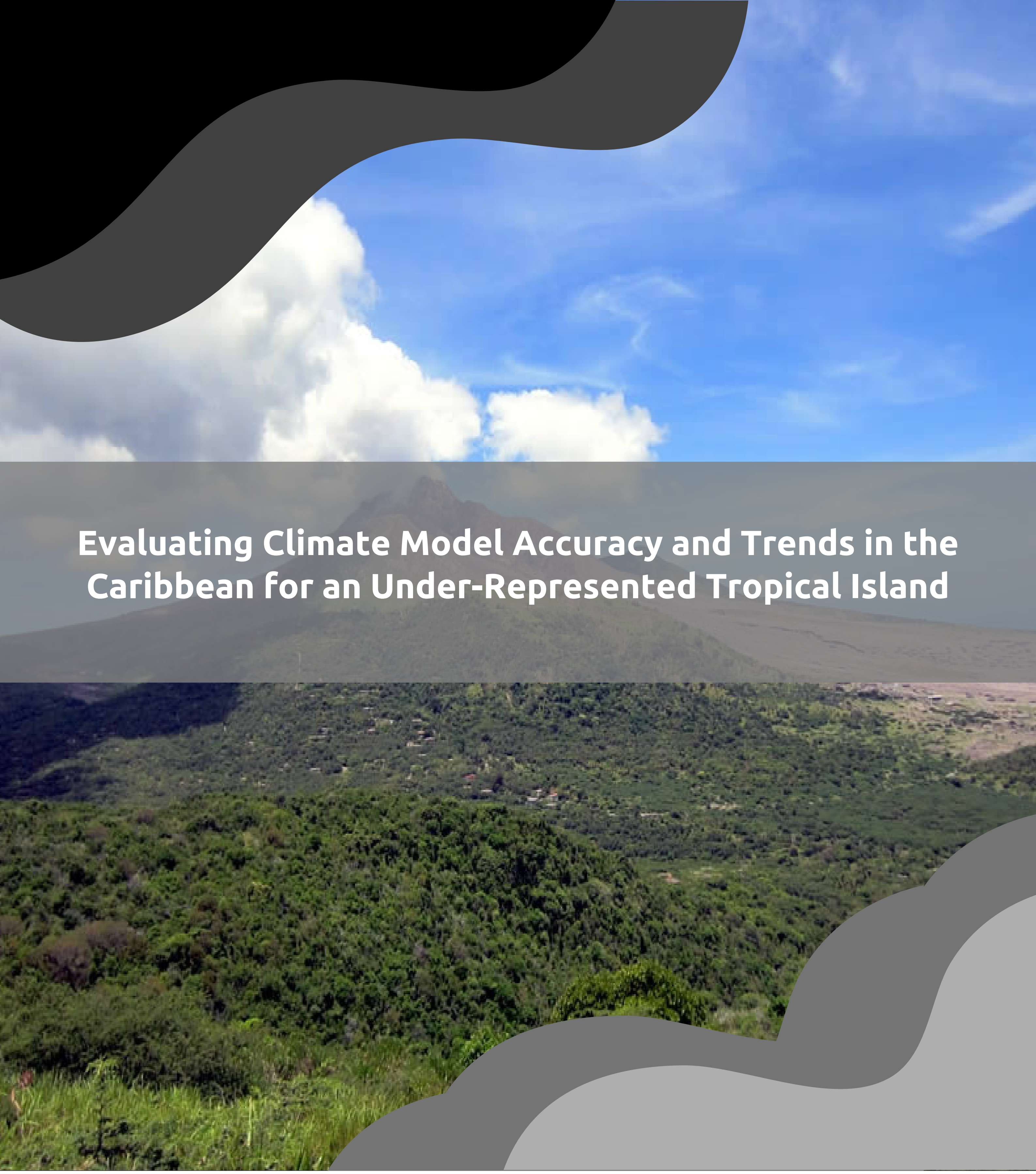

Evaluating Climate Model Accuracy and Trends in the Caribbean for an Under-Represented Tropical Island

the climate centre

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Introduction

- Montserrat is a small but ecologically significant British Overseas Territory in the Lesser Antilles, Eastern Caribbean, located in tropical low latitude areas with a population of around 5,000 (World Fact Book, 2026). It is a volcanic island formed by the subduction of oceanic crust of the North American plate beneath the Caribbean plate (ScienceDirect, n.d.).
- Its rugged topography has four volcanic regions: the Silver Hills, the Centre Hills, the Soufriere Hills, and the South Soufriere Hills (The University of the West Indies Seismic Research Centre, n.d). The active Soufrière Hills volcano erupted in 1995, destroying the then capital city of Plymouth, resulting in mass outward human migration, and the creation of an exclusion zone in the southern part of the island where visitors are not allowed (Montserrat Tourism Authority, n.d.).
- Montserrat is situated in a tropical rainforest climate and receives higher annual rainfall than other Leeward Islands, with precipitation varying across different topographic zones. The island lacks basic climate data to establish a baseline of conditions (FAO, n.d.). Temperatures of the island are warm and consistent throughout the year, averaging approximately 27 °C, which are moderated by trade winds. The wet season covers July to November, coinciding with the Atlantic Hurricane Season. Extreme rainfall has the potential to trigger flash floods once every 3 years, however this is based on data from nearby countries rather than Montserrat itself. Drought occurs approximately every 4-5 years during the dry season and roughly every 10-12 years during the wet season (Van Meerbeeck, Zermoglio, & Bonnin Roncerel, 2021).
- Montserrat's Centre Hills forest reserve is a recognised biodiversity hotspot and the last stronghold of many endemic and restricted-range species, notably birds, which has resulted in the creation of several Important Bird Areas (IBAs) on the island (Oppel et al. 2015). The island supports approximately 700 native plant species, 1,287 invertebrate species, and 15 native amphibian and reptile species (UKOTCF, 2020). Flagship species include the Montserrat Oriole (Icterus oberi), the Montserrat racer (Alsophis manselli), and the mountain chicken frog (Leptodactylus fallax).
- Despite its ecological significance, Montserrat remains under-represented in climate science. Small Caribbean islands typically cannot be resolved at the coarse spatial resolution of global climate models, making local validation and projection difficult (Brotons et al. 2024).
- What climate studies have been performed indicate that the island will experience nearly year-long extreme heat events by the 2040s, and the frequency of category 4 and 5 hurricanes is expected to increase by 25%–30%, but there will be an overall slight reduction in total rainfall (Van Meerbeeck, Zermoglio, & Bonnin Roncerel, 2021).
- This study attempts to improve the knowledge gap by evaluating how temperature, rainfall, and cloud cover have evolved in Montserrat's tropical island context, and assess the accuracy of CMIP6 projection with respect to ERA5 reanalysis data, as well as exploring the potential moderating effects

of Stratospheric Aerosol Injection (SAI) geoengineering on projected warming.

Fig. 1 Animals found in Montserrat include: the Montserrat Racer (left) and the Montserrat Oriole (middle). An aerial view of Montserrat (right).

Methods

- Three complementary datasets were used: ERA5 reanalysis data (ECMWF's fifth-generation global atmospheric reanalysis; Hersbach et al. 2020), and CMIP6 (Coupled Model Intercomparison Project Phase 6; Eyring et al. 2016) climate model projections, supplemented by Stratospheric Aerosol Injection (SAI) scenario outputs.
- ERA5 data, available from 1940 to near-present at 0.25° × 0.25° horizontal resolution, was used for historical reanalysis and validation. CMIP6 multi-model ensemble data was used for future projections through to 2100 under the SSP5-8.5 ('high emissions') and SSP2-4.5 ('intermediate emissions') scenarios.
- SAI scenario data was sourced from two Earth System Models: CESM (Community Earth System Model) and UKESM (UK Earth System Model), representing stratospheric aerosol injection simulations designed to assess the potential temperature-moderating effects of solar radiation management.
- Climate variables investigated included ambient air temperature, rainfall, and cloud cover. Data availability varied across datasets, limiting direct cross-dataset comparisons for some variables.
- Daily and sub-daily data were aggregated to annual values capturing annual minimum, mean, and maximum, as well as the 25th to 75th percentile range. Linear regression was used to quantify trends over time unless otherwise stated. Correlations between datasets were assessed using Pearson's R^2.
- ERA5 and observational data were compared over their overlapping period to evaluate reanalysis skill at representing Montserrat's local conditions. CMIP6 model outputs were similarly evaluated against ERA5 for the historical period to assess model performance in this topographically complex island context.
- SAI simulations from CESM and UKESM were compared to the corresponding no-SAI baseline to quantify the projected cooling effect of stratospheric aerosol injection on regional temperatures.

Results

Air temperature

- ERA5 2m air temperature (t2m) data for Montserrat (1940–2025) showed a mean annual temperature of 26.0°C, with annual means ranging from 25.3°C (1974) to 27.2°C (2024).
- ERA5 t2m showed a warming trend of +0.0085°C per year over the 1940–2025 period, representing a total regression-based increase of +0.72°C and an absolute first-to-last-year change of +0.80°C, below the global average warming of approximately 1.2°C observed over the same period (NASA, n.d.; NCEI NOAA, n.d.).
- CMIP6 multi-model mean temperature for 2015 for SSP245 (28.4°C) and SSP585 (29.8°C) overestimates ERA5's 2015 value of 26.3°C by approximately 2.1°C and 3.5°C, indicating a systematic warm bias in model representation of Montserrat's local conditions. However, the observed ERA5 values were still within the 25th to 50th percentile of CMIP6 average annual values.
- CMIP6 projected annual mean temperature increase from 2015 to 2100 under SSP5-8.5 is +5.85°C (absolute) or +5.99°C (regression), rising from 29.8°C to 35.7°C. Under SSP2-4.5, the multi-model mean projects a more moderate warming of +2.7°C (absolute) or +2.9°C (regression) over the same period — both scenarios already starting from a state of warm bias relative to ERA5.
- SAI simulations (CESM and UKESM, 2035–2069) begin warmer than the CMIP6 multi-model mean temperature at ~31.1°C, and reduce to ~30.1°C. While not a like-for-like comparison, SAI outputs are from specific models rather than the full multi-model ensemble. It results in an average difference of approximately −1.0°C.

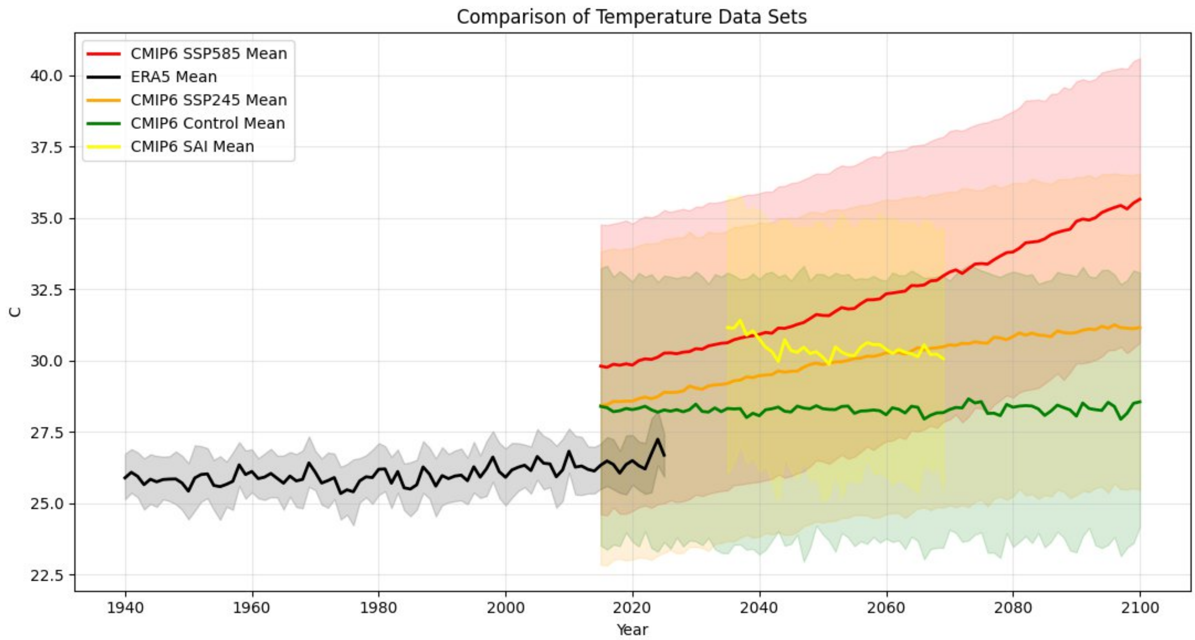

Fig. 2 ERA5 and CMIP6 air temperature values from 1940 to 2025 and 2015 to 2100, respectively. Air temperature values under select SAI scenarios are plotted from 2035 to 2069.

Rainfall

- ERA5 total precipitation data for Montserrat (1940–2025) yielded a mean annual rainfall of approximately 891 mm/yr, with high interannual variability (annual means ranging from ~593 mm in 1971 to ~1,777 mm in 1942).
- Linear regression of ERA5 annual rainfall showed a very small decreasing trend of −0.65 mm/yr, representing a total regression-based change of approximately −55 mm over the 85-year record — indicating no substantial long-term trend in mean annual rainfall.
- CMIP6 multi-model mean annual precipitation for 2015 for SSP245 (~161 mm/yr) and SSP585 (~107 mm/yr) substantially underestimates ERA5's long-term mean of ~891 mm/yr, likely reflecting the inability of coarse-resolution GCMs to resolve Montserrat's orographic rainfall enhancement (Herrera et al., 2020).
- CMIP6 projections show an increase in rainfall, with SSP5-8.5 showing an increase of approximately +110 mm/yr (regression) or +113 mm/yr (first-to-last year), rising from ~161 to ~274 mm/yr, though both scenarios remain a substantial underestimate relative to observed rainfall.

Cloud cover

- ERA5 total cloud cover (tcc) data for Montserrat (1940–2025) showed a mean annual cloud fraction of 0.44 (44%), with substantial interannual variability ranging from 0.37 (1968) to 0.51 (2011).
- Linear regression of ERA5 tcc showed an essentially flat trend (+0.2% across 1940 to 2025), though the absolute change from 1940 (0.48) to 2025 (0.45) represents a slight reduction of 3.1% cover.
- CMIP6 multi-model mean cloud cover for 2015 for SSP245 (~30.4%) and SSP585 (~29.8%) substantially underestimates ERA5's long-run mean of ~44%, a bias of approximately −14%.
- CMIP6 SSP2-4.5 projects minimal change in cloud cover through to 2100 (regression: −0.41%; first-to-last year: +0.17%) and SSP5-8.5 projects a small decrease of −1.5 % (regression) or −1.95 % (first-to-last year), from 30.4% to 28.5%. Both scenarios indicate broadly stable or slightly declining cloud cover in the model ensemble, though the large baseline underestimation compared to ERA5 substantially limits confidence in these projections.

Discussion

- Results indicate that while annual average rainfall has remained relatively stable and cloud cover has decreased only slightly, Montserrat faces severe warming under high-emission scenarios: CMIP6 SSP5-8.5 projects a mean temperature increase of +5.85°C by 2100, rising to a mean annual temperature of 35.7°C, a trajectory that would profoundly alter the island's ecosystems and the native species that depend on them.
- However, CMIP6 models systematically overestimate temperature and also underestimate both cloud cover and rainfall relative to observational data for Montserrat. These biases are consistent with broader documented issues of CMIP6 performance in the Caribbean, with academic studies questioning the reliability of precipitation projections in particular, stemming from the

fact that CMIP6 model resolution is too low to properly resolve the islands and the small-scale processess. This is particularly true for surface moistening and orographic processes, which are noted as being absent, and which may ultimately lead to an underestimation of precipitation (Brotons et al. 2024).

- SAI geoengineering, as modelled by CESM and UKESM, indicates a potential reduction in warming of approximately 1°C, which could provide a partial buffer against the most severe temperature projections. However, the effects of SAI on regional precipitation and cloud dynamics introduce additional uncertainties that require further investigation in a Caribbean context.
- These findings highlight that under-represented small island states such as Montserrat, where local topography fundamentally shapes the climate, require targeted regional modelling efforts, including higher-resolution downscaling, to produce reliable climate projections.
- Increased investment in both observational infrastructure and tailored climate modelling for small Caribbean islands is urgently needed. Without accurate local-scale projections, conservation managers and policymakers lack the evidence base to implement effective adaptation responses for biodiversity and communities in these vulnerable regions.

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