4 *Egypt. J. Phys.* **Vol. 53,** pp. 43-55 (2025)

Egyptian Journal of Physics

https://ejphysics.journals.ekb.eg/

The Impact of Climate Change on Extreme Weather Events: Salalah Regional Analysis

Mohammed M. AlShaikh[1,2*], Khalafallah O. Kassem[3], Emad A. Ahmed[4] and Eman F. El-Nobi[3]

[1] *Faculty of Science, Smart Management of Climate Change Program, South Valley University, Qena, Egypt.*
[2] *Meteorology Specialist, Oman Civil Aviation Authority, Salalah, Oman.*
[3] *Faculty of Science, Physics Dep., Atmospheric Phy. Lab., South Valley University, Qena, Egypt.*
[4] *Faculty of Computers and Information, Computer Science Dep., South Valley University, Qena, Egypt*

Abstract

Climate change is expected to alter the frequency and intensity of extreme weather events, increasing the risk of flash floods and prolonged droughts, particularly in water-scarce regions like Oman. While changes in precipitation and temperature have been observed, a comprehensive long-term trend analysis remains limited. This study analyzes extreme climate events in Salalah, Oman, using daily precipitation and temperature records from 1990 to 2023. Climate indices were derived using the RClimDex software package to assess variability and trends in extreme weather conditions. The findings reveal a statistically significant rise (at P-value < 0.05) in mean minimum temperature index (TMINmean) alongside a decline in cold nights (TN10P) and cold spell duration (CSDI) indicating a pronounced warming trend during nighttime hours. The Diurnal Temperature Range (DTR) has also decreased, further supporting the shift toward higher nocturnal temperatures. The Simple Daily Intensity Index (SDII) indicates a significant rise in precipitation intensity, despite the relative stability in wet day frequency. In addition, four precipitation indices show significant trends at P-value <0.10 , the indices are the extreme precipitation indices very wet days (R95p), extremely wet days (R99p), Max 1-day precipitation amount (RX1day), and Max 5-day precipitation amount (RX5day) suggest an increase in high-intensity rainfall events. These results highlight the growing prevalence of nocturnal warming and intensified rainfall extremes, with significant implications for heat stress, hydrological resources, and urban adaptation. The study emphasizes the necessity for proactive climate adaptation strategies to mitigate the escalating risks associated with climatic variability in the region.

Keyword: Climate Change, Extreme Weather Events, RClimDex , Temperature Trends, Precipitation Variability, Salalah Region,

Introduction

Climate change has emerged as one of the most pressing global challenges, manifesting through increased frequency and intensity of extreme weather events. The study of extreme climate indices (ETCCDI) has provided significant insights into the patterns of temperature extremes, precipitation variability, and their associated impacts. Studies indicate a significant increase in warm nights (TN90p) globally, with a rise of 6.8% per decade (Ahmad, 2020). Minimum temperature trends exhibit a warming rate of +0.55°C per decade, surpassing maximum temperature trends, which increase at a rate of +0.32°C per decade (AlSarmi, 2014). The diurnal temperature range (DTR) has declined, suggesting a stronger warming effect during nighttime (Alexander et al., 2006). In the Arabian Peninsula, the duration of heatwaves has increased by 14 days per decade, with extreme nighttime temperatures rising by +3.6% per decade (AlSakkaf et al., 2024). In Iran, the growing season length (GSL) has extended by 18–22 days, affecting agricultural cycles (Ghassabi et al., 2024 and Sohrabi et al., 2024).

Global precipitation trends exhibit inconsistencies, with extreme rainfall events (RX1day) increasing in some regions while declining in others (Frich et al., 2002). In Ecuador, wet-day precipitation has increased by 7.4%, but the number of rainy days has decreased, resulting in more intense but less frequent rainfall (Santillán

*Corresponding author: Mohammed M. AlShaikh, E-mail: mohammed.alshaikh@caa.gov.om, Tel. 0096895206020
Received: 26 April 2025; Accepted: 28 May 2025
DOI: 10.21608/ejphysics.2025.378334.1108

Quiroga et al., 2023). Similarly, in Maharashtra, India, monsoon onset has been delayed by approximately four days over the past 30 years, disrupting water resource planning (Khobragade, 2023). Extended growing seasons in arid regions may initially benefit crops; however, they also lead to increased water stress and heat-induced yield reductions (Ghassabi et al., 2024). Moreover, the decline in cold days and frost events impacts traditional cropping cycles in temperate regions (Alexander et al., 2006). The increase in extreme rainfall (RX5day) has elevated flood risks in the UK, with 10-year return period rainfall increasing by +8.4% (Fowler et al., 2005). Conversely, drought frequency is rising in semi-arid zones, with precipitation declining by −3.1% per decade in Iran's highlands (Ghassabi et al., 2024). Rising nighttime temperatures contribute to heat stress-related illnesses, particularly in urban areas (AlSakkaf et al., 2024). Additionally, the increasing frequency of heatwaves has heightened cooling demand in buildings, exacerbating energy crises in arid regions (Iqbal, 2018). Extreme weather events, including temperature extremes and intense precipitation, have become more frequent due to climate change (IPCC, 2021). These changes have significant implications for water resources, agriculture, and ecosystem sustainability. Salalah, located in the southern part of Oman, experiences unique climatic conditions due to the influence of the monsoon (Khareef) season (Al Rawas & Valeo, 2010). Despite its distinct seasonal rainfall pattern, long-term trends in temperature and precipitation extremes remain underexplored. This study aims to assess climate variability in Salalah by analyzing historical climate data and identifying trends in extreme climate indices (Fowler et al., 2005).

Study Area

Salalah (17.03°N, 54.07°E; elevation: 12 meters above sea level), as illustrated in Fig.1, is Oman's second-largest city and the administrative capital of the Dhofar Governorate. Strategically located on a fertile coastal plain adjoining the Arabian Sea and backed by the Dhofar mountain range, the city plays a pivotal role in the southern region's economy, governance, and cultural heritage. According to the 2023 national census, Salalah's population reached 388,837.

The city is characterized by a unique monsoon-influenced semi-arid maritime climate, shaped by its proximity to the Indian Ocean and exposure to the southwest monsoon (Khareef). This climatic regime results in a distinct seasonal contrast, with moderate rainfall between June and September and predominantly arid conditions for the remainder of the year. The seasonal precipitation supports key sectors of the local economy, particularly agriculture and tourism, making the understanding of climatic variability vital for sustainable resource management and disaster preparedness (Al-Habsi, et al., 2014).

Fig. 1. (a): The site location of the study area, Map of Sultanate of Oman,
(b): and satellite image of Salalah plain and adjacent Jabal Al-Qara.

To evaluate the climatic profile of Salalah, daily meteorological records from 1990 to 2023 were analyzed to identify thermal and hydrological trends relevant to environmental planning and tourism sustainability. In terms of temperature characteristics, the daily maximum temperature (Tmax) averaged 29.9°C, ranging from a minimum of 19.9°C in January to an extreme maximum of 45.8°C recorded in June. The daily minimum temperature (Tmin) averaged 23.5°C, with values extending from 13.5°C in January to a peak of 30.6°C in May. This narrow diurnal range underscores the thermal stability of the coastal zone. The overall daily mean temperature during the period was 26.4°C, reaffirming Salalah's classification as a climatically mild region.

With respect to humidity, the average maximum relative humidity (RHmax) was 79.4%, with extreme values reaching 100% during the month of July, typically coinciding with the peak of the Khareef season, characterized by persistent fog, mist, and cloud cover. Conversely, the average minimum relative humidity (RHmin) was 53.9%, with the lowest recorded value of 1% in January and a maximum of 100% in August. This seasonal contrast highlights the distinct transition between the dry winter and the humid summer monsoon.

Precipitation patterns reveal distinct seasonal peaks. Salalah's average daily rainfall was relatively low at 0.28 mm, consistent with its semi-arid classification. However, the city is subject to episodic extreme rainfall events, as evidenced by a maximum daily total of 228.4 mm recorded in May, likely associated with monsoonal surges or tropical disturbances from the Arabian Sea. These events have significant implications for local hydrological systems and highlight the necessity for continuous long-term monitoring.

Collectively, these climatic parameters define the unique environmental context of Salalah and serve as essential inputs for climate extremes analysis.

Methodology

Meteorology for the Salalah region during the period 1990–2023 (Oman Meteorology, 2023). Trends in daily values of maximum and minimum temperatures, as well as precipitation, were analyzed using the RClimDex software, developed by Zhang and Yang (2004) at the Climate Research Branch of the Meteorological Service of Canada. Additionally, ClimDex, an Excel-based tool created by Gleason (2001) at NOAA's National Climatic Data Center, has been used since 2001 for calculating climate extremes indices. The software incorporates data quality control procedures, including flagging daily temperature records as missing when the minimum temperature exceeds the maximum. Furthermore, daily maximum and minimum temperature values were treated as outliers if they fell outside the range of four standard deviations from the mean, and negative precipitation values were also treated as missing data. Detailed guidelines for software installation, setup, and index calculations are available in Zhang and Yang (2004)

Results and Discussions

The RClimDex software, developed by Environment Canada and endorsed by the ETCCDI, calculates 27 climate indices. Two indices will not be studied due to lack of data (the Frost Days (FD0) index, which measures the number of days with minimum temperatures below 0°C, and the Ice Days (ID0) index, which tracks the number of days per year with maximum temperatures below 0°C). So that 25 indices, 14 temperature-related and 11 precipitation-related will be studied to capture variations in intensity, frequency, and duration of extreme climate events (Zhang & Yang, 2004). In this study, we focus on the indices that exhibit statistically significant trends at the 5% significance level based on the Mann–Kendall test. Out of the 25 indices, 9 demonstrate significant trends—8 related to temperature and 1 to precipitation. These are summarized in Table 1 and Fig. 2–10.

TABLE 1. Indices with significant variation

Index	Indicator name	Slope	Standard error	P-value < 0.05	Variance (R^2)
CSDI	Cold spell duration indicator	0.659	0.20	0.003	0.25
DTR	Diurnal temperature range	0.033	0.005	0.000	0.60
TMIN mean	Mean minimum temperature	0.040	0.007	0.000	0.49
TN10P	Cool nights	0.515	0.110	0.000	0.42
TN90P	Warm nights	0.531	0.120	0.000	0.39
TNn	Min Tmin	0.040	0.018	0.029	0.14
TNx	Max Tmin	0.026	0.011	0.027	0.14
TR20	Tropical nights	0.788	0.280	0.008	0.20
SDII	Simple daily intensity index	0.130	0.062	0.044	0.13

The Cold Spell Duration Index (CSDI), as shown in Fig.2, quantifies the number of consecutive days with minimum temperatures below the 10th percentile. This index exhibits a statistically significant downward trend over the past three decades (*slope* = -0.659, $R^2 = 0.25$, $p = 0.003$), suggesting a clear reduction in the frequency and duration of cold spells in the region. This observed trend is consistent with global warming projections, which anticipate fewer cold extremes in subtropical and mid-latitude zones (Alexander et al., 2006).

The solid trend line indicates a persistent decline, while the dashed line captures interannual variability, highlighting that although occasional cold events still occur, their frequency is diminishing. In Salalah, this warming—especially during winter months—may have ecological implications, such as the disruption of plant dormancy cycles and altered migration timing for birds that depend on seasonal cues.

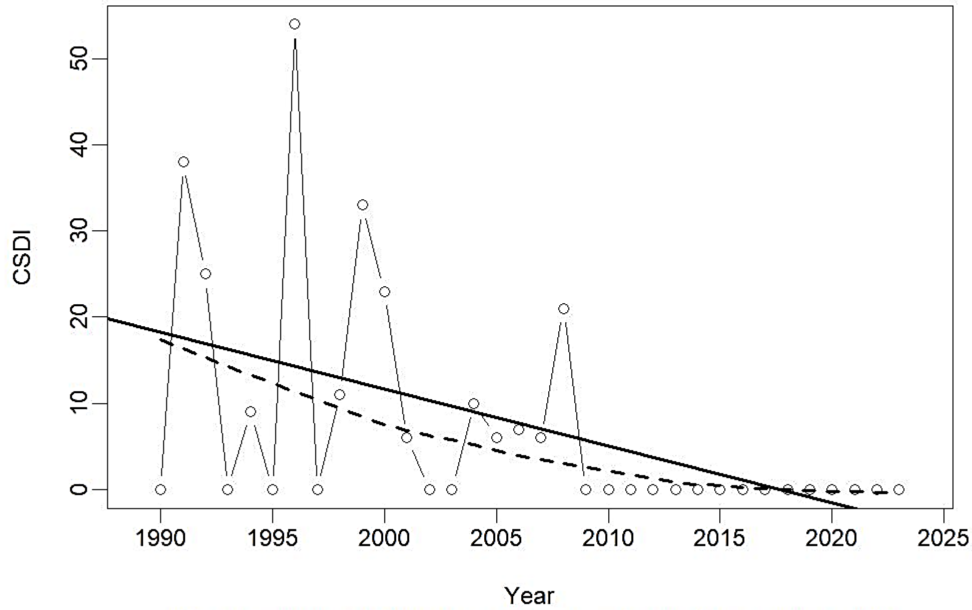

Fig. 2. CSDI index of Salalah (1990-2023)

Moreover, reduced cold spells can foster the proliferation of pest populations, which are normally regulated by colder winters (AlSarmi and Washington, 2014). These biological changes may further affect agriculture, biodiversity, and water resource management, as ecosystems historically adapted to periodic cold conditions may shift their phenological patterns and habitat dynamics. This aligns with findings by Williams et al. (2015), who emphasize that milder winters disrupt species synchrony, reduce cold-driven mortality, and accelerate ecological mismatches between organisms and their environments.

The Diurnal Temperature Range (DTR) index, illustrated in Fig.3, measures the difference between daily maximum and minimum temperatures. Over the study period, this index shows a statistically significant downward trend (*slope = -0.033, R^2 = 0.60, p < 0.001*), indicating that nighttime temperatures are rising more rapidly than daytime temperatures. This narrowing of DTR is a well-documented signal of anthropogenic climate change, commonly linked to increased atmospheric humidity and enhanced cloud cover, which trap outgoing longwave radiation and reduce nocturnal cooling (Alexander et al., 2006).

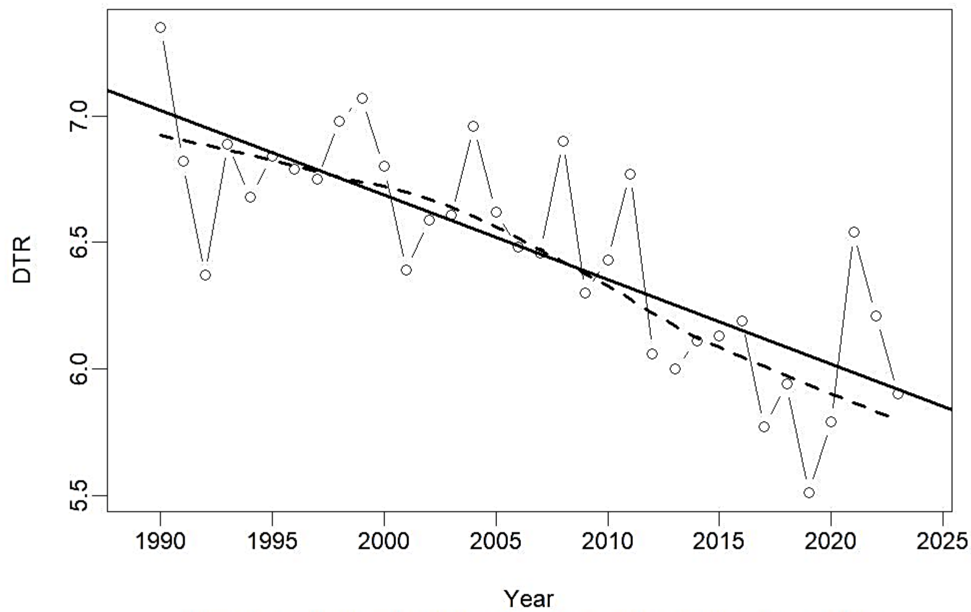

Fig. 3. DTR index of Salalah (1990-2023)

The solid trend line denotes a steady decline in DTR, while the dashed line captures year-to-year variability. From a health perspective, warmer nights are associated with heightened heat stress and disrupted sleep patterns, particularly among vulnerable groups such as the elderly and individuals with chronic illnesses (AlSakkaf et al., 2024).

In the agricultural sector, reduced diurnal variability can negatively affect crops that depend on cooler night temperatures for optimal growth, with species such as fruit orchards experiencing declines in yield and quality due to insufficient thermal contrast (Frich et al., 2002). Ecologically, a decreasing DTR can disrupt temperature-dependent biological cycles, altering predator–prey interactions, phenological events, and potentially leading to biodiversity shifts in sensitive ecosystems. These multifaceted impacts emphasize the need for adaptive strategies such as climate-smart agriculture and urban heat mitigation planning to protect human and environmental systems in a warming world.

The TMINmean index, illustrated in Fig.4, represents the mean of daily minimum temperatures. Over the past three decades, it displays a strong and statistically significant upward trend (*slope = 0.04,* $R^2 = 0.49$*,* $p < 0.001$), reflecting a consistent increase in nighttime temperatures. This trend is consistent with global climate assessments, which attribute rising minimum temperatures to the combined effects of increased greenhouse gas concentrations, enhanced atmospheric moisture, and urban heat island dynamics (Alexander et al., 2006).

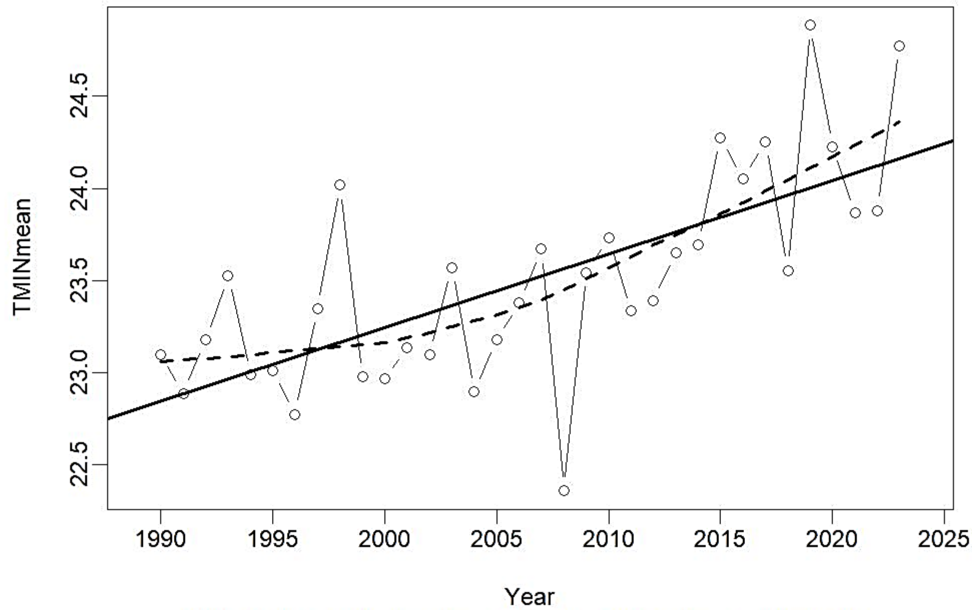

Fig. 4. TMINmean index of Salalah (1990-2023)

The solid trend line demonstrates a clear and steady rise in TMINmean, while the dashed line, although subject to interannual fluctuations, follows a parallel upward path—reinforcing the robustness of the warming signal. From an ecological and agricultural standpoint, elevated nighttime temperatures reduce the duration of critical nocturnal cooling periods, affecting physiological processes in plants and increasing nighttime heat stress in both human and animal populations.

These observations align with broader scientific findings indicating that minimum temperatures are rising at a faster rate than maximum temperatures, a distinctive and well-documented signature of anthropogenic climate change (Frich et al., 2002). Such warming patterns carry implications for phenological shifts, reduced crop resilience, and challenges to thermal regulation across ecosystems, necessitating adaptive responses in land use, public health, and food production systems.

The TN10p index, depicted in Fig.5, quantifies the frequency of cold nights—defined as instances where the minimum temperature falls below the 10th percentile relative to a reference period. Over the past three decades, this index reveals a statistically significant downward trend (*slope = -0.515,* $R^2 = 0.42$*,* $p < 0.001$), indicating that cold nights are becoming increasingly infrequent. This trend aligns with broader warming patterns observed across the Arabian Peninsula, where cold temperature extremes have markedly diminished due to regional climate change (AlSarmi & Washington, 2014).

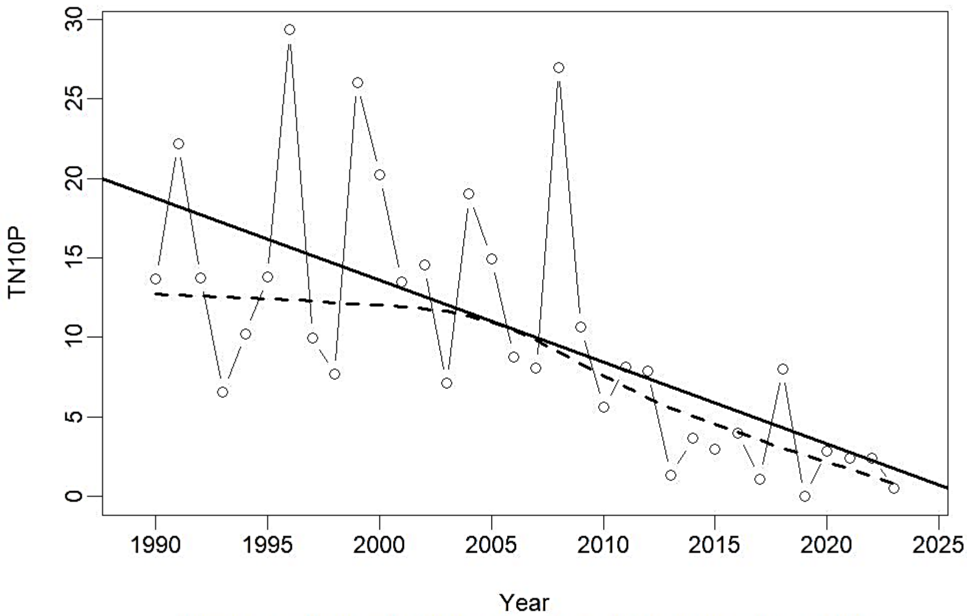

Fig. 5. TN10p index of Salalah (1990-2023)

The solid trend line illustrates a pronounced decline in cold nights, while the dashed line reflects interannual variability influenced by atmospheric and oceanic conditions. The combination of a steep negative slope and a relatively high coefficient of determination confirms a robust warming signal. This pattern is consistent with global findings that attribute the decline in cold nights to anthropogenic greenhouse gas emissions and enhanced atmospheric heat retention, particularly during nighttime hours (Zhang et al., 2005, 2011).

From a practical standpoint, the reduction in cold nights carries significant implications for energy systems, especially in warmer climates. Fewer naturally cool nights may increase reliance on air conditioning and refrigeration, leading to elevated energy consumption and potential stress on power infrastructure. Moreover, the sustained warming of nighttime minima may further alter thermal comfort thresholds, agricultural schedules, and ecological balances in climate-sensitive regions.

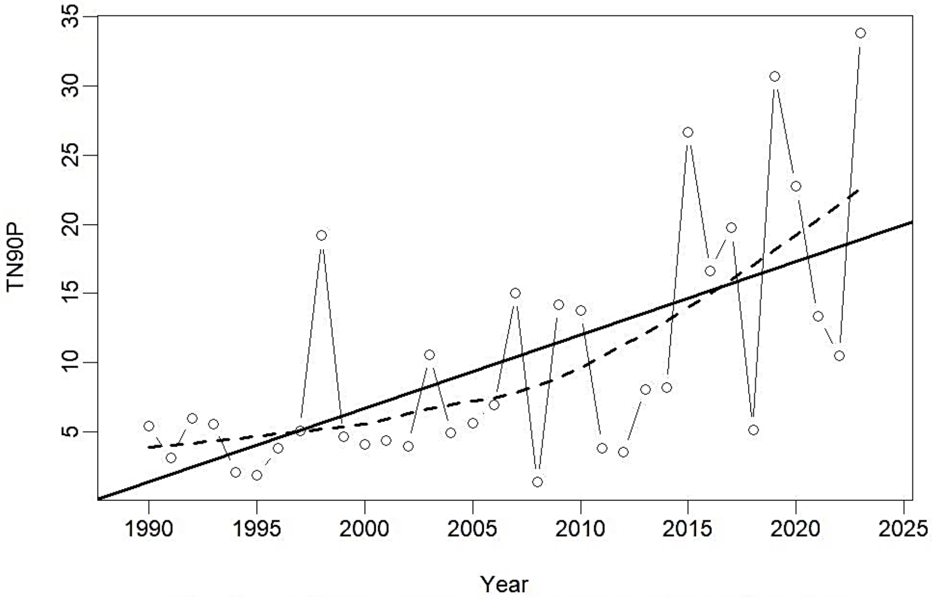

Fig. 6. TN90p index of Salalah (1990-2023)

The TN90p index, shown in Fig. 6, tracks the frequency of warm nights—defined as nights when minimum temperatures exceed the 90th percentile relative to a base period. The index demonstrates a statistically significant upward trend (*slope = 0.531,* R^2 *= 0.39,* $p < 0.001$), confirming that hot nights are becoming increasingly prevalent. This trend complements the warming observed in the TMINmean index and is consistent with regional and global studies documenting the amplification of nighttime warming, particularly in subtropical and tropical regions (Russo & Sterl, 2011 and Alexander et al., 2006).

The solid trend line illustrates a persistent rise in the frequency of warm nights, while the dashed line shows short-term variability likely influenced by monsoonal dynamics and sea surface temperature anomalies. This pattern reflects increased atmospheric moisture and altered circulation systems, which enhance nocturnal heat retention—a hallmark of climate change driven by anthropogenic emissions.

These results have broader implications for public health, as warmer nights exacerbate heat stress and reduce opportunities for physiological recovery during rest periods. From an energy perspective, they may lead to higher overnight cooling demands, especially in urban areas affected by heat island effects. The sustained increase in warm nights reinforces the need for resilient infrastructure, early warning systems, and adaptive cooling strategies in climate-vulnerable regions.

The TNN index, as illustrated in Fig.7, represents the coldest minimum temperature recorded annually. Over the study period, it exhibits a statistically significant upward trend (slope = 0.04, $R^2 = 0.14$, $p = 0.029$), indicating that even the coldest nights are becoming progressively warmer. This warming suggests a weakening of winter cooling cycles, which could have substantial implications for hydrological and ecological systems in regions like Salalah—particularly where seasonal temperature contrasts influence groundwater recharge, biodiversity, species dormancy, and agricultural phenology.

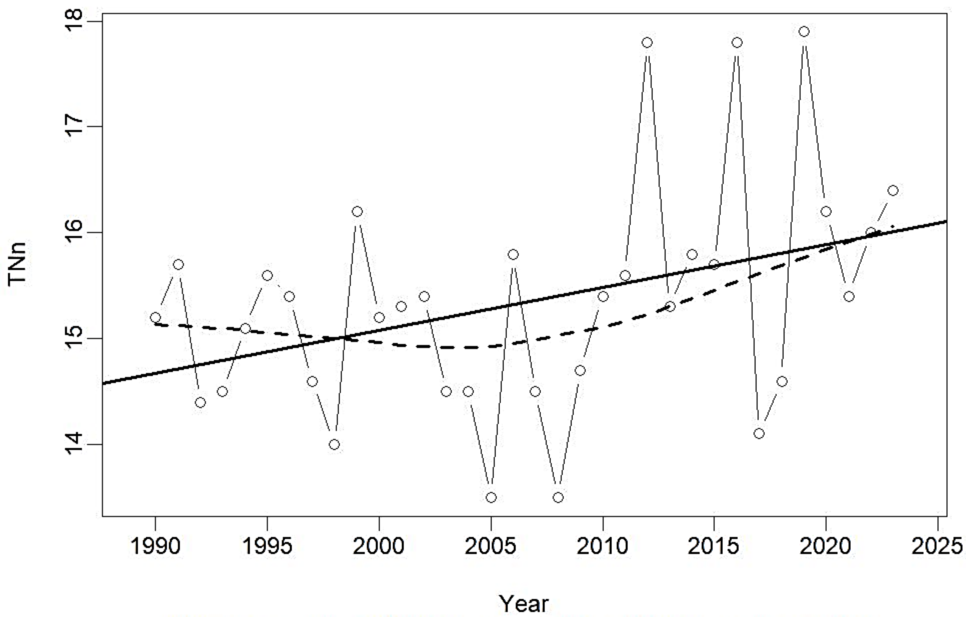

Fig. 7. TNN index of Salalah (1990-2023)

The solid trend line reflects a gradual increase in the coldest night temperatures, signaling a decline in both the intensity and frequency of extreme cold events. Meanwhile, the dashed line, though marked by short-term fluctuations, mirrors a similar upward trajectory likely influenced by atmospheric circulation anomalies, such as shifts in subtropical jet streams or high-pressure systems.

These findings align with global climate studies that report a reduction in cold temperature extremes, especially in coastal and low-latitude areas where nighttime warming is more pronounced. The observed TNN trend also supports broader patterns of asymmetric warming—where minimum temperatures increase faster than maximum temperatures (Frich et al., 2002). This reinforces the need for integrated adaptation strategies in climate-sensitive sectors, including water resource management, agriculture, and ecosystem conservation.

The TNX index, illustrated in Fig.8, reflects the monthly maximum of daily minimum temperatures and demonstrates a statistically significant upward trend (slope = 0.026, $R^2 = 0.14$, $p = 0.027$), indicating an increase in the frequency of extreme warm nights. The persistent rise observed across multiple minimum temperature indices—such as TMINmean, TN90P, TNN, and TNX—suggests that climate change in Salalah is primarily manifested through elevated nighttime temperatures.

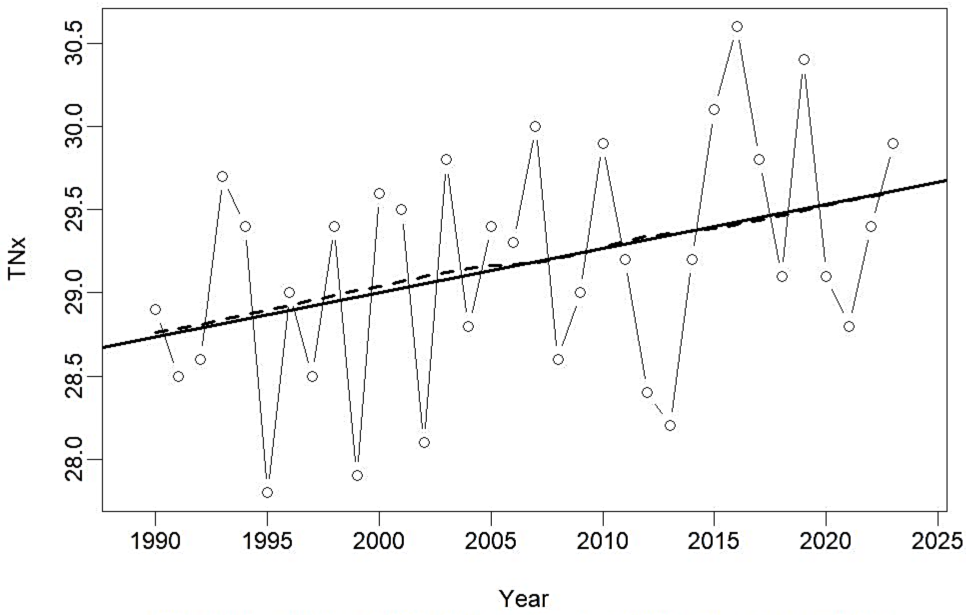

Fig. 8. TNX index of Salalah (1990-2023)

This trend is consistent with observations in other subtropical and arid regions, where increased atmospheric water vapor has been linked to intensified nighttime warming (AlSakkaf et al., 2024). The solid line in Fig. 8 underscores the long-term warming signal, while the dashed line reflects short-term variability, indicating that heatwave-associated nocturnal warming occurs intermittently rather than steadily. These findings are supported by global studies showing that increased cloud cover and latent heat retention significantly contribute to the amplification of nighttime temperature extremes (Zhou, 2016).

The TR20 index, depicted in Fig. 9, represents the annual count of tropical nights (minimum temperature > 20°C) and shows a statistically significant upward trend (slope = 0.788, R^2 = 0.20, p = 0.008). This confirms that Salalah is experiencing increasingly frequent warm nights each year. The observed rise in TR20 has important implications for public health and energy demand, as elevated nighttime temperatures contribute to reduced thermal comfort, higher heat stress, and greater electricity use for cooling systems.

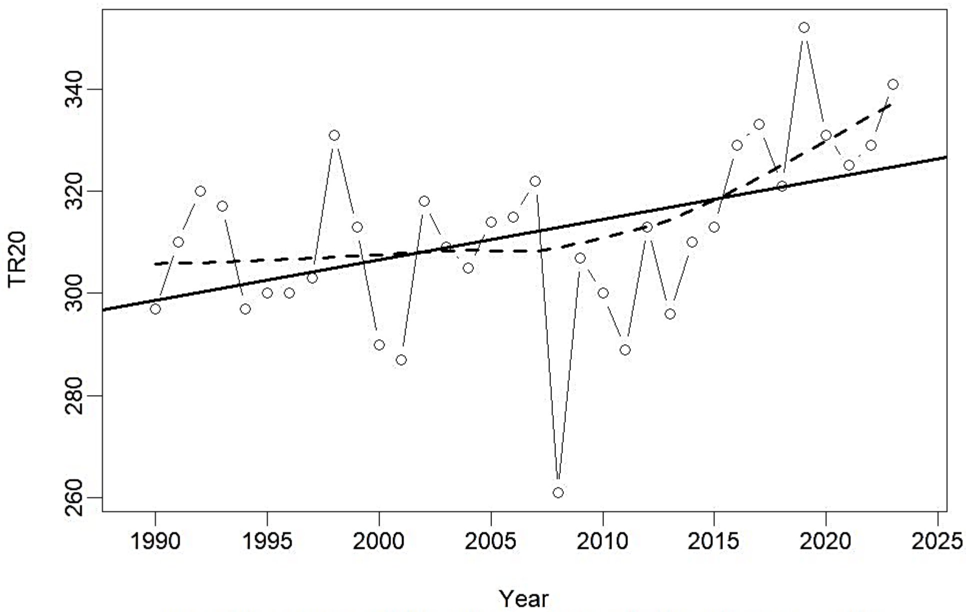

Fig. 9. TR20 index of Salalah (1990-2023)

This trend aligns with global climate projections that suggest tropical and coastal areas are facing longer periods of elevated nocturnal temperatures, driven by rising sea surface temperatures and atmospheric circulation changes. The graph's solid line illustrates a steady increase in tropical nights, while the dashed line highlights fluctuations due to interannual climate variability. These findings are consistent with global observations of warmer nights becoming more common, particularly in low-latitude regions (Alexander et al., 2006).

The Simple Daily Intensity Index (SDII), illustrated in Fig.10, measures the average precipitation intensity on wet days (PRCP ≥ 1.0 mm). The analysis reveals a statistically significant upward trend (slope = 0.13, R^2 = 0.13, p = 0.044), indicating that while the frequency of rainfall events has not notably increased, their intensity has become greater. This observation aligns with findings from AlSarmi (2014), who documented a regional shift in the Middle East toward fewer but more intense precipitation events—likely driven by enhanced convective storm activity.

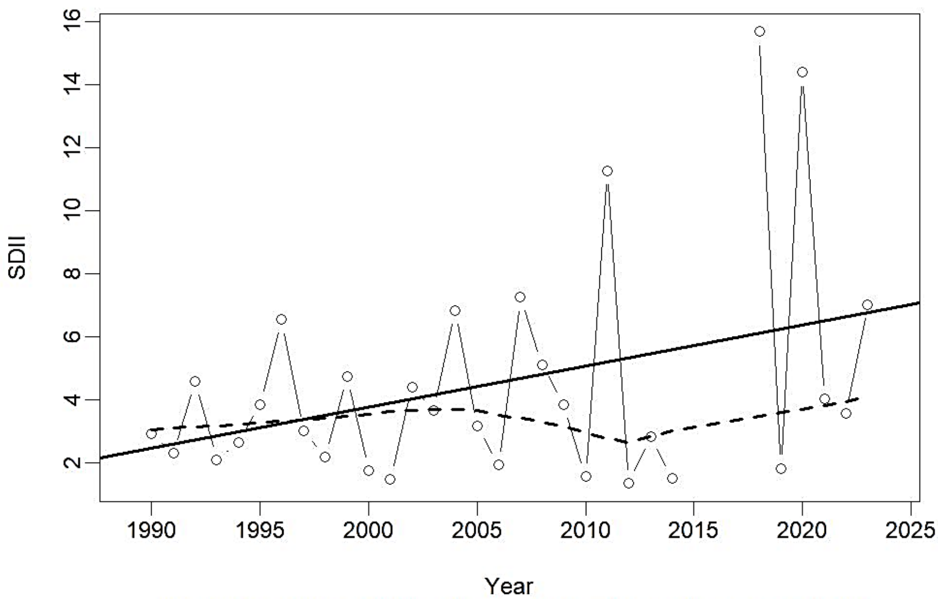

Fig.10. SDII index of Salalah (1990-2023)

The solid line in Fig.10 reflects the steady rise in precipitation intensity, while the dashed line captures periodic fluctuations, indicative of the sporadic and extreme nature of heavy rainfall events. These results reflect broader climate change patterns, where warming atmospheric conditions intensify the hydrological cycle, leading to more vigorous rainfall episodes even in traditionally arid regions (IPCC, 2021).

The other remaining 16 indices shown in Table (2) were found having insignificant trends at p-value ≤ 0.05. For instance, the Consecutive Dry Days (CDD) index exhibits a weak and statistically insignificant decreasing trend, suggesting no significant change in dry spell duration despite interannual variability. This pattern is characteristic of arid and semi-arid regions, where precipitation variability is high, yet long-term trends remain elusive (Frich et al., 2002).

Regarding precipitation, most indices, including annual total wet-day precipitation (PRCPTOT) show weak increasing trends, though not statistically significant. However, some extreme precipitation indices increased significantly with P-value < 0.1 such as, very wet days index R95p p-value = 0.08, and extremely wet days index R99p p-value = 0.062, suggest that a greater proportion of annual rainfall is occurring in intense events, consistent with global findings on extreme precipitation intensification due to rising atmospheric moisture content (Fowler et al., 2005; Zhang et al., 2005, 2011). This trend is further supported by the simple daily intensity index (SDII), which exhibits a statistically significant increase as mentioned earlier, indicating that rainfall events are becoming more intense despite no significant change in their frequency (AlSarmi, 2014). Moreover, the RX1day index, which measures the highest single-day rainfall event per year, exhibits a positive trend, p-value = 0.059, and the RX5day index, which represents the maximum five-day total rainfall, exhibits a strong increasing trend p-value = 0.079) indicating that extreme one-day and multi-day rainfall events are becoming more intense. This trend suggests an increasing risk of flash floods, highlighting the need for improved urban drainage and water management infrastructure to mitigate potential flood hazards (Alexander et al., 2006). This trend aligns also with findings by AlSakkaf et al. (2024), who reported that climate change is amplifying extreme precipitation in subtropical coastal regions, likely driven by rising sea surface temperatures and shifting monsoon dynamics.

TABLE 2. Indices with insignificant variation at P-value less than 0.05

Indices	Indicator name	Slope	Standard error	P-value	Indicator name
RX1day	Max 1-day, precipitation amount	1.775	0.898	0.059	13.1
RX5day	Max 5-day precipitation amount	2.461	1.346	0.079	11.4
R95p	Very wet days	2.643	1.459	0.08	10.2
R99p	Extremely wet days	1.771	0.911	0.062	11.5
R10mm	Number of heavy precipitation days above 10 mm	0.063	0.038	0.111	8.5
PRCPTOT	Annual total wet-day precipitation	2.106	1.748	0.238	4.8
WSDI	Warm spell durationindicator	0.144	0.127	0.267	3.8
SU25	Summer days	-0.102	0.102	0.324	3
TMAXmean	mean maximum temperature	0.005	0.007	0.454	1.8
CWD	Consecutive wet days	-0.03	0.04	0.464	1.9
CDD	Consecutive dry days	-0.338	1.273	0.793	0.2
TX90p	Warm days	0.055	0.09	0.544	1.2
TXN	Min Tmax	-0.011	0.028	0.687	0.5
TXX	Max Tmax	-0.02	0.053	0.707	0.4
TX10p	Cool days	-0.04	0.112	0.722	0.4
GSL	Growing season Length	-0.001	0.008	0.874	0.1

Moreover, the Growing Season Length (GSL) index remains stable with no statistically significant trend, suggesting that agricultural productivity in Salalah is still largely regulated by seasonal monsoon rainfall rather than temperature-driven changes (Ghassabi et al., 2024). The Warm Spell Duration Index (WSDI) exhibits a weak increasing trend, suggesting a potential rise in prolonged warm periods, though the change remains statistically insignificant (Alexander et al., 2006).

The R10mm index, which measures the number of days per year with daily precipitation exceeding 10mm, shows a weak increasing trend, suggesting a potential rise in moderate-intensity rainfall events. However, the lack of statistical significance indicates that this trend may be driven by interannual variability rather than a sustained climatic shift. This pattern aligns with findings by Frich et al. (2002), who observed that many arid and semi-arid regions experience increasing variability in rainfall intensity rather than an overall rise in total precipitation.

The SU25 index, which represents the number of summer days (Tmax > 25°C), exhibits a statistically insignificant downward trend, suggesting that the annual count of warm days has remained relatively stable. This stability is likely due to Salalah's monsoon-driven climate, which helps regulate maximum temperature extremes and prevents significant increases in heatwaves, unlike inland regions (Frich et al., 2002).

The TMAXmean index, which represents the mean maximum temperature, exhibits a weak upward trend, indicating that while maximum temperatures may be rising, the trend remains statistically insignificant. This lack of strong warming in daytime temperatures is likely influenced by Salalah's monsoonal climate, which moderates peak temperatures through increased cloud cover and oceanic moisture influx during summer (AlSakkaf et al., 2024).

The TX10P index, which measures the frequency of cool days (maximum temperature below the 10th percentile), shows a slight but statistically insignificant decline. This suggests no strong evidence of a decreasing trend in cool days, aligning with global studies that indicate a slower reduction in daytime cold extremes compared to nighttime cold extremes.

The TX90P index, which measures the frequency of warm days (maximum temperature exceeding the 90th percentile), exhibits a slight but statistically insignificant upward trend. This suggests a potential increase in warm days, though the change remains weak. Previous studies (Frich et al., 2002)

The TXN index, representing the annual minimum maximum temperature, exhibits a slight but statistically insignificant downward trend. This suggests that the lowest maximum temperatures have remained relatively stable, likely influenced by interannual variability and broader climate patterns. Similarly, TXx, which represents the annual highest maximum temperature, also shows a weak and non-significant decline.

The Consecutive Wet Days (CWD) index, which measures the longest continuous period of wet days (precipitation >1mm), exhibits a weak and statistically insignificant downward trend. This suggests that while interannual fluctuations exist, the overall duration of prolonged wet periods has remained relatively stable over the past three decades.

Conclusion

The analysis of climate indices in Salalah/ Oman over the past three decades reveals significant trends associated with rising minimum temperatures and increasing precipitation variability, while other indicators remain largely stable or exhibit weak trends.

The Cold Spell Duration Index (CSDI) shows a statistically significant decline (slope = -0.659, R^2 = 25, p-value = 0.003), indicating a substantial reduction in cold spells. This aligns with broader global warming projections that predict a decrease in cold extremes in subtropical and mid-latitude regions. Additionally, the TN10P index has significantly declined, reinforcing the warming trend in minimum temperatures. Meanwhile, the mean minimum temperature (TMINmean) exhibits a strong and statistically significant upward trend, confirming that nighttime temperatures are rising more rapidly than daytime temperatures, likely due to increased atmospheric moisture and cloud cover trapping outgoing longwave radiation. The Diurnal Temperature Range (DTR) also shows a pronounced decline, further supporting the hypothesis that nighttime warming is outpacing daytime temperature increases.

Overall, the analysis confirms that climate change in Salalah is primarily manifested through rising nighttime temperatures and an increasing contribution of extreme rainfall events to total precipitation, while long-term changes in dry spells, total precipitation, and warm daytime extremes remain statistically inconclusive. The observed warming, particularly in nighttime temperatures, has implications for human health, agriculture, and urban planning, necessitating adaptation strategies to mitigate heat stress and ensure climate-resilient infrastructure. Additionally, the shift towards more intense precipitation events increases the risk of flash floods, underscoring the need for improved water resource management and flood mitigation measures. Future research should focus in phenological changes in vegetation, soil moisture dynamics, and hydrological modeling to assess the broader ecological and socio-economic impacts of these climatic shifts.

Authors' contributions

Mohammed M. AlShaikh: writing—original draft and editing, data processing, data curation, and investigation and formal analysis. Eman F. El-Nobi: writing—original draft and editing, data processing, data curation, and investigation. E. A. Ahmed: Methodology, reviewing, and editing. Kh. O. Kassem: investigation, writing—review, editing and supervision.

Funding statement

Not available.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper.

Declaration of Conflict of Interest

The authors declare no conflict of interest.

References

Ahmad, W. (2020) Climate change assessment using climate indices. *International Journal for Research in Applied Science & Engineering Technology,* **8**(9), 876–885. https://www.academia.edu/download/64550733/604.pdf

Al Rawas, G. A., & Valeo, C. (2010) Evaluating the effect of climate change on water resources in arid regions: A case study of Salalah, Oman. *Hydrological Sciences Journal*, **55**(6), 1023–1035. https://www.tandfonline.com/doi/abs/10.1080/02626661003718318

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G. and Vazquez-Aguirre, J. L. (2006) Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres,* **111**(D5). https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2005JD006290

Al-Habsi, M., Al-Rawas, G. A. and Charabi, Y. (2014) Analysis of climate variability and trends in Salalah, Oman. *Arabian Journal of Geosciences,* **7**(6), 2271–2281. https://link.springer.com/article/10.1007/s12517-012-0825-0

AlSakkaf, A. S., Al-Mashaqbeh, S. and Rahman, M. (2024) Assessing exposure to climate extremes over the Arabian Peninsula using ERA5 reanalysis data. *Atmospheric Research,* **300**, 107224. https://www.sciencedirect.com/science/article/pii/S0169809524000061

AlSarmi, S. (2014) Observed climate change in the Arabian Peninsula. *Arabian Journal of Geosciences*, **7**(3), 881–901.

AlSarmi, S. (2014) Recent observed climate change over the Arabian Peninsula and its impact on the extreme weather events. *Arabian Journal of Geosciences,* **7**(3), 999–1017. https://link.springer.com/article/10.1007/s12517-012-0839-7

AlSarmi, S. H. M. (2014) *Recent climate change over the Arabian Peninsula: Trends and mechanisms* [Doctoral dissertation, University of Oxford]. Oxford University Research Archive. https://ora.ox.ac.uk/objects/uuid:39a76447-65a8-4e30-a4fa-70f531fc91e0

Fowler, H. J., Kilsby, C. G., and O'Connell, P. E. (2005) Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resources Research,* **41**(6). https://doi.org/10.1029/2002WR001778

Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A. M. G. and Peterson, T. (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research*, **19**(3), 193–212. https://www.int-res.com/abstracts/cr/v19/n3/p193-212/

Intergovernmental Panel on Climate Change (IPCC) (2021) *Climate change 2021: The physical science basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

Zhang, X. and Yang, F. (2004) *RClimDex (1.0) User Manual*. Climate Research Branch, Environment Canada. Retrieved from https://rcc.acmad.org/procedure/RClimDexUserManual.pdf

Zhang, X., Aguilar, E., Sensoy, S., Melkonyan, H., Taghipour, A. and Albert, P. (2005) Trends in Middle East climate extremes indices. *International Journal of Climatology,* **31**(8), 1153–1167. https://doi.org/10.1002/joc.2170

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. M. G. K., Peterson, T. C. and Zwiers, F. W. (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, **2**(6), 851–870. https://doi.org/10.1002/wcc.147

Zhou, L. (2016) Desert amplification in a warming climate. *Scientific Reports,* **6**, Article 31065. https://doi.org/10.1038/srep31065

Oman Meteorology (2023) *Daily maximum and minimum temperature and precipitation data for Salalah region (1990–2023)*. Directorate General of Meteorology, Civil Aviation Authority, Oman. Available at: https://drive.google.com/file/d/1J7ciYIvWMuqiROjFRnlTQZjBZhP73Kbp/view?usp=sharing

أثر التغير المناخي على الظواهر الجوية المتطرفة: دراسة تحليلية لمدينة صلالة

محمد بن محفوظ الشيخ [1,2*]، خلف الله عمر قاسم[3]، عماد علي أحمد[4] وإيمان فؤاد النوبي[3]

[1] كلية العلوم، برنامج الإدارة الذكية للتغيرات المناخية، جامعة جنوب الوادي، قنا، مصر.
[2] أخصائي أرصاد جوية، الهيئة العامة للطيران المدني العمانية، صلالة، سلطنة عمان.
[3] كلية العلوم، قسم الفيزياء، معمل فيزياء الغلاف الجوي، جامعة جنوب الوادي، قنا، مصر.
[4] كلية الحاسبات والمعلومات، قسم علوم الحاسب، جامعة جنوب الوادي، قنا، مصر.

يتوقع أن يؤدي التغير المناخي إلى تغيّر في تكرار وشدة الظواهر الجوية المتطرفة، مما يزيد من مخاطر الفيضانات المفاجئة والجفاف، لاسيما في المناطق الشحيحة المياه مثل سلطنة عمان. تهدف هذه الدراسة إلى تحليل تطرف المناخ في مدينة صلالة خلال الفترة من 1990 إلى 2023، بالاعتماد على بيانات يومية للهطول ودرجات الحرارة، باستخدام برنامج RClimDex لاشتقاق 25 مؤشرًا مناخيًا معتمدًا دوليًا. أظهرت النتائج ارتفاعًا معنويًا في متوسط درجات الحرارة الدنيا (TMINmean) بمعدل 0.04 درجة مئوية سنويًا ($P < 0.001$ ، $R^2 = 0.49$)، إلى جانب انخفاض في عدد الليالي الباردة (TN10P) بمعدل 0.515 يومًا سنويًا ($P < 0.001$ ، $R^2 = 0.42$)، وتراجع في مدة الموجات الباردة (CSDI) بمعدل 0.659 يومًا سنويًا ($P = 0.003$). كما سجل مؤشر الفرق الحراري اليومي (DTR) انخفاضًا بمعدل 0.033 درجة مئوية سنويًا ($P < 0.001$، $R^2 = 0.60$)، ما يدل على تسارع الاحترار الليلي مقارنة بالنهار. وفيما يخص الهطول، أظهر مؤشر شدة الأمطار (SDII) زيادة معنوية بمعدل 0.13 ملم في اليوم سنويًا ($P = 0.044$) ، كما سُجلت زيادات دالة إحصائيًا عند مستوى دلالة 0.10 في مؤشرات الأمطار الغزيرة، حيث بلغ معدل الزيادة في أيام الأمطار الشديدة جدًا (R95p) 2.64 ملم/سنة ($P = 0.08$) ، وفي الأيام القصوى (R99p) 1.77 ملم/سنة ($P = 0.062$) ، وفي أعلى مطر يومي (RX1day) 1.78 ملم/سنة ($P = 0.059$) ، وفي أعلى مجموع مطري خلال خمسة أيام (RX5day) 2.46 ملم/سنة ($P = 0.079$). تعكس هذه النتائج التوجه المتزايد نحو احترار ليلي واضح وارتفاع في شدة الهطول المطري، بما ينذر بآثار بيئية وإنسانية كبيرة تشمل ارتفاع معدلات الإجهاد الحراري، وتغيرات في النظم الزراعية، وزيادة خطر الفيضانات المفاجئة. وتوصي الدراسة بضرورة تبني استراتيجيات وطنية للتكيف المناخي تشمل تطوير البنية التحتية الحضرية، وتحسين إدارة المياه، وتعزيز نظم الإنذار المبكر في المناطق المعرضة للخطر.