

Climate change in Oman: Historical data and projections under contrasting scenarios SSP5-8.5 and SSP1-1.9



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ABSTRACT

Climate change is broader than global warming, as it includes changes in precipitation patterns, rising sea levels, and other environmental shifts. Global surface temperature increased by 1.1 °C during 2011–2020 compared to 1850–1900, while 2024, the warmest year in the past 175 years, was 1.55 °C above that baseline. This study examines historical and projected features of climate change in Oman using data from the Climate Change Knowledge Portal, which applies climate models such as CMIP6, ERA5, and N-SLC. Results show that between 1971 and 2020, Oman's average warming rate was 0.025 °C/year, with regional variations from 0.017 °C/year in Duqm to 0.048 °C/year in Buraimi. Projections suggest stronger warming of 0.064–0.074 °C/year under the high-emission SSP5-8.5 scenario or weaker warming of 0.01 °C/year under the low-emission SSP1-1.9 pathway. By 2099, maximum June temperatures may rise by 7.11 °C, and sea levels by up to 1.39 m by 2150. No significant rainfall anomaly has yet been observed.

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1. Introduction

The Representative Concentration Pathway (RCP) is a concept used in climate change research (because of collaboration between experts and modelers in the fields of climate, emissions, and terrestrial ecosystems) to conveniently express projected greenhouse gas (GHG) emissions in terms of their resultant radiative forcing (RF) (van Vuuren et al., 2011). The term (radiative forcing or RF) refers to the perturbation introduced in the energy budget of the Earth's planet, caused by altering the scattering and absorbing properties of the atmosphere about incoming solar radiation and reflected terrestrial radiation. Radiative forcing is the difference between the amount of energy that enters the Earth's atmosphere from the sun (incoming solar radiation) and the amount of energy that leaves the Earth's atmosphere (terrestrial infrared radiation), and this radiative forcing is quantified in units of watts per square meter of Earth's surface area (W/m^2), which is an energy flux (Bellouin, 2015). This alteration is due to gradually changing the chemical composition (such as

increasing carbon dioxide “CO₂” and hydrofluorocarbons “HFC”) or changing the physical composition (such as the clouds and aerosols) of the atmosphere, as well as changing the ground albedo due to anthropogenic human activities (Bellouin et al., 2020; Marzouk, 2023). The RCP values refer to expected radiative forcing in 2100, expressed in W/m^2 . Doubling the atmospheric concentration of CO₂ compared to preindustrial times around 1850 (thus, increasing the carbon dioxide fraction from about 280 ppm to 560 ppm) causes a radiative forcing of 3.7 $Watt/m^2$. In 2016, the global CO₂ concentration reached about 400 ppm. In 2011, RF was estimated to be about $2.3 \pm 1 W/m^2$.

Originally, four RCP projections were suggested (Bienvenido-Huertas et al., 2021); namely, RCP 2.6 (an emissions mitigation scenario) (NOAA, 2013), RCP 4.5 (an intermediate low-emissions scenario), RCP 6.0 (an intermediate high-emissions scenario), and RCP 8.5 (a scenario for very high greenhouse gas emissions). A fifth optimistic RCP value of 1.9 was introduced after the adoption of the Paris Agreement, and this RCP 1.9 represents a mitigation pathway compatible with the target of 1.5 °C warming limit compared to preindustrial times. RCP 2.6 is compatible with the primary goal of the 2015 Paris Agreement (limiting global warming to a level well below 2 °C compared to preindustrial levels) (Horowitz, 2016), while RCP 1.9 is compatible with the secondary goal of limiting that warming to 1.5 °C.

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The Representative Concentration Pathways (RCP) were used as inputs to the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5) climate model, which informed the Fifth Cycle of the Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN) (IPCC, 2014). CMIP (Coupled Model Intercomparison Project) is an international climate modeling project by the World Climate Research

Program (WCRP) (wcrp-climate.org), and this project provides climate projections that help in understanding historical and future climate changes (wcrp-cmip.org). CMIP is an essential tool for the Intergovernmental Panel on Climate Change (IPCC) as well as other international and national climate assessment task forces. Table 1 summarizes some characteristics of the five RCP scenarios for global GHG emissions.

Table 1: Characteristics of the five representative concentration pathways (RCP)

RCP	RF	Expected temperature rise in 2100 (compared to preindustrial levels)	GHG emissions trend
1.9	1.9	1.5 °C	Very rapidly declining emissions (very stringent mitigation scenario)
2.6	2.6	2.0 °C	Rapidly declining emissions (stringent mitigation scenario)
4.5	4.5	2.4 °C	Slowly declining emissions (intermediate scenario)
6.0	6.0	2.8 °C	Stabilizing (constant) emissions
8.5	8.5	4.3 °C	Rising emissions (very high warming scenario)

While the Representative Concentration Pathways (RCP) were sufficient quantitative descriptors for the climate change scenarios in AR5 and CMIP5, they do not address the climate change impact on social and economic development. Therefore, the socioeconomic context of the RCP was absent. In the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) climate model, which informed the Sixth Cycle of the Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN); the emphasis shifted from RCP to a new set of narratives that depicts possible socioeconomic futures. These introduced textual descriptors are referred to as Shared Socioeconomic Pathways (SSP). There are five socioeconomic scenarios in climate change research (five SSPs), namely SSP1, SSP2, SSP3, SSP4, and SSP5. It is worth mentioning that neither CMIP5 nor CMIP6 is a single climate model. Rather, each one is a collection of coupled (as the name implies) models for producing multi-model ensemble scenarios with various climate variables.

It is probably adequate to clarify here that when we speak about socioeconomic development, we refer to a cluster of factors such as population, urbanization level (portion of the population living in urban communities or smart cities) (Wang and Zhao, 2018), economic activities and international trade (Fedorenko et al., 2021), social equality, educational system (Broer et al., 2019), lifestyle and consumption pattern, institutional structure, technology development (Popp, 2011), agriculture (Creutzig et al., 2015), alternative energy system, and comfortable mobility modes. These factors delineate the way we live, including the way we utilize lands, the way we generate electricity (Azhar Khan et al., 2014), and the way we store and convert energy (Lu et al., 2019). Table 2 summarizes some characteristics of the five SSP scenarios for global socioeconomic development (IPCC, 2019).

Because a Shared Socioeconomic Pathway (SSP) is a qualitative description of future status through the 21st century, it is not sufficient to run an Integrated Assessment Model – IAM (such as CMIP6) that captures the Energy-Environment-Economy

nexus and the socio-economic impacts of climate change mitigation. Therefore, an SSP choice can be coupled with a Representative Concentration Pathway (RCP) to yield a well-defined framework for climate and socioeconomic projections.

In the Sixth Cycle of the Assessment Report (AR6) by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN), five SSP-RCP pairs were particularly selected and explored when investigating possible futures of warming and emissions till 2100. These are summarized in Table 3.

The SSP1-1.9 framework is a scenario that combines SSP1 (Sustainability: Taking the Green Road) with RCP 1.9 (radiative forcing of 1.9 W/m² in 2100), and it is the closest to the Paris Agreement secondary target of a 1.5 °C global warming limit. The SSP1-2.6 framework is a scenario that combines SSP1 (Sustainability: Taking the Green Road) with RCP 2.6 (radiative forcing of 2.6 W/m² in 2100), and it is well aligned with achieving the Paris Agreement primary target of 2 °C global warming.

It is worth mentioning here that the World Meteorological Organization (WMO, 2025a; 2025b) announced that a global warming incident of 1.5 °C was observed in 2024, where the global average surface temperature was 1.55±0.13 °C (with an uncertainty margin of 0.13 °C) above the 1850-1900 average (WMO, 2025a). That year (2024) was the warmest in the 175-year observational record (WMO, 2025b). However, this single year warming of 1.55 °C in 2024 should be confused with the 1.5 °C or the 2 °C warming limit of the Paris Agreement. The stated target warming limits pertain to a trend of warming that was observed over years or decades. When this trend and temporal averaging are factored in, then global warming (global surface temperature) reached 1.1 °C in 2011-2020 above 1850-1900 levels (NOAA, 2025c).

It should be noted that some RCP values are not realistic for some SSP scenarios. For example, the low-RF cases of RCP 1.9 and RCP 2.6 are not suitable for SSP3 due to the regional rivalry implied in SSP3, which impedes global coordination for comprehensive emissions mitigation efforts (Hoch et

al., 2021). It should also be noted that an RCP value in CMIP5 or AR5 does not exactly mean the same GHG emissions in CMIP6 or AR6, due to possible differences in the contribution of individual greenhouse gases (such as methane “CH₄” and carbon dioxide “CO₂”) to the radiative forcing, but the two values can still be treated as similar. For example, SSP5-8.5 has a higher CO₂ emission level

than RCP 8.5, while RCP 8.5 has a higher CH₄ level. These differences lead to small deviations in the radiative forcing values at 2100. Therefore, while the radiative forcing (RF) levels are indicated to be equal (such as when considering SSP2-4.5 and RCP 4.5), they should be viewed as approximate rather than as precise 2100 values.

Table 2: Characteristics of the five shared socioeconomic pathways (SSP)

SSP	Brief name	Description
		A peak and then a decline in population (about 7 billion in 2100) Significant efforts toward sustainability High income Low inequality
SSP1	Sustainability - Taking the green road	Green energy and sustainable economic practices Effective land-use regulation Less resource-intensive consumption Low-ghg emission systems Low challenges to mitigation Low challenges to adaptation
		Medium population growth (about 9 billion in 2100) Describes a future that continues on current trajectories Medium income
SSP2	Middle of the road	Only a gradual reduction in inequality Moderate economic growth Moderate technological progress Moderate environmental awareness Medium challenges to mitigation Medium challenges to adaptation
		High population growth (about 13 billion in 2100) Low income Continued inequalities
SSP3	Regional rivalry - A rocky road	Material-intensive consumption and production Fragmented world (countries prioritize self-reliance and security over cooperation) Barriers to international trade Limited technological advancement High challenges to mitigate High challenges to adaptation
		Medium population growth (about 9 billion in 2100)
SSP4	Inequality - A road divided	A world with high inequality (wealthy regions focus on technology and carbon reduction, while poorer regions face significant challenges) Medium income but significant inequality within and across regions Low challenges to mitigation High challenges to adaptation (low adaptive capacity)
		A peak and then a decline in population (about 7 billion in 2100) High income Reduced inequalities Free international trade
SSP5	Fossil-fueled development - Taking the highway	Resource-intensive production and consumption A future driven by rapid economic growth and high energy demands Economy and lifestyles are primarily reliant on fossil fuels (with little effort to mitigate climate change) High challenges to mitigate Low challenges to adaptation (high adaptive capacity)

Table 3: Five important SSP-RCP pairs in the IPCC (2019) sixth assessment report (AR6), and the five corresponding projected increases in global surface temperature (in °C), relative to the average global surface temperature of the period 1850–1900

SSP-RCP	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
	Best estimate	Very likely range	Best estimate	Very likely range	Best estimate	Very likely range
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

2. Research goals and methods

The current study aims primarily to present selected data about climate change in Oman, based on both historical information and future projections. The four scopes of this climate change are (1) surface air temperature (mean and maximum), (2) precipitation, (3) mean sea level rise in the Omani Exclusive Economic Zone (EEZ), and

(4) tropical cyclone occurrence frequency. The current research work is founded on qualitative and quantitative analysis of publicly available climate data for Oman, using the Climate Change Knowledge Portal (CCKP) (WBG, 2025) of the World Bank Group (WBG).

The use of a single source of raw data might be viewed as a limitation. However, we consider it an advantage because it results in coherence in the data.

On the other hand, curating data from multiple sources can lead to discrepancies and incorrect interpretations due to different assumptions, climate models that simulate the physical processes of the Earth and the atmosphere, reference periods, and terminologies (Braconnot et al., 2012; IPCC, 2014). Also, the use of public data supports the reproducibility and transparency of the results presented here, which can be easily verified and replicated by others. Furthermore, because the raw data accessed for conducting the current research is backed by a globally reputable and renowned institution (the World Bank Group), the accuracy and reliability of our results are therefore implied.

Historical climate data for Oman in CCKP (WBG, 2025) were derived from either ERA5 (fifth generation ECMWF ReAnalysis for the global climate and weather) (ECMWF, 2020, 2022b) at a spatial surface resolution of $0.5^\circ \times 0.5^\circ$ ($50 \text{ km} \times 50 \text{ km}$) or CMIP6 multi-model ensemble historical simulation. Climate projection data for Oman in CCKP were modeled using the Sixth Phase of the Coupled Model Intercomparison Projects (CMIP6), overseen by the WCRP, and the climate projection data for Oman in CCKP were presented at a spatial surface resolution of $0.25^\circ \times 0.25^\circ$ ($25 \text{ km} \times 25 \text{ km}$). Historical and projected sea level data (WBG, 2025) for Oman in CCKP were provided by NASA's Sea Level Change Team (N-SLCT). Historical data about tropical cyclones (also called hurricanes and typhoons) in CCKP were primarily based on simulated tropical cyclones produced by the Columbia University HAZard Model (CHAZ) (Lee et al., 2018; 2020; 2022).

The contribution of the current work includes carefully selecting subsets of data to be processed to support the goals of the study. Also, the organization of the processed results and the discussion made about them allow transforming them from isolated pieces of information into useful insights.

The findings presented in this study can be helpful to researchers interested in a summary of key climate change aspects in Oman, as well as to a general audience interested in climate change in general. In addition, a global segment of the readers may also benefit from this study through the explanations provided for various specialized terms in climate change and its modeling. Also, the introduced Climate Change Knowledge Portal (CCKP) tool and its powerful capabilities can aid in further exploitation of this free online resource for investigating climate change in geographic locations other than Oman.

3. Results

Whereas climate change is a global phenomenon, its impact varies locally depending on various factors, such as the geographic location and its solar radiation, dominant economic activities, terrain, water bodies, national support toward sustainable development, and social awareness of environmental issues. Since this study is concerned with the Sultanate of Oman, in the current subsection, we

shed some light on expected climate change aspects in the country based on both historical data and predictions up to 2150. To emphasize these changes and their negative impact, we use the most alarming framework of SSP5-8.5 for future projections. To also explore the most-promising mitigation possibilities, we contrast these results with those from the framework of SSP1-1.9 for future projections (when this framework is not available, it is substituted with the slower mitigation framework of SSP1-2.6).

3.1. Mean surface air temperatures

According to the CMIP6 multi-model ensemble, the average mean surface air temperature (AMSAT) in Oman was 27.21°C in 1950 (historical simulation), and it increased to 28.18°C in 2014 (historical simulation).

According to the SSP5-8.5 framework, AMSAT in Oman is expected to increase from 28.18°C in 2014 to 33.35°C in 2100. Despite this predicted large increase of 5.17°C between 2014 and 2100 according to the SSP5-8.5 framework, this should be interpreted carefully because it is a (one year to one year) comparison, rather than a trend over a range of years. Such a point-to-point comparison can be misleading in terms of exaggerating or attenuating the change because of the natural variability involved from one year to another. For example, in the winter solstice month of December, the average mean surface air temperature in Oman was 19.39°C in 1952, it then dropped to 16.94°C in 1964 (the coldest record between 1952 and 2020), and then increased to 22.74°C in 2001 (the hottest record between 1952 and 2020), and then decreased to 21.43°C in 2020. In the summer solstice month of June (Marzouk, 2024; van der Meersch and Wolkovich, 2025), the average mean surface air temperature in Oman was 33.18°C in 1955, it then dropped to 32.37°C in 1977 (the coldest record between 1955 and 2020), and then increased to 35.24°C in 1998 (the hottest record between 1955 and 2020), and then decreased to 34.49°C in 2020.

According to the SSP1-1.9 framework, AMSAT in Oman is expected to increase from 28.18°C in 2014 by a small amount to 28.81°C in 2100. Again, this predicted small increase of 0.63°C between 2014 and 2100 in the SSP1-1.9 framework should be interpreted carefully because it can be part of the natural variability from one year to another. The average mean surface air temperature (AMSAT) in Oman (historically simulated) has been fluctuating slightly between 1950 and 2014. For example, it was 27.21°C in 1950, and it was at a lower value of 27.02°C in 1964, and at a higher value of 27.62°C in 1991.

To suppress the interfering natural variability (noise) in the temperature, a trend over a period should be considered. As a result, examining the trend of the annual average mean surface air temperature (AMSAT) in Oman over the period 1971-2020 shows a warming trend in the entire country, but with varying intensities between $0.017^\circ \text{C}/\text{year}$ in the coastal city of Duqm (in Al Wusta

governorate) to 0.048 °C/year in the inland city of Buraimi (in Al Buraimi governorate) (Marzouk, 2021). For the whole of Oman, a statistically significant (almost 100% significance level) average warming trend of 0.025 °C/year was observed for the same period of 1971-2020; while a lower trend of 0.022 °C/year was observed for an extended period of 1951-2020 (also statistically significant, with almost 100% significance level).

Between 2051 and 2100 (50-year period), the warming trends in the average mean surface air temperature (AMSAT) according to the SSP5-8.5 framework projections for Oman are expected to become worse (faster) than the historical data. These projections suggest a warming trend that ranges from a minimum of 0.064 °C/year in the coastal city of Sur (Ash Sharqiyah South governorate) to a maximum of 0.074 °C/year in the inland city of Buraimi (Al Buraimi governorate).

Between 2051 and 2100 (50-year period) also but using the SSP1-1.9 framework projections for Oman, the warming trends in the average mean surface air temperature (AMSAT) are expected to become better (slower) than the historical data. These projections suggest a warming trend that is nearly uniform in the entire country of Oman, at a pace of only 0.01 °C/year. Although the SSP1-1.9 framework is aligned with net-zero CO₂ emissions globally around 2050, and limiting the global warming to 1.5 °C above preindustrial levels, with the global warming (anomaly in the average mean surface air temperature or AMSAT) potentially peaking at 1.5 °C midcentury before declining to 1.4 °C by 2100; this does not contradict the still-increasing AMSAT in Oman between 2051-2100 according to the SSP1-1.9 predictions in CCKP. This is because the decline in the global surface temperature refers to the average over the entire Earth (both land and oceans). Oceans and other water bodies occupy about 70.8% of the Earth's surface, while lands cover the remaining 29.2% portion (Dangayach and Pandey, 2024; Kogan, 2022). Oceans and water in general respond differently to heating than land does due to their large thermal mass (de Szoek, 2021). Thus, it is possible to have two counteracting influences, with the mean in-ocean surface temperatures declining while the mean air temperatures (at 2 meters above ground) still increasing, leading ultimately to a vanishing overall change in the area-weighted average temperature change.

According to the SSP5-8.5 framework, the average mean surface air temperature (AMSAT) for the winter month of December is projected to increase from 21.01 °C (a historical reference value for the period 1995-2014) to 29.01 °C in 2099 (this does not reflect a monotonic increase from one year to the next year but involves fluctuations across years). This corresponds to an increase of 8.00 °C during the 21st century. However, the projected mean surface air temperature anomaly between the future 20-year period of 2080-2099 and the reference 20-year historical period of 1995-2014 is

5.16 °C (50th percentile or median), with the 10–90th percentile range being 3.36–7.03 °C.

According to the SSP1-2.6 framework (the SSP1-1.9 framework was not available for monthly air temperature projection at CCKP), the average mean surface air temperature (AMSAT) for the winter month of December is projected to increase from 21.01 °C (a historical reference value for the period 1995-2014) to 23.21 °C in 2098 (the value at 2099 was not easily identifiable; this alternative 2098 value does not reflect a monotonic increase from one year to the next year, but involves fluctuations across years). This corresponds to an increase of 2.20 °C during the 21st century. However, the projected mean surface air temperature anomaly between the future 20-year period of 2080-2099 and the reference 20-year historical period of 1995-2014 is 1.21 °C (50th percentile or median), with the 10–90th percentile range being 0.55–2.32 °C.

According to the SSP5-8.5 framework, the average mean surface air temperature (AMSAT) for the summer month of June is projected to increase from 34.27 °C (a historical reference value for the period 1995-2014) to 41.71 °C in 2099 (again, this does not reflect a monotonic increase from one year to the next year, but involves fluctuations across years). This is an increase of 7.44 °C during the 21st century. However, the projected mean surface air temperature anomaly between the future 20-year period of 2080-2099 and the reference 20-year historical period of 1995-2014 is 4.72 °C (50th percentile or median), with the 10–90th percentile range being 2.97–6.29 °C.

According to the SSP1-2.6 framework (again, the SSP1-1.9 framework was not available for monthly air temperature projection at CCKP), the average mean surface air temperature (AMSAT) for the summer month of June is projected to increase from 34.27 °C (a historical reference value for the period 1995-2014) to 35.57 °C in 2097 (the value at 2099 or 2098 were not easily identifiable; this alternative 2097 value does not reflect a monotonic increase from one year to the next year, but involves fluctuations across years). This is an increase of 1.30 °C during the 21st century. This 1.30 °C increase is comparable to the projected mean surface air temperature anomaly between the future 20-year period of 2080-2099 and the reference 20-year historical period of 1995-2014, which is 1.24 °C (50th percentile or median), with the 10–90th percentile range being 0.65–2.10 °C.

3.2. Maximum surface air temperatures

It might be of interest to inspect also the average maximum (rather than mean) surface air temperature in the summer month of June in Oman. Compared to a historical value of 40.96 °C (a reference value for the period of 1995-2014), this temperature is expected to reach 48.07 °C in 2099 according to the SSP5-8.5 framework (reflecting an increase of 7.11 °C during the 21st century, but this does not reflect a monotonic increase from one year

to the next year, but involves fluctuations across years), while this is expected to reach 43.59 °C in 2099 according to the SSP1-2.6 framework (again, the SSP1-1.9 framework was not available for monthly air temperature projection at CCKP), and this shows an increase of 2.63 °C during the 21st century (again, this does not reflect a monotonic increase from one year to the next year, but includes fluctuations across years).

Similarly, it might be of interest to inspect the average maximum (rather than the mean) surface air temperature in the winter month of December in Oman. Compared to a historical value of 26.61 °C (a reference value for the period 1995-2014), this temperature is expected to reach 33.39 °C in 2099 according to the SSP5-8.5 framework (reflecting an increase of 6.78 °C during the 21st century, but this does not reflect a monotonic increase from one year to the next year, but involves fluctuations across years), while this is expected to reach 26.28 °C in 2099 according to the SSP1-2.6 framework (again, the SSP1-1.9 framework was not available for monthly air temperature projection at CCKP), and this actually shows a favorable drop of 0.33 °C ($26.28 - 26.61 = -0.33$ °C) during the 21st century (again, this does not reflect a monotonic increase from one year to the next year, but involves fluctuations across years).

3.3. Precipitation

Historical data of annual precipitation (mm) in Oman between 1951 and 2020 show that no statistically significant trend was observed. Therefore, the precipitation aspect of climate change is not given attention in this study.

3.4. Sea level

Globally, historical sea level data show a significant rise, with the mean sea level (MSL) rising by approximately 210–240 millimeters (mm) in 2024 compared to 1880 (a period of 144 years). Furthermore, more than one-third of this rise has happened in the last 25 years (only 17.4% of the 144-year period), and this highlights an accelerating trend.

The term Exclusive Economic Zone (EEZ) refers to a region of the sea, extending 200 nautical miles (230 miles or 370 km) from a country's territorial sea (NOAA, 2025a; 2025b) (which stretches for 12 nautical miles or 22.22 km from the coasts). Within the Exclusive Economic Zone, a coastal country has jurisdiction over both living and nonliving resources. In the Exclusive Economic Zone (EEZ) of Oman, the sea-level rise between 1993 and 2024 was about 120 mm (0.12 m). Compared to the 2005 reference point (representing the period of 1995-2015), the Omani EEZ MSL rose in 2020 was 0.05 m.

According to the SSP5-8.5 framework, this Omani EEZ MSL rise is expected to reach 0.24 m in 2050, then 0.80 m in 2100, and 1.39 m in 2150. These sea-level rise values correspond to the 50th percentile

(the median) of the predicted range, and they are relative to the 2005 reference point (representing the period of 1995-2015).

According to the SSP1-1.9 framework, the Omani EEZ MSL rise is expected to reach 0.18 m in 2050, then 0.38 m in 2100, and 0.57 m in 2150. These sea-level rise values correspond to the 50th percentile (the median) of the predicted range, and they are relative to the 2005 reference point (representing the period of 1995-2015). The SSP1-1.9 sea level rise values are much smaller than their counterparts under the SSP5-8.5 framework. For example, the SSP1-1.9 rise in 2100 is less than one-half of the SSP5-8.5 value ($0.38 \div 0.80 = 47.5\%$). Similarly, the SSP1-1.9 rise in 2150 is also less than one-half of the SSP5-8.5 value ($0.57 \div 1.39 = 41.0\%$).

3.5. Cyclones

Tropical cyclones (of any of their six categories) are considered anomalies or rare events by themselves. Thus, it is difficult to identify a trend for them from historical data, and it is even more difficult to identify how this trend (if it exists) or how their occurrence pattern responds to climate change in future projections. In addition, the CCKP tool provides cyclone projections only under one framework, which is the intermediate SSP2-4.5 ("Middle of the road" with radiative forcing of 4.5 W/m² in 2100), which is neither of the two extreme frameworks (SSP1-1.9 and SSP5-8.5) we are interested in. Therefore, we extract from the CCKP only information about the historical occurrence of cyclones in Oman, and how this compares with a regional benchmarking zone (the Indian Ocean) as well as globally.

First, we present in Table 4 the definition of the six levels (classes) of tropical cyclones, with increasing intensity based on the maximum sustained wind speed. Such use of the fluid speed to classify the flow regime is commonly exercised in environmental or engineering investigations involving gas or liquid flows. This classification is known as the Saffir-Simpson Hurricane Scale (Simiu et al., 2007).

Second, we present in Table 5 a descriptive statistical analysis in the form of annual occurrence frequencies (total number of simulated tropical cyclones per year). Table 5 covers the entire world, the Indian Ocean, the Omani Exclusive Economic Zone (EEZ), and Oman (landfalls) for each of the six cyclone levels. These data are median values (50th percentile), based on historical data from 1951 to 2014.

From Table 5, the stronger categories 2-5 cyclones are very rare in Oman. Category 1 cyclones have a low frequency of 0.079 in the Omani Exclusive Economic Zone (once per 13 years on average), and a lower frequency of 0.036 as landfalls (once per 28 years on average). It is the tropical storms that are more frequently observed in Oman, with a frequency of 0.288 in the Omani Exclusive Economic Zone (once per 3.5 years on average), and a lower

frequency of 0.182 as landfalls (once per 5.5 years on average). Compared to the benchmarking cases (Indian Ocean and globally), these frequencies are very small. For example, the average occurrence frequency of all cyclone types in the Omani Exclusive Economic Zone is only 1.6% of the average occurrence frequency in the Indian Ocean ($0.438 \div 27.150 = 1.61\%$).

Table 4: Six levels of tropical cyclones

Cyclone level	Maximum sustained speed (knots)	Maximum sustained speed (km/h)
Tropical storm	34 to < 64	63 to < 118.5
Category 1	64 to < 83	118.5 to < 154
Category 2	83 to < 96	154 to < 178
Category 3	96 to < 113	178 to < 209
Category 4	113 to < 137	209 to < 254
Category 5	≥ 137	≥ 254

Table 5: Occurrence frequency (per year) for the six cyclone levels in four zones

Cyclone level	Globally	Indian Ocean	Oman (EEZ)	Oman (landfalls)
Tropical storm	47.950	12.190	0.288	0.182
Category 1	18.100	4.760	0.079	0.036
Category 2	10.060	2.770	0.034	0.010
Category 3	11.130	3.200	0.022	0.005
Category 4	10.270	3.070	0.013	0.002
Category 5	4.140	1.170	0.002	0.000
Sum	101.650	27.150	0.438	0.235

4. Discussion

Based on the presented results, climate change can have a big impact on Oman if not quickly mitigated. Climate change is a global phenomenon, and thus its mitigation also should be through global collaboration. We use this section to comment on three auxiliary topics.

4.1. Prognosis of SSP1-1.9

Although we used the SSP1-1.9 framework (which limits global warming to about 1.5 °C by 2050 and aims for net-zero CO₂ emissions by 2050) to present optimistic climate projections for Oman, we consider this framework unrealistic in practice. Our conclusion is based on an evaluation of 53 transition elements in the global clean energy system, as defined and assessed by the International Energy Agency (IEA) in its Tracking Clean Energy Progress (TCEP) report published in July 2023 (IEA, 2023b). Among these elements, only three were found to be fully on track with the IEA's Net Zero CO₂ Emissions by 2050 (NZE) scenario: (1) solar photovoltaic systems, (2) electric vehicles, and (3) energy-efficient lighting.

4.2. Implications of climate change for Oman

According to the International Energy Agency (IEA), a warming climate in Oman (in terms of the average annual temperature) has been observed in the last decade (2013-2022) (IEA, 2023a). Such a trend, along with altered precipitation behavior, has undesirable consequences for the country. This weather anomaly is likely to continue, and this triggers:

1. A big increase in peak electricity demand due to the intensified use of air conditioning.
2. Possible decline in the electricity generation efficiency at the country's gas-fired power plants. It should be noted that the electricity generation in Oman is dominated by natural gas firing, which was responsible for a share of 96% in 2024. Gas-fired power plants in Oman typically operate

according to the combined-cycle gas turbine (CCGT) cycle (Al-Sarihi and Bello, 2019).

3. Oman is one of the most water-stressed countries in the world (Odhiambo, 2017). A shift in the precipitation patterns in Oman may pose serious challenges. This may lead to aggravating freshwater availability due to a decrease in the cumulative annual rainfall. Linked to electricity, such accentuated freshwater scarcity can cause an increase in energy demand due to the deployment of more desalination plants. At the same time, precipitation anomalies in the form of unusually heavy incidents of rain and storm water may damage power infrastructure and harm existing farms.

It is important to recognize the responsible and forward-looking policies adopted by Omani authorities, particularly through institutions such as the Ministry of Energy and Minerals (MEM) and Hydrogen Oman (Hydrom). These institutions are driving genuine sustainability transitions in a country long identified as a major exporter and consumer of oil and gas (Al-Abri et al., 2019; Valeri, 2020). Their efforts to address climate change are evident in national initiatives, including the large-scale expansion of solar energy and the development of a national roadmap to position Oman as a leading producer of hydrogen and its derivatives (Al-Abri et al., 2024).

4.3. Limitations and uncertainties in climate modeling

Third, we affirm the existence of uncertainties in climate models. This is an inevitable limitation, as expected in numerical modeling in general (Snyder et al., 2024; Tyagi et al., 2024). For example, a reported uncertainty analysis based on CMIP6 showed a root mean square error (RMSE) of about 2.05 °C for the daily maximum surface air temperature, and about 2.73 °C for the daily minimum surface air temperature (Xu et al., 2023). Such deviations are attributed to different factors, such as the approximations implied by climate reanalysis, where observation data are numerically

converted into a temporal evolution at a spatially finer and consistent grid (Carta et al., 2013; ECMWF, 2022a). In addition, parametrization is another source of uncertainty. This refers to assigning a quantitative parameter to represent an environmental process or a physical property (McFarlane, 2011), such as the surface albedo that represents the reflection of incoming radiation (Kuipers Munneke et al., 2011). Another climatic process that requires parametrization is the radiation balance at the top of the atmosphere. This process depends on factors such as cloud cover, vegetation, snow, and sea ice albedo. Determining appropriate parameter values often involves calibration (or tuning) of the climate model, where the model is run multiple times. The difference between model predictions and observed data—referred to as “systematic error” or “bias”—is then used to guide the selection of the most suitable parameter values (Kerkhoff et al., 2014; Maraun, 2016).

5. Conclusions

In the current study, we provided a summary of different climate change activities in the Sultanate of Oman between 1950 and 2150. Two future projections were explored, forming a lower bound and an upper bound for expected changes based on the global response to the climate issues and actions taken to combat these changes. The following findings can be stated:

- Global warming is statistically proven in Oman, with an average rate of about 0.025 °C/year throughout 1971-2020. This rate varies locally between 0.017 °C/year and 0.048 °C/year.
- According to the worst-case scenario of SSP5-8.5, outdoor conditions in Oman can become much harsher in 2100, with the average maximum temperature in June exceeding 48 °C, while the average maximum temperature in December exceeding 33 °C. These averages do not reflect normal variability across days, and do not reflect local heating sources (urban heat islands, for example (Gartland, 2012) that can further accentuate the thermal discomfort and impedance of human activities. The harm to crops and livestock is an additional risk.
- According to the best-case scenario of SSP1-1.9, outdoor conditions in Oman may not change remarkably in 2100 from their conditions at the beginning of the 21st century.
- There is no distinguishable change in the precipitation pattern in Oman because of climate change over the period of 1951-2020.
- The sea level rise in the Omani Exclusive Economic Zone (EEZ) is already occurring, with an increase of about 50 mm between 2005 and 2020 (leading to an average rising rate of about 3.3 mm/year). According to the SSP5-8.5 framework, this rise may reach 0.80 m in 2100 and 1.39 m in 2150.

According to the SSP1-1.9 framework, a lower rise of 0.38 m in 2100 and 0.57 m in 2150 is expected.

- Between 2050 and 2150, the average annual sea level rise according to the SSP5-8.5 framework is 1.15 cm/year.
- Between 2050 and 2150, the average annual sea level rise according to the SSP1-1.9 framework is 0.39 cm/year.
- Tropical cyclones have been a rare phenomenon in Oman (compared to the Indian Ocean or global records), with tropical storms being the prevalent class that reach the country or its Exclusive Economic Zone.

List of abbreviations

AMSAT	Average Mean Surface Air Temperature
AR5	Fifth Assessment Report of Climate Change
AR6	Sixth Assessment Report of Climate Change
CCGT	Combined-Cycle Gas Turbine
CCKP	Climate Change Knowledge Portal of the World Bank Group
CHAZ	Columbia HAZard Model
CMIP5	Fifth Phase of the Coupled Model Intercomparison Project
CMIP6	Sixth Phase of the Coupled Model Intercomparison Project
ECMWF	European Centre for Medium-Range Weather Forecasts
EEZ	Exclusive Economic Zone
ERA5	Fifth-Generation ECMWF Reanalysis for the Global Climate and Weather
GHG	Greenhouse Gas
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MEM	Omani Ministry of Energy and Minerals
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration (United States)
N-SLCT	NASA Sea Level Change Team
NZE	Net Zero CO ₂ Emission by 2050 Scenario (International Energy Agency)
ppm	Parts per Million
PV	Photovoltaic
RCP	Representative Concentration Pathway
RF	Radiative Forcing
RMSE	Root Mean Square Error
SSP	Shared Socioeconomic Pathway
TCEP	Tracking Clean Energy Progress
WBG	World Bank Group
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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