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Natural Hazards and Earth System Sciences
Discussions

Simulated rainfall extremes over southern Africa over the 20th and 21st centuries

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Abstract. In Southern Africa, precipitation is a crucial variable linked to agriculture and water supply. In addition, extreme precipitation causes devastating flooding, and heavy rainfall events are a significant threat to the population in this region. We analyse here the spatial patterns of extreme precipitation and its projected changes in the future. We also investigate whether the Agulhas Current, a major regional oceanic current system, influences those events. For this purpose, we analyse simulations with the regional atmospheric model CCLM covering the last decades and the 21st century. The simulations are driven by atmospheric reanalysis and by two global simulations. The regional simulations display the strongest precipitation over Madagascar, the Mozambique channel, and the adjacent mainland. Extreme rainfall events are most intense over the mountainous regions of Madagascar and Drakensberg and the African Great Lakes. In general, extremes are stronger in the Summer Rainfall Zone than in the Winter Rainfall Zone.

Extremes are projected to become more intense over the South African coast in the future. For the KwaZulu-Natal Province, the heaviest rainfall event in the future is twice as strong as the strongest extreme simulated in the historical period and the recently observed disastrous extreme event in April 2022. The impact of the Agulhas Current System on strong rainfall events over the South African coast does not clearly appear in the simulations.

1 Introduction

Southern Africa, located in the tropics and subtropics of the African continent, is divided into various climatic zones determined by the seasonality of their precipitation regimes and their precipitation amounts. Close to the equator, precipitation is driven by the Intertropical Convergence Zone (ITCZ) (Reason, 2017). In the southwest, Namib and Kalahari desert regions receive very little precipitation throughout the year (Reason, 2017). The southeast region and Madagascar are impacted by precipitation weather systems reaching this area from the Indian Ocean (Walker, 1990). In contrast, the uttermost southwest and the south coast have a Mediterranean-type climate with precipitation linked to the Southern Hemisphere westerly storm track (Chevalier and Chase, 2016; De Kock et al., 2022). Southern Africa generally receives yearly precipitation in austral summer and is, therefore, denoted the Summer Rainfall Zone (SRZ). Only in the southwest, most of the rainfall falls in austral winter and is, thus, called the Winter Rainfall Zone (WRZ). Whereas the mean precipitation regimes in this region are well known, much less is known about the spatial distribution of extremes and their possible changes under future climate change. Here, we

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Discussions

analyse simulations with the regional climate model CCLM to address the spatial patterns of extreme rainfall, their trends in the observational period and their projected future changes.

In a previous paper (Tim et al., 2023), we analysed the mean precipitation and its trends over the late 20th and 21st centuries simulated by the same regional atmospheric model. We compared it to several observational data sets. The evaluated past trends are spatially very inhomogeneous and strongly depend on the type of data set and the analysed period. Nevertheless, most data sets agree upon increased precipitation in large parts of southern Africa over the past few decades. By contrast, the projected future trends are negative in South Africa and other surrounding areas.

This study investigates heavy rainfall events with the same set of atmospheric simulations (described in the following section). Analyzing and understanding the occurrence and projected future of extreme rainfall is very important for prevention and adaptation. Heavy rainfall events cause devastating floods, landslides, and loss of lives, homes, infrastructure and farmland, and together with storms as compound events, can impact the coastal population even more dramatically.

One cause of extreme precipitation, especially on the east coast of southern Africa, is the landfall of tropical cyclones (Malherbe et al., 2012), such as the cyclones Idai and Kenneth in April 2019 (Mawren et al., 2020). Also, cut-off lows can cause very severe storms with extreme rainfall over the south and east coast of South Africa (Favre et al., 2013), such as the recent event in the KwaZulu-Natal province in South Africa in April 2022 (Thoithi et al., 2023). Cut-off lows are low-pressure systems that occur when isolated from the westerlies and displaced equatorward. Large parts of South Africa are affected by extreme precipitation related to cut-off lows. Therefore, we analysed not only extreme precipitation over the whole of southern Africa but also paid special attention to the South African coast, the mega city Cape Town and the KwaZulu-Natal province.

Another reason to focus on the coastline is the possible impact of the Agulhas Current along this coast. This warm surface current has been shown to impact mean precipitation (Tim et al., 2023), by its modulation of the sea surface temperature (SST), which can affect the evaporation from the ocean and the atmospheric circulation itself (Rouault et al., 2002). Thus, a closer look at the possible connection between the Agulhas Current and precipitation extremes seems warranted.

2 Data and methods

2.1 Data

To analyse extreme rainfall in southern Africa, we used three simulations with the atmospheric regional model CCLM (COSMO model in CLimate Mode, $https://www.clm-community.eu/$). We performed these simulations in the context of the BMBF-funded project CASISAC (Changes in the Agulhas System and its Impact on Southern African Coasts). These simulations cover southern Africa (10 °W-55 °E, 0 -55 °S, Fig.1) and have a horizontal resolution of 16km. A hindcast simulation is driven by the atmospheric reanalysis data set JRA-55 (Kobayashi et al., 2015), covering the period 1958-April 2020. The historical simulation (1951-2013) and the scenario simulation (2014-2099, which incorporates the emissions scenario of greenhouse gases SSP5-8.5 (Lee et al., 2021)), are driven by global climate simulations with the coupled model FOCI (Flexible Ocean and Climate Infrastructure, Matthes et al. (2020), with interactive ozone chemistry). From these coupled simulations, we derived the indices that describe the Agulhas Current system (see below). Additionally, we analyzed the ERA5 reanalysis (Hersbach

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences Discussions

et al., 2020) for validation purposes and regarding a recent extreme event in the province of KwaZulu-Natal in South Africa. This reanalysis data has a horizontal resolution of 31 km and covers the period from 1940 to the present.

2.2 Methods

To define extremes in rainfall, we choose the 99th percentile of simulated daily mean precipitation in each of the three CCLM simulations. When analysing the whole Winter Rainfall Zone (WRZ, 15 °E - 20 °E and 28 °S - 35 °S) and whole Summer Rainfall Zone (SRZ, covering the whole simulation domain except the WRZ) of the simulation domain, percentiles are calculated for each simulation and generally for each grid cell separately. However, for the smaller regions like the coastal city Cape Town and the province KwaZulu-Natal, the spatial mean is calculated before the percentiles are computed.
The strength of the Agulhas Current and Agulhas leakage has been calculated as volume transport in the FOCI simulations used to drive the historical and future CCLM simulations. The Agulhas Current is defined here as the volume transport at a transect at 32 °S. The Agulhas leakage is defined as the amount of water originating in the Agulhas Current at 32 °S and crossing the Good Hope Line, thus leaving the Cape Basin and entering the South Atlantic (Ansorge et al., 2005) within 5-year windows.
Trends are estimated for the annual maximum of daily precipitation. We applied the Theil-Sen method (Ohlson and Kim, 2015). This method is a non-parametric trend estimator that is more robust against the presence of outliers and deviations of the linear trend residuals from a normal distribution. Therefore, it is more adequate than the Ordinary Least Squares linear regression on time, which is usually applied to estimate linear trends.

3 Results

3.1 Validation - Comparison of Extremes with ERA5

Here we compare the extrema derived from the ERA5 reanalysis and the CCLM hindcast simulation. Figure 1 displays the spatial distribution of the 99% percentiles of daily precipitation of both data sets. The percentiles of ERA5 are calculated here for the period 1979 to 2020, while the extremes of the hindcast simulation of CCLM are derived from 1958-2019. ERA5 shows lower values of the 99th percentiles. Thus, extremes are generally less intense in the reanalysis data set than simulated by CCLM, but this can be explained by the different spatial resolutions of the two data sets. For instance, assuming, for the sake of argument, that precipitation has no spatial autocorrelation whatsoever, the more coarsely resolved data set (ERA5, 31 km resolution) should display a temporal standard deviation about twice smaller than the more finely resolved data set (CCLM, 16 km resolution), since each grid-cell average represents an area about four times as large. Since precipitation does have a finite spatial autocorrelation, this reduction of standard deviation will be smaller than that of factor two. Nevertheless, both data sets agree upon regions of weaker and stronger extreme events. Extreme events are more intense over Madagascar, the Drakensberg region and the African Great Lakes, while weaker extremes occur along the west coast.
Thus, the spatial distribution of precipitation extremes seems to be generally realistically simulated by CCLM.

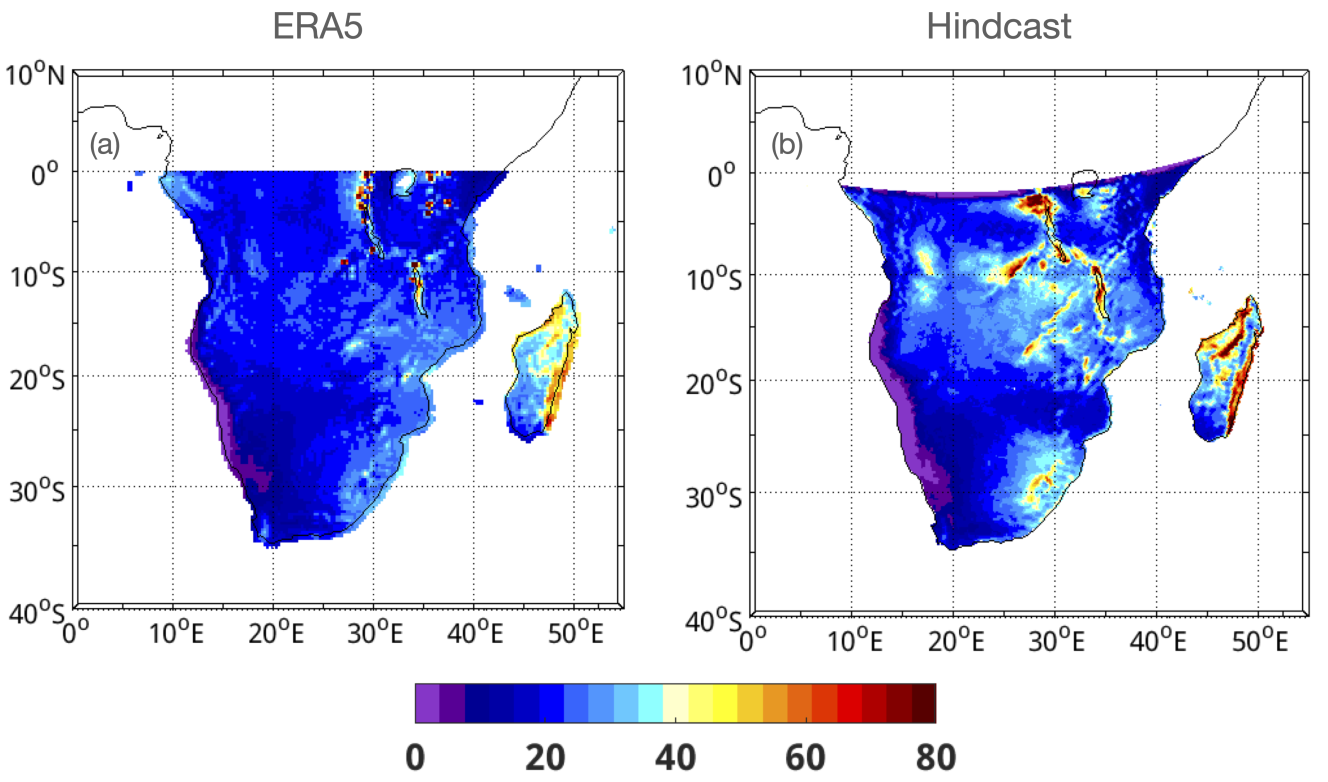

Figure 1. Threshold of the 99th percentile of precipitation of (a) ERA5 and (b) the hindcast simulation of CCLM.

3.2 Absolute and yearly maxima of daily precipitation

This section investigates where the strongest rainfall occurs in the simulation domain and how intense the strongest rainfall events are.

When looking at the whole domain of the CCLM simulations covering southern Africa, the strongest precipitation for both periods is simulated over the Mozambique channel. The maximum precipitation is 2225.8 mm/day on the 24th of February 2001 in the historical simulation and 1874.6 mm/day on the 2nd of May 2092 in the scenario run. When taking only rainfall over land into account, the maximum is lower, with 1279,9 mm/day over the coast over Tanzania on the 1st of April 1989 (historical) and 1097.9 mm/day over Madagascar on the 28th of January 2031 (scenario) (Fig. 2). When restricting the analysis to the mainland (0-40 °E, 15-55 °S), a daily maximum of 942.5 mm/day and 979.2 mm/day are the highest values on the 9th of February 1966 over Zimbabwe and on the 17th of January 2020 over the coast of Mozambique between Beira and Maputo. Thus, the heaviest rainfall occurs in the Mozambique channel for both simulation periods, over Madagascar, and the adjacent mainland, over Mozambique, Tanzania, and Zimbabwe.

Figure 3 shows the temporal linear trend of the yearly precipitation maxima. For the historical simulation (Fig. 3a), annual maximum precipitation becomes stronger along the south and east coast of South Africa. By contrast, annual maximum precip-

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Discussions
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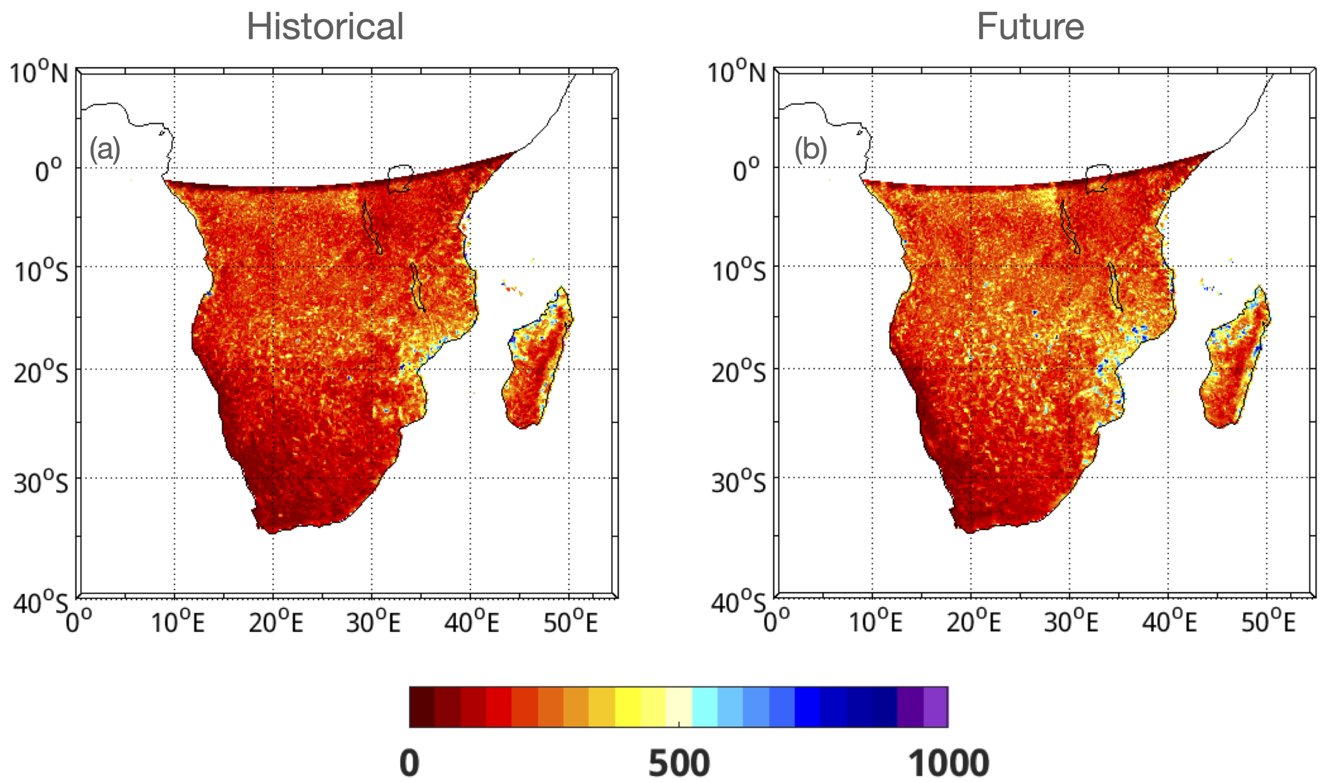

Figure 2. Maximum of daily precipitation in the (a) historical and (b) scenario simulations of CCLM, in mm/day.

itation is reduced in the WRZ along the west coast of South Africa and in most of the country's inland. Extreme precipitation intensity strongly decreases in the north of Madagascar. In the scenario simulation, the annual maximum precipitation changes are mainly negative in the west of southern Africa and positive in the east of South Africa (Fig. 3b).

Comparing the trends of extreme precipitation with the trend of mean precipitation, the historical simulation displays similar spatial patterns of trends. In both magnitudes, mean and daily extremes, there is an increase on the south coast of South Africa and a decrease in the interior. In the scenario simulation, by contrast, the pattern of mean and extreme precipitation trends differ (Tim et al., 2023). For the simulated future, mean precipitation decreases in almost the whole domain (Tim et al., 2023), whereas yearly maximum precipitation is simulated to increase in the east of the country, including the coastal city Durban in southern KwaZulu-Natal, a region we will further investigate later in this paper.

3.3 Extreme rainfall in the summer and winter rainfall zones

In this section, we separately analyse the spatial patterns and intensity of extreme precipitation in the SRZ and WRZ in the historical and scenario simulations. We calculated the extreme rainfall (99th percentile of daily rainfall) for each model grid cell (Fig. 4) and the mean precipitation for those extremes above the 99th percentile.

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Discussions

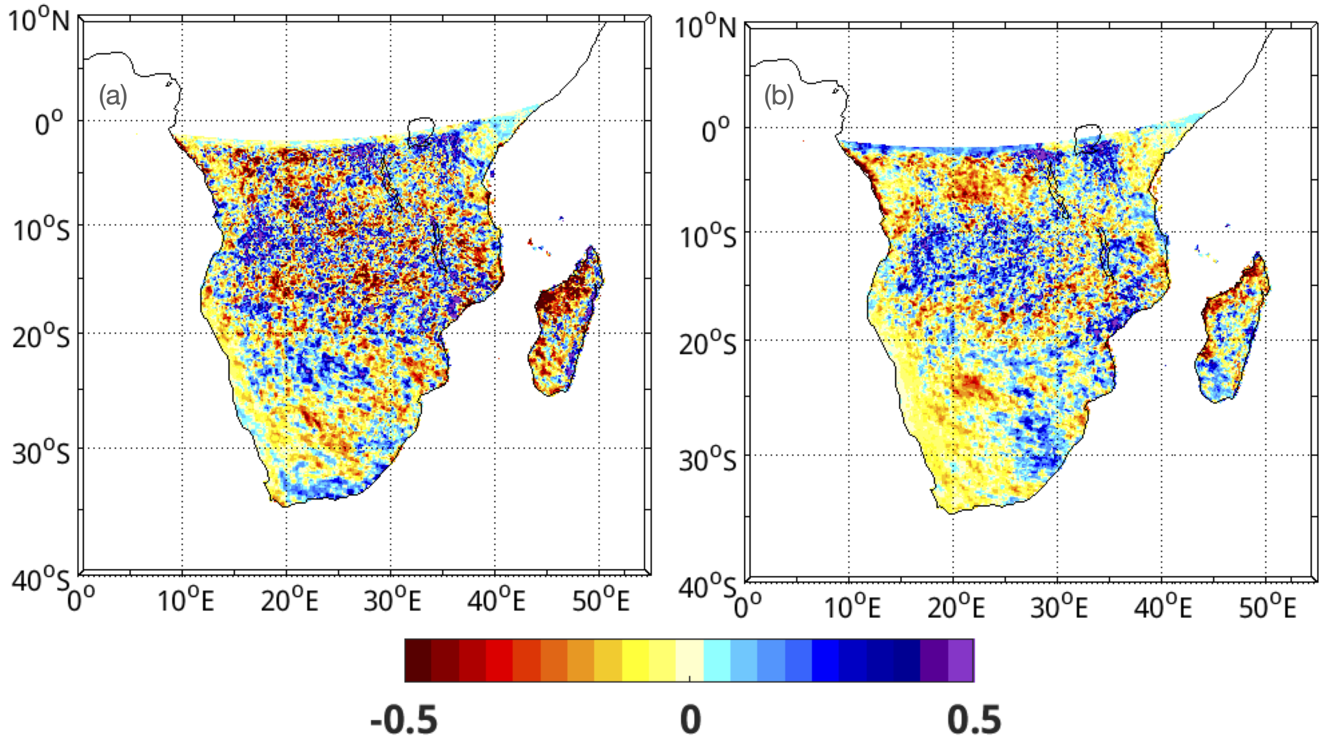

Figure 3. Trend of the annual maximum of daily precipitation in (a) the historical simulation and (b) scenario simulation of CCLM, in mm/day per year.

In both simulations, as for ERA5 and the hindcast simulation, especially weak extreme events occur on the west coast of South Africa, Namibia, and Angola. The Drakensberg region, Madagascar, and the African Great Lakes are areas of stronger extremes.

For the SRZ, considering the spatial average of the extreme percentiles over the grid cells belonging to this region, this is similar to the historical and scenario simulations (29 mm/day). The highest grid-cell-scale percentile is found in the future, with 290 mm/day. Regarding the intensity of the extreme events, the spatial mean of extreme events is similar in the historical simulation (50 mm/day) and the scenario run (51 mm/day). The most intense rainfall event is simulated in the historical simulation (1280 mm/day), followed by the scenario (1098 mm/day).

For the WRZ, the spatial means of the extreme percentiles are similar in the historical and scenario simulations (12 mm/day). The same is true for the spatial mean of extreme precipitation. Rainfall extremes are of similar intensity in the historical simulation (22 mm/day) and future simulation (21 mm/day). The highest threshold (37 mm/day) and strongest extreme (209 mm/day) are simulated in the historical simulation.

Regarding the timing of extreme events, they are not more frequent in the second half of each simulation period for both rainfall zones.

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences Discussions

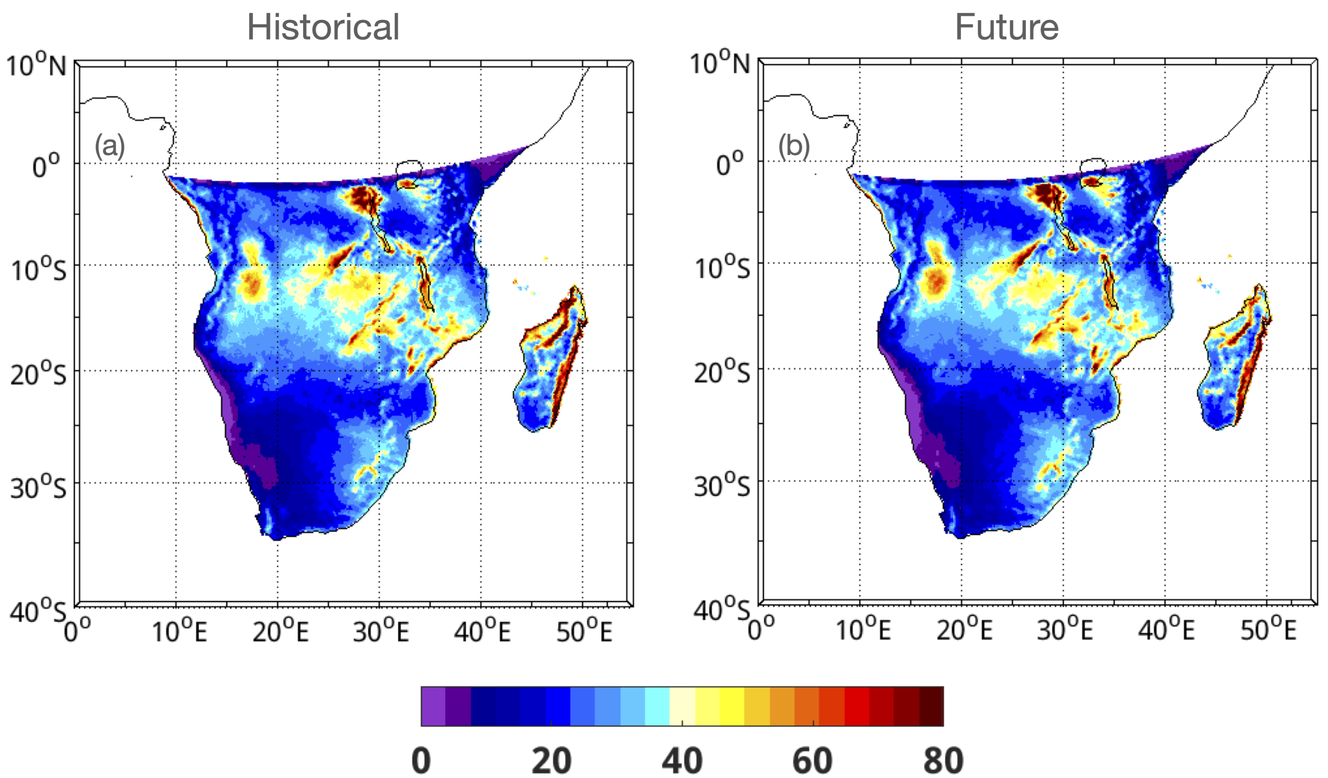

Figure 4. Threshold of the 99th percentile of precipitation of (a) the historical and (b) the scenario simulation of CCLM.

Thus, extremes are less intense in the WRZ than in the SRZ, they are not projected to become more intense in the future and tend to occur equally spread throughout time.

3.4 Extreme rainfall at the coast of South Africa

Here, we analyse the extreme rainfall on the coastline (a coastal strip of 200km width south of 28 °S, see Fig. 5). The coastline is more vulnerable to devastating consequences for the population, as heavy rainfall may occur in compound events simultaneously with flooding due to storms like tropical cyclones and storm surges in river deltas. Furthermore, we are interested in the impact of the Agulhas Current on extreme precipitation and, as a coastal current, its influence would be largest on coastal rainfall.

The 99th percentile of precipitation of this coastal band shows the following features of heavy rainfall events. The maximum daily precipitation is higher over the east coast than over the south and west coast. This is mirrored by the 99th percentile for each grid box. Extreme precipitation is more intense over the east coast than the south and west coast (Fig. 5).
The value of the 99th percentile is very close in the two simulations. The spatial maximum of the 99th percentile is 46 mm/day

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

for the historical simulation and 47 mm/day for the future simulation. The mean percentile is, with 20 mm/day, the same for both simulations.

The mean of the extreme events is nearly of the same strength in both simulations (32 mm/day and 34 mm/day). But the strongest extreme event is much stronger in the future simulation (604 mm/day), than in the historical simulation (383 mm/-day).

Regarding the time evolution of extremes, extremes occur equally throughout the simulation periods (Fig. 6).

Looking at the causes of these extreme events reveals that tropical cyclones cause these extremes in 12.9 % of the historical simulation and 11.2 % of the cases in the future. Cut-off lows are behind fewer extremes, 5.7 % (historical) and 4.0 % (scenario). To attribute the causes of the precipitation extremes to one of the other circulation patterns, we calculated the minimum of the sea level pressure (SLP) for each extreme event and used a simplified local characterization of cyclones and cut-off lows. If the minimum SLP is located between 30 °E and 55 °E and north of 30 °S, it is assumed the pattern corresponds to a tropical cyclone. We attribute the extreme to a cut-off low if the minimum SLP is between 15 °E and 40 °S and between 30 °S and 40 °S. Our basic classification also reveals a slight decrease in the occurrence of tropical cyclones and cut-off lows from the past to the future.

In summary, extremes evaluated over the entire coastline are stronger in the future simulation than in the past simulation. However, extreme events do not become more frequent in the 21st century in the scenario simulation, and tropical cyclones are more often the cause than cut-off lows. Both are projected to hit the region less frequently in the future than in the past.

We further analysed the impact of the Agulhas Current System on heavy rainfall events at the South African coast in the historical and scenario simulations. For this, we derive the annual indices of the strength of the Agulhas Current and the Agulhas leakage and correlate them with the number of extremes per year. For both simulations, historical and scenario simulation, it turns out that the spatial sum of the number of extremes is not significantly correlated with both Agulhas indices, the strength of Agulhas Current and the strength of Agulhas leakage. Nevertheless, the correlation between the number of extremes is positive with the Agulhas Leakage and negative with the Agulhas Current when both indices lead the time series of the number of extremes by one year. As the Agulhas leakage has intensified and the Agulhas Current has weakened during the past decades, and both are projected to continue to do so in the future (Tim et al., 2023), this may indicate that the Agulhas Current System as a whole could contribute to extremes becoming more frequent in the future.

The spatial correlation map (Fig. 7) shows the spatial pattern of the correlation coefficient of Agulhas Current and Agulhas leakage intensity with the number of extremes per year without a time lag. It can be seen that the correaltions with the Agulhas Current changes in the historical and in the scenario simulation. Correlations are mainly negative for the past, indicating more extremes with weak Agulhas Current. At the same time, this is only true for the east coast and Cape Town and north of it in the future. If this correlation indicates a causal link, the weakening of the Agulhas Current in the future would lead to more extreme events but less extreme events over the south coast and the northern west coast.

The Agulhas leakage is also mainly negatively correlated with the number of extremes in the past. Thus, interpreting the correlation as a causal link, strengthening the Agulhas leakage has led to fewer extremes in the past decades, apart from a small

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Discussions

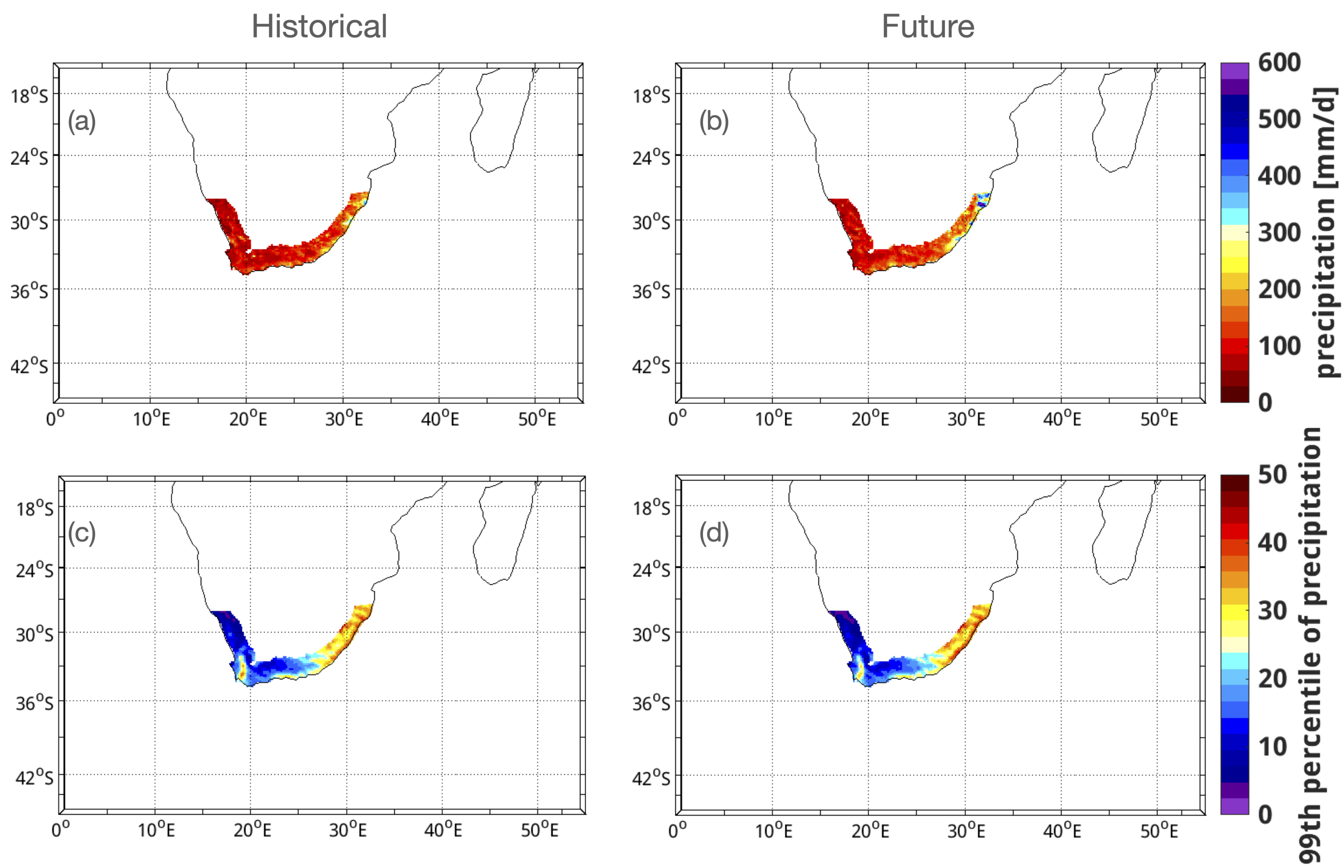

Figure 5. Maximum of daily precipitation and 99th percentile of daily maximum precipitation of (a) and (c) the historical simulation and of (b) and (d) the scenario simulation of CCLM.

coastal band along the east coast. In the future, the strengthening of the Agulhas leakage is projected to cause more extreme events along the east coast and less extreme events along the south and west coast.

Thus, as for the spatial sum of extreme events, the Agulhas Current System is simulated to contribute to more extreme events in the future along the east coast of South Africa. By contrast, extreme events along the south and west coast could be reduced by the effect of the Agulhas Current System in the future.

However, it has to be kept in mind that found correlations are generally low and that the impact of the strength of the Agulhas Current System on extremes might not be as relevant as other drivers.

3.5 Extreme rainfall in Cape Town

The recent drought in the Cape Town area showed the fragility of the water supply in this region. Extreme rainfall may help to fill the rainfall reservoirs but also are a threat causing severe flooding, especially on desiccated land.

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Discussions

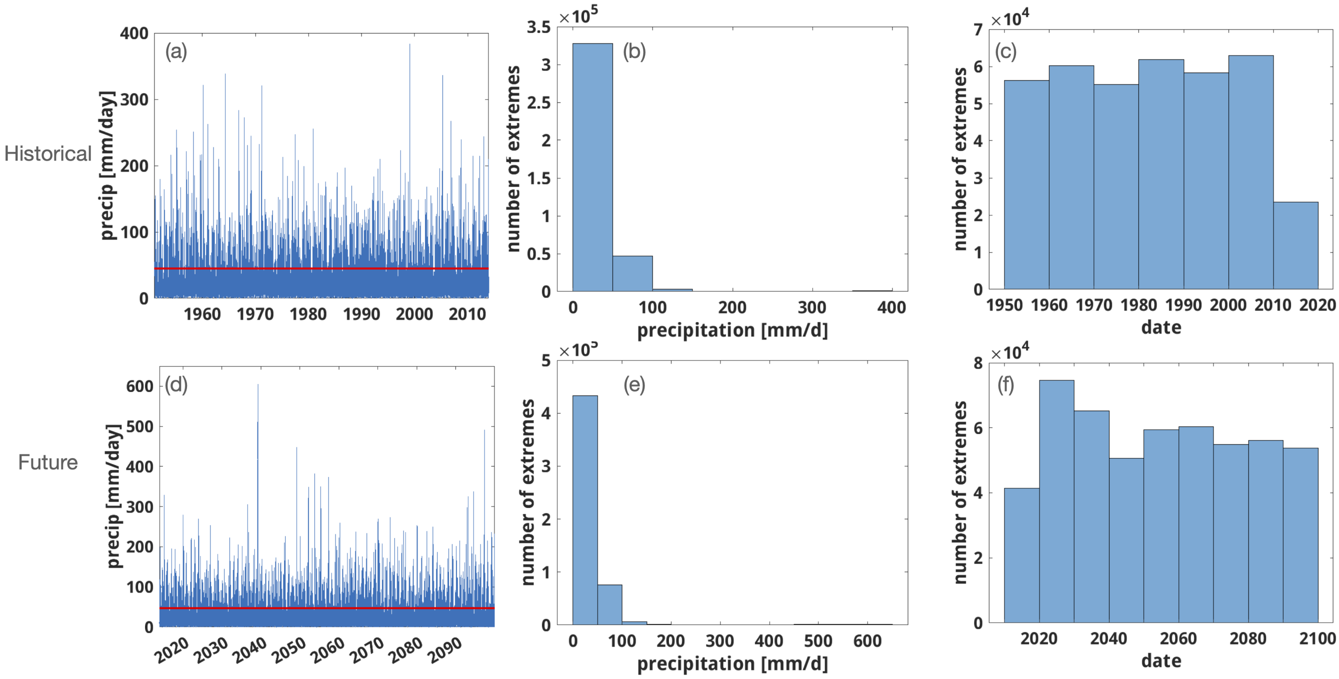

Figure 6. Extremes at the coastline (99th percentile). Time series of spatial maximum daily precipitation amounts, histograms of the number of extremes regarding the strength and the date (a), (b), and (c) for the historical simulation, and (d), (f) and (g) for the scenario simulation of CCLM. The red line indicates the spatial maximum of the 99th percentiles.

For the analysis focused on extreme precipitation around Cape Town, we spatially average the rainfall in the Cape Town area (18.1-18.7 °E, 33.5-34.6 °S). As for the whole WRZ, the 99th percentile threshold is similar in both simulations. However, the strongest extreme event is simulated in the historical simulation (74 mm/day). Thus, the scenario simulation does not produce stronger extremes than those already simulated in the historical simulation. In addition, when evaluating the temporal distribution of the extremes along the simulations, the most intense extreme events occur in the early simulation periods, with almost no extreme events simulated in the last 20 years of both simulation periods in this region.

3.6 Extreme rainfall in KwaZulu-Natal

The KwaZulu-Natal region witnessed in April 2022 an extreme rainfall event with severe flooding. We additionally analysed the simulated extremes for this region in particular. For this purpose, we spatially averaged rainfall over land in the region 28.9-32.9 °E, 26.8-31.1 °S. As the event in 2022 took place over two consecutive days, we also calculated the two-day sum in both simulations.

Comparing the CCLM simulations to the reanalysis, the model daily maximum precipitation values show a good agreement with ERA5. Within the period 1979-2020, ERA5 has a maximum daily rainfall of 335 mm/day at 32.8 °E, 27.0 °S, a 2-day

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
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Discussions

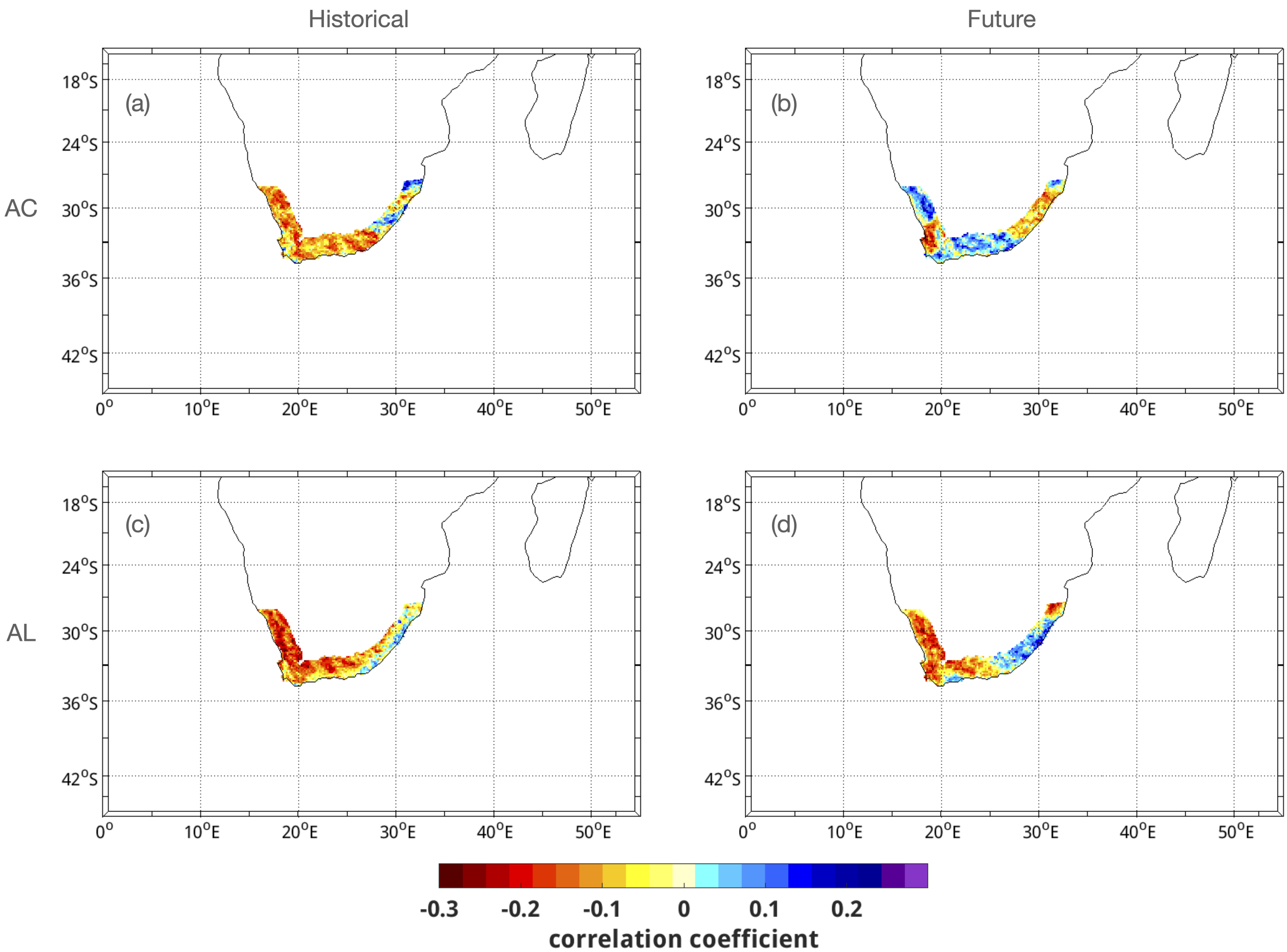

Figure 7. Correlation coefficient of the Agulhas Current System with the yearly number of extremes. (a) Agulhas Current and number extremes of the hindcast simulation, (b) Agulhas Current and number extremes of the scenario simulation, (c) Agulhas leakage and number extremes of the hindcast simulation, and (d) Agulhas leakage and number extremes of the scenario simulation.

sum of 403 mm/2 days and no significant trend over the observational period (Fig. 8).
Looking only at the observed days of this specific extreme event (8th to 16th of April 2022), ERA5 displays a day sum of 261 mm/day on the 11th of April at 31.3 °E, 29.3 °S and a 2-day sum of 313 mm/2days over the period 11th to 12th of April 2022 (Fig. 9).

Unfortunately, the hindcast simulation does not cover this event, so a direct comparison between observations and CCLM is impossible for this particular event. Still, we can compare this extreme event with the strongest events simulated in the

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences Discussions

historical and scenario simulations. In these simulations, the absolute extremes also occur in a similar location of 32.2 °E, 28.6 °S and 31.6 °E, 28.7 °S (Fig. 8). We found that the highest value in this region in the historical simulation is 383 mm/day, and much higher in the scenario simulation (604 mm/day). Considering two-day sums, the highest value in the historical simulation (524 mm) is similar to the one observed in April 2022 April (450 mm) but it is much higher in the scenario simulation (801 mm). However, there is no significant trend over time in this region's yearly maximum of daily or 2-day sum rainfall amounts, either in the historical or scenario simulation.

Thus, the extreme event in April 2022 was of the same magnitude as the extreme rainfall simulated in the historical simulation. The projected maximum daily precipitation for the future is around double the rainfall amount simulated for the past by CCLM or displayed in ERA5.

Regarding possible adaptation measures, it is necessary to understand the causes of extreme events. Therefore, we looked at the precipitation pattern and the atmospheric circulation during the most intense 2-day extreme events in KwaZulu-Natal in the historical and scenario simulation of CCLM, of ERA5 (covering the period 1979-2020) and of ERA5 for the extreme event in April 2022. The precipitation pattern during the strongest 2-day precipitation events of the historical and scenario CCLM simulation as well as for ERA5 (1979-2020) and the recent extreme even, in April 2022, are shown in figure 10, the SLP field of these events are shown in figure 11 and the corresponding wind fields can be seen in figure 12. From the precipitation pattern and the SLP and wind patterns, the difference between the observed and simulated events becomes obvious. The most extreme rainfall event simulated over KwaZulu-Natal in the historical period happened on the 23rd-24th of February 1996, right in the north of the province. The rainfall event in the scenario simulation occurred on the 17th-18th of March 2039 around Richards Bay. This event is much stronger than the ones simulated by CCLM for the past or displayed ERA5. The extreme rainfall in ERA5 occurred on the 28th-29th of September 1987 along most of the coast of KwaZulu-Natal. In contrast, the recently observed extreme event (11th-12th of April 2022) was more local, centred around Durban.

The SLP pattern over the ocean is similar for the future simulation and both ERA5-cases. The subtropical highs over the Indian and Atlantic Oceans are stronger. Their patterns suggest an intensified SLP over the western subtropical Indian Ocean is important for such an extreme rainfall event. The SLP over land varies among the cases. There was no clear deviation from the mean in SLP over South Africa in April 2022 in ERA5, whereas there was a decreased SLP during the extreme event in ERA5 (1979-2020). The scenario simulation shows an even stronger decrease over KwaZulu-Natal and other parts of the mainland. Also, in the scenario simulation, a local minimum is displayed in the Mozambique channel, which might be a tropical cyclone. By contrast, the SLP pattern over the oceans in the historical simulation differs from the other three cases. The subtropical highs are only very slightly intensified and not connected. A negative pressure anomaly, located south of the continent, separates them. Pressure over the land is reduced by around 5 hPa.

The wind pattern reflects what we have just described for the SLP pattern. In all cases, there are strong, intensified winds over the adjacent ocean towards the coastline. Again, the event in the historical simulation differs from the other three cases. In

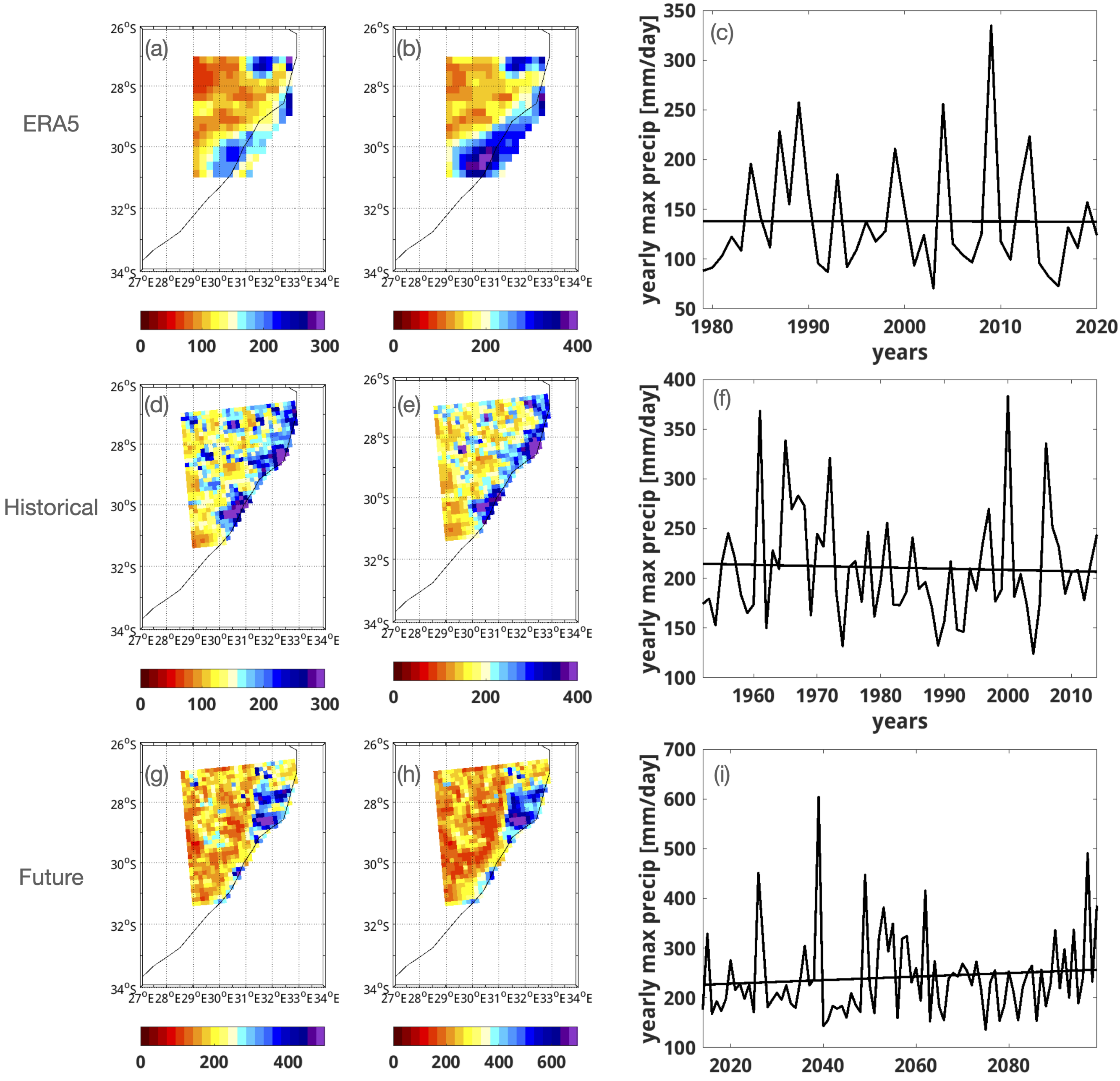

Figure 8. Maximum of daily precipitation (mm/day), maximum of 2-days-sum precipitation (mm/2-days), and time series of yearly maximum, (a), (b), and (c) of ERA5, (d), (e), and (f) of the historical simulation, and (g), (h), and (i) of the scenario simulation of CCLM.

the historical simulation, two branches of strong easterlies reach the coast, whereas in the scenario simulation, the clockwise
245 circulation in the north of KwaZulu-Natal indicates again a cyclone. For both events in ERA5, the wind field is similar but with

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

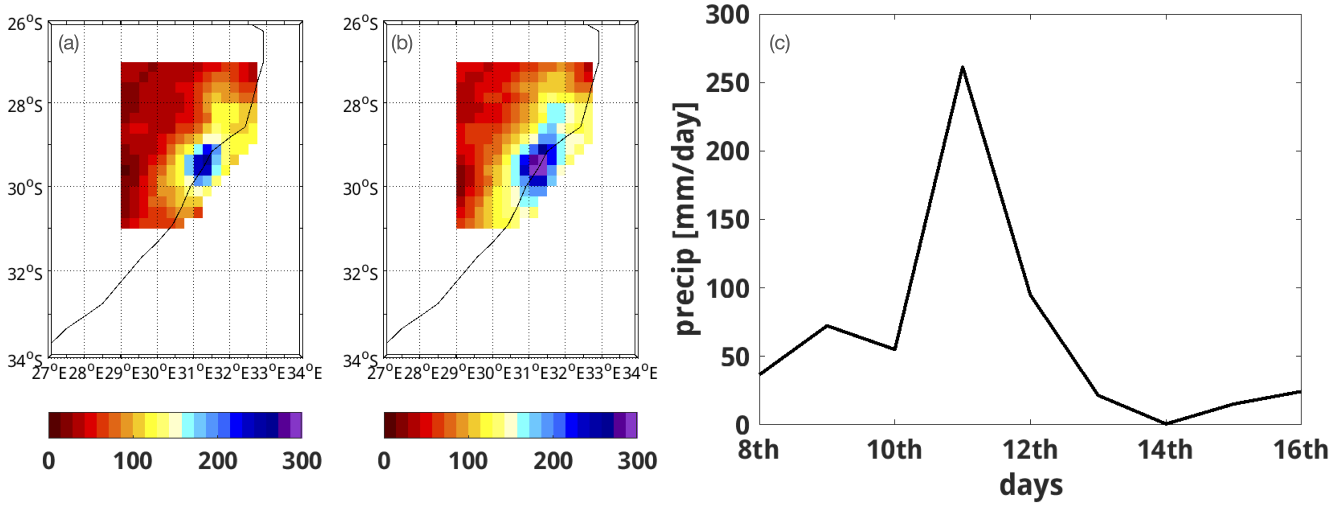

Figure 9. (a) Maximum of daily precipitation (mm/day), (b) maximum of 2-days-sum precipitation (mm/2-days) and (c) time series of daily precipitation of ERA5 for the extreme event in KwaZulu-Natal between the 8th and the 16th of April 2022.

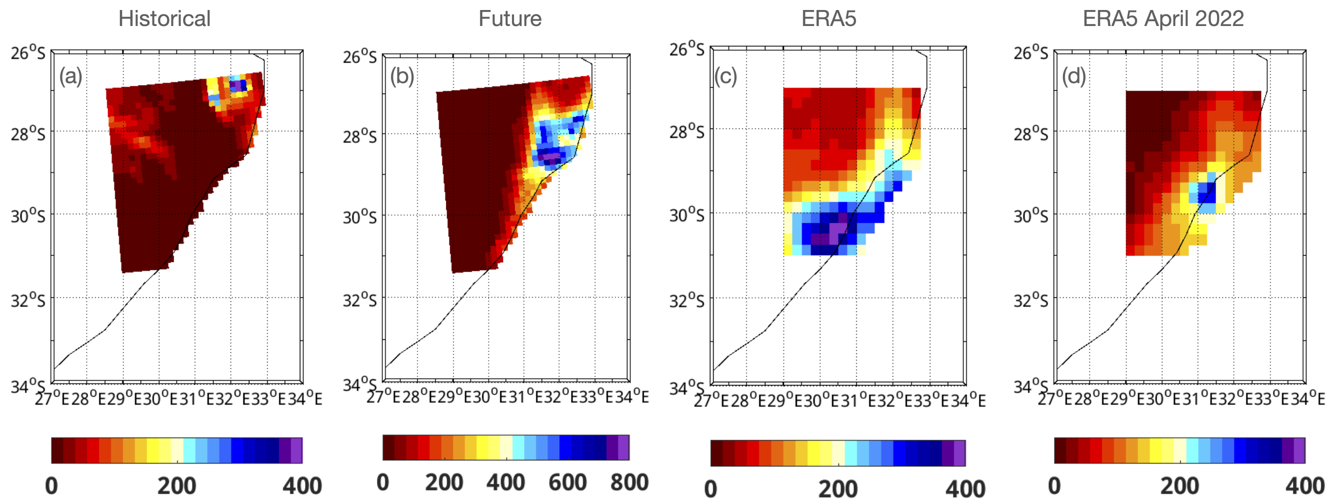

Figure 10. Precipitation pattern of the 2-day maximum of daily precipitation of (a) the historical CCLM simulation, (b) the scenario CCLM simulation, (c) ERA5, and (d) ERA5 of the extreme event in KwaZulu-Natal between the 8th and the 16th of April 2022. Values are given in mm per 2 days.

more coastal parallel wind in April 2022 and more zonal winds in September 1987.

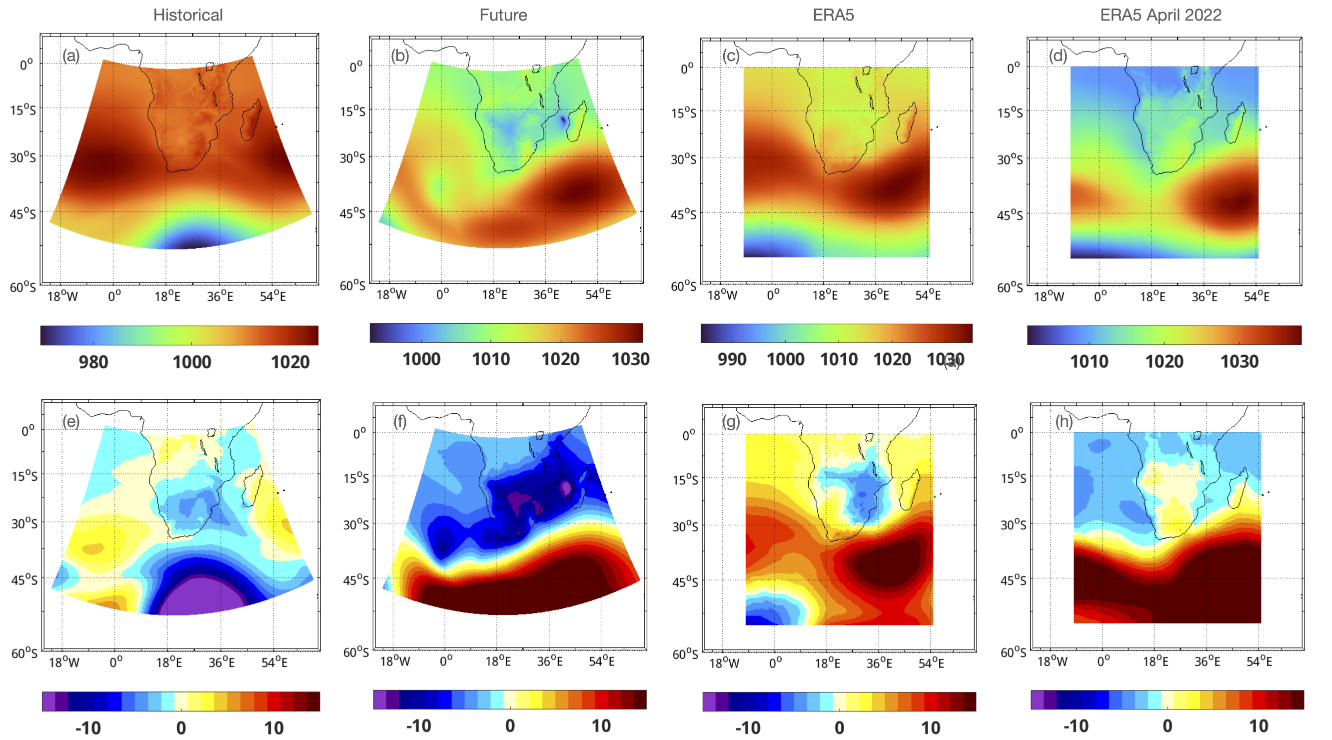

Figure 11. Sea level pressure pattern (a-d) and its anomaly (e-h) for the 2-day maximum of daily precipitation of (a, e) the historical CCLM simulation, (b, f) the scenario CCLM simulation, (c, g) ERA5, and (d, h) ERA5 of the extreme event in KwaZulu-Natal between the 8th and the 16th of April 2022. Values are given in hPa.

Thus, the atmospheric circulation in these 4 cases of extreme precipitation in KwaZulu-Natal is not the same, but they share some general characteristics. An intensified subtropical high over the Indian Ocean and a low in the rainfall region favours wet and moist air transport from the Indian Ocean to the coastal KwaZulu-Natal region, causing intense precipitation events.

4 Discussion and conclusions

As stated by the IPCC in their Regional fact sheet - Africa (AR6), heavy precipitation events are projected to increase in frequency and intensity almost everywhere in Africa due to climate change. In their figure, one can see that the southern African WRZ is an exception to this high-confidential statement for the African continent. There, the annual maximum daily precipitation is not projected to increase. Changes are minimal for this region. Nevertheless, for west southern Africa (WSAF), they report a decrease in observed and projected mean precipitation and an increase in observed heavy precipitation and pluvial flooding. Similar results are stated for eastern and southern Africa (ESAF), with an observed decrease in mean precipitation and an observed and projected increase in heavy precipitation and pluvial flooding. Thus, the current state of research agrees

Natural Hazards and Earth System Sciences
Open Access
Discussions

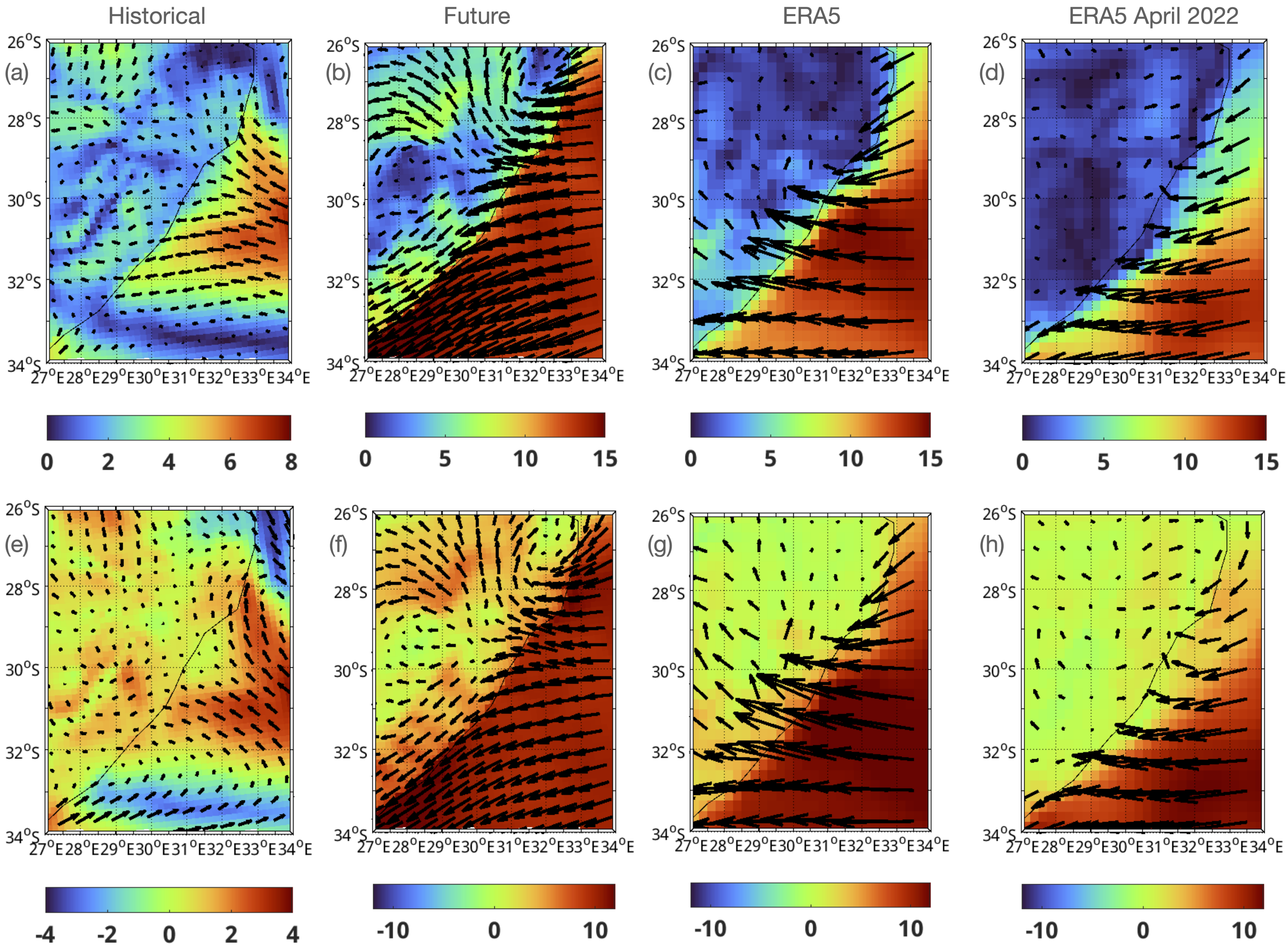

Figure 12. Wind pattern (a-d) and its anomaly (e-h) of the 2-day maximum of daily precipitation of (a, e) the historical CCLM simulation, (b, f) the scenario CCLM simulation, (c, g) ERA5, and (d, h) ERA5 of the extreme event in KwaZulu-Natal between the 8th and the 16th of April 2022. Speed is given in colours in m/s, the wind direction is represented by arrows and wind speed by the length of the arrows.

upon a decrease in observed mean precipitation, an increase in observed heavy precipitation and a projected increase of heavy precipitation for most of Africa, except the WRZ.

Tropical cyclones are projected to increase in intensity and associated rainfall for a 2 °C global temperature rise, with medium confidence (Pörtner et al., 2019). At the global scale, there is also only low confidence in a change in the frequency of tropical cyclones in a future climate (Pörtner et al., 2019). Extremes are expected to intensify due to climate change as the amount of moisture in the warmer atmosphere is expected to rise and rises much faster than the total precipitation amount. Thus, precipitation intensity would increase, but the duration or frequency of events decrease (Trenberth et al., 2003).

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Discussions

In the following, our results are listed and compared to these previous findings summarized by the IPCC.

- Extremes in the SRZ and WRZ:
  Extremes in ERA5 are less intense than simulated by CCLM. Thus CCLM overestimates the daily sum of precipitation of the 99th percentile of precipitation. Nevertheless, the regional differences in extreme event intensity over the study region are represented well by CCLM.
  Extremes are weaker in the WRZ than in the SRZ in the historical and scenario CCLM simulations. In both regions, they are not projected to become more intense in the future and tend to occur equally spread throughout time.
  This agrees with the behaviour of extremes in the regions hit by tropical cyclones and cut-off lows located in the SRZ of Southern Africa (Reason, 2017). However, contrary to our findings, CMIP5 models do show an increase of the 99% percentile of daily rainfall amounts in austral summer in the future (Pohl et al., 2017). For the WRZ, our results agree with the model study of Dosio et al. (2021). They also found no intensification of rain intensity in model simulations. The expected intensification of extremes in the SRZ is the scenario simulation is not simulated by our CCLM. Thus, our results agree with the IPCC summary only for the WRZ, but not for the SRZ.

- South African coastline:
  Contrary to the inland, the most intense precipitation extreme is projected for the future, whereas mean precipitation weakens (Tim et al., 2023). Thus, more extreme precipitation falls on generally drying soil, which is more prone to flooding and erosion. Tropical cyclones cause 13 % (historical) and 11 % (scenario) of the extreme events, whereas cut-off lows lead to 6 % (historical) and 4 % (scenario) of the extreme events at the coastline. Thus, tropical cyclones are more often the driver of a coastal extreme rainfall event and both causes are projected to become less frequent in the future than in the past.
  Here, our results agree with the ones of IPCC's ESAF. As extremes are more intense in the east of our coastline, the spatial maximum of the extremes represents most likely the eastern part of the South African coastline and not their WRZ part. Furthermore, we found a slight decrease in cyclone frequency for coastal South Africa, while the IPCC stated low confidence of tropical cyclone frequency globally.

- Impact Agulhas Current:
  The impact of the strength of the Agulhas Current System on extreme rainfall over the South African coast might be small, as correlations to extreme precipitation are weak. Nevertheless, our simulations indicate that the weakening of the Agulhas Current and the strengthening of the Agulhas leakage in the future might contribute to more extreme events along the east coast of South Africa and fewer extremes along the south and west coast.
  The study of Rouault et al. (2002) shows that the climatologically warm ocean surface of the Agulhas Current can intensify storms and enhance the resulting extreme precipitation over the adjacent land. Thus, the SST of the Agulhas Current may contribute to the strong rainfall events by additional atmospheric moisture over the current that would occur without the Agulhas Current. However, although the strength of the Agulhas Current and leakage may influence extreme

https://doi.org/10.5194/nhess-2023-147
Preprint. Discussion started: 23 August 2023

Natural Hazards and Earth System Sciences
Open Access
Discussions

precipitation, other factors are, in the simulation, more important. The impact of the Agulhas Current and Agulhas leakage strength on the SST seems too small to substantially impact precipitation extremes.

- Cape Town:
  For the area of Cape Town, precipitation extremes are projected to weaken in the future, as for the whole WRZ.
  This agrees with previous findings by Abiodun et al. (2017), who found that the intensity and frequency of extreme rainfall events and annual precipitation totals are projected to decrease over Cape Town. The IPCC states no projected intensification of extremes for this region. One reason might be the more southward location of cut-off lows in the future, as it has been the case in 2017, adding to the severity of the drought (Abba Omar and Abiodun, 2020). As the westerlies are projected to shift southward (Tim et al., 2019), cut-off lows might not reach the Western Cape leading to less extreme events of this type.

- KwaZulu-Natal:
  The extreme event in April 2022 was of the same magnitude as the extreme rainfall simulated in the historical simulation. The projected maximum daily precipitation for the future is around double the rainfall amount simulated by CCLM or displayed ERA5 in the past decades. This agrees with the projected intensification of heavy precipitation and pluvial flooding for the ESAF and the projected increase in tropical cyclone intensity reported by the IPCC.

However, in the simulations and the ERA5 reanalysis, the atmospheric circulation related to extreme precipitation in KwaZulu-Natal are not always the same, although they share some characteristics. Generally, an intensified subtropical high over the Indian Ocean and a low in the rainfall region favours wet and moist air transport from the Indian Ocean to coastal KwaZulu-Natal, causing intense precipitation events. Previous studies have also found that precipitation extremes in this region may originate in different circulation patterns. Cut-off lows, like in April 2022, and tropical cyclones, like in April 2019, are two main atmospheric patterns related to extreme rainfall events in KwaZulu-Natal and along the coast further north. (Mawren et al., 2020; Thoithi et al., 2023). There is no consensus about the change in the number of tropical cyclones. Some studies state that it is projected to decrease with climate change (Walsh et al., 2019; Muthige et al., 2018; Fitchett, 2018), but confidence is low (Pörtner et al., 2019). Nevertheless, the literature agrees upon a projected increase in the intensity and an increase of the associated rainfall (Walsh et al., 2019; Pörtner et al., 2019).

Data availability. CCLM and FOCI simulations are available upon request

Author contributions. All authors designed the analysis and wrote the manuscript. NT and EZ set up and ran the CCLM simulations.

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Discussions

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