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Articles

Evidence of climate change in the hyper-arid region of the southern coast of Peru, head of the Atacama Desert

Evidencias de cambio climático en la región hiperárida de la costa sur de Perú, cabecera del desierto de Atacama

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Abstract

The effect of climate change in this region is considered as one of the driest in the world, according to the evidence found and recorded, may be favorable or unfavorable for water availability. In this work, we seek to evaluate and validate the evidence of climate change such as droughts and floods that are occurring in the southern region of Peru and northern Chile called the headwaters of the Atacama Desert. The analysis of the interrelationships and climate trends was carried out, to demonstrate conditions of climate change about the occurrence of alluviums. In recent years, extraordinary precipitation events have occurred that have generated surface storage, vegetation growth, and alluvial surface flows in areas where they were not normal. The return periods of said extraordinary events were calculated. Likewise, *la mancha caliente* ("the hot blob") —detected by NOAA— brought with it, temperature anomalies between 4 and 6 ° C, and has a high probability of being the agent causing local rainfall in the study area. We consider these events as evidence of climate change; the normal conditions have been altered and the damage is irrefutable, it must be specified, for example, that a large part of the road infrastructure, services, buildings, etc., are not designed to take these conditions into account current climate, therefore, it is necessary to establish the safety regulations and adaptation of buildings to these new conditions that are being presented.

Keywords: Climate change, droughts, floods, the most, hyper-arid region, Atacama Desert.

Resumen

El efecto del cambio climático en esta región, considerada como una de las más secas del mundo según las evidencias encontradas y registradas, puede darse como favorable o desfavorable para la disponibilidad hídrica. En este trabajo se busca evaluar y validar las evidencias de cambio climático, como sequías y aluviones, que se vienen presentando en la región sur de Perú y norte de Chile, denominada cabecera del desierto de Atacama. Se realizó el análisis de las interrelaciones y tendencias del clima para evidenciar condiciones de cambio climático en relación con la ocurrencia de aluviones. En los últimos años se han presentado eventos extraordinarios de precipitación que han generado almacenamientos superficiales, crecimiento de vegetación y flujos en superficie tipo aluvión en zonas donde no es normal que se presenten. Se calcularon los periodos de retorno de dichos eventos extraordinarios. Asimismo, La mancha caliente —detectada por la NOAA— trajo consigo anomalías de temperatura entre +4 y +6 °C, y tiene una alta probabilidad de ser el agente causante de las precipitaciones locales atípicas en la zona de estudio. Estos eventos los consideramos como evidencias de cambio climático; las condiciones normales se han alterado y los daños son fehacientes. Se debe precisar, por ejemplo, que gran parte de la infraestructura vial, servicios, edificaciones, etcétera, no están diseñados tomando en cuenta las condiciones climáticas actuales, por tanto es necesario establecer una nueva normatividad de seguridad y adecuación de edificaciones ante las condiciones climáticas presentes.

Palabras clave: cambio climático, sequía, aluvión, lomas, región hiperárida, desierto Atacama.

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Introduction

The increase in the world population will continue to affect the environment. Land cover change, deforestation, agriculture, and the increase in the number of dams will be associated with reduced water and sediment discharges to the sea, and large impacts on downstream ecosystems and coastal areas (Mahe *et al*., 2013). Changes in water availability in deserts due to humans have important implications from a local, regional, or global level (Mahowald, 2007). Arid regions have a fragile and sensitive climate and ecological environment. Water resources are extremely necessary to maintain an ecological balance (Zhang, 2000; Wang & Qin, 2017). Arid terrestrial ecosystems play an important role in global biophysical processes by reflecting and absorbing solar radiation and maintaining the balance of atmospheric components (Gaur & Squires, 2018).

The Atacama Desert forms one of the main hyper-arid deserts in the world (Hartley & Chong, 2002). Studies suggest that desertification began at 14 Ma during the global climatic desiccation. The region has a hyper-arid climate. It is located in the extreme south of Peru and north part of Chile (Pino, Ramos, Mejía, Chávarri, & Ascensios, 2020; Pino *et al*., 2019a; Pino, Chávarri, & Ramos, 2018; Pino *et al*., 2017). The coast and the entire western slope are located directly in what Rau *et al*. (2017) identify as units 7, 8 and 9 in their regionalization of rains of the Pacific slope, areas with annual precipitation below 400 mm. In the study area, the precipitation does not exceed 10 mm per year and corresponds to the head of the Atacama Desert, considered one of the driest in the world (Ritter *et al.*, 2019; Sarricolea, Herrera-Ossandon, & Meseguer-Ruiz, 2017). Likewise, the coastal aquifers in northern Chile provide a unique opportunity to understand climate variability in the currently hyper-arid Atacama Desert. Atacama's hyperaridity has been attributed to its subtropical location, cold waters over the adjacent southeastern Pacific Ocean, and the presence of the Andes Mountains (Garreaud, Molina, A., & Farias, 2010).

In the Desert, the long-term average rainfall is 1 mm/year in some areas. However, localized coastal storms can occur with a recurrence interval of 15-20 years that may locally exceed 20 mm per event (Vargas, Ortlieb, & Rutllant, 2000). Large-rare storms generate short-lived surface runoff and small endorheic lagoons. Two root causes of the active role of groundwater in nature were identified: its ability to interact with the environment and the systematized spatial distribution of its flow (Tóth, 1999). Interaction and flow occur simultaneously on all scales of space and time, albeit at correspondingly varying rates and intensities (Back, 1966; Boelter & Verry, 1977; Deere & Patton, 1971; De-Vries, 1974; Domenico & Palciauskas, 1973; Fogg & Kreitler, 1982); Galloway, 1978; Garven, 1989; Garven, Ge, Person, & Sverjensky, 1993; Gerrard, 1981; LaFleur, 1984; Stuyfzand, 1993; Wallick, 1981; Williams, 1970; Yaalon, 1963; Zaruba & Mencl, 1969).

According to the latest reports of climatic behavior in the northern region of the Atacama Desert, southern Peru and northern Chile, rainfall has evolved favorably. There are records of water accumulation in the form of small lagoons, which generates a significant change in the water availability of this region (Pino, 2019b; Pino-Vargas, Montalvan-Díaz, & Avendaño-Jihuallanga, 2019). This region is considered as one of the driest in the world, according to the scientific evidence found and currently recorded. The effect of climate change on the conditions of this region may be considered favorable or unfavorable for water availability.

This work seeks to evaluate and validate the evidence of climate change such as droughts and floods that have been occurring in the southern region of Peru and northern Chile called the head of the Atacama Desert.

Materials and methods

Historical information was collected from studies, reports, technical reports, data collection from meteorological stations in the scope of the study. The methodology consisted of analyzing the interrelationships between climate and geology, paleoclimates in the region and atmospheric ocean interactions such as the Hot Blob that occurred between the end of 2019 and the first months of 2020 in the South Pacific. With this approach, we look for interactions to explain the evidence that demonstrates climate change in the head of the Atacama Desert.

Information gathering and data source

The southern region of Peru and northern Chile, where the head of the Atacama Desert is located, has been studied for many years by different public and private Peruvian institutions such as the Geological Mining and Metallurgical Institute (INGEMMET), National Water Authority (ANA), Tacna Regional Government (GORE) and Tacna Special Project (PET), among others. In the country and specifically in the region, SENAMHI records data from Conventional Meteorological, Automatic Meteorological, Conventional Hydrological and Automatic Hydrological stations (Figure 1).

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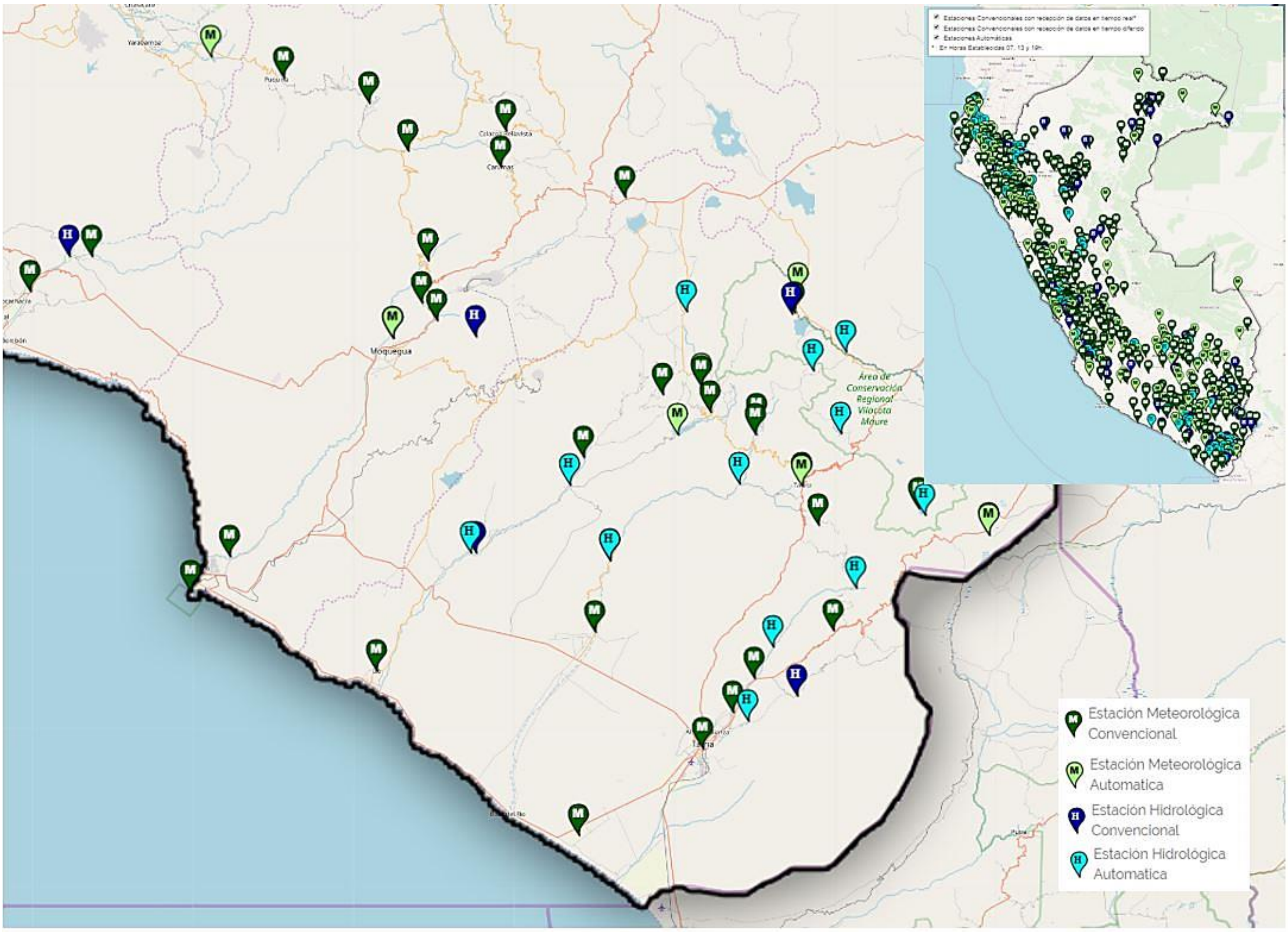

Figure 1.Map of stations in the southern region of Peru: Conventional Meteorological, Automatic Meteorological, Hydrological Conventional and Automatic Hydrological. (Source SENAMHI, Peru)

Description of the study area

The region is located in the south of Peru and north of Chile (Figure 2). It belongs to the so-called head of the Atacama Desert which is characterized by its extreme aridity. The coastal zone specifically corresponds to the Atacama Desert (Ritter *et al*., 2019; Sarricolea *et al*., 2017), the driest in the world. The eastern Andean part of the region corresponds to the central-western sector of the Altiplano, in which the accumulated annual precipitation is relatively low (300-700 mm/year), and the temporal variability is very marked (Garreaud, Vuille, & Clement, 2003; Valdivia, Thibeault, Gilles, García, & Seth, 2013). The current trends of change in climatic patterns have produced a distinctive and continuous increase in surface temperature, which can generate diverse effects on climatic and eco-hydrological factors in ecosystems throughout the region (Valdivia *et al*., 2013).

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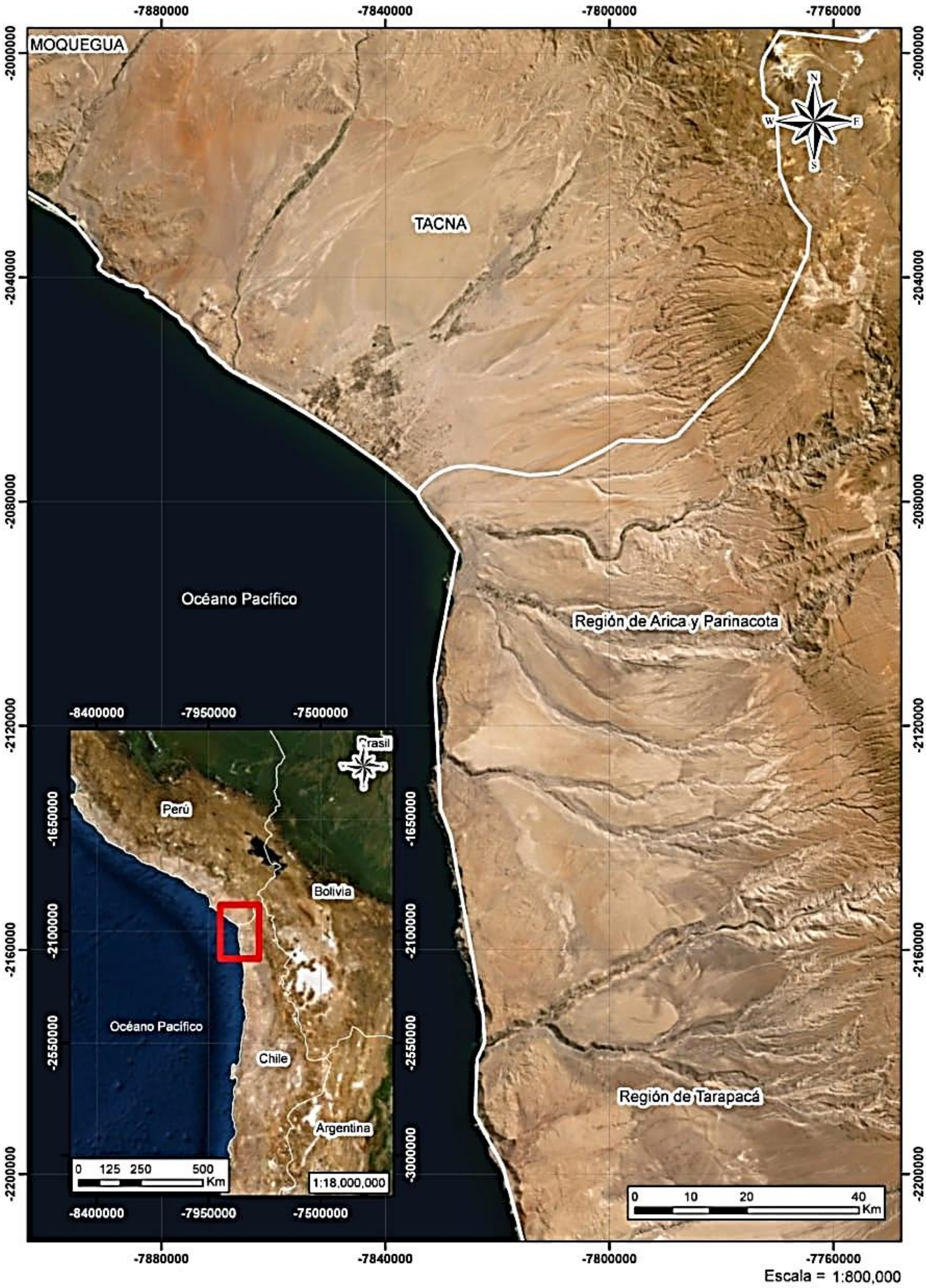

Figure 2. Location map of the study area, southern Peru and northern Chile, known as the head of the Atacama Desert.

Geology and climate

The history of the climate during the Late Quaternary at the head of the Desert is complex, according to the sedimentary records of various areas of the Atacama Desert. From the beginning of the hyper-arid conditions in the Middle Miocene, the climate was characterized by an alternation of arid and less arid periods (Vargas *et al*., 2000; Vargas, Rutllant, & Ortlieb, 2006; Rech, Currie, Michalski, & Cowan, 2006; Jordan, Kirk-Lawlor, Blanco, Rech, & Cosentino, 2014). Recent storms such as the one in March 2015 over the northern coast of Chile, with catastrophic consequences for the urban population, should be considered in the study of climatic variations in the region (Jordan *et al*., 2015; Bozkurt, Rondanelli, Garreaud, & Arriagada, 2016; Wilcox *et al*., 2016).

The relief of the western slope of the Cordillera de la Costa shows a growing increase in the intensity of erosion with increasing latitude. This increase is not uniform. Tectonic-related processes such as littoral subsidence/uplifting and fault activity, and on the other hand, the erosion of paleotopography and increased precipitation, affect the morphology of the coastal edge relief of northern Chile (Quezada, Cerda, & Jensen, 2010). Although the Atacama Desert has existed for at least 90 Ma, it is considered that the onset of hyperaridity was more likely to have developed progressively with the elevation of the Andes as they reached elevations between 1000 and 2000 m, along with the intensification of a cold upward Peruvian current between 15 and 10 Ma (Houston & Hartley, 2003). Ritter *et al*. (2019) refers that their data imply an early onset of hyperaridity in the central region of the Atacama Desert, interrupted by more humid periods, but probably still arid ones.

Paleoclimates in the region

Hyper-arid environments have always been present, at least locally, in South America during the last 120 Ma (Zúñiga-Reinoso & Predel, 2019). The existence of Tamarugos forests in such early times, about 10 ka, suggests the certain availability of water resources. (Rivera-Díaz, 2018). The hyperaridity of the Atacama Desert is closely related to the development of copper and nitrate/iodine minerals with regional tectonics and global paleoclimatic changes in the Cenozoic era. The hyper-arid condition in the Atacama Desert prevailed at least before 9.47 Ma and it can be traced back to the middle Miocene (Sun, Bao, Reich, & Hemming, 2018).

The halite-encrusted salt flats (salt pans) present at low elevations in the hyper-arid core of the Atacama Desert in northern Chile are unique features of one of the driest and possibly oldest deserts on Earth. These landscapes are known to have been shallow freshwater lakes and wetlands during the last glacial period and formed periodically between ~46.9 ka and 7.7 ka (Pfeiffer *et al*., 2018). The exhibition of ancient coastal terraces of Lake Quillagua-Llamara Soledad, in the central Atacama Desert, provides new insights into the paleohydrology of the driest desert on Earth. The lake developed in a paleo-endorheic drainage system (274 ± 74 ka) before draining into the Pacific due to the incision of the Loa River canyon (Ritter *et al*., 2019).

Prior to the extreme precipitation event that occurred between March 24 and 26, 2015, and that had a strong impact on northern Chile, the scenarios of the wettest paleoclimatic intervals had been attributed only to sources of moisture from the east or southwest. These events are the first opportunity to evaluate an important regional precipitation event in relation to the hypothetical paleoclimate scenarios previously investigated (Jordan *et al*., 2019).

Ocean-Atmospheric Interactions

The combination of the barrier effect of the high Andes Mountains, the permanence of the Southeast Pacific anticyclone and the Humboldt Current system, explains why this region does not receive the humid air masses from the Atlantic. Rainfall is practically nil. Annual rainfall values, which are of a few millimeters, are calculated based on interannual averages that span several decades. In the Atacama Desert, the rains are so scarce that several years, and even decades, can pass without "precipitation" of more than a few millimeters. With respect to ocean-atmospheric interactions, it is interesting to analyze in the Atacama Desert the relationship that may exist between the very scarce rains and the ocean-climatic anomaly ENSO (El Niño Southern Oscillation) in the longest possible time.

Tropical disturbances have been theoretically and in situ shown to excite long-range atmospheric responses in the form of Rossby wave teleconnections resulting from the equatorial-to-polar gradient of the planetary vorticity. An extreme teleconnection event occurred during March 2015 in the Southeast Pacific. As a result, extremely high temperatures were observed in southwestern South America and the Antarctic Peninsula, simultaneously with an extreme event of rain and flooding in the desert Atacama Desert (Rondanelli, Hatchett, Rutllant, Bozkurt, & Garreaud, 2019).

Despite the persistent aridity of the Atacama Desert, the coastal desert climate of northern Chile undergoes pronounced fluctuations on the interannual and interdecadal time scales (Schulz, Boisier, & Aceituno, 2012). In terms of interannual variability, rainfall appears to be largely modulated by ENSO.

Recent evidence of climate change

For precipitation anomalies, the uncertainty is so great that it is not possible to ensure that the projected changes, even more at the end of the 21st century, are totally attributable to climate change, and to differentiate the fraction that may be part of the natural variability of the system (Sarricolea *et al*., 2017). Changes that occur on the interannual and decennial time scales overlap with a long-term decrease in precipitation during the 20th century (Schulz *et al*., 2012).

The Atacama Desert has experienced a series of very unusual rain events in the last three years (Figure 3), which generated the formation of hypersaline lagoons not previously recorded that have lasted several months (Azua-Bustos *et al*., 2018).

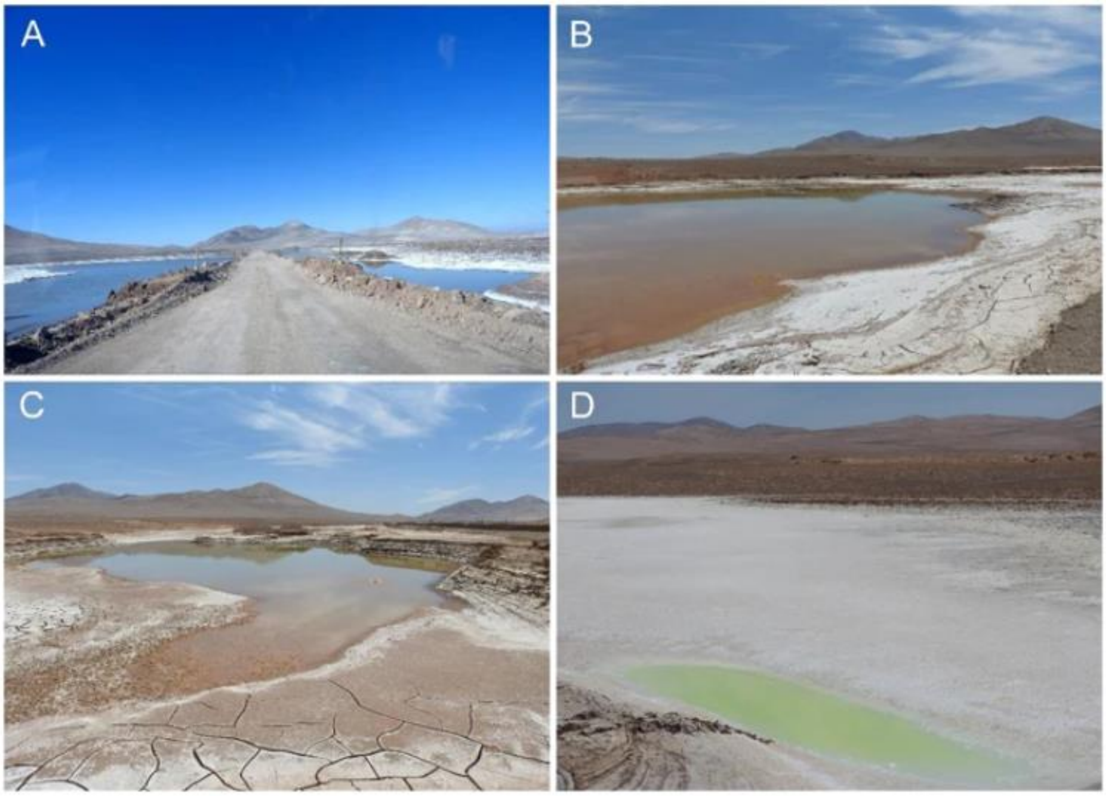

Figure 3. Lagoons formed after the rain event of June 7, 2017 in the Yungay region. (A) Lagoons seen on July 8, 2017. (B, C, and D)

Large, medium, and small lagoons. Images taken on November 11, 2017.

Precipitation and Floods

Tacna is a city located in the south of Peru and on the border with Chile, the region corresponding to the head of the Atacama Desert. Last Summer 2020, two important precipitation events occurred in this city, according to the National Meteorology and Hydrology Service (SENAMHI) and to data from our automatic climate station located on the campus of the Jorge Basadre Grohmann National University. These events recorded maximum precipitation intensity values on January 23, 2020 with 10.4 mm/h and on February 21 with 16.8 mm/h (Figure 4), which has caused alluvial-type flow in the Caramolle and El Diablo streams, resulting in the latter the loss of three human lives. February 21 event produced foods that left the loss of 3 human lives and great economic losses in the city (Figure 5).

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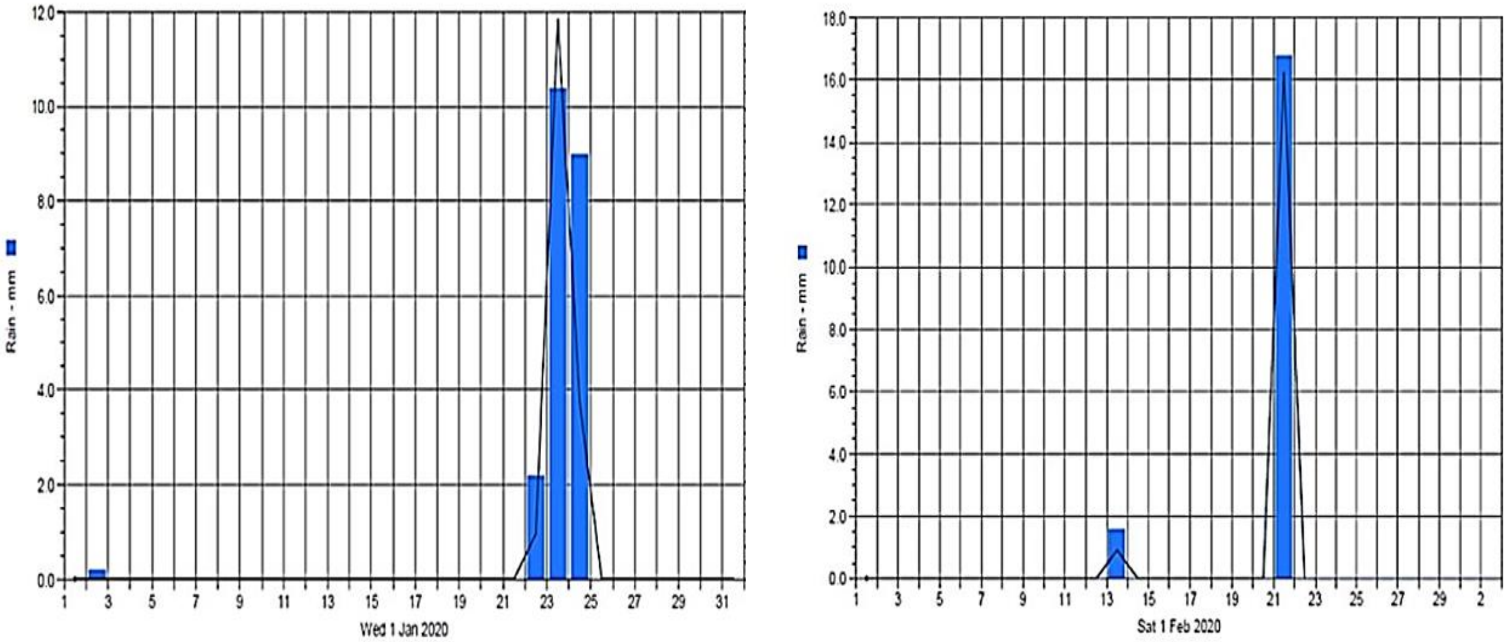

Figure 4. Precipitation recorded on January 23 and February 21, 2020, in the city of Tacna and its surroundings.

Figure 5. On February 22, 2020, *Diario Gestión* reports: Huaycos in Tacna left three people dead.

Figure 6 shows the behavior of total daily precipitation in mm/day. Obviously, the precipitation events that have occurred this year have been much greater than in the last 28 years.

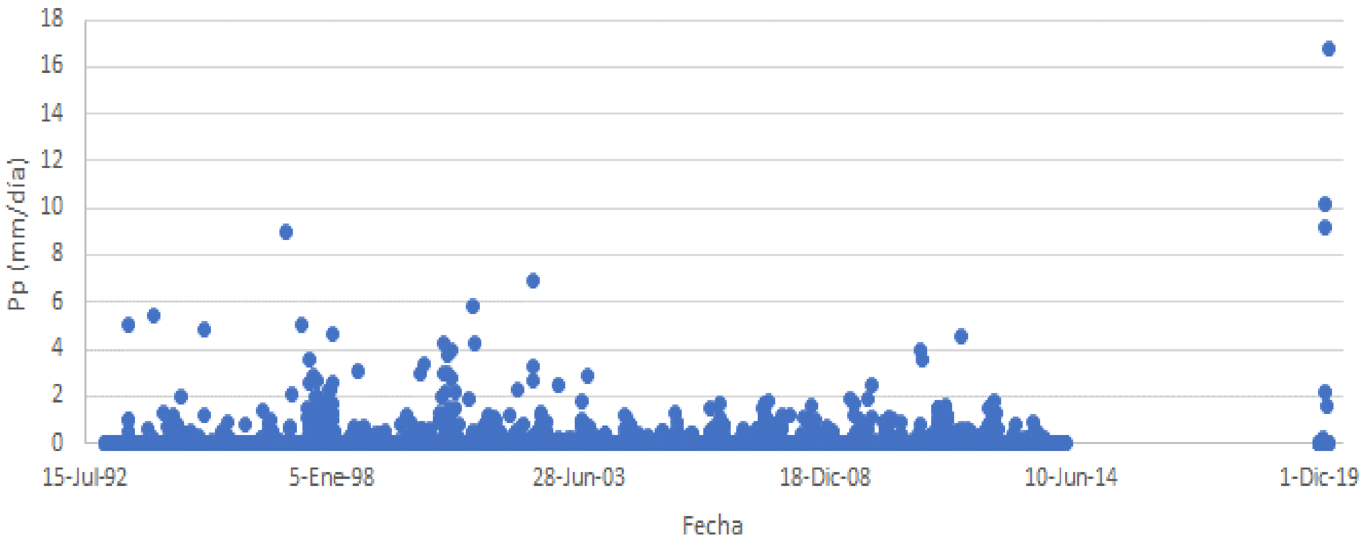

Figure 6. Total daily precipitation (mm/h), UNJBG Station (Period from Jan 1, 1993 to Feb 21, 2020).

In order to calculate the return period for the events of January 23 and February 21 of 2020, the corresponding frequency analysis was carried out. The tests of adjustment to probabilistic distributions were the following: extreme value, lognormal, normal, rayleigh, Weibull and exponential.

The probabilistic distribution which obtained the best fit was Weibull.

Figure 7 shows the adjustment of the (a) Weibull distribution, (b) the corresponding duration curve, obtaining a return period of 185.2 years for the event of 10.2 mm/day that occurred on January 23, 2020. In the same way, the (c) Weibull distribution and the (d) duration curve for February 21, 2020, obtained a return period of 312.5 years for the 16.8 mm/day event.

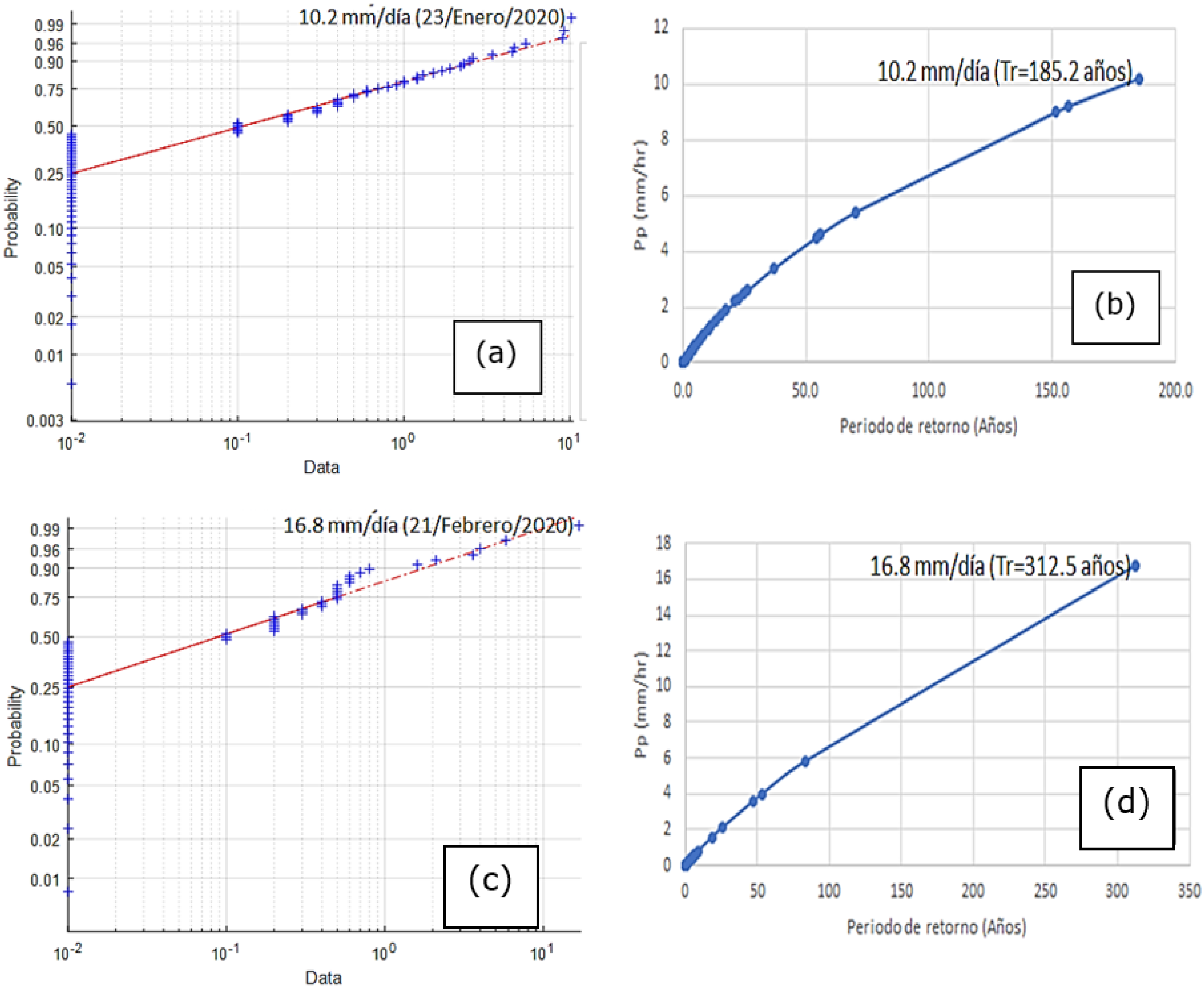

Figure 7. (a, c) Weibull Probability Distribution on January 23 and February 21, 2020, and (b, d) Daily precipitation duration curve on January 23 and February 21, 2020.

On the other hand, the analysis of the total daily rainfall recorded by the Cerro Blanco automatic station was carried out. This station is located about 12.0 km away from the UNJBG station. Figure 8 shows the location of the Cerro Blanco station, which has 06 years of information (from 2015 to 2020).

Figure 8. Location map of Cerro Blanco Station.

Despite the little information recorded by the Cerro Blanco automatic station, it was interesting to analyze what happened during the months of January and February of the 06 mentioned years.

Figure 9 shows that (a) for the month of January, the highest daily total rainfall occurred on January 29, 2019 and the second highest daily total rainfall occurred on January 23, 2020. (b) For the month of February 2020, the highest daily total rainfall occurred on the 21st.

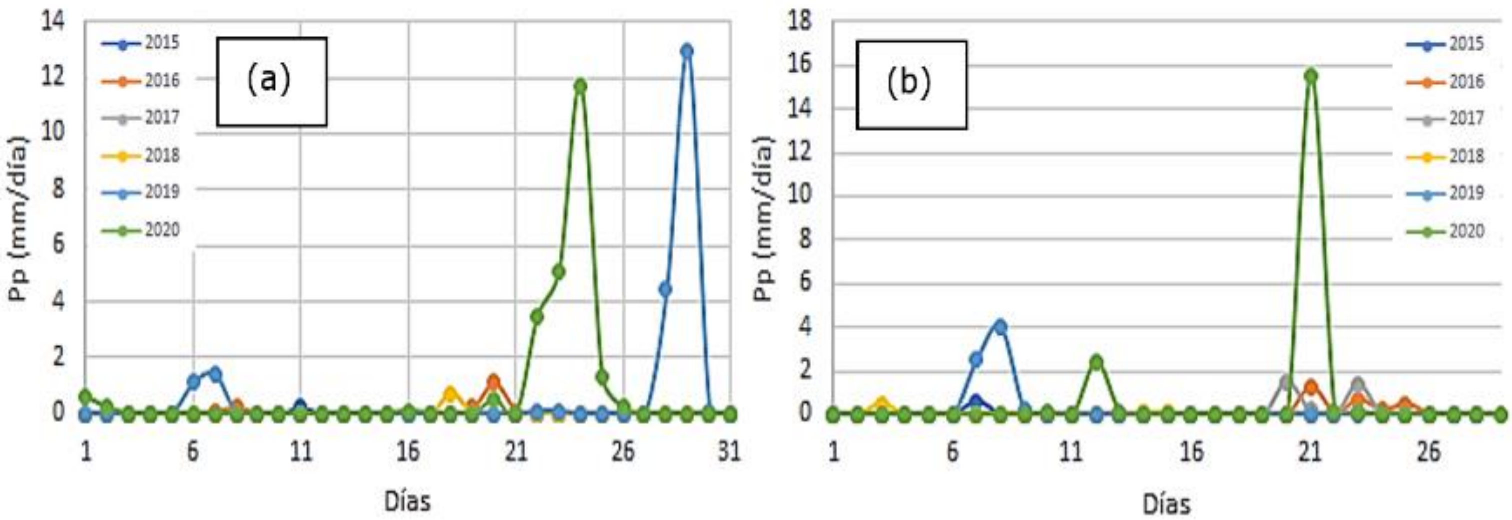

Figure 9. Maximum daily rainfall period 2015-2020, Cerro Blanco Automatic Station. (a) month of January. (b) February.

In summary, Figure 10 shows that the highest daily total rainfall in the area of the city of Tacna occurred in January 2019 and February 2020.

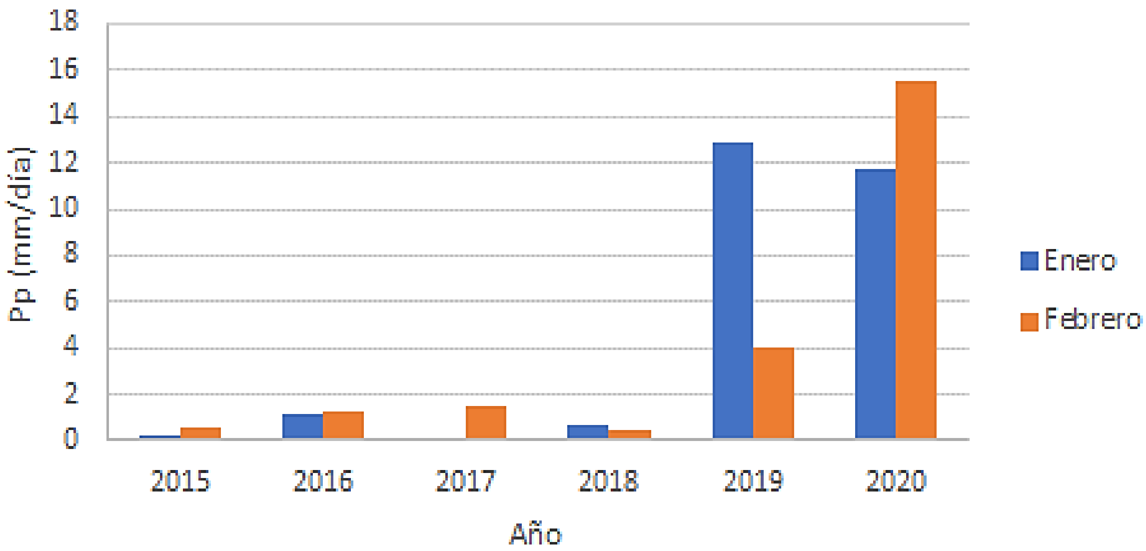

Figure 10. Maximum daily rainfall months January 2019 and February 2020, Cerro Blanco Automatic Station.

Despite the little information (06 years), which determines a low representativeness, it seemed interesting to have an idea of the return period of the daily total rainfall events of the events indicated above.

In this case, the best probabilistic distribution that was adjusted to the daily total rainfall information during the month of January was the lognormal. The return period calculated for the 12.9 mm/day event that occurred on January 29, 2019 was 103.1 years (Figure 11). Similarly, the best probabilistic distribution that was adjusted to the daily total rainfall information during the month of February was also the lognormal. The return period calculated for the 15.5 mm/day event that occurred on February 21, 2020 was 200 years. It should be noted that the analysis carried out for the Cerro Blanco automatic station is only referential, due to the little information recorded so far by said station.

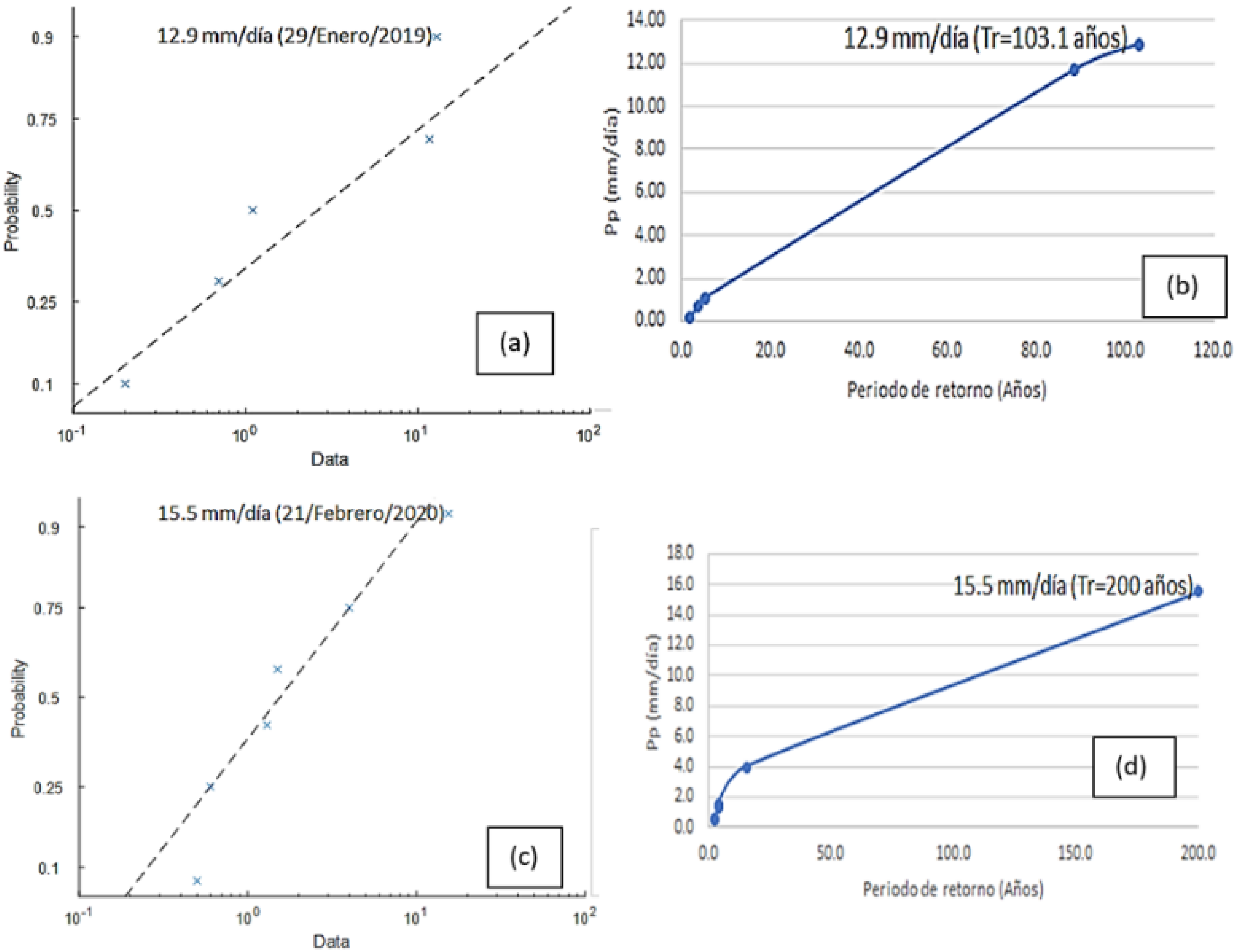

Figure 11. (a) Lognormal Probability Distribution – January; (b) January daily rainfall duration curve; (c) Lognormal Probability Distribution – February; (d) February daily rainfall duration curve.

In Figure 12, 04 Landsat 7 images may be seen which correspond to the days before and after the rain events of January 23 and February 21, 2020. The celestial tonality of the images is related to the surface moisture of the soil:

a) Between the images of December 31, 2019 and February 1, 2020, the event of January 23, 2020 occurred. It is possible that the soil of the Caplina basin has absorbed this amount of rain.

b), c) Between the images of February 1 and March 4, 2020, the event of February 21 occurred. The image shows the highest surface soil moisture. The supersaturation of the inter-basin between the Caplina and Sama basins is remarkable.

d) Finally, the image of March 20, after 16 days of the event of February 21, 2020, shows the redistribution of the surface soil moisture in the Caplina and Sama basins.

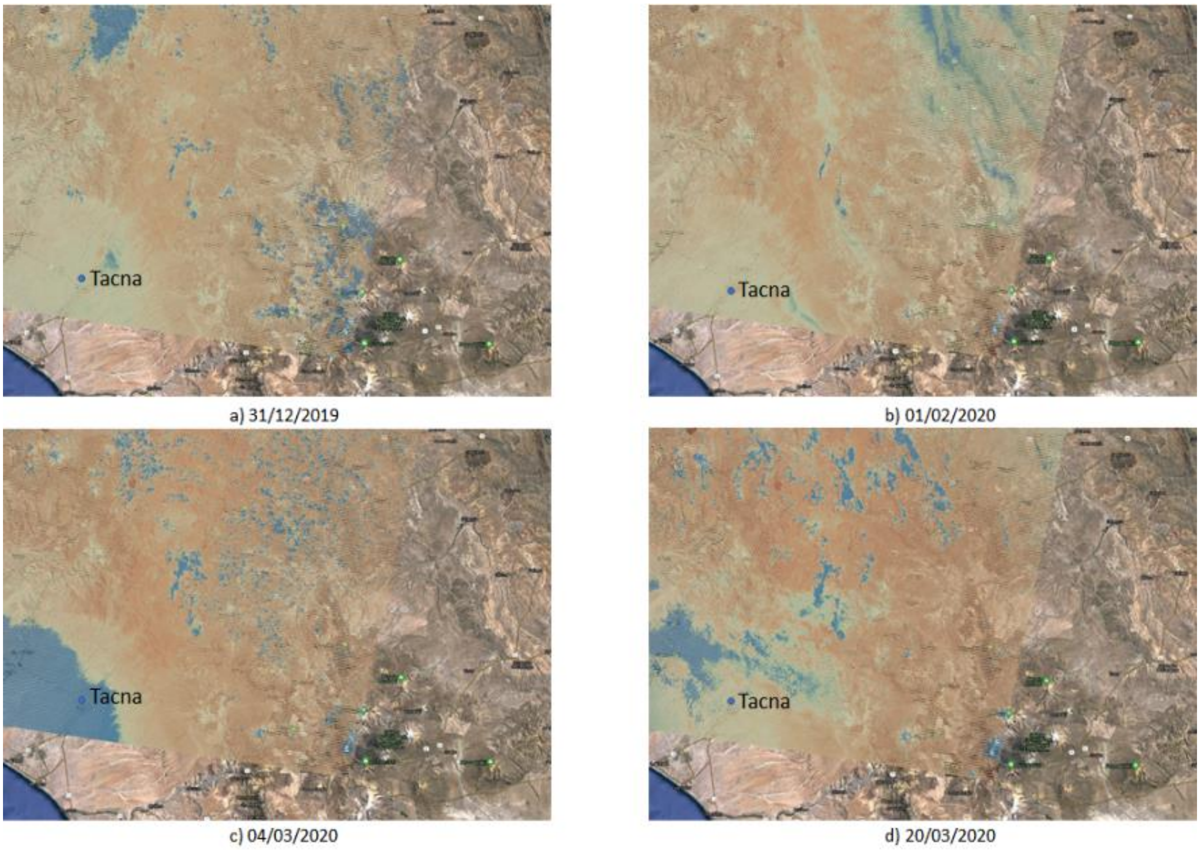

Figure 12. Landsat 7 images corresponding to days before and after the rain events of January 23 and February 21, 2020.

Based on Sentinel images (Figure 13), the soil moisture index was obtained in the basins of Locumba, Sama and Caplina. The image of February 26 corroborates the saturation of the soil after the event of February 21. Later, after almost a month of the indicated event, the redistribution of soil moisture is shown.

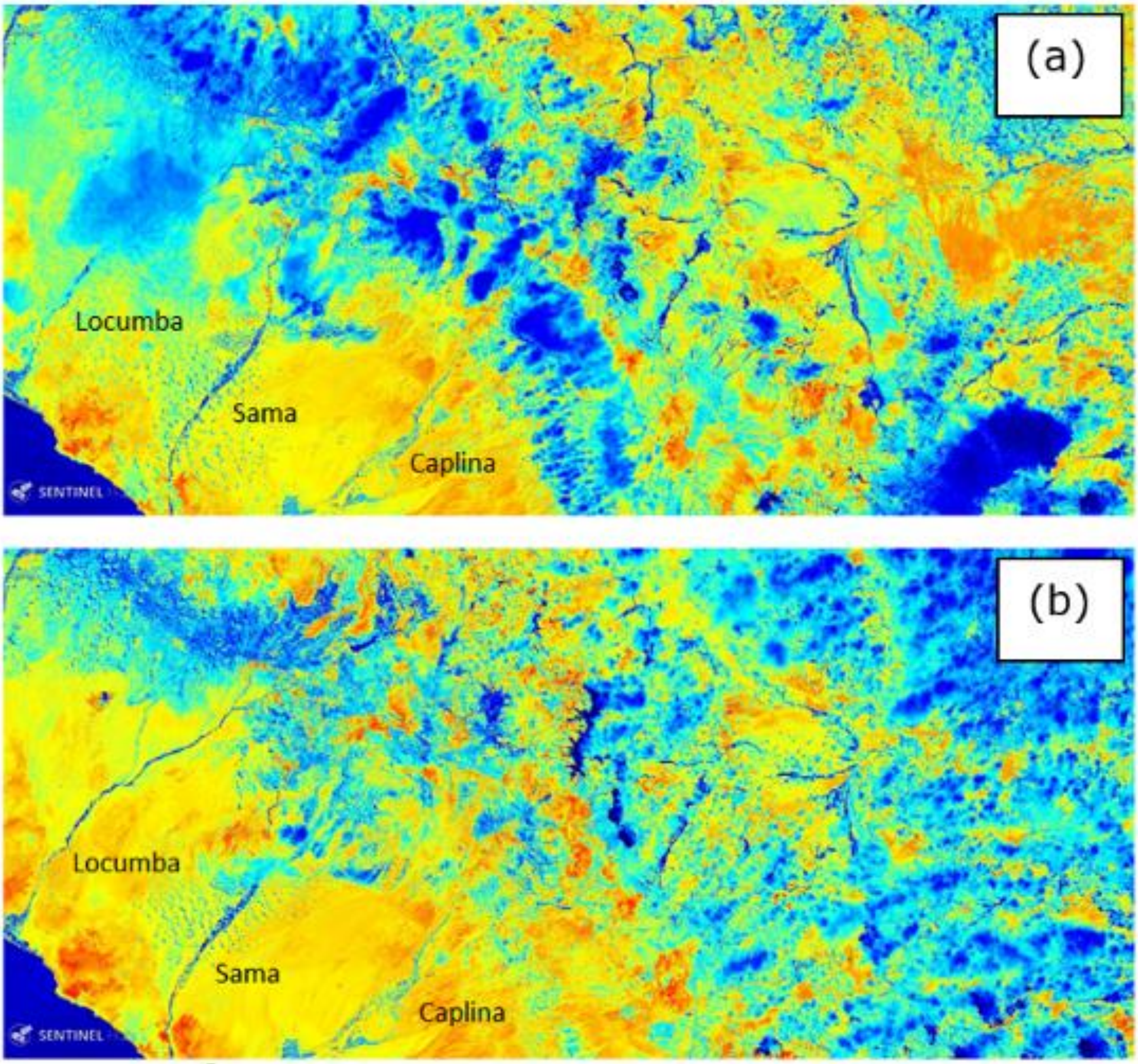

Figure 13. Soil moisture index based on Sentinel images, for the basins: Locumba, Sama and Caplina: (a) February 26, 2020; (b) March 25, 2020.

In this way, it can be affirmed that the saturation of the soil, particularly in the Caramolle and Diablo streams as a result of previous

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rain events, was a determining factor for the large flood of February 21, 2020.

Based on information collected by the FIAG UNJBG automatic station, it can be corroborated that the atmospheric moisture during the events of January 23 and February 21, 2020 was close to saturation, so less solar irradiation and greater relative moisture were recorded, as shown in Figure 14 and Figure 15.

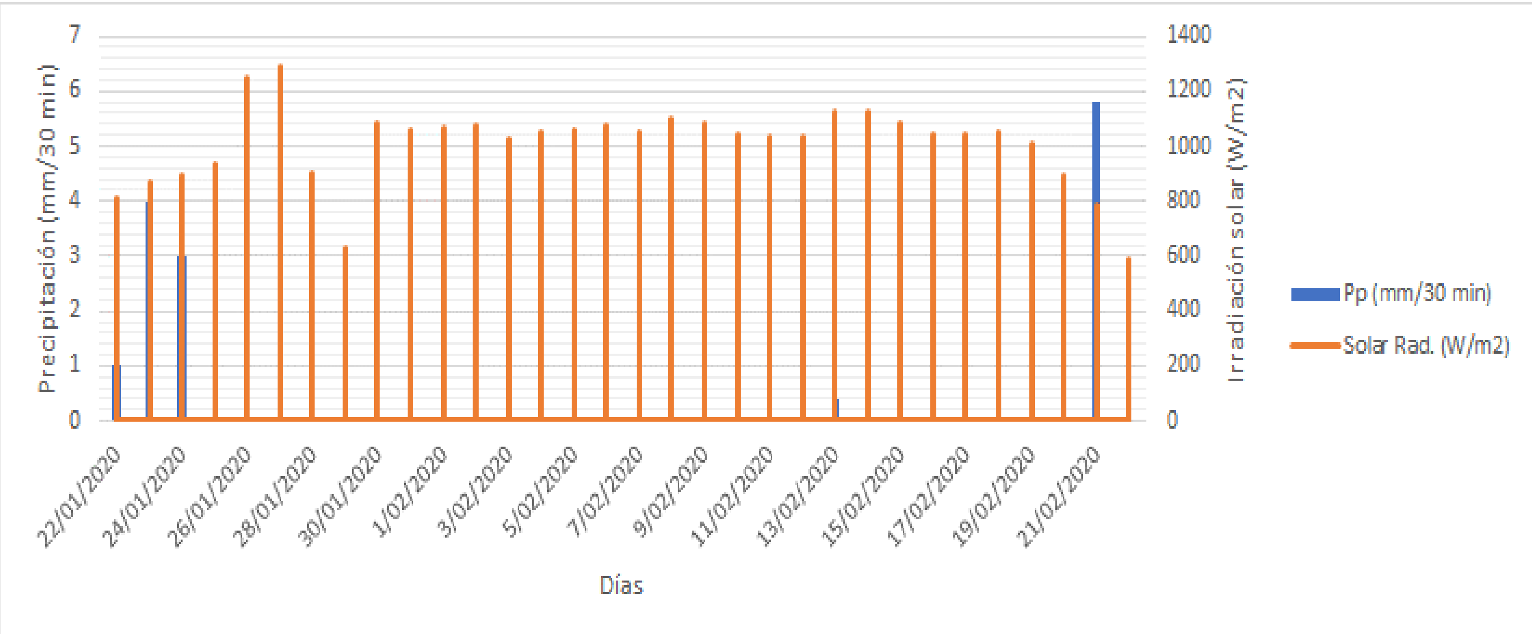

Figure 14. Solar radiation, rainfall automatic station FIAG UNJBG.

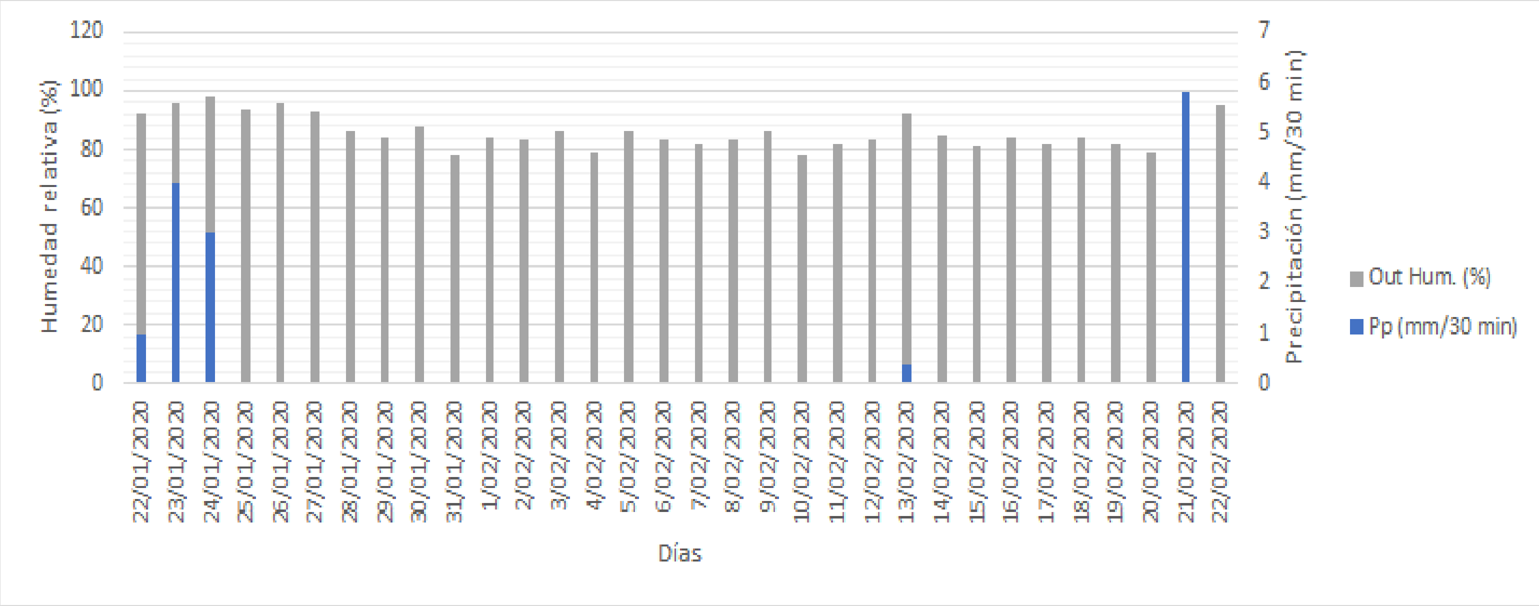

Figure 15. Relative moisture, rainfall automatic station FIAG UNJBG.

In 1927, a huayco (mudslide) activated the Quebrada del Diablo and left the city of Tacna devastated, according to the book "Tacna: Historia y Folclore" ("Tacna: History and Folcklore") by Fortunato Zora Carvajal. 93 years ago, a huayco ran through two streams in Tacna and carried away buried bodies from the General Cemetery. A similar tragedy occurred on February 21, 2020 in the city (Figure 16).

Figure 16. Location of the alluvial zone (Source © Copyright 2020, EOS DATA ANALYTICS, Inc., Land Viewer, LANDSAT 8).

The Hot Blob

According to NOAA, the Hot Blob is a gigantic area of surface hot water which appeared near New Zealand covering an area of approximately one million square kilometers, with temperature anomalies between 4 and 6 °C. (Figure 17). This phenomenon was detected at the beginning of October, reaching its maximum level in December 2019. Its origin has been attributed to the presence of high atmospheric pressure and weak winds, staking the water, which was overheated on its surface by solar radiation.

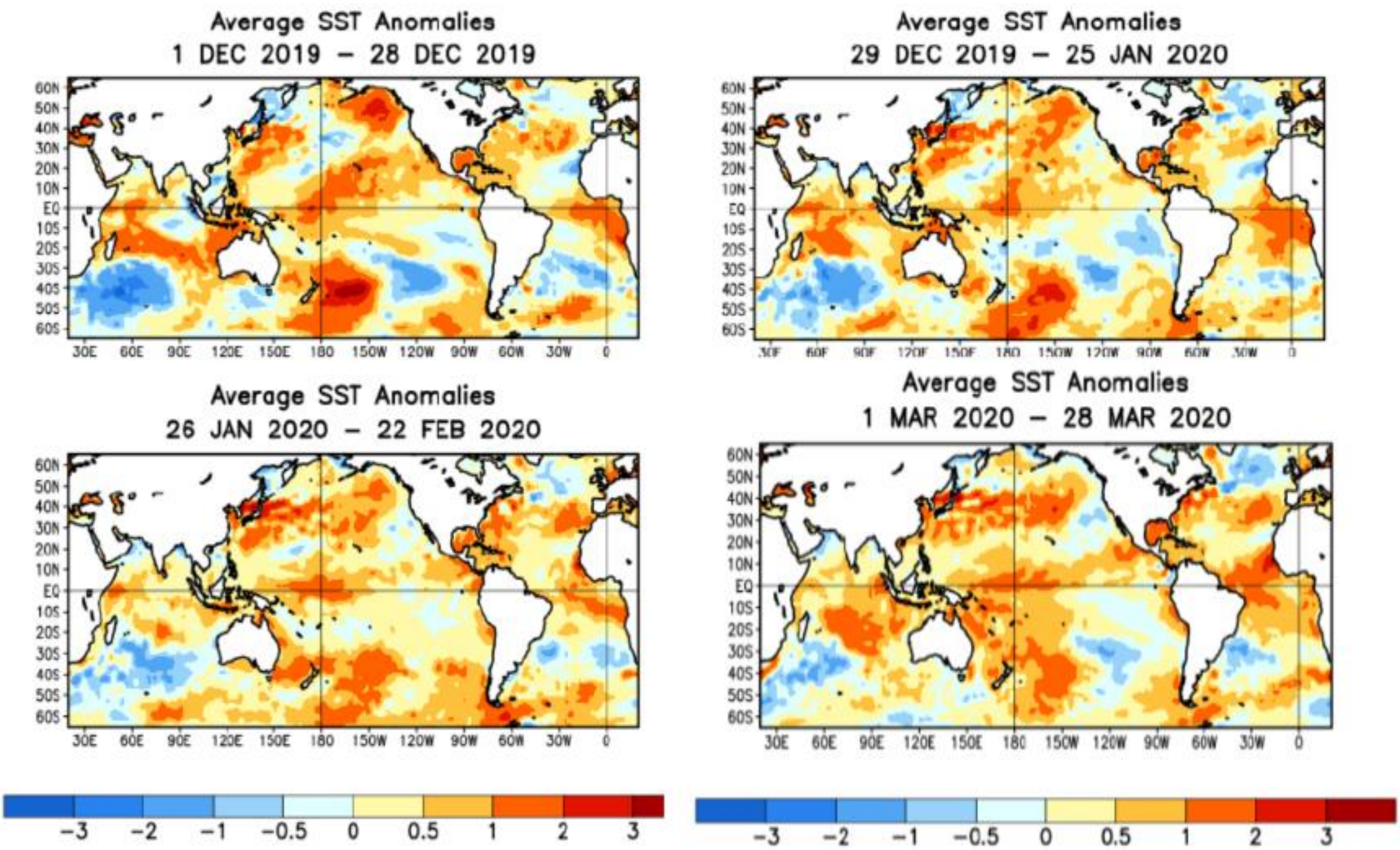

Figure 17. Evolution of The Hot Blob of the South Pacific (NOAA, 2020).

In September 2019, a warm Kelvin Wave spread and reached South America during December and January (NOAA, 2020). During the month of February 2020, sea surface temperatures (SSTs) were above average and were evident across the western, central, and eastern Pacific Ocean.

Results and Discussion

We must understand how the climate will change and whether human activities may influence the climate (Frisken, 1971). What we are sure of today is that it is climate change. In the past, they were produced by the natural variability of the earth's climate system and today we record an additional variable that corresponds to changes induced by anthropic factors.

Knowledge about climate change implies the modification of the atmosphere chemical composition and its repercussions on the planet's climates, as well as in aspects related to the economic, social, legal, and ethical implications of this problem, both on a global and local scale (Molina, Sarakhán, Carabias, García-Méndez, & García-Calderón, 2017).

In Summer 2020, as previously specified, there were anomalous rainfall in the city of Tacna and its surroundings, which caused the entry of floods on the right bank of the Caplina River, which natural course has been modified, settling the city of Tacna, specifically the Quebrada Del Diablo. While, on the left bank, in the Arunta hill there was seed germination and vegetation development, which is seen for the first time in the last 80 or 90 years (Figure 18).

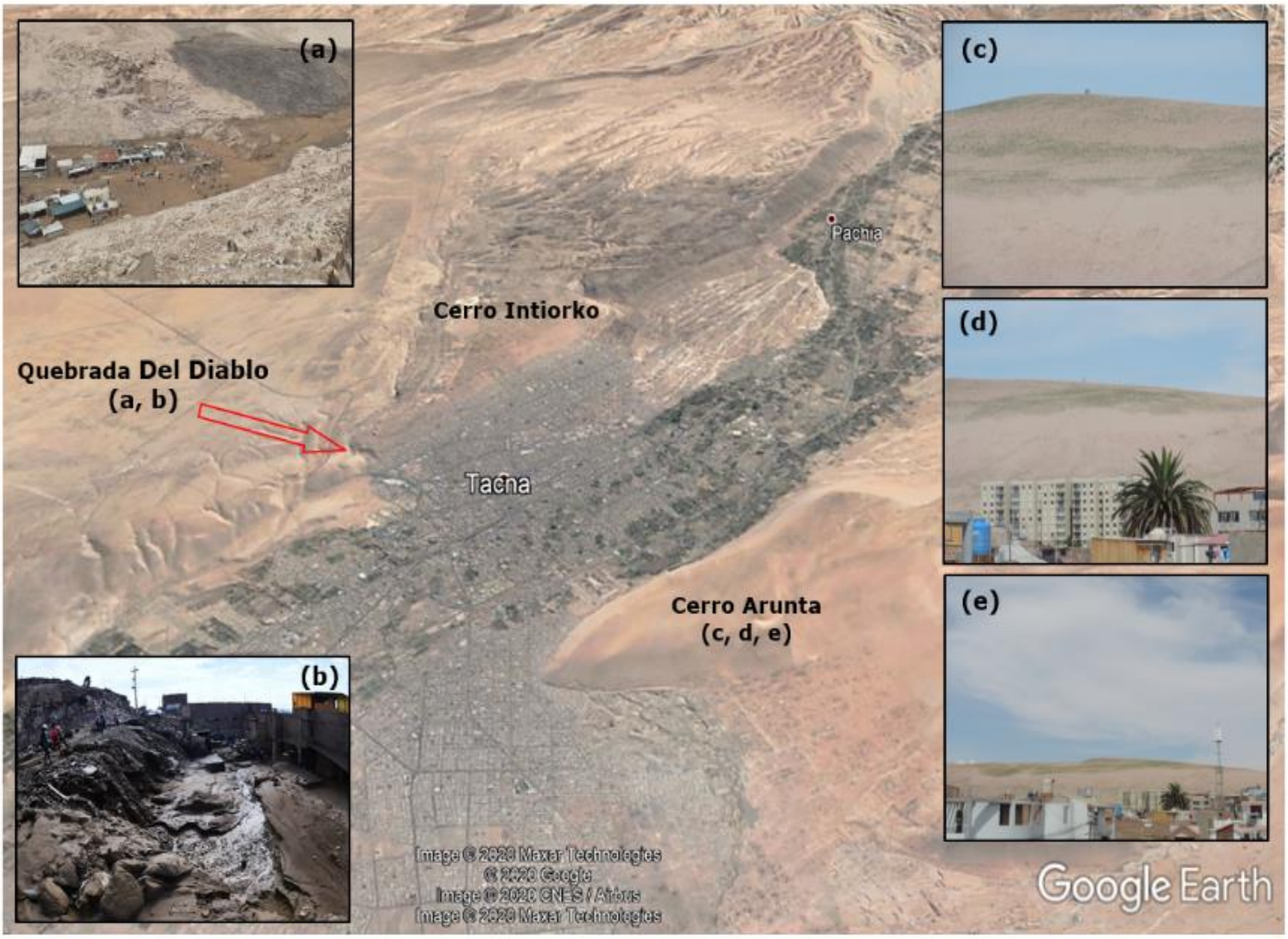

Figure 18. Right bank flood is recorded in the Quebrada del Diablo (a, b) and vegetation development on the left bank Cerro Arunta (c, d, e), February 2020.

The Hot Blob detected by NOAA originated temperature anomalies between 4 and 6 ° C and has a high probability of being the causative agent of atypical local rainfall in the study area. This was detected at the beginning of October 2019. Its effect overheated the surface seawater in the southern part of the country, triggering atypical rainfall in January and February 2020.

Conclusion

In recent years, in the head of the Atacama Desert, northern Chile and southern Peru, there have been extraordinary events of precipitation that have generated surface storage, vegetation growth and alluvial-type surface flows in areas where they were not present, such as documented in this work and which triggering factor may be attributed to La Mancha Caliente detected by NOAA. This produced temperature anomalies between 4 and 6 °C, as well as the soil antecedent moisture and atmospheric moisture transfers from the Atlantic. We consider these events as evidence of climate change in this region. Normal conditions have been altered and the damage is irrefutable. It should be specified, for example, that a large part of the road infrastructure, services, buildings, etc., are not designed considering the current climatic conditions, therefore, it is necessary to establish new regulations for the safety and adaptation of buildings according to the climate conditions. It is evident that there is a contrast between prolonged droughts and intense rains that, in the latter case, trigger floods that are rare in this region.

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