1	Circulation pattern controls of summer temperature anomalies in
2	southern Africa
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#### 22 Abstract

23 This study investigates the relationship between circulation patterns and austral summer temperature anomalies in southern Africa. The results show that the formation of continental 24 25 lows tends to increase the partial atmospheric layer thickness. Further, the distinct variabilities of high and low pressure under the circulation types, influence air mass advection from the 26 adjacent oceans, as well as atmospheric stability over land. Stronger anticyclonic circulation at 27 the western branch of the Mascarene high enhances low-level cold air advection by southeast 28 winds, decreases thickness, and lowers the temperature over a majority of the land in southern 29 Africa. Conversely, a weaker Mascarene high, coupled with enhanced cyclonic activity in the 30 southwest Indian Ocean increases low-level warm air advection and increases temperature 31 anomalies over vast regions in southern Africa. The ridging of a closed South Atlantic 32 anticyclone at the southern coast of southern Africa results in colder temperatures in the tip of 33 southern Africa due to enhanced low-level cold air advection by southeast winds. However, 34 when the ridge is weak and westerly winds dominate the southern coast of southern Africa, 35 temperature increases in these areas. The northward track of the Southern Hemisphere mid-36 latitude cyclone, which can be linked to the negative Southern Annular Mode, reduces the 37 temperature in the southwestern part of southern Africa. Also, during the analysis period, El 38 Niño and the positive Subtropical Indian Ocean dipole were associated with temperature 39 increases over the central parts of southern Africa; while the positive Indian Ocean dipole was 40 linked to a temperature increase over the northeastern, northwestern, and southwestern parts of 41 southern Africa. 42

Keywords: temperature, circulation types, Subtropical Indian Ocean dipole, Southern Annular
Mode, El Niño, Indian Ocean dipole, Mascarene high, South Atlantic anticyclone

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#### 46 Highlights

The spatiotemporal variations of temperature over southern Africa are coupled with
 large-scale circulation patterns modulating warm and cold air advection.

49 2. Climate drivers heterogeneously influence temperature over the land in southern Africa
50 through control of regional circulation patterns.

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## 54 **1. Introduction**

Rising global temperatures resulting from both anthropogenic emissions and natural variability 55 impact virtually all aspects of livelihood, ranging from mortality rate (Lee and Sheridan, 2018; 56 Sheridan and Dixon, 2017) and labor productivity (Knittel et al., 2020) to the rate and 57 magnitude of climate extremes (Alimonti et al., 2022), among others. Climate predictions and 58 projections are important for mitigating the consequences of rising temperatures by enhancing 59 preparedness against extreme climate events as well as developing climate policies against 60 future dangerous climate change. A major challenge in forecasting climate events, such as 61 extreme temperatures, stems from the incomplete understanding of the physical mechanisms 62 that drive the climate (Flato et al., 2014). Therefore, there is a need for studies that aim to 63 improve the understanding of the atmospheric processes that govern the earth's climate. 64 Enhanced knowledge of the atmospheric processes that govern the climate can serve as a 65 benchmark for improving climate forecasts. In the regional context of southern Africa, which 66 is vulnerable to anthropogenic climate change due to its economic conditions and geographical 67 location at the descent region of the Hadley circulation (Baudoin et al., 2017), this study aims 68

to enhance the understanding of the large scale circulations that modulate the summertemperatures in southern Africa.

Several studies have hinted at the role of climate drivers in modulating atmospheric circulations 71 72 over southern Africa (Dieppois et al., 2015; Hoell et al., 2015; Lyon and Mason, 2007; Malherbe et al., 2014; Manatsa et al., 2017; Reason and Rouault, 2005) and other regions in the 73 globe (Pirhalla et al., 2022). Among the climate drivers, the sea surface temperature (SST) 74 patterns of the Subtropical Indian Ocean Dipole (SIOD) and the Southern Annular Mode 75 (SAM) have a direct impact on the climate of southern Africa because they exist in the mid-76 latitude oceans of the Southern hemisphere (i.e., the subtropical Indian Ocean, and the Southern 77 Ocean). In addition, the Indian Ocean Dipole (IOD) and the El Niño Southern Oscillation 78 (ENSO) have a remote influence on the climate of southern Africa (Reason and Jagadheesha, 79 2005). Moreover, the imprint of the ENSO signal can be found in the SAM, IOD and SIOD 80 modes since all the climate drivers generally influence SST anomalies in the southwest Indian 81 Ocean as well as the anticyclonic circulation of the Mascarene high. (Ding et al., 2012; 82 Ibebuchi, 2021; Morioka et al., 2015). Therefore, this study also investigates the impact of the 83 climate drivers on temperature variability in southern Africa. 84

The link between synoptic circulations and precipitation in southern Africa has been widely 85 documented (Burls et al., 2019; Engelbrecht et al., 2015; Engelbrecht and Landman, 2016; 86 Lennard and Hegerl, 2015; Mahlalela et al., 2019; Wolski et al., 2018). Also, studies have 87 highlighted the possible impact of the SAM on temperature anomalies in southern Africa. For 88 example, using regression analysis, (Gillett et al., 2006) investigated the impact of positive 89 SAM on temperatures in the Southern Hemisphere (with the inclusion of southern Africa), 90 however, the negative SAM was not considered and the associating physical processes were 91 not analyzed in detail. Also for other regions in the Southern Hemisphere, such as Australia and 92

South America, studies have addressed the relationship between the SAM and surface 93 temperatures (Hendon et al., 2007; Silvestri and Vera, 2009). Further, the majority of available 94 works of literature on the IOD and SIOD, with regard to the climate of southern Africa, focus 95 on the relationship between the climate drivers and rainfall variability in southern Africa 96 (Behera and Yamagata, 2001; Hoell et al., 2015; Ibebuchi, 2023; Reason, 2001), and less 97 attention is given to temperature. Given that these climate drivers impact the amplitude and 98 frequency of circulation types (CTs), this study goes further to decompose in time, the distinct 99 circulations in southern Africa and then analyze the mechanisms through which the individual 100 CTs impact surface temperature and relative humidity (that contributes to heat stress) in 101 102 southern Africa. Thus, the major added value of this study to the literature is the improved understanding of the physical processes through which large-scale circulations influence the 103 spatial variations and magnitude of summer temperatures in southern Africa. 104

This study is structured as follows, Section 2 presents the data and methods the study is based on; the results are presented in Section 3; Section 4 contains the discussion of the results and conclusions.

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112 **2 Data and methodology** 

113 2.1 Data

High-resolution reanalysis data is obtained from ERA5 (Hersbach et al., 2020). The ERA5
reanalysis data sets obtained are sea level pressure (SLP); 850 hPa wind vectors, relative 5

humidity, specific humidity, 850 hPa geopotential height; and 1000 hPa geopotential height. 116 Gridded observed 2 m average temperature is obtained from the Climate Prediction Center 117 Unified Temperature (CPC) Global dataset 118 (https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html). All data sets are obtained at daily 119 temporal resolution from 1979 to 2021. The horizontal resolution of the ERA5 reanalysis data 120 is 0.25° longitude and latitude, and 0.5° longitude and latitude for the gridded CPC 2 m 121 temperature data. Also, correspondence between ERA5 and gridded CPC temperature data has 122 been reported (Roffe and van der Walt, 2023), which strengthens the choice of using both data 123 sets for our analysis. 124

125 2.2 Methodology

This current study is incremental work from previous research that applied circulation typing 126 to study circulations in southern Africa at multiple spatial scales (Ibebuchi, 2023a), hence the 127 same classified CTs are used. A major advancement in this study is that these same CTs are 128 now being used to investigate the mechanisms through which circulation patterns modulate the 129 magnitude and spatial variations of austral summer (i.e., December to February – DJF) 130 temperature in southern Africa. We consider austral summer as that is when absolute 131 temperatures are highest in the study region, and thus, most impactful. The spatial extent for 132 the CT classification is 0° to 50.25°S and 5.25°E to 55.25°E (Fig. 1). The adjacent maritime 133 regions that act as moisture sources to the landmass were included. Further, when the CTs are 134 linked to temperature over the landmass, typically, to make a distinction with the tropical 135 landmass, southern Africa might be defined to include landmass from about 10°S and poleward. 136 Nonetheless, we have included the tropical latitudes (i.e., up to 0° latitude) to capture variability 137 in the cross-equatorial northeast trade winds. This is because the cross-equatorial northeast 138 trade winds play a role in defining convergence in the Angola Low and the Mozambique 139

140 Channel that both impact the climate of southern Africa. However, we focus our analysis on
141 the temperature anomalies under the distinct CTs on land from 10°S and poleward.

The obliquely rotated T-mode (variable is time series and observation is grid points) principal 142 143 component analysis (Compagnucci and Richman, 2008) applied in a fuzzy approach is used for the classification of the CTs. The details of the classification approach are given in Appendix 144 A. The classification of the CTs with rotated T-mode PCA is a time decomposition technique. 145 Singular value decomposition is applied to the correlation matrix containing the correlation 146 between the SLP fields at the distinct daily time series in the analysis period. The resulting PC 147 loadings which designate the amplitude of the set of circulation patterns at a given day is used 148 to assign CT(s) within the signal range to a given day, which imply the CTs that occurred on 149 the day in question. 150

We apply map composting of different climate variables to examine the relationship between 151 the classified CTs and DJF temperatures in southern Africa. We have used SLP composites to 152 investigate the horizontal variations of pressure under each of the CTs, which can also be 153 suitable for characterizing continental heating (i.e., in areas with continental lows) as well as 154 atmospheric stability at the boundary layer, and convective activity over the adjacent oceans. 155 We defined the thickness of the atmospheric layer as the vertical distance in meters between 156 two the 1000 hPa and 850 hPa pressure levels. This is because, we found that from iterative 157 pre-evaluations, relatively, the thickness layer values between 1000 hPa and 850 hPa accurately 158 capture the spatiotemporal variations of 2 m mean temperature values in the study region. Thus, 159 we define thickness as the difference between the height at 850 hPa and the height at 1000 hPa. 160 Positive thickness values are related to positive temperature anomalies and negative thickness 161 values are related to negative temperature anomalies. In addition to analyzing the SLP and 162 atmospheric layer thickness, composites of 850 hPa (that is, the height above the eastern 163

escarpment of southern Africa) winds are analyzed to establish the prevailing winds under each
CT. Thus, analyzing the SLP, wind directions, and thickness enables documenting low-level
cold and warm air advection under each CT.

Given the high seasonality of temperature, to enable a robust diagnosis of the temperature 167 values and other variables used to diagnose temperature patterns under each CT, we rely on 168 composite anomaly values during DJF. The composite anomaly is calculated as the difference 169 between the days assigned to a CT and the 1981-2010 DJF climatology of the variable in 170 question. Regression analysis was used to investigate, at each grid point in the region of 171 assessment, the association between climate drivers (SAM, ENSO, IOD and SIOD) and 172 temperature variability in southern Africa. The statistical significance of the association, based 173 on the regression model, is tested at a 95% confidence level. To control for false discovery rate 174 in the multiple hypothesis testing, we used the Benjamini-Hochberg procedure (Benjamini and 175 Yekutieli, 2001), which assumes that the hypotheses being tested are independent. 176

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#### 179 **3 Results**

The standardized SLP composites for the days when the classified CTs occurred during the 180 analysis period are shown in Figure 1. The CTs in Figure 1 were externally validated using SLP 181 182 data from a different reanalysis product (Ibebuchi 2022c) and a suite of CMIP6 general circulation models (Ibebuchi 2022b). While the CTs are not confined to occur in any specific 183 season, the spatiotemporal structure and dynamics of the CTs can also be influenced by seasonal 184 variations in large-scale processes such as diabatic heating, thus the CTs tend to be dominant 185 in specific seasons when the prevailing (seasonal) atmospheric condition favors their 186 mechanisms (Fig. A1). Pressure variations over the adjacent oceans are used to infer convective 187 8

activity in these locations – anticyclonic (cyclonic) circulations over the oceans imply
suppressed (enhanced) convection. Similarly, pressure variations over the landmass can be used
to infer continental heating or atmospheric stability at the boundary layer – anticyclonic
(cyclonic) circulations over the land imply a relatively stable (unstable) atmosphere.

Next, for the classified CTs in Fig. 1, we look at the composite anomaly patterns of DJF atmospheric layer thickness between 1000 hPa to 850 hPa (Fig. 2a), temperature (Fig. 2b), and 850 hPa relative humidity (Fig. 3); and composite patterns of 850 hPa wind vectors (Fig. 4). These figures will be interpreted coherently, based on the asymmetric patterns of the CTs (i.e., the positive phase and the negative phase). We focus our analysis of the composite anomaly maps in Figs 2 to 3 mostly on the regions (i.e., group of grid points) with robust changes.

Generally, the composite patterns reveal that under each CT, the DJF temperature anomalies 198 are characterized by spatial heterogeneity (Fig. 2b). A possible explanation for the spatial 199 heterogeneity of temperature anomalies under each CT can be due to the distinct regional 200 climates in southern Africa. Under the asymmetry of each CT (i.e., the negative and positive 201 phases) temperature variations are least in the deep tropics  $(10^{\circ}S - 0^{\circ})$  mostly because diabatic 202 heating (and SLP) have fewer variations in the deep tropics. However, as noted earlier, the 203 major focus of the temperature anomalies is on southern Africa. Fig. 2a indicates that for the 204 205 asymmetry of a given CT, and depending on the circulation features, there appear to be coherent temperature patterns in the central parts of southern Africa – mostly at landmasses close to the 206 southwest Indian Ocean - at the southwestern parts of southern Africa, characterized by the 207 Mediterranean type of climate, and at the southern tip of southern Africa. Thus, the regional 208 climate types of the aforementioned regions contribute to defining the overall spatial 209 210 heterogeneity of the temperature anomaly patterns under each CT.

CT1+/CT1 – present variations in the subtropical ridge south of South Africa. Under CT1+ 211 the mid-latitude cyclone is relatively more enhanced at the south coast of southern Africa (Fig. 212 1). The associating wind pattern at the south coast of southern Africa under CT1+ is westerly 213 (Fig. 4), and thickness anomaly is positive over South Africa except for the western tips, and 214 also thickness anomaly is positive at the central parts of southern Africa except for large parts 215 of Mozambique and Madagascar (Fig. 2a). Regions with positive thickness anomaly indicate 216 warm advection and are generally associated with a positive temperature anomaly (Fig. 2b) as 217 well as a negative relative humidity anomaly (Fig. 3). 218

Conversely, under CT1 – the South Atlantic ridge is enhanced at the south coast of southern 219 Africa, driving cold air, southeast into the southern African domain (Fig. 1 and Fig. 4), and also 220 cyclonic activity is relatively more enhanced in the southwest Indian Ocean compared to CT1+. 221 Given the cold air advection on the south coast of southern Africa, the thickness anomaly is 222 negative over vast regions in South Africa (Fig. 2a). Under CT1 -, the thickness anomaly is 223 also negative over the central domains of southern Africa where the cold air from the South 224 Atlantic high-pressure system advects, except for parts of Mozambique and Madagascar given 225 the enhanced low-pressure system (that is, convective activity) over the oceans that results to 226 warm air advection. Resultantly, regions with positive (negative) thickness anomaly values are 227 generally characterized by positive (negative) temperature anomalies and negative (positive) 228 229 relative humidity anomaly values (Fig. 2 and Fig. 3). The analysis of CT1+/CT1 – indicates that cold advection resulting from circulation at the subtropical ridge implies lower thickness 230 and lower temperature values in the regions where the cold air penetrates; similarly, 231 enhancement of convective (or cyclonic activity) in the southwest Indian Ocean, results in 232 warmer temperatures at the coastal landmasses. 233

Further, CT2+ presents circulation variability associated with enhancement of the anticyclonic 234 235 circulation at the western branch of the Mascarene high and enhancement of the mid-latitude cyclone south of South Africa (Fig. 1). Hence the wind patterns are southeast over the southwest 236 Indian Ocean, driven by the Mascarene high, and westerly, at the south coast of southern Africa 237 (Fig. 4). Given that cold air advection from the South Atlantic anticyclone is weakened at the 238 south coast of southern Africa, thickness anomaly is strongly positive at the south coast of 239 southern Africa (Fig. 2a) as well as temperature anomaly (Fig. 2b). However, since the 240 Mascarene high drives colder southeast winds into large parts of southern Africa, thickness 241 anomaly is negative and temperature anomaly is negative over large parts of southern Africa. 242 243 Resultantly, over the central parts of southern Africa, the pattern of CT2+ brings positive relative humidity anomaly, but negative relative humidity anomaly over parts of the southern 244 tips that are anomalously warmer (Fig. 3). CT2 - is characterized by opposing (and 245 asymmetric) circulation features, relative to CT2+, and so brings warmer (colder) temperatures 246 over the central parts (southern tips) of southern Africa. 247

CT3+ is related to positive SAM and CT3 – is related to negative SAM (Ibebuchi 2021). We 248 recall that the SAM through its control of circulation in the mid-latitudes significantly impacts 249 the regions in southern Africa with the Mediterranean type of climate, that is, the Western Cape 250 Province located in the southwestern part of southern Africa. Based on the climatology of the 251 regions in southern Africa with the Mediterranean type of climate, the enhancement of the mid-252 latitude cyclones on the south coast of southern Africa under CT3 - (Fig. 1), and the 253 associating westerly winds (Fig. 4) allow cold fronts to sweep across the southwestern parts of 254 southern Africa. Thus, under CT3 – Figure 2a shows a zonal dipole-like structure of thickness 255 256 anomaly whereby the eastern (western) region of South Africa has positive (negative) thickness anomaly values. As a result, temperature anomaly is positive (negative) in the eastern (western) 257 region of South Africa (Fig. 2b). Also, the relative humidity anomaly is negative (positive) in 258 11

the eastern (western) region of South Africa (Fig. 3) - an indication of a saturated atmosphere 259 that eventually results in frontal rainfall in the western domain of South Africa. For the large 260 parts in the central regions of southern Africa, Fig. 2 shows that under CT3 - thickness and 261 temperature anomalies are positive and relative humidity anomaly is equally negative (Fig. 3). 262 The reason is that while CT3 - is dominant in winter seasons (Fig. A1), nonetheless during its 263 occurrence in DJF, SST and convergence are higher in the southwest Indian Ocean, and 264 continental heating is equally higher compared to austral winter (JJA). Thus, during DJF, the 265 displacement of atmospheric blocking by the western branch of the Mascarene high, and the 266 resultant weakening of cold advection, allows warmer ocean waters in the southwest Indian 267 Ocean (Vigaud et al., 2009). Hence, during the occurrence of CT3 – in DJF, warm air 268 advection from the southwest Indian Ocean, driven by the northeast trade winds (Fig. 4), leads 269 to a warmer climate in large parts of southern Africa. 270

Further, CT3+ is associated with increased SLP in the mid-latitudes, but not the closed and 271 elongated South Atlantic anticyclone that results in cold air advection from the Southern Ocean 272 to large parts of South Africa (cf CT1 - in Fig. 4). In this case (of CT3+), cold air advection 273 to the eastern part of South Africa results from southeast winds driven by the western branch 274 of the Mascarene high. Therefore, under CT3+ due to the cold air advection, the eastern part of 275 South Africa has a negative thickness anomaly (Fig. 2a), negative temperature anomaly (Fig. 276 277 2b), and positive relative humidity anomaly (Fig. 3). Since westerly winds and the associating cold fronts are suppressed south of South Africa, the western region of South Africa has a 278 positive thickness anomaly (Fig. 2a), positive temperature anomaly (Fig. 2b), and negative 279 relative humidity anomaly (Fig. 3). For the central parts of southern Africa, due to the enhanced 280 cold air advection by southeast winds driven by Mascarene high, negative thickness and 281 temperature anomaly prevails over the central regions (Fig. 2) coupled with positive relative 282 humidity anomaly (Fig. 3). 283

For the other CTs, similar patterns of variations in the pressure systems and the associating cold 284 (warm) air advection, reduces (increase) the thickness of the air layer, resulting in negative 285 (positive) temperature anomalies in preferred regions. For example, CT5 - reinforces the 286 findings from CT1 – that when the South Atlantic Ocean high pressure is closed, ridging at 287 the southern coast of southern Africa, large parts of South Africa become colder due to 288 enhanced cold air advection (Fig. 1 to Fig. 4); and CT6+ depicts very similar pattern but with 289 stronger amplitude. CT6 – also reinforce previous findings that when southeast winds are 290 enhanced by the circulation at the western branch of the Mascarene high then cold air advection 291 292 to the eastern regions and large parts of southern Africa implies colder conditions in the study domain (Fig. 1 to Fig. 4). 293

CT7+/CT7 – is related to the positive/negative SIOD (Ibebuchi, 2023). Under CT7+/CT7 – 294 the southwest Indian Ocean is warmer/cooler, based on the enhanced cyclonic/anticyclonic 295 activity; in addition, the boundary layer in large parts of southern Africa is relatively 296 unstable/stable under CT7+/CT7 - . For CT7+, the pressure gradient between the South 297 Atlantic high-pressure and the continental low results in cold air advection from the South 298 Atlantic Ocean and the Southern Ocean to South Africa, but warm air advection from the 299 (warmer) southwest Indian Ocean to the central regions of South Africa (Fig. 1, Fig. 2a and Fig. 300 4). Therefore, while colder temperatures are evident in the south and southwestern parts of 301 302 South Africa, CT7+ brings warmer temperatures to the central domains of southern Africa (Fig. 2 to Fig. 3). Conversely, in CT7 - cold advection from the southwest Indian Ocean prevails 303 over the central parts of southern Africa (Fig. 2a and Fig. 4) and coupled with the stable 304 305 atmosphere, leads to negative temperature anomalies over the central parts of southern Africa (Fig. 2b). But due to enhanced blocking of the mid-latitude cyclones at the southern coast of 306 southern Africa, the activity of cold fronts that bring colder temperatures to the southwestern 307

part of southern Africa is weakened so that the southwestern parts of southern Africa havepositive temperature anomalies.

CT9 – is remarkable and results in widespread positive temperature anomaly in South Africa 310 311 (Fig. 2b). This is because of the meridional pressure gradient between the low pressure in the Mozambique Channel and the western branch of the Mascarene implying that colder southeast 312 winds from the Mascarene high do not penetrate the eastern parts of South Africa (Fig. 1 and 313 Fig. 4) coupled with the absence of the closed South Atlantic anticyclone at the southern coast 314 of southern Africa. However, the pattern of CT9 - also imply that colder air from the western315 branch of the Mascarene high move towards the low pressure in the Mozambique Channel, 316 penetrating the central parts of South Africa and partly adjusting to westerly towards 317 Madagascar (Fig. 4); this flow pattern brings negative thickness anomaly and colder 318 temperatures to the central parts of southern Africa. 319

From Fig. A2, regions with a robust decrease in temperatures, for example, the western parts in 320 CT3 - and CT6+, and the eastern parts in CT7 - (Fig. 2b), are mostly associated with low 321 specific humidity; and regions with a robust increase in temperatures are mostly associated with 322 high specific humidity, for example, the southeastern parts under CT3 - and CT6+ and the323 southern parts under CT9 - . This is generally because a warmer (colder) atmosphere can hold 324 more (less) moisture. However, there are exceptions to this, for example under CT1 -, where 325 326 negative temperature anomaly at the southern parts of southern Africa is associated with positive specific humidity anomaly. This is because moisture content over the landmass is also 327 modulated by other factors such as advection and moisture uptake over the oceans. 328

## 329 <u>Relationship between climatic modes and temperature variability over southern Africa</u>

330 Previous studies linked the CTs in Fig. 1 to climatic modes of variability. CT3+/CT3 - was

found to be modulated by the SAM (Ibebuchi 2021) such that CT3+(CT3-) is related to 14

positive (negative) SAM. CT5+/CT5 - was found to be modulated by the Nino 3.4 index 332 (Ibebuchi 2022a), such that CT5 – (CT5+) is related to El Niño (La Niña). CT7+/CT7 – was 333 found to be modulated by the SIOD (Ibebuchi 2023a), such that CT7+(CT7-) is related to 334 the positive (negative) SIOD. CT9+/CT9 - was equally found to be modulated by the IOD 335 (Ibebuchi 2023b) such that CT9+(CT9-) is related to the negative (positive) IOD. The 336 frequency of these CTs is modulated by these large-scale modes of variability, and thus 337 338 represent the regional-scale manifestations of the modes. That is the CTs are the physical mechanism through which these modes impact southern African temperatures. 339

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In addition to the control of DJF temperatures by the climatic modes indirectly through the CTs, 341 as shown in Figs 1 and 2, we also apply regression maps to examine the *direct* association 342 between these well-known climatic modes and temperature in southern Africa. Figure 5 shows 343 this association is spatially heterogeneous with a dipole structure especially over the 344 southwestern and east-central parts of southern Africa. In terms of significant temperature 345 increase, from Fig. 5, El Niño is associated with an increase in temperature over the central 346 parts of southern Africa. The positive phase of the IOD is associated with an increase in 347 temperature over the northeastern, northwestern and southwestern parts of southern Africa. The 348 positive SAM is associated with temperature increase, mostly over the southwestern parts of 349 southern Africa, while the SIOD is associated with temperature increase over the 350 central/northcentral parts of southern Africa. 351

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#### 355 4 Discussion

The study by Liu et al. (2022) found that high-frequency atmospheric signals are crucial for 356 improving sub-seasonal predictability of precipitation in most land monsoon regions. The high 357 358 frequency intraseasonal variability was found to be responsible for a significant portion of the total intraseasonal variability and generally dominates the sub-seasonal predictability of various 359 land monsoons. Liu et al. (2022) suggested that high frequency variability is necessary for 360 enhancing predictability of climate variables such as precipitation and temperature at sub-361 seasonal time scales. The inclusion of high frequency variability in the CTs created in this work 362 with the application of rotated T-mode PCA to daily SLP (Ibebuchi 2022a), in line with the 363 recommendation of Liu et al. (2022), is necessary for the enhanced predictability of climate 364 variables such as precipitation and temperature. This is because the multi-scale interaction 365 between synoptic and inter-annual signals is connected by tropical and extratropical 366 atmospheric signals affecting these CTs, on the intraseasonal time scales. 367

The majority of the studies linking atmospheric circulations to the climate of southern Africa 368 369 are focused on precipitation (Barimalala et al., 2020; Fauchereau et al., 2009; Jury, 2015). Other studies have equally examined the relationship between climate drivers and precipitation 370 variability in southern Africa (Hart et al., 2013; Hoell et al., 2015; Reason and Jagadheesha, 371 2005). Indeed, the studies concur that the hydroclimate of southern Africa is modulated by 372 large-scale circulations. However, little attention has been given to the relationship between 373 synoptic to large-scale circulations in southern Africa and temperature anomalies in southern 374 African landmass. Among such studies, Gillet et al. (2006) investigated the relationship 375 between the SAM and temperature in Southern Hemisphere landmasses. The authors found 376 that positive SAM can be related to temperature increases over the southwestern parts of 377 southern Africa, but temperature decreases over some northeastern parts. The results from Gillet 378

et al. (2006) are consistent with the regression analysis between annual temperature anomalies 379 and the SAM index in this study (Fig. 5). Also, the circulations through which positive SAM 380 increases temperature of the southwestern parts of southern Africa (i.e., CT3+) is shown to be 381 a poleward shift of westerly winds, which in turn suppresses the passage of cold fronts over the 382 southwestern parts of southern Africa. The positive IOD increases SST over the tropical western 383 Indian Ocean (Saji, 1999) and alters atmospheric circulations over southern Africa (Mantasa et 384 al. 2011). Our results indicate that the SST pattern of the positive IOD is linked to temperature 385 increase over Madagascar, the northeastern, northwestern and southwestern parts of southern 386 Africa. Similarly, during El Niño and positive SIOD events, which are both associated with 387 388 SST increase in the southwest Indian Ocean, temperature increase in some central parts of southern Africa can be expected. Also, El Niño and the positive SIOD appears to be related to 389 temperature decreases over the southwestern parts of southern Africa possibly due to weakening 390 of high-pressure adjacent to South Africa. 391

A previous study by Ibebuchi (2022b) investigated the effects of climate change on the 392 atmospheric circulation types in southern Africa; it was found that under future climate change 393 the frequency of occurrence, amplitude and spatial configuration of the classified CTs in this 394 work are expected to change. Consequently, the relationship between atmospheric circulations 395 over southern Africa and temperature variability will be impacted by climate change. As 396 documented in Ibebuchi (2023), CMIP6 climate models projected summer periods of weaker 397 circulation at the western branch of the Mascarene high due to warmer southwest Indian Ocean 398 temperatures (i.e., CT4-) as well as summer periods of stronger circulation at the western branch 399 400 of the Mascarene high due to a more positive SAM (i.e., CT3+). As shown in Figure 2a, a more 401 positive SAM i.e., CT4+ (warmer southwest Indian Ocean i.e., CT3-) will imply warmer temperatures over the southwestern (southeastern) parts of southern Africa. 402

The climate of Southern Africa is influenced by a complex interplay of feedbacks between the 403 atmosphere and surface processes. Changes in vegetation cover can impact the surface albedo. 404 surface roughness, and evapotranspiration rates, which affect the temperature patterns in a 405 region (e.g., Tran et al. 2017). For example, Clark and Arritt (1995) reported that vegetative 406 cover can have a direct influence on increasing convective precipitation, by not only providing 407 shade to reduce the conduction of heat into the soil (and thus increasing available heat energy 408 in the atmosphere), but also via the extraction of soil moisture. Moreover, a study by 409 Engelbrecht et al. (2015) used a regional climate model to project future temperature changes 410 in Africa, finding that in (southern) Africa as temperature increases, the soils become drier 411 412 through enhanced evaporation; and this, in turn, impacts vegetation.

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#### 417 **Conclusions**

This study investigated the mechanisms through which synoptic circulations control atmospheric layer thickness, temperature, relative and specific humidity in southern Africa, during the austral summer season. We also examined the impact of the SAM, IOD, ENSO and SIOD on temperatures in southern Africa. Our results on the synoptic circulations that modulate summer temperature in southern Africa can be summarized as follows:

The temperature in southern Africa exhibits spatial heterogeneity under the classified
 CTs. Thus, the distinct regional climate zones within the southern African landmass
 contribute to defining the spatial variations of temperature anomalies under a given CT.

2. Generally, two asymmetric variabilities in the semi-permanent high-pressure system 426 influence regional temperature variations in southern Africa. First is when the South 427 Atlantic Ocean high pressure is closed, and ridges at the southern coast of southern 428 Africa; this synoptic circulation pattern is associated with the southeast wind to the 429 southern parts of southern Africa from the ridging high pressure and causes cold air 430 advection and negative temperature anomalies in the southern tip of southern Africa. 431 Conversely, when the South Atlantic high is weak on the southern coast of southern 432 Africa, westerly winds dominate over the southern coast of southern Africa, the 433 thickness anomaly value is positive, and the temperature anomaly is positive in the 434 435 southern parts of southern Africa. Second, when the anticyclonic circulation at the western branch of the Mascarene high is stronger, cold air advection by southeast winds 436 is enhanced into large parts of southern Africa, reducing the atmospheric thickness layer 437 and resulting in negative temperature anomalies. Conversely, when the anticyclonic 438 circulation at the western branch of the Mascarene high is weak during the summer 439 season, atmospheric blocking of the low-pressure system from the tropics is weakened 440 as well, allowing enhanced cyclonic/convective activity in the southwest Indian Ocean; 441 the implication is enhanced warm air advection into parts of southern Africa, increased 442 443 thickness and positive temperature anomalies in parts of southern Africa. Hence when conditions are favorable, southeast winds from the semi-permanent high-pressure 444 systems are mostly associated with colder temperatures in southern Africa. 445

Other variabilities that modulate summer temperature anomalies in southern Africa and
interfere with circulations in the high-pressure systems are the formation of continental
lows and the trough in the Mozambique Channel. Continental lows increase instability
at the boundary layer, increase thickness, and summer temperature anomalies. Further,
the strengthening of the Mozambique Channel trough coupled with a weak South

451 Atlantic anticyclone at the southern coast of southern Africa can be implicated to cause 452 widespread warming over South Africa. This is because the aforementioned circulation 453 pattern (i.e., CT9 -) increases the pressure gradient between Mascarene high and the 454 low pressure in the Mozambique Channel so that cold air advection to South Africa is 455 significantly limited.

- 456 4. Overall, at the synoptic scale, summer temperature anomalies in Madagascar are
  457 modulated by cold advection from the Mascarene high and warm advection resulting
  458 from a weaker Mascarene high and warmer southwest Indian Ocean waters.
- 5. Climate drivers such as SAM, ENSO, IOD and the SIOD impact temperatures over
  southern Africa. El Niño and positive SIOD are associated with temperature increase
  over the central parts of southern Africa. Positive SAM and positive IOD are associated
  with temperature increase over the southwestern parts of southern Africa, while
  additionally positive IOD is linked to temperature increase over the northwestern and
  northeastern parts of southern Africa.

465

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- 612
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- 614 FIGURES
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a)





- (a) and 2 m temperature anomaly during DJF for the classified CTs in Fig. 1



Fig. 3 Standardized composite anomaly maps of 850 hPa relative humidity during DJF for theclassified CTs in Fig. 1



Fig. 4 Composite maps of SLP (black contours) and 850 hPa wind (green vectors) for theclassified CTs in Fig. 1. The Contour interval is 3 hPa



Fig. 5 Regression map of a) Nino 3.4 index; b) IOD index; c) SAM index; and d) SIOD index
d) onto annual mean temperature anomaly in southern Africa from 1979 to 2021. Stippling
shows grid points that are not statistically significant at a 95% confidence level.

Appendix A 



Fig. A1 Annual cycle of the CTs in Fig. 1. Y axis is the relative frequency of occurrence of theCTs and the x-axis is the calendar months.

#### 661



Fig. A2 Standardized composite anomaly maps of 850 hPa specific humidity during DJF forthe CTs in Fig. 1

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# 667 <u>Classification of circulation types using the obliquely rotated T-mode PCA</u>

The classification of the CTs is completely eigenvector-based (Richman 1981, 1986). It involves the application of obliquely rotated PCA to the T-mode matrix (variable or column matrix is time series and row matrix is grid points) of z-score standardized SLP field. The SLP field is standardized to give equal weight to all days in the analysis period. Singular value decomposition is applied to the correlation matrix, containing the correlation between SLP observations at each time in the analysis period, to obtain the PC scores, eigenvalues, and

eigenvectors. The PC scores capture the spatial variability patterns, and the eigenvectors localize the spatial patterns in time. To make the eigenvectors responsive to rotation and to become correlations between the PC scores and the standardized SLP field, the eigenvectors are multiplied by the square root of their corresponding eigenvalues so that they become PC loadings that can be longer than a unit length. To enhance the physical interpretability of the PC loadings they were rotated obliquely using Promax at a power of 2. The oblique rotation simplifies the structure of the PCs by maximizing the number of near-zero loadings, so that unique time series with large loading magnitudes are clustered under a given PC. Given that we desire to analyse both dominant and (rare) patterns associated with extremes, of which the latter is often located in higher order PCs, we decide on the optimal number of PCs to retain and rotate by iteratively increasing the number of PCs until the next added PC is least unique from the already retained PCs. Since each PCs contains asymmetric patterns separated by the sign of the PC loadings, following its efficacy, in previous studies,  $\pm 0.2$  is used in this study to separate PC loadings in the signal range from PC loadings in the noise range. Introducing the threshold allows a day can be classified under more than one PC pattern insofar as the PC has signal magnitude > [0.2] on that day. Hence each retained PC gives two asymmetric classes (i.e., clusters above or below the  $\pm 0.2$  threshold) and the SLP mean of the days in a given class is the CT. 

Circulation pattern controls of summer temperature anomalies in
southern Africa
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724 Abstract

This study investigates the relationship between circulation patterns and austral summer 725 temperature anomalies in southern Africa. The results show that the formation of continental 726 lows tends to increase the partial atmospheric layer thickness. Further, the distinct variabilities 727 728 of high and low pressure under the circulation types, influence air mass advection from the adjacent oceans, as well as atmospheric stability over land. Stronger anticyclonic circulation at 729 730 the western branch of the Mascarene high enhances low-level cold air advection by southeast winds, decreases thickness, and lowers the temperature over a majority of the land in southern 731 Africa. Conversely, a weaker Mascarene high, coupled with enhanced cyclonic activity in the 732 southwest Indian Ocean increases low-level warm air advection and increases temperature 733 anomalies over vast regions in southern Africa. The ridging of a closed South Atlantic 734 anticyclone at the southern coast of southern Africa results in colder temperatures in the tip of 735 southern Africa due to enhanced low-level cold air advection by southeast winds. However, 736 when the ridge is weak and westerly winds dominate the southern coast of southern Africa, 737 temperature increases in these areas. The northward track of the Southern Hemisphere mid-738 latitude cyclone, which can be linked to the negative Southern Annular Mode, reduces the 739 temperature in the southwestern part of southern Africa. Also, during the analysis period, El 740 Niño and the positive Subtropical Indian Ocean dipole were associated with temperature 741 increases over the central parts of southern Africa; while the positive Indian Ocean dipole was 742 743 linked to a temperature increase over the northeastern, northwestern, and southwestern parts of southern Africa. 744

Keywords: temperature, circulation types, Subtropical Indian Ocean dipole, Southern Annular
Mode, El Niño, Indian Ocean dipole, Mascarene high, South Atlantic anticyclone

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## 748 Highlights

The spatiotemporal variations of temperature over southern Africa are coupled
 with large-scale circulation patterns modulating warm and cold air advection
 Climate drivers heterogeneously influence temperature over the land in southern

Africa through control of regional circulation patterns.

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# 756 **1. Introduction**

Rising global temperatures resulting from both anthropogenic emissions and natural variability 757 impact virtually all aspects of livelihood, ranging from mortality rate (Lee and Sheridan, 2018; 758 Sheridan and Dixon, 2017) and labor productivity (Knittel et al., 2020) to the rate and 759 magnitude of climate extremes (Alimonti et al., 2022), among others. Climate predictions and 760 761 projections are important for mitigating the consequences of rising temperatures by enhancing preparedness against extreme climate events as well as developing climate policies against 762 763 future dangerous climate change. A major challenge in forecasting climate events, such as extreme temperatures, stems from the incomplete understanding of the physical mechanisms 764 that drive the climate (Flato et al., 2014). Therefore, there is a need for studies that aim to 765 improve the understanding of the atmospheric processes that govern the earth's climate. 766 Enhanced knowledge of the atmospheric processes that govern the climate can serve as a 767 36

benchmark for improving climate forecasts. In the regional context of southern Africa, which
is vulnerable to anthropogenic climate change due to its economic conditions and geographical
location at the descent region of the Hadley circulation (Baudoin et al., 2017), this study aims
to enhance the understanding of the large scale circulations that modulate the summer
temperatures in southern Africa.

Several studies have hinted at the role of climate drivers in modulating atmospheric circulations 773 over southern Africa (Dieppois et al., 2015; Hoell et al., 2015; Lyon and Mason, 2007; 774 Malherbe et al., 2014; Manatsa et al., 2017; Reason and Rouault, 2005) and other regions in the 775 globe (Pirhalla et al., 2022). Among the climate drivers, the sea surface temperature (SST) 776 patterns of the Subtropical Indian Ocean Dipole (SIOD) and the Southern Annular Mode 777 (SAM) have a direct impact on the climate of southern Africa because they exist in the mid-778 latitude oceans of the Southern hemisphere (i.e., the subtropical Indian Ocean, and the Southern 779 Ocean). In addition, the Indian Ocean Dipole (IOD) and the El Niño Southern Oscillation 780 (ENSO) have a remote influence on the climate of southern Africa (Reason and Jagadheesha, 781 2005). Moreover, the imprint of the ENSO signal can be found in the SAM, IOD and SIOD 782 modes since all the climate drivers generally influence SST anomalies in the southwest Indian 783 Ocean as well as the anticyclonic circulation of the Mascarene high. (Ding et al., 2012; 784 Ibebuchi, 2021; Morioka et al., 2015). Therefore, this study also investigates the impact of the 785 climate drivers on temperature variability in southern Africa. 786

The link between synoptic circulations and precipitation in southern Africa has been widely documented (Burls et al., 2019; Engelbrecht et al., 2015; Engelbrecht and Landman, 2016; Lennard and Hegerl, 2015; Mahlalela et al., 2019; Wolski et al., 2018). Also, studies have highlighted the possible impact of the SAM on temperature anomalies in southern Africa. For example, using regression analysis, (Gillett et al., 2006) investigated the impact of positive

SAM on temperatures in the Southern Hemisphere (with the inclusion of southern Africa), 792 793 however, the negative SAM was not considered and the associating physical processes were not analyzed in detail. Also for other regions in the Southern Hemisphere, such as Australia and 794 South America, studies have addressed the relationship between the SAM and surface 795 temperatures (Hendon et al., 2007; Silvestri and Vera, 2009). Further, the majority of available 796 works of literature on the IOD and SIOD, with regard to the climate of southern Africa, focus 797 on the relationship between the climate drivers and rainfall variability in southern Africa 798 (Behera and Yamagata, 2001; Hoell et al., 2015; Ibebuchi, 2023; Reason, 2001), and less 799 attention is given to temperature. Given that these climate drivers impact the amplitude and 800 801 frequency of circulation types (CTs), this study goes further to decompose in time, the distinct circulations in southern Africa and then analyze the mechanisms through which the individual 802 CTs impact surface temperature and relative humidity (that contributes to heat stress) in 803 804 southern Africa. Thus, the major added value of this study to the literature is the improved understanding of the physical processes through which large-scale circulations influence the 805 spatial variations and magnitude of summer temperatures in southern Africa. 806

This study is structured as follows, Section 2 presents the data and methods the study is based on; the results are presented in Section 3; Section 4 contains the discussion of the results and conclusions.

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## 814 2 Data and methodology

815 2.1 Data

816 High-resolution reanalysis data is obtained from ERA5 (Hersbach et al., 2020). The ERA5 reanalysis data sets obtained are sea level pressure (SLP); 850 hPa wind vectors, relative 817 818 humidity, specific humidity, 850 hPa geopotential height; and 1000 hPa geopotential height. Gridded observed 2 m average temperature is obtained from the Climate Prediction Center 819 (CPC) Global Unified 820 Temperature dataset (https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html). All data sets are obtained at daily 821 temporal resolution from 1979 to 2021. The horizontal resolution of the ERA5 reanalysis data 822 is 0.25° longitude and latitude, and 0.5° longitude and latitude for the gridded CPC 2 m 823 temperature data. Also, correspondence between ERA5 and gridded CPC temperature data has 824 been reported (Roffe and van der Walt 2023), which strengthens the choice of using both data 825 826 sets for our analysis.

827 2.2 Methodology

This current study is incremental work from previous research that applied circulation typing 828 to study circulations in southern Africa at multiple spatial scales (Ibebuchi, 2023a), hence the 829 same classified CTs are used. A major advancement in this study is that these same CTs are 830 now being used to investigate the mechanisms through which circulation patterns modulate the 831 magnitude and spatial variations of austral summer (i.e., December to February - DJF) 832 temperature in southern Africa. We consider austral summer as that is when absolute 833 temperatures are highest in the study region, and thus, most impactful. The spatial extent for 834 the CT classification is 0° to 50.25°S and 5.25°E to 55.25°E (Fig. 1). The adjacent maritime 835 836 regions that act as moisture sources to the landmass were included. Further, when the CTs are linked to temperature over the landmass, typically, to make a distinction with the tropical 837 838 landmass, southern Africa might be defined to include landmass from about 10°S and poleward. Nonetheless, we have included the tropical latitudes (i.e., up to 0° latitude) to capture variability
in the cross-equatorial northeast trade winds. This is because the cross-equatorial northeast
trade winds play a role in defining convergence in the Angola Low and the Mozambique
Channel that both impact the climate of southern Africa. However, we focus our analysis on
the temperature anomalies under the distinct CTs on land from 10°S and poleward.

The obliquely rotated T-mode (variable is time series and observation is grid points) principal 844 component analysis (Compagnucci and Richman, 2008) applied in a fuzzy approach is used for 845 the classification of the CTs. The details of the classification approach are given in Appendix 846 A. The classification of the CTs with rotated T-mode PCA is a time decomposition technique. 847 Singular value decomposition is applied to the correlation matrix containing the correlation 848 between the SLP fields at the distinct daily time series in the analysis period. The resulting PC 849 loadings which designate the amplitude of the set of circulation patterns at a given day is used 850 to assign CT(s) within the signal range to a given day, which imply the CTs that occurred on 851 the day in question. 852

We apply map composting of different climate variables to examine the relationship between 853 the classified CTs and DJF temperatures in southern Africa. We have used SLP composites to 854 investigate the horizontal variations of pressure under each of the CTs, which can also be 855 suitable for characterizing continental heating (i.e., in areas with continental lows) as well as 856 atmospheric stability at the boundary layer, and convective activity over the adjacent oceans. 857 We defined the thickness of the atmospheric layer as the vertical distance in meters between 858 two the 1000 hPa and 850 hPa pressure levels. This is because, we found that from iterative 859 pre-evaluations, relatively, the thickness layer values between 1000 hPa and 850 hPa accurately 860 capture the spatiotemporal variations of 2 m mean temperature values in the study region. Thus, 861 we define thickness as the difference between the height at 850 hPa and the height at 1000 hPa. 862

Positive thickness values are related to positive temperature anomalies and negative thickness values are related to negative temperature anomalies. In addition to analyzing the SLP and atmospheric layer thickness, composites of 850 hPa (that is, the height above the eastern escarpment of southern Africa) winds are analyzed to establish the prevailing winds under each CT. Thus, analyzing the SLP, wind directions, and thickness enables documenting low-level cold and warm air advection under each CT.

Given the high seasonality of temperature, to enable a robust diagnosis of the temperature 869 values and other variables used to diagnose temperature patterns under each CT, we rely on 870 composite anomaly values during DJF. The composite anomaly is calculated as the difference 871 872 between the days assigned to a CT and the 1981-2010 DJF climatology of the variable in question. Regression analysis was used to investigate, at each grid point in the region of 873 assessment, the association between climate drivers (SAM, ENSO, IOD and SIOD) and 874 temperature variability in southern Africa. The statistical significance of the association, based 875 on the regression model, is tested at a 95% confidence level. To control for false discovery rate 876 in the multiple hypothesis testing, we used the Benjamini-Hochberg procedure (Benjamini, and 877 Yekutieli, 2001), which assumes that the hypotheses being tested are independent. 878

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#### 881 **3 Results**

The standardized SLP composites for the days when the classified CTs occurred during the analysis period are shown in Figure 1. The CTs in Figure 1 were externally validated using SLP data from a different reanalysis product (Ibebuchi 2022c) and a suite of CMIP6 general circulation models (Ibebuchi 2022b). While the CTs are not confined to occur in any specific season, the spatiotemporal structure and dynamics of the CTs can also be influenced by seasonal 41 variations in large-scale processes such as diabatic heating, thus the CTs tend to be dominant
in specific seasons when the prevailing (seasonal) atmospheric condition favors their
mechanisms (Fig. A1). Pressure variations over the adjacent oceans are used to infer convective
activity in these locations – anticyclonic (cyclonic) circulations over the oceans imply
suppressed (enhanced) convection. Similarly, pressure variations over the landmass can be used
to infer continental heating or atmospheric stability at the boundary layer – anticyclonic
(cyclonic) circulations over the land imply a relatively stable (unstable) atmosphere.

Next, for the classified CTs in Fig. 1, we look at the composite anomaly patterns of DJF atmospheric layer thickness between 1000 hPa to 850 hPa (Fig. 2a), temperature (Fig. 2b), and 850 hPa relative humidity (Fig. 3); and composite patterns of 850 hPa wind vectors (Fig. 4). These figures will be interpreted coherently, based on the asymmetric patterns of the CTs (i.e., the positive phase and the negative phase). We focus our analysis of the composite anomaly maps in Figs 2 to 3 mostly on the regions (i.e., group of grid points) with robust changes.

Generally, the composite patterns reveal that under each CT, the DJF temperature anomalies 900 901 are characterized by spatial heterogeneity (Fig. 2b). A possible explanation for the spatial heterogeneity of temperature anomalies under each CT can be due to the distinct regional 902 climates in southern Africa. Under the asymmetry of each CT (i.e., the negative and positive 903 phases) temperature variations are least in the deep tropics  $(10^{\circ}S - 0^{\circ})$  mostly because, diabatic 904 heating (and SLP) have fewer variations in the deep tropics. However, as noted earlier, the 905 major focus of the temperature anomalies is on southern Africa. Fig. 2a indicates that for the 906 907 asymmetry of a given CT, and depending on the circulation features, there appear to be coherent temperature patterns in the central parts of southern Africa – mostly at landmasses close to the 908 909 southwest Indian Ocean - at the southwestern parts of southern Africa, characterized by the Mediterranean type of climate, and at the southern tip of southern Africa. Thus, the regional 910

911 climate types of the aforementioned regions contribute to defining the overall spatial912 heterogeneity of the temperature anomaly patterns under each CT.

913 CT1+/CT1 – present variations in the subtropical ridge south of South Africa. Under CT1+ 914 the mid-latitude cyclone is relatively more enhanced at the south coast of southern Africa (Fig. 1). The associating wind pattern at the south coast of southern Africa under CT1+ is westerly 915 (Fig. 4), and thickness anomaly is positive over South Africa except for the western tips, and 916 also thickness anomaly is positive at the central parts of southern Africa except for large parts 917 of Mozambique and Madagascar (Fig. 2a). Regions with positive thickness anomaly indicate 918 warm advection and are generally associated with a positive temperature anomaly (Fig. 2b) as 919 well as a negative relative humidity anomaly (Fig. 3). 920

Conversely, under CT1 – the South Atlantic ridge is enhanced at the south coast of southern 921 Africa, driving cold air, southeast into the southern African domain (Fig. 1 and Fig. 4), and 922 cyclonic activity is relatively more enhanced in the southwest Indian Ocean compared to CT1+. 923 Given the cold air advection on the south coast of southern Africa, the thickness anomaly is 924 negative over vast regions in South Africa (Fig. 2a). Under CT1 -, the thickness anomaly is 925 also negative over the central domains of southern Africa where the cold air from the South 926 Atlantic high-pressure system advects, except for parts of Mozambique and Madagascar given 927 the enhanced low-pressure system (that is, convective activity) over the oceans that results to 928 warm air advection. Resultantly, regions with positive (negative) thickness anomaly values are 929 generally characterized by positive (negative) temperature anomalies and negative (positive) 930 relative humidity anomaly values (Fig. 2 and Fig. 3). The analysis of CT1+/CT1 - indicates 931 that cold advection resulting from circulation at the subtropical ridge implies lower thickness 932 and lower temperature values in the regions where the cold air penetrates; similarly, 933

enhancement of convective (or cyclonic activity) in the southwest Indian Ocean, results inwarmer temperatures at the coastal landmasses.

Further, CT2+ presents circulation variability associated with enhancement of the anticyclonic 936 937 circulation at the western branch of the Mascarene high and enhancement of the mid-latitude cyclone south of South Africa (Fig. 1). Hence the wind patterns are southeast over the southwest 938 Indian Ocean, driven by the Mascarene high, and westerly, at the south coast of southern Africa 939 (Fig. 4). Given that cold air advection from the South Atlantic anticyclone is weakened at the 940 south coast of southern Africa, thickness anomaly is strongly positive at the south coast of 941 southern Africa (Fig. 2a) as well as temperature anomaly (Fig. 2b). However, since the 942 Mascarene high drives colder southeast winds into large parts of southern Africa, thickness 943 anomaly is negative and temperature anomaly is negative over large parts of southern Africa. 944 Resultantly, over the central parts of southern Africa, the pattern of CT2+ brings positive 945 relative humidity anomaly, but negative relative humidity anomaly over parts of the southern 946 tips that are anomalously warmer (Fig. 3). CT2 - is characterized by opposing (and 947 asymmetric) circulation features, relative to CT2+, and so brings warmer (colder) temperatures 948 over the central parts (southern tips) of southern Africa. 949

CT3+ is related to positive SAM and CT3 – is related to negative SAM (Ibebuchi 2021). We 950 recall that the SAM through its control of circulation in the mid-latitudes significantly impacts 951 the regions in southern Africa with the Mediterranean type of climate, that is, the Western Cape 952 Province located in the southwestern part of southern Africa. Based on the climatology of the 953 regions in southern Africa with the Mediterranean type of climate, the enhancement of the mid-954 latitude cyclones on the south coast of southern Africa under CT3 - (Fig. 1), and the 955 associating westerly winds (Fig. 4) allow cold fronts to sweep across the southwestern parts of 956 southern Africa. Thus, under CT3 – Figure 2a shows a zonal dipole-like structure of thickness 957

anomaly whereby the eastern (western) region of South Africa has positive (negative) thickness 958 959 anomaly values. As a result, temperature anomaly is positive (negative) in the eastern (western) region of South Africa (Fig. 2b). Also, the relative humidity anomaly is negative (positive) in 960 the eastern (western) region of South Africa (Fig. 3) - an indication of a saturated atmosphere 961 that eventually results in frontal rainfall in the western domain of South Africa. For the large 962 parts in the central regions of southern Africa, Fig. 2 shows that under CT3 - thickness and 963 temperature anomalies are positive and relative humidity anomaly is equally negative (Fig. 3). 964 The reason is that while CT3 - is dominant in winter seasons (Fig. A1), nonetheless during its 965 occurrence in DJF, SST and convergence are higher in the southwest Indian Ocean, and 966 continental heating is equally higher compared to austral winter (JJA). Thus, during DJF, the 967 968 displacement of atmospheric blocking by the western branch of the Mascarene high, and the resultant weakening of cold advection, allows warmer ocean waters in the southwest Indian 969 Ocean (Vigaud et al., 2009). Hence, during the occurrence of CT3 - in DJF, warm air 970 advection from the southwest Indian Ocean, driven by the northeast trade winds (Fig. 4), leads 971 to a warmer climate in large parts of southern Africa. 972

Further, CT3+ is associated with increased SLP in the mid-latitudes, but not the closed and 973 elongated South Atlantic anticyclone that results in cold air advection from the Southern Ocean 974 to large parts of South Africa (cf CT1 - in Fig. 4). In this case (of CT3+), cold air advection 975 976 to the eastern part of South Africa results from southeast winds driven by the western branch 977 of the Mascarene high. Therefore, under CT3+ due to the cold air advection, the eastern part of South Africa has a negative thickness anomaly (Fig. 2a), negative temperature anomaly (Fig. 978 2b), and positive relative humidity anomaly (Fig. 3). Since westerly winds and the associating 979 cold fronts are suppressed south of South Africa, the western region of South Africa has a 980 positive thickness anomaly (Fig. 2a), positive temperature anomaly (Fig. 2b), and negative 981 relative humidity anomaly (Fig. 3). For the central parts of southern Africa, due to the enhanced 982 45

cold air advection by southeast winds driven by Mascarene high, negative thickness and
temperature anomaly prevails over the central regions (Fig. 2) coupled with positive relative
humidity anomaly (Fig. 3).

986 For the other CTs, similar patterns of variations in the pressure systems and the associating cold (warm) air advection, reduces (increase) the thickness of the air layer, resulting in negative 987 (positive) temperature anomalies in preferred regions. For example, CT5 - reinforces the 988 findings from CT1 – that when the South Atlantic Ocean high pressure is closed, ridging at 989 the southern coast of southern Africa, large parts of South Africa become colder due to 990 991 enhanced cold air advection (Fig. 1 to Fig. 4); and CT6+ depicts very similar pattern but with stronger amplitude. CT6 - also reinforce previous findings that when southeast winds are 992 enhanced by the circulation at the western branch of the Mascarene high then cold air advection 993 to the eastern regions and large parts of southern Africa implies colder conditions in the study 994 domain (Fig. 1 to Fig. 4). 995

CT7+/CT7 - is related to the positive/negative SIOD (Ibebuchi, 2023). Under CT7+/CT7 -996 the southwest Indian Ocean is warmer/cooler, based on the enhanced cyclonic/anticyclonic 997 activity; in addition, the boundary layer in large parts of southern Africa is relatively 998 unstable/stable under CT7+/CT7 - . For CT7+, the pressure gradient between the South 999 Atlantic high-pressure and the continental low results in cold air advection from the South 1000 1001 Atlantic Ocean and the Southern Ocean to South Africa, but warm air advection from the (warmer) southwest Indian Ocean to the central regions of South Africa (Fig. 1, Fig. 2a and Fig. 1002 4). Therefore, while colder temperatures are evident in the south and southwestern parts of 1003 1004 South Africa, CT7+ brings warmer temperatures to the central domains of southern Africa (Fig. 2 to Fig. 3). Conversely, in CT7 - cold advection from the southwest Indian Ocean prevails 1005 1006 over the central parts of southern Africa (Fig. 2a and Fig. 4) and coupled with the stable

atmosphere, leads to negative temperature anomalies over the central parts of southern Africa
(Fig. 2b). But due to enhanced blocking of the mid-latitude cyclones at the southern coast of
southern Africa, the activity of cold fronts that bring colder temperatures to the southwestern
part of southern Africa is weakened so that the southwestern parts of southern Africa have
positive temperature anomalies.

CT9 – is remarkable and results in widespread positive temperature anomaly in South Africa 1012 (Fig. 2b). This is because of the meridional pressure gradient between the low pressure in the 1013 Mozambique Channel and the western branch of the Mascarene implying that colder southeast 1014 winds from the Mascarene high do not penetrate the eastern parts of South Africa (Fig. 1 and 1015 Fig. 4) coupled with the absence of the closed South Atlantic anticyclone at the southern coast 1016 of southern Africa. However, the pattern of CT9 - also imply that colder air from the western1017 branch of the Mascarene high move towards the low pressure in the Mozambique Channel, 1018 penetrating the central parts of South Africa and partly adjusting to westerly towards 1019 Madagascar (Fig. 4); this flow pattern brings negative thickness anomaly and colder 1020 temperatures to the central parts of southern Africa. 1021

From Fig. A2, regions with a robust decrease in temperatures, for example, the western parts in 1022 CT3 - and CT6+, and the eastern parts in CT7 - (Fig. 2b), are mostly associated with low 1023 specific humidity; and regions with a robust increase in temperatures are mostly associated with 1024 high specific humidity, for example, the southeastern parts under CT3 - and CT6+ and the1025 southern parts under CT9 - . This is generally because a warmer (colder) atmosphere can hold 1026 more (less) moisture. However, there are exceptions to this, for example under CT1 -, where 1027 1028 negative temperature anomaly at the southern parts of southern Africa is associated with positive specific humidity anomaly. This is because moisture content over the landmass is also 1029 1030 modulated by other factors such as advection and moisture uptake over the oceans.

1031 Relationship between climatic modes and temperature variability over southern Africa

1032 Previous studies linked the CTs in Fig. 1 to climatic modes of variability. CT3+/CT3 - wasfound to be modulated by the SAM (Ibebuchi 2021a) such that CT3+(CT3-) is related to 1033 1034 positive (negative) SAM. CT5+/CT5 - was found to be modulated by the Nino 3.4 index (Ibebuchi 2021b), such that CT5 – (CT5+) is related to El Niño (La Niña). CT7+/CT7 – was 1035 found to be modulated by the SIOD (Ibebuchi 2023a), such that CT7+(CT7-) is related to 1036 the positive (negative) SIOD. CT9+/CT9 - was equally found to be modulated by the IOD 1037 (Ibebuchi 2023b) such that CT9+(CT9-) is related to the negative (positive) IOD. The 1038 frequency of these CTs is modulated by these large-scale modes of variability, and thus 1039 represent the regional-scale manifestations of the modes. That is the CTs are the physical 1040 mechanism through which these modes impact southern African temperatures. 1041

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In addition to the control of DJF temperatures by the climatic modes indirectly through the CTs, 1043 as shown in Figs 1 and 2, we also apply regression maps to examine the *direct* association 1044 between these well-known climatic modes and temperature in southern Africa. Figure 5 shows 1045 this association is spatially heterogeneous with a dipole structure especially over the 1046 southwestern and east-central parts of southern Africa. In terms of significant temperature 1047 increase, from Fig. 5, El Niño is associated with an increase in temperature over the central 1048 parts of southern Africa. The positive phase of the IOD is associated with an increase in 1049 temperature over the northeastern, northwestern and southwestern parts of southern Africa. The 1050 positive SAM is associated with temperature increase, mostly over the southwestern parts of 1051 southern Africa, while the SIOD is associated with temperature increase over the 1052 central/northcentral parts of southern Africa. 1053

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## 1058 4 Discussion

The study by Liu et al. (2022) found that high-frequency atmospheric signals are crucial for 1059 1060 improving sub-seasonal predictability of precipitation in most land monsoon regions. The high 1061 frequency intraseasonal variability was found to be responsible for a significant portion of the total intraseasonal variability and generally dominates the sub-seasonal predictability of various 1062 land monsoons. Liu et al. (2022) suggested that high frequency variability is necessary for 1063 enhancing predictability of climate variables such as precipitation and temperature at sub-1064 seasonal time scales. The inclusion of high frequency variability in the CTs created in this work 1065 with the application of rotated T-mode PCA to daily SLP (Ibebuchi 2022a), in line with the 1066 recommendation of Liu et al. (2022), is necessary for the enhanced predictability of climate 1067 variables such as precipitation and temperature. This is because the multi-scale interaction 1068 between synoptic and inter-annual signals is connected by tropical and extratropical 1069 atmospheric signals affecting these CTs, on the intraseasonal time scales. 1070

The majority of the studies linking atmospheric circulations to the climate of southern Africa 1071 1072 are focused on precipitation (Barimalala et al., 2020; Fauchereau et al., 2009; Jury, 2015). Other 1073 studies have equally examined the relationship between climate drivers and precipitation 1074 variability in southern Africa (Hart et al., 2013; Hoell et al., 2015; Reason and Jagadheesha, 2005). Indeed, the studies concur that the hydroclimate of southern Africa is modulated by 1075 1076 large-scale circulations. However, little attention has been given to the relationship between synoptic to large-scale circulations in southern Africa and temperature anomalies in southern 1077 1078 African landmass. Among such studies, Gillet et al. (2006) investigated the relationship 49

between the SAM and temperature in Southern Hemisphere landmasses. The authors found 1079 1080 that positive SAM can be related to temperature increases over the southwestern parts of southern Africa, but temperature decreases over some northeastern parts. The results from Gillet 1081 et al. (2006) are consistent with the regression analysis between annual temperature anomalies 1082 and the SAM index in this study (Fig. 5). Also, the circulations through which positive SAM 1083 increases temperature of the southwestern parts of southern Africa (i.e., CT3+) is shown to be 1084 1085 a poleward shift of westerly winds, which in turn suppresses the passage of cold fronts over the southwestern parts of southern Africa. The positive IOD increases SST over the tropical western 1086 Indian Ocean (Saji, 1999) and alters atmospheric circulations over southern Africa (Mantasa et 1087 1088 al. 2011). Our results indicate that the SST pattern of the positive IOD is linked to temperature increase over Madagascar, the northeastern, northwestern and southwestern parts of southern 1089 Africa. Similarly, during El Niño and positive SIOD events, which are both associated with 1090 1091 SST increase in the southwest Indian Ocean, temperature increase in some central parts of southern Africa can be expected. Also, El Niño and the positive SIOD appears to be related to 1092 temperature decreases over the southwestern parts of southern Africa possibly due to weakening 1093 of high-pressure adjacent to South Africa. 1094

A previous study by Ibebuchi (2022b) investigated the effects of climate change on the 1095 atmospheric circulation types in southern Africa; it was found that under future climate change 1096 the frequency of occurrence, amplitude and spatial configuration of the classified CTs in this 1097 work are expected to change. Consequently, the relationship between atmospheric circulations 1098 over southern Africa and temperature variability will be impacted by climate change. As 1099 1100 documented in Ibebuchi (2023), CMIP6 climate models projected summer periods of weaker 1101 circulation at the western branch of the Mascarene high due to warmer southwest Indian Ocean temperatures (i.e., CT4-) as well as summer periods of stronger circulation at the western branch 1102 1103 of the Mascarene high due to a more positive SAM (i.e., CT3+). As shown in Figure 2a, a more 50

positive SAM i.e., CT4+ (warmer southwest Indian Ocean i.e., CT3-) will imply warmer
temperatures over the southwestern (southeastern) parts of southern Africa.

The climate of Southern Africa is influenced by a complex interplay of feedbacks between the 1106 1107 atmosphere and surface processes. Changes in vegetation cover can impact the surface albedo, surface 1108 roughness, and evapotranspiration rates, which affect the temperature patterns in a region (e.g., Tran et 1109 al. 2017). For example, Clark and Arritt (1995) reported that vegetative cover can have a direct influence 1110 on increasing convective precipitation, by not only providing shade to reduce the conduction of heat 1111 into the soil (and thus increasing available heat energy in the atmosphere), but also via the extraction of 1112 soil moisture. Moreover, a study by Engelbrecht et al. (2015) used a regional climate model to project 1113 future temperature changes in Africa, finding that in (southern) Africa as temperature increases, the soils 1114 become drier through enhanced evaporation; and this, in turn, impacts vegetation.

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## 1119 Conclusions

1120 This study investigated the mechanisms through which synoptic circulations control 1121 atmospheric layer thickness, temperature, relative and specific humidity in southern Africa, 1122 during the austral summer season. We also examined the impact of the SAM, IOD, ENSO and 1123 SIOD on temperatures in southern Africa. Our results on the synoptic circulations that modulate 1124 summer temperature in southern Africa can be summarized as follows:

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• The temperature in southern Africa exhibits spatial heterogeneity under the classified CTs. Thus, the distinct regional climate zones within the southern

1127 African landmass contribute to defining the spatial variations of temperature 1128 anomalies under a given CT.

Generally, two asymmetric variabilities in the semi-permanent high-pressure 1129 system influence regional temperature variations in southern Africa. First is 1130 when the South Atlantic Ocean high pressure is closed, and ridges at the southern 1131 coast of southern Africa; this synoptic circulation pattern is associated with the 1132 southeast wind to the southern parts of southern Africa from the ridging high 1133 pressure and causes cold air advection and negative temperature anomalies in 1134 1135 the southern tip of southern Africa. Conversely, when the South Atlantic high is weak on the southern coast of southern Africa, westerly winds dominate over 1136 the southern coast of southern Africa, the thickness anomaly value is positive, 1137 and the temperature anomaly is positive in the southern parts of southern Africa. 1138 Second, when the anticyclonic circulation at the western branch of the 1139 Mascarene high is stronger, cold air advection by southeast winds is enhanced 1140 into large parts of southern A frica, reducing the atmospheric thickness layer and 1141 resulting in negative temperature anomalies. Conversely, when the anticyclonic 1142 circulation at the western branch of the Mascarene high is weak during the 1143 summer season, atmospheric blocking of the low-pressure system from the 1144 tropics is weakened as well, allowing enhanced cyclonic/convective activity in 1145 1146 the southwest Indian Ocean; the implication is enhanced warm air advection into parts of southern Africa, increased thickness and positive temperature anomalies 1147 in parts of southern Africa. Hence when conditions are favorable, southeast 1148 1149 winds from the semi-permanent high-pressure systems are mostly associated with colder temperatures in southern Africa. 1150

Other variabilities that modulate summer temperature anomalies in southern 1151 • Africa and interfere with circulations in the high-pressure systems are the 1152 formation of continental lows and the trough in the Mozambique Channel. 1153 Continental lows increase instability at the boundary layer, increase thickness, 1154 and summer temperature anomalies. Further, the strengthening of the 1155 Mozambique Channel trough coupled with a weak South Atlantic anticyclone at 1156 the southern coast of southern Africa can be implicated to cause widespread 1157 warming over South Africa. This is because the aforementioned circulation 1158 1159 pattern (i.e., CT9 - ) increases the pressure gradient between Mascarene high and the low pressure in the Mozambique Channel so that cold air advection to 1160 South Africa is significantly limited. 1161

Overall, at the synoptic scale, summer temperature anomalies in Madagascar are
 modulated by cold advection from the Mascarene high and warm advection
 resulting from a weaker Mascarene high and warmer southwest Indian Ocean
 waters.

Climate drivers such as SAM, ENSO, IOD and the SIOD impact temperatures over southern Africa. El Niño and positive SIOD are associated with temperature increase over the central parts of southern Africa. Positive SAM and positive IOD are associated with temperature increase over the southwestern parts of southern Africa, while additionally positive IOD is linked to temperature increase over the northwestern and northeastern parts of southern Africa.

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## 1173 **Declarations**

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1181 **Ethics approval**: No human subject is involved in this study and Figures belong to the authors. The 1182 paper is also not under consideration in any Journal. There is also no conflict of interest in this paper

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- 1321 FIGURES
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- 1324 Fig. 1 z-score standardized SLP composite of the classified CTs
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- (a) and 2 m temperature anomaly during DJF for the classified CTs in Fig. 1





Fig. 3 Standardized composite anomaly maps of 850 hPa relative humidity during DJF for theclassified CTs in Fig. 1



Fig. 4 Composite maps of SLP (black contours) and 850 hPa wind (green vectors) for theclassified CTs in Fig. 1. The Contour interval is 3 hPa



Fig. 5 Regression map of a) Nino 3.4 index; b) IOD index; c) SAM index; and d) SIOD index
d) onto annual mean temperature anomaly in southern Africa from 1979 to 2021. Stippling
shows grid points that are not statistically significant at a 95% confidence level.

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#### Appendix A



Fig. A1 Annual cycle of the CTs in Fig. 1. Y axis is the relative frequency of occurrence of the CTs and the x-axis is the twelve calendar months in a year. 



Fig. A2 Standardized composite anomaly maps of 850 hPa specific humidity during DJF forthe CTs in Fig. 1

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# 1374 <u>Classification of circulation types using the obliquely rotated T-mode PCA</u>

The classification of the CTs is completely eigenvector-based (Richman 1981, 1986). It 1375 involves the application of obliquely rotated PCA to the T-mode matrix (variable or column 1376 matrix is time series and row matrix is grid points) of z-score standardized SLP field. The SLP 1377 field is standardized to give equal weight to all days in the analysis period. Singular value 1378 decomposition is applied to the correlation matrix, containing the correlation between SLP 1379 observations at each time in the analysis period, to obtain the PC scores, eigenvalues, and 1380 eigenvectors. The PC scores capture the spatial variability patterns, and the eigenvectors 1381 localize the spatial patterns in time. To make the eigenvectors responsive to rotation and to 1382 become correlations between the PC scores and the standardized SLP field, the eigenvectors 1383 65

1384	are multiplied by the square root of their corresponding eigenvalues so that they become PC
1385	loadings that can be longer than a unit length. To enhance the physical interpretability of the
1386	PC loadings they were rotated obliquely using Promax at a power of 2. The oblique rotation
1387	simplifies the structure of the PCs by maximizing the number of near-zero loadings, so that
1388	unique time series with large loading magnitudes are clustered under a given PC. Given that we
1389	desire to analyse both dominant and (rare) patterns associated with extremes, of which the latter
1390	is often located in higher order PCs, we decide on the optimal number of PCs to retain and
1391	rotate by iteratively increasing the number of PCs until the next added PC is least unique from
1392	the already retained PCs. Since each PCs contains asymmetric patterns separated by the sign of
1393	the PC loadings, following its efficacy, in previous studies, $\pm 0.2$ is used in this study to
1394	separate PC loadings in the signal range from PC loadings in the noise range. Introducing the
1395	threshold allows a day can be classified under more than one PC pattern insofar as the PC has
1396	signal magnitude > 0.2  on that day. Hence each retained PC gives two asymmetric classes (i.e.,
1397	clusters above and below the $\pm$ 0.2 threshold) and the SLP mean of the days in a given class
1398	is the CT.
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