Projecting rainfall changes over the South American Altiplano

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Abstract

Consistent with its high elevation (>4000 m) and subtropical location (15-25°S), the central Andes are expected to become warmer during the 21st century, affecting the population, ecosystems and glaciers on the so-called South American Altiplano. Future changes in regional precipitation (even their sign) have been more difficult to estimate, partly because of the low-resolution of current global climate models (GCMs) relative to the cross-mountain scale of the Andes. Nevertheless, summer-season rainfall over the Altiplano exhibits a strong dependence on the magnitude of the zonal flow in the free troposphere, as quantified in this work using station data. Since GCMs indicate a consistent increase in westerly flow over the central Andes, hindering moisture transport from the interior of the continent, a simple regression analysis suggests a significant reduction (10-30%) in Altiplano precipitation by the end of this century under moderate to strong greenhouse gases emission scenarios.
1. Introduction

The South American Altiplano is a closed, high-level plateau (~ 4000 m ASL) located in the central Andes between 15°S and 22°S. Bordered to the west by the Peru-Chile coastal desert and to the east by the humid Bolivian lowlands, the Altiplano exhibits a semiarid climate (Aceituno 1993; Garreaud et al. 2003), with annual mean precipitation ranging from about 600 mm in the northeast to <200 mm in the southwest. Most of the precipitation (>70%) occurs during austral summer (DJF, Fig. 1a) when mid- and upper-level easterly wind brings moist air that feed convective storms over the plateau (Garreaud 1999; Falvey and Garreaud 2005). Summer precipitation exhibits significant synoptic variability, largely explained by the local boundary layer moisture and zonal wind aloft (Garreaud 2001). The rest of the year the Altiplano is influenced by mid-level westerly flow that brings very dry air from the Pacific and precipitation events are nearly nonexistent (Vuille and Ammann 1997). At interannual timescales, there is a tendency for more (less) basin-wide precipitation during La Niña (El Niño) years that is also largely explained by the intensity of the zonal flow aloft (Garreaud and Aceituno 2001; Vuille and Keimig 2004).

Given its semiarid climate and strong seasonality, future changes in summer precipitation and temperature over the Altiplano will affect water availability for human consumption, agriculture, glaciers and ecosystems (e.g., Bradley et al. 2006). GCM-based projections of climate change during the 21st century under the A2 scenario consistently show a free-tropospheric warming as high as +5°C over the central Andes (Bradley et al. 2006), and a regional climate simulation (RCM) indicates a similar increase in surface air temperature...
(Urrutia and Vuille 2009). In contrast, expected changes in central Andes precipitation remain poorly determined in the CMIP3 GCMs runs (Christensen et al. 2007). Seth et al. (2010) and Thibeault et al. (2010) examined nine GCMs over the central Andes and found a tendency for a slight increase in precipitation during the rainy season and a slight decrease during the early season. In contrast, the RCM results by Urrutia and Vuille (2009) imply a decrease in summer precipitation over the central Andes south of 12°S.

To further illustrate the uncertainty in projections of precipitation, the vertical axis in Fig. 2 shows the rainfall change ($\Delta P$) between the end of the century (2070-2099) under the A2 scenario and the baseline period (1970-1999) for 11 GCMs used in the IPCC-AR4 (see details in Table 1). Considering the Altiplano$^2$ as the grid boxes with elevation >3000 m between 10° and 25°S, we calculated the area average and range (max-min) of the $\Delta P$ for each model. There is significant dispersion in the magnitude and even the sign of $\Delta P$. Five models indicate an increase in precipitation and five a decrease, resulting in an insignificant multimodel mean change of 1 mm/month.

The lack of a robust trend in regional precipitation severely limits our capacity to foresee environmental changes over the Altiplano. To advance this issue, here we exploit the observed relationship between zonal wind aloft—a large-scale variable more reliable in GCMs— and Altiplano precipitation. Granted, this approach only allows us projecting precipitation changes that are congruent with changes in zonal flow, but given the strong coupling between these two fields over much of the Altiplano we argue that such signal is a significant fraction of the total change.

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$^2$ Because of their coarse resolution, some of the CMIP3 GCMs do not have terrain elevation above 3000 m ASL in the central Andes and were not considered in our analysis.
2. **Zonal wind - precipitation relationship**

The relationship between zonal wind aloft and precipitation over the Altiplano (easterly-wet / westerly-dry) holds at synoptic, seasonal and interannual time-scales. This relationship has mostly been derived using proxy data such as cold cloud fraction (Vuille and Keimig 2004), outgoing longwave radiation (Garreaud and Aceituno 2001), glacier mass balance (Francou et al., 2003; Vuille et al. 2008), or very limited rainfall records (Falvey and Garreaud 2005). To our knowledge, however, only one study of Vuille (1999) has used actual precipitation observations from 6 meteorological stations over the Plateau. Here we use monthly rainfall records from 108 stations in the central Andes above 3500 m (Fig. 2) from 1948 to 2007 (variable record length but at least 10 years worth of data) from the Global Historical Climate Network (GHNC version 2; Vose et al. 1992). Large-scale circulation was characterized using the NCEP-NCAR reanalysis from 1948 onwards (Kalnay et al. 1996).

Figure 1b shows the correlation between monthly (December, January and February) zonal wind at the 200 hPa level ($U_{200}$) in a grid box centered over the Altiplano (17.5°S-70°W) and concurrent rainfall at each station. The result appears robust as the whole 108 stations exhibit negative $P - U_{200}$ correlation, 88% of them significant at the 95% confidence level, including stations located within the Plateau and farther north over the tropical Andes. The $P - U_{200}$ correlations are largest ($r^2 \sim 0.6$) along the western (dry) side of the Altiplano and decrease towards the eastern (humid) side. Because of the spatial coherence of the zonal wind field over the central Andes, very similar results are obtained if using $U_{200}$ interpolated to each station coordinates. We also verified that monthly mean values of $U_{200}$ are strongly and negatively correlated with the number of days with
easterly wind (u < 0) during the month, and not much influenced by few days with strong westerly or easterly flow. That explains the much better linear fit between zonal flow aloft and precipitation at monthly (or longer) timescales relative to results using daily values (Garreaud and Seluchi 2003).

3. Projected changes in upper-level winds

Projected changes in zonal wind are now examined using 11 CMIP3 GCMs (Table 1). Unlike precipitation, large-scale circulation is considered a reliable output from current GCMs (Christensen et al. 2007). Here we focus on the wind changes between the last 30 years of the A2 (2070-2099) and 20C3M (1970-1999) scenarios. Figure 3a shows the multimodel summer mean difference in the 200 hPa wind field (ΔUV_{200}) over the South American sector and adjacent oceans. Upper-level westerly flow becomes stronger (ΔU_{200} > 0) in two zonally elongated bands: one at subtropical latitudes (10-30°S) and the other at high latitudes (poleward of 50°S). In between (~ 40°S) the westerlies slightly decrease in the future. Overall, no significant changes in the meridional flow or in the strength or position of the Bolivian high are apparent. The isobaric map is complemented by the latitude-pressure cross section of zonal wind differences at 70°W shown in Fig. 3b. Weakening (strengthening) of the tropospheric westerlies at midlatitudes (high latitudes) is consistent with the projected poleward shift of the SH storm track in a warmer world (Yin 2005). Near and above the tropopause, however, the westerlies increase at midlatitudes and a tongue of ΔU_{200} > 0 extends downward into the troposphere at subtropical latitudes, causing anomalous westerly winds over the central Andes at upper and middle levels. Easterly winds are expected to intensify only above the equatorial Andes.
The multimodel mean difference in zonal flow over the Altiplano is not too large ($\Delta U_{200} \sim +1-3 \text{ m s}^{-1}$) but it is superimposed on a weak baseline easterly flow. The summer mean “divide” between mid-level easterly and westerly flow (i.e., the $U = 0 \text{ m s}^{-1}$ contour in Fig. 3b) is at 20°S in current climate but it could move as far north as 10°S by the end of the century in scenario A2. To gauge the consistency of the zonal wind differences over the Altiplano, let us look again at Fig. 2 whose horizontal axis shows, for each model, $\Delta U_{200}$ interpolated to 17.5°S, 70°W. In contrast to $\Delta P$, all the models predict enhanced westerlies (or decreased easterlies) with a significant multimodel mean of $\Delta U_{200} = 2.5 \text{ m s}^{-1}$. The weakening of the easterly flow over the Altiplano during the 21st century is also found in more benign emission scenarios, with multimodel mean $\Delta U_{200}$ of 1.6 and 2.3 m s$^{-1}$ for B1 and A1B, respectively. We also verified (in 7 of the 11 GCMs with daily data) that the enhanced summer-mean westerlies in the future are associated with a decrease in the number of days with easterly wind.

The summertime enhanced westerlies at subtropical latitudes and the retraction of the easterlies into lower latitudes set the stage for drier than current conditions across much of the central Andes. What is the prospect for a shift in precipitation seasonality? To answer this question, we examined the multimodel mean annual cycle of $U_{200}$ over the Altiplano calculated for the current and future climate (not shown). The westerly component becomes stronger year round (but for a weak easterly difference in May-June) with the largest differences in summer. Indeed, the narrow window of time when $U_{200} < 0$ in current climate (DJF) is absent in the future simulation that exhibits monthly mean westerly winds over the Altiplano year round. That suggests a shortening and weakening of the rainy season instead of a shift.
4. Projected changes in precipitation

We now estimate at each station \(i\) the wind-driven change in summer precipitation as
\[
\Delta P_i^* = \beta_i \Delta U_{200},
\]
where \(\Delta U_{200}\) is the multimodel mean interpolated at 17.5°S-70°W and
\[
\beta_i = r(P_i, U_{200}) \sigma(P_i)/\sigma(U_{200})
\]
is the slope of the linear fit calculated using the observations in section 2. The results are shown in terms of absolute change (\(\Delta P_i^*\), Fig. 1c) and the difference relative to the current climatology (\(100 \times \Delta P_i^*/\bar{P}\), Fig. 1d). Other alternatives to calculate \(\Delta P_i^*\) (e.g., using \(\Delta U_{200}\) interpolated to the station coordinates) produce very similar results.

Because of the weaker easterly flow, the central Andes exhibit a decrease in precipitation towards the end of the century that, averaged over all stations, equals 16.5, 15.3 and 10.8 mm/month for the A2, A1B and B1 scenario, respectively. The absolute change in A2 is as large as -30 mm/month along the western and central part of the Altiplano (Fig. 1c) but decreases (< -10 mm/month) on the eastern side where the coupling between \(U_{200}\) and \(P\) is weaker. When considering the relative changes, a north-south gradient is also evident with differences from -10% in the northern sector down to -35% in the south (Fig. 1d).

The decrease in precipitation over the Altiplano obtained from our multi-GCM regression are generally consistent (in sign and magnitude) with the projections by Urrutia and Vuille (2009) based on their single-RCM dynamical downscaling, but do not support the tendency for a more intense rainy season found in the GCM-based analysis by Seth et al. (2010) and Thibeault et al. (2010). We have refrained from calculating precipitation changes in other seasons, because the very low precipitation leads to an insignificant \(P-U_{200}\) relationship. Nevertheless, as discussed before, westerly wind anomalies will prevail
almost year round in the future, increasing the westerly flow from fall to spring, thus hindering any expansion of the rainy season.

Finally, we verified that future climate scenarios satisfy the underlying hypothesis in the P-U\textsubscript{200} relationship, namely, a marked zonal gradient in mid-tropospheric moisture across the central Andes. To this end, Fig. 4 shows the summer mean of the water vapor mixing ratio ($\overline{q}_{600}$) at 600 hPa at 17.5°S over the Pacific ocean (75°W) and the Bolivian lowlands (65°W) for current climate and the A2 scenario. In current climate, almost all models capture the marked moisture gradient between the very dry Pacific sector (~2 g kg\textsuperscript{-1}) and the more humid conditions to the east of the Andes. In the future climate there is a generalized moistening at low-latitudes (e.g., Held and Soden 2006) and the multimodel mean $\overline{q}_{600}$ increases at both sides of the central Andes. Relative to the (simulated) current conditions, the multimodel mean increase is ~1.5 g kg\textsuperscript{-1} over the Bolivian lowlands but only ~0.5 g kg\textsuperscript{-1} over the Pacific sector. More importantly, to the west of the Andes $\overline{q}_{600}$ remains below 3 g kg\textsuperscript{-1} in most of the GCMs, a value below the threshold for moist convection over the Altiplano (Falvey and Garreaud 2005), so the predicted westerly flow will continue hindering precipitation. Although in current climate mid-tropospheric moisture over the lowlands east of the Andes has a slightly significant relationship with Altiplano rainfall in most stations, its effect is conditioned to the occurrence of easterly winds. Thus, the increase in moisture over the continent will hardly attenuate the wind-driven drying trend over the Altiplano.
5. Concluding remarks

The Altiplano region is poorly resolved in current GCMs given their relative coarse resolution relative to the narrow Andes Mountains. Not surprisingly, direct analysis of GCM outputs results in inconsistent, non-significant precipitation changes over the Altiplano, in contrast with a robust warming trend expected for the rest of the 21st century. To circumvent this problem, in this work we exploited a rather strong relationship between mid-tropospheric zonal winds and precipitation over the central Andes to project changes in regional rainfall for the end of the 21st century. In current climate, Altiplano rainfall is largely concentrated in austral summer and an easterly-wet / westerly-dry pattern has been found in synoptic, seasonal and interannual timescales. The relationship was quantified by using more than 100 rain gauges along the central Andes and NCEP reanalysis winds. The linear correlations are largest ($r^2 \approx 0.6$) along the western (dry) side of the Altiplano and decrease eastward towards the more humid side of the Plateau. When examining the projected changes in free-tropospheric wind (a reliable output from GCMs) we found an almost year-round increase in westerly flow at middle- and upper-levels over the central Andes. That results in a decrease of the moisture transport towards the Altiplano from the interior of the continent during summer, reducing the summer precipitation between 10-30% relative to current values. This approach only permits an estimation of the part of the precipitation change due to wind aloft change. However, the GCMs consistency of the $\Delta U_{200}$ sign and the strong relationship observed with wind and precipitation in current climate indicate that this wind-driven summer precipitation change is a significant fraction of the total change. The rest of the year the Altiplano would continue as dry as in present conditions, which when
added to the increase in surface air temperature (>3°C) signals a complicated prospect for the water resources in this semiarid region.

Acknowledgements

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References


### Tables

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**TABLE 1**: CMIP3 GCMs used in this study: modeling center, official name, mean horizontal resolution of the atmospheric component, number of grid points with an altitude higher than 3000m and available type of data.
FIG. 1: (a) DJF observed monthly precipitation mean (mm/month) over 1948-2007. (b) Correlation between monthly (DJF) U_{200} from NCEP-NCAR reanalysis at the 17.5°S-70°W grid point (located by the green square) and observed precipitation at each station for the 1948-2007 period. Circles with yellow outline indicate significant correlations based on t-test at 95%. (c) DJF Wind-driven estimated rainfall change (in mm/month) between the 2070-2099 and 1970-1999 periods (from the A2 and 20C3M simulations) for each station. (d) Same as (c) but relative to the DJF 1970-1999 observed monthly mean precipitation. Thin black line indicates the 4000 m topographic contour.
FIG. 2: Scatter-plot of the summer (DJF) mean ΔP (in mm/day) and ΔU_{200} (in m/s) between the 2070-2099 and 1970-1999 periods from the A2 and 20C3M simulations, for 11 GCMs considered in this study (Table 1). The black filled circle is the multi-model mean. ΔP mean is calculated only averaging the model grid points in the (10°S-25°S)/(62°W-77°W) region with an elevation higher than 3000m. Vertical lines represent the min/max ΔP over these grid points. ΔU_{200} is calculated at the grid point nearest of 17.5°S-70°W. Horizontal lines indicate min-max ΔU_{200} at 70°W over the (10°S-24°S) section.
FIG. 3: (a) Multimodel mean difference of summer (DJF) wind at 200 hPa between the 2070-2099 and 1970-1999 periods from the A2 and 20C3M simulations. (b) Black contours indicate the DJF zonal wind multimodel mean (in m s$^{-1}$) over the 1970-1999 period. In colors, multimodel mean difference (in m s$^{-1}$) of summer DJF U$_{200}$ across the 70°W section between the 2070-2099 and 1970-1999 periods from the A2 and 20C3M simulations. In (a) and (b), green point indicates the location of the 17.5°S-70°W reference point. Little black points indicate where more than 9 models agree on the sign of the difference.
FIG. 4: Summer (DJF) mean of the water vapor mixing ratio (in g/kg) at 600 hPa at 17.5°S over the Pacific ocean (75°W) and the Bolivian lowlands (65°W) for current observed climate (OBS), current simulated climate (20C3M) and the A2 scenario (SRESA2). For observed climate, grey closed circles are the DJF mean from NCEP/NCAR reanalysis, with the interannual standard deviation represented by the horizontal bars. Open circles are median values from few radiosonde data (Falvey and Garreaud; 2005). For 20C3M and A2 scenario, filled circles are the multimodel DJF mean over the 1970-1999 and 2070-2099 periods respectively, and each vertical bar represents one of the 11 GCMs used in this work (Table 1).