Changing Climate in the Bolivian Altiplano:CMIP3 Projections for Extremes of Temperature and Precipitation

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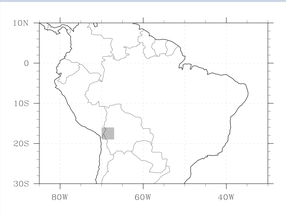

Figure 1. Region analyzed in this study: the Altiplano.

Indicator	Definition	Units
Extreme temperature range (ETR)	Difference between the highest and lowest temperature observations within a given year	K
Frost days (FD)	Total number of days with minimum temperature <0° C	days
Growing Season Length (GSL)	Number of days between the first period when mean T_{day} >5°C for >5 d and the first period when mean T_{day} <5° C for >5 d	days
Heat wave duration index (HWDI)	Max. period of at least 5 d when T_{max} >5°C above the 1961-1990 daily T_{max} average	days
Warm nights (Tn90)	Percent of time in a year when T_{min} >90th percentile of minimum temperature for a particular calendar date	%
Precip >10 mm (R10)	Number of days with precip. ≥ 10 mm d^{-1}	days
Consecutive dry days (CDD)	Maximum number of consecutive dry days (R_{day} <1 mm)	days
5 day precipitation (R5d)	Maximum 5-day precipitation total	mm
Precip >95th percentile (R95T)	Fraction of total annual precipitation from events >the 1961-1990 95th percentile	%
Precipitation intensity (SDII)	Annual total precipitation divided by the number of days with precip. ≥ 1 mm d^{-1}	mm d^{-1}

Table 1. Annual extreme indices as defined by *Frich et al.*, 2002.

20th Century Temperature and Precipitation Annual Cycles

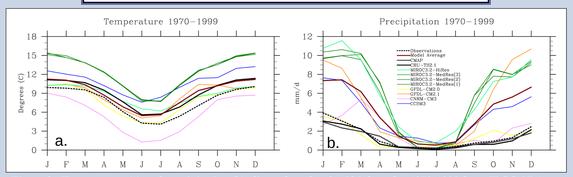

Figure 2. Temperature (a) and precipitation (b) climatology for the Altiplano for 1970-1999 from IPCC AR4 models (colors), CRU and CMAP gridded observations (solid black and gray), and station data (dotted black). Multi-model averages are shown in brown. *CMAP data were available from 1979-99.

Projected 21st Century Temperature Differences : 2020-49 and 2070-99

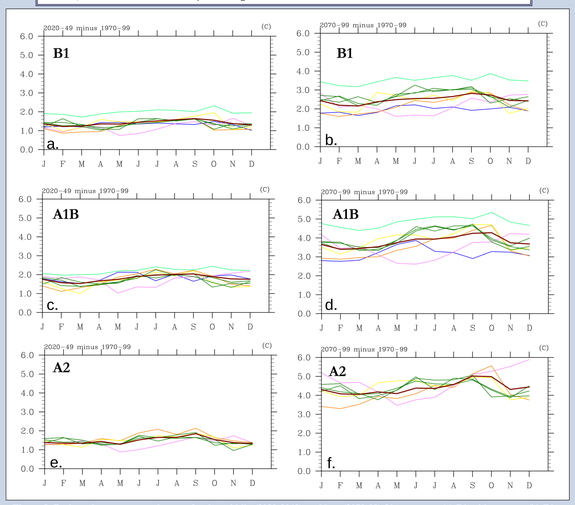

Figure 3. Projected temperature changes for the middle (2020-2049) and late (2070-99) 21st century: (a) B1 mid-century, (b) B1 late-century, (c) A1B mid-century, (d) A1B late-century, (e) A2 mid-century, and (f) A2 late century. See Figure 2 for model legend.

Projected 21st Century Precipitation Differences : 2020-49 and 2070-99

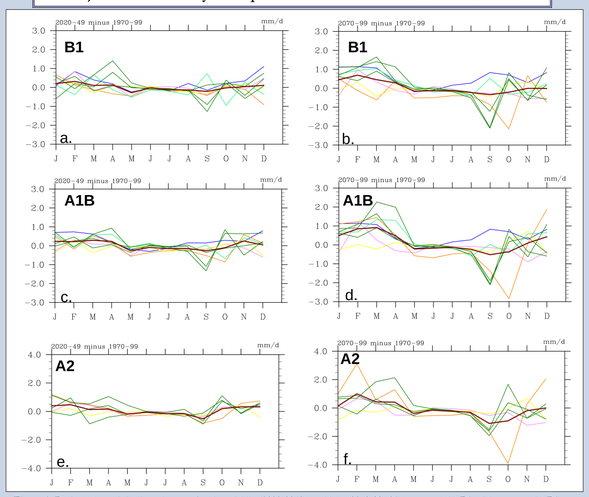

Figure 3. Projected precipitation changes for the middle (2020-2049) and late (2070-99) 21st century: (a) B1 mid-century, (b) B1 late-century, (c) A1B mid-century, (d) A1B late-century, (e) A2 mid-century, and (f) A2 late century. See Fig. 2 for model legend.

INTRODUCTION

•The Altiplano is a high plateau (~3600 to 4300 m) with a semi-arid climate located in the central Andes of South America. The rainy season, which is associated with the South American Monsoon System (SAMS), occurs from Oct-Apr. Most of the annual precipitation occurs from Dec-Feb (*Seth et al.*, 2008; *Garcia et al.*, 2007; *Garreaud and Aceituno*, 2001).

•The Altiplano is an important agricultural region — ~ 50% of the population practices traditional agriculture; not relying on irrigation. Water shortages and frost are major constraints. Low amounts of precipitation, high rates of evapotranspiration, and poor soils affect the amount of water available for agriculture (*Garcia et al.*, 2007; *Geerts et al.*, 2006).

•Extreme climate and weather events have profound impacts on human health, society, and the natural environment and may be more frequent and more intense in the future. Assessment of regional-scale projections of climate extremes are directly relevant to impacts-researchers and stakeholders (*Easterling et al.*, 2000 and *Tebaldi et al.*, 2006).

•This research compares projected changes in mean temperature and precipitation with projected changes in temperature and precipitation based extreme indices as defined by *Frich et al.* (2002) (see Table 1) for the Altiplano, and examines how changes in the annual distribution of temperature and precipitation may result in higher frequencies of extreme events in the future.

•Projected changes in temperature and precipitation may have important implications for agriculture and water supplies in the Altiplano.

•Because of the coarse resolution of Global Climate Models (GCMs), the results for a region as small as the Altiplano should be taken with caution.

Model Name	Model or Obs.	Scenarios
NCAR CCSM3	CCSM3	B1, A1B
Meteo-France, Centre National de Recherches Meteorologiques, CM3 Model	CNRM-CM3	B1, A1B, A2
NOAA Geophys. Fluid Dynamics Laboratory, CM2.0 Model	GFDL-CM2.0	B1, A1B, A2
NOAA Geophys. Fluid Dynamics Laboratory, CM2.1 Model	GFDL-CM2.1	B1, A1B, A2
CCSR/NIES/FRCGCC, MIROC Model V3.2, medium resolution	MIROC3.2-MedRes	B1, A1B, A2
CCSR/NIES/FRCGC, MIROC Model V3.2, high resolution	MIROC3.2-HiRes	B1, A1B
Climate Prediction Center Merged Analysis of Precipitation	CMAP	
Univ. of East Anglia Climatic Research Unit (CRU) Global 0.5° Monthly Time Series, Version 2.1	CRU-TS2.1	

Table 2. Datasets used in this analysis.

DATA AND METHODOLOGY

DATA:

•Data were obtained from the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP3) archive (*Meehl et al.*,2007) (see Table 2).

•Gridded temperature and precipitation data from the University of East Anglia's Climatic Research Unit (CRU-TS2.1) (*Mitchell and Jones*, 2005) were obtained for comparison with the 20th century simulations.

•Gridded precipitation data from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) CPC Merged Analysis of Precipitation (CMAP) (*Xie and Arkin*, 1996) were obtained for comparison with simulated 20th century precipitation.

METHODS:

All calculations are area averages of data for the northern Altiplano: 16° to 19°S and 67° to 70°W (see Figure 1).

ANNUAL CYCLE:

•Differences in the mean climatology for the mid-century and late century were calculated based on the 1970-99 averages of precipitation and temperature for each scenario.

•T-tests were performed on monthly, seasonal and annual precipitation differences to determine whether any of the projected changes are significant at the 95% confidence level.

EXTREME INDICES:

•Eight of the ten extreme indices defined by *Frich et al.* (2002) were analyzed for the 20th century model experiments and three future climate scenarios. [*The length of the growing season (GSL) in the Altiplano is more defined by the onset and length of the rainy season rather than by temperature; precipitation >10 mm (R10) is an arbitrary fixed threshold (see *Alexander et al.* 2006) that may not be meaningful for the Altiplano, therefore GSL and R10 were excluded from this analysis.]

•Standardized time series of annual extreme indices (1900-2099) were calculated to show possible future trends for each emission scenario. An average of the standardized anomalies of the selected models was calculated to provide a multi-model average of the time series for each index. Each multi-model average was smoothed using a 10 year running average. The base period used is 1960-2099.

•Probability density functions (PDFs) were calculated from multi-model averaged time series to show possible future changes in the distributions of the indices. The B1, A1B, and A2 emissions scenarios for the middle (2020-2049) and late (2070-2099) 21st century were compared to two periods from the 20th century model experiments (1940-1969 and 1970-1999).

RESULTS

MEAN CLIMATOLOGY

TEMPERATURE:

20th Century:

•Most of the models overestimate temperature relative to CRU data and station observations, but the timing of the annual cycle is well represented. *The multi-model average is strikingly similar to the CRU data.*

21st Century projected changes:

•Middle century (2020-49)

•Multi-model averages project increases in temperature ranging between ~ 1-2° C for all scenarios.

•The largest temperature increases occur during the dry season and early rainy season (September)

•Late century (2070-99)

•Multi-model averages project increases in temperature ranging between ~ 3-5° C. for all scenarios.

•The largest temperature increase will extend further into the early rainy season (October).

PRECIPITATION

20th Century:

•Most of the models overestimate precipitation during the rainy season relative to CRU, CMAP, and station data. The multi-model average overestimates precipitation by more than twice the observed amounts from Sep-May, but clearly shows the dry season, especially from Jun-Aug.

21st Century projected changes:

Monthly, seasonal, and annual change in precipitation are summarized in Table 3.

•Middle century (2020-49)

•Precipitation may increase during the main rainy season (Dec-Apr) (2.8% to 5%).

•Late century (2070-99)

•Precipitation increases during the main rainy season become more pronounced relative to the late 20th century (5% to 7.1%).

•Precipitation during the early rainy season (Sep-Nov) (-5.3% to -17%) becomes significantly lower relative to the late 20th century.

There may be little or no change in total annual precipitation, but by 2070-99, the Altiplano may experience a shorter, more intense rainy season and a more pronounced dry season.

Qualitatively, these changes are consistent with earlier results of the authors (see *Seth et al.*, 2008), providing evidence that these projected changes in the character of precipitation are not dependent on the models selected or the scenarios used!

EXTREME INDICES

TEMPERATURE BASED INDICES:

•Temperature based extreme indices appear to reflect the projected changes in mean temperature.

•The behaviors of *frost days*, *heat waves* and *warm nights* are consistent with what would be expected in a warmer climate.

•The increase in ETR suggests the possibility that maximum daily temperatures may rise more quickly than minimum daily temperatures.

•The lowest temperatures of the year for the Altiplano occur during the dry season in austral winter. In future projections, the dry season remains very dry. The lack of atmospheric moisture may prevent daily minimum temperatures from increasing at the same rate as daily maximum temperatures.

PRECIPITATION BASED INDICES:

•All of the precipitation based extreme indices analyzed for the Altiplano increase by the end of the 21st century.

•The increase in CDD may be a result of the extended dry season suggested by changes in the annual cycle.

•Mean annual precipitation is projected to change little, if at all → Increases in R5D, R95T, and SDII suggest that future precipitation in the Altiplano may occur less frequently but individual precipitation events may be more intense.

	B1				A1B				A2			
	Mid-Cent.		Late Cent.		Mid-Cent.		Late Cent.		Mid-Cent.		Late Cent.	
	mm/d	%	mm/d	%	mm/d	%	mm/d	%	mm/d	%	mm/d	%
Jan	0.21	2.8	0.30	4.1	0.24	3.2	**0.50**	**6.8**	**0.36**	**5.7**	0.14	2.1
Feb	0.32	4.3	**0.68**	**9.2**	0.22	2.9	**0.85**	**11.4**	**0.44**	**6.9**	**1.00**	**15.5**
Mar	0.11	1.7	**0.40**	**6.4**	0.29	4.7	**0.91**	**14.8**	0.12	2.0	0.43	7.6
Apr	0.13	3.7	0.21	6.1	**0.23**	**6.8**	**0.48**	**14.0**	0.17	5.3	**0.41**	**13.2**
May	**-0.28**	**-19.4**	-0.12	-8.3	**-0.26**	**-18.2**	**-0.22**	**-15.2**	**-0.19**	**-15.7**	**-0.38**	**-32.1**
Jun	-0.02	-2.7	**-0.13**	**-20.9**	-0.09	-14.0	**-0.17**	**-26.8**	-0.07	-15.3	**-0.16**	**-36.8**
Jul	**-0.13**	**-24.9**	**-0.18**	**-34.5**	**-0.15**	**-28.8**	**-0.12**	**-23.8**	**-0.16**	**-40.3**	**-0.23**	**-56.8**
Aug	**-0.13**	**-15.1**	**-0.23**	**-26.3**	**-0.14**	**-16.6**	**-0.24**	**-27.5**	**-0.16**	**-26.9**	**-0.30**	**-49.3**
Sep	-0.21	-7.6	**-0.29**	**-10.3**	**-0.27**	**-9.7**	**-0.52**	**-18.6**	**-0.53**	**-21.8**	**-1.08**	**-44.3**
Oct	-0.02	-0.5	**-0.38**	**-7.9**	-0.10	-2.1	**-0.36**	**-7.5**	0.17	3.9	**-0.90**	**-20.5**
Nov	0.04	0.7	-0.03	-0.6	0.25	4.5	0.10	1.8	0.30	5.7	-0.19	-3.5
Dec	0.11	1.7	-0.03	-0.4	0.04	0.7	**0.43**	**6.5**	0.30	4.8	0.00	0.1
ANN	0.11	0.2	0.20	0.4	0.25	0.5	**1.63**	**3.4**	0.75	1.8	-1.27	-3.0
SON	-0.20	-1.5	**-0.70**	**-5.3**	-0.12	-0.9	**-0.78**	**-5.9**	-0.06	-0.5	**-2.18**	**-17.8**
DJFMA	**0.87**	**2.8**	**1.56**	**5.0**	**1.02**	**3.3**	**3.2**	**10.2**	**1.4**	**5.0**	**2.0**	**7.1**
MJJA	**-0.56**	**-16.0**	**-0.66**	**-19.1**	**-0.65**	**-18.6**	**-0.8**	**-21.7**	**-0.6**	**-22.1**	**-1.1**	**-40.7**

Table 3. Multi-model projected precipitation changes for the B1, A1B, and A2 scenarios for 2020-49 and 2070-99. Bold indicates values that are statistically significant at the 95% confidence level.

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TEMPERATURE-RELATED EXTREMES

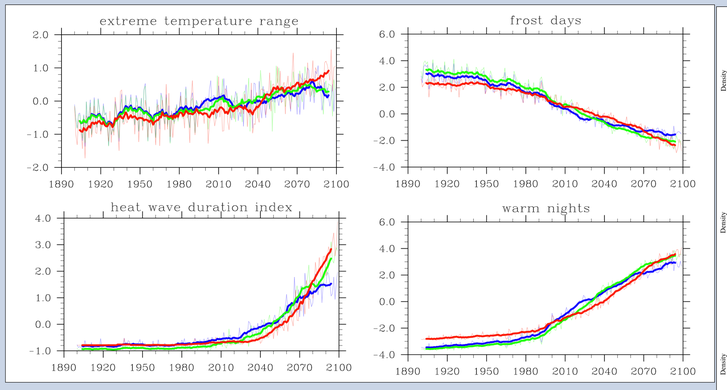

Figure 4 (Above). Simulated time series of temperature-related extreme indices for 1900-2099 for the Altiplano. All time series represent multi-model averages of the standardized time series for each model which are smoothed by a 10-year running average (thick lines). Year to year variations are shown in the background. 21st century scenarios are shown for the B1 (blue), A1B (green), and A2 (red) scenarios. 20th century anomalies are also shown as colored to denote the 21st century scenarios used to standardize each time series.

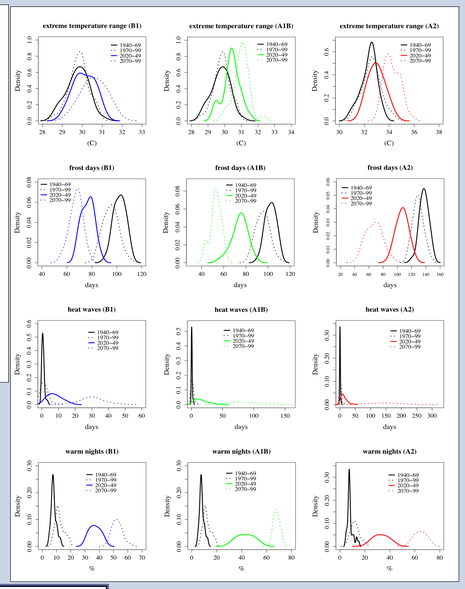

Figure 5 (Right). PDFs of multi-model averages showing changes in the distributions of temperature- related extreme indices for the Altiplano. Two periods from the 20th century are compared to projections for the middle (2020-49) and late 21st century(2070-99) for each scenario.

PRECIPITATION-RELATED EXTREMES

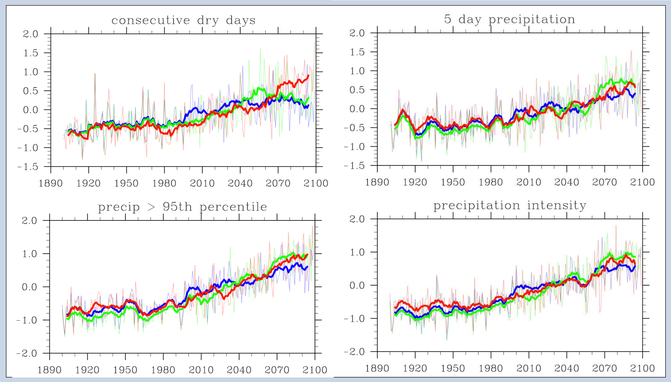

Figure 6 (Above). Simulated time series of precipitation-related extreme indices for 1900-2099 for the Altiplano. All time series represent multi-model averages of the standardized time series for each model which are smoothed by a 10-year running average (thick lines). Year to year variations are shown in the background. 21st century scenarios are shown for the B1 (blue), A1B (green), and A2 (red) scenarios. 20th century anomalies are also shown as colored to denote the 21st century scenarios used to standardize each time series.

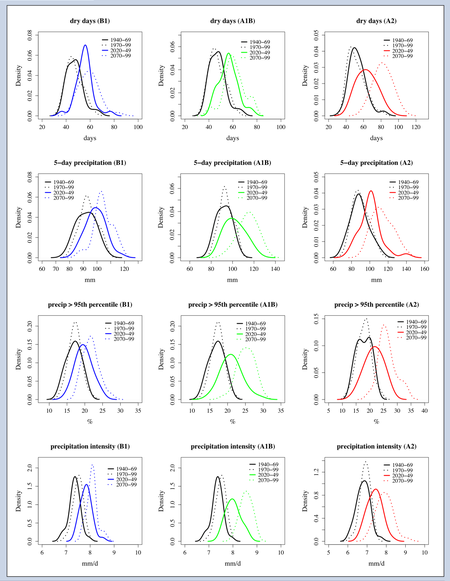

Figure 7 (Right). PDFs of multi-model averages showing changes in the distributions of temperature-related extreme indices for the Altiplano. Two periods from the 20th century are compared to projections for the middle (2020-49) and late 21st century(2070-99) for each scenario.

DISCUSSION

Possible future changes in the characteristics of temperature and precipitation for the Altiplano:

•A shorter more intense rainy season with an extended dry season.

•The largest temperature increases coincide with the early rainy season and extend into October by 2070-99.

•Reduced numbers of FD and increases in the frequency of heat waves and warm nights. ETR is projected to increase.

•Higher numbers of CDD. Individual rainfall events may occur less often, but increase in their intensity.

Despite the mixed results for projected changes in total annual precipitation for the Altiplano, the results for projected changes in seasonal precipitation amounts are consistent across all three scenarios in both the middle and late 21st century. The qualitative agreement of these results with those from our earlier work (see *Seth et al.*, 2008) also suggests that the results are not sensitive to either the scenario used or models examined.

Implications for agriculture and water resources:

•Fewer FD and more *warm nights* may be beneficial for agriculture in the Altiplano if water supplies are adequate.

•Expected higher temperatures and more frequent *heat waves* may introduce other stresses on crops and also reduce the amount of moisture available for plant growth by increasing rates of evapotranspiration.

•Warmer nighttime temperatures may also negatively affect soil moisture. Reduced soil moisture in the early rainy season could delay the sowing dates of certain crops, such as some varieties of quinoa (*Aguilar and Jacobsen*, 2003).

•The projected increase in CDD may be a result of the reduced precipitation in the early rainy season. A delay in the onset of the rainy season could delay the sowing date of late varieties of quinoa, requiring the use of early varieties instead (*Aguilar and Jacobsen*, 2003). Other crops may also be affected by these potential changes, requiring changes in agricultural practices.

•The higher occurrence of heavy precipitation events may result in more frequent flash flood events for the Altiplano. Quinoa is also adversely affected by excessive amounts of rainfall and over-saturated soil conditions (*Aguilar and Jacobsen*, 2003).

•Inhabitants of the Andes depend on glacial melt-water to supplement precipitation during the dry season. In the next several decades, many glaciers in the Andes may disappear completely (*Bradley et al.*, 2006). The projected reductions in glacial melt-water, together with the potential changes in the length and intensity of the rainy season may have serious impacts on future water supplies and agriculture in the Altiplano.

*GCM simulations in regions of complex topography, like the Altiplano, may not adequately represent the effects of altitude on precipitation. The results of temperature related variables such as *frost days* and *warm nights* may also be affected by the poor representation of the altitude.

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