

Article

Climate Change of Near-Surface Temperature in South Africa Based on Weather Station Data, ERA5 Reanalysis, and CMIP6 Models

Ilya Serykh ^{1,2} , Svetlana Krasheninnikova ¹ , Tatiana Gorbunova ¹ , Roman Gorbunov ^{1,*} , Joseph Akpan ³ , Oluyomi Ajayi ⁴, Maliga Reddy ⁵ , Paul Musonge ⁶ , Felix Mora-Camino ⁷  and Oludolapo Akanni Olanrewaju ⁷ 

- ¹ A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS, 299011 Sevastopol, Russia; iserykh@ocean.ru (I.S.); svetlanabk@mail.ru (S.K.); gorbunovatyu@gmail.com (T.G.)
 - ² Shirshov Institute of Oceanology of RAS, 117997 Moscow, Russia
 - ³ Industrial Engineering, Durban University of Technology, Durban 4001, South Africa; 22176142@dut4life.ac.za
 - ⁴ Izovutha Pty, Durban 3610, South Africa; oluyomi@izovutha.co.za
 - ⁵ Public Management and Economics, Durban University of Technology, Durban 4001, South Africa; reddy@dut.ac.za
 - ⁶ Faculty of Engineering, Mangosuthu University of Technology, Durban 4001, South Africa; musonge.paul@mut.ac.za
 - ⁷ Institute of System Science, Durban University of Technology, Durban 4001, South Africa; felixmora@id.uff.br (F.M.-C.); oludolapoo@dut.ac.za (O.A.O.)
- * Correspondence: gorbunov@ibss-ras.ru

Abstract

This study investigates changes in Near-Surface Air Temperature (NSAT) over the South African region using weather station data, reanalysis products, and Coupled Model Intercomparison Project Phase 6 (CMIP6) model outputs. It is shown that, based on ERA5 reanalysis, the average NSAT increase in the region (45–10° S, 0–50° E) for the period 1940–2023 was 0.11 ± 0.04 °C. Weak multi-decadal changes in NSAT were observed from 1940 to the mid-1970s, followed by a rapid warming trend starting in the mid-1970s. Weather station data generally confirm these results, although they exhibit considerable inter-station variability. An ensemble of 33 CMIP6 models also reproduces these multi-decadal NSAT change characteristics. Specifically, the average model-simulated NSAT values for the region increased by 0.63 ± 0.12 °C between the periods 1940–1969 and 1994–2023. Based on the results of the comparison between weather station observations, reanalysis, and models, we utilize projections of NSAT changes from the analyzed ensemble of 33 CMIP6 models until the end of the 21st century under various Shared Socioeconomic Pathway (SSP) scenarios. These projections indicate that the average NSAT of the South African region will increase between 1994–2023 and 2070–2099 by 0.92 ± 0.36 °C under the SSP1-2.6 scenario, by 1.73 ± 0.44 °C under SSP2-4.5, by 2.52 ± 0.50 °C under SSP3-7.0, and by 3.17 ± 0.68 °C under SSP5-8.5. Between 1994–2023 and 2025–2054, the increase in average NSAT for the studied region, considering inter-model spread, will be 0.49–1.15 °C, depending on the SSP scenario. Furthermore, climate warming in South Africa, both in the next 30 years and by the end of the 21st century, is projected to occur according to all 33 CMIP6 models under all considered SSP scenarios. The main spatial feature of this warming is a more significant increase in NSAT over the landmass of the studied region compared to its surrounding waters, due to the stabilizing role of the ocean.

Keywords: climate warming; South Africa; air temperature; CMIP6 models; SSP projections



Academic Editors: Cheng Li,
Fei Zhang, Mou Leong Tan and Kwok
Pan Chun

Received: 11 May 2025

Revised: 16 June 2025

Accepted: 17 June 2025

Published: 1 August 2025

Citation: Serykh, I.; Krasheninnikova, S.; Gorbunova, T.; Gorbunov, R.; Akpan, J.; Ajayi, O.; Reddy, M.; Musonge, P.; Mora-Camino, F.; Olanrewaju, O.A. Climate Change of Near-Surface Temperature in South Africa Based on Weather Station Data, ERA5 Reanalysis, and CMIP6 Models. *Climate* **2025**, *13*, 161. <https://doi.org/10.3390/cli13080161>

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1. Introduction

Modern global climate warming is impacting the world economy and is a primary driver of diverse changes in many sectors of economic activity, including in Southern Africa, particularly the Republic of South Africa. Changes in air temperature affect agriculture, tourism, biodiversity, and vegetation in the region. Extreme Temperature Events (ETEs), such as heatwaves, warm spells, cold waves, and cold spells, have catastrophic impacts on human health and ecosystems [1–3]. Abrupt changes in near-surface temperature can determine mortality rates among young and elderly populations, who are particularly vulnerable [4–7]. It is projected that the frequency, intensity, and duration of ETEs will increase due to climate change. The frequency and duration of extremely high temperatures are increasing in South Africa, while extremely low temperatures are decreasing [8]. According to the latest IPCC report [2], climate change has increased the likelihood of heatwaves and droughts over land surfaces in most African countries. These impacts are expected to be twice as severe over land surfaces compared to marine ecosystems. These phenomena have disastrous consequences for human health and ecosystems, such as increased mortality, morbidity, stress, discomfort, livestock losses, fire hazards, reduced productivity, crop failures, water scarcity, and a decline in quality of life. Such weather events are becoming commonplace in South Africa [8].

Coastal zones are fragile and complex dynamic systems that are increasingly threatened by the combined impacts of anthropogenic stress and climate change [9]. South Africa experiences a moderate level of natural hazard associated with the threat of drought and desertification. High temperatures lead to a greater rate of evaporation and plant transpiration, resulting in water loss from soil and vegetation [10]. South Africa experienced severe droughts in 2016 and 2017, leading to critical water shortages in major cities across the country. The combined effect of reduced rainfall and increased temperatures is expected to exacerbate the existing water security problem in the region [10].

Currently, a promising direction is the investigation of meteorological parameters in South Africa using various types of data: measurements from weather stations [11–21], high-resolution atmospheric reanalyses [22], and models. Earth System Models (ESMs) allow not only for the analysis of fields and the dynamics of parameter changes on a historical dataset up to the present but also for the calculation of climate projections for the near-term future, considering scenario-based changes in greenhouse gases [10]. Before analyzing the dynamics of air temperature, it is necessary to compare reanalyses and models with weather station data.

Near-Surface Air Temperature (NSAT) has been investigated by various researchers for different purposes. In predicting future climate in the semi-arid catchment of Bahi in Tanzania using CMIP6 scenarios, AWI-CM-1-1-MR, MRI-ESM2-0, EC-Earth3, and EC-Earth3-Veg for temperature were chosen according to their highest performance in Taylor Skill Score (TSS) and their ensemble used afterwards. TSS 0.90 and 0.65 were obtained for both minimum and maximum temperature ensembles, respectively. The scenarios of SSP1-2.6 and SSP5-8.5 from CMIP6 for 2080s predictions indicated an overall average minimum temperature increase between 0.2 and 4.5 °C and for maximum temperature between 0.8 and 2.8 °C [23].

In the investigation of climate change impacts on temperature extremes in Iran, Afghanistan, Pakistan, Turkmenistan, Azerbaijan, Armenia, Turkey, and Iraq, M.J. Zareian et al. [24] used a regional ensemble of CMIP6 models. With the climate extreme indices used, maximum temperature is expected to increase in the eight West Asian countries, with the most anticipated to be in Turkmenistan, with a projected increase of more than 5 °C under the SSP5-8.5 scenario.

An ensemble of 40 models from the CMIP6 was adopted by [25] to assess in a comprehensive manner the projected changes in key climate and solar energy parameters over Africa. The result of the application, depending on the emission scenario, revealed a significant warming pattern throughout the continent, with 1.0 to 5.0 °C range in temperature increases by the end of the century.

Thus, developing climate projections, providing warnings, and preventing the consequences of climate change can significantly impact the economic development of the region. Projections of NSAT changes for the near and long-term future are crucial for policymakers, development agents, and disaster prevention personnel to make informed decisions regarding adaptation to and mitigation of extreme weather events, and to foster the economic development of South Africa.

The aim of this study is to investigate climate change in NSAT in South Africa using weather station data, ERA5 reanalysis, and CMIP6 models, with the goal of assessing projections of its change until the end of the 21st century, considering various scenarios of changing greenhouse gas concentrations in the atmosphere. The following section looked at the data and methodology adopted for this study. Section 3 presents the results from NSAT changes at weather stations. Section 4 is the discussion surrounding the result with management implications from the South African point of view to its bridging within science, policy, and governance. The final section concludes.

2. Materials and Methods

This study utilized monthly average Near-Surface Air Temperature (NSAT) data—air temperature at a 2 m height from the surface (T_a , °C) from weather stations in South Africa [26] (Figure 1, Table 1). As shown in Figure 1, the distribution of weather stations is highly uneven. The start dates of the NSAT time series available from these weather stations are also heterogeneous (Table 1). Nevertheless, NSAT data from weather stations represent direct instrumental observations, which are used to calculate the results of reanalyses.

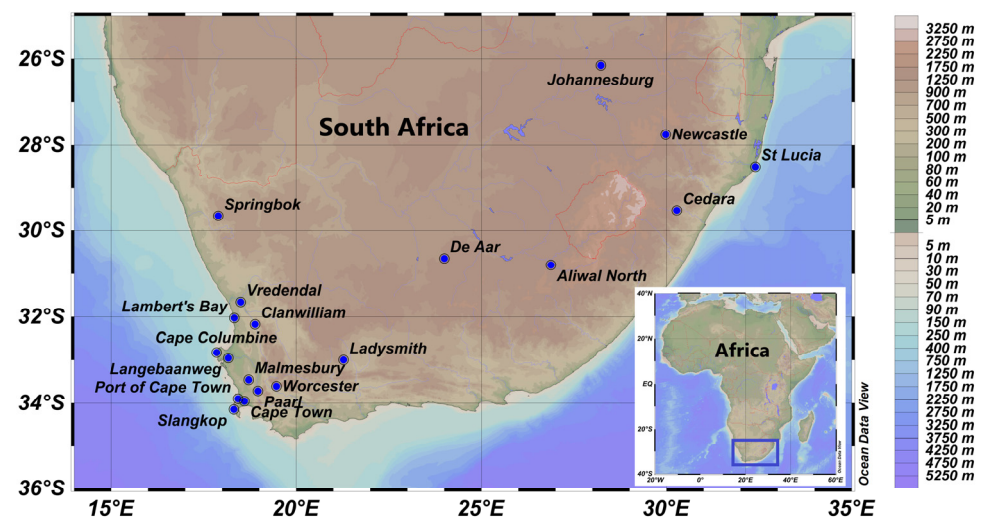


Figure 1. Location of studied area and weather stations.

This study used monthly average NSAT data from the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts for the period 1940–2023, with a regular spatial resolution of $0.25^\circ \times 0.25^\circ$ [27]. Based on the ERA5 reanalysis, average NSAT values were calculated for each year using monthly average values for the study region ($45^\circ\text{--}10^\circ\text{ S}$, $0^\circ\text{--}50^\circ\text{ E}$). Additionally, NSAT data from the NASA MERRA-2 satellite observation reanalysis on a $0.5^\circ\text{ lat.} \times 0.625^\circ\text{ long.}$ grid for the period 1980–2023 [28] and

the NCEP/NCAR reanalysis with a resolution of $2.5^\circ \times 2.5^\circ$ for the period 1948–2023 [29] were used, which confirmed the results obtained using ERA5.

Table 1. Characteristics of near-surface air temperature (T_a , $^\circ\text{C}$) data from South African weather stations. H, m—height above sea level.

Weather Stations	S, $^\circ$	W, $^\circ$	H, m	Period
Vredendal	−31.66	−18.50	23	1958–2023
Springbok	−29.66	−17.90	1007	1940–2023
Slangkop	−34.15	−18.32	8	1999–2023
Paarl	−33.72	−18.97	109	1960–2023
Clanwilliam	−32.18	−18.89	100	1982–2023
Malmesbury	−33.46	−18.72	102	1998–2023
Langebaanweg	−32.96	−18.17	32	1974–2023
Lambert’s Bay	−32.03	−18.33	94	1999–2023
Cape Town	−33.96	−18.60	42	1940–1976, 1978–1990, 1993–2023
Port of Cape Town	−33.90	−18.43	0	1999–2023
Worcester	−33.61	−19.47	270	1989–2022
Johannesburg	−26.15	−28.23	1720	1941–2023
Cape Columbine	−32.83	−17.85	67	1950–2023
De Aar	−30.65	−24.00	1287	1940–2023
Aliwal North	−30.80	−26.88	1351	1940–2021
Newcastle	−27.76	−29.98	1238	1985–2017
Ladysmith	−33.00	−21.28	538	1960–2023
St Lucia	−28.50	−32.40	107	1960–2012
Cedara	−29.53	−30.28	1071	1959–2023

Calculations from Earth System Models (ESMs) within the framework of the CMIP6 project’s future climate change scenarios were analyzed [30,31]. The study used results from the Historical experiment for 1940–2014 from 33 CMIP6 models, listed in Table 2, which were supplemented with results from the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 experiments for 2015–2099 from the same runs of these models [32]. Four continuous datasets for 1940–2099 were created, containing the same portion from the Historical experiment for 1940–2014 and different portions from the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 experiments for 2015–2099. The Historical experiment incorporates the influence of the following major external forcings acting on the global climate system: greenhouse gas forcing, anthropogenic aerosols, volcanic eruptions, and changes in solar activity. In the SSP experiments, the primary role is played by radiative forcing (W/m^2) resulting from potential changes in greenhouse gas concentrations in the atmosphere under various scenarios of future global economic development.

The SSP experiments differ from each other in their scenarios of changing greenhouse gas concentrations in the atmosphere. The influence of these concentrations is present in the SSP experiments in the form of radiative forcing, with values of 2.6, 4.5, 7.0, and $8.5 \text{ W}/\text{m}^2$ by the end of the 21st century. The magnitude of this radiative forcing is indicated in the listed names of the SSP experiments [33]. Projections of future emissions and concentrations of greenhouse gases, aerosols, and ozone-depleting substances are based on assumptions about how socio-economic systems may evolve during the 21st century, but other factors are also considered. Emissions from natural sources, such as the ocean and land biosphere, are generally considered constant or evolving in response to anthropogenic forcing and projected climate change. The SSP experiments also include natural forcings, such as projected changes in solar irradiance and the long-term average background forcing from volcanoes, while individual volcanic eruptions are not accounted for.

Table 2. Difference in average near-surface air temperature (ΔT_a , °C) over the South African region for various observation periods, calculated from different CMIP6 models and scenarios (SSP), along with their minimum, maximum, and average values and standard deviations.

Organization	Model Name	ΔT_a Between 1994–2023 and 1940–1969, °C Historical H SSP2-4.5	ΔT_a Between 2025–2054 and 1994–2023, °C				ΔT_a Between 2070–2099 and 1994–2023, °C			
			SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
1	2	3	4	5	6	7	8	9	10	11
AS-RCEC	TaiESM1	0.55	1.14	1.14	1.14	1.40	1.77	2.54	3.19	4.02
AWI	AWI-CM-1-1-MR	0.90	0.63	0.71	0.88	0.82	0.73	1.55	2.43	2.81
BCC	BCC-CSM2-MR	0.65	0.53	0.73	0.78	0.81	0.71	1.45	2.37	2.68
CAMS	CAMS-CSM1-0	0.48	0.45	0.50	0.64	0.73	0.61	1.23	1.87	2.28
CAS	CAS-ESM2-0	0.53	0.83	0.86	0.78	1.09	1.35	2.23	2.83	3.70
CAS	FGOALS-f3-L	0.77	0.67	0.74	0.85	1.00	0.76	1.56	2.37	2.96
CAS	FGOALS-g3	0.62	0.45	0.64	0.81	0.73	0.35	1.19	2.04	2.34
CCCma	CanESM5	0.86	0.85	0.96	1.13	1.17	1.07	1.99	3.36	4.08
CCCma	CanESM5-CanOE	0.91	0.73	0.96	1.04	1.15	0.91	1.97	3.26	4.14
CMCC	CMCC-CM2-SR5	0.71	0.73	0.75	0.78	0.89	1.04	1.80	2.24	3.05
CMCC	CMCC-ESM2	0.72	0.62	0.70	0.63	0.90	1.12	1.83	2.23	3.16
CNRM-CERFACS	CNRM-CM6-1	0.60	0.82	0.92	0.88	1.07	1.19	2.15	2.91	3.94
CNRM-CERFACS	CNRM-CM6-1-HR	0.54	0.89	0.90	0.96	1.14	1.40	2.30	3.04	3.86
CNRM-CERFACS	CNRM-ESM2-1	0.58	0.81	0.86	0.89	1.00	1.28	2.10	2.93	3.62
CSIRO-ARCCSS	ACCESS-CM2	0.65	0.90	1.00	1.08	1.09	1.38	2.23	3.10	3.83
CSIRO	ACCESS-ESM1-5	0.64	0.64	0.85	0.78	0.98	0.83	1.72	2.46	2.94
EC-Earth-Consortium	EC-Earth3	0.69	0.64	0.69	0.81	0.82	0.88	1.66	2.54	3.11
EC-Earth-Consortium	EC-Earth3-Veg	0.66	0.64	0.63	0.79	0.83	0.80	1.60	2.51	3.02
INM	INM-CM4-8	0.58	0.44	0.54	0.68	0.79	0.37	1.11	1.85	2.31
INM	INM-CM5-0	0.47	0.42	0.57	0.71	0.67	0.45	1.01	1.73	2.02
IPSL	IPSL-CM6A-LR	0.60	0.71	0.80	0.91	0.96	0.83	1.81	2.72	3.48
MIROC	MIROC-ES2L	0.64	0.51	0.53	0.65	0.76	0.62	1.32	2.11	2.56
MIROC	MIROC6	0.51	0.53	0.56	0.61	0.75	0.68	1.31	1.93	2.41
MOHC	UKESM1-0-LL	0.72	0.97	1.19	1.33	1.38	1.29	2.50	3.56	4.42
MPI-M	MPI-ESM1-2-LR	0.63	0.42	0.67	0.67	0.65	0.41	1.21	2.08	2.35
MRI	MRI-ESM2-0	0.50	0.78	0.82	0.86	1.05	1.05	1.72	2.51	3.14
NASA-GISS	GISS-E2-1-G	0.59	0.74	0.76	0.83	0.99	0.79	1.67	2.47	3.17
NCAR	CESM2	0.47	0.82	0.87	0.98	1.11	1.27	2.21	2.85	3.88
NCAR	CESM2-WACCM	0.63	0.84	0.88	0.85	1.13	1.23	2.16	2.79	3.95
NCC	NorESM2-LM	0.43	0.41	0.47	0.49	0.69	0.52	1.18	1.70	2.34
NCC	NorESM2-MM	0.55	0.45	0.56	0.64	0.76	0.61	1.33	1.93	2.64
NIMS-KMA	KACE-1-0-G	0.69	0.98	1.03	1.14	1.24	1.47	2.24	3.09	3.75
NOAA-GFDL	GFDL-ESM4	0.67	0.51	0.59	0.81	0.76	0.58	1.32	2.31	2.57
Minimum		0.43	0.41	0.47	0.49	0.65	0.35	1.01	1.70	2.02
Maximum		0.91	1.14	1.19	1.33	1.40	1.77	2.54	3.56	4.42
Standard Deviation		0.12	0.19	0.18	0.18	0.20	0.36	0.44	0.50	0.68
Average		0.63	0.68	0.77	0.84	0.95	0.92	1.73	2.52	3.17

In the 6th phase of the CMIP project (CMIP6), the number of participating models has increased, their spatiotemporal resolution has been improved, and the scenarios for calculating the future climate have been modified. However, the spatial resolution of CMIP6 models (1–2°) is still quite coarse for taking into account the influence of local features that determine the regional climate [34]. Nevertheless, they provide a quantitative basis for assessing climate change in the reports of the IPCC [35]. To reduce the overall error of model calculations, the results were averaged over a sufficiently large ensemble of 33 models (Table 2). This average value across the models was taken as the “best estimate” model for analyzing long-term climate changes, which primarily depend on the impact of the external forcings mentioned above [36]. Suppressing errors by averaging over an ensemble of models is an advantage of this approach, while smoothing out internal natural climate variability is its disadvantage [37].

For reanalyses and models, NSAT anomalies were calculated by subtracting the average annual cycle (climatology) from the monthly average values at each grid point. Based on the World Meteorological Organization’s (WMO) recommendation to use a 30-year average as the climatology, the earliest 30-year period available for ERA5, 1940–1969, was used as the climatology in this study. Annual average NSAT anomalies were then calculated and

are considered hereafter. Since estimates of linear trends are highly sensitive to the initial and final values of the time series, our analysis of long-term climate changes is based on a comparison of anomalies averaged over the 30-year periods 1940–1969 and 1994–2023, using both ERA5 reanalysis data and the combination of Historical and SSP model results (see above), as well as for the periods 2025–2054 and 2070–2099 using model results under the SSP scenarios. Model results were averaged over the entire ensemble of 33 models. Note that when using a single climatology for the entire period, the difference in anomalies between periods is equal to the difference in temperatures.

This study utilizes hydrodynamic (non-statistical) models, consisting of various components of the climate system. This enables the possibility to extend calculations to assess the future state of the climate (to make so-called “climate projections”) based on the specification of different external forcings (radiative forcing), determined by the selected SSP scenarios of future changes in greenhouse gas concentrations in the atmosphere. A projection is a description of what could happen in the future under various scenarios of human development; it allows for significant changes in the set of boundary conditions that can affect it.

The ensemble of 33 CMIP6 models considered allows for the estimation of the uncertainty in climate projections for each of the SSP scenarios. In the early decades, natural (internal) climate variability contributes the most to the uncertainty in projections; in the mid-21st century, inter-model spread introduces the greatest uncertainty; and by the end of the 21st century, the uncertainty is most strongly influenced by differences between the SSP scenarios [38,39]. It is important to keep in mind that various CMIP6 models employ different methods for representing the same physical, chemical, and biological processes; different ways of specifying the depth of the boundary layer; and differ in the spatial resolution and parameterization of processes with spatial scales smaller than the grid cell (so-called subgrid processes), among other factors. All of this introduces significant differences in the results of the 33 CMIP6 models analyzed. It can be reasonably assumed that each of the CMIP6 models contains its own random errors, which are suppressed when averaging over a sufficiently large ensemble, which is commonly done when analyzing the results of CMIP6 models [40].

Thus, this study employed an ensemble approach, consisting of averaging the results of 33 CMIP6 models and estimating the inter-model spread (standard deviation). We believe that this approach is the most justified for assessing future long-term climate changes. Each of the CMIP6 models contain errors due to their extreme complexity, but these errors are not correlated with the errors of other models [40]. Therefore, when averaging over a sufficiently large ensemble (more than 30 members), the errors of different models are suppressed, as they can be likened to white noise. Based on this, and the use of anomalies instead of nominal values, no bias correction was applied to the CMIP6 model outputs relative to observed data. When averaging over the ensemble, the main part of the randomness is suppressed, and the response to external forcing, which plays a decisive role in climate projections over a long time interval (until the end of the 21st century), is revealed.

To ensure that the contribution of CMIP6 models to the ensemble was equal, only one run from each of the 33 models was used. To obtain average NSAT fields from the 33 CMIP6 models, the results of each model were first linearly interpolated onto a common $1^\circ \times 1^\circ$ grid. The Historical experiment results end in 2014, and the SSP experiment results begin in 2015. In cases where the averaging period encompassed this transition, the final average value included results from the Historical experiment up to 2014 and, starting from 2015, results from the SSP experiments. This methodology has already been applied by us

for analyzing temperature changes in the western Russian Arctic region and is described in more detail in [37].

Correlation analysis. To assess the relationships between the time series of NSAT anomalies derived from three independent data sources, we employed Pearson correlation using the XLSTAT 2016 add-in for Microsoft Office Excel 2016. A preliminary analysis was conducted to ensure that each time series conformed to a normal distribution. The statistical significance of each correlation coefficient was evaluated using Student's *t*-test with a significance level of $p = 0.05$ [41]. For time series with 75 data points, correlation coefficients with absolute values greater than 0.4 ($-0.4 > r > 0.4$) were considered statistically significant.

Trend analysis. We investigated the long-term trends in NSAT using the non-parametric Mann–Kendall test [42,43], which is appropriate for detecting statistically significant increasing or decreasing trends in a variable over time, particularly when the data may not be normally distributed. The Mann–Kendall test was applied to the 75-year time series (1940–2014) and 30-year time series (1994–2023) to assess the significance of any observed trends.

3. Results

3.1. Correlation and Trend Analysis

The Table 3 shows the average, maximum, and minimum values, as well as the standard deviation, of NSAT anomalies from the CMIP6 model ensemble, the ERA5 reanalysis, and two weather stations (Springbok, De Aar) for the general period 1940–2014, covering all types of data.

Table 3. Summary statistics of average, maximum, and minimum values and standard deviation of NSAT anomalies from the CMIP6 model ensemble, the ERA5 reanalysis, and two weather stations (Springbok, De Aar) for the general period 1940–2014.

Variable	Observations	Obs. With Missing Data	Obs. Without Missing Data	Min.	Max.	Mean	Std. Deviation
CMIP6_Histoprical	75	0	75	−0.199	0.792	0.199	0.242
ERA5	75	0	75	−0.423	0.733	0.211	0.275
Springbok	75	0	75	−1.771	1.029	0.000	0.498
De Aar	75	0	75	−1.419	1.481	0.000	0.642

The correlation matrix of Table 4 displays the relationships between NSAT anomalies derived from three independent data sources, all spanning the 1940–2014 period. The data sources include the following: (1) the averaged output of the 33-member CMIP6 model ensemble; (2) the ERA5 reanalysis dataset; and (3) measurements from three representative weather stations.

Table 4. Correlation matrix (Pearson ($n-1$)).

Variables	CMIP6_Histoprical	ERA5	Springbok	De Aar
CMIP6_Histoprical	1	0.8	0.1	0.6
ERA5	0.8	1	0.2	0.8
Springbok	0.1	0.2	1	0.4
De Aar	0.6	0.8	0.4	1

Values in bold are different from 0 with a significance level $\alpha = 0.05$.

The strongest positive correlation in NSAT anomalies was observed between the CMIP6 model ensemble and the ERA5 reanalysis dataset ($r = 0.8$), indicating good agreement between these two data sources. Furthermore, NSAT anomalies at the De Aar weather

station showed significant positive correlations with the corresponding anomalies derived from the 33 CMIP6 model ensemble ($r = 0.6$) and the ERA5 reanalysis ($r = 0.8$), suggesting that the CMIP6 model ensemble and the reanalysis effectively capture the NSAT long-term changes in this location.

Application of the Mann–Kendall test to assess long-term trends over the period 1940–2014 revealed statistically significant increasing trends ($p < 0.05$) in NSAT for all three data types: weather station observations, CMIP6 model simulations, and the ERA5 reanalysis, supporting a conclusion of regional warming.

3.2. Changes at Weather Stations

NSAT data from 19 weather stations were analyzed (Table 1, Figure 2). Among them, weather stations covering the longest continuous observation period of 1940–2023 were identified. The data series at Cape Town and Johannesburg weather stations were reconstructed with the mean values and the value at the neighboring weather station, respectively. There were five such stations: Springbok, Cape Town, De Aar, Johannesburg, and Aliwal North. Over this period, all weather stations show an increase in ΔT_a , with the largest increase of 1.7°C at the De Aar weather station (in the central part of South Africa) and the smallest increase of 0.1°C at the Aliwal North weather station (in the western coastal part of Africa) (Table 5, Figure 2). The highest average NSAT was observed at the Springbok weather station ($17.72 \pm 0.42^\circ\text{C}$), and the lowest ($15.25 \pm 0.54^\circ\text{C}$ and $15.84 \pm 0.62^\circ\text{C}$) at the Aliwal North and Johannesburg weather stations, respectively. For these five stations, the period 1940–1969 was analyzed separately. At the Springbok ($\Delta T_a = 0.05^\circ\text{C}$) and De Aar ($\Delta T_a = 0.05^\circ\text{C}$) stations, no significant trend was identified for 1940–1969, while at the Johannesburg and Cape Town weather stations a significant decrease in NSAT was found for this period, with $\Delta T_a = -1.1$ and -1.5°C , respectively (Table 5).

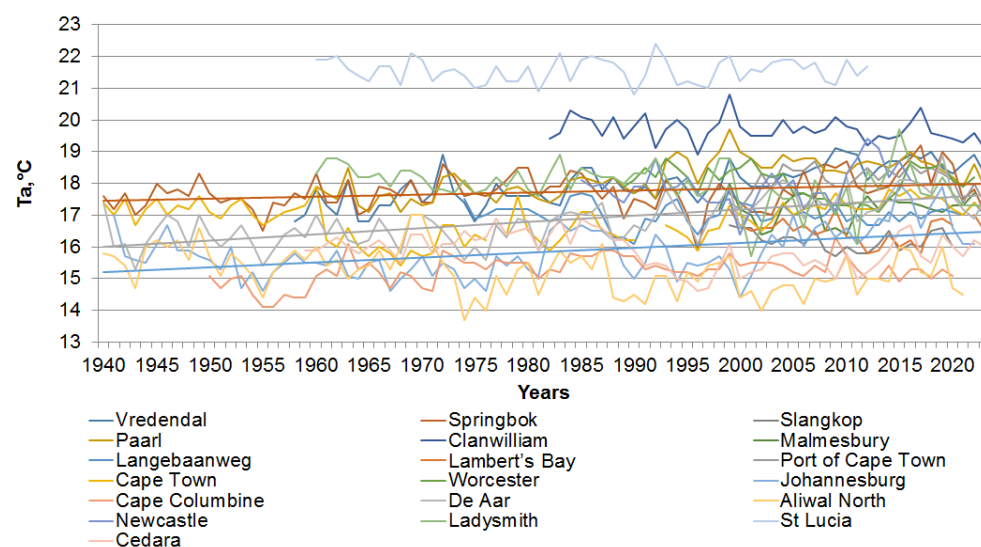


Figure 2. Interannual variability of annual average near-surface air temperature (T_a , $^\circ\text{C}$). Straight lines indicate their linear trends.

The period 1994–2023 was also considered for 10 weather stations. It is noteworthy that opposite trends in NSAT change were identified at different weather stations over this period. Significant positive NSAT trends were identified at the Vredendal, Springbok, Johannesburg, Cape Town, De Aar, and Cedara weather stations, and significant negative trends were identified at Paarl and Clanwilliam (Table 5). The remaining NSAT trends (Table 5) for 1994–2023 were found to be insignificant by the Mann–Kendall test.

Table 5. Minimum, maximum, and average values, standard deviations, and long-term changes of near-surface air temperature (ΔT_a , °C) from weather station data in South Africa for different periods.

Meteostations	Years	T_{amin} , °C	T_{amax} , °C	$T_{aev} \pm \sigma$, °C	ΔT_a , °C
Vredendal	<u>1994–2023</u>	17.4	19.1	18.39 ± 0.37	0.95
	1940–1969	16.49	18.34	17.55 ± 0.30	0.05
Springbok	<u>1994–2023</u>	15.91	19.16	17.83 ± 0.52	0.42
	1940–2023	15.91	19.16	17.72 ± 0.42	0.15
Paarl	<u>1994–2023</u>	17.9	19.7	18.62 ± 0.26	−0.5
Clanwilliam	<u>1994–2023</u>	18.9	20.8	19.66 ± 0.27	−0.35
Langebaanweg	<u>1994–2023</u>	16.4	17.8	17.05 ± 0.21	−0.15
	1940–1969	14.6	17	15.53 ± 0.39	−1.1
Johannesburg	<u>1994–2023</u>	14.4	18	16.26 ± 0.68	2.1
	1941–2023	14.4	18	15.84 ± 0.62	1.3
Cape Town	1940–1969	15.4	17.9	16.83 ± 0.54	−1.5
	<u>1994–2023</u>	15.9	17.8	17.11 ± 0.35	1.1
	1940–2023	15.7	17.9	16.83 ± 0.51	0.4
	1940–1969	15.3	17.0	16.32 ± 0.38	0.95
De Aar	<u>1994–2023</u>	16.1	18.9	17.45 ± 0.46	0.9
	1940–2023	15.3	18.9	16.81 ± 0.57	1.7
	1940–1969	14.4	17.0	15.63 ± 0.39	0.1
Aliwal North	1994–2021	14.0	16.0	14.99 ± 0.41	0.4
	1940–2021	13.7	17.0	15.25 ± 0.54	0.95
Ladysmith	<u>1994–2023</u>	15.7	19.7	17.68 ± 0.58	0.3
Cedara	<u>1994–2023</u>	14.6	16.7	15.56 ± 0.42	1.1

Note: The periods for which the comparison of NSAT data from meteorological stations with the results obtained using the CMIP6 ensemble of models are underlined. The periods with the longest series of NSAT observations at meteorological stations are highlighted in bold.

Thus, the dynamics of NSAT during individual 30-year periods are heterogeneous at various weather stations. However, a comparison of the earlier period, 1940–1969, and the later observation period, 1994–2023, showed that the average values at all weather stations are lower in the earlier period than in the later period. In other words, long-term changes in NSAT at various weather stations in the South Africa demonstrate a similar trend—climate warming.

3.3. Changes Based on ERA5 Reanalysis and CMIP6 Models

Annual average NSAT anomalies, calculated from ERA5 reanalysis and averaged over the South African region (45–10° S, 0–50° E) (Figure 3, black line), generally demonstrate a positive linear trend over the period 1940–2023, which, when estimated using the least squares method, is 0.11 ± 0.04 °C. Furthermore, this increase in NSAT occurred unevenly over time. Thus, from 1940 until approximately the mid-1970s, long-period (interdecadal) changes in NSAT in the study region were small. A rapid increase in NSAT in the South African region began around the mid-1970s and continues to the present day. It is not possible to indicate more precisely the beginning of this warming due to the short-period (interannual) variability of the time series of average NSAT anomalies in the study region. Nevertheless, the beginning of the above-mentioned warming can be linked to the climate shift of 1976/1977, which occurred in the Pacific Ocean and had a global impact [44]. Pauses in the increase in average NSAT in the South African region can also be noted, occurring approximately in the first half of the 1990s and in the 2000s. The pause in the first half of the 1990s can be linked to the powerful eruption of Mount Pinatubo in 1991, which had a global cooling effect for several years due to the ejection of a large amount of aerosols into the stratosphere [45]. The temporary cessation of the increase in average NSAT in the South African region in the 2000s is most likely associated with a global warming hiatus caused by conditions in the Pacific Ocean similar to La Niña, in which the ocean at depths greater than 300 m absorbed more heat compared to its upper layer [46]. In the 2010s, this warming pause ended and the NSAT of the study region resumed its increase, which continues to

the present day. Thus, the variations in average NSAT in the South African region are influenced by changes in global temperature, which are characterized by both the climate shifts of 1976/1977 and 1998/1999 associated with the Pacific Decadal Oscillation (PDO)—a large-scale mode of natural climate variability [47], and by the influence of external forcings on the global climate system.

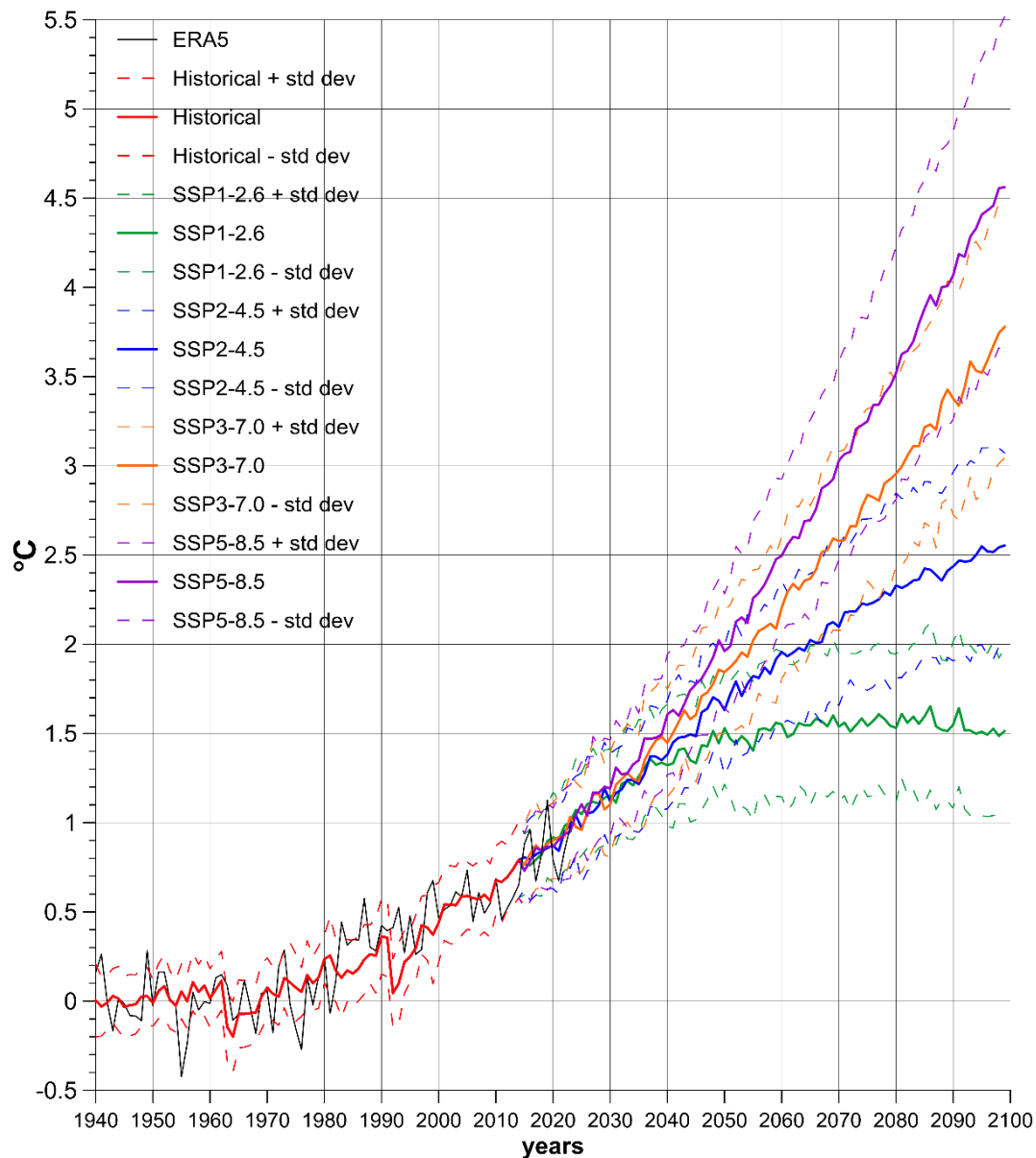


Figure 3. Interannual variability of annual average near-surface air temperature anomalies (T_a , °C) over the South African region based on ERA5 data (black) for 1940–2023 and based on CMIP6 model experiment results for the following scenarios: Historical (red) for 1940–2014, SSP1-2.6 (green), SSP2-4.5 (blue), SSP3-7.0 (orange), and SSP5-8.5 (purple) for 2015–2099. The boundaries of the variability ranges of the 33 CMIP6 models (standard deviation) are represented by dashed lines.

El Niño-Southern Oscillation (ENSO) has a significant influence on interannual climate variability in the South African region [48,49]. This impact is also evident in the graph of changes in average NSAT anomalies in the study region for 1940–2023 (Figure 3, black line). For example, local maxima in NSAT in 1983, 1987, 1998, and 2016 can be linked to the strong El Niño events observed in these years and those that began in the years preceding them. During El Niño events, the surface temperature increases and evaporation

risers in the equatorial Pacific Ocean [50]. The warm and humid air rises into the upper layers of the troposphere and condenses there, releasing additional latent heat. Due to the equatorial Walker cells, this heat spreads first throughout the tropics and then, with the help of the Hadley cell, to the mid-latitudes, causing positive NSAT anomalies, including in the South African region. During La Niña events, the opposite situation is observed, which can lead to negative NSAT anomalies in the study region. Such local minima in NSAT were observed in the South African region, for example, in 1976, 2011, and 2021, during strong and prolonged La Niña events. It is important to note that the influence of ENSO on the interannual NSAT anomalies in the South African region has a delayed effect, meaning that it typically manifests in the year following the onset of El Niño and La Niña events. This makes it possible to forecast interannual NSAT anomalies in the South African region with approximately one year's lead time, but studying this issue requires further research.

Changes in annual average NSAT anomalies averaged over the results of the Historical experiment of 33 CMIP6 models for 1940–2014 (Figure 3, red line) demonstrate climate warming in the South African region. Thus, between the periods 1940–1969 and 1994–2023, the average model NSAT values increased by 0.63 ± 0.12 °C (Table 2, column 3). Similarly to the ERA5 data, weak changes in NSAT are observed from 1940 until approximately the mid-1970s in the ensemble of 33 CMIP6 models. The only exception is a decrease in average model NSAT for several years in the 1960s, which is apparently associated with the eruption of Mount Agung in 1963, which, like the eruption of Mount Pinatubo, had a global cooling effect for 2–3 years [45]. As with the ERA5 data, an increase in NSAT in the study region is observed approximately from the mid-1970s onwards in the average model CMIP6 values, interrupted for several years by the eruptions of the El Chichón volcano in 1982 and Mount Pinatubo in 1991.

Thus, the changes in annual average NSAT anomalies in the South African region from the ensemble of 33 CMIP6 models accurately reproduce the changes from the ERA5 data. Moreover, the interannual variability of NSAT from ERA5 almost completely falls within the inter-model spread indicated in Figure 3 by the dashed lines. Furthermore, the eruptions of large volcanoes cause local minima in NSAT in the South African region on the interannual timescale, both in the ERA5 data and in the modeling results, since they are a consequence of the influence of external forcings on the climate system. These negative NSAT anomalies in the South African region can be predicted with approximately one year's lead time after the onset of large volcanic eruptions occurring in the tropics and having an explosive character, due to which the ejected aerosols reach the stratosphere, spread, and remain there for several years.

It should be noted that, because the periods of natural climate variability modes may not coincide in different CMIP6 models, for example, the periods of ENSO [51], averaging over the ensemble of models suppresses natural climate variability. And in the resulting average model ensemble values, the influence of external forcings acting on the climate system is mainly manifested. These external forcings primarily include radiative forcing from the greenhouse gas content in the atmosphere and the screening effect of aerosols of both volcanic and anthropogenic origin, as well as the influence of variations in solar activity on total solar irradiance [40].

Therefore, it can be assumed that the above-mentioned features of the NSAT time series in the South African region based on average model ensemble values are caused by external forcings on the global climate system, which led to changes in global temperature that manifested in the study region. The results presented in IPCC reports provide grounds for asserting that, on interdecadal timescales, such an external forcing exerting the main influence on the global climate is a change in radiative forcing due to anthropogenic increases in greenhouse gas concentrations in the atmosphere [38,40]. At the same time, the

average model ensemble NSAT values do not reproduce the influence of natural climate variability modes such as ENSO and PDO, which also affect the study region but require separate investigation.

Throughout the period 1940–2023, the annual average NSAT anomalies in the South African region changed unevenly, not only over time but also spatially (Figure 4). Thus, climate warming in the study region occurred more noticeably over land (by approximately 1 °C) than over its water areas (by approximately 0.5 °C). According to ERA5 data, the annual average NSAT increased most significantly over land in a number of areas of South Africa (Figure 4c), which is apparently related to their relief and climatic features. According to ERA5 data, the annual average NSAT increased most significantly in the mountainous areas of southern and southeastern South Africa, as well as in the coastal areas of Namibia. However, these regional maxima of NSAT increase may also be related to errors in the model used in ERA5 in reproducing certain physical mechanisms in conditions of complex terrain, as well as to the limited availability of observational data in these areas during the initial part of the study period.

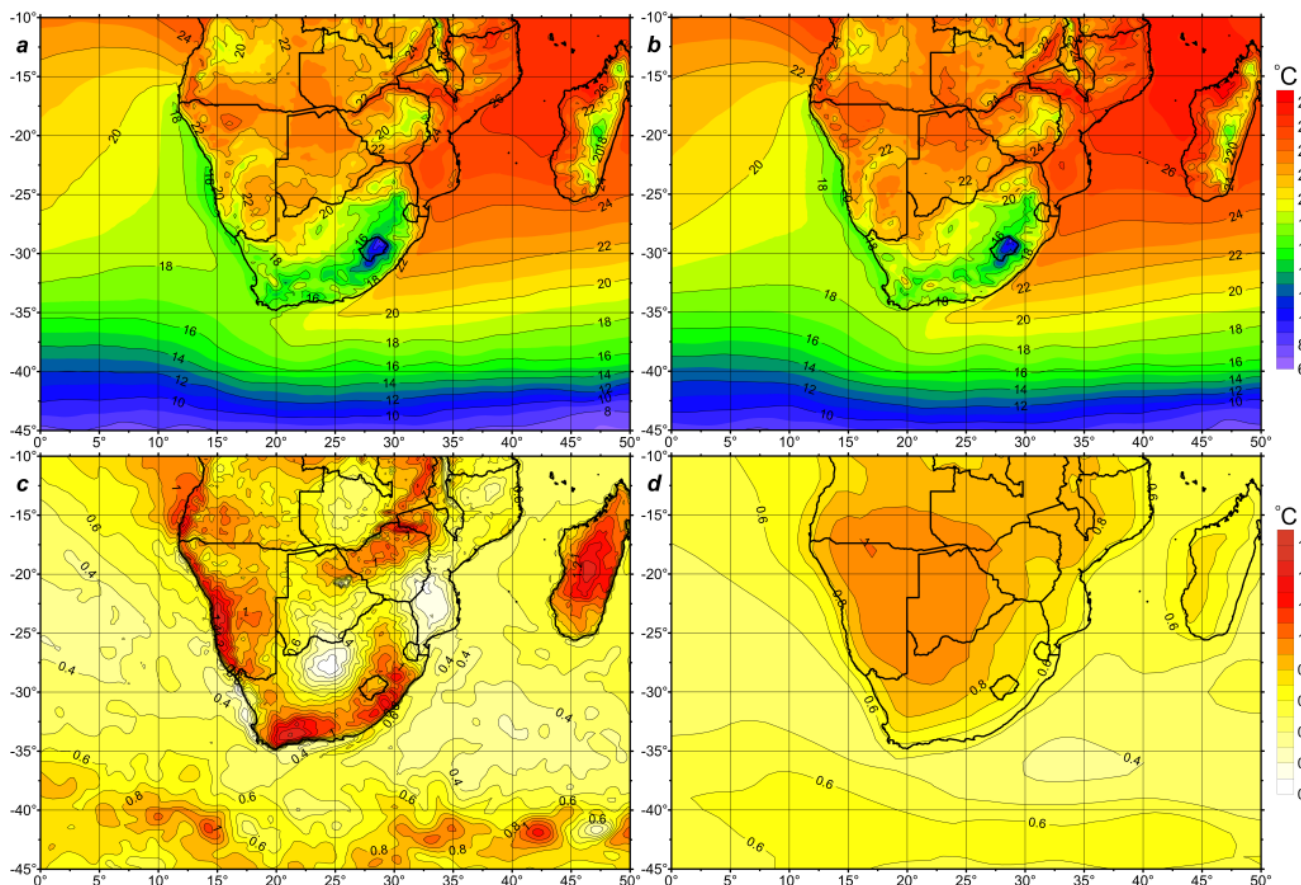


Figure 4. Average Near-Surface Air Temperature (NSAT) (T_a , °C) from ERA5 reanalysis for 1940–1969 (a) and 1994–2023 (b). Difference between the average NSAT (ΔT_a , °C) for 1994–2023 and 1940–1969 from ERA5 reanalysis (c) and from 33 CMIP6 models (Historical and SSP2-4.5 experiments) (d).

The ensemble of 33 CMIP6 models demonstrates a less detailed spatial distribution of changes in annual average NSAT on land compared to ERA5, with the largest areas of NSAT increase located in the central part of the analyzed region, reaching up to +1 °C (Figure 4d). This may be due to the coarser spatial resolution of CMIP6 models (1–2°) compared to ERA5 data (0.25°). At the same time, the ensemble of 33 CMIP6 models agrees closely with ERA5 data in reproducing the increase in NSAT over the oceanic surface of

the study region, where the NSAT increase averages $0.5\text{ }^{\circ}\text{C}$ in both ERA5 and the CMIP6 ensemble (Figure 4).

Thus, both the ERA5 reanalysis data and the results of the ensemble of 33 CMIP6 models demonstrate an increase in NSAT over the land area of the study region that is almost twice as large as the increase in NSAT over its water area. This difference can be explained by the stabilizing role of the ocean, whose surface, due to heat exchange with its deep layers, which have a high heat capacity, heats up more slowly than the soil surface and the lower layer of the atmosphere. Thus, the deep layers of the ocean, accumulating heat, slow down the increase in temperature of its surface and the NSAT above it.

Given the obtained results, it can be concluded that the CMIP6 model ensemble generally reproduces the NSAT increase in the South African region for 1940–2023 but does not account for some local features on land. This provides a basis for assessing future NSAT changes in the study region based on climate projections obtained from the SSP experiments of the same ensemble of 33 CMIP6 models. However, it should be taken into account that some local features of these changes may differ from the average model values due to the insufficiently high spatial resolution of the CMIP6 models. It should also be taken into account that the average model values suppress natural climate variability modes such as ENSO and PDO, which influence the interannual and interdecadal NSAT anomalies in the South African region, respectively. Another significant uncertainty in the NSAT projection by the CMIP6 model ensemble is introduced by the inability to accurately predict large volcanic eruptions in advance, which have a cooling effect on both global temperature and the NSAT in the study region.

Based on the SSP experiments of the ensemble of 33 CMIP6 models, the increase in the annual average NSAT in the South African region will continue until the end of the 21st century, but the magnitude and temporal dynamics of this increase differ significantly between different greenhouse gas emission scenarios (Figure 3). Thus, according to the SSP1-2.6 scenario, with the most significant and immediate emission reductions, the average NSAT in the study region will slow down its increase by the middle of the 21st century, and in the second half it will stabilize altogether (Figure 3, green line). However, the average NSAT will still increase between 1994–2023 and 2070–2099 by $0.92 \pm 0.36\text{ }^{\circ}\text{C}$ (Table 2, column 8). According to the SSP2-4.5 scenario, with less significant and smoother CO_2 emission reductions, the increase in the average NSAT in the study region will slow down throughout the 21st century but will not cease (Figure 3, blue line). According to this scenario, the average NSAT will increase between 1994–2023 and 2070–2099 by $1.73 \pm 0.44\text{ }^{\circ}\text{C}$ (Table 2, column 9). According to the SSP3-7.0 scenario, in which the increase in greenhouse gas concentrations in the atmosphere will continue at roughly the same rate as it is happening now, the average NSAT in the South African region will increase linearly throughout the 21st century (Figure 3, orange line). And in this case, the average NSAT in the study region will increase between 1994–2023 and 2070–2099 by $2.52 \pm 0.50\text{ }^{\circ}\text{C}$ (Table 2, column 10). According to the most extreme SSP5-8.5 scenario, in which anthropogenic greenhouse gas emissions will increase with acceleration, the average NSAT in the South African region will increase with positive acceleration (Figure 3, purple line) and will increase between 1994–2023 and 2070–2099 by $3.17 \pm 0.68\text{ }^{\circ}\text{C}$ (Table 2, column 11).

When analyzing the CMIP6 projections of changes in the average NSAT of South Africa (Figure 3), it is noteworthy that the results of the SSP experiments differ little from each other during the first few decades. Thus, the changes in the average NSAT between 1994–2023 and 2025–2054 are $0.68 \pm 0.19\text{ }^{\circ}\text{C}$, $0.77 \pm 0.18\text{ }^{\circ}\text{C}$, $0.84 \pm 0.18\text{ }^{\circ}\text{C}$, and $0.95 \pm 0.20\text{ }^{\circ}\text{C}$ for the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 experiments, respectively (Table 2, columns 4–7). It follows that, according to the ensemble of 33 CMIP6 models, in the next 30 years there will be an increase in the average NSAT of the South African region

with a spread of 0.49–1.15 °C, with little dependence on the SSP scenario of greenhouse gas emissions. Moreover, the increase in the average NSAT in the study region in the next 30 years is reproduced by all, without exception, the CMIP6 models considered under any of the considered SSP scenarios, with a range of 0.41–1.40 °C from the minimum to the maximum value. It is also noteworthy that the inter-model spread of NSAT projections for the next 30 years is weakly dependent on the SSP scenario (Table 2) and changes little over time (Figure 3). However, in the estimates of changes in the average NSAT between 1994–2023 and 2070–2099, the inter-model spread increases and begins to depend more strongly on the SSP scenario, with values ranging from 0.36 to 0.68 °C. Also, as for the next 30 years, all 33 CMIP6 models project an increase in the average NSAT in the South African region by the end of the 21st century under any of the SSP scenarios, but in the range from a minimum value of 0.35 °C to a maximum value of 4.42 °C, with a significant dependence on the CO₂ emission scenario (Table 2, columns 8–11).

The ensemble of 33 CMIP6 models projects an increase in the average NSAT between 1994–2023 and 2070–2099 unevenly across the South African region (Figure 5). Thus, according to this ensemble, the NSAT will increase much more noticeably over the land of the study region than over its water areas. Moreover, the magnitude of this uneven NSAT increase depends on the SSP experiment. Thus, according to the most favorable SSP1-2.6 scenario, the NSAT over land will increase on average by 1.2 °C, while over the ocean it will increase by 0.8 °C (Figure 5a). According to the most extreme SSP5-8.5 scenario, the increase in NSAT over land will average 4.2 °C, while over the ocean it will average 2.6 °C (Figure 5d). As mentioned above, a more significant increase in NSAT over the land area of the study region compared to its water area can be associated with the high heat capacity of the ocean, which accumulates heat and thus has a smoothing effect on the increase in its surface temperature. This also affects the coastal areas of the study region, where the increase in NSAT is significantly less compared to the inland areas of South Africa (Figure 5).

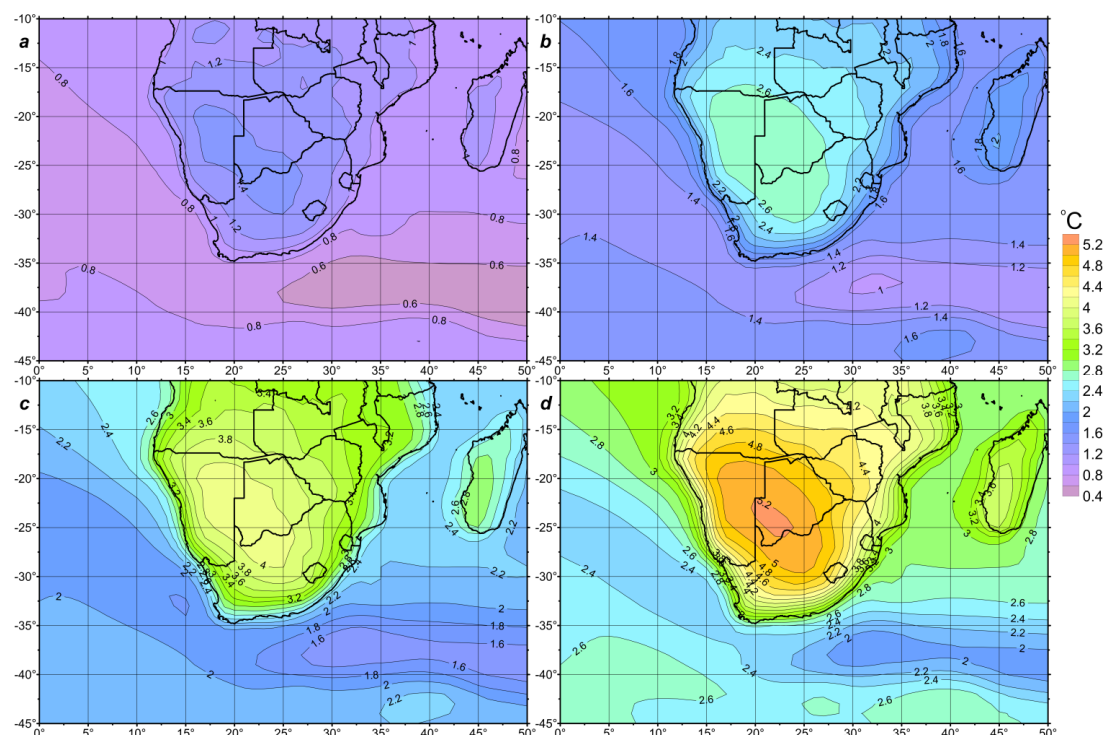


Figure 5. Fields of changes in average near-surface air temperature (ΔT_a , °C) from 33 CMIP6 models between 1994–2023 and 2070–2099 based on the results of the SSP1-2.6 (a), SSP2-4.5 (b), SSP3-7.0 (c), and SSP5-8.5 (d) scenarios.

4. Discussion

4.1. Changes Based on Weather Station Data

Table 6 shows long-term trends in annual average temperature changes in the South African region according to different authors. Most climate studies of the South African region rely on the database of the South African Weather Service (SAWS) as the main source [8]. In this study, different weather station data were used, taken from a different source [26].

Data from 23 weather stations in the study region for 1960–2003 showed positive trends in the time series of annual average maximum temperatures, 13 of which were significant, with higher trends for central stations than for those closer to the coast [21]. Urban stations, on average, have lower NSAT trends than non-urban stations [11,21].

Trends in average seasonal temperature showed that they are not constant throughout the year, with the average trend for autumn showing a maximum and for spring showing a minimum T_a [21]. Estimates of long-term changes in surface temperature in South Africa for 1940–1989 showed that no real evidence of general changes in average monthly temperatures was found for this period, and only a small number of stations showed a significant increase in average annual temperature, all of which are located along the coast [52]. Similar observations were made for East Africa [20] and the Zimbabwe area [16]. It was also found that temperature trends do not coincide between seasons. As the results of early studies show, it is advisable to investigate trends for a shorter time scale—trends for individual seasons and months. This will allow for the identification of more detailed regional features of temperature changes in the South African region than with annual average time series [21]. Trends in the daily temperature range also show that results on a regional basis do not necessarily coincide with general global trends, which have been negative over the last century [53].

Table 6. Long-term trends in annual average temperature changes in the South African region according to different authors.

Period, Years	Location	ΔT_{aev} , °C	Data Type	Authors
1940–1989	Along the coast of South Africa	Significant positive trend	Weather stations	[52]
1991–2003/ 1960–1990/ 1960–2003	Southern Africa	+0.09/+0.11/+0.13	Weather stations	[21]
1979–2010	All Africa	Significant positive trend	MSU, RSS, UAH	[54]
1960–2009	Southern Africa	Significant positive trend	Weather stations	[55]
1960–2010	Southern Africa/Central South Africa	Maximum and minimum temperatures significantly increased/minimum temperatures decreased	Weather stations, models	[56]
1960–2016	Southern Africa	Annual trend of maximum temperature increase at a rate of 0.02 °C per year	Weather stations	[57]
1950–1999	Southern Africa	0.02 °C per year 0.12 °C per decade 0.18 °C per decade in winter and 0.09 °C per decade in summer	5 models of GCM CMIP6	[10]

Average temperatures in the 1990s were significantly higher than in previous decades (18.48 °C in 1991–2003 compared to 18.18 °C in 1960–1990). However, temperature trends in South Africa have not increased in the last decade. The average temperature trend for 1991–2003 is 0.09 °C per decade, compared to 0.11 °C per decade for 1960–1990. A fairly strong increase in average temperature was observed in the early 1980s, which was the main reason for the overall temperature increase over the entire period from 1960–2003. While the average trend of annual average temperatures is 0.13 °C per decade for 1960–2003, insignificant trends of 0.04 °C per decade and 0.01 °C per decade were found for 1960–1982 and 1983–2003, respectively. The 1982–1983 rainy season was one of the driest and hottest in most of South Africa due to the extreme El Niño event, but it appears that average temperatures have not fully recovered since then. Temperature trends are partially caused

by El Niño and La Niña events [21]. However, El Niño and La Niña events do not play a significant role in the observed substantial temperature increases in late summer [58].

Significant trends of T_a increase from 1979–2010 have been found across Africa using total lower tropospheric temperature data from the Microwave Sounding Unit (MSU) from the Remote Sensing System (RSS) and University of Alabama in Huntsville (UAH) datasets [54]. Southern Africa will experience more significant warming than the global average, and this could have serious consequences for the environment, economy, and society [2]. During the summer season, significantly higher temperature values were observed in the regions of North and South Africa in 1995–2010 than in 1979–1994. However, in the winter months significant warming was concentrated in northern Africa. When comparing the last two decades with the period 1979–1990, warming is observed in the same regions and is concentrated in 2001–2010. The presented results indicate that climate change in Africa is likely not primarily a result of changes in the ENSO (a teleconnection that has been previously shown to affect climate in some parts of Africa) [54]. Instead, climate change is likely due to other natural climate variability and/or may be a result of human activity. However, even without establishing specific causes, the most important conclusion [54] is the demonstration that a significant increase in temperatures in Africa occurred between 1979 and 2010. Analysis of long-term time series shows that warming has accelerated since the mid-1960s in South Africa [55]. Maximum temperatures have increased significantly throughout South Africa for all seasons, while an increase in minimum temperatures has been shown for most of the country. A notable exception is the central interior of South Africa, where minimum temperatures have decreased significantly [56].

4.2. Based on Reanalyses

In regions with a limited amount of data, such as southern Africa, reanalysis products are of particular interest [22]. Over the period 1979–2021, the performance of three reanalysis products based on ERA5 (i.e., AgERA5, ERA5, and ERA5-Land) was previously studied for their spatiotemporal representation of average summer (November–March) and winter (May–September) temperatures, as well as the characteristics of seasonal average cold and heat waves in terms of the number of events and days and magnitude across southern Africa. Compared to the grid of reference temperature observation data from the NOAA Climate Prediction Center (CPC), the reanalysis datasets adequately reproduced the spatiotemporal characteristics of average daily temperatures with high area-averaged correlations ($r > 0.8$) [22], which provides a basis for using ERA5 in this study. Overall, according to ERA5 reanalysis, temperature is modeled quite well, with the exception of the coastal plain of Namibia, where the modeling shows an anomalously high temperature, related to the inability to extend the influence of the cold Benguela Current inland [59]. This may be related to difficulties in processing complex topography and capturing large-scale circulation patterns.

4.3. Changes Based on Models

Due to climate change, an increase in ambient temperature of 3–4 °C along the coast of South Africa and 6–7 °C inland is projected over a period of more than 80 years [4].

Tshiala et al. [60] analyzed long-term future climate data from the average of five Global Climate Models (GCMs) from CMIP6 to study the impact of climate change on extreme temperature in four major cities in South Africa. The overall result shows that the annual trends of all temperature indices analyzed in this study significantly increase for both scenarios (SSP2-4.5 and SSP5-8.5), with the exception of some lower extreme temperature indices (i.e., the number of cool days, cold nights, and cold spells). However, some indices did not show any trend for some stations during the historical period. The

study also showed that coastal cities had a slower increase in higher extreme weather indices compared to inland cities. However, the opposite was true for lower extreme indices (such as the number of cool days, cold nights, cool day temperature, and cold spells).

A rapid increase in both maximum and minimum temperatures is projected [2,61,62]. The probability of extremely high temperatures increases, as evidenced by the annual increase in the number of hot days, the hottest day temperature, and warm spells. A low risk of extremely low temperatures is also indicated by the decreasing annual trends in the number of cold nights, the coldest night temperature, and cold spells [10], which supports the findings of [1,3,54,63].

It has been shown that there is a significant difference between inland and coastal cities in the overall trends of extreme temperature indices under changing climate conditions [3,10,64]. The number of hot days and their temperature are decreasing, while the number of cold days is also decreasing, but their temperature is increasing in coastal areas compared to inland areas. This makes coastal areas milder and less variable in air temperature (lower diurnal temperature ranges).

4.4. Implications on Urban Governance and Nature Management Adaptations in South Africa

This study has significant implications for South Africa's future environmental management and urban development, revealing complex and regionally distinct patterns of climate change based on findings from the NSAT in South Africa, which were derived from comparative data from weather stations, ERA5 reanalysis, and CMIP6 model outputs. The highlights of the divergence of South African trends from global patterns make it more timely, creating an urgent need for a shift in thinking regarding the planning and management of urban areas and natural landscapes in South Africa.

Such actions are necessary to support the implementation of the Climate Change Act of 2024 (currently in draft discussion) [65], which builds on the National Climate Change Response Implementation Framework [66] and the National Environmental Management Act [67] which, in the framework of sustainable development, support the creation of an efficient response to climate change and a fair, long-term shift for South Africa toward a low-carbon, climate-resilient economy and society.

The findings from this study lay the groundwork for province-specific climate modeling and monitoring, which can guide further research in South Africa aimed at promoting sustainable development governance with a focus on agricultural sustainability and the transformative adaptation of provinces for urban resilience through temperature criteria-based assessment. This necessity stems from the discrepancies in temperature trends between the interior and the coast, as well as the expected significant warming. Rapid increases in both maximum and minimum temperatures are disproportionately impacting inland communities, necessitating immediate action to mitigate the effects of heat. Therefore, strategies based on province-specific temperature data to reduce the urban heat island effect should be incorporated into urban planning.

With more detailed studies on how these specific temperature and precipitation changes affect urban heat, urban planners would be able to prioritize coastal resilience by implementing appropriate measures such as green infrastructure, installing reflective surfaces, encouraging passive cooling building designs, improving stormwater management, and flexible building regulations that address the impacts of climate change.

An additional increase of 6–7 °C in inland temperatures projected for the next 80 years necessitates a fresh examination of how each South African province manages its water resources, irrigation systems for farming, and the resilience of existing infrastructure. Consequently, the slower increase in South Africa's extreme weather indices, a reduction in cold days, and a rise in temperatures in coastal towns may indicate a trend toward a milder, less variable climate.

Therefore, it seems likely that alterations will occur in South African ecosystem dynamics, including changes in precipitation patterns and rising sea levels, even though coastal towns are less susceptible to severe heat waves. All these uncertainties make it essential to take proactive measures driven by province-specific climate data to adapt all aspects of development in South African urban planning and environmental management, as this study found that NSAT increased consistently in all CMIP6 models, regardless of future scenarios.

The use of localized climate data is crucial for developing data-driven and regionally sensitive urban infrastructure policies. A transition toward detailed, province-specific climate modeling and monitoring is necessary due to the differences in seasonal temperature trends and the variation in NSAT trends between urban and non-urban stations. This strategy supports the creation of adaptation plans by utilizing localized data and spatial planning, which accurately targets the area's most at risk, as outlined in the National Climate Change Response Implementation Framework [66] and policy lever 5 of the Integrated Urban Development Framework of South Africa [68].

4.5. Bridging Science, Policy, and Governance

Bridging the gap between climate science, policy, and governance is central to achieving a climate-resilient future. However, a significant challenge lies in the political economy of climate adaptation, where short-term political interests often overshadow long-term climate risks [69]. Governance structures must shift from reactive approaches to proactive, evidence-based policymaking that is grounded in climate science and informed by localized risk assessments [70,71].

Furthermore, the integration of scientific knowledge into decision-making requires an inclusive governance model that incorporates indigenous knowledge and local community participation [72]. Many climate adaptation policies fail due to their top-down nature, which neglects the lived realities of vulnerable populations. A co-production approach, where scientists, policymakers, and local communities engage in mutual learning and knowledge generation, is essential for designing effective climate adaptation strategies [73–75].

The urgency of climate change necessitates regulatory reforms that embed climate science into legal frameworks. Countries with strong climate governance, such as Germany and Sweden, have institutionalized climate adaptation laws that mandate evidence-based policymaking. The Netherlands, on the other hand has linked climate policy to the country's unique vulnerability to sea level rise—to its tradition as an environmental policy innovator [76–78]. South Africa must adopt similar legislative frameworks that ensure accountability and compliance in implementing climate resilience strategies.

Furthermore, addressing systemic governance fragmentation is critical. Climate change adaptation requires intersectoral collaboration between urban planning, agriculture, water management, and disaster risk reduction sectors [79,80]. Establishing an inter-ministerial climate task force could enhance coordination, ensuring that scientific insights translate into actionable policies across all spectrums of governance.

In summary, closing the gap between climate science and governance is critical for South Africa's climate resilience. A proactive, data-driven, and inclusive governance approach is essential for safeguarding South Africa's urban and natural landscapes against escalating climate impacts. By embedding climate resilience into governance frameworks, South Africa can mitigate risks, enhance its adaptive capacity, and foster sustainable urban and environmental management practices.

5. Conclusions

The main result obtained is the correspondence of NSAT changes in South Africa for 1940–2023 between weather station data, ERA5 reanalysis, and an ensemble of 33 CMIP6

models. Moreover, the interannual variability of NSAT based on ERA5 reanalysis almost completely falls within the inter-model spread of CMIP6. It is shown that, according to ERA5 reanalysis, the increase in average NSAT in the region (45–10° S, 0–50° E) for 1940–2023 was 0.11 ± 0.04 °C. Furthermore, from 1940 to the mid-1970s, weak interdecadal NSAT changes were observed, and after the mid-1970s, rapid warming began in the region. Between the periods 1940–1969 and 1994–2023, the average model values of NSAT in the studied region increased by 0.63 ± 0.12 °C. The spatial distribution of NSAT changes in the South African region according to the CMIP6 model ensemble also turned out to be quite close to ERA5, considering the coarser resolution of the models. Thus, the warming of the climate in the studied region for 1940–2023 occurred more noticeably over land (approximately 1 °C) than over its water area (approximately 0.5 °C). Thus, it can be concluded that the CMIP6 model ensemble satisfactorily reproduces the NSAT changes in the South African region during the instrumental observation period. Based on this, the results of this ensemble can be used to analyze projections of future NSAT changes in the studied region, which was done for the SSP scenarios until the end of the 21st century. It was found that the NSAT increase in South Africa will occur according to the results of all 33 studied CMIP6 models under any of the considered SSP scenarios, both in the next 30 years and by the end of the 21st century. The CMIP6 model ensemble showed that the average NSAT of South Africa will increase between 1994–2023 and 2070–2099 by 0.92 ± 0.36 °C under the SSP1-2.6 scenario, by 1.73 ± 0.44 °C under SSP2-4.5, by 2.52 ± 0.50 °C under SSP3-7.0, and by 3.17 ± 0.68 °C under SSP5-8.5. Between 1994–2023 and 2025–2054, the increase in the average NSAT of the studied region, taking into account the inter-model spread, will be 0.49–1.15 °C, depending on the SSP experiment.

The rapid increase in NSAT in South Africa in the mid-1970s, as shown by the CMIP6 model ensemble, in which natural climate variability is almost completely suppressed, can largely be explained by the influence of external forcing on the global climate system. These external forcings primarily include the following: changes in the concentration of greenhouse gases in the atmosphere, anthropogenic aerosol emissions, major volcanic eruptions, and variations in solar activity. Nevertheless, the NSAT changes in the studied region are also influenced by natural climate variability modes, which primarily include ENSO on interannual timescales and PDO on interdecadal timescales. Thus, local NSAT maxima in 1983, 1987, 1998, and 2016 can be linked to the strong El Niño events observed in those years, and local NSAT minima in 1976, 2011, and 2021—to strong and prolonged La Niña events. The temporary cessation of the increase in average NSAT in the South African region in the 2000s is most likely related to a pause in global warming caused by conditions in the Pacific Ocean similar to La Niña. But the study of the influence of natural climate variability modes on the NSAT of the South African region requires further research.

Author Contributions: Conceptualization, I.S., S.K., T.G., R.G., J.A., O.A. and O.A.O.; methodology, I.S., S.K., R.G. and J.A.; software, I.S.; validation, I.S., S.K., T.G., R.G., J.A., O.A., M.R. and P.M.; formal analysis, I.S., S.K. and O.A.; investigation, I.S., S.K., T.G. and R.G.; resources, I.S. and S.K.; data curation, I.S., S.K., T.G. and F.M.-C.; writing—original draft preparation, I.S. and S.K.; writing—review and editing, T.G., R.G., J.A., O.A., M.R., P.M., F.M.-C. and O.A.O.; visualization, I.S. and S.K.; supervision, T.G.; project administration, T.G.; funding acquisition, T.G. and M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out within the framework of a scientific project “Assessment of vulnerability of coastal ecosystems in the tropical zone to climate change for the purpose of adapting of governance nature management” (Agreement of the MSHE No. 075-15-2024-657) and funded by MSHE and by NRF of South Africa.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare that this study received funding from NRF of South Africa and MSHE under project № 075-15-2024-657. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication. Author Oluyomi Ajayi was employed by the company Izovutha Pty. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CMIP6	Coupled Model Intercomparison Project phase 6
CPC	Climate Prediction Center
ENSO	El Niño-Southern Oscillation
ESM	Earth System Model
ETE	Extreme Temperature Event
GCMs	Global Climate Models
NSAT	Near-Surface Air Temperature
PDO	Pacific Decadal Oscillation
SAWS	South African Weather Service
SSP	Shared Socioeconomic Pathway
TSS	Taylor Skill Score
WMO	World Meteorological Organization

References

1. Mbokodo, I.; Bopape, M.-J.; Chikoore, H.; Engelbrecht, F.; Nethengwe, N. Heatwaves in the Future Warmer Climate of South Africa. *Atmosphere* **2020**, *11*, 712. [\[CrossRef\]](#)
2. Trisos, C.H.; Adelekan, I.O.; Totin, E.; Ayanlade, A.; Efitre, J.; Gemed, A.; Kalaba, K.; Lennard, C.; Masao, C.; Mgaya, Y.; et al. Africa. In *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK, 2022.
3. Kapwata, T.; Gebreslasie, M.T.; Wright, C.Y. An analysis of past and future heatwaves based on a heat-associated mortality threshold: Towards a heat health warning system. *Environ. Health* **2022**, *21*, 112. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Wichmann, J. Heat effects of ambient apparent temperature on all-cause mortality in Cape Town, Durban and Johannesburg, South Africa: 2006–2010. *Sci. Total Environ.* **2017**, *587–588*, 266–272. [\[CrossRef\]](#)
5. Campbell, S.; Remenyi, T.A.; White, C.J.; Johnston, F.H. Heatwave and health impact research: A global review. *Health Place* **2018**, *53*, 210–218. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Scovronick, N.; Sera, F.; Acquafredda, F.; Garzena, D.; Fratianni, S.; Wright, C.Y.; Gasparrini, A. The association between ambient temperature and mortality in South Africa: A time-series analysis. *Environ. Res.* **2018**, *161*, 229–235. [\[CrossRef\]](#)
7. Chersich, M.F.; Wright, C.Y. Climate change adaptation in South Africa: A case study on the role of the health sector. *Glob. Health* **2019**, *15*, 22. [\[CrossRef\]](#)
8. Van Der Walt, A.J.; Fitchett, J.M. Extreme temperature events (ETEs) in South Africa: A review. *S. Afr. Geogr. J.* **2021**, *104*, 70–88. [\[CrossRef\]](#)
9. Almar, R.; Boucharel, J.; Graffin, M.; Abessolo, G.O.; Thoumyre, G.; Papa, F.; Ranasinghe, R.; Montano, J.; Bergsma, E.W.J.; Baba, M.W.; et al. Influence of El Niño on the variability of global shoreline position. *Nat. Commun.* **2023**, *14*, 3133. [\[CrossRef\]](#)
10. Mengistu, A.G.; Woyessa, Y.E.; Tesfahuney, W.A.; Steyn, A.S.; Lee, S.S. Assessing the impact of climate change on future extreme temperature events in major South African cities. *Theor. Appl. Climatol.* **2024**, *155*, 1807–1819. [\[CrossRef\]](#)
11. Hughes, W.S.; Balling, R.C. Urban influences on South African temperature trends. *Int. J. Climatol.* **1996**, *16*, 935–940. [\[CrossRef\]](#)
12. Plummer, N. Temperature variability and extremes over Australia. Part 1: Recent observed changes. *Aust. Meteorol. Mag.* **1996**, *45*, 233–250.
13. Torok, S.J.; Nicholls, N. A historical annual dataset for Australia. *Aust. Meteorol. Mag.* **1996**, *45*, 251–260.
14. Hoffmann, J.A.J.; Nuonoez, S.E.; Vargas, W.M. Temperature, humidity and precipitation variations in Argentina and the adjacent sub-Antarctic region during the present century. *Meteorol. Z.* **1997**, *6*, 3–11. [\[CrossRef\]](#)
15. Rosenblüth, B.; Fuenzalida, H.A.; Aceituno, P. Recent temperature variations in southern South America. *Int. J. Climatol.* **1997**, *17*, 67–85. [\[CrossRef\]](#)

16. Unganai, L.S. Surface temperature variation over Zimbabwe between 1897 and 1993. *Theor. Appl. Climatol.* **1997**, *56*, 89–101. [CrossRef]
17. Zheng, X.; Basher, R.E.; Thompson, C.S. Trend detection in regional-mean temperature series: Maximum, minimum, mean, diurnal range, and SST. *J. Climate* **1997**, *10*, 317–326. [CrossRef]
18. Salinger, M.J.; Mullan, A.B. New Zealand climate: Temperature and precipitation variations and their links with atmospheric circulation 1930–1994. *Int. J. Climatol.* **1999**, *19*, 1049–1071. [CrossRef]
19. Collins, D.A.; Della-Marta, P.M.; Plummer, N.; Trewin, B.C. Trends in annual frequencies of extreme temperature events in Australia. *Aust. Meteorol. Mag.* **2000**, *49*, 277–292.
20. King'uyu, S.M.; Ogallo, L.A.; Anyamba, E.K. Recent trends of minimum and maximum surface temperatures over Eastern Africa. *J. Climate* **2000**, *13*, 2876–2886. [CrossRef]
21. Kruger, A.C.; Shongwe, S. Temperature trends in South Africa: 1960–2003. *Int. J. Climatol.* **2004**, *24*, 1929–1945. [CrossRef]
22. Roffe, S.J.; van der Walt, A.J. Representation and evaluation of southern Africa's seasonal mean and extreme temperatures in the ERA5-based reanalysis products. *Atmos. Res.* **2023**, *284*, 106591. [CrossRef]
23. Hersi, N.A.M.; Mulungu, D.M.M.; Nobert, J. Prediction of future climate in semi-arid catchment under CMIP6 scenarios: A case study of Bahi (Manyoni) catchment in Internal Drainage basin (IDB), Tanzania. *Phys. Chem. Earth* **2023**, *129*, 103309. [CrossRef]
24. Zareian, M.J.; Dehban, H.; Gohari, A. Changes in temperature and precipitation extremes over Western Asia: A regional ensemble from CMIP6. *Atmos. Res.* **2024**, *311*, 107707. [CrossRef]
25. Adigun, P.; Ogunrinde, A.T.; Dairaku, K.; Adebisi, A.A.; Xian, X. The future of photovoltaic energy potential in Africa under higher emission scenarios: Insights from CMIP6 multi-model ensemble analysis. *Sol. Energy* **2025**, *285*, 113078. [CrossRef]
26. Weather and Climate. Air Temperature and Precipitation by Months and Years. Available online: <http://www.pogodaiklimat.ru/history.php> (accessed on 5 October 2024). (In Russian)
27. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2495. [CrossRef]
28. Gelaro, R.; McCarty, W.; Suárez, M.J.; Todling, R.; Molod, A.; Takacs, L.; Randles, C.A.; Darmenov, A.; Bosilovich, M.G.; Reichle, R.; et al. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *J. Climate* **2017**, *30*, 5419–5454. [CrossRef]
29. Kalnay, E.; Kanamitsu, M.; Kistler, R.; Collins, W.; Deaven, D.; Gandin, L.; Iredell, M.; Saha, S.; White, G.; Woollen, J.; et al. The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.* **1996**, *77*, 437–472. [CrossRef]
30. NOAA Physical Sciences Laboratory. Climate Protection Web Portal: Maps [MM]. Available online: <https://psl.noaa.gov/ipcc/ocn/> (accessed on 5 October 2024).
31. NOAA Physical Sciences Laboratory. Climate Protection Web Portal: CMIP6 Maps [MM]. Available online: <https://psl.noaa.gov/ipcc/cmip6/> (accessed on 5 October 2024).
32. Eyring, V.; Bony, S.; Meehl, G.A.; Senior, C.A.; Stevens, B.; Stouffer, R.J.; Taylor, K.E. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **2016**, *9*, 1937–1958. [CrossRef]
33. O'Neill, B.C.; Tebaldi, C.; van Vuuren, D.P.; Eyring, V.; Friedlingstein, P.; Hurtt, G.; Knutti, R.; Kriegler, E.; Lamarque, J.-F.; Lowe, J.; et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **2016**, *9*, 3461–3482. [CrossRef]
34. Efimov, V.V.; Volodin, E.M.; Anisimov, A.E.; Barabanov, V.S. Regional projections of climate change for the Black Sea—Caspian Sea area in the late XXI century. *Phys. Oceanogr.* **2015**, *5*, 49–66. [CrossRef]
35. Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.* **2012**, *93*, 485–498. [CrossRef]
36. Reichler, T.; Kim, J. How well do coupled models simulate today's climate? *Bull. Amer. Meteor. Soc.* **2008**, *89*, 303–312. [CrossRef]
37. Serykh, I.V.; Tolstikov, A.V. Climatic changes of air temperature in the western part of the Russian Arctic in 1940–2009 according to ERA5 data and CMIP6 models. *Arkt. Ekol. I Ekon. [Arct. Ecol. Econ.]* **2024**, *14*, 334–349. (In Russian) [CrossRef]
38. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; p. 1535.
39. Lehner, F.; Deser, C.; Maher, N.; Marotzke, J.; Fischer, E.M.; Brunner, L.; Knutti, R.; Hawkins, E. Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. *Earth Syst. Dynam.* **2020**, *11*, 491–508. [CrossRef]
40. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Pean, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. (Eds.) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021; p. 2391. [CrossRef]
41. Müller, P.H.; Neuman, P.; Storm, R. *Tafeln der Mathematischen Statistik*; VEB Fachbuchverlag: Leipzig, Germany, 1973; p. 274.
42. Kendall, M.G. *Rank Correlation Methods*; Charles Griffin: London, UK, 1975.
43. Mann, H.B. Non-parametric test against trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]

44. Miller, A.J.; Cayan, D.R.; Barnett, T.P.; Graham, N.E.; Oberhuber, J.M. The 1976–77 climate shift of the Pacific Ocean. *Oceanography* **1994**, *7*, 21–26. [\[CrossRef\]](#)
45. Gregory, J.M.; Andrews, T.; Good, P.; Mauritsen, T.; Forster, P.M. Small global-mean cooling due to volcanic radiative forcing. *Clim. Dyn.* **2016**, *47*, 3979–3991. [\[CrossRef\]](#)
46. Meehl, G.A.; Arblaster, J.M.; Fasullo, J.T.; Hu, A.; Trenberth, K.E. Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nat. Clim. Change* **2011**, *1*, 360–364. [\[CrossRef\]](#)
47. Bond, N.A.; Overland, J.E.; Spillane, M.; Stabeno, P. Recent shifts in the state of the North Pacific. *Geophys. Res. Lett.* **2003**, *30*, 2183. [\[CrossRef\]](#)
48. Philippon, N.; Rouault, M.; Richard, Y.; Favre, A. The influence of ENSO on winter rainfall in South Africa. *Int. J. Climatol.* **2012**, *32*, 2333–2347. [\[CrossRef\]](#)
49. Gore, M.; Abiodun, B.J.; Kucharski, F. Understanding the influence of ENSO patterns on drought over southern Africa using SPEEDY. *Clim. Dyn.* **2020**, *54*, 307–327. [\[CrossRef\]](#)
50. Tyrrell, N.L.; Dommenges, D.; Frauen, C.; Wales, S.; Rezny, M. The influence of global sea surface temperature variability on the large-scale land surface temperature. *Clim. Dyn.* **2015**, *44*, 2159–2176. [\[CrossRef\]](#)
51. Serykh, I.V.; Sonechkin, D.M. Global El Niño–Southern Oscillation Teleconnections in CMIP6 Models. *Atmosphere* **2024**, *15*, 500. [\[CrossRef\]](#)
52. Muhlenbruch-Tegen, A. Long-term surface temperature variations in South Africa. *S. Afr. J. Sci.* **1992**, *88*, 197–205.
53. Easterling, D.R.; Karl, T.R.; Gallo, K.P.; Robinson, D.A.; Trenberth, K.E.; Dai, A. Observed climate variability and change of relevance to the biosphere. *J. Geophys. Res.* **2000**, *105*, 22833–22848. [\[CrossRef\]](#)
54. Collins, J.M. Temperature Variability over Africa. *J. Climate* **2011**, *24*, 3649–3666. [\[CrossRef\]](#)
55. Kruger, A.C.; Sekele, S.S. Trends in extreme temperature indices in South Africa: 1962–2009. *Int. J. Climatol.* **2013**, *33*, 661–676. [\[CrossRef\]](#)
56. MacKellar, N.; New, M.; Jack, C. Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. *S. Afr. J. Sci.* **2014**, *110*, 13. [\[CrossRef\]](#)
57. van der Walt, A.J.; Fitchett, J.M. Exploring extreme warm temperature trends in South Africa: 1960–2016. *Theor. Appl. Climatol.* **2021**, *143*, 1341–1360. [\[CrossRef\]](#)
58. Kruger, A.C. The Influence of the Decadal-Scale Variability of Summer Rainfall on the Impact of El Niño and La Niña Events in South Africa. *Int. J. Climatol.* **1999**, *19*, 59–68. [\[CrossRef\]](#)
59. Moalafhi, D.B.; Evans, J.P.; Sharma, A. Influence of reanalysis datasets on dynamically downscaling the recent past. *Clim. Dyn.* **2017**, *49*, 1239–1255. [\[CrossRef\]](#)
60. Tshiala, M.F.; Olwoch, J.M.; Engelbrecht, F.A. Analysis of Temperature Trends over Limpopo Province, South Africa. *J. Geogr. Geol.* **2011**, *3*, 13–21. [\[CrossRef\]](#)
61. Seneviratne, S.I.; Nicholls, N.; Easterling, D.; Goodess, C.M.; Kanae, S.; Kossin, J.; Luo, Y.; Marengo, J.; McInnes, K.; Rahimi, M.; et al. Changes in climate extremes and their impacts on the natural physical environment. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*; Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2012; pp. 109–230.
62. Engelbrecht, F. *Green Book—Detailed Projections of Future Climate Change over South Africa*; Technical Report (CSIR/BE/SPS/ER/2019/0005/C); CSIR: Pretoria, South Africa, 2019; p. 49.
63. Kruger, A.C.; Rautenbach, H.; Mbatha, S.; Ngwenya, S.; Makgoale, T.E. Historical and projected trends in near-surface temperature indices for 22 locations in South Africa. *S. Afr. J. Sci.* **2019**, *115*, 50–58. [\[CrossRef\]](#)
64. Hardin, A.W.; Liu, Y.; Cao, G.; Vanos, J.K. Urban heat island intensity and spatial variability by synoptic weather type in the northeast U.S. *Urb. Clim.* **2018**, *24*, 747–762. [\[CrossRef\]](#)
65. South Africa Government Gazette. Act No. 22 of 2024: Climate Change Act, 2024. Jul. 23, 2024. Cape Town. Available online: https://www.gov.za/sites/default/files/gcis_document/202407/50966climatechangeact222024.pdf (accessed on 19 February 2024).
66. South Africa Government Gazette. The National Climate Change Response Implementation Framework. 29 October 2012. Available online: <https://saaqis.environment.gov.za/Lekgotla%20Proceedings/2012/4.2-climate-change-response-implementation-framework.pdf> (accessed on 5 October 2024).
67. South Africa Government Gazette. National Environmental Management Act, 1998 Act No. 107. 27 November 1998. Cape Town. Available online: https://www.gov.za/sites/default/files/gcis_document/201409/a107-98.pdf (accessed on 5 October 2024).
68. Department of Cooperative Governance & Traditional Affairs. South Africa’s National Urban Development Policy—The IUDF: An Overview. September 2020. Pretoria. Available online: <https://iudf.co.za/wp-content/uploads/2020/09/IUDF-Brochure.pdf> (accessed on 5 October 2024).
69. Hulme, M. 1.5 °C and climate research after the Paris Agreement. *Nature Clim. Change* **2016**, *6*, 222–224. [\[CrossRef\]](#)

70. Ziervogel, G.; Cowen, A.; Ziniades, J. Moving from Adaptive to Transformative Capacity: Building Foundations for Inclusive, Thriving, and Regenerative Urban Settlements. *Sustainability* **2016**, *8*, 955. [\[CrossRef\]](#)
71. Herrfahrdt-Pähle, E.; Schlüter, M.; Olsson, P.; Folke, C.; Gelcich, S.; Pahl-Wostl, C. Sustainability transformations: Socio-political shocks as opportunities for governance transitions. *Glob. Environ. Change* **2020**, *63*, 102097. [\[CrossRef\]](#)
72. Nalau, J.; Becken, S.; Schliephack, J.; Parsons, M.; Brown, C.; Mackey, B. The Role of Indigenous and Traditional Knowledge in Ecosystem-Based Adaptation: A Review of the Literature and Case Studies from the Pacific Islands. *Wea. Climate Soc.* **2018**, *10*, 851–865. [\[CrossRef\]](#)
73. Lemos, M.C.; Morehouse, B.J. The co-production of science and policy in integrated climate assessments. *Glob. Environ. Change* **2005**, *15*, 57–68. [\[CrossRef\]](#)
74. Wyborn, C.; Datta, A.; Montana, J.; Ryan, M.; Leith, P.; Chaffin, B.; Miller, C.; van Kerkhoff, L. Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annu. Rev. Environ. Resour.* **2019**, *44*, 319–346. [\[CrossRef\]](#)
75. Norström, A.V.; Cvitanovic, C.; Löf, M.F.; West, S.; Wyborn, C.; Balvanera, P.; Bednarek, A.T.; Bennett, E.M.; Biggs, R.; de Bremond, A.; et al. Principles for knowledge co-production in sustainability research. *Nat. Sustain.* **2020**, *3*, 182–190. [\[CrossRef\]](#)
76. Meadowcroft, J. Climate change governance. In *World Bank Policy Research Working Paper, 4941*; World Bank: Washington, DC, USA, 2009.
77. Hölscher, K.; Frantzeskaki, N.; Loorbach, D. Steering transformations under climate change: Capacities for transformative climate governance and the case of Rotterdam, the Netherlands. *Reg. Environ. Change* **2019**, *19*, 791–805. [\[CrossRef\]](#)
78. Castán Broto, V. Urban Governance and the Politics of Climate Change. *World Dev.* **2017**, *93*, 1–15. [\[CrossRef\]](#)
79. Pelling, M.; Leck, H.; Pasquini, L.; Ajibade, I.; Osuteye, E.; Parnell, S.; Lwasa, S.; Johnson, C.; Fraser, A.; Barcena, A.; et al. Africa's urban adaptation transition under a 1.5° climate. *Curr. Opin. Environ. Sustain.* **2018**, *31*, 10–15. [\[CrossRef\]](#)
80. Birkmann, J.; Liwenga, E.; Pandey, R.; Boyd, E.; Djalante, R.; Gemenne, F.; Leal Filho, W.; Pinho, P.F.; Stringer, L.; Wrathall, D. Poverty, Livelihoods and Sustainable Development. In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 1171–1274. [\[CrossRef\]](#)

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