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Article

# Global Warming Forecast Using Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP)

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## Abstract

This study aims at delineating specific proven features of climate change in the Sultanate of Oman since 1950, and also highlighting potential features of the climate change in the Sultanate of Oman up to 2150 under the worst future scenario of SSP5-8.5 (the unsustainable Fifth Shared Socioeconomic Pathway "Fossil-fueled development - Taking the highway", coupled with a high radiative forcing of 8.5 W/m<sup>2</sup> in 2100), and under the best future scenario of SSP1-1.9 (the sustainable First Shared Socioeconomic Pathway "Sustainability - Taking the green road", coupled with a low radiative forcing of 1.9 W/m<sup>2</sup> in 2100). The study is primarily based on public data from the CCKP (Climate Change Knowledge Portal of the World Bank Group), which in turn utilizes a set of climate simulation tools or datasets, such as CMIP6 (Sixth Phase of the Coupled Model Intercomparison Project), ERA5 (fifth generation ECMWF ReAnalysis for the global climate and weather), and N-SLC (NASA's Sea Level Change). The study shows that the warming trend in the mean average air temperature of the surface in the Sultanate of Oman based on historical data between 1971 and 2020 is 0.025 °C/year (100% statistically significant), or a 1 °C increase every 40 years. However, this country-level overall warming rate varies spatially, being highest in Buraimi (0.048 °C/year, or 1 °C increase every 21 years) and lowest in Duqm (0.017 °C/year, or 1 °C increase every 59 years). These warming rates within Omani lands may escalate (for a projection period of 2051-2100) to between 0.064 °C/year and 0.074 °C/year according to the SSP5-8.5 scenario, or weakened to only 0.01 °C/year according to the SSP1-1.9 scenario. Compared to the 40.96 °C historical value (as a reference level for the period between 1995 and 2014), the average maximum air temperature of the surface in June is expected to reach about 48.07 °C in the year 2099, according to the framework SSP5-8.5 (reflecting an increase of 7.11 °C). The mean sea level (MSL) at the Exclusive Economic Zone (EEZ) of Oman may rise by 1.39 m in 2150 (relative to the level of 2005) according to the SSP5-8.5 scenario. This is attenuated to only 0.57 m according to the SSP1-1.9 scenario. No proven precipitation anomaly has been observed so far in Oman. Tropical cyclone data show very rare occurrences, and this is mostly limited to the least-damaging class of tropical storms.

**Keywords:** climate change; SSP; RCP; precipitation; anomaly

## 1. Introduction

### 1.1. Climate Change versus Global Warming

Climate change is a broader phenomenon than global warming because it is not limited to the increase in temperature, but it is linked to other anomalies such as altered precipitation patterns and sea level rise. The global surface temperature rise in 2011-2020 was 1.1 °C above preindustrial levels (between 1850 and 1900). The year 2024 (warmest in the last 175-year period) was 1.55 °C warmer than the average of 1850-1900. The impacts of climate change caused by anthropogenic (human-

based) processes [1,2] can affect many facets of human comfort and lifestyle, economic activities, livestock and wildlife, and the planet's ecosystem.

### 1.2. Representative Concentration Pathway (RCP)

The term "Representative Concentration Pathway" or "RCP" as utilized within the context of climate change helps in describing the emissions of GHG (greenhouse gases) based on their radiative forcing effect [3]. In turn, the term "Radiative Forcing" or "RF" as utilized within the context of climate change represents a state of imbalance in terms of the budget of energy for the Earth. This imbalance is a result of altered radiative scattering properties [4] and radiative absorption properties of the atmosphere with regard to the incident electromagnetic solar radiation and the reflected terrestrial radiation [5,6].

The term radiative forcing (RF) can be defined as the imbalance between (1) the level of energy received by the atmosphere of the Earth from the sun (this is an incoming component of the solar electromagnetic radiation), and (2) the level of energy leaving the atmosphere of the Earth (this is a terrestrial component the solar electromagnetic radiation). This radiative forcing (RF) can be expressed numerically in terms of power per unit surface area of the Earth ( $W/m^2$ ). This quantification value represents a flux of energy [7,8]. In the year 2016, the global concentration of carbon dioxide ( $CO_2$ ) reached about 400 parts per million (ppm). In the earlier year 2011, the radiative forcing was predicted to reach a level of  $2.3 W/m^2$  (with an uncertainty margin of 1) approximately [9].

At the beginning, only four Representative Concentration Pathways were proposed [10]. These are:

- (1) Representative Concentration Pathway 2.6, which represents the mitigation of greenhouse gas (GHG) emissions [11]
- (2) Representative Concentration Pathway 4.5, which represents an intermediary scenario of low greenhouse gas (GHG) emissions [12],
- (3) Representative Concentration Path 6.0, which represents another intermediary scenario of high GHG emissions [13],
- (4) Representative Concentration Path 8.5, which represents an unfavorable case of very high emissions [14].

Later, an additional, more optimistic Representative Concentration Pathway was proposed (Representative Concentration Pathway 1.9). This occurred after adopting the Paris Agreement. Such Representative Concentration Pathway 1.9 corresponds to a favorable mitigation scenario that is consistent with the  $1.5^\circ C$  target for global warming, relative to the pre-industrial period [15,16].

On the other hand, Representative Concentration Pathway 2.6 is consistent with the  $2^\circ C$  target (the less-stringent target for the Paris Agreement) [17]. The Representative Concentration Pathway 1.9 can be viewed as representing the more-stringent target of the Paris Agreement, where the warning level is curbed within only  $1.5^\circ C$  [18].

The RCP scenarios are utilized as data that feed into the climate model CMIP5 (the 5th Phase of the Coupled Model Intercomparison Project) [19]. It is useful to add here that the Coupled Model Intercomparison Project (by WCRP) is an international project for modeling climate [20], thereby facilitating our comprehension of changes in the climate, both in the past (as historical records) and the future (as predictions) [21]. The Coupled Model Intercomparison Project can be viewed as very instrumental for IPCC (Intergovernmental Panel on Climate Change) [22].

The next table (Table 1) provides a summary of some features of the five Representative Concentration Pathways.

**Table 1.** Summary of the 5 RCP scenarios.

Representative Concentration Pathway	Radiative Forcing	Expected temperature increase in the year 2100	Trend of greenhouse gas emissions
RCP1.9	1.90	1.50 °C	Highly fast drop in emissions
RCP2.6	2.60	2.00 °C	A fast drop in the emissions
RCP4.5	4.50	2.4 °C	Slowly declining emissions (intermediate scenario)
RCP6.0	6.00	2.8 °C	Stabilizing (constant) emissions
RCP8.5	8.50	4.3 °C	Increasing GHG emissions

### 1.3. Shared Socioeconomic Pathways (SSP)

In the updated CMIP6 climate model (6th Phase of the Coupled Model Intercomparison Project), a change in the focus took place, moving RCP scenarios to a newly introduced five textual narratives. These narratives describe potential socio-economic situations [23].

The general term “socio-economic development” can be viewed as indicative of multiple elements. They cover the population size [24–27], the level of urbanization [28,29], various economic activities as well as the international trade [30,31], social equality [32,33], educational system [34–37], consumers’ behavior and their lifestyle [38,39], organizational layout [40], technological progress [41], the farming and agricultural sector [42], and novel systems of energy generation [43,44]. Such mentioned elements of socio-economic development influence the life pattern, and this includes how lands are used [45] and how power is produced at a large scale [46].

In the following table (Table 2), we provide selected properties of the newly introduced Shared Socioeconomic Pathways [47,48].

**Table 2.** Selected properties of SSP.

Shared Socioeconomic Pathway	Title	Remarks
SSP-1	Sustainability (taking the green road)	<ul style="list-style-type: none"> <li>• Large attempts toward sustainability</li> <li>• Income: high</li> <li>• Inequality: low</li> </ul>
SSP-2	Middle of the road	<ul style="list-style-type: none"> <li>• Mild growth of the global population</li> <li>• describes a future that continues on current trajectories</li> <li>• Income: medium</li> <li>• Inequality: reduction, but only a gradual one</li> </ul>
SSP-3	Regional rivalry - A rocky road	<ul style="list-style-type: none"> <li>• Strong growth in the global population</li> <li>• Income: low</li> <li>• Inequality: remains (continued)</li> </ul>

SSP-4	Inequality - A road divided	<ul style="list-style-type: none"> <li>• Growth in global population: intermediate</li> <li>• Inequality: high</li> <li>• Income: intermediate</li> </ul>
SSP-5	Fossil-fueled development  (taking the highway)	<ul style="list-style-type: none"> <li>• Non-monotonic profile of the global population (an increase, followed by a decrease)</li> <li>• Income: high</li> <li>• Inequality: dropped</li> </ul>

#### 1.4. SSP-RCP Frameworks

Given that a specific SSP represents a qualitative depiction of forecast condition, additional information is needed for conducting an IAM (Integrated Assessment Model) [49], in which the EEE (Environment/Energy/Economy) nexus, as well as socio-economic effects of combating climate change, are predicted [50]. Therefore, a choice of a Shared Socioeconomic Pathway can be coupled with a Representative Concentration Pathway (RCP) to yield a well-defined framework for climate and socioeconomic projections.

In AR6 (the Sixth Cycle of the Assessment Report) by IPCC of the United Nations, five pairs (SSP-RCP) were selected and explored when examining possible situations of global warming and emissions till 2100. The five pairs are listed in the next table (Table 3) [51].

**Table 3.** Special pairs of (Shared Socioeconomic Pathway - Representative Concentration Pathway).

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

It can be useful to add here that WMO (the World Meteorological Organization) indicated that an incident of 1.5 °C global warming took place in 2024 [52], and that year was the hottest over a period of more than 174 years [53]. There is no contradiction, however. The explanation is that the incident of 1.55 °C temperature rise in 2024 is different from the 1.5 °C target or the 2 °C target for global warming, which are based on a trend [54]. If time averaging is taken into consideration, the actual global temperature rise becomes only 1.1 °C in the decade of 2011 to 2020 [55].

We also comment here that some Representative Concentration Pathways are compatible with a given Shared Socioeconomic Pathway [56,57].

We also comment here that RF scores in the Representative Concentration Pathways of version 5 (AR5) do not necessarily have the same meaning as in version 6 (AR6) [58].

## 2. Methodology and Contribution

Our research work relies on analytical processing of open-access data of climate. The main source is CCKP (Climate Change Knowledge Portal) [59].

The past data of climate in CCKP [60] were obtained using ERA5 [61–63] (with an equal surface spacing of fifty kilometers) or CMIP6. On the other hand, CCKP [64] was used for future forecasting.

The data about sea level [65,66] are based on the results of N-SLCT [67]. Past records of hurricanes [68] are mainly from CHAZ simulations [69–71].

The results presented in the current study facilitate a better understanding of the climate anomalies in the Sultanate of Oman.

Our study can also attract the attention of the audience from different parts of the world, because the analysis presented is applicable, in principle, to other countries.

### 3. Results (Part 1: Mean Surface Air Temperatures)

Based on the (Shared Socioeconomic Pathway 5 - Representative Concentration Pathway 8.5) scenario, the Average Mean Surface Air Temperatures (AMSAT) in the Sultanate of Oman are predicted to rise between (2014 value of 28.18 °C) and (2100 value of 33.35 °C).

This estimated rise (5.17 °C) is a year-to-year difference. It does not reflect a robust trend. As an example, during December (the month of the winter solstice) [72], the AMSAT in 1952 was 19.39 °C. However, it then decreased in 1964 to 16.94 °C. During June (the month of the summer solstice) [73], AMSAT in 1955 was 33.18 °C. Later, it decreased in 1977 to 32.37 °C. Subsequently, in 1998, it rose to 35.24 °C.

To mitigate the influence of noise (natural variability) in the temperature, one needs to construct a trend. Therefore, the examined trend of AMSAT in the Sultanate of Oman between 1971 and 2020 shows a trend of warming. However, this is spatially an average for the whole country. It is lowest (0.17 °C/decade) in Duqm, located in Al Wusta governorate, to 0.48 °C/decade in Al Buraimi, located in Al Buraimi governorate. The country's trend of warming is 0.25 °C/decade between 1971 and 2020. However, it is 0.22 °C/decade between 1951 and 2020.

Based on the (Shared Socioeconomic Pathway 1 - Representative Concentration Pathway 1.9) scenario, there is still an expected warming pattern in AMSAT between 2051 and 2100, at a rate of only 0.1 °C/decade. The (Shared Socioeconomic Pathway 1 - Representative Concentration Pathway 1.9) scenario is compatible with reaching zero carbon dioxide emissions (net emissions) near 2050. A peak of global warming of about 1.5 °C is possible midcentury, and then this warming level can decline by 2100 to 1.4 °C [74]. It should be noted that the gradual drop in the global surface temperature (GST) is based on the average over Earth, covering both dry surfaces and water bodies. Water bodies (like oceans) have a surface percentage of about 71% [75,76]. Such water bodies tend to be affected by heating in a different (slower) way than dry lands [77,78]. As a result, there is a possibility of having two opposing factors. In such a case, the average water-body temperature declines, but the average dry-land temperature rises [79]. Eventually, the net results are roughly canceling out the overall change in temperature [80], causing the temperature to remain nearly steady.

### 4. Results (Part 2: Maximum Surface Air Temperatures)

After inspecting the profiles of the Average Mean Surface Air Temperatures (AMSAT), we move here to the Average Maximum Surface Air Temperatures. Considering that average maximum surface air temperature in June, then when the historical value of 40.96 °C (between 1995 and 2014) is taken as a reference, then a rise of 7.11 °C during the twenty-first century is expected (reaching 48.07 °C in 2099). This follows the forecasting of the (Shared Socioeconomic Pathway 5 - Representative Concentration Pathway 8.5) scenario.

On the other hand, the (Shared Socioeconomic Pathway 1 - Representative Concentration Pathway 2.6) scenario suggests a rise of 2.63 °C in 2099, reaching 43.59 °C.

For December, the reference temperature of 26.61 °C (between 1995 and 2014) can be used. The (Shared Socioeconomic Pathway 5 - Representative Concentration Pathway 8.5) scenario suggests an increase in 2099 to the temperature of 33.39 °C (a change of 6.78 °C).

On the other hand, the (Shared Socioeconomic Pathway 1 - Representative Concentration Pathway 2.6) scenario suggests a drop of 0.33 °C in 2099, reaching 26.28 °C.

## 5. Results (Part 3: Precipitation)

Because past records of yearly precipitation (expressed in mm) for the Sultanate of Oman over the period 1951-2020 do not suggest reliable trends of variation, we propose a statement that precipitation (as an element of climate change) in the Sultanate of Oman can be treated as free from important anomalies.

Consequently, we do not dedicate additional analysis to that climate change element in our study.

## 6. Results (Part 4: Sea Level)

Rather than limiting the analysis to the Sultanate of Oman, we start with a global insight. Past information regarding the sea level suggests a large increase. Specifically, MSL (mean sea level) increased by about 0.225 m in the year 2024 relative to the year 1880.

In addition, more than 1/3 of the mentioned increase in MSL occurred in the recent twenty-five-year period. This indicates a nonlinear trend whose rate increases over time.

EEZ (Exclusive Economic Zone) [81–85] extends 200 nm or 370 kilometers from a national coast [86–88]. Within Oman's EEZ, an increase of approximately 0.12 m in the sea level took place over the period 1993–2024. If this is compared with a datum value that corresponds to the year 2005 (more precisely, the interval between 1995 and 2015), then Oman's Exclusive Economic Zone mean sea level rose by about 50 mm in the year 2020.

## 7. Results (Part 5: Cyclones)

When analyzing the occurrence of hurricanes or tropical storms, one may face a challenge in terms of reaching statistically significant outcomes. This is because these events are naturally uncommon. Therefore, identifying a clear trend despite the limited data points becomes difficult.

The difficulty increases when the goal extends to identifying the influence of climate change on such a trend (in case it exists) of the frequency or pattern of such anomalous events. Furthermore, the Climate Change Knowledge Portal furnishes cyclone predictions for one scenario, namely (Shared Socioeconomic Pathway 2 - Representative Concentration Pathway 4.5). This limitation does not permit contrasting two extreme predictions of the two scenarios of (Shared Socioeconomic Pathway 1 - Representative Concentration Pathway 1.9) and (Shared Socioeconomic Pathway 5 - Representative Concentration Pathway 8.5).

Consequently, we for the Climate Change Knowledge Portal data for the Sultanate of Oman about past occurrences of cyclones. We enriched this by contrasting it with the Indian Ocean (regional reference) as well as globally (worldwide reference).

We list in the next table (Table 4) how the types of tropical cyclones are divided based on the speed (maximum) of the air wind. The categorization method given in the table is referred to as SSHS (Saffir-Simpson Hurricane Scale) [89,90].

**Table 4.** Tropical cyclone definition.

Level	Peak wind speed (knots)	Pea wind speed (kilometers/hour)
<b>Tropical Storm</b>	34 to <64	63 to <118.5
<b>Category-1</b>	64 to <83	118.5 to <154
<b>Category-2</b>	83 to <96	154 to <178
<b>Category-3</b>	96 to <113	178 to <209
<b>Category-4</b>	113 to <137	209 to <254
<b>Category-5</b>	≥ 137	≥254

## 8. Discussion

As a remark, we point out here that the (Shared Socioeconomic Pathway 1 - Representative Concentration Pathway 1.9) scenario was chosen here as a representative forecasting route for desirable climate productions in the Sultanate of Oman. However, one may think that such an attractive scenario is actually not attainable practically. The reason for this idea is that most of the transitioning components toward a global clean energy system were found not to be progressing satisfactorily [91]. The components that were described as progressing well toward their targets were only

- (1) PV (photovoltaic) power systems
- (2) EV (electric vehicles)
- (3) LCL (low-consumption lighting)

As a second remark, we would like to recognize and affirm sustainability-oriented policies or regulations made in the Sultanate of Oman recently. Governmental bodies such as Hydrom (Hydrogen Oman) and MEM (Ministry of Energy and Minerals) support the transition away from fossil fuels. This is particularly interesting because the Sultanate of Oman has been traditionally viewed as a big consumer as well as an exporter of oil and natural gas [92,93]. These energy shifts enable decelerating the change in the climate. These energy shifts are noticeable through various national actions. These include large-scale investment in photovoltaic (PV) systems [94]. They are also reflected in the national roadmap for the Sultanate of Oman, aiming for the country to become a key player in the global market of green hydrogen or blue hydrogen and the low-emission derivatives of hydrogen [95].

## 9. Concluding Remark

Through the presented study, a summary of different climate-change activities in the Sultanate of Oman was given. These span the wide period from 1950 to 2150.

We examined two different scenarios of climate forecasting. One of the represents optimistic, favorable conditions, while the other represents pessimistic, unfavorable conditions.

The current study calls for global cooperation among governments, corporations, and communities to combat the change in the climate. Financial support and/or awareness might be needed to incentivize the transition to new styles of life and operations that do not incur heavy penalties on people, either directly or indirectly.

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**Data Availability Statement:** The data that support the findings of this study are available within the article itself. They were derived from public datasets as indicated by the relevant references.

## Nomenclature (in Alphabetical Order)

**AMSAT** This is the average mean surface air temperature (the word “mean” here indicates a mean within the day, rather than being the maximum or the minimum within the day; the word “average” here indicates averaging over a period of time, such as the annual average over the days of a whole year)

**AR5** Fifth Assessment Report of climate change by the Intergovernmental Panel on Climate Change (IPCC), 2014

**AR6** Sixth Assessment Report of climate change by the Intergovernmental Panel on Climate Change (IPCC), 2021

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