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Climate change amplification in the Peruvian Altiplano: multimodel projections of warming and precipitation under contrasting emission scenarios

Jhonatan Hinojosa-Mamani[1], Adderly Mamani-Flores[2*], Jorge Apaza-Ticona[3], Vicente Alanoca-Arocutipa[4], Germán Belizario-Quispe[5], Duverly Joao Incacutipa-Limachi[6], Julian Apaza-Chino[7]

[1] Professor at the National University of the Altiplano Puno, Peru

*Corresponding author E-mail: adderlymamani@unap.edu.pe

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Abstract

High-elevation regions of the Andes are particularly sensitive to climate change because relatively small shifts in temperature and precipitation can alter water availability, agricultural systems, and ecosystem functioning. This study assesses the magnitude, spatial variability, and uncertainty of projected climate change across the Peruvian Altiplano through the twenty-first century. A multimodel ensemble of 9 Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation models was evaluated under the RCP2.6, RCP4.5, and RCP8.5 emission pathways. Model outputs were interpolated to a common 1° × 1° grid and compared with the 1986–2005 baseline. Temporal changes were assessed using linear trends and the Mann–Kendall test, while spatial differences were evaluated using Student's t-tests at the 95% confidence level. Intermodel standard deviation and the signal-to-noise ratio were used to characterize projection uncertainty. Results indicate a persistent and statistically significant warming across the Altiplano, with mean temperature increases reaching 1.47 °C, 2.56 °C, and 4.52 °C during 2071–2100 under RCP2.6, RCP4.5, and RCP8.5, respectively. Precipitation is projected to increase by approximately 5%, 6%, and 11% under the same scenarios, although its spatial distribution is substantially heterogeneous. Temperature increases are particularly pronounced toward the northern and northeastern sectors, whereas precipitation changes exhibit contrasting patterns, including reductions in southern areas during earlier projection periods, especially under RCP8.5. The signal-to-noise analysis indicates that projected changes generally exceed intermodel variability in most periods and scenarios, although precipitation exhibits greater uncertainty under high-emission forcing. These findings demonstrate that climate change in the Peruvian Altiplano is characterized not only by substantial warming but also by spatially differentiated hydroclimatic responses. The projected changes underscore the importance of incorporating regional climate variability and model uncertainty into long-term water-resource management, agricultural adaptation, ecosystem conservation, and territorial planning in high-Andean environments.

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1. Introduction

Climate change is arguably one of the most pressing environmental issues of the twenty-first century. This is due to its capacity to alter weather patterns on a global scale in a way that is both extensive and permanent. In addition, because of the Great Alteration, high mountain areas such as the Peruvian Altiplano may experience climate changes greater than those experienced by lower elevations because of the higher sensitivity of their climates and the socio-environmental vulnerabilities of their populations [1]. The changes to surface air temperature and precipitation directly affect hydrology and the availability of freshwater, agricultural productivity, biological diversity, and ecosystem resilience. Therefore, it is important to fully understand the projected climate change trends for this region [2].

Global climate modelling has advanced so that there are now better projections of climate change; for example, the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5) includes a number of new models [1]. These models are now essential for determining what climate path a particular geographical region may take in the future because of varying levels of greenhouse gas emissions. Through the various RCP (Representative Concentration Pathways) scenarios — including low (RCP2.6), medium (RCP4.5), and high (RCP8.5) emissions — it is possible to predict changes in a variety of important climate indicators (such as temperature and precipitation) for times from the next few decades until the end of the twenty-first century.

The region of Puno in southern Peru is subject to unique climatological influences due to its elevation (above 3,800 m) and its proximity to Lake Titicaca. The interaction between large-scale oceanic systems and regional atmospheric circulation results in Puno having a cold and semi-arid climate with great variability; therefore, any disturbance from climate change will likely occur locally. Although an increasing amount of data has become available over time, gaps still remain in our understanding of climate projections in the Andean region [3].

Previous studies indicate that climate models (e.g., CMIP5) accurately model global weather patterns; however, these models have limitations when looking at smaller spatial scales. Consequently, using multiple climate models is a better way to reduce uncertainty related to how different GCMs may model a specific location and to produce more robust climate trend estimates than relying on one specific model [1]. For this reason, using nine climate models together as a single dataset when analyzing future trends in Puno would provide more accurate projections than could be obtained from just one model and offer more robustness for interpreting the results.

The evaluation of surface air temperature and precipitation is essential because these variables act as direct indicators of climate change. Previous projections at the global level show a clear trend of continued warming and an increase in precipitation under high-emission scenarios, but such trends may manifest themselves differently in specific regions [4]. Since Puno relies heavily on climate-sensitive activities, such as high Andean cattle ranching, subsistence agriculture, and water supply, understanding the magnitude and direction of these changes is especially important for territorial planning and climate adaptation.

The analysis of the projections chronologically and geographically assists in determining how big the changes are likely to be, and where they will be distributed [5], [6]. By knowing which areas in Puno (north, central, and south) are likely to experience the most dramatic climatic changes, managers can plan for those changes and develop differentiated responses.

In addition to assessing trends and evaluating the variability of projections by analyzing the dispersion among individual models and between the empirical signal-to-noise ratio (i.e. identifying the likelihood that each model will produce an accurate result), the statistical assessment of the strength of trend signals allows researchers to make more informed decisions about the reliability of the projections. The objective of this study is to use the

results of a standardized ensemble of models to assess temperature and rainfall projections for the Puno Region for the remainder of the century. This will provide important information to help develop effective planning strategies for adaptation, risk management, and environmentally sustainable practices in response to possible climate changes. The results of this research are intended to help fill the growing gap in the demand for more specific climate impact analyses for areas of very high environmental sensitivity.

The objective of this study is to assess projected air temperature and precipitation changes for the Puno study domain under three RCP scenarios. Linear trends, spatial anomalies, and intermodel spread are used to describe the magnitude, direction, and consistency of the projections. The signal-to-noise ratio compares the ensemble-mean change with intermodel dispersion; it does not estimate the probability that a model is correct. In this study, "climate amplification" refers to the phenomenon whereby the projected regional temperature anomaly exceeds the corresponding global mean anomaly under the same emission scenario and reference period. This definition is descriptive and comparative: it quantifies the magnitude of regional warming relative to the global signal, but it does not, by itself, establish elevation-dependent warming or identify its underlying physical causes (e.g., snow-albedo feedback, changes in soil moisture, or atmospheric circulation). The term is used here to characterize the degree to which the Puno study domain is projected to warm faster than the global average, which is relevant for adaptation planning in high-Andean environments.

2. Literature review

Climate change is among the most researched of the many environmental factors of the past few decades because of its global impact on natural and socio-economic systems. Increased greenhouse gas concentrations as a result of human activity have resulted in a sustained rise in the average temperature of Earth, along with a change in the pattern of precipitation [7]. The Intergovernmental Panel on Climate Change (IPCC) has stated that the changes predicted for the 21st century will have major implications on the amount of water available, the amount of diversity in living organisms, and the level of ecological stability, particularly in vulnerable areas of the Earth such as the mountainous regions of southern Peru.

Climate modelling has been developed into a major resource for an understanding of the climate system and for projecting what is likely to happen in the future regarding climate. Global Climate Models (GCMs) are simulations of physical, chemical and biogeochemical processes occurring in the atmosphere, oceans (hydrosphere), ice sheets (cryosphere) and living organisms (biosphere). GCMs enable the evaluation of the effect of different emission levels and levels of radiative forcing upon the climate [8]. In addition, GCMs have limitations regarding their ability to model small-scale regional processes. Therefore, researchers have been using multi-model approaches in order to produce more reliable climate projections.

The Coupled Model Intercomparison Project Phase 5 (CMIP5) represents one of the largest efforts to evaluate, standardize and compare the various Global Climate Models (GCM's) using a consistent methodology. CMIP5 is a collaborative effort amongst numerous global research centers that enables researchers to produce historical simulations and make climate projections under a variety of greenhouse gas mitigation and emissions scenarios [9]. The importance of CMIP5 is that CMIP5 provides a robust and transparent way to compare model output and is used extensively in IPCC Assessment reports and in studies on climate change in Latin America, including the Andes region.

CMIP5 incorporates the Representative Concentration Pathways (RCP) as part of the climate scenarios that provide potential future climate conditions at a number of radiative forcing levels for the year 2100. The RCP2.6 pathway represents a strong mitigation scenario in which emissions reach a peak level early and decrease thereafter; the RCP4.5 pathway is referred to as an intermediate stabilization scenario and the RCP8.5 pathway projects the potential for continued high emissions with no decline. Use of these pathways allows us to investigate how sensitive the climate system might be to various future conditions and is hence needed to assess potential impact in vulnerable areas [10]. Surface air temperature is an important climate change driver, and

thus an important variable for climate change analysis. Surface air temperature impacts several processes including evapotranspiration, energy balance, and hydrological dynamics. These processes are being impacted by the strong rate of warming, local feedbacks, such as reduced snow cover, changes in soil moisture, and changes in atmospheric circulation have resulted in High Mountain Regions warming faster than other regions [11]. In addition, these temperature variations in the Andes Altiplano will affect Water availability for crops and produce food, Agricultural productivity, and Ecosystem Stability (fragile ecosystems).

Air temperature influences evapotranspiration, the surface energy balance, and hydrological processes. Warming may therefore affect agricultural water demand and ecosystem conditions in the Altiplano. Potential feedback involving snow cover, soil moisture, and atmospheric circulation provide a physical context for regional responses, but their individual contributions are not quantified in this study.

Precipitation (rain) is another key climate change variable, and precipitation variability directly impacts water recharge, agricultural productivity, erosion and hydrometeorological risks. However, the uncertainty of projecting future precipitation lies in its high degree of complexity (fed by multiple atmospheric processes), as seen in abrupt topography (Puno). Climate change has demonstrated prior studies to intensify the hydrological cycle, leading to more rainfall in some regions, left with no rain in other areas and higher frequency of extreme weather conditions. In addition, the heterogeneity of rainfall through space & time creates the critical need for robust statistical methods, multi-model analysis of projected precipitation [12].

One of the final aspects of climate projection evaluation is uncertainty analysis. The use of multiple models (i.e., the use of multi-model assemblies) permits estimation of the range of differences among many simulations and offers an estimate of the signal-to-noise ratio. Uncertainty analysis is critical for assessing model reliability in climate projections. Although the climate system is too complex to be fully represented by any single model, assembling information from many different climate projections produces higher quality estimates of climate projections and therefore provides more reliable data for the development of adaptation measures using scientific knowledge. In vulnerable areas like Puno, an understanding of climate uncertainties will be necessary for developing effective adaptation strategies based on science.

Precipitation controls water inputs to catchments and influences agricultural production and hydrological variability. Its simulation is challenging in mountainous terrain because global models only partly resolve topography and moisture-transport processes. Projected changes in mean precipitation must be distinguished from changes in heavy-rainfall intensity, duration, and frequency; the latter require dedicated extreme-index analyses. Projection uncertainty includes differences among models, internal climate variability, and differences among forcing scenarios. Intermodel spread characterizes one component of this uncertainty and should not be interpreted as a complete probability distribution of future climate. Ensemble summaries remain useful for adaptation planning when their spatial resolution, assumptions, and limitations are made explicit.

3. Research method

3.1. Study area

The ongoing research project will be in Peru's Altiplano region (Puno), which averages 3820 m above sea level. It is situated near the world's highest navigable lake, Titicaca. The combination of high altitude, complicated geography and sensitivity to weather events creates very special climate conditions for this area. The study site will be defined as approximately Lat., -15.824075° S., Long., -70.01862° W., within the vicinity of the Nacional de Altiplano University, and these traits give Puno significant potential ecosystem vulnerabilities resulting from Climate Change, which justifies more intensive future assessments. Although this study is framed within the Peruvian Altiplano and uses the Puno region as a reference, the analysis does not cover the entire Puno administrative region or the whole Peruvian Altiplano. Because CMIP5 outputs were interpolated to a common 1° × 1° grid (~100 km × 100 km), the effective study domain consists of a limited number of grid cells covering the central-southern Peruvian Altiplano, including the Lake Titicaca area and the reference coordinates.

Therefore, the results should be interpreted as a regional climate signal averaged over that set of cells, rather than as a detailed intra-regional assessment of the entire Puno region. This limitation is particularly relevant for north–south spatial interpretations and for any local-scale use of the anomaly maps.

3.2. Research design

The data from this study were used using the CMIP5 (Coupled Model Intercomparison Project Phase 5) assembly model [13]. The data presented in this study are presented with a resolution of 1.0º x 1.0º (100 km x 100 km). (http://cmip-pcmdi.llnl.gov/cmip5/index.html). To assess the discrepancy between model drift and forced trends in CMIP5 models, the period from 1985 to 2005 was analyzed using historical simulations [14].

Throughout this study, the temperature variable analyzed is the daily maximum near-surface air temperature (tasmax) from the CMIP5 models. Annual values correspond to the annual mean of daily maximum near-surface air temperature, expressed in °C. This variable is distinct from mean surface air temperature (tas) and from absolute annual maximum temperature. All references to "surface air temperature," "maximum temperature," or "annual maximum temperature" in this manuscript should be understood as referring to this specific variable, unless otherwise stated.

Databases of results from nine climate models have been selected for climate change projections in Puno under the RCP scenarios. Table 1 provides an overview of the partner institution and the atmospheric model component of these GCMs. These models include 20th century climate simulations and 21st century climate projections under the RCP2.6, RCP4.5, and RCP8.5 scenarios. For RCP2.6, total radiative forcing peaks at about 3 W m–2 around 2050 and decreases thereafter. RCP4.5 is a stabilization scenario, with total radiative forcing increasing until 2070 and then remaining stable. On the other hand, RCP8.5 is a scenario of continuous increase in radiative forcing, with levels of approximately 8.5 W m–2

In previous research, an assessment of the ability of these Global Climate Models (GCMs) to represent the current climate was conducted. In this study, the focus is on projecting climate changes in Puno under a variety of RCP scenarios. Based on previous research, it is considered that using a set of multiple models is more appropriate for these projections than relying solely on a single model [15]. Therefore, the temperature and precipitation projections under the RCP scenarios are derived from the arithmetic mean of the 9 GCM result set. In addition, all data is interpolated in a common 1°×1° grid to obtain the model as a whole and make the comparison between simulations and observations. The projections refer to the base period 1986-2005. Table 1 lists nine CMIP5 models. The scenarios considered are RCP2.6, RCP4.5, and RCP8.5, with nominal radiative forcing levels of 2.6, 4.5, and 8.5 W m−2, respectively, in 2100.

Table 1. Global climate models of the CMIP5 project

N.º	Model CMIP5	Institution	Resolution (° lon × ° lat)
1	BCC-CSM1	Beijing Climate Center Climate System Model version 1 (BCC-CSM1)	128 × 64
2	CanESM2	Canadian Earth System Model version 2	128 × 64
3	CNRM-CM5	National Center for Meteorological Research Climate Model version 5	256 × 128
4	GISS-E2-R	Goddard Institute for Space Studies Model E version 2 with Russell ocean model	144 × 90
5	FGOALS-s2	Flexible Global Ocean-Atmosphere-Land System Model—spectral version 2	128 × 108
6	MIROC-ESM	Model for Interdisciplinary Research on Climate–Earth System (MIROC-ESM)	128 × 64
7	MIROC-ESM-CHEM	Atmospheric Chemistry Coupled Version of the Model for Interdisciplinary Research on Climate–Earth System	128 × 64

N.º	Model CMIP5	Institution	Resolution (° lon × ° lat)
8	MRI-CGCM3	Meteorological Research Institute Coupled General Circulation Model version 3	320 × 160
9	MPI-ESM-LR	Max Planck Institute Earth System Model—Low Resolution	192 × 96

3.3. Climate models and data sources

The projections used come from the Coupled Model Intercomparison Project Phase 5 (CMIP5), an international effort to standardize and compare global climate models. Nine GCMs were selected that feature complete simulations of the historical climate of the twentieth century and projections of the twenty-first century under the RCP2.6, RCP4.5 and RCP8.5 scenarios. The models included include scientific institutions of recognized relevance, such as the Beijing Climate Center (BCC-CSM1), the Canadian Centre for Climate Modelling (CanESM2), the Centre National de Recherches Météorologiques (CNRM-CM5), the Goddard Institute for Space Studies (GISS-E2-R), MIROC-ESM, MPI-ESM-LR, MRI-CGCM3, among others.

CMIP5 was selected for this study for three main reasons. First, CMIP5 provides a well-established, standardized, and extensively validated ensemble of climate models that has been widely used in regional climate studies across the Andes and other high-mountain regions, facilitating comparison with previous work [16], [3], [15]. Second, the 9 GCMs selected here offer complete historical simulations (1985–2005) and projections under the three RCP scenarios (RCP2.6, RCP4.5, RCP8.5), which allows for a consistent multi-model assessment of both low- and high-emission pathways. Third, at the time this analysis was designed, CMIP5 represented the most widely documented ensemble for the Peruvian Altiplano, and its use ensures methodological continuity with prior regional studies. While CMIP6 provides updated scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) and improved model physics, its inclusion is beyond the scope of this study and is recommended for future research

All data were interpolated at a common spatial resolution of 1° × 1° (approx. 100 km × 100 km), which allows the results of different models to be homogenized and compared with the observations recorded during the base period 1986–2005. The historical simulations used cover the period 1985–2005, to evaluate the ability of the models to represent the current climate before generating projections.

It is important to note that the 1° × 1° resolution implies that the study area is represented by a reduced set of grid cells. Consequently, the projections presented correspond to an aggregated regional domain covering the central-southern Peruvian Altiplano and the Puno area, and not to the entire Puno administrative region or the whole Peruvian Altiplano. Spatial differences identified between the north, center, and south should be understood as gradients within that grid-cell domain, not as an exhaustive characterization of each subregion.

The study employed a descriptive-projective design with a quantitative approach to analyze future changes in daily maximum near-surface air temperature (tasmax) and precipitation in Puno during the 21st century, using an assemblage of nine CMIP5 Global Climate Models under the RCP2.6, RCP4.5 and RCP8.5 scenarios. The data, interpolated to a common resolution of 1°×1°, were compared with the base period 1986–2005, evaluating temporal trends by linear regression and statistical significance with the Mann–Kendall test. Anomaly maps are used to highlight the spatial pattern of the multimodel average, using a 95% Student's t-test to assess the geographic significance of the changes and analyzing the uncertainty in the assembly through the intermodel standard deviation and signal to noise ratio to estimate the robustness of the projections.

The signal-to-noise ratio (λ) was computed as the ratio between the absolute value of the multimodel ensemble-mean change (signal) and the intermodel standard deviation (noise) for each period and scenario; $\lambda = |\Delta\bar{T}| / \sigma_models$, where $\Delta\bar{T}$ is the multimodel ensemble-mean change relative to the reference period 1986–2005, and σ_models is the standard deviation of the individual model changes around the ensemble mean. A value of $\lambda > 1$ indicates that the projected change exceeds the intermodel spread, suggesting a more robust signal; $\lambda < 1$

indicates that the intermodel dispersion is larger than the projected change, implying lower confidence in the signal. This ratio characterizes ensemble consistency and should not be interpreted as a probability that a given projection is correct. This integrated approach provides a sound basis for describing the magnitude, direction, and reliability of projected climate change in a high alpine environment based on temporal, spatial, and statistical characteristics.

4. Results

Using a multi-model assembly of CMIP5 results, it was found for all climate models that there would be significant changes in both surface temperature and precipitation through to the year 2100. The change was found under all scenarios (RCP2.6, RCP4.5, RCP8.5) using Puno, Peru as a test case. Projections show a robust warming signal accompanied by a progressive increase in precipitation, with magnitudes intensifying as radiative forcing levels increase. These patterns reflect not only the climatic sensitivity of the highland region, but also the regional amplification of changes with respect to the global average.

Figure 1 shows the time series of the annual mean of daily maximum near-surface air temperature (tasmax) and annual precipitation in Puno for the 20th century simulations and the 21st century projections under the three RCP scenarios. The data observed are the monthly temperature from 2071 - 2100, called and the precipitation over Puno. Table 2 presents the changes in annual mean daily maximum near-surface air temperature (tasmax) and precipitation for each 30-year period and the corresponding linear trends for the period from 2011 to 2100 both globally (including land and ocean) and in Puno. The warming trend in Puno during the period 2011–2100 is 0.06 °C/10a for RCP2.6, 0.21 °C/10a for RCP4.5, and 0.50 °C/10a for RCP8.5. The average warming for the last 30 years of the 21st century (2071–2100) is +1.47 °C for RCP2.6, +2.56 °C for RCP4.5, and +4.52 °C for RCP8.5. These results indicate that the projected annual maximum temperature time series shows variation trends like those of emissions trajectories. Under the RCP2.6 scenario, temperature is projected to continue increasing until approximately 2050, after which it is expected to decrease slightly and subsequently stabilize. Under the RCP4.5 scenario, temperature is projected to increase until approximately 2070, followed by a period of relative stabilization toward the end of the century. Under RCP8.5, temperature is projected to continue increasing throughout the twenty-first century. In addition, the average regional rainfall over Puno is projected to continue increasing in the future.

The chart depicts how maximum yearly temperature and yearly precipitation have changed from 1901 until 2100. The chart indicates that historical simulations fit well with what was observed from 1986 through to 2005, which shows that the selected climate models can reproduce baseline climate conditions correctly. However, there is a gradual increase in the differences between future climate projections after 2011, as represented by the RCP Scenarios. For temperature, the linear trend for 2011–2100 was 0.06 °C/10a (RCP2.6), 0.21 °C/10a (RCP4.5), and 0.50 °C/10a (RCP8.5), all 95% significant. These trends are clearly accentuated towards the middle and end of the twenty-first century, reflecting the cumulative response of the climate system to the increase in greenhouse gases.

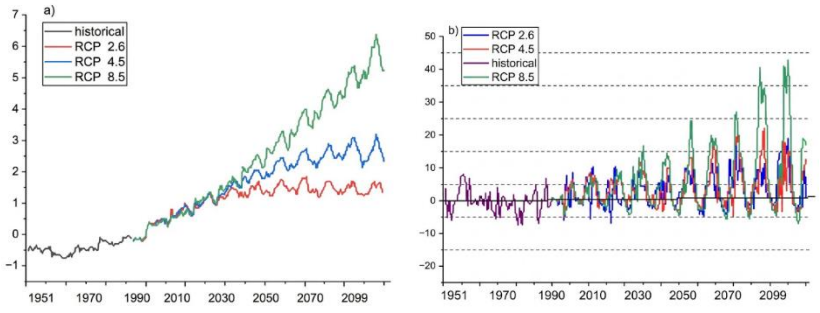


Figure 1. Temporal evolution of annual mean daily maximum near-surface air temperature (tasmax) and annual precipitation over the Puno study domain from 1951 to 2100. Observations, historical simulations, and future projections under RCP2.6, RCP4.5, and RCP8.5 are shown.

Analysis by 30-year periods reveals that the projected warming by the end of the twenty-first century (2071–2100) reaches +1.47 °C under RCP2.6, +2.56 °C under RCP4.5, and +4.52 °C under RCP8.5, the latter representing the strongest warming scenario. These values exceed the corresponding global temperature anomalies, indicating a greater projected warming magnitude in the Puno study domain. Under the intermediate RCP4.5 scenario, temperature is projected to continue increasing until approximately 2070, followed by a slight stabilization toward the end of the century. Under the mitigation-oriented RCP2.6 scenario, warming is projected to increase until mid-century, followed by a slight decrease or stabilization during the final decades, consistent with the trajectory of this emission pathway.

Figure 1 presents the time series of annual mean daily maximum near-surface air temperature (tasmax) and annual precipitation over the Puno study domain from 1951 to 2100. The black line represents the observed data, while the dark violet line corresponds to historical climate simulations. The red, blue, and green lines represent the future projections under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. The historical simulations and future projections are evaluated relative to the reference period 1986–2005. The figure therefore distinguishes the observed climate record, historical model simulations, and projected future conditions.

Regarding precipitation, the results show a more heterogeneous spatial and temporal behavior. Until approximately 2030, the three trajectories show similar increases. However, they are markedly different later. The linear trend for 2011–2100 was 0.4 %/10a (RCP2.6), 0.2 %/10a (RCP4.5), and 1.1 %/10a (RCP8.5). The average precipitation increases for 2071–2100 was estimated at +5.32 %, +5.63 %, and +10.99 % for the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. The largest changes in mean annual precipitation are projected under RCP8.5. These results indicate a greater increase in annual precipitation totals relative to the baseline period, although they do not provide direct evidence of changes in seasonal variability or the intensity and frequency of extreme hydrometeorological events.

Table 2. Changes in temperature in the world and Puno

Years	**Air temperature °C**			**Precipitation %**		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
2011-2040	0.75	0.78	0.88	1.4	1.4	1.5
2041-2070	1.07	1.44	2.07	2.3	2.7	3.4
2071-2100	1.06	1.80	3.55	2.5	3.6	5.9
Linear trend per decade	0.06	0.17	0.44	0.18	0.37	0.74
Changes in Puno						
Years	Air temperature °C			Precipitation %		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
2011-2040	0.86	0.92	0.93	1.67	3.08	3.32
2041-2070	1.43	1.97	2.55	3.20	3.10	5.28
2071-2100	1.47	2.56	4.52	5.32	5.63	10.99
Linear trend per decade	0.06	0.21	0.5	0.4	0.2	1.1

The Mann–Kendall test was applied [17] to determine the statistical significance of all linear trends, which are expressed in °C/10 a for temperature and %/10 a for precipitation. All trends were found to be statistically significant with a confidence level of 95%. Changes in surface air temperature and precipitation are calculated in relation to the reference period 1986-2005.

The increase in rainfall for the three RCP scenarios is similar until approximately 2030; however, after this point, they begin to show different characteristics. In the case of RCP2.6, rainfall remains at an approximate level of 11% until 2070 (Fig. 1b). The rate of increase in precipitation for the period 2011 to 2100 is 0.4%/10 a for RCP2.6, 0.2%/10 a for RCP4.5 and 1.1%/10 a for RCP8.5. The average increase in precipitation for the set of models during the last 30 years of the 21st century is +5% for RCP2.6, +6% for RCP4.5 and +11% for RCP8.5 (Table 2).

4.1. Spatial changes in temperature and precipitation

Figure 2 illustrates the spatial distribution of projected changes in annual mean daily maximum near-surface air temperature (tasmax) under the three RCP emission scenarios. The maps show the spatial differences in projected warming relative to the 1986–2005 reference period. The comparison highlights the differences in the magnitude and spatial distribution of warming across the Puno study domain under the respective emission pathways[18]. These projections are interpreted at the 1° × 1° grid-cell scale and do not resolve local topographic variations. The spatial patterns should therefore be understood as regional climate signals rather than as detailed representations of local temperature conditions.

The spatial patterns described (greater warming toward the north, precipitation redistribution with decreases in the south during the early period) correspond to the 1° × 1° grid cells representing the study domain. Given the model resolution, these results do not resolve topographic or local variations within the Puno region.

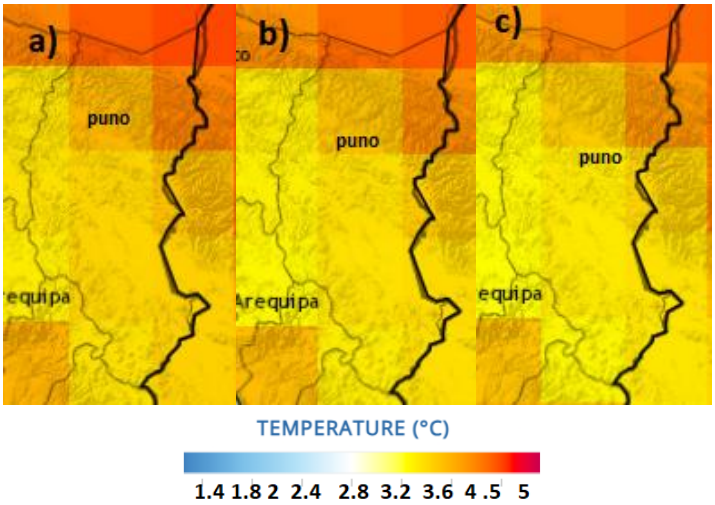


Figure 2. Spatial distribution of projected changes in annual mean daily maximum near-surface air temperature (tasmax, °C) over the Puno study domain relative to the 1986–2005 reference period. The three panels represent the RCP2.6 (a), RCP4.5 (b), and RCP8.5 (c) scenarios for the 2071–2100 projection period.

Changes in surface air temperature (°C) relative to the base period 1986–2005 for (a) RCP2.6, (b) RCP4.5, and (c) RCP8.5, for three time periods: early period (2011–2040, left column), middle period (2041–2070, center column), and late period (2071–2100, right column). Stippling indicates statistical significance at the 95% confidence level according to Student's t-test.

Geographic assessment through spatial analysis reveals geographic patterns of modifications. Figure 2 demonstrates that temperatures across the geographic region are experiencing generally increasing temperature trends and greater intensity as we travel northwards. Based on RCP8.5 the predicted temperature anomalies at the end of this century are expected to exceed the +4.5 °C level indicating that the local thermal regimes of Puno will undergo significant changes. With less intense levels of temperature increases occurring under the lowest possible forcing scenarios, we are still able to confirm (at 95%) through Student's t-test that Puno will still experience a heat increase significantly greater than its historical average temperature even under the most stringent types of mitigation methods.

Emission scenarios, like lower emission scenarios, show less temperature increase than higher emission scenarios. The temperature during the first period (from about 2000 to 2040), when compared across the three RCP scenarios, is approximately the same or close to each other (approximately 1.1ºC). The RCP2.6 scenario produces a regional average increase of approximately 1.4ºC during the period of approximately 2041-2070. The temperature in this RCP2.6 scenario is then projected to remain consistent at the 1.4ºC mark for the next 30 years (from 2071-2100). The RCP4.5 scenario produces a regional average increase of approximately 2.0ºC

during the period of approximately 2041-2070, which is slightly less than the average increase of 2.5ºC at the end of the 21st century. In comparison, the RCP8.5 scenario produces a large amount of warming, increasing approximately 3.0ºC during the period of 2041-2070, and approximately 4.5ºC at the end of the 21st century.

Figure 3 illustrates the spatial distribution of projected changes in mean annual precipitation across the Puno study domain under the three RCP scenarios. The spatial patterns indicate greater projected precipitation increases in the northern and northeastern sectors, whereas some southern grid cells show decreases during the initial projection period. These differences highlight the spatial heterogeneity of the projected precipitation response. However, the maps represent changes in mean annual precipitation and should not be interpreted as direct evidence of changes in extreme rainfall events, flooding, or soil erosion.

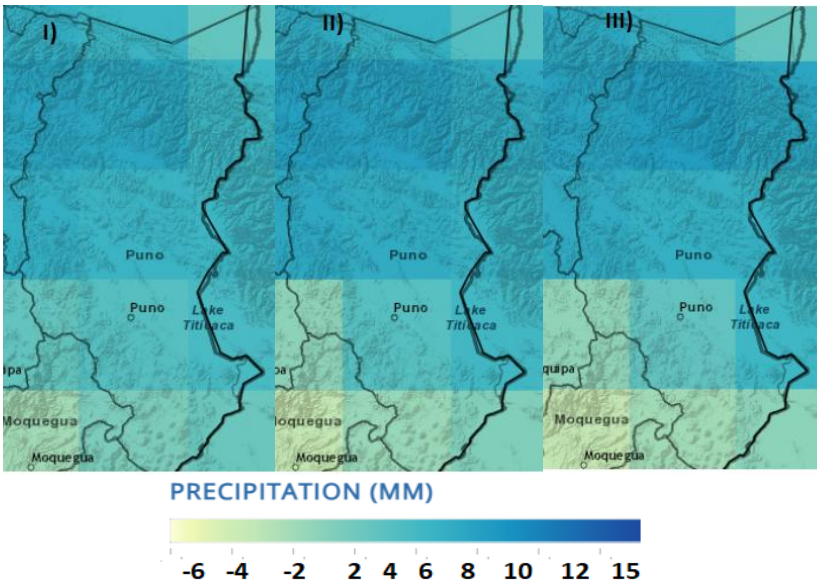


Figure 3. Spatial distribution of projected changes in annual mean precipitation (mm) over the Puno study domain relative to the 1986–2005 reference period. The three panels represent the RCP2.6 (a), RCP4.5 (b), and RCP8.5 (c) scenarios for the 2071–2100 projection period.

Changes in precipitation (mm) relative to the base period 1986–2005 for (a) RCP2.6, (b) RCP4.5, and (c) RCP8.5, for three time periods: early period (2011–2040, left column), middle period (2041–2070, center column), and late period (2071–2100, right column). Stippling indicates statistical significance at the 95% confidence level according to Student's t-test.

Precipitation changes in the Puno region between 2011 and 2040 are illustrated in Figure 3 as having been redistributed spatially. The north/northeast areas experienced the largest increase in precipitation; conversely, the south experienced a decrease in precipitation, particularly when using RCP8.5. The topography, regional circulation, and lake-atmosphere interactions all contributed to the observed differences between these regions. Most of the territory showed consistent increases in precipitation during the later years; however, there were significant spatial gradients associated with these increases. The statistically significant trend observed supports the conclusion that a significant portion of the observed precipitation changes will not be due to climate model uncertainty.

4.2. Uncertainty about multi-model ensemble projection

There are many uncertainties associated with modelling climate change using multiple models, and when analyzing these uncertainties, it is important to take account of the following: Dispersion of Results from the Models - By assessing the dispersion or standard deviation (σ) of the results produced by different models, you can gain an understanding of the magnitude of uncertainty associated with the projected climate changes. Since there is a greater range of variation between the results in the various models, it shows how much simulated

climate responses differ from each other. Signal-to-noise Ratio (λ) - The ratio compares the absolute value of the multimodel ensemble-mean projected change (signal) with the intermodel standard deviation (noise), following $\lambda = |\Delta\bar{T}| / \sigma_models$. When $\lambda > 1$, the projected change exceeds the intermodel spread, indicating a more robust signal. When $\lambda < 1$, intermodel dispersion dominates, indicating lower confidence in the projected change. When $\lambda > 1$, it implies that the projections are credible because the strength of the model's projections (signal) outweighs the variability in the model outputs (noise). Conversely, when $\lambda < 1$, it indicates that projections are much less credible than when the λ value is greater than one, due to increased variability (dispersion) among the multiple model outputs, making it difficult to determine whether there is a clear climate trend.

When analyzing climate change projections, one must take into account not only the associated uncertainties but also to what degree you are able to be confident about these projections. While many quantitative measures exist to quantify model credibility, they do not replace the qualitative model evaluation processes and ability of an individual model's ability to adequately represent relevant climate processes.

The existence of uncertainty associated with climate change projections does not diminish the value or usefulness of those projections. Uncertainty should not be regarded as a synonym of ignorance, but as a reality we will all have to address. This means that in order to establish robust, actionable strategies in an uncertain future, it is important that decision-makers learn how to adequately assess uncertainty, rather than using it as an excuse for lack of action [18].

In addition, analysis of uncertainty indicated that there was a signal-to-noise ratio of more than 1 for the multimodel assembly for most periods and scenarios, indicating an increase in the reliability of projections. The multimodel assembly results showed higher dispersion among models for precipitation simulations relative to RCP8.5, which conforms to the inherently greater variability associated with precipitation. Nevertheless, the overall trends were consistent and converged among all models, further confirming the robustness of the results.

Overall, results show an increase in both temperature and rainfall in the Puno Region during the 21st Century, with increasing climate risks associated with high-emission scenarios. The information produced by this work provides crucial information for the adaptation of planning within sectors considered sensitive to climate change, such as water security, agriculture and climate risk management in high elevation Andean regions.

5. Discussion

The CMIP5 multi-model ensemble indicates the 21st-century Puno Region will experience continued and substantial warming, much like what the IPCC has indicated on a global scale (IPCC, 2014). In this case, the predicted amount of warming for the Puno Region under the projected increase of CO_2 emissions using the RCP8.5 emissions scenario is higher than the global average, indicating a regional amplification of climate change. This confirms previous findings of other researchers that The higher the elevation, the greater the degree of climatic change being experienced due to the impacts of feedback mechanisms, altitude/distance from the equator, and heightened climate sensitivity [19].

Temperature behaviors are evolving in a manner depending on the emissions pathway (RCP) applied to the model, with a divergent path towards decoupling from shoaling/warming for RCP2.6, while the warming trajectories for both RCP4.5 and RCP8.5 followed a constant upward path to 2100. In essence, it is due to the degree of radiative forcing that future climates will evolve in an identical fashion and lead to the same amount of warming that the high latitudes of Andean regions and Andean cultures will face. Where strict mitigation measures are taken, some stabilization of the regional climate system may occur; By contrast, under high greenhouse gas emission scenarios, the projected warming is substantially greater and may place additional pressure on the environmental conditions that support Andean ecosystems and agricultural systems [20].

The projected precipitation response is characterized by substantial spatial and temporal heterogeneity across the Puno study domain. Although the multimodel ensemble indicates an increase in mean annual precipitation

by the end of the twenty-first century, the magnitude and spatial distribution of this change vary across emission scenarios and projection periods. Greater increases are projected in the northern and northeastern sectors, whereas some southern grid cells exhibit decreases during the initial projection period. These contrasting patterns may reflect the combined influence of regional topography, atmospheric circulation, and interactions between Lake Titicaca and the surrounding atmosphere, although the individual contribution of these processes was not explicitly assessed in this study [21]. Importantly, the projected changes refer to annual mean precipitation and should not be interpreted as evidence of changes in the frequency, intensity, or duration of extreme rainfall events.

Under the RCP8.5 scenario, the ensemble projects a simultaneous increase in annual mean temperature and precipitation, reaching approximately 4.52 °C and 10.99%, respectively, during 2071–2100 relative to the 1986–2005 baseline. These changes indicate a substantial modification of the projected regional climate conditions, with potential implications for water availability, agricultural activities, and ecosystem management in the Peruvian Altiplano. However, the projected increase in mean annual precipitation does not necessarily imply more frequent or intense extreme rainfall events, nor does it directly establish an increase in flood occurrence or associated infrastructure damage. Such impacts depend on additional factors, including rainfall intensity and duration, antecedent soil moisture, catchment characteristics, and land-use conditions, which were not explicitly evaluated in this study [22]. Therefore, the results should be interpreted as an indication of changing background hydroclimatic conditions rather than as a direct assessment of future hydrometeorological hazards.

The multimodel ensemble shows broad agreement regarding the direction of projected temperature and precipitation changes, although differences remain in the magnitude of the anomalies across individual models. The statistically significant trends identified through the Mann–Kendall test and the spatial differences assessed using Student's t-test provide evidence of systematic changes relative to the reference period. Nevertheless, these statistical results should not be interpreted as direct evidence of causal attribution to external forcing, since the analyses do not explicitly separate the contributions of anthropogenic forcing, internal climate variability, and other potential sources of uncertainty. Rather, the consistency of the multimodel projections across the emission scenarios provides support for the interpretation of a persistent regional warming signal and a scenario-dependent response in mean annual precipitation. The use of multiple models therefore helps characterize the range and consistency of projected changes, without eliminating the uncertainty associated with individual climate simulations [23].

Despite the general consistency of the multimodel ensemble, precipitation projections exhibit greater intermodel dispersion, particularly under the RCP8.5 scenario. This uncertainty reflects the challenges associated with representing regional atmospheric processes, including convection, moisture transport, and interactions between atmospheric circulation and complex topography. In this context, signal-to-noise ratios ($\lambda > 1$) indicate that the ensemble-mean projected changes exceed the corresponding intermodel standard deviation for most periods and scenarios. However, this measure reflects agreement among model projections rather than the probability that a particular outcome will occur. Consequently, precipitation projections should be interpreted with appropriate caution, particularly when considering their potential implications for regional water-resource management and climate adaptation [24].

The projected combination of rising temperatures and changes in mean annual precipitation may influence regional hydroclimatic conditions through modifications in evapotranspiration, soil-moisture dynamics, and water availability. Nevertheless, the magnitude and direction of these potential impacts cannot be established directly from the climate variables analyzed in this study. In particular, the projections do not provide sufficient evidence to determine future changes in water availability for specific uses, agricultural water requirements, flood frequency, or soil erosion processes [25]. These outcomes depend on additional hydrological, geomorphological, and land-use factors that require dedicated assessment. Accordingly, the findings provide a climatic reference for future research and support the integration of higher-resolution climate projections with hydrological and environmental impact models to inform territorial planning and adaptation policies.

Overall, the results indicate that urgent & coordinated responses are required to meet the demands of the future climate due to the changes we are seeing in Puno, and that there is a need for a comprehensive and integrated approach that incorporates ecosystem-based adaptation, sustainable use of water resources, and implementation of mitigation strategies at the regional level. Overall, the results highlight the importance of coordinated responses to the projected climatic changes in Puno. An integrated approach incorporating ecosystem-based adaptation, sustainable water-resource management, and regional mitigation strategies is essential to address potential climate-related challenges. Further improvements in climate modeling and increased investment in regional studies using higher-resolution datasets are also needed to improve the understanding of climatic processes in the high Andes [26]. The findings of this research contribute to the scientific knowledge base and provide a regional reference for the development of evidence-based public policies addressing climate change challenges in the twenty-first century.

The projected climatic conditions for the remainder of the twenty-first century, based on the nine CMIP5 global climate models under the RCP2.6, RCP4.5, and RCP8.5 scenarios, indicate substantial changes in temperature and mean annual precipitation across the Puno study domain. These findings are consistent with previous regional research by Moya et al. [2], who identified spatial differences in projected temperature and precipitation changes between northern and southern Peru. Their results also highlighted greater warming and precipitation increases in northern areas compared with southern sectors, although some southern areas may experience precipitation reductions during initial projection periods under high-emission scenarios. The spatial patterns identified in the present study are broadly consistent with these previous findings, particularly regarding the north–south differences in projected climatic changes. Furthermore, the stronger warming projected under RCP8.5 reinforces the importance of considering alternative emission pathways when assessing future climate conditions in the Peruvian Altiplano. Nevertheless, direct comparisons with previous studies should be interpreted cautiously because differences in climate models, spatial resolution, reference periods, and emission scenarios may influence the magnitude of the reported projections. In general, the projected ranges and trends of both surface air temperature and precipitation will be greater in Puno, especially under the RCP8.5 emissions scenario than was observed in the overall study; and it is also interesting to note that the warming projected under the RCP8.5 emissions scenario will be substantially greater than that projected under the highest SRES emission scenario, the A2 emissions scenario, as described by [27].

While the use of the RCP scenarios has helped to reduce the uncertainty associated with projecting climate change on a regional basis, further research continues to be needed. Future studies should incorporate CMIP6 simulations under the SSP scenarios, which provide updated emission pathways, improved representation of atmospheric processes, and higher spatial resolution. Comparison between CMIP5 and CMIP6 ensembles would help to assess the robustness of the projections presented here and to refine regional adaptation strategies. Additional research is particularly necessary to enhance climate models, evaluate and modify emission scenarios, and assess uncertainties pertaining to regional model dispersion.

6. Conclusions

The reported CMIP5 ensemble projects warming in the Puno study domain under all three RCP scenarios. Relative to 1986–2005, temperature increases during 2071–2100 are 1.47 °C under RCP2.6, 2.56 °C under RCP4.5, and 4.52 °C under RCP8.5. The regional anomalies exceed the global values in Table 2, indicating climate amplification as defined in the Introduction (i.e., a regional temperature anomaly larger than the global mean anomaly under the same scenario and reference period). However, a quantitative amplification interpretation requires confirmation that both calculations use comparable variables, models, and spatial averaging. These values refer specifically to the annual mean of daily maximum near-surface air temperature (tasmax) and should not be directly equated with changes in mean surface air temperature (tas) or minimum temperature (tasmin), which may exhibit different magnitudes. Mean precipitation increases during 2071–2100 are 5.32%, 5.63%, and 10.99% under RCP2.6, RCP4.5, and RCP8.5, respectively. Spatial heterogeneity means

that these domain averages do not imply uniform changes across Puno. The study does not quantify changes in extreme rainfall, seasonal drought, or flood frequency.

The multimodel approach summarizes the central response and intermodel spread without eliminating model uncertainty. Signal-to-noise ratios ($\lambda = |\Delta\bar{T}| / \sigma_models$) describe ensemble consistency and should be interpreted alongside model performance and the limitations of the spatial resolution.

The spatial resolution of 1° × 1° and the limited number of grid cells covering the Puno area restrict the interpretation of results to an aggregated regional scale. Future studies with higher-resolution regional models will be needed to assess intra-regional and local changes in the Peruvian Altiplano.

The reported projections motivate further assessment of adaptation needs in Puno. Priority extensions include regional model evaluation, higher-resolution climate simulations, analysis of climate extremes, and explicit modelling of impacts on water resources and agriculture. Complete documentation of the source data and calculations is needed before these projections are used for local decisions.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Jhonatan Hinojosa-Mamani: conceptualization, methodology, formal analysis, and visualization; Adderly Mamani-Flores: conceptualization, interpretation of results, and writing (original draft preparation); Jorge Apaza-Ticona: data curation and validation; Vicente Alanoca-Arocutipa: investigation and interpretation of results; Germán Belizario-Quispe: methodology and critical revision of the manuscript; Duverly Joao Incacutipa-Limachi: supervision and critical revision of the manuscript; Julian Apaza-Chino: literature review and writing (review and editing). All authors contributed to the intellectual development of the manuscript, reviewed the final version, and approved its submission.

Declaration of use of AI in the writing process

The authors used ChatGPT (OpenAI) during the preparation of this manuscript to assist with language refinement, grammatical editing, and improvement of textual clarity. The authors reviewed and edited the generated content as necessary and take full responsibility for the accuracy, integrity, and final version of the manuscript.

References

[1] E. Lujano, L. S. Hidalgo, R. Díaz, B. Tapia, and A. Lujano, “Cambios proyectados de los recursos hídricos bajo escenarios de emisiones RCP 4.5 y 8.5 de modelos climáticos globales del CMIP5 en el Altiplano Peruano,” *Rev. Investig. Altoandinas*, vol. 18, no. 2, pp. 195–204, 2016. https://doi.org/10.18271/ria.2016.200

[2] A. Moya-Álvarez, J. Ortega-León, and X. Jurado-Pacheco, "Evaluación del Modelo Climático Global MIROC5 y estimaciones de temperatura y precipitaciones para las zonas sur y norte del Perú," *Apunt. Cienc. Soc.*, vol. 5, no. 2, 2015. https://doi.org/10.18259/acs.2015028

[3] J. Sanabria, J. Marengo, and M. Valverde, "Escenarios de cambio climático con modelos regionales sobre el Altiplano Peruano (Departamento de Puno)," *Rev. Peru. Geo-Atmosférica*, no. 1, pp. 134–149, 2009.

[4] S. del Aguila and F. Espinoza-Montes, "Impacto del cambio climático en las descargas futuras de una cuenca altoandina de Perú al 2100," *Tecnol. Cienc. Agua*, vol. 15, no. 1, pp. 111–155, 2024. https://doi.org/10.24850/j-tyca-15-01-03

[5] E. Tosal, "Restricciones en la sensibilidad climática emergiendo del análisis de fluctuaciones de la temperatura global," 2022. *[Publication type and institution need to be identified.]*

[6] Y. Nava Assad, "Comparación de escenarios de cambio climático en la cuenca hidrográfica del Río La Antigua," M.S. thesis, Universidad Nacional Autónoma de México, 2020.

[7] J. Sota and M. Lagos-Zúñiga, "Proyecciones de eventos hidro-meteorológicos extremos en una cuenca del Altiplano chileno, bajo el escenario de cambio climático SSP5-8.5," *Rev. SOCHID*, vol. 37, no. 1, 2022.

[8] E. Rodríguez, J. Parodi, F. González, and M. Montoya, "Proyecciones climáticas," *Agencia Estatal de Meteorología*, vol. 10, no. 2, pp. 477–516, 2018. https://doi.org/10.31978/014-18-009-X.29

[9] C. A. Bonilla-Ovallos and O. J. Mesa Sánchez, "Validación de la precipitación estimada por modelos climáticos acoplados del proyecto de intercomparación CMIP5 en Colombia," *Rev. Acad. Colomb. Cienc. Exactas Fís. Nat.*, vol. 41, no. 158, pp. 107–118, 2017. https://doi.org/10.18257/raccefyn.427

[10] R. Castillo, R. Montero, J. Amador, and A. M. Durán, "Cambios futuros de precipitación y temperatura sobre América Central y el Caribe utilizando proyecciones climáticas de reducción de escala estadística," *Rev. Climatol.*, vol. 18, pp. 1–12, 2018.

[11] O. C. Penalba and V. C. Pántano, "Proyecciones de los flujos de agua en el suelo a partir de los modelos climáticos globales del CMIP5 en Sudamérica y su impacto regional," *RADA*, vol. 10, pp. 1–13, 2019.

[12] M. A. Altamirano del Carmen, "Atribución de la influencia antropogénica en la tendencia de la temperatura en México en el periodo 1910 a 2005," Ph.D. dissertation, Universidad Nacional Autónoma de México, 2021.

[13] T. Andrews, J. M. Gregory, M. J. Webb, and K. E. Taylor, "Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models," *Geophys. Res. Lett.*, vol. 39, no. 9, 2012. https://doi.org/10.1029/2012GL051607

[14] J. Yin, "Century to multi-century sea level rise projections from CMIP5 models," *Geophys. Res. Lett.*, vol. 39, no. 17, Art. no. L17709, 2012. https://doi.org/10.1029/2012GL052947

[15] M. Gaetani and E. Mohino, "Decadal prediction of the Sahelian precipitation in CMIP5 simulations," *J. Climate*, vol. 26, no. 19, pp. 7708–7719, 2013. https://doi.org/10.1175/JCLI-D-12-00635.1

[16] U. Manzanilla-Quiñones, G. Pozo-Montuy, P. Delgado-Valerio, A. R. Martínez-Sifuentes, and O. A. Aguirre-Calderón, "Escenarios climáticos (CMIP-5) para la Reserva de la Biosfera Pantanos de Centla, Tabasco, México," *Ecosistemas Recur. Agropecu.*, vol. 8, no. 1, Art. no. 2588, 2021. https://doi.org/10.19136/era.a8n1.2588

[17] L. Fei and Y. Gao, "The projected Siberian High in CMIP5 models," *Atmos. Ocean. Sci. Lett.*, vol. 8, no. 4, pp. 179–184, 2015. https://doi.org/10.3878/AOSL20140101

[18] SENAMHI, "Evaluación de los modelos CMIP5 del IPCC en el Perú," 2013. *[The original title and report details need to be completed.]*

[19] L. E. Andersen and R. Mamani Paco, *Cambio Climático en Bolivia hasta 2100: Síntesis de Costos y Oportunidades*. La Paz, Bolivia, 2009.

[20] D. Villalobos, "Análisis actual y proyecciones de la temperatura y precipitación del Norte Grande y su Altiplano en Chile: Variabilidad (1970–2013) y cambio climático en el escenario futuro RCP 8.5 (2080)," thesis, Universidad de Chile, 2016.

[21] J. D. Pabón Caicedo, "Cambio climático en Colombia: Tendencias en la segunda mitad del siglo XX y escenarios posibles para el siglo XXI," *Rev. Acad. Colomb. Cienc. Exactas Fís. Nat.*, vol. 36, no. 139, pp. 261–278, 2012.

[22] P. Sarricolea and H. Romero, "Variabilidad y cambios climáticos observados y esperados en el Altiplano del norte de Chile," *Rev. Geogr. Norte Gd.*, no. 62, pp. 169–183, 2015. https://doi.org/10.4067/S0718-34022015000300010

[23] J. C. Alarcón Hincapié and J. D. Pabón Caicedo, "El cambio climático y la distribución espacial de las formaciones vegetales en Colombia," *Colomb. For.*, vol. 16, no. 2, pp. 171–185, 2013. https://doi.org/10.14483/udistrital.jour.colomb.for.2013.2.a04

[24] M. Sánchez and J. Olave, "Revisión: ¿Puede el cambio climático afectar la producción de quinoa (*Chenopodium quinoa* Willd.) en el Altiplano chileno?," *IDESIA*, vol. 37, no. 1, pp. 19–24, 2019. https://doi.org/10.4067/S0718-34292019005000202

[25] W. C. Choque Marca and J. C. Torrico Alvino, "Efectos y medidas adaptativas al cambio climático en sistemas agropecuarios del Altiplano: Revisión de literatura," *Horiz. Acad.*, vol. 4, no. 2, pp. 221–249, 2024. https://doi.org/10.70208/3007.8245.v4.n2.42

[26] L. E. Andersen, L. C. Jemio Mollinedo, and H. Valencia, *La economía del cambio climático en Bolivia: Impactos en el sector agropecuario*. Washington, DC, USA: Banco Interamericano de Desarrollo, 2014. https://doi.org/10.18235/0012677

[27] H. Valencia and L. E. Andersen, "Cambio climático en Bolivia hasta 2100: Análisis de los impactos sobre el sector agropecuario," 2009. *[Publication details and original document need to be confirmed.]*