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Climatological characteristics in the extreme hyper-arid region of Pampas de La Joya, Peru. Astrobiological approach in four years of observation: 2004–2008

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Abstract: This study reports the environmental conditions of temperature, moisture and radiation for four years (May 2004 to July 2008) in the area known as Pampas de La Joya in southern Peru, which recently has been considered as a new Mars analogue. The period of evaluation includes the El Niño Southern Oscillation (ENSO) during the months of September 2006 to March 2007, which, despite not having catastrophic effects like its predecessor on 1997–1998, showed an interesting increase in humidity. Our data describe the extreme conditions present in the region and their relationship with the presence of potential habitats that could allow for the survival of micro-organisms. The average environmental temperature was 18.9 °C, with a maximum of 35.9 °C and a minimum of −4.5 °C. The annual average incident solar radiation was 508 W m^{-2}, with high near 1060 W m^{-2} at noon during the driest period between September and March. The average relative humidity (RH) was 29.5, 20.1 and 20.4% for air, soil and rock, respectively. The RH had higher values at night due to fog during the months of June and August, and during the early morning between December and March. During the months of ENSO event there were four episodes of precipitation (1.1, 1.5, 2.0 and 0.9 mm), of which three increased soil and rock moisture on an average more than 45% and persisted for over 15 days after precipitation, while the atmospheric environment had no significant variations. Finally, quartz rocks and evaporite minerals colonized with micro-organisms were found as the only micro-habitats, in this region, capable of supporting life in this extreme environment.

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Key words: hyper-arid soils, extreme environments, Atacama Desert, Pampas de La Joya, Mars analogues.

Introduction

Although, present global monitoring of climatic conditions is carried out via ground-based meteorological stations and satellite observations, regional and localized environmental conditions of geographic zones which are not considered valuable for anthropological use, such as deserts and high mountain lands, have only been evaluated on a limited basis. Because these poorly examined regions could provide noteworthy explanations to past and current geologic, geomorphologic, chemical and/or biological processes on Earth that in turn could have significant implications to future global changes, it is important that they become the subject of further detailed assessment. The lack of specific data sets is most often due to the challenges of the placement of meteorological stations in locations of interest which are difficult to access. The Atacama Desert, localized along the West coast of South America between 10 and 30° South latitude, is an interesting example of such problem. Despite the placement of meteorological stations in the important cities on the Peruvian and Chilean coasts, the climatic data from large areas of the desert are insufficient. Indeed, the data used for determining the climatology of this 3000 km long desert are mostly extrapolations of data from the surrounding cities and of certain stations that are practically non-existent over 3000 m of altitude (Houston & Hartley 2003). The wide variability in the geomorphology of the region causes the emergence of interesting microclimates, which in turn generate abrupt humidity gradients and an amazing natural laboratory characterized by extreme environmental conditions that should be better studied. This desert owes its extreme aridity to the climatic regime determined by a rain shadow effect of the Andes, which blocks the Amazon humidity, and the presence of the South Pacific anticyclone, which is usually stable in position with a small shift of a few degrees south in the summer (Trewartha 1961; Rutllant *et al*. 1998; Houston & Hartley 2003; Hartley *et al*. 2005). Interestingly, the geological and mineralogical evidence of the soil have suggested that these extreme conditions have persisted between 15 and 25 Ma, with some humid episodes in the last 4 Ma, making this desert the oldest on Earth (Dunai *et al*. 2005; Evenstar *et al*. 2005).

An interesting study of the microclimatic characteristics in the Atacama Desert was carried out by McKay *et al*. (2003) in the hyper-arid area of Yungay, Chile between ∼22° and 26° South latitude. That work described the moisture, temperature, radiation and wind present between the years 1994 and 2000, including the ENSO event of 1997–1998. Importantly, these data demonstrated the harsh features of this area as a habitat for life on Earth, which were the initial justification in order to consider it as a possible analogue to Mars (McKay *et al*. 2003). Additionally, McKay *et al*. (2003) suggest that the ENSO effect did not bring significant rain or increased moisture to the extreme arid region of the central Atacama, which accords with previous data that showed the rains did not penetrate the desert core since around 20 000 years (Betancourt *et al*. 2000).

On the other hand, Pampas de La Joya is located between the 15° and 17° South latitude, approximately 1000 km to the North from Yungay. Recently, this region has been reported to contain soils with some properties that seem to be present on the Martian regolith, such as very low levels of organic matter, a highly oxidizing matrix, and the presence of rich-Fe minerals and evaporitic salts (Valdivia-Silva *et al*. 2009, 2011). Geologically, Pampas de La Joya may be defined as a broad geomorphic unit characterized by an uplifted plain mainly floored by Precambrian gneisses and granites limited on the northeast and southwest by the Andean foothills and the Cordillera de La Costa, respectively, (Fig. 1), elevated to an average height of 1200 m a.s.l., which is divided into several sectors by the spectacular gorges of the Sihuas and Vitor rivers carved across the volcanic and sedimentary cover into the crystalline basement. Interestingly, this area seems to be younger compared to Yungay, because Pampas de La Joya does not show high amounts of exotic salts whose accumulation is likely due to the age of the hyper-arid conditions (Michalski *et al*. 2004; Valdivia-Silva *et al*. 2011). Indeed, hyper-arid conditions are enhanced at Pampas de La Joya because the Cordillera de la Costa is a topographic barrier that condenses most humidity on the lee side of the wind coming, from the Pacific Ocean. On this side of the range clouds commonly touch the ground-producing fogs that are used by xerophytes to live precariously on a rock surface. These physical factors suggest a new scenario in order to evaluate the environmental conditions at the beginning of the formation of deposits in hyper-arid soils. In addition, even though this area is more susceptible to the ENSO effects because of its greater proximity to the Equatorial region than Yungay, preliminary data of the precipitation at nearby cities did not have any relationship with data taken at the driest core of the Pampas de La Joya (Valdivia-Silva *et al*. 2011).

This study (1) describes the meteorological data, including temperature, moisture and radiation in Pampas de La Joya, including the ENSO (2006–2007), which, despite not having as drastic consequences as the previous one (Takayabu *et al*. 1999), apparently gives a source of moisture to the soils; (2) discusses the potential niches capable of supporting life in extremely arid zones like this part of the desert; and (3) gives a comparative frame with the extremely dried region of Yungay in order to establish future survival models of organisms in arid conditions such as Mars'.

Methods

Site description

Our study site is named 'Pampas de La Joya' or alternatively 'La Joya Desert' and is located at ∼70 km Southwest from Arequipa city, Peru, along the South Pacific coast, at about latitudes 16°S–17°S, and at longitudes of 71.5°W–72.5°W, and at approximately between 1000 and 2000 m a.s.l. (Fig. 1). The total area of this region forms part of the Atacama Desert belt, inside of the hyper-arid area (Houston & Hartley 2003). Our specific area of analyses encompasses an area of 96 km^2 referred in this paper as the 'quadrangle of interest' (diagonal coordinates: 16°38.386′S–72°2.679′W; 16°44.986′S–71°58.279′W) (Fig. 2). This quadrangle presents the more interesting locations of evaporitic minerals, quartz and soils with high oxidant activity and very low levels of organic matter (Valdivia-Silva *et al*. 2009, 2011).

Instrumentation

The meteorological data were monitored annually between the years 2004 and 2008, using data HOBO (Onset Inc.) logger operated by one-year classic batteries and connected to sensors and rain gauges placed at four different sites in the studied zone (Table S1 available online at http://journals.cambridge.org/IJA, Fig. 2). The measurements were taken with a frequency of 30 minutes. The assessed data were environmental, soil and rock temperature (°C); relative air humidity (%); soil humidity at a depth of 15 cm, beneath the rocks and the shallow soil layer between the rocks; precipitation (mm); the photosynthetically active radiation (400–700 nm) ($\mu mol\ m^{-2}\ s^{-1}$); and UV radiation (this latter evaluated only since June 2006 to March 2008) ($W\ m^{-2}$).

The HOBO recorders (Nos. H08-004-02 and H08-006-04; Onset Inc.) of relative humidity (RH), temperature and light intensity, present four entrance channels to store data transmitted by each specific sensors; they are programmable start/date time, and are capable of storing up to 7943 and 32 500 measures, respectively (8-bit resolution). The operation range for temperature is −20 °C to 70 °C and the RH is 0–95% without condensation. The temperature (T) sensor can evaluate a range of −20 °C to 70 °C, with an accuracy of ±0.7 °C to 21 °C, a 1-minute time response and a resolution of 0.4 °C to 21 °C.

The humidity sensor can assess an RH range of 25–95% at 27 °C at <10 second interval, without condensation, with an accuracy of ±5%, a 10-minute time response (in air) and an accuracy in time of ±1 minute/week to 20 °C.

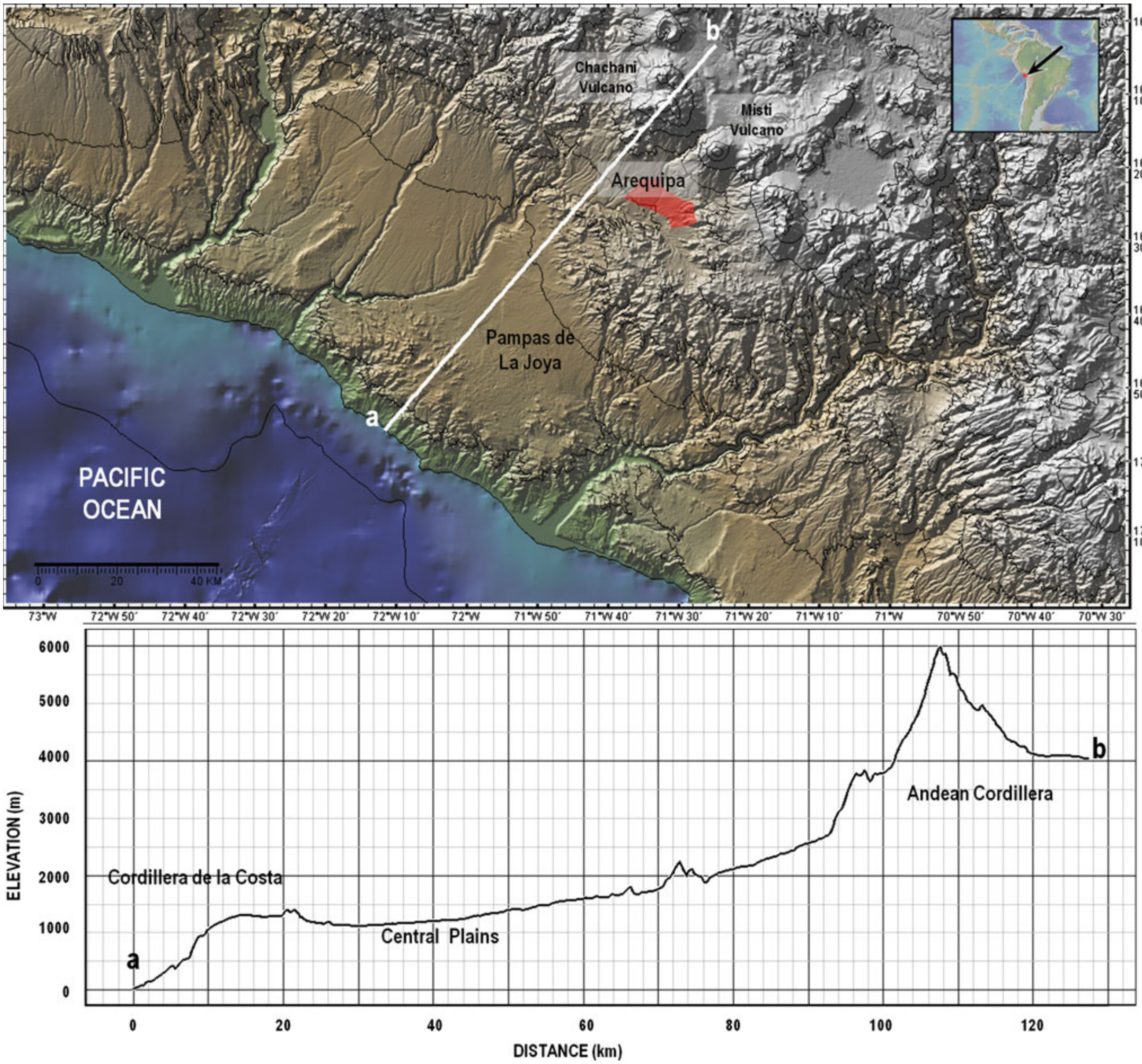

Fig. 1. Location of the Pampas de La Joya in the extremely dry region of the Atacama Desert in southern Peru. The city of Arequipa is located ~70 km away at the foothill of the volcanoes Misti, Chachani and Pichu-Pichu. The white line in the top corresponds with the cross-section of the desert. (Map source: free software GeoMapApp 3.0.)

The RH sensors at extremely dry soils in Pampas de La Joya are an excellent way to monitor the soil humidity because their output is linear with RH (McKay *et al.* 2003; Davis *et al.* 2010). Additionally, a sensor ECH2O-20 (Decagon Devices Inc.) was placed under stone in order to measure the soil capacitance which is dependent on the budget water content. Conductivity probes were also placed under stone. The test is based on a decrease in voltage between two wires 5 mm apart, referenced to a 2.2 kΩ resistor utilizing a 2.5 V alternating current excitation. In addition, a qualitative sensor was placed on the surface in order to detect the condensed humidity of the desert (Leaf Wetness Sensor, SpectrumTechnologies Inc.). The dew sensor recorded a signal from 0 to 1 that is dependent on the amount of moisture present on the sensor surface. There is no quantitative calibration for this unit, but its proper operation was confirmed after three years in the field. The sunlight intensity sensor (pyranometer) consists of a silicon detector sensible to light with a wavelength of 400–1100 nm, and a mean error of <10%.

The precipitation registry was carried out by two autonomous rain gauges (No. RG3; Onset Inc.), with a one-year battery, an integrated HOBO sensor for temperatures, and a 64 kb memory stick. The maximum precipitation frequency detected is 12.7 cm h^{-1}, with an accuracy of ±1.0% (20 mm h^{-1}), and a resolution of 0.2 mm. The UV radiation record was taken by the UV sensor, SU-100 (Apogee Instruments Inc.), which measures wavelengths between 250 and 400 nm, expressed in μmol m^{-2} s^{-1}.

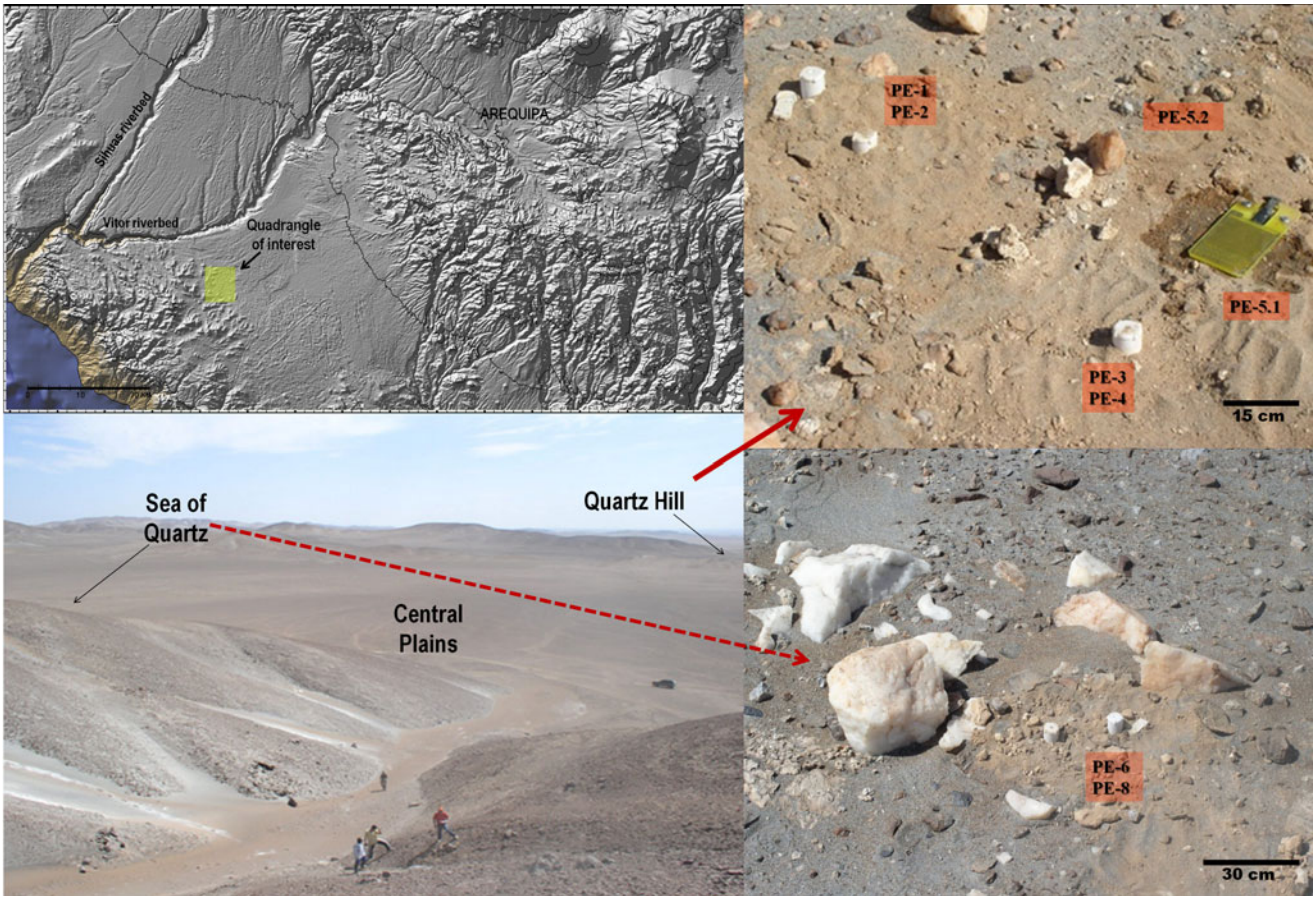

Fig. 2. Location of the study area (or quadrangle of interest) in the Pampas de La Joya, and the main areas of observation and data collection (Sea of Quartz, Central Plains, and Quartz Hill). The specific locations of the instruments are described in Table S1. (Map source: free software GeoMapApp 3.0.)

All sensors were calibrated according to the manufacturer's instructions. The dates that the HOBO sensors were deployed were May 2004 and July 2004. The rain gauge was installed in August 2004. The UV sensor was placed in June 2006. The brand of sensors used in this study was previously validated by other studies carried out by our research group in Yungay, Antofagasta-Chile, and Pico de Orizaba, Veracruz-Mexico (Pérez-Chavez *et al*. 2000; McKay *et al*. 2003, 2009; Cruz-Kuri *et al*. 2009).

Additionally, we used temperature, wind (speed and direction) and moisture (including daily absolute humidity) data obtained by the government-owned meteorological stations of Servicio Nacional de Metereología e Hidrología del Perú (SENAMHI, 2010) located in La Joya city (16°41.927′S, 71°54.55′W), and of the Peruvian Air Force located 16 kilometres away from the quadrangle of interest inside the hyper-arid area (16°46.48′S, 71°53.30′W).

Results and discussion

The summary of the meteorological data collected during the 4-year evaluation (May 2004 to July 2008) is presented in Table S2 (available online at http://journals.cambridge.org/IJA). The list includes the average values of the air and the rock temperature, the RH of the air, under the rocks and soil, as well as the precipitation and sunlight radiation. The data from sunlight radiation were collected from June 2006 to March 2008.

Temperature

The temperature regime in Pampas de La Joya is temperate and similar to the other areas in the Atacama Desert, in contrast to other, extremely hot (Mojave and Saharan) or cold (the dry valleys in the Antarctic) desert areas in the world (McKay *et al*. 2009). Thus, the maximum temperature recorded during the 4 years of recollection was 35.9 °C and the minimum was −4.5 °C. The environmental average temperature was 18.9 °C, which shows that this region is about 2.5 °C warmer in comparison with the mean obtained for the Yungay region, which was 16.5 °C (McKay *et al*. 2003). Figure 3 shows the daily environmental average temperature and the rock temperature during 2005, besides the minimum and maximum temperatures obtained monthly during that year. Generally, the maximum daily environmental temperature reached 30 °C throughout the year; whereas the minimum daily temperature depended on the season of the year: during May and August,

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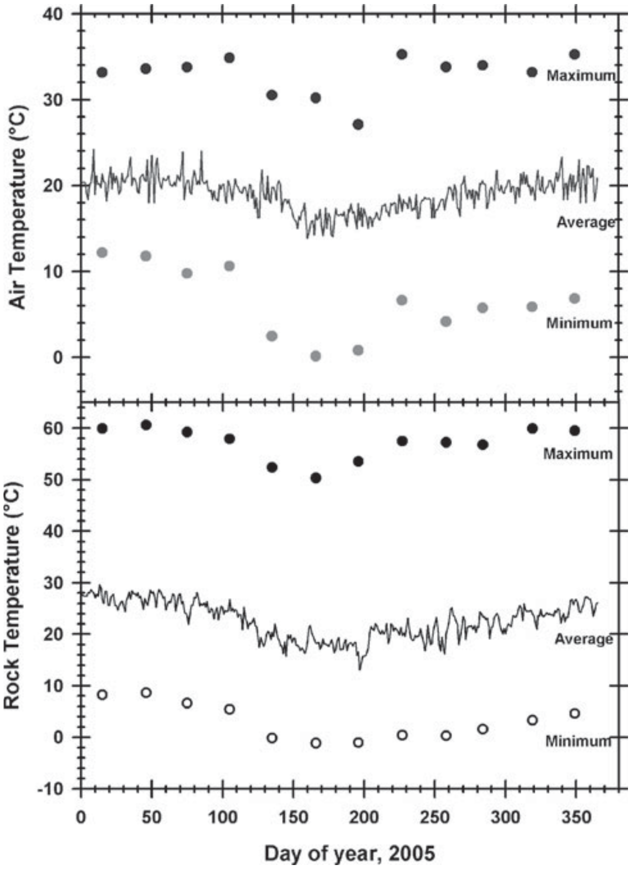

Fig. 3. Daily average values (lines) and monthly maximum–minimum values (dots) of the air and rock temperatures in Pampas de La Joya for the year 2005.

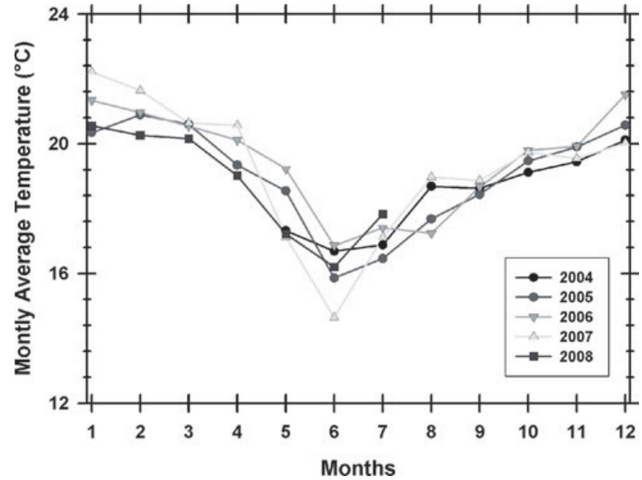

Fig. 4. Monthly average temperatures in Pampas de La Joya from May 2004 to July 2008.

the minimum temperature reached −4.5 °C, while the rest of the year reached 4 °C. Furthermore, the soil rock temperature reached a maximum of 60 °C and a minimum of −6 °C. The presence of this temperature oscillation in the rock was evident because of the high mechanical fragmentation (thermoclastic) found everywhere in the bedrock of desert. Interestingly, this process has strongly been associated with rock weathering (McKay *et al.* 2009). The average temperature of the rocks taken during the 4 years of recording was 25.2 °C (~ 6 °C more than the environment), which is significantly different to the average of air temperature (Mann–Whitney *U*-test, $p<0.05$). The variability found in our data present a similar behaviour to the temperature data recorded in the Yungay region (McKay *et al.* 2003). The temperature, in general, was not affected by the ENSO event during 2006 and 2007, as it is evidenced by the little variation on the monthly or inter-annual values throughout the 4 years evaluated (Fig. 4). Interestingly, when comparing the monthly means of the air temperature during those 4 years, there were no substantial differences among them (ANOVA, $p=0.12$). Only, the monthly mean of the temperature of June 2007 showed a statistically significant value with respect to the rest [$p=0.02$], defining this month as the coldest of the entire studied period. Certainly, our data showed that the coldest months in Pampas de La Joya are May, June and July, which coincide with the winter season and the fog entrance, as will be explained below. Data sets for 2004 and 2008 were incomplete, but the annual average temperatures were 18.3 and 18.7 °C, respectively.

Moisture

The whole registry of the humidity sensors during the 4 years of evaluation, expressed as the monthly average values, is shown in Fig. 5. The moisture due to condensation (dew) was scarce during the 4-year evaluation (values <1) except for September and October 2006, where heavy precipitations occurred and were related to the ENSO event. There was a positive response from the sensor, particularly during the nights of the months of June, July and August, which coincide with the cold temperature and the presence of dense night fog. It is also interesting to note that precipitations lower than 1 mm did not generate a response in the dew sensor higher than '1'. When no rains fall, or with precipitations lower than 1.1 mm, the soil humidity remained close to 30%, which is extremely arid for soils (McKay *et al.* 2003; Davis *et al.* 2010).

Interestingly, only the three precipitations in September and October 2006 (see Table 1) raised the monthly mean of RH close to 50% (Fig. 5) or the daily mean to 100% during the events (Fig. 6). The humidity under the rocks presented the same pattern as the soil, although it kept a little more of the moisture *in situ*. Curiously, the RH of the air did not present important variations during or after the precipitations, and they remained between 25 and 35%. The increase in the RH in the months close to June, July and August occurred mainly during the night and was caused by the entrance of fog. At this time, the RH values reached more than 75%, which agree with the previous observations of Fabré *et al.* (2006), and allows the formation of 'hills' or 'lomas' (specific zones with temporary vegetation), but only in areas where topography is flat (generally located below 500 m a.s.l.) and there is communication with the coast (Cereceda *et al.* 2002). In most cases, the seasonal fog is not sufficient to allow the growth of macroscopic organisms. The increase of RH during January, February and

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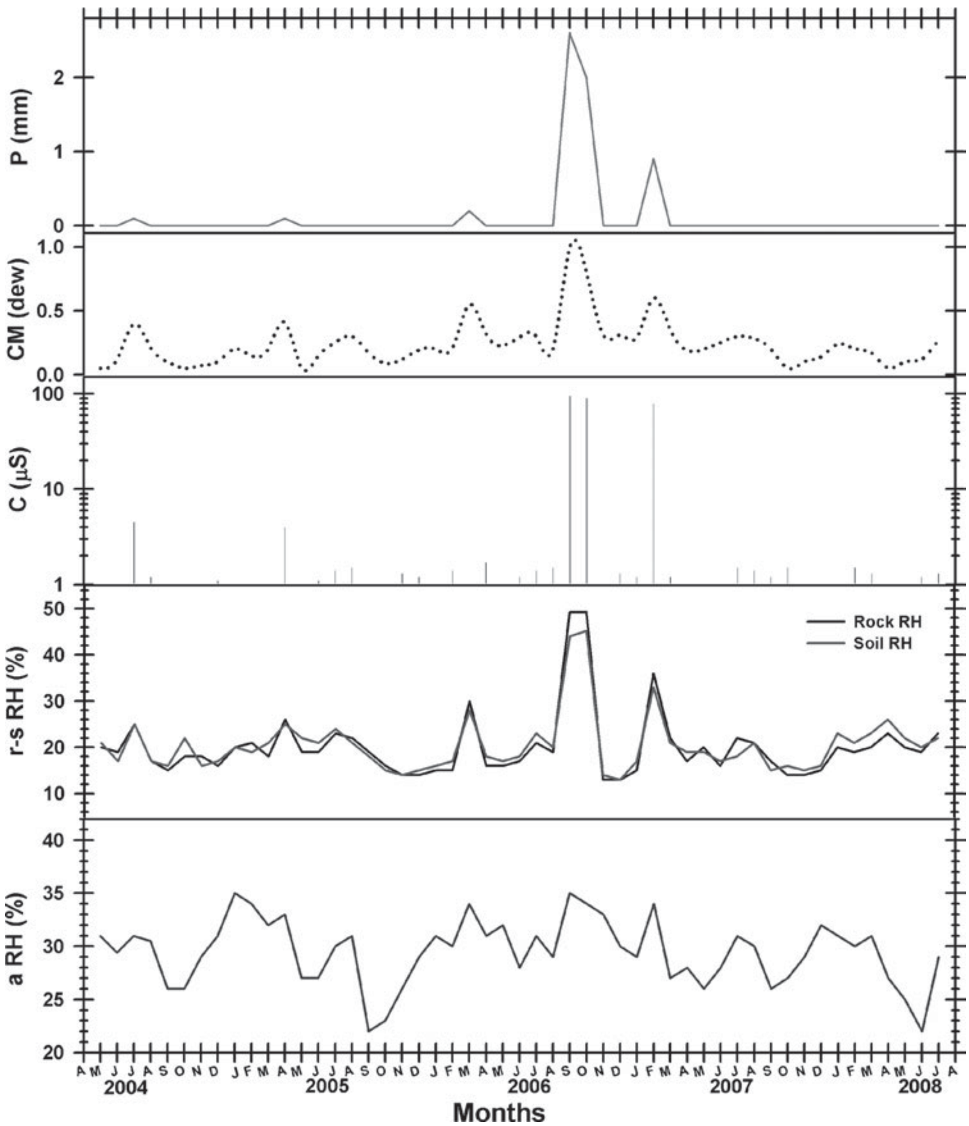

Fig. 5. Monthly moisture patterns in Pampas de La Joya. *Top panel* shows the precipitation levels (in mm). *Second panel* shows values of dew or condensed moisture (values are ranged between 0 and 1). *Third panel* shows the conductivity (C) beneath the rocks (in µS). *Fourth panel* shows RH in soil surface and under the rocks. *Bottom panel* shows the RH in air (in %).

Table 1. *Rain events in Pampas de La Joya (May 2004–July 2008)*

Date	Precipitation (mm)
17 de Julio 2004	0.1
16 de Abril 2005	0.1
14 de Marzo 2006	0.2
12 de Setiembre 2006	1.1
14 de Setiembre 2006	1.5
3 de Octubre 2006	2.0
12 de Febrero 2007	0.9

Rain events during the ENSO event are indicated by italics.

March is due to the increased humidity from the rains, which fall in the nearby coastal regions and in some inter-Andean basins connected with the sea due to rivers that come from the glaciers in the Andean Cordillera. Importantly, the average value of RH close to 35% is not enough to allow the growth of visible forms of vegetation.

During the 4 years of evaluation, seven precipitations events were recorded (Table 1), two of them were on the detection limit of the rain gauge ($\sim$0.1 mm) and one in 0.2 mm; which might suggest fog condensation instead of precipitation. The events with rain higher than 1.1 mm coincided with the ENSO event in 2006–2007.

The seven events of rain occurred mainly during the nights and lasted up to 20 minutes, which supports the hypothesis that condensation of heavy fog occurred in the minor events, instead of a real precipitation. During the ENSO, four precipitations were recorded, three of them in September and October (1.1, 1.5 and 2.0 mm). These events gave a considerable increase to humidity of the soil, under the rocks and subsoil (10–15 cm below the surface) for more than 15 days (Fig. 6). The increases in soil moisture under the rocks

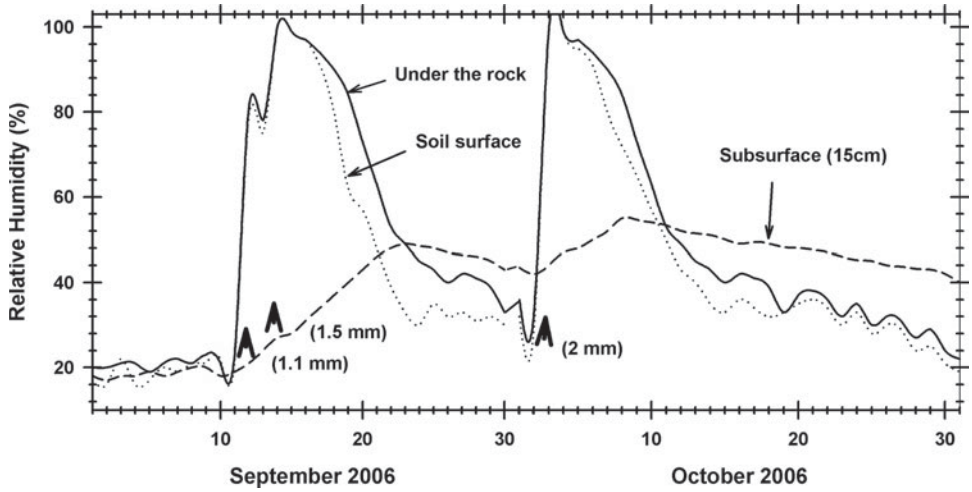

Fig. 6. Detailed plot of the rain events of 12 and 14 September, and 3 October 2006 (indicated by arrows) and the consequent soil moisture. RH values of soil surface, under the rocks and shallow subsurface (15 cm) are plotted. Importantly, high moisture levels at 15 cm below the soil surface are retained two and three times compared to levels on the surface.

confirmed the penetration of the precipitations during the ENSO (Figs. 5 and 6). After the subsequent rainfalls on 12 and 14 September (1.1 and 1.5 mm, respectively), the RH of the soil and under the rocks increased above the basal conditions up to 15 days after the events (Fig. 6). In addition, the shallow subsurface (~15 cm depths) showed that RH rose progressively from values of ~20% to about ~50% after 10 days from the precipitation. This observation suggests slower processes of water infiltration due to soil layers with higher density and lower porosity, which in turn prevents rapid evaporation. Curiously, 20 days later, another rainfall event was recorded at the hyper-arid area (2 mm) and the RH in the subsurface increased faster from ~40% to ~55% in only 6 days. This is probably due to the previous rain events, which caused processes of dissolution on the first soil layer and the drag of salts carried down by the water into rock cracks to greater depths. So, a new precipitation followed closely in time might have generated more free water in the pore space of the soil than the earlier events. Moreover, the subsoil humidity remained at 35% up to 20 days after the last event and did not return to the pre-rain values (~25%) until nearly a month later. Definitely, this process was unique in the desert, because if the precipitation on 14 September had not happened (or the one on 3 October), the values of RH in the subsoil would have returned to the values before the rain much more rapidly, as was observed in Yungay (McKay *et al.* 2003). Certainly, the precipitation in that region on 11 May 1997 (2.3 mm) showed that the RH of the soil remained more than 20 days after reaching the maximum value between the eighth and ninth day after the event. Importantly, our study has not recorded that RH climbed back from the subsoil to the surface. Davis *et al.* (2010) conducted a series of simulated rain experiments in the arid core region of Yungay, Chile. They observed that simulated rains above 2 mm, showed a return of water to the surface from subsurface due to upward migration of water vapour 24 h after the rain simulation. Additionally, they found that the shallow surface was a strong barrier to the diffusion of moisture into the deeper layers. Here, our observations did not show these behaviours. The hyper-arid conditions in Pampas de La Joya are younger than Yungay (~5 versus 25 Ma, respectively) (Valdivia-Silva *et al.* 2011), so that geochemical processes for the genesis of hard crusts (duricrust) deposits of salts might even be in progress. This fact could explain the greater diffusion downward and minor climb back of RH found in these soils compared with those of Yungay (McKay *et al.* 2003). Importantly, the quantities of water vapour that returned to the surface did not show biological significance, but might be important for the salt transport during the thickening of the crust layers.

On the other hand, the RH of the soil surface and under rocks went down faster in just 7–8 days after reaching values close to 80% (with the first rain of 1.1 mm) and to 100% (with the next precipitation on the second day of 1.5 mm and the following one 20 days later of 2 mm). The RH under the rocks kept the humidity a little bit longer than the soil, but it could not be regarded significant. Given that the precipitations occurred in September and October 2006, they were attributed to the precipitation increase on the Peruvian coast associated with the ENSO event. Whereas the precipitation of 2.3 mm in Yungay had its origin in ENSO from 1997 to 1998 (Ulloa *et al.* 2001), which caused huge ravages on the Peruvian northern coast, the events at the hyper-arid core of Pampas de La Joya for those years were not analysed. Because there is no correlation between rainfalls recorded by meteorological stations on La Joya town and the central plains of the Pampas de La Joya (data no shown), our data only might suggest similar or major precipitation events during that period in the core of the desert. One study suggested that the main source of water for hypolithic bacteria like cyanobacterium in the hyper-arid environment of Negev desert is the condensate humidity (Friedmann *et al.* 1967; Friedmann & Ocampo-Friedmann 1977). Our observations in Pampas de La Joya do not seem to be the main source of humidity, just like in the case of Yungay, Chile (McKay *et al.* 2003). However, it is well known that the water

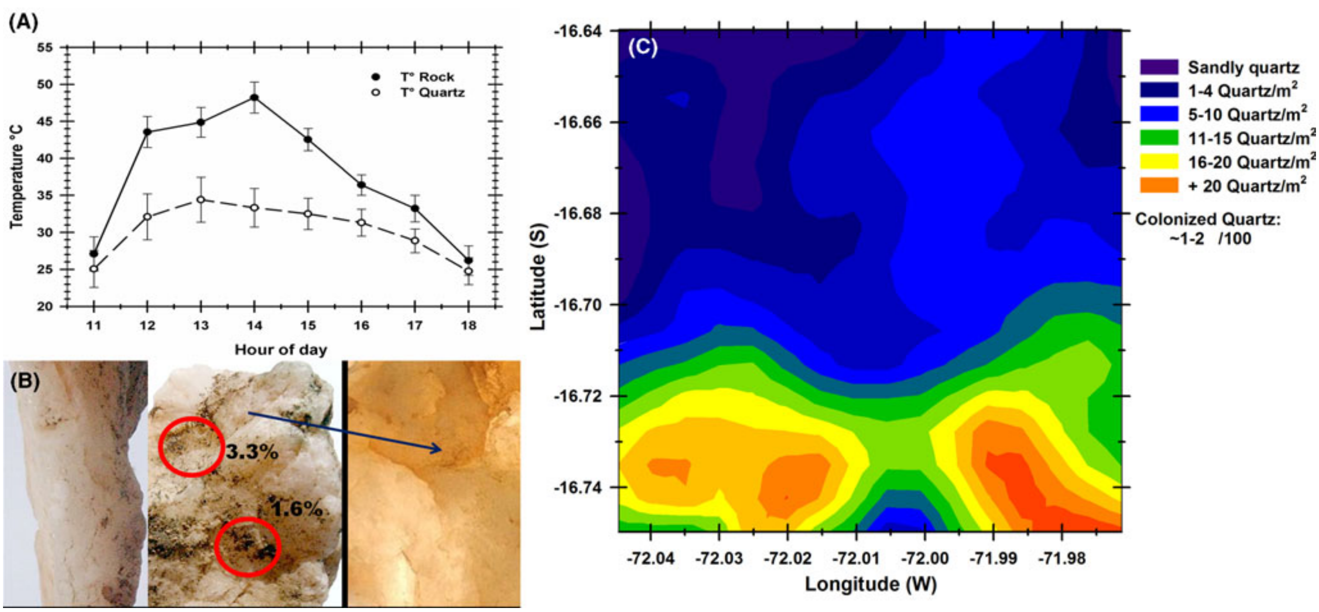

Fig. 7. Quartz rocks as potential habitats for micro-organisms in Pampas de La Joya. (a) Effect of quartz as a thermal damping material compared to other rocks in the desert. (b) Quartz allows sufficient photosynthetically active radiation (PAR) to permit the growth of micro-organism colonies. (c) Quartz distribution in the study area in Pampas de La Joya. Various factors that prevent the colonization of these rocks require further study.

molecules trapped in the cracks and pores of certain kind of rocks, salts and minerals, in addition to a relative 'long-term' humidity in the subsoil, may allow the presence of micro-organisms (Warren-Rhodes *et al*. 2006; Wierzchos *et al*. 2006; Davila *et al*. 2008).

Moreover, a preliminary evaluation of the temperature of the rocks in the desert showed that quartz had characteristics of temperature damping, even in the hours when the rocks had temperatures higher than 50 °C, which allowed a longer time of condensation of water and avoided a faster evaporation (Fig. 7(a)). This fact was confirmed with an infrared portable thermometer (Omega ETR), in quartz rocks from Yungay (Azúa-Bustos *et al*. 2011) and Pampas de La Joya regions (Figs. 7(a) and (b)). Moreover, in colonized quartz minerals, the levels of radiation for photosynthesis reached values between 3.2 and 0.4% under the rocks, corroborating that these types of rocks are excellent habitats for autotrophic micro-organisms (Fig. 7(b)). Although just 1 or 2 out of 100 quartzes are colonized, the factors that modify this fact still remain poorly understood, but might be explained by the RH changes and microclimates (Davila *et al*. 2008), the type of salt minerals, or probably by the presence of strong oxidants in surrounding areas, which impact the metabolic activity of micro-organisms (Navarro-González *et al*. 2003; Quinn *et al*. 2007; Valdivia-Silva *et al*. 2009). An interesting point is the fact that, in spite of the existence of a certain level of dew in the desert due to the fog or dew condensation, it is not enough to allow the growth of macroscopic organisms on the zone. Only rain increased the values of humidity in the soil. Considering the abundance of quartz in Pampas de La Joya (Fig. 7(c)), Yungay, and probably in Mars (Banfield 2002; Warren-Rhodes *et al*. 2006; Warren-Rhodes *et al*. 2007), it is an interesting possibility for biological exploration. An ongoing study in this area is evaluating the relationship and distribution between quartz, soil moisture and the presence of endolithic cyanobacteria, which might solve some questions.

Figure 8 shows the typical humidity on any day in July, with increased humidity at night because of fog, and a day of September (same year), when all day was dry. Figure 8(a) depicts humidity nearly to saturation levels around midnight and at dawn, but which remained constant until early morning when sun temperature and radiation rise. When compared with a dry day (Fig. 8(b)), sun temperature and radiation had no significant difference, but the relative and absolute humidity values undoubtedly show the low environmental humidity of the desert.

Solar radiation and wind

The solar radiation values are summarized in Table S2. The monthly average is taken from daily values every month, just in radiation hours of the day (from 5.15 hours up to 18.30 hours), where the solar radiation diminishes nearly to zero. The Pampas de La Joya has no clouds. The mean annual solar radiation was 408 W m^{-2}, with a maximum of 1060 W m^{-2} at noon in the driest days between the months of September and April, and slightly lower during the most humid days between May and August. The surface radiation is high and heats the rocks up to 20 °C higher than the air, a fact that is confirmed by the coincidence of the maximum rock temperature with the maximum solar radiation (Fig. 8). Importantly, the annual average of solar radiation in Pampas de La Joya was higher than the annual value found in Yungay (336 W m^{-2}) (Mckay *et al*. 2003). This fact might be related to the variations at the ozone hole (Liley & McKenzie 2006).

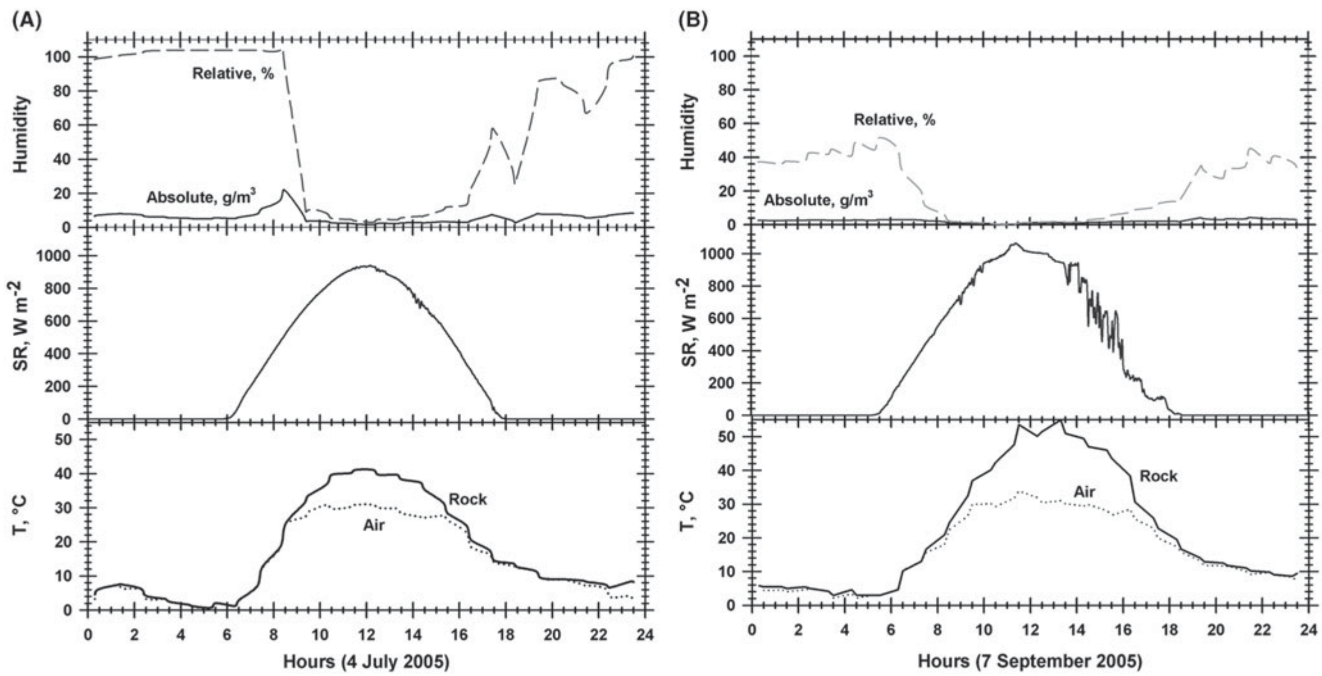

Fig. 8. Daily cycle of air moisture (relative and absolute humidity), solar radiation (SR), and air and rock temperatures, comparing one day with night fog (4 July 2005) versus another with no night fog (7 September 2005). Solar radiation did not have any significant difference between them.

On the other hand, the data of speed and direction of winds in this area corroborated their important correlations with temperature and moisture, as it was demonstrated in previous reports throughout the Atacama Desert (Moody 1979; Escobar 1993; McKay *et al*. 2003). In general, the more the wind speed increased, the more temperature values were recorded, and inversely with the moisture (data not shown). The wind direction for these dry hot winds was from the northwest towards the southeast with oscillation between 180° and 260°. The wind speeds were between 5 and 20 m/s and mainly in the early morning and in the afternoon. The down slope winds from Andean mountains (on the northeast and east, see Figs. 1 and 2) contributed weakly compared to the winds from the Pacific Ocean. So, similar to the Chilean region, winds may be an important transport mechanism for salts and minerals, and would tend to accumulate material on the east and southeast sides of the desert plains.

Conclusions and astrobiological perspectives

The distribution of living organisms, organic matter and chemical properties in Mars-like environments on Earth can be used as a model to guide the investigation of possible habitable environments on Mars (McKay 2004). Recently, Mar de Cuarzo (Sea of Quartz), located into our quadrangle of interest in Pampas de la Joya in southern Peru has been demonstrated to contain soils with similar characteristics to those found on the Martian surface (Valdivia-Silva *et al*. 2011), such as : (a) hyper-arid soils with a lower concentration of organic matter, (b) geomorphologic Martian features, (c) similar physical properties to Martian landing sites, (d) dramatically low levels of micro-organisms, and (e) high oxidant activity during thermal and labelled release experiments. While we are aware that the current environmental conditions on Earth are different from those present on Mars, geologic and atmospheric conditions between the 4.5 and 3.8 Ga ago are thought to have been very similar, including a thick CO_2 atmosphere, active volcanism and large bodies of stagnant water, among other characteristics (McKay & Davis 1991). When Mars entered a dramatic period of dehydration after losing its atmosphere, these conditions could have given great adaptive strength to potential micro-organisms present there, indeed, if they ever existed. This hypothesis can be somewhat explored in hyper-arid environments that have extreme conditions for the survival of life. In this study, we described the extreme climatic conditions of the hyper-arid region of Pampas de La Joya, based on 4 years of climatologic observations, in order to understand the possible limits for life, principally related to the availability of water required to support biological organisms in soil or rocks. Similar to the Yungay region, which is considered the driest location on Earth (McKay *et al*. 2003; Ewing *et al*. 2006), Pampas de La Joya presented very low precipitation and insufficient water for the growth of macroscopic organisms. Interestingly, this region showed the presence of shorter moisture transects near the driest areas, facilitating the study of geochemical processes and the influence of moisture in the soils. Our observations demonstrated a very low relative ground humidity that only increases with a rainfall greater than 1 mm, but which also lasts only for a short time on the surface making it unavailable for use by living organisms. High temperatures in the soil and rocks after sunrise combined with very low temperatures after dusk, causes mechanical fragmentation of rocks and dramatic and abrupt thermal changes that make it nearly impossible for the survival of micro-organisms trying to eke out a meagre existence within these rocks. Throughout the deserts of the western coast of South America, marine layer fogs appear to be the principle mechanism to provide sufficient water to support a surprising extent of biodiversity that includes hypolithic cyanobacteria (Warren-Rhodes *et al*. 2006), non-lichenized fungi (Conley *et al*. 2006), lichens (Rundel 1978) and even cacti (Rundel *et al*. 2007). However, the hyper-arid core of Yungay does not appear to support abundant microbial photosynthetic communities (Warren-Rhodes *et al*. 2006) beyond specialized niche communities such as endolithic cyanobacteria hidden in halite salt outcrops (Wierzchos *et al*. 2006) and possible subsurface bacterial communities (Drees *et al*. 2006). In the same way, 1000 km to the north of the Yungay area, the Pampas de la Joya presents extreme conditions for life. Preliminary counts of micro-organisms for the Pampas de La Joya soils were similar to results previously measured by different techniques in Yungay ($\sim 10^4$–10^6 CFU/g) (Drees *et al*. 2006; Lester *et al*. 2007; Warren-Rhodes *et al*. 2007; Valdivia-Silva *et al*. 2011) suggesting a similar process for survival of organisms in hyper-arid soils despite lower organic concentration. The comparison of the type of micro-organisms present in these soils versus those found in Yungay could help provide a better understanding of the processes of bacterial evolution in the dry limit.

Finally, this study remarks that (1) the ENSO effect of 2006–2007 did not bring significant rain or increased moisture to Pampas de La Joya region, (2) dew and fog were not a significant source of moisture in the soil, (3) for rains events larger than 1.1 mm, moisture was retained in soils at shallow subsurface (15 cm) for more time than in soil at the surface ($\sim$15 versus 30 days, respectively), (4) despite three consecutive rain events, the penetration of liquid water beneath rocks was shown not to be sufficient for bacterial colonization, (5) the presence of possible potential habitats, such as quartz minerals and evaporitic deposits in this desert, constitute an important point of comparison for other hyper-arid regions with demonstrated biological colonization, and (6) our data might be used as a guide against which to compare the water movement in the upper permafrost of Mars, where the melting of underground ice is probably the only likely source of liquid water.

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