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Intraseasonal Descriptors and Extremes in South African rainfall. Part I: Summer Climatology and Statistical Characteristics

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Abstract

2 Rainfall extremes are of major and increasing importance in semi-arid countries and their 3 variability has strong implications for water resource and climate impacts on the local societies and environment. Here, we examine intraseasonal descriptors (ISDs) and wet extremes in austral 4 summer rainfall (November-February) over South Africa (SA). Using daily observations from 5 225 rain gauges and ERA5 reanalysis between 1979 and 2015, we propose a novel typology of 6 wet extreme events based on their spatial fraction, thus differentiating large- and small-scale 7 extremes. Long-term variability of both types of extreme rainfall events is then extensively 8 9 discussed in the context of ISDs.

The results demonstrate that using 7% of spatial fraction simultaneously exceeding the local 10 threshold of the 90th percentile produces remarkable results in characterizing rainfall extremes 11 into large- and small-scale extremes. Austral summer total rainfall is found to be primarily 12 shaped by large-scale extremes which constitute more than half of the rainfall amount under 13 observation, and nearly half in ERA5. Observation (ERA5) shows an average of 8 ± 5 (20 ± 7) days 14 per season associated with large-scale extremes, which are comprised in 5 ± 3 (10 ±3) spells with 15 16 an average persistence of at least 2 days. Overall, we find a strong dependence of total rainfall on the number of wet days and wet spells that are associated with large-scale extremes. We also find 17 that large- and small-scale extremes are well-organized and spatially coherent in nature yet 18 extreme conditions during small-scale events are found sporadic over the region, contrasting 19 with large-scale events for which extreme conditions are found over a larger and coherent region. 20

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25 Key-Words

- South Africa Intraseasonal Descriptors Rainfall Extremes Climate Variability —
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29 **1.** Introduction

Most of South Africa (SA hereafter) experiences a rainy season in austral summer (November to 30 31 February; Pohl et al., 2014; Favre et al., 2016). Located at the interface between the tropics and the mid-latitudes of the Southern Hemisphere, while being surrounded by two thermally 32 33 contrasted oceans (Rouault et al., 2003), SA is subject to both the influence of tropical convection and temperate dynamics (Washington and Todd, 1999; Hart et al., 2010; Vigaud et 34 35 al., 2012). Together with highly heterogeneous vegetation and topography, these tropical and temperate influences form a mosaic of climates in association with contrasted surface 36 atmospheric characteristics such as rainfall amount and temperature which strongly vary in time 37 and space. Like many semi-arid regions in the tropics, SA depends heavily on the quality of its 38 rainy seasons, as irrigation remains rather rare in this region (Crétat et al., 2012; Masupha et al., 39 2016). Thus, rainfall variability and forecasting at fine spatial and temporal scales are a matter of 40 crucial importance for SA agriculture and economy (Conway et al., 2015). 41

In SA, during the austral summer, precipitation events are generally associated with moist 42 atmospheric convection, ranging in scale from single-cell storms to organized systems, such as 43 Mesoscale Convective Complexes (MCCs; Blamey and Reason, 2013), squall lines (Rouault et 44 al., 2002) and tropical storms (Reason and Keibel, 2004; Reason, 2007; Malherbe et al., 2012, 45 2014; Fitchett and Grab, 2014). Cut-off lows (COLs) can also lead to extreme rainfall in SA, but 46 they are rare during the summer season (Favre *et al.*, 2013). In austral summer, three key regions 47 (namely southwest Indian Ocean, tropical western Indian Ocean, and tropical southeast Atlantic 48 Ocean) are known to inject moisture flux into the southern African continent (Desbiolles et al., 49 2018; Rapolaki et al., 2019, 2020). The dominant rain-bearing systems over the region are 50 synoptic-scale cloud bands, known locally as Tropical Temperate Troughs (TTTs; Manhique et 51 al., 2011; Hart et al., 2013; Macron et al., 2014; James et al., 2020). TTTs correspond to 52 synoptic-scale cloud bands that link tropical instability over the subcontinent with an upper-53 54 tropospheric frontal system embedded in the mid-latitude westerly circulation (Todd and Washington, 1999; Todd et al., 2004; Hart et al., 2010) and bring about 30-60% of summer 55 rainfall over subtropical SA (Hart et al., 2013; Macron et al., 2014). The remaining 40-70% of 56 the summer rainfall amounts are provided by rain-bearing mechanisms linked to tropical 57

58 convection, such as regional thermal low-pressure (Reason *et al.*, 2006) or the Madden-Julian

59 Oscillation (MJO; Pohl et al., 2007). Rapolaki et al. (2019) highlighted that, over the Limpopo

60 River Basin, 48% of extreme events are associated with TTTs, 28% with tropical low-pressure

systems, 14% with mesoscale convective systems, and 10% with COLs.

Intraseasonal descriptors (hereafter ISDs) are defined as wet and dry sequences of days during 62 the rainy season (Ratan and Venugopal, 2013; Gitau et al., 2015, 2018). Examining ISDs 63 provides various intrinsic characteristics of a rainy season, such as the average number of wet 64 and dry days, persistence of spells, intensity of wet spells and total rainfall. Similar studies 65 focused on other regions, such as equatorial East Africa (Camberlin et al., 2009; Moron et al., 66 2013; Gitau et al., 2015, 2018; Philippon et al., 2015), have already demonstrated their relevance 67 and usefulness in climate diagnostics and prediction. However, analyses devoted to ISDs remain 68 quite rare in SA. Tennant and Hewitson (2002) found that anomalously wet rainy seasons tend to 69 experience a larger number of heavy rainy days (>20 mm.day⁻¹). Cook et al. (2004) highlighted 70 that moisture anomalies between wet and dry spells were strongly related to the Kalahari low. 71 They also stated that wet years were characterized by longer and more intense wet spells, rather 72 than by a greater number of wet spells (Cook et al., 2004). Similarly, previous studies found a 73 strong relationship between dry spells and El Niño Southern Oscillation (ENSO), suggesting 74 potential predictability of ISDs using this relationship (Usman and Reason, 2004; Reason et al., 75 2005; Crétat et al. 2012.). Physically, El Niño conditions could act to shift TTTs eastwards over 76 the Mozambique Channel (Nicholson and Kim, 1997; Cook, 2000, 2001; Misra, 2003; 77 Nicholson, 2003; Dieppois et al., 2015, 2016, 2019), thereby enhancing the number of dry spells 78 79 over the continent. The relationship between TTTs and ENSO has been confirmed and further 80 documented by Fauchereau et al. (2009) and Pohl et al. (2018). During La Niña a low-pressure develop over southern Africa, which is related to anomalous upward motion and enhanced 81 82 moisture fluxes into and over the region which results in rainfall surplus while El Niño is linked 83 with high-pressure over southern Africa, which is associated with anomalous downward motion and reduced moisture fluxes into and over the region which result in rainfall deficit during 84 austral summer season (Ratnam et al., 2014; Hoell et al., 2015). 85

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The severity and frequency of wet and dry extreme events are likely to increase at the global scale as a response to anthropogenic emissions of greenhouse gases (Donat *et al.*, 2016). This statement is also true for SA rainfall (Mason and Joubert, 1997; Mason *et al.*, 1999; Shongwe *et al.*, 2009; Engelbrecht *et al.*, 2013; Pinto *et al.*, 2016). Future scenarios include a combination of decreasing numbers of rainy days and increasing intensity of extreme rainy days (Pohl *et al.*, 2017), which are likely to modify the intrinsic characteristics of intraseasonal spells in the future.

This study aims to provide fundamental and up-to-date knowledge about the intrinsic 93 characteristics of wet and dry ISDs. First, we provide an overall assessment of ISDs, in which 94 extremes are embedded using the latest available observation archive and a state-of-the-art 95 reanalysis product. This study then proposes a novel typology of extreme rainfall events, based 96 on their spatial fraction as a base criterion, disentangling rainfall events into large-scale and 97 small-scale extremes. To our knowledge, there is hitherto no study that addresses the spatial 98 99 dimension in the definition of rainfall extremes over the region, despite its importance for predictions over other regions (Lu et al., 2017; Oueslati et al., 2017). In this paper, we calculate 100 and discuss the intrinsic characteristics of large- and small-scale extremes in the context of ISDs 101 over SA. The contribution made should be of interest for a wide range of the scientific 102 community working on seasonal forecasts. Such results also have considerable importance for 103 stakeholders in the environmental, agricultural, energy, water and economic sectors. A 104 companion paper will further assess how these different types of extreme events vary in time, 105 and/or are modulated by modes of large-scale variability at different timescales ranging from the 106 synoptic scale to decadal variability. 107

This paper (Part I), more specifically dedicated to the mean characteristics of rainfall extremes in SA, is organized as follows. Section 2 presents datasets and methodology. Section 3 provides an assessment of wet and dry ISDs and their summer climatology over SA. Section 4 is dedicated to defining criteria to identify extreme rainfall events and to facilitate their categorization into large- and small-scale extreme events. Section 5 addresses an assessment of large- and smallscale rainfall extremes in the definition of ISDs. Section 6 summarizes the results and establishes the main conclusions.

115 2. Data and Methodology

116 2.1. In-situ and reanalysis data

Observed daily rainfall data from 225 stations (hereafter OBS), spanning 50 years between 1965 and 2015, in which missing values represent less than 1%, were retrieved from the archives of the Water Research Commission of South Africa, which constitutes a dense network of 2625 stations (http://www.wrc.org.za; Fig. 1a).

In addition, we used state-of-the-art ERA5 reanalysis to compare and cross-validate our results. 121 ERA5 reanalysis (Copernicus Climate Change Service, 2017; Hersbach et al., 2020) is the 5th 122 generation reanalysis available from the European Center for Medium-Range Weather Forecasts 123 (ECMWF), providing $0.25^{\circ} \times 0.25^{\circ}$ resolution of hourly gridded outputs of surface and 124 atmospheric fields at the global scale, spanning 1979 to the present. ERA5 has now been 125 extended to 1950–1978 but the lack of assimilation of satellite data before 1979 raises the 126 question of the homogeneity of the dataset, the detailed evaluation of which is mandatory before 127 using it. However, it is not the scope of the present study, hence our choice to consider a 128 common period of 36-years (1979-2015). 129

130 To focus on the summer rainfall regions, a seasonality test was then applied on OBS and ERA5 (Crétat et al., 2012). Using the seasonality test, only the stations and grid-points for which at 131 least 50% of annual rainfall occurred during an extended austral summer (October to March) 132 were retained. The spatial distribution of the percentage of summer rainfall in OBS and ERA5 is 133 presented in Figure 1a-b. Regarding ERA5, all grid-points (AGP) and those nearest to OBS (NN) 134 were used in this study. The Comparing the NN and AGP fields of ERA5 is particularly 135 important in order to examine whether the network is dense enough to study rainfall extremes. 136 The NN and AGP fields of ERA5 have here been named ERA5-NN and ERA5-AGP, 137 respectively. 138

To define new metrics accounting for the typology of rainfall extremes, we focused on the austral summer season (October–March), and we analyzed two distinct baseline periods (1965–2015) for OBS and (1979–2015) for ERA5. By considering extended austral summer seasons and the two distinct baseline periods for the computation of 90th percentile values, we gained two advantages: i) a longer period for OBS ensures statistical robustness of lowfrequency decadal variability; ii) longer seasons also include rainfall onset (October) and cessation (March) months (discussed later in the companion paper). For all remaining objectives, we restricted the study to the period dating 1979–2015 and to the core of the rainy season (November–February).

148 **2.2.** Methods

149 **2.2.1.** Definition of intraseasonal descriptors at the regional scale

A threshold of 1.0 mm.day⁻¹ was used to delineate wet from dry days (Gitau *et al.*, 2013, 2015). A unified definition for wet and dry spells was obtained as suggested in several previous studies (Ratan and Venugopal, 2013; Gitau *et al.*, 2015, 2018). A wet (dry) spell is defined as a duration of "*i*" wet (dry) days preceded and followed by a dry (wet) day. As summarized in Table 1a-b, various ISDs, which are associated with wet and dry spells, are computed for each station and grid-point using OBS and ERA5. Multi-year variability of each ISD is then assessed using seasonal average computed at the regional scale (cf. Section 3).

To quantify and compare temporal variability, commonly used statistical metrics were applied to each ISD: mean (μ), standard deviation (SD), root mean square error (RMSE) and coefficient of variation (CV: Asmat and Athar, 2017; Asmat *et al.*, 2018). The Mann Kendall (MK) nonparametric test was used to perform the trend analysis (Mann, 1945; Kendall, 1957). Pearson's correlations were computed to quantify the dependence of total rainfall on ISDs.

162 **2.2.2.** Assessment of rainfall extremes

163 *a) Local threshold for rainfall extremes*

We first computed the 90th percentile of daily rainfall amount of each station and grid-point, 164 which were retrieved from the aforementioned seasonality test, over the two climatological 165 baseline periods as described in Section 2.1. The 90th percentile values were calculated by 166 removing all values below 1.0 mm.day⁻¹ for more robust identification of extreme rainfall events. 167 The comparisons of the spatial distributions of the 90th percentile, as calculated before and after 168 removing non-rainy and drizzle days (i.e. days with less than 1.0 mm), are presented in Figure 169 170 2a-b and Figure 2c-d respectively. This choice made the evaluation less sensitive to measurement accuracy and to the tendency of some numerical models to produce an excessive number of 171 drizzle events (Frei et al., 2003; Gitau et al., 2015; Maraun, 2016). A similar sensitivity to 172

drizzle days was found to be more pronounced in ERA5; thus, not removing drizzle days would have led to underestimating the 90th percentiles. The 90th percentile threshold is calculated based on a normal distribution, and we note that it did not significantly differ from one calculated based on a theoretical extreme value distribution (Gumbel distribution, cf. Fig S1c-d). This suggests the statistical robustness of the approach used to calculate the extreme thresholds in this study.

179 b) Regional threshold for rainfall extremes

A novel typology of rainfall extremes based on the spatial fraction of rainfall events is then 180 proposed. The spatial fraction of an extreme event is defined as the number of stations or grid-181 points that simultaneously reach the 90th percentile regardless of their location on the day of the 182 event. A similar methodology has been successfully used for the identification of heat waves in 183 West Africa (Oueslati et al., 2017). The principal reason for using the spatial fraction as a base 184 criterion is to differentiate localized, or small-scale extreme events from large-scale extreme 185 186 events. On one hand, small-scale extreme events are related to isolated convective cells and therefore stochastic in nature, rendering them highly unpredictable. On the other hand, large-187 188 scale extreme events are embedded in large-scale modes of climate variability, hence potentially more predictable. The spatial fraction of extreme events depends on the density of the network, 189 190 but also on its anisotropy, which is likely to cause some issues in the estimation of the spatial extension of the events because the stations are not uniformly distributed in space. In reference to 191 this assumption, the spatial fraction of events is here quantified using both the ERA5–NN and 192 ERA5-AGP fields. The comparison between ERA5-NN and ERA5-AGP fields makes it 193 possible to assess whether or not the network is dense enough to study rainfall extremes. The 194 density might not be sufficient if ERA5-NN exhibits substantially different properties than in 195 ERA5-AGP. Thus, a caution is required to interpret the results related to large- and small-scale 196 extremes as: i) the extremes are not characterized here based on environmental consequences but 197 from an atmospheric point of view considering the characteristics of rainfall field itself; ii) 198 considering the use of administrative boundaries, limitation in observation along with using NN 199 and AGP fields of ERA5 yet there is a likelihood that some events that may have major 200 environmental consequences, are not necessarily captured; iii) resolution of reanalysis is 201

particularly important to capture small-scale extreme events. Section 4.1 addresses a brief
 assessment conducted in defining a robust and relevant threshold of spatial fraction.

204 c) Spatial characteristics of rainfall extremes

Based on the defined threshold of spatial fraction, we first separated all days associated with 205 large- and small-scale extreme events (cf. Section 4.1). The average characteristics of both types 206 of extremes were then assessed in terms of frequency and intensity for each station and grid 207 point. The frequency and intensity were computed based on two criteria: i) average number of 208 days exceeding the 1.0 mm threshold during large- and small-scale extreme events; ii) average 209 number of days exceeding the 90th percentile threshold during large- and small-scale extreme 210 211 events. For the sake of clarity, in this paper, this analysis is only provided for OBS (cf. Section 4.2). 212

213 d) Spatial coherence of rainfall extremes

An analysis addressing the spatial coherence of large- and small-scale extremes is also provided. 214 Here, we analyze the density of stations recording rainfall on the days of large- and small-scale 215 extremes based on the same method used to address the spatial characteristics of extreme events 216 i.e.: i) considering all stations recording rainfall >1.0 mm on the day of the event; ii) considering 217 only those stations which exceeded their 90th percentile on the day of the event. The density of 218 the stations was assessed using a narrow bin size of 0.5° , corresponding to the stations that are 219 located within approximately 55 kilometers over latitudes and 43 kilometers over longitudes (cf. 220 Section 4.3). 221

222 2.2.3. Definition of intraseasonal descriptors associated with rainfall extremes

Large- and small-scale extreme rainy days were first obtained from the typology of rainfall extremes (cf. Section 4). Both types of events were then explicitly considered in the context of ISDs. By placing these events in the framework of ISDs, we were able to further explore the climatology and intrinsic properties of such events on an interannual timescale. Thus, several ISDs associated with large- and small-scale rainfall extremes were assessed using OBS and ERA5. A brief description of extreme ISDs is presented in Table 2. To quantify and compare temporal variability and trends, the same statistical metrics as introduced in Section 2.2.1 areused in Section 5.

3. ISDs at the regional scale

232 3.1. Multi-year variability of ISDs

The average spatial distribution of each ISD is presented in Figure 3. A spatial gradient from 233 234 southwest to northeast clearly prevails in all ISDs, as northeastern regions are much wetter than southern regions in all wet ISDs (Fig. 3a). Meanwhile, dry ISDs show larger values over the 235 southwestern regions denoting drier conditions (Fig. 3b), in agreement with Crétat *et al.* (2012). 236 When compared with OBS, ERA5 displays nearly realistic responses for all ISDs in terms of 237 spatial distribution but shows some biases when spatial average is assessed (cf. Figure S2). 238 Notably, ERA5 overestimates the values in all wet ISDs, except for the intensity of wet spells 239 (Fig. S2a). Such overestimations of seasonal rainfall in ERA5 could be related to a higher 240 number of wet spells with weaker intensity (WS and WSI panels in Fig. 3 and 4). In addition, 241 looking at the spatial distribution of biases in ISDs, we note that the intensity of wet spells is 242 underestimated throughout the region (WSI panel in Fig. S3b). Meanwhile, the overestimation of 243 the number of wet days is more pronounced from the northeast to the southwest (WD panel in 244 Fig. S3b). ERA5 also largely underestimates the number of wet spells, especially in regions of 245 higher altitude (>1400 m above sea level), such as the Drakensberg region (WS panel in Fig. 246 247 S3b). This suggests that ERA5 struggles to break the continuity of rainy days within a spell, which results in fewer but more prolonged spells (WS and WSP panels in Fig. S3b). 248

Reanalysis bias over the African continent across three generations of ECMWF reanalysis is 249 extensively discussed in Gleixner et al. (2020). This study highlights substantial improvements 250 251 in ERA5 achieved by improved model physics and data assimilation schemes. In this study, we 252 still note significant discrepancies between ERA5 and observations in ISDs as discussed above. The foremost problem in ERA5 is its ability to produce a realistic response for those regions 253 characterized by a complex terrain (Wang et al., 2019), given the fact that such regions tend to 254 have a lower number of observations. In SA, the average biases that we find in intraseasonal 255 256 characteristics could also result from similar constraints, since the northeastern part of SA is characterized by a complex topography that often enhances the biases present in numerical 257 models (Favre et al., 2016; Koseki et al., 2018). 258

Figure 4 presents the statistical distribution and multi-year variability of ISDs. Both ERA5–NN 259 and ERA5-AGP fields show consistent results in all wet and dry ISDs (see violin plots in Fig. 260 261 4), suggesting that the density of observational archives used for OBS (i.e. 225 stations) is sufficient to monitor the spatial and temporal variability of ISDs throughout SA. Regarding wet 262 ISDs, OBS and ERA5 display an average of 20±4 and 44±6 days over a season, respectively 263 (WD panel in Fig. 4a). These wet days are driven by 13±2 spells for OBS and 17±2 spells for 264 ERA5 (WS panel in Fig. 4a). For OBS (ERA5), the austral summer season is composed of 90 265 (70) dry days and 12 (16) dry spells (DD and DS panels in Fig. 4b). Although biases exist in 266 ERA5, multi-year variability appears realistic with a statistically significant correlation (>0.8) to 267 OBS for most of the wet and dry ISDs (Table 3). 268

The average number of wet days exceeding the 90th percentiles is 2 and 4 in OBS and ERA5, 269 270 respectively (WD_{P90} panel in Fig. 4a). As discussed above, ERA5 also overestimates the number of wet days, including the number of wet days exceeding the 90th percentiles. The temporal 271 272 patterns of extreme wet days and total rainfall show coherent peaks in both ISDs between 1993–94 and 1999–2000 (WD_{P90} and TR panels in Fig. 4a), which clearly indicates that the 273 274 wettest years tend to correspond to the largest seasonal occurrences of extremes. Overall, the CV remains higher OBS in most of wet and dry ISDs as compared to ERA5, whereas ERA5-NN 275 exhibits slightly lower RMSE as compared to ERA5-AGP (Table 3). No significant trends 276 appear in any ISD, except in the intensity of wet spells, which increases in OBS (ERA5-AGP) at 277 a rate of +3.23 (+2.06) mm.dav⁻¹, based on the Mann Kendall trend test at p=0.05 (Table 3). 278

279 **3.2.** Contribution of ISDs to total seasonal rainfall

The relationship between total rainfall and ISDs was assessed using point-wise correlation (Fig. 5). Overall, all wet ISDs exhibit a positive correlation with total rainfall, but the wet spells show a negative correlation over the northeastern regions in ERA5 (WS panels in Fig. 5a). Such negative correlations between wet spells and total rainfall over the northeastern regions, where the elevation is the highest, may once again highlight the limitation of ERA5 over complex terrains (cf. Figure S3). Regarding the relationship between dry ISDs (Thoithi *et al.*, 2020) and total rainfall, a significant negative relationship logically prevails (Fig. 5b).

The correlation of two ISDs, WD and WD_{P90} with total rainfall is particularly strong, exceeding 287 0.8 (significant at p=0.05) in almost all grid-points (WD and WD_{P90} panels in Fig. 5a). This 288 289 indicates that the anomalously wet seasons primarily correspond to a higher number of wet and 290 extreme wet days, thereby confirming the results of Tennant and Hewitson (2002). In addition to point-wise correlations, we also estimated the contributions of ISDs to austral summer rainfall at 291 292 the regional scale, using spatially averaged time series (lower right corner of each panel in Fig. 5). The highest correlations are >0.94 and significant at p=0.05 and are found for WD and 293 WD_{P90} consistently with the point-wise correlations. This highlights the critical importance of 294 the two ISDs in shaping the rainfall variability over SA. 295

296 4. Rainfall extremes

297 4.1. Typology of extreme rainfall events

Here, we use the average spatial fraction of extreme rainfall events as a base criterion to 298 differentiate large- and small-scale extreme events. Theoretically, large-scale extreme events 299 should be embedded in large-scale modes of climate variability, and therefore show greater 300 potential predictability. Meanwhile, small-scale extreme events are more likely related to 301 isolated or organized convective cells, such as MCCs, which are stochastic in nature, and thus 302 less predictable (Blamey and Reason, 2013). Thus, large-scale extreme events must exhibit a 303 higher fraction of stations or grid-points simultaneously reaching the extreme threshold as 304 305 compared to small-scale extremes. Moreover, it is also reasonable to speculate that large-scale extreme events are less frequent as compared to small-scale extremes in the austral summer 306 season. To differentiate the characteristics of these two contrasting types of extremes, we assess 307 here their multivariate distributions in terms of duration, spatial fraction, frequency and intensity 308 309 (Fig. 6).

Defining a robust and relevant threshold for the spatial fraction of events was critically important. Given the aforementioned biases in the reanalysis, we rely solely on OBS to develop a relevant definition for the typology of extreme rainfall events (upper two panels in Fig. 6). In OBS, the higher event intensity (>27 mm.day⁻¹) and lower frequency lies above a spatial fraction of 7% (Fig. 6). A threshold of 7% for the spatial fraction therefore appears to be a good compromise to differentiate large- and small-scale extreme events. In order to assess the sensitivity to this threshold, we also considered 5% and 6% thresholds, and quantified the differences in the average characteristics of small- and large-scale extremes by assessing them in the context of ISDs. We found that, using other thresholds, large-scale extremes resulted in high frequency, thus obscuring distinct characteristics as compared to small-scale extremes (results not shown). The physical properties and the variability of the extreme rainfall events retrieved

from the typology are further discussed in the context of ISDs in Section 5.

4.2. Spatial characteristics of rainfall extremes

Figure 7a (left panel) displays the average frequency of days exceeding the 1.0 mm threshold 323 during large-scale extreme events for each station. Stations located along the preferable location 324 325 of continental TTTs (bringing rainfall over SA: Fauchereau et al., 2009; Macron et al., 2014) tend to exhibit the highest frequency, which accounts for 4-7 days.season⁻¹ (left panel in Fig. 326 7a). This suggests that synoptic scale rain-bearing systems could be responsible for large-scale 327 extremes. When considering the 90th percentile threshold, an average frequency of 1-4328 days.season⁻¹ was shown by all stations during large-scale extreme events (right panel in Fig. 329 7a). It is interesting to note that each station exhibits extreme conditions from 1 to 4 times in a 330 season. However, for each event, in order to qualify as a large-scale extreme event, at least 7% of 331 the stations should attain their 90th percentile threshold on the same day. This suggests that 332 during each event, a distinct set of stations responds with extreme conditions which depend 333 exclusively on the synoptic features of the rain-bearing system and storm track. When analyzing 334 the intensity of large-scale extreme events by considering either the 1.0 mm or 90th percentile 335 threshold, we note that the intensity of large-scale events is spatially uniform. This finding thus 336 suggests that such extreme events bring sustained extreme conditions over the entire region (Fig. 337 338 7c).

Different patterns of event frequency emerge when examining small-scale extremes (Fig. 7b). Here, a SW–NE gradient prevails, especially when event frequency is computed by considering the 90th percentile threshold (right panel in Fig 7b). In particular, northeastern parts of SA show a higher frequency of small-scale extremes. These results are consistent with the findings of Blamey and Reason (2013) who demonstrated that the northeastern region of SA is the preferable location of MCCs. A SW–NE gradient is also quite visible for event intensity when computed by considering the 1.0 mm threshold (left panel in Fig. 7d). No remarkable differences appear over the region when the intensity is computed by considering the 90th percentile
threshold (right panel in Fig. 7d). This result may be explained by the fact that the 90th percentile
threshold of each station remains the same for large- and small-scale extremes.

In summary, a uniform distribution of frequency and intensity, computed either by considering the 1.0 mm or the 90th percentile threshold, indicates that large-scale extremes result from coherent rain-bearing systems with uniform extreme conditions throughout the spatial extension of the events. Meanwhile, during small-scale extreme events the extreme conditions largely prevail over the northeastern parts of SA.

4.3. Spatial coherence of rainfall extremes

In this section, we assess the spatial coherence of large- and small-scale extremes. This analysis is particularly important in the context of large-scale extremes as it indicates whether extreme conditions during events are: i) uniformly distributed over the spatial extension of the events, suggesting that large-scale extremes are spatially coherent; ii) sporadically located, suggesting there could be an aggregation of small-scale events occurring at the same time.

Figure 8 presents the density of the stations exceeding 1.0 mm.day⁻¹ during the large-scale 360 361 extreme events according to their latitude and longitude. A well-organized, nearly unimodal distribution of station density clearly prevails during all large-scale extreme events, fitting well 362 with the distribution of the stations in the observational network. This suggests that the latter are 363 spatially coherent in nature. Figure 9 duplicates this analysis for the core of the large-scale 364 extreme events, where rainfall intensity causes the extreme threshold excess (i.e. only the 365 stations exceeding their local 90th percentile of daily rainfall amounts). These stations also 366 display organized and spatially coherent patterns, with unimodal distributions clearly prevailing. 367 This suggests that during these events, the extreme wet conditions also show strong spatial 368 coherence, most events being characterized by one single large-scale core rather than many 369 370 smaller ones. Taken together, the results displayed in Figures 8-9 lead us to discard the hypothesis of several smaller and/or scattered events occurring at the same time. They also 371 increase our confidence in the method used here to track large-scale rainfall extremes in SA. 372

The same analysis was then replicated for small-scale extreme events. As small-scale events are 373 higher in number, for the sake of clarity we show the results for the month of January only 374 375 (similar results were obtained for the other months and are not shown). Figure S4 shows the collective response of stations recording >1.0 mm.day⁻¹ of rainfall during small-scale extreme 376 events. Small-scale extreme events also exhibit an organized extension of rain-bearing systems 377 over latitudes and longitudes, but with slightly fewer stations in each bin (Fig. S4). Figure S5 378 displays the number of stations exceeded their 90th percentile in each 0.5° bin during the small-379 scale extreme events. Interestingly, we notice that extreme conditions occur only sporadically 380 and locally over the region during small-scale events (Fig. S5). Over longitudes, the over-381 representation of events located between 28°E and 33°E could denote the influence of MCCs 382 over eastern SA (Fig. S5b), confirming the results reported by Blamey and Reason (2013). Taken 383 together, these results suggest that the spatial extension of the rain-bearing system remains quite 384 similar between small-scale and large-scale events, suggesting that they have the same physical 385 nature (except for a larger proportion of MCCs in the case of small-scale extremes). However, 386 the core regions associated with heavy rainfall dramatically change, showing that the rain-387 388 bearing systems mostly differ in the size of their core, bringing the largest rainfall amounts and thereby causing the climatic wet extreme. 389

In summary, analyzing the spatial coherence of rainfall extremes provides a remarkable 390 advantage in monitoring the collective behavior of all stations during extreme events. The results 391 demonstrate that using a 7% threshold of spatial extension as a base criterion to differentiate 392 393 large- and small-scale extremes is robust and leads to separate events that drastically differ in terms of spatial coherence. Although both types of extremes can be considered as spatially 394 coherent, as rainfall events occur over a large region at the same time, extreme conditions only 395 occur sporadically over the region during small-scale events, contrasting with large-scale events 396 397 for which extreme conditions are found over a larger and coherent region. This suggests that the nature of corresponding rain-bearing systems is the same, but that their intensity changes, an 398 issue that will be further discussed and explored in Part II. 399

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401 5. Intraseasonal characteristics of rainfall extremes

In this section, large- and small-scale extreme rainfall events are examined in the context ofISDs.

404 5.1. Multi-year variability of large-scale rainfall extremes

The average characteristics and multi-year variability of ISDs associated with large-scale 405 extremes are displayed in Figure 10a. OBS (ERA5) shows an average of 8±5 (20±7) days 406 associated with large-scale extremes, which are included in 5 ± 3 (10±3) spells.season⁻¹, with an 407 average persistence of 2 days (WD_{EXT} WS_{EXT} and WSP_{EXT} panels in Fig. 10a). In OBS (ERA5) 408 total rainfall of about 167±36 (129±30) mm.season⁻¹ is driven by wet spells associated with 409 410 large-scale extreme events (TR_{EXT} panels in Fig. 10a). The multi-year variability of ISDs is well captured by ERA5–NN and ERA5–AGP fields, with statistically significant correlations to OBS 411 at p<0.05 (Table 4a). Nevertheless, the intensity of wet spells remains highly underestimated by 412 ERA5-NN and ERA5-AGP which shows average wet spell intensity of about 25.49 and 25.21 413 414 mm.day⁻¹ respectively (WSI_{EXT} panels in Fig. 10a). In addition, in OBS, larger seasonal rainfall variability seems related to the smaller number of wet spells and wet days, as well as more 415 416 intense events, but this is not identified in ERA5. Importantly, the observational network is found to be dense enough to study the variability of extreme ISDs associated with large-scale 417 418 rainfall extremes, since there are no major differences in the results obtained with ERA5-NN and -AGP (Fig. 10a). In all ISDs associated with large-scale extreme events, the CV remains 419 420 higher in OBS than in ERA5 (Fig. 10a). Meanwhile, ERA5-NN exhibits lower RMSE as compared to ERA5-AGP, when computed with respect to OBS (Table 4). No significant trend 421 422 appears in most ISDs, except a significant increase of 2.30 spells.season⁻¹ identified in the observed number of wet spells, based on the Mann Kendall trend test at p=0.05 (Table 4a). 423

Relationships between seasonal total rainfall and ISDs associated with large-scale extremes are presented in Figure 11a. In all datasets, large-scale extreme ISDs exhibit strong positive correlations with total rainfall (significant at p<0.05), except for the intensity of wet spells (Fig. 11a). Overall, we find a strong association between seasonal total rainfall and the number of wet days and wet spells associated with large-scale extremes, as identified in OBS. The performance of ERA5 is still weaker, especially in the relationship between wet spells and total rainfall. This leads to conclusions similar to those presented in Section 3 above, regarding the limitations ofERA5 in producing realistic wet spells and intensity.

432 5.2. Multi-year variability of small-scale rainfall extremes

Analysis of ISDs associated with small-scale extremes is presented in Figure 10b. In OBS 433 (ERA5), the frequency of days associated with small-scale extremes is 80±9 (48±7 for NN and 434 64 \pm 7 for AGP), with an average frequency of 19 \pm 3 (24 \pm 3) spells.season⁻¹ (WD_{EXT} and WS_{EXT}) 435 panels in Fig. 10b). These spells are, by construction, highly localized in space, with an average 436 spatial extension of 1.5%-2.5% over the SA domain, but they do exhibit a persistence of 2-4 437 days on average (WSP_{EXT} and ME_{EXT} panels in Fig. 10b). OBS and ERA5 fields show average 438 wet spells intensity of about 41.86 and 21.49–22.14 mm.day⁻¹ (WSI_{EXT} panels in Fig. 10b) which 439 is quite like the average wet spell intensities noted for large-scale extremes. The plausible 440 explanation of this similar behavior is that both types of extremes are first tracked by using local 441 90th percentile threshold which is indeed same for each station or grid-point. These extremes are 442 recognized differently in terms of spatial fraction (number of stations or grid-points which 443 exceed the 90th percentile threshold simultaneously during a spell; cf. Section 4.1). 444

In ERA5 (especially ERA-NN) and OBS, a significant trend appears in the intensity of wet 445 spells associated with small-scale extreme events indicating a $+2.0 \text{ mm.day}^{-1}$ average increase in 446 the spell's intensity (Table 4). Although the contribution of small-scale extremes to total rainfall 447 is quite low as compared to that of large-scale extremes, the increasing trend in the intensity of 448 449 such highly localized storms could nonetheless have crucial importance, especially for the agricultural sector, among others. Such intensification of rainfall extremes could be a 450 consequence of ongoing climate change (Kendon et al., 2017, 2019; Pohl et al., 2017) and could 451 be due to the so-called Clausius-Clapevron scaling, linking air warming trends to rainfall 452 453 intensity increase through hygrometry (Betts and Harshvardhan, 1987; Trenberth et al., 2003; Pall et al., 2006; Kharin et al., 2007; O'Gorman and Schneider, 2009; Muller et al., 2011; 454 Westra et al., 2014). The relationship between the ISDs associated with small-scale extremes and 455 the seasonal total rainfall amount is presented in Figure 11b. Except for the relationship between 456 wet days associated with small-scale extremes and total rainfall, we note weak or negative 457 relationships between ISDs and total rainfall (Fig. 11b). Table 4 summarizes the relevant 458 statistics for small-scale extreme ISDs. 459

The role of small-scale extremes in shaping total rainfall variability is moderate in austral 460 summer. One plausible explanation for this is that the small-scale extremes are highly localized 461 462 and are embedded in spatially coherent rain-bearing systems, which are mostly associated with non-extreme rainfall conditions over the region, as already discussed in Section 4.4. ERA5 fields 463 show contrasting behaviors in small-scale extremes, as opposed to the results reported for large-464 scale extreme in Section 5.1. In addition, the long-term variability of a few small-scale extreme 465 ISDs (i.e. wet spells and wet spell intensity) is not fully realistic in ERA5, as demonstrated by 466 weaker and non-significant correlations between both ERA5 fields and OBS (Table 4b). On the 467 other hand, weaker yet significant correlations between ERA5 fields and OBS ranging from 468 0.42–0.79 are noted in other small-scale extreme ISDs (Table 4b). This implies that the density 469 of the observational network might not be sufficient to detect most of these highly localized 470 small-scale events, and/or that higher resolution reanalysis is required to skillfully capture these 471 472 events.

473 5.3. Respective contribution of large- and small-scale extremes to seasonal rainfall 474 amount

Figure 12 displays the contribution of large-scale, small-scale and non-extreme rainfall to 475 476 seasonal total rainfall amount. In OBS (ERA5), total rainfall associated with large-scale extremes shows an average contribution of about 58% (41%-45%), against 11% (6%) for small-scale 477 extremes (see, pie plots in Figure 12). This shows how dependent the region is on a small 478 number of events that concentrate most of the rainfall. Although ERA5 overestimates austral 479 480 summer rainfall amounts (Section 3.1), it underestimates the contribution of rainfall extremes to total amounts. In ERA5, summer rainfall is mainly driven by non-extreme events, as opposed to 481 482 OBS, where more than half of the summer rains seem to be associated with large-scale extreme events. The biases in ERA5 may result from an overestimation of the spatial extension of rain-483 bearing systems over the region, due to: i) perfectible model physics and/or strong internal 484 variability, e.g. to simulate the small-scale atmospheric convection, and/or; ii) a limited amount 485 of available radiosonde data to constrain the reanalysis, or an assimilation technique that could 486 extend atmospheric instability over too large regions. 487

Interestingly, during the 1981–82 and 1991–92 seasons, large-scale extremes do not contribute to rainfall amount, as rainfall is mostly driven by non-extreme rainfall in OBS (contributing to

>90%; Fig. 12). These two seasons are, however, extremely dry, with seasonal rainfall amounts 490 30%-42% lower than normal, as noted in OBS (Fig. 12). Such results are not found in ERA5, 491 492 although a closer examination of these two seasons reveals that: i) total rainfall deficit also exist in ERA5 which accounts up to 22%–40%, which is quite close to the OBS (see, TR panel in Fig. 493 3); ii) ERA5 overestimates total rainfall and spatial fraction, which is why ERA5 could capture 494 the few large-scale extreme events during these seasons (see, TR_{FXT} and SF_{FXT} panels in Fig. 495 10a). In addition, these two seasons correspond to strong El Niño episodes, and it is well-496 understood that El Niño episodes can favor dry conditions over SA, and particularly large 497 rainfall deficits (see, for instance, Dieppois et al., 2015, 2016, 2019; Pascale et al., 2019). 498

499 On the contrary, in 1996–97 and 2000–01, the contribution of large-scale extremes to total rainfall amount exceeds 79%. Results from these wettest seasons tie in well with previous studies 500 501 (Hoell and Cheng, 2018), highlighting a synchronous influence of La Niña, active Angola Low and SIOD phasing, bringing together a substantial surplus of rainfall over SA over those specific 502 503 seasons. It is therefore likely that such connections do exist between rainfall extremes and different modes of variability. Thus, in the companion paper, we attempt to provide a 504 505 comprehensive assessment of how rainfall extremes respond under low (interannual and decadal) 506 and high (intraseasonal and synoptic) frequency modes of climate variability.

507 6. Conclusions and discussion

This study first examines the average characteristics of wet and dry intraseasonal descriptors in South Africa during the austral summer season from 1979 to 2015. A focus is then placed on extreme daily rainfall events. Using OBS and ERA5 reanalysis, extreme rainfall events are grouped into two types, according to their spatial fraction, separating large-scale and small-scale extremes. An investigation is then carried out to examine the spatial coherence of such extremes. Finally, for the first time in a region-wide study, large- and small-scales of extremes are explicitly assessed in the definition of intraseasonal descriptors.

The observational network of 225 stations provides an adequate spatial resolution to examine general rainfall characteristics and large-scale extremes in terms of intraseasonal descriptors. This is also true for ERA5, as the reanalysis performs remarkably well in the analysis of largescale extremes, when analyzed using its nearest neighbor and all-grid-point fields. Nevertheless, 519 compared to OBS, ERA5 shows larger biases in reproducing small-scale extremes, thereby 520 confirming that such reanalysis is primarily suited to analysis of large-scale climate processes 521 and mechanisms.

522 Strong correlations between wet days (including extreme wet days) and total rainfall indicates 523 that anomalously wet seasons generally correspond to higher numbers of extreme events. 524 Summer SA rainfall is found to be primarily associated with large-scale extremes, which account 525 for more than half of the seasonal amount in OBS, and nearly half of it in ERA5. The 526 contribution and variability of small-scale extremes are not consistent across datasets and remain 527 quite low. Moreover, the density of the observational network and the spatial resolution of 528 current global reanalysis might not be sufficient to skillfully capture these events.

529 This study is a first step towards a more profound understanding of rainfall extremes in the region. The results demonstrate that using a threshold of 7% network density as base criterion 530 531 and as a metric for the spatial fraction produces good quality results in characterizing rainfall extremes over the region. The 7% threshold used to differentiate large- vs small scale events is 532 found not only relevant for the observational network, but also for ERA5-NN and ERA5-AGP. 533 Based on our results, we find that large-scale extremes are well-organized and spatially coherent 534 in nature. Meanwhile, small-scale extreme events, which might be related to mesoscale 535 convective complexes, are highly localized in space and prevail largely over the northeastern 536 537 parts of SA.

An added value of this work resides in the first presentation of a detailed mapping of rainfall variability over South Africa, including large- and small-scale extreme events, as well as nonextreme rainfall contribution. Such studies have immediate and considerable implications for theoretical and applied climate variability-based studies. These include, but are not limited to, societal sectors related to environment and energy, hydrology modeling and water resource management, and more specifically to agriculture, especially given the fact that South Africa is highly dependent on rain-fed agriculture.

545 In the companion paper (Part II) of this study, we attempt to assess the relationships of large- and 546 small-scale extremes with low-frequency (interannual- and decadal-scale) and high-frequency 547 (intraseasonal- and synoptic-scale) modes of variability. Such a typology of extremes will also be

completed by considering their duration which is particularly important to differentiate short-548 and long-lived large-scale events. The latter may be considered as potentially high-impact 549 550 rainfall events leading to high environmental or societal impacts, a question of major and everincreasing importance under climate change. 551

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Figure 1. Spatial distribution of the percentage of rainfall during ONDJFM for OBS (a) for ERA5 (b). The unqualified stations are indicated by black "×" symbols based on the seasonality test and other quality control measures.



Figure 2. The 90th percentile threshold of rainfall computed after omitting the values = 0 for OBS (a) and for ERA5 (b). The 90th percentile threshold of rainfall after omitting the values <1 for OBS (c) and for ERA5 (d).

76x86mm (600 x 600 DPI)



Figure 3. The average spatial distribution of ISDs, set of three column panels on the left (right) refers to the wet ISDs (dry ISDs) for OBS, ERA5–NN and ERA5–AGP. The statistics are averaged over the period of 1979–2015 for the austral summer season NDJF.

165x209mm (500 x 500 DPI)



Figure 4. The average time series (line plots) and overall statistical distribution (violin plots) for wet ISDs (a) and for dry ISDs (b). The black line in each time series panel refers to the OBS, the red line is used to indicate ERA5–NN and the blue line for ERA5–AGP.



Figure 5. The spatial distribution of point-wise correlation of ISDs with total rainfall. The first set of three column panels on the left refers to the wet ISDs (a) and the set of three columns of panels on the right refers to the dry ISDs (b). The statistics are averaged over the period of 1979–2015 for NDJF using OBS, ERA5–NN and ERA5–AGP. The temporal correlations are presented in the lower right corner of each panel.



Figure 6. The frequency and intensity of extreme rainfall events as a function of average spatial fraction and duration. The set of three panels in the left column refers to frequency (a) and the set of three panels in the right column refers to intensity (b), distributed row-wise from top to bottom for OBS, ERA5–NN and ERA5–AGP respectively. The vertical red line at 7% spatial fraction separates each panel in two quadrants which distinguishes the two panels are from the top to be the two panels are panels.

which distinguishes the typology of rainfall extremes. The right (left) quadrant is associated with large-scale (small-scale) extreme rainfall events.



Figure 7. Average frequency computed over each station during large-scale extremes (a) and small-scale extremes (b) by considering the number of days exceeding 1.0 mm during events (left panel) and the 90th percentile during events (right panel). Same presentation for intensity in (c) and (d).



Figure 8. Spatial extension of large-scale extremes over latitudes (a) and over longitudes (b) computed by considering only those stations which exceeded 1.0 mm during large-scale extreme rainfall events with bin size = 0.5°. The histogram in each panel shows the frequency of the stations in each bin, whereas the black-dashed line in each panel represents the density of the stations provided as reference over latitudes and longitudes. Lines in distinct colors represent the density of the stations associated with each day of rainfall event in the respective seasons.



Figure 9. Spatial extension of large-scale extremes over latitudes (a) and over longitudes (b) computed by considering only those stations which exceeded the 90th percentile during large-scale extreme rainfall events with bin size = 0.5°. The black-dashed line in each panel represents the density of the stations provided as reference over latitudes and longitudes. Lines in distinct colors represent the density of the stations associated with each day of rainfall event in the respective seasons. For better visualization of density patterns, the y-axis has been reduced, and the histogram removed.



Figure 10. The average time series and overall statistical distribution (violin plots) of the ISDs associated with large-scale extremes (a) and for ISDs associated with small-scale extremes (b). The black line in each panel refers to the OBS, the red line indicates ERA5–NN and the blue line represents ERA5–AGP.



Figure 11. The scatter plot represents the statistical relationship between seasonal total rainfall and the extreme ISDs distributed row-wise from top to bottom for each descriptor. The set of five panels in the left column refers to large-scale extremes (a) and the set of five panels in the right column refers to small-scale extremes (b). In each panel OBS is indicated by the black symbol "●", ERA5–NN by the red symbols "●" and ERA5–AGP is presented in blue "◆" symbols.



Figure 12. The stacked bar plot represents the overall contribution to the total rainfall in a season associated with large-scale extremes in red, small-scale extremes in blue and non-extreme contribution in green for OBS in the left panel, for ERA5–NN in the middle panel and ERA5–AGP in the right panel. Three pie plots at the bottom of each panel represent the overall distribution of total rainfall based on large-, small-scale and non-extreme rainfall variability averaged over the period of 1979–2015.



Figure. S1: Sample size used to compute 90th percentile (a), 90th percentile threshold computed by considering normal distribution (b), theoretical extreme value computed by Gumbel distribution (c) and the difference of both methods (d).

165x127mm (300 x 300 DPI)



Figure. S2: The average seasonal bias of ISDs, set of first three rows containing seven panels from top refers to the wet ISDs (a) and set of three panels in bottom refers to the dry ISDs (b). OBS minus ERA5–NN is displayed by a red line and OBS minus ERA5–AGP is presented with a blue line.

165x111mm (300 x 300 DPI)



Figure. S3: Altitude of stations in meters (a). The two columns from left are associated with spatial bias in the wet ISDs (b). The third column from left is associated with spatial bias in the dry ISDs (c). The stations located at >1400 meters are indicated by triangle symbols in each panel.

152x223mm (300 x 300 DPI)









Table. 1: The description of the wet ISDs (a) and dry ISDs (b). Columns 1-5 represent the 1	ISD
name, acronym, description, unit and scale respectively.	

a) Wet ISDs				
ISD Name	Acronym	Description	Unit	Scale
Wet Days	WD	Average number of wet days in a season	Days	Seasonal
Wet Days >90th Percentile	WD _{P90}	Average number of days exceeding the 90th percentile threshold	Days	Seasonal
Wet Spells	WS	Average number of wet spells in a season	Spells	Seasonal
Wet Spell Persistence	WSP	Average persistence of wet spells in a season	Days	Seasonal
Wet Spell Intensity	WSI	Average intensity of wet spells in a season	mm.day ⁻¹	Seasonal + Daily
Spatial Fraction	SF	Average spatial fraction associated with total rainfall amount in a season	Percent (%)	Seasonal + Daily
Total Rainfall	TR	Total rainfall amount in a season	mm.season ⁻¹	Seasonal + Daily
b) Dry ISDs				
Dry Spells	DS	Average number of dry spells in a season	Spells	Seasonal
Dry Days	DD	Average number of dry days in a season	Days	Seasonal
Dry Spell Persistence	DSP	Average persistence of wet spells Days Sea		Seasonal

Table. 2: The description of extreme ISDs. Columns 1–5 represent the ISD name, acronym, description, unit and scale respectively.

Extreme ISDs				
ISD Name	Acronym	Description	Unit	Scale
Wet Days	WD _{EXT}	Average number of wet days associated with large- and small- scale extreme events in a season	Days	Seasonal
Wet Spells	WS _{EXT}	Average number of wet spells associated with large- and small- scale extreme events in a season	Spells	Seasonal
Wet Spell Persistence	WSP _{EXT}	Average persistence of wet spells associated with large- and small-scale extreme events in a season	Days	Seasonal
Wet Spell Intensity	WSI _{EXT}	Average intensity of wet spells associated with large- and small- scale extreme events in a season	mm.day ⁻¹	Seasonal + Daily
Spatial Fraction	SF _{EXT}	Average spatial fraction associated with total rainfall amount driven by large- and small-scale extreme events in a season	Percent (%)	Seasonal + Daily
Total Rainfall	TR _{EXT}	Total rainfall amount associated with large- and small-scale extreme events in a season	mm.season-1	Seasonal + Daily

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Table. 3: Average Statistics of ISDs in the austral summer season computed over the period 1979–2015 using OBS, ERA5–NN and ERA5–AGP. Column 1 refers to the acronym of ISD. Columns 2–9 refer to the Mean, SD, CV, RMSE w.r.t OBS, R², correlation of ISDs w.r.t OBS, correlation of ISDs w.r.t total rainfall and trend respectively.

ISD	Mean	± SD	CV %	RMSE w.r.t OBS	R ²	CC w.r.t OBS	CC w.r.t TR	Trend
				OBS				
WD	20.66	3.68	17.83		0.00		0.94*	0.03
WD _{P90}	2.39	0.86	35.76		0.09		0.98*	1.74
WS	12.90	1.70	13.14		0.01		0.86*	0.29
WSP	1.53	0.11	7.05		0.00		0.87*	0.00
WSI	7.09	0.90	12.76		0.28		0.86*	3.23*
SF	17.30	3.07	17.75		0.00		0.94*	0.07
TR	270.12	72.17	26.72		0.04			0.99
DD	90.40	3.79	4.19		0.00		-0.14	0.40
DS	12.71	1.73	13.61		0.01		0.87*	0.53
DSP	10.96	3.01	27.46		0.07		-0.79*	-1.40
	_			ERA5-NN	I			
WD	43.53	6.65	15.28	23.13	0.00	0.93*	0.95*	-0.23
WD _{P90}	4.44	1.48	33.41	2.17	0.04	0.95*	0.97*	1.19
WS	17.00	1.45	8.55	4.22	0.01	0.80*	0.56*	0.35
WSP	2.49	0.33	13.40	0.99	0.00	0.90*	0.91*	-0.26
WSI	3.93	0.51	13.04	3.20	0.09	0.88*	0.88*	1.65
SF	36.51	5.55	15.20	19.43	0.00	0.93*	0.95*	-0.16
TR	311.01	73.15	23.52	45.49	0.01	0.96*		0.64
DD	73.00	6.03	8.25	18.18	0.00	0.49*	-0.89*	0.07
DS	16.66	1.50	9.00	4.08	0.01	0.81*	0.56*	0.38
DSP	5.51	1.37	24.87	5.77	0.03	0.89*	-0.82*	-0.86
				ERA5-AG	Р			
WD	44.55	5.98	13.42	24.07	0.00	0.92*	0.95*	-0.10
WD _{P90}	4.52	1.42	31.29	2.23	0.06	0.94*	0.97*	1.19
WS	17.19	1.14	6.65	4.43	0.01	0.77*	0.49*	0.45
WSP	2.51	0.32	12.94	1.00	0.00	0.90*	0.91*	0.00
WSI	3.89	0.45	11.47	3.25	0.11	0.88*	0.88*	2.06*
SF	37.36	4.98	13.33	20.21	0.00	0.92*	0.95*	-0.01
TR	316.05	66.96	21.19	49.65	0.02	0.97*		0.56
DD	71.49	5.21	7.29	19.43	0.00	0.55*	-0.84*	-0.01
DS	16.86	1.19	7.06	4.29	0.01	0.79*	0.50*	0.20
DSP	5.69	1.30	22.85	5.60	0.04	0.92*	-0.79*	-1.05

* Significant at p=0.05 according to Pearson's correlation and Mann Kendall non-parametric trend test.

Table. 4: Average statistics of extreme ISDs associated with large-scale extreme events (a) and small-scale extreme (b) in the austral summer season computed over the period 1979–2015 using OBS, ERA5–NN and ERA5–AGP. Column 1 refers to the acronym of ISDs. Columns 2–9 refer to the Mean, SD, CV, RMSE w.r.t OBS, R², correlation of ISDs w.r.t OBS, correlation of ISDs w.r.t total rainfall and trend respectively.

a) Large-scale Extremes										
ISD	Mean	± SD	CV%	RMSE w.r.t OBS	R ²	CC w.r.t OBS	CC w.r.t TR	Trend		
					OBS					
WD _{EXT}	8.03	5.35	66.66		0.06		0.93*	1.53		
WS _{EXT}	4.88	2.55	52.28		0.08		0.82*	2.30*		
WSPEXT	1.70	0.57	33.21		0.01		0.49*	0.34		
WSIEXT	43.86	5.08	11.58		0.00		0.49*	0.74		
SFEXT	10.61	1.71	16.13		0.00		0.43*	1.02		
TR _{EXT}	166.68	36.55	21.93		0.05			1.69		
ERA5-NN										
WD _{EXT}	20.14	7.12	35.37	12.67	0.04	0.86*	0.92*	1.37		
WS _{EXT}	10.47	3.20	30.57	6.50	0.06	0.56*	0.61*	1.28		
WSPEXT	1.95	0.55	28.31	0.74	0.00	0.43*	0.53*	0.00		
WSI _{EXT}	25.49	1.60	6.27	19.19	0.01	0.38*	0.14	0.23		
SFEXT	16.14	2.45	15.19	6.70	0.02	0.51*	0.50*	0.26		
TR _{EXT}	136.95	29.96	21.88	42.28	0.05	0.72*		0.94		
				F	ERA5-AGP					
WD _{EXT}	20.61	6.93	33.60	13.18	0.05	0.83*	0.90*	1.23		
WS _{EXT}	10.39	3.22	30.97	6.39	0.02	0.59*	0.65*	0.66		
WSPEXT	2.02	0.49	24.37	0.76	0.02	0.43*	0.43*	1.50		
WSIEXT	25.21	1.18	4.69	19.49	0.02	0.36*	0.21	1.10		
SFEXT	15.33	2.30	15.02	5.91	0.03	0.53*	0.53*	0.86		
TR _{EXT}	129.50	28.01	21.63	46.65	0.06	0.72*		1.10		
				b) Small-sca	le Extremes					
					OBS					
WD _{EXT}	79.33	8.84	66.66		0.11		0.48*	1.75		
WS _{EXT}	19.83	3.21	52.28		0.01		-0.20	0.76		
WSPEXT	4.16	1.09	33.21		0.01		0.31	0.16		
WSIEXT	41.86	2.28	11.58		0.08		0.38*	1.81		
SFEXT	1.89	0.29	16.13		0.11		0.82*	1.73		
TR _{EXT}	29.57	7.44	21.93		0.16			2.17*		
				-	ERA5-NN					
WD _{EXT}	48.25	7.18	35.37	31.89	0.00	0.62*	0.54*	-0.12		
WS _{EXT}	24.42	2.90	30.57	6.29	0.00	0.01	0.29	0.49		
WSPEXT	1.99	0.33	28.31	2.37	0.00	0.55*	0.30	-0.20		
WSI _{EXT}	22.14	0.91	6.27	19.87	0.16	-0.02	-0.38*	2.00*		
SFEXT	2.37	0.34	15.19	0.58	0.02	0.43*	0.24	0.86		
TR _{EXT}	20.02	4.01	21.88	10.87	0.05	0.74*		1.40		
				ŀ	ERA5-AGP					
WD _{EXT}	64.28	6.93	33.60	16.65	0.01	0.62*	0.40*	-0.59		
WS _{EXT}	24.14	2.95	30.97	5.43	0.00	0.42*	-0.14	0.67		
WSPEXT	2.72	0.54	24.37	1.70	0.01	0.59*	0.32	-0.99		
WSIEXT	21.49	0.70	4.69	20.48	0.13	0.27	-0.04	2.22*		
SFEXT	2.04	0.28	15.02	0.32	0.07	0.51*	0.60*	1.43		
T	17.22	3 55	21.63	13 36	0.10	0 70*		1.89		

* Significant at p=0.05 according to Pearson's correlation and Mann Kendall non-parametric trend test.



Graphical Abstract. This study addresses the intraseasonal descriptors (ISDs) and wet extremes in austral summer rainfall (November–February) over South Africa (SA). We propose a novel typology of wet extreme events based on their spatial fraction, thus differentiating large- and small-scale extremes. The attention is then given to the spatial characteristics and coherence of rainfall extremes. Long-term variability of both types of extreme rainfall events is also provided in the context of ISDs. Our results show that austral summer total rainfall is primarily shaped by large-scale extremes which constitute more than half of the rainfall amount under observation, and nearly half in ERA5. Overall, we find a strong dependence of total rainfall on the number of wet days and wet spells that are associated with large-scale extremes. We also find that large- and small-scale events are found sporadic over the region, contrasting with large-scale events for which extreme conditions are found over a larger and coherent region.