



Systematic Spatio-Temporal Analysis of Long Term Trends and Surface Warming Thresholds Over Oman

Baiju Dayanandan¹ · Aon Abbas¹ · Ajay Parottil² · Vinoj Velu³ · Soumyajyoti Jana⁴ · Ahmed Al Harrasi¹ · Mohammed Safi Al Kalbani⁵ · Rahma Al Nadhairi⁵ · Humaid AlBadi⁶

Received: 4 July 2025 / Revised: 26 September 2025 / Accepted: 28 September 2025
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Abstract

This study presents a comprehensive assessment of long-term surface air temperature trends over Oman using ground measurements and ERA5 from 1981 to 2020. The Mann-Kendall (MK) test and Sen's slope estimator was applied to identify trends; results reveal significant nationwide non-uniform warming, with average (T_{avg}), maximum (T_{max}), and minimum (T_{min}) temperatures rising by 0.23 ± 0.16 °C decade⁻¹, 0.25 ± 0.16 °C decade⁻¹, and 0.23 ± 0.20 °C decade⁻¹, respectively. Seasonal trends show spring (MAM) warming to be the most rapid, followed closely by autumn (SON), while summer (JJA) exhibits consistent increases across all metrics. Winter (DJF) displays the slowest warming. Decadal intensification is evident post 2000, with 2011–2020 ranking as the warmest decade on record. The frequency and extent of extreme temperature days have increased sharply, driven by a rapid warming trend since the 2000s. Central Oman in the recent decade records over 110 days annually with $T_{avg} > 36$ °C, while days with $T_{max} > 45$ °C and nights with $T_{min} > 30$ °C (tropical nights) have more than tripled. Regionally, a strong and consistent warming pattern is evident across northern and central Oman, particularly reflected in T_{max} and T_{min} trends. Northern Oman experiences the most pronounced and persistent rise in temperature. Central Oman shows notable warming with more variability in some areas. In contrast, southern Oman exhibits relatively weaker trends, with the least warming observed overall. Overall, Oman is warming 1.2–2.3 times faster than the global average but slightly slower than the broader Arabian Peninsula, making it an intermediate yet vulnerable climate hotspot.

Graphical Abstract

This Study First Validates high-resolution ERA5 Reanalysis Data (1981–2020) against Ground observations. It Then Uses this Validated Dataset To Provide a Comprehensive spatio-temporal Analysis of long-term Temperature Trends and Surface Warming Thresholds across Oman. The Methodological Framework Integrates Statistical Trend Analysis of Decadal and Seasonal Temperature (Mann–Kendall and Sen's slope), Alongside Decadal variations, Anomaly assessments, and Extreme Temperature Events Such as Days with $T_{avg} > 36$ °C, $T_{max} > 45$ °C, and Tropical Nights with $T_{min} > 30$ °C. Spatially Explicit Trend Maps and threshold-exceedance Frequency Plots Were Generated Using Python and ArcGIS, with Regional Segmentation into North, Central, and South Oman To Capture Climatic heterogeneity. Results Reveal Significant Nationwide Warming, with Average (T_{avg}), Maximum (T_{max}), and Minimum (T_{min}) Temperatures Increasing at Rates of 0.23 °C, 0.25 °C, and 0.23 °C Per Decade, respectively. The Strongest Warming Occurred in Northern Oman, Particularly during Spring (MAM) and Autumn (SON), while Central Regions Showed the Highest Frequency of Extreme Heat Days. Decadal Comparisons Highlight Accelerated Warming post-2000, with 2011–2020 Being the Warmest Decade on record. Oman's

✉ Baiju Dayanandan
baiju@unizwa.edu.om

¹ Natural and Medical Sciences Research Centre, University of Nizwa, Birkat Al Mawz, Oman

² Atmospheric Chemistry Observations & Modelling, NSF, National Centre for Atmospheric Research (NCAR), CO, USA

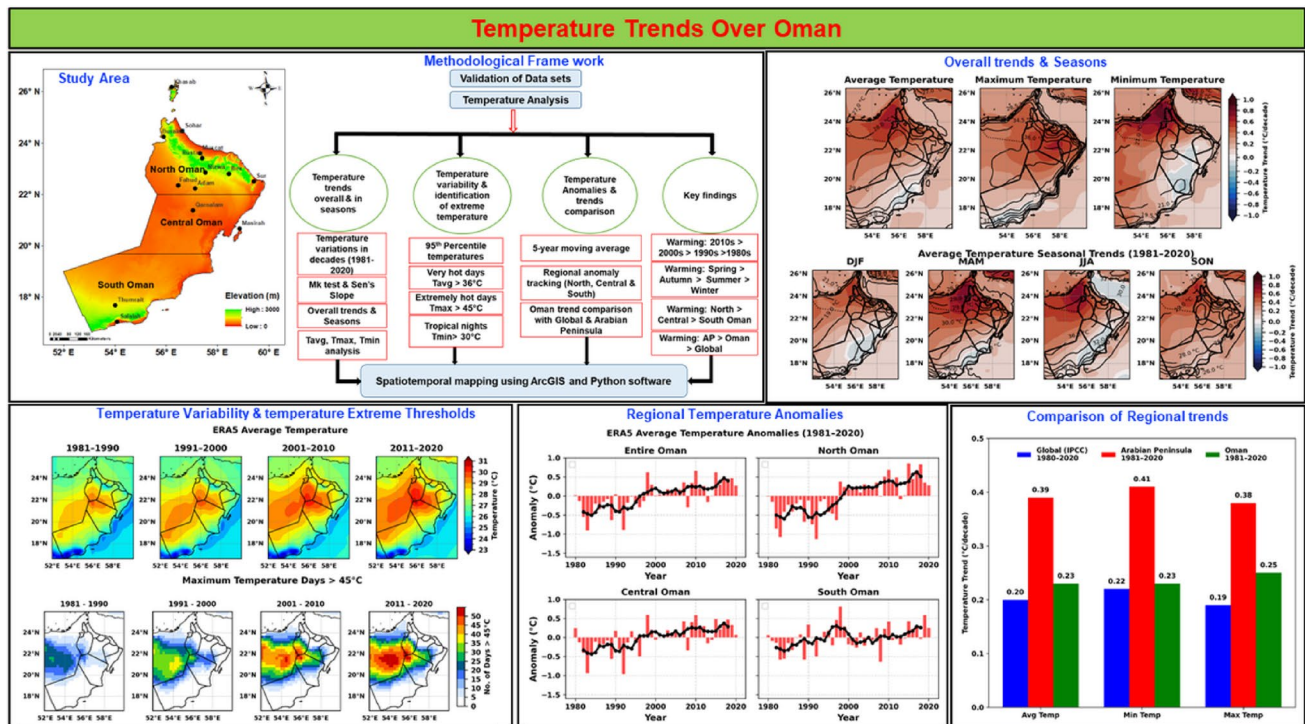
³ Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

⁴ Indian Institute of Tropical Meteorology, Maharashtra, India

⁵ Oman Environment Authority, Muscat, Oman

⁶ Oman Civil Aviation Authority, Muscat, Oman

Warming Exceeds the Global Average but Remains Slightly below the Broader Arabian Peninsula Rates. These Findings Underscore the Critical Need for region-specific Climate Adaptation Strategies in Water Resource management, Public health, agriculture, and Energy Planning



Highlights

- First comprehensive four-decade (1981–2020) validation of ERA5 against ground observations in Oman confirms its high accuracy for climate analysis.
- Long-term warming detected: average, maximum, and minimum temperatures increased by 0.23–0.25 °C per decade.
- Strong seasonal differences identified: spring (MAM) and autumn (SON) show the fastest warming, while winter (DJF) lags behind.
- Post-2000 acceleration observed, with 2011–2020 emerging as the warmest decade on record.
- Critical thresholds quantified: central Oman now records >110 days annually with $T_{avg} > 36$ °C; days with $T_{max} > 45$ °C and tropical nights ($T_{min} > 30$ °C) have tripled.
- Regional contrasts revealed: northern Oman shows the strongest and most persistent warming, while southern Oman exhibits weaker and more variable trends.
- Oman's warming is 1.2–2.3 times faster than the global average but slightly slower than the broader Arabian Peninsula, positioning it as an intermediate yet vulnerable hotspot.
- Results provide a robust baseline for future hypothesis-driven studies and inform climate adaptation strategies for health, water, energy, and agriculture.

Keywords Surface temperature trends · Oman climate warming · Extreme heat events · ERA5 validation · Regional warming variability

1 Introduction

The World Meteorological Organization (WMO) reports that by January 2025 the global surface temperature anomaly averaged +1.75 °C relative to the late-19th-century baseline, and 18 of the previous 19 months exceeded the

1.5 °C threshold (Wmo 2025). Global surface temperatures have risen by nearly 1.1 °C since the late 19th century, with accelerated warming since the mid-20th century (IPCC 2021). Since 2000, record breaking temperatures have become more frequent, highlighting the intensifying impacts of climate change (Adeyeri et al. 2022; Lee et al.

2024). Temperature change impacts are already evident through frequent disasters, posing serious threats to ecosystems, infrastructure, and human livelihoods worldwide (Abbass et al. 2022; Rawat et al. 2024). Ongoing warming is profoundly affecting Earth's systems. For instance, rising sea levels are accelerating due to oceanic heat uptake and ice melt (Hamlington et al. 2024). Furthermore, biodiversity loss, directly linked to rising temperatures, severely threatens ecosystem stability and human quality of life (Keck et al. 2025). This extreme heat is already a major global health risk, linked to an estimated 489,000 deaths annually between 2000 and 2019 while in Europe alone, the 2022 summer heatwave was associated with 61,672 excess deaths (WHO 2024).

Middle East and North Africa (MENA) is one of the areas known to be the most exposed to the effects of climate change (Dogar 2020; Dogar 2018; Dogar, Kucharski et al. 2017; Dogar and Sato 2018, 2019), with temperatures increasing at almost twice the global average rate (Ripple et al. 2023). Among them, the Arabian Peninsula is one of the main hotspots of warming because it warms about 3-fold higher than the rest of the world (Zittis et al. 2022a, b). There is an indication on climate projections that temperatures in the region might increase by $2.6\text{ }^{\circ}\text{C} \pm 0.57\text{ }^{\circ}\text{C}$ by the year 2100 following a low-emissions scenario and up to $7.6\text{ }^{\circ}\text{C} \pm 1.53\text{ }^{\circ}\text{C}$ when a high-emissions scenario is realized (IPCC 2021). Various regions within the MENA region such as the Arabian Peninsula, Algeria, Mauritania and even Elburz Mountains in Iran are already seeing a high rate and high temperature warming and in some regions, the summer temperatures could rise by up to 9 Celsius in the worst emitting scenario (Malik et al. 2024).

Extreme temperatures, including record-breaking heat, pose serious risks to the Arabian Peninsula, which is already very hot, dry, and has limited freshwater sources. Heatwaves have become more frequent and intense, such as the record temperature of $53.9\text{ }^{\circ}\text{C}$ recorded in Kuwait in July 2016 (Merlone et al. 2019). Similar extreme temperatures have been reported in other Gulf countries, with Saudi Arabia experiencing over $52\text{ }^{\circ}\text{C}$. In the United Arab Emirates, long-term trends show that the average temperature (T_{avg}) has increased by about $1\text{ }^{\circ}\text{C}$, while rainfall has dropped by more than 50% since the 1980s (Almazroui et al. 2014). Yemen has experienced a consistent increase in temperatures over the past three decades, with warming occurring at a rate higher than the global average. Between 1971 and 2020, average temperatures rose by approximately $0.42\text{ }^{\circ}\text{C}$ per decade (Bank 2023b). In Iran, significant warming trends were detected, with the highest increase observed in annual T_{min} $0.47\text{ }^{\circ}\text{C decade}^{-1}$ and the lowest in annual T_{max} $0.4\text{ }^{\circ}\text{C decade}^{-1}$ during 1978–2017 (Kazemzadeh et al. 2022).

These changes are part of a broader regional climate trend. Studies have shown warming patterns at different levels: across the Arab world (Donat et al. 2014a), nationally in Saudi Arabia (Almazroui et al. 2014; Athar 2014), and even locally in urban areas (Alghamdi and Moore 2014; Rehman and Al-Hadhrami 2012). Together, they show a clear increase in T_{avg} , T_{max} and T_{min} temperatures across the region. This highlights the urgent need for detailed climate studies and effective adaptation plans. Because regions like the Arabian Peninsula are warming faster than others, it is essential to understand where and when these changes are happening. Only then can policies and mitigation efforts be properly tailored to the region's specific climate conditions.

High summer temperatures and aridity across the Arabian Peninsula (AP) are largely driven by atmospheric subsidence associated with circulation patterns, which often manifest as intense heatwaves and dust storms (Chakraborty et al. 2006; Tyrlis et al. 2013). The region's climate variability is strongly modulated by large-scale teleconnections such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the North Atlantic Oscillation (NAO) (Attada et al. 2018; Barlow et al. 2016; Dasari et al. 2017; Dogar et al. 2019; Rizou et al. 2015). In addition to atmospheric teleconnections, volcanism and ocean circulation also significantly influence regional climate variability (Dogar et al. 2020, 2022). Atmospheric circulation over the AP is typically dominated by subtropical high-pressure systems and thermal lows. These systems reinforce subsidence, reduce wind strength, and trap heat, thereby enhancing extreme summer temperatures (Gandham et al. 2025).

Anomalous pressure systems can further elevate humidity levels and suppress cooling winds like the Shamal, diminishing evaporative cooling and intensifying heat stress (Dogar, Kucharski et al. 2017). At the same time, remote drivers exert a compounding influence: ENSO and NAO phases together explain much of the interannual temperature variability, with the concurrence of La Niña and a negative NAO phase often linked to the most severe warming episodes and marine heatwaves in the region (Dogar and Almazroui 2022; Donat et al. 2014b; Lachkar et al. 2025). In summer, persistent Shamal winds amplify heat extremes through subsidence, hot-air advection, and dust loading, while seasonal rises in dust, sulfate, and organic carbon aerosols strengthen radiative forcing and atmospheric heating, dominated by coarse dust from the Horn of Africa and regional arid areas (Al Senafi and Anis 2015; Alawad et al. 2023; Dayanandan et al. 2022, 2025; Yu et al. 2016). Beyond these natural and regional processes, anthropogenic forcing is now recognized as the dominant background driver. Rising greenhouse gas concentrations enhance downward long-wave radiation and preferentially warm nighttime minima, thereby narrowing the diurnal temperature range (Dogar

2019). Long-term aerosol loading and radiative impacts further amplify heating (Dayanandan et al. 2021; Kaskaoutis et al. 2023; Osipov et al. 2022). Projections show rising risks of surpassing 50 °C and the emergence of super- and ultra-extreme heatwaves under high-emission scenarios (Christidis et al. 2023; Donat et al. 2014a; Francis and Fonseca 2024; Zittis et al. 2021). Together, circulation, teleconnections, aerosols, and human forcing make the Arabian Peninsula a global warming hotspot, highlighting the urgency of localized studies in Oman.

Study concerning global warming is of great concern in the Middle East, because it is highly vulnerable to temperature change (Touma and Nablusi 2021). The Arabian Peninsula, characterized by its arid climate, limited freshwater resources, and dependence on climate-sensitive sectors, is considered one of the global hotspots of warming, with temperature increases projected to exceed the global mean (Lelieveld et al. 2016). Oman that is situated at the south eastern end of the Arabian Peninsula is a high profile candidate study. Oman's hot arid climate inherently exposes it to extreme heat. The temperatures within the country have increased by 1.4 °C over the past century, exceeding the global increase (Shapland 2023). The effects for Oman's environment, economy, and health are deep seated and encompass changes in water supply, agricultural production, and energy demand (Al-Sakkaf et al. 2024). Oman's unique climate driven by varied topography, monsoon-influenced coasts, and arid interiors differs from the rest of the Arabian Peninsula. Despite this, it is underrepresented in regional climate research, with most studies focusing on broader Middle Eastern patterns (Hereher 2019). A recent study with ERA5 data found robust trends towards warming and non-uniform changes in precipitation within Oman and the need for local climate studies (Al-Sakkaf et al. 2024).

Oman is highly vulnerable to climate change, yet detailed studies of recent meteorological trends are still limited. To address this critical gap, this study provides a comprehensive, high-resolution assessment of surface temperature patterns in Oman from 1981 to 2020. The primary objectives of this work are to: Validate the performance of the ERA5 reanalysis dataset against ground observations and compare it with MERRA-2, CRU, and NCEP/NCAR to identify the most reliable product for climate analysis over Oman. Examine long-term trends in average (T_{avg}), maximum (T_{max}), and minimum (T_{min}) temperatures at national, regional, and seasonal scales using the Mann–Kendall test and Sen's slope estimator. Quantify decadal variability, with a special focus on the accelerated warming period post-2000. Analyze the spatio-temporal frequency of extreme temperature thresholds ($T_{avg} > 36$ °C, $T_{max} > 45$ °C, $T_{min} > 30$ °C) to assess growing heat stress. Contextualize Oman's warming rate by comparing it with global and Arabian Peninsula averages.

Finally, we synthesize these findings to assess Oman's status as a regional climate hotspot and discuss the implications for climate adaptation and policymaking.

2 Study Area, Datasets, and Data Evaluation

2.1 Study Area

Oman is located in the southeastern part of the Arabian Peninsula, covering an area of approximately 309,500 km² (El Kenawy et al. 2020). By the year 2025, an estimate 5.3 million people are expected to live in Oman (NCSI 2025). Its Arabian Sea and Gulf of Oman 3,000 km. coastal regions along the Arabian and the Gulf of Oman affect the climatic pattern where the inland areas surrounded by Rub al Khali desert makes the country both arid and semi-arid (Marzouk 2021). The country is rich in topographies including deserts, plains, and highlands such as Al Hajar and Dhofar mountain range resulting in climatic regions as dry as arid to the semiarid (Dorvlo et al. 2008; Kwarteng et al. 2009). This difference produces extreme temperatures, the humidity along the coast and dry of the inland affects the vegetation and ecology of the areas. Cyclones sometimes crossing the Arabian Sea also influence weather patterns and fluctuations in temperature, defining the environment and natural resources of Oman (UNFCCC 2023). The temperature of Oman varies with regions and decades. In Oman, the average seasonal temperature (T_{avg}) varied between winter (DJF) to 32.76 °C in summer (JJA), with spring (MAM) and autumn (SON) averaging 28.88 °C and 27.96 °C, respectively. The average minimum temperature (T_{min}) followed a similar pattern, rising from 15.64 °C in DJF to 23.00 °C in MAM, 22.00 °C in SON, and reached its climax at 26.83 °C in JJA. The average maximum temperature (T_{max}) was highest in JJA at 38.73 °C, followed by MAM (35.17 °C), SON (34.18 °C), and DJF (26.68 °C), reflecting Oman's hot summers and milder winters (Bank 2024).

2.2 Data Sets

To identify the most reliable dataset for temperature analysis in Oman, we evaluated four reanalysis and gridded datasets: ERA5, MERRA-2, NCEP/NCAR Reanalysis-2, and CRU TS 4.08. Their performance was assessed using monthly mean temperature data from 14 observation stations across Oman, obtained from the Oman Civil Aviation Authority. The station locations, shown in Fig. 1, represent diverse climatic regions coastal, desert, and mountainous providing a robust basis for comparison. These ground based observations serve as the benchmark for evaluating the accuracy of

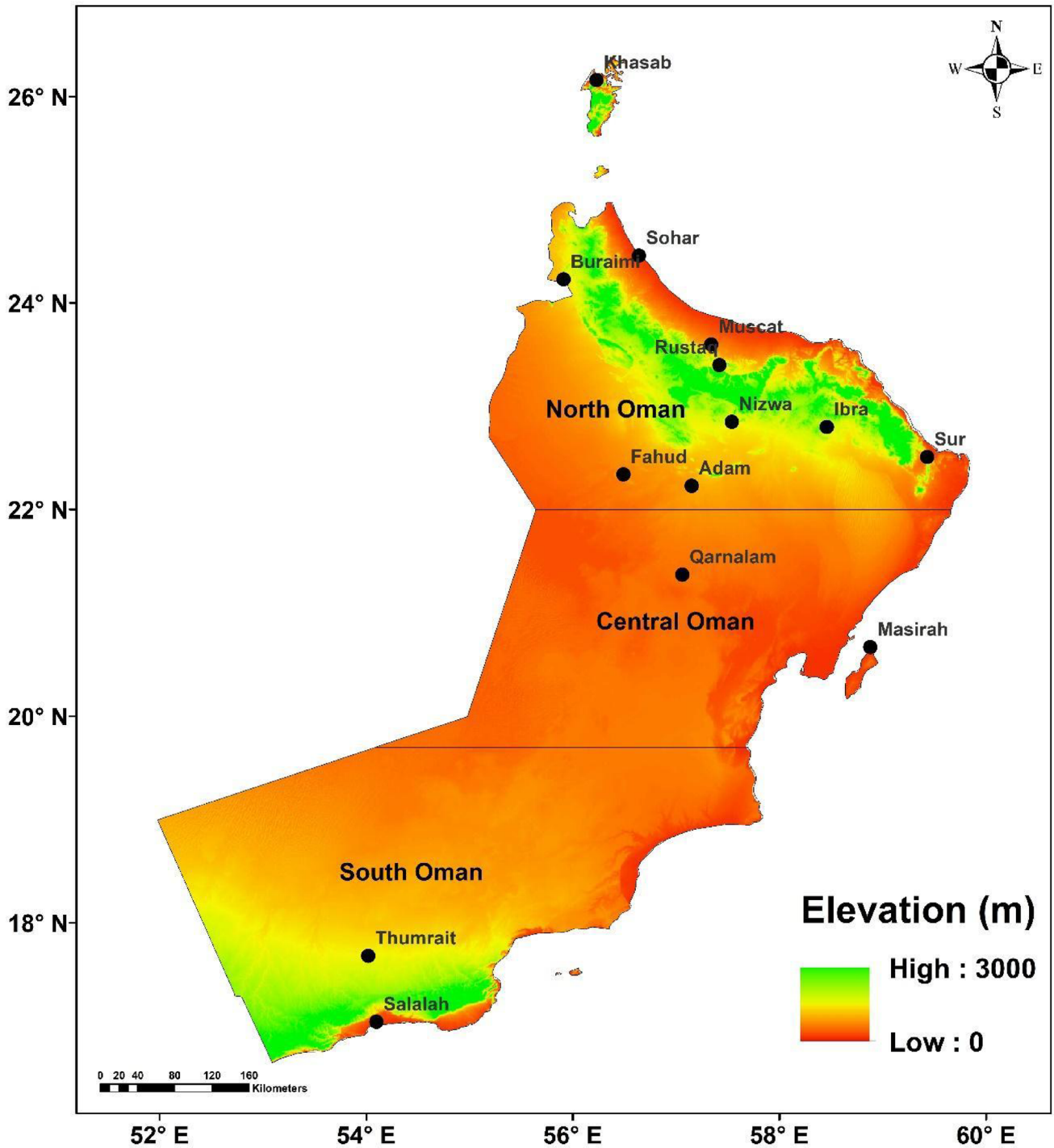


Fig. 1 Elevation map of the study area in Oman, showing regional zones North, Central, and South Oman. Dots indicate the meteorological stations used for dataset evaluation

the datasets. Below, we describe the datasets used in this analysis.

2.2.1 ERA5

A key focus in atmospheric and climate science research is the acquisition of high precision temperature and precipitation data with fine spatial and temporal resolution. This is particularly important in regions where ground-based weather stations are sparse, inconsistent, or entirely lacking. To address these challenges, reanalysis datasets have become essential tools, with the European Centre for Medium-Range Weather Forecasts (ECMWF) (Thépaut et al. 2018), leading efforts through successive products starting with ERA-40 and followed by ERA-Interim in 2006, which provided global climate data at ~ 80 km resolution, 60 vertical levels, and six-hourly outputs, widely used for studying climate variability and long-term trends (Dee et al. 2011). In 2019, ERA5 developed under the Copernicus Climate Change Service (C3S) as the fifth-generation reanalysis replaced its predecessor by offering significantly improved spatial (~ 31 km) and temporal (hourly) resolution, based on the Integrated Forecasting System (IFS Cycle 41r2) and a refined 4D-Var data assimilation method that incorporates tens of millions of daily observations from satellites, aircraft, weather balloons, buoys, and surface stations (Hersbach et al. 2020, 2023; Soci et al. 2024).

ERA5 performs better than ERA-Interim in simulating synoptic-scale weather systems, sea surface temperatures, cloud microphysics, precipitation-evaporation balance, and surface-atmosphere coupling. It also provides higher confidence because of its 10-member Ensemble of Data Assimilations (EDA), which gives three-hourly uncertainty statistics. These are crucial for robust trend analysis in areas with limited data or high climate sensitivity (Tarek et al. 2020). ERA5 shows lower temperature anomalies than ERA-Interim. It also captures interannual variability more accurately (Gbode et al. 2023; Gleixner et al. 2020). For long-term studies, ERA5 has been back-extended to 1940. This 2023 back-extension fixes issues from the preliminary ERA5 release (ERA5.P), such as surface pressure bias and poor tropical cyclone representation. Improvements include better assimilation of IBTrACS data and an enhanced spin-up period, which produce more reliable temperature records (Bell et al. 2021; Soci et al. 2024).

The global observing system has made significant progress since 1940 when only 17,000 assimilated observations per day were supported in ERA5 until today when this number exceeds 25 M per day (Soci et al. 2024). ERA5 depicts much better improvements over ERA-Interim (Clelland et al. 2024). ERA5 has the hourly, daily and monthly data such as the minimum, maximum and average temperature.

It enables climate analysis in detail at times and assists in identifying extreme events such as heatwaves, droughts, and excessive rains. It is broadly applicable in climate science: monitoring and validation of climate models, and in hydrological and agricultural applications. Due to its exceptional resolution, frequent re-processing, and unlimited access through Copernicus Climate Data Store, it provides a fundamental data source to international and regional climate research (Hersbach et al. 2020; Ramon et al. 2019). Compared to previous reanalysis, ERA5 is much better with its more realistic temperature and precipitation predictions, particularly after 1970 and improved coverage of the variability of climate and trends in the atmosphere, which is of great importance to extract climate information in data-scarce areas, such as arid Oman (Soci et al. 2024; Tarek et al. 2020). We used hourly ERA5 to conduct a precise assessment of temperature dynamics over the territory of Oman in this research.

2.2.2 MERRA-2

MERRA-2 is a reanalysis of the whole atmosphere that incorporates satellite and in situ measurements made by the Global Modelling and Assimilation Office (GMAO) the NASA. It is 0.5° (latitude) 0.625° (longitude). It is between 1980 and the current times. MERRA-2 has an advantage over its predecessor, as it includes the recent hyperspectral radiance and microwave data (Gelaro et al. 2017). It covers the time period between 1880 and recent times with hourly and monthly statistics at a spatial resolution of 0.5° latitude and 0.625° longitudes. Noteworthy, in the context of MERRA-2 is that the data assimilation takes place by incorporating the latest satellite data, but keeping them consistent across observing systems. The dataset also represents the better characterization of aerosols, land surface conditions, temperature and precipitation, which makes the dataset of great relevance in climate research, atmospheric studies and hydrological modelling (Bosilovich 2015). MERRA-2 provides robust reanalysis quantities of air temperature, surface fluxes, soil moisture, and radiation, used in numerous applications including the substantiation of the studies devoted to the climate variability and the extreme weather events (Reichle et al. 2017).

2.2.3 CRU

One of the most widely used global gridded climate datasets is the Climatic Research Unit Time-Series (CRU TS) dataset, developed by the Climatic Research Unit at the University of East Anglia. It provides monthly temperature data on a $0.5^\circ \times 0.5^\circ$ latitude–longitude grid over land areas. The CRU TS dataset spans nearly 120 years (from 1901 to

the near-present) and is regularly updated, making it a valuable resource for temperature analysis and impact studies. Although it does not cover data-sparse regions well, its long temporal coverage and extensive treatment of global land areas make it a key dataset for climate model validation and regional or global climate comparisons. Each station's data is quality-controlled, and an angular-distance weighting method is used to interpolate observations, ensuring consistent spatial coverage (Harris et al. 2014), the CRU TS dataset still remains an essential index to validate climate models, conduct global and regional studies on trends, as well as impacts due to its comprehensive and geographical continuous coverage. In this study, it is the latest version CRU TS4.08, that has been used.

2.2.4 NCEP/NCAR

NCEP/NCAR Reanalysis (R1) was initiated in 1948 and develops the consistent atmospheric data combining the numerical weather prediction modelling with global observational data (Kalnay et al. 2018). This reanalysis attempt was followed by NCEP/NCAR Reanalysis-2 (R2) that enhanced the assimilation scheme, thus extending the data coverage (Kanamitsu et al. 2002). These reanalyses have been widely used in climate studies and provide a valuable data source for understanding long-term climate time series and atmospheric variability. They include air temperature, wind, humidity, and pressure at multiple levels, typically with a spatial resolution of $2.5^\circ \times 2.5^\circ$ and timescales ranging from sub-daily to monthly (Kistler et al. 2001). Regardless of relative low resolution, NCEP/NCAR reanalysis is still popular to reveal climate dynamics and variability on long-term scales.

2.3 Evaluation of Data

To identify the most reliable dataset for representing temperature trends across Oman, several statistical techniques were employed to evaluate the accuracy and consistency of the available datasets. The stations used for validation are indicated in the study area map as black dots in Fig. 1. Figure 2 presents the Taylor diagrams illustrating the comparative performance of each dataset across selected stations. MERRA-2 performs well at several stations, particularly coastal locations such as Salalah and Sur, where it shows high correlation but tends to slightly underestimate standard deviation. NCEP exhibits large variability in performance across stations: it performs moderately well in some inland sites like Fahud and Thumrait but shows significant deviation in others, often underestimating variability (standard deviation < 1) and producing lower correlation values (typically between 0.6 and 0.85). CRU generally performs the

worst among the four datasets, with consistently lower correlation coefficients and standard deviations far from unity across almost all stations, indicating poor representation of observed temperature fluctuations. These discrepancies are particularly prominent at interior and high-altitude stations like Ibra and Qarn Alam, where topographic and microclimatic effects are stronger.

ERA5 is positioned closest to the reference point (black star) in nearly all diagrams, indicating high correlation (often above 0.95) and a normalized standard deviation close to 1, reflecting its ability to accurately reproduce both the phase and amplitude of observed temperature variability. Such good performance is clearly seen in weather stations such as Muscat, Sohar, Nizwa, Adam, among others, where ERA5 slightly coincides with the reference point.

Many studies tested the ERA5 dataset on the global scale and all of them report that it outperformed all other datasets (Alriah et al. 2022; Arshad et al. 2021; Hamed et al. 2021; Ma et al. 2021). Untested, ERA5 has become the most accurate dataset of representing the temperature pattern in Oman, although MERRA-2 can be decent as an alternative. Also, many authors have already verified that ERA5 is one of the best and most consistent datasets in the Arabian Peninsula (Fonseca et al. 2022; Odnoletkova and Patzek 2021). Such results demonstrate that high quality data such as ERA5 are important in providing climate data that makes accurate analysis and standards of decision making when managing the region. To the analysis that follows it is seasonal and decadal scales in the year, especially T_{avg} , T_{max} , and T_{min} temperatures. The analysis is carried out decades wise to detect long term patterns and fluctuations based on the period between 1981 and 2020.

3 Results

3.1 Long-Term and Seasonal Temperature Trends in Oman

Long-term and Seasonal temperature trends are important signs of climate change, helping us understand how the climate in a region is changing over time and these trends play a major role in understanding Oman's present and future temperature change.

Figure 3(a) illustrates a statistically significant warming trend in T_{avg} , T_{max} , and T_{min} (p -value < 0.05), as confirmed by the Mann-Kendall test, with the magnitude of change quantified using Sen's slope estimator. Across most of Oman, T_{avg} exhibits a consistent and widespread warming pattern. In Northern Oman, especially along the north-western coast and interior, the warming is more intense, reaching its peak in the far northwest. In Central Oman,

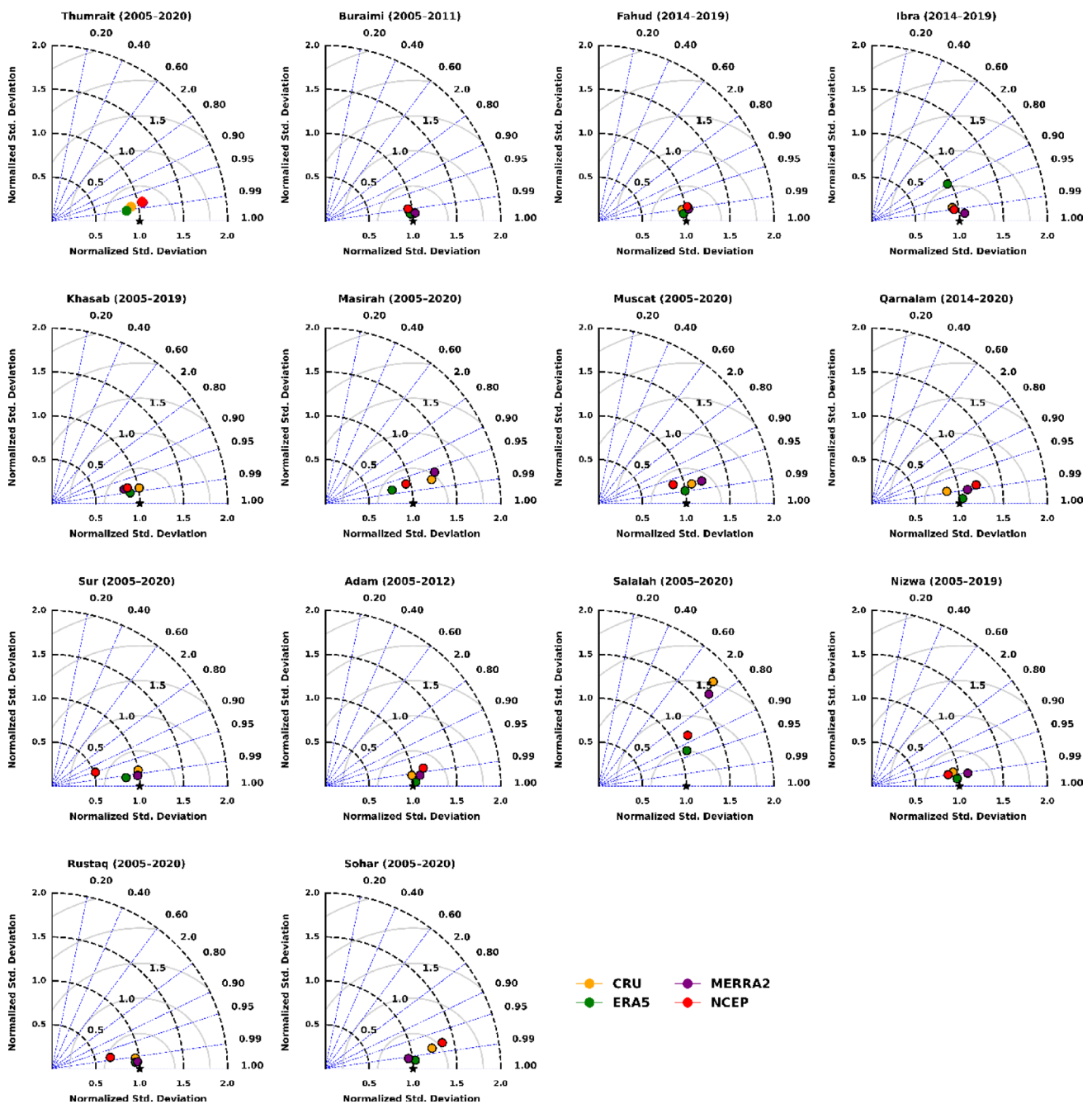


Fig. 2 Taylor diagram showing the statistical comparison of observed and reanalysis temperature data with Oman Meteorological data for different time periods at various stations

the warming is slightly lower compared to the north. In Southern Oman, the trends are more variable, with cooling observed in the coastal plain and southern highlands, while the interior desert regions show a warming pattern. These regional differences for T_{avg} are summarized in Table 1. A similar but distinct pattern is observed for T_{max} , which also shows a broadly increasing trend throughout Oman. Northern Oman shows a notable rise, particularly over the interior plains and northeastern mountainous areas. Central

Oman experiences the highest T_{max} increase in the country, especially in the central interior. In contrast, Southern Oman displays less warming trends, with lower warming in some coastal and highland areas, while the desert interior shows a moderate increase. T_{min} trends reveal greater regional variation. Northern Oman shows consistent warming, especially in the northwest. Central Oman presents a mixed pattern, with warming in the northern parts and weaker trends elsewhere. In Southern Oman, T_{min} trends are generally weaker

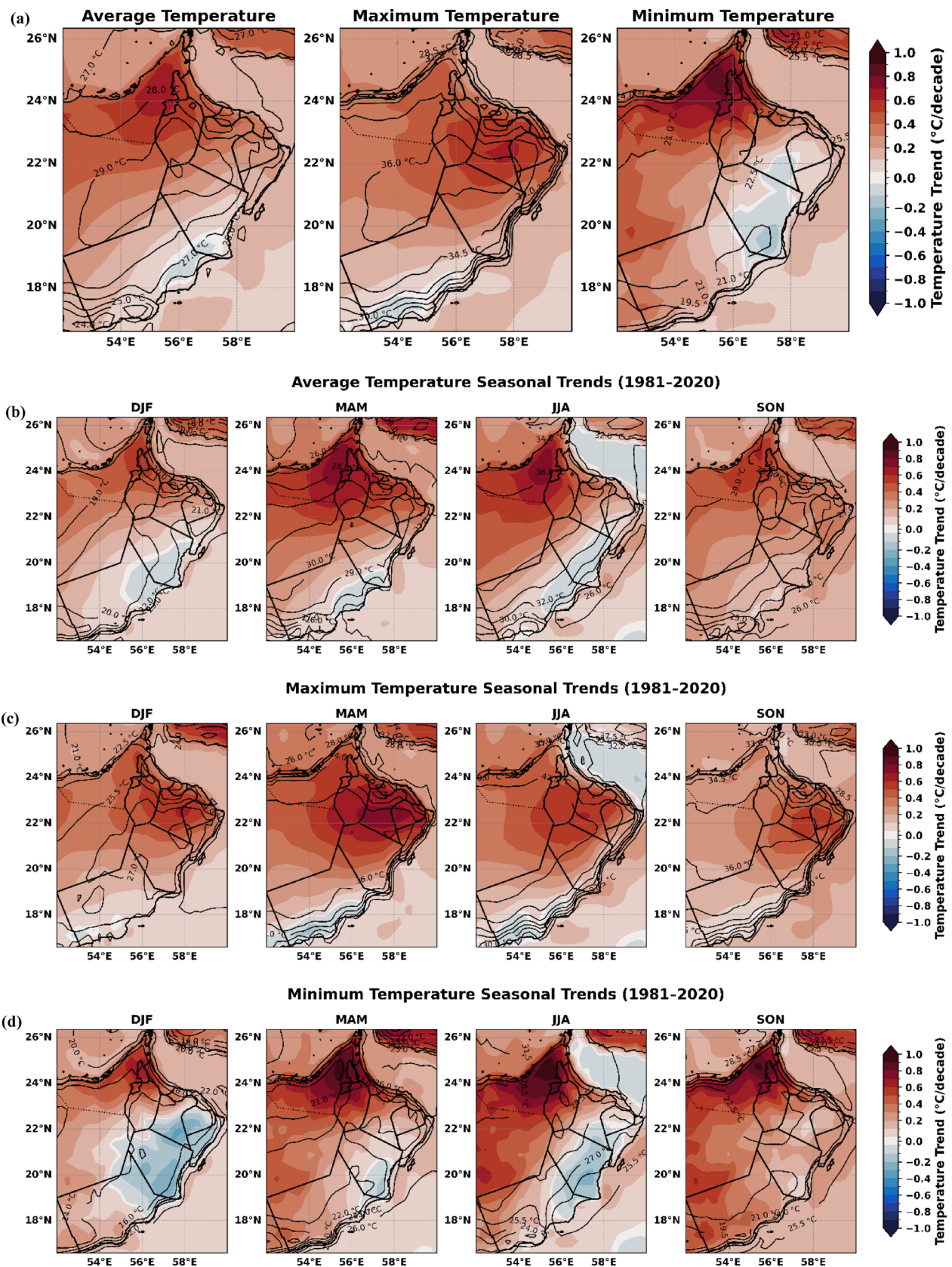


Fig. 3 Spatial distribution of temperature trends over Oman from ERA5 data (1981–2020). **(a)** Long-term trends in average (T_{avg}), maximum (T_{max}), and minimum (T_{min}) temperatures; **(b)** Seasonal trends in T_{avg} ; **(c)** Seasonal trends in T_{max} ; **(d)** Seasonal trends in T_{min}

Table 1 Results of decadal temperature trends (°C/decade) across Oman by region

Region	T_{avg}	T_{max}	T_{min}
Oman	0.23 ± 0.16	0.25 ± 0.16	0.23 ± 0.20
Northern Oman	0.32 ± 0.17	0.33 ± 0.17	0.31 ± 0.23
Central Oman	0.20 ± 0.10	0.34 ± 0.12	0.10 ± 0.12
South Oman	0.09 ± 0.06	0.10 ± 0.07	0.15 ± 0.12

and more variable. As shown in Table 1, these trends collectively highlight the stronger warming in northern and central regions compared to the south. The average for the entire country confirms a general warming trend across all three temperature variables.

These spatial signals align with site-based evidence from the high-altitude Jabal Al Akhdar region (northeastern Oman), where 1979–2012 trends show increases of 0.79 °C, 0.27 °C, and 0.15 °C per decade for T_{min} , T_{avg} , and T_{max} , respectively, with a particularly strong rise in nighttime temperatures, indicating heightened climatic sensitivity at elevation (Al-Kalbani and Coll 2015). Seasonally, upward trends in T_{min} , T_{avg} , and T_{max} over the past four decades are significant in most regions, with spring and autumn exhibiting stronger warming than summer and winter. Overall, Oman's climate has warmed substantially across all three temperature variables, consistent with regional literature for the Arabian Peninsula and surroundings (Almazroui et al. 2012; Alsarmi and Washington 2011b; Athar 2014; Donat et al. 2013; Hartmann et al. 2013; Zarenistanak et al. 2014).

During winter (DJF), North Oman experiences a consistent rise in all temperature metrics, with particularly notable increases along the northern coastal and inland regions. Central Oman also shows warming trends during this season, with T_{max} increasing moderately, while T_{min} indicates slight cooling, resulting in relatively low T_{avg} changes. In contrast, Southern Oman exhibits the weakest warming signals, especially in T_{min} and T_{avg} , which can be attributed to localized nocturnal cooling and terrain-driven variability. February records the strongest daytime and average warming, particularly in northern Oman trends are consistent with station-based analyses over Oman and the wider Peninsula (Al-Kalbani and Coll 2015; Alghamdi 2023; Alsarmi and Washington 2011a). As winter transitions to spring (MAM), warming becomes widespread and more intense. North Oman leads this seasonal change with robust increases across T_{avg} , T_{max} , and T_{min} , especially in the inland areas. Central Oman also records significant warming, particularly in T_{max} , while T_{min} shows milder increases. In South Oman, warming trends are weaker but still observable across all three variables. April shows the highest overall rise across the country, while May records the steepest nighttime warming, especially in northern Oman trend align with spring, summer transition reported in regional monthly trend studies (Alghamdi 2023; Alsarmi and Washington

2011a). Spring warming is likely driven by intensified solar radiation, lower cloud cover, and early seasonal transitions, particularly across elevated interior regions.

In summer (JJA), the warming patterns continue with a stronger regional contrast. North Oman displays marked increases in T_{max} and T_{avg} , particularly over elevated and interior locations, while T_{min} shows more spatial variability. Central Oman mirrors this trend, with T_{max} showing considerable increases and both T_{avg} and T_{min} following suit. In the south, however, the presence of the Khareef (monsoon) suppresses warming especially in T_{min} leading to subdued changes in both T_{avg} and T_{max} . This reflects the effect of cloud cover and monsoon-driven microclimates in tempering summer heat in the southern coastal zone. June shows the strongest daytime and average warming, while July nights warm the fastest in northern Oman aligning with evidence that summer T_{min} rises are prominent across the northern/continental sector of the Peninsula (Alghamdi 2023). Autumn (SON) marks a return to consistent warming across the country. North Oman shows continued increases in all variables, with T_{min} rising the most prominently in some areas. Central Oman maintains significant warming across T_{avg} , T_{max} , and T_{min} , with trends remaining steady from earlier seasons. South Oman, while still the least affected, experiences more notable warming in T_{min} than in the other two variables, likely due to residual monsoon humidity delaying nighttime cooling. September records the peak average and daytime warming in northern and central Oman, while October shows the strongest nighttime warming in northern and southern regions. In autumn, September displays peak T_{avg} and T_{max} warming across northern and central Oman, and October shows the highest T_{min} increases, particularly in the north and south, consistent with documented autumnal amplification and extended warm-season conditions in the region (Alghamdi 2023; Alsarmi and Washington 2011a). Collectively, Fig. 3; Table 2 highlight that northern Oman warms fastest in T_{avg} and T_{max} , while the south shows milder trends but notable October–November nighttime increases. In parallel, extreme heat events (hot days/nights) are becoming more frequent especially in central and northern Oman in line with Peninsula-wide increases in warm-day and tropical-night counts and the Eastern Mediterranean–Middle East hotspot diagnosis (Alghamdi 2022; Zittis et al. 2022a, b).

3.2 Decadal Variability in Surface Air Temperature

A study of Oman's ERA5 temperature climatology from 1981 to 2020, a robust and reliable dataset, shows decadal temperature variations in T_{avg} , T_{max} , and T_{min} . Figure 4 (a) illustrates the decadal changes in T_{avg} across Oman from 1981 to 2020, highlighting temperature variability

Table 2 Results of decadal seasonal temperature trends (°C/decade) across Oman by region

Seasons	Temp.	Entire Oman	North Oman	Central Oman	South Oman
DJF	T_{avg}	0.18±0.14	0.29±0.13	0.09±0.08	0.07±0.07
	T_{max}	0.24±0.16	0.36±0.16	0.29±0.11	0.09±0.06
	T_{min}	0.13±0.18	0.22±0.20	-0.07±0.12	0.09±0.12
MAM	T_{avg}	0.28±0.20	0.44±0.19	0.25±0.12	0.10±0.10
	T_{max}	0.31±0.21	0.45±0.19	0.43±0.17	0.09±0.11
	T_{min}	0.28±0.22	0.41±0.24	0.14±0.11	0.18±0.15
JJA	T_{avg}	0.23±0.22	0.24±0.26	0.18±0.16	0.10±0.10
	T_{max}	0.23±0.19	0.23±0.25	0.35±0.13	0.09±0.09
	T_{min}	0.24±0.27	0.26±0.31	0.11±0.20	0.14±0.17
SON	T_{avg}	0.27±0.12	0.33±0.14	0.27±0.054	0.19±0.06
	T_{max}	0.24±0.11	0.30±0.12	0.35±0.09	0.13±0.06
	T_{min}	0.32±0.18	0.35±0.22	0.24±0.07	0.31±0.14

throughout the country. During the 1981–1990 period, temperatures were relatively moderate, with the warmest areas located in the north western interior part of the country where values approached 28.5 °C. Central Oman experienced T_{avg} between 26.0 °C and 27.5 °C. In South Oman, particularly the southern highlands and coastal areas, temperatures ranged from 23.0 °C to 25.5 °C, likely influenced by higher elevations and oceanic proximity. In the following decade 1991–2000, warming became more evident, particularly in the north western part of Central Oman, where temperatures exceeded 29.0 °C in some areas. Central Oman experienced a broader and more uniform warming, with temperatures rising between 27.5 °C and 28.5 °C while inland parts of North Oman warmed slightly, and the northern coastal belt remained relatively unchanged. South Oman showed minor warming in the interior desert areas, although the highlands and coastal fringe maintained cooler conditions around 23.5 °C to 25.5 °C. Between 2001 and 2010, warming became more pronounced in all regions. North Oman, especially the northwest, saw inland temperatures exceed 29.5 °C, with coastal areas warming to 27.5–28.0 °C. Central Oman showed stronger warming with a large zone exceeding 28.5 °C, and the previously identified hot spot expanded into more central areas. In South Oman, especially the desert interior, T_{avg} increased significantly to around 27.0 °C, although the southern mountainous and coastal regions remained relatively cooler, with visible warming compared to previous decades. This accelerated warming in Oman is consistent with observed trends across the Arabian Peninsula, which has been identified as a regional hotspot for climate change (Zittis et al. 2022a, b). Recent studies have documented similar decadal increases in both mean and extreme temperatures in neighboring countries.

The period from 2011 to 2020 recorded the highest T_{avg} across the entire study period. In North Oman, particularly the northwest and foothill zones, temperatures exceeded 30.0°C, indicating a sharp intensification of heat. Central

Oman experienced widespread warming, with large areas reaching between 28.5°C and 30.0°C, making it the warmest region overall. The hot zone in the north western part of the Rub' al Khali desert further expanded southward and eastward. Even South Oman, including traditionally cooler highlands and coastal zones, experienced noticeable warming, with interior regions surpassing 27.5 °C and elevated areas reaching above 26.0 °C. Altogether, the warming trend became increasingly widespread and intense over time, affecting all regions and highlighting the influence of both geographic features and long-term climate change across Oman.

The spreading pattern of T_{max} warming over Oman is illustrated in Fig. 4(b), presents the decadal variation in T_{max} highlighting a clear and progressive warming trend, particularly in the interior and desert regions. During the first decade (1981–1990), T_{max} was highest in the central and north western interior parts of Oman, including the northern edge of the Rub' al Khali desert, where values reached around 34.0 °C. Central Oman recorded T_{max} between 32.0 °C and 33.5 °C, while North Oman, especially the coastal areas, remained in a range from 29.0 °C to 31.0 °C. South Oman, particularly the southern highlands and coastal areas, experienced the lowest T_{max} , mostly ranging between 26.0 °C and 29.0 °C due to elevation and oceanic influence. In the 1991–2000 decade, warming became more widespread and intensified in the interior with much of Central and North Oman recording T_{max} above 33.5 °C. The hot zone in the northwest expanded slightly, and the coastal north remained relatively stable below 31.0 °C. In South Oman, T_{max} increased modestly in interior desert areas, while highland and coastal regions remained within range of 26.0 °C to 28.5 °C. Between 2001 and 2010 the warming trend accelerated across all regions. In Central Oman and the north western interior, temperatures reached and exceeded 35.0 °C while broader areas of North Oman warmed above 32.0 °C. The warming extended eastward and southward into areas that were previously less affected. South Oman,

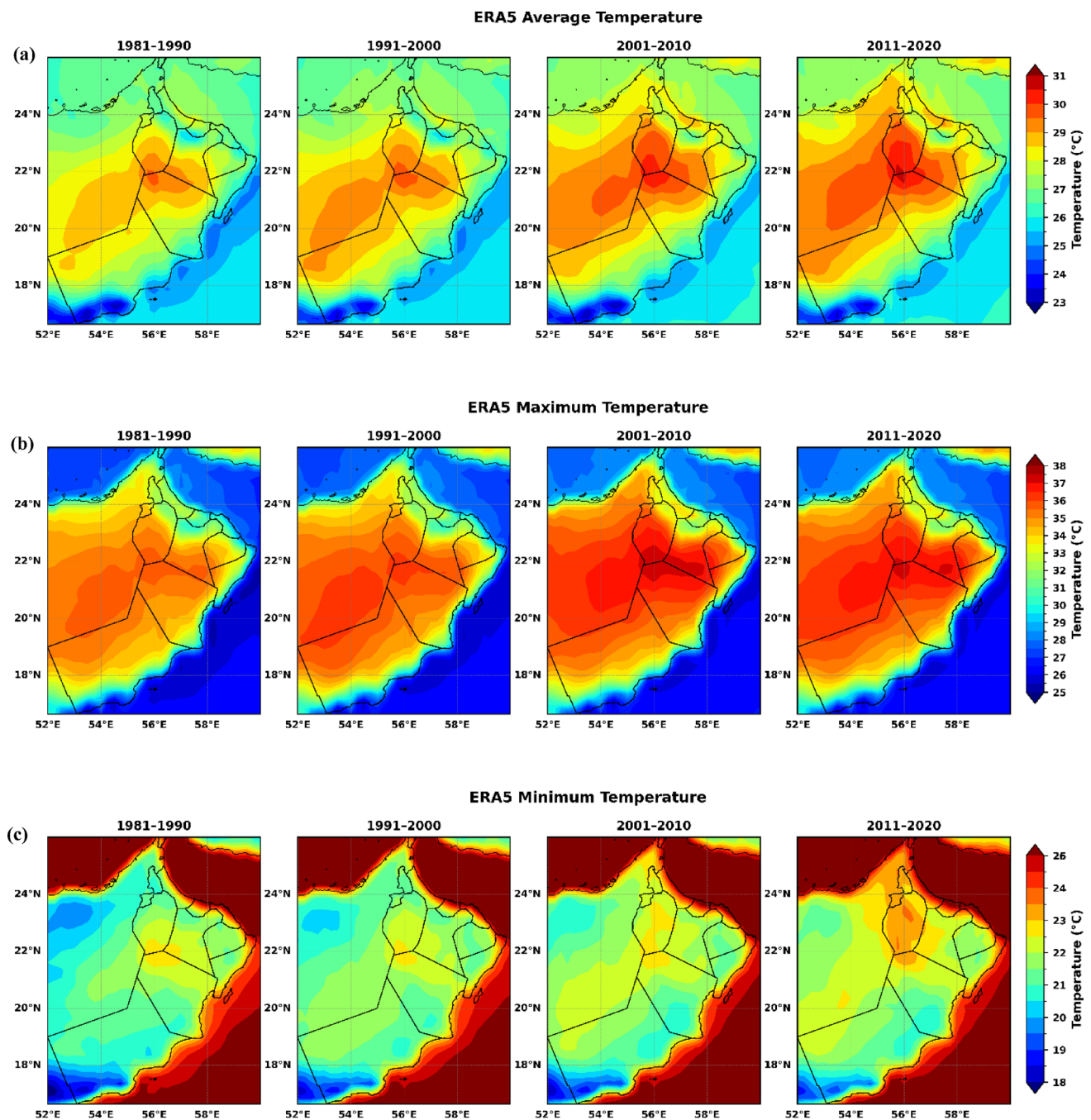


Fig. 4 Spatial distribution of ERA5 reanalysis temperature data, showing (a) T_{avg} , (b) T_{max} , and (c) T_{min} from 1981 to 2020

including desert interiors, showed noticeable increases with temperatures ranging from 29.0 °C to 31.5 °C, while southern highlands remained relatively cooler but still showed an upward shift compared to earlier decades.

The period from 2011 to 2020 marks the most pronounced warming with T_{max} across much of Central and North Oman exceeding 35.0 °C and peaking around 36.0 °C in localized hotspots within the northwest. Even traditionally cooler northern coastal zones warmed up to above

32.0 °C. In South Oman, inland deserts warmed further, reaching 31.5 °C to 33.0 °C, while southern highland and coastal areas also recorded an increase, with temperatures rising above 28.0 °C. Overall, the spatial expansion of high T_{max} zones across Oman is evident, with interior regions warming faster and more significantly than coastal or high-altitude areas, reflecting the increasing intensity of daytime heat likely driven by long-term climate change and regional atmospheric dynamics.

Figure 4 (c) displays the decadal evolution of T_{\min} , revealing a gradual but consistent increase in night time temperatures over time. In the early decade 1981–1990, the lowest T_{\min} were observed in the southern highlands and south western interior, with values dropping below 19.0°C in some areas. Central Oman experienced moderate T_{\min} ranging from 21.0°C to 22.5°C, while the north western interior, including parts of the northern Rub' al Khali desert, showed slightly higher values near 23.0 °C. Along the coasts, especially in North Oman and the south eastern shores T_{\min} were relatively high, reaching up to 24.5 °C due to maritime influence. In the 1991–2000 decade, temperatures increased slightly across most of the interior, particularly in Central and North Oman where values became more uniformly distributed around 22.0 °C to 23.5 °C. The coastal zones remained warm, while cooler zones in the southern mountainous areas continued to register lower temperatures below 20.0 °C.

From 2001 to 2010 warming trends intensified further. T_{\min} across the northern interior rose above 23.0 °C, while Central Oman saw a broader region warming to between 22.0 °C and 23.0 °C. Although southern Oman exhibited lower temperatures compared to other regions, most of the interior deserts warmed above 21.0 °C, with only the high elevation south western corner maintaining values close to or slightly below 20.0 °C. The most significant change is evident in the 2011–2020 period, where T_{\min} rose further across nearly the entire country. In North Oman, the north western areas saw minimum values exceeding 24.0 °C indicating warmer nights. Central Oman experienced a widespread shift to 23.0 to 24.0 °C particularly in inland and lower elevation zones. South Oman also warmed notably, with most of the region exceeding 21.5 °C and many areas approaching 23.0 °C, except for the extreme south western highlands where values remained slightly lower. Overall, these changes highlight a consistent upward shift in night time temperatures across Oman.

The pronounced warming observed in the most recent decade, particularly in the interior regions, aligns with findings from Saudi Arabia, where the rate of warming has significantly accelerated post-1990 (Almazroui 2020). The consistent rise in temperatures is particularly critical for human health and ecosystem stress (Alahmad et al. 2022). The widespread nature of this warming suggests a dominant role for large-scale atmospheric changes superimposed on local feedback mechanisms.

3.3 Variation in Extreme Temperature Threshold

Temperature trend over Oman shows warming in the whole country but with different rates of rise in different parts. Threshold indices are used to denote the number of days

on which a value of temperature is above a certain threshold for T_{avg} , T_{max} and T_{min} temperatures. Regulation of local temperature thresholds is necessary to create proper early warning systems for heatwaves in order to prevent heat related disease and death (Hamed et al. 2024; Lelieveld et al. 2016). In the Middle East, the relationship between heat indices and physiological stress responses such as core body temperature, cardiovascular strain, and hydration levels differs from those in temperate regions due to extreme arid conditions, high solar radiation, and socio cultural factors such as outdoor occupational exposure and traditional clothing (Al-Wathinani et al. 2023; Epstein and Moran 2006). Further, climatic conditions are also important in attracting tourists to particular locations (Zare et al. 2018). This study on Oman is critically important, as it delivers localized insights into extreme temperatures (95th percentile) and establishes region-specific thresholds. These findings can inform targeted heat health adaptation strategies and early warning systems, tailored to Oman's unique climatic and demographic conditions.

Figure 5(a) shows that the number of very hot days, defined as days with average temperature (T_{avg}) above 36 °C, has increased decade by decade. During the 1981–1990 period, very few regions in Oman experienced days where the average temperature rose above 36 °C. In the northern part of the country, especially along the coastal and mountainous areas, almost no days were recorded above this threshold. In Central Oman, a few locations experienced less than 20 days per year with T_{avg} greater than 36 °C. The southern regions of Oman, including Dhofar, remained largely unaffected during this time, with virtually no days exceeding 36 °C. In the 1991–2000 decade, a slight increase in the number of hot days was observed compared to the 1980s. Central Oman began to record around 20 to 40 days annually with T_{avg} surpassing 36 °C. However, the northern regions of Oman still showed only minor changes, continuing to experience very few hot days. Southern Oman maintained its pattern of low frequencies, with only negligible increases in the number of days over 36 °C. The situation changed more noticeably in the 2001–2010 period. There was a considerable rise in the frequency of extremely hot days. Central Oman experienced between 40 and 80 days per year with T_{avg} exceeding 36 °C. Northern Oman, especially in some inland areas, started to observe 20 to 40 days annually above the 36 °C threshold. While the southern regions still showed relatively low numbers, the northern parts of Dhofar began to see some increase, signaling a gradual warming trend. In the most recent decade, 2011–2020, a significant escalation was evident. Central Oman recorded between 100 and over 110 days annually with T_{avg} greater than 36 °C. The inland areas of Northern Oman also witnessed a sharp rise, reaching 80 to 100 days per year. Even in Southern Oman, where

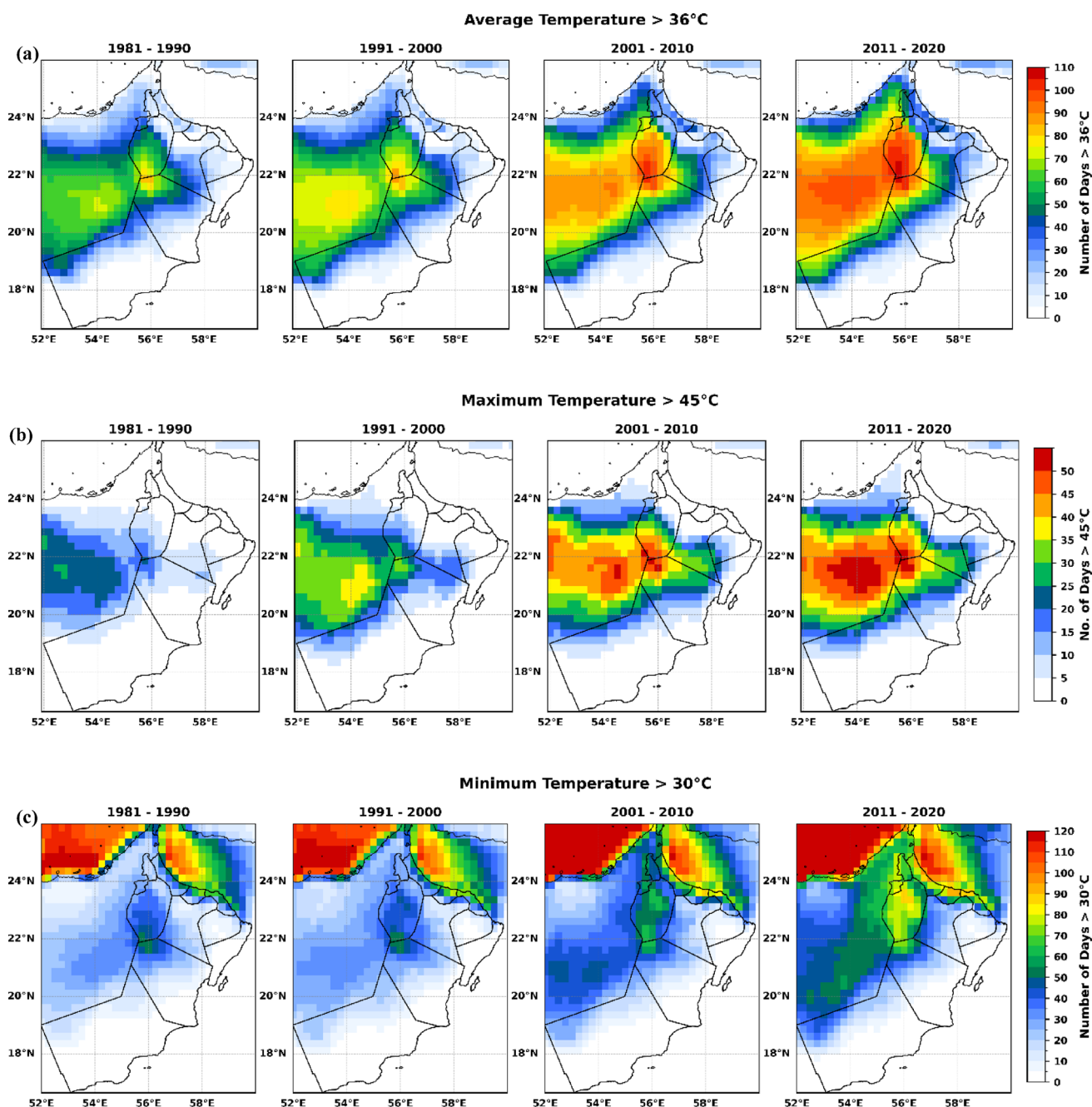


Fig. 5 Annual exceedance of 95th Percentile temperature thresholds in Oman (1981–2020), (a) 36 °C, (b) 45 °C, (c) 30 °C, based on ERA5 daily T_{avg} , T_{max} , and T_{min} data

such events were previously rare, the northern sections began experiencing 30 to 40 hot days annually. Overall, the data reflect a clear intensification of extremely hot days over Oman from the 1980s through 2020, with the most dramatic increases occurring during the last two decades. This trend highlights the increasing intensity and geographic spread of extreme heat throughout the country.

Figure 5(b) illustrates the increasing trend in the annual number of days with T_{max} exceeding 45 °C, across Oman

from 1981 to 2020. During the initial period of 1981–1990, such extreme heat events were rare, with most of Oman, including the North and South, experiencing very few or no days surpassing this threshold. The following decade, 1991–2000, saw a slight increase, particularly in the interior deserts of Central Oman, where isolated spots began to record up to 10 days per year above 45 °C, while Northern and Southern Oman remained largely unaffected. Moving into the period of 2001–2010, Central Oman experienced a

noticeable rise, with regions recording 10 to 30 days annually of T_{\max} exceeding 45 °C. Northern Oman also began to show small inland pockets with days above this extreme, though still fewer than 10 annually. The most recent decade, 2011–2020, witnessed a dramatic surge in the frequency of these extreme T_{\max} . Central Oman recorded 30 to 50 days annually with T_{\max} above 45 °C, with some areas exceeding 50 days. Northern Oman also showed a significant increase, reaching 10 to 30 days in certain regions. While Southern Oman remained comparatively cooler, its northern edges started to experience rare occurrences of extreme heat. This trend clearly points toward a marked and alarming intensification of extreme maximum temperatures across Oman over the observed period.

The most worrying trend is the rise in very warm nights, where T_{\min} stays above 30 °C as shown (Fig. 5c). These nights make it hard for people and animals to cool down, which can be dangerous for their health. In the 1980s, North Oman's coastal areas already had 100 to 120 warm nights a year. Over time, these nights spread further inland. By 2011 to 2020, most of the northern part of the country had more than 130 such nights a year. In Central Oman, warm nights increased from 20 to 30 days in the 1980s to 90 to 110 by the last decade. That's more than three times higher. South Oman also saw an increase, with warm nights rising to 30 to 50 days in the northern areas by 2020. This shows that cooler nights are becoming less common everywhere. It is estimated that the warmer weather will also have a significant impact on the occurrence of warm nights.

Overall, all parts of Oman are facing more frequent and intense heat, but the patterns vary. Central Oman is now the hottest both during the day and at night. North Oman is especially affected by warm nights. South Oman is still cooler but also showing signs of warming. The last 20 years have seen the fastest rise in temperatures.

The spatio-temporal rise in temperature demonstrates that extreme heat is becoming more widespread and frequent, intensifying the challenges posed by climate change. Potential impacts include adverse effects on public health, increased energy demand for cooling, reduced agricultural crop yields, and heightened ecosystem stress. The decline in cool nights exacerbates these risks. These findings underscore the critical importance of implementing proactive adaptation strategies to safeguard population health, natural resources, and economic infrastructure.

Rising temperatures in Oman have cascading impacts across critical sectors. Agriculture is particularly vulnerable: water scarcity, recurrent drought, and desertification have already reduced cereal yields by 5–10% over the past decade, with projections of 15–30% declines by 2080 under high-emission scenarios (Bank 2023a; FAO 2022). Vegetable crops such as tomatoes, potatoes, onions, and cabbage

staples of nutrition and rural livelihoods are highly sensitive to both heat and drought stress (Scheelbeek et al. 2020; Zhang et al. 2018).

Public health outcomes are also tightly coupled with temperature thresholds. Increasing frequencies of extreme heat days and warm nights elevate morbidity and mortality risks, straining healthcare infrastructure (Canton 2021; Weinhhammer et al. 2021). In the Eastern Mediterranean and Middle East, these risks are intensified by rapid population growth, urbanization, and displacement, amplifying exposure to heat stress (Al-Delaimy 2020; Watts et al. 2021). In Oman, rising T_{\min} and T_{\max} are already linked to greater incidences of heat-related illnesses and additional pressure on water resources (Bank 2024).

Energy demand represents a further dimension of vulnerability. Cooling requirements are escalating with urbanization and industrialization, driving higher electricity consumption across MENA (Change 2023). Elevated ambient temperatures reduce power plant efficiency, increase grid stress, and aggravate the water energy tradeoffs in countries like Oman that rely heavily on desalination. By 2050, warming of 1.5–3 °C is projected to significantly increase peak load demand and grid instability risks, magnifying competition for scarce resources (Qasem and Scholz 2025).

These interactions demonstrate how threshold exceedances propagate through the water–energy, food and health. Integrating sectoral perspectives into climate assessments strengthens the applied value of temperature trend analyses and provides a foundation for targeted adaptation strategies in Oman and the broader MENA region.

3.4 Regional Temperature Anomalies

Regional analysis of temperature anomalies across Oman is essential for understanding the spatial and regional dynamics of climate change in this climatically sensitive region. All three regions exhibit increasing trends in T_{\max} , T_{\min} , and T_{avg} temperature, though the intensity, consistency, and timing of warming differ. North Oman shows the most pronounced and consistent warming trend across all temperature anomalies. During the 1980s and early 1990s, anomalies were predominantly negative, indicating cooler than average conditions. However, a strong and steady shift toward positive anomalies began in the late 1990s. Both T_{\max} and T_{\min} increased sharply during the 2000s, with T_{\max} anomalies peaking in the 2010s, frequently exceeding +1.0 °C. T_{\min} anomalies also followed a strong upward trend, signaling reduced night time cooling and increased heat stress. The 5-year moving average confirms this persistent and accelerating warming, particularly over the last two decades. T_{avg} anomalies largely mirrored T_{\max} patterns, suggesting that daytime heating dominates the region's

warming. The consistency and magnitude of warming in North Oman indicate the most rapid temperature changes among the three regions.

The warming trend in Central Oman is evident but progresses more gradually, with greater year to year variability than in the north. Anomalies in the 1980s and 1990s were generally negative or near neutral, particularly for T_{\min} and T_{avg} . From the early 2000s, T_{max} anomalies became steadily positive, reflecting a long-term shift toward hotter days. T_{\min} anomalies showed a more modest rise, with occasional dips throughout the 2000s and 2010s. Despite fluctuations, the 5-year moving averages reveal a persistent upward trend for both T_{max} and T_{\min} . T_{avg} anomalies reflect this warming trajectory, though the rate remains moderate compared to North Oman. Overall, Central Oman exhibits stable warming, particularly in daytime temperatures, with signs of increasingly warmer nights in recent years.

In contrast, South Oman displays the most variable temperature anomaly patterns among the three regions. The 1980s and early 1990s were characterized by predominantly negative anomalies across all indices. A warming shift emerged in the late 1990s, particularly for T_{\min} . However, T_{max} anomalies remained inconsistent throughout the 2000s and 2010s, alternating between positive and negative values suggesting less uniform daytime warming. T_{\min} anomalies showed a steadier increase, especially after 2010, indicating a gradual rise in night time temperatures. T_{avg} anomalies followed a similar trend, with an overall warming signal but notable interannual variability. The inconsistent T_{max} pattern may result from seasonal climatic influences that moderate extreme daytime heating, though the long term trend remains upward.

The results underscore that North Oman is experiencing the most rapid and intense warming, particularly in daytime temperatures. Central Oman follows with a steadier but less dramatic trend, while South Oman shows a more delayed and variable response, with greater fluctuations over time. Across all regions, rising T_{\min} anomalies highlight growing concerns about night time heat, which has implications for human health and ecological resilience. While the entire country is warming, the rate, consistency, and seasonal dynamics differ significantly by region. A key driver of Oman's warming trend is the El Niño-Southern Oscillation (ENSO). During El Niño events marked by elevated Pacific Sea surface temperatures Oman typically experiences warmer and drier conditions, intensifying heat extremes. Notable peaks in T_{max} and T_{avg} anomalies, especially in Northern Oman (Fig. 6), align with strong El Niño periods such as 1997–98, 2015–16, and 2019–20. While Central and Southern Oman also exhibit warming during these events, the south displays greater variability, likely due to monsoon influences. Even though La Niña sometimes brings short

periods of cooling, the overall trend in Oman is still clear warming. This shows anthropogenic climate change could be the dominant force behind rising temperatures in Oman. Overall, the data confirms that Northern Oman has experienced the strongest warming, followed by Central Oman, whereas Southern Oman shows more fluctuation but still an upward trend. T_{max} anomalies are most intense in the north, while T_{\min} anomalies show that night time warming is becoming a significant concern across all regions. The variations in temperature over the period 1981–2020 exhibit significant regional differences across Oman, reflecting the diverse geographical and climatic characteristics that influence temperature trends in each area.

The decrease of the traditional relationship between ENSO and the Indian monsoon over the last few decades may have occurred as a result of Eurasian warming and changes in the Walker circulation (Dogar et al. 2024; Dogar, Kucharski et al. 2017; Dogar, Stenchikov, Dogar et al. 2017a, b; Dogar and Almazroui 2022; Kumar et al. 1999, 2025). These changes may also affect the regional outcomes of ENSO all over the Arabian Peninsula, which covers Oman. El Niño events might have triggered the rise in temperature in 2002, 2003, 2009, and 2010 (Santoso et al. 2017). The National Oceanic and Atmospheric Administration (NOAA) reports that El Niño in 2015/2016 was the warmest year on record (Jacox et al. 2016). The warming was mainly noticeable after 2000, particularly from 2010 to 2020. Urbanization, especially in Northern Oman, and other geographical factors are associated with this tendency. In general, the north of the country has seen higher warming than the center and southern regions. Additionally, studies show that the relationship between ENSO and regional climate is evolving.

4 Comparison of Temperature Trends in Oman with Global and Regional Patterns.

The warming trend observed in Oman over the past four decades' contrasts with broader global climate change patterns, yet the rate of increase is particularly higher than the global average. The analysis of Oman's temperature records over the past four decades reveals a clear warming signal across maximum (T_{max}), average (T_{avg}), and minimum (T_{\min}) temperatures have risen by 0.23 ± 0.16 , 0.25 ± 0.16 , and 0.23 ± 0.20 °C per decade, respectively, confirming a warming trend across all metrics. Figure 7 illustrates these long-term changes, expressed per decade, and provides context by comparing Oman's trends with those of the global mean and the Arabian Peninsula.

When compared to global climate trends, Oman's rates are consistently higher. According to (IPCC 2021), Earth's

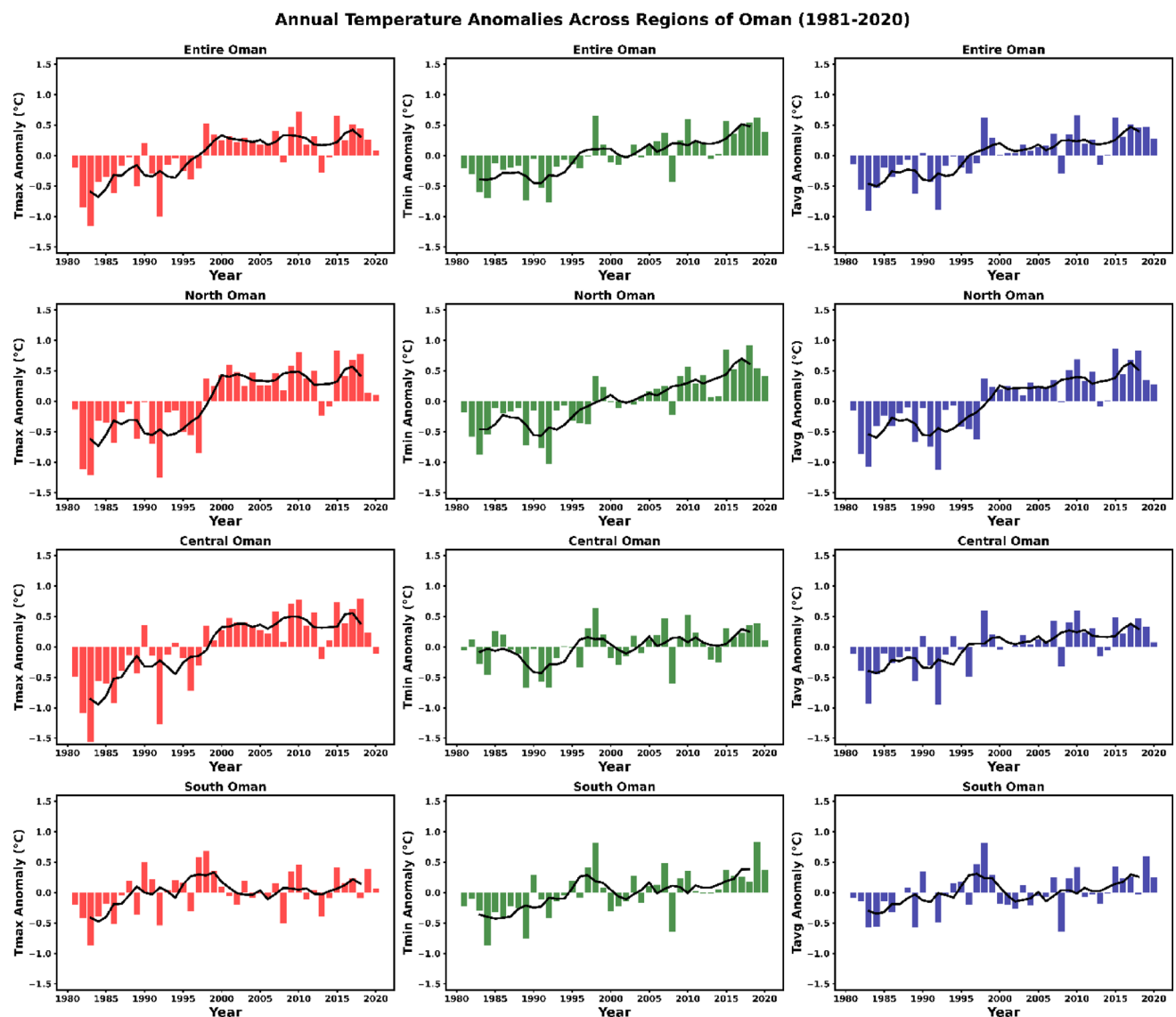


Fig. 6 Temperature anomalies (5-year moving average) over homogeneous regions for 1981–2020, relative to the 1981–2020 ERA5 baseline

mean surface temperature has increased by approximately 1.1 °C since the late 19th century, equivalent to 0.2 °C per decade between 1979 and 2021, driven primarily by anthropogenic greenhouse gas emissions. Globally, nighttime temperatures (T_{\min}) are rising the fastest, at about 0.22 °C per decade, followed by T_{avg} at 0.20 °C and T_{max} at 0.19 °C. This pattern, where nights warm faster than days, has been widely attributed to urbanization, land-use change, and atmospheric moisture feedbacks (Watson & team 2001; Wmo 2020; Yue and Hashino 2003). Oman follows this characteristic global signal but exhibits larger magnitudes. For example, Central Oman during spring (MAM) warms 1.63 times faster than the global T_{avg} rate, while North Oman in spring shows T_{max} increases 2.37 times faster than the global baseline, particularly during

spring and for daytime extremes, with clear implications for heat risk and sectoral adaptation.

However, when Oman's rates are placed against the Arabian Peninsula, the picture shifts. The Arabian Peninsula as a whole show higher warming trends, with T_{max} , T_{avg} , and T_{min} rising by 0.38 °C, 0.39 °C, and 0.41 °C per decade, respectively, confirming the region as one of the global climate hotspots. For example, Saudi Arabia alone recorded increases of 0.6 °C per decade for T_{max} and 0.64 °C for T_{min} between 1978 and 2019 (Almazroui 2020), while other Gulf countries, including the UAE, Kuwait, Iran, and Iraq, also report rates of 0.4–0.7 °C per decade (Alsarmi and Washington 2011b; Nasrallah and Balling Jr 1993; Rahimzadeh et al. 2009). The analysis of the 41-year record (1979–2019) reveals a statistically significant warming trend across the Arabian Gulf. The observed warming rates range from 0.1

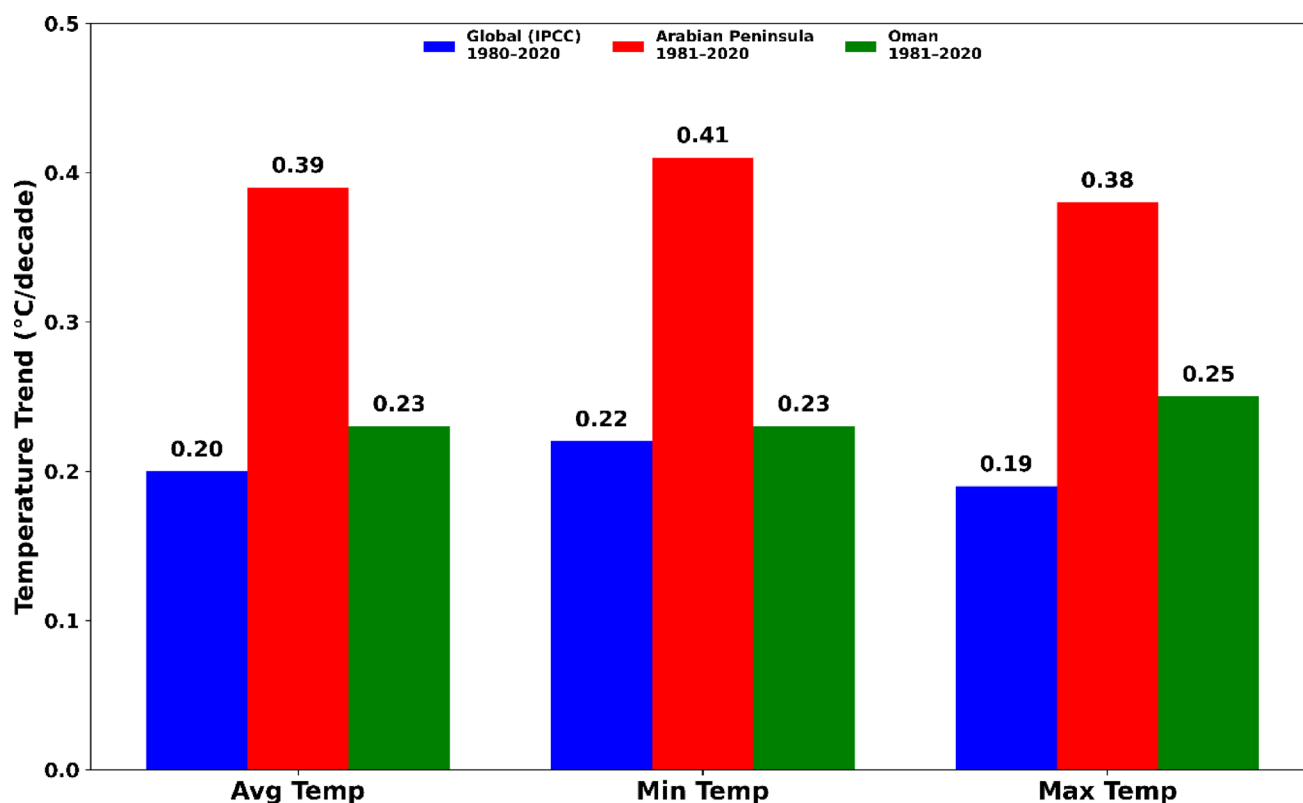


Fig. 7 Observed temperature trends °C/decade for Global (IPCC, 1979–2021), Arabian Peninsula, and Oman different regions and seasons (1981–2020) across T_{avg} , T_{min} and T_{max} temperatures

to 0.6 °C per decade, with the most pronounced increase located in the Northern Gulf (Al Senafi et al. 2024). Against this regional benchmark, Oman’s warming is relatively weaker. In comparison, the Middle East and North Africa (MENA) region has experienced even more rapid warming, with regional temperature increases ranging from 0.36 °C to 0.45 °C dec⁻¹ (Hadjinicolaou et al. 2023). T_{min} increases in particular are slower, with North Oman during spring showing only 0.24 times the Arabian Peninsula average, and South Oman during winter registering just 0.18 times the regional rate.

The spatial and seasonal differences across Oman are also evident. The strongest warming is concentrated in northern and central regions, especially in spring, while southern Oman displays more moderate increases across all metrics. The mean air temperature at the University of Buraimi, located in Al Buraimi Governorate in Northwest Oman, has been increasing at a rate of about 0.039 °C per year (≈ 0.39 °C per decade) during the period 1981–2019 (Marzouk 2021). This indicates a clear long-term warming trend in the research area. Urban areas such as Sur, Sohar, and Dubai stand out, where T_{min} has risen at more than 1.0 °C per decade, reflecting the influence of enhanced urban heat island effects (Alsarmi and Washington 2011b; Jaber et al. 2023). These findings emphasize the significant

role of coastal environments, topography, and land-use change in shaping local temperature patterns.

This additional warming can be attributed to an arid climate regime, sharp rise in anthropogenic activities as well as regional climate feedback. The trends of Oman are at a lower level when compared to the regional average, but it is higher when compared to global rates indicating a balanced diurnal warming. The narrow range of trends of T_{max} and T_{min} in Oman indicates the mitigated regional effect of topography and the cooling by the coast. Additionally, inter-annual variability linked to ENSO events (e.g., in 1998, 2016, and 2020) has contributed to short-term temperature spikes in Oman (NOAA 2021), although the long-term warming trend remains primarily anthropogenic, amounting to a cumulative rise of 1.8 °C to 2.1 °C over the past 40 years (IPCC 2021). Extreme heat events are strongly attributed to human influence (Christidis et al. 2023; Lelieveld et al. 2016), while aerosols add to this effect, with Oman showing regime shifts and radiative impacts (Dayanandan et al. 2022, 2025). Overall, greenhouse gases and aerosols together intensify warming and extremes, leaving a clear anthropogenic signal on Oman’s climate in line with regional patterns.

5 Conclusion

This study presents a comprehensive analysis of four decades (1981–2020) of surface warming over Oman, utilizing high-resolution ERA5 reanalysis data validated against ground observations. Oman is warming significantly, with national trends of 0.23 °C, 0.25 °C, and 0.23 °C per decade for Tavg, Tmax, and Tmin, respectively. This rate is 1.2–2.3 times faster than the global average but slightly slower than the broader Arabian Peninsula. Warming is spatially heterogeneous. Northern Oman exhibits the most rapid and consistent warming, Central Oman shows strong daytime heating and the highest frequency of extreme heat days, while Southern Oman has weaker and more variable trends. A pronounced acceleration in warming is observed post-2000, with the decade 2011–2020 being the warmest on record. The frequency of extreme heat events has more than tripled in some regions, with Central Oman now experiencing over 110 days annually with Tavg > 36 °C. Seasonal analysis reveals spring (MAM) and autumn (SON) as the fastest-warming seasons, with northern regions warming most intensely during these periods.

These findings underscore Oman's status as a vulnerable climate hotspot. The accelerating and uneven nature of warming necessitates region-specific adaptation policies. Priority actions should include: Implementing advanced heat-health warning systems tailored to local temperature thresholds, especially for urban and northern regions. Developing integrated resource management plans to address escalating water scarcity and energy demand for cooling, particularly in central and inland areas. Promoting climate-resilient crops and water-efficient irrigation to safeguard food security against heat and drought stress.

This study provides a robust foundation for further work, including downscaled climate projections for Oman, detailed attribution studies to quantify the roles of anthropogenic forcing versus natural variability (e.g., ENSO, NAO, volcanism), and sector-specific impact assessments linking the trends identified here to outcomes in hydrology, ecology, and human health. Under the leadership of His Majesty Sultan Haitham bin Tarik, Oman is advancing clean energy and sustainability efforts to address climate change. Committed to net-zero emissions by 2050 under Oman Vision 2040, the country is taking critical steps to build a climate-resilient future.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s41748-025-00874-x>.

Acknowledgements The authors sincerely thank the University of Nizwa administration for their continued support and encouragement. They also express gratitude to the Natural and Medical Sciences Research Centre, University of Nizwa, for providing essential research

facilities. Additionally, we express our appreciation to Civil Aviation authority for providing temperature data and Environmental Authority of Oman for their valuable support and collaboration throughout the research.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability The ERA5 reanalysis data used in this study are publicly available from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu>). Ground station data were obtained from the Civil Aviation Authority, Oman, under data-sharing agreement.

Declarations

Competing Interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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