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Climate trends and projections for the Andean Altiplano and strategies for adaptation

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Abstract. Climate variability and change impact production in rainfed agricultural systems of the Bolivian highlands. Maximum temperature trends are increasing for the Altiplano. Minimum temperature increases are significant in the northern region, and decreases are significant in the southern region. Producers' perceptions of climate hazards are high in the central region, while concerns with changing climate and unemployment are high in the north. Similar high-risk perceptions involve pests and diseases in both regions. Altiplano climate projections for end-of-century highlights include increases in temperature, extreme event frequency, change in the timing of rainfall, and reduction of soil humidity. Successful adaptation to these changes will require the development of links between the knowledge systems of producers and scientists. Two-way participatory approaches to develop capacity and information that involve decision makers and scientists are appropriate approaches in this context of increased risk, uncertainty and vulnerability.

1 Introduction

Globalization, climate variability and climate change are increasing food insecurity in tropical regions (Valdivia et al., 2010; Lobell et al., 2008). Agriculture in these regions often does not have functioning institutions to protect against risk – especially in rainfed production systems. Farmers in regions like the Andes rely on local knowledge and institutions to address uncertainty and risks, which have proven to work for centuries (Gilles and Valdivia, 2009; Mayer, 2002; Valdivia and Gilles, 2001; Orlove et al., 2000; Valdivia et al., 1996). Altiplano landscapes are characterized by a high degree of variation, which makes negotiating uncertainty at the local level a key issue for adaptation. In this article the climate of the Altiplano and the risks farmers face are presented, followed by how – under increased uncertainty – adaptive capacities can be developed to address change. The premise of the research presented here is that participatory processes that link local and scientific knowledge systems are critical to building the capacity to deal with change in the Andes.

2 Climate – trends and change – and risks in five landscapes

The impacts of climate variability on farming systems in the Altiplano are well documented (Sperling et al., 2008; Valdivia, 2004). Farmers in the Altiplano have always faced recurrent droughts, floods and frosts but climate change is presenting new challenges that reduce crop production such as increased pressure from pests and plant disease and shifts in the onset and intensity of rains. Observed climate trends are analyzed for three Altiplano regions, followed by an analysis of risk perceptions and shocks to rural livelihoods of five landscapes in the northern and central regions. Finally, climate projections for extreme events and soil humidity for the Altiplano and implications are discussed.

2.1 Trends

Statistical analysis of historical records of 14 meteorological stations in the Altiplano show some decline in the monthly rainfall for the early rainy season months (October through December), but no significant trends ($p\text{-value} = 0.6$) in annual precipitation (Valdivia et al., 2010). Figure 1 presents

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Table 1. Socioeconomic characteristics by groups in the Bolivian Altiplano (2006).

Region	Northern Altiplano Groups			Central Altiplano Groups		
Group	I	II	III	I	II	III
Variable						
Age (years)*	52.5	35	59	53	32.9	62.4
Education (years)*	7.6	6.8	3.8	6.5	8.5	3.6
Farming cash income (US$)*	1500	500	412	2300	1250	636
Total cash income (US$)*	2200	1000	823	4600	2500	1770

Source: Valdivia et al. (2007), * Significant differences $p < 0.05$ between groups by region: I productive households in the middle of their life cycle, II young households starting their productive life cycle, III elderly households in later stage of the life cycle.

the GIS-based geostatistical analysis of temperatures and rainfall. Maximum temperatures are increasing throughout (p-value = 0.005). Minimum temperatures are also increasing throughout the year in the northern and central Altiplano, especially in winter (May through September) (p-value = 0.0015). On the other hand, minimum temperatures have dropped in the southern Altiplano (p-value = 0.006), which may be a result of changing production systems, clearing of agricultural land and increasing desertification that may reduce atmospheric water vapor.

Implications

Observed trends have already had substantial impact on agriculture. Frost is becoming less of a limiting factor in the northern and central parts where $T_{\min}$ is rising. Farmers are shifting their production systems from more extensive and resilient rainfed crops to short-season, high-value and irrigated crops such as onions or peas in the north where the rising temperatures are clearly felt by producers. Farmers are dividing their plots and are planting throughout the growing season, increasing their dependence on limited irrigation water. Although these practices could be seen as local adaptations, strongly driven firstly by climate but also by market opportunities, they have resulted in further fragmentation of already small fields, conflicts between water users, pressure on fragile soils and in some cases increased incidence of pests and diseases. In the drier central Altiplano, later onset of the rainy season has more severe impact on farming than in the northern region due to the lack of irrigation. This means that the few crops that can grow in this region must be planted later. In a cold environment such as that of the central Altiplano (even with rising temperatures), later planting increases the risk of crop failure because crops may not reach maturity before the onset of fall frosts. Thus, late onset of the rainy season could lead to an increased frequency of crop failures or losses if adaptation actions are not rapidly planned. Finally, less incidence of frosts in both regions threatens production of *chuño* (freeze-dried potatoes), which through centuries has been the source of food security because it can be stored for five years or more.

2.2 Perceptions of risks and shocks in the livelihoods of families in rural landscapes

To understand the relationship of the production systems, geography and climate impacts on the livelihoods of farmers, 330 households were interviewed. Data about the impact of climate on farming and about hazard threat perceptions in 2006 covered a 200 km transect, and included five landscapes, three in a watershed in the northern Altiplano region and two in the central Altiplano region. The watershed lowlands in the north are on the shores of Lake Titicaca at 3815 m a.s.l.; the mid elevation landscape is 12 km up the watershed; and the high elevation landscape, more pastoral than cropping, is 20 km from the lake. The central Altiplano landscapes are in two different agroecological zones, the flat lowlands where dairy production has developed, and the highlands where cropping takes place mostly with animal plow. Analysis of the data using cluster analysis identified groups at different stages in the life cycle (p-value < 0.05), with differences in income levels and importance of farming and non-farming activities between and within regions (Table 1). Education levels are higher among those in the early stages of the life cycle, and income is highest in the productive groups. The central Altiplano region has higher income levels, and the share from farming is higher.

The perceived risks – the threat each hazard represents to their livelihood – and the impact of hazards on crops and animals differed in intensity by landscape and region (see Table 2). In most landscapes hazards were a very strong threat. Perceived frost, floods and hail hazards were high in both landscapes of the central Altiplano. Hail hazards were mostly felt in the higher elevation landscape of this region. Concerns in the north were especially high regarding the changing climate, loss of soil fertility, and becoming unemployed, consistent with the overall low income and greater importance of off-farm income (migration). Production shocks related to pests were particularly prevalent and perceived as a high threat in both regions, consistent with increased warming trends. Perceptions of flood hazards were high in the lowlands of the northern Altiplano, near Lake Titicaca. In the mid- and high elevations, perceptions of environmental

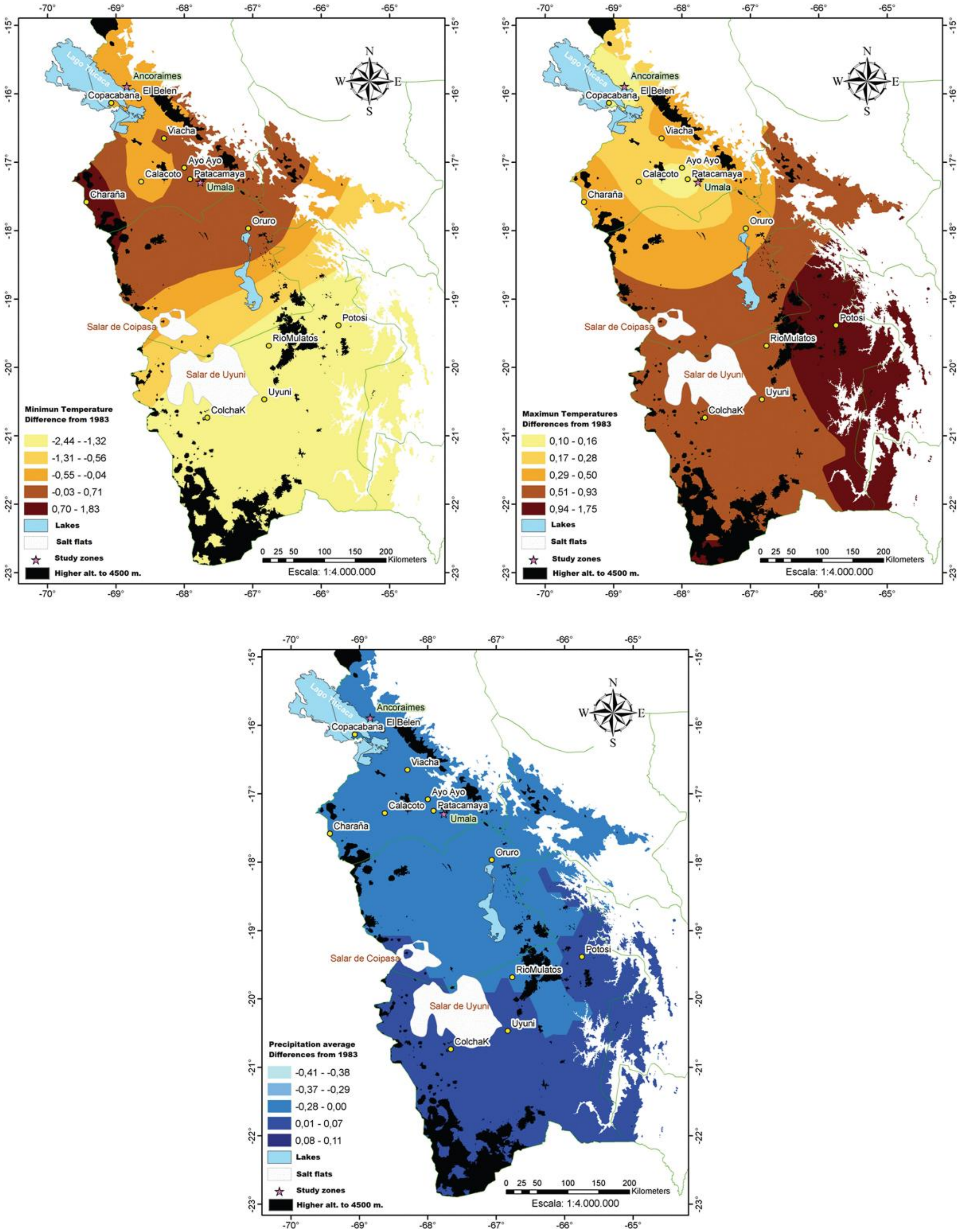

Fig. 1. Differences in the mean of Minimum and Maximum Temperature and Precipitation records, before and after 1983 for the Bolivian Altiplano. Source: Valdivia et al. (2010).

Table 2. Location and risk perceptions average index[1] and losses (%) by climate, social and market hazards and shocks in the Bolivian Altiplano (2006).

Type of Hazard/Landscapes	Northern Altiplano Ancoraimes Municipality			Central Altiplano Umala Municipality	
Location	Low	Mid	High	Low	High
Elevation (m a.s.l.)	3815	3850–3890	4200	3770–3805	4070–4012
Number of respondents (N)	57	65	27	127	54
Perceptions (index)					
Hail for crops and animals	3.51	3.97	3.56	3.85	4.28
Floods	3.96	3.82	3.85	4.42	4.00
Drought	2.41	2.97	2.67	2.96	3.00
Frost	3.89	4.06	3.59	4.35	4.50
Changing climate	3.79	4.17	4.11	3.87	3.53
Crop pests	3.68	4.11	3.78	3.13	3.67
Soil fertility loss	3.91	4.23	4.00	3.44	3.68
Low livestock price	3.84	4.12	3.78	3.72	3.83
Unemployment of an adult	3.70	4.23	4.04	2.33	2.98
Shocks Experienced in 2006 (percent)					
Drought, percent losses* $n = 34$	40	23	0	27	18
Floods, percent losses $n = 50$	21	0	28	28	12
Frosts, percent crop losses $n = 107$	19	19	25	22	0
Hail, percent crop losses $n = 48$	17	22	20	21	21
Pests, percent crop losses $n = 278$	28	32	22	12	11
Frost, percent livestock losses $n = 40$	29	25	30	9	5
Disease, percent livestock losses $n = 164$	14	17	18	18	15

Source: Household Survey Data Practices and Strategies in the Bolivian Altiplano, SANREM CRSP LTRA4.
[1] The index is the average of responses to the question with 1 = not a threat, 2 = minimal threat; 3 = moderate threat; 4 = very strong threat, 5 = extreme threat.
* n indicates the number of households who experienced losses.

(soils) and social threats were high – localities with less income, education, and land. High perceptions of risk coupled with low levels of income mean that farmers weigh the present more than the future in their livelihood decisions.

2.3 Climate change extremes and soil moisture

Simulations from eleven Coupled Model Intercomparison Project version 3 (CMIP3) (Meehl et al., 2007) global coupled climate models have been analyzed for present and future climate scenarios (Table 3). Current climate model resolution cannot provide accurate climate projections in the Altiplano because of the complex topography, but the use of high to intermediate resolution climate models may provide reliable qualitative information about the direction of future trends (Seth et al., 2010). Trends have been analyzed for four extreme temperature indices (extreme temperature range, frost days, warm nights, and heat waves) and four precipitation extreme indices (consecutive dry days, 5 day precipitation, precipitation > 95th percentile, and precipitation intensity). Modeled extreme indices use the definitions of Frich et al. (2002). Changes in the annual cycle of soil moisture and future trends in spring (OND) and summer (JFM) soil moisture have also been analyzed. Analysis is focused on the northern Altiplano, which is defined here as 16–19° S and 67–70° W. Model calculations represent area-averages of this region. All significance tests were performed at the 90 % confidence level.

2.3.1 Extremes

Extreme temperature indices have been calculated for La Paz/El Alto (16.50° S/68.18° W, 4061 m), using the US National Climatic Data Center's (NCDC) Global Surface Summary of the Day (GSOD), covering 1973–2007 (see Thibeault et al., 2010). Mann–Kendall tests were used to identify significant trends. Direct comparison of modeled and observed extreme indices is not possible because of differences in definitions and issues with comparing point and area-averaged data (Alexander and Arblaster, 2009; Chen and Knutson, 2008), but identifying consistencies in the directions of trends between simulated and observed temperature extremes provides insight into model projections.

Precipitation indices were not calculated because of missing data.

Only two stations in the Altiplano have adequately long records of high quality daily temperature and precipitation observations suitable for extremes analysis. Significant increasing trends have been identified in several precipitation indices at Patacamaya, Bolivia, suggesting a shift toward less frequent but more intense precipitation (Haylock et al., 2006; Thibeault et al., 2010). No significant trends in temperature extremes were identified at Patacamaya (Vincent et al., 2005). Significant increasing trends in *warm nights* and *warm spells* were identified at La Paz/El Alto, covering 1973–2007 (Thibeault et al., 2010). Increasing trends were also identified in *frost days* and the *extreme temperature range*. The simultaneous increases in warm nights and frost days, both based on daily minimum temperatures, are unexpected but may be explained by an increase in the frequency of clear nights when precipitation at La Paz/El Alto decreases in frequency, similar to what is found at Patacamaya (Thibeault et al., 2010).

Multi-model projections of frost days, heat waves, and warm nights show trends consistent with warmer temperatures projected for the Altiplano (Fig. 2) (Thibeault et al., 2010). The increasing trend in the *extreme temperature range* suggests that the Altiplano will continue to experience some very low minimum temperatures while maximum temperatures increase. Projected trends are significant at the 90 % confidence level, and with the exception of frost days, consistent with the direction of observed trends at La Paz/El Alto.

Multi-model projections show significant increasing trends in all precipitation indices, and share the same signs as trends identified at Patacamaya by Haylock et al. (2006) (Thibeault et al., 2010) (Fig. 3). Results are consistent with annual cycle projections for an extended dry season, weaker early rainy season, and more intense summer peak rainy season (Seth et al., 2010; Thibeault et al., 2010).

2.3.2 Soil moisture projections

Changes in soil moisture were evaluated for the A2 scenario (Thibeault, 2010). Multi-model means show that soil moisture starts to decrease throughout the annual cycle by 2020–2049, though some models project an increase during the rainy season (Fig. 4a). By 2070–2099, there is good agreement among the models that soil moisture reductions will increase throughout the annual cycle, even in the peak rainy season (Fig. 4b). Multi-model time series of seasonal soil moisture show reductions in spring (OND) throughout the 21st century (Fig. 5a), consistent with projections for lower rainfall and higher temperatures (Seth et al., 2010; Thibeault et al., 2010). Lower summertime (JFM) soil moisture is expected from mid-century onward (Fig. 5b). Higher precipitation intensity is likely to lead to an increased runoff ratio as rainfall rates exceed the infiltration capacity of the soil. Increased evapotranspiration from higher temperatures will further reduce Altiplano soil moisture.

With the exception of frost days, projected trends in climate extremes share the same sign as observed trends at Patacamaya and La Paz/El Alto. The combination of higher temperatures, changes in precipitation timing and intensity, and soil moisture reductions are likely to increase the climate-related risks to rural agriculture in the Altiplano as greenhouse warming progresses.

3 Uncertainty and adaptive capacities – linking knowledge systems

3.1 Uncertainty and decisions

Uncertainty about climate is likely to increase and the existing knowledge farmers have to make decisions related to climate may not be able to inform future decisions because they are based on experience with past conditions; new knowledge will be required. People assess risks using rules-based and association-based (experiential) systems (Slovic and Weber, 2002). When the results of association- and rules-based systems conflict, decision makers revert to their experience (traditional/local knowledge). Altiplano farmers will likely rely on traditional knowledge when it conflicts with probabilistic forecasts (Valdivia et al., 2010). In this context of uncertainty, Slovic and Weber (2002) suggest that two-way participatory communication may enhance local knowledge by providing salient knowledge to the decision-makers. This process creates common expectations and language that can be used to discuss alternative strategies. Farmers can listen to the forecasters, make their own observations and derive lessons beyond the conclusions made by researchers. The participatory research is a mechanism for linking knowledge systems, identifying barriers as well as courses of action. In order to enhance adaptation to climate change in the Altiplano, the knowledge systems of meteorologists and those of indigenous farmers need to be linked.

3.2 Adaptive capacity in a context of uncertainty and food insecurity

The forecast community must meet many challenges in order to bring this knowledge link to pass. The first challenge is the farmer's lack of access to useful meteorological data that has both technical and socioeconomic dimensions. The Altiplano is characterized by a myriad of microclimates. In such cases, the production of locally useful meteorological forecasts requires a high density of weather stations. However, the Altiplano region is characterized by a low density of stations, exacerbated by the fact that few stations have the quality of data needed to identify trends. There were only 14 stations in the Altiplano with 35 yr or more of quality data and only two stations with data to model extreme events in a region with an area of approximately 240 000 square

Table 3. CMIP3 coupled ocean–atmosphere models used in extremes and soil moisture (SM) analyses. Atmospheric resolution is shown in longitude by latitude degrees, respectively. Ocean resolution is defined as the number of grids in longitude and latitude, respectively. Models and scenarios used in the extremes and soil moisture analyses are given. 20c3m denotes 20th century simulation. B1, A1B, and A2 denote low, medium, and high emissions scenarios for 21st century simulations, respectively.

Modeling Center	Model	Atmosphere Resol.	Ocean Resol.	Extremes Scenarios	SM Scenarios
National Center for Atmospheric Research	CCSM3	1.4 × 1.4	320 × 395	20c3m, B1, A1B	20c3m, A2
Meteo-France, Centre National de Recherches Meteorologiques	CNRM-CM3	2.8 × 2.8	180 × 170	20c3m, B1, A1B, A2	
US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.0	2.5 × 2	360 × 200	20c3m, B1, A1B, A2	20c3m, A2
US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.1	2.5 × 2	360 × 200	20c3m, B1, A1B, A2	20c3m, A2
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	MIROC3.2-MedRes	2.8 × 2.8	256 × 192	20c3m, B1, A1B, A2	20c3m, A2
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	MIROC3.2-HiRes	1.1 × 1.1	320 × 320	20c3m, B1, A1B	
National Center for Atmospheric Research	PCM	2.8 × 2.8	360 × 180	20c3m, B1, A1B, A2	
Institut Pierre Simon Laplace	IPSL-CM4	3.75 × 2.5	180 × 170	20c3m, B1, A1B, A2	
Meteorological Research Institute	MRI-CGCM2.3.2	2.8 × 2.8	144 × 111	20c3m, A1B, A2	20c3m, A2
Max Planck Institute for Meteorology	ECHAM5	1.9 × 1.9	192 × 189		20c3m, A2
UKMO/Hadley Centre for Climate Prediction and Research	HadCM3	3.75 × 2.5	288 × 144		20c3m, A2

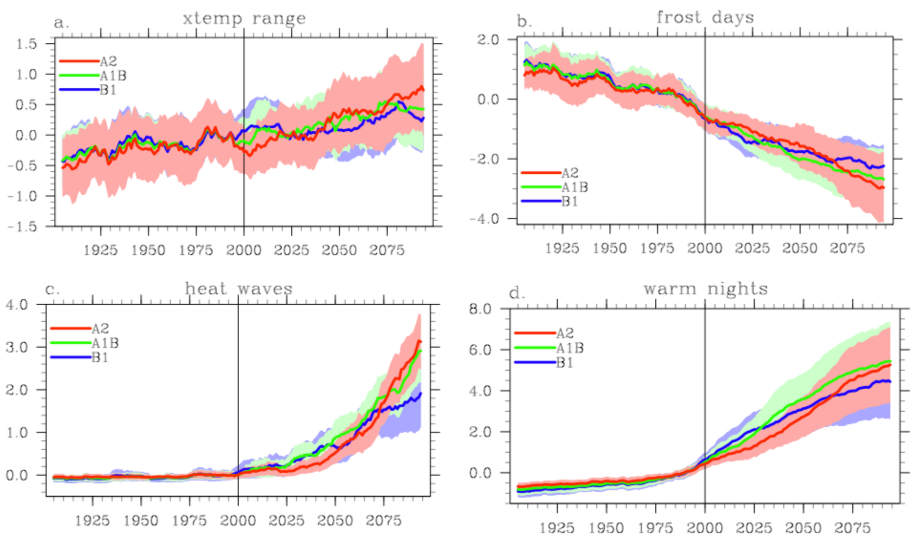

Fig. 2. Simulated Altiplano temperature extreme indices for 1901–2099. Time series have been standardized for each model, then averaged to provide a multi-model time series for each scenario. Thick lines show 10-yr running averages. Shading represents the width of one standard deviation of the ensemble mean. The 21st century scenarios are shown for the B1 (blue, 8 models), A1B (green, 9 models), and A2 (red, 7 models) scenarios. Source: Thibeault et al. (2010).

kilometers (Valdivia et al., 2010). Downscaling of the global models is also a challenge in this context. The scale of existing models is too large to be translatable to the local level. In addition, projections from climate models focus on average changes in temperature and precipitation, and changes in extreme event frequencies. Farmer decisions must be based on estimates of rainfall distribution and extreme events within the cropping year. The socioeconomic dimension has several elements. First, there is a lack of knowledge about climate trends that inhibits the creation of adaptation strategies. In addition, farmers do not trust forecasts generated outside of their immediate area (Gilles and Valdivia, 2009). Second, demographic changes are reducing the adaptive capacity of traditional production systems. Increased population has led to the division of land into ever smaller farms and shorter fallow periods (Valdivia et al., 2007). Traditionally, Altiplano farmers minimized weather related risks by planting crops in a variety of micro-environments, no longer possible with present farm sizes. Population pressures have led farmers to migrate seasonally, creating labor shortages that restrict the number of adaptive alternatives as well.

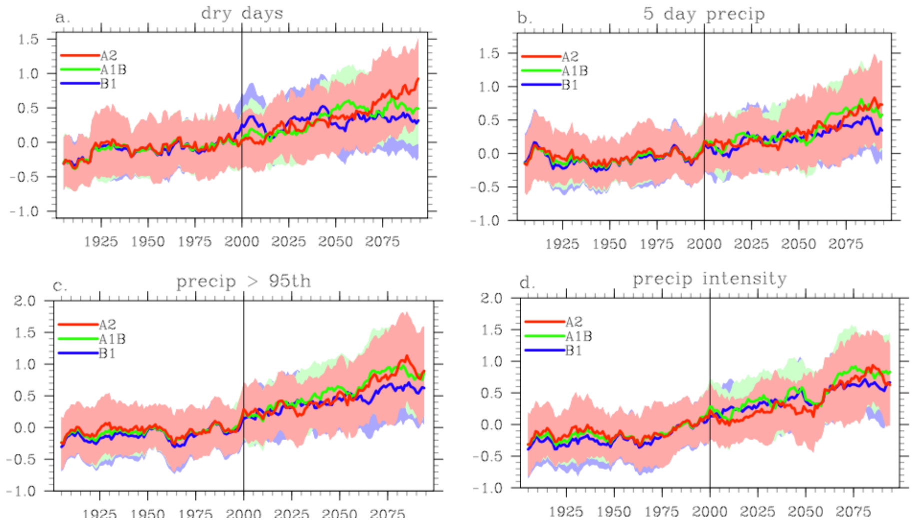

Fig. 3. As in Fig. 2, but for Altiplano precipitation extreme indices. Source: Thibeault et al. (2010).

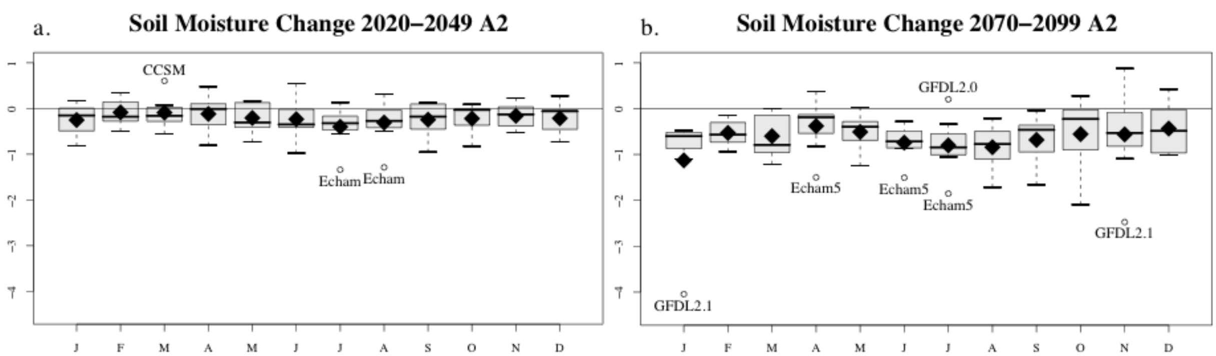

Fig. 4. Normalized soil moisture differences (A2 minus 1970–1999) for the middle (**a**. 2020–2049) and late 21st century (**b**. 2070–2099). Multi-model averages are indicated by black diamonds. Source: Thibeault (2010).

3.3 A participatory strategy for linking formal and local knowledge systems

Because of the challenges described above, neither scientific forecasts nor local knowledge can by themselves guide smallholder adaptation to climate change. However, a participatory process involving forecasters and producers could do so. Identifying adaptive strategies is a lengthy process, so the first step would be to secure the commitment of participating communities. Once that is obtained, a series of meetings between the team and producers could be carried out where producers express their concerns about climate change and risk, and discuss how they could deal with these concerns. At the same time, forecasters would present their estimates of change and their observation of trends to the communities in order to help producers begin to think about adaptation strategies. During this process, care should be taken to involve men and women of all ages and resource levels, because viability of adaptive strategies depends on the characteristics and resource endowments of producers as well as physical and biological constraints. Following this step, efforts would be made to correlate forecast data from national weather services by installing weather stations in communities to help farmers in specific microclimates. In addition, discussions about adaptation strategies should continue and local experiments with possible adaptive strategies carried out. The process would facilitate a common language, as well as knowledge of each other addressing issues of trust. The two-way process would build the knowledge networks (which may be social and political) that enable agency or ability to act. These knowledge networks would include government agencies and non-governmental organizations that can provide technical assistance and resources to assist in adaptation. This process would be farmer driven but expert assisted, in order to provide the flexibility needed to find appropriate strategies for different microclimates and resource endowments.

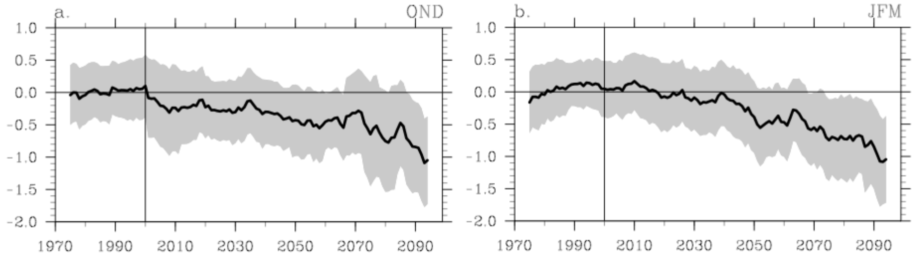

Fig. 5. Simulated time series of normalized Altiplano soil moisture anomalies for 1970–2099 relative to the base period 1970–1999: OND **(a)** and JFM **(b)**. The 21st century A2 simulations were appended to 20th century simulations. The resulting time series were normalized for each model, then averaged to provide a multi-model time series. Thick lines indicate the 11-yr running average. Shading represents the width of one standard deviation of the ensemble mean. Source: Thibeault (2010).

4 Conclusions

The Altiplano is diverse in social and ecological conditions. Changes in climate trends along with climate change projections underscore the need for approaches that can develop capacities and knowledge for adaptation. The most vulnerable families also express the highest concerns with climate and other hazards, because of the difficulties to cope with the consequences of the hazards. Two cause/effect knowledge gaps inhibit the development of adaptive capacity in the Altiplano and filling these gaps should be a priority. The first is that current adaptive strategies have not been evaluated scientifically, creating a need to monitor these long-term with farmers. The second is the lack of a link between farmers and national weather services. Participatory research and collaboration between farmers and the climate community can contribute to build the human, social and political capitals to support a network that focuses on the process of developing knowledge for adaptation. Adaptive capacity in this context will entail connecting institutions, building networks, and negotiating local and new knowledge to deal with uncertainty and inform strategies that build the capacity to adapt.

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