Assessing Exposure to Climate Extremes over the Arabian Peninsula Using ERA5 Reanalysis Data: Spatial Distribution and Temporal Trends

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Abstract

Understanding climate extremes and indices is crucial for addressing climate change impacts, including the increased variability in local weather patterns and extreme events. Previous studies on the Arabian Peninsula (AP) have been limited by sparse station data and restricted spatial coverage. To overcome this limitation, this paper aims to assess the spatial distribution and temporal trends of temperature and precipitation indices suggested by the Expert Team on Climate Change Detection and Indices (ETCCDI) using ERA5 reanalysis data from 1951 to 2020 for the AP. Additionally, this study investigated the changes relative to the reference period (1951–1980). The modified Mann-Kendall test and Sen's Slope estimator are utilized to detect significant trends and estimate their magnitude. Results revealed that ERA5 was consistent with previous studies that utilized in-situ station data, offering a more detailed picture of the affected areas. The findings indicated a significant warming trend in temperature indices, with an increase of over 1°C per decade observed across several areas, including the northern AP, and certain regions experiencing a discrepant change of 3°C increase compared to the reference period. Changes in rainfall indices indicate a shift in rainfall patterns from the AP's fertile southwest regions towards more intense patterns in specific eastern regions, including Oman, Kuwait, Saudi Arabia, and Yemen. However, the precipitation temporal trends are weak in magnitude and variable spatially, with dominant decreases in both intensity (-10 mm per decade) and frequency indices (-5 days per decade). Some locations are subject to the combined effects of most heatwave indicators simultaneously, while flood indicators and yet others by drought indicators influence others. All these locations have been accurately identified in this study. The findings provide valuable information regarding the region's climate change vulnerability and adaptation needs.

Keywords: Arabian Peninsula; ERA5; Climate indices; Significant trends; Yemen

1. Introduction

Climate change is now among the most urgent challenges of the century (WHO, 2018), with significant effects on human life, ecosystems, and economic activities. Among the various aspects of the changing climate, the study of climate extremes is of particular importance, as they are often associated with high-impact events such as heatwaves, droughts, and heavy precipitation that can cause severe damage to both natural systems and human lifestyle (Easterling et al., 2000; Fischer et al., 2021). In this context, the Expert Team on Climate Change Detection and Indices (ETCCDI) has suggested a broad set of indicators to examine extremes in the climate (Karl et al., 1999), which have been extensively employed in various regional and global analyses. Research on climate extremes and indices and their trends is an important topic among researchers to measure and verify climate change in an area of interest. To that end, numerous investigations have been conducted on both a regional and national scale in diverse regions worldwide (Ahmed et al., 2017; Bhatti et al., 2020; Donat et al., 2014; Gunawardhana et al., 2018; Islam et al., 2021; Nashwan et al., 2019; Ng et al., 2022; Shahid, 2010; Walt and Fitchett, 2021; Zhang et al., 2005; Zittis et al., 2022). Understanding previous TempPrec extremes is critical for designing more extensive and long-term climate resilience measures (Hamed 2021; Yu et al. 2015). Assessing variations in rainfall extremes is critical in order to estimate the potential implications of climate change, such as catastrophic floods and prolonged periods of drought, as well as organizing climate change mitigation and adaption strategies (Almazroui and Saeed, 2020; Kotwicki and al Sulaimani, 2009). The severe implications of TempPrec extremes mean that extensive study on them utilizing longer records is necessary for each country or region (Odnoletkova and Patzek, 2021). This is especially significant for the AP, which has a semiarid and arid environment (Almazroui, 2020a; Kwarteng et al., 2009).

The Arabian Peninsula (AP) region is vulnerable to climate variability and change, especially climate extremes, which can significantly impact water resources, agriculture, and human health (Almazroui et al., 2022; Donat et al., 2014; Zhang et al., 2005). Consequently, several studies of climatic extremes over AP have been undertaken (Almazroui et al., 2022; Alsarmi and Washington, 2014; Donat et al., 2014; Zhang et al., 2005). Almazroui et al. (2022) examined temperature and precipitation (TempPrec) extremes over Saudi Arabia during 1978-2021. It revealed significant trends in climate extremes, including increased heatwaves and heavy precipitation events. Alsarmi and Washington (2014) used in-situ observations from 23 stations spread over the AP from 1970 to 2008. They found significant warming trends, while precipitation trends were slight and insignificant, except for the PRCPTOT (annual total precipitation in wet days) index. Donat et al. (2014) collected in-situ observations from 61 stations across the Middle East and North Africa (MENA), including 13 stations in the AP, from 1961 to 2010. Their findings indicated warming trends throughout the region, with precipitation patterns exhibiting reduced uniformity, increased temporal and spatial variability, and a prevalence of drying trends in the AP. Zhang et al. (2005) analyzed in-situ observations from 52 stations in the Middle East, including 9 stations only in the AP, from 1950 to 2003, revealing a considerable rise in temperature extremes such as warm days and nights, as well as changes in precipitation patterns, including an increase in consecutive dry days. Excluding data from in-situ meteorological stations, Khan et al. (2019) utilized the daily gridded precipitation dataset APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation) over Malaysia and showed a drop in rainy days together with a rise in wet spells and the maximum one-day precipitation. ERA5 reanalysis data was utilized by Odnoletkova and Patzek (2021) to investigate trends in temperature extremes and human comfort indices in Saudi Arabia from 1979 to 2019, revealing significant warming trends in all seasons, along with an increase in the frequency and intensity of heatwaves, which have negative impacts on human comfort and health. Most previous studies have utilized the Mann-Kendall (MK) test (Hamed, 2008) and Sen's slope estimator (Sen, 1968). However, there is a lack of studies that have employed the Modified Mann-Kendall (MMK) test on the AP, which is considered superior (Khan et al., 2019). Khan et al. (2019) employed the MK and MMK tests, revealing that the MMK test rejected most of the significant trends observed by the MK test over Malaysia and provided more details.

Most studies conducted earlier have examined TempPrec extremes over the AP. However, it is worth noting that most of these studies, regardless of their quality, relied on sparse station records and limited temporal periods. As a consequence, there are fewer spatial coverages, particularly over remote areas such as deserts and mountains (Almazroui et al., 2022, 2014; Alsarmi and Washington, 2014; Gunawardhana et al., 2018; Hereher, 2016; Zhang et al., 2005). Across AP, Donat et al. (2014) used data from 13 stations, Zhang et al. (2005) used nine stations, and AlSarmi and Washington (2011, 2014) used 21 and 23 stations, respectively. Tarawneh and Chowdhury (2018) used data from only three stations in Saudi Arabia. Recently, Almazroui et al. (2022) used data from 24 stations in Saudi Arabia, which covers around 80% of the AP's area. However, many places in the AP lack sufficient stations, such as Yemen, which ranked the peninsula's second-largest nation, covering 527,970 km^2 (AL-wesabi et al., 2022). Moreover, the terrain in the AP is diverse, with towering mountains, plateaus, plains, valleys, and coasts, all of which necessitate more densely well-distributed monitoring stations to observe meteorological phenomena in these areas as per the requirements laid out by the World Meteorological Organization (WMO) within its "Guide to Meteorological Instruments and Methods of Observation WMO-No. 8" (WMO, 2021) for station density thresholds and guidelines that are challenging to fully conform to Giazzi et al. (2022). To fill these gaps, this study employs the ERA5 reanalysis dataset, a cutting-edge worldwide climate reanalysis product prepared by the European Centre for Medium-Range Weather Forecasts (ECMWF). Using ERA5 data offers an unprecedented opportunity to overcome the data scarcity issue in the AP, as it provides a consistent and high-resolution representation of climate variables across the entire region, including areas with limited or no observational stations.

This research utilizes the ERA5 reanalysis data to investigate both temperature and precipitation extremes and trends using MMK over the whole AP, which will contribute significantly to advancing our understanding of this topic in this region. Under the stress of climate change and population inflow to this region, this research aims to characterize the geographical distribution of trends and changes in TempPrec indices within AP from 1951 to 2020, based on the indices suggested by ETCCDI using ERA5 reanalysis data. Specifically, the study aims to (1) identify the spatial changes in TempPrec indices over AP, (2) examine the temporal trends of these indices over the study period, and (3) highlight climate-affected areas, including those prone to heatwaves, droughts, and floods, for long-term socioeconomic planning. The findings of this investigation will shed light on the changing nature of climate extremes in the AP, which could inform decision-making processes related to the region's climate change adaptation and risk management. The study's findings will likely provide the groundwork for future studies on the region's impact of global warming.

2. Study Area and Data

2.1. Arabian Peninsula

The Arabian Peninsula (latitude 12–33°N and longitude 34–61°E) is a historical, vast, and diverse region in the Middle East, covering a significant portion of the Arabian subcontinent (**Fig. 1**). The peninsula covers an area of approximately 3.2 million km^2. It includes the following countries listed from largest to smallest in terms of area: Saudi Arabia, Yemen, Oman, the United Arab Emirates (UAE), Kuwait, Qatar, and Bahrain. The AP has a diverse landscape, varying from the coastline along the Arabian Gulf and the Red Sea to deserts and mountains in the interior with elevations of more than 3,000 m.

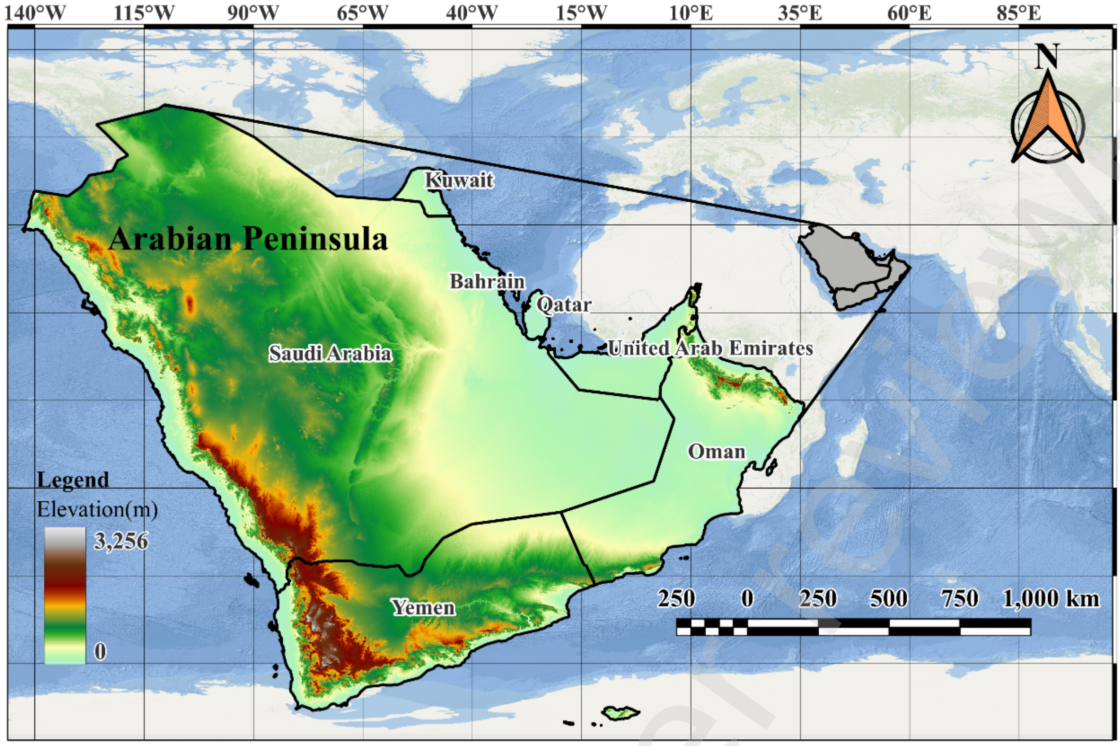


Fig. 1. The study area location with elevation.

AP is characterized by a predominantly arid climate with vast deserts and rugged mountains. Despite its harsh environmental conditions, the region has considerable social and economic significance, being home to millions of people and playing a crucial role in global energy production and trade (Sedaoui, 2022). The AP represents the most significant global reservoir of petroleum (Saleh M. Billo, 1982). The augmentation of the economy in nations including Qatar, the UAE, Bahrain, Saudi Arabia, Kuwait, and Oman has attracted a large influx of migrant workers to the AP, making them hubs for business and commerce due to abundant petroleum resources (Aker and Aghaei, 2019). However, the AP's harsh climate, water scarcity, and reliance on fossil fuels make it particularly susceptible to the influences of climate change (Almazroui et al., 2017). **Fig. 2** depicts the magnitude of the AP's vulnerability to climate change. It reflects the rapid tendency and impact of change over the past seven decades in the AP. The left column in **Fig. 2** shows the daily mean values for the reference period (1951-1980). The middle and right columns depict the changes from the reference period during the second period (1971-2000), and the recent period (1991-2020), respectively. The temperature changes clearly reflect how much the AP has been influenced by global warming. Certain regions currently experience a warming of more than 2°C difference compared to the reference period. The amounts of rainfall received in the AP have decreased dramatically compared to the reference period, requiring urgent action and full preparedness for the resulting consequences.

Given the accelerated urbanization and population influx in this region, understanding the influence of climate extremes is crucial for developing sustainable development policies and strategies (Lin et al., 2020; Zhao et al., 2019). Diverse climatic conditions, including arid deserts, coastal areas, and high-altitude mountains, distinguish the AP. The AP climate is dominated by the Indian monsoon's effect and the movements of the Inter-Tropical Convergence Zone (Almazroui et al., 2012). Climatic extremes, such as high temperatures, heavy rainfall, and drought, are common over the AP and can have significant environmental, social, and economic impacts (AlSarmi and Washington, 2011).

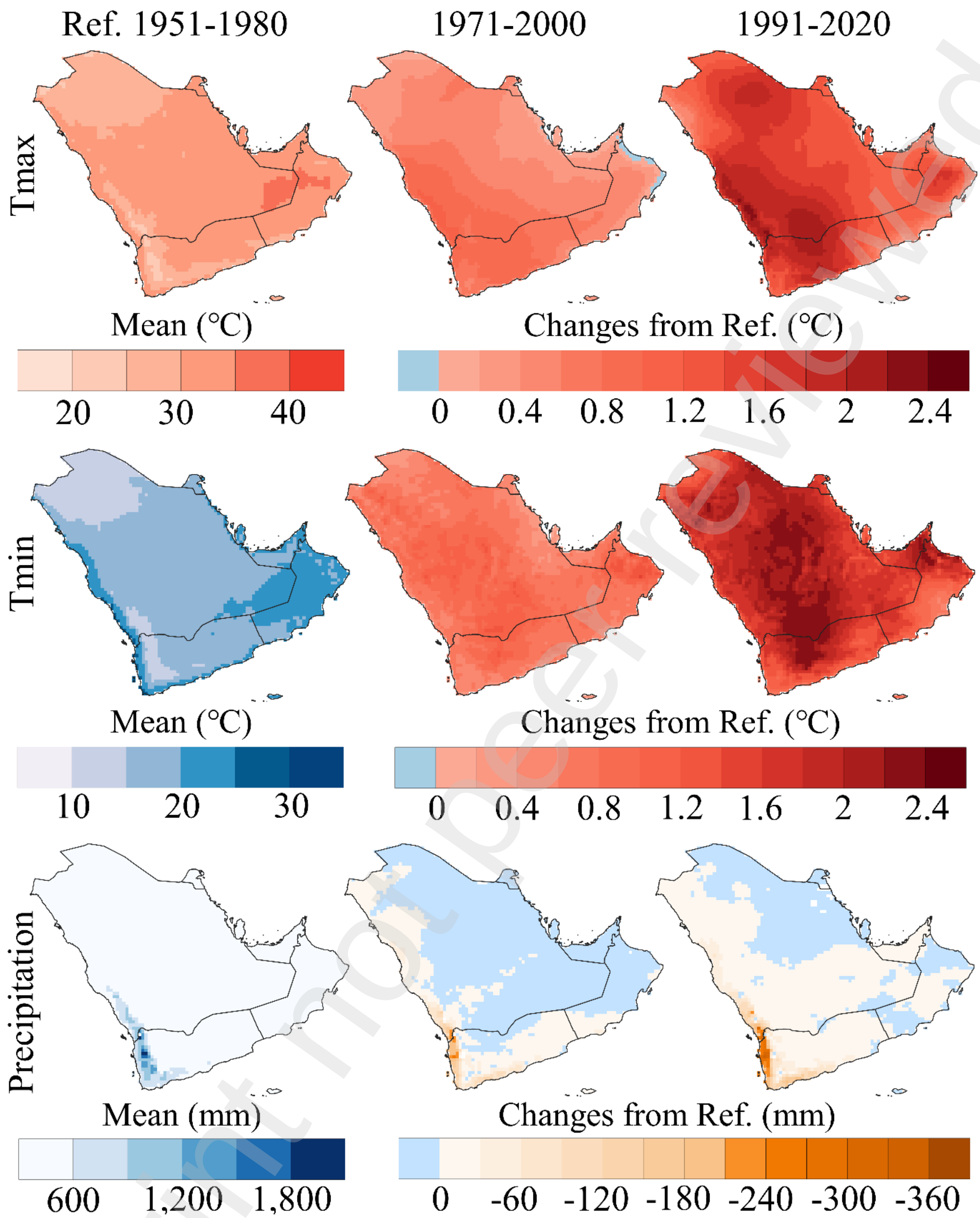


Fig. 2. Spatial distribution of the changes in the key climate variables used in this study: maximum temperature (Tmax), minimum temperature (Tmin), and precipitation.

2.2. ERA5

The insufficiency of observation stations goes against the rising requirements of the scientific community (You et al., 2013), particularly when it comes to evaluating extreme events (Donat et al., 2014). As a result, climate change analysis requires long-term data and a fine spatial resolution (Lei et al., 2022). Studies on climate extremes and their trends are predominantly reliant on rainfall and Tmin/Tmax that is observed via in-situ meteorological stations (Almazroui et al., 2022; Alsarmi and Washington, 2014; Donat et al., 2014; Gunawardhana et al., 2018; Islam et al., 2021; Ng et al., 2022; Zhang et al., 2005). Although utilizing meteorological stations in the AP yields some positive results, several drawbacks still exist (Donat et al., 2014). This is attributed to the inequitable distribution of the in-situ observations across AP and the inadequate count of stations, as well as missing data, which usually results in unsatisfactory spatiotemporal features, especially in the vast regions of the Rub Al-Khali desert (or Empty Quarter) and Yemen, where the meteorological stations are very sparse. To overcome this, other datasets have been used. These datasets can be split into three categories depending on the data sources and models used: satellite-based datasets, interpolated surface observation datasets, and reanalysis datasets (Jiang et al., 2021).

This study used reanalysis data because it is an excellent choice when it comes to climatological applications due to its fine spatiotemporal resolution, diverse data classifications, and worldwide extent (Kaiser-Weiss et al., 2019; Kalnay et al., 1996; Mavromatis, 2022). The reanalysis datasets have been extensively used as compared to the other two data categories (Fonseca et al., 2022; Golshani et al., 2022; Lei et al., 2022). Advancements in data assimilation techniques, satellite remote sensing, land surface, and atmospheric models have gradually increased the temporal and spatial resolution of reanalysis datasets (Nakamura et al., 2022). ERA5 reanalysis data was chosen over other reanalysis datasets because it has a higher spatial resolution (0.25°, ~31 km), temporal resolution (hourly), and temporal coverage (1940-present). It also performs better over the AP than other frequently utilized reanalysis datasets (Fonseca et al., 2022; Odnoletkova and Patzek, 2021). The ERA5 reanalysis dataset was created by utilizing a vast array of measurement and remote sensing data through a retrospective analysis of historical information by the European Center for Medium-Range Weather Forecasts (Hersbach et al., 2020). ERA5 is the fifth-generation reanalysis dataset, an extension of the well-known ERA product family, including ERA-Interim and ERA-40, created by the ECMWF.

Several studies used ERA5 to investigate climate extremes (Ali et al., 2023; Lei et al., 2022; Li et al., 2022; Xu et al., 2022; Zhao et al., 2023). Li et al. (2022) utilized the ERA5 reanalysis dataset to examine the period and quantity of frost days in response to climate change. Avila-Diaz et al. (2021) investigated TempPrec extremes as defined by the ETCCDI for regional and global reanalysis datasets. Their study revealed that ASRv2 and ERA5 show the highest levels of performance. ERA5 has been used for many research studies over AP (Al-Mutairi et al., 2023; Fonseca et al., 2022; Francis et al., 2021; Golshani et al., 2022; Saeed et al., 2023; Safieddine et al., 2022). Fonseca et al. (2022) examined the climate conditions and seasonal changes in the AP from 1979 to 2019 using ERA5 data. Saeed et al. (2023) studied how circulation patterns in mid-latitudes affect the variability of winter temperatures in the AP by utilizing NCEP and ERA5 reanalysis data. The ERA5 data were validated against observations from weather stations worldwide (Li et al., 2020) and over major towns in Saudi Arabia and showed good performance (Odnoletkova and Patzek, 2021). However, AL-Falahi et al. (2020) reported that the efficacy of ERA5 in predicting rainfall rates in Yemen's highland region was limited due to the location's characteristics and the limited ground stations. It may also result from insufficient quality control procedures for the station data before use. Nevertheless, numerous investigations have assessed the ERA5 dataset across the globe and found better-performing results (Alriah et al., 2022; Arshad et al., 2021; Dubache et al., 2021; Hamed et al., 2021; Ma et al., 2021; Randriatsara et al., 2022). Arshad et al. (2021) revealed that ERA5 accurately tracks rain gauges across various climate regions in Pakistan. Furthermore, the ERA5 dataset has been extensively employed as a point of reference in many studies conducted across the AP (Bawadekji et al., 2022; Francis et al., 2021; Horan et al., 2023; Komurcu et al., 2020; Odnoletkova and Patzek, 2021; Safieddine et al., 2022) and other regions (Ali et al., 2023; Hamed et al., 2023b, 2022; Khadka et al., 2022; Zuluaga et al., 2021).

For this study, hourly precipitation and 2m temperature records from 1951 to 2020 were employed to determine rainfall, Tmax, and Tmin daily data. This data was sourced from the latest reanalysis, ERA5, developed by ECMWF (Hersbach et al., 2020). Regardless of the climate in AP, this study used ERA5 to analyze all ETCDDI indices. The ETCDDI details can be found in

Table 1.

Table 1
Definitions of the ETCCDI indices that were utilized in this study.

El.	IDs	Indicator Name	Definition	Units
Temperature	***Duration indices***			
	FD	Frost days	Annual count of days when daily Tmin < 0º C.	Days
	ID	Icing days	Annual count of days when daily Tmax < 0º C.	
	SU	Summer days	Annual count of days when daily Tmax > 25º C.	
	TR	Tropical nights	Annual count of days when daily Tmin > 20º C.	
	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when Tmax>90th percentile.	
	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when Tmin>10th percentile.	
	GSL	Growing season length	Annual (1st Jan to 31st Dec in Northern Hemisphere (NH)) count between the first span of at least 6 days with daily mean temperature >5ºC.	
	Absolute indices			
	TXx	Max Tmax	Annual mean of monthly max value of daily Tmax	°C
	TNx	Max Tmin	Annual mean of monthly max value of daily Tmin	
	TXn	Min Tmax	Annual mean of monthly min value of daily Tmax	
	TNn	Min Tmin	Annual mean of monthly min value of daily Tmin	
	DTR	Diurnal temp. range	Annual mean difference between Tmax and Tmin	
	Relative indices			
	TN10p	Cool nights	Percentage of days when Tmin < 10th percentile	%
	TN90p	Warm nights	Percentage of days when Tmin > 90th percentile	
	TX10p	Cool days	Percentage of days when Tmax < 10th percentile	
	TX90p	Warm days	Percentage of days when Tmax > 90th percentile	
Precipitation	***Intensity indices***			
	RX1day	Max 1 day PR amount	Annual max 1-day precipitation (PR)	mm
	RX5day	Max 5 days PR amount	Annual max consecutive 5-day PR	
	SDII	Simple daily intensity index	Annual total PR divided by the number of wet days (defined as PR >=1.0mm) in the year	
	R95pTOT	Very wet days	Annual total PR when PR >95th percentile	
	R99pTOT	Extremely wet days	Annual total PR when PR >99th percentile	
	PRCPTOT	Annual total wet-day PR	Annual total PR in wet days (PR >=1mm)	
	Frequency indices			
	R10	Heavy PR days	Annual count of days when PR >=10mm	Days
	R20	Very heavy PR days	Annual count of days when PR >=20mm	
	CDD	Consecutive dry days	Max number of consecutive days with PR <1mm	
	CWD	Consecutive wet days	Max number of consecutive days with PR >=1mm	

More details on definitions of the core indices given at http://etccdi.pacificclimate.org/list_27_indices.shtml

3. Methodology

The Expert Team on Climate Change Detection and Indices (ETCCDI) was established by Frich et al. (2002) to present a wide range of climate indices and indicators with the goal of creating relevant extreme indices that are consistent across wide territories. The ETCCDI suggests a comprehensive compilation of 27 fundamental indices, comprising 11 indices for rainfall and 16 indices for temperature.

Table 1 summarizes the ETCCDI indices utilized in this study. The ETCCDI indices allow for direct monitoring of climate trend strength and frequency. Therefore, these indices were used in this study due to the comprehensive list of the indices being provided and its suitability to be employed for comparative assessment (Sa'adi et al., 2023). The analysis was performed using R (v4.1.3; R Core Team 2023) code script. All ETCCDI core indices of extreme climate were calculated by the *climdex.pcic* R package (David Bronaugh, 2020). This package contains functions such as *climdex.su* and *climdex.id* to compute all climate indices at each grid box based on the input data and assign the result to a corresponding variable. There are 3927 grid boxes throughout the AP. The code then processed time series data, calculated extreme values, and generated raster files for different measures and time periods. Furthermore, Sen's Slope and MMK tests were calculated using the functions *sens.slope* and *pwmk* from the packages *trend* (Pohlert, 2023) and *modifiedmk* (Patakamuri and O'Brien, 2021), respectively. Finally, the spatiotemporal maps of the climate indices and their trends throughout all periods were prepared using QGIS software (QGIS Development Team, 2023).

A 30-year time frame with overlapping 10-year periods was utilized to examine the changing patterns of the extremes. The 30 years (1951-1980) was selected as a reference period, and the other two periods (1971-2000 and 1991-2020) to represent the change or difference from the reference period (Hamed et al., 2023b). In this study, the MMK test was used to determine the significance of the trend in the variables explored, while Sen's Slope was used to quantify the change. Sen's Slope and MK have both been extensively utilized in the literature. The MMK test is deemed to be more precise and adaptable than the original MK test in detecting patterns in hydro-meteorological records (Khan et al., 2019; Nashwan et al., 2019). MMK is less likely to falsely detect a trend in autocorrelated data, such as the data used in this study (Yue and Wang, 2004). The slopes (*T*) between any two successive points of data in a time series of (*N*) observations are used to calculate the rate of change (*Qs*):

$$Q_s = \begin{cases} \frac{T(N+1)}{2} & \text{if } N \text{ is odd} \\ \frac{\frac{TN}{2} + T\left(\frac{N+2}{2}\right)}{2} & \text{if } N \text{ is even} \end{cases} \quad (1)$$

A positive *Qs* number represents an increase, whereas a negative value represents a decrease.

4. Results

The spatial changes and temporal significant trends for the temperature (Absolute, Relative, and Duration) and precipitation (Frequency and Intensity) sets of indices utilized in the present research to describe the climate variability of TempPrec extremes across AP are explained in the following sub-sections.

4.1. Changes and Trends in Absolute Indices

To understand the temperature variability in the AP, 30-year mean patterns of the annual time scale for the Absolute Temperature Indices were analyzed and shown in **Fig. 3**, and the temporal trends and their significance at $p<0.05$ were calculated and shown in **Fig. 4**. The utilization of reanalysis data offers a significant advantage by providing precise results for each grid box within the area of interest. Generally, in compliance with previous studies on the AP, warming patterns are well observed. The changes are gradually decreasing for DTR and increasing for the rest of the absolute indices. Among the absolute indices, TXn, TXx, TNn, and TNx are increasing overall AP areas, with some even displaying statistical significance trends. Among the absolute indices, TNx exhibits the most significant change, with an increase of greater than 3℃ above the reference period. During the period 1991-2020, most of the Kingdom of Saudi Arabia (KSA) and Yemen experienced a warming change of more than 2℃ in the maximum of the Tmin (TNx) index compared to the reference period. The DTR index is decreasing gradually in most regions. The highest decreasing change (>-1℃) was observed over the UAE, the interior and northwest of KSA, and the highlands of north Oman during 1991-2020. This shows that the Tmin is rising slower than the Tmax, and maybe the Tmax is rising quicker than the Tmin, or both are happening simultaneously.

The spatial distribution for the significant trends (p-value less than 0.05) is illustrated in **Fig. 4** for all Absolute Temperature Indices for the three specified time frames, namely 1951-1980, 1971-2000, and 1991-2020. During all defined periods, all absolute indices showed significant increasing trends, except for the DTR index, where a few minor decreasing trends are noticed in the Empty Quarter desert, northern Oman, and several parts of the UAE during the first period, and a slight downward trend (-0.25°C per decade) covers most parts of Yemen during the recent period. Between 1991 and 2020, a notable increasing trend of more than 1°C per decade was observed in TNn, TNx, and TXx indices, particularly in the northern AP. The trends in TXn during all periods are observed in limited areas but with higher magnitude.

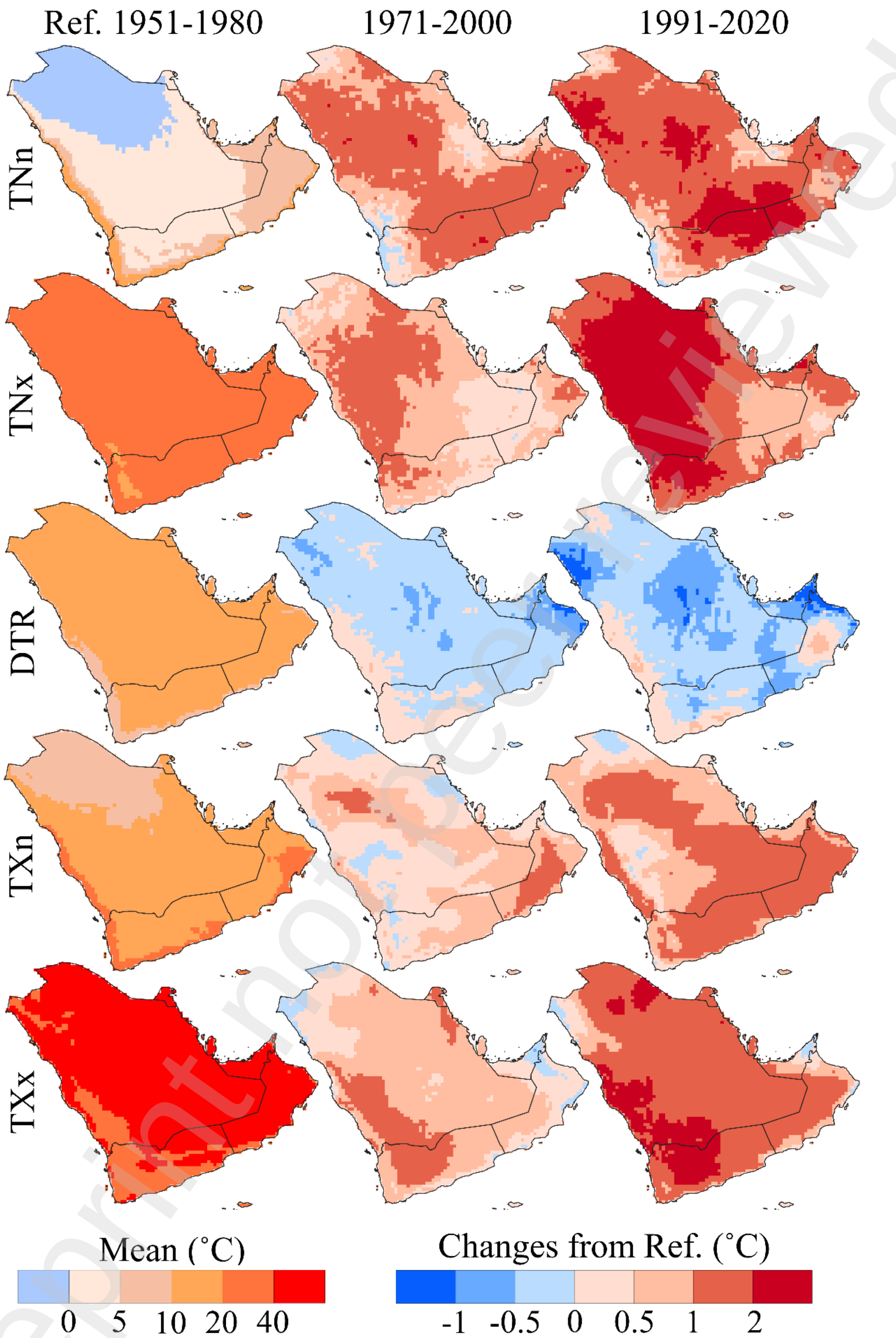


Fig. 3. Spatial distribution of the Absolute Temperature Indices obtained from ERA5 reanalysis data. The left column represents the annual mean of the reference period (1951-1980), and the middle and right columns represent the changes (differences) from the reference period.

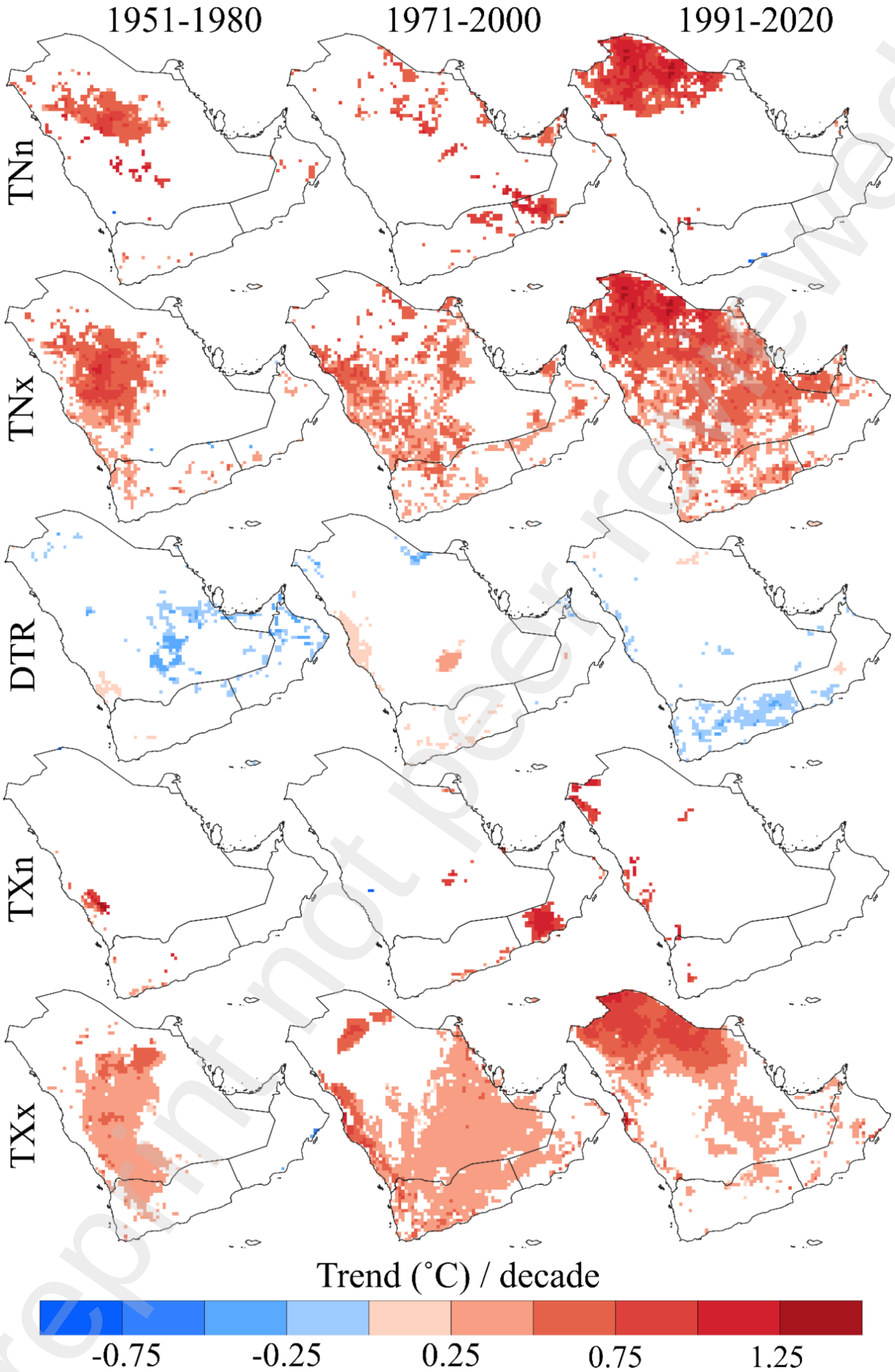


Fig. 4. Spatial pattern of the significance trends ($p < 0.05$) in Absolute Temperature Indices obtained from ERA5 for the three defined periods. The colors represent the rate of change.

4.1.1. Changes and Trends in Relative Indices

The changes in Relative Temperature Indices TN10p, TX90p, TN90p, and TX10p are presented in **Fig. 5**. These indices are served to characterize changes in temperature extremes. According to ETCCDI (2020), cool days (TX10p) indicate the proportion of days when the Tmax surpasses the tenth percentile. This represents the frequency of unusually cold days, while cool nights (TN10p) mean the frequency of occasions when Tmin falls below the 10th percentile. This represents the frequency of unusually cold nights. **Fig. 5** shows a decreasing change in both TN10p and TX10p throughout both recent periods, where a slower value represents cold temperatures. During 1991-2020, most regions of the AP experienced decreased cold days and nights by more than -5% than the reference period. Similarly, TX90p (warm days) indicates the ratio of days when the highest recorded temperature surpasses the 90th percentile. This represents the frequency of unusually hot days, while TN90p (warm nights) means the proportion of days when the Tmin is under the tenth percentile. This represents the frequency of unusually warm nights. Both TX90p and TN90p indices show a gradually increasing change from the reference period during the recent study periods. The highest change in TN90p (~50%) is located over the southwest highlands of Yemen and KSA, while Yemen's north-central areas have shown the highest change (~50%) in TX90p. These changes suggest that the climate is becoming warmer overall, with more warm extremes and fewer cold extremes.

The significant trends ($p < 0.05$) for all Relative Indices are depicted in **Fig. 6**. From 1951 to 1980, significant declining trends in cool days (TX10p) were observed in the western regions of the AP as well as in central Yemen. Similarly, the trends in cool nights (TN10p) exhibited a decrease over the AP's northern and central regions. Conversely, increasing trends were observed across all periods in the TX90p and TN90p indices. The highest trends in warm days and nights were observed in the northern AP during 1991-2020. Additionally, there has been a significant increasing trend in warm nights along the southern shores of Yemen recently.

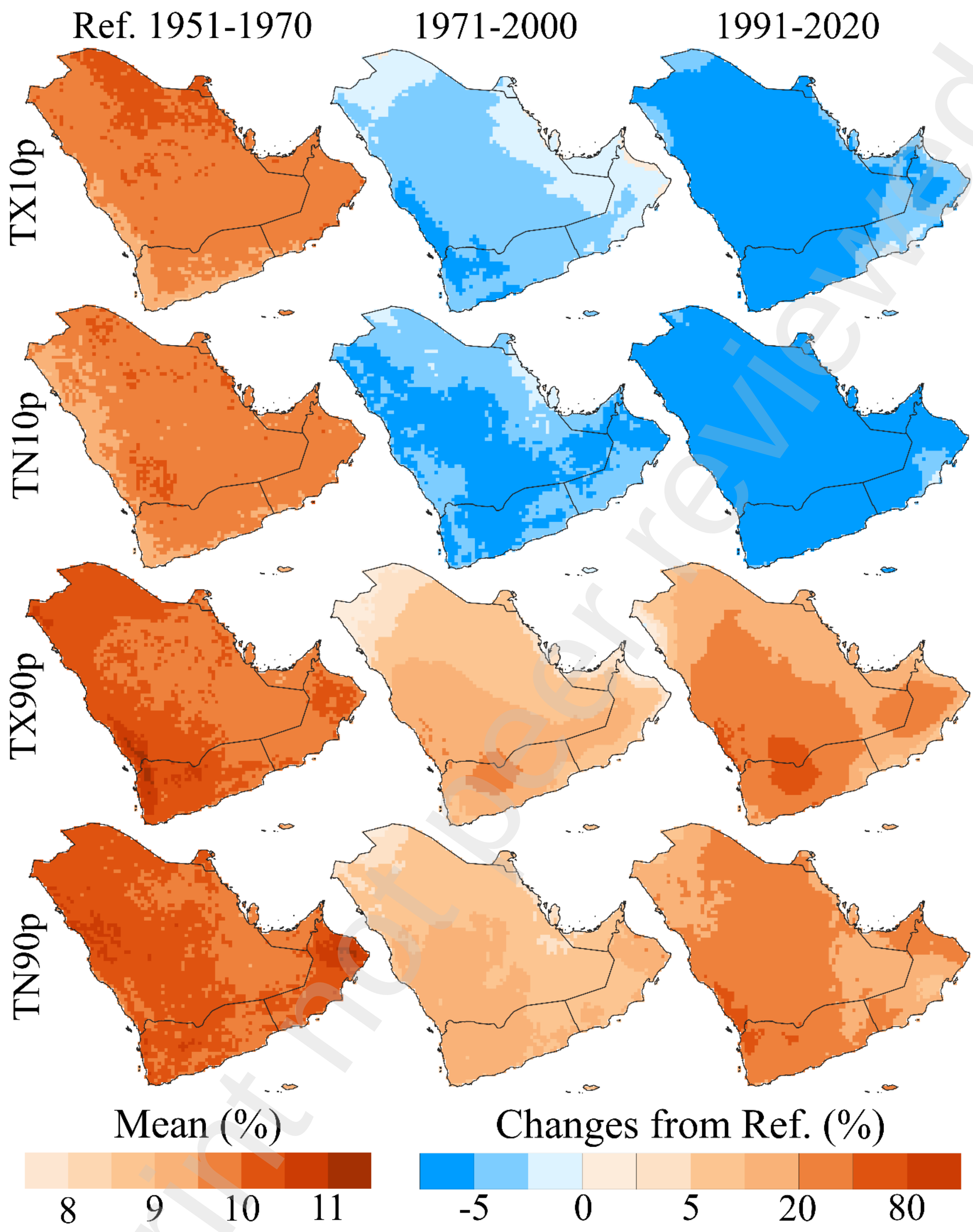


Fig. 5. Same as **Fig. 3** but for Relative Temperature Indices.

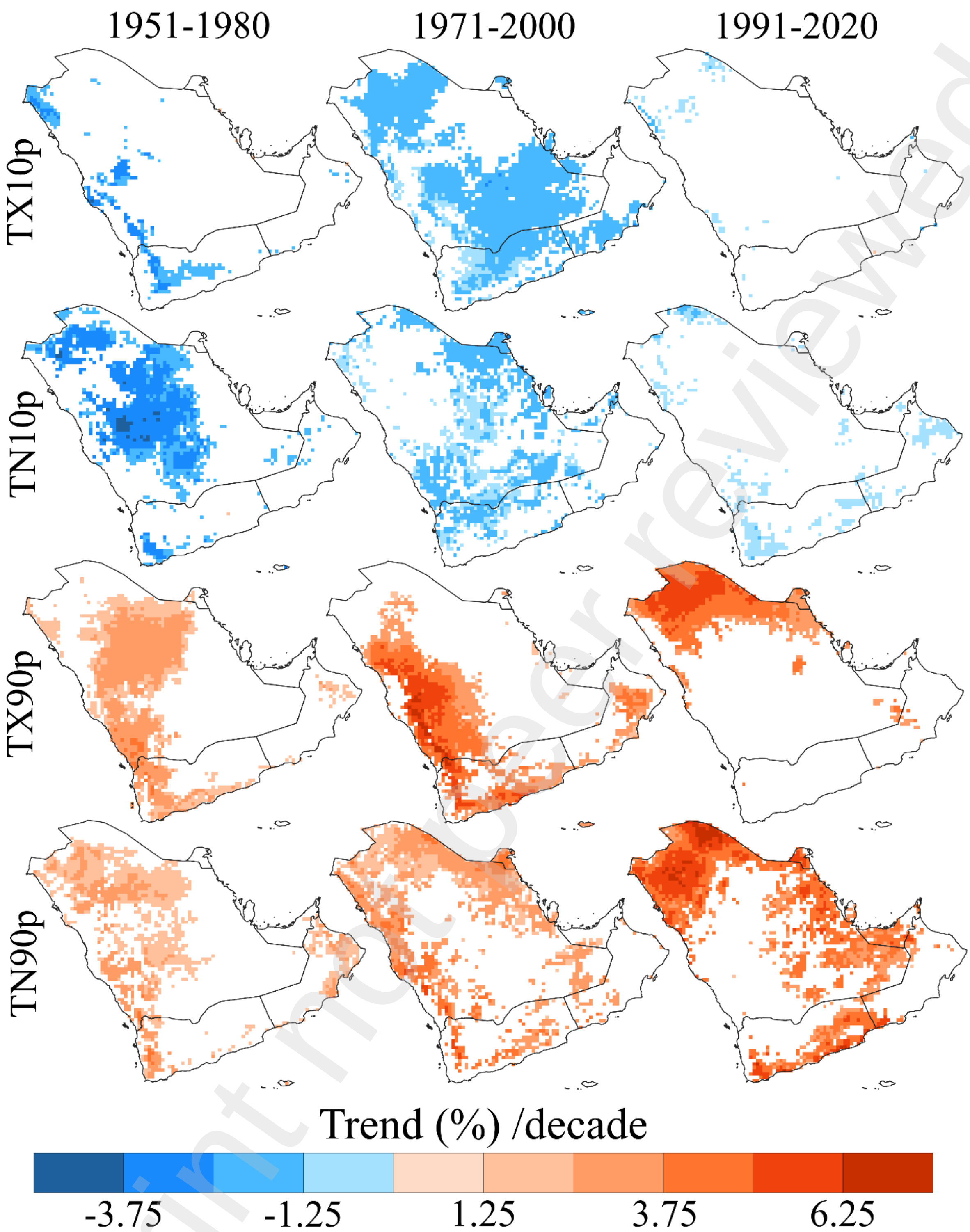


Fig. 6. Same as **Fig. 4** but for Relative Temperature Indices.

4.1.2. Changes and Trends in Duration Indices

The changes in Duration Temperature Indices, including Ice days (ID), Warm Spell Duration Indicator (WSDI), Frost days (FD), Tropical nights (TR), Growing Season Length (GSL), Summer days (SU), and Cold Spell Duration Indicator (CSDI) are presented in **Fig. 7**. These indices are used to determine changes in temperature duration. There is a dominant increasing trend in the TR, SU, and WSDI indices across most of the AP for both recent periods compared to the reference period. The highest change (80 days) of these indices is spread over the highlands of KSA and Yemen. Increasing SU, TR, and WSDI indices in the AP indicate a warming climate. This warming climate is characterized by more hot days, warmer nights, and longer periods of sustained heat. The duration of the growing season, also known as GSL, is determined by the time span between the initial and final instances when the temperature in a year is sufficiently warm to support plant growth, which has increased lightly and gradually over the northern and central KSA. Frost Days (FD) has a gradually decreasing change over the northern AP during both recent periods regarding the reference period. A gradually decreasing change in CSDI was observed for most of Yemen and KSA and over northern Oman during both recent periods. The Ice Days (ID) index has almost no changes during both periods. Most previous studies ignored the Growing Season Length (GSL), Frost Days (FD), and Ice Days (ID) indices due to local climate characteristics (Almazroui, 2020b; Almazroui et al., 2022; Alsarmi and Washington, 2014). However, ERA5 showed reasonably considered results for GSL and FD indices over northern AP, as mentioned above.

The significant trends when $p < 0.05$ for all Duration Indices are presented in **Fig. 8** for the three specific time frames. Generally, WSDI, TR, and SU have raised trends in overall defined periods except for WSDI during 1951-1980 where it has increased and decreased slightly. The highest observed trends were in WSDI over the AP's southwest highlands (22 days per decade) during 1971-2000 and over northern AP (20 days per decade) during 1991-2020. GSL and ID didn't show any notable trends over all periods. Frost Days (FD) and CSDI indices show scattered decreasing trends across several regions in AP. The lowest trend decrease (6 days per decade) is observed over the north AP. Overall, these statistically significant trends, i.e., the increases in SU, TR, and WSDI, along with the decreases in FD and CSDI indices, suggest a clear warming trend in the AP.

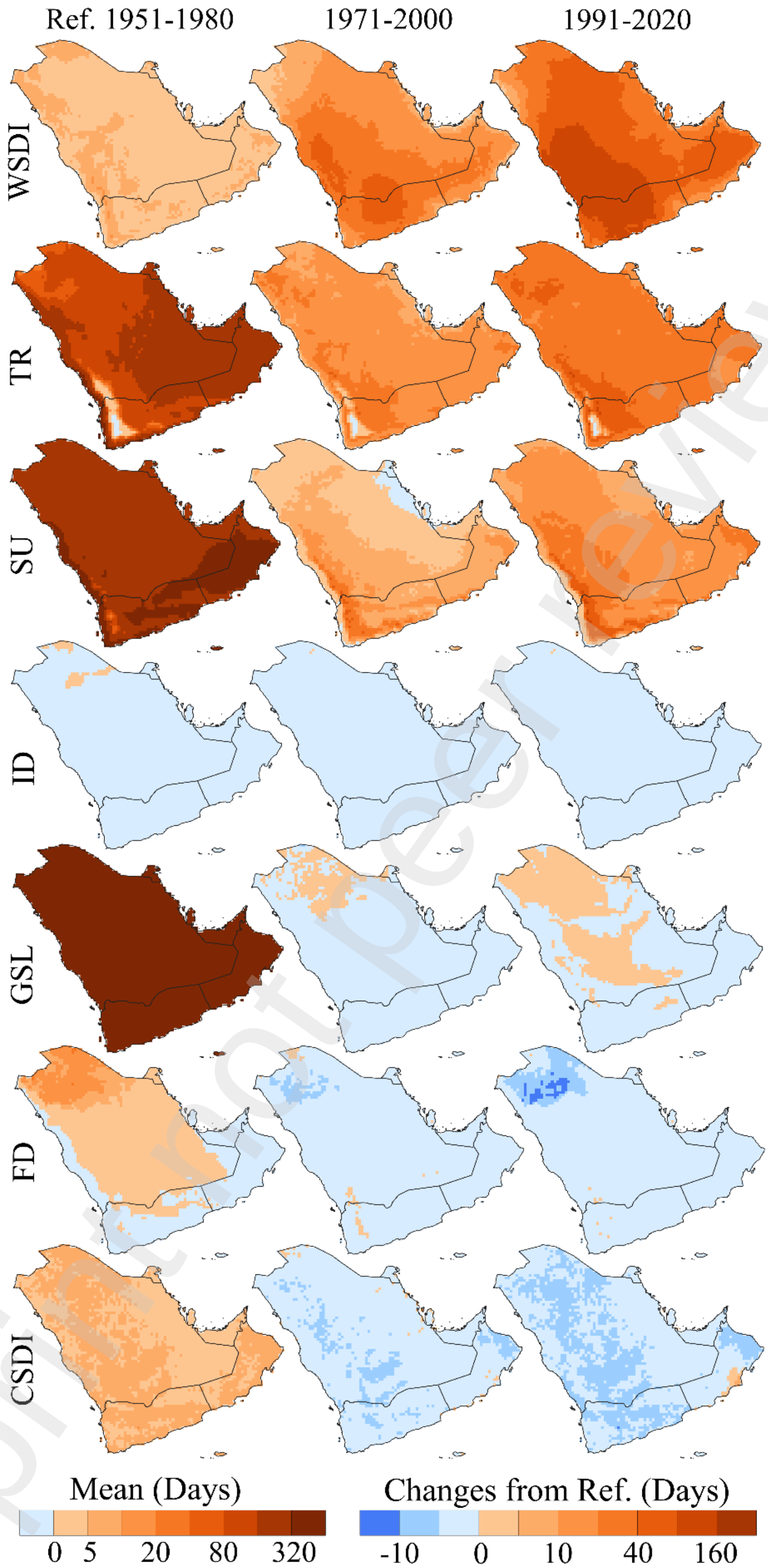
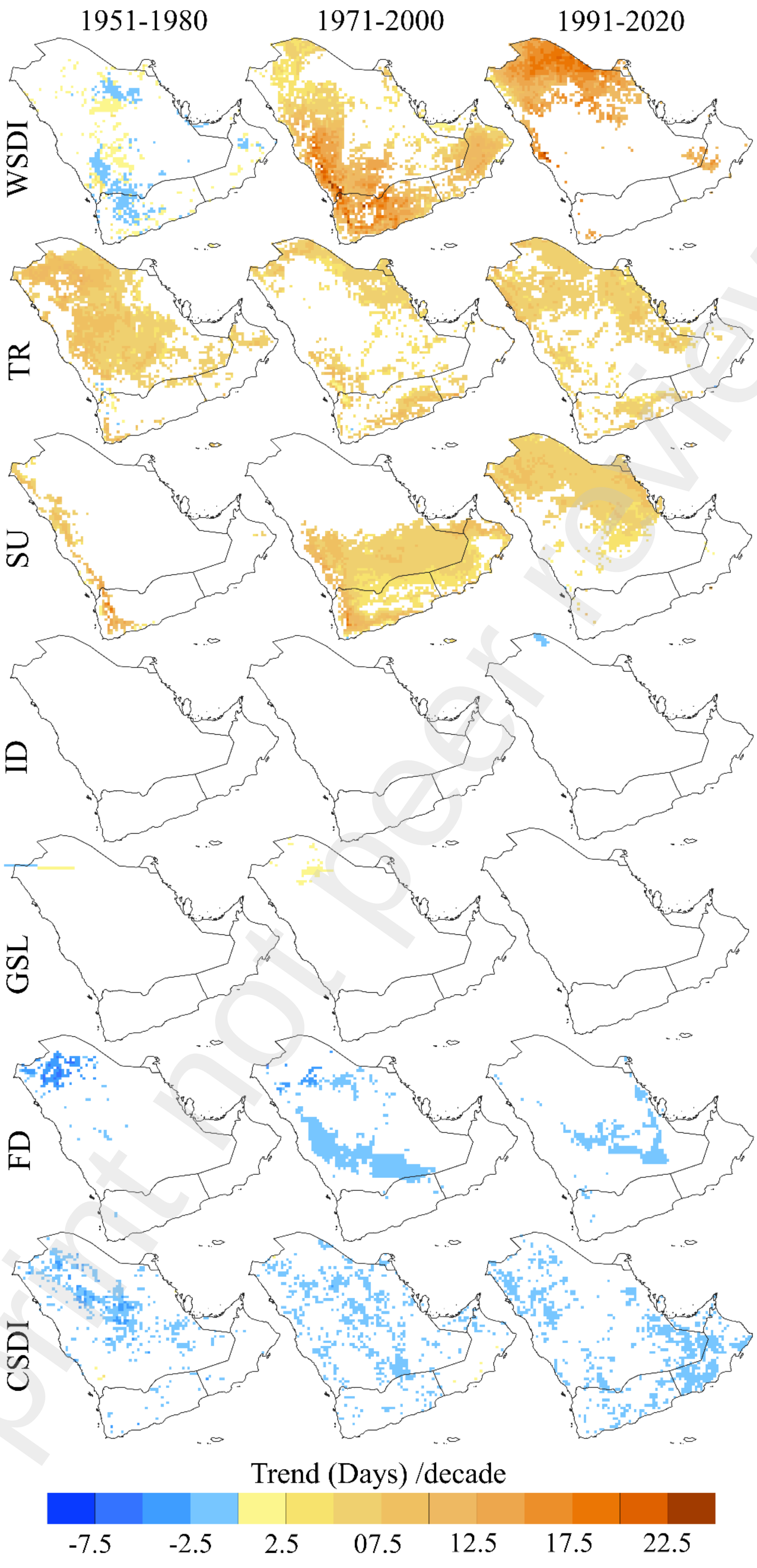


Fig. 7. Same as **Fig. 3** but for Duration Temperature Indices.



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404 **Fig. 8.** Same as **Fig. 4** but for Duration Temperature Indices.

4.2. Changes and Trends in Intensity Indices

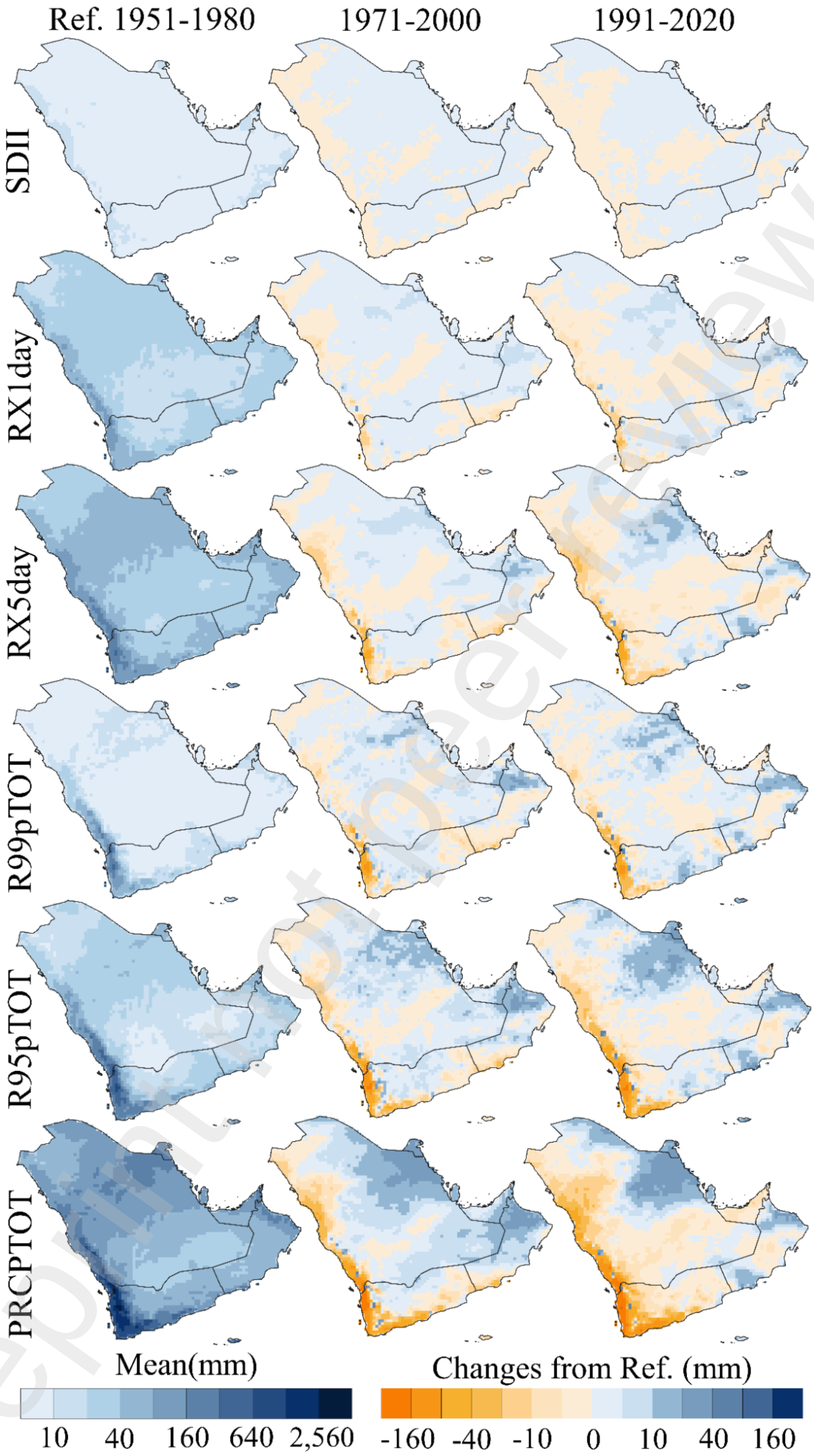
Among the Intensity Precipitation Indices shown in **Fig. 9**, and according to ETCCDI (2020), these indices capture specific facets of precipitation. The maximum 1-day/5-day precipitation amount (RX1day/5day) indices focus on the duration and intensity of extreme rainfall events, while R95pTOT and R99pTOT highlight the heavy and very heavy precipitation's contribution to the total amount. PRCPTOT provides a measure of total precipitation, regardless of intensity. The Simple Daily Intensity Index (SDII) describes the mean quantity of precipitation that occurs on a wet day. The changes in the SDII index were observed to be relatively small, indicating only modest shifts in daily precipitation intensity. However, Over the eastern areas, there was a minor decrease in the SDII index during both periods, suggesting a slight reduction in daily precipitation intensity. Conversely, the western regions exhibited a small increase in the SDII index, indicating a slight upturn in daily precipitation intensity.

Maximum one-day precipitation (RX1day) represents the maximum amount of precipitation in a single day. Similar to SDII, the western coastal areas have slightly and gradually decreased RX1day over the two recent periods. This indicates a lower occurrence of intense one-day precipitation incidents along these shorelines. At the same time, most other areas of the AP have a slight but positive change in RX1day, including specific small regions such as Al-Bahah and Abha in KSA, Salalah and northern Oman, heading towards a much more intense single-day rainfall amount. The same applies to the RX5day index, which represents the cumulative precipitation. It is also similar and gradual in change. The highest positive change in the RX5day index (30mm) is located over the middle eastern regions of Saudi Arabia, southern Kuwait, Al-Mukalla and Al-Ghaydah cites in the southern shoreline of Yemen, and northern and southern Oman.

The R95/99pTOT (Precipitation from days exceeding the 95/99th percentile) indices represent wet and extremely wet events, respectively. They show a gradual change, with a negative change over the southwestern coasts of KSA and Yemen and a positive change over several regions in the east regions. This indicates that there are more intense precipitation events occurring in these regions. Southern Kuwait, central and eastern Saudi Arabia, Dhofar province, and the northern mountainous ranges in Oman, including the capital city Muscat, have recently received the highest precipitation (R95/99pTOT). The total rainfall amount (PRCPTOT) is similar to R95/99pTOT. PRCPTOT has decreased in several regions during both periods, leading to desertification or drought. At the country level, Qatar, Bahrain, and

Kuwait experienced a positive change in PRCPTOT during the last two periods, while the UAE received less precipitation when compared to the reference period. Particular locations in the southwestern highlands of KSA, as well as the eastern areas of KSA, and the northern and southern parts of Oman, have experienced the highest changes in the PRCPTOT index during the recent period. In Yemen, PRCPTOT has mostly decreased, except in the high western mountain peaks, the highest in the AP (Peaklist.org, 2006), namely Jabal Al-Nabi Shuaib and Jabal Al-Tayyal. Similar to RX1day, the city of Salalah in the Dhofar region has undergone a noticeable positive change in precipitation amounts during the recent period, contrasting with the previous period.

The statistically significant trends ($p<0.05$) for all intensity indices are presented in **Fig. 10** for the three designated time frames. During all periods, all intensity indices except PRCPTOT show a scattered negative trend over some areas of the AP. These decreasing trends are gradual among the three time periods. There is a noticeable increasing trend located in southern Kuwait during 1971-2000 and at the top northern AP during 1991-2020 in most intensity indices. The highest decreasing trend (-160 mm per decade) in PRCPTOT is located over parts of the southwestern highlands of the AP during the recent period.



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456 **Fig. 9.** Same as **Fig. 3** but for Intensity Precipitation Indices.

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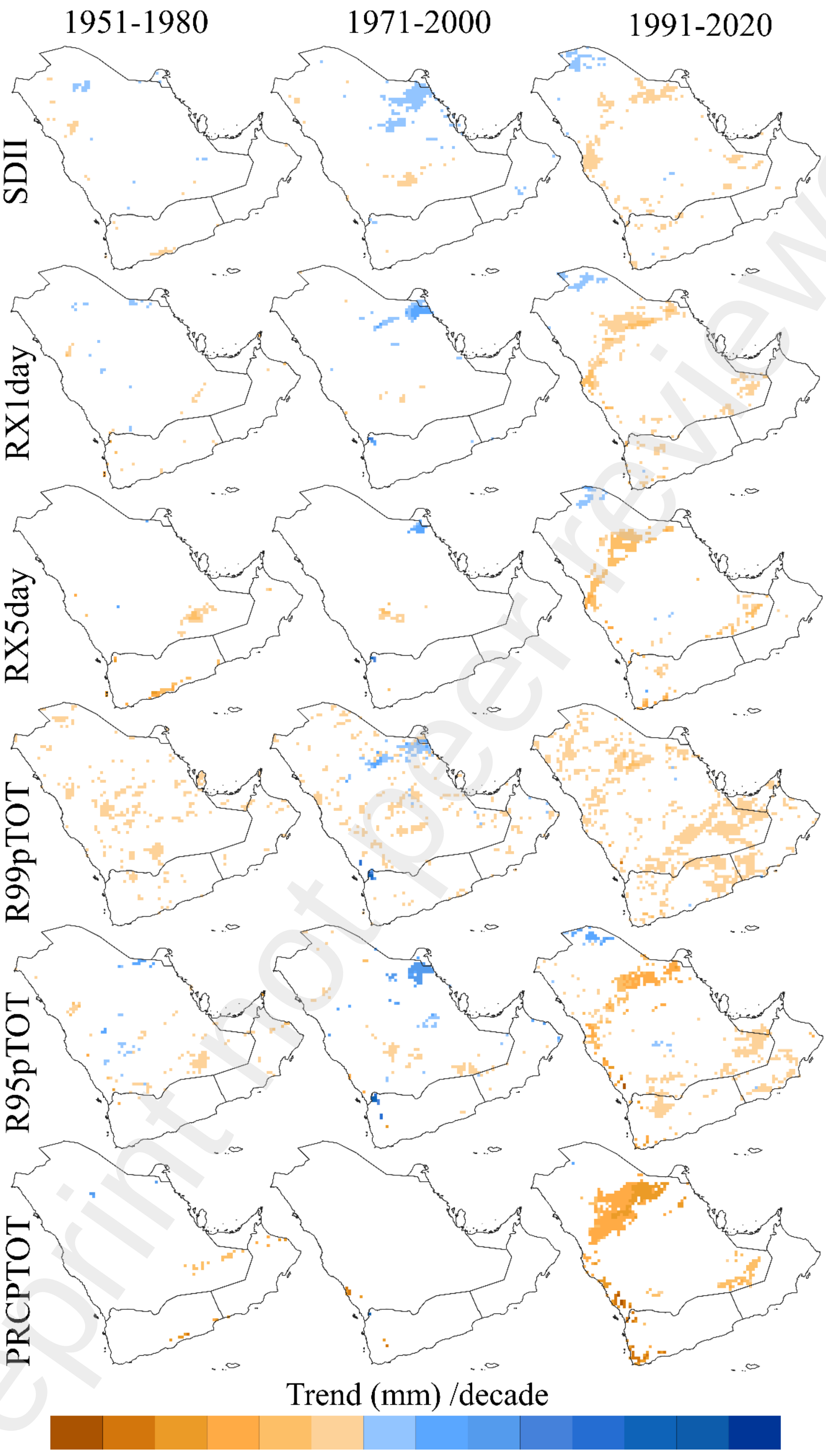

Fig. 10. Same as **Fig. 4** but for Intensity Precipitation Indices.

4.2.1. Changes and Trends in Frequency Indices

Frequency Precipitation Indices shown in **Fig. 11** provide good insights into precipitation magnitude. The changes in these indices were gradual from 1971-2000 to 1991-2020. Unlike the RX1/5day indices, which focus on extreme precipitation events over a specific duration, R10 and R20 are based on threshold exceedances regardless of duration. It can be observed that heavy rainfall (R10) has slightly decreased in the western and southern areas of the AP, while it has increased slightly in the eastern areas, except for the UAE, which experienced a slight decrease in R10. The highest decrease was observed over the western highlands of Yemen during 1991-2020 compared to the reference period. The Consecutive Wet Days (CWD) index clearly depicts the Fertile western highlands within the reference period (1951-1980). The changes in CWD are similar to R10 and R20. The highest decrease in CWD was observed over the western highlands of Yemen during 1971-2000 and 1991-2020. The decrease in CWD suggests a decline in continuous precipitation over time. The reduction in the duration of precipitation may result in decreased water availability for agriculture, ecosystems, and human consumption. It may result in water stress and affect the overall water resources in the fertile regions of Yemen. Consecutive Dry Days (CDD) considers a threshold below which precipitation is negligible or nonexistent. CDD dominates most of the AP during the reference period, reflecting its climate. Changes in CDD are disparate among the grid boxes. The changes seem to be gradual between 1971-2000 and 1981-2020. Parts of Saudi Arabia, Oman, Qatar, Kuwait, and the UAE are heading towards a decrease in dry spells, in contrast to Yemen, where more dry periods are trending. Moreover, Wet spells (CWD) decreased over Yemen recently. Furthermore, Yemen has a higher predominant CDD index than other countries in the AP during both recent periods, indicating that dry spells are more persistent and severe in Yemen. Socotra, the largest and most important Yemeni island and one of the main tourist destinations in Yemen, also has a high CDD value.

The trends (statistically at a significant level of $p < 0.05$) for all frequency indices are presented in **Fig. 12** for the three defined periods. Overall, the trends in rainfall patterns are scattered and observed over fewer grids across the AP. There are gradually decreasing trends in heavy and very heavy rainfall (R10/20) during all periods in several parts of the AP. Most trends in CWD are weak or non-significant, with the weak trend being negative. Similarly, the trends in Consecutive Dry Days (CDD) demonstrate both fewer decreasing and increasing trends over the AP during all periods.

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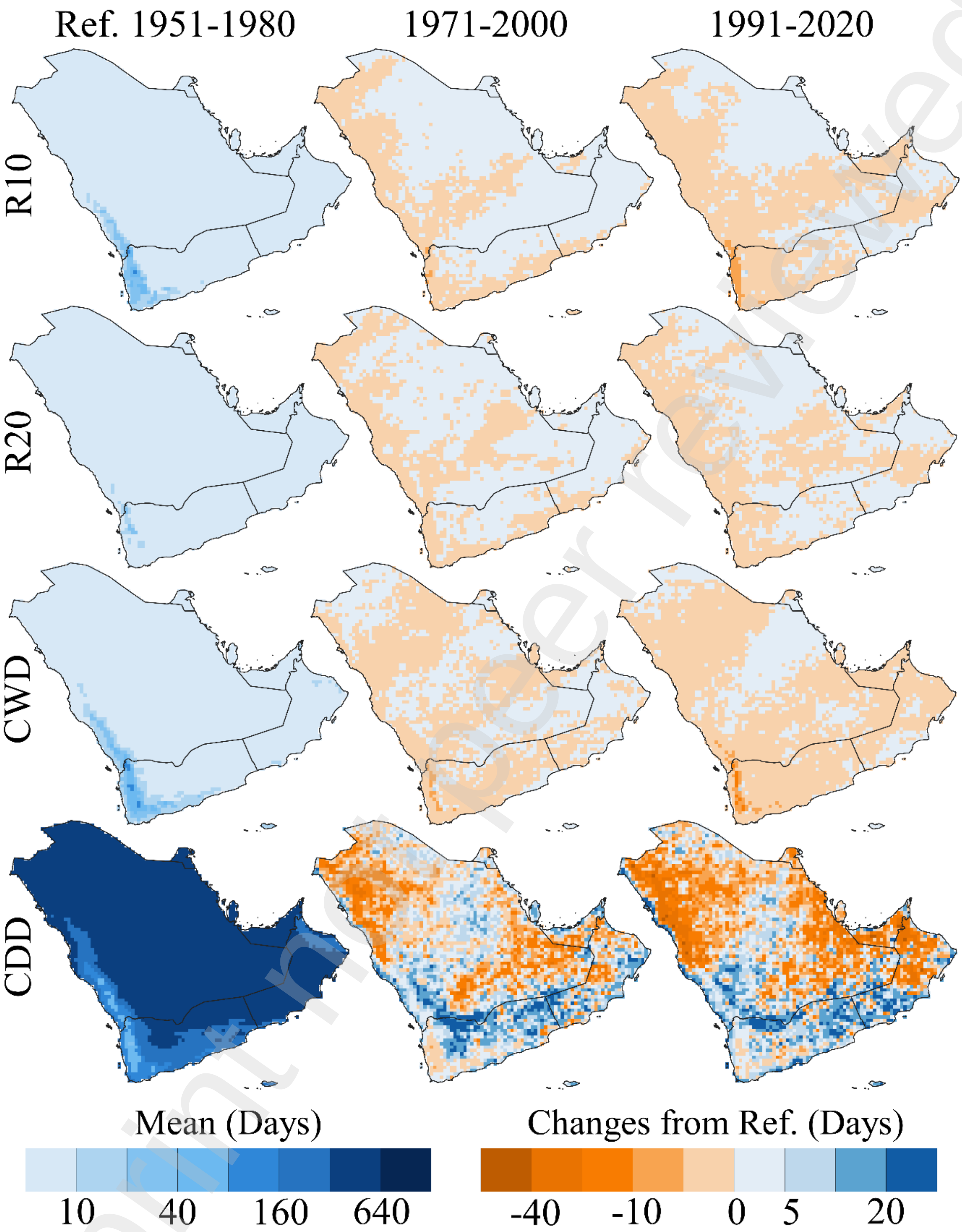

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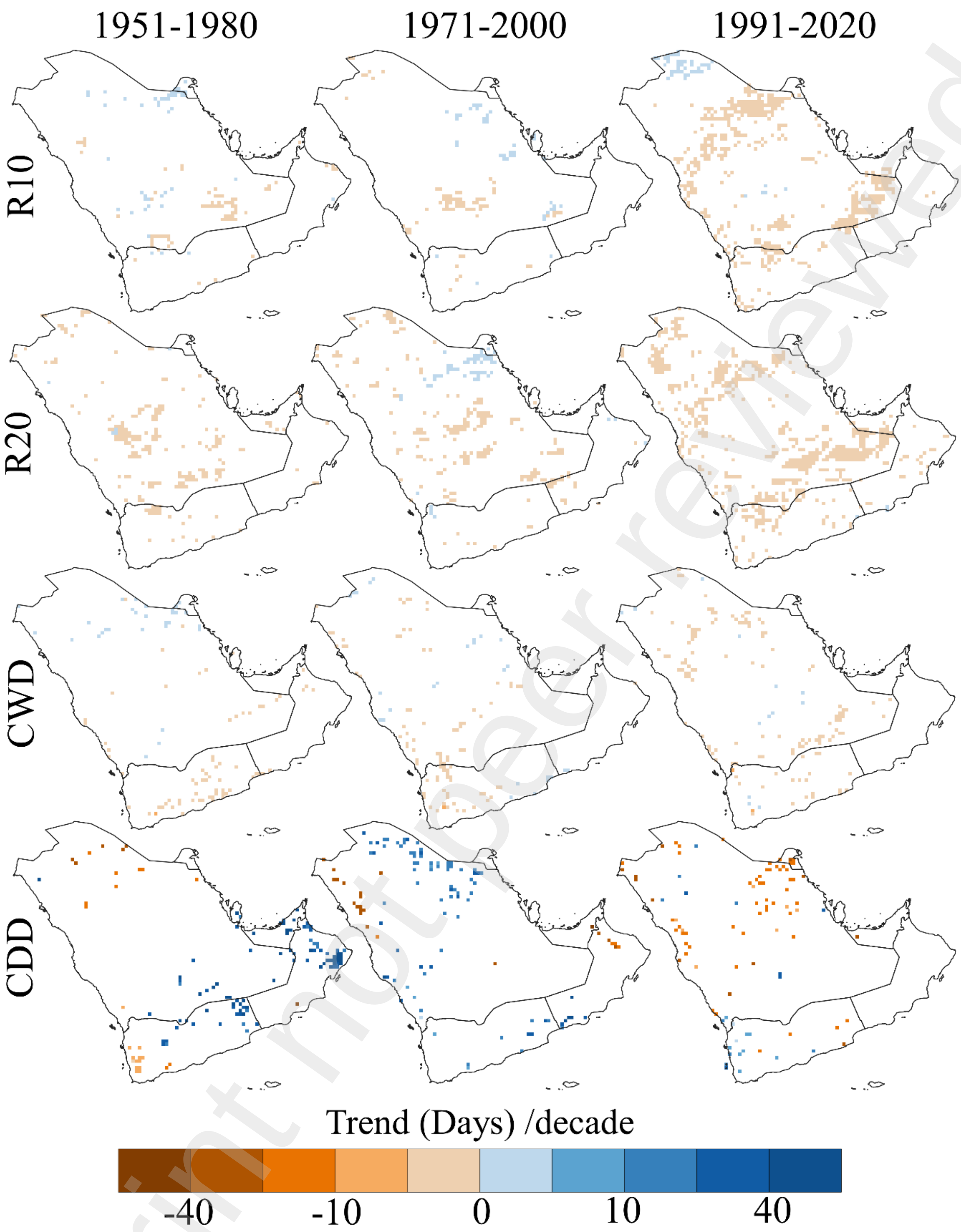
495 **Fig. 11.** Same as **Fig. 3** but for Frequency Precipitation Indices.



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497 **Fig. 12.** Same as **Fig. 4** but for Frequency Precipitation Indices.

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5. Discussion

Alexander et al. (2006) explained that there is still a lack of appropriate and reliable data for monitoring climate changes, particularly climate extremes, in many regions, especially remote areas. Despite being the second-largest country on the peninsula (AL-wesabi et al., 2022), data from weather stations located in Yemen has been omitted from most previous studies in the region. This may be due to the country's strict climate data-sharing policies(AL-Falahi et al., 2020). To overcome these barriers, the present study aims to investigate the spatial distribution along with temporal trends concerning extreme TempPrec indices throughout the AP employing the indices suggested by ETCCDI using the ERA5 reanalysis data. The utilization of reanalysis data offers a significant advantage by providing precise results for each single grid box within the area of interest. This helped to highlight the affected areas accurately. According to Lei et al. (2022), ERA5 was found to be a reliable dataset for analyzing precipitation extremes in China, with a strong correlation between simulated and actual precipitation data. For temperature, Xu et al. (2022) documented that ERA5 data are reliable for simulating temperature data and identifying extreme temperature events. Velikou et al. (2022) found that ERA5 performs well in replicating extreme temperatures even across Europe, such as heatwaves and cold spells.

The findings of this paper's analysis of all temperature indices generally indicate a clear warming trend across all parts of the AP. Extensive regions have experienced warming exceeding the threshold of 2°C, with some areas even surpassing the 3°C threshold compared to the reference period. The northern and northeastern regions recently experienced higher warming rates in TNn, TNx, and TXx (>1°C per decade) than the rest of the AP. The Qaisumah station in Saudi Arabia, recorded temperature breaks, with Tmax reaching 50.8°C in 2007 (Christidis et al., 2023). These warming patterns align with the outcomes of prior research efforts carried out across AP utilizing station data (Alghamdi and Moore, 2014; Almazroui, 2020b; Almazroui et al., 2022, 2014; Alsarmi and Washington, 2014; Donat et al., 2014; Odnoletkova and Patzek, 2021; Zhang et al., 2005). This highlights the reliability and credibility of the ERA5 reanalysis data over AP (Odnoletkova and Patzek, 2021). Conversely, Gunawardhana and Al-Rawas (2014) reported that TXx and TNn have decreased over Muscat, Oman, during 1986-2011. However, our findings show no significant trends, higher positive changes in TNn, and lower changes in TXx over Muscat during all periods.

Based on **Fig. 2** and **4**, it is evident that the Tmin has increased more than the Tmax. As a result, the DTR trends and changes have decreased, consistent with prior research over

AP (Alghamdi and Moore, 2014; Almazroui, 2020b; Almazroui et al., 2022, 2014; Alsarmi and Washington, 2014; Odnoletkova and Patzek, 2021) and globally (Sun et al., 2019). However, the decreasing trends in DTR during the recent period are limited over Yemen (**Fig. 4**), possibly due to discrepancies in trend analysis methods. It is worth noting that Xu et al. (2022) found that ERA5 did not accurately capture the trend of the DTR over China. The changes in warm nights and days (TN90p/TX90p) are greater than the changes in cold nights and days (TN10p/TX10p) from the reference period, agreeing with the prior investigation (Almazroui, 2020b; Almazroui et al., 2014; Donat et al., 2014; Odnoletkova and Patzek, 2021). This suggests that the region is experiencing more frequent and intense heatwave events. This also suggests that extreme warm temperatures are becoming more common while extreme cold temperatures are less prevalent. It implies a potential change in the overall temperature regime of the region. The highest change, exceeding 80% compared to the reference period, is observed in the areas along the shared borders between Yemen and Saudi Arabia. Duration indices provided further evidence of a warming climate in the AP. Years without a cold wave are more frequent than those without a heat wave, which are exceedingly rare.

Overall, the rise in temperature extremes will undoubtedly affect various environmental sectors like energy production and water-related industries, agriculture, and service catering to religious travellers. Furthermore, TempPrec extremes over AP may also have an impact due to large-scale circulation and diversified topography (Abid et al., 2018; Almazroui et al., 2019; Attada et al., 2019; Charabi, 2009; Donat et al., 2014; Rashid et al., 2020). According to the findings of Donat et al. (2014), significant positive correlations were observed between the Southern Oscillation Index (SOI) and DTR at various locations in the AP and northeast Africa. Additionally, they noted that during La Niña seasons, the DTR tends to be higher than El Niño seasons. Hamed et al. (2023a) reported that the populations in Saudi Arabia, the UAE, and Qatar would be most affected by the change in temperature extremes. It is worth mentioning that the central regions of Yemen and the southwestern regions of KSA have experienced the most significant warm changes in compound TXx, TX90p, SU, TR, and WSDI indices compared to the reference period. These compound changes demonstrate the severity of extreme temperature events, such as heat waves, from which these regions suffer (Jiang et al., 2023). To adapt to more frequent and intense heatwave events, these areas should undertake measures including: 1) enhancing early warning systems for heatwaves; 2) providing cooling centres and other services for people vulnerable to heat stress; 3) promoting water conservation and efficiency measures; and 4) investing in renewable energy sources. More appropriate strategies and summery for policy makers are discussed by Odnoletkova and Patzek (2021).

By taking these actions, these regions can better protect their populations and resources from the impacts of future heatwave spells.

The spatial distributions of precipitation extremes throughout the AP have shown minor and non-significant trends (**Fig. 10** and **12)** when compared to temperature extremes, which aligns with the findings of most studies in the literature. The lack of clear trends in the AP's precipitation might be related to the high temporal and spatial variability of precipitation within a topographically diverse and arid environment (AlSarmi and Washington, 2011; Nasrallah and Balling, 1996). By observing the changes in all rainfall indices shown in **Fig. 9** and **11**, a noticeable shift in the spatial distribution of rainfall from the fertile western regions to the eastern regions of the AP can be observed. This shift explains the recent increasing trend in rainfall over Kuwait (Al-Qallaf et al., 2020) and eastern Saudi Arabia, especially Dammam city (Almazroui, 2020c). The rainfall indices exhibit varied changes, with some regions experiencing an increase while others experiencing a decline (Almazroui et al., 2012). During 1991-2020, all precipitation indices have shown small significant declining trends. Similar to temperature findings, the spatial distributions and temporal trends of precipitation indices revealed by this study are consistent with most prior research on the AP, which suggests the credibility and validity of ERA5 reanalysis data in assessing climate extremes over the region.

In recent years, Oman has experienced an increasing susceptibility to heavy rainfall events (Alimohammadi and Malakooti, 2018; Deshpande et al., 2010; Gunawardhana and Al-Rawas, 2014). Specifically, the city of Salalah in Oman has seen simultaneous increase changes in most intensity rainfall indices (RX1/5day, R95/99pTOT, and PRCPTOT) during the recent period, as opposed to 1971-2000 when compared to the reference period. This is consistent with the recent hurricanes that have hit the city (EM-DAT, 2023; FloodList, 2023; Mansour, 2019). Similarly, several other regions in the AP have been affected by compound intensity rainfall indices, including RX1/5day, R95/99pTOT, and PRCPTOT. These regions include the northern and southern coasts of Oman, the central and eastern regions of KSA, the highlands of southwestern AP, southern Kuwait, and Socotra Island in Yemen (**Fig. 9**). Therefore, more attention should be directed towards flood planning in these regions, including efforts to 1) enhance drainage systems, construct flood barriers, and implement proper urban planning; 2) improve early warning systems by investing in advanced meteorological technologies, such as weather radar and automated monitoring stations; 3) strengthen emergency preparedness and response; 4) raise public awareness; 5) create floodplain zoning; and 6) construct levees and dams. The combination of higher values of the CDD index and lower values of the PRCPTOT and CWD indices presents a clear indication of drought. This combination of indices is observed concurrently in Yemen during both periods, signalling the presence of impending dry spells that require careful consideration. To achieve that, several steps must be taken, including 1) stopping the fighting and promoting peace and stability; without peace, there can be no hope for a sustainable future; 2) providing funding for water conservation and rainwater harvesting projects; and 3) promoting drought-resistant crops. Yemen is extremely vulnerable to climate change and its impacts, and the ongoing conflicts have made it difficult to respond to them (Schulman, 2021).

The uniqueness of this study manifests in its innovative methodological approach. This research moves beyond using limited station data from specific locations, a common limitation in previous studies. Instead, it leverages ERA5 reanalysis data across the entirety of the AP, offering a more comprehensive overview of the regional climate. Unlike most or all prior studies that employed the MK method to investigate trends alone, this study utilizes the superior MMK method. Moreover, the study broadened its analysis to cover changes from the reference period. Furthermore, the study stands out in its temporal scope, spanning seven decades, further subdivided into three distinct periods. This expansive timeframe and detailed segmentation allow for a nuanced understanding of climate change over the AP.

6. Conclusion

Studying climate extremes in the AP is essential for understanding the potential impacts of climate change on the region and informing adaptation and mitigation strategies. In order to address the limited availability of local in situ data and policies across the AP, this study made use of ERA5 reanalysis data to examine the spatial patterns and temporal trends of the ETCCDI-defined extreme TempPrec indices within the AP between 1951 and 2020. The analysis concluded a common warming trend across the AP, with most of them being statistically significant. Warm extremes, which include warm nights and days, have gotten more severe and frequent, alongside the duration of warm spells has also increased in most regions. Conversely, cold extremes have declined, suggesting an accelerating warming trend. The warming change (trend) exceeded the threshold of 2°C (1°C/decade^{-1}) in many regions, indicating a rapid rate of temperature increase. This aligns with the results of previous research and underscores the reliability of the ERA5 reanalysis data. Warming trends in temperature indices will likely impact environmental sectors, including agriculture, water resources, and sectors that provide services to religious travellers.

Regarding precipitation, rainfall indices indicate a shift in rainfall patterns from the AP's fertile southwest regions towards more intense patterns in specific eastern regions, including Oman, Kuwait, KSA, and Yemen. The temporal trends are weak in magnitude and variable spatially, with dominant decreases in both intensity indices (-10 mm per decade) and frequency indices (-5 days per decade). This indicates a shift towards more short, intense rainfall events with longer dry periods in between, necessitating attention to flood and drought planning. Conversely, Yemen encounters reduced rainfall amounts, leading to drought. These findings emphasize the need to account for the observed trends in climate extremes when planning for the future in the AP region. This study recommends:

1. Drought risks in Yemen are rising, calling for urgent implementation of adaptation strategies in water resource management and agriculture.
2. Parts of Oman, Yemen, and Saudi Arabia should invest in flood prevention and management to limit potential impacts.
3. Proactive adaptation is crucial as the AP experiences widespread warming, exceeding 2°C temperature increases.
4. Climate variability must be considered in long-term water, agriculture, and urban development planning.
5. Continuous monitoring using other reanalysis data, such as the Climate Forecast System Reanalysis (CSFR) and Modern-Era Retrospective Analysis for Research and Applications (MERRA-2). This can provide valuable insights into regional climate trends and support evidence-based decision-making.

Further work is needed to investigate the region's Compound Drought and Heatwave CDHW events. The above recommendations aim to guide future research on areas requiring attention and action.

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Data availability

The ERA5 reanalysis data (ERA5 hourly data on single levels from 1940 to the present) can be downloaded freely from the link: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form

CRediT authorship contribution statement

Ali Salem Al-Sakkaf: Conceptualization, Methodology, Software, Writing –original draft, Visualization, Investigation. **Jiahua Zhang:** Funding acquisition, Supervision. **Fengmei Yao**: Conceptualization, Funding acquisition, Writing – review & editing, Supervision. **Mohammed Magdy Hamed:** Methodology, Software, Writing – review & editing, preparation. **Claudien Habimana Simbi**: Writing – review & editing. **Arslan Ahmed:** Writing – review & editing. **Shamsuddin Shahid:** Software, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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