Climate Variability and Trends in Bolivia

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ABSTRACT
Climate-related disasters in Bolivia are frequent, severe, and manifold and affect large parts of the population, economy, and ecosystems. Potentially amplified through climate change, natural hazards are of growing concern. To better understand these events, homogenized daily observations of temperature (29 stations) and precipitation (68 stations) from 1960 to 2009 were analyzed in this study. The impact of the positive (+) and negative (−) phases of the three climate modes (i) Pacific decadal oscillation (PDO), (ii) El Niño–Southern Oscillation (ENSO) with El Niño (EN) and La Niña (LN) events, and (iii) Antarctic Oscillation (AAO) were assessed. Temperatures were found to be higher during PDO(+), EN, and AAO(+) in the Andes. Total amounts of rainfall, as well as the number of extreme events, were higher during PDO(+), EN, and LN in the lowlands. During austral summer [December–February (DJF)], EN led to drier conditions in the Andes with more variable precipitation. Temperatures increased at a rate of 0.1°C per decade, with stronger increases in the Andes and in the dry season. Rainfall totals increased from 1965 to 1984 [12% in DJF and 18% in June–August (JJA)] and decreased afterward (−4% in DJF and −10% in JJA), following roughly the pattern of PDO. Trends of climate extremes generally corresponded to trends of climate means. Findings suggest that Bolivia’s climate will be warmer and drier than average in the near-term future. Having entered PDO(−) in 2007, droughts and LN-related floods can be expected in the lowlands, while increasing temperatures suggest higher risks of drought in the Andes.

1. Introduction
Climate variability impacts human and natural systems in Bolivia mainly through floods and droughts, with single El Niño (EN) and La Niña (LN) events affecting thousands of people and leading to economic losses of millions of U.S. dollars (USD). The EN events of 1982/83 and 1997/98 and LN events of 2007/08 affected about 1.6 million, 135,000, and 619,000 people with economic losses of about 837,515, and 758 million USD, respectively (UNDP 2011). Climate change may alter the frequency and intensity of such natural hazards (Field et al. 2012). The Plurinational State of Bolivia, a developing country with one-third of the labor force working in the agricultural sector (www.ine.gob.bo), is considered to be extremely vulnerable to climate change (World Bank 2011). Bolivia’s disaster deficit index (DDI) (the ratio of the potential economic loss caused by a natural disaster to the country’s economic resilience) is estimated at 1.47, expressing the country’s inability to cope with extreme disasters (Cardona and Carreño 2010). Understanding the country’s climate variability is therefore of great national interest.

Important sources of climate variability in South America include the Pacific decadal oscillation (PDO;
Mantua et al. 1997), El Niño-Southern Oscillation (ENSO; Smith and Sardeshmukh 2000), and the Antarctic Oscillation (AAO; Thompson and Wallace 2000; Garreaud et al. 2009). PDO is the leading principal component of monthly sea surface temperature anomalies in the Pacific Ocean north of 20°N and exhibits a decadal oscillation between warm [PDO(+)] and cold [PDO(−)] phases. ENSO is a coupled oceanic and atmospheric oscillation of the equatorial Pacific switching between warm (EN) and cold phases (LN) with an irregular oscillation ranging from 2 to 7 years. An AAO is defined as the leading principal component of 850-hPa geopotential height anomalies south of 20°S. PDO, ENSO, and AAO are associated with the following temperature and precipitation anomalies in South America. Garreaud et al. (2009) found positive correlations between surface air temperature and PDO and ENSO in many parts of South America, including Bolivia, with highest correlations in the Andes. Regarding rainfall, the same study shows negative (positive) correlations of rainfall anomalies and PDO in some parts of South America, mainly north (south) of about 10°S. Negative correlations between ENSO and rainfall exist in December–February (DJF) in the Bolivian Andes and positive correlations in June–August (JJA) in the Bolivian lowlands. Ronchail and Gallaire (2006) found negative (positive) precipitation anomalies during EN (LN) events in the Altiplano, confirming previous studies (e.g., Vuille et al. 2000). ENSO-related anomalies are associated with the strength and position of the Bolivian high (see also section 2) (Vuille 1999; SENAMHI 2009). Regarding the AAO, the associated precipitation anomalies are strongest in southern Chile and along South America’s subtropical east coast (Garreaud et al. 2009).

Along climate variability, long-term climate trends have been detected in South America. In the tropical Andes, mean surface air temperatures have increased from 1950 to 1994 by 0.15°C per decade (Vuille et al. 2003). The same study found no clear pattern on trends in annually accumulated rainfall. Espinoza Villar et al. (2009) found a negative trend in rainfall in the Amazon basin (756 stations) with an annual rate of −0.32% during 1975–2003. Break tests showed that this decrease has been particularly important since 1982. Ronchail (1995) found a positive precipitation trend throughout Bolivia (29 stations) from the mid-1960s until the end of the series in 1984. A similar trend was found in the southern Amazon of Brazil (86 stations) by Marengo et al. (2004) with a positive trend from the mid-1960s until about 1990. Marengo et al. (2004) associates the shift from negative to positive anomalies in the 1970s with the switch from the cold to the warm PDO phase in 1976/77. Toledo (2010) found a negative precipitation trend from 1982 to 2007 in Bolivia’s northern lowlands (20 stations). In the Bolivian Altiplano, Seth et al. (2010) detected a negative precipitation trend for the months September to November and a positive trend for January to March from 1960 to 2008 (3 stations); however, neither trend was statistically significant. Regarding climate extremes, numerous studies have detected significant increases in extreme temperature events, consistent with a warmer climate in South America (e.g., Vincent et al. 2005; Alexander et al. 2006; Seth et al. 2010; Thibeault et al. 2010; Marengo et al. 2011). The overall confidence in these trends however is estimated to range from low to medium, due to insufficient evidence or spatial variations in many regions (Field et al. 2012, Table 2.3).

Previous research on observed climate variability and trends listed above is of varying spatial scale and frequently included only very few Bolivian stations. The lack of spatial and temporal detail makes it difficult to apply this information to Bolivia, given the country’s heterogenic topography. This motivated us to analyze climate variability and trends of temperature and precipitation means and extremes from a large number of Bolivian stations, distinguishing among seasons and climatologically contrasting regions. Our analysis aims for a better understanding of historic climate variability and trends, knowledge that in turn can be used for disaster risk reduction, as well as to aid adaptation to, and further research on regional climate change in Bolivia.

The following sections describe our study area, methods, results, and discussion. The method section outlines the data and theory of our approach, describing data homogenization, analysis of variance, and trends. The results section quantifies climate variability and trends of means and extremes. Our discussion interprets the results in the context of existing literature and elaborates on the principal findings.

2. Study area

Bolivia is a tropical country measuring more than one million km² (Fig. 1a). Its main altitudinal divisions are lowlands (<800 m MSL), Andean slopes (800–3200 m MSL), and highlands (Altiplano; >3200–6500 m MSL). Temperature and precipitation gradients lead to the formation of contrasting vegetation zones, including Amazonian rain forest in the northern lowlands, dry deciduous forest (Chiquitania and Chaco) in the southern lowlands, and alpine grasslands in the Altiplano (Fig. 1b).

Temperatures decrease with altitude, with annual mean maximum temperatures ranging from 32°C in the lowlands to 16°C in the highlands (Altiplano) (Figs. 1d,e). The number of warm days (see Tables A1 and A2 for...
FIG. 1. (a) Location of Bolivia; (b) vegetation zones with 1) Amazonian rain forest, 2) cloud forest (Yungas), 3) dry forest (Chiquitania), 4) Chaco, 5) savannahs, 6) Pantanal, 7) Andean valleys with Tucumano forest, and 8) Altiplano with mountain ranges (Navarro and Ferreira 2004); (c) location of regions NLL, SLL, NAS, SAS, and AP; monthly mean maximum temperature (°C) in (d) DJF with locations of 29 meteorological stations and (e) JJA; (f) warm-spell duration (days); monthly mean precipitation (mm month$^{-1}$) in (g) DJF with locations of 68 meteorological stations and (h) JJA; (i) annual precipitation (mm yr$^{-1}$); (j) consecutive dry days (days); (k) consecutive wet days (days); (i) rainfall intensity [mm (wet days)$^{-1}$]. Climate indices are defined in Tables A1 and A2.
level jet (LLJ) located at about 925–850 hPa (ward from the Amazon to subtropical plains by a low-
Deflected by the Andes, moisture is transported south-
high, Bolivian high, LLJ, and SACZ together form the
formation of the upper-level Bolivian high at 200 hPa
heat over the Amazon and Andean slopes leads to the
(SACZ). Simultaneously, the release of condensational
a southeastward extension toward the Atlantic Ocean,
level, 100 000–150 000 km2 from January to March in the lowland savannas with
corresponding to patterns of yearly rainfall.
these climate patterns are shaped by the following
synoptic-scale systems. In austral summer (DJF) a low
pressure system called Chaco low intensifies at 25
2010). These climate patterns are shaped by the following
southern Andean slopes, and 4 (20) in the Altiplano.
2 (9) in the northern Andean slopes, 10 (15) in the
northern lowlands, 2 (4) in the southern lowlands,
250 to
winter (JJA) coincide with the wet and dry season, re-
SACZ weaken, leading to less moisture transport from
main components of the South American monsoon
system (SAMS) (Zhou and Lau 1998), affecting rainfall
in DJF. In austral winter (JJA), the Chaco low and the
southern Andean slopes, northern lowlands, southern
lowlands, northern Andean slopes to the Altiplano and
ranges from <250 to >2000 mm yr−1 (Fig. 1i). Much
higher values (>5000 mm yr−1) along the northern An-
dean slopes are documented by Bolivia’s National Ser-
vice of Meteorology and Hydrology (SENAMHI 2009)
from stations not included in this research. Seasonal
rainfall ranges from 50 to 250 mm month−1 and from 0 to
60 mm month−1 in DJF and JJA, respectively (Figs. 1g,h).
Consecutive dry days increase from the lowlands to the
Altiplano, ranging from less than 1 month in the north-
westerly winds prevail in Bolivia, preventing moisture transport from
the lowlands to the Andes in JJA (Vuille 1999).

3. Methods

a. Data

Our data consisted of meteorological observations,
reanalysis data, and indices from various climate modes
(PDO, ENSO, AAO, and others). From a total of 108
meteorological stations provided by SENAMHI we se-
lected all stations that covered at least 30 years with
less than 25% of missing data. We made one exception
to the rule for a station with 29 years of data in a region
with low station density. We tested all stations for ho-
mogeneity and excluded all stations with more than five
changepoints within 30 years (see also section 3b on data
homogenization). This left us with 29 and 68 stations of
daily temperature (minimum and maximum) and pre-
cipitation measurements, respectively (Figs. 1d,g). Tem-
perature (precipitation) was measured by 11 (20) stations
in the northern lowlands, 2 (4) in the southern lowlands,
2 (9) in the northern Andean slopes, 10 (15) in the
southern Andean slopes, and 4 (20) in the Altiplano.
Observation periods varied among stations, ranging
from 29 to 94 years. On average, observations lasted
from 1960 to 2009, covering 50 years with less than 8% missing data.

Vertically integrated moisture flux convergence (VIMFC) (kg m−1 s−1) was calculated from surface
pressure and 3D fields of specific humidity and zonal and
meridional components of wind speed from the National
Centers for Environmental Prediction–National Center
for Atmospheric Research (NCEP–NCAR) reanalysis
dataset (2.5° × 2.5°) (Kalnay et al. 1996):

\[
\text{VIMFC} = \frac{1}{g} \int_{300hPa}^{1000hPa} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dp,
\]

where \( q \) is the specific humidity (kg H2O kg−1), \( p \) is the
pressure (Pa), \( u \) and \( v \) are the zonal and meridional
component of wind speed (m s−1), and \( g \) is the gravita-
tional acceleration (m s−2) (Zomeren and Delden 2007).
From the numerous PDO indices available, we used the index from Zhang et al. (1997) with an updated version available at http://jisao.washington.edu/pdo/ (Fig. 2). The ENSO index was obtained from Smith and Sardeshmukh (2000) with an updated version available at www.esrl.noaa.gov/psd/enso. This ENSO index identified EN and LN events for months when both the SST and Southern Oscillation index (SOI) exceeded the 20th percentile. Most EN events occurred during PDO(+), whereas all LN events during PDO(−). From 1960 to 2009, there were a total of 7 EN events and 5 LN events. The AAO index was obtained from Thompson and Wallace (2000) with an updated version available at www.jisao.washington.edu/aao/. In addition to PDO, ENSO and AAO we also looked at numerous other climate modes, including the Atlantic multidecadal oscillation (AMO; Enfield et al. 2001), as well as the Atlantic and Pacific Meridional Mode (AMM and PMM, respectively; Chiang and Vimont 2004), all available at www.esrl.noaa.gov/psd/data/climateindices/list/. However, AMO, AMM, and PMM had no significant impact on climate variability in Bolivia and are therefore not presented in the results section.

b. Data homogenization

Prior to data homogenization, all values were converted to missing values if precipitation was negative, and if daily minimum temperature exceeded daily maximum temperature. In case of the latter, both minimum and maximum values were set to missing values. The data were then homogenized by detecting and adjusting for multiple changepoints, using the software RHtestV3 (http://www.clivar.org/organization/etccdi/etccdi.php). Changepoints not related to climate processes can be introduced by changes in measurement instruments, measurement location, or measurement procedures. Adjusting for changepoints homogenizes the data such that temporal variations are assumed to be caused by climate processes only. There are three fundamental differences between the nature of temperature and precipitation series. Temperature series have a more Gaussian-like distribution, may contain negative and positive values, and are continuous. Precipitation series do not have a Gaussian distribution, only contain nonnegative values, and are not continuous. Given these differences, methods for changepoint detection and adjustment slightly differ for temperature and precipitation series. However, in both cases, changepoint detection is based on the two-phase regression model (Wang 2003). Here, a time series is divided into segments, and a linear regression is fitted to each segment:

\[ X_t = \begin{cases} \mu_1 + \beta_1 t + \epsilon_t, & 1 \leq t \leq c \\ \mu_2 + \beta_2 t + \epsilon_t, & c < t \leq n \end{cases} \]

where \( \{X_t, i = 1, \ldots, N\} \) is a data series observed at times \( t_1 < \ldots < t_c < \ldots < t_n \), and \( \{\epsilon_t\} \) is the zero-mean independent random error with a constant variance. Changepoints occur when the mean (step type) and/or the slope (trend type) among segments changes. Thus, the time \( c \) is a changepoint if \( \mu_1 \neq \mu_2 \) (step type) and/or if \( \beta_1 \neq \beta_2 \) (trend type). In the case of temperature,
a penalized maximal $t$ and $F$ test identify $c$ and test for its statistical significance (Wang 2008). In the case of precipitation, $c$ is identified and tested for statistical significance with two maximal $F$ tests (Wang et al. 2010). Changepoints were adjusted with the quantile-matching (QM) adjustment (Wang et al. 2010). This approach homogenizes the data by adjusting the series in such a way that the empirical distributions of all segments of the detrended series match each other. Series are detrended by subtracting the estimated linear trend component from the series. This detrended series is then used to develop empirical cumulative distribution functions (ECDF) for each segment of the base series, and to define the adjustments needed to make the base series homogeneous. Regarding precipitation, it is necessary to model the event occurrence and the non-zero amounts separately. Days without precipitation are not altered. To promote a high quality level, we excluded all stations with more than five changepoints within 30 years. The impact of homogenization was assessed by comparing trends from 2 datasets, one where homogenization was applied to all stations with changepoints, and the other where homogenization was not applied. In theory, homogenization should eliminate all artificial trends. In practice however, homogenization may (i) not change a trend, (ii) eliminate a trend, (iii) introduce a trend, or (iv) change the direction of a trend. We considered homogenization to be successful for cases (i) and (ii) and not successful for cases (iii) and (iv). Since trend detection varied among indices, we chose two indices that indicated whether homogenization was successful or not. We chose the two basic and straightforward indices of total annual precipitation (prcptot) and monthly maximum temperature (txx). We then built a final database that consisted of stations with homogenized time series for which homogenization was successful and stations with nonhomogenized time series for which changepoints were absent or homogenization was unsuccessful. This conservative approach avoided many questionable impacts of homogenization, without having to reduce the number of stations.

### Table 1. Number of all stations (Total), stations without changepoints (No CPs), not homogenized stations despite the existence of changepoints (NH despite CPs), and homogenized stations (Homogenized) for maximum temperature (Tmax), minimum temperature (Tmin), and precipitation (Prec).

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>No CPs</th>
<th>NH despite CPs</th>
<th>Homogenized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax</td>
<td>29</td>
<td>11</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Tmin</td>
<td>29</td>
<td>4</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>Prec</td>
<td>68</td>
<td>21</td>
<td>21</td>
<td>26</td>
</tr>
</tbody>
</table>

![Figure 4](image-url)
The RHtest revealed that the majority of time series did contain changepoints. According to this test, only 11 maximum and 4 minimum temperature time series (38% and 14% of stations) and 21 precipitation time series (31% of stations) were assessed to be homogeneous (Fig. 3). About half of the temperature and 93% of the precipitation time series exhibited no more than two changepoints per 30 years. In most cases, homogenization did not introduce or change the sign of a trend of the time series. This did occur though for 6 temperature and 21 precipitation time series (21% and 31% of stations) (Table 1). The homogenization from these stations was rejected and the not-homogenized time series were used for further analysis instead. Some temperature time series included more than five changepoints per 30 years. These stations were retained for further analysis if their corresponding minimum or maximum temperature series did not exceed five changepoints per 30 years.

c. Climate means and extremes

Monthly and annual values of climate means and extremes were calculated from daily data applying the following decision rules. Monthly values were calculated if no more than 3 days were missing in a month, while annual values were calculated if no more than 15 days were missing in a year. No annual value was calculated if any one month’s data was missing. Regarding climate extremes, we calculated 27 indices defined by the Expert Team on Climate Change Detection and Indices (http://www.clivar.org/organization/etccdi/etccdi.php). Indices can be grouped into five categories: absolute indices, threshold indices, percentile-based indices, duration indices and others. There were 17 indices related to temperature and 10 to precipitation. (Names, definitions and example values of indices are provided in Tables A1 and A2 in the appendix.) Some threshold indices (e.g., summer days) were initially designed for temperate climates. Such indices were nevertheless useful in higher (colder) and in drier regions of Bolivia. We included one user-defined threshold index more suitable for the tropics, namely the annual count of days with maximum temperatures exceeding 30°C (su30). Climate indices were computed with the software RClimDex (http://www.clivar.org/organization/etccdi/etccdi.php).

d. Variability

We quantified the impacts of the PDO, ENSO, and AAO on anomalies of climate means and extremes for five climatologically contrasting regions, namely the northern lowlands (NLL) and southern lowlands (SLL) (<800 m MSL), northern Andean slopes (NAS) and southern Andean slopes (SAS) (800–3200 m MSL) and Altiplano (AP) (>3200–6500 m MSL). The north–south division was defined at 18°S, roughly distinguishing between a wet northern and a dry southern part. We applied an analysis of variance (ANOVA) to the station data, declaring PDO phases, ENSO phases, AAO phases, regions, and seasons as treatments. Impacts were expressed as differences in the mean and the corresponding confidence interval. The statistical significance of changes in the mean was verified using a t test and a significance level of 5%. Following the approach from Silva et al. (2011), we accounted for the impacts of the warm and cold phases of PDO on ENSO as follows. If the EN year occurred during PDO(+) [PDO(−)], the anomalies were
calculated by subtracting the mean value of neutral years during the PDO(+) [PDO(−)] from the value of the particular EN month. In case of LN, all events occurred during PDO(−). Thus, LN anomalies were calculated by subtracting the mean value of neutral years during the PDO(−) from the value of the particular LN month. We classified a year as an EN or LN year if the EN or LN event occurred either during December, January, or February.

e. Trends

First we determined appropriate periods for trends in climate means. For this purpose we calculated the standardized anomalies (i.e., anomalies divided by the standard deviation) of monthly temperature and precipitation from all stations from 1960 until 2009. We computed the monthly mean of these anomalies across all stations, checked that the data were normally distributed, and detected the optimal positioning and number of changepoints that marked a shift in the mean, using the Segment Neighborhood method (Auger and Lawrence 1989). We then smoothed the data applying a locally weighted polynomial regression (LOESS; Cleveland and Devlin 1988) and tested the robustness of the changepoints and of the shape of smoothed curve by excluding stations. Appropriate periods for calculating trends were then identified from minima and maxima of the smoothed curve and from the changepoints of the standardized anomalies. Periods contained one changepoint and started and ended with a minimum and maximum (or vice versa) of the smoothed curve. In addition, we calculated standardized anomalies from 1944 to 2010 for a subset of 10 rainfall time series that were assessed to be homogeneous using the RHTest and that exceeded 60 years of data. These stations were distributed throughout Bolivia and included Cochabamba, Concepción, La Paz, Magdalena, Potosí, Roboré, San Borja, San Calixto, Sucre, and Trinidad.

Trends were calculated for each station separately (confidence intervals in Figs. 4 and 7) and for spatially interpolated values (maps in Figs. 6 and 11), applying a linear regression analysis with the least squares approach and tested for significance using the Mann–Kendall trend test (Mann 1945). The spatial interpolation was achieved with the Cressman function (Cressman 1959) and accounted for the orographic effects on temperature by bringing actual temperatures down to sea level before, and back to real height after the interpolation. For this we used a local lapse rate of \(-3.4^{\circ}\text{C km}^{-1}\) \(R^2 = 0.9\) derived from our data of monthly mean maximum temperature, as well as station heights and a digital elevation model.

Regarding climate extremes, trends of all indices were computed for the whole time series of each individual station, as well as for two contrasting precipitation subperiods for selected indices [very wet days (r95p), rainfall intensity (sdii), consecutive dry days (cdd), and consecutive wet days (cwd)]. As for climate means, trends were calculated with a linear regression analysis using the least squares approach and tested for significance using the Mann–Kendall trend test (Mann 1945). The more the stations agreed on a trend, the more likely this trend was due to a general trend and not due to any site specific disturbance. We considered an index to show a clear signal if more than one-third of all stations detected either significant increasing or decreasing values and if more than 75% agreed on the direction of change. We applied this rule to Bolivia as a whole and to the three regions of lowlands, Andean slopes, and Altiplano.
4. Results

a. Climate means

1) TEMPERATURE

Impacts of climate modes were assessed by comparing positive against negative phases of PDO and AAO, as well as ENSO events against neutral years. In DJF, temperatures were generally warmer in the Andes during PDO(+) and AAO(+) with significant changes as big as 1.1°C (Fig. 4). In JJA, temperatures were higher in the Andes during PDO(+) and AAO(+) and lower in the northern lowlands during EN and southern lowlands during AAO(+) (Table 2).

Standardized temperature anomalies showed an overall increasing trend with a changepoint located in 1986/87, coinciding with an EN event (Fig. 5). A smoothed curve revealed a steady increase of temperature between 1965 and 2004 and short-term negative trends during 5 years before and after this period. The increase of standardized temperature anomalies from 1965 to 2004 was statistically significant (Mann–Kendall trend test with $p < 0.05$), with most stations having detected a temperature increase of 0.18°C per decade, corresponding to an overall increase of 0.48°C from 1965 to 2004.

About half of the stations detected significant increases in temperature (17 stations in DJF and 14 stations in JJA). No significant changes were detected by 10 and 13

FIG. 7. Differences in (a) annual precipitation anomalies (mm yr$^{-1}$) and monthly precipitation anomalies (mm month$^{-1}$) of (b) DJF and (c) JJA, comparing PDO(+) to PDO(−), El Niño events to neutral years, La Niña events to neutral years, and AAO(+) to AAO(−) for NLL, SLL, NAS, SAS, and AP. Dots present the difference of the means, while the bars show the respective confidence intervals with a probability of 95%. Black dots denote statistically significant changes with a significance level of 5% (t test).
stations during DJF and JJA, respectively. Highest trends were detected during JJA in the Andes (Fig. 6). Some cooling has also occurred in this season close to the Titicaca Lake.

2) PRECIPITATION

Annual rainfall was higher in the lowlands during PDO(+) (196 mm yr\(^{-1}\)), EN (105 mm yr\(^{-1}\)), and LN (143 mm yr\(^{-1}\)) (Fig. 7). In DJF, rainfall was higher in the lowlands during PDO(+) (35 mm month\(^{-1}\)) and LN (36 mm month\(^{-1}\)) and lower during EN in the Andes (-26 mm month\(^{-1}\)). In JJA, rainfall in the northern lowlands was higher during EN (15 mm month\(^{-1}\)) and lower during AAO(+) (-10 mm month\(^{-1}\)). PDO- and ENSO-related rainfall anomalies in DJF were accompanied by corresponding changes in moisture convergence (Fig. 8). In the southern lowlands, moisture convergence anomalies during PDO(+) opposed observations, but were not statistically significant.

Monthly standardized precipitation anomalies showed oscillating trends with changepoints located in 1972 and 1988, the first one just before and the second just after an EN event (Fig. 9a). The smoothed curve revealed an increasing trend from about 1965 until 1984 and a decreasing trend from about 1985 until 2004. The increase and decrease of standardized precipitation anomalies from these two periods were both statistically significant (Mann–Kendall trend test with \( p < 0.05 \)). Standardized anomalies from 10 homogenous (RHtest) stations and >60 years of data revealed a similar pattern.
Here, however, the negative trend that started around 1985, continued until the end of the time series in 2010 (Fig. 9b). The LOESS curve remained below 0 throughout 1944 until 1972 with a minimum located around 1965. Annual standardized precipitation anomalies revealed a very similar pattern, following the basic structure of the PDO index (Fig. 10).

Most stations detected an increase in precipitation from 1965 to 1984 by 12% in DJF and 18% in JJA and from 1984 to 2004 by 24% in DJF and 210% in JJA (Table 2). Most stations with significant trends agreed on the sign of the trend. Statistically significant positive (negative) trends were detected by 17 (0) stations in DJF and 9 (1) stations in JJA from 1965 to 1984 and by 1 (11) stations in DJF and 3 (1) stations in JJA from 1985 to 2004 (Table 2). Positive trends during 1965–84 and negative trends during 1985–2004 were most evident in DJF in the lowlands (Fig. 11). In JJA and in the Andes, trends were less uniform. Trends during March to May (MAM) and September to November (SON) were generally increasing from 1965 to 1984 and decreasing from 1985 to 2009 (not shown).

### b. Climate extremes

Temperature-related climate indices revealed a warming trend throughout Bolivia with significantly more warm nights and days (tn90p, tx90p), fewer cool nights and days (tn10p, tx10p), fewer frost days (fd0), longer warm spells (wsdi), more summer days (su25), and higher monthly minimum of daily minimum temperatures (tnn) (Fig. 12). Other significant trends included more tropical nights (tr20) and more days when maximum monthly temperatures were above 30°C (su30) in the lowlands. Furthermore, we detected a longer growing season (gsl), higher monthly maximum and minimum temperatures (ttx, tnx), and a shorter duration of cold spells (csdi) in the Altiplano. Given the oscillating trend in rainfall, only two indices showed a coherent pattern, with an increase in cwd and a decrease in sdii in the lowlands.

Extreme precipitation events differed significantly among PDO, ENSO, and AAO phases. PDO(+) led to more intense or more frequent r95p in the northern and southern lowlands, more frequent cwd in the northern lowlands, and higher sdii in the southern lowlands (Table 3). EN led to less cdd and cwd in the Altiplano, while LN led to more intense or frequent r95p in the northern lowlands. During AAO(+), consecutive wet days were more frequent in the Altiplano.

Standardized anomalies of selected extreme precipitation events revealed the following trends for 1965–84 and 1985–2009. The r95p and sdii followed the basic pattern of annual precipitation (Fig. 13a). In the case of very wet days, 9 stations detected significant increases from 1965 to 1984 and 6 stations significant decreases from 1985 to 2004, whereas in the case of rainfall intensity, a fairly equal amount of stations detected increases and decreases from 1985 to 2004, whereas in the case of rainfall intensity, a fairly equal amount of stations detected increases and decreases from 1965 to 1984 and 11 stations detected significant decreases from 1985 to 2004 (Table 4). The number of cdd and consecutive wet days also followed the basic pattern of annual precipitation, with generally more (less) cdd (cwd) in years with less rainfall. Consecutive dry days decreased from 1960 until the 1980s and remained relatively constant afterward (Fig. 13b), with 5 stations detecting significantly decreasing trends from 1965 to 1984 and 11 stations detecting significant decreases from 1985 to 2004 (Table 4). The number of cwd, on the other hand, increased from 1965 to 1984 but also remained relatively constant afterward, with 10 stations detecting significantly increasing trends from 1965 to 1984.

### 5. Discussion

We quantified the impacts of PDO, ENSO, and AAO on temperature and precipitation means and extremes and detected trends from 1960 to 2009 in Bolivia, distinguishing among climatologically contrasting regions and seasons. Temperatures were found to be higher during PDO(+), EN, and AAO(+) in the Andes. Total amounts of rainfall, as well as the number of extreme events, were higher during PDO(+), EN, and LN in the lowlands. During austral summer (DJF), EN led to drier conditions in the Andes with more variable precipitation.
Temperatures increased at a rate of 0.1°C per decade, with stronger increases in the Andes and in the dry season. Other climate modes (AMO, AMM, and PMM) revealed no significant impacts on climate variability in Bolivia. Rainfall totals increased from 1965 to 1984 (12% in DJF and 18% in JJA) and decreased afterward (−4% in DJF and −10% in JJA), following roughly the pattern of PDO. Trends of climate extremes generally corresponded to trends of climate means.

These findings are subject to some remaining uncertainties, beyond those quantified, because of the following methodological issues. (i) Stations were not evenly distributed among regions, with low station densities in the southern lowlands and Altiplano. We encourage the installation of additional meteorological stations to better monitor climate variability and trends in these remote areas. (ii) Data homogenization was challenging given that changepoints were not previously documented. Our approach, rejecting data homogenization when it introduced or changed the sign of the direction of a trend, was of a rather practical nature. However, given the strong agreement among stations on the direction of significant trends of temperature and precipitation means, and given that 10 homogenous (RHtest) stations reproduced the same basic patterns in rainfall trends as all stations combined, we are confident in our results. Nevertheless, it would be very beneficial for future research to start documenting any changes in measurement instruments, sites, and procedures. (iii) Our analysis of variance was not able to distinguish between impacts from the PDO, ENSO, AAO, and other sources, including climate change. Thus, part of the temperature differences among PDO and AAO phases was likely due to enhanced greenhouse gases rather than to the climate modes, given that most PDO(−) and AAO(−) years occurred earlier, while most PDO(+) and AAO(+) years later. Thus, the recent switch to PDO(−) in 2007 does not imply that temperatures will return to the values of the previous PDO(−) phase. (iv) Finally, the increasing length of the growing season (gsl) detected in the Altiplano must be interpreted with care. The index assumes that the growing season is limited by temperature only. In the Altiplano however, the growing season is limited by both temperature

![Fig. 11. Trends of monthly precipitation [mm (10 yr)^{-1}] from (a) 1965 to 1984 and (b) 1985 to 2004 in DJF. (c),(d) As in (a) and (b), but for JJA. Black lines encircle areas of statistical significance with a p value < 0.05, applying a Mann–Kendall significance test for linear trends.](image-url)
and rainfall. Given that rainfall decreased since 1985 and that higher temperatures were likely to have increased evapotranspiration, the growing season may not have increased after all. We therefore recommend developing an index for which growing-season length is limited by both temperature and precipitation.

Despite limitations and differences in methods, data, and scale, our results confirmed and complemented numerous findings from the literature, including warmer conditions during PDO(+) and EN in DJF in the Andes, more rainfall during PDO(+) in the lowlands and less rainfall during EN in DJF in the Bolivian Andes (Garreaud et al. 2009). Rainfall anomalies during the wet season can be explained by changes in moisture convergence. However, this did not apply for rainfall anomalies during PDO(+) in the southern lowlands. A possible alternative cause of enhanced rainfall here may be a stronger low-level jet.

Magnitudes of positive anomalies of mean and extreme rainfall related to PDO(+) and ENSO in the northern lowlands were comparable, making PDO(+) appear as a period with constant EN-like or LN-like conditions. Possible reasons for this counterintuitive similarity are differences in sample size and the fact that PDO anomalies included ENSO years as well as years with extreme weather from non-ENSO events. We also note that ENSO anomalies were not always extreme. This made a separation of the contribution of PDO(+), EN, and LN challenging.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Treatment</th>
<th>NLL</th>
<th>SLL</th>
<th>NAS</th>
<th>SAS</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>r95p (mm yr⁻¹)</td>
<td>PDO</td>
<td>71.2</td>
<td>91.1</td>
<td>7.2</td>
<td>-11.0</td>
<td>-3.5</td>
</tr>
<tr>
<td></td>
<td>El Niño</td>
<td>39.0</td>
<td>-17.7</td>
<td>-13.8</td>
<td>4.9</td>
<td>-9.9</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>63.3</td>
<td>5.6</td>
<td>-17.7</td>
<td>-4.8</td>
<td>-3.4</td>
</tr>
<tr>
<td></td>
<td>AAO</td>
<td>-29.1</td>
<td>3.8</td>
<td>-0.5</td>
<td>-10.8</td>
<td>-6.4</td>
</tr>
<tr>
<td>cdd (days)</td>
<td>PDO</td>
<td>-2.1</td>
<td>-2.0</td>
<td>-2.3</td>
<td>-8.4</td>
<td>-4.0</td>
</tr>
<tr>
<td></td>
<td>El Niño</td>
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<td>-10.3</td>
<td>-2.7</td>
<td>-2.7</td>
<td>-11.4</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>-5.3</td>
<td>0.9</td>
<td>-4.4</td>
<td>-0.4</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>AAO</td>
<td>0.9</td>
<td>-1.6</td>
<td>-3.8</td>
<td>-3.3</td>
<td>-7.5</td>
</tr>
<tr>
<td>cdd (days)</td>
<td>PDO</td>
<td>0.8</td>
<td>0.7</td>
<td>-0.1</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>El Niño</td>
<td>-0.2</td>
<td>-0.8</td>
<td>-0.7</td>
<td>-0.7</td>
<td>-1.1</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>1.1</td>
<td>0.7</td>
<td>1.7</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>AAO</td>
<td>0.1</td>
<td>0.4</td>
<td>0.5</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>cdd (days)</td>
<td>PDO</td>
<td>0.2</td>
<td>2.0</td>
<td>-0.2</td>
<td>-0.6</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>El Niño</td>
<td>0.0</td>
<td>-0.5</td>
<td>-0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>0.2</td>
<td>-0.3</td>
<td>-0.3</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>AAO</td>
<td>-0.6</td>
<td>-0.5</td>
<td>-0.1</td>
<td>-0.7</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

Fig. 12. Percentage of stations with significantly increasing (gray) and decreasing (white) values of selected climate indices in (a) all of Bolivia, (b) lowlands, (c) Andean slopes, and (d) Altiplano. Significance was tested with a Mann–Kendall trend test ($p < 0.05$).
Our estimated temperature trend of 0.1°C per decade is comparable but lower than the trend of 0.15°C per decade detected by Vuille et al. (2003). Differences may be due to the larger number of lowland stations used in our study. The fact that temperature trends were higher in the Andes compared to the lowlands (Fig. 6) may explain why our overall trend was slightly lower.

Our positive precipitation trend from 1960 to 1984 confirmed results from Ronchail (1995) and Marengo (2004). The shift from mainly negative to mainly positive anomalies in the 1970s may be associated with the shift from the cold to the warm PDO phase in 1976/77, as also suggested in Marengo et al. (2004). The negative trend from 1985 to 2004 confirmed the decrease of rainfall after 1982 documented in Espinoza Villar et al. (2009) as well as Toledo (2010), and may be related to decreasing values of the PDO index. Observed decadal trends in annual rainfall anomalies showed considerable similarities with the PDO index, and no similarities with numerous other climate modes, including AAO, AMO, AMM, and PMM, suggesting that the PDO is a principal driver of decadal rainfall variability in Bolivia.

We conclude that Bolivia’s climate is likely to continue to be warmer and drier than average in the near-term future. Since the PDO switched to a cold phase in 2007, not only the total rainfall but also the frequency and intensity of wet days, as well as the number of consecutive wet days and rainfall intensity, are likely to

![FIG. 13](image)

![TABLE 4](image)
continue to be below average in the lowlands, increasing the risks of drought and partly associated wild fires. ENSO-related floods, however, can occur nevertheless. An increasing risk of drought can also be expected in the Andes, given the above-average temperature rise there. The current dry conditions in the lowlands may reverse back to wetter conditions, while rainfall in the Andes may become even less, once the PDO reverses from its cold to its warm phase.

The impact of climate change on the PDO and ENSO are highly uncertain. Most global circulation models (GCMs) used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) do not properly represent the PDO for historic runs and show no significant changes under climate change scenario A1B (Furtado et al. 2011). The same models also do not agree on whether enhanced greenhouse gas emissions change the frequency and/or intensity of ENSO significantly (Collins et al. 2010). Projections from the most recent generation of climate models for the Fifth IPCC Assessment Report (AR5) are still to be assessed.

For future research we recommend analyzing the physical mechanism behind the rainfall trends in more depth, especially focusing on the role of the PDO. Furthermore, we encourage developing threshold values that can be associated with historical disasters. Such values can be incorporated in an early warning system, which should also include the PDO index in addition to the ENSO index.

### Table A1. Temperature-related climate indices (Abs. = absolute, Thr. = threshold, Perc. = percentile based, Dur. = duration, and O. = others). AP and LL are values from two example stations from the Altiplano (El Alto, La Paz) and the lowlands (El Trompillo, Santa Cruz de la Sierra), averaged from 1960 to 2009.

<table>
<thead>
<tr>
<th>Category</th>
<th>Identifier</th>
<th>Indicator name</th>
<th>Definition</th>
<th>Unit</th>
<th>AP</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs.</td>
<td>txx</td>
<td>Max Tmax</td>
<td>Monthly max value of daily max $T$</td>
<td>°C</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>tnx</td>
<td>Max Tmin</td>
<td>Monthly max value of daily min $T$</td>
<td>°C</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>tnn</td>
<td>Min Tmax</td>
<td>Monthly min value of daily max $T$</td>
<td>°C</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>tnn</td>
<td>Min Tmin</td>
<td>Monthly min value of daily min $T$</td>
<td>°C</td>
<td>−10</td>
<td>6</td>
</tr>
<tr>
<td>Thr.</td>
<td>fd0</td>
<td>Frost days</td>
<td>Annual count when Tmin $&lt; 0$°C</td>
<td>Days</td>
<td>190</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>id0</td>
<td>Ice days</td>
<td>Annual count when Tmax $&lt; 0$°C</td>
<td>Days</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>su25</td>
<td>Summer days 25</td>
<td>Annual count when Tmax $&gt; 25$°C</td>
<td>Days</td>
<td>296</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>su30</td>
<td>Summer days 30</td>
<td>Annual count when Tmax $&gt; 30$°C</td>
<td>Days</td>
<td>166</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>tr20</td>
<td>Tropical nights</td>
<td>Annual count when Tmin $&gt; 20$°C</td>
<td>Days</td>
<td>0</td>
<td>194</td>
</tr>
<tr>
<td>Perc.</td>
<td>tn10p</td>
<td>Cool nights</td>
<td>Tmin $&lt; 10$th percentile</td>
<td>Days</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>tx10p</td>
<td>Cool days</td>
<td>Tmax $&lt; 10$th percentile</td>
<td>Days</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>tn90p</td>
<td>Warm nights</td>
<td>Tmin $&gt; 90$th percentile</td>
<td>Days</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>tx90p</td>
<td>Warm days</td>
<td>Tmax $&gt; 90$th percentile</td>
<td>Days</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Dur.</td>
<td>gsl</td>
<td>Growing-season length</td>
<td>In Southern Hemisphere, days between first span after 1 Jul of &gt;5 days with Tmean $&gt; 5$°C and first span after 1 Jan of &gt;5 days with Tmean $&lt; 5$°C</td>
<td>Days</td>
<td>283</td>
<td>364</td>
</tr>
<tr>
<td></td>
<td>wdsi</td>
<td>Warm-spell duration</td>
<td>Days with $&gt; 5$ consecutive days when Tmax $&gt; 90$th percentile</td>
<td>Days</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>csdi</td>
<td>Cold-spell duration</td>
<td>Days with $&gt; 5$ consecutive days when Tmin $&lt; 10$th percentile</td>
<td>Days</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>O.</td>
<td>dtr</td>
<td>Diurnal temperature range</td>
<td>Monthly mean diff between Tmax and Tmin</td>
<td>°C</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table A2. Precipitation-related climate indices. AP and LL are values from two example stations from the Altiplano (El Alto, La Paz) and the lowlands (El Trompillo, Santa Cruz de la Sierra), averaged from 1960 to 2009. PRCP = precipitation.

<table>
<thead>
<tr>
<th>Category</th>
<th>Identifier</th>
<th>Indicator name</th>
<th>Definition</th>
<th>Unit</th>
<th>AP</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs.</td>
<td>rx1day</td>
<td>Max 1-day PRCP</td>
<td>Monthly max 1-day PRCP</td>
<td>mm day$^{-1}$</td>
<td>31</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>rx5day</td>
<td>Max 5-day PRCP</td>
<td>Monthly max consecutive 5-day PRCP</td>
<td>mm day$^{-1}$</td>
<td>66</td>
<td>154</td>
</tr>
<tr>
<td>Thr.</td>
<td>r10</td>
<td>No. days $&gt; 10$ mm day$^{-1}$</td>
<td>Annual count of days when PRCP $&gt; 10$ mm</td>
<td>Days</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>r20</td>
<td>No. days $&gt; 20$ mm day$^{-1}$</td>
<td>Annual count of days when PRCP $&gt; 20$ mm</td>
<td>Days</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>Perc.</td>
<td>r95p</td>
<td>Very wet days</td>
<td>Annual total PRCP when RR $&gt; 95$th percentile</td>
<td>mm</td>
<td>117</td>
<td>308</td>
</tr>
<tr>
<td></td>
<td>r99p</td>
<td>Extremely wet days</td>
<td>Annual total PRCP when RR $&gt; 99$th percentile</td>
<td>mm</td>
<td>37</td>
<td>91</td>
</tr>
<tr>
<td>Dur.</td>
<td>cdd</td>
<td>Consecutive dry days</td>
<td>Max no. of consecutive dry days with RR $&lt; 1$ mm</td>
<td>Days</td>
<td>59</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>cwd</td>
<td>Consecutive wet days</td>
<td>Max no. of consecutive dry days with RR $&gt; 1$ mm</td>
<td>Days</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Other</td>
<td>sdii</td>
<td>Simple daily intensity index</td>
<td>Annual total PRCP divided by the no. of wet days (defined as PRCP $&gt; 1$ mm) in the year</td>
<td>mm day$^{-1}$</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>prcptot</td>
<td>Annual total wet-day PRCP</td>
<td>Annual total PRCP in wet days (RR $&gt; 1$ mm)</td>
<td>mm yr$^{-1}$</td>
<td>608</td>
<td>1433</td>
</tr>
</tbody>
</table>
To conclude, we hope this research will contribute to a better understanding of historic climate variability and trends, and provide a basis for discussion on climate-related disasters and research on regional climate change in Bolivia. Our findings may encourage further developing early warning systems for natural hazards and strategies for adaptation to climate change.

Acknowledgments. This research was supported by the Departmental Pilot Program of Adaptation to Climate Change (PDACC) as well as the project Raising the Alert about Critical Feedbacks between Climate and Land Use Change in Amazonia (AMAZALERT). PDACC is carried out by the Fundación Amigos de la Naturaleza (FAN) as well as the departmental government of Santa Cruz and funded by the embassy of the Netherlands. AMAZALERT is jointly funded by the European 7th Framework Programme and national organizations. We thank the Bolivian National Service of Meteorology and Hydrology (SENAMHI) for the provision of the meteorological data. We are thankful for the support of CONARADE, 2010: Plan de atencion de la emergencia humanitaria y agropecuaria por sequia para el chaco Boliviano. We are grateful for the remarks from Prof. Dr. Wilco Hazeleger and Dr. Sarah Kew. We are grateful for the constructive comments from three anonymous reviewers who have helped to improve the quality of this paper.

APPENDIX

Supporting Tables
Tables A1 and A2 provide definitions and example values of climate indices.

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