows appear to be geographically locked and form only over
280 the Angola region. By contrast tropical lows, shown in blue, travel east and west across the African
281 continent. However, these circulation features linger in the region of interest, appearing to become
282 anchored at around 20°E. This is at odds with tropical low-pressure systems observed in Australia
283 and India, which are predominantly transient systems (Hunt et al. (2016), Berry et al. (2011) and
284 Hurley and Boos (2015)). Although a small number of tropical lows form in the Atlantic ocean,
285 they only rarely cross either east or west across the West African coast. This behaviour is reflected
286 across the all the years in the study period from 1979 to 2015 (not shown).

287 In the dry El Niño summer of 2015-2016, the Angola Heat Low lasted well into February (Figure
288 7). Meanwhile, the moist circulation features rarely reached the Angola region at all. By contrast,
289 the wet El Niño summer of 1997-1998 featured numerous semi-stationary tropical lows in the
290 Angola Low region. The extremely wet La Niña summer of 1999-2000 featured a large number of
291 tropical low events tracking across the African continent from December onwards, many of which
292 lingered in the Angola region. Of particular note is ex-Tropical Cyclone Eline, which penetrated
293 mainland Africa in late February after crossing the Indian Ocean and reached 20°S (Reason and
294 Keibel, 2004). However, in the drier La Niña summer of 2010-2011, although tropical low events
295 were identified over southern Africa, none persisted in Angola for over a week. Inspired by these

296 qualitative observations, the next section aims to clarify the inter-annual relationship between the
297 phases of the Angola Low, ENSO and precipitation.

298 **4. Bearing on Precipitation**

299 On an inter-annual time-scale, the Angola Low is believed to have an important connection to
300 regional precipitation across southern Africa (Mulenga, 1998). This may have a modulating impact
301 on the relationship between southern African precipitation and the El Niño Southern Oscillation
302 (ENSO). The El Niño phase of ENSO is typically associated with drought in southern Africa, a
303 result of the shift in the Walker Circulation. The 1982-1983 and 2015-2016 El Niños both occurred
304 in years where the Angola Low was weak, and resulted in severe drought. The 1997-1998 El Niño,
305 however, coincided with a strong Angola Low and a drought was not observed.² The differences
306 between these El Niño summers have been well studied. Reason and Jagadheesha (2005) found
307 that the inter-annual variability of the Angola Low modulates the rainfall impacts of ENSO. Lyon
308 and Mason (2007) confirmed the role of the Angola Low and also found that high sea surface
309 temperatures near Southern Africa and anomalous shifts in Walker circulation all contributed to
310 the increase in precipitation in 1997-1998 as compared to 1982-1983.

311 The separation of the Angola Low into the Angola Heat Low and the Angola Tropical Low adds
312 clarity to its relationship with ENSO and precipitation. An Angola Heat Low Index (AHLI) and
313 an Angola Tropical Low Index (ATLI) have been created by counting the number of days per year
314 when each class of Angola Low has been identified from November to March, and normalising
315 such that the maximum value of the index is 1. The normalised sum of the AHLI and the ATLI is
316 referred to as the Angola Low Index (ALI). It may be expected that the indices are anti-correlated,

²These three summers featured the strongest El Niño events of the study period, with average Niño 3.4 SST indices from November to March respectively 2.15, 2.28 and 2.14. The November - March southern African GPCP precipitation anomaly for the two drought summers was over 1.5 standard deviations below the 1979-2015 mean, while the 1997-1998 precipitation anomaly was within 0.25 standard deviations of the mean.

317 since both indices will be dependent on the date of the transition from the Angola Heat Low to the
318 Angola Tropical Low. If the transition is earlier (later) than normal, then there will be more (fewer)
319 tropical low days and less (more) heat low days. However, we found that this anti-correlation was
320 in fact very weak, with $R=-0.12$.

321 Table 1 shows the results of linear regressions of the ATLI, the AHLI and the ALI onto to the
322 November-March average Niño 3.4 SST index. The AHLI is not dependent on Niño 3.4 SST
323 ($R^2=0.01, p=0.27$). The ATLI has an R^2 coefficient 0.04 ($p=0.029$). However, the regression pa-
324 rameter of the Niño 3.4 SST index switches sign. As a consequence, the ALI does not exhibit a
325 significant dependence on the Niño 3.4 SST index ($R^2=0.04, p=0.30$). This suggests that consider-
326 ing the Angola Heat Low and the Angola Tropical Low as a single feature obscures the relationship
327 between the Angola Low and ENSO.

328 Average GPCP November to March precipitation over southern Africa (south of 15° S) was
329 regressed first against the Niño 3.4 SST index alone, and partial regressions were performed on the
330 residual precipitation against the residual Angola Low indices, with regression statistics displayed
331 in Table 2. Regression statistics of precipitation on the ATLI index alone are also shown. Niño 3.4
332 SST alone was found to explain 52% of the variance ($p<0.001$), and the partial regression onto the
333 ATLI explained a further 27% of the variance ($p=0.001$). However, the partial regression onto the
334 AHLI did not increase variance explained and was not significant at the 0.05 level. This suggests
335 that it is the Angola Tropical Low, and not the Angola Heat Low, which modulates the impact of
336 ENSO on southern African precipitation, and that combining the effects of the Angola Tropical
337 Low and the Angola Heat Low adds noise to this signal ($R^2=0.17, p=0.010$).

338 Figure 8 shows scatter plots of the variables used in the first two regressions described in Table 2,
339 with colours representing the calculated and predicted GPCP precipitation per summer over south-
340 ern Africa. The coloured dots show the GPCP precipitation per summer while the coloured lines

show the predictions based on the respective regressions. The black line indicates the regression of the ATLI on the Niño 3.4 SST index.

Adding the ATLI as a variable in the regression (Figure 8, lower panel) explains the variation among the three strongest El Niño events, in contrast to the ENSO only regression (Figure 8, upper panel). Furthermore, the difference between the strong La Niña summers starting in 1988, 2007 and 1999 is also explained by the inclusion of the ATLI in the regression. Neither regression predicts the precipitation of 1994 and 2005, which both had strong rainfall anomalies but occurred during the neutral ENSO phase and featured moderate tropical low indices.

These regression results imply that the component of the variation in the Angola Low that is independent of ENSO is correlated to the summer mean precipitation across southern Africa. We do not attempt to further examine this correlation here, or make any statements regarding causation or modes of variability. However, we note that future attempts to characterise the modulation of precipitation variability by the Angola Low should take the separation of the Angola Heat Low and the Angola Tropical Low into account.

5. Anchoring Processes

Section 3 demonstrated that the climatological Angola Low is the combined effect of a series of heat lows and tropical lows. The heat lows tend to form and remain exclusively over the Angola Low region. In contrast, tropical lows track across tropical southern Africa, but linger over east Angola. Therefore, tropical lows are more likely to persist in east Angola than elsewhere. If the tropical lows instead tracked away from Angola as quickly as they track towards it, then the climatological depth of the Angola Low would be diminished. Thus, the placement of the Angola Low in the late summer climatology originates from the behaviour of these transient synoptic-scale systems. Throughout the tropics, moist convecting lows are generally transient features and

do not usually exhibit the stationary behaviour of the tropical lows in the Angola Region. This section therefore aims to discover why southern African tropical lows behave in this manner.

An analysis of the vorticity budgets of the Angola Low phases was carried out in order to explain the motion and structure of the lows. Equation 1 shows the vorticity budget in the form that has been studied. Here, ζ is relative vorticity, \mathbf{v} and \mathbf{v}_h are the 3D and 2D velocities respectively, ω is vertical velocity in pressure coordinates and \mathbf{F} is the friction term of the momentum equation. This balance indicates that the possible sources and sinks of vorticity are advection, stretching, twisting and friction. The friction term cannot be directly computed from resolved model variables, and so is represented by a subgrid-scale residual term.

$$\underbrace{\frac{\partial}{\partial t}(\zeta)}_{\text{tendency}} + \underbrace{\mathbf{v} \cdot \nabla(\zeta + f)}_{\text{advection}} + \underbrace{(\zeta + f) \nabla_h \cdot \mathbf{v}_h}_{\text{stretching}} - \underbrace{\hat{k} \cdot \left(\frac{\partial \mathbf{v}}{\partial p} \times \nabla \omega \right)}_{\text{twisting}} - \underbrace{\hat{k} \cdot (\nabla \times \mathbf{F})}_{\text{subgrid-scale/friction}} = 0 \quad (1)$$

Vertical profiles of the terms of the vorticity budget at the centroids of both heat lows (red) and tropical lows (blue) are shown in Figure 9. For both phases of the Angola Low, the largest source term in the budget is the stretching term, and the largest sink term is friction. This implies vorticity is created by the amplification of cyclonic absolute vorticity in a convergent airmass. Convergence may amplify either relative or planetary vorticity, and may be decomposed into two terms, $\zeta \nabla_h \cdot \mathbf{v}_h$ and $f \nabla_h \cdot \mathbf{v}_h$ to reflect this. The majority of this cyclonic acceleration is balanced by an opposing frictional force, but some fraction of it contributes to increasing the cyclonic vorticity of the system.

The dominant role of the stretching term is consistent with the general theory of cyclonic vortices on a rotating plane. A low-pressure anomaly is associated with uplift and convergent inflow, which is rotated by the Coriolis force to create cyclonic vorticity. However, a closer analysis of the

stretching term indicates that a convergent anabatic sea breeze provides a second order source of stretching which may play a role in anchoring tropical lows to the Angola region.

Figure 10 shows the vertical cross-section of the anabatic sea breeze as it crosses the coastline at 11-19°S. From this it is apparent that the anabatic sea breeze initiates at midday and then advects inland. As it crosses the coastline, the anabatic sea breeze rises up the escarpment and continues its trajectory upwards such that its presence is apparent up to 600 hPa. As it approaches the coast and proceeds upwards, the zonal wind strengthens and hence diverges, causing a plume of divergence (coloured red) rising from the ocean. The direction of the wind ensures that this plume is directed upwards and eastwards, and rises up over the plateau. The anabatic sea breeze slows down due to friction directly above the land surface, causing horizontal convergence (coloured blue). This alternating pattern of divergence and convergence, also reflected in vertical and onshore winds, resembles a topographically generated gravity wave. A second trough of convergence is faintly visible at 19:00, centred at around 500 hPa. Throughout the course of the night, the gravity wave is advected inland by its own surface winds, and steadily decays. By 01:00 it is apparent 5° east of the coastline. The anabatic sea breeze is present in the diurnal climatology every month of the year (not shown), although it is strongest in November when the surface heating is greatest. The surface convergence has the capacity to generate vortex stretching, which can invigorate low-pressure systems located in the same region. Meanwhile, the divergence above the boundary layer would generate negative vortex stretching and inhibit the convection.

Figure 11 shows the six hourly climatological surface irrotational winds averaged from November to February. The main feature that is apparent is the westerly anabatic sea breeze blowing across the south west African coastline. The blue colours along the west coast in the left column represent the location of the surface convergence maximum associated with the anabatic sea breeze. The red colours in the right column represent the associated divergence maximum higher

408 in the atmosphere. Both the convergence and divergence zones form bands stretching along the
409 western and southern coastlines, which move inland overnight. By 01:00, two regions of strong
410 convergence remain: one at 16 E, 16 S and the other at 18.5E, 24S. Based on Figure 4, the former
411 is a preferred location of both Angola heat lows and tropical lows. The latter is coincident with the
412 Kalahari Heat Low. The divergence zone in Figure 11 at 19:00 - directly east of the Angola coast
413 - is completely devoid of heat lows and tropical lows in Figure 4. This suggests that the surface
414 convergence and mid-tropospheric divergence of the anabatic sea breeze does indeed influence the
415 placement of the Angola Low in the climatological average.

416 Because the centroids of the Angola lows are variable and the location of the coast is fixed, it
417 is difficult to compare the stretching due to convergent inflow and the anabatic sea breeze in the
418 same reference frame. We solve this problem by compositing lows centred at a fixed distance from
419 the coast. Figures 12 and 13 show cross-sections of longitude against pressure for both stretching
420 terms of the vorticity budget of heat lows and tropical lows respectively at different times of the
421 day. The full vorticity budgets of these composites are shown in the supplementary figures. The
422 first two columns are composited over lows centred 5° of longitude east from the coast, while
423 the lows composited in the second two columns were centred 8° degrees east from the coast.
424 Because the divergence from the anabatic sea breeze travels approximately 6° inland (Figure 11),
425 the anabatic sea breeze may be expected to influence the western set of lows, but not the eastern
426 set. When performing significance testing on these composites, we tested the null hypothesis that
427 each vorticity budget term was equal zero. This means that the alternative hypothesis would imply
428 that a vorticity budget term was a significant source or sink of cyclonic vorticity. This was tested
429 using the Student's t-test, with autocorrelation and false discovery rates controlled for as per the
430 other regressions described in Section 2.

431 In order to unpack the influence of the anabatic sea breeze on the Angola Low, it is useful to
432 consider the influence on the Angola Heat Low and Angola Tropical Low separately. As alluded
433 to in section 3b, the anabatic sea breeze is a fundamental component of the Angola Heat Low.
434 The idealised heat low of Rácz and Smith (1999) featured convergent low-level sea breezes in
435 the afternoon, which were rotated by the Coriolis force into a cyclonic vortex overnight. The sea
436 breezes of Rácz and Smith (1999) originated from all directions. However on a larger continent
437 and in the presence of easterly trade winds, westerly sea breezes dominated (Spengler and Smith,
438 2008). The sea breeze is a consequence of the meso-scale temperature gradient between the hot
439 land surface and the cold ocean to the west. It is therefore a mechanism through which direct
440 thermal heating may be converted into vorticity. The heating of the easterly trade winds as they
441 rise over the plateaus of southern Africa is also expected to play a key role in the formation of the
442 heat lows. However, the sea breeze provides a large component of the convergent inflow which
443 creates cyclonic vorticity through stretching.

444 In our study, the importance of the sea breeze to the heat lows is apparent in Figure 12. At 19:00,
445 the cyclonic vorticity of the heat low is very small and the primary source of vorticity for lows near
446 the coast in the eastern composite is planetary vorticity stretching associated with the sea breeze.
447 By 01:00, this vorticity source has intensified the cyclonic vortex, and relative vorticity stretching
448 has become an important term. By 07:00, the cyclonic vortex is still strong but the stretching terms
449 are both greatly reduced, suggesting that the horizontal convergence has dropped (consistent with
450 Figure 10). At 13:00, the vortex and both stretching terms are both weakened once again. Heat
451 lows located further from the coast in the western composite experience a similar diurnal cycle,
452 however the initial planetary vorticity stretching originates from a different source. Significantly,
453 63% of all heat lows occurred within 5 degrees of the coast.

454 The influence that the anabatic sea breeze has on the Angola Tropical Low is more complicated
455 and requires further investigation. In the eastern composite of Figure 13, the main source of
456 stretching comes from the relative vorticity convergence at 01:00 and 07:00. The signature of the
457 anabatic sea breeze can be seen in the planetary vorticity stretching term, however this influence
458 is limited to within 6 degrees of the coast and does not impact on the cores of the tropical lows.
459 In the western composite of Figure 13, both stretching terms contribute more cyclonic vorticity
460 at the core of the tropical lows. Planetary vorticity stretching carries a strong signature of the
461 anabatic sea breeze and contributes to a vorticity source at the cores of the tropical lows about
462 half as strong as that contributed by relative vorticity stretching. Relative vorticity stretching is
463 stronger in western composite than the eastern composite, which could be due to the anabatic sea
464 breeze influence. Together, these results imply that vorticity stretching due to the convergence of
465 the anabatic sea breeze can be a second order vorticity source for tropical lows centred within 6
466 degrees of the coast.

467 The vorticity sink associated with the divergent tail of the anabatic sea breeze is of similar order
468 of magnitude as the vorticity source terms in every case. This divergence zone may act as a
469 barrier to eastward propagating tropical lows and prevent them from crossing the coast into the
470 Atlantic Ocean. The full vorticity budget of the western composite (see supplementary figures)
471 also indicates that low-level cyclonic vorticity is advected inland from the western coast at 19:00
472 by the anabatic sea breeze. Therefore, the anabatic sea breeze may cause the tropical lows to
473 linger in the Angola region, as can be observed in Figure 7 in section 3. This means that the
474 climatology average contains a larger number of days featuring tropical lows. Therefore, the
475 action of the anabatic sea breeze deepens the Angola Low and intensifies its cyclonic vorticity in
476 the climatological average.

477 **6. Discussion and Conclusions**

478 This paper has shown that the Angola Low can be separated on a synoptic-scale into two distinct
479 phases - the Angola Heat Low and the Angola Tropical Low. It was found that this distinction clar-
480 ifies the link between the Angola Low, the precipitation and ENSO on an inter-annual time-scale.
481 The Angola Tropical Low is stronger during La Niña seasons. However, the relationship between
482 ENSO and the Angola Low Indices was relatively weak and we found that the Angola Low under-
483 goes considerable variability independent of ENSO. A partial linear regression of southern African
484 precipitation on the Niño 3.4 SST index and an Angola Tropical Low Index was found to explain
485 the large variance in precipitation during the three strongest El Niño summers in the study period,
486 two of which were associated with severe droughts while a third experienced average rainfall. This
487 regression also did well at explaining the variance between precipitation during the three strongest
488 La Niña summers in the study period.

489 These regression results suggest that the Angola Tropical Low is important for southern African
490 rainfall. The tropical low events were found to be dynamically similar to monsoon low-pressure
491 systems which form throughout the tropical landmasses. However, the key difference between
492 the southern African tropical lows and those observed elsewhere was their propensity to linger in
493 the Angola region. This semi-stationary behaviour is fundamental to the impact that the Angola
494 Tropical Low has on the climatological Angola Low. While each transient tropical low spends
495 a 2-3 days directly impacting the weather of any given area, a semi-stationary tropical low may
496 impact the weather for several weeks, building up a stronger influence on the seasonal climate.

497 Vorticity budget analysis has demonstrated that an anabatic sea breeze circulation plays an im-
498 portant role in anchoring the tropical lows to the Angola region. The impact of the sea breeze on
499 the tropical lows is secondary to the processes which create the tropical lows and only acts as an

500 anchoring mechanism, rather than a formation mechanism. The anabatic sea breeze was shown
501 to be divergent in the mid-troposphere near the coast and convergent near the surface and fur-
502 ther inland, which enhances the stretching vorticity budget term. This vorticity source strengthens
503 the Angola Low inland and weakens it near the coast, inhibiting eastward tracking tropical lows
504 from crossing the coast. An equivalent point of view is that the uplift of the eastern branch of
505 the anabatic sea breeze enhances the convection of the tropical lows, while the subsidence asso-
506 ciated with the westward branch of the anabatic sea breeze overturning inhibits convection. This
507 overturning circulation can be clearly seen in Figure 10.

508 By considering the synoptic expression of the Angola Low, this paper has revealed the mech-
509 anisms which drive it, namely heat lows, tropical lows and the anabatic sea breeze. This work
510 opens up several avenues of future research. The processes that link the Angola Low to southern
511 African precipitation, such as TTCBs and wet spells, should be studied taking into account the
512 two phases of the Angola Low. A process-based analysis of the Angola Low in CMIP and AMIP
513 models should examine how well the models represent the three mechanisms listed above. These
514 findings will therefore support efforts to reduce uncertainty around future projections of southern
515 African precipitation.

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601 ary layer: Okaukuejo, Namibia, during SAFARI-92. *Journal of Geophysical Research*, **101 (19)**,
602 23 757–23 766.

603	LIST OF TABLES	
604	Table 1.	Regression statistics from the regressions of the annual Angola Tropical Low
605		Index (ATLI), Angola Heat Low index (AHLI) and combined Angola Low In-
606		dex (ALI) on the Niño3.4 SST Index. 31
607	Table 2.	Regression statistics for five regressions of southern African November - Febru-
608		ary southern African GPCP precipitation. (1): precipitation regressed onto
609		ENSO, (2-4): partial regressions of the residual of precipitation onto the resid-
610		uals of the ATLI, the AHLI and the ALI and (5): precipitation regressed onto
611		the ATLI. 32

612 TABLE 1. Regression statistics from the regressions of the annual Angola Tropical Low Index (ATLI), Angola
613 Heat Low index (AHLI) and combined Angola Low Index (ALI) on the Niño3.4 SST Index.

	ATLI	AHLI	ALI
R ²	0.13	0.04	0.03
N	37	37	37
Constant Coefficient	0.48	0.45	0.54
Constant Standard Error	0.04	0.03	0.03
Constant Coefficient P Value	<0.001	<0.001	<0.001
Niño 3.4 SST Coefficient	-0.08	0.03	-0.03
Niño 3.4 SST Standard Error	0.04	0.03	0.03
Niño 3.4 SST P Value	0.029	0.265	0.299

614 TABLE 2. Regression statistics for five regressions of southern African November - February southern African
615 GPCP precipitation. (1): precipitation regressed onto ENSO, (2-4): partial regressions of the residual of precip-
616 itation onto the residuals of the ATLI, the AHLI and the ALI and (5): precipitation regressed onto the ATLI.

	Niño 3.4 Only	ATLI+Niño 3.4	AHLI+Niño 3.4	ALI+Niño 3.4	ATLI Only
R ²	0.52	0.27	0.00	0.17	0.36
N	37	37	37	37	37
Variable	ENSO	ATLI	AHLI	ALI	ATLI
Partial Regression?	No	Yes	Yes	Yes	No
Constant Coefficient	17.30	N/A	N/A	N/A	14.29
Constant Standard Error	0.29	N/A	N/A	N/A	0.75
Constant Coefficient P Value	<0.001	N/A	N/A	N/A	<0.001
Variable Coefficient	-1.72	4.05	0.01	4.32	6.21
Variable Standard Error	0.28	1.10	1.55	1.59	1.41
Variable P Value	<0.001	<0.001	0.997	0.010	<0.001

LIST OF FIGURES

- Fig. 1.** Mean geopotential height (filled contours) and winds (vectors) at 800 hPa over southern Africa over the months of December, January and February from 1979 to 2015. The Angola Low is visible as a low-pressure system featuring cyclonic circulation centred at 13°S and 20°E. The red box indicates the primary region of interest for this study. 35
- Fig. 2.** Log-scaled phase space heatmaps of relative vorticity, stability and humidity in the Angola Low region on days featuring cyclonic relative vorticity exceeding $4 \times 10^{-5} \text{s}^{-1}$. Top: 800 hPa Relative Vorticity against 700 hPa stability, and bottom: 800 hPa specific humidity against 700 hPa stability. Blue areas show tropical low grid cells, while red areas show heat low grid cells. 36
- Fig. 3.** Vertical profiles of relative vorticity (left, first row), divergence (right, first row), potential temperature (left, second row), potential vorticity (right, second row), equivalent potential temperature (left, third row), potential temperature lapse rate (right, third row), vertical velocity (left, fourth row), and specific humidity (right, fourth row) during Angola Low events. Heat low profiles are shown in red and tropical low profiles are blue. Solid lines indicate the median value of the distributions, while the coloured bands represent one standard deviation either side of the median. 37
- Fig. 4.** Monthly heat map histograms of the locations where cyclonic circulations ($\zeta < -4 \times 10^{-5} \text{s}^{-1}$) with neutral and unstable dry static stability have been identified in each month. The panels show monthly occurrences of neutrally stratified cyclones with $\frac{\partial\theta}{\partial z} < 0.0033 \text{Km}^{-1}$ at 700 hPa (left column) and stably stratified cyclones with $\frac{\partial\theta}{\partial z} > 0.0033 \text{Km}^{-1}$ at 700 hPa (right column). The colour-scale represents the average number of events occurring at each grid point in a given year. 38
- Fig. 5.** Composite west-east cross-sections with height of zonal wind (left column), meridional wind (centre) and potential temperature (right column) for heat low events (see text for definitions) at 01:00 (top row), 07:00 (second row), 13:00 (third row) and 19:00 (fourth row). Stippling shows the statistically significant points using a threshold of $p_{FDR}^* = 0.037$ 39
- Fig. 6.** Composite vertical west-east cross-sections with height of zonal wind (top left), meridional wind (top right), relative vorticity (centre left), divergence (centre right), potential vorticity (bottom left), and temperature anomaly (bottom right) for tropical low events (see text for definitions). Stippling shows the statistically significant points using a threshold $p_{FDR}^* = 0.040$ 40
- Fig. 7.** Top row: Longitude - time plots of the locations where cyclonic circulations ($\zeta < -4 \times 10^{-5} \text{s}^{-1}$) have been identified in selected years between 11 and 18°S. Red dots: Neutrally stratified with $\frac{\partial\theta}{\partial z} < 0.0033 \text{Km}^{-1}$ at 700 hPa, Blue dots: stably stratified with $\frac{\partial\theta}{\partial z} > 0.0033 \text{Km}^{-1}$ at 700 hPa. Colour intensity represents cyclonic vorticity. Years shown are, from left to right, 1992-1993, 1997-1998, 1999-2000, 2002-2003, 2008-2009, 2010-2011 and 2015-2016. The bottom row shows a map of southern Africa with the domain of the above panel coloured in grey and is provided for context. 41
- Fig. 8.** Scatter plots of November - March Niño 3.4 SST index and ATLI. Point colours represent GPCC precipitation over African mainland south of 15°. Line colours represent (top) precipitation predicted by the Niño 3.4 SST index only regression (column 1 of Table 2) and (bottom) precipitation predicted by the Niño 3.4 SST and ATLI regression (column 2 of Table 2). The black line shows the predicted ATLI for each value of the Niño 3.4 SST index

661	(column 1 of Table 1). Labels indicate the year in which each season starts, e.g. 99 for	
662	1999-2000.	42
663	Fig. 9. Vertical profiles of vorticity budget terms during Angola Low events. Red: heat lows, Blue:	
664	tropical lows. The solid line indicates the composite mean, and the coloured regions repre-	
665	sent one standard deviation either side of the mean. The vorticity budget terms are labelled	
666	as per Equation 1, and the subgrid-scale term represents friction.	43
667	Fig. 10. November-February climatology diurnal winds and horizontal divergence across the Angola	
668	Coast at 11-19°S. Vectors show zonal and vertical winds, red colours divergence and blue	
669	colours convergence. The times of the day for each panel are: 01:00 (top left), 07:00 (top	
670	right), 13:00 (bottom left) and 19:00 (bottom right). The x -axis is degrees of longitude East	
671	of the coastline.	44
672	Fig. 11. Irrotational component of diurnal surface winds in the November to February climatology	
673	with column maximum convergence (left) and divergence (right) across southern Africa.	
674	The times of the day for each panel are: 13:00 (first row), 19:00 (second row), 01:00 (third	
675	row) and 07:00 (fourth row).	45
676	Fig. 12. Vertical cross-sections of vorticity budget stretching terms at time 01:00 (first row), 07:00	
677	(second row), 13:00 (third row), and 17:00 (fourth row). The first and third columns show	
678	stretching of relative vorticity, and the second and fourth columns show stretching of plan-	
679	etary vorticity. The first two columns show composites of heat low events located 5 degrees	
680	from the coast, while the second two show heat low events located 8 degrees from the coast.	
681	The cross-section is taken across the latitude of the vortex centres. The x -axis is °E of the	
682	coast. Black contours indicate the cyclonic vorticity ($2 \times 10^{-5} \text{ s}^{-1}$ contour interval). Stip-	
683	pling shows the statistically significant grid points, determined based on a threshold $p_{FDR}^* =$	
684	0.027.	46
685	Fig. 13. Vertical cross-sections of vorticity budget stretching terms at time 01:00 (first row), 07:00	
686	(second row), 13:00 (third row), and 17:00 (fourth row). The first and third columns show	
687	stretching of relative vorticity, and the second and fourth columns show stretching of plan-	
688	etary vorticity. The first two columns show composites of tropical low events located 5	
689	degrees from the coast, while the second two show tropical low events located 8 degrees	
690	from the coast. The cross-section is taken across the latitude of the vortex centres. The	
691	x -axis is °E of the coast. Black contours indicate the cyclonic vorticity ($2 \times 10^{-5} \text{ s}^{-1}$ con-	
692	tour interval). Stippling shows the statistically significant grid points, determined based on	
693	a threshold $p_{FDR}^* = 0.020$	47

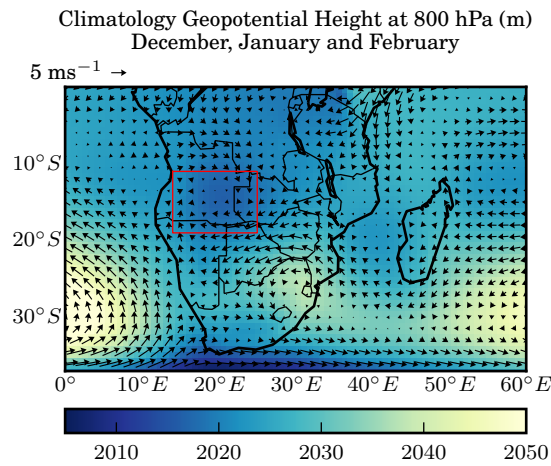


FIG. 1. Mean geopotential height (filled contours) and winds (vectors) at 800 hPa over southern Africa over the months of December, January and February from 1979 to 2015. The Angola Low is visible as a low-pressure system featuring cyclonic circulation centred at 13°S and 20°E. The red box indicates the primary region of interest for this study.

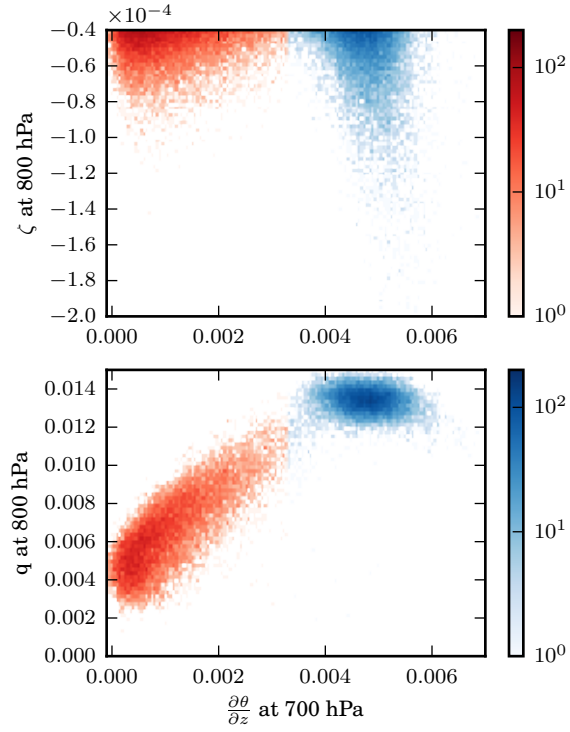


FIG. 2. Log-scaled phase space heatmaps of relative vorticity, stability and humidity in the Angola Low region on days featuring cyclonic relative vorticity exceeding $4 \times 10^{-5} \text{s}^{-1}$. Top: 800 hPa Relative Vorticity against 700 hPa stability, and bottom: 800 hPa specific humidity against 700 hPa stability. Blue areas show tropical low grid cells, while red areas show heat low grid cells.

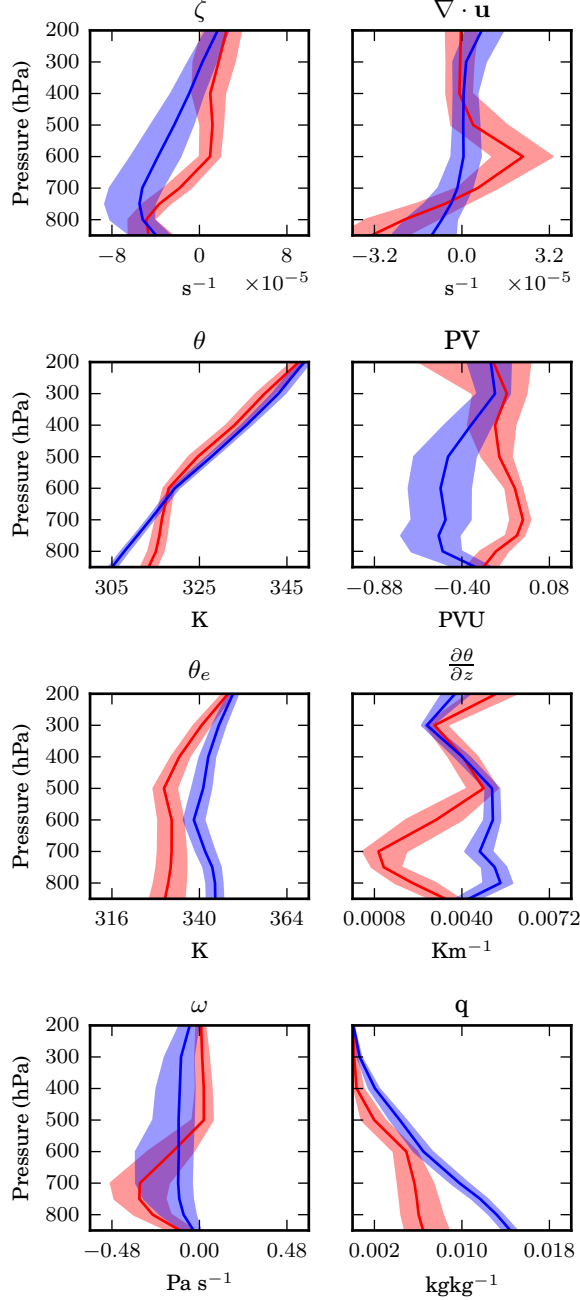


FIG. 3. Vertical profiles of relative vorticity (left, first row), divergence (right, first row), potential temperature (left, second row), potential vorticity (right, second row), equivalent potential temperature (left, third row), potential temperature lapse rate (right, third row), vertical velocity (left, fourth row), and specific humidity (right, fourth row) during Angola Low events. Heat low profiles are shown in red and tropical low profiles are blue. Solid lines indicate the median value of the distributions, while the coloured bands represent one standard deviation either side of the median.

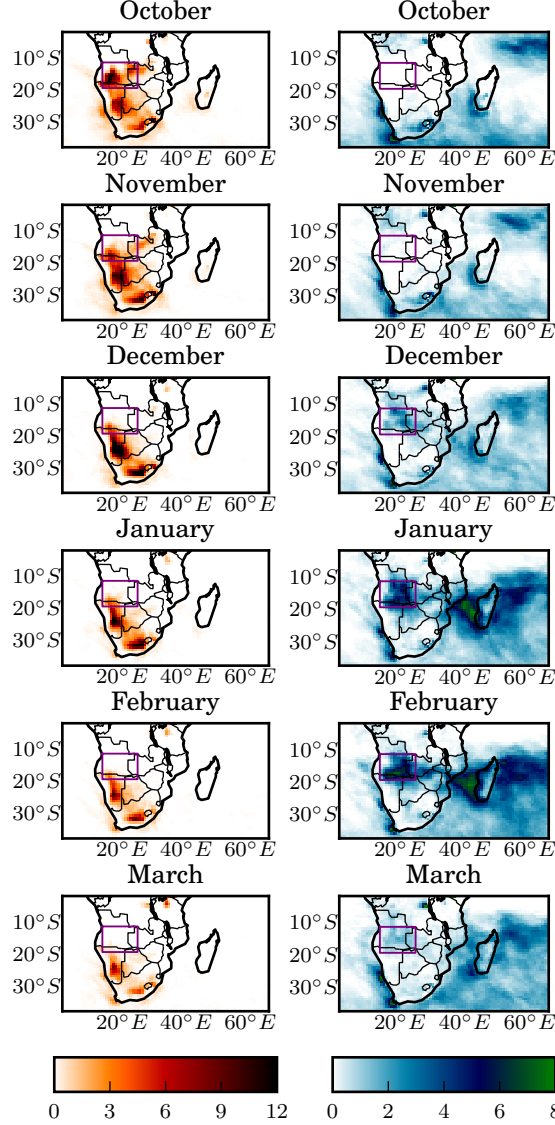


FIG. 4. Monthly heat map histograms of the locations where cyclonic circulations ($\zeta < -4 \times 10^{-5} \text{ s}^{-1}$) with neutral and unstable dry static stability have been identified in each month. The panels show monthly occurrences of neutrally stratified cyclones with $\frac{\partial\theta}{\partial z} < 0.0033 \text{ Km}^{-1}$ at 700 hPa (left column) and stably stratified cyclones with $\frac{\partial\theta}{\partial z} > 0.0033 \text{ Km}^{-1}$ at 700 hPa (right column). The colour-scale represents the average number of events occurring at each grid point in a given year.

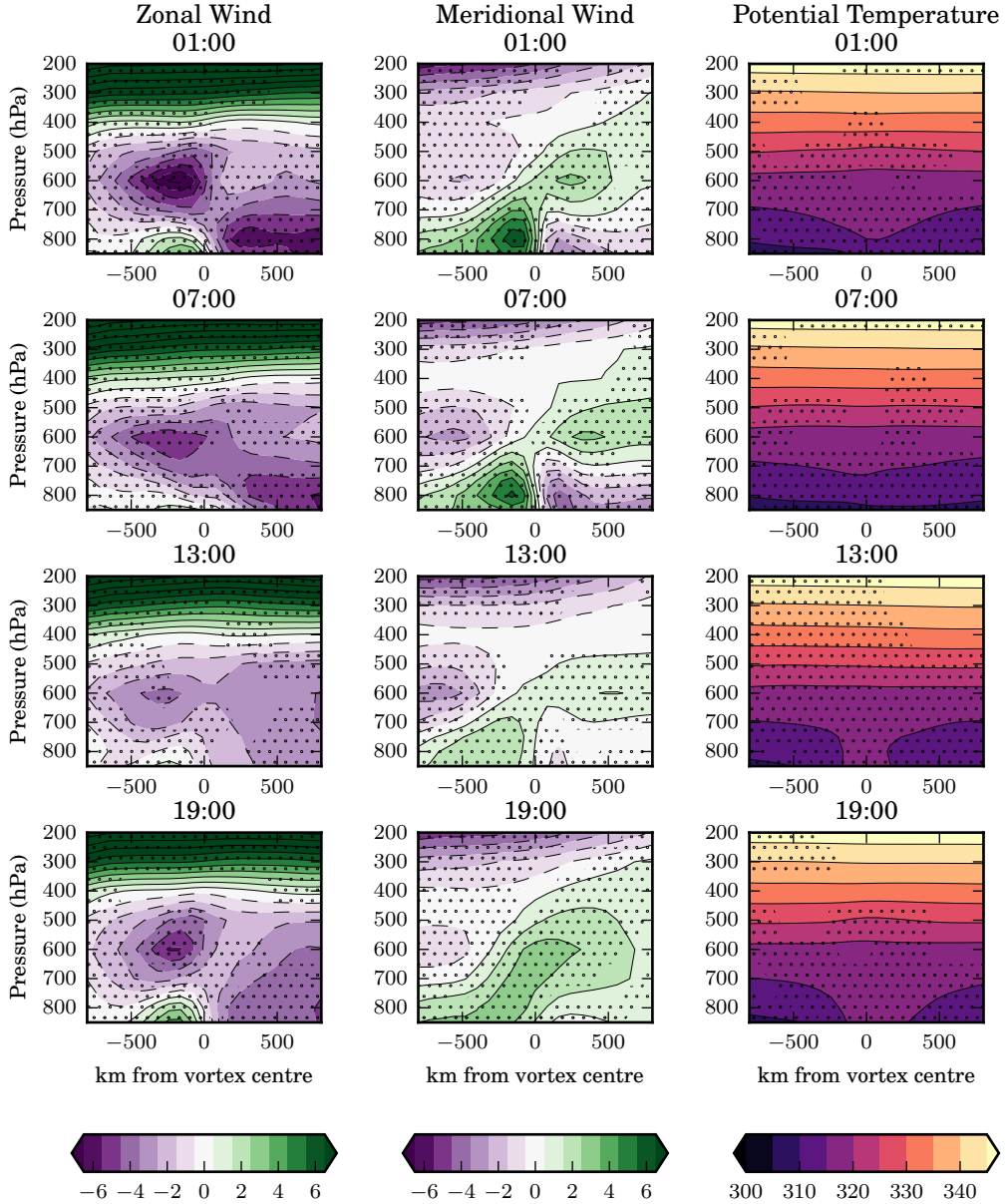


FIG. 5. Composite west-east cross-sections with height of zonal wind (left column), meridional wind (centre) and potential temperature (right column) for heat low events (see text for definitions) at 01:00 (top row), 07:00 (second row), 13:00 (third row) and 19:00 (fourth row). Stippling shows the statistically significant points using a threshold of $p_{FDR}^* = 0.037$.

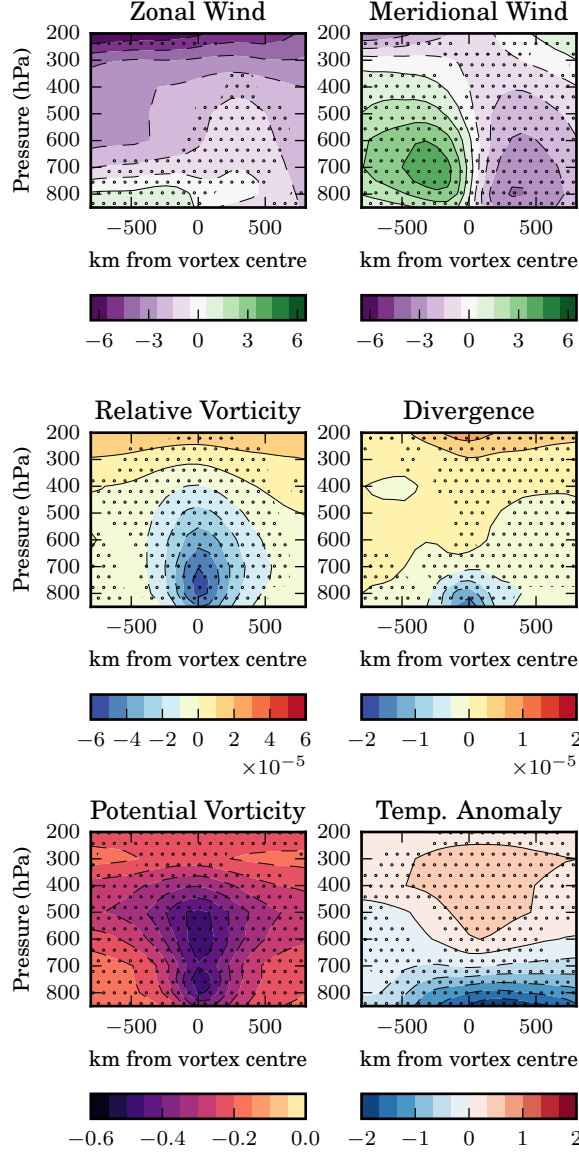


FIG. 6. Composite vertical west-east cross-sections with height of zonal wind (top left), meridional wind (top right), relative vorticity (centre left), divergence (centre right), potential vorticity (bottom left), and temperature anomaly (bottom right) for tropical low events (see text for definitions). Stippling shows the statistically significant points using a threshold $p_{FDR}^* = 0.040$.

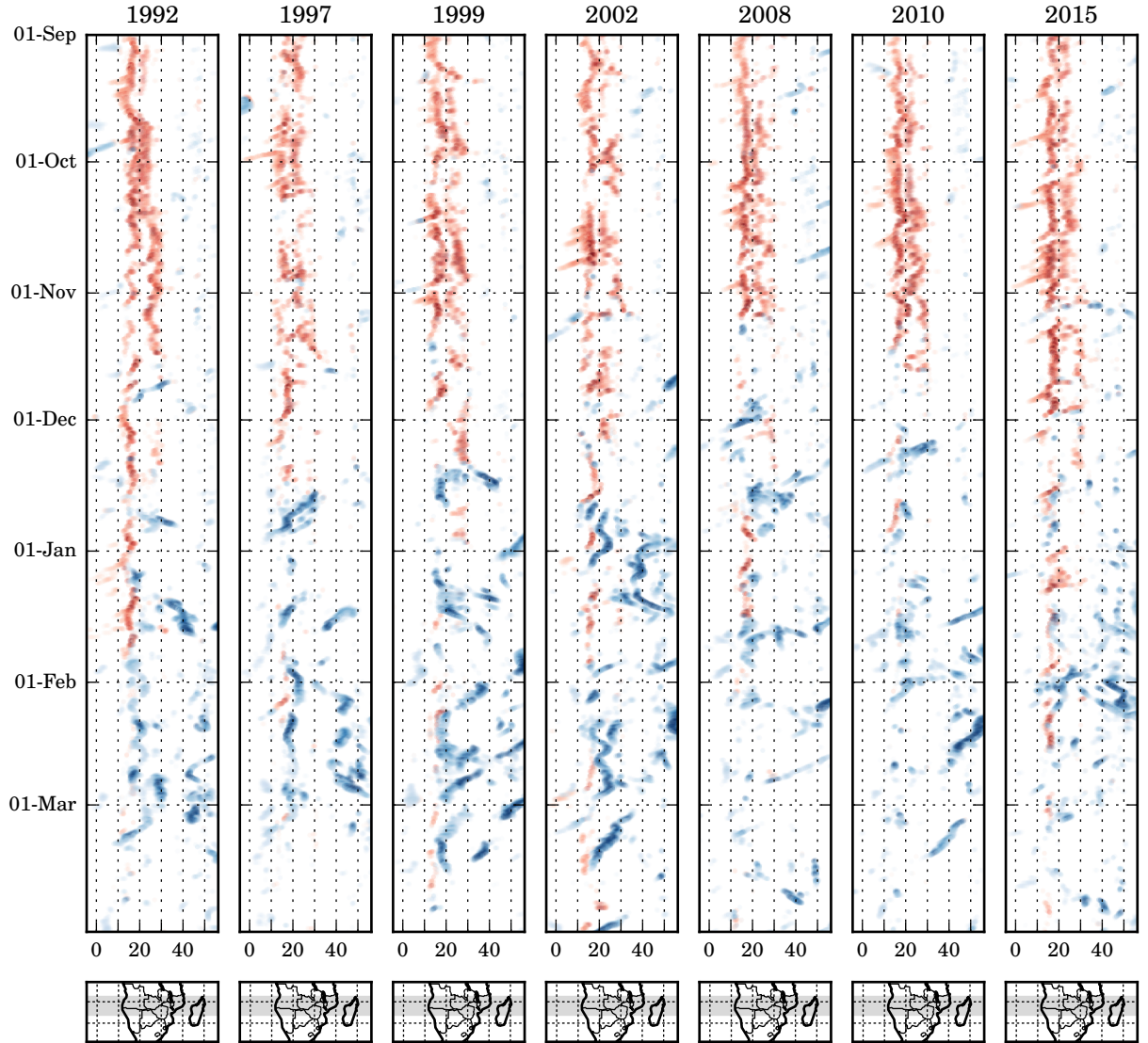


FIG. 7. Top row: Longitude - time plots of the locations where cyclonic circulations ($\zeta < -4 \times 10^{-5} \text{ s}^{-1}$) have been identified in selected years between 11 and 18°S. Red dots: Neutrally stratified with $\frac{\partial\theta}{\partial z} < 0.0033 \text{ Km}^{-1}$ at 700 hPa, Blue dots: stably stratified with $\frac{\partial\theta}{\partial z} > 0.0033 \text{ Km}^{-1}$ at 700 hPa. Colour intensity represents cyclonic vorticity. Years shown are, from left to right, 1992-1993, 1997-1998, 1999-2000, 2002-2003, 2008-2009, 2010-2011 and 2015-2016. The bottom row shows a map of southern Africa with the domain of the above panel coloured in grey and is provided for context.

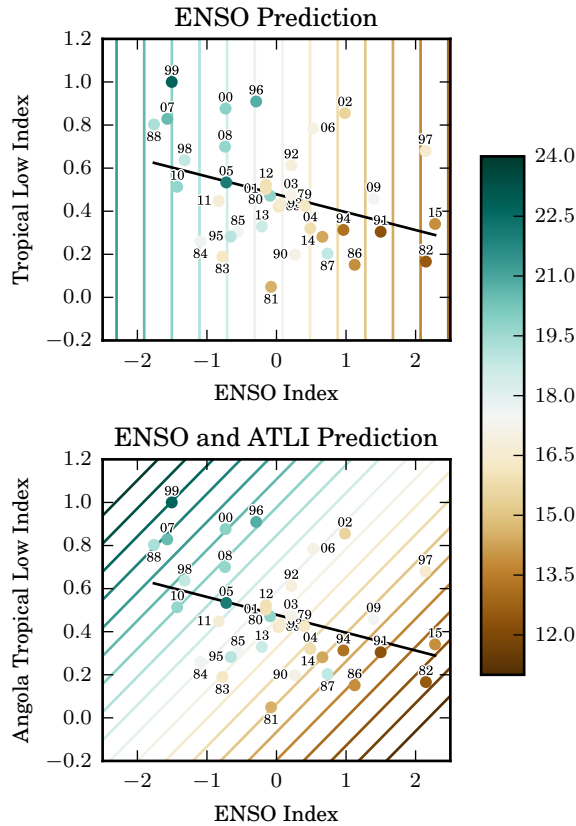
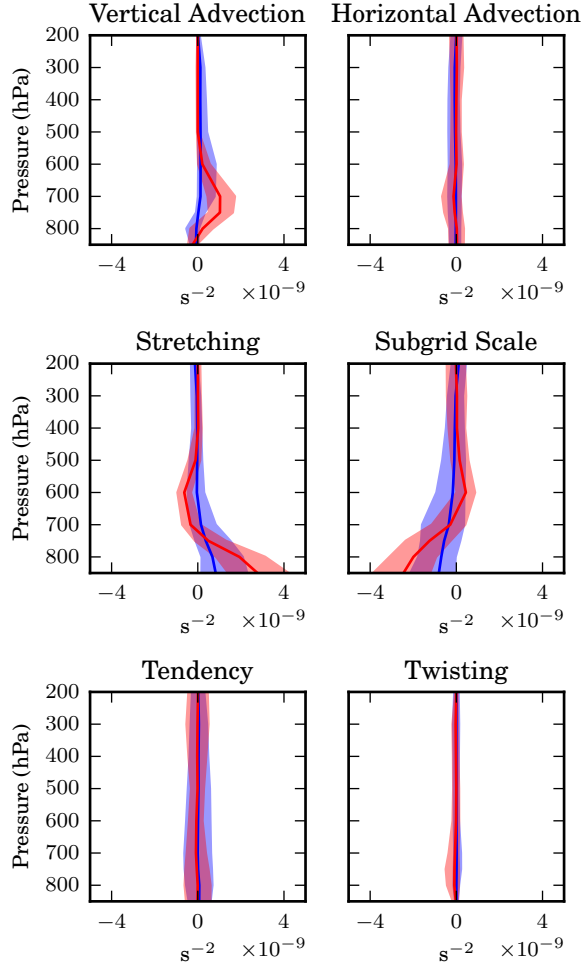


FIG. 8. Scatter plots of November - March Niño 3.4 SST index and ATLI. Point colours represent GPCC precipitation over African mainland south of 15°. Line colours represent (top) precipitation predicted by the Niño 3.4 SST index only regression (column 1 of Table 2) and (bottom) precipitation predicted by the Niño 3.4 SST and ATLI regression (column 2 of Table 2). The black line shows the predicted ATLI for each value of the Niño 3.4 SST index (column 1 of Table 1). Labels indicate the year in which each season starts, e.g. 99 for 1999-2000.



733 FIG. 9. Vertical profiles of vorticity budget terms during Angola Low events. Red: heat lows, Blue: tropical
 734 lows. The solid line indicates the composite mean, and the coloured regions represent one standard deviation
 735 either side of the mean. The vorticity budget terms are labelled as per Equation 1, and the subgrid-scale term
 736 represents friction.

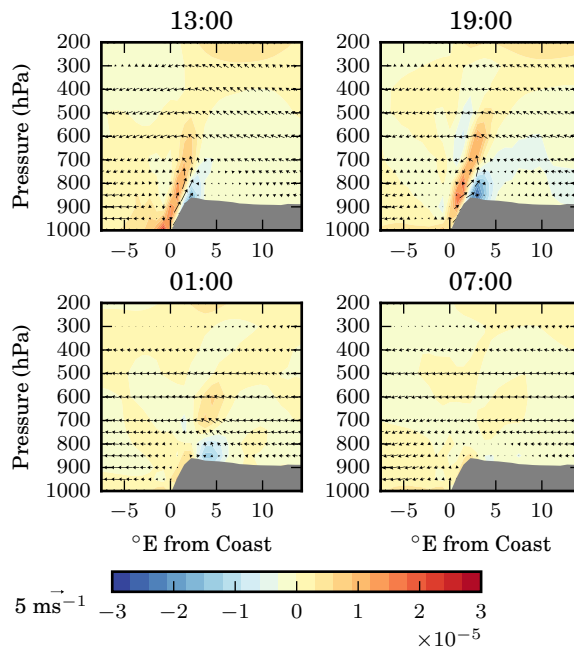


FIG. 10. November-February climatology diurnal winds and horizontal divergence across the Angola Coast at 11-19°S. Vectors show zonal and vertical winds, red colours divergence and blue colours convergence. The times of the day for each panel are: 01:00 (top left), 07:00 (top right), 13:00 (bottom left) and 19:00 (bottom right). The x-axis is degrees of longitude East of the coastline.

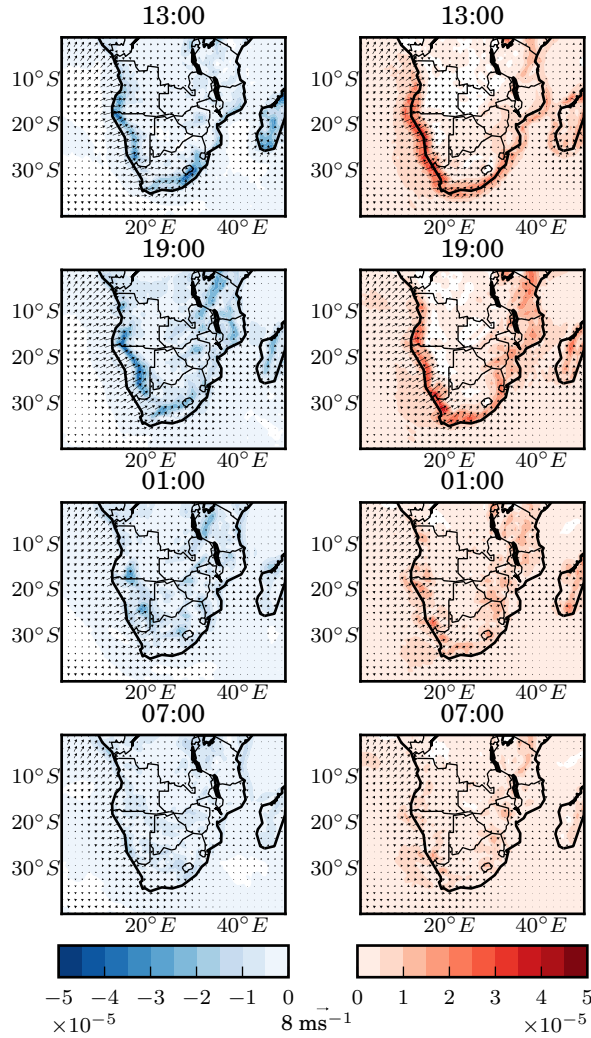


FIG. 11. Irrotational component of diurnal surface winds in the November to February climatology with column maximum convergence (left) and divergence (right) across southern Africa. The times of the day for each panel are: 13:00 (first row), 19:00 (second row), 01:00 (third row) and 07:00 (fourth row).

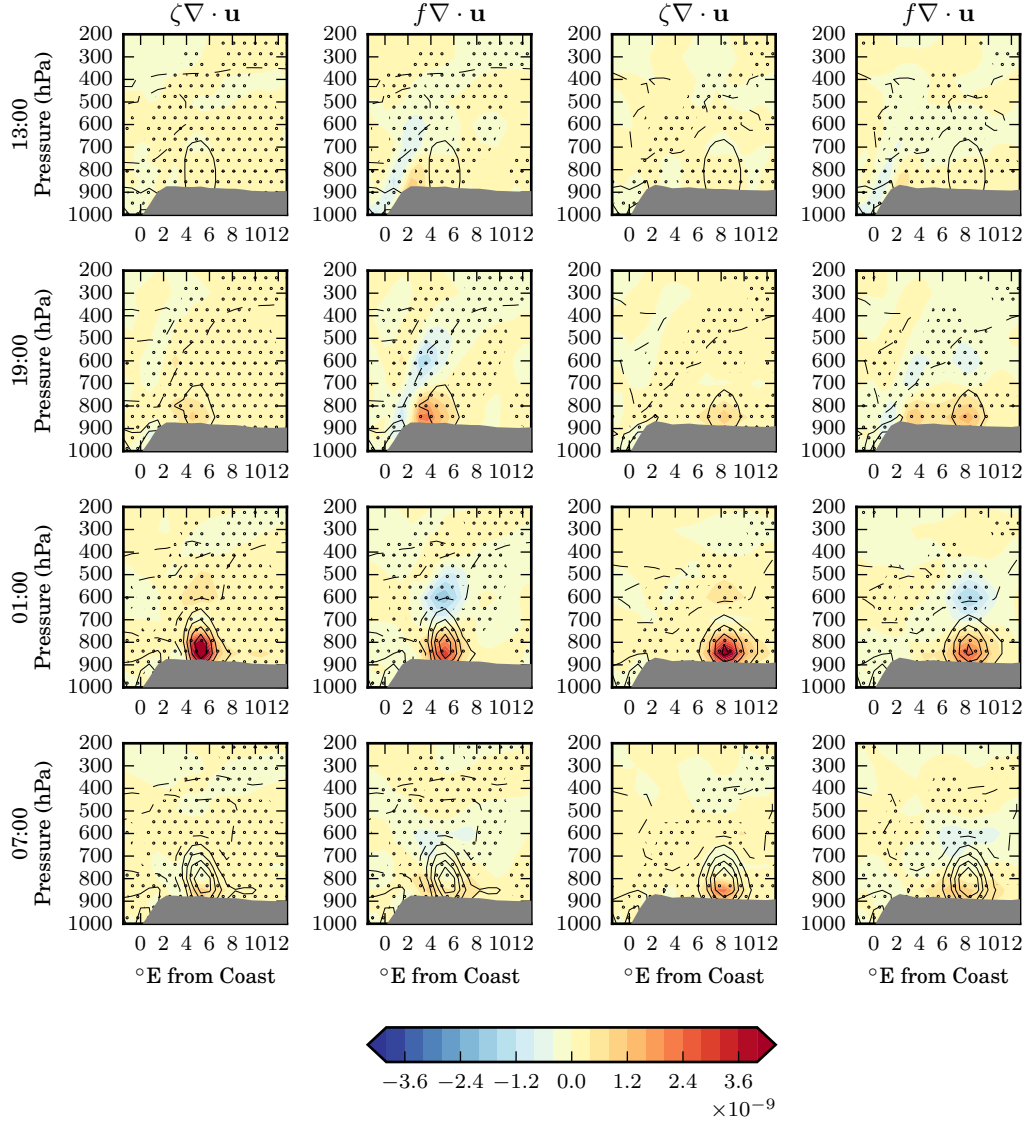


FIG. 12. Vertical cross-sections of vorticity budget stretching terms at time 01:00 (first row), 07:00 (second row), 13:00 (third row), and 17:00 (fourth row). The first and third columns show stretching of relative vorticity, and the second and fourth columns show stretching of planetary vorticity. The first two columns show composites of heat low events located 5 degrees from the coast, while the second two show heat low events located 8 degrees from the coast. The cross-section is taken across the latitude of the vortex centres. The x -axis is °E of the coast. Black contours indicate the cyclonic vorticity ($2 \times 10^{-5} \text{ s}^{-1}$ contour interval). Stippling shows the statistically significant grid points, determined based on a threshold $p_{FDR}^* = 0.027$.

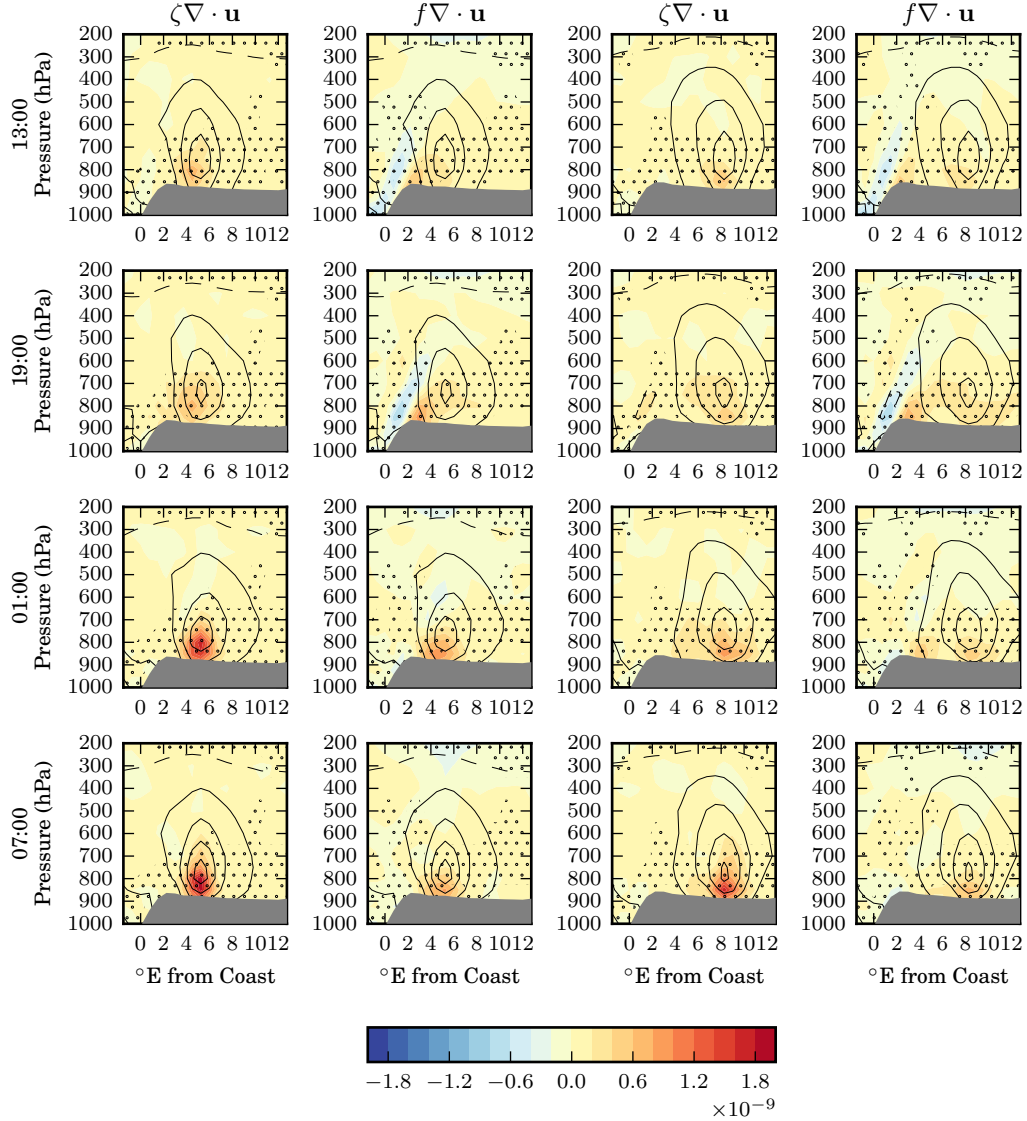


FIG. 13. Vertical cross-sections of vorticity budget stretching terms at time 01:00 (first row), 07:00 (second row), 13:00 (third row), and 17:00 (fourth row). The first and third columns show stretching of relative vorticity, and the second and fourth columns show stretching of planetary vorticity. The first two columns show composites of tropical low events located 5 degrees from the coast, while the second two show tropical low events located 8 degrees from the coast. The cross-section is taken across the latitude of the vortex centres. The x -axis is $^{\circ}\text{E}$ of the coast. Black contours indicate the cyclonic vorticity ($2 \times 10^{-5} \text{ s}^{-1}$ contour interval). Stippling shows the statistically significant grid points, determined based on a threshold $p_{FDR}^* = 0.020$.