Circulation pattern controls of wet days and dry days in Free State, South Africa

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Abstract
Atmospheric circulation is a vital process in the transport of heat, moisture, and pollutants around the globe. The variability of rainfall depends to some extent on the atmospheric circulation. This paper investigates synoptic situations in southern Africa that can be associated with wet days and dry days in Free State, South Africa, in addition to the underlying dynamics. Principal component analysis was applied to the T-mode matrix (variable is time series and observation is grid points at which the field was observed) of daily mean sea level pressure field from 1979 to 2018 in classifying the circulation patterns in southern Africa. 18 circulation types (CTs) were classified in the study region. From the linkage of the CTs to the observed rainfall data, from 11 stations in Free State, it was found that dominant austral winter and late austral autumn CTs have a higher probability of being associated with dry days in Free State. Dominant austral summer and late austral spring CTs were found to have a higher probability of being associated with wet days in Free State. Cyclonic/anti-cyclonic activity over the southwest Indian Ocean, explained to a good extent, the inter-seasonal variability of rainfall in Free State. The synoptic state associated with a stronger anti-cyclonic circulation at the western branch of the South Indian Ocean high-pressure, during austral summer, leading to enhanced low-level moisture transport by southeast winds was found to have the highest probability of being associated with above-average rainfall in most regions in Free State. On the other hand, the synoptic state associated with enhanced transport of cold dry air, by the extratropical westerlies, was found to have the highest probability of being associated with (winter) dryness in Free State.

1 Introduction
Parts of southern Africa have already started experiencing extreme conditions (e.g. drought) (Sousa et al. 2018; Archer et al. 2019), and drought conditions are expected to increase in southern Africa under greenhouse-induced climate change (IPCC 2013). The hydroclimate of South Africa which is located at the subtropical high-pressure cell is relatively more vulnerable to a changing climate making it necessary for enhanced predictability of extremes in the region, in addition to understanding the underlying mechanism associated with extreme events at specific regions. Free State is centrally located in South Africa, and its economy is largely dependent on maize agriculture. According to Zuma-Netshiukhwi et al. (2013), most farmers in parts of the Free State are unfamiliar with the application of weather forecasts and still depend on their experience and traditional knowledge for farming decision-making. Thus there is the need for studies that extend the predictability of rainfall in Free State, which can also be of benefit to water decision-makers. This paper examines how specific synoptic situations in southern Africa can be used to forecast the probability of wet and dry events in the Free State.

The concept of synoptic climatology deals with the connection between large-scale atmospheric circulations and local surface variables. It involves the classification of the circulation patterns in a region, and the linkage of the classified patterns to the variability of surface variables in a local region, for example in Andorra (Esteban et al. 2005), in the whole Pyrenees (Lemus-Canovas et al. 2019); in Austria (Seibert et al. 2007) among many others. When used to explain surface variables, classification of circulation patterns can be considered as a method of statistical downscaling (Maraun and Widmann 2018), which involves the correlation of clustered days with a similar
Cook (2000) noted that the variability in the strength and
normally correlates with enhanced rainfall in southern Africa.
Austral summer rainfall variability in southern Africa is
influenced by a low level (at about 850 hPa) land-based
convergence zone (Tyson 1986; Cook 2000; Ninomiya
2008; Lazenby et al. 2016), called the South Indian Ocean
Convergence Zone (SICZ). The SICZ which extends off
the southeast coast of southern Africa is the major large-
scale feature that modulates the hydroclimate of southern
Africa.

Relaxation of trade winds during the austral warm sea-
sons, at the region of the Angola warm current, lead to the
development of a warm pool in the region (Reason and
Smart 2015). Moisture from the warm pool feeds into
the Angola low, which is a tropical low during austral sum-
mer associated with moist convection (Munday and Wash-
ington 2017). During austral summer, moisture from the
cross-equatorial northeast trade wind also feeds into the
Angola low. The cyclonic circulation associated with the
Angola low transports moisture from the warm pool and the
tropical Indian Ocean to the (eastern) subtropical regions
of southern Africa. According to Vigaud et al. (2009), the
Inter-tropical Convergence Zone (ITCZ) modulates the SICZ
through the Angola low – the sustenance of the Angola
low can be related to the enhancement of the ITCZ. The
anti-cyclonic circulation at the South Indian Ocean’s high-
pressure strengthens southeast winds, and thus enhances
moisture advection into southern Africa from the southwest
Indian Ocean. Low-level convergence of the moisture from
the southwest Indian Ocean advected by easterly winds and
the moisture advected from the tropical South Atlantic
Ocean (warm pool) by the circulation at the Angola low, cre-
ate the foundation zone of the SICZ (Cook 2000). According
to Cook (2000) the Agulhas current equally influences the
SICZ through the enhanced evaporation in the region. Addi-
tionally, rainfall variability in South Africa is also modulated
by sea surface temperature (SST) anomalies in the Agulhas
current (Walker 1990).

Sylla et al. (2011) noted that diabatic heating and mois-
ture convergence are two phenomena that lead to deep
conditional instability, which enhances convective rain-
fall. Enhanced diabatic heating, leads to the formation of a
thermal tower (typically in the western regions of southern
Africa), known as the continental tropical low. The con-
tinental tropical low is associated with enhanced vertical
velocity and convective instability. Thus in the presence of
adequate moisture at the boundary layer, its occurrence nor-
ma|ly correlates with enhanced rainfall in southern Africa.
Cook (2000) noted that the variability in the strength and
position of the South Indian Ocean high pressure and con-
tinental heating are the major factors that affect the position
and strength of the SICZ.

During austral winter (JJA) the northward track of the
mid-latitude cyclones allows cold fronts to sweep across
the regions in South Africa with the Mediterranean climate
leading to enhanced winter rainfall in the southwestern
regions of South Africa (e.g. Western Cape).

This paper uses the concept of obliquely rotated principal
component analysis (PCA), applied to the T-mode matrix
of a climatic variable that explains atmospheric circulation
(Richman 1981; Martin-Vide et al. 2008), in obtaining the
circulation types (CTs) in southern Africa. For the charac-
terization of how the mechanism of the individual CTs could
be related to rainfall in Free State, the concept of moisture
flux convergence (Kuo 1965) at 850 hPa will be incorpo-
rated in the analysis. Several researchers have found that the
parameterization of convective rainfall could be well linked
to the concept of moisture convergence (Sylla et al. 2011;
Loriaux et al. 2017).

The focus of this paper is thus structured as follows:

1. Principal component analysis will be used as an eigen-
vector-based classification tool to obtain an ample set of
CTs in southern Africa.
2. Physically motivated correlation between the mechanism
of the CTs and rainfall variability in Free State will be
investigated.

2 Data and methodology

Classification of CTs is achieved with gridded reanalysis
mean sea level pressure (SLP) from the European Center for
Medium-Range Weather Forecasts (ECMWF), ERA-Interim
(Dee et al. 2011). Divergence and wind vector data sets at
850 hPa are also obtained from ERA-Interim. The original
temporal resolution of the data sets is 6 h, from 1979 to
2018. Daily averages are computed, for the complete analy-
sis period. The horizontal resolution of the ERA-Interim
SLP dataset is 0.75° × 0.75°. The spatial coordinate for the
circulation typing is 5.25° E–55.25° E and 6° S–50.25° S.
The adjacent oceans are included to capture moisture advec-
tion processes. Daily rainfall data from 11 stations in Free
State, obtained from http://www.dwa.gov.za/Hydrology/
Verified/hymain.aspx, for the 1979–2018 period, are used in
characterizing the rainfall characteristics of the CTs in Free
State, South Africa (Fig. 1). The dotted red lines in Fig. 1
are the geographical locations of the selected rainfall stations
in Free State. The selection of the stations is based on hav-
ing complete daily rainfall estimates for the chosen analysis
period (i.e. 1979–2018), which is long enough (greater than
Fig. 1 The location of the local study region, Free State, in South Africa. The red dots are the location of the 11 selected rainfall stations in Free State.
signal, and for a given retained component, further clustering of the component loadings into negative high loadings and positive high loadings using a specified threshold will decrease the internal distances among classes so that there is greater similarity between days grouped under a given class (Richman and Gong 1999). Thus each component yields two classes and the SLP composite of the days grouped under a class is the circulation type (CT). Richman and Gong (1999) recommended that threshold values within the range of 0.2–0.35 will be sufficient to separate the PCs; here ±0.2 is used. A detailed explanation of all the subjective decisions followed in the classification is explained in Ibebuchi (2021a).

For the linkage of the CTs, classified in this paper, to wet days (dry days) in Free State, wet days (dry days) clustered under each CT, are characterized as the count of days, per station, with daily rainfall amount greater than (less than) 0.3 mm (Brisson et al. 2011; Plavcova et al. 2013).

The rainfall characteristics of each CT, concerning the probability of being associated with dry days and wet days, are calculated using Eqs. 1 and 2, respectively.

\[
P_{d_i} = \frac{d_i}{N_i} \times 100, \quad i = 1 \ldots n
\]

(1)

\[
P_{w_i} = \frac{w_i}{N_i} \times 100, \quad i = 1 \ldots n
\]

(2)

\(P_{d_i}\) is the percentage of dry days for a given CT; \(d_i\) is the total number of dry days for the CT in question; \(N_i\) is the total number of days clustered under a given CT. \(P_{w_i}\) is the percentage of wet days in a given CT, and \(w_i\) is the total number of wet days for the CT in question and \(n\) is the number of CTs classified.

Further analysis of the operational mechanism of the CTs associated with wet and dry conditions in Free State is made using moisture flux and divergence field at 850 hPa. The 850 hPa height is chosen since it is the height above the eastern escarpment. Moisture flux is calculated as the product of specific humidity and wind speed.

### 3 Study regions

Southern Africa is located between three oceans – the Southern Ocean (south of South Africa), the South Atlantic Ocean, and the South Indian Ocean. The western subtropical regions of Southern Africa are relatively drier than the eastern regions due to the influence of the cold Benguela current. Rainfall is mostly in austral summer (DJF), except for the southwestern regions of South Africa that are characterized by the Mediterranean climate. The local study region, Free State, is a province in South Africa. Its altitude is about 1600 m above sea level. Figure 2 shows the annual cycle of rainfall, for four stations in Free State. Late austral autumn to early austral spring (May–October) is relatively the driest months, while late austral spring to early austral autumn (November-March) is relatively the wettest months.

Fig. 2 Annual cycle of rainfall at four of the selected rainfall stations in Fig. 1
Similar results were obtained for other stations in Fig. 1. Daily rainfall amounts are relatively highest during austral summer months (DJF). Generally, based on the Mann–Kendall test (Mann 1945; Kendall 1975) for linear trends, at a 95% confidence level, the trend in wet days, dry days, and annual average rainfall in the selected stations are not statistically significant (not shown).

4 Results

4.1 Circulation types in southern Africa

By retaining 9 optimal components, 18 CTs were classified. Table 1 shows the explained variance for each of the retained components. Figure 3 shows the SLP composites (i.e. CTs) classified in the study region. Figure 4 shows the annual cycle for each CT in Fig. 3. In as much as it is common for the CTs to occur at any time of the year, the CTs can be further classified with respect to their dominance in either austral winter/autumn season or austral summer/spring season. The dominant period of a given CT is also when its rain-bearing or rain-suppressing mechanism is most likely to be expressed. CT1, CT6, CT7, CT9, CT11, CT14, and CT16 can be grouped as winter/autumn CTs. CT9 and CT11 extend dominance into early austral spring (September/October). Generally, they can be analogous to CTs associated with cold seasons. Similarly, CT2, CT3, CT5, CT8, CT10, CT12, CT13, CT15, and CT18 can be grouped as austral summer/spring CTs. Their dominant periods are within the range of October (late austral spring) to February (late austral summer). CT5, CT2, and CT3 extend dominance into early austral autumn (March/April). The occurrence of CT4 was a bit mixed up—it has a high probability to occur, almost homogeneously, at any time of the year. CT17 is specifically an austral spring dominant pattern. In general, CT2, CT5, CT8, CT10, CT12, CT13, CT15, and CT18 can be grouped as warm-season CTs.

The probability of occurrence of the CTs (Fig. 5) was calculated as the ratio of the number of days clustered under the CT to the total number of days in the study period (i.e. 14,610 days). CT1 is the most occurred cold season CT in the study period, followed by CT9. CT5 similarly, is the most occurred warm-season CT, followed by CT8. CT5 is the austral summer climatology of atmospheric circulation in the study region. CT12 and CT18 are relatively rare CTs. CT1 is close to the climatological mean state of SLP field variability in the study region (Moleteni et al. 1990).

The oblique rotation allows inter-correlation between the component scores, and also a day might have high loadings (> 0.2) under more than one retained component so that the classification procedure allows for the grouping of a day under more than one CT, which logically implies the CTs that occurred on the day in question. Since the classified data is continuous, overlapping of the classified variable is physically realistic (Gong and Richman 1995). As a result, the sum of the percentages in Fig. 5 does not add up to 100%. Atmospheric circulation is a continuum and this justifies the relaxation of a rigid grouping (e.g. K-means clustering), which allows a day to be classified under only one CT, which logically implies the CTs that occurred on the day in question. Since the classified data is continuous, overlapping of the classified variable is physically realistic (Gong and Richman 1995). As a result, the sum of the percentages in Fig. 5 does not add up to 100%. Atmospheric circulation is a continuum and this justifies the relaxation of a rigid grouping (e.g. K-means clustering), which allows a day to be classified under only one CT, which logically implies the CTs that occurred on the day in question. Since the classified data is continuous, overlapping of the classified variable is physically realistic (Gong and Richman 1995). As a result, the sum of the percentages in Fig. 5 does not add up to 100%.

Table 1 Percentage of variance explained by the retained components

| Component | Explained variance (%) |
|-----------|------------------------|
| 1         | 41.9                   |
| 2         | 17.6                   |
| 3         | 14.5                   |
| 4         | 8.2                    |
| 5         | 4.7                    |
| 6         | 2.8                    |
| 7         | 2.0                    |
| 8         | 1.7                    |
| 9         | 1.2                    |
wet days when either of these dry CTs occurs—supporting the fact they are truly dry synoptic situations in Free State. For each of the 11 stations, CT6 has the highest probability of being associated with dry days.

Figure 8 shows the SLP field; moisture flux and divergence field at 850 hPa, during CT6 and CT14. Under CT14 a high-pressure system and associating divergence are evident over Free State and the Greater Agulhas region. This leads to subsidence (rainfall suppression), and reduction of convective activity at the Agulhas current, which is a principal source of moisture to South Africa. Under CT6, the mid-latitude cyclone strengthens and tracks further north so that westerly wind is enhanced in the advection of cold drier to Free State. While the synoptic situation of CT6 favors cold fronts to sweep across the southwestern regions of South Africa (Reason and Rouault 2005; Ibebuchi 2021b), here it is shown that the band of westerly rather suppresses rainfall in the Free State. This is because, in addition to the transport of drier air from the Benguela regions, moist southeasterly winds from the southwest Indian Ocean are
weakened. Moreover, Jury (2015) highlighted that during El Niño events when anomalous rainfall decrease is expected in southern Africa, westerly winds transport cold dry air onto the South Africa plateau. Hence at the synoptic scale, enhanced dryness in Free State can be attributed to large-scale subsidence, suppression of convection at the Greater Agulhas region, and advection of cold dry air from the Benguela region by extratropical westerly winds.

From Fig. 6 (bottom panel), for the warm season CTs, i.e. CT2, CT3, CT5, CT8, CT10, CT12, CT13, CT15, and CT18, the probability of dry days in these CTs are generally less, relative to the cold season CTs. Figure 6 (top panel) shows the distribution of the probability of each CT to bring wet days across the 11 stations. For the eleven selected stations in Free State, Fig. 8 shows the regions under the dominant influence of a given CT, based on having the highest probability of bringing wet days (Fig. 7A) and the probability of bringing extreme rainfall (Fig. 7B). An extreme rainfall day for each CT was characterized as the count of days with daily rainfall amount greater than the 99 percentile rainfall value, per station. Figure 6 and Fig. 7 show that CT12 has the highest chances of being associated with widespread extreme rainfall in most regions in Free State. Southwestern regions in Free State are more likely to be influenced by the dynamics of CT15. Some regions are under the influence of CT13. However, the application of the classification scheme to other SLP gridded data sets (e.g. Ibebuchi 2021b) reproduced all the CTs except CT13, suggesting that it might be an artifact of ERA-Interim. Hence more focus will be placed on CT15.

From Fig. 8, at the synoptic scale, extreme rainfall in most regions in Free State under CT12 can be attributed to the strengthening of the South Indian Ocean high-pressure. This leads to enhanced low-level advection of
moisture by the southeast wind. Also, under CT12 the off-shore movement of the thermal low into the South Atlantic east Coast and the weakening of the South Atlantic Ocean high-pressure reflect moistening of the western subtropical boundary layer. Thus, more moisture is available to be advected into Free State by westerly winds. On the other hand, CT15 reflects enhanced convergence of moist winds from the Angola warm current and cross-equatorial trade wind into the Angola low. The western branch of the South Indian Ocean high-pressure is equally weakened so that fewer southeast winds penetrate Free State compared to CT12. However, the continental tropical low evident in this synoptic situation, coupled with the enhanced cyclonic activity at the Agulhas region, and the enhanced convergence at the Angola low are generally favorable for the enhancement of deep convection at preferred regions in Free State. In general, extreme rainfall in Free State can be attributed to enhanced transport of moisture by southeast and southwest winds into the local study region; the formation of continental tropical lows at the western regions of southern African, coupled with enhanced cyclonic activity in the Agulhas region.

From the classification scheme in this paper, the March 1988 incidence in Free State which was accompanied by heavy flood episodes on 10 and 11 March (Walker and Lindesay 1989) can be attributed to the occurrence and persistence of CT12 from 10 March, to 11 March when it also co-occurred with CT15. The average rainfall on 10 March alone for the eleven selected stations in Free State is 45 mm, and 32 mm on 11 March. Figure 9 shows the SLP, 850 hPa moisture flux, and specific humidity for 10 and 11 March 1988. Similar to the synoptic features of CT12 (c.f. Figs. 3,
8), a weaker anticyclonic circulation at the South Atlantic Ocean high-pressure; the offshore movement of thermal low into the South Atlantic east coast; and stronger anticyclonic circulation at the western branch of the South Indian Ocean high-pressure, resulting in enhanced low-level moisture transport by moist southeast and southwest winds into the southern African mainland is evident during these days. Also with the occurrence of CT15 on 11 March, a cyclonic circulation can be seen over Angola so that northwest winds are evident compared to 10 March. Thus the persistence of the synoptic state of CT12 from 10 to 11 March 1988 contributed significantly to the flood incidence.

**5 Discussion**

In this study, the CTs in southern Africa were classified and linked to rainfall variability in Free State, South Africa. The CTs associated with the higher probability of being associated with wet days and dry days in Free State were noted. The mechanisms, in the light of moisture flux and convergence, through which the selected CTs can influence the intensity and spatial variability of rainfall across 11 stations in Free State were equally analyzed.

Using obliquely rotated PCA on the T-mode matrix of the SLP data set (Richman 1981), 18 CTs were classified and each CT was found to be related to the probability of a specific weather event in the local climate. CTs dominant in austral summer and austral late spring—when SST is high at the southwest Indian Ocean—were found to be associated with a higher possibility of bringing wet days to Free State. Austral winter and austral late autumn dominant CTs—when SST is low at the southwest Indian Ocean—were found to be associated with a higher possibility of bringing dry days to Free State. The results are in line with the finding of Reason and Mulenga (1999) that SST anomalies at the southwest Indian Ocean explain to a good extent the inter-seasonal variability of rainfall in South Africa.

The synoptic situation associated with the highest probability of wet days and extreme wet days in Free State is characterized by stronger anti-cyclonic circulation at the South Indian Ocean high-pressure leading to the enhanced low-level transport of moisture from the southwest Indian Ocean by southeast winds. It equally features moistening of the Benguela current due to a weaker state of the South Atlantic Ocean high-pressure (Vigaud et al. 2009). Accord-

**6 Conclusions**

From the classification of CTs in southern Africa and the linkage of the CTs to wet days, heavy wet days, and dry days from eleven rainfall stations in Free State, it was found that wet/dry conditions in Free State are prevalent in warm/cold seasons when convective activity is high/low in the southwest Indian Ocean. At the synoptic scale, wet days in Free State can be associated with (i) enhanced low-level transport of moisture by strong anticyclonic circulation at the western branch of the South Indian Ocean high-pressure coupled with the moistening of the Benguela...
Fig. 8 Physical mechanism associated with the CTs with the highest probability of wet days and dry days in Free State. Color is the composite of the divergence field at 850 hPa with the unit in 10^6/s, the green vector is moisture flux at 850 hPa with the unit in g/kg m/s. Vector scale is written on top of the maps.

Fig. 9 Composites of SLP, 850 hPa moisture flux, and specific humidity on 10 March and 11 March 1988. Contour is SLP in hPa, the interval is 3 hPa. Color is specific humidity in g/kg. Vector is moisture flux and vector scale is written on the map.
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region, (ii) and enhanced convective activity at the Agulhas current coupled with the formation of continental tropical lows at the western regions of southern Africa. On the other hand, dry conditions in Free State can be associated with (i) anticyclonic activity on the landmasses and the Greater Agulhas region, (ii) and transport of cold dry air to Free State by the extratropical westerly winds.

The findings in this study extend the predictability of rainfall in Free State both under the current climate and for studies based on future climate change conditions and thus can be useful to water decision policy-makers and for a local weather agency. An increase in SST is among the signals of global warming; however at the synoptic scale, during austral summer, a weaker (stronger) circulation at South Indian Ocean high-pressure might imply weakening (strengthening) of the hydroclimate of Free State due to diminished (enhanced) advection of moisture by southeast winds. However, a weakening of advection might still be compensated by enhanced moisture uptake at the adjacent oceans, so that extremes in rainfall might still be possible in Free State.

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**Declarations**

**Availability of data and material** ERA-Interim reanalysis data sets are available at: [https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim](https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim) and the station rainfall data sets are available at [http://dwa.gov.za/Hydrology/Verified/hymain.aspx](http://dwa.gov.za/Hydrology/Verified/hymain.aspx).

**Conflict of interest** There are no conflicts of interest in this paper.

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