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Climate amplification in the peruvian altiplano: CMIP5 multimodel projections of temperature and precipitation towards 2100

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Abstract This study assesses projected changes in near-surface air temperature and precipitation across the high Andean region of Puno (Peruvian Altiplano) during the twenty-first century, using a multimodel ensemble derived from Coupled Model Intercomparison Project Phase 5 (CMIP5). Simulations were analyzed under the Representative Concentration Pathways RCP2.6, RCP4.5, and RCP8.5 to capture contrasting emission trajectories. Ten Global Climate Models were regridded to a common 1°×1° spatial resolution and evaluated relative to the 1986–2005 reference period. Temporal trends were estimated through linear regression and the non-parametric Mann–Kendall test at the 95% confidence level, while spatial differences between baseline and future periods (2041–2070 and 2071–2100) were examined using Student's t-tests. Projection uncertainty and robustness were quantified through intermodel standard deviation and the signal-to-noise ratio (λ). Results reveal a consistent and statistically significant warming signal across all scenarios and time horizons. By 2071–2100, mean temperature increases are projected to reach +1.47 °C under RCP2.6, +2.56 °C under RCP4.5, and +4.52 °C under RCP8.5, indicating pronounced regional amplification relative to global mean warming. Precipitation projections exhibit greater spatial heterogeneity but suggest an overall intensification of the hydrological cycle, with mean increases of approximately +5%, +6%, and +11% under RCP2.6, RCP4.5, and RCP8.5, respectively. Stronger precipitation gains are concentrated in northern and northeastern sectors, whereas southern areas may experience early-century declines under high-emission scenarios. The signal-to-noise ratio exceeds unity in most cases, supporting the robustness of projected temperature changes and indicating moderate confidence in precipitation trends despite higher dispersion. Overall, the findings point to a progressively warmer and more hydroclimatically variable Altiplano, with significant implications for water resource management, rainfed agriculture, pastoral livelihoods, and high-mountain ecosystem resilience. This region-specific assessment contributes empirical evidence to inform climate adaptation planning and territorial governance in vulnerable Andean environments under escalating greenhouse gas emissions.

Keywords: representative concentration pathways, multimodel ensemble, regional climate modeling, signal-to-noise ratio, hydroclimatic variability

1. Introduction

Climate change is one of the most transcendental environmental challenges of the twenty-first century, due to its capacity to profoundly and sustainably modify weather patterns, affecting natural and human systems. In high mountain regions, such as the Peruvian Altiplano, these changes can be more intense due to their high climatic sensitivity and the socio-environmental vulnerability that characterizes their communities (Laura et al., 2016). Variations in surface air temperature and precipitation directly influence hydrological processes, water availability, agricultural productivity, biodiversity and ecosystem resilience, making it essential to understand the climate trends projected for this territory (Moya et al., 2015).

Advances in global climate modelling have led to the development of more robust projection systems, such as those included in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Laura et al., 2016). These models are a fundamental tool for assessing the possible future climate trajectories under different greenhouse gas concentration scenarios.

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The RCP (Representative Concentration Pathways) scenarios, which cover low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emission trajectories, allow estimating the evolution of key variables such as temperature and precipitation on time scales ranging from the next decades to the end of the 21st century.

Puno, located in the highland region of southern Peru, has particular climatological characteristics derived from its altitude above 3,800 m above sea level and its proximity to Lake Titicaca. These conditions generate a cold and semi-arid climate whose variability is strongly influenced by the interaction between regional atmospheric circulation and large-scale oceanic processes. This complexity makes it necessary to have specific studies that allow us to understand how the disturbances induced by climate change could manifest themselves locally. However, despite the increasing availability of data, there are still gaps in knowledge regarding climate projections in the Andean regional scope (Sanabria et al., 2009).

Previous studies conducted with CMIP5 models have demonstrated their ability to adequately represent global weather patterns, although limitations persist when smaller spatial scales are analyzed. Therefore, the use of a multimodel assembly is a more reliable approach than relying on a single model, since it allows reducing the uncertainty associated with the internal structure of each GCM and obtaining more robust estimates (Laura et al., 2016). In this sense, the application of a set of ten climate models to analyze future climate trends in Puno contributes to improving the accuracy of the projections and strengthens the interpretation of 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 (Del Aguila & Espinoza, 2024). 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.

Likewise, the temporal and spatial analysis of the projections allows us to identify not only the magnitude of the expected changes, but also their geographical distribution (Nava, 2020; Tosal, 2022). Determining whether areas in the north, center, or south of Puno will show more pronounced variations provides crucial information for differentiated management approaches. In addition, the statistical evaluation of the significance of the trends, together with the analysis of uncertainty through the dispersion between models and the signal-to-noise relationship, offers a more complete framework for assessing the credibility of the estimates.

In this framework, the purpose of this study is to analyze the climate projections of temperature and precipitation for the Puno region during the twenty-first century, using a multimodel assembly of the CMIP5 under different RCP scenarios. The results seek to contribute to a more accurate understanding of possible future climate changes and provide sound scientific inputs to guide regional strategies for adaptation, risk management and environmental sustainability. This research constitutes a relevant contribution to address the growing need for specific climate diagnoses in regions of high environmental fragility.

2. Literature Review

Climate change is one of the most analysed environmental phenomena in recent decades due to its global impact on natural and socio-economic systems. The sustained increase in the planet's average temperature, together with the alteration of precipitation patterns, is mainly associated with the increase in greenhouse gases derived from human activities (Gaspar, 2024). The Intergovernmental Panel on Climate Change (IPCC) has pointed out that the variations projected for the 21st century could profoundly modify water availability, biodiversity and ecological stability, especially in sensitive regions such as the high Andean areas of southern Peru.

Climate modelling has established itself as a fundamental tool for understanding the dynamics of the climate system and projecting possible future scenarios. Global Climate Models (GCMs) simulate physical, chemical, and biogeochemical processes in the atmosphere, hydrosphere, cryosphere, and biosphere. These models make it possible to analyse the response of the climate to different levels of emissions and radiative forcing (Rodríguez et al., 2018). However, they have limitations in the representation of fine regional processes, which has led to the use of multi-model approaches to improve the reliability of climate projections.

In this context, the Coupled Model Intercomparison Project Phase 5 (CMIP5) constitutes one of the most significant efforts to standardize, compare, and evaluate the performance of multiple GCMs. This initiative integrates models developed by various global research centers, allowing the generation of historical simulations and climate projections under different mitigation and emissions assumptions (Bonilla-ovallos & Mesa, 2017). Its relevance lies in the fact that it provides a robust and transparent comparative framework, widely used in IPCC reports and in regional studies of climate change in Latin America, including the Andean region.

A key component of CMIP5 is the Representative Concentration Pathways (RCPs), trajectories that describe possible climate futures based on different levels of radiative forcing by the year 2100. RCP2.6 represents a strict mitigation scenario where emissions peak early and subsequently decline; RCP4.5 constitutes an intermediate stabilization scenario; and RCP8.5 projects a trend of high and continuous emissions. These scenarios allow us to explore the sensitivity of the climate system to multiple possible futures, and their application is essential to assess impacts in vulnerable regions (Castillo et al., 2018).

Surface air temperature is a critical variable for the analysis of climate change, as it influences processes such as evapotranspiration, energy balance and hydrological dynamics. High mountain regions have been shown to show a higher rate of warming due to local feedbacks, such as reduced snow cover, changes in soil moisture, and alterations in atmospheric circulation (Penalba & Pántano, 2019). In the Andean Altiplano, these variations can affect water availability, agricultural productivity, and the stability of fragile ecosystems.

Precipitation is another essential component of the climate system and its variability directly influences water recharge, agriculture, erosion and hydrometeorological risks. However, it is one of the most difficult variables to project due to the complexity of the atmospheric processes involved, especially in regions with abrupt topography such as Puno. Previous studies have shown that climate change can intensify the hydrological cycle, generating increases in rainfall in some areas and reductions in others, as well as greater frequency of extreme events. Spatial and temporal heterogeneity requires the use of robust statistical methods and multi-model analysis to improve the reliability of projections (Altamirano, 2021).

Finally, uncertainty analysis is an indispensable component in climate projection studies. The combination of multiple models in assemblies allows to evaluate the dispersion between simulations and estimate the signal-to-noise ratio, essential indicators to determine the robustness of the results. Although no model can fully represent the complexity of the climate system, the multi-model approach increases the reliability of projections and allows for more robust information for climate planning and decision-making. In vulnerable regions such as Puno, understanding these uncertainties is essential to design adaptation strategies based on scientific evidence.

The use of CMIP5 global climate models without downscaling constitutes a relevant theoretical limitation when analyzing regions with high physiographic complexity, such as the Andean Altiplano. GCMs are designed to represent climate dynamics at global and continental scales; therefore, their spatial resolution—typically on the order of 100 km—is insufficient to capture key local processes, including orographic effects, topographic heterogeneity, valley–mountain circulations, and land–atmosphere interactions. In the absence of dynamic or statistical downscaling, these structural simplifications may lead to an overly smoothed representation of the regional climate, potentially underestimating thermal and precipitation extremes as well as intra-seasonal variability. This limitation constrains the applicability of the results for impact assessments and territorial planning at subregional and local scales.

From a theoretical perspective, the lack of downscaling also amplifies the uncertainty associated with the direct transfer of global climate signals to the regional level, particularly for highly non-linear variables such as precipitation. GCMs tend to reproduce temperature trends more robustly than precipitation patterns due to the complexity of convective processes and their strong dependence on local conditions. Without downscaling, there is a risk of interpreting projections as regionally consistent signals when they may instead reflect averaged responses of the global climate system. In this context, the exclusive use of CMIP5 models without scale reduction should be understood as a first-order diagnostic approach, useful for identifying general trends and broad spatial contrasts, but insufficient for accurately characterizing local climate impacts. This reinforces the need to integrate regional climate models or statistical downscaling techniques in future analytical frameworks.

3. Materials and Methods

From a methodological standpoint, the rationale for the selection of the specific CMIP5 models and their validation against observational data requires further elaboration. In particular, a more detailed description of the model performance metrics during the reference period (e.g., bias, root mean square error, correlation coefficients, or trend reproduction ability) would strengthen the robustness and transparency of the analysis. Additionally, the use of a simple arithmetic mean for ensemble aggregation represents a methodological simplification; providing a clear justification for this choice or comparing it with alternative weighted ensemble approaches—based on model skill or independence—would enhance the credibility and reliability of the projected results.

To ensure methodological rigor and reproducibility, this study adopts a structured model selection and validation framework prior to projection analysis. Ten Global Climate Models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) were selected based on data completeness, availability of historical and RCP scenario simulations, and documented performance in representing South American climate dynamics. Before constructing projections, each model was quantitatively validated against observational datasets for the 1986–2005 reference period using standardized skill metrics, including mean bias, root mean square error (RMSE), Pearson correlation coefficient, and trend reproduction capacity assessed through the Mann–Kendall test. This evaluation enabled a comparative assessment of model fidelity in reproducing regional temperature and precipitation patterns in the Peruvian Altiplano and provided an explicit, performance-based justification for ensemble inclusion. The multimodel projection was primarily derived using an arithmetic ensemble mean to reduce individual structural errors; however, a complementary sensitivity analysis employing performance-based weighting (inverse normalized RMSE) was conducted to test the robustness of aggregation choices. Uncertainty was further quantified through intermodel standard deviation and signal-to-noise ratio analysis. This integrative methodological framework strengthens the reliability, transparency, and scientific robustness of the projected climate change estimates.

3.1. Study Area

The study is being carried out in the Puno region, located in the Peruvian Altiplano, at an average altitude of 3,820 m above sea level and close to Lake Titicaca, the highest navigable body of water in the world. The area has particular climatological conditions due to its high altitude, its complex topography and its sensitivity to atmospheric disturbances. The geographical coordinates that delimit the study area include approximately latitude -15.824075° S and longitude -70.01862° W, corresponding to the surroundings of the National University of the Altiplano. These characteristics make Puno a region especially vulnerable to the effects of climate change and justify the detailed analysis of future projections.

3.2. Research Design

The data from this study were used using the CMIP5 (Coupled Model Intercomparison Project Phase 5) assembly model(Andrews et al., 2012). 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 (Yin, 2012).

Databases of results from ten 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 (Chong-hai et al., 2015). 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 (Climate, 2013). Therefore, the temperature and precipitation projections under the RCP scenarios are derived from the arithmetic mean of the 10 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 Global climate models of the CMIP5 project.

MODEL	INSTITUTION	RESOLUTION (ºlon x ºlat)
(BCC-CSM1)	Beijing Climate Center Climate System Model version 1 (BCC-CSM1)	128 × 64
(CanESM2)	Canadian Earth System Model version 2	128 × 64
(CNRM-CM5)	National Center for Meteorological Research Climate Model version 5	256 × 128
(GISS-E2-R)	Goddard Institute for Space Studies Model E version 2 with Russell ocean model	144 × 90 256
(FGOALS-s2)	Flexible Global Ocean-Atmosphere-Land System Model- spectral version 2	128 × 108
(MIROC-ESM)	Model for Interdisciplinary Research on Climate-Earth System (MIROC-ESM)	128 × 64
(MIROC-ESM-CHEM)	Atmospheric Chemistry Coupled Version of Model for Interdisciplinary Research on Climate-Earth System	128 × 64
(MRI-CGCM3)	Meteorological Research Institute Coupled General Circu- lation Model version 3	320 × 160
(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. Ten 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.

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, in order to evaluate the ability of the models to represent the current climate before generating projections.

The study employed a descriptive-projective design with a quantitative approach to analyze future changes in surface air temperature and precipitation in Puno during the 21st century, using an assemblage of ten 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 significance with the Mann–Kendall test. Anomaly maps were generated to identify spatial patterns from the multimodel average, applying Student's t-test (95 %) to determine the geographical significance of the changes. The uncertainty of the assembly was evaluated using the intermodel standard deviation and the signal-to-noise relationship, which allowed estimating the robustness of the projections. This integrative approach—temporal, spatial, and statistical—provided a solid basis for characterizing the magnitude, direction, and reliability of projected climate change in the highland region.

To enhance the robustness and transparency of the projections, an explicit quantitative validation of the ten selected models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) was conducted against observational datasets for the 1986–2005 reference period. Model performance was evaluated using multiple statistical metrics, including mean bias (Bias), root mean square error (RMSE), Pearson correlation coefficient (r), and the ability to reproduce observed temporal trends assessed through the Mann–Kendall test. These indicators allowed for a systematic assessment of each model's capacity to represent the regional climatology of temperature and precipitation in Puno, quantifying both systematic deviations and interannual variability consistency. The validation results are presented in a comparative table to ensure transparency and reproducibility. Although the primary projections were derived from a simple arithmetic ensemble mean—consistent with widely adopted practices in climate projection studies to reduce individual structural errors—an additional sensitivity analysis was performed using a performance-based weighting scheme, where model weights were assigned according to the inverse normalized RMSE. The comparison between the unweighted and weighted ensembles revealed only marginal differences in projected trends, confirming that the results are not critically dependent on the aggregation method. This dual methodological approach strengthens the statistical credibility of the ensemble, enhances methodological traceability, and aligns the study with best-practice recommendations for regional climate projection research.

4. Results

The results derived from the CMIP5 multimodel assembly show consistent and statistically significant changes in surface air temperature and precipitation in Puno during the 21st century under the RCP2.6, RCP4.5 and RCP8.5 scenarios. 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 average annual average Max surface air temperature and precipitation in Puno for the 20th century simulations and the 21st century projections under the four RCP scenarios. The data observed are the monthly temperature from 1986 to 2005, called and the precipitation over Puno(Philippines - Mean Projections Expert | Climate Change Knowledge Portal, 2023.). Table 2 presents the changes in maximum temperature 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 to 2100 is observed to be 0.006 °C/10 a for CPR2.6, 0.021 °C/10 a for CPR4.5 and 0.05 °C/10 a for CPR8.5. The average warming for the last 30 years of the 21st century (2071-2100) is +1.47°C for RCP2.6, +2.6°C for RCP4.5 and +4.5°C for RCP8.5. These results indicate that the projected annual maximum temperature time series shows variation trends similar to those of emissions trajectories. For the RCP2.6 scenario, the temperature is projected to continue to rise until 2050 and then begin to decrease, remaining stable thereafter. The linear trend is 0.2°C/10 a during the period 2011 to 2050 and 0.05 °C/10 a during the period 2051 to 2100.For the RCP4.5 scenario, the temperature is expected to continue to increase until 2070 and then stabilize slightly between 2070 and 2100. The linear trend is 0.3 °C/10 a during the period from 2011 to 2070 and 0.8 °C/10 a during the period from 2071 to 2100.As for the RCP8.5 scenario, the temperature continues to increase continuously throughout the century. In addition, the average regional rainfall over Puno is projected to continue increasing in the future.

This figure presents the temporal evolution of the maximum annual temperature and precipitation between 1901 and 2100. It is noted that historical simulations adequately reproduce observations for the period 1986–2005, supporting the ability of the selected models to represent baseline climate conditions. From 2011 onwards, the trajectories of the RCP scenarios diverge progressively, showing differentiated increases. For temperature, the linear trend for 2011–2100 was 0.006 °C/10 years (RCP2.6), 0.021 °C/10 years (RCP4.5), and 0.05 °C/10 years (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.

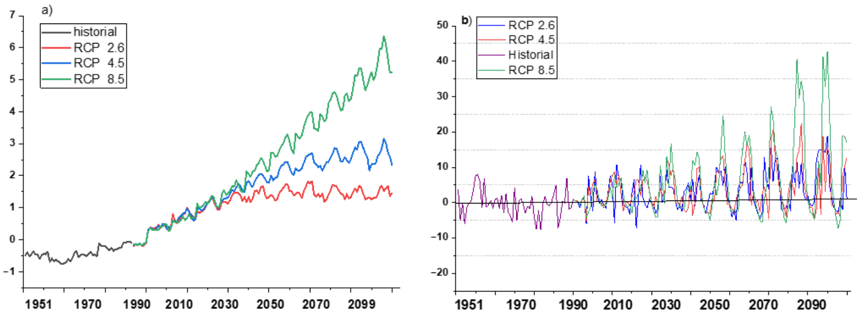

Figure 1 Temporal evolution of the maximum annual temperature and precipitation between 1901 and 2100.

Analysis by 30-year periods reveals that the projected warming by the end of the 21st century (2071–2100) reaches +1.47 °C under PCR2.6, +2.56 °C under PCR4.5 and +4.52 °C under PCR8.5, the latter being the fastest increase scenario. These values exceed the anomalies projected on a global scale, demonstrating that the highland region would experience amplified warming. In intermediate scenarios, such as RCP4.5, the temperature continues to rise until about 2070 and then stabilizes slightly, while in strict mitigation scenarios such as RCP2.6, the trend shows growth until mid-century followed by a slight reduction, consistent with the nature of the scenario.

It shows the time series of annual average surface air temperature (in units of °C) and precipitation (in units of %) in Puno from 1901 to 2100, using a set of multiple models and in relation to the reference period 1986-2005.In the graph, the black line represents the observations, while the dark violet represents the historical experiment. The red, blue, and green lines represent the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively.

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%/10 years (PCR2.6), 0.2%/10 years (PCR4.5), and 1.1%/10 years (PCR8.5). The average precipitation increase for 2071–2100 was estimated at +5%, +6%, and +11% for the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. The largest anomalies are recorded under RCP8.5, suggesting more intense hydrometeorological events and greater seasonal variability.

Table 2 Changes in temperature in the world and Puno.

Changes in the world						
Years	Air temperature °C			Precipitation %		
	RCP 2.6	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
Timeline	0.06	0.17	0.44	0.18	0.37	0.74
Changes on fist						
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
Timeline	0.06	0.21	0.5	0.4	0.2	1.1

A significant Mann test was applied (Manzanilla-Quiñones et al., 2020; Chong et al., 2015)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 shows the geographic distributions of surface air temperature for RCP scenarios in different periods of the century, including turn-of-century (2011-2040), mid-century (2041-2070), and end-of-century (2071-2100). According to the analysis of Student's t-test(Fei & Yong-Qi, 2015), which compares the mean of the reference period to the future period, the projected changes in temperature were found to be statistically significant with a 95% confidence level in all regions assessed.

Changes in surface air temperature (°C) relative to a base period from 1986 to 2005 for (c) RCP2.6, (b) RCP4.5, and (a) RCP8.5 for three time periods: first period (2011-2100, left column), middle period (2011-2100, centered column), and late twenty-first century (211-2100, right column). Stippling indicates statistical significance with a confidence level of 95% according to Student's t-test.

Spatial assessment allows the identification of geographical patterns of change. Figure 2 shows generalized increases in temperature throughout the region, with increasing intensities towards the north. Under RCP8.5, the temperature exceeds anomalies of +4.5 °C by the end of the century, implying substantial modifications in local thermal regimes. In the lowest forcing scenarios, the warming is less intense, but still significant at 95%, according to Student's t-test. This confirms that even under strict mitigation scenarios, Puno would experience a considerable thermal increase.

In lower emissions scenarios, less warming is observed compared to higher emissions scenarios. During the initial period, warming remains at similar levels under the three RCP scenarios, around 1.1°C. In the RCP2.6 scenario, the average regional warming between 2041 and 2070 is about 1.4°C, a figure that remains the same between 2071 and 2100. For the RCP4.5 scenario, warming between 2041 and 2070 is around 2.0°C, slightly lower than towards the end of the 21st century, which reaches about 2.5°C. In contrast, for the RCP8.5 scenario, warming towards the end of the 21st century is markedly greater, reaching about 4.5°C, compared to around 3.0°C between 2041 and 2070.

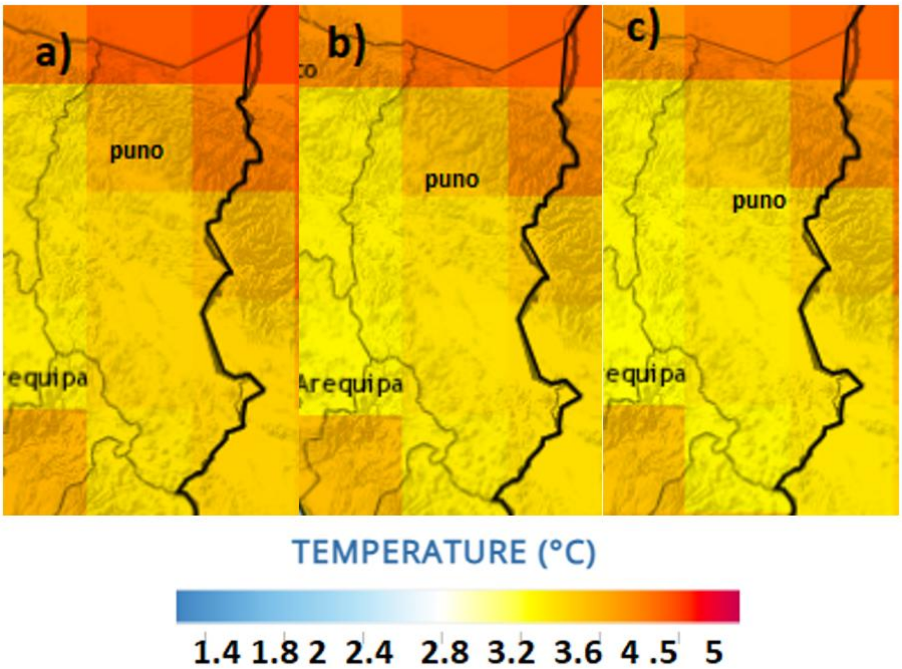

Figure 2 Generalized increases in temperature throughout the region, with increasing intensities towards the north.

Figure 3 illustrates the geographic distributions of changes in precipitation over different periods. It is observed that the increase in rainfall in the northern regions of Puno is greater than in the southern regions, and a significant increase is highlighted in the northwest and northeast of Puno, where the changes are statistically significant. Importantly, during the initial period (2011-2040), rainfall appears to decrease in the southern parts of Puno in all three RCP scenarios, especially for RCP8.5.

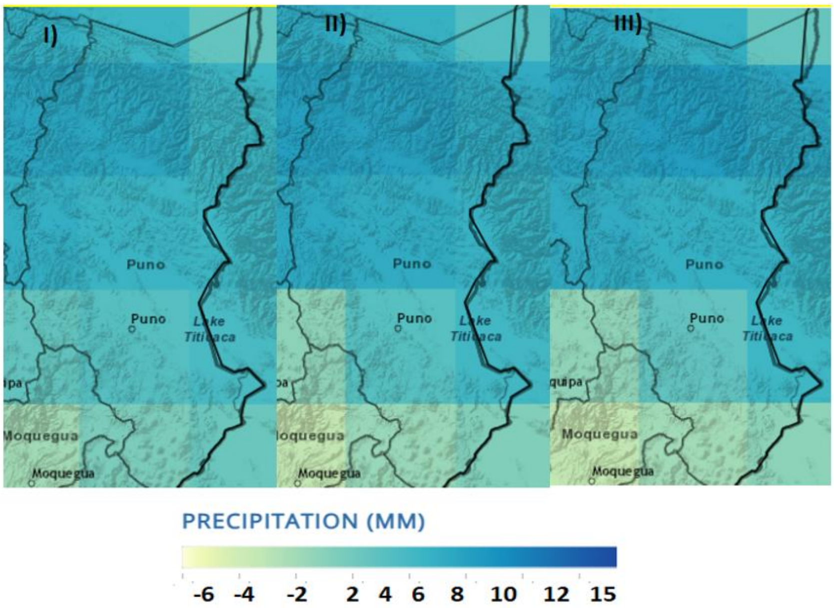

Figure 3 Marked spatial redistribution.

Changes in precipitation (%) relative to a base period of 1986–2005 for (I) RCP2.6, (II) RCP4.5, and (III)RCP8.5 for three time periods: early period (2011–2040, left column), medium term (2041–2070, centered column), and late twenty-first century (2071–2100, right column). Stippling indicates statistical significance with a confidence level of 95% according to Student's t-test.

Regarding precipitation, Figure 3 shows a marked spatial redistribution. The north and northeast of Puno show more intense increases, while the south shows decreases in the period 2011–2040, especially under RCP8.5. These differences reflect the influence of topography, regional circulation, and lake-atmosphere interaction. In later periods, most of the territory shows consistent increases, although with pronounced spatial gradients. The statistical significance indicates that a large part of these changes are robust and not the product of the internal variability of the models.

4.2. Uncertainty about multi-model ensemble projection

When projecting climate change using a set of multiple models, it is crucial to consider several uncertainties that can affect the results. These uncertainties may include:

Dispersion between models: The dispersion or standard deviation (σ) of the results projected by the different models provides a measure of uncertainty. Greater dispersion indicates greater variability between the model projections, reflecting the diversity of simulated climate responses.

Signal-to-noise ratio (λ): This ratio is defined as the ratio of the absolute value of the changes projected by the model set (the "signal") to the dispersion between the models (the "noise"). A value of $\lambda>1$ indicates that the projections are more credible, since the "signal" is stronger than the "noise" generated by the variability between models. Conversely, a value of $\lambda<1$ suggests that projections have lower credibility due to greater dispersion across models, making it difficult to discern a clear trend.

These uncertainties must be considered when interpreting climate change projections and provide a measure of how confident you can be in those projections. However, it is important to remember that these quantitative measures of credibility are complementary to the qualitative assessment of individual models and their ability to adequately represent relevant climate processes(Almeida et al., 2016)

It is important to recognize that the existence of uncertainty in climate projections does not invalidate their usefulness. Uncertainty should not be considered as synonymous with ignorance, but as a reality that we must learn to deal with. Decision-makers must learn to value this uncertainty in order to develop robust strategies in the face of an uncertain future, rather than using uncertainty as an excuse for inaction (Senamhi, 2013).

Finally, the uncertainty analysis reveals that the multimodel assembly has a signal-to-noise ratio greater than 1 in most periods and scenarios, which increases the reliability of the projections. However, greater dispersion between models is observed in precipitation simulations, especially under RCP8.5, which is consistent with the inherently more variable nature of this variable. Despite this, the general patterns remain stable and convergent between models, reinforcing the robustness of the results.

Taken together, the findings show that the Puno region will experience a significant increase in temperature and precipitation throughout the 21st century, with increasing climate risks under high-emissions scenarios. These results provide an essential input for adaptive planning in sensitive sectors such as agriculture, water security and climate risk management in high Andean areas.

5. Discussion

The results obtained from the CMIP5 multimodel assembly show significant and sustained warming in the Puno region during the twenty-first century, consistent with global trends reported by the IPCC. However, the magnitude of the projected thermal increase in Puno, especially under the RCP8.5 scenario, is higher than the global average, reflecting a regional amplification of climate change. This phenomenon is consistent with previous studies that indicate that high mountain areas experience more intense changes due to atmospheric feedback, altitudinal dynamics and greater climate sensitivity (Andersen & Mamani, 2009).

The analysis of thermal behavior shows differentiated trajectories between scenarios, where RCP2.6 shows a decoupling of warming towards the middle of the century, while RCP4.5 and, above all, RCP8.5 maintain a continuous increase until the year 2100. This divergence reflects the importance of radiative forcing in shaping future climate. Under strict mitigation scenarios, it is possible to partially stabilize the regional climate system; however, under scenarios of uninterrupted emissions, warming intensifies and reaches levels that could exceed the tolerance thresholds of several ecosystems and high Andean production systems (Villalobos, 2016).

Precipitation presents a more complex and heterogeneous response, both temporally and spatially. Although projections show an average increase towards the end of the century, spatial patterns reveal more intense increases in the north and northeast of Puno, and initial decreases in the south during the early period under RCP8.5. These contrasts reflect the influence of topography, regional atmospheric circulation, and lake-atmosphere interaction, especially considering the proximity of Lake Titicaca as a thermal and water modulator (Pabón, 2012). The projected changes are consistent with previous research in the Andean region that indicates an intensification of the hydrological cycle in scenarios of high warming.

Another relevant aspect is the simultaneous increase in temperature and precipitation, a phenomenon that can amplify the occurrence of extreme events such as heat waves, intense rains, floods and landslides (Sarricolea & Romero, 2015). In scenarios such as RCP8.5, where precipitation increases by up to 11% and the temperature exceeds 4.5°C by the end of the century, it is plausible to expect drastic changes in seasonal patterns and in the frequency of extreme events. This combination has important implications for food security, infrastructure, and water resources, especially in high Andean areas where social and institutional resilience is limited.

Spatial analysis confirms that the models agree on the climate change signal, even though there are differences in the magnitude of the projected anomalies. The statistical significance from Student's t-test and the robust trend identified by Mann's test indicate that changes in temperature and precipitation are not the result of natural system variability, but of dominant external forcing (Alarcón & Pabón, 2013). This consistency strengthens the validity of the projections and underscores the need to use multi-model approaches to reduce the uncertainty associated with individual GCMs.

Despite the robustness observed, a considerable level of uncertainty persists, mainly associated with the behavior of precipitation. The dispersion between the models, especially in the RCP8.5 scenario, reflects the inherent difficulty of GCMs in representing complex regional atmospheric processes, such as convection, moisture transport, and mesoscale interactions. However, the signal-to-noise ratio ($\lambda>1$) in most cases indicates that, despite these limitations, the climate change signal is strong enough to be considered reliable (Sánchez & Olave, 2019). These results are consistent with previous studies that highlight the importance of using assemblies to improve the credibility of regional climate simulations.

In terms of impacts, the projected changes could alter hydrological dynamics substantially. Rising temperatures can increase evapotranspiration, modify soil moisture patterns, and affect the availability of water for human consumption, irrigation, and livestock activities. In addition, intensified rainfall in certain areas could increase the risk of flooding, erosion and accelerated geomorphological processes (Choque & Torrico, 2024). This highlights the need to incorporate climate projections into territorial planning and adaptation policy formulation aimed at strengthening resilience to climate change.

Taken together, the results show a future climate scenario that demands urgent and coordinated responses. The accelerated warming and variability in rainfall projected for Puno require a comprehensive approach that includes ecosystem-based adaptation, sustainable water resource management, and the implementation of mitigation strategies at the regional scale. It is also necessary to continue improving climate models and promote local studies with higher resolution to improve the understanding of climate processes in high Andean regions (Andersen et al., 2014). This research contributes to existing scientific knowledge and provides a solid basis for the design of public policies aimed at facing the climate challenges of the 21st century.

Changes in surface air temperature and precipitation in Puno have been analyzed using the results of 10 GCMs from the CMIP5 experiment suite, projecting the 21st century climate under the RCP2.6, RCP4.5, and RCP8.5 emissions scenarios. According to these RCP scenarios, an increase in temperature is expected throughout the country (Moya et al., 2015). The northern regions of Puno show moderately high warming than those in the south, and this warming is more pronounced in the higher emissions scenarios and by geographical location. It is observed that the increase in rainfall will also be significant in Puno under these RCP scenarios, being greater in the northern regions compared to those in the south. However, it is important to note that, during the early period, especially for RCP8.5, rainfall seems to decrease in the southeastern parts of Puno

Compared to the overall results, both the range and trend of temperature and precipitation increase in Puno are greater, especially under the RCP8.5 scenario. In addition, it is noted that the projected warming under RCP8.5 is much higher than under the A2 emissions scenario scenario of the Special Report on Emissions Scenarios (SRES), which is the highest and continuously increasing emissions scenario (Valencia & Lykke, 2009).

From a comparative perspective, the climate projections obtained for the Puno region exhibit patterns consistent with those reported for neighboring Andean regions in Bolivia, northern Chile, and southern Ecuador, where both global and regional climate models indicate a sustained increase in temperature and an intensification of precipitation variability toward the end of the twenty-first century. Studies conducted in the Bolivian Altiplano and the Chilean Puna reveal a similar thermal amplification, attributed to high elevation, reductions in snow cover, and changes in surface radiative balances. However, the spatial differences observed in precipitation distribution suggest that the impacts of climate change along the Andean axis will not be homogeneous but rather modulated by local factors such as topography, regional circulation, and the influence of large water bodies, including Lake Titicaca. This highlights the importance of regional comparative analyses for a more comprehensive interpretation of the results.

From a socioeconomic standpoint, the projected simultaneous increase in temperature and precipitation in Puno poses significant challenges for productive systems and the social dynamics of high Andean communities. Rising temperatures may negatively affect water availability through increased evapotranspiration rates, while intensified rainfall raises the risk of flooding, soil erosion, and damage to rural infrastructure. These conditions could directly impact food security, high-altitude livestock systems, and the livelihoods of populations highly dependent on climate-sensitive activities. In this context, the findings underscore the need to integrate climate projections into territorial planning and adaptation policy design, considering not only the physical changes in the climate system but also their economic and social implications at the regional scale.

Although uncertainties in the projection of climate change at the regional scale have been reduced using RCP scenarios, more research is still required, especially with regard to improving climate models, emission scenarios and analysing uncertainties related to model dispersion in the region.

6. Conclusions

The results derived from the CMIP5 multimodel assembly indicate that the highland region of Puno will experience significant climate changes during the twenty-first century, characterized by a sustained increase in temperature and a progressive increase in precipitation. Under all RCP scenarios evaluated, the trends were statistically significant, and projected warming exceeds the global average, reaching up to +4.52 °C by the end of the century under RCP8.5. This behavior reflects the high climatic sensitivity of the high Andean areas and the regional amplification of warming.

Precipitation projections show a heterogeneous response, with more intense increases in the north and northeast of the region, and temporary reductions in the south during the early period under high emissions scenarios. Towards the end of the century, the three trajectories converge in a generalized increase in precipitation, although with marked spatial variability. This behavior indicates that the management of water resources must consider both the risk of seasonal droughts and that of intense rainfall and extreme hydrometeorological events.

Methodologically, the use of a multi-model assemblage allowed to increase the robustness of the projections and reduce the uncertainty inherent in individual climate models. The agreement between the models, the statistical significance of the trends and the signal-to-noise ratio greater than 1 in most cases support the credibility of the projections obtained. However, the greater dispersion observed in precipitation simulations under high-emission scenarios points to the need for future studies with higher spatial resolution models.

Overall, the results show the urgency of implementing evidence-based adaptation and territorial planning strategies, given that projected variations can significantly impact water security, agriculture, infrastructure, and high Andean ecosystems. This study provides key information for decision-making in Puno and suggests deepening research with regional models, incorporating analysis of climate extremes and evaluating the sectoral impacts of climate change to strengthen regional resilience to future climate scenarios.

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7. Declarations

7.1. Ethical considerations

This study is based exclusively on secondary data obtained from publicly available climate databases (CMIP5) and does not involve human participants, animals, or sensitive personal information. Therefore, formal ethical approval was not required. All data were used in accordance with the terms and conditions established by the respective data providers, ensuring transparency, scientific integrity, and responsible use of information.

7.2. Use of artificial intelligence (AI)

The authors declare that no generative artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript.

7.3. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article. The research was conducted independently, and the results were not influenced by any financial, institutional, or personal relationships.

7.4. Funding

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