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Appraisal of Daily Temperature and Rainfall Events in the Context of Global Warming in South Australia

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Abstract: In recent decades, there have been significant problems worldwide related to global warming and the intensification of extreme temperature and rainfall events. This research evaluated daily temperature and rainfall indices trends to identify whether warming signals have occurred in South Australia over the past fifty years. Extreme cold, hot, and rainfall events were calculated using climatic data from 37 weather stations. A Mann-Kendall test was used for trend analysis with Sen's estimator. As a result, we determined that for the 1970-2021 period, the maximum and minimum temperatures increased by 1.1 and 0.7 °C, respectively, while precipitation had a negative trend (-52.2 mm/period). Since statistical significance was found in analysing extreme cold and hot events, we find that warming signals have several impacts on South Australia. In the case of rainfall events, we identified a heterogeneous pattern characterised by a reduction in the annual amount, and an increase in extreme rainfall events. The findings enable us to conclude that the area shows signs of global warming that could affect the intensity and magnitude of droughts. This information is essential for continuing with current management strategies to adapt and mitigate the effects of global warming in South Australia.

Keywords: rainfall and temperature trends; climate change; South Australia; Southern Hemisphere

Introduction

Global warming is a critical issue, causing significant changes to the Earth's climate and natural systems, with far-reaching consequences for human society and the environment [1]. The increase in global temperatures is mainly due to human activities such as burning fossil fuels and deforestation, resulting in rising sea levels, more frequent and intense heatwaves, droughts, floods, severe storms, and changes in precipitation patterns [2,3]. Furthermore, global warming affects ecosystems, biodiversity, agriculture and food security, water resources, and human health and well-being [4,5]. It also contributes to economic and social inequalities, as vulnerable populations and developing countries are often the hardest hit by the effects of climate change [6].

Addressing global warming requires urgent action to reduce greenhouse gas emissions and transition to a low-carbon economy [7]. Therefore, it will require a coordinated international effort involving governments, businesses, and individuals to change energy production and use, transportation, land use, and waste management [8].

Australia is one of the major countries in the Southern Hemisphere and has been heavily affected by global warming. The continent has experienced record-breaking temperatures, drought, and strong winds, with the summer of 2019-2020 being the hottest on record [9]. The devastating bushfire season of 2019-2020 destroyed millions of hectares of land, killed wildlife and livestock, and claimed

several human lives [10–12]. Global warming also affects Australia's marine ecosystems, with rising sea temperatures and ocean acidification causing coral bleaching and other negative impacts on marine life [13].

The study area for this research is South Australia (SA), a state located in the southern central part of the country. It shares borders with Western Australia to the west, the Northern Territory to the north, Queensland to the northeast, New South Wales to the east, and Victoria to the southeast. The state covers an area of 983,400 km² and has a population of around 1.8 million people [14]. Rainfall decreases from north to south, and also east to west, with the highest precipitation in the southeast and lower values in the northeast and west. The temperature is highest in the north and decreases towards the south (Figure 1).
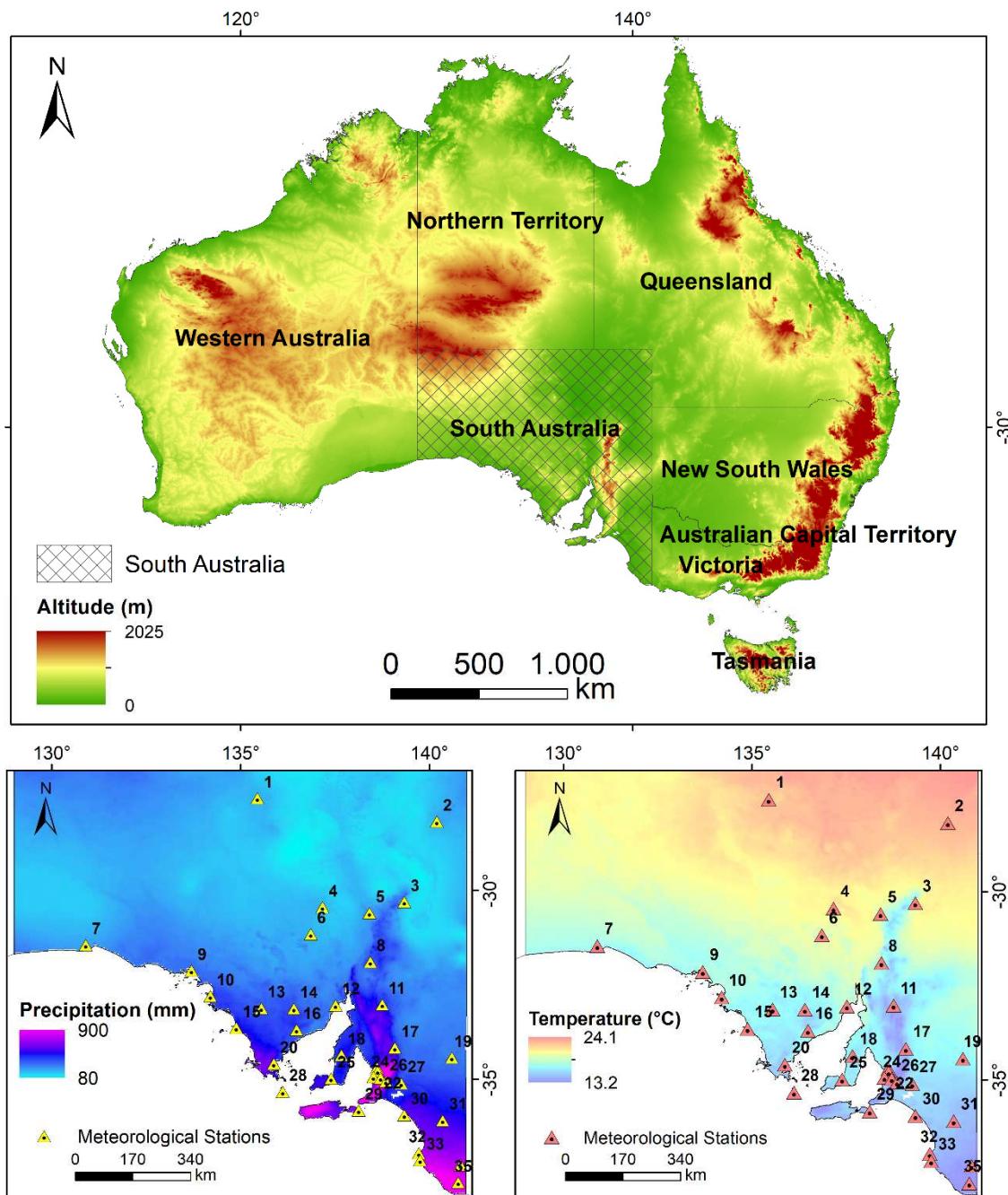

Figure 1. A. Location map, B. Rainfall spatial distribution with the weather stations, and C. thermal spatial distribution with the weather stations.

SA is renowned for its diverse landscapes, ranging from the arid Outback to the fertile wine regions of the Barossa Valley and Adelaide Hills. The area produces high-quality food, wine, and mineral resources such as copper, gold, and uranium. The state's largest city, Adelaide, serves as its capital and is home to over 75 % of its population. SA is a crucial economic hub, with agriculture, mining, manufacturing, and tourism all contributing significantly to its economy. However, the region has experienced significant changes in climate patterns due to climate change and global warming [15]. Partly in response to climate, and partly due to Government led adaptation measures, SA has become a leader in renewable energy, with significant investments in wind and solar power [16,17].

Extreme temperature events require strict risk management and adaptation strategies that rely on accurately understanding climate patterns [18]. Assessing daily temperature and rainfall events is crucial in understanding the impact of global warming at a regional or local scale. The daily analysis is vital because it provides a highly accurate way to identify the intensity and magnitude of thermal and rainfall variability [19]. Despite the critical significance of analysing climate variability with daily measurements, studies on extreme daily temperature and rainfall events in South Australia have been scarce. We have limited knowledge about how climatic trends in extreme temperature and precipitation events affect this region. For all these reasons, this study aimed to identify warming signals and changes in rainfall patterns over the past 50 years in SA to improve the management of climate risk, adaptation, and mitigation practices required in the area.

Materials and Methods

Maximum and minimum temperatures, standard deviation, and annual precipitation were calculated from 37 weather stations in SA (Table 1). The meteorological information was obtained for different periods but standardised between 1970 and 2021. The data was downloaded from the Bureau of Meteorology of the Australian Government (http://www.bom.gov.au/).

The time series were pre-processed using automated scripts to correct mistakes such as topographical errors, inconsistencies in the data, and labelling issues following the method described in [20]. The output files were then carefully checked to prevent potential processing errors. We conducted quality control and homogeneity assessments using the RClimDex Software [21] and RHTest V4 Software (Wang et al. 2010), both of which were created by the Expert Team on Climate Change Detection and Indices (ETCCDI) and are freely available. RHTest V4 uses a penalised maximal t-test and a maximal F-test set in a recursive algorithm, which allows for temporal homogeneity analysis of daily data from the 37 weather sites [22–24]. We applied climatic homogenisation to adjust for the fact that climate variations caused temporal changes in the corrected data. We also considered non-climate variables in our data, such as shifts in the station's environment, location, and instrumentation, that might affect the accuracy of the data trends [24]. Due to these factors, we were able to obtain missing data and outliers. It is worth noting that some stations had periods with missing information. Therefore, we extended the study period to 1970-2021 to establish statistical significance in this research.

Table 1. Weather stations, location, height, period, mean maximum and minimum temperature, and precipitation annual amounts with their standard deviation.

ID	Weather station	Lat	Long	Altitude	Period	Tmax	Tmin	Pp
1	Woomera Aerodrome	-31.16	136.86	167	1949-2021	25.8 ± 6.5	12.7 ± 5.1	179.8 ± 81.4
2	Andamooka	-30.45	137.17	76	1965-2021	26.1 ± 6.6	13.8 ± 5.7	181.9 ± 100.9
3	Oodnadatta Airport	-27.56	135.45	117	1939-2021	29.1 ± 6.7	12.7 ± 5.3	168.8 ± 99.7
4	Arkaroola	-30.31	139.34	318	1938-2021	25.7 ± 6.4	11.5 ± 6.1	246.8 ± 160.9
5	Leigh Creek Airport	-30.6	138.42	259	1982-2021	26.3 ± 6.9	12.8 ± 5.9	207.8 ± 102.2
6	Moomba Airport	-28.18	140.2	38	1995-2021	29.6 ± 6.8	15.5 ± 6.7	161.7 ± 126.3
7	Ceduna Amo	-32.13	133.7	15	1939-2021	23.5 ± 4.05	10.4 ± 3.5	293.4 ± 84.4
8	Cleve	-33.7	136.49	193	1986-2021	22.5 ± 4.7	11.6 ± 3.3	399.1 ± 97.2
9	Kimba	-33.14	136.41	280	1920-2021	23.8 ± 5.9	10.4 ± 4.1	341.9 ± 106.1

10	Kyancutta	-33.13	135.55	59	1930-2021	25.2 ± 5.8	9.3 ± 3.6	310.6 ± 79.09
11	Elliston	-33.65	134.89	7	1882-2021	21.5 ± 3.5	11.8 ± 2.9	422.6 ± 100.1
12	Streaky Bay	-32.81	134.2	45	1865-2021	23.3 ± 4.61	13.2 ± 2.9	371.8 ± 97.6
13	Nullarbor	-31.45	130.9	64	1888-2021	23.8 ± 3.5	10.8 ± 3.94	186.9 ± 147.8
14	Neptune Island	-35.34	136.12	32	1957-2021	18.6 ± 2.58	13.8 ± 1.9	403.2 ± 143.9
15	Whyalla Aero	-33.05	137.52	9	1945-2021	23.7 ± 4.8	11.5 ± 4.7	243.7 ± 96.1
16	North Shields (Port Lincoln Aws)	-34.6	135.88	9	1992-2021	22.2 ± 3.7	11.3 ± 3.3	379.6 ± 92.8
17	Hawker	-31.9	138.44	340	1882-2021	24.5 ± 6.7	10.8 ± 5.4	300.4 ± 121.1
18	Adelaide Airport	-34.95	138.52	2	1955-2021	21.5 ± 4.7	11.5 ± 3.4	438.4 ± 102.8
19	Adelaide West Terrace	-34.93	138.58	29	1839-2021	21.8 ± 5.05	12.02 ± 3.38	521.3 ± 115.7
20	Cape Jaffa	-36.97	139.72	17	1991-2021	19.2 ± 3.9	12.4 ± 2.3	488 ± 111.8
21	Cape Willoughby	-35.84	138.13	55	1881-2021	18.1 ± 2.8	12.8 ± 2.4	528.6 ± 129.8
22	Coonawarra	-37.29	140.83	57	1985-2021	20.4 ± 5.06	8.1 ± 2.4	563.3 ± 112.6
23	Edinburgh RAAF	-34.71	138.62	17	1972-2021	22.6 ± 5.46	11.1 ± 3.9	417.2 ± 112.9
24	Eudunda	-34.18	139.09	420	1882-2021	21.1 ± 6.03	9.2 ± 3.4	445.1 ± 120.7
25	Keith	-36.1	140.36	29	1906-2021	22.3 ± 5.58	9.2 ± 2.9	453.9 ± 101.8
26	Loxton Research Centre	-34.44	140.6	30	1984-2021	23.9 ± 5.9	9.08 ± 4.01	260 ± 77.6
27	Maitland	-34.37	137.67	185	1879-2021	21.7 ± 5.4	11.24 ± 4.02	487.8 ± 131.4
28	Maningie	-35.96	139.34	3	1864-2021	21.03 ± 4.1	10.41 ± 2.7	441.4 ± 145.1
29	Mount Barker	-35.07	138.85	359	1861-2021	20.2 ± 5.2	8.2 ± 2.7	748.5 ± 193.2
30	Mount Gambier Aero	-37.75	140.77	63	1941-2021	19.02 ± 4.4	8.2 ± 2.3	714.6 ± 123.5
31	Mount Lofty	-34.98	138.71	685	1985-2021	22.9 ± 5.1	8.7 ± 2.8	791.4 ± 123.6
32	Murray Bridge	-35.12	139.26	33	1885-2021	15.9 ± 4.8	9.8 ± 3.5	714.6 ± 205.2
33	Parafield Airport	-34.8	138.63	10	1929-2021	22.5 ± 5.4	10.8 ± 3.8	431.2 ± 103.6
34	Price	-34.3	138	2	1944-2021	22.8 ± 4.6	11.2 ± 3.7	322.8 ± 88.9
35	Robe	-37.16	139.76	3	1860-2021	18.1 ± 3.3	10.9 ± 2.01	621.5 ± 134.8
36	Warooka	-34.99	137.4	53	1861-2021	21.2 ± 4.5	11.6 ± 3.07	438.7 ± 97.8
37	Yongala	-33.03	138.76	521	1881-2021	22.01 ± 6.6	7.4 ± 4.3	345.4 ± 125

We have employed gap-filling techniques to complete the time series of the 37 weather stations. To achieve this, we utilised Principal Component Analysis (PCA), an effectively used method to fill gaps in climate time series [19,25–27]. This approach enables the creation of a new set of variables by linearly combining the original variables, thereby effectively capturing most of the observed variance in the original data. We computed initial guess values from linear models between each station and its neighbours.

Subsequently, we computed daily extreme temperature and rainfall events defined by the ETCCDI, including hot and cold extreme events and other indices described in Table 2. These provide a comprehensive overview of temperature and rainfall statistics. Zhang et al. [30] reviewed these indices, which are composed of percentile-based absolutes, duration, and threshold indices (Chen et al. 2017). In that regard, we added Maximum temperature (Tmax) and Minimum temperature (Tmin). As such, we applied 23 indices subdivided into four categories: User-defined indices, Extreme hot temperature events, Extreme cold temperature events, and rainfall events (Table 2). We assessed these indices at two spatial scales. The first corresponds to the local analysis, considering the 37 weather stations. The second relates to the regional analysis by analysing the thermal and rainfall pattern for the entire study area. Ferrelli et al. [19] employed the same method to examine the effects of global warming on the Pampas (Argentina).

Finally, we calculated linear trends (at the local and regional scale) in extreme temperature and rainfall indices using the non-parametric Mann-Kendall test [31,32] with a significance threshold of α = 0.05. Moreover, to quantify rates of change, we applied Sen's slope estimator (Sen 1968) using the "trend" package [33]. The use of this technique has two benefits. First, it is a non-parametric test, so the data do not need to be normally distributed. Second, the inhomogeneous time series used in this test resulted in poor sensitivity to abrupt breaks. The data values are assessed as an organised time series [34]. Some research shows that persistence, serial correlation, and scaling hypotheses can

increase the probability of rejecting the correct null hypothesis [35]. However, we initially processed the dataset to remove the serial correlation's influence on the test's results.

Table 2. Daily temperature and precipitation indices. Modified from [19,24,36]. We presented separately hot extremes, cold extremes, precipitation extremes and user-defined indices.

Index ID	Index name	Definition	Units
Temperature indices - User Defined			
Tmax	Maximum temperature	The annual mean value of daily maximum temperature for the period 1970 - 2021	°C
Tmin	Minimum temperature	The annual mean value of daily minimum temperature for the period 1970 - 2021	°C
Extreme hot temperature events			
TXx	Max Tmax	The maximum monthly value of the daily maximum temp	°C
TNx	Max Tmin	The maximum monthly value of the daily minimum temp	°C
TX90p	Warm days	Percentage of days when TX > 90th percentile	Days
DTR	Diurnal temperature range	The monthly mean difference between TX and TN	°C
SU25	Summer days	Annual count when TX (daily maximum) > 25 ºC	Days
TR20	Tropical nights	Annual count when TN (daily minimum) > 20 ºC	Days
TN90p	Warm nights	Percentage of days when TN > 90th percentile	Days
Extreme cold temperature events			
TXn	Min Tmax	The monthly minimum value of the daily maximum temp	°C
TNn	Min Tmin	The monthly minimum value of the daily minimum temp	°C
FD0	Frost days	Annual count when TN (daily minimum) < 0 ºC	Days
Rainfall events			
PRCPtot	Annual total wet-day precipitation	Annual total PRCP in wet days (RR > 1mm)	mm
CDD	Consecutive dry days	Maximum number of successive days with RR < 1mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR > 1mm	Days
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP > =1 mm) in the year	mm/day
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP > 10mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP > 20mm	Days
R30	Number of extreme precipitation days	Annual count of days when PRCP > 30 mm	Days
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm

Results

Temperature and rainfall trends

The maximum temperature has increased throughout the entire weather station suite analysed in SA, with most of the area experiencing significant changes (100 % of the weather stations), showing a generally increasing trend. The minimum temperature has shown a positive trend in most of SA (86 % of the weather stations), except for one (Cape Jaffa) that showed a negative tendency (-0.2 °C/period, p = 0.88). The annual precipitation during wet days has decreased (78 % of the total), but positive trends have been identified in the coastal zones (+22 mm/period, p = 0.83) and in the north of the study area (Figure 2).
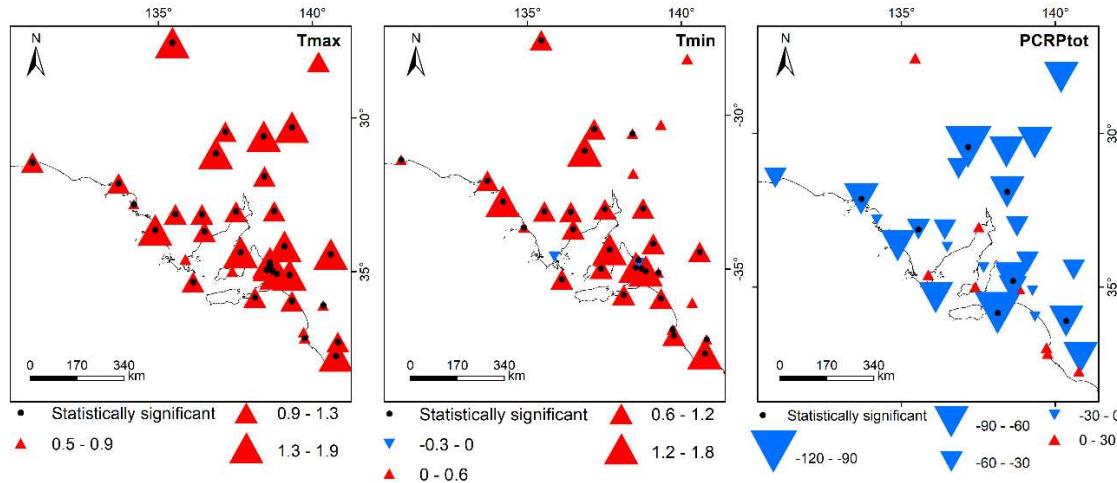
Figure 2. Trends and significance of Maximum temperature (Tmax), Minimum temperature (Tmin), and annual precipitation during wet days (PCRPtot).

Figure 3 presents the regional behaviour of Maximum (Tmax) and Minimum Temperature (Tmin) and the Annual total wet-days precipitation (PCRPtot) for the 1970-2021 period. We identify a significant increase in the Tmax (+1.1 °C, p < 0.01), as well as in Tmin (+0.7 °C, p < 0.01). In the case of PCRPtot, the trend presented a non-significative decrease (-52.2 mm/period, p = 0.73) (Figure 3).
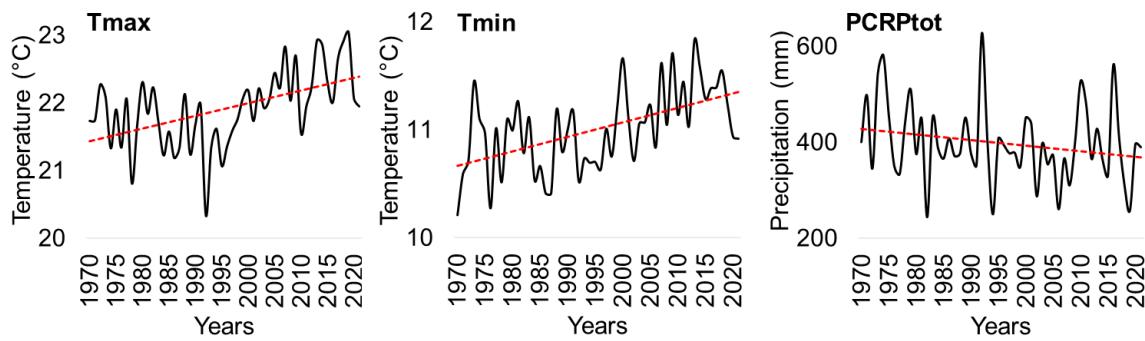
Figure 3. Regional behaviour of maximum temperature (Tmax), minimum temperature (Tmin), and the annual total wet-days precipitation (PCRPtot) for the period 1970 - 2021.

Extreme hot temperature events

Extreme hot events in SA have shown a general increase from 1970 to 2021. These indices are the most relevant indicators of global warming in the region. In this context, most indices showed positive and significant trends across the entire area. Hotter Days (TXx) has demonstrated an increase ranging from 3.7 °C to 2.4 °C. Positive trends were statistically significant (p < 0.05), while negative

ones were not (p > 0.05). The maximum monthly value of the daily minimum temp (TNx) showed a similar pattern, with 98 % of the region showing positive trends (Figure 4).

The most significant change was observed in Summer Days (SU25), with 100 % of weather stations showing positive trends, and over 81 % being statistically significant. We analysed the same pattern with Warm Days (TX90p), where all weather stations showed a positive tendency, but statistical significance was only identified in 18.9 % of the area. Moreover, Tropical Nights (TR20) increased significantly in most of SA, except for the coastal region, where this index showed negative values. Warm Nights (TN90p), on the other hand, showed a general negative trend (Figure 4).
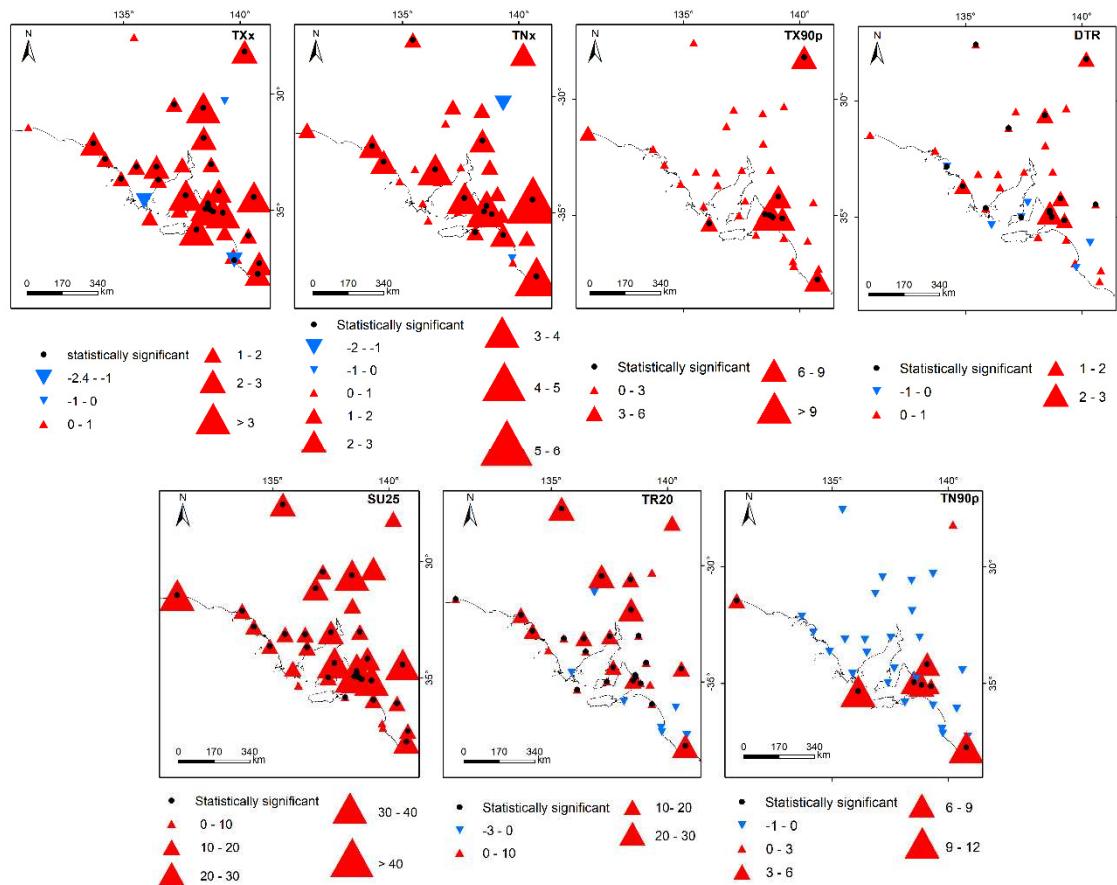
Figure 4. Trends and significance of the Extreme hot events. Results for hottest days (TXx), the maximum monthly value of the daily minimum temp (TNx), warm nights (TX90p), DTR, summer days (SU25), tropical nights (TR20), and warm days (TN90p) are shown.

At a regional scale, Hottest Days (TXx), Summer Days (SU25), and Tropical Nights (TR20) showed the highest increase (p < 0.01) with a total of 1.9 °C, 20.7 days, and 7.8 days per period, respectively. The sharp rise in SU25 and TR20 occurred from 2000 to 2021 at rates of 0.68 and 0.21 days per year, respectively. Warm Days (TN90p) and Nights (TX90p) registered a moderate increase (p < 0.05) with regional values of 5.8 and 0.8 days per period, respectively. The other hot extremes lacked regional significance (Figure 5).
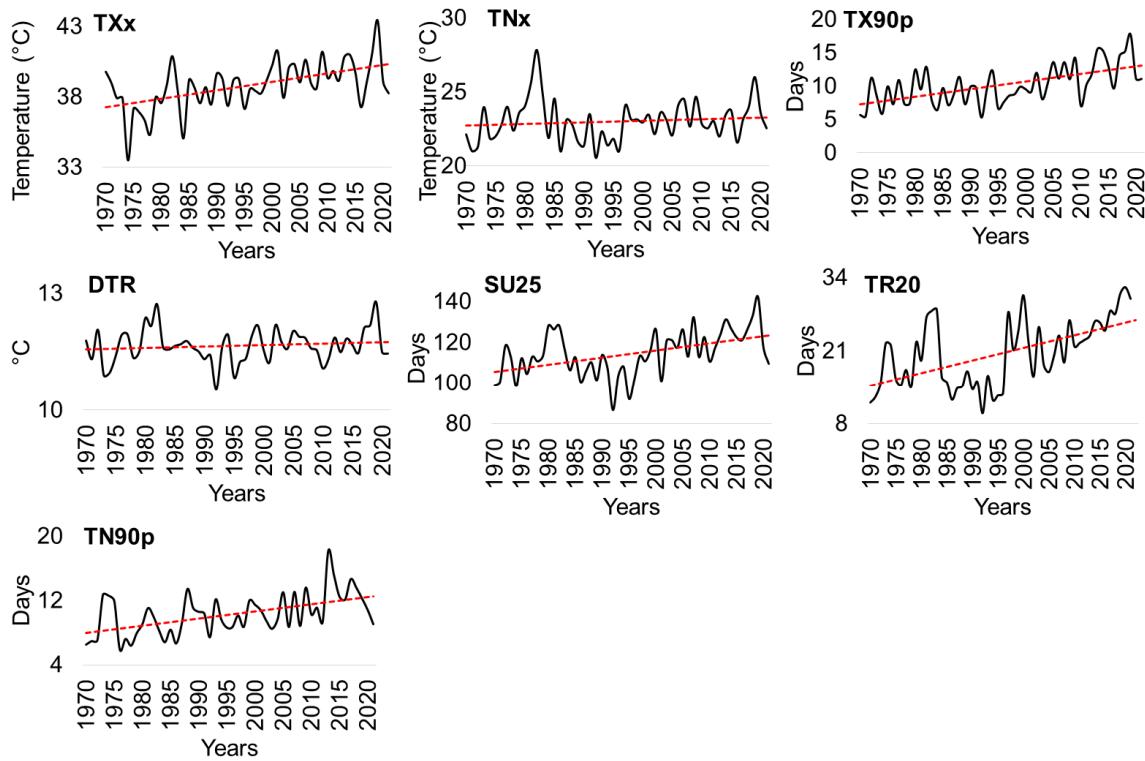
Figure 5. Regional behaviour of the Extreme hot events. Results for hottest days (TXx), the maximum monthly value of the daily minimum temp (TNx), warm nights (TX90p), DTR, summer days (SU25), tropical nights (TR20), and warm days (TN90p) are shown.

Extreme cold temperature events

The spatial distribution of extreme cold events is presented in Figure 6. Coolest Days (TXn) shows an increase of up to 3°C per period in the north, northeast, and west of SA. However, statistical significance was only identified in 35 % of the area. TNn shows a heterogeneous pattern, with values oscillating between -3°C and 3.4°C per period. Frost days (FD0) show a general decrease in most of the study area (68% of the weather stations). Consistent with extreme hot events, cold events also indicate global warming signals by increasing the minimum value of maximum temperature and reducing frost days (Figure 6).
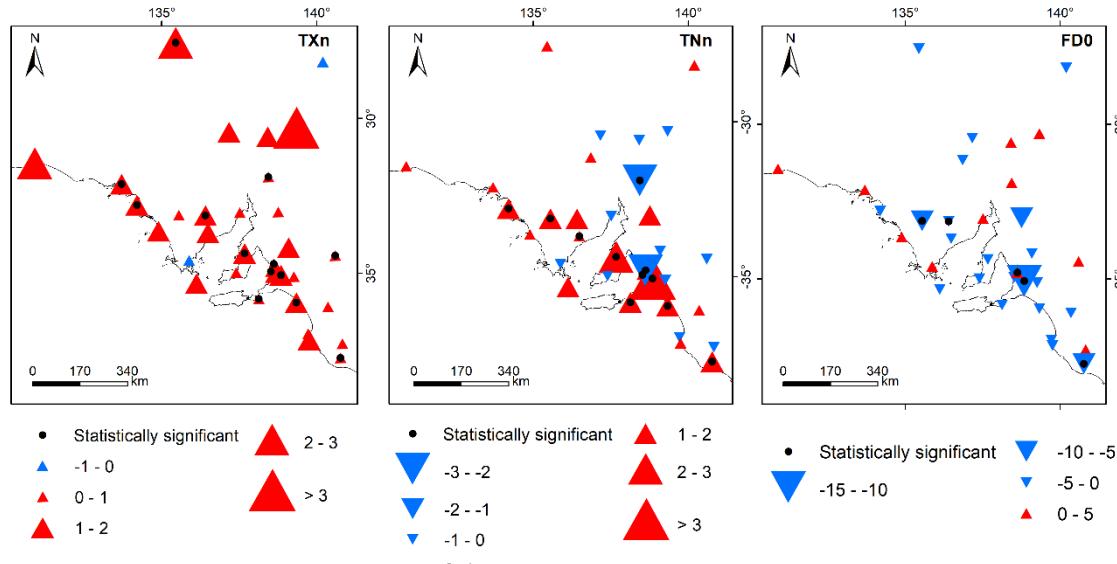
Figure 6. Trends and significance of Extreme cold events in SA. Results for the monthly minimum value of the daily maximum temperature (TXn), the monthly minimum value of the daily maximum temperature (TNn), and frost days (FDO) are shown.

At the regional scale, we observed an increase of 0.4°C per period in hottest days (TXx), but there was no significant evidence. The monthly minimum value of the daily maximum temp (TNn) registered a rise of +0.9°C from 1970 to 2021. Finally, frost days (FD0) was significantly reduced by 6.2 days per period (Figure 7).
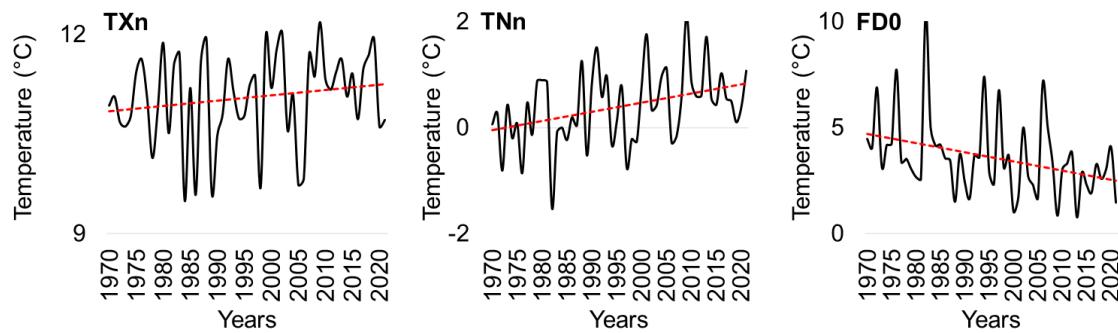
Figure 7. Regional behaviour of the Cold Extremes. Results for the monthly minimum value of the daily maximum temperature (TXn), the monthly minimum value of the daily maximum temperature (TNn), and frost days (FDO) are shown.

Daily rainfall events

Rainfall events were subdivided into general events and those related to storms and wet days. Figure 8 presents the spatial distribution of Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), SDII, Rx1day, and Rx5days. As observed during the precipitation trend analysis, most indices showed negative trends (CDD, CWD, and SDII). However, some areas were identified where the precipitation rained for one and five days changed. These areas, located in the central north of SA and the coast, registered an increase of up to 16 mm in Rx1day and 20 mm in Rx5days from 1970 to 2021. This situation is related to more severe rainfall events in the study area (Figure 8).

SA did not represent statistical changes in these indices at a regional scale, except for CWD. CDD showed oscillations related to the rainfall variability of the study area. The instability of consecutive wet days was -1.9 days per period ($p < 0.05$), but it was higher in coastal regions (-4.8 days per period). The same pattern was observed in the analyses of Rx1day and Rx5days (Figure 9).

Precipitation and wet days demonstrated a heterogeneous pattern. Heavy rainfall increased in coastal areas by more than 5 mm during 1970-2021 but, decreased in the continental region. Extremely heavy storms (R20p) are generally reduced in the region, except for the coastal zone in the central north and central east. Very heavy precipitation (R30p) had a similar pattern to R20p, but they demonstrated increased extreme precipitation events. Despite this, the changes observed in the study period are not climatically significant (Figure 10). Wet days (R95p) showed critical changes. They reduced from 20 to 60 days per period in the north and by more than 20 days per period in the south and coastal areas. Very wet days (R99p) showed similar behaviour, but the increase was less (3.2 days per period; Figure 10). The trend analyses for the 50-year study period demonstrated that heavy precipitation increased by 0.3 mm. The rest of the indices showed a negative trend in the region but with slight variations (Figure 11).
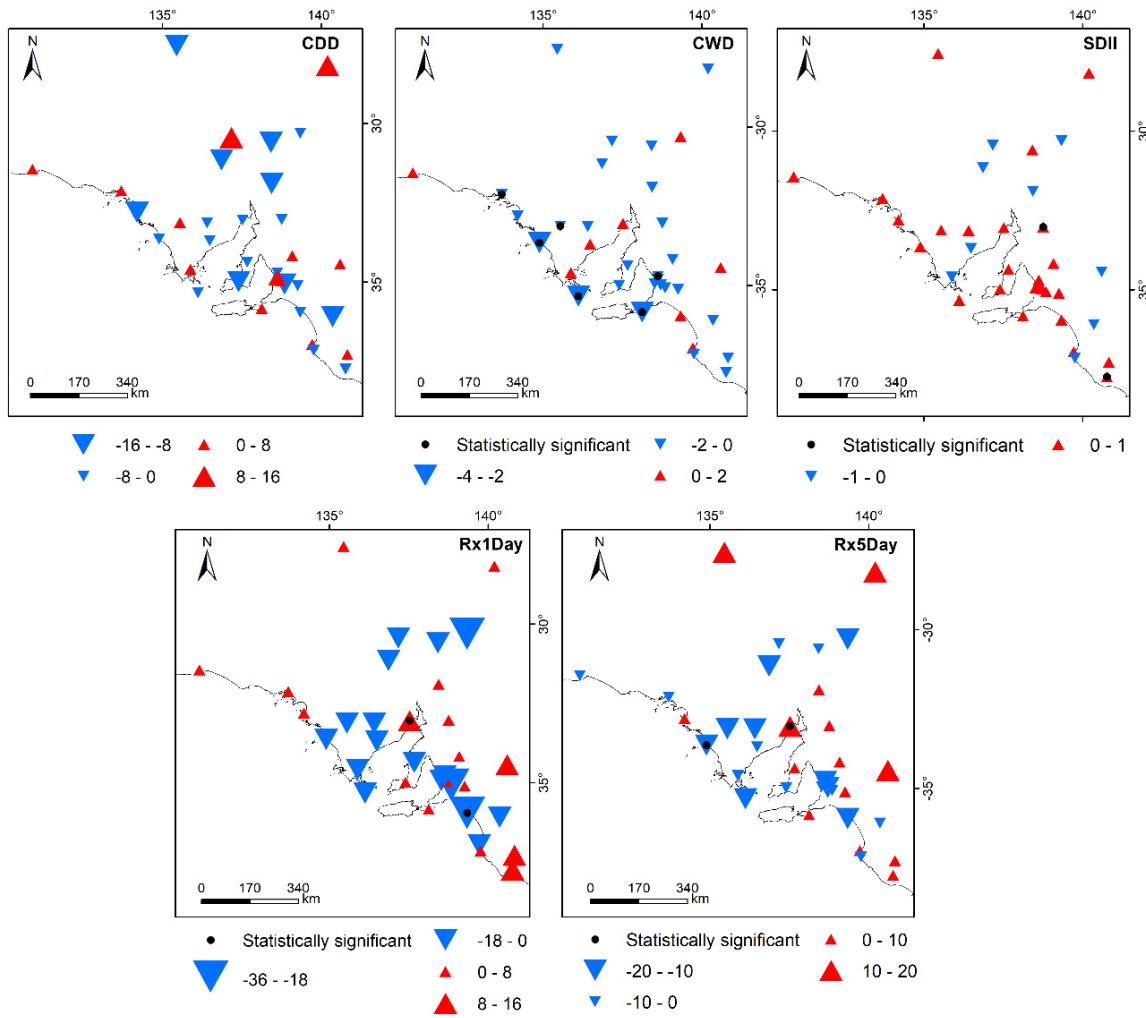
Figure 8. Precipitation daily events. Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), annual total precipitation divided by the number of wet days in the year (SDII), Monthly maximum 1-day precipitation (Rx1day), and Monthly maximum consecutive 5-day precipitation (Rx5days) are shown.
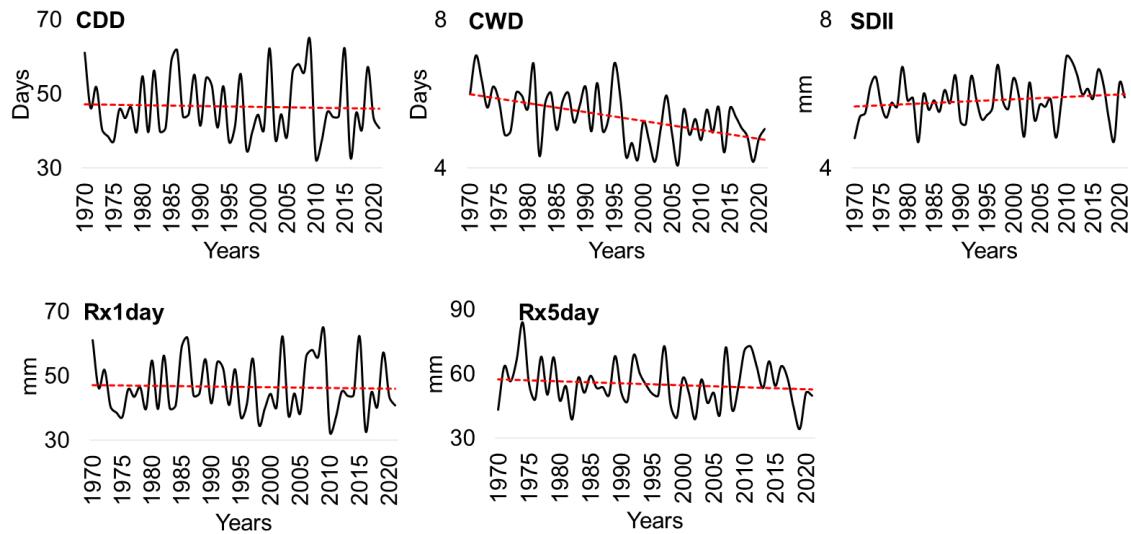

**Figure 9.** Regional behaviour of the precipitation extremes.
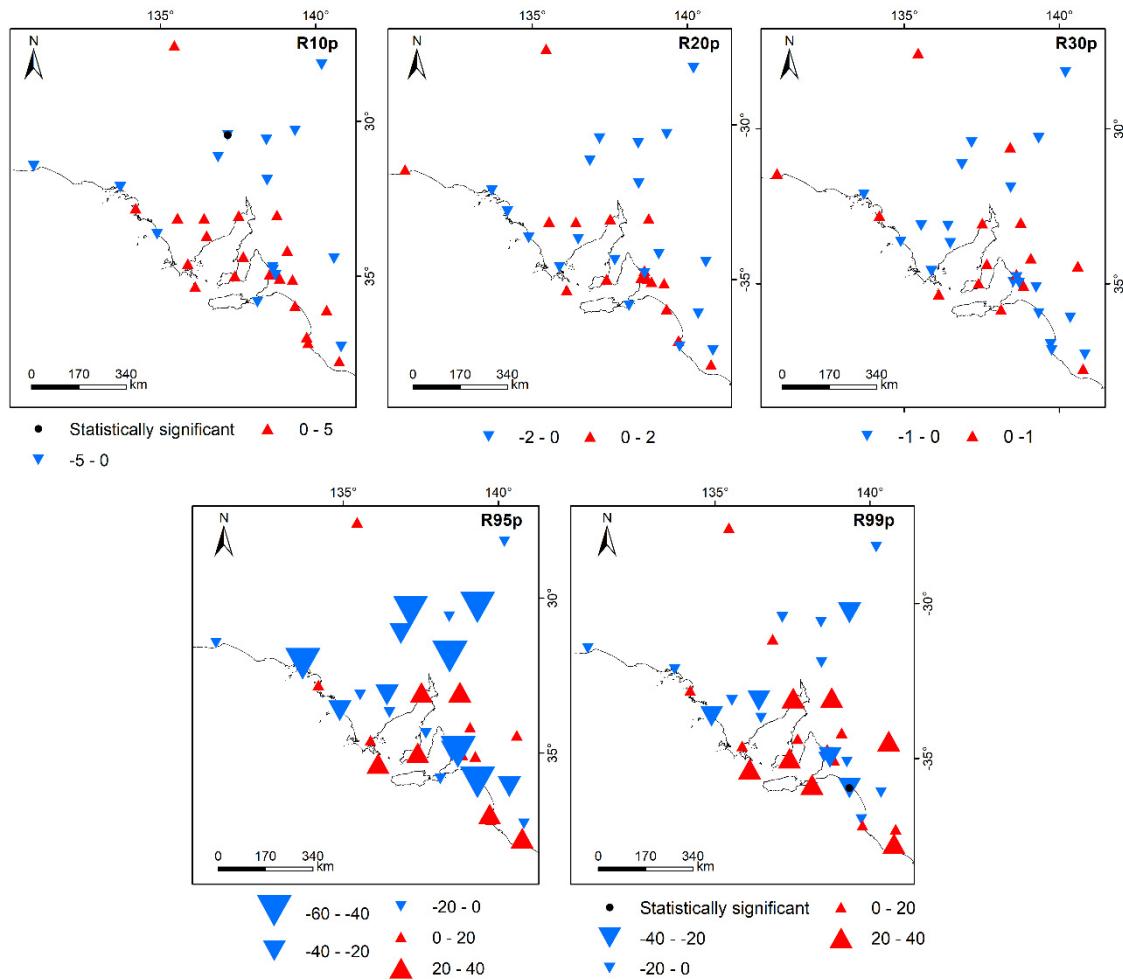
Figure 10. Precipitation daily events. R10p, R20p and R30p indicate the annual count of days when the annual total wet-day precipitation PRCP > 10mm, >20mm, or >30mm respectively, and R95p and R99p indicate the annual total PRCP when RR > 95th and >99th percentile respectively.
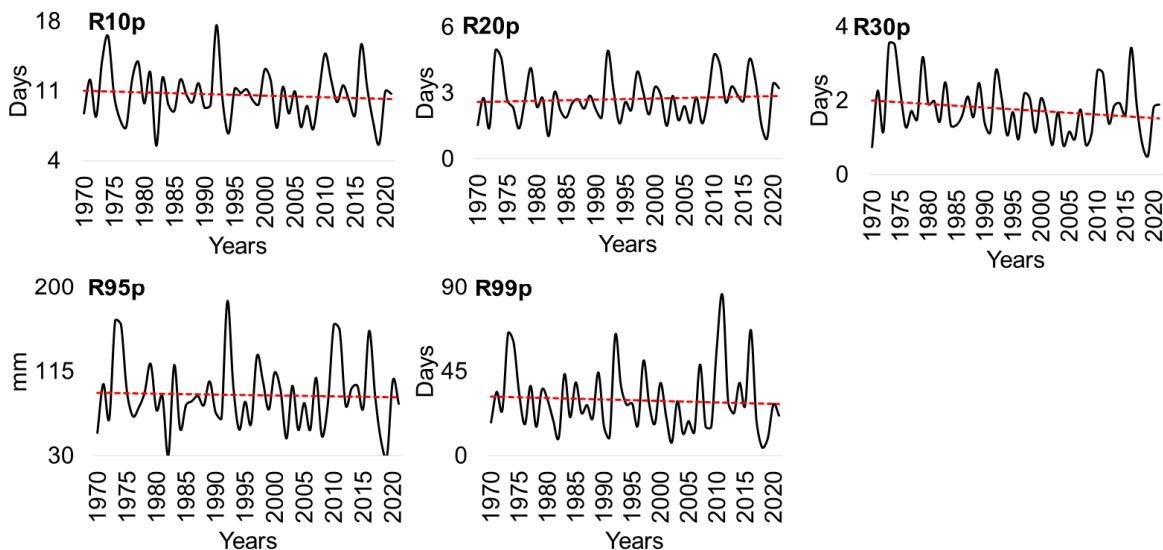
Figure 11. Regional behaviour of the precipitation extremes.

Discussion

The assessment of extreme temperature and rainfall events in South Australia showed signals of the effects of global warming. Analyses of trends at local and regional scales allow us to identify spatial and temporal changes over the last 50 years. The importance of applying this methodology is demonstrated by its ability to detect thermal and rainfall patterns worldwide [18,19,37]. Global warming triggers particular climate extremes, including increasing frequency of cold nights and days and growing warm days and nights [38]. Analysis of extreme hot events identified a generally positive trend, demonstrating the region's exposure to the effects of global warming, which is observed in other temperate areas of the Southern Hemisphere, such as Pampas in Argentina [19]. Moreover, the effects of global warming impact many other regions of the world [39].

Significant increases were observed in summer days and tropical nights in South Australia. Cold events registered similar patterns as extreme hot events, with an increase in minimum temperature that impacted the number of frost days. The reduction in the number of frost days and the increase in cold and hot events are related mainly to excessive heat, which may dry the soil and inhibit vegetation growth [18]. These changes could affect croplands and livestock in South Australia, two susceptible activities related to the change in thermal patterns. Furthermore, the positive and significant temperature trend demonstrated its effects on crop flowering, delaying the growing season, and shortening the critical period, generating diminishing yields [40]. Remarkably, the effects on the growing season are a consequence of the increment of minimum temperature. However, in temperate climates, the increase in minimum temperature could create longer growing seasons during autumn and spring [38,41].

While the temperature increases homogeneously, precipitation has a heterogeneous pattern, as is common worldwide. Changes in thermal and rainfall patterns observed in South Australia evidence the effects of global warming. The most critical impact of these changes is related to the ecological environment due to reducing environmental services [42]. Along the same line, the hydrological cycle could be affected because of the increase in evapotranspiration and extreme rainfall events [43]. One of the most significant impacts of global warming is its effect on the population. South Australia has over 1.8 million inhabitants, and it is demonstrated that this phenomenon affects the quality of life. For instance, the increase in maximum temperature could severely impact cardiovascular and respiratory diseases [44], vector-borne diseases, and rise in mortality rates [43].

Extreme precipitation events may lead to an increase in the intensity and frequency of flooding, which can impose substantial costs on aquatic and terrestrial ecosystems, human societies, and the economy. Changes in flood characteristics not only depend on the spatial distribution, time evolution, and rarity of precipitation but also on antecedent soil moisture conditions [45,46] (Sharma et al., 2018; Blöschl et al., 2017). In our study, we identified a decrease in rainfall patterns across the entire area. However, despite the overall decrease in precipitation during the study period, extreme rainfall events increased in the central-eastern and coastal regions of South Australia. According to [44], precipitation extremes may change differently from total precipitation. The simplest expectation is that precipitation extremes should scale with low-level atmospheric moisture content, which increases at a rate of about 6–7 % K^{-1} warming, as predicted by the Clausius–Clapeyron relationship [44]. Therefore, global warming and anthropogenic aerosols are considered major components affecting extreme precipitation changes [e.g., 44, 45].

In this context, technological innovation and entrepreneurial activity can help to address global warming by developing new technologies that reduce the cost of renewable energy or increase the efficiency of existing technologies, entrepreneurs can help to drive the transition to a low-carbon economy [51].

Finally, it is necessary to provide crucial information for stakeholders to design adaptation and mitigation strategies for reducing the effects of climate change. The relevance of the results obtained in this manuscript could be the basis for generating a management plan oriented to mitigate the adverse impacts on crop yield, grasslands, livestock, and water availability [18], and improve human

life quality [19,52]. Trend analyses based on daily data demonstrate an essential tool for generating management plans focused on environmental sustainability [53].

Conclusion

We have identified global warming signals' magnitude, intensity, and persistence over the last 50 years in South Australia using 24 climate extreme indices. We found remarkable warming signals trends in both hot and cold extreme events. Cold indices, such as Frost days, showed negative trends, while the monthly minimum value of the daily maximum temperature (TXn) and the monthly minimum value of the daily minimum temperature (TNn) registered an increase. Moreover, most extreme hot events, such as summer days, warm days and nights, and tropical nights, presented a significant and positive change in most of the study area.

Rainfall had different impacts on local and regional scales. However, the analysis of precipitation presented a heterogeneous pattern. We demonstrated that although rain is decreasing regionally, heavy and extreme storms have become more severe locally in the last 50 years.

Finally, it is worth noting that based on the evidence presented in this manuscript, it would be crucial for generating or reorient sustainable management plans to mitigate and adapt to changes in the structure and function of ecosystems and reduce human diseases related to global warming.

Conflicts of interest: The authors declare that they have no conflicts of interest.

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