RAINFALL EXTREMES IN NORTHERN CHILE: CLIMATOLOGY, TRENDS, AND ECOSYSTEM RESPONSES IN SALT MARSH REGIONS

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Abstract: A spatio-temporal analysis of precipitation extremes and vegetation state in the region of the Atacama Desert is presented. Precipitation in itself may be considered as extreme in large areas of the region, and its temporal pattern follows that of the annual rythm: mostly in the summer (winter) in the northern (southern) areas, with no discernible trends observed for any of the analysed precipitation indices during the period 1979-2019. Vegetation response has a 2-month lag with respect to precipitation in the north, and in the southern part it does not follow the precipitation temporal distribution, suggesting that it is dependent not only on precipitation but also on other water sources such as snowmelt and ground water. Significant trends of vegetation stress (negative NDVI trends) are found in the southern area, and the opposite for the northern subdomain (period 2000-2020).

Keywords: Precipitation extremes, water resources, Salt Marshes, Antofagasta

Resumé : Cette étude est une analyse spatio-temporelle des extrêmes de précipitations et de l'état de la végétation dans la région du désert d'Atacama. Les précipitations sont extrêmes dans de vastes zones de la région, et elles suivent un rythme annuel, pluies d'été (hiver) dans les zones au nord (sud), et aucune tendance n'est observée au cours de la période 1979-2019. La réponse de la végétation survient 2 mois après les précipitations dans le nord, et dans la partie sud, elle ne suit pas le tempo des précipitations, ce qui suggère qu'elle dépend non seulement des précipitations mais aussi d'autres sources d'eau telles que la fonte des neiges et les eaux souterraines. Des tendances significatives de stress de la végétation (tendances négatives du NDVI) sont manifestes dans la zone sud (période 2000-2020), mais pas dans le sous-domaine nord.

Mots-clés: Précipitations extrêmes, ressources en eau, marais salants, Antofagasta.

Introduction

The Atacama Desert, in the north of Chile, is one of the driest in the world (Romero et al., 2013; Sarricolea and Romero, 2015; Sarricolea et al., 2017) despite its location in the tropical region (between 21-25°S). Local ecosystems are adapted to harsh drought conditions, nevertheless they are dependent on the annual rhythm of precipitation whose shifts can have a very important impact on water availability and social and ecological systems, in addition to the fossil waters of the high-Andean aquifers (Marazuela et al. 2019). Among the threats to these socio-ecosystems is the decline of the communities, which are abandoning their economic practices, cultural identity, and local knowledge, resulting in the loss of ancestral cultivation lands, the thousand-year-old irrigation system and complex transhumance circuits of Andean Camelids that constitutes their heritage (Liu et al., 2019; Romero and Opazo, 2019). In addition, the mining activity present in the region requires an acute need for water resources that depends almost exclusively on summer rainfall caused by the South America monsoon, and which is stored in salt flats and in the ground. Thus, the conservation of this type of wetland (Bofedales or peatland) is of great importance for the maintenance of the diversity of the regional flora and fauna (Chavez et al., 2019), but also for cultural preservation and for conflict management (Liu and Agusdinata, 2020).

Our study focuses on the spatial and temporal changes in precipitation, in an area where aridity is permanent and the most critical climatic feature, and where water availability depends on sources located in the Andean highlands. Latitude, altitude, and exposure to atmospheric humidity explain large differences in the amount and variability of rainfall in places where nature conservation, mining, agriculture, tourism and indigenous communities are increasingly competing for water resources. Salar de Atacama is today the main center of lithium production at world scale. The analysis of the relationships between climate, ecology and culture are fundamental to avoid the collapse of these unique places.

1. Data and Methods

1.1. Study area

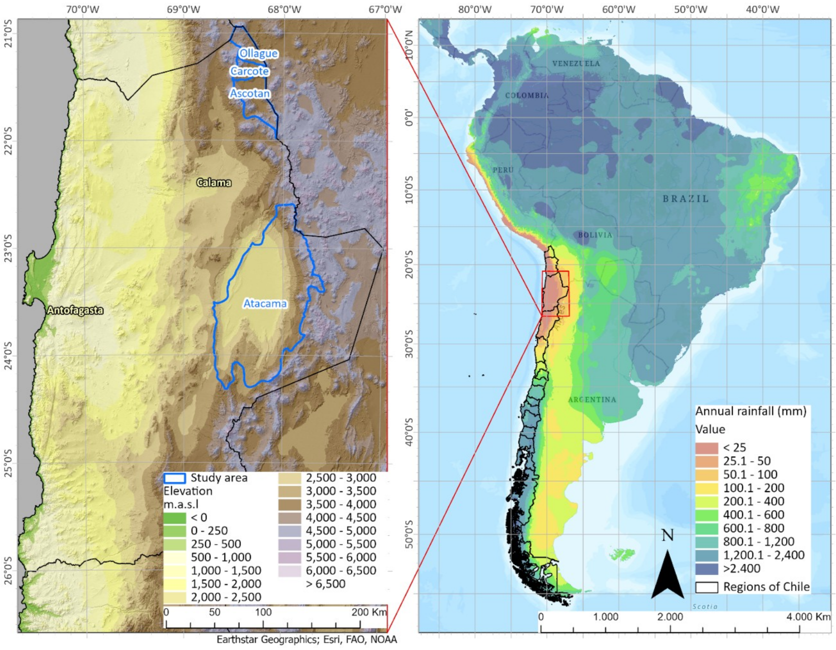

figure 1. Topographic map of northern Chile and the high Andean salt flats (left) and mean annual precipitation of the South American region (right) according to Fick and Hijmans (2017).

The study area is the so-called Chilean 'Altiplano' at the eastern margin of the Atacama Desert (Figure 1). This area is characterized by a plateau that exceeds 3000 meters above sea level, with high solar radiation. Synoptically, the area is affected by the action centers of the Pacific (Southeastern Pacific anticyclone and subpolar low pressures) and the Atlantic (Intertropical Convergence Zone). The most important basins in the area correspond to salt flats in high-altitude Andean wetlands that are both natural and irrigated by the communities. These wetlands are affected by changes in the variability of both annual and extreme precipitation amounts.

1.2. Precipitation and Vegetation Proxy Data

We used the daily, 0.05° spatial resolution precipitation estimates provided by the Center for Climate and Resilience Research Meteorological dataset (CR2MET; Boisier et al. 2018), and freely available at: https://www.cr2.cl/downloads/cr2met/. This dataset combines rain gauge observations (874 across Chile) and ERA5 estimates to yield a fine-scale precipitation fields for the entire country. The period considered is January 1979- December 2019, covering 41 years (2020 data stopped in September). No distinction is made between solid (frozen) and liquid precipitation. MODIS data for the period 2000-2020, retrieved from daily, atmosphere-corrected, bidirectional surface reflectance, are used to evaluate vegetation state and processes, and was obtained at https://modis.gsfc.nasa.gov/data/dataprod/mod13.php.

1.3. Methods

We examined the mean climatological spatio-temporal distribution of precipitation, as well as the widely used extreme precipitation indices proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI; Alexander et al. 2006). These indices are used here with slight modifications, in particular with regard to the threshold of 1mm, often used as a cut-off value to define rain events. In the extremely arid region close to the Atacama Desert any rainfall above zero might indeed be considered as a rain event, and oftentimes even as extreme events. Table 1 shows the indices considered in this work.

Table 1. List of precipitation extreme indices, definitions and units, adapted from the ETCCDI. Source : http://etccdi.pacificclimate.org/list_27_indices.shtml, accessed on 5 August 2019.

Index	Index name	Definition	Units
RR	Wet days	Number of days with precipitation (P) > 0 mm	days
R99p	Extremely wet days	Number of days with P ≥ 99^{th} percentile of precipitation (P99) in the 1979-2019 period.	days
RX5day	Max 5-day precipitation	Maximum 5-day accumulated P in one year	mm
SDII	Single day intensity index	$SDII_j$ = SUM(Rain > 0)/Rmm_j where Rmm_j represents the number of wet days in a period j	mm/day
CDD or CWD	Maximum number of consecutive dry or consecutive wet days	Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where RRij < 1mm (CDD) or RRij > 0 mm (CWD)	days

The Normalized Difference Vegetation Index (NDVI) was used to assess vegetation state, commonly used for spatio-temporal analysis and comparisons of vegetation canopy greenness, a composite property of leaf area, chlorophyll, and canopy structure. Precipitation trends were calculated using linear regression (with significance estimated at 95%), and NDVI trends were estimated with Sen's slope with Mann-Kendall test (significance at 90%).

2. Results

Figures 2 and 3 show the annual state of precipitation and of extreme indices in the region. The mean annual precipitation in the northern salt marshes is of 100 ± 50 mm; in the Salar de Atacama, conditions are extremely arid, with mean annual precipitation of 25 ± 25 mm. The aridity is also reflected on the P99 and on the mean annual SDII values: between 8-9 mm and 1.5 mm/day, respectively in the northern salt marshes, but only 3 mm/day and less than 0.3 mm/day around Salar de Atacama. The number of days with precipitation range from 30 to 40 days in the northern area, but only between 5-10 days in the Salar de Atacama, half of each can be consecutive (CWD, Fig 3c). RX5day is twice as large (20-30mm) in the north than in the Salar de Atacama (5-10mm).

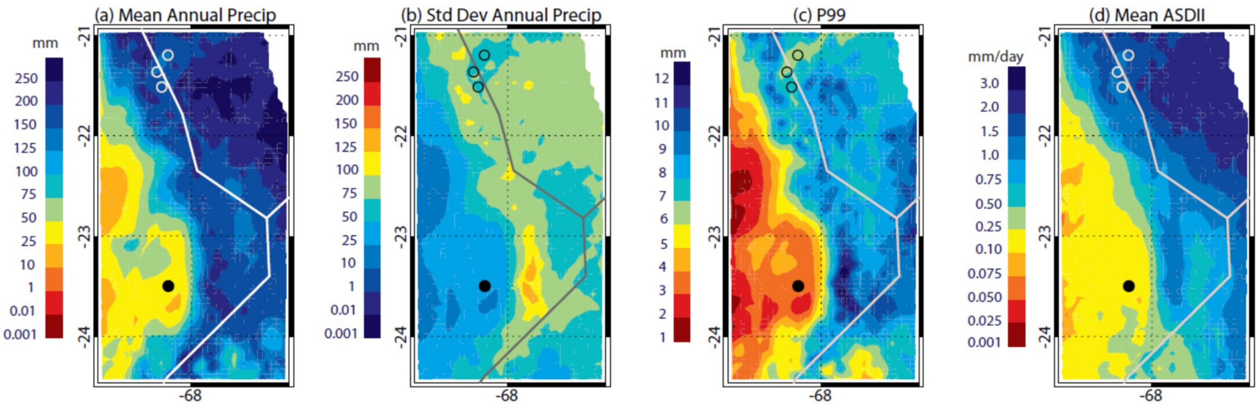

figure 2: (a) Mean annual precipitation (mm) for the 1979-2019 period; (b) Standard deviation of annual precipitation (mm) for the same period; (c) P99, that is, the value of rainfall corresponding to the 99^{th} percentile (mm); and (d) mean simple daily intensity index (SDII; mm/day). Circles correspond to the areas of Salar de Ollague, Salar de Carcote, Salar de Ascotan (open circles, from north to south) and Cuenca del Salar de Atacama (filled circle).

The yearly-based indices analysis needs to be complemented by a more refined investigation on the timing of the precipitation, as well as on the frequency and timing of anomalies. Analysis of the monthly distribution of precipitation, RR and SDII, for the northern salars and the Salar de Atacama (not shown) shows that the northern salars receive most of its precipitation during the (austral) summer, mainly in the period of December – February. The intensity of rainfall is stronger in this period as well. The Salar de Atacama has sporadic, weak precipitation that is spread throughout the year, although mostly present during winter months (May-August). A notable feature is that the median value of precipitation, RR, and SDII is zero for the remainder of the year, with precipitation occurrences considered as outliers.

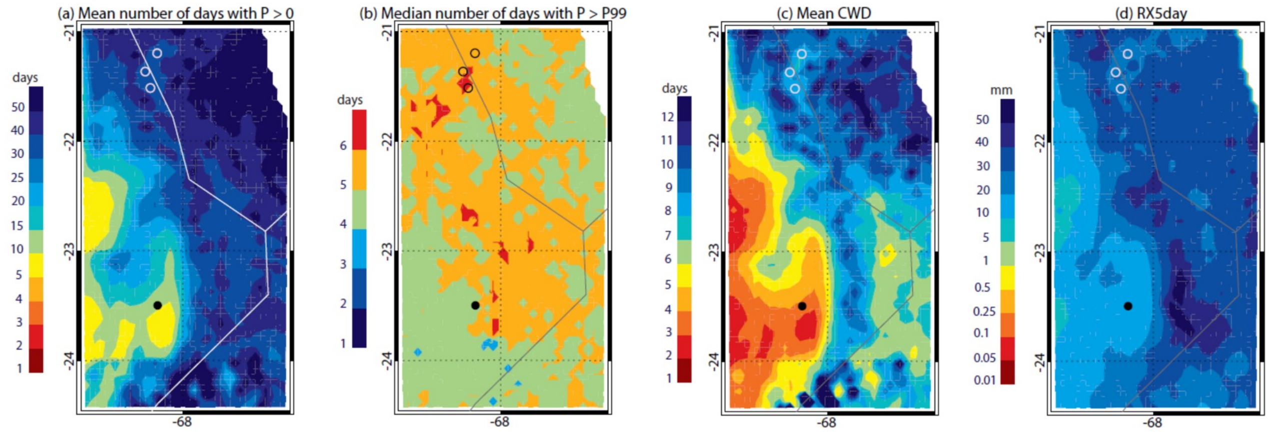

figure 3: (a) number of rainy days (P > 0); (b) median number of extremely wet days; (c) mean number of consecutive wet days (CWD); (d) maximum accumulated 5-day precipitation (RX5day; mm). Circles correspond to the areas of Salar de Ollague, Salar de Carcote, Salar de Ascotan (open circles, from north to south) and Cuenca del Salar de Atacama (filled circle).

Figure 4 shows the time series of precipitation and extreme indices for the studied period, for the Salars regions. It is possible to discern some periods in which dry conditions were prolonged for all parameters, for example, between 2006-2010 and again between 2013-2017 in the northern Salars, and between 1988-1996 (except 1990) in the Salar de Atacama. Droughts (rainfall) seem to become more frequent in the northern (southern) areas, however, no significant linear trends were identified for any of the variables.

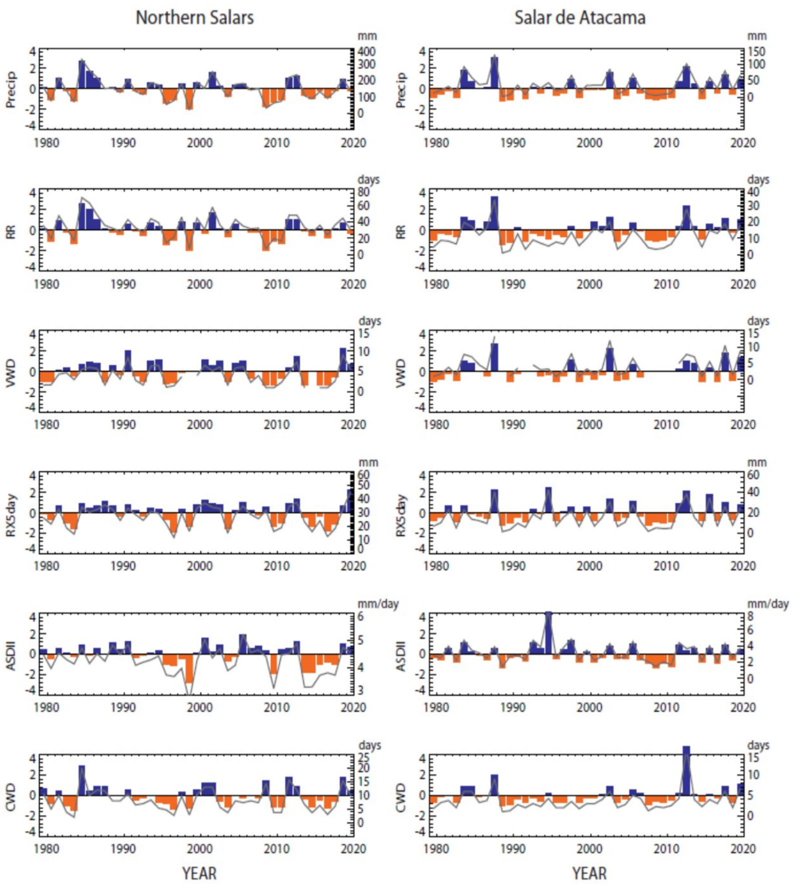

figure 4: Time series of precipitation and extreme precipitation indices (see Table 1), for the northern Salars (left column) and the Salar de Atacama (right column). Colored bars and left axis correspond to normalized anomalous values (T values), and lines correspond to the annual value.

Concerning the NDVI, when reviewing the aggregated results by month and by salt flat, April stands out as the month with the highest value, and comparatively, the Salar de Atacama is the one with the highest NDVI, followed by Ollague, Carcote and Ascotan (Figure 5). Vegetation response has a 2-month lag with respect to precipitation in the north, and in the southern part it does not follow the precipitation temporal distribution, suggesting that in this area, vegetation activity is dependent mostly on energy and on other water sources such as snowmelt and ground water. Since 2011 the NDVI time series values have increased (Figure 7), which has been documented by other works (Chavez et al., 2019).

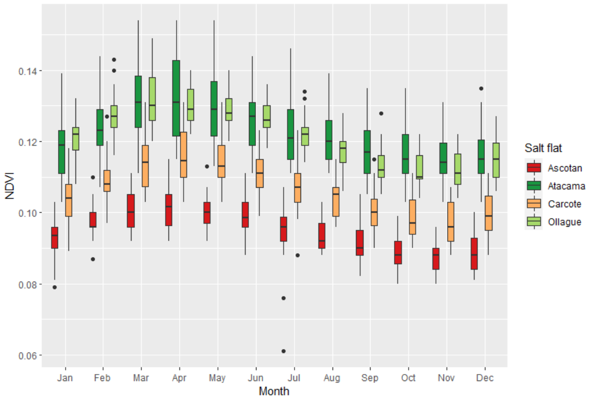

figure 5: Monthly distributions of NDVI for each studied salt flat.

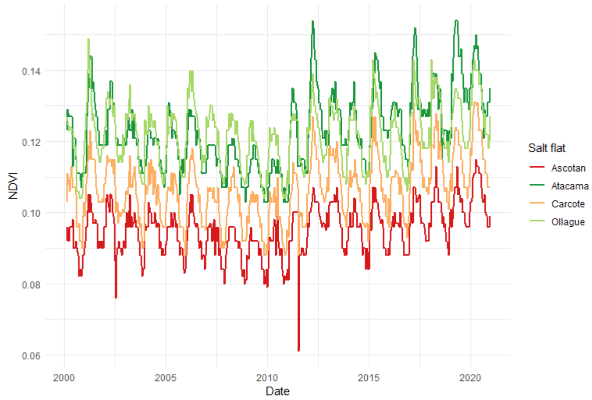

figure 6: Time series of monthly NDVI for each studied salt flat (period: 2000-2020).

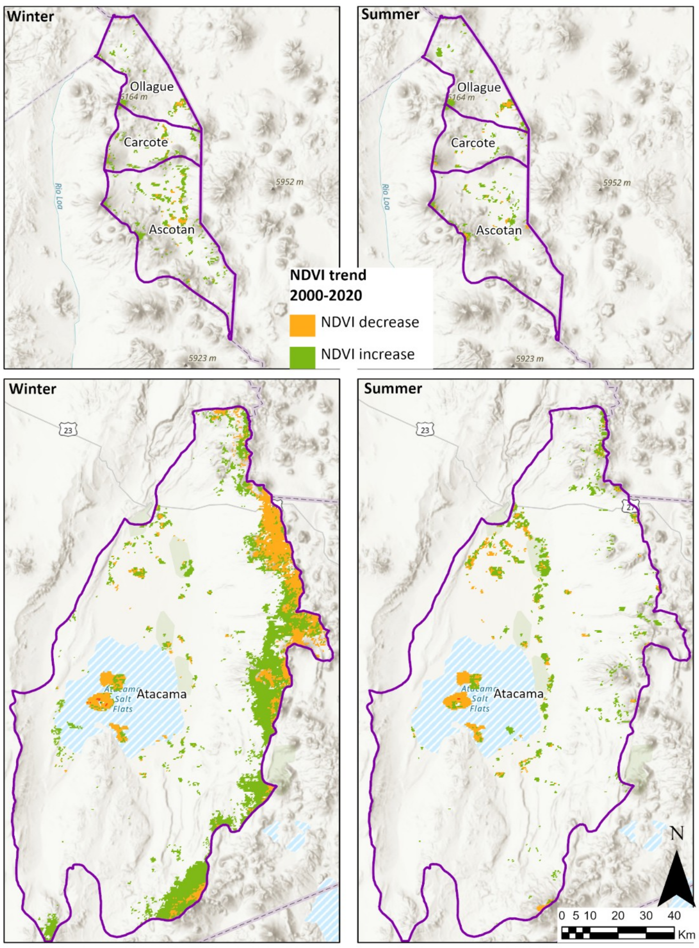

figure 7: NDVI trend maps for summer and winter in the studied salt flats (period 2000-2020). Only areas with statistically significant trends are represented.

Figure 7 illustrates the 2000-2020 winter (JJA) and summer (DJF) trends of NDVI in both the northern salt flats and the Salar de Atacama. Notice that only areas with significant trends are shown. Few and small patches of vegetation located mainly along the salars runoff tributaries present some increment in winter season that are however, reduced and spread during summer in Ollague, Ascotán y Carcote salt flats.

In Salar de Atacama it is interesting to observe the increasing NDVI in winter along the medium height mountains, but also the decreasing features in the uppermost ecological belts, where most of the rainfall and water recharge of the basins are taking place. The summer activation of the streams located in the eastern border of the salar is a result of the agricultural lands that are still irrigated by local communities. However, one of the most remarkable environmental changes is observed in the intervention areas of lithium mining in the Atacama Salar where decreasing values are indicating relevant levels of degradation (Liu et al., 2019).

Discussion and Conclusions

The Antofagasta salt marsh regions have been historically and culturally managed for agricultural and pasture purposes for indigenous communities and for mining goals during the last decades. Extreme seasonal and interannual variation of rainfall in an area of generalized aridity does not allow the representation of any temporal trend and, as a consequence, irregularity and uncertainty have become relevant sources of resilience for socioecological systems. However, the selected salt flats are in the center of the main Chilean mining activities, which are in turn, important sources of economic income for this country. In socio-ecological terms only a small part of the salt flats is protected area for nature and cultural conservation. NDVI analyses demonstrates that vegetation covers are very scarce and present large monthly, seasonal and interannual variations. Vegetation response has a 2-month lag with respect to precipitation in the north, and in the southern part it does not follow the precipitation temporal distribution, suggesting that NDVI is energy constrained, and that other water sources such as snowmelt and ground water may be important. Other sources of waters and mining extractions should be taken into consideration to understand the vegetation performance, which presence and distribution correspond almost exclusively to wetlands and creeks in this arid area.

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