The use of multi-model ensembles of IPCC 4th Assessment Report climate simulations for projections of Bolivian precipitation and temperature

Honors thesis

Athena Eyster, UMID 69621965

Department of Geological Sciences

The University of Michigan,

e-mail: aeyster@umich.edu

April 2010

Academic advisor: Prof. Chris Poulsen **Signature:**____________________________

Second Reader: Prof. Dave Lund **Signature:**____________________________

ABSTRACT

The temperature and precipitation changes for 2009-2098 were examined under the SRES A1B scenario. Twenty-three models were compared to observations from 1970-1999 of three variables: precipitation, temperature and mean sea level pressure. Demerit points were assigned to models using three systems: comparisons of seasonality, pattern correlations and magnitudes, and sub-zero pattern correlations. This resulted in nine total categories. If models were extreme in any three of the categories, they were not used in the projections. Sixteen models were selected to use in projections of future climate. These models were combined to achieve a multi-model ensemble. The multi-model trends for precipitation and temperature were analyzed along with the individual models with highest and lowest trends. Trends were analyzed for the whole Bolivian region, the Altiplano zone, and Amazon Basin zone. A trend of 0.408±0.005 K/decade was found for the multi-model average, which was significant above natural variability. The projected trends were much greater than the observed temperature trends from 1910-1999, which was 0.046±0.018 K/decade. In addition temperature trends were examined for the 30-year intervals of 2009-2028, 2029-2068, and 2069-2098. The annual precipitation trends were not significant above natural variability; however, there was a significant increase in summer precipitation over Bolivia and the Amazon Basin.

INTRODUCTION

According to the International Panel on Climate Change (IPCC), warming of the global climate system is unequivocal. Climate change refers to a persistent change in the climate, identified by changes in the mean and/or the variability of its properties. Although climate change is caused by a variety of factors, there is very high confidence that human activities since 1750 have contributed to warming (IPCC, 2007). There is evidence from observations of increases in global average temperatures, melting of snow and ice and rising global average sea level (IPCC, 2007).

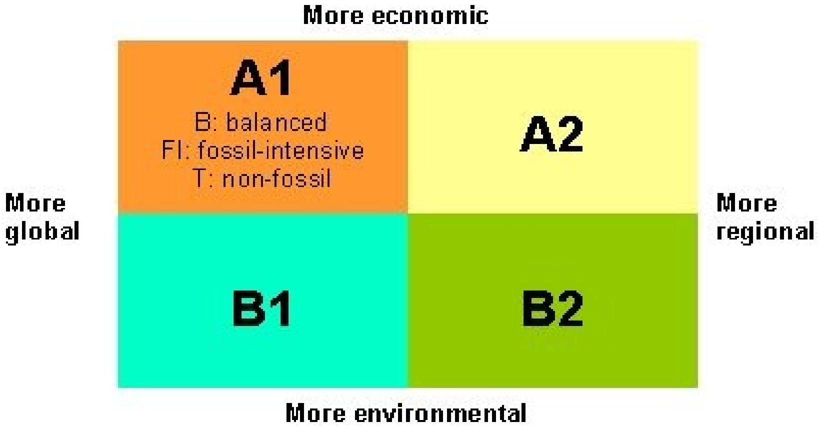
Numerous models have been developed to forecast the long-term impact of global and regional climate change. These models involve the physical processes in the atmosphere, ocean, cryosphere and land surface and the coupling between them. This study focuses on projections of climate over Bolivia, a region that is particularly vulnerable to climate change (as is explained below) and that has been largely overlooked by climate modelers. The last study to focus exclusively on Bolivia was done by Paz Rada et al. in 1997. With the new advances in GCMs, a more recent analysis is in order. In this study, results from twenty-three IPCC climate model control runs were compared to historical Bolivian observations of mean sea level pressure (MSLP), temperature, and precipitation. From the comparisons, the sixteen models judged to be acceptable at simulating historic climate were used to project Bolivian precipitation and temperature for 2009-2098 using the SRA1B scenario. These results are compared to those presented in the 1997 Paz Rada study.

CLIMATE CHANGE MODELS

More than twenty research centers around the world have developed and used very sophisticated models, which simulate global climate. A common set of simulations using these models was coordinated through the Intergovernmental Panel on Climate Change (IPCC, 2007), described in the IPCC 2007 report, and archived by the Program for Climate Model Diagnostics and Intercomparisons (PCMDI). In order to predict possible climate change, many climate research centers have developed numerical Global Climate models (GCMs). According to the IPCC General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment, GCMs represent processes on the earth's surface and are currently the best tools for simulating the effect of climate system response in the global setting (IPCC-TGICA, 2007).

The models are run with six IPCC emission scenarios of socioeconomic change. These scenarios are not predictions. Instead, a scenario is a possible future based on a given set of assumptions based on energy use, emissions, land use and general climate system behavior. The IPCC Special Report on Emissions Scenarios (SRES) describes four families of scenarios: A1, A2, B1 and B2 (Fig. 1) (Nakicenovic et al., 2000). The A1 scenario assumes very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. Also, technology is assumed to be easily spread due to increased globalization. The three groups in the A1 family are characterized by differences in the use of energy resources: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). The A2 scenario involves a very heterogeneous world with high population growth, slow economic development and slow technological change. Changes are regionalized and development does not occur on a global scale. The B1 scenario assumes the same global population as A1, but with greater emphasis on sustainability. In this scenario, there is intermediate population and economic growth, and instead of technological growth, global solutions of sustainability in economics, society and environment are important. The B2 scenario assumes high population growth, though lower than in A2, intermediate economic growth, and emphasizes local solutions to economic, social, and environmental sustainability (IPCC-TGICA, 2007). No likelihood has been attached to any of the SRES scenarios.

Figure 1. Simplistic representation of SRES climate scenarios. The A families are focused more on economics than the more environmental B families, while the focus of the 1 families are global compared to the more regional 2 families. (Murdoch, 2003)



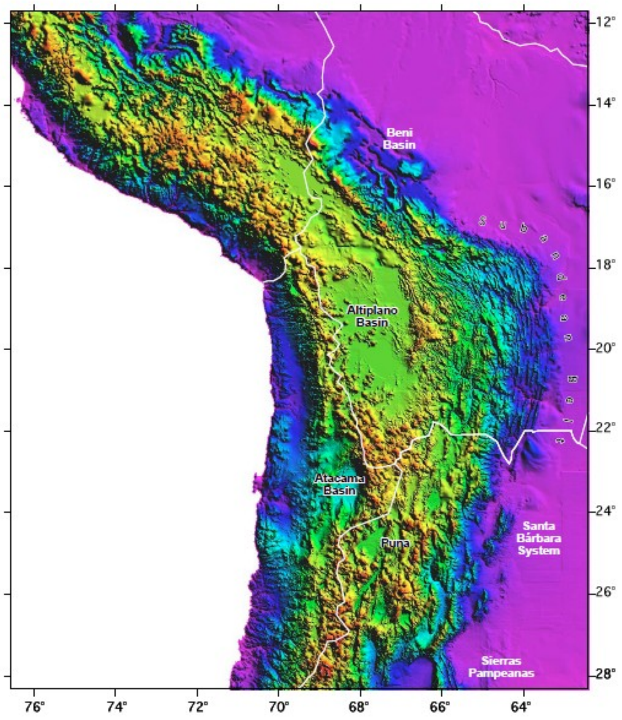
Although much has been done to study climate changes on the global scale, less has been done on regional scales. As the majority of people and other life forms live on regional and local levels, it is important to understand how climate change affects smaller areas. To increase understanding of regional climate changes, two methods are utilized. One of these involves regional climate models (RCMs), however, there are still large differences between observations and model outputs. More study is needed to make RCMs effective at representing regional and local changes (Buytaert et al., 2010). The other involves analyzing multiple GCMs over a specific region to assess climate changes. These studies include regions such as South America (Carril et al., 1997, Bombardi et al., 2009), Australia (Suppiah et al., 2007) and the Pacific Northwest (Mote et al., 2008). Most projections are derived from multiple model results, using simple averages or weighted values based on statistical measures of model reliability, such as the correlation between observed and simulated climate patterns. It is accepted that projections from models that simulate the present climate well are more likely to be reliable at capturing future climate. A major uncertainty in the use of GCMs to simulate regional climate lies in topography. Although topography has a great influence on regional changes, the GCMs unfortunately represent the variations of climate that would occur on a smooth planet with similar land-sea distributions and large smooth bumps where the Earth has major mountain ranges.

BOLIVIA AND CLIMATE CHANGE

The purpose of these projections is to raise awareness, provide input to risk assessments, and underpin the development of mitigation and adaptation strategies. Given that projections are commonly used in risk management, it is hoped that these climate change projections will assist in planning for climate change.

Bolivia is a county in South America, that is located between 57^{o} 26' and 69^{o} 38' W and between 9^{o} 38' and 22^{o}53'S. The main geographic zones in the Bolivian region are the Andean-Altiplano zone, the sub-Andean zone, and the Plata and the Amazon Basins. The Andes run in two parallel ranges (Fig. 2), called cordilleras. The western range (Cordillera Occidental) runs along the Peruvian and Chilean borders. The eastern range (Cordillera Oriental) runs from Peru to Argentina. The Plateau is generally defined as the broadening of the 3km elevation contour. From this definition, the plateau is 1800km long and 350-400km wide. The average elevation of the plateau is 3.65 km (Almandinger et al., 1997).

Figure 2. Map showing the topography of the Central Andes and part of Bolivia. The Altiplano basin is the extremely flat area in the center of the figure, and the Amazon basin is in the top right.(Almandinger et al.,1997)



As a result of the diverse geography, many different ecosystems occur in Bolivia. The richness of the biodiversity means that many different species will be affected by climate change. Low-income groups in developing countries are the most exposed to climate change impacts. By most socioeconomic indicators, Bolivia is one of the poorest countries in Latin America and has a very large divide between the rich and poor (Oxfam, 2009).

Carril et al. (1997) studied climate change over South America using four GCMs. The models MPI and UKMO were deemed worthy by Carril et al. to use in projections. In addition, two of the models, NCAR and GFDL were considered unacceptable, due to their poor simulations of historic climate from 1980 to 1989. The MPI and UKMO models were used in climate projections from 1997-2067. The two models disagreed in the general temperature projections over central South America, although they were in agreement for winter warming over Brazil. The models also did not agree on general precipitation changes, though they did agree on a decrease in summer precipitation over Venezuela. Also both models projected a decrease in winter precipitation and an increase of summer precipitation over coastal Central America.

The most recent study of South American climate change was conducted by Bombardi et al. (2009), who used climate models to simulate the South American monsoon system (SAMS). Ten IPCC GCMs with daily resolution of precipitation were used. Most IPCC models were found to misrepresent the Intertropical Convergence Zone (ITCZ) and thus did not fully capture the monsoonal cycle over northeast Brazil and northwest South America. MIHR, MIMR, MRGCM were found to be the best at recreating the SAMS onset, duration, precipitation and inter annual variability. ECHAM5, GFCM20 and GFCM21 were the worst at simulating the above characteristics. Projected precipitation was analyzed over 2081-2100, and discrepancies in annual precipitation were found. The most significant feature was a decrease in precipitation for central and eastern Brazil. An overall decrease in daily precipitation was found, which combined with the overall lack of an annual trend, resulted in speculation that the frequency of extreme precipitation and drought events would increase.

Only one study has previously focused on the Bolivian region. Paz Rada et al. (1997), analyzed climate scenarios over Bolivia in 1997 using climate models GISS, UK89, CLIM, CCCM, GFDL R-30. The study found that GISS, and UK89 were the best fit to historic climate from 1951-1980. The combined model average simulated a temperature increase of 0.375ºC/decade over 2000-2080. The models varied on projected annual precipitation trends, one predicted a decrease, and the other predicted an increase. However, both models simulate a precipitation decrease for the typically rainy summer months and a slight increase for the drier winter months.

METHODS

AREAS, SEASONS, MODELS AND VARIABLES STUDIED

For this study, the Bolivian region was used in examining model accuracy and climate projections. In addition, two zones within the region were used, the Altiplano and Amazon Basin. Because GCMs have coarse resolution, it would be impractical to resolve the differences between the Sub-Andean zone and the Andean-Altiplano and the basins. Therefore the Sub-Andean zone was not analyzed. In addition, climate was analyzed for only one of the basins, the Amazon basin, because it was larger than the Plata basin and thus more data would be available from the coarse resolution GCMs. The Bolivian region was defined to be from 10°S to 23°S and from 291°E to 302°E. The location of the Altiplano was approximated by the square 18°S to 23°S degrees latitude by 291°E to 294°E. The location of the Amazon Basin was approximated by the square of 10°S to 15°S by 294°E to 297°E. As Bolivia is in the southern hemisphere, the summer season was defined as being the months December-January-February, fall was defined as being March-April-May, winter was defined as June-July-August, and finally spring was defined as being September-October-November.

In order to use the models to predict future regional climate change, it must first be determined how well the models can simulate historic regional climate. The A1B scenario was chosen as the scenario for emissions, as it is not an extreme scenario. Also, it was most frequently chosen by global modeling groups in their simulations of future climate, so many models were available for use. For the SRESA1B scenario, the anthropogenic forcings are held constant after 2100 (Taylor, 2007). See Table 1a and 1b for the names, resolution and forcings, flux adjustments and frequency of coupling of the 23 models that used A1B.

All 23 A1B models were assessed for their reliability in simulating the historic Bolivian climate though the examination of how they replicated the observed spatial patterns and magnitudes of MSLP, temperature and precipitation. Also models were judged on how well they simulated the seasonality of precipitation and temperature. Surface air temperature and precipitation were studied because they are the climate fields that affect humans the most. Although MSLP is sensitive to thermodynamical behavior of the models that factor into general circulation, it has less direct effects on humans (Carril et al., 1997). Therefore, in this study MSLP was only used in comparisons of historical climate, and not for climate projections. It is important to note that precipitation is dependent on topography that is poorly represented by current models (Semenov & Stratonovitch 2010**)**. Mountains such as the Andes, which are important in for Bolivia, are poorly represented with the coarse resolution of models.

Table 1a. IPCC Models and associated properties. Key to forcings: GHGs (Greenhouse gases)-CO2,CH4,N2O,O3,CFC11, CFC12, SD-sulfate (Boucher), BC-black carbon, O-ozone, DD-mineral/desert dust, SS-sea salt, LU-land use, V-volcanic aerosol, SO-Solar Irradiance, OC-Organic Carbon (Randall et al.,2007 & PCMDI website)

Groups (country)	Model (abr. name)	Horizontal resolution (o)	Forcings used in the model	Flux adjustment	Frequency of coupling
Bjerknes Centre for Climate Research (Norway)	BCCR-BCM2.0 (BCM2)	1.9x1.9	GHG, SD,BC,SS,DD, O (stratospheric and tropospheric)	no	1 day
Canadian Centre for Climate Modelling and Analysis (Canada)	cccma_cgcm3_1_T63 (CGHR)	1.9x1.9	SD, GHGs.	heat and fresh water	1 day
Canadian Centre for Climate Modelling and Analysis (Canada)	cccma_cgcm3_1_T47 (CGMR)	2.8x2.8	SD, GHGs.	heat and fresh water	1 day
Météo-France / Centre National de Recherches Météorologiques (France)	CNRM-CM3 (CNCM3)	2.8x2.8	GHGs,SD,O,BC,SS,DD Atmospheric chemistry-simple ozone transport	no	1 day
CSIRO Atmospheric Research (Australia)	CSIRO-Mk3.0 (CSMK3)	1.9x1.9	SD, GHGs , O	no	15 minutes
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group. (Germany / Korea)	ECHO-G (ECHOG)	3.9x3.9	GHGs, SD, SI, SO, V, O-tropospheric	heat, water, outside sea ice region	1 day
LASG / Institute of Atmospheric Physics (China)	FGOALS-g1.0 (FGOALS)	2.8x2.8	GHGs, SD,O	no	1 day (ocean) 1 hour (atmosphere, land and sea ice)
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM2.0 (GFCM20)	2.5x2.0	GHGs, SD, O, V,SO, LU, OC, BC,SS, DD, SI	no	2 hour (atmosphere-ocean)
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM2.1 (GFCM21)	2.5x2.0	GHGs, SD, O, V,SO, LU, OC, BC,SS, DD, SI Semi-Lagrangian transports	no	2 hour (atmosphere-ocean)
NASA / Goddard Institute for Space Studies (USA)	GISS-AOM (GIAOM)	4.0x3.0	GHG, SD,SS	no	1 hour
NASA / Goddard Institute for Space Studies (USA)	GISS-EH (GIEH)	4.0x5.0	GHG, DD,OC,BC,SS,V, SD,SI, LU,SO,O	no	4 hours
NASA / Goddard Institute for Space Studies (USA)	GISS-ER (GIER)	4.0x5.0	SS, OC, BC, V, SD, SI, GHG, DD,SO, LU,O	no	30 minutes

Table 1b. IPCC Models and associated properties. Key to forcings: GHGs (Greenhouse gases)- CO2,CH4,N2O,O3,CFC11, CFC12, SD-sulfate (Boucher), BC-black carbon, O-ozone, DD-mineral/desert dust, SS-sea salt, LU-land use, V-volcanic aerosol, SO-Solar Irradiance, OC-Organic Carbon (Randall et al.,2007 & PCMDI website)

Groups (country)	**Model**	**Horizontal resolution (º)**	**Forcings used in the model**	**Flux adjustment**	**Frequency of coupling**
Hadley Centre for Climate Prediction and Research / Met Office(UK)	UKMO-HadCM3 (HADCM3)	3.75x2.5	GHGs, SD,SI, O-Tropospheric/stratospheric atmospheric chemistry-Sulphate aerosols produced by oxidation of SO2.	no	1 day
Hadley Centre for Climate Prediction and Research / Met Office (UK)	UKMO-HadGEM1 (HADGEM)	1.9x1.25	GHGs, SI, SD, SS, BC, LU, O, OC, V, SO atmospheric chemistry-Sulphate aerosols produced by oxidation of SO2.	no	1 day
Institute for Numerical Mathematics (Russia)	INM-CM3.0 (INCM3)	5.0x4.0	GHGs (no O2, CFC11, CFC-12 or other CFCs), SD, V, SO	yes, water from ocean to atmosphere	1 hour (atmosphere-sea ice) 6 hours (atmosphere-open sea)
Instituto Nazionale di Geofisica e Vulcanologia (Italy)	INGV-SXG (INGSXG)	1.13x1.13	GHGs,SD	no	1.5 hours
Institut Pierre Simon Laplace (France)	IPSL-CM4 (IPCM4)	2.5x3.7	GHGs,SD, SI, ice-sheets thickness changes	no	30 min (atmospheric-land surface) 1 day (atmosphere-ocean, atmosphere-sea ice& ocean-sea ice)
Center for Climate System Research -The University of Tokyo (Japan)	MIROC3.2 (hires) (MIHR)	1.12x1.12	GHGs, SD, SI,DD, SS, BC, OC, SO, V, O- tropospheric and stratospheric, LU	no	3 hours
Center for Climate System Research -The University of Tokyo (Japan)	MIROC3.2 (medres) (MIMR)	2.8x2.8	GHGs, SD, SI,DD, SS, BC, OC, SO, V, O- tropospheric and stratospheric, LU	no	3 hours
Max Planck Institute for Meteorology (Germany)	MPI_ECHAM5 (MPEH5)	1.9x1.9	GHGs, (CO2, CH4, N2O, F11, F12),SD,SI, O-stratosphere	no	1 day (atmosphere and ocean-sea ice)
Meteorological Research Institute (Japan)	MRI-CGCM (MRCGCM)	2.8x2.8	GHGs (no O2), SD,SO	heat, water & momentum	1day
National Center for Atmospheric Research (USA)	NCAR_CCSM (NCCCSM)	1.4x1.4	GHGs,O, BC,SS,DD,V, SO Atmospheric chemistry-GHG undergoes chemical processes, & the sulfur cycle.	no	1 day (ocean) 1 hour (atmosphere-land-ice)
National Center for Atmospheric Research (USA)	PCM1 (NCPCM)	2.8x2.8	GHGs, SD,O,SO,V	no	1 day (ocean) 1 hour (atmosphere-land-ice)

As a regular model run progresses, some climate variables such as precipitation, temperature, and received solar radiation drift away from observations and stop being physically possible. This development of simulation systematic biases is termed climate drift. Climate drift limits usefulness of climate models. Two major sources of climate drift are the lack of equilibrium of the component models' initial conditions and incompatibilities in the fluxes across component model interfaces (Bryan, 1998). Climate drift is an indication of problems in the physics of the component models and highlights areas that need improvement. In some of the models, flux adjustments were applied to correct for climate drift.

Multiple versions of some models exist. In all but the GFDL-CM case, the differences between the versions involved the model resolution. For the GFDL-CM case, version 2.0 has a B grid for vertical advection, while version 2.1 implements a finite volume technique for advection (Stouffer et al., 2008). In addition, version 2.1 uses smaller ocean viscosity in the extratropics and a stronger subpolar gyre (Stouffer et al., 2008). In addition, the climate drift in version 2.1 is much smaller than in version 2.0 (Stouffer et al., 2008).

ASSESSMENT OF MODEL ACCURACY

For each of the 23 models shown above, the results from each model's 20C3M run were compared with observations for the period 1970-1999. The 20C3M run period starts mid-19th century with greenhouse gases increasing as observed through the 20th century. The initial state is taken from the state of the pre-industrial control (PICTL) simulation. The forcing agents of the 20C3M run are greenhouse gases (CO2, CH4, N2O and CFCs), sulfate aerosol direct effects, volcanoes, and solar forcing determined from historical records (Taylor, 2007).

The precipitation and temperature values used for observations were taken from the global CRU TS3.0 datasets for the period 1901-2006 (Mitchell T & Jones, P., 2005). The time series gridded data are based on an archive of monthly mean temperatures provided by more than 4000 weather stations distributed around the world. The datasets are on high resolution grids of 0.5° x 0.5° degrees. These datasets were downloaded from the BADC website, www.badc.nerc.ac.uk/data/cru.

The MSLP values used for observations were taken from the NCEP/NCAR Reanalysis 1 project. NCEP Reanalysis data was provided by the NOAA/OAR/ESRL PSD in Boulder, Colorado, from their web site at http://www.esrl.noaa.gov/psd/. Historic data from 1948 to the present was assimilated using a state-of-the-art analysis/forecast system. The resolution of the historical data is 2.5° x2.5° on a global grid.(Kalnay et al.,1996)

In order to compare the simulations with observations, the pattern correlation and area root mean square error were calculated for the summer, spring, fall, winter seasons, as defined above, and annually averaged for 1970-1999. A spatial pattern correlation coefficient of 1.0 indicates a perfect match between the observed and simulated spatial pattern. A root mean square error (RMS error) of 0.0 indicates a perfect match between the observed and simulated magnitudes.

In addition, the models used in projections should follow the observed seasonality of precipitation and temperature. For the precipitation over the whole Bolivian region (Fig. 3), HADGEM displays a late onset of winter precipitation and extreme summer precipitation. For the Altiplano zone (Fig. 4), neither FGOALS nor IPCM simulated the seasonal precipitation variations between summer and winter. For the Amazon Basin zone (Fig. 5), HADGEM poorly simulated the onset of winter precipitation. Both INGSXG and CNCM3 simulations had the highest precipitation in March. In contrast, according to observations, precipitation should be highest in December/January.

Figure 3. Bolivian Precipitation: Seasonality of Models and Observations

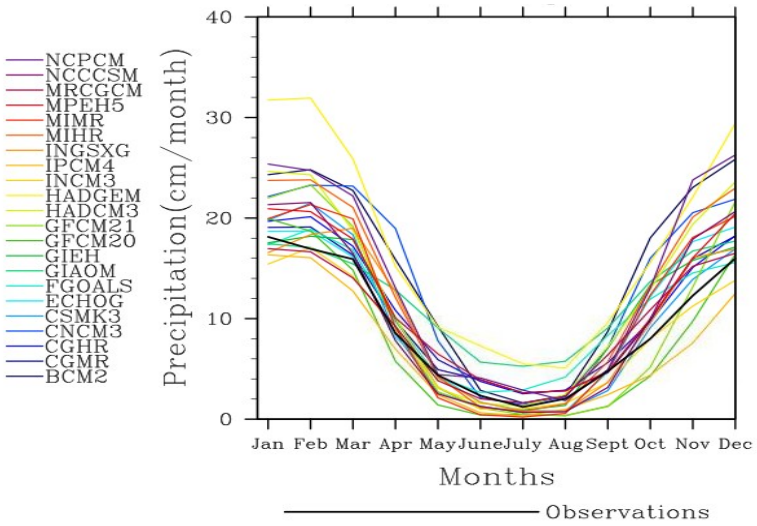


Figure 4. Altiplano Precipitation: Seasonality of Models and Observations

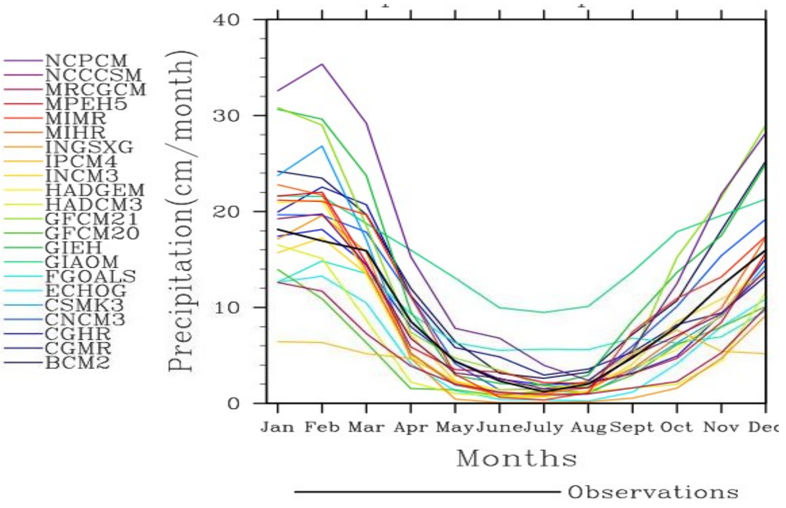
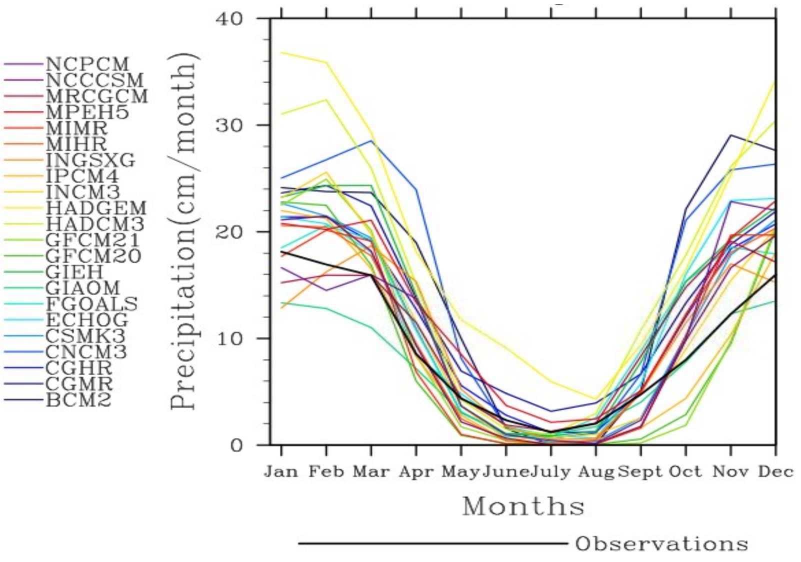
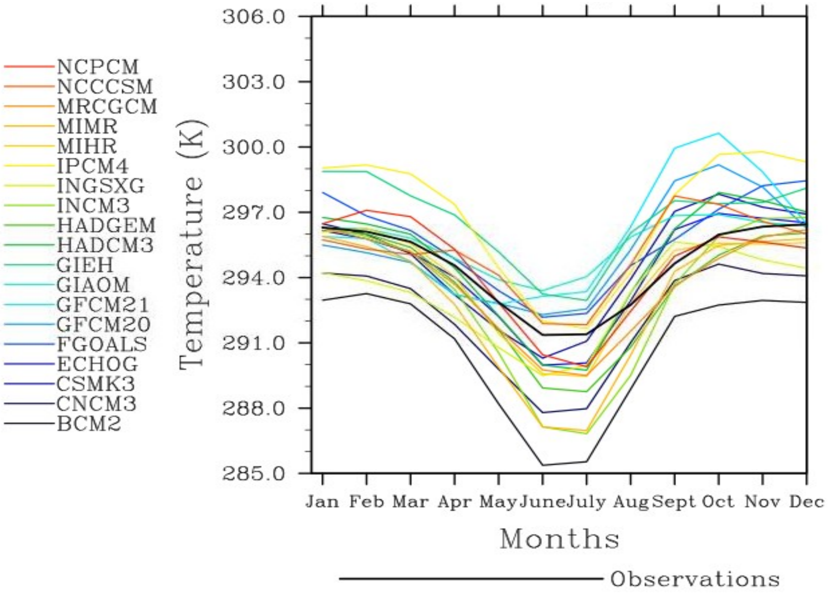


Figure 5. Basin Precipitation: Seasonality of Models and Observations



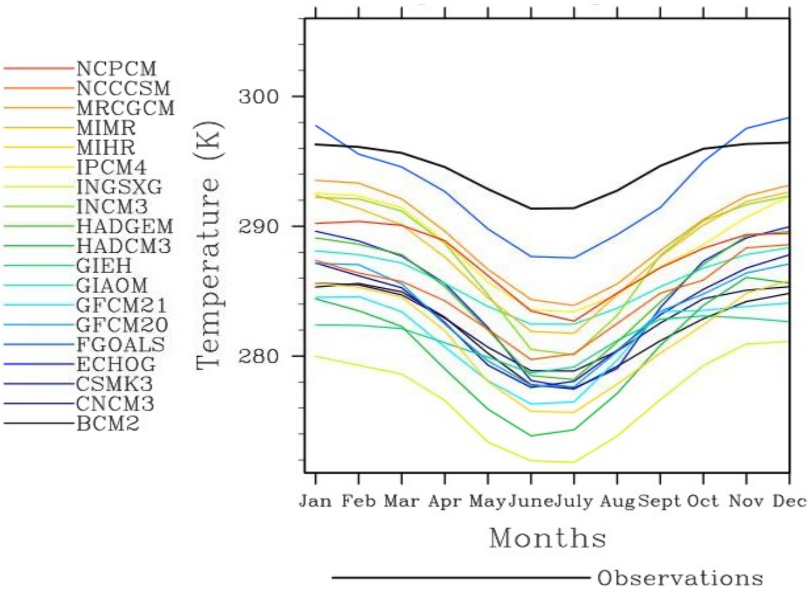
Seasonal variation was also explored for the temperature of the Bolivian region and the two zones. For regional Bolivian temperature (Fig. 6), three models stood out in their poor simulation of historic climate. The GFCM21 and GFCM20 models displayed temperature maximums in the spring instead of summer. In the GIEH model, winter temperature onset was too early.

Figure 6. Bolivian Temperature: Seasonality of Models and Observations



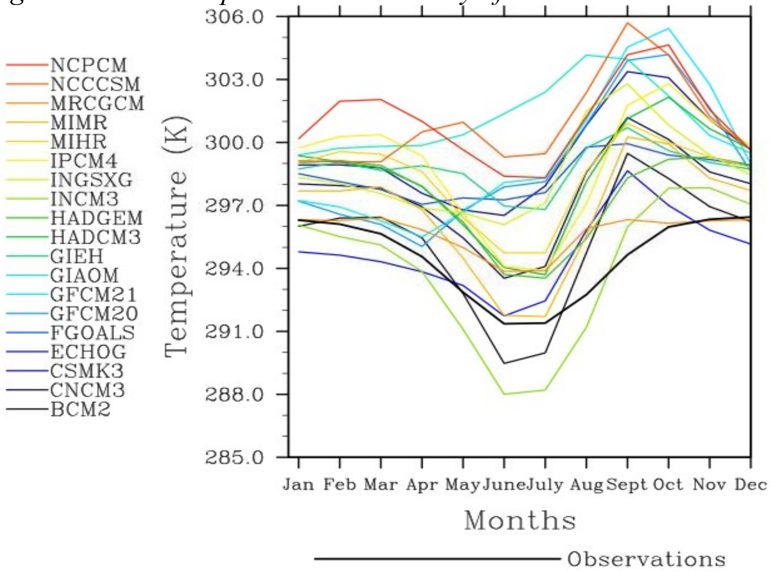
For the Altiplano zone (Fig. 7), although the different models varied in magnitudes of temperature, they all displayed similar patterns to the observations. Most of the models simulated temperatures lower than the observations. Because the magnitude of temperature is not in question, but the pattern of change in temperature, this is not very significant.

Figure 7. Altiplano Temperature: Seasonality of Models and Observations



For the Amazon Basin (Fig. 8) most model simulations showed higher summer temperatures than did the observations. Most of the models showed a temperature maximum in the spring that was not present in observations. The NCPCM model displayed a temperature maximum in the early fall and spring and a temperature decrease during the winter. However, the six worst models were GFCM21, GFCM20, GIAOM, FGOALS, NCCCSM, and INGSXG. The models GFCM21, GFCM20 and GIAOM all had no winter decrease in temperature and a temperature maximum in the spring. FGOALS had no real season changes in temperature. NCCCSM displayed a temperature increase in late fall-early winter and a maximum temperature in the spring instead of summer. INGSXG displayed a temperature maximum in the spring instead of the summer, and had a poorly defined decrease in temperature for the winter.

Figure 8. Basin Temperature: Seasonality of Models and Observations



Given the shortcomings identified in many of the models, it is tempting to limit the projections to the 'best' models. However, this may not realize the underlying uncertainty and range. Therefore, models were judged as acceptable unless identified as extreme by a subjective demerit point process (Whetton, 2005 & Suppiah et al. 2007). This process involved assigning demerit points through three different systems. The first system took into account low pattern correlations and high RMS error, the second, pattern correlations less than zero, and the third, poor seasonality.

In the first demerit system and for each variable category (MSLP, precipitation and temperature) one point was assigned for a pattern correlation less than 0.8. An additional point was assigned for a pattern correlation less than 0.6. For precipitation RMS error, points were assigned for values greater than 10 and greater than 12. For temperature RMS error, points were assigned for values greater than 5 and greater than 6. Finally, for mean sea level pressure RMS error points were assigned for values greater than 0.6 and greater than 1. In the second demerit system, a demerit point was assigned each time a pattern correlation was less than zero. Finally, two points were assigned in demerit system 3 each time a model did not simulate a winter minimum of precipitation and temperature. If the model did represent the winter minimums, but did not simulate the correct seasonal onset of precipitation or temperature or did not represent the correct summer maximum, one point was assigned (Table 2).

Table 2. Models with demerit systems and points: excessive values bolded, and extreme models highlighted

Model	Demerit System 1				Demerit System 2			Demerit System 3	
	MSLP	Precipitation	Temperature	Total	MSLP	precipitation	temperature	precipitation	temperature
BCM2	1	**16**	5	22	0	1	0		
CGHR	10	10	X	20	**4**	0	x		
CGMR	10	11	X	21	**4**	0	x		
CNCM3	1	**16**	0	17	0	0	0	1	
CSMK3	10	12	0	22	**3**	0	0		
ECHOG	9	8	5	22	0	0	0		
FGOALS	7	9	**18**	**34**	0	1	1	**2**	**2**
GFCM20	8	**17**	0	26	0	**3**	0		**2,2**
GFCM21	8	11	3	22	1	0	0		**2,2**
GIAOM	10	11	1	22	**4**	1	0		**2**
GIEH	**20**	8	2	**30**	**5**	2	0	1	1
GIER	**15**	14	3	**32**	**5**	**4**	0		
HADCM3	12	8	0	20	**5**	0	0	1	
HADGEM	10	**16**	0	26	0	0	0	**1,1**	
INCM3	10	10	**10**	**30**	1	0	0		
INGSXG	10	8	0	18	**4**	2	0	**2**	1
IPCM4	3	11	5	19	0	0	0	1	
MIHR	0	**14**	0	14	0	1	0		
MIMR	5	11	**11**	27	0	**3**	0		
MPEH5	10	8	X	18	**4**	0	X		
MRCGCM	10	11	**12**	**33**	0	0	0		
NCCCSM	0	**16**	0	16	0	2	0		**2**
NCPCM	10	11	1	22	1	**5**	0		1

The extreme models were identified as models that had excessive values in three of four categories. Two of the categories were in demerit system 1, one of which was in system 2 and another of which was in system 3. Excessive values in demerit system 1, category 1, were determined by calculating the mean and standard deviation for each variable. When the demerit points of a variable for a model exceeded those of one standard deviation above the mean, the field was bolded, indicating that the value was excessive. The excessive values for demerit system 1, category 2, were those that had total demerit points that exceeded 27. The value of 27 was determined by adding up the values of one standard deviation above the mean for precipitation and mean sea level pressure. For system 2, all values greater than 2 were deemed excessive. For system 3, excessive values were equal to or greater than 2 points. Finally, extreme models were those that had extreme values in three of the four categories and are seen highlighted in orange in Table 2.

From this process, FGOALS, GCM20, GIER, GIEH, and MIMR were judge to be extreme and were not used in the subsequent projections. From this method, ECHOG was best, as it was the only model with zero demerit points for systems 2 and 3, and low demerit points for demerit system 1. ECHOG used flux adjustments, six forcings and one day frequency of coupling. All of the extreme models varied in number of forcings and coupling frequency. One thing they had in common was the lack of flux adjustments.

There was some similarity between models that were evaluated to poorly simulate historic climate in this study and models that were evaluated to poorly simulate historical climate in previous studies, Paz Rada et al. (1997), Carril et al. (1997) and Bombardi et al. (2009). All three previous studies treated GFDL models as poor simulators of historic climate. From this study's analysis, GFCM20 was deemed extreme, but not GFCM21. In addition both Carril et al and Paz Rada et al. viewed a UKMO model as acceptable for use in projections, and from the demerit point analysis used in this study, both UKMO models were viewed as acceptable (HADGEM and HADCM3).

PROJECTIONS FOR 2010-2098

Average multi-model ensemble projections are more robust than individual models because they cancel offsetting errors (Piercea et al., 2009) & (Suppiah et al., 2007). Therefore, projections presented in this section are based on the ensemble average of the best sixteen climate models as determined above for the SRES A1B scenario. In addition, individual models were examined to consider the full range of projections for Bolivia.

There was no temperature data available for the A1B run for the models CGHR and INGSXG. As a result, those models were not included in multi-model averages for temperature projections, but were included in precipitation projections. For both precipitation and temperature, NCPCM SRA1B projection ends at 2098. As a result, the future projections were taken over the interval 2009-2098 in order to use NCPCM. In all cases, the statistical significance was calculated to evaluate whether the trend could be explained by the natural variability. In all cases, if the statistical p-value (the observed significance level) was less than 0.05, the trend was deemed significant. Area averages for each model were calculated and then an area-averaged time series was obtained. The multi-model average of the time series was then calculated.

TEMPERATURE

Multi-Model Ensemble Averages

The Bolivian multi-model average displayed a significant annual temperature trend of 0.408±0.005 K/decade. This was over 10 times greater than the trend in temperature from observations from 1910-1999, which was 0.046±0.018 K/decade. The average annual temperature trend was 8% higher than the two-model projection of Paz Rada et al. (1997), which was 0.375ºC/decade. The multi-model ensemble trends for the Bolivian, Altiplano and Basin zones over the time interval of 2009-2098 are shown in table 3. The trends of the multi-model ensemble mean temperatures are all significant.

Table 3. Ensemble temperature trends for 2009-2098, along with observed Bolivian trends for 1910-1999

	Ensemble temperature trends (K/decade)			Observed trends (K/decade)
	Bolivia	Altiplano	Basin	Bolivia
Annual mean	0.408±0.005	0.414±0.004	0.422±0.005	0.046±0.018
Summer	0.366± 0.007	0.392±0.007	0.355±0.009	0.031± 0.020 (not significant)
Fall	0.384±0.006	0.399±0.006	0.390±0.007	0.033±0.022 (not significant)
Winter	0.437±0.008	0.441±0.007	0.471±0.009	0.065± 0.027
Spring	0.445±0.006	0.425±0.006	0.472±0.009	0.059±0.024

The multi-model temperature trends were positive for all fields. Winter and spring seasons will experience the greatest increases in temperature for both zones and the Bolivian region as a whole. The differences were significant between all fields except for winter and spring trends in the Basin. According to this study, the Amazon Basin zone will experience the greatest increase in temperature in the spring and winter periods, but the smallest increase in the summer seasons. Overall, the Basin zone will experience the greatest annual mean increase in temperature.

Individual Models

Individual model climate trends (Table 4) were significant for all areas and season but one (i.e. Basin summer, model NCPCM). Similar to the multi-model average trends, the lowest and highest trends were at their maximum levels for the winter and spring months. There was one exception, the Altiplano zone, where winter and summer had the highest trends.

Table 4. Maximum and Minimum temperature trends for 2009-2098 from individual models

	Bolivia		Altiplano		Basin	
	High (K/decade)	Low (K/decade)	High (K/decade)	Low (K/decade)	High(K/decade)	Low(K/decade)
Annual	0.585±0.016 (MIHR)	0.193±0.012 (NCPCM)	0.607±0.028 (MPEH5)	0.188±0.011 (NCPCM)	0.673± 0.039 (HADCM3)	0.155±0.01 (NCPCM)
Summer	0.527±0.019 (MIHR)	0.157±0.021 (NCPCM)	0.615±0.044 (MPEH5)	0.179±0.016 (NCPCM)	0.565±0.053 (HADCM3)	------ (NCPCM)
Fall	0.558±0.036 (HADCM3)	0.190±0.025 (NCCCSM)	0.598±0.037 (MPEH5)	0.178±0.013 (NCPCM)	0.653±0.045 (HADCM3)	0.155 ±0.028 (NCPCM)
Winter	0.634±0.024 (MIHR)	0.219±0.027 (NCPCM)	0.684±0.0450 (ECHOG)	0.193±0.024 (NCCCSM)	0.739±0.032 (MIHR)	0.229±0.034 (NCPCM)
Spring	0.706±0.048 (MIHR)	0.206±0.025 (NCPCM)	0.613±0.027 (MPEH5)	0.201±0.021 (NCPCM)	0.812±0.066 (MPEH5)	0.158± 0.033 (NCPCM)

The Bolivian region had the least extreme trends, the highest low trends, except for summer; and the lowest high trends, except spring. The trends for the Basin displayed the greatest difference between the high and low trends, he lowest low trends for all seasons except winter, and the highest high trends except for summer Basin. All of the Bolivian low trends were greater than the 1910-1999 observed trends, so that, even in the mildest simulations, the Bolivian region will experience a marked increase in temperature.

NCPCM and NCCCSM, both NCAR models, projected the lowest temperature trends, with NCPCM dominating all but two fields. Both performed well in simulating historic climate temperatures. NCPCM was only lacking in its pattern correlations for precipitation. NCCCSM was ineffective at simulating seasonality of precipitation, had low pattern correlations, and high RMS errors for precipitation. NCPCM had five forcings and NCCCSM had seven forcings and used atmospheric chemistry. Both had 1day ocean coupling and 1hour atmospheric, land, and ice coupling.

The models that projected the highest temperature trends were HADCM3, MPEH5, and MIHR. HADCM3 provided the majority of the high trends for the Basin. HADCM3 had poor pattern correlation for MSLP but performed adequately at simulating historic climate in other fields. The model included atmospheric chemistry and had 1-day coupling frequency with four forcing agents. MPEH5, which had poor pattern correlation for MSLP and lacked temperature data for the CM20 run, provided the highest trends for the Altiplano. MPEH5 had five forcings and a 1-day coupling frequency. MIHR, which demonstrated the highest trends for the entire Bolivian region, had poor precipitation RMS errors and pattern correlations when compared to observations, but performed very well in all other fields. The MIHR model had 11 forcings and a 3-hour coupling frequency.

The models that projected the lowest trends had a much shorter frequency time for atmosphere, land, and ocean coupling than those that projected the highest trends. Besides coupling frequency, no other single factor distinguishes the high trend models from the low trend models.

In addition, temperature variability was analyzed by looking at the average trend of standard deviation through time. No significant change in the standard deviations of the models was found, implying that extreme heat spells or cold weather would not affect the Bolivia region or the Altiplano or Basin zones individually.

Trends for 30 year intervals

The trends for the following 30-year periods: 2009-2038, 2039-2068, 2069-2098 were computed for seasonal and annual changes in temperature for the Bolivian region, and the Altiplano and Basin zones. All the average trends for different time periods are statistically significant for all areas.

Figure 9. Bolivian Temperature Trends

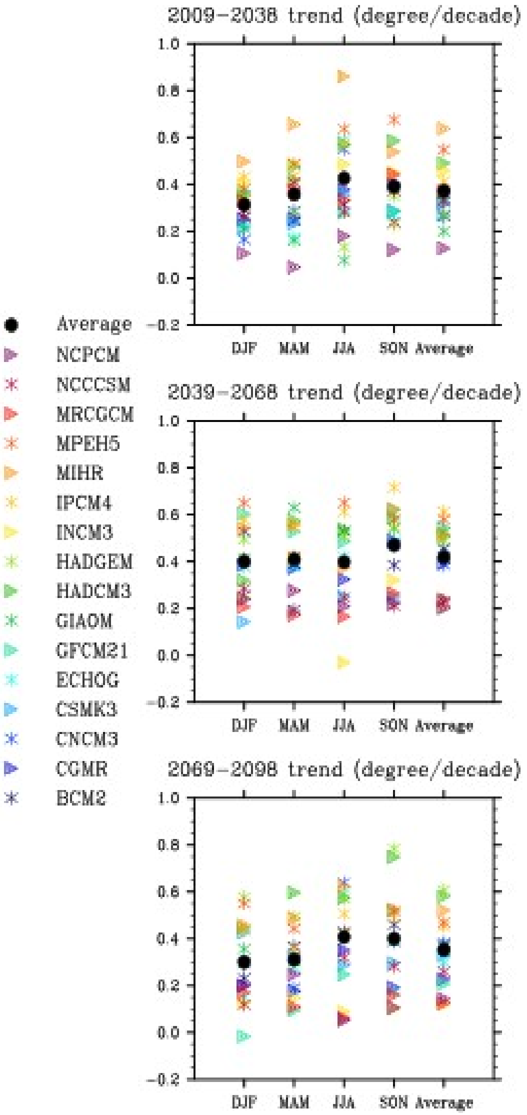


Figure 10. Altiplano Temperature Trends

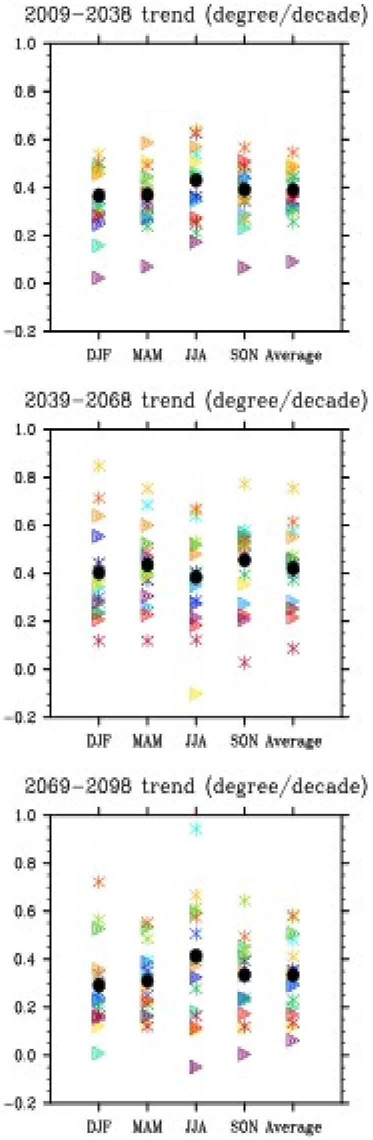
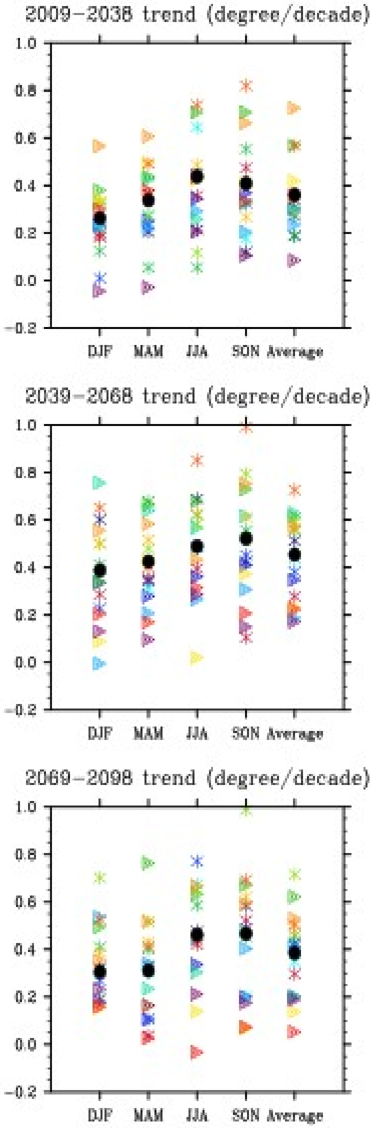


Figure 11. Basin Temperature Trends



The Bolivian trends (Fig. 9) are largest for 2039-2068, except for the winter, in which 2069-2098 trends are the same as for the previous 30 years. The variability is least for 2009-2028 and largest for the 2069-2098 period.

For the Altiplano zone (Fig.10), the greatest trend in winter is 2009-2038. For all other seasons and the annual average, the greatest trends are for 2039-2069. The variability between the different periods is smallest for 2039-2069 and greatest for 2069-2098.

For the Basin zone (Fig.11), the average multi-model ensemble trends are greatest for 2069-2098, just as for the Bolivian trends. In addition, the Basin trends are similar to the Bolivian trends in that the variability in projected temperature is least for 2009-2028 and greatest for 2069-2098.

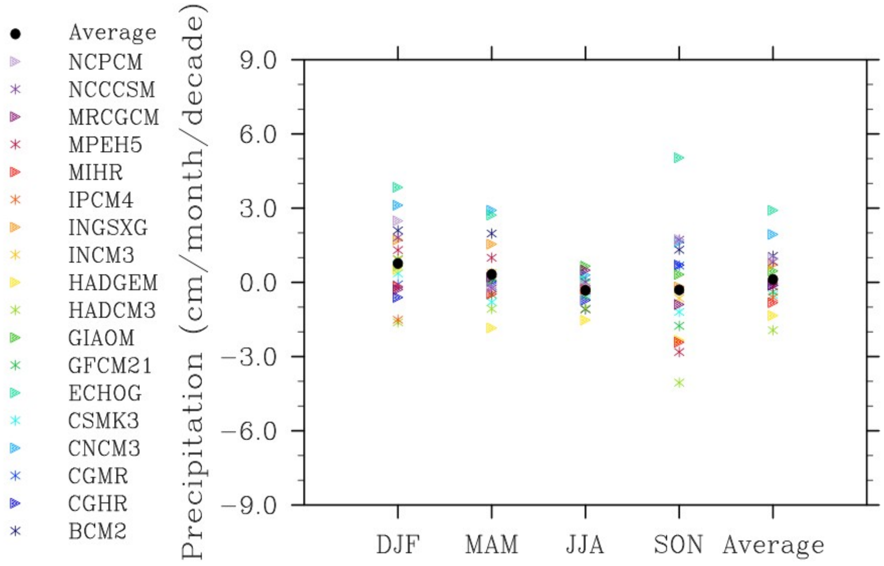
The Altiplano will have the greatest increase in temperature and least variability during the mid-century. The Basin will experience the greatest changes in temperature during the latter part of the century, with increasing variability as the century progresses.

PRECIPITATION

Multi-Model Ensemble Averages and Significant Individual Models

Projected precipitation trends were not as significant as those for temperature. There were no significant ensemble average annual trends for any of the areas studied. However, there were significant ensemble average summer increases in precipitation.

Figure 12. Bolivian precipitation trends for 2009-2098



In the Bolivian region (Fig.12), the summer ensemble average demonstrated a significant trend of 0.765.±0.205 cm/year/decade. The other regional multi-model average precipitation trends were not significant above natural variability. However, seven of the individual models displayed trends that were significant above the natural variability (Table 5).

Table 5. Statistically significant Bolivian precipitation trends for 2009-2098, ensemble averages also shown.

Models	Annual Trend (cm/year/decade)	Summer Trend (cm/year/decade)	Fall Trend (cm/year/decade)	Winter Trend (cm/year/decade)	Spring Trend (cm/year/decade)
BCM2	1.072± 0.323	2.100±0.6795	1.975± 0.792	-------	-------
CNCM3	1.938±0.283	3.119±0.555	2.916±0.768	-------	1.638±0.656
ECHOG	2.913±0.297	3.842±0.515	2.721±0.581	-------	5.037±0.612
INGSXG	0.719±0.263	1.723±0.552	1.545±0.609	-------	-------
NCCCSM	0.828±0.234	1.811±0.531	-------	-------	-------
NCPCM	0.977± 0.415	2.487±0.984	-------	-------	1.729±0.702
Ensemble Average	0.121±0.084 not significant	0.765.±0.205	0.327±0.185 not significant	-0.320±0.070 not significant	-0.302±0.179 not significant

For the Altiplano (Fig. 13), the overall multi-model averages for the annual and seasonal precipitations did not have significant trends; however, eight models did exhibit significant trends, all of which were positive (Table 6). Some models projected negative trends in precipitation, but none of those were significant above the natural variability.

Figure 13. Altiplano Precipitation Trends

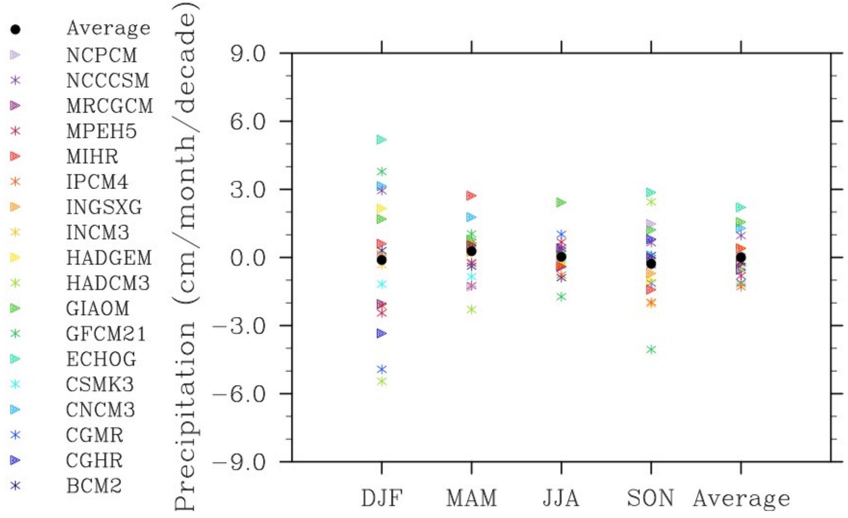


Table 6. Statistically significant Altiplano precipitation trends for 2009-2098, ensemble averages also shown.

Model	Annual Trend (cm/year/decade)	Summer Trend (cm/year/decade)	Fall Trend (cm/year/decade)	Winter Trend (cm/year/decade)	Spring Trend (cm/year/decade)
CGMR	-------	-------	-------	1.0120± 0.552	-------
CNCM3	1.289±0.235	3.144± 0.693	1.775±0.741	-------	-------
ECHOG	2.206±0.406	5.191±0.900	-------	-------	2.865±0.758
GFCM21	3.784± 1.434	-------	-------	-------	-------
GIAOM	1.558±0.530	1.694±0.768	-------	2.423±1.090	-------
HADCM3	-------	-------	-------	-------	2.449±0.775
MIHR	-------	-------	2.721±1.041	-------	-------
NCCCSM	0.967±0.377	2.944±0.776	-------	-------	-------
Ensemble averages	0.008± 0.088 not significant	-0.112±0.254 not significant	0.273±0.185 not significant	0.031±0.104 not significant	-0.278±0.161 not significant

For the Basin (Fig.14), the summer multi-model average of precipitation had a significant positive trend of 1.155±0.335 cm/year/decade. Four models produced significant trends for the Basin zone (Table 7).

Figure 14. Basin Precipitation Trends

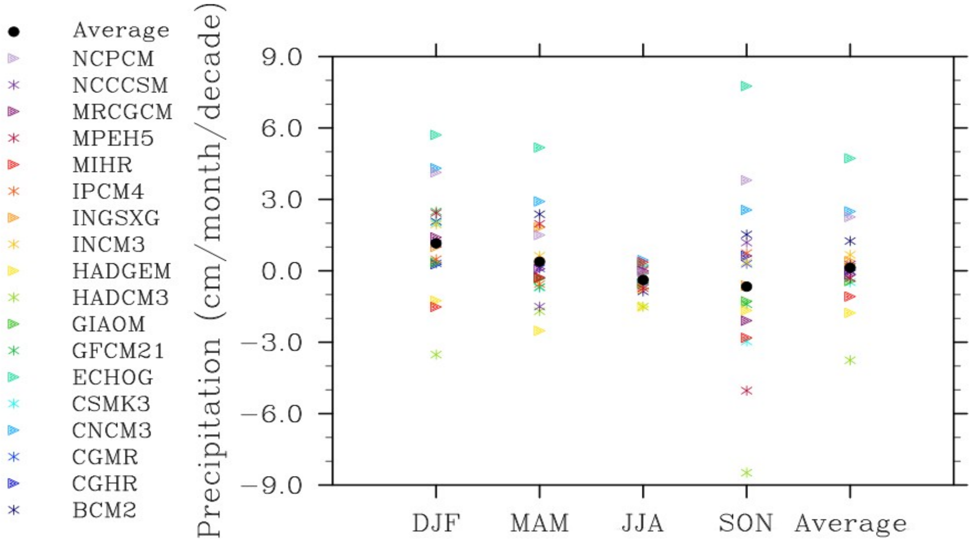


Table 7. Statistically significant Basin precipitation trends for 2009-2098, ensemble averages also shown.

Model	Annual Trend (cm/year/decade)	Summer Trend (cm/year/decade)	Fall Trend (cm/year/decade)	Winter Trend (cm/year/decade)	Spring Trend (cm/year/decade)
CGHR	1.251±0.321	-------	-------	-------	-------
CNCM3	2.494±0.562	4.308±1.079	-------	-------	2.558±1.237
ECHOG	4.725±0.384	5.708±0.901	5.178±0.866	-------	7.759±0.942
NCPCM	2.261±0.415	4.134±1.048	-------	-------	3.804±0.794
Ensemble averages	0.130±0.133 not significant	1.155±0.335	0.382±0.273 not significant	-0.380±0.083 not significant	-0.663±0.274 not significant

The models CNCM3 and ECHOG had significant trends for the Bolivian region and Altiplano and Basin zones. They both had significant trends for annual, summer and spring seasons in all areas. NCCCSM had significant trends for the Bolivian region and the Altiplano. NCPCM had significant trends for the Bolivian region and the Basin zone. Of the three areas examined, models projected significant trends in the winter for only one area, the Altiplano. ECHOG was the best model in simulating historic climate, so perhaps it may be more accurate than the other models, indicating a greater likelihood of precipitation increase.

Also, the presence of extreme precipitation events was analyzed through the behavior of the standard deviation of precipitation over five year intervals as a function of time. There was no significant trend in the standard deviation, regardless of season or averaged location.

In addition, although the multi-model annual precipitation projection lacked significant trends for 2009-2098, when analyzed over the periods of 2009-2198, there was a significant annual Bolivian trend of 0.082±0.036cm/year/decade.

DISCUSSION

Temperature increases were found for all seasons and areas analyzed. These increases in temperature will shift ecological systems to higher elevations and cooler temperatures. As temperature increases, there is associated decrease soil moisture. This may lead to savanna replacing tropical forests, and semi-arid vegetation will tend to be replaced by arid vegetation (IPCC, 2007). This will have negative consequences for biodiversity and natural resources. Also, increases in temperature will negatively affect crop productivity, which may result in an increase of hunger and malnutrition among the population. Increasing temperatures will also result in losses of glaciers and smaller mountain snow packs, which provide seasonal fresh water for drinking and for irrigation. This may be offset by increases in precipitation in areas other than the Altiplano. Increased temperatures will also affect freshwater lakes and rivers by changing their physical and chemical properties. Increased salinization of groundwater supplies may also occur, with mainly negative impacts on freshwater species and water quality (IPCC, 2007).

Significant summer precipitation increases were found for the Bolivian region and the Basin zone, but not for the Altiplano. For people living near rivers, increased precipitation may result in increased deaths, diseases and injury due to flooding (IPCC, 2007). The Amazon Basin currently has high levels of deforestation, which makes the area particularly vulnerable to flooding during heavy precipitation (Oxfam, 2009). In addition, future increases in precipitation may also affect the runoff patterns, water supplies, water quality and flood risks. The projected increase in precipitation in the Basin and general Bolivian region may offset the loss of glacial water resources due to increases in temperature. The precipitation data for the Altiplano, in contrast, shows no significant precipitation increase, and thus that area may be more at risk for a decrease in available water. Without dramatic improvements to education, health care, public health initiatives, infrastructure development, and economic development, Bolivia may not be able to respond effectively during the changing climate (IPCC, 2007).

The annual Bolivian precipitation projections in this study are similar to those determined in the 1997 study of Paz Rada et al.: the precipitation trend was not significant. However, in the previous study, both models projected a precipitation decrease for the summer and an increase for the winter months. Paz Rada's results differed from those found in this study, which predicted a summer precipitation increase for the Bolivian region, but no statistically significant winter trend. The numbers and types of models used in the studies may have caused these differences. In the Paz Rada et al.(1997) study, only two models were used in projections, while in this study, sixteen models were used for precipitation projections. In addition, the models used in the previous study were older versions, improvements and additions to new models may have made a difference.

The demerit point process used to accept and reject models based on their simulation of the historic climate was somewhat arbitrary. This may have limited the accuracy of this study. The use of a more objective process that involved weighting models according to their performance at simulating historic climate would improve this study. For example, weights could be assigned based on pattern correlations and RMS errors for temperature, precipitation and MSLP instead of demerit points (Whetton et al. 2007).

Another limitation may have been the coarse resolution of GCMs, as many small-scale processes cannot be modeled and must be approximated. While acceptable for global projections, this can result in problems for regional studies, especially for precipitation. This study therefore could be improved by using finer resolutions of the GCMs. These could be obtained by downscaling of the GCMs, through methods such as dynamic downscaling, statistical downscaling and weather generators.

Although Bolivia is a discrete political subdivision, as Bolivia has such a wide variety of geographic areas, it might be meaningless to examine climate projections over Bolivia as a whole. Instead projections for each zone could be based on models that performed best for just that zone. This may improve the accuracy of the projections for a particular area.

SUMMARY

After comparing 23 models to observations of historic climate for mean sea level pressure, temperature and precipitation, extreme models were eliminated using a demerit method. Using the remaining 16 models, trends for projected precipitation and temperature for the next 90 years were examined. The multi-model average was used to determine the most likely temperature projection. Individual model high and low trends were examined in order to ascertain the full range of projected change.

The resulting multi-model average temperature trends were significant for all seasons and areas while summer precipitation was significant only for the Bolivian region and Basin zone. In addition to having a significant summer precipitation increase of 1.155+-0.335 cm/year/decade, the Basin will also experience the greatest spring and winter increase in temperature as well as the greatest annual temperature increase. For almost all seasons and for all areas the temperature increase will be greatest mid-century.

These findings may provide a useful addition to our knowledge of the expected climate changes in Bolivia because they challenge some of the conclusions of the prior study of Paz Rada et al.: low annual temperature trends, winter increase in precipitation and summer decrease in precipitation. Thus Bolivia will be hotter and experience greater summer precipitation than had been previously projected.

Acknowledgments

This paper benefited from Professor Chris Poulsen as the research advisor, and Professor Rob Van der Voo as undergraduate advisor. Special thanks to Professor Dave Lund, who agreed to step in as the second reader.

LITERATURE CITED

Allmendinger, R., T., Jordan, S., Kay, and B. Isacks. "The Evolution of the Altiplano-Puna Plateau of the Central Andes." Annual Review of Earth and Planetary Sciences, 25 (1997):139–74

Buytaert, W., M. Vuille, A. Dewulf, R. Urrutia, A. Karmalkar, and R. Celleri "Uncertainties in climate change projections and regional downscaling: implications for water resources management." Hydrology and Earth System Sciences Discussions, 7 (2010): 1821–1848

Bombardi, R. & L. Carvalho. "IPCC global coupled model simulations of the South America monsoon system." Climate Dynamics, 33 (2009): 893–916.

Bryan, F. "Climate Drift in a Multicentury Integration of the NCAR Climate System Model." Journal of Climate, 11 (1998): 1455-1471

Carril, C., C. Meneândez & M. Nunä Ez. "Climate Change Scenarios over the South American Region: An Intercomparison of Coupled General Atmosphere-Ocean Circulation Models." International Journal of Climatology, 17 (1997): 1613-1633.

CRU Datasets. University of East Anglia Climate Research Unit (CRU). British Atmospheric Data Centre. (2008) 03/9/2010. <badc.nerc.ac.uk/data/cru>

Giorgi F., B. Hewitson, J. Christensen, M. Hulme, H. von Storch, P. Whetton, R. Jones, L. Mearns, and C. Fu. "Regional climate change information – evaluation and projections". In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu, D (eds) Climate Change 2001 – The Scientific Basis. Cambridge University Press, (2001): 583-638.

IPCC: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, (2007)104 pp.

IPCC-TGICA: General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version 2. Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, (2007) 66 pp.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, and R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne & D. Joseph. "The NCEP/NCAR 40-year reanalysis project." Bulletin of the American Meteorological Society, 77 (1996): 437-470

Mitchell, T. & P. Jones. "An improved method of constructing a database of monthly climate observations and associated high-resolution grids." International Journal of Climatology, 25 (2005): 693-712

Mote, P., E. Salathé, V. Dulière, & E. Jump. "Scenarios of future climate for the Pacific Northwest. Report prepared for King County, WA by the Climate Impacts Group" University of Washington, Seattle, WA, USA. (2008)

Murdock, T. "Canadian Climate Impacts Scenarios: Emissions." Canadian Institute for Climate Studies. University of Victoria. 2003. <www.cics.uvic.ca/scenarios/index.cgi?More_Info-Emissions>

Nakicenovic, N. et al. "Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change". Cambridge University Press, Cambridge, U.K., (2001). 599pp.

Oxfam: Bolivia, climate change, poverty, and adaptation. Report by Oxfam International in Bolivia. Prepared by James Painter, Simon Ticehurst, Agrario Urgel & Sarah Best. Oxfam International, Obrajes. La Paz, Bolivia. (2009)

Paz Rada, O., S., Romero Crespo & F. Tejada Miranda. "Analysis of climate scenarios for Bolivia." Climate Research, 9 (1997): 115-120.

"CMIP3 Climate Model Documentation, References, and Links." The Program for Climate Model

Diagnosis and Intercomparison (PCMDI). Lawrence Livermore National Laboratory. (2007) <http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php>

Piercea, D., T. Barnetta, B. Santerb & P. Glecklerb. "Selecting global climate models for regional climate change studies." PNAS, 106.21 (2009): 8441-8446.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R. Stouffer, A. Sumi, and K. Taylor, 2007: Climate models and their evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., et al., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and NewYork, NY, USA.

Semenov, M, & P. Stratonovitch. "Use of multi-model ensembles from global climate models for assessment of climate change impacts." Climate Research, 41 (2010): 115-120.

Stouffer, R., A. Broccoli, T. Delworth, K. Dixon, R. Gudgel, I. Held, R. Hemler, T. Knutson, Hyun-Chul Lee, M. Schwarzkopf, B. Boden, M. Spelman, Winton, and Fanrong Zeng. "GFDL's CM2 Global Coupled Climate Models. Part IV: Idealized Climate Response." Journal of Climate, Special Section, 19 (2006): 723-740

Suppiah, R., K. Hennessy, P. Whetton, K. McInnes, I. Macadam, J. Bathols, J. Ricketts and C. Page. "Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report." Australian Meterological Magazine, 56 (2007): 131-152.

Taylor, K., C. Covey, K. AchutaRao, M. Fiorino, P. Gleckler, T. Phillips, and K. Sperber. "IPCC Standard Output from Coupled Ocean-Atmosphere GCMs." WGCM Climate Simulation Panel with the assistance of PCMDI. (2007) <www-pcmdi.llnl.gov/ipcc/standard_output.html>

Whetton P, P. Rayner, A. Pittock, M. Haylock. "An assessment of possible climate change in the Australian region based on an intercomparison of general circulation modeling results." Journal of Climate, 7 (1994): 441–463