



RESEARCH ARTICLE

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Key Points:

- The seasonal cycle of the Angola Low involves a transition from a heat low in austral spring to a tropical low in austral summer
- During summer 40–60% of the variability in coupled model rainfall is associated with the simulated strength of the Angola Low
- Climate models with a stronger Angola Low simulate enhanced northerly moisture flux and an increased rate of moisture convergence

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Circulation controls on southern African precipitation in coupled models: The role of the Angola Low

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Abstract In southern Africa, models from the latest Coupled Model Intercomparison Project produce a wide variety of rainfall climatologies. Differences between models in rainfall amount reach 70% in the rainy season (December–February; DJF), and the median model overestimates rainfall by between 15 and 40% throughout the annual cycle. This paper investigates the role of an understudied regional circulation feature, the Angola Low, in differentiating between model estimates of precipitation. In austral spring, the Angola Low is a heat low, driven by strong surface heating whereas in DJF it is more similar to a tropical low and is associated with moist instability. In the austral summer, we find that the simulated strength of the Angola Low is associated with between 40 and 60% of the intermodel variability in model mean rainfall across the subcontinent. The relationship is particularly strong along a northwest, southeast axis aligned from Angola down to the Mozambican Channel. Along this axis, models with stronger Angola Lows simulate enhanced, by up to $50 \text{ g kg}^{-1} \text{ ms}^{-1}$, northeasterly and northwesterly moisture transport. The enhanced southward moisture flux in models with relatively deep Angola Lows increases the rate of moisture convergence in central areas of the subcontinent and reduces moisture divergence across the Mozambican coast. The results highlight the need to better understand the links between the Angola Low and southern African rainfall and suggest that improving the simulation of the Angola Low can help to constrain model estimates of southern African rainfall.

1. Introduction

Southern Africa is characterized by a tight coupling between climate and society [Conway *et al.*, 2015]. Rain-fed agriculture supports a large proportion of the regional economy and rainfall-sensitive hydroelectric sources sustain energy production in a number of countries including Zambia [World Bank, 2014]. Understanding how the magnitude and distribution of rainfall will change in response to increasing atmospheric greenhouse gases is therefore important. However, southern Africa's climate system is complex and is driven by a complicated mix of global, local, tropical, and temperate climate processes [Reason *et al.*, 2006]. This presents a stern test for the coupled climate models which are critical to projections of future change and variability. The reliability of these models must be evaluated if we are to provide useful climate information for adaptation purposes.

Model evaluation studies in southern Africa have uncovered large differences between climate models, especially in their estimates of historical rainfall [Hewitson and Crane, 2006; Christensen *et al.*, 2007; Nikulin *et al.*, 2012; Kalognomou *et al.*, 2013; Dieppois *et al.*, 2015]. While models reproduce the annual cycle of rainfall well, there is a large spread between ensemble members in rainfall amount (Figure 1). The spread is particularly severe in austral summer (December–February; DJF), the main rainy season, when the wettest model simulates 70% more rain than the driest model (difference of 2 mm d^{-1} ; Table 1). Moreover, the median model simulates between 15 and 40% more rainfall throughout the annual cycle compared to satellite and rain gauge data sets (Figure 1), with the largest absolute differences occurring in the summer season ($\sim 0.6 \text{ mm d}^{-1}$). The pattern of the rainfall biases is also remarkably consistent amongst models and reanalyses (Figure 2). For most models the largest biases, of between 6 and 12 mm d^{-1} , are concentrated in central and eastern areas with some models exhibiting a dipole structure of increased rainfall over the subcontinent and reduced rainfall over Madagascar. This is worrying given the extensive use of Coupled Model Intercomparison Project (CMIP5) models for projecting future regional climate change, not least because the circulation is partly driven by the diabatic heating associated with the rainfall process.

The large variation in model rainfall during austral summer presents an opportunity to explore the regional circulation controls underlying model rainfall climatology. One potential control is the model simulation of the Angola Low (AL), a cyclonic feature which forms during the austral summer. Variation in the strength

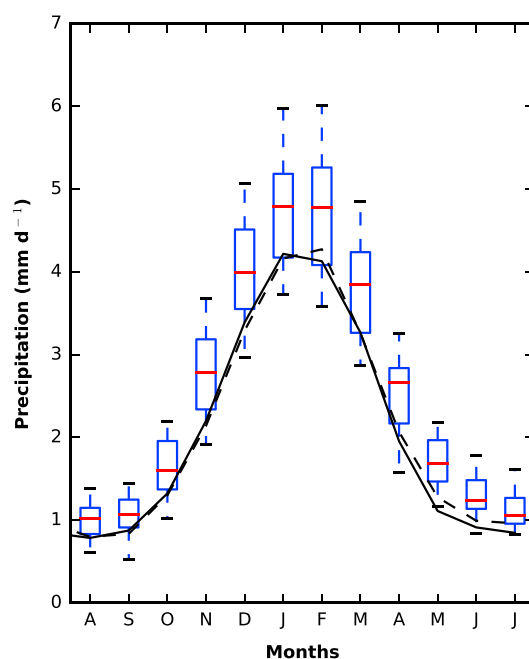


Figure 1. Mean (1979–2005) annual cycle of southern African rainfall (averaged over 10–52°E, 10–35°S) in CMIP5 models (box plots) compared to CMAP (dashed line) and GPCP (solid line). The red lines show the median model for each month, the box encompasses the interquartile range of models, and the tails represent the full range.

of the low has been shown to distinguish between wet and dry years in the interannual record [e.g., Cook *et al.*, 2004] and is also important for synoptic weather events [e.g., Hart *et al.*, 2010]. In this paper, we aim to evaluate the representation of this feature in the CMIP5 ensemble, to determine whether inter-model differences in its simulation are associated with the spread of rainfall in the CMIP5 ensemble.

Despite its importance, the mean state and seasonal cycle of the Angola Low remains poorly understood. Some studies refer to the Angola Low as a heat low, while others treat it like a tropical low in analysis. The first aim of this paper is therefore to better understand the climatological structure and seasonal cycle of the Angola Low. The rest of the paper focuses more specifically on the CMIP5 ensemble and will answer the following three questions:

1. What is the climatological structure of the Angola Low during DJF in reanalyses and models?

Table 1. CMIP5 Models and Reference Satellite/Rain-Gauge Data Sets Used in This Study^a

Data Set	Institution	Mean DJF Precipitation (mm d^{-1}) (10–52°E, 10–35°S)
CMCC-CM	Centro Euro-Mediterraneo sui Cambiamenti Climatici	3.55
bcc-csm1-m	Beijing Climate Centre	3.82
GISS-E2-H	Goddard Institute for Space Studies	3.85
GPCP	Mesoscale Atmospheric Processes Laboratory, NASA	3.91
CMAP	Climate Prediction Centre (CPC), National Oceanic and Atmospheric Administration	3.92
CMCC-CESM	See CMCC-CM	4.05
FGOALS-g2	State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics	4.16
MRI-ESM1	Japan Meteorological Agency	4.19
CanESM2	Canadian Centre for Modelling and Analysis	4.27
MIROC-ESM	National Institute for Environmental Studies (Japan), Atmosphere and Ocean Research Institute (University of Tokyo), Japan Agency for Marine-Earth Science and Technology	4.37
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace	4.71
IPSL-CM5B-LR	See IPSL-CM5A-MR	4.87
MPI-ESM-MR	Max Planck Institute for Meteorology	4.91
HadGEM2-ES	Met Office Hadley Centre	4.92
CNRM-CM5-2	Centre National de Recherches Météorologiques	4.96
CESM1-CAM5	National Centre for Atmospheric Research	5.01
CESM1-BGC	See CESM1-CAM5	5.17
BNU-ESM	Beijing Normal University	5.26
NorESM1-M	Norwegian Climate Centre	5.26
GFDL-CM3	Geophysical Fluid Dynamics Laboratory	5.39
ACCESS1-3	The Centre for Australian Weather and Climate Research	5.45
MIROC5	See MIROC-ESM	5.80
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	5.95

^aData sets are ordered from dry to wet according to mean December–February (DJF) precipitation. Reference data sets are shown in bold.

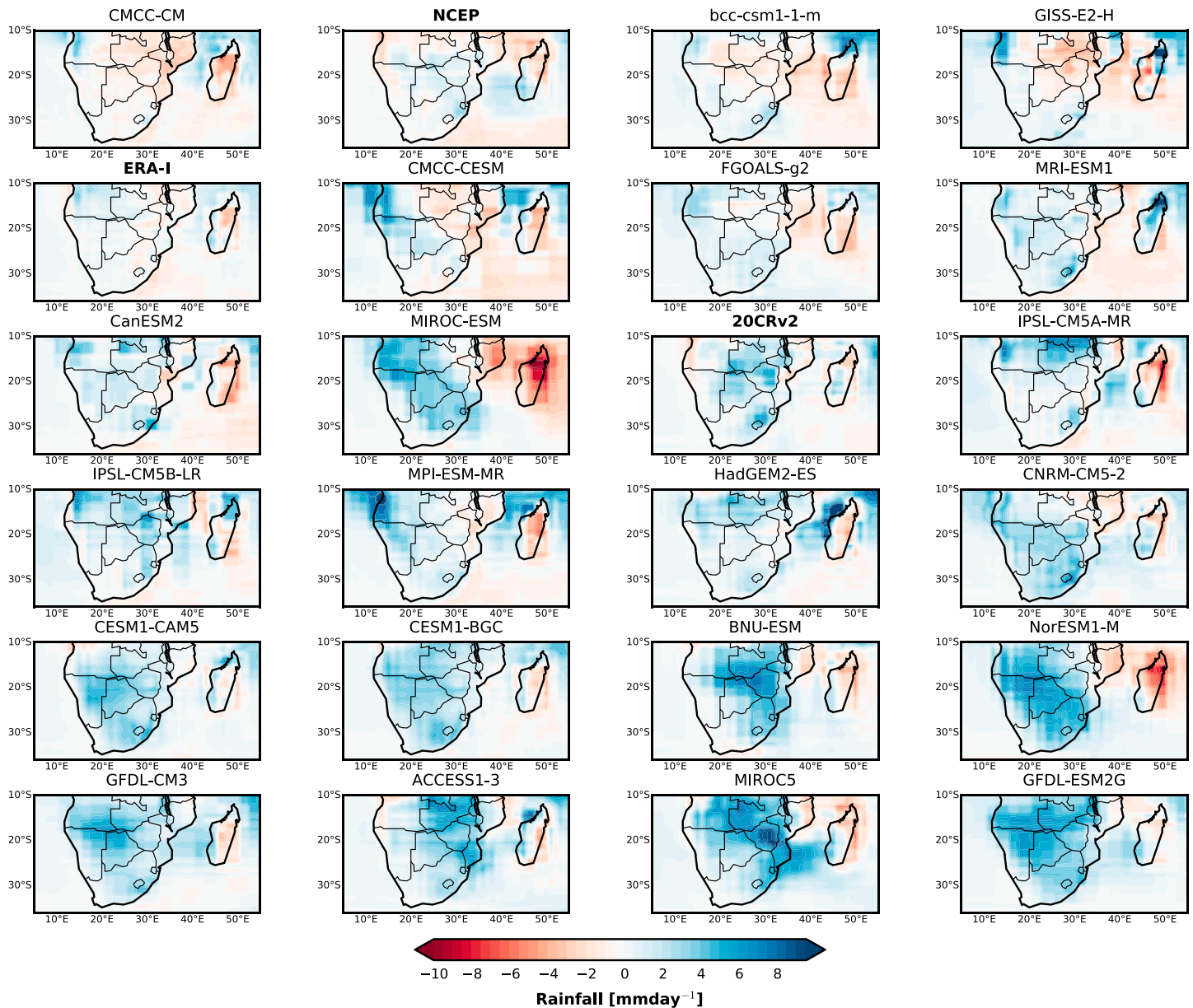


Figure 2. Mean rainfall (1979–2005) in CMIP5 models minus satellite-rain gauge estimates. Satellite rain gauge estimates are a mean of GPCP and CMAP climatology.

2. Is the intermodel variability in the strength of the Angola Low related to variation in model rainfall?
3. Are there differences in moisture circulation patterns between models with relatively strong and weak Angola Lows?

The paper is organized as follows: we provide background on the Angola Low and outline the data sets used in the following two sections. Section 4 presents a characterization of the mean state and seasonal cycle of Angola Low based on reanalyses data, and section 5 examines the simulation of the Angola Low in CMIP5 models. In section 6 we evaluate the relationship between model simulation of the Angola Low and rainfall before investigating the relationship between the strength of the Angola Low and moisture flux patterns in section 7. We discuss results and conclude in section 8.

2. Background: The Angola Low

The Angola Low is a low-pressure system which forms in the plateau region to the east of the Angolan and Namibian highlands (Figure 3). While a number of studies have looked at the variation of the Angola Low on

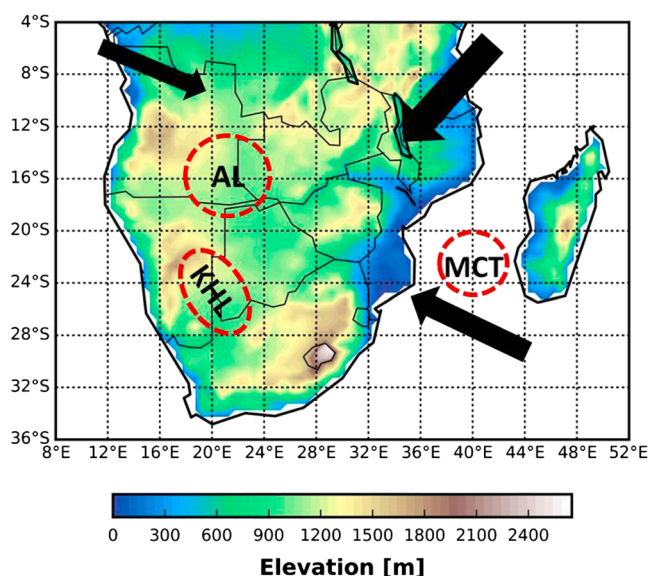


Figure 3. Topography (shaded) and key features of southern African climate during December–February. Black arrows denote key moisture transport pathways. Red dashed circles represent low-level cyclonic circulation; Angolan Low (AL), Kalahari heat low (KHL), and Mozambique Channel trough (MCT). Topography data are from USGS GTOPO30 global digital elevation model.

synoptic and interannual timescales, particularly in reference to rainfall variability [e.g., Cook *et al.*, 2004; Fauchereau *et al.*, 2009; Hart *et al.*, 2010], very little is known about the seasonal cycle of the Angola Low or why it develops. In the present section we briefly review the literature on the Angola Low in relation to rainfall variability in observations and climate models. In the following section we will examine the mean state and seasonal cycle of the Angola Low in reanalyses.

2.1. Variability of the Angola Low and Southern African Rainfall

On a synoptic scale, the intensification of the Angola Low is associated with enhanced local convection [Hermes and Reason, 2009b] increased westerly moisture transport from the southeast Atlantic [Rouault, 2003; Cook *et al.*, 2004; Hermes and Reason, 2009b] and penetration of moisture-bearing north-easterlies deep into the subtropics

[Hart *et al.*, 2010]. These processes increase the convergence of low-level winds in the Angola region and in the area to the southeast. When coupled with the passing of a midlatitude wave, the intensification of the Angola Low can precipitate the formation of northwest-southeast orientated cloud bands [Hart *et al.*, 2010; Macron *et al.*, 2014]. These tropical-temperature troughs are important contributors to regional rainfall [Harrison, 1984; Todd and Washington, 1998; Macron *et al.*, 2014], especially in marginal rainfall areas [Hart *et al.*, 2013] and transfer latent energy and angular momentum poleward [Todd and Washington, 1998; Reason *et al.*, 2006].

The interannual variability of the Angola Low is associated with rainfall variability across southern Africa. For a sample of wet and dry years, Cook *et al.* [2004] show that in wet late summers (January–March; JFM) there is a 10% increase in the strength of the Angola Low, while dry JFMs are associated with a 20% decrease in strength of the Angola Low. The increase in strength of the low during wet years is accompanied by enhanced westerly moisture transport from the southeast Atlantic and stronger northeasterly inflow from the western tropical Indian Ocean [Cook *et al.*, 2004; Vigaud *et al.*, 2009]. These two enhanced moisture transport pathways increase the rate of low-level moisture convergence in the subcontinental interior [Cook *et al.*, 2004].

In some years, the variation in strength of the Angola Low is tied to the El Niño–Southern Oscillation (ENSO)–southern Africa teleconnection. By forcing an atmosphere-only climate model with El Niño-type sea surface temperature (SST) patterns, Cook [2000] demonstrates that there tends to be anomalously high geopotential heights over the Angolan–Namibian region during El Niño events. This inhibits the circulation associated with the Angola Low and reduces poleward moisture transport. This result is corroborated by Reason and Jagadheesha [2005], who show that moisture circulation associated with the Angola Low is suppressed during some El Niño events in the National Centers for Environmental Prediction (NCEP) reanalyses.

2.2. Climate Model Representation of the Angola Low

The ability of climate models to reproduce southern African rainfall climatology may depend in part on the model reproduction of the climatological Angola Low. In comparing an atmosphere-only climate model (HadAM3) with reanalyses data, Reason and Jagadheesha [2005] note that the model underestimates the strength of the Angola Low during the late summer season (January–March). This could be related to the

negative bias in continental rainfall compared to satellite data seen in this model. The authors argue that deficiencies in capturing Angola Low could also affect the modeling of ENSO over the region. This latter point is consistent with *Dieppois et al.* [2015] who use empirical orthogonal function analysis to evaluate the regional circulation produced in CMIP5 models during model El Niño events. They find that models tend to underestimate subcontinental high pressure anomalies both near the surface and at 500 hPa and suggest that “this could explain why [El Niño] dry conditions over southern Africa are not correctly reproduced through its influence on the Angola Low” (pp2433).

More recently, *Lazenby et al.* [2016] found that the wet biases in CMIP5 models (Figures 1 and 2) are also found in the ensemble of climate models contributing to the Atmospheric Model Intercomparison Project (AMIP) which are driven by observed SSTs. Both sets of ensembles, AMIP and CMIP, tend to simulate excessive moisture circulation in the Angola Low compared to reanalyses. By extension, *Lazenby et al.* [2016] argue that the simulation of the Angola Low could be an important control on excessive precipitation in throughout the CMIP5 ensemble (Figure 1) independently of SST biases. Here we test this hypothesis by investigating whether the mean simulation of the Angola Low can differentiate between model rainfall climatologies.

3. Data

We compare model rainfall with satellite/rain-gauge estimates from the Global Precipitation Climatology Project (GPCP) monthly precipitation data set [*Adler et al.*, 2003] and Climate Prediction Center Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997]. We interpolate the satellite data sets to $1^\circ \times 1^\circ$ grids and evaluate mean rainfall over a 26 year period from 1979 to 2005. Both of these data sets reliably reproduce the spatial patterns of precipitation over southern Africa and compare well against station data [*Kalognomou et al.*, 2013; *Novella and Thiaw*, 2013]. *Novella and Thiaw* [2013] provide a detailed discussion of the performance of these data sets over southern Africa.

The focus of the study is historical data (1979–2005) from a sample of 21 models in the CMIP5 ensemble [*Taylor et al.*, 2012]. The full list of models used along with their mean December to February (DJF) rainfall in the area $10\text{--}52^\circ\text{E}$, $10\text{--}35^\circ\text{S}$ is provided in Table 1. Differences between simulations arising from choice of initial conditions used to drive the model runs are negligible when considering long-term climatology [e.g., *Hawkins and Sutton*, 2009], and here we only use one ensemble member (r1i1p1) per model. Models are regridded by bilinear interpolation to a common $1^\circ \times 1^\circ$ grid for ease of comparison.

We use reanalysis data in section 4 to characterize the Angola Low. We include three reanalyses: NCEP-reanalyses [*Kalnay et al.*, 1996], ERA-Interim [*Dee et al.*, 2011], and 20th Century Reanalyses version 2 (20CRv2) [*Compo et al.*, 2011]. NCEP and ERA-Interim are chosen due to their widespread use in climate research and because they are frequently used to drive high-resolution regional models. We include the 20CRv2 following *Zhang et al.* [2013], who identify it as one of the best reanalyses for reproducing southern African climate and its variability. The reanalyses' estimates of precipitation are produced from short-range forecasts and do not assimilate rainfall observations. Consequently, we do not use the reanalyses as a reference data set for precipitation. Moreover, observational data in the Angolan region is scarce: there is no radiosonde data available and very few climate stations with reliable data [*Wilk et al.*, 2006]. As a consequence, reanalyses' estimates of circulation are relatively unconstrained in the region, and we avoid passing judgment on the reliability of model circulation by comparison. Nevertheless, it is interesting to see whether models are reproducing the Angola Low in a similar way to reanalyses and to examine the consistency between reanalyses' estimates of mean climate.

Finally, to identify the minimum atmospheric pressure level for evaluating the near-surface Angola, we use surface pressure data from the Grootfontein weather station in Namibia (19.6°S and 18.2°E ; 1400 m). These data are available on $>90\%$ of days between 1991 and 2002.

4. Characterizing the Angola Low

4.1. The Mean State and Seasonal Cycle of the Angola Low

In the core of the austral summer the Angola Low is identified as the minimum in 850 hPa geopotential height across Africa (Figure 4). It forms on the Bie Plateau, at $16\text{--}20^\circ\text{S}$ and $18\text{--}22^\circ\text{E}$, and is at the southern limit of a northeast to southwest orientated trough of low pressure extending from the Turkana desert in Ethiopia

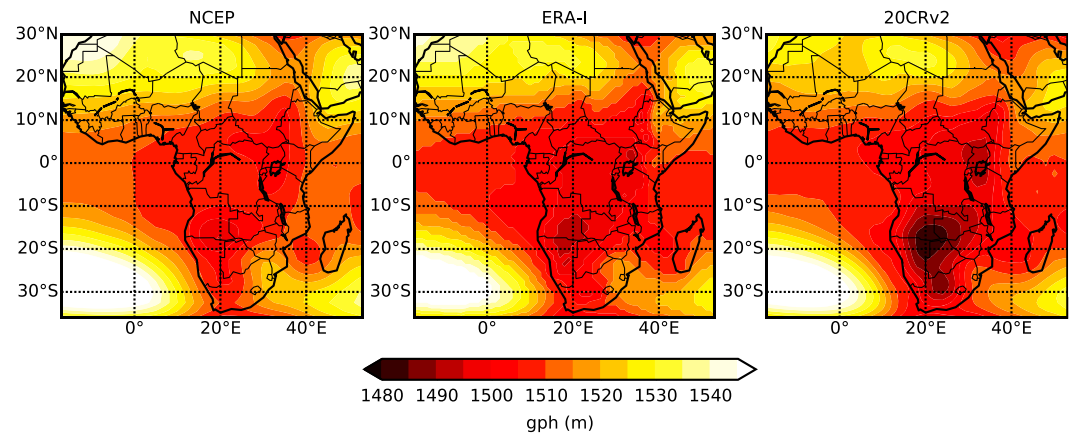


Figure 4. Mean DJF 850 hPa geopotential height in reanalyses (1979–2005).

through central Africa. This trough of low pressure in central Africa is associated with the Intertropical convergence Zone (ITCZ). The low surface pressure associated with the Angola Low sits to the west of the meridional arm of the ITCZ which extends over Tanzania and sets up a strong zonal pressure gradient between the southern African landmass and the adjacent subtropical high-pressure systems in the South Atlantic and South Indian Oceans.

While all three reanalyses produce a similar location of minimum geopotential height, there are notable differences in the intensity of the Angola Low. 20CRv2, and, to a lesser extent, ERA-Interim simulate lower 850 hPa geopotential heights than NCEP. 20CRv2 simulates a noticeable southward extension of the low geopotential height in the Kalahari region. This is less pronounced in the other two reanalyses. All reanalyses reproduce a secondary area of relatively low geopotential height in the Mozambican channel. This depression forms due to the dynamical adjustment of the easterlies, through vortex modification, as they flow over the southern Madagascan topography. The differences between reanalyses are further evidence of the poor observational constraint in the region, and there is no clear a priori reason why one reanalyses should be better than another. We will discuss whether this has a bearing on their simulation of rainfall in section 6.

The seasonal cycle of the Angola Low may provide important insights as to its origins (Figure 5). The low-pressure system first develops over southern Africa in October. At this time it is one of two areas of low geopotential height south of the equator, the other forming between Lake Tanganyika and Lake Victoria in northwestern Tanzania. In the austral spring (October–November; ON), the area of low geopotential height over Angola, at 15–16°S, is located slightly to the north of the area of maximum surface heating (Figure 5). In this region there are weak negative vertical gradients in equivalent potential temperature ($d\theta_e/dP < 0$; Figure 6), and steep slopes in potential temperature (θ) contours. This is indicative of the dry convection associated with strong surface heating and the formation of a heat low. *Adebiyi and Zuidema* [2016] show that the strong meridional temperature gradient between the October–November heat low and convection to the north is important in setting up the southern branch of the African Easterly Jet.

In December, the minimum in 850 hPa geopotential height remains in the Angola region at approximately 17°S, while the area of maximum surface heating shifts further south into the Namib and Kalahari Deserts (Figure 5). An extension of low geopotential height at 850 hPa forms over the Namib Desert in response to this high surface heating. The latitude–height cross section in December (Figure 6) shows two distinct features. The Angola Low, the minimum in 850 hPa geopotential height, now forms in a region of relatively strong vertical θ_e gradients. Such strong gradients in θ_e are indicative of moist instability and tend to be associated with moist convection. To the south, there are only weak vertical gradients in θ_e , due to a lack of moisture availability. Where present, these weak gradients are driven by intense surface heating associated with subcontinental heat low, which is now situated over the western Kalahari Desert.

As the summer season progresses into January and February, the Angola Low is stationary at 17°S, while the highest surface temperatures move farther south, following the seasonal cycle in insolation. By February, the

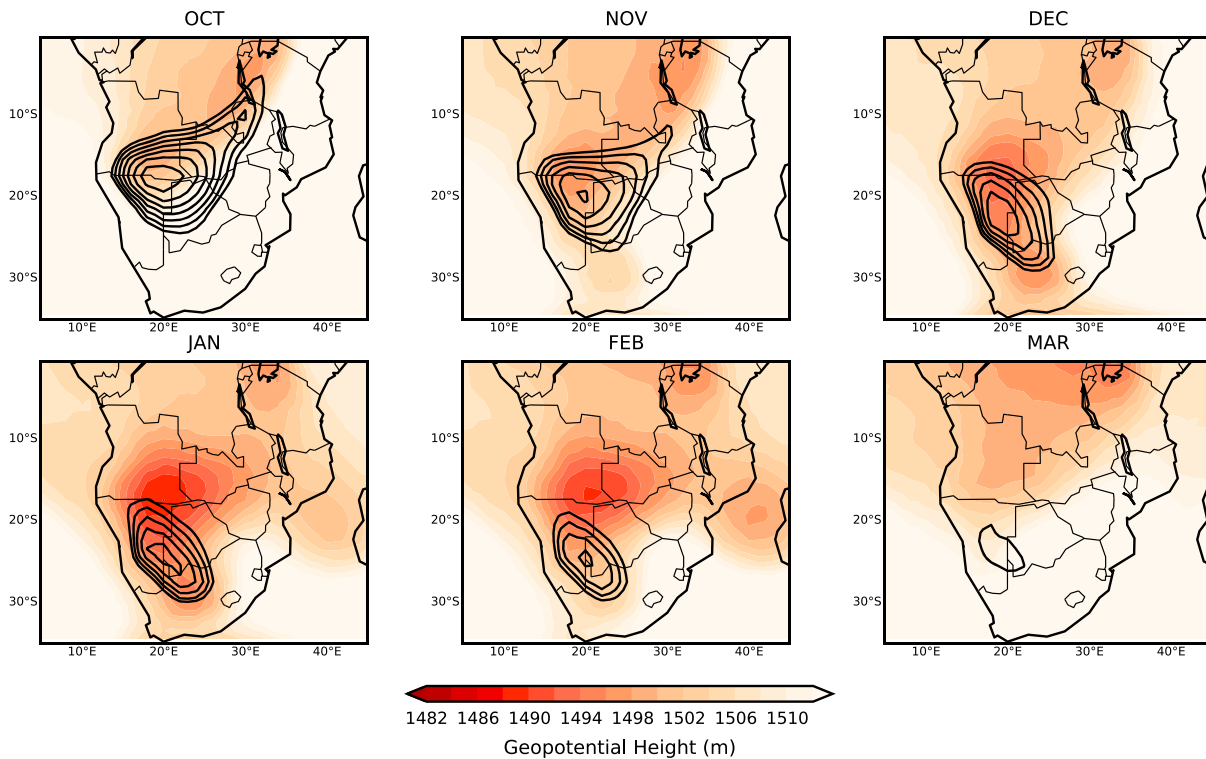


Figure 5. Austral summer (October to March) monthly progression of the Angola Low and southern African heat low in an ensemble mean of reanalyses. Shaded areas are mean 850 hPa geopotential heights (1979–2005), and contours are of 850 hPa potential temperature. The first contour is at 310 K, and the contour interval is 0.5 K.

heat low (25°S), is separated from the Angola Low by 8° of latitude. The vertical structure of the troposphere in January and February is qualitatively similar to the structure in December. In March the region of low 850 hPa geopotential heights in southern Africa moves to northern Angola and a weakened heat low remains over Namibia. While the Angola Low is still present, it is much weaker and not as obvious in the mean climatology. The lowest geopotential heights south of the equator are now associated with tropical convection in the Democratic Republic of Congo (DRC) and northern Tanzania.

The seasonal cycle of the Angola Low provides some insight into whether the Angola Low, in its mean state, is a heat low or a tropical low. In middle to late spring (ON), the Angola Low and the subcontinental heat low are barely distinguishable. In the core of the summer season (DJF), however, the heat low shifts south into the Kalahari (now the Kalahari heat low) and is distinct from the Angola Low. At this stage in the season, the Angola Low is driven by moist instability. Given the different forms of the Angola Low in the spring and summer, it seems sensible to focus on just one season for the analysis of the CMIP5 ensemble. Given that the largest biases in rainfall are in the core of the summer season (Figure 1) and that a tropical low may have a more direct relationship with rainfall, we focus on this season (December to February; DJF) in our analysis.

4.2. Defining the Angola Low for Intermodel Comparison

We identify the Angola Low as the lowest 5% of DJF mean 850 hPa geopotential height values within a large southern African domain (5–55°E, 0–35°S). There is a sharp boundary at the southern limit of the subcontinent to avoid the detection of midlatitude low pressure associated with westerly disturbances. An Angola Low index is defined by the mean geopotential height within this mask. We use this definition to compare Angola Low strength between models and reanalyses.

The lower tropospheric levels available in CMIP5 are 925 hPa, 850 hPa, and 700 hPa. The 850 hPa surface corresponds to an approximate height of 1500 m, slightly higher than height of average regional topography (Figure 3). Mean DJF surface pressure at the Grootfontein station is 854 hPa with a standard deviation of 2.9. The 850 hPa height is therefore suitable for capturing the near-surface low. In reanalyses, the 5% threshold

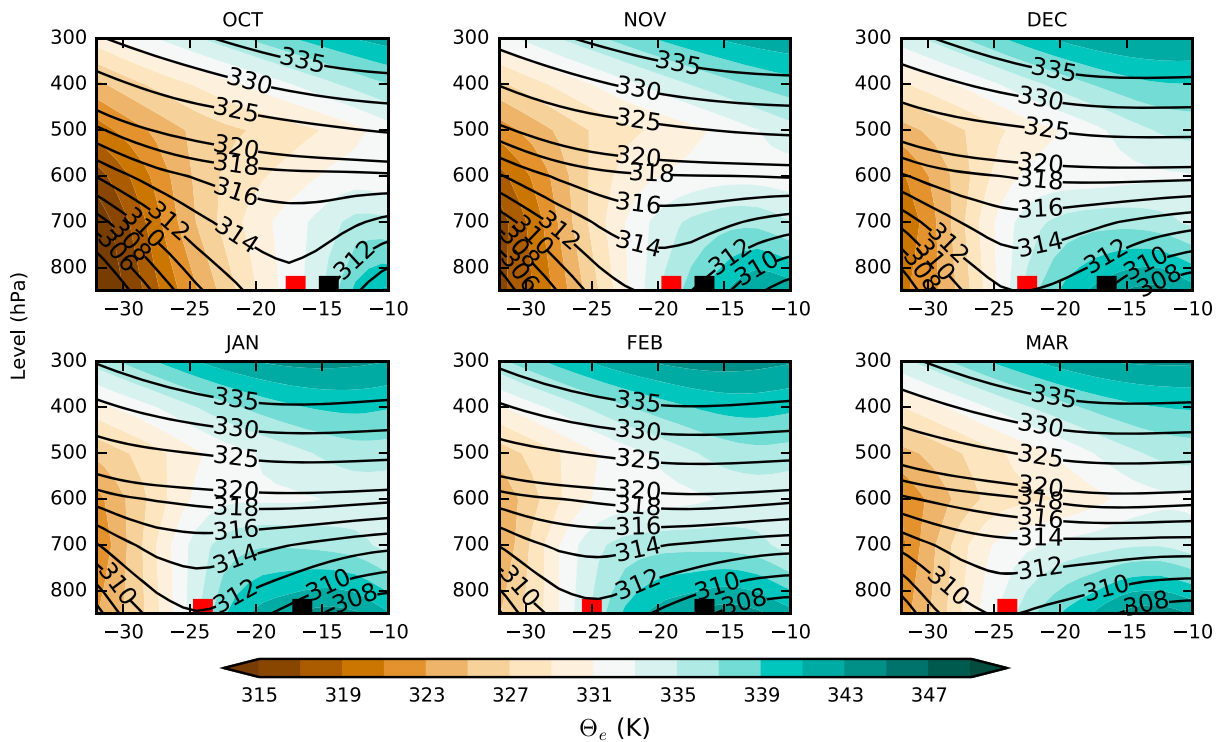


Figure 6. Austral summer (October to March) mean monthly latitude-height cross sections of equivalent potential temperature (θ_e ; shaded) and potential temperature (θ ; contours) in an ensemble mean of reanalyses. Longitudes are averaged over 18–24°E. The black rectangle represents the minimum in 850 hPa geopotential height associated with the Angola Low, and the red rectangle represents the maximum in potential temperature associated with the subcontinental heat low. Note in March, the presence of the Angola Low in the mean climatology is unclear so no rectangle is plotted.

accurately constrains the low to the Angolan-Namibian border; higher thresholds (e.g., 10%) include strong influences from the Kalahari heat low to the south and equatorial convergence to the north.

The vertical structure of the Angola Low is examined using vertical velocity (dP/dt) and geopotential height anomalies. Geopotential height anomalies are computed as a deviation from mean geopotential height over the large southern African domain for each pressure level.

5. The Angola Low in CMIP5 Models

5.1. The Near-Surface Angola Low

The location of the Angola Low is reproduced well by the majority of CMIP5 models (Figure 7). All models, with exception of GISS-E2-H, simulate the location of Angola Low at the confluence of the Namibian, Angolan, and Botswanan borders. In the GISS model, there are two discrete minimums in geopotential height: one in the Angola region and another stretched zonally across the tropical subcontinent. In models other than GISS-E2-H, the latitude of the minimum geopotential height varies from 15 to 20°S, and the longitude varies from 18 to 22°E. In some models (e.g., NorESM1-M, GFDL-ESM2G, and MPI-ESM-MR), the area of low pressure extends quite far south into Namibia. This could indicate a southward extension of austral summer rain band in these models. Nevertheless, the location of the Low as simulated by models is in broad agreement with reanalyses products and corresponds well with the area of enhanced moisture convergence identified by Cook *et al.* [2004], Reason and Jagadheesha [2005], and Reason *et al.* [2006].

The height of the 850 hPa surface varies by up to 20 m between models. The variation is particularly evident as models progress from dry to wet, with drier models in the ensemble tending to simulate higher geopotential heights (weaker lows) than wetter models. The relationship between model Angola Low strength and simulated rainfall will be explored in detail in section 6.

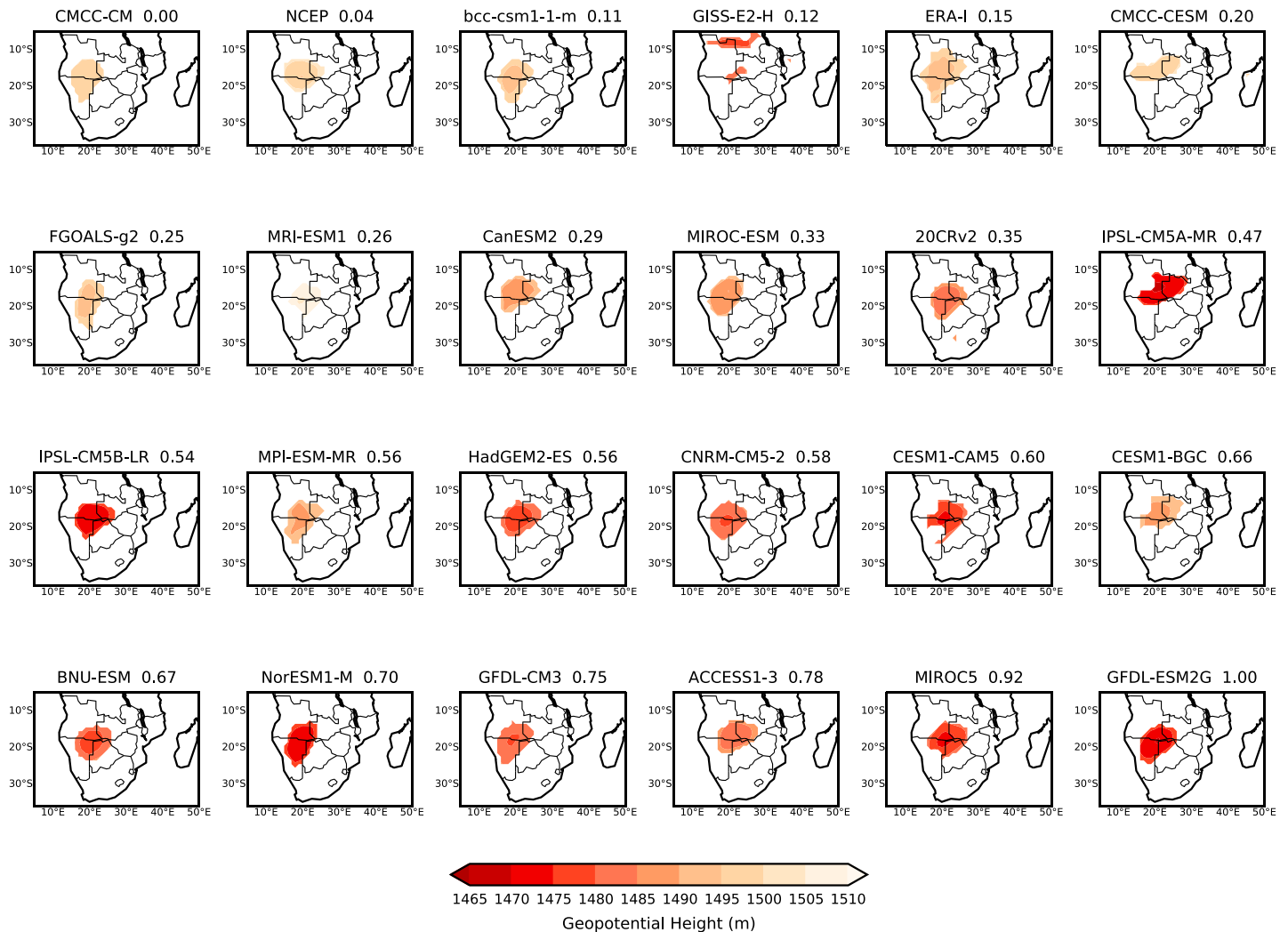


Figure 7. Mean DJF Angolan Low in CMIP5 models and reanalyses. Models and reanalyses are ordered from driest model (top left) to wettest model (bottom right). The Angolan Low is defined by lowest 5% of 850 hPa geopotential height. Model rainfall is shown above each composite expressed as index between 0 and 1 using equation $\frac{x_i - x_{\min}}{R}$ where x_i is mean DJF rainfall for an individual model (10–52°E; 10–35°S, Table 1), x_{\min} is mean DJF rainfall for the driest model (CMCC-CM), and R is the range between the wettest (GFDL-ESM2G) and driest (CMCC-CM) models.

5.2. Vertical Structure of the Angolan Low

The vertical structure of the Angola Low is important for its influence on southern African climate. In both models and reanalyses, the center of the Angola Low coincides with negative geopotential height anomalies in the middle to lower troposphere and positive geopotential anomalies at higher levels (Figure 8). This is accompanied by rising air throughout the tropospheric column up to 200 hPa. As proposed in section 4, this suggests that in the DJF the Angola Low should be identified as a tropical low rather than a heat low, as it is not capped by midlevel subsidence.

In most models, the center of the Angola Low, indicated by the black rectangle, is located at the southern edge of maximum vertical velocity associated with tropical convection. There is significant variation between models in the magnitude of vertical velocity in the AL region. In drier models and reanalyses the rate of uplift is modest, between -0.04 and 0.06 Pa s^{-1} , while in the wettest models the rate of uplift is almost doubled, reaching -0.10 Pa s^{-1} over the Angola Low region. The latitudinal extent of the area of uplift also differs between models. In some models (e.g., NorESM1-M and MIROC-ESM) there is a wide band of very strong uplift spanning over 5–10° of latitude. In other models (e.g., ACCESS1-3 and HadGEM2-ES) there is a narrow band of strong vertical velocity, occupying less than 5° of latitude. The differences amongst models are also

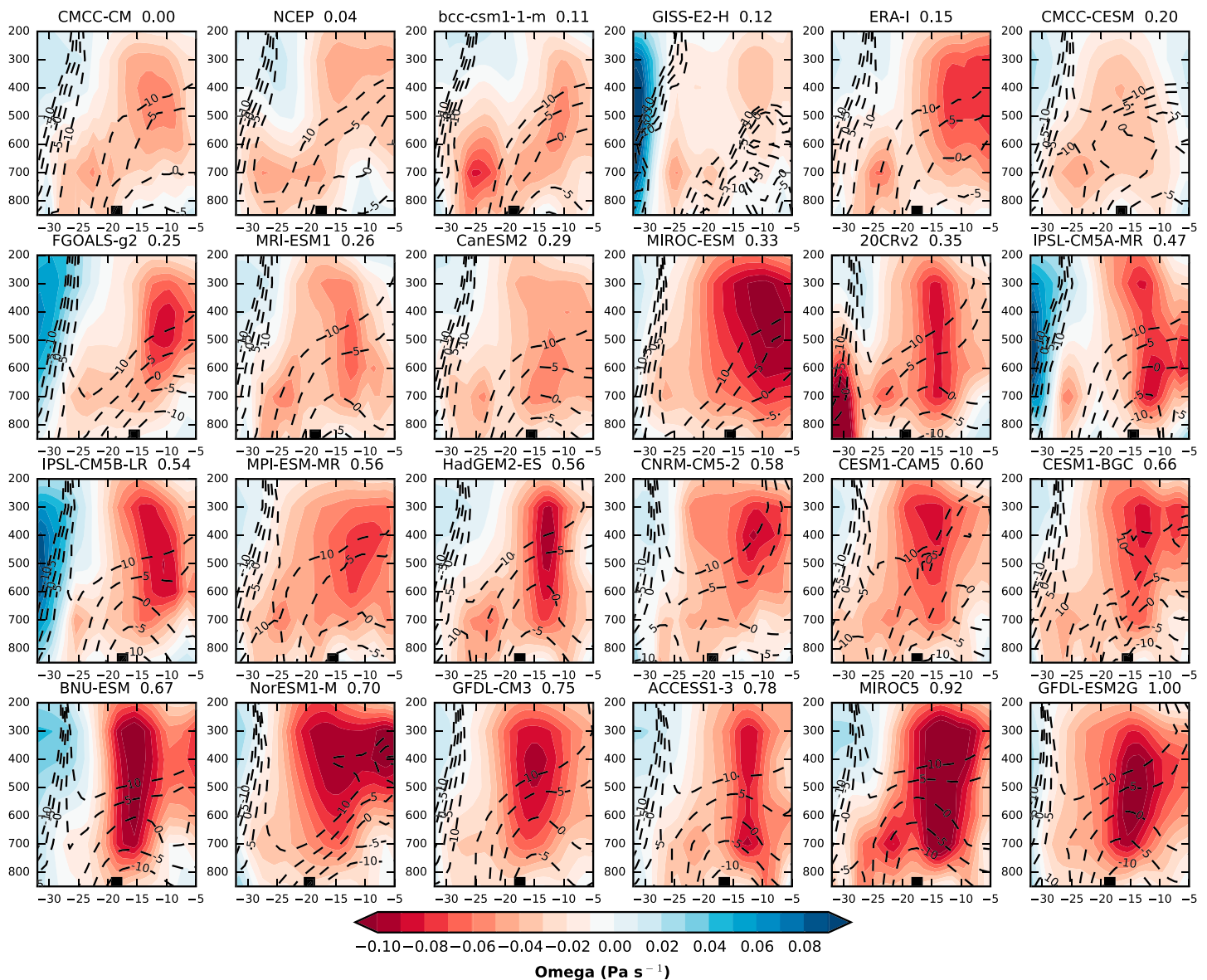


Figure 8. Mean DJF latitude-height cross sections of vertical velocity (Pa s^{-1} ; shaded) and geopotential height anomaly (contours; interval 5 m) for CMIP5 models and reanalyses. Models are ordered and rainfall index shown as in Figure 7. Longitudes are averaged over 18–24°E. The black rectangle in each composite represents the latitude of minimum 850 hPa geopotential height associated with the Angolan Low in each model or reanalyses.

found between reanalyses. ERA-Interim and NCEP reanalyses simulate a relatively weak and wide band of rising air north of the Angola Low, while 20CRv2 simulates a stronger but narrower band of rising air.

The Kalahari Heat Low is evident in some of the models (e.g., CMCC-CM, bcc-csm1-1-m, IPSL-CM5A-MR, and MIROC5) and in all three reanalyses. It is identified as the area to the south of the Angola Low (at approximately 25°S) where ascent up to 600 hPa is capped by subsidence aloft (Figure 8) and surface heating reaches a sub-continental maximum (Figure 5). Geopotential height anomalies in these models and reanalyses take a domed form tilting downward toward the Kalahari Heat Low. This implies that there could be some degree of interaction between tropical convection and the formation of the heat low, in a manner similar to the Sahara Heat Low [Lavaysse *et al.*, 2009; Adebisi and Zuidema, 2016]. If model simulation of rainfall and circulation in the African tropics is linked to their simulation of southern African climate, biases in these regions could be related.

Other models (e.g., MIROC-ESM, NorESM1-M, and GFDL-ESM2G) fail to reproduce subsidence aloft and simulate rising air throughout troposphere in whole subtropical region. Synoptically, this is seen during some

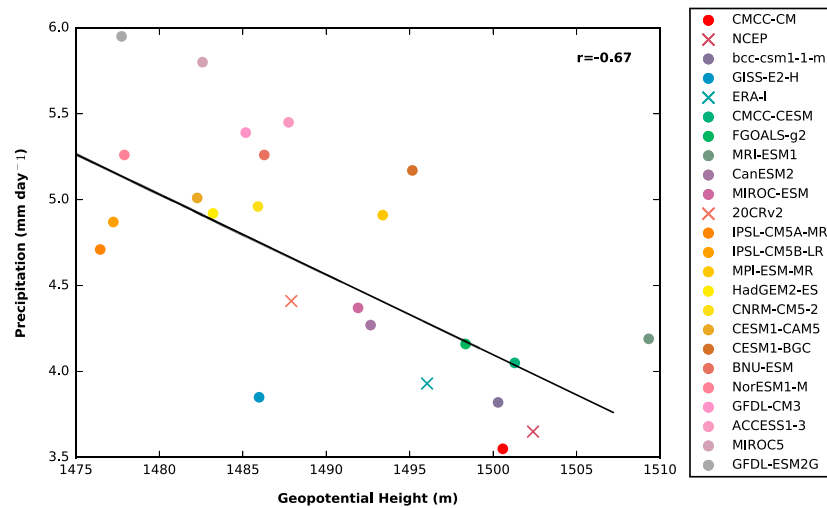


Figure 9. Relationship between DJF mean Angolan Low Index (see section 4.2 for details) and mean southern African rainfall (10–35°S;10°E–52°E). Models are indicated by dots, reanalyses by crosses. Note that the linear regression and Pearson's test do not include reanalyses.

tropical temperate trough events when an elongated trough forms between the Angola region and north-west South Africa [Hart *et al.*, 2010]. If the same process were happening in models, this could help to explain biases in precipitation seen in Botswana and South Africa in a number of CMIP5 models [Dieppois *et al.*, 2015] (Figure 2). The accurate reproduction of the Kalahari Heat Low could therefore be additional influence on the simulation of southern African rainfall. It is beyond the scope of this paper to explore this hypothesis.

6. The Angola Low and Rainfall

There is a negative relationship between the Angola Low index and rainfall across CMIP5 models (Figure 9). Models with a stronger Angola Low (lower geopotential height) tend to simulate more rainfall over the subcontinent ($r = -0.67$; $p = 0.0009$). There appears to be a strong coupling between model rainfall and the strength of their Angola Low; the slope of the regression line (-0.05) indicates that for every decrease of 5 m geopotential height there is an approximate 0.25 mm d^{-1} increase in rainfall. This relationship is perhaps expected given the way in which the Angola Low influences the interannual variability of southern African rainfall (section 2.1).

A few models do not conform to this relationship. For example, the GISS-E2-H model simulates relatively low 850 hPa geopotential heights (1486 m) despite being relatively dry. This may be caused by the northward location of its geopotential trough shown in Figure 7. When the GISS model is removed from analysis (not shown), the correlation improves to 0.74. Reanalyses, indicated by crosses on Figure 9 conform to the overall relationship. NCEP is the driest amongst the reanalyses and also simulates the weakest Angola Low (1503 m 850 hPa geopotential height). If the reanalyses are included in the Pearson's test, the correlation improves marginally ($r = 0.71$). It is interesting that drier models (e.g., CMCC-CM, bcc-csm1-m, and FGOALS-g2), which have rainfall amounts similar to satellite-rain gauge products (Figure 1), simulate the strength of the Angola Low in a similar way to reanalyses.

Figure 10 shows spatially how much of the variance between model rainfall is associated with the strength of the Angola Low. There is a strong relationship between the model Angola Low strength and gridbox rainfall in Angola and in the region stretching down to the southeast over the Mozambican Channel. In the core of the NW-SE band, the strength of the Angola Low is associated with between 40 and 60% of variance in model rainfall. The relationship between the Angola Low and rainfall in models weakens somewhat in the region of the Chimanimani mountains in Zimbabwe and the Drakensburg in South Africa. In these areas, local differences in model orography may dominate over large-scale circulation in influencing rainfall intensity. As model rainfall over large parts of southern Africa is associated with the simulation of the Angola Low, it

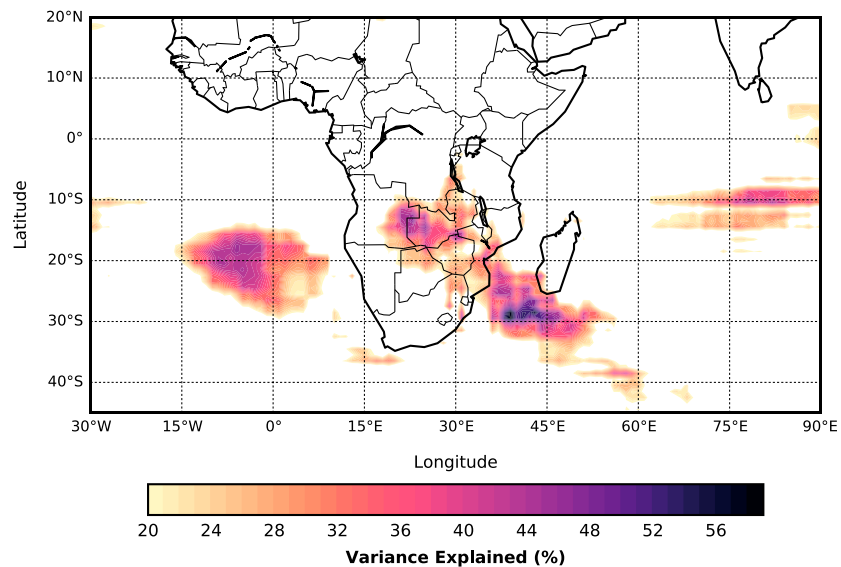


Figure 10. The percentage of intermodel variance in gridbox precipitation associated with the models' Angolan Low Index (see section 4.2 for details). Relationship is for mean DJF climatology, and variance predicted is calculated based on r^2 . Values below 20% are not significant at $p < 0.05$ and are masked.

follows that models which are poor at simulating the Angola Low are also likely to contain larger biases in their simulation of southern African rainfall.

The relationship between Angola Low strength and rainfall within the Angolan region is simple and can be explained by the enhanced vertical velocity in models with a strong compared to weak Angola Low (Figure 8). The northwest-southeast extension of the relationship is reminiscent of the structure of the South Indian Convergence Zone (SICZ) [Cook, 2000] and could relate to increased southward export of moisture in models with stronger cyclonic circulation. This is explored in the following section.

There is a strong association between the modeled strength of the Angola Low and rainfall over the southeast Atlantic (Figure 10). Models with a stronger low tend to simulate more precipitation here. This is a region of low rainfall both in models and in reality (not shown), and moisture transport emanating from the Angola Low is unlikely to affect rainfall patterns. A more plausible explanation for this relationship might be a concomitant westward shift of the South Atlantic High in models with strong Angola Lows, weakening the inhibition of rainfall. This could be related to the strong warm SST bias observed in many CMIP5 models in the southeast Atlantic [Wang *et al.*, 2014].

7. Moisture Circulation and the Angola Low

On synoptic and interannual timescales a stronger Angola Low is associated with enhanced regional moisture circulation (section 2.1). Figure 11 shows the differences in low-level (850 hPa) moisture flux and divergence between models with a relatively strong and weak Angola Lows. In models with a stronger low, there is enhanced moisture inflow ($20\text{--}40\text{ g kg}^{-1}\text{ ms}^{-1}$) from the northwest which flows cyclonically around the low feeding the eastern portion of the subcontinent. This flow, originating in the central African convective region, enhances moisture convergence to the east of the low in northwest Zambia. The anomalous northwesterlies merge with an enhanced northeasterly moisture flow ($20\text{--}50\text{ g kg}^{-1}\text{ ms}^{-1}$) out of southern Tanzania where moisture flux is strongly divergent. Together, these anomalous transport pathways increase the southward export of moisture and act to both enhance moisture convergence in central areas and reduce the divergence of moisture across the Mozambican coast. It is noticeable that areas of comparatively enhanced convergence or reduced divergence in the strong Angola Low set of models correspond to the areas where the strength of Angola Low is correlated with increased rainfall (Figure 10). The magnitude of moisture flux anomalies in models with a strong Angola Low compared to those with a weak low is similar to the magnitude of differences in moisture flux between wet and dry years [Cook *et al.*, 2004, Figure 13].

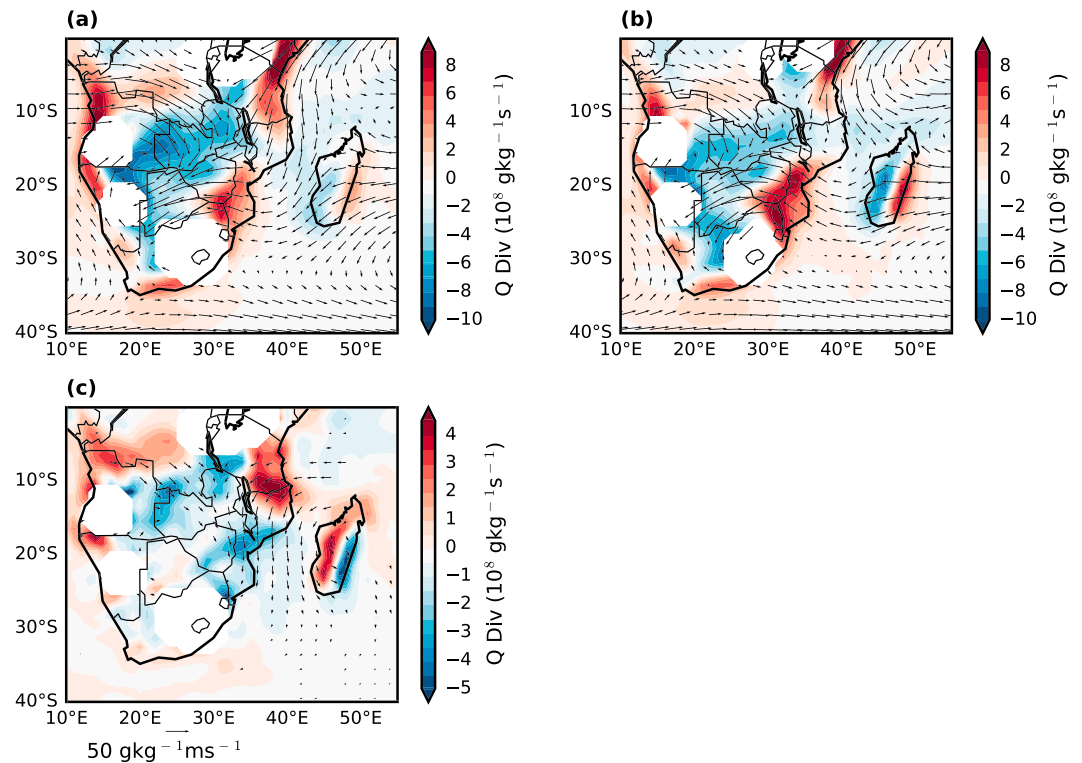


Figure 11. Mean DJF moisture flux and divergence at 850 hPa in (a) seven models with strongest Angolan Low, (b) seven models with weakest Angolan Low, and (c) strongest Angolan Low models minus weakest Angolan Low models. In Figure 11c we have only plotted moisture flux vectors where either meridional or zonal moisture flux values were significantly different between the two sets of models. Significance was calculated using Student's *t* test.

The excessive monsoonal northeasterly flow into the subcontinent is accompanied by reduced, or even absent, northwesterly flow recurving toward Madagascar in models with a strong Angola Low. This acts to reduce moisture convergence in northeastern Madagascar in these models and may explain, in part, the dipole pattern of dry precipitation biases over northern Madagascar, and wet biases over the Mozambican coast (Figure 2). The northwesterly flow toward Madagascar is also thought to be important for regional ocean dynamics, and, in particular, in the formation of the Seychelles-Chagos Thermocline Ridge (SCTR) [Hermes and Reason, 2008]. Variations in the SCTR depth can influence the incidence of tropical cyclones forming in the southwestern Indian Ocean [Hermes and Reason, 2009a], and thus, this deficiency in models could have important consequences for the modeling of extreme events and may impact on model rainfall climatology.

We assess quantitatively the relationship between intermodel variability in Angola Low strength and southward moisture export in Figure 12. The strength of the Angola Low is associated with 40–70% of the variability in meridional moisture flux in the Mozambican Channel. This corresponds with the enhanced northwesterly and northeasterly moisture transport in models with a strong Angola Low (Figure 11). Again, the strength of this relationship is improved if the anomalous GISS-E2-H model is removed from analysis (not shown). The northwest, southeast axis along which the relationship is strong is similar to the relationship between Angola Low strength and rainfall (section 6 and Figure 10). This suggests that the modulation of the strength of the Angola Low amongst models occurs contemporaneously with intermodel rainfall variability as a consequence of the increased southward export of moisture along the SICZ axis.

To the southwest of Madagascar this relationship is especially strong; the modeled strength of the Angola Low is associated with 65–70% of the variability in meridional moisture transport. In this region a topographically induced trough frequently forms (Figure 3). Easterly moisture transport from the south Indian Ocean is deflected northward on the western flank of this trough. In models with a weak Angola Low (Figure 11b) this effect is evident, with the easterly moisture feed deflected to the northwest across the Mozambican coast. In

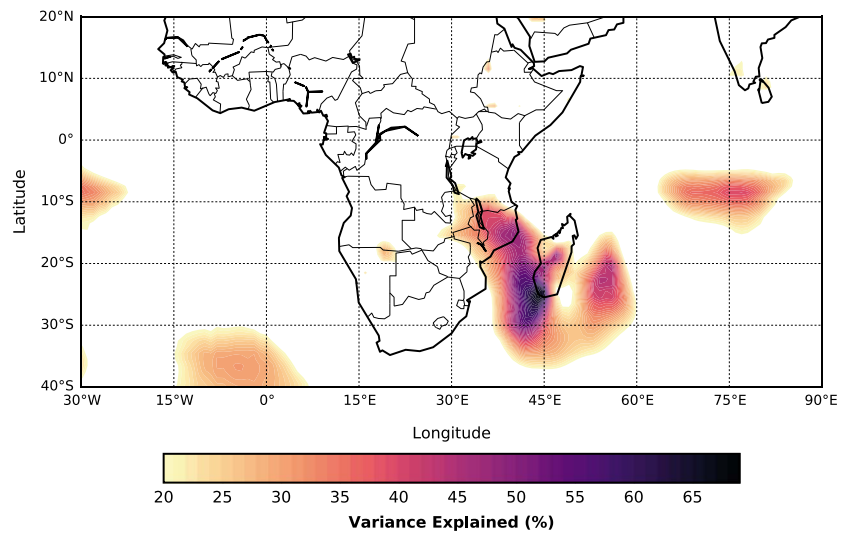


Figure 12. The percentage of intermodel variance in gridbox meridional moisture flux predicted by the models' Angolan Low Index (see section 4.2 for details). Relationship is for mean DJF climatology, and variance explained is calculated based on r^2 . Values below 20% are not significant at $p < 0.05$ and are masked.

models with a strong Angola Low, this transport is zonal (Figure 11a), accounting for the greater poleward moisture transport. It is difficult to untangle cause and effect here. One explanation is that a poorly reproduced Mozambican trough could enhance strength of the low by increasing direct moisture inflow to the subcontinent. This may explain the very strong relationship found here and suggests that the model representation of this feature warrants further study.

8. Discussion and Conclusion

8.1. Discussion

This paper explores the links between the Angola Low, regional circulation, and rainfall in CMIP5 models and reanalyses. The Angola Low is an area of low surface pressure, located between 16–20°S and 18–22°E, which is evident in the mean climate from the start of austral spring (October). In the austral spring (ON), the Angola Low is a heat low, formed in response to high surface temperatures in the Angola region. As the season progresses into austral summer (DJF), its climatological structure changes and is more similar to a near-equatorial trough. At this stage, it is characterized by strong negative gradients in θ_e in the lower troposphere.

There is significant variation in the strength of the Angola Low amongst CMIP5 models. Across a northwest to southeast orientated band, this variation in strength is associated with between 40 and 60% of the variation in rainfall amongst models. These results are consistent with the hypotheses of *Reason and Jagadheesha* [2005] and *Dieppois et al.* [2015], who suggest that the representation of the Angola Low in climate models might be associated with errors in summer rainfall in southern Africa. The elevated rainfall simulated in models with a stronger Angola Low corresponds to moisture circulation and divergence anomalies across the subcontinent. Models with a stronger low contain enhanced northwesterly and northeasterly moisture transport in the eastern portion of the subcontinent. This is accompanied by enhanced convergence in north central areas of the subcontinent and enhanced (reduced) divergence in southern Tanzania (eastern Mozambique). This supports *Lazenby et al.*'s [2016] hypothesis that CMIP5 biases in the strength of the Angola Low are associated with exaggerated moisture circulation patterns across the subcontinent. The moisture circulation biases have implications for poleward transport of latent energy and angular momentum and could encourage more frequent or intense tropical temperate interactions in climate models.

The underlying drivers of model variation in the strength of the Angola Low remain unclear. One plausible candidate is model representation of topography. For a similar low-pressure system on the Brazilian Plateau (20°S, 55°W), *Grimm et al.* [2007] and *Kodama et al.* [2012] emphasize the importance of local topography in the formation of the cyclonic anomaly. Model experiments which removed [*Grimm et al.*, 2007] or

smoothed [Kodama *et al.*, 2012] the topographic gradients in the Plateau region demonstrated that the formation and intensity of the low is contingent on patterns of regional topography. However, amongst CMIP5 models, there is no simple relationship between model resolution (a proxy for topography) and the strength of the Angola Low (not shown). This indicates that while topography is likely to be important in the formation of the Angola Low, there are other model processes which may be more important for explaining model diversity in its strength.

Another candidate for intermodel variability in Angola Low strength is the representation of local surface-atmosphere feedbacks. For the Brazilian Plateau low pressure, Grimm *et al.* [2007] propose a mechanistic link between dry spring conditions and wet summer conditions over the Brazilian Plateau. They suggest that dry spring conditions can lead to high surface temperatures which encourage moisture convergence over high elevations. They confirm the plausibility of this hypothesis by reducing soil moisture in a regional climate model in spring time, subsequently observing an increase in moisture convergence and rainfall in the following summer season compared to a control run. Precipitation over the Brazilian Plateau may then play a dominant role as an atmospheric heat source in sustaining the cyclonic circulation [Kodama *et al.*, 2012]. Similar processes could be at play for the Angola Low, as the seasonal cycle of the Angola Low (Figures 5 and 6) involves a transition from a heat low in spring, driven by high surface temperatures, to a tropical low in summer. Model variability in representing this seasonal cycle, including land-atmosphere feedbacks and convection, could play a role in the model diversity in the strength of the Angola Low. This is the subject of ongoing work.

The three reanalyses appear to conform to the relationship between the strength of the Angola Low and rainfall. NCEP is the driest amongst the reanalyses and has the weakest low, while 20CRv2 is the wettest and has a substantially stronger low. The circulation patterns between reanalyses differ slightly (e.g., Figures 4 and 8), with 20CRv2 simulating a more intense Angola Low which extends farther south than the other two reanalyses. Despite this, the rainfall response is similar between the reanalyses ($<0.8 \text{ mm d}^{-1}$). Differences amongst reanalyses reflect the observations used for assimilation and idiosyncratic model structure. The 20CRv2 reanalyses only assimilate synoptic surface pressure, monthly SST, and sea ice distribution [Compo *et al.*, 2011], whereas NCEP and ERA-Interim assimilate a larger range of variables [Kalnay *et al.*, 1996; Dee *et al.*, 2011]. This could explain why NCEP and ERA-interim are more similar to each other than they are to 20CRv2.

Most of the drier models in the ensemble (excluding GISS-E2-H) are in better agreement with both the satellite/rain gauge estimates of regional rainfall magnitudes (Figure 1) and reanalyses simulations of the Angola Low (Figures 7 and 8). It is tempting to conclude that these models are more reliable at simulating southern African precipitation than the wetter models in the ensemble. However, observational data in the Angolan region are scarce and satellite products, such as GPCP and CMAP, and reanalyses are not well constrained by station observations [Wilk *et al.*, 2006; Zhang *et al.*, 2013]. It is therefore unclear which models are faithfully reproducing the Angola Low and related circulation. In the absence of long-term observations, a targeted observational campaign aimed at characterizing the Angola Low would be useful. Even if only for one season, rainfall data and vertical profiles of temperature, humidity, and pressure obtained from radiosondes would help to assess the reliability of reanalysis products.

In DJF, the continental heat low forms over the Kalahari and is evident in latitude-height cross sections of subtropical southern Africa (Figures 6 and 8). In reanalyses, this is present at between 25 and 30°S and is characterized by weak uplift in the lower troposphere and subsidence aloft. It is similar in structure, to other heat lows, such as the Sahara Heat Low [Lavaysse *et al.*, 2009], although less intense. Some models (e.g., bcc-csm1-m and IPSL-CM5A-MR) reproduce this feature well, while others simulate rising air throughout the troposphere across subtropical latitudes to the south of the Angola Low. This may be related to the excessive precipitation in the western half of the subcontinent reported by Dieppois *et al.* [2015] and suggests that model reproduction of this feature is worthy of further study.

In the reanalyses, and in models where the Kalahari Heat Low is reproduced, contours of geopotential height anomalies suggest that there is some interaction between tropical convection and the formation of the heat low. Local axisymmetric circulation could create the clear skies needed for the strong surface heating associated with the heat low (Figure 5). This is consistent with Reason [2016] who suggests that the Botswana High, which lies above the heat low at 500 hPa, is generated in response to tropical precipitation to the

northeast. This raises the possibility of connections between model biases in the Congo region and those in southern Africa. However, the lack of observational data in the Congo makes it very difficult to evaluate these biases [e.g., Washington *et al.*, 2013], and process-based model evaluation is needed to help constrain model rainfall estimates [Creese and Washington, 2016].

8.2. Conclusion

Coupled climate model biases are often difficult to understand due to the range of possible climatic influences which can operate on a number of spatial and temporal scales. This is particularly the case with the southern Africa climate system which extends through tropical and temperate regions and is influenced by both regional and global SST dynamics. This paper has attempted to tackle this complexity by focusing on one circulation feature: the Angola Low and relating it to the variation in model precipitation.

The results presented show a link between the strength of the Angola Low and rainfall in southern Africa. This implies that improvements to the simulation of the Angola Low may also improve simulations of regional precipitation. As climate change in southern Africa is likely to be expressed through influences on regional circulation features, assessing the future changes to the Angola Low could place important constraints on the plausibility of future climate scenarios.

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