DUST AND AEROSOLS IN THE ATACAMA DESERT

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Abstract

The Atacama Desert is one of the driest and oldest deserts on Earth. The extreme scarcity of rainfall and hence very limited runoff, paired with endorheism, allow sediments and deposited materials to largely remain in the pedosphere and for long periods of time, thereby leading to the generation of thick sediment, salt, and soil deposits. Aerosols are the main inputs of exogenous material to this system. The dominant aerosols deposited in the region are from sea spray, soil and salar playa deflation, volcanic emissions, along with secondary aerosols. The whole Atacama region receives particulate matter (minerals, salts, organic compounds, and microorganisms of variable content) from the Pacific Ocean, the coastal desert, and the Andes Cordillera and Altiplano. Some water may reach the western margin of the Atacama hyper arid core due to fog advection via the Coastal Cordillera.

However, despite its aridity, large dust outbreaks from the Atacama Desert are rare. Atmospheric deposition is of great relevance for the landscape evolution of the Atacama Desert. This review summarizes current knowledge on the evolution of the landscape and the climatic conditions that led to it, and the salt and soil deposits, along with other geophysical features, in order to identify the frontier of aerosol research in the Atacama Desert.

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Introduction

The dust cycle is an integral part of the Earth system (Carslaw et al., 2010; Shao et al., 2011) and the arid zones are of special interest since they are indicated as the main dust sources (Kohfeld et al., 2007). Dust in the atmosphere affects the climate through several ways, e.g. scattering, absorbing and reflecting radiation or serving as nuclei for cloud formation and altering their optical properties and lifetime, and influencing precipitation processes (Andreae and Crutzen, 1997; Mahowald et al., 2014). Dust also has a significant impact on the biosphere, e.g. fertilizing the Amazon rainforest (Yu et al., 2015) and enhancing the marine productivity (Schulz et al., 2012) due to the fact that aerosols carry carbon, iron, phosphorus, among other relevant nutrients (Shao et al., 2011). This supply is of great significance because of the role of dust in the elemental cycling and its influence on the community structures of vegetation (Jiao et al 2018; Jickells et al. 2005; Mahowald et al. 2014).

The Atacama Desert, one of the oldest and most arid deserts on Earth, offers a unique view of the importance of atmospheric inputs of elements to soils since the deposited material tends to remain in the pedosphere and not to be leached (Amundson, 2003). This is because large areas of the Atacama Desert experience decades without rainfall, so the arid landscape and its hyper arid core are not subjected to water erosion regularly, except for the few rivers, some of which intermittent, that are fed by highland precipitation. These rivers, especially ephemeral ones produced by rare rainfall events, are important for dust-related processes since their erosive action produce and mobilize fine sediments which can be entrained by wind once they are desiccated. Permanent rivers such as the Loa

River (21.4 ºS), for instance, crosses the hyperarid core of the Atacama, and have produced extremely deep canyons in the landscape. To the north, also within the hyper arid core of the Atacama, rivers such as the Lluta (18.4 ºS), Vitor (18.7 ºS), and the Camarones (19.2 ºS) are present. To the south of the Loa, located at 26.4ºS, the intermittent Salado River can be found, whereas in the southern margin of the Atacama Desert, the Copiapo River (27.4 ºS) is present within the transition zone to a semi-arid conditions according to Ewing et al (2006). Some of these rivers maintain valleys in their path, usually homonymous with the name of the river, and their discharge to the Pacific Ocean produce wetlands. Recently, we have observed the impact of extreme rainfall over the Atacama landscape by flooding, e.g., the 2015 and 2017 events (see Section 1.4).

The variation of water tables of aquifers within the hyperarid core is also relevant since once the water level decreases, sediments may be exposed and suspended by the wind. Conversely, water tables very close to the surface can keep the soil moist, which allows the trapping of atmospheric deposits and prevents their re-suspension. As dust accumulates it reduces the rate of evaporation and increases surface soil moisture, leading to further dust accumulation (Pye, 1987). Moreover, the aquifers recharge produced by rainfall, that are rare and eventually extreme, washes the atmosphere scavenging ions and transferring salts from the atmosphere to soils and also to surface water bodies and aquifers together with salts accumulated in snow and ice glaciers mobilized by melting and the consequent water runoff (Barraza et al., 2021; Gamboa et al., 2019; Houston, 2002; Sepúlveda et al., 2014; Urrutia et al., 2019).

Although there are areas of active water erosion in the Atacama Desert, in general the landscape present very low erosion rates (Jungers et al., 2013; Placzek et al., 2010), and a smooth topography (Clarke, 2006; Riquelme et al., 2007) due to the continuing accumulation of the atmospheric deposits (Clarke, 2006), enabled by the hyper-aridity conditions prevalent there for millions of years.

Despite its hyper aridity, the Atacama Desert rarely sees strong dust outbreaks. Thus, considering the limited sediment removal, the atmospheric deposition of dust has been suggested as the parent material of the local soil (Ewing et al. 2006; Wang et al. 2014). It is believed that strong dust outbreaks are inhibited in the Atacama because of the local climatic and topographic conditions such as wind regimes and the cordilleras acting as natural barrier (Reyers et al., 2019). Dust emission nevertheless occurs, for instance, as dust devils and non-rotating dust plumes (Jemmett-Smith et al., 2015). Dust devils are driven by the strong thermal instability of the atmospheric boundary layer triggered by the diurnal solar heating of soils and the intrusion of the cold air from the Pacific Ocean into the Atacama (Kurgansky et al., 2011). Wind erosion is also associated with wind gusts, which have a stronger effect in the afternoon when the southerly wind is strongest (Flores-Aqueveque et al., 2010). Ground-based reports on dust aerosol emission and transport are typically restricted to the spatially sparse network of meteorological stations, which is common in uninhabited desert regions (e.g., Shao et al., 2013, Cowie et al., 2014).

Once aerosols of marine, lithogenic, biogenic, volcanic, and anthropogenic origin are emitted, the suspended material is mixed and transported by winds and partially deposited dry or wet in the Atacama Desert. These inputs, which may carry nutrients and water (as fog), are of special relevance in the hyperarid core, where plants and microorganisms have adapted to hyper arid, high UV radiation, and hyper saline environments. Advective fog, a form of liquid aerosol, is deposited in an area from the coast of the Atacama to ca. 90 km inland (Rech et al., 2003) and below 1000 m a.s.l. (Del Río et al., 2018), allowing the formation of microenvironments in soil crusts, sediments, subsoil, and under or inside rocks, such as quartz and halite (Azua-Bustos et al., 2015; McKay et al., 2003; Parro et al., 2011; Valdivia-Silva et al., 2012; Warren-Rhodes et al., 2019; Wierzchos et al., 2011). Such circumstances do facilitate deliquescence and water retention, and act as shelters to microorganisms against the extreme radiation and desiccation.

Hence, the Atacama Desert represents a unique environment due to the extreme climatic conditions and their effects on the landscape and life development. In this paper, we review several studies related to the Atacama Desert landscape, soil surfaces, wind erosion, atmospheric deposition, synoptic conditions, fog occurrence, among others. We analyze the processes of aerosol emission and transport, and the environmental conditions that direct the spatial and temporal dynamics of atmospheric deposition. In addition, we describe the possible sources of dust and their characteristics, along with the characteristics of the soils where they are deposited. Finally, we describe the fog deposition process and its potential consequences for the environment and life.

1. Geography and Climate of the Atacama Desert

Landscape evolution theories indicate that the topography inherently records the interaction between climatic, tectonic, and surface processes. Consequently, geological and topographic information can be used to assess erosion and topographic evolution (Bishop, 2013). This is especially relevant when processes such as dust entrainment and atmospheric deposition occur, where the former involves wind erosion of soil surfaces and the latter modifies the topography by dust accumulation.

The Atacama Desert is situated in the western coast of central South America, from northern Peru (5º S) to near La Serena (30° S) (Chile), nevertheless, in Peru, the desert strip is called the Peruvian Desert (or the Sechura Desert) (Goudie, 2013). The Atacama Desert has an extended history that goes back to at least the late Eocene and possibly to the Triassic (Goudie, 2013), and is one of the driest and oldest deserts on Earth (Azua-Bustos et al. 2012; Rech et al. 2003). These main features allow this desert to act as a terrestrial record of climate and landscape evolution since several millions of years, which is a very valuable asset. The aforementioned closed relation between climatic, tectonic, and surface processes are evidenced in the Atacama, e.g., in the relation of the Andes uplift and the Humboldt Current development, the respective consequences of moisture blocking and decreasing air humidity offshore, and the desertification of the Atacama Desert as stated by several authors (Dunai et al., 2005; Garreaud et al., 2010; Hartley and Chong, 2002; Houston and Hartley, 2003; Lamb and Davis, 2003; Rech et al., 2019).

The Atacama is bounded to the west by the Pacific Ocean and by the western Andes Cordillera to the east, where the Altiplano and the Puna de Atacama give it continuity (see Fig. 1). Cold waters of the Humboldt Current prevail near the coast preventing precipitation in the coastal areas (Houston and Hartley, 2003), although wetting fogs occur, and occasional high rainfall years associated with El Niño conditions may cause great floods (Goudie, 2013). Besides its hyperaridity, the Atacama Desert is also characterized by its extreme profound diurnal thermal variation, a smooth topography, several mountain ranges, soils with very low concentration of organic matter, and extraordinary deposits of nitrate (among other salts as explained by Michalski et al 2004), salt lakes and playas (salars), among others (see Fig. 1).

Regarding dust cycling, the paleoclimate is a relevant topic to address since the availability of dust may be affected by climatic conditions, e.g., arid surfaces are more prone to wind erosion. Thus, knowing the history of the climate in the Atacama, we can outline and suggest areas and/or periods in which dust were more available, especially during dry periods. Moreover, changes in the landscape are registered in the geological record and topography, which have been studied in the Atacama addressing, for instance, denudation and erosion rates.

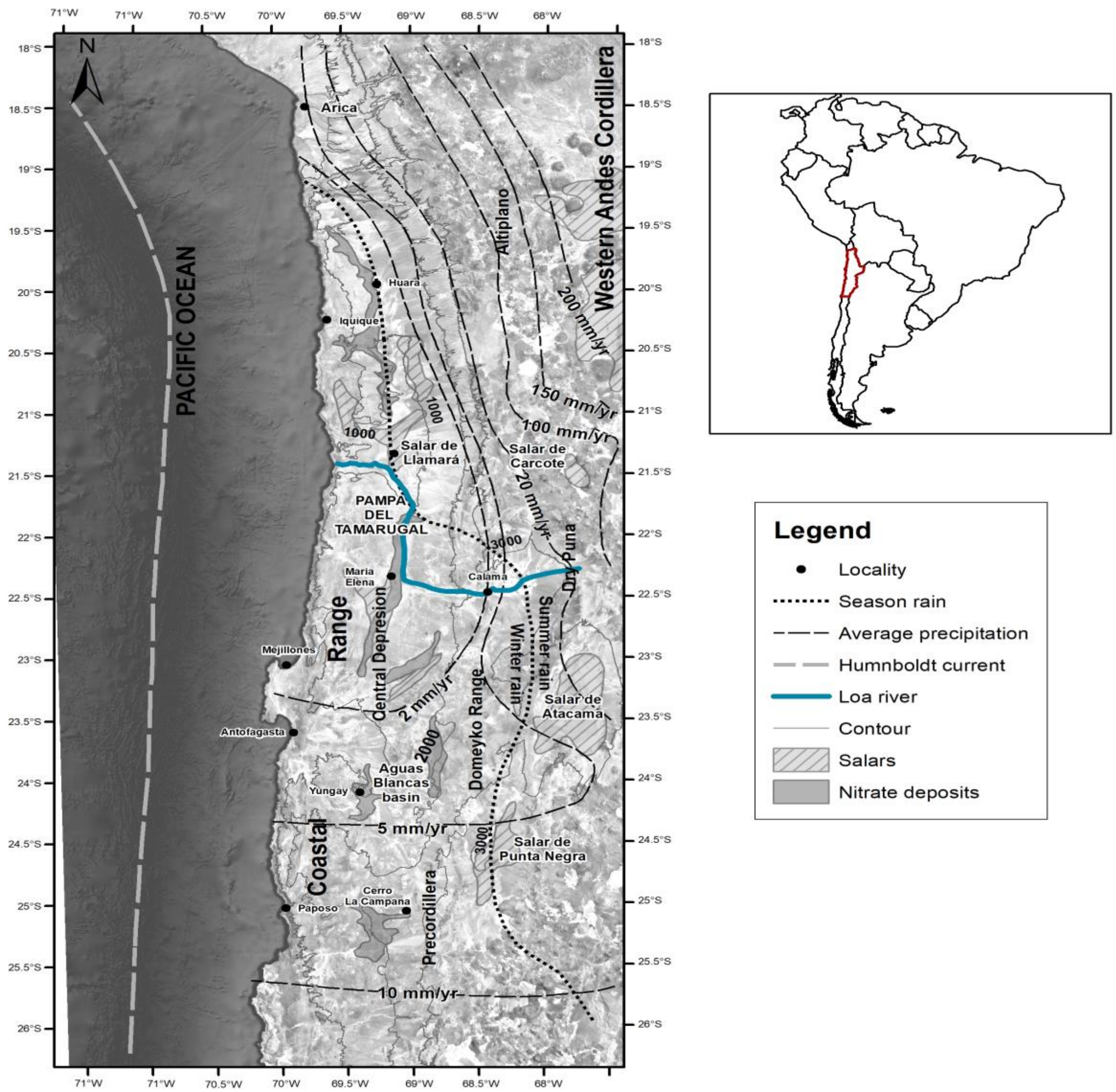

Figure 1. Geographic map of the Atacama Desert. Main physiographic units of the Atacama (Tapia et al., 2018), and salars and nitrate deposits distribution are shown (Finstad et al., 2016). Dashed black lines indicate rainfall rates, and seasonal rainfall regime is marked by the black dotted line separating west and east areas with the respective rainfall season predominance (Ritter et al., 2018). Humboldt current is shown offshore the Atacama and some localities are indicated in the map. **(Colors should be used)**

1.1 Geography of the Atacama Desert

The Atacama Desert is associated with the cold Humboldt Current that moves northwards form the Antarctica. The Atacama is classified as "basin and range" desert type, i.e., arid areas dominated by alternating mountains and systems of enclosed drainage, common in areas of tectonic activity such as the south-western United States, the majority of Iran, Afghanistan and Pakistan, parts of central Asia, and the dry coastal deserts of Chile and Peru (Goudie, 2013).

The physiography of the Atacama Desert in northern Chile can be divided into five N-S elongated units arranged eastwards: (1) Coastal Cordillera; (2) Central Depression; (3) Pre-Andean Cordillera (or Precordillera); (4) Altiplano, and (5) Western Andes Cordillera (see Fig. 1 and Fig. 2). These units are the result of the active Andean orogeny after the middle Cretaceous and the terrain features produced by the compression and subduction of the oceanic plate below the continental crust (Tapia et al., 2018 and references therein). Thus, from west to east, a very narrow (or non-existent in some areas) Coastal Plain (also known as marine terraces) connects with the Coastal Cordillera, a mountain range (~1500 m; Amundson et al., 2012) that reaches in its peak up to 3000 m a.s.l. (~ 24.5 °S) (Tapia et al., 2018). To the west of this range, vaporized water from the Pacific Ocean is transported as fog and retained by the high coastal summits of the continent. To the east of this range, the situation turns to a dryer landscape, which decreases in elevation and gives way to a longitudinal central valley, locally known as Central Depression. This desert extension, usually referred as the hyper arid core of the Atacama, represents a conjunction of pediment surfaces and longitudinal basins characterized by isolated Cenozoic sedimentation and arid climatic conditions

(Riquelme et al., 2007). This unit, called Pampa del Tamarugal (PdT) from the Loa River to the north, presents a distinctive topography, evidenced by a plateau-like relief formed by sedimentary material, which explains the relative regularity of its topography (Quezada and Cerda, 2003). To the east of the Central Depression, the more prominent relief feature within the hyperarid core of the Atacama rises, the Precordillera also known as Sierra de Moreno in PdT and Domeyko Cordillera to the south of the Salar de Atacama (Tapia et al., 2018). The Domeyko cordillera reaches elevations of up to 5000 m asl, and separates the Central Depression from a narrow, discontinuous pre-Andean depression that contains numerous internally drained salars (Amundson et al., 2012). To the east, in the Western Cordillera, Neogene stratovolcanoes reach 2,000 meters over the Altiplano (average 4000 m a.s.l.) (Jordan et al., 2014), a high plateau composed by a series of intermontane tectonic trenches infilled with sediments (Neogene evaporitic, siliciclastic, and volcanic successions; Jordan et al., 2014), characterized by large basins occupied by salars (Goudie, 2013). The Altiplano contained large bodies of water in the past, e.g., the Salar de Uyuni in the Bolivian Altiplano, that today represent the major source of dust in South America (Goudie, 2013). This general physiography framework exists as far south as Vallenar (~28°S), at which point the Central Depression disappears as a distinct geographical feature, and series of mountain ranges, of increasing elevation, extend from the coast inland (Amundson et al., 2012), the so called Transverse Valleys.

Within the Atacama Desert, it is possible to find several stratigraphic units, which reflect the evolution that the landscape has undergone over millions of years (e.g., Evenstar et al., 2017, 2009; Jordan et al., 2014). It has been suggested that the paleosurface of the Atacama Desert is composed of several paleosurfaces, which were formed by aggradational or degradational processes that occurred from the Miocene (Jordan et al., 2014) to the Pleistocene (Evenstar et al., 2009). In this regard, Evenstar et al (2017) identified six age-based and regionally extensive stratigraphic units distributed at ca. 35-23 Ma; 23-19 Ma; 18-13 Ma; 12-11 Ma; 8-7 Ma; and 5-3 Ma. Deposition of each of these units ceased abruptly, marked by hiatuses dated at ~23 Ma, ~19 Ma, ~13 Ma, ~11 Ma, ~7 Ma and ~3 Ma, which may be linked to periods of less erosion due to more arid periods (see 1.3). Just as the (paleo) climate presented spatial and temporal variability, as demonstrated by paleoclimatic records, this variability has been experienced by the processes of aggradation and degradation, so the product of these, i.e., the formation of these surfaces, is not continuous throughout the desert. Moreover, the several surfaces may also have been subjected to post-depositional reworking during wet periods in conjunction with the exfoliation of boulder surfaces according to Evenstar et al (2017).

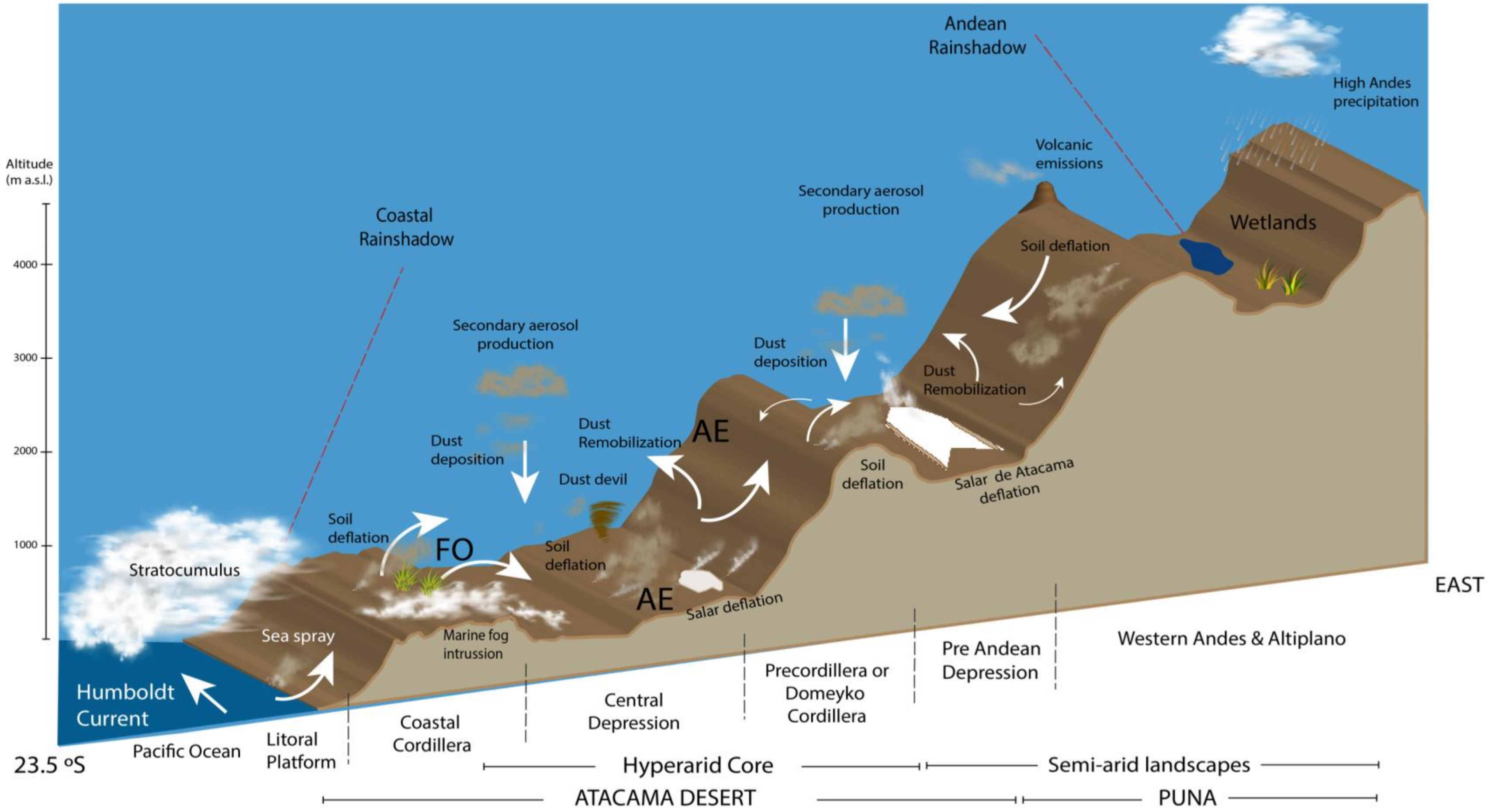

Figure 3. Illustration of dust dynamics in the Atacama Desert. White arrows represent wind mobilization of entrained soils, sediments, and aerosols. Plants are shown in the Coastal Cordillera (FO = fog oases) and over the Precordillera (Wetlands). Marine and volcanic contributions are denoted as well as the secondary aerosol production. AE stands for anthropogenic emissions such as mineral smelters and mining operations. Red dashed lines are a representation of the double rain shadow that affects the Atacama. Objects are not to scale, and the extent of the physiographic units is only for illustrative purposes. **(Colors should be used)**

1.2 Atacama Desert Landscape

The current landscape of the Atacama Desert ranges from the less dry areas, mainly represented by fog oases (lomas), and restricted to coastal areas influenced by marine fog (Rundel et al., 1991; Rundel and Mahu, 1976), and few wetlands, located in the dry puna, immediately east of the Atacama (Rech et al., 2002); to the absolute hyperarid desert, a broad expanse of the Atacama Desert almost entirely devoid of precipitation and vascular plants in the Central Depression (Latorre et al., 2002; Maldonado et al., 2005; Squeo et al., 2006). One consequence of the long-term intense aridity to what the Atacama has been subjected is that it contains massive nitrate deposit, likely the most famous and important of the world. Nitrate is a highly soluble salt and can only be accumulated under very dry conditions (Goudie, 2013). It is also possible to find rare iodate and perchlorate salts, as well as abundant chloride, sulfate, and borate salts (Ericksen, 1981a), partially fed by atmospheric deposition (Cosentino et al., 2015; Ewing et al., 2006; Li et al., 2019; Michalski et al., 2004; Rech et al., 2003; Wang et al., 2014), analogously to the salt occurrence on the surface of Mars (Catling et al., 2010; Hecht et al., 2009; Stern et al., 2017). Between Taltal (25 ºS) and Chañaral (29 ºS), the character of hillslope soils, as well as soils on non-sloping land surfaces, undergoes a fundamental change compared to landscapes to the north. Sulfate in soils of all slope positions declines greatly due to increased rainfall, and carbonates become the dominant secondary mineral in soils as plant density (and resulting soil CO_2 concentrations) increases (Amundson et al., 2012).

Another consequence of hyperaridity is that erosion rates are extremely slow and geomorphic surfaces can survive for long periods of time (Placzek et al., 2010). Morphological features of the Atacama (ancient and modern) are formed mainly by the action of fluvial erosion and deposition generated by the Andean runoff that has formed perennial and many ephemeral rivers which have modified the landscape, e.g., through deep incisions (up to 1200 m) in many sections of these rivers during the Pliocene (1–3 Ma), as a consequence of tectonic uplift and sea-level change, as well as fluctuations in climate (Houston, 2006). Despite of this, only relatively minor subsequent phases of aggradation and incision have taken place (Latorre et al., 2005; Rech et al., 2002) as the fluvial impacts on the landscape became greatly reduced in the late Pliocene to early Pleistocene (Amundson et al., 2012). This almost negligible modification of the landscape during the Quaternary has allowed the preservation of alluvial landforms (Dunai et al., 2005; Ritter et al., 2018) produced from the late Miocene onwards (Amundson et al., 2012).

During the Holocene, short-term but significant fluctuations have also occurred, evidenced by the establishment of temporary wetlands at specific locations (e.g., Quebrada Puripica) and the consequent fluctuating vegetation on the margins of the arid to hyper-arid regions represented by the Domeyko Cordillera. Despite this climatic oscillations, it appears unlike they would have caused a major overall shift from the generally arid conditions, except locally through supply of both surface and groundwater (Clarke, 2006). Surficial features suggest episodes of increased rainfall during the Quaternary, evidenced e.g., by deposits of a small endorheic basin (Ritter et al., 2019), erosion/ deposition cycles (Jungers et al., 2013), hillslope zebra (stone) stripes, rills and colluvial deposits on hillslopes (Amundson et al., 2012; May et al., 2020, 2019; Medialdea et al., 2020; Owen et al., 2013), and the presence of pipes that run sub-horizontally below the soil surface (Amundson et al., 2012).

Surficial processes rates are spatially heterogeneous in the Atacama (Evenstar et al., 2009). Placzek et al (2014) analyzed the concentrations of cosmogenic nuclides in more than 100 samples across two east-west transects within the central Atacama Desert (22-26°S). Recent cosmogenic nuclide-based studies suggest that erosion (Placzek et al., 2010), soil (Owen et al., 2011), and fluvial activity (Jungers et al., 2013) are ongoing, but slow in the central Atacama. In relation to this, Kober et al (2007), suggested a relation between erosion rates with elevation and modern precipitation rates. Thus, at the hyperarid Coastal Cordillera and the Western Escarpment along with the northern part of the Atacama Desert, erosion rates are extremely low and of the order of 10–100 cm My^{-1}, whereas at higher altitudes, where the landscape transitions to semi-arid environments due to more frequent rainfall, erosion rates increase at the Western Cordillera and range up to 4600 cm My^{-1}. Sediment production and supply from high altitudes, e.g., the western Andean slope, is very limited (Kober et al., 2007), although it may be variable along watercourses. For instance, sediment generation, transport and deposition in the Rio Lluta catchment is not a simple and continuous (steady-state) process according to the catchment-wide denudation rates and TCN-derived erosion rates from adjacent bedrock hillslope interfluves obtained by Kober et al (2009). There are similarities in the upper catchment (Western Cordillera) but they differ markedly from each other in the Western Escarpment and the Coastal Cordillera region.

In a previous study, Placzek et al (2010) described the landscape along a transect ca. 23º S. The authors found out that the Coastal Cordillera is one of the more active landscapes in this transect, where active alluvial fans and recent debris flows are prominent features within a few km of the coast. It is also common to find exposed bedrock exposures both on the Coastal Cordillera and along the coastal plain, and gypsum in soil within the Coastal range above ∼1000 m, whereas soil carbonate is present closer to the coast. Inland, the Central Depression presents substantially slower erosion rates than its eastern and western margins; however, even the driest part of this transect has erosion rates comparable to those of other deserts, ranging from 0.2–0.4 m My^{-1}. The entire Central Depression is within the hyperarid core (absolute desert) and all landforms here are mantled by a thick cover of loess, gypsum, and in some places nitrate, giving hillslopes a rounded and subdued appearance. Hillslopes often present rocks clusters (boulder fields) which are indicative of some downslope movement of rocks. According to the cosmogenic nuclides assessment carried out by Placzek et al (2010), results indicate that the most stable landscape elements in the hyperarid core are boulder fields, with exposure ages of 1.5–2.6 Ma.

Regarding Central Depression soils, Pfeiffer et al (2021) described both hillslope and alluvial soils in the hyperarid Atacama. About them, the authors evidenced the long-term accumulation of atmospherically deposited salts in a landscape free of vegetation as mentioned by Placzek et al (2010). Hillslope soils develop on weakly fragmented bedrock lacking evidence of chemical weathering and soils become thinner towards the hilltop and thicker towards the footslope. Soil in all the studied sites have a similar sequence of horizons with a very porous and conductive layer of anhydrite on top of a cemented gypsum layer, which is mostly impermeable except for vertical cracks that penetrate up to ~1.5 m deep. Moreover, Pfeiffer et al (2021) described large scale polygon structures that extend to the surface occurring on 1.5 to m scales, and pipes development on top of the impermeable sulfate layer at several locations. These pipes converge with gullies on hillslopes, and pipe outflows in alluvial fans. Mantling of upper hillslopes depends on the location, and could be soil or rock, whereas zebra stripes commonly develop on the middle slope section, and rills occur more frequently toward the lower slope positions.

About the flanks of the Domeyko Cordillera, Placzek et al (2010) situated them within the absolute desert and described features similar to those of the Central Depression. Although Domeyko hillslopes are thickly mantled in gypsum and loose soils, visible rilling is present and bedrock is occasionally exposed at high elevation, where active alluvial fans and channels are present near the crest. The Andean Flank also present active alluvial fan surfaces along the fringes of salar basins. Incised channels, often with perennial water, transport water and sediment from the highlands. Bedrock is frequently exposed and rocky soils generally contain carbonate, meanwhile the vegetative cover increases up to the 0 °C isotherm.

Moreover, Amundson et al (2012) described the hyperarid basin of Aguas Blancas in the Central Depression (see Fig. 1). There, they found rare surface runoff events that generate sheetwash and rills. In this area, the authors observed two dramatically different landscapes, but they are both still present. The previously active bedrock source areas for Pliocene alluvial fans, and debris flows that are currently “frozen” in

Quaternary salt. Additionally, the authors examined hillslope soils to the south of Antofagasta (23.5ºS), and described changes in the soils. In the Pliocene or earlier, hillslopes were mantled with silicate-derived soil but this was stripped off and locally deposited as alluvial fans (late Pliocene to early Pleistocene) that now block or otherwise cause a rearrangement of Pliocene and earlier river channels. The hillslopes have largely accreted a soil mantle of dust and salt since the apparent late Pliocene stripping, suggesting a decline in annual precipitation of at least 125 mm $year^{-1}$ or more. Moreover, at the latitude of present-day Chañaral (~26.5°S), hillslopes are largely denuded of salts and dust. This suggests that a rainfall threshold has been exceeded, which in turn facilitates fluvial processes capable of removing fine materials from slope surfaces. Finally, the authors calculated rates of soil production (bedrock conversion to a mobile soil mantle) about ≤1 m My^{-1} near Antofagasta, increasing to 2–3 m My^{-1} at Chañaral, and are up to >20 m My^{-1} at La Serena (120 mm). Present rates of bedrock conversion to soil are strongly linked to rainfall, and the rates in the Aguas Blancas region are among the lowest rates yet reported on Earth. Moreover, in this basin, a significant amount of soil mass on hillslopes is composed of sulfates and other salts and dust that must be (~50% or more of volume) derived from atmospheric deposition (Amundson et al., 2012).

In environments with limited runoff and scarcity of vegetation as the Atacama Desert, wind erosion may play a major role shaping the landscape, however it is probably the least quantified erosion process worldwide (Carretier et al., 2018). Hillslopes, for instance, are typically shaped by the interplay of sediment production due to bedrock weathering and atmospheric deposition, and sediment loss due to erosion by wind, water (overland flow) and gravity induced processes (Mather et al., 2014; Owen et al., 2011). Hence, the Atacama is a suitable place for wind erosion transport analysis and few studies have taken advantage of this context (e.g. Benison 2017; Flores-Aqueveque et al. 2010). The effect of wind erosion in the Atacama is evidenced by the presence of high winds, high aeolian particle loads and widespread wind erosional features (Wang et al., 2017), e.g. soil deflation (Rech et al. 2003), sand ripples, among others (see Fig. 3). Nevertheless, wind erosion of the landscape can be compensated by the atmospheric deposition of dust and salts (Michalski et al., 2004). This is evidenced in the Central Depression, where the influx of sulfate rich aeolian dust has caused a smoothed appearance of the landscape and hills. Moreover, some quebradas (ravines) have reworked dust and mantled their floors. In pre-Andean basins, such as the Atacama Basin and Salar de Atacama, aerosol deposition is ongoing, which is in contrast to some adjacent areas where deformation processes occur (Clarke, 2006).

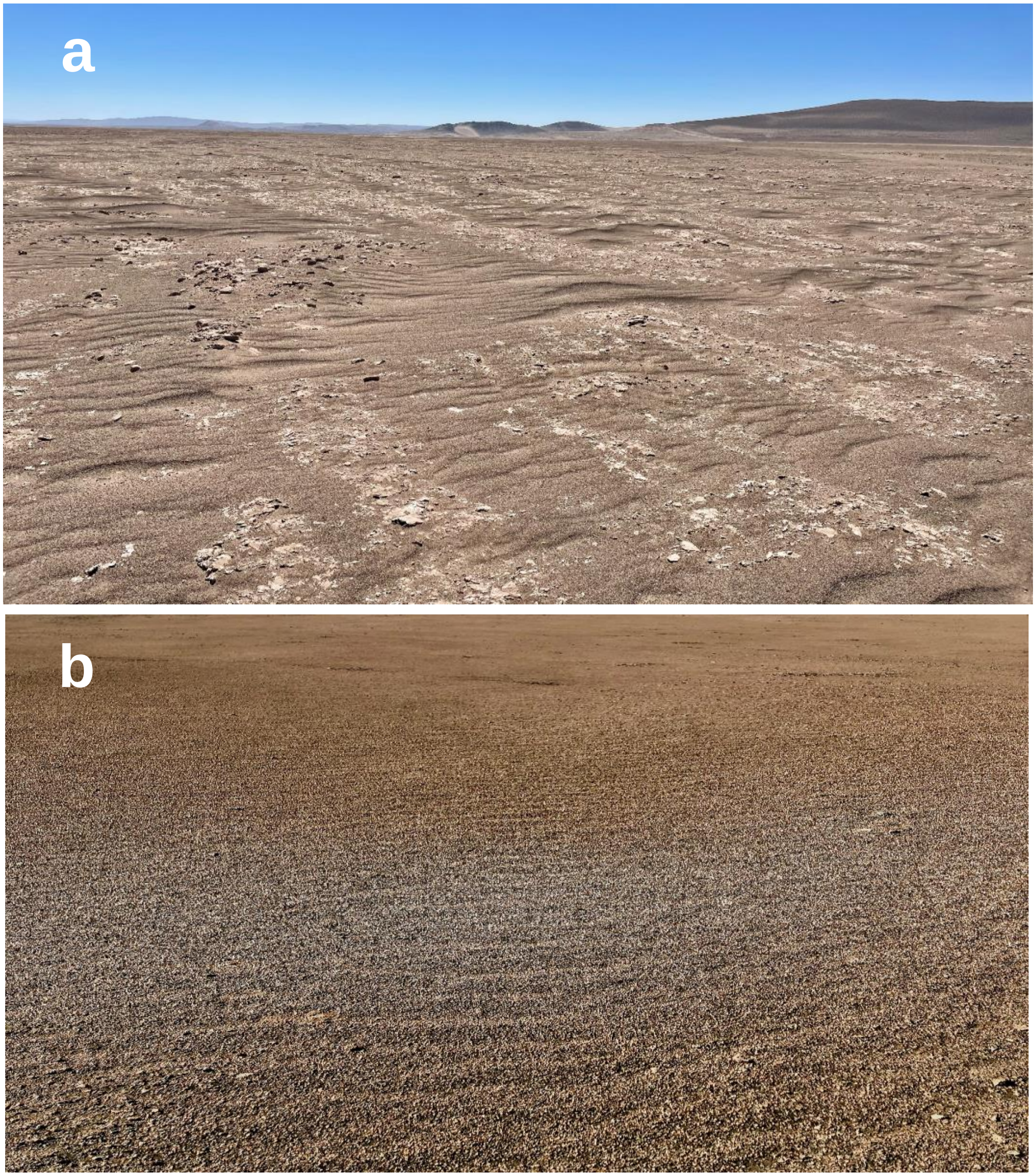

Figure 3. Deflated soil near (a) the Salar de Llamara in the Central Depression showing transverse ripples (N-S oriented) to the wind direction. (b) Smaller E-W oriented ripples in the eastern slope of the Coastal Cordillera are shown.

1.3 Climate and Paleoclimate in the Atacama Desert

The Atacama Desert ranks among the most arid areas of the world (Dunai et al., 2020; Ritter et al., 2018; Rundel and Mahu, 1976), and in consequence represents one of harshest environments on Earth. Aridity is enhanced by the effect of a major two-sided rain shadow projected by the Andes Cordillera to the east and by the Coastal Cordillera to the west, lower but remarkably high mountains that limit the inflow of advective moisture to the Atacama (Bull et al., 2018). Additional factors are the zonal position of the Atacama Desert in relation to the Hadley circulation; its distance from the main Atlantic–Amazonian source of moisture; and its proximity to the Humboldt Current (Houston and Hartley, 2003).

For the modern climate monitoring of the Atacama Desert in Chile, in 2017, a network of 15 permanent weather stations were installed by the Collaborative Research Center (CRC) 1211 (Dunai et al., 2020) within the Atacama Desert in Chile. The weather stations were set along three west-east transect at ca. 19-20ºS, 21.4ºS, and 25ºS, respectively, from the coastal platform to the Precordillera (Hoffmeister, 2018). After more than 30 months of observation, the average annual temperature calculated was 16.1°C with 36.0°C and -3.79°C in Salar de Llamara (in the Central Depression, see Fig. 1) as the maxima and minima recorded, respectively. The annual average incoming radiation was 255.9 W m^{-2} peaking in the Central Depression, and winds averaged 3.11 m s^{-1}, with the strongest at Cerro Campana (2550 m a.s.l.), located in the transition between the Central Depression and the Domeyko Cordillera (Precordillera), recording 18.1 m s^{-1} and NE direction.

Specifically, in the Central Depression, i.e., excluding data from the western slope of the Coastal Cordillera, between 19.5°S and 25°S, winds averaged 3.44 m s^{-1}, where the fastest came from SW, SE and NE. Below ~2600 m a.s.l., a mean annual precipitation of 0.001±0.12 mm $year^{-1}$ was calculated from the reported data. About potential evapotranspiration (PET), a rate of 1–2 mm day^{-1} was reported by Mintz and Walker (1993). Hence, with an average annual precipitation lower than 5% of potential evapotranspiration, this area can be classified as hyper-arid (UNEP, 2011).

Arid conditions in the Atacama Desert go back at least from ca. 9 to 37 Ma (Dunai et al., 2005; Evenstar et al., 2009; Kober et al., 2007; Nishiizumi et al., 2005). To assess the age of cessation of erosion, as a consequence of aridification, Dunai et al (2005) analyzed the cosmogenic nuclide concentration on erosion-sensitive landforms in the Coastal Cordillera (~19°35'S and ~70°10'W) in order to reveal the exposure ages of the collected samples. According to their results, the authors proposed an onset of aridity at 37 Ma, with an intensification leading to hyper arid conditions in the Atacama since 25 Ma. Moreover, they considered that the hyper arid conditions favored the uplift of the high Andes (as proposed by Lamb and Davis 2003), which in turn contributed to increase the rain shadow cast by this mountain range, enhancing aridity and allowing the current conditions of hyperaridity. In this sense, Ritter et al. (2018) dated pre-Miocene exposure ages in clasts (~28 Ma and ~34 Ma), which would have required an immobile or less disturbed landscape development during the Oligocene. Also, the authors revealed several episodes of enhanced fluvial erosion and deposition terminated at ~19, ~14, ~9.5 Ma immediately south of the Loa River (~21.5 ºS), which implies subsequent more arid periods with less rainwater, and identified that large scale fluvial modification of the landscape ceased by ~2–3 Ma. Hence, a hypothesis of a singular early and unique aridity onset is refutable and the one supported by the authors, which indicated an early onset of hyperaridity in the core of the Atacama Desert and an aridification process occurring with the interruption of wetter periods (although more or less arid), is more plausible. Wetter periods may produce more sediment due to fluvial erosion and, conversely, drier periods are more favorable to aeolian relocation due to desiccation of sediment deposits and aeolian erosion.

More evidence regarding wetter and variable past in the Atacama Desert has been described by several authors (Diederich et al., 2020; Gayo et al., 2012; Hartley and Chong, 2002; Herrera et al., 2018; Jordan et al., 2020, 2019, 2014; Medialdea et al., 2020; Nester et al., 2007; Placzek et al., 2010; Rech et al., 2019; Ritter et al., 2019, 2018; Sáez et al., 2016, among others). For instance, Rech et al. (2006) evidenced a shift in paleo soils within the Calama basin (~22.5 ºS, ~69ºW) between 19 and 13 Ma, which was recorded in sediment cores, and thus documenting the change from calcic Vertisols to extremely mature salic Gypsisol, which evidences a reduction in precipitation from > 200 mm yr^{-1} to < 20 mm yr^{-1}. Another piece of evidence of this paleoclimate variability is the one provided by Rech et al (2019), who through the analysis of fossil soils from along an 800-km transect (19–25ºS) stated that lower Miocene (24–20 Ma) soils are chemically weathered and contain soil carbonate, indicative of a vegetated landscape and semi-arid climate. In contrast, gypsum dominates massive (2–5 m thick) upper middle Miocene soils that formed on a hyperarid landscape devoid of vegetation. The authors link this change in paleo soils (to hyperarid conditions) with the rain shadow initiation along the west coast of South America, and inferred a minimum age for the development of the Central Andean rain-shadow of 15 Ma and a strengthening during the late middle Miocene (12–10 Ma). This would be also coincident with the strengthening of the Humboldt Current in the subtropical South Pacific, which may have been crucial to the desiccation of the Atacama from the late Miocene (Garreaud et al., 2010). After the strengthening of the Andean rain-shadow and the Humboldt current establishment, a consequent and extensive arid period is observed, which extends into the Pliocene and upper Pleistocene (Table 1). Concordantly, Jordan et al (2014) assessed the landscape modification through geomorphology, stratigraphy, and pedogenic data and identified four different arid intervals at 11 - 5.5; 4.5 – 4; 3.6 – 2.6; 2.2 – 1 Ma, and repeated intervals during the last 1 Ma. Each of these arid periods were followed by short lived wetter conditions of ca. a million year or less. Moreover, Houston (2006) reported ancient morphological features formed by Andean runoff and its fluvial erosion that formed perennial and many ephemeral rivers which have modified the landscape (deep incisions) during the Pliocene (1–3 Ma), as a consequence of tectonic uplift and sea-level change, as well as fluctuations in climate. Despite of this, only relatively minor subsequent phases of aggradation and incision have taken place (Latorre et al., 2005; Rech et al., 2002) as the fluvial impacts on the landscape became greatly reduced in the late Pliocene to early Pleistocene (Amundson et al., 2012).

From middle to upper Pleistocene, hyperaridity was interrupted by several precipitation events in millennial and orbital time scales. Diederich et al (2020), built a 68,000 years reconstruction of precipitation variations through the assessment of the sediment infill of the Huara (~20 ºS) clay pan basin and other records, and identified several wet periods for the Atacama. The authors indicate wet conditions within the Huara record (ca. 67.8 - 61 ka) following the correlation with the Salar de Uyuni record and its lacustrine phase dated to ca. 60-55 and 70-65 ka. These wetter conditions are followed by dry spells at Huara, Salar Grande, and Salar de Atacama (see Fig. 1 for location). After this, several pluvial phases within the Huara record extents from 58-33.6 ka, interrupted by short-term arid conditions. After this, prolonged moister conditions occurred at the northern edge of the hyperarid core (28.5-16.4 ka). This is consistent with the interpretation of marine sediments from northern Chile, which indicate a low aeolian contribution, implying wet conditions. From 28.8 to 18.0 ka, the Huara record shows a swing back to arid conditions, although the peak wet phase at the Salar de Atacama occurred almost simultaneously (26.7-16.5 ka). Additionally, the Huara clay pan registered a flooding event ~17 ka, which indicates a wet phase synchronous with the first phase of the Central Andean Pluvial Event (CAPE I). This event was responsible for recharge and generate paleo-lakes and wetlands and have been documented by several authors (Diederich et al., 2020; Finstad et al., 2016; Gayo et al., 2012; Herrera et al., 2018; Medialdea et al., 2020; Pfeiffer et al., 2018; Quade et al., 2008; Workman et al., 2020). During the late Pleistocene to mid Holocene (ca. 14-8 ka), the Huara record points to overall dry climate conditions concordant with the Salar Grande records (21°S), where hillslope activity was strongly reduced (Medialdea et al., 2020). A higher aeolian sediment content in the terrigenous fractions of marine sediments offshore northern Chile at 27.5°S (Stuut and Lamy, 2004) and 30°S (Bernhardt et al., 2017) suggest prevailing arid conditions during the Late Pleistocene and Early Holocene even beyond the hyperarid core. Contrarily to the sites from the Coastal Cordillera, further to the east elevated water levels in the Salar de Atacama (Bobst et al., 2001), wetlands in various parts of the Atacama Desert (Quade et al., 2008; Rech et al., 2002) and formation of rodent middens (Betancourt et al., 2000) highlight a distinct wetter phase between ca. 14 and 10 ka, which is known as the "Central Andean Pluvial Event II" (CAPE II; Quade et al., 2008). Between 12.1-11.4 ka, a wet period in the PdT and upstream was reported by Gayo et al (2012). Within the southern coast of the Atacama, Herrera et al (2018) found that coastal deep wells (at Michilla, 22.75 ºS) were recharged ca. 14.5 to 10 ka during CAPE II, which could be associated to past recharge by air masses coming from the Atlantic. In the Altiplano, this wetter period corresponds to the "Coipasa" paleolake phase. The divergent precipitation patterns during this interval, with differing conditions to the north and south of the Loa River, and western parts of the Atacama simultaneous with wetter conditions in the eastern part and the Altiplano, points to a moisture source from the east that could not reach the Huara clay pan and other areas of the coast. Additionally, CAPE II is archeologically important since it facilitated the establishment of Paleo-Indian communities in the Atacama Desert, e.g., in the Quebrada de Mani (Workman et al., 2020).

More recently, Nester et al (2007) identified an important event during the Holocene, which allow phreatophytes trees to grow (prosopis sp.) in Pampa del Tamarugal (PdT) drainages between 1070 and 700 ka (calibrated years before present), which implies higher water tables. This recharge event corresponds to the Medieval

Climatic Anomaly (MCA) and is characterized by its wet impact in the southern portion of the Atacama (northern Chile), opposite to the hydrological dry impact in the coastal Peru, which is consistent with La Niña dominance. This wetter period is also coincident with the reported by Gayo et al (2012), who examined organic material from relict fluvial terraces inserted within four dry and unvegetated valleys (21 ºS - 21.5 ºS) that also drain into the endorheic basin of PdT, and identified an expansion of the riparian and wetland ecosystems from 1010-710 ka. Additionally, Tully et al (2019) identified several dense paleowetlands within the Calama Basin supported by the Río San Salvador from 11.1 to 9.8, 6.4 to 3.5, 2.8 to 1.3, and 1.0 to 0.5 ka. Finally, according to Herrera et al (2018), spring waters south of the 23ºS were recharged by the arrival of moist air masses from the Pacific Ocean 1-5 ka, when the area was already inhabited. The previous periods and dates were gathered and are presented in Table 1.

Table 1. Significant events and periods in the paleoclimate timetable of the Atacama Desert

Epoch	Since kyr	Until kyr	Period significance	Reference
Holocene	1.01	0.71	Expansion of riparian and wetlands ecosystems	Gayó et al., 2012
	1.1	0.7	Increase of water discharge within the Pampa del Tamarugal basin due to the Medieval Climatic Anomaly (MCA)	Nester et al., 2007
	4.7	present	Wetter climate	Saez et al., 2016
	5	1	Coastal aquifers recharge	Herrera et al., 2018
Upper Pleistocene	11		Cessation of carbonate formation	Nester et al., 2007
	11.75		Increase of water discharge within the Pampa del Tamarugal basin	Nester et al., 2007
	12.1	11.4	Expansion of riparian and wetlands ecosystems due to the Central Andean Pluvial Event (CAPE)	Gayó et al., 2012
	12.2	9.8	Wetter climate	Saez et al., 2016
	14.5	10	Recharge of profound aquifer in coastal desert (Michilla) due to the Central Andean Pluvial Event (CAPE)	Herrera et al., 2018
	14.5		Wetter climate	Saez et al., 2016
	17.6	14.2	Expansion of riparian and wetlands ecosystems due to the Central Andean Pluvial Event (CAPE)	Gayó et al., 2012
	17.75	13.75	Increase of water discharge within the Pampa del Tamarugal basin	Nester et al., 2007
Lower Pleistocene	2200	1000	Hyperarid interval within Pampa del Tamarugal basin	Jordan et al., 2014

Table 1. Significant events and periods in the paleoclimate timetable of the Atacama Desert (cont.)

Epoch	Since	Until	Period significance	Reference
	kyr	kyr		
Pliocene	3000	2000	Cessation of fluvial erosion	Ritter et al., 2018
	3600	2600	Hyperarid interval within Pampa del Tamarugal basin	Jordan et al., 2014
	4500	4000	Hyperarid interval within Pampa del Tamarugal basin	Jordan et al., 2014
Upper Miocene	9500		Termination of episodes of enhanced fluvial erosion and deposition	Ritter et al., 2018
	11000	5500	Hyperarid interval within Pampa del Tamarugal basin	Jordan et al., 2014
Middle Miocene	12000		Arid conditions (onset of aridity)	Jordan et al., 2014
	12000	10000	Beginning of aridity between mid and late Miocene	Rech et al., 2019
	12000	10000	Strengthening Andean rain shadow	Rech et al., 2019
	14000		Termination of episodes of enhanced fluvial erosion and deposition	Ritter et al., 2018
Lower Miocene	15000		Central Andes uplift and rain shadow strengthening	Rech et al., 2019
	19000		Termination of episodes of enhanced fluvial erosion and deposition	Ritter et al., 2018
Oligocene	24000	20000	Vegetated soils and semi-arid landscape. Soils chemically weathered with carbonate presence	Rech et al., 2019
	28000		Stagnant landscape development during the Oligocene	Ritter et al., 2018
Eocene/ Oligocene	34000		Stagnant landscape development during the Oligocene	Ritter et al., 2018

1.4 Recent Climate Events in the Atacama Desert

In the Atacama Desert, rainfall presents temporal and spatial variability, e.g., in the Calama and Salar de Atacama basins, most of the annual precipitation occurs during the austral summer, while 200 km to the south it occurs during the winter (June to September) (Betancourt et al., 2000). In the Fig. 1 it is possible to observe this distribution as a limit between west and east regions that usually receive precipitations during winter or summer, respectively. Moisture sources of the Summer-rainfall-dominated areas are located east of the Andes, whereas Winter-rainfall sourced in the Pacific Ocean dominates south of the dry core (Houston and Hartley, 2003; Ritter et al., 2018) and are associated with a northward migration of extratropical storm fronts during positive phases of ENSO (Garreaud and Aceituno, 2001), and is sensitive to long-term changes in the sea-surface temperature of the Pacific. This increased rainfall during El Niño-like conditions is evidenced, e.g., by the El Niño-induced extreme rain event in 2015 (Ritter et al., 2018). Moreover, Latorre et al (2011) stated that there is a relationship between rainfall and ENSO in tropical to subtropical northern Chile, which depends on altitude and latitude, e.g., the central Andes receive more summer rainfall during La Niña years, whereas El Niño years, which are dry on the Altiplano, are associated with rare winter rainfall events along the coast of northern Chile.

During the Anthropocene (Ruddiman, 2013) in the Atacama Desert, long-term records of precipitation are rare. This because of the sparse population, and a relatively short duration of settlement (Schween et al., 2020). Pfeiffer et al (2021) presented a brief summary of the rare pluvial events from 1881 onwards that complement a previous compilation done by Ortlieb (1995), which covers the period between 1796 and 1992. During the last three decades, remarkable rainfall events have occurred in the Atacama Desert. Among these, the 1991 (Garreaud and Rutllant, 1996), 2001 (Houston, 2006), 2015 (Jordan et al., 2020, 2019; Pfeiffer et al., 2021; Scott et al., 2017) and 2017 (Azua-Bustos et al., 2018; Jordan et al., 2020; Schulze-Makuch et al., 2018; Scott et al., 2017) rain events were documented.

On June 18th of 1991, a rainfall that averaged rate of 5-14 mm h^{-1}, with a maximum of up to 24 mm h^{-1} occurred in Antofagasta city area, which was considered a "hundred-year" rainfall at the time (Garreaud and Rutllant, 1996), and coincided with the development phase of El Niño (Vargas et al., 2006). This wind and rain storm was caused by a winter cold front that migrated northward and reached the coastal desert and part of the interior desert, causing precipitation in Baquedano (17.5 mm) and Aguas Verdes (33.5 mm) but did not extend towards northern or eastern localities as Quillagua, Calama and San Pedro de Atacama. The anomalous northward advance of the cold air and associated frontal disturbance was the result of a blocking SW of the southern cone of the Americas and a weakening of the subtropical anticyclone. This event had catastrophic consequences provoking dozens of deaths (Vargas, 1995), and destructive debris flows on the Coastal Escarpment hillslopes (Vargas et al., 2006).

Another relevant event occurred in February 2001, where widespread flooding occurred throughout the Atacama Desert of northern Chile and southern Peru. Among the effects reported by Houston (2006), the flooding was particularly severe in the Río Loa basin where several bridges were ruptured and the city of Calama inundated. As far as is known, this is the first recorded historical event in the Atacama Desert of such magnitude and impact. The author also reported considerable erosion, e.g., from the Quebrada de Tuina (pre–Andean Cordillera), where 5 km^3 of sediments were redistributed towards the Calama basin, which meant an erosion of 70 mm in the catchment. Some other impacts were incisions of 2-5 meters wide due to the formation of new channels or the growth of others, high sediment concentrations in the Salado and Loa rivers, aggradation of large volumes of sand, gravel bars and crevasse splays. Moreover, overbank flooding and mudflows occurred almost universally within the Atacama (in perennial and ephemeral catchments), and the deposition of fine-grained sediments over large areas (hundreds of km^2) and considerable thickness (~1 m). The author also indicated that this type of events in the Atacama Desert, i.e., floods, are generally caused by exogenous rains, provoked by the La Niña phenomenon.

Over a three-year timespan, from 2015 to 2017, there were two extremely uncommon, major precipitation events in the Atacama Desert, as well as several smaller, more typical storms (Jordan et al., 2020). From 24 to 26 March 2015, a warm-season storm brought rain and snow across a major portion of the Atacama (Jordan et al., 2020), which caused rainfall rates and quantities to exceed many historical records (Pfeiffer et al., 2021). Among the precipitation records of this event, Jordan et al (2020) mentioned that 80–90 mm of liquid precipitation fell at some locations in both the mountains and the lowlands. The driver for this event was a synoptic-scale weather system, a cutoff cold upper- level low system that traversed the Pacific Ocean at a time of unusually warm temperatures of Pacific surface water (Jordan et al., 2019). This led to greater potential for erosion and sediment transport than typical of more common moderate precipitation scenarios which usually include widely distributed snow (Jordan et al., 2019). Here, the results of a reconnaissance from N to S transecting through the plant-free expanse of the Atacama Desert, between 22 and 26 ºS, are examined in relation to evidence of past runoff activity coupled with soil architecture and soil hydraulic properties. In order to study the rainfall effects and its potential to activate geomorphic processes, Pfeiffer et al (2021) examined a transect between 22-26 ºS, whose results suggest that the rain initiated some minor runoff processes on the upper hillslopes and concluded that the event was too small to reactivate many features that appear to be driven by larger, less frequent storms. Despite this, in some river valleys there was catastrophic damage to property and loss of life, whereas other regions with similar precipitation amounts exhibited little to no surface disturbance (Jordan et al., 2015; Scott et al., 2017). The second significant precipitation event occurred two years later, 6–7 June 2017, with widespread snowfall above 2700 m a.s.l. and rain reported at many lowland gauges (up to 40 mm). A major difference between those two major precipitation events was the role of rain compared to snow: because runoff of surface water is delayed where snow accumulates, streamflow in response to the June 2017 event was delayed and diminished (Jordan et al., 2020).

Other events recorded occurred in 2012, which had landscape consequence near Quebrada de Guatacondo. There, channel walls were plastered with remnants of at least three recent mudflows that occurred in early 2012. The same event in 2012 deposited extensively sediments on a fan that is like-wise characterized by both channelized and overbank flows (Morgan et al., 2014). Jordan et al (2020) add two more minor events. One of them took place between 8–11 August 2015, when a strong winter-season storm impacted the Pacific coastal region, with up to 30 mm of precipitation. This caused infrastructure damage and deaths in cities built at the toe of the steep coastal mountain slope, although most of the interior stations received only trace amounts of rain. The second one occurred on 25–27 June 2016, and brought up to 22 mm rain to coastal communities and snow to the southeastern mountains. Only one interior rain gauge reported a few millimeters of precipitation.

According to their field observations after 2015 rainfall, Pfeiffer et al (2021) suggest that larger scale rainfalls have occurred throughout the Quaternary, and that there are fossilized (or infrequently active) features in various stages of “repair” that provide evidence of rainfall re-occurrence. Thus, the Atacama landscapes largely escaped overland flow alteration due to the high infiltration rate capacity caused by the salt-rich soils, estimated to average 78 mm h^{-1} for hillslopes and 244 mm h^{-1} for alluvial soils. Interestingly, hyperarid landscape within the Atacama are able to provided temporarily favorable conditions for the activity of specialized microorganisms after the rare precipitation event of 2015 until water activity fell again beneath a critical threshold (Schulze-Makuch et al., 2018).

Historical floods, debris and mudflows in the region are mostly associated with rainfall that occurs in the Andean Pre-cordillera and Cordillera such as the Great Atacama floods of 2001 in the Loa River basin (Houston, 2006), flash floods in 2000, and mud/debris-flows in 2012 at the Pampa del Tamarugal (Houston, 2002; Morgan et al., 2014; Sepúlveda et al., 2014). During these events, rainfall did not occur in the absolute desert or at least was not recorded (Pfeiffer et al., 2021) but their impact through landslides arrived to the Central Depression, for instance, to the Pampa del Tamarugal, which allowed aquifer recharge (Houston, 2002).

2. The Dust cycle in the Atacama Desert

Atmospheric dust constitutes a large portion of the atmospheric aerosol loading (Kohfeld & Tegen, 2007) and here we define it as the set of aerosols of marine, pedogenic, lithogenic, biogenic, volcanic and anthropogenic origin emitted (and mixed) into the atmosphere during surface wind events. Aerosols correspond to the set of solid and liquid particles suspended in the atmosphere that, in fact, include dust. (Pöschl, 2005). The atmospheric dust loadings can be paired with different aerosols sources such as sea spray, volcanic eruptions, industrial emission, fire debris, secondary aerosols and cosmic dust (Pye, 1987), and even microorganisms (Griffin, 2007). Due to the varied origin of these particles, the different processes to which they have been subjected, and the geographic location of sources, dust differ in particle size, grain shape, composition, and mineralogic properties (Choobari et al 2014). With particle diameters in the range of 1 –10^5 nm (Pöschl, 2005), these particles include from freshly nucleated clusters containing a few molecules to crustal soil dust particles (McMurry, 2000).

The global dust cycle, e.g., described by Shao et al. (2011), includes five major stages: (1) entrainment of soil particles into the atmosphere, (2) atmospheric transport, (3) eolian transformation, e.g. through mixing with other aerosol types, (4) deposition, and (5) the particle stabilization, e.g. through chemical binding of clay minerals. This cycle involves a range of processes occurring on spatial scales from local to global and on temporal scales from seconds to millions of years. In South America, dust sources are centered especially to the east of the Atacama Desert (Bolivian Altiplano), the coastal desert of Perú and Chile, and the Andes and Patagonia in Argentina (Marx et al., 2018); the so called arid diagonal (Saukel et al., 2011).

Compared to other regions, the Atacama Desert is a minor contributor to the global dust budget quite unlike North Africa (Ginoux et al., 2012). This may be explained by the topography of the Atacama, which resembles a set of elongated bowls of different sizes, positioned west-east and to different elevations, limited by high mountain ranges that act as natural dust traps, forcing the rework – or remobilization - of the deposited material (see Fig. 2). In consequence, the dust cycle here has mostly a local reach and is almost isolated from the global cycle with some episodic exceptions such as the entrained dust plume from the Atacama Desert occurred in July 2016 and analyzed by Reyers et al (2019).

The dust cycle in the Atacama Desert is represented in the Fig. 2. In this, it is possible to observe that dust entrainment is produced by near surface winds and dust devils (where the latter are frequently observed in the Central Depression, see Fig. 4) that mobilize or suspend particles of soil, salar playas and sediments (see section 2.1 and 2.2). The transport of this material relies on the local wind circulation that generally is from west to east and vice versa (Li et al., 2019; Wang et al., 2014), following more complicate paths in valleys (see section 3). During aeolian transport, dust is mixed with water particles, sea salts and organic compounds contained in the recurrent coastal fog (see section 3.3), e.g., within the fog influence zone (<1200 m a.s.l.) and may be deposited wet during the night and early mornings, before fog evaporates and dissipates. Nevertheless, we infer that dry deposition is the general mechanism for dust settling because of the limited penetration of fog inland. In addition to primary aerosols, secondary aerosols are produced and deposited inland, i.e., particles formed locally by atmospheric chemistry (e.g., nitrate and sulfate compounds from gaseous oxide precursors; Michalski et al., 2004) that settle and accumulate in soils. From the east, wind-eroded soils in the Altiplano and Puna contribute dust, which is likely to have higher concentrations of organic compounds, nutrients, and microorganisms due to the greater abundance of plants, while the volcanic contribution is occasional and limited. Also, in this higher zone, wet deposition of dust is more feasible due to the more recurrent precipitations and the washout produced by summer showers, the so-called “Altiplanic winter”. Once dust is deposited, the material is accumulated or remobilized (reworked) by winds usually within the margins of the Atacama.

The relevance of the deposition process lies in the fact that it is the atmospheric particulate material that is deposited dry or wet on desert soils that initiate pedogenesis (Ewing et al., 2006; Wang, 2013; Wang et al., 2014) and has been indicated as the source of nitrate, sulfate, and chlorides, among others, in the Atacama Desert (Ericksen, 1981; Rech et al., 2003). Nitrates are probably the result of the long-term accumulation of secondary aerosols produced in the atmosphere, while the sulfates would have a component derived from the marine influence through the fog, the same as for chloride, at least in the zone of marine fog influence, and by the re-mobilization of halite from soils and salars in the Central Depression (Voigt et al., 2020). These salts are long-term accumulated under hyper arid conditions that provide minimum runoff and reduced leaching of the Atacama soils (Ericksen 1981; Ewing et al. 2006; Michalski et al. 2004).

Figure 4. Dust devil spotted in the Central Depression within the Maria Elena district at 13:43 local time. Several dust devils were observed along several kilometers in the area. For reference, electricity towers in the picture are about 25 m high.

2.1. Entrainment of Dust and its Sources in the Atacama Desert

Dust entrainment or emission is the process by which fine particles are emitted from soil surfaces by strong winds, which typically occurs in regions of sparse or no vegetation (< 15% vegetation cover) (Kohfeld & Tegen., 2007). Because of water scarcity, much of the Atacama Desert is almost entirely deprived of plants, making the surface soils prone to wind erosion. Despite this, dust storms are rare in this desert (Reyers et al., 2019).

Ginoux et al. (2001) describes potential dust sources in the Atacama Desert. Their model assumes that in areas with pronounced topographic variations, sediments available as dust sources are primarily accumulated in valleys and depressions. For each 1° x 1° grid cell a source function S is obtained which represents the topographic contrast in the 10° x 10° surrounding area of that grid cell by means of the maximum and minimum elevation. This source function represents the erodibility factor at every grid cell, and only land surfaces with bare soil are considered as possible dust sources. Note that only major valleys are identified as potential dust sources by this approach, while small-scale features like canyons are not captured realistically. Fig. 5 shows the results of the potential dust sources in the Atacama Desert. Due to the topographic features, potential dust sources are restricted to some areas in the Central Depression and to near coastal plateaus in Northern Chile and Southern Peru, while Precordillera and the Andes itself are not considered as dust sources. North of the Loa River, the topography of the area have distinctive features as the plateau-like relief formed by sedimentary material, which explains the relative regularity of its topography. Also, this unit is bounded to the west by the Coastal Cordillera, which appears as a walled cliff at the sea with an approximate elevation of 300 meters and ocasionally connect with the coastal platform, a feature that is incissed by the drainage of large regional ravines in the form of big canyons (Quezada and Cerda, 2003). Thus, easterlies in this area may face less obstacles than south of the Loa River to produce dust plumes as the described by Reyers et al (2019). However, the dust source function is generally low for the area of interest when compared to other major deserts of the world, like the Sahara or the Taklimakan Desert, for which values of more than 0.4 are reported (Ginoux et al., 2001). According to the model results, it is possible to observe that major potential dust sources are located in northern Atacama, between 17 and 19 ºS, where the (dimensionless) erodibility factor index is 0.1 (out of 1).

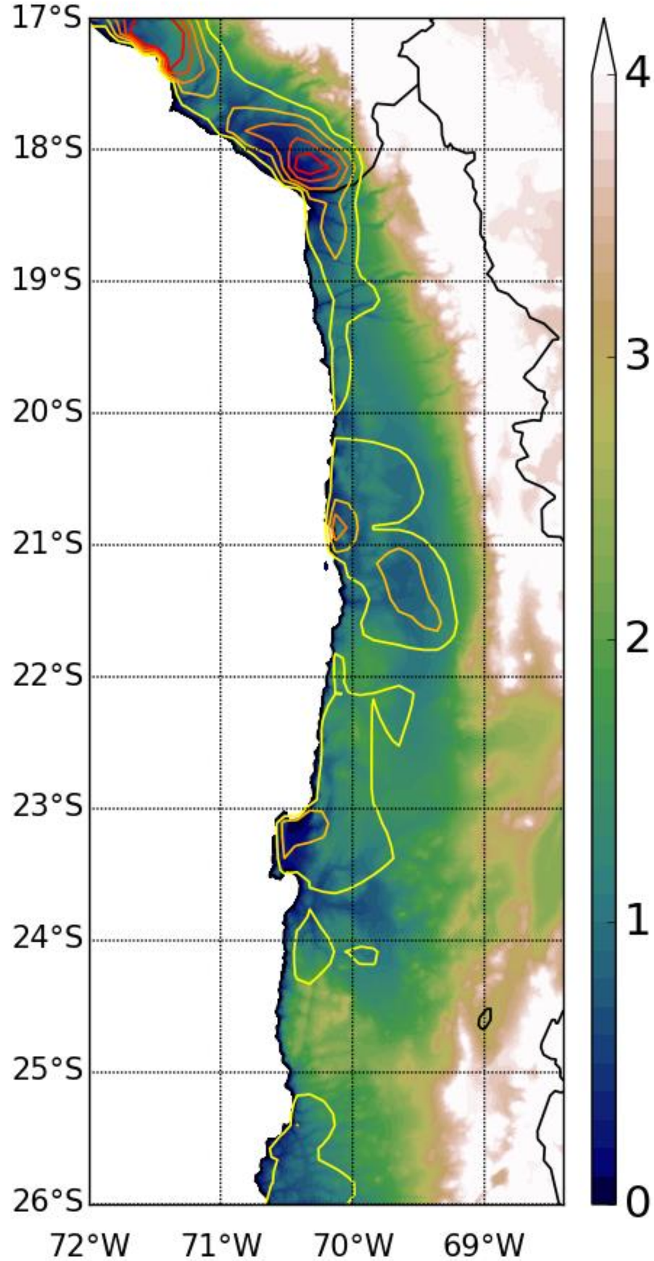

Figure 5. Orography (colored scale at right; in km) from the ETOPO1 Global relief model of the NOAA and the dust source function (S) as obtained by the model of Ginoux et al. (2001). Contours, ranging from 0.02 in yellow to 0.1 in red, represent erodibility factor (0 to 1). For more information see main text. **(Colors should be used)**

As was mentioned before, the dust source function of Ginoux et al. (2001) only considers topographic features, whereas soil erodibility additionally depends on other factors regarding the landscape and soil properties. The potentially erodible area of a landscape is controlled by the density of plants and other roughness elements such as cobbles or boulders, while soil erodibility is controlled by intrinsic properties of soils, such as the clay fraction, and the combined influence of temporal soil properties of moisture, aggregation, surface crusting and the availability of loose erodible material (Webb and Strong, 2011). The content of clay size particles in a soil (grain size distribution) is a relevant factor since its presence favors the particle cohesion and lead to the formation of aggregates, while the soil organic matter and moisture content affects the aggregates stability (Goudie and Middleton, 2006). Moreover, some other soil surfaces such as desert pavements, soil crusts, and high mass objects arranged on the topsoil can make erodibility even lower. Desert pavements consist of a one- to two-particle-thick layer of closely packed, angular to sub rounded gravel. They are one of the more prominent soil surfaces of arid regions (McFadden et al. 1987) and have developed in the Atacama Desert (Ericksen 1981). For instance, Berger and Cooke (1997) reported well developed stone pavement over alluvial fans across the Atacama Desert: in the Salar de Navidad (600 m a.s.l.), Salar de Atacama (2300 m a.s.l.) and Aguas Calientes Norte (4350 m a.s.l.).

While the full diversity of soils in the Atacama Desert is not fully understood, Finstad et al. (2014) provides an overview of typical features of geomorphic surfaces widespread in this desert. In that research, the authors described two distinctive pedohydrological regimes: (i) alluvial fans and related terraces dominated by sparse downward soil water movement, and (ii) dry lake beds or nearby environs impacted by the upward migration of waters driven by evaporation; both cases with salt crust near the surface.

For alluvial fans, Finstad et al. (2014) selected a well-drained soil in a post-Miocene alluvial fan in the Yungay area (~24°S) previously reported by Ewing et al. (2006), considering that rare rainfall events occurred over the past millions of years have distributed atmospheric-derived salts in the soil profile. Ewing et al (2006) described the upper 146 cm of the pit as gypsum/anhydrite sequence overlying an indurated halite zone. In the first 39 cm of the soil profile, the concentration of gypsum exceeds that of anhydrite, suggesting wetter conditions likely due to fog precipitation, while below 39 cm and down to the halite profile, anhydrite is dominant.

Along the soil profile, petrogypsic horizons (39-71 cm), followed by gypsic (71-85 cm), gypsic-salic (85-102 cm) and salic (102-122 cm) horizons were found, over the halite horizon. More recently, Pfeiffer et al (2021) examined the “Ewing’s pit” in Yungay and described a post-2015-rainfall soil profile consisting of an incomplete desert pavement overlaying a ~15 cm thick layer of low density (bulk density ~ 0.7 g cm^{-3}), highly porous anhydrite polygons with aeolian dust concentrated in the polygon interfaces. Below that, gypsum/anhydrite polygons of much higher density and width extend to a >1 m depth. The porous material can retain the recent deposited atmospheric dust which add clay-size particles to the soils. XRD analysis performed by Ewing et al. (2006) indicated that the silicate dust (0.2–2 and 2–20 µm fractions) in deposition samples contained smectite, chlorite and kaolinite. This constant input of fine mineral particles, along with the development of desert pavement (Ewing et al., 2006) and salt crust (Davila et al., 2008) may enhance the stability of the Yungay and analogue regions within the Atacama Desert reducing the wind erosion and, in consequence, dust entrainment. Moreover, hillslope sites within the hyperarid core examined by Pfeiffer et al (2021) tend to have similar features to Yungay soils (pavement, soft porous anhydrite polygons), although the thickness and continuity of the sulfate layers is lower than on level alluvial fan surfaces. Additionally, the development of vesicular (Av) horizons (see Fig. 6) and crack polygons diminishes the available material (salt, silt, coarse sand, volcanic parent material, etc.; Howell 2009) to be entrained by the migration of particles underground. A set of pictures of Yungay soils is given at Figure 6. The second case given by Finstad et al (2014) corresponds to soils from the Salar de Llamara (~21°S), which represent a short chronosequence between Pleistocene and mid-Holocene. Two soils were examined where both have an indurated salic horizon at the surface comprised almost entirely of halite, with thicknesses ranging from 22 to 51 cm. These crusts, formed by the aggregation of soil particles, enhance the surface roughness and in consequence lessen the erodibility of the soil by winds and thus the dust entrainment.

After a rain event in the Atacama Desert in 2015 (see section 1.4), soil surfaces did not collapse and maintained high rates of infiltration, but measurable physical and chemical changes occurred (Pfeiffer et al., 2021). Aguilar et al., (2020) calculated a mean erosion of 1.3 mm caused by the individual extreme storm. According to Pfeiffer et al (2021), after the rain stopped, soil surfaces were harder and more compact, less erodible, and with a higher bulk density. Moreover, a thin layer of efflorescence salt composed by gypsum, bassanite, and thenardite formed by the penetration of the rainfall into the surface, and the upward migration of more soluble $NaSO_4$ from the large $CaSO_4$ matrix occurred. Less than a year later of the rain event, the accumulation of gypsum in soil surface was less, and likely disrupted by wind deflation and/or fog influences. Gypsum presence is explained by the conversion from hydrated anhydrite, along with bassanite, and/or through anhydrite dissolution and reprecipitation as bassanite and gypsum (Shen et al., 2020). These changes in the gypsum/anhydrite concentrations are also supported by Voigt et al (2020), who later found gypsum on the surface soil where anhydrite used to dominate prior the rain event, as shown by several authors (Pfeiffer et al., 2021 and references therein).

Added to salt crusts, biological soil crusts (BSCs) have been developed in the Atacama Desert, along with vegetation patches. BSCs are living consortia of pioneer species in hostile environments such as cyanobacteria, green algae, lichens, and mosses, whose development provides physical protection against wind erosion, leading to thickened loose soil profiles beneath the crust (Wang, 2013; Wang et al., 2017). Widespread BSC communities were identified in a remote valley in the Atacama Coastal Cordillera, in the southern margin of the Salar Grande (~21.22°S, 69.90°W, ~800 m a.s.l.), a basin filled with massive salt mineral deposits. Moreover, vegetation occurrence is limited in the Atacama, being mainly restricted to fog oases in the coastal desert, and aquifers and rivers in the Central Depression and pampas, excluding the Puna vegetation. In the Central Depression, there are established plant communities such as the tropical thorn forest dominated by *Prosopis tamarugo*

Phil. (Garrido et al., 2018) in the Pampa del Tamarugal basin and further plant communities in the ravines and intermittent waterways around and northwards the Loa River. Tillandsia vegetation is present over the Coastal Cordillera indicating fog presence due to their dependence on atmospheric water supply (see section 3.3.1).

Finally, another soil feature of the Atacama that may reduce dust entrainment, and in consequence dust outbreaks, are the undulating surface (stress) fractures that also serve as topographic lows that concentrate cobbles/boulders and coordinate into a polygonal network, i.e., patterns visible at the ground. These cracks of several tens centimeters of width and few meters of diameter offer natural shelters to salt, sediment, and surface clasts that fill the voids. The center of the polygons, a few centimeters below the edges, also exhibits a micro-relief adding microtopographic complexity to the smooth landscape (Howell, 2009). Fields of boulders are common around bases of hills in the Atacama Desert and has been suggested that their transport is triggered mainly by the regular seismic events (Matmon et al., 2015; Quade et al., 2012; Sager et al., 2020). Several clusters have been reported along the Atacama Fault, e.g. in Sierra del Buitre (~23.5°S) (Quade et al., 2012); many clusters in the Yungay area (Matmon et al., 2015; Navarro-González et al., 2003) and the here reported boulder fields in the Pampa Remiendos; an elongated north south oriented zone of ca. 1 ha by 24.24°S and 70.28°W. These rock fields represent obstacles for dust mobilization and may force the fast deposition of material.

In order to characterize the wind erosion process in the coast of the Atacama Desert around Mejillones Peninsula (23°S), Flores-Aqueveque et al (2010) analyzed data from sediment traps and from a field experiment performed over the flat geomorphology of the area. With this data and using the model proposed by Marticorena and Bergametti (1995), the authors computed a threshold friction velocity for soil erosion of 0.31 m s^{-1}, which was exceeded only during a small fraction of the whole measurement period and always during the afternoon when a peak in the S–SW winds occurred. It should be noted that this research is dedicated to the study of sand mobilization and used samples from 17 sites representing the varied soil surfaces from rich gravel soil and partially encrusted to others more prone to wind erosion, in order to represent the pampa surface heterogeneity. They also found that the wind-erodible fraction of these soils (particles with diameter < 840 mm) was always a mixture of at most three lognormally distributed populations of sand grains (Alfaro et al., 2011). The protecting effect of non-erodible elements was considered by the mean of the overall soil roughness. Complementarily, Alfaro et al. (2011) proposed a model for the uptake, transport, and deposition towards the bay of wind-eroded mineral particles in the same area as the Flores-Aqueveque et al. (2010) study.

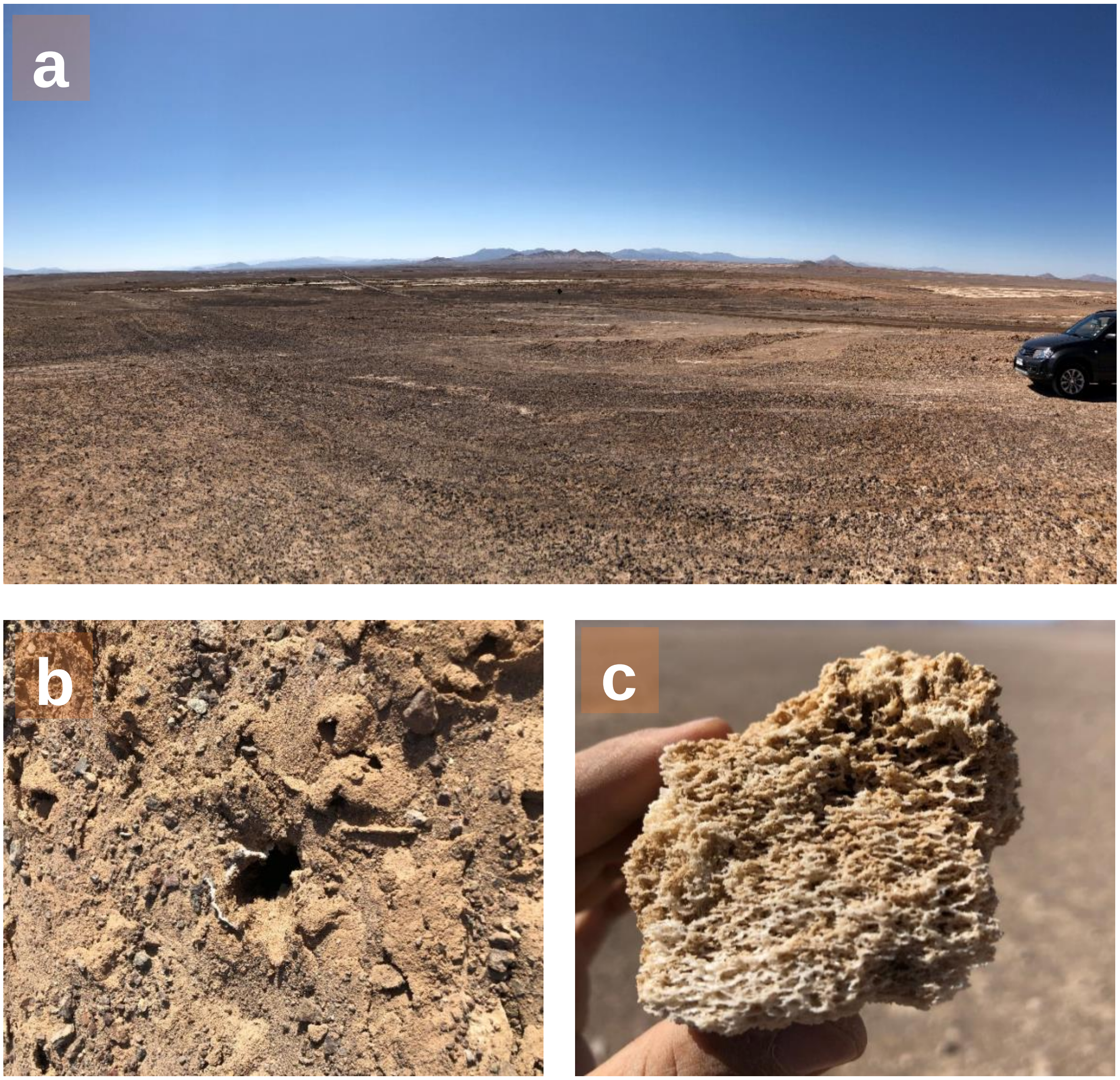

Figure 6. Soils of Yungay area. At the top (a) is shown a panoramic view of Yungay surface soil near the “oasis”. It is possible to see the major development of soil pavement. To the left, at the bottom (b), a photograph of the soil surface with pavement and vesicules development is given. Also note the inflated surface around the central vesicule. To the right (c), a photograph of a salt structure is given. These kind of structures near the surface at 5 cm depth in the Yungay area, near the studied pit by Ewing et al. (2006).

2.2. Origin of aerosols deposited in the Atacama Desert Soils

Due to the size, concentration, and uniqueness of the salt deposits in the Atacama Desert, their origin has been studied for decades, being the deposition of aerosols and their long-term accumulation in the soil suggested as one of the main mechanisms of dust and salt supply to this landscape (Berger and Cooke, 1997; Böhlke et al., 1997; Ericksen, 1983; Ericksen, 1981; Ewing et al., 2006; Grousset et al., 2003; Jiao et al., 2018; Michalski et al., 2004; Pfeiffer et al., 2021; Rech et al., 2003; Reich and Bao, 2018; Voigt et al., 2020; Wang et al., 2017, 2014). Hence, aerosols deposition is closely related to the occurrence of the widespread salt deposits in the Atacama. Moreover, it has been suggested that the local distribution of salt deposits are largely a function of remobilization of existing salts by occasional rainfall (Michalski et al 2004), aeolian transport (Berger and Cooke, 1997), capillary action (Mueller, 1968), groundwater discharge, possibly hydrothermal reworking (Pueyo et al., 1998), and sedimentation (Michalski et al 2004).

Among the main atmospheric salt inputs, the following have been suggested: aerosols with extra-local origin (nitrate, iodate, perchlorate) (Böhlke et al., 1997; Claridge and Campbell 1968; Ericksen 1981), direct volcanic emissions (sulfates) (Berger and Cooke, 1997; Oyarzun and Oyarzun, 2007), and marine aerosols coming from the Pacific Ocean (nitrates, sulfates chlorides and iodates) (Ericksen 1981, Rech et al. 2003). In addition, anthropogenic emission sources have also been identified such as copper smelters and other industries in the desert (Voigt et al., 2020; Wang et al., 2014).

The atmospheric circulation helps to understand the spatial and temporal precipitation composition in the regional and local hydrological cycle (Valdivielso et al., 2020). Therefore, the presence and composition of aerosols entrained in the rain drops influence both surface and groundwater. In this sense, recently, it has been found that in the hyper-arid core, the deflation of the local salts from the Central Depression (sulphate rich paleosoils and highly soluble salts accumulation) contributes to the precipitation composition, and certainly in the groundwater composition, in the highest parts of the Domeyko Cordillera, over 3400 m a.s.l. and to the east of the Central Depression, discarding the marine aerosols contribution at this distance inland (Gamboa et al., 2019). To the north of the Salar de Atacama, the scarce precipitation comes from the north and northeast via the Amazon basin, and from the southeast via the Gran Chaco in summer. Whereas, the winter precipitation is largely sourced by frontal systems originating from the Pacific in form of snow, their effect on aquifer recharge has been discussed (Valdivieso et al., 2020 and references therein). Urrutia et al (2019) estimated that snow is an important input flow to the hydrological system in winter, while Moran et al (2019) considered that aquifers are not recharged, because there is sublimation (between 20 and 30%), and there are no permanent seasonal ice fields. However, as will be discussed later in this section, snow and glacier ice from the Andes are capable of accumulating salts and thus recharging water bodies. The transport and deposition of the local salt aerosols also contribute to the chemical composition of the rain and watercourses in other hyper-arid regions (Jódar et al., 2020).

According to Michalski et al. (2004), the major part of nitrates and other soluble salts found in soils of the Atacama Desert are the result of the aerosol deposition produced by photochemical conversion of gas-to-particles processes, i.e., secondary aerosols, and as a minor contribution, marine aerosols and local land sources. Other studies using stable isotope supported this idea (Bao and Gu, 2004; Böhlke et al., 1997). For instance, Rech et al (2003) and Cosentino et al., (2015) using S and Sr isotopes demonstrated a strong influence of marine aerosols on soil gypsum/anhydrite development, although this effect was limited to areas where sea spray penetrates 90 km inland (Rech et al., 2003), below 1000 m a.s.l. (Del Río et al., 2018) (see section 3.3). For higher lands, where soils contain higher levels of nitrate, perchlorate, and iodate, the authors stated that these were produced by the extensive aeolian reworking of salar flats in the Atacama and the Altiplano, and were indicated as the main source for Ca and S. Additionally, these authors support the idea of a tropospheric N input since the spatial distribution of high-grade nitrate deposits appears to correspond with areas that receive the lowest fluxes of local marine and salar salt. Marine aerosols may be comprised by sea salt constituents, inorganic S (Rech et al., 2003) and N (Michalski et al., 2004), organic C and N, as well as Ca and inorganic C from degradation of marine invertebrates shells (Moore and Blough, 2002). Michalski et al (2004) estimated that the larger deposits of salts in the Atacama Desert have been accumulated from atmospheric depositions in a period of 200,000 to 2 million years under similar arid conditions to present-day.

Regarding the deposition of aerosols in the Central Depression, several authors have indicated that hillslopes and soils within the hyperarid core tend to accumulate salt and dust from atmospheric depositions (e.g., Cosentino et al., 2015; Ewing et al., 2006; Medialdea et al., 2020; Owen et al., 2013; Pfeiffer et al., 2021). Furthermore, active aeolian deposits were documented south of Pica (20.5ºS, 69.3ºW), around Quebraba Infiernillo, and Longacho and Chintaguay Flexura (20.6 ºS), where Blanco and Tomlinson (2013) reported well-sorted sands in unconsolidated condition, medium to coarse-grained, composed mainly of sub-spherical volcanic and plutonic delitic grains, and monominerals of delphosphate, quartz, pyroxene, amphibole and epidote, rich in magnetite (5-10%). Among these deposits, crescentic, mantle, longitudinal, and transverse dunes were observed. Another modern dunes were reported by Cosentino and Jordan (2017) between 20 and 21.5 ºS within the Central Depression (PdT) and at the Coastal Cordillera. Besides, Vásquez et al (2018) reported siliciclastic alluvial playa sediments from aeolian and evaporitic processes around the Salar de Llamara area. Some old aeolian deposits were also reported in the same geological location, usually more to the east of 69.20ºW but also close to the Central Depression. These Upper-Miocene to Pliocene deposits were described by the authors as medium to coarse, well-sorted, rounded sandstones, with planar or trough cross-stratification, in metric-scale sets. They are intercalated in the piedmont deposits or are located at their base.

Another work on aerosol deposition is from Pfeiffer et al (2019) reporting hydrated $CaCl_2$-rich soils that formed ~ 50-cm-thick aeolian material deposits over a layer of indurated halite in a narrow gorge between the Cerro Soledad and Cerro Salar to the west of the Salar de Llamara. Soils were relatively moist in this region, with a measured surface water content of 12.6 wt% (mass percentage concentration), decreasing to 5.9 wt% at 40 cm depth. The authors suggested that probably fog is responsible for these wetter conditions, which causes a vertical gradient in the available water in the soil profile. The wet surface stabilizes the soil surface and acts as a dust trap, allowing dust deposits to accumulate.

To the west of the Central Depression, an interesting phenomenon occurs in the west of the Salar de Carcote (or Salar de San Martín) at 21.36°S. Ericksen and Salas (1990) reported the existence of gypseous ramparts in this salar, which consist of low ridges formed by nodular gypsum of 50-100 cm high, formed by the deposition of wind-borne aerosols and the subsequent evaporation of water. Additionally, they found gypsum dunes on the lee side of several salars in the Andean Highlands, produced by wind deflation of newly deposited saline material on the salar surfaces.

Analyzing soils of the Atacama Desert to study atmospheric particles and the atmospheric deposition phenomenon has uncertainties due to the scarce knowledge of (1) aerosol deposition rates in this desert, (2) transformations of dust particles and salts once deposited on the soil, (3) concentrations in the atmosphere of colloids or very fine particles difficult to settle, (4) impacts of ongoing human activities that generate aerosols, (5) processes across geological time scales including paleoclimate, and others. One difficulty is that material forming the soils and transported to the region by the atmosphere has been accumulated over long time periods. For instance, Ericksen (1981) suggested that the accumulation of saline materials from the atmosphere in soils may has started in the middle Miocene (10-15 Ma), and continued until today.

Modern aerosol depositions in the Atacama Desert can be directly observed, but there is no dense measurement network for routine observations of aerosol deposition. This is not specific to the Atacama Desert, but a typical limitation for largely uninhabited desert regions worldwide. Deposition measurements rather stem from field campaigns and instruments installed for a limited time period (Zheng et al., 2017; Figgis et al., 2018; Wang et al., 2020). To date, there is no systematic dust deposition data acquisition or available datasets that allow for more exact representation of the deposition rates in the different seasons of the year and for periods of climatic variations in relation to for example ENSO events. A few studies collected and analyzed the atmospheric depositions in the Atacama Desert (Li et al., 2019), with Ewing et al. (2006) being the first one describing depositions in the Atacama . The authors quantified the deposition rates of major ions (Na^+, Ca^{2+}, NO^{3-}, Cl^- and SO_4^{2-}) at three sites along a 300 km north-south transect in the Central Depression, and observed significant spatial variations in ion depositions. From north to south, the sampling locations were Yungay (24 ºS) within the hyperarid core, Altamira (25.5ºS), and the southernmost location nearby Copiapo (27.3 ºS), where the latter represented the semi-arid transition. In Yungay, a deposition rate of 4±2 g m^{-2} $year^{-1}$ was measured by the authors and at all sites. They found evidence of both marine and salar-derived solutes in atmospheric depositions to the soils, as well as silicate dust inputs containing clay minerals. In this case, water-soluble salts comprised 44 ± 15% of total airborne particle mass. Moreover, Na and Cl accounted for 10–15% of total mass in air and dust samples, suggesting a significant sea salt component in soils (20– 30%).

Although the Coastal Cordillera works as a barrier that limits the entry of marine primary and secondary aerosols into the Central Depression, aerosols pass through ravines that connect the hyper arid core with the coast, and eventually settles in the desert. It was considered by Michalski et al. (2004) that the main component of marine aerosols reaching the desert surface were likely particles roughly 1 µm in diameter or smaller, where the submicron fraction was readily entrained into the free troposphere. Once there, smaller particles can be transported over great distances, and can grow during cloud processing to micron size particles that are then removed by deposition. Considering this, Ewing et al (2006) took air samples at a coastal site and compare it with the inland sampling locations. The authors found that coastal airborne particles had about 10-fold more Na and Cl in the coarse fraction, which suggests that 90% of coarse sea salt may be deposited during the transport of airborne particles inland. Close to Yungay, Owen et al (2013) set three passive collectors at Oficina Rosario, 70 km to the southeast of Yungay. After two years of dust collection, they calculated a mean deposition rate of 3.6 ± 0.4 g m^{-2} $year^{-1}$. Moreover, deposition rates of NO_3^-, Cl^-, and SO_4^{2-} were significantly lower than the calculated by Ewing et al (2006) at Yungay, with the rate of sulfate deposition (0.554±0.013 g m^{-2} $year^{-1}$) being the largest. In contrast, the ratio of silicate material to soluble material was larger than Yungay's, but still comparable. This difference, explained the authors, is due to different geographic settings which control fog movement inland, as Yungay is a valley that crosses the Coast Range and provides a route for fog advection, whereas Oficina Rosario is located on the lee side of a laterally-continuous section of the Coast Range which blocks fog from moving inland.

Another study by Wang et al. (2014) set up ten dust traps along a west-east transect (23ºS) (MT) from the Mejillones Peninsula (~23°S, 70.5°W) to the Andean plateau (~23°S, 67.5°W). The authors reported the chemical, mineral, and nitrate isotopic compositions of atmospheric deposition, and found an abrupt decline in the Na^+ or Cl^- deposition between the first and second trap located at the west and east of Coastal Cordillera, respectively. Nevertheless, they found no clear trends for Na^+ distribution inland showing that Na inputs were not exclusively from marine origin. In addition, the authors underline the importance of anthropogenic sources due to industrial activities related to the production of NO_x and the erosion of soils produced by off-road vehicles and surface mining in the case of $CaSO_4$. At the coast, SO_4^{-2} came not only directly from seawater but also likely from atmospheric transport. They also explain that it is associated with the oxidation of SO_2 in the atmosphere into sulfate by OH radicals, H_2O_2 and O_3. Furthermore, Li et al. (2019) supported Wang et al (2014) results and also found greater deposition rates of insoluble particles ranging from 3.8 to 149.0 g m^{-2} $year^{-1}$, and a high interannual variability on soluble salts and insoluble particles which was attributed to changes in winds. A recent study by Voigt et al. (2020) focused on the spatial distribution of sulfates, chlorides, and nitrates in the Atacama Desert soils, along three west-east transects at 19.5°S, 21°S and 24.5°S. The authors indicated that chloride derived from sea sprays are the main natural source of Cl and Na, although wind erosion and salt re-deposition from salars are also included as a minor and local source for Na and Cl. Additionally, they suggested a large impact of anthropogenic emissions regarding exceptionally high Na/Cl ratios in present-day aerosols analyzed by Wang et al. (2014) and Li et al. (2019). Li et al. (2019) determined changes in aerosol depositions in the Atacama between two periods of sampling, 2007–2009 (Wang e al., 2014) and 2010-2011, where the deposition of dust (insoluble particles) increased by 3.6 times over time in the Andes, emphasizing the importance of a long-term monitoring of insoluble dust fluxes.

A latter experiment were performed by Azua-Bustos et al., (2019), who evaluated aerosol deposition along two west-east transects starting near Iquique (20ºS) and Tocopilla (22ºS), and ca. 63 and 51 km long, respectively. Each transect considered three sampling points, and the Iquique transect (IT) had three sampling dates, while the Tocopilla (TT) only two. At each sampling point, ten empty Petri dish plates were left to assess the amount of dust arriving at each site/date. From the published results, it is possible to observe that within both transects, mean dust mass captured was larger than 4 g m^{-2} during the sampling period of one day on June 30th and August 30th, and October 27th in IT and TT, respectively. Although, an important intra-plate variability was reported, the authors found that the amount of dust arriving at each site of the IT was up to four times higher in the afternoon hours, which is coincident with the time of the day at which winds have been reported to be stronger in the hyperarid core. These results indicate differences in calculated atmospheric deposition rates in the Atacama Desert from those reported by Wang et al., (2014) and Li et al (2019) (MT), with annual deposition rates above 5 g m^{-2} $year^{-1}$ and 4 g m^{-2} $year^{-1}$, respectively, at similar sampling sites. Moreover, Ewing et al (2006) reported a deposition rate of 4 ± 2 g m^{-2} $year^{-1}$ within the hyper arid core, 50 km far from the coast (at Yungay, 24.1 ºS), and Owen et al (2013) indicated a 3.6 g m^{-2} $year^{-1}$. These apparent discordances can be explained by several reasons. Firstly, the method of collection differs. All mentioned works, excepting Azua-Bustos (2018), stated the use of metal passive dust traps mounted in a distance of at least 1 m from the ground surface, in order to avoid the accumulation of saltating sand. It is not clear whether Azua-Bustos et al (2018) collected dust at ground level or higher. Also, the location of TM is further south (>50 km) than TT, as well as Yungay and Of. Rosario, and the relief conditions are different in the 3 transects (IT, TT, MT) and at Of. Rosario. For example, the IT is located on a plateau-like area, due to the change of topography south and north of the Loa as explained in section 1.2, with a cliff facing the Pacific, while in the TT, a ravine connects the coast and the inland desert, and finally, the MT sites are located behind the coastal range. These topographic differences may influence aeolian dynamics and consequently atmospheric deposition. Furthermore, there may be differences also in the availability of material to be suspended, in addition to the year-to-year changes indicated by Li et al (2019). Further research is needed to better understand these differences.

The chemical composition of the dust particles is very varied and contains both organic and inorganic compounds which are of natural and anthropogenic origin (Azua-Bustos et al., 2019; Barraza et al., 2021; Ewing et al., 2006; Li et al., 2019; Wang et al., 2014). In the case of the Atacama Desert, it would be expected that the inorganic components would mostly be of natural origin related to the mineralogical components of the soil, and to a lesser extent comprise of organic compounds due to the scarcity of vegetation, with also some type of anthropogenic contribution due to the significant mining activity in the region. However, the content of salts in deposited aerosols has a greater relevance since it has been proven that it can be transferred to groundwater via atmospheric washing and thus recharging aquifers because of rains and snow melting (Gamboa et al., 2019; Voigt et al., 2020). The composition of atmospheric deposition was studied by Wang et al (2014) (among others) who indicated that the major mineral (>5% by mass) assemblage in atmospheric bulk deposition in a transect from the coast to the Andes sites was anorthite–quartz–albite–gypsum. Moreover, the atmospheric load deposited along the same ten dust traps was rich in Cl^-, NO_3^-, SO_2^-, Na^+, and Ca^{2+}, which totaled over 90% of the dissolvable salt mass, with small amounts of NH^+, Mg^{2+} and K^+ cations. Complimentary, Li et al (2019) obtained coincident results where deposition rates of soluble salts ranging from 0.2 to 6.0 g m^{-2} yr^{-1} and displayed a general decreasing trend from the coast to the Andes. Further south, Barraza et al (2021) studied the aerosol deposition in the Tapado Glacier. Their results showed that in this point of the Andes Cordillera, the sources of major soluble ions were still aeolian dust (38%) from the Atacama Desert (including mining sites), together with natural weathered sulphates (27%), anthropogenic nitrates (25%), and coastal aerosols (10%). The major ion load of the winter snowpack is dominated by Ca^{2+} (60%), SO_4^{2-} (16%) and NO_3^- (13%), and there is little influence from marine air masses at the site, with most SO_4^{2-}, Mg^{2+}, Ca^{2+} and Na^+, derived from non-sea salt sources (Sinclair and MacDonell, 2016)

3. Transport and Deposition of Dust and Aerosol in the Atacama Desert

The transport of materials driven by wind action plays an important role in desert systems where it represents the predominant input of exogenous material (Wang 2013; Wang et al. 2014). Once deposited, soluble salts accumulate due to the hyper aridity that affects this area along with insoluble dust, together generating soil deposits. In the following subsections transport mechanism and conditions that allow these phenomena are described in large and local scale, and finally the role of fog and the effect over the landscape and life are discussed.

3.1. Large-scale atmospheric processes driving aerosol transport and deposition.

The synoptic conditions in Northern Chile are dominated by a stable surface anti-cyclone over the subtropical Southeast Pacific (Garreaud et al., 2010) and a rather zonal westerly flow in the troposphere aloft due to a gentle south-to-north geopotential height gradient. However, different large-scale circulation patterns can disturb these dominating features. Using two-year wind measurements from a station at Sierra Gorda (~23°S), Jacques-Coper et al (2015) demonstrate that synoptic-scale winds connected with mid-tropospheric circulation patterns can influence or superpose the local near-surface wind systems. For example, the 5 % highest mean diurnal wind speeds and the 5 % lowest mean nocturnal wind speeds at Sierra Gorda are associated with mid-tropospheric geopotential height anomalies which are centered off the Atacama coast north of 30°S. These results indicate that the northwesterly flow at the foreside of troughs occurring far north over the subtropical Southeast Pacific reinforce the diurnal near-surface westerly winds and distinctly reduce the nocturnal easterly winds. Weakest westerlies during day, in contrast, occur in case of undisturbed synoptic conditions. A more complex picture is revealed when near-surface winds at different sites of the Atacama Desert are taken into account, as was done by (Reyers and Shao, 2019) who analyzed mid-tropospheric cutoff lows off the coast of the Atacama Desert. Cutoff lows are segregated troughs which form from deepening negative geopotential height anomalies. While for the near-surface wind at a station close to Sierra Gorda the impact of cutoff lows on the diurnal and nocturnal wind regime is similar to the findings of Jacques-Coper et al. (2015), an opposite synoptic forcing is found for the local wind system at a station located in a plain further south (~23.8°S), i.e. wind speeds are lower during day and slightly higher during night. At a station located at ~25°S cutoff lows facilitate reduced wind speeds throughout the day. Despite this heterogeneous forcing, it can nevertheless be concluded that upper-level cyclonic anomaly patterns over the subtropical Southeast Pacific may influence dust-emitting winds and deposition of aerosols in the Atacama Desert.

In the morning hours of July 8, 2016, an unusual dust storm occurred over the Atacama Desert. To the authors' best knowledge, it is the only strong dust event that has ever been reported for the Atacama Desert. It turned out that this event was triggered by a particular temporal evolution of a mid-tropospheric trough west of the Atacama Desert (Reyers et al., 2019). When the trough approached the Andes it zonalised, thus leading to upper-level horizontal convergence over the Northern Atacama. Owing to mass conservation, these processes finally lead to a strong acceleration of the easterly downslope winds (for more details see Reyers et al. 2019), which usually prevail during this daytime. At a near-coastal station in Northern

Atacama (~18.8°S) wind speeds of more than 12 m s^{-1} were observed during the event, whereas the average wind speed during winter is less than 3 m s^{-1} at this site. Consequently, a dense dust plume was released and transported hundreds of kilometers west- and southwestwards. This event clearly shows that upper-level circulation patterns may be very important for landscape evolution and dispersion of microbial life via massive dust translocation. However, many questions are still open. For example, it is unclear where the emitted dust was deposited after this event, and there is large uncertainty about the frequency of occurrence of such events in the recent and the paleoclimate.

The impact of the El Nino Southern Oscillation (ENSO) on near-surface winds in the Atacama Desert is found to be rather low. While for Central Chile strongly reduced and slighter increased wind speeds occur during El Nino and La Nina events, respectively, the effect of ENSO on wind velocities at stations north of 23°S is only weak (Watts et al., 2017). According to these findings, ENSO only marginally influences the dust cycle in the hyper-arid core of the Atacama Desert.

North of the Atacama Desert, along the Pisco-Ica desert in Southern Peru (14ºS), eventual dust storms develop 4 or 5 times per year, usually in the afternoons towards the end of austral winter (Escobar Baccaro, 1993; Quijano, 2013). These events are locally known as “Paracas” events and occur over the extremely dry coastal desert due to strong southerly winds along southern Peru, with typical speeds exceeding 10 to 15 m s^{-1}, blowing from the South –Southeast (S-SE) (Briceño-Zuluaga et al., 2017). Using daily MODIS images, Briceño-Zuluaga et al (2017) identified 15 emission days and more than 21 polygonal probable source-areas. The authors reported 65 widespread independent plumes from different sources, suggesting that emission processes vary within a wide range of extension and intensity. As observed in MODIS images by Briceño-Zuluaga et al (2017), the coastal region of the Ica desert proved to contribute the most to active emission, with transport of this material northwestward towards the ocean, although a significant fraction of entrained material is transported into the continent over the Pisco-Paracas area (Gay, 2005). Briceño-Zuluaga et al (2017) results showed that dust loads follow alongshore equatorward trajectories according to the used model, and fine particles (3-10 µm) plumes spread northwestward (up to 300 km for the finer ones) from the emission sources. Moreover, they indicate that coarsest 90 µm particles reach up to 50 km downwind from the sources. According to the research results, the authors concluded that dust fluxes during Paracas wind events originate over the coastal zone, where strong winds forced by steep Alongshore (sea-level) Pressure Gradient (APG) develop. Synoptic-scale meteorological composites from NCEP/NCAR reanalysis data show that Paracas wind events (steep APGs) are mostly associated with the strengthening of anticyclonic conditions in northern Chile, that can be attributed to cold air advection associated with an incoming trough.

In order to evaluate directly the importance of recent wind-transported material in the eastern equatorial Pacific and its sources, Prospero and Bonatti (1969) sampled atmospheric dust during a cruise of RV Pillsbury in 1967, between 10ºN and 15ºS, and 115-80ºW, in front of the coasts of Ecuador and Peru. The authors identified two sources of the collected material due to differences in the mineralogy of two groups of samples and wind regimes. They concluded that the supply of aeolian dust to ocean sediments south of the intertropical convergence zone (ITCZ) is less than on its northern side. For the samples collected south of the ITCZ, they identified the Peruvian coastal desert and the Atacama Desert as the source regions. As low-level winds in these regions flow parallel to the coast, they are not conducive to the transport of dust far out to sea, which accounts for the lower collection rates (0.14 μg m^2) when compared to the domain north of the ITCZ. A possible pathway of the Atacama depositions over the Pacific Ocean relates to the entrainment of dust produced by southern winds and their east (and upslope) inland components (Alfaro et al., 2011; Flores-Aqueveque et al., 2015, 2010; Garreaud et al., 2003; Muñoz et al., 2018, 2013; Reyers et al., 2019; Reyers and Shao, 2019) paired with the local relief, which allow dust incorporation in the atmosphere and then transported by the SE trade winds and distribute it above the ocean (Saukel et al., 2011).

A modern spatial pattern of aeolian-derived marine sediments in the eastern equatorial and subtropical Pacific (10°N to 25°S) was presented by Saukel et al (2011). The authors found that the two source areas for marine sediments in the Southeast Pacific Ocean, the coastal desert of Peru and the Atacama Desert in northern Chile, distinctly differ in the amounts of feldspars and chlorite. While quartz and feldspars, which are products of weathered volcanic rocks and physically weathered metamorphic rocks, are delivered from both source areas, feldspars are reduced off northern Peru, pointing to the Atacama as the major source. Another marker used by the authors is related to clay-mineral composition of sediments, in which illite is a robust indicator that continuously decreases in a northern direction, indicating that dust transport from the Atacama Desert dominates.

3.2. Local atmospheric processes driving aerosol transport and deposition.

In the Atacama Desert, wind erosion is associated with wind gusts (Flores-Aqueveque et al., 2010; Kurgansky et al., 2011). Field studies using dust traps along a west-east transect in the Atacama Desert (~23°S) reveal that atmospheric depositions in the inland region are mainly controlled by the local entrainment of insoluble dust and soluble salts (Wang et al. 2014; Li et al. 2019). This is because marine inputs are strongly reduced due to the blocking by the Coastal Cordillera (Rech et al. 2003), and the input from the Andes is low due to an upslope air flow which prevails at large parts of the daytime (Li et al. 2019). The primary local driver controlling the dust transport and deposition in the Atacama Desert is thus the near-surface thermally driven wind system, which is a result of the interplay of extreme insolation and the local topography, revealing a strong diurnal cycle. During daytime, the strong heating of inland surfaces generates a sea breeze with westerly winds in the hyper-arid Atacama Desert and upslope air flows at the Andes Cordillera (e.g. Jacques-Coper et al., 2015; Muñoz et al., 2018). These winds are further accelerated by the strong insolation effects at the western slopes of the Andes ("Andean pumping"; Rutllant et al., 2013). Consequently, strong near-surface westerly flows with wind speeds of up to 20 m s^{-1} may be generated, not only at the Andes Cordillera but also in the Central Depression and in coastal valleys (Muñoz et al. 2018) and are thus potentially important for the entrainment of surface dust particles. At night, when the land surfaces are rapidly cooling, the wind regime shifts to easterly downslope winds. These downslope winds are particularly strong in broad valleys extending from the Andes to the lower plains of the Atacama Desert (Muñoz et al. 2018), where they form down-valley low-level jets with hourly averaged wind speeds of up to 20 m s^{-1} in the cold season. The jets are concentrated along the central axes of the valleys and are driven by the pressure gradient resulting from the near-surface cooling along sloping valley axes (Muñoz et al., 2013).

Another mechanism generating dust-emitting winds are dust devils. These rotating plumes of dust aerosols are caused by thermal instability are frequently observed in the Atacama Desert (Kurgansky et al., 2011; Metzer et al., 2010; Saukel et al., 2011). According to Kurgansky et al. (2011), one of the few studies on dust devils in the Atacama Desert, they mainly occur between 11:30-16:30 local time, when the air temperature is highest, reaching mean wind speeds of 2–8 m s^{-1}. Towards the afternoon, when westerly winds develop, the number and diameter of the dust-devils increase with vortex diameters of a few meters to about 20 m. Moreover, gypsum dust devils have been reported in the Atacama as well. Benison (2017) observed whirling air columns moving large gypsum crystals entrained from saline pan surfaces, transported a few kilometers away (ca. 5 km) and deposited in large dune-like mounds.

The relative importance of wet and dry deposition fluxes varies with the seasons, with rainfall amounts and with location. Considering the arid climate of the Atacama Desert, dry deposition might be the general rule, at least in the central hyper-arid areas. According to Pye (1987) conditions for dry deposition are: (i) a reduction in wind velocity and turbulence allowing aerosols to sink, (ii) the aerosols are 'captured' by collision with rough, moist or electrically charged surfaces, and/or (iii) the particles become charged and form aggregates which sink faster to the ground. In large parts of the Atacama Desert wind speeds are distinctly reduced at nighttime, with velocities hardly exceeding 5 m s^{-1} at most sites of the hyper-arid core (e.g., Muñoz et al., 2018). Furthermore, observations from wind towers reveal that even lower wind speeds may occur during the transition between the diurnal and nocturnal wind regimes (Jacques-Coper et al., 2015; Muñoz et al., 2018), also in the afore mentioned valleys with strong nocturnal low-level jets (Muñoz et al., 2013). Hence, conditions for dry deposition of dust and aerosols are particularly beneficial during these transition periods.

3.3. Fog as water provider and sea spray mobilizer inland the Atacama Desert

Fog corresponds to liquid water particles suspended in the atmosphere, i.e., liquid aerosols mixed with salts and organics (Cereceda et al., 2002). Due to the scarcity of rainfall and rivers in the Atacama Desert, fog is considered one of the main inputs of water and salts to local ecosystems and landscape, particularly for those established on the Coastal Cordillera and the west portion of the Central Depression (see section 3.3.1). Convective fog found along the coast of the Atacama Desert correspond to a massive cloud named stratocumulus formed over the Pacific Ocean and moved hundreds of kilometers onshore by westerly winds towards the Atacama (Cereceda et al., 2002) (see Fig. 7). The thermal inversion produced by the subsidence of warm air, typical of these latitudes, generates a first humid and cold marine layer, intensified by the Humboldt Current and the deep-sea upwelling (Osses et al., 2017). Thus, stratocumulus is found between 500 and 1000 m a.s.l. and present ca. 300 m thickness average. Once it gets inland, the cloud contacts the continent plains and the Coastal Cordillera, remarkably in coastal mega cliffs, being considered then as fog or “Camanchaca” as it is locally known. Alternatively, orographic fog is formed near the coast, in situ on the first windward slope facing the sea, and where higher mountains or special forms of the relief and coastline work as obstacles that oblige the incoming air mass to ascend and cool by expansion, condensing the water vapor and generating fog, as explained by Cereceda et al (2002). According to this latter study, a third type -radiation fog- was noted in the Pampa del Tamarugal (PdT) in the Central Depression. Radiation fog occurs due to the condensation of atmospheric vapor as a result of the strong temperature decrease at night (Cereceda et al., 2008; Farias et al., 2005).

In the coast the stratocumulus cloud deck frequently moves onshore into the desert and thus generates advective fog (Cereceda et al., 2008). The transport of fog inland is able to reach the east slope of the Coastal Cordillera and the western portion of the Atacama Desert using corridors in the Coastal Cordillera, where plants are episodically seen (see Fig. 9). The amount of fog on the coast of the Atacama Desert, both in Chile and Peru, presents seasonal variations throughout the year, with the minimums being recorded during the summer months (Osses et al., 1998), which adds to the interannual variability that can vary between 15-19% according to data published by Cereceda et al. (2008) for the period 1998-2005 for Alto Patache and Cerro Guatalaya, respectively. The Southeast Pacific (SEP) acts as an ocean–atmosphere interconnected system that determines the fog water variability through the year. The inter-annual variability of fog water content measured at the coast of the hyperarid Atacama Desert is closely related to the local and meso-scale sea surface temperature and low cloud cover inside the SEP realm. (Del Río et al., 2018)

Wet deposition of aerosols can occur either below a cloud, when raindrops, snowflakes or hail-stones scavenge dust as they fall, or within a cloud when dust particles are captured by water droplets and descend to the ground when the precipitation falls (Goudie and Middleton, 2006). For the Atacama Desert, wet deposition is typically restricted to the western region below altitudes of 1300 m a.s.l. (due to fog) and to the Altiplano and Andes Cordillera (due to rain- and snowfall). The spatial extend of the stratocumulus peaks in winter and at night, and accordingly the fog water flux reveals a maximum at the coastal cliff in altitudes between 750 and 850 m a.s.l. during the cold season (Cereceda et al., 2008).

To assess the mean spatial distribution of the coastal fog, we utilize satellite remote sensing data. The Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite provides a Level 2 Cloud Mask product (Ackerman et al., 2017) which assigns the categories “confident cloudy”, “probably cloudy”, “probably clear” and “confident clear” to grid points at a 1 km resolution. From this product, we derive the mean total cloud cover (TCC) by dividing the number of all cloudy cases by the total number of available overpasses for a 16-year period (2003–2018) for each grid point. The TCC can be considered a proxy for the frequently occurring marine stratocumulus clouds. By only considering July, August and September, we focus on the main fog season (austral winter). Furthermore, daily overpasses at around 14:00 and 02:00 local time are distinguished so that the daytime and nighttime situations can be visualized (Fig. 8).

During the nocturnal maximum, the cloud advection reaches the coastal mountain range leading to fog formation. Fog corridors can be identified for regions with lower topographic heights allowing the stratocumulus to penetrate the coastal mountain range, e.g., at Punta Chomache (21.13°S), Punta Chipana, Punta Patache (20.81ºS), Punta Chucumata, and Punta Gruesa (20.21°S). Through some of these corridors between Iquique and the mouth of the Rio Loa (21.4°S), fog can reach even into the PdT. These coastal and interior corridors have been described previously by Farias et al (2005) and are visualized here at a higher resolution (Fig. 8). Furthermore, the extended region of our analysis allows identification of additional corridors farther North, e.g., around Arica, and farther South, e.g., to the North of the Mejillones Peninsula in Morro Moreno (23.46°S), and around Antofagasta (23.65°S). The latter one also allows penetration into the Central Valley.

The water quality of coastal fog in northern Chile has been examined by Schemenauer and Cereceda (1992) for coastal sites north of La Serena (~29.30 ºS) and Sträter et al. (2010) at the Alto Patache fog oasis (~20.85). These studies reported chemistry of advective fog captured in traps, indicating pH value means of 4.99±0.86 and 4.65±0.89 (Schemenauer and Cereceda, 1992) and between 2.9 and 3.5 (Sträter et al., 2010). Also, both studies report high ionic concentrations coming from sea salt.

Fog is one of various sources for salt deposits within the Atacama Desert (Cosentino et al., 2015; Ewing et al., 2006; Owen et al., 2013; Rech et al., 2003; Voigt et al., 2020; Wang et al., 2014), with the importance of fog decreasing inland due to the reduction of its occurrence (Rech et al., 2003; Wang et al., 2014). Interested in understanding fog impact on atmospheric deposition in soils, Wang et al (2014) compared ionic composition of passively collected dust samples near Mejillones (MT) (see section 2.2) , a Salar Grande fog sample (SGF), and an El Tofo (29.26°S, 71.15°W) fog sample (ETF) which has been collected and analyzed previously by Schemenauer and Cereceda (1992). When comparing the samples from MT dust samples and the ETF, Wang et al (2014) found a similar ionic composition, despite small discrepancies in Ca^{2+}, Mg^{2+} and Cl^{-}. Furthermore, the SGF sample was considerably more enriched in Ca^{2+} than ETF (67-fold), and had a Ca^{2+}/SO_4^{-2} molar ratio of ~ 1 similar to gypsum minerals found on the surface of Salar de Grande, near where the fog was collected, indicating that local dust sources are involved. Enhanced NO_3^{-} concentration by a factor of 25.4 compared to the ETF, and a factor of six compared to the MT suggests that the SGF may have been subject to anthropogenic NO_x emissions from the nearby Tocopilla city and power plants to the north. Thus, SGF ion content was considerably impacted by dust from Salar Grande and anthropogenic emissions.

Besides dust, fog may also carry pollutants as indicated by Farias et al (2005) and the aforementioned situation. In this sense, Sträter et al (2010) sampled fog in the fog oasis Alto Patache (20.82°S, 70.82°W) in July and August 2008. The authors found that pH of convective fog varied between 2.9 and 3.5, whereas orographic fog exhibited a pH of 2.5. Moreover, high percentages of sulfate and very high enrichment factors (versus sea salt) of heavy metals were found. According to this, the authors concluded that anthropogenic activity caused high concentrations of heavy metals and contributed to the low pH of fog. In this case, specifically mineral processing facilities, ship traffic, and power plants are the main responsible.

Wang et al (2014) suggested that fog was an important driver of atmospheric deposition at MT (~20%). Fog water droplets efficiently scavenge gaseous species from the atmosphere, enhancing coastal deposition of large marine aerosols. However, fog may not significantly impact inland transport of small particles (sea salts, non-sea salt Ca^{2+}, and secondary NO_3^- and SO_4^{2-}). Thus, fog water droplets carry salts into the Atacama which crystallize once water is vaporized (Wang et al., 2014). Cosentino et al (2015) suggested that calcium sulfate crystals recently formed within the hyperarid core after wet deposition from marine aerosols. Fog also modifies the landscape and impacts the dust cycle, as salt inputs could contribute to surface soil crusting and thereby minimize wind erosion (Owen et al., 2013).


b
DÖRR
TL 12:00:01 21.10.17 23 C 100
WS3

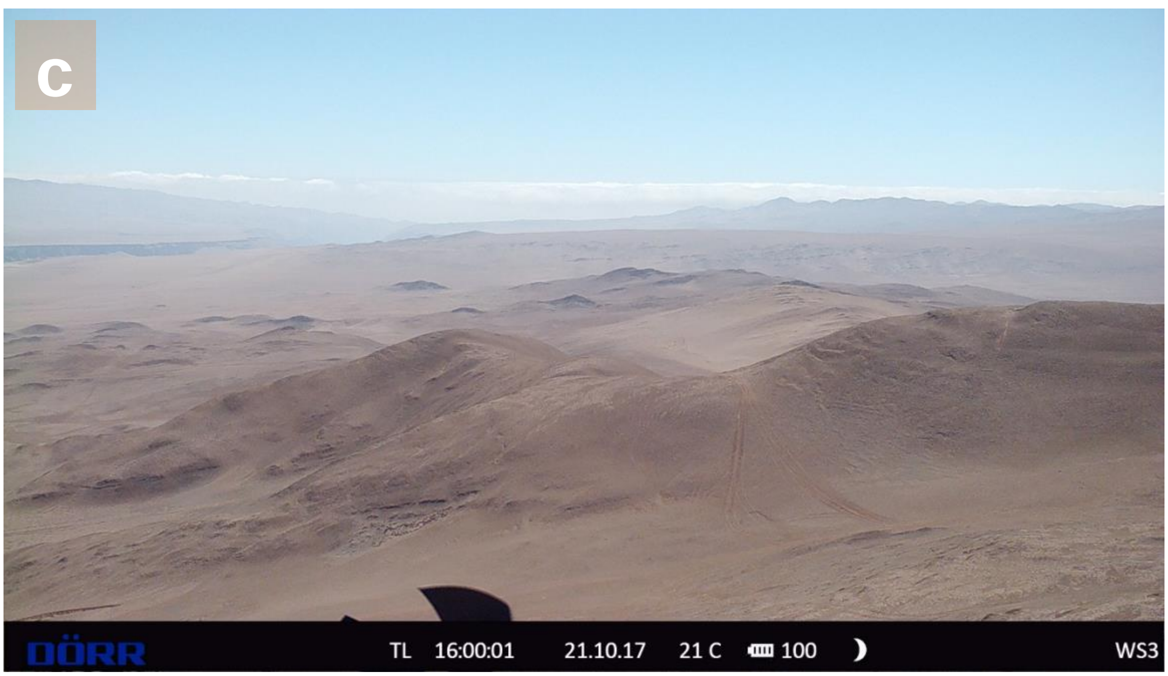
c
DÖRR
TL 16:00:01 21.10.17 21 C 100
WS3

Figure 7. Set of pictures showing the cycle of fog close to the coast near the Loa river canyon within the Atacama Desert at 8.00 (a), 12.00 (b), 16.00 (c) and 20.00 (d) local time. Pictures were taken from a camera trap located in Cerro de Calate at 1148 m ASL (May and Hoffmeister, 2018). During the morning, fog is dissipating due to solar heating. After completely disapearing at noon, fog moves back inland during the afternoon covering the landscape by the sunset.

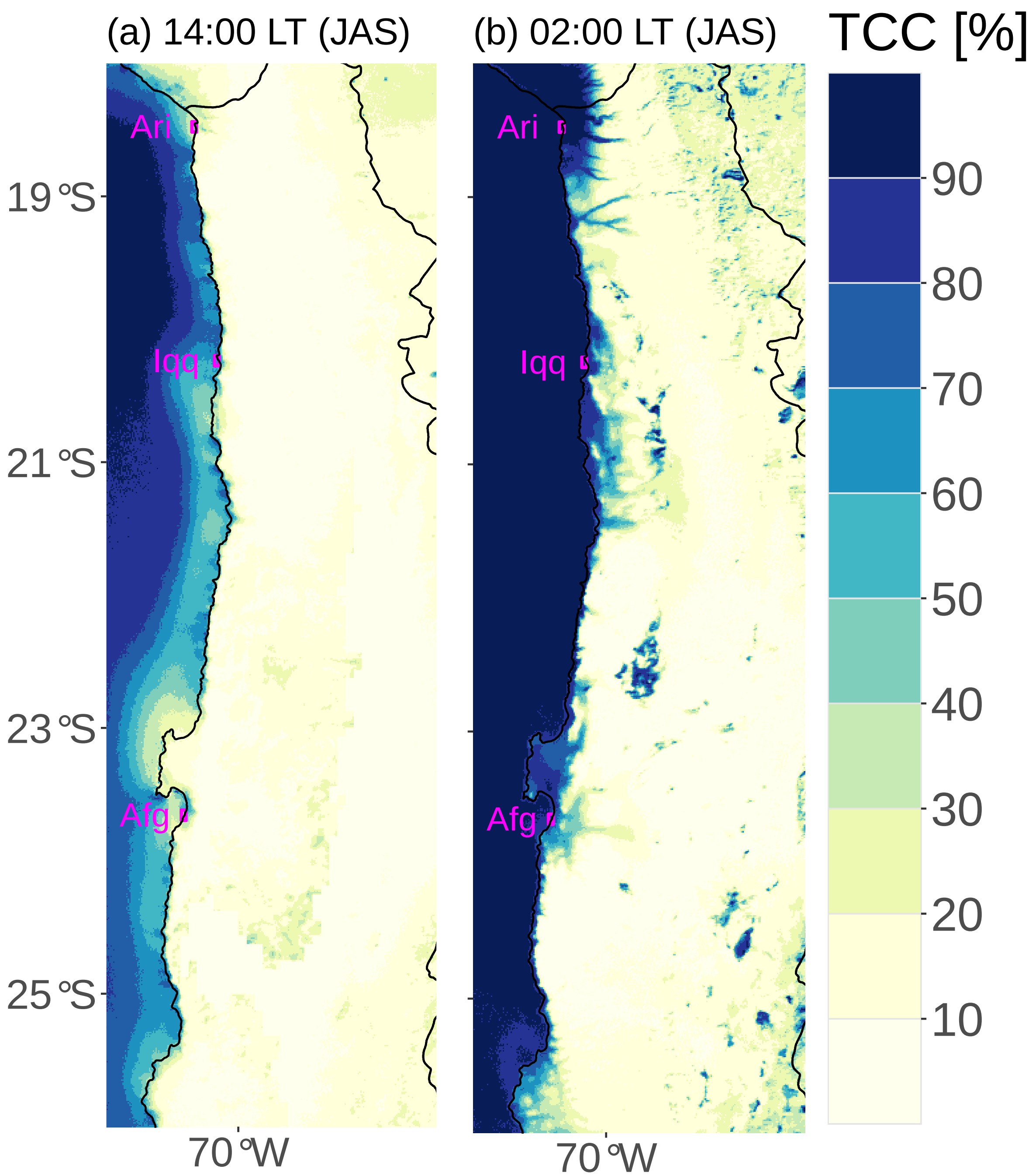

Figure 8. MODIS mean total cloud cover (TCC) for austral winter seasons (July, August, September) within a 16-year period (2003–2018). TCC is used as a proxy for the coastal stratocumulus over ocean and for fog over land in winter at 14:00 (a)

and at 02:00 (b) local time. Magenta points represent the locations of the coastal cities Arica (Ari), Iquique (Iqq) and Antofagasta (Afg). **(Colors should be used)**

3.3.1. Life and atmospheric deposition in the Atacama Desert

As water is an extremely scarce resource in the Atacama Desert, life faces extreme environmental conditions that have forced highly specialized adaptation of organisms to thrive (Azua-Bustos et al., 2012). Thus, plants and microorganisms are distributed in patches across this desert, particularly in places with higher relative water availability. The vegetation is restricted mainly to a narrow belt along the coast that receives water from fog, deep valleys that cross the desert, and the western flank of the Andes (Moreira-Muñoz, 2011) (see Fig. 2). Something similar happens with microorganisms in the hyper arid core, whose distribution in soil is defined by fog presence, being the wet deposition of marine aerosols the most important source of water for native plants, biological soil crusts (Cáceres et al., 2007), and microbial communities (e.g., Azúa-Bustos et al., 2011; Gómez-Silva, 2018a; McKay et al., 2003) in the hyperarid Atacama.

On the coastal cliff along the Atacama Desert, fog oases and Tillandsia fields are representative of the island-like plant formations. Among them, 4 ecosystems may be differentiated according to the predominance: cacti, shrub formation, Bromeliaceas (tillandsias) and annual plants, being the latter supported by the rare rains (Cereceda et al., 2002), and hence ephemeral. Lomas or fog oases are phytogeographic units that generally contain a high number of endemic genera and species (Mostacero et al 1996; Rundel et al. 1991), and have more stablished communities. A complete map for fog oases location was published by Rundel et al. (1991). Among other plant communities in the Atacama, Tillandsia fields are present to the north of the Loa River and in southern Peru (see Fig. 9). These plants have colonized the coastal desert and the Central Depression, being an indicator of fog reach since they obtain water from it. Curiously, Tillandsia facilitate not only the local atmospheric water deposition to the soil beneath, but also the mineral dust deposition. According to Latorre et al. (2011), *Tillandsia landbeckii* plants act as sand traps, which is accumulates downwind from these plants in near-horizontal layers. They spread over the sand, thereby maximizing their profile toward the wind and fog, and creating a small incipient dune-like structure. Successive stages of growth, dieback and colonization explain the unusual stratigraphy (and increased height with age) seen in these dunes. Some other plants population that captures mineral dust and possibly fog are Saltgrass *Distichlis spicata*. These plants usually grow in salar (salt lakes) margins and get water from aquifers. When it is possible, these plants grow in columns trapping the circulating dust, using it as accretion material.

The Atacama Desert contains regions that represent the most extreme hyperarid soils known. Considering that water availability is the primary controlling factor for microbial activity, biomass and diversity in desert soils (Connon et al., 2007), the distribution of soil microorganisms is defined by the occurrence of fog in the hyperarid Atacama. As the air humidity decreases from the coast towards to the east, so does the density of biological soil crust (Cáceres et al., 2007). Despite of this, in places with extreme dry conditions which are used as analog to the Martian surface (Gómez-Silva et al., 2007; McKay et al., 2003b; Navarro-González et al., 2003), microorganisms still can be found in the hyper arid core of the desert and have been reported, e.g. in Altamira, Yungay station, Lomas Bayas, Maria Elena, Salar Grande, Salar Soronal, Pozo Almonte, and Humberstone; all locations between 700 and 2000 m a.s.l. (Contador et al., 2020). Moreover, soil microorganisms present a relative fast response to fog water presences, as shown by (Jones et al., 2018). Nevertheless, fog is not distributed uniformly and extremely dry soils (Navarro-González et al., 2003) occur in locations where fog is blocked by high coastal mountains (Rech et al 2003). A distribution map of microorganisms is available in the Atacama Database (http://www.atacamadb.cl).

Due to the new knowledge generated regarding the microbiology of the Atacama Desert is that today we understand this region not as a barren soil but as a territory colonized by a rich microbiota that includes extremophiles and extreme-tolerant microorganisms (Gómez-Silva, 2018b). These organisms have been found in soil crusts (biological soil crusts) (Wang et al., 2017), soil subsurface and sediments (Parro et al., 2011; Warren-Rhodes et al., 2019) and as lithobiontic life (Gómez-Silva, 2018b), excluding of course the aquatic microbial life. These terrestrial microorganisms rely on the collection of liquid water from incoming fog and/or water vapor condensation and deliquescence on or within halite and quartz rock surfaces. In the case of microbial endolithic communities from halites exposed to coastal fogs and high relative humidity, Robinson et al. (2013) concluded that these were more diverse and that their archaeal and bacterial assemblages were accompanied by a novel algae related to oceanic picoplankton of the Mamiellales. In contrast, they found no algae in the Yungay pinnacles. The same was stated by Warren-Rhodes et al. (2006) for hypolithic cyanobacteria, whose diversity decreases progressively along an aridity transect (south-north) between Copiapo and Yungay. Moreover, they determined that hypolithic cyanobacteria are rare and exist on small, spatially isolated areas in the middle of microbiologically unpopulated bare soil. Azúa-Bustos et al. (2011) reported complex associations of cyanobacteria, archaea, and heterotrophic bacteria along the coast of the Atacama, 1.5 km from the Pacific Ocean, inhabiting the undersides of translucent quartz stones. They concluded that colonization rates in these areas, which receive virtually no rain but mainly fog, are significantly higher than those reported inland in the Central Depression at the same latitude and in consequence, the Coastal Cordillera offers a more benign sites for the development of microbial life.

The more robust microbial life inhabiting the ocean and the coastal desert is prone to be transported inland through wind mobilization using passages in the Coastal Range. This was proven by Azua-Bustos et al. (2019) who, using Petri dishes exposed to atmospheric deposition in the coast, Coastal Cordillera and the Central Depression of the Atacama Desert, were able to cultivate and identify different strains of microorganisms, some of them native of the oceans (e.g. O*ceanobacillus oncorhynchi, Bacillus oceanisediminis, Brachybacterium paraconglomeratum and Bhargavaea cecembensis*) and from plant rhizosphere (e.g. the bacterial specie *Bacillus simplex* and the fungal specie *Ophiosphaerella herpotricha*) coming possibly from the sparse plant-covered areas of fog oases on top of the hills of the Coastal Cordillera. Also, airborne bacteria were reported possibly coming from further and unknown places (*Kocuria flava*, an actinobacteria and *Bacillus* *altitudinis*). Authors also studied the daytime when more microorganisms were collected revealing that late afternoon transport is more abundant and, in consequence, a wet deposition due to fog is more feasible. This timetable is coincident with faster coastal winds coming from south and southwest that penetrates into the desert and displace towards the Andes.

Nevertheless, the arrival of organic compounds and microorganisms may be affected and oxidized by the chemical reactivity of surface soils in the Atacama. The production of secondary aerosols and oxidative agents occurs due to atmospheric chemistry from gaseous oxide precursors such as NH_3, NO_2, NO_3, SO_2 and their reaction with O_3 and OH radicals powered by the extreme solar radiation to which the Atacama is subjected (Ewing et al., 2006; Quinn et al., 2005). Some hyper arid environments such as Yungay in the Atacama Desert are rich in highly oxidative dust (Quinn et al., 2005), which is produced by these reactions and is capable of produce sulphuric and nitric acid. The presence of these acids in soils is important because during nighttime, when water is more available due to fog and humidity penetration, may react oxidizing the deposited organic compounds and microorganisms arrived to the Atacama, especially after the sunset, affecting the availability of nutrients and toxins for plants, diversity of microbial life, activity and colonization, and the mechanisms for organic compounds degradation and cycling. Relevantly, it is likely that oxidants are formed by photochemical reactions among the interfaces soil/dust/atmosphere in an analog way to that suggested for Mars and be responsible for the presence of iodates chromates, perchlorate, among others detected in that planet (Quinn et al., 2005).

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Figure 9. At the top (a), a field of Tillandsias over the south-western slope of the Cerro de Calate is shown, to the north the Loa river canyon (visible in the picture). At the bottom (b), several alive specimens of tillandsias are shown next to a buried dead mat of tillandsias.

4. Concluding remarks

The scientific literature indicates that the Atacama Desert is (one of) the oldest and driest deserts on Earth and, in consequence, the scarce leaching and run off associated with precipitation affecting soils and salt deposits are typically negligible. These characteristics makes the Atacama Desert an ideal environment to study and constraint the temporal and spatial dynamics of atmospheric depositions and their long-term accumulation in the soils.

In the last two decades several efforts characterized atmospheric depositions including measurements of deposition rates in the Atacama Desert. Based on reviewing the past research, we conclude that the aerosols deposited in the Atacama Desert, both from local and remote aerosol sources, play an important role in the formation of soil and salt deposits, and vary in aerosol deposition amount and chemical composition in space and time. For instance, the western Atacama is strongly influenced by fog and sea spray on soil gypsum/anhydrite with depositions of soluble salts (Rech et al., 2003), while the eastern margin has more insoluble material components from the Andes and further eastern deflated soils (Li et al., 2019). Moreover, the redistribution of salts from deflated salars (playas) was also denoted being very important in the Central Depression (Ewing et al., 2006; Rech et al., 2003). All of the above mentioned processes correspond to the aeolian redistribution of particles but contributions from (secondary) aerosols produced directly in the atmosphere have also been suggested, e.g., nitrate and sulfate deposits (Ericksen, 1983; Ewing et al., 2006; Rech et al., 2003; Wang et al., 2014).

The examination of the deposited aerosols has been done by setting several series of passive dust traps arranged in west-east and north-south oriented transects in order to ponder the influence of sea sprays (W-E) and aridity (N-S), along with the examination of soils (Ewing et al., 2006; Li et al., 2019; Wang et al., 2014). To the west of the Atacama, the Humboldt Current flows northwards from Antarctica. Consequently, the marine upwelling of colder waters develops immediately offshore and leads to a high biological productivity in the coastal ocean (Marín and Olivares, 1999; Moore et al., 2002). As a result, it would not be rare to find Na, Cl (Ewing et al., 2006), inorganic S (Rech et al., 2003) and N (Michalski et al., 2004) in the Atacama soils transported by westerly winds from the Pacific Ocean. Thus, the aerosol loading may be rich in inorganic compounds and also supply organic C and N, as well as Ca (Wang et al., 2014) and inorganic C from marine organisms (Moore et al., 2002), water and even microorganisms (Azua-Bustos et al., 2019). From the Andes and Altiplano, easterly winds can carry mineral dust, volcanic emissions, organic compounds from the more vegetated areas, and alluvial sediments mobilized by the summertime rains. These easterlies are not uncommon as they are related to a southward shift of the Bolivian High, an upper-level feature that frequently develops in austral summer (e.g., Reyers et al., 2020).

Aside from the natural aerosol sources, aerosols associated with anthropogenic activity must be considered. The Atacama Desert is affected by industrial mineral exploitation, because of the massive salt and metal deposits harbored within. These aerosol-producing activities comprise not only the mining activity itself but for instance also the mineral and manpower transport, fossil fuel burning, and smelting processes. Several authors have suggested that nitrate, sulfate, Na and Ca loads in the atmosphere may be emitted by anthropogenic sources in the Atacama Desert (Ewing et al., 2006; Voigt et al., 2020; Wang et al., 2014). Moreover, exceptionally high Na/Cl ratios were found in present day aerosol samples (Wang et al., 2014; Li et al., 2019), along with an excess of Cl in the Atacama soils which can be confirmed to represent a large impact of anthropogenic emissions (Voigt et al., 2020).

Despite the hyper aridity and deprivation of plants in much of the Atacama Desert, making the surface soils, anhydrite dust and gypsum, prone to wind erosion, dust storms are rather rare and less intense in comparison to North Africa. In principle, this may be explained by low erodibility of the soil, low emissivity of the prevailing winds, or a combination of the two. Our review suggests a low erodibility of the undistrubed soils in the Atacama Desert in the present climate due to (1) the hyper aridity leading to low fluvial activity and hence the extremely low rates of erosion, (2) the typical presence of non-erodible objects, such as boulders and cobbles, and (3) the occurrence of desert pavements, soil crusts, salt nodules and crusts, and soil vesicular surface horizons. These characteristics reduce or inhibit the mobilization and entrainment of desert-dust particles, even when there are strong winds. Case studies of past dust storms indicate that a sufficient erosivity of winds can occur, but the typically prevailing weather in the present climate seem unfavourable for generating sufficiently strong and persistent winds. Further research is needed to fully understand the occurrence and long-term changes of dust storms in the Atacama Desert in the context of the geological and anthropogenic changes of the local soils.

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