



ENSO Influence on Coastal Fog-Water Yield in the Atacama Desert, Chile

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ABSTRACT

Fog water represents an alternative, abundant and currently unexploited fresh water resource in the coastal Atacama Desert (~20°S). Here, the stratocumulus clouds meet the Coastal Cordillera, producing highly dynamic advective marine fog, a major feature of the local climate that provides water to a hyper-arid environment. One of the main issues that arises in harvesting fog water is our limited understanding of the spatial and inter-annual variability of fog clouds and their associated water content. Here we assess the role of regional-wide El Niño Southern Oscillation (ENSO) forcing on local inter-annual fog-water yields along the coast of Atacama. We contrast 17 years of continuous fog-water data, with local and regional atmospheric and oceanographic variables to determine the link between them and the inter-annual dynamics of fog in northern Chile. Sea surface temperature (SST) in ENSO zone 1 + 2 shows significant correlations with offshore and coastal Atacama SST, as well as with local low cloud cover and fog water yields, which go beyond the annual cycle beat, exposing a potential causal link and influence of ENSO on fog along the Atacama. On the inter-annual time scale, we found that when ENSO 3 + 4 zone SST, specifically during summer, overcome a > 1°C temperature threshold, they incite significantly higher summer fog water yields and explain 79% of the fog variability. Furthermore, satellite images displaying regional extent Sc cloud and fog presence during ENSO extremes reveal higher cloud abundance during El Niño at this latitude. However, 75% of the yearly fog water is collected during winter, and does not appear to be affected in a significant manner by Pacific oscillations. Thus, our results suggest that the utilization of fog as a fresh water resource may be sustainable in the future, regardless of ENSO-induced variability in the region.

Keywords: Southeast Pacific (SEP); Stratocumulus cloud; Fog-water; El Niño Southern Oscillation (ENSO); Estación Atacama UC Oasis de Niebla Alto Patache.

INTRODUCTION

Due to the extremely low levels of precipitation in the coastal Atacama, there are very limited and in some cases no fresh water sources available (Núñez and Varela, 1965) (e.g., the city of Iquique has an average precipitation rate of 0.6 mm year⁻¹, DMC, 2016). Therefore, fresh water is expensive (Oyarzún and Oyarzún, 2011), making access to water a major social and economic issue in the region (Alonso, 2001). As an example, coastal fishing villages in the region typically have no electricity or basic sewage and

can only access fresh water through truck deliveries, which occur weekly or even less frequently. This problem has intensified along with the heterogeneous economic progress taking place in the region, which in recent decades has been associated with large-scale mining operations (CIDERH, 2013).

Despite historical uses of fog water by ancient cultures in coastal Atacama (Beresford-Jones *et al.*, 2015), nowadays advective-fog represents an alternative, abundant and unexploited fresh water resource in the coastal Atacama Desert (Larraín *et al.*, 2002; Cáceres *et al.*, 2007; Cereceda *et al.*, 2008a). Fog water consists of the collection of fog droplets using different instruments and its potential as a fresh water resource has been successfully demonstrated in various countries that experience concerns with regards to water-provision. Fog water has been used on all continents, in countries with average water yields that vary depending

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on the local climate and topographic conditions from 3 to $10 \text{ L m}^{-2} \text{ day}^{-1}$ (Klemm, 2012). Yearly fog water yields in the coastal Atacama Desert average over $7 \text{ L m}^{-2} \text{ day}^{-1}$ (Larraín *et al.*, 2002; Cereceda *et al.*, 2008a), which afford a water supply based on fog for local settlements (fishing villages) and low scale economics activities (Osses *et al.*, 2000; Schemenauer *et al.*, 2007). Worldwide fog-water initiatives have proven to be economically, socially and environmentally sustainable (Cereceda *et al.*, 1997; Shanyengana *et al.*, 2002; Olivier 2004; Klemm, 2012). Nonetheless, one of the main issues that arise in harvesting fog water is our limited understanding of the spatial and inter-annual variability of fog clouds and their associated water content in the Atacama. These clouds are the result of the regional-scale interaction between oceanic, atmospheric and local-scale geographic factors, which have remained mostly unattended when studying fog water content.

Fog water has been collected in northern coastal Chile at the Estación Atacama UC Oasis de Niebla Alto Patache (referred to herein as Alto Patache), as well as on nearby Cerro Guatalayasince 1998 (Fig. 1(a)). In this paper, we

compare 17 years (1998–2014) of continuous monthly fog-water data from Alto Patache and Cerro Guatalaya with local and regional atmospheric and oceanographic variables, in order to assess the main interactions that could be affecting the inter-annual dynamics of fog in northern coastal Chile. Detailed knowledge as to the spatiotemporal variability of fog and the relationship between this variability and the Southeast Pacific (SEP) oceanographic and atmospheric realms remains mostly unknown. We therefore aim to explore the role of offshore climate and surface ocean conditions on the presence of fog clouds, their water content and how these parameters vary through time. To accomplish this goal we applied multi-scale geographic analysis, including the use of satellite remote sensing and local observations. We analyzed the spatial and temporal variability of fog availability under different El Niño Southern Oscillation (ENSO) conditions, and thereby assessed the potential and sustainability of fog water for use as a future freshwater resource in the Atacama Desert. In this work, our main research objective is to evaluate the role of regional-scale forcing on the local availability of

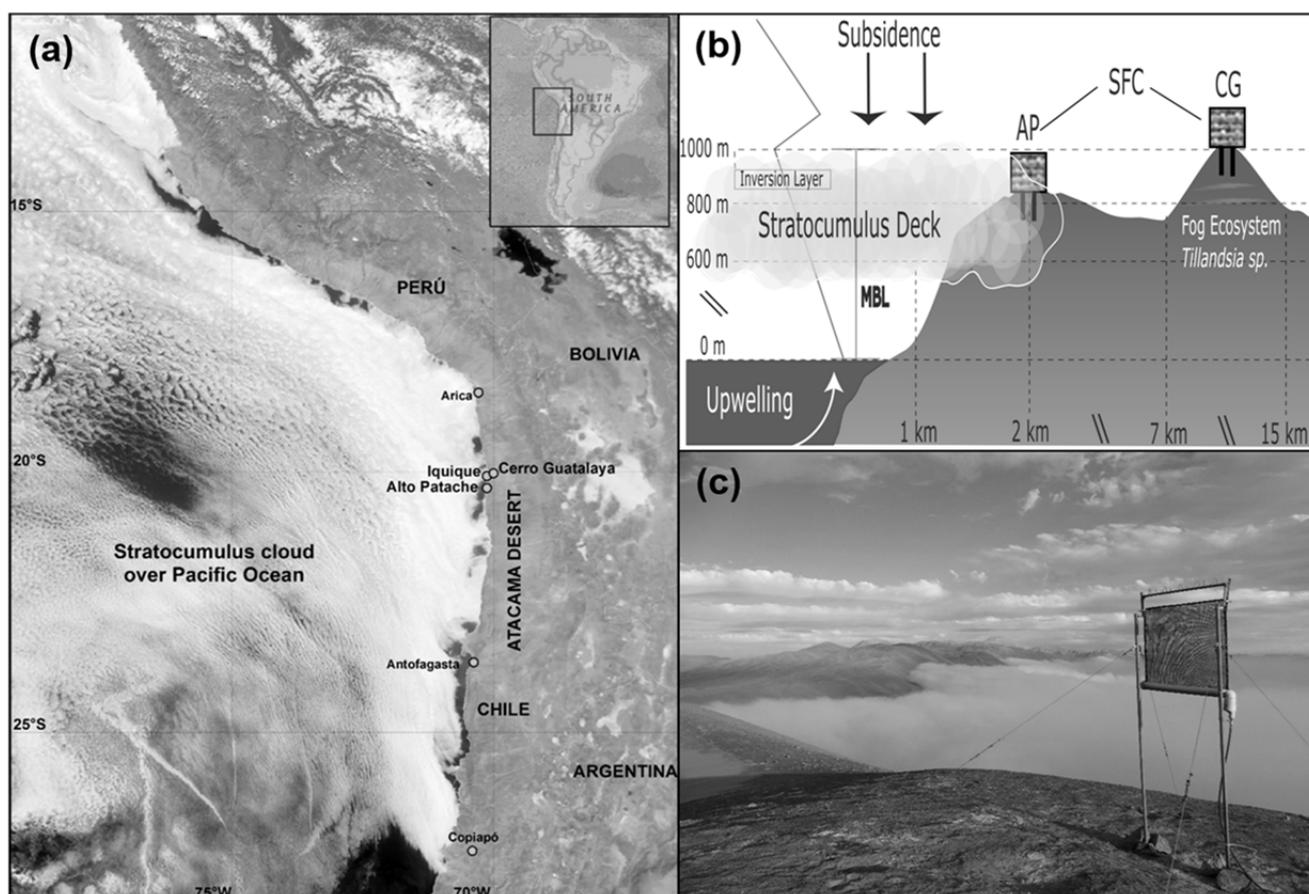


Fig. 1. Geographical context for fog in the coastal Atacama Desert, study sites and the standard fog collectors (SFC). (a) The stratocumulus deck at the coastal Atacama Desert. This cloud deck results in the existence of a well-defined fog belt within a vertical stretch below about 1,000 m a.s.l. along the Coastal Cordillera, where atmospheric tiny droplets are abundant most of the year (base image: *Aqua/Modis L1 product*, August 1, 2014, 18:43 UTC); (b) Schematic topographic profile of coastal setting. The two SFC sites of Alto Patache (AP) and Cerro Guatalaya (CG) are shown for reference; (c) the SFC at Alto Patache is constructed from 1 m^2 Raschel polypropylene mesh that stands two meters above the ground. This SFC has been measuring fog data since January 1998. MBL: Marine boundary layer.

fog clouds and water content along the coastal Atacama Desert, northern Chile (19°–21°30'S), and its relationship to ENSO inter-annual variability (Garreaud *et al.*, 2008a). The main scientific questions guiding this research are as follows: how does the sea surface temperature (SST), both nearshore and offshore, affect the inter-annual variability in fog clouds and fog water yields? Does ENSO variability affect Atacama fog water yields?

The Fog Bank in the Coastal Atacama Desert

In the coastal Atacama, the SEP stratocumulus (Sc) clouds meet the Coastal Cordillera, producing highly dynamic advective marine fog (Fig. 1(a)), which is a major feature of the local climate that provides water to a hyper-arid environment and isolated ecosystems (Cereceda *et al.*, 1999; Muñoz-Schick *et al.*, 2001; Larrain *et al.*, 2002; Pinto *et al.*, 2006; Cereceda *et al.*, 2008a; Westbeld *et al.*, 2009; Latorre *et al.*, 2011; Stanton, 2015). Organisms living in these extreme conditions have developed highly specialized adaptation strategies to deal with the seasonal availability of fog water (Masuzawa 1985; Rundel and Dillon, 1998; Muñoz-Schick, 2001; Pinto *et al.*, 2006; Borthagaray *et al.*, 2010). The annual Sc cloud cycle in the coastal Atacama is well-documented, with increased presence and spatial extent during the austral winter and early spring and decreased presence during the austral summer (Fariás *et al.*, 2005; Cereceda *et al.*, 2008b). Climate variability in the SEP is primarily controlled by ENSO, which modulates changes in SST and the intensity of anticyclone air-subsidence, which in turn exert a direct influence on fog water yields (Park and Leovy, 2004; Garreaud *et al.*, 2008a). Nonetheless, inter-annual variability in fog water availability still needs to be assessed in detail along the Atacama coastline, where for the most part long-term data records are lacking.

The extensive Sc deck in the SEP is produced by the thermal-inversion of air, which is created by large-scale air

subsidence in the subtropical Pacific Anticyclone (Fig. 2). This subsidence is intensified by the cold Humboldt Current and the upwelling of cool waters along the western South American coast (Garreaud *et al.*, 2001; Rutllant *et al.*, 2003; Montecinos and Pizarro, 2005; Cereceda *et al.*, 2008a; Serpetzoglou *et al.*, 2008; Bretherton *et al.*, 2010). In the Atacama, the structure of the low troposphere includes a lower well-mixed and humid cool air, the marine boundary layer (MBL) that extend upwards until about 1000 m a.s.l. and is limited by the air subsidence thermal inversion. Above this layer, extreme dry conditions persist in a free atmosphere (Garreaud *et al.*, 2001; Rutllant *et al.*, 2003; Cereceda *et al.*, 2008b).

The annual fog-cloud cycle (Fig. 3) is primarily determined by the seasonality of large-scale air subsidence and coastal SSTs. During winter and spring, colder SSTs and warmer air above the thermal inversion layer generate a stronger temperature inversion, resulting in better conditions for cloud development. During summer and early autumn, a higher and weaker thermal inversion layer allows thermal interactions between the MBL and the dry air above (Garreaud *et al.*, 2007; Cereceda *et al.*, 2008a). The daily cycle is strongly influenced by local onshore – offshore air exchanges; cloudiness peaks during the night, sunset and early morning due to low atmospheric temperatures, whereas mid-day solar radiation dissipates the fog bank (Garreaud and Muñoz, 2004; Cereceda *et al.*, 2008a; Muñoz *et al.*, 2011). At the local scale, topographic features such as hillslope, aspect, altitude, and ground morphology control fog presence, distribution, and liquid water content within the Coastal Cordillera (Osses *et al.*, 1998; Cereceda *et al.*, 2002; Osses *et al.*, 2007). For example, ongoing research reveals differences of 70% in fog water yields in less than a 150 meters vertical profile (Osses, P. Personal communication). Furthermore, the Atacama is punctuated by fog corridors that connect the coast and inland realms (Fariás *et al.*, 2005).

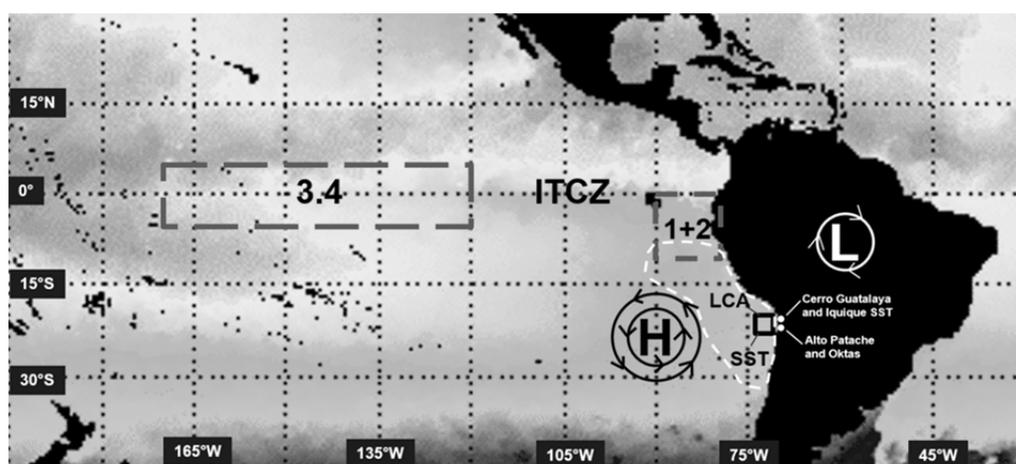


Fig. 2. Atmospheric and oceanographic multiscale indexes analyzed in this study. White dots show location of local data, including the two standard fog collectors, the Iquique coastal sea surface temperature (SST) and the oktas cloud cover from the Iquique airport. Black box show the meso-scale area offshore Atacama, corresponding to Low Cloud Amount (LCA) and SST. Outline dashed line boxes represent the regional data, including the ENSO 3.4 and 1 + 2 SST zones. White dashed line show the prevailing area of the Southeastern Pacific stratocumulus. Inter Tropical Convection Zone (ITCZ), High pressure (H), Low pressure (L).

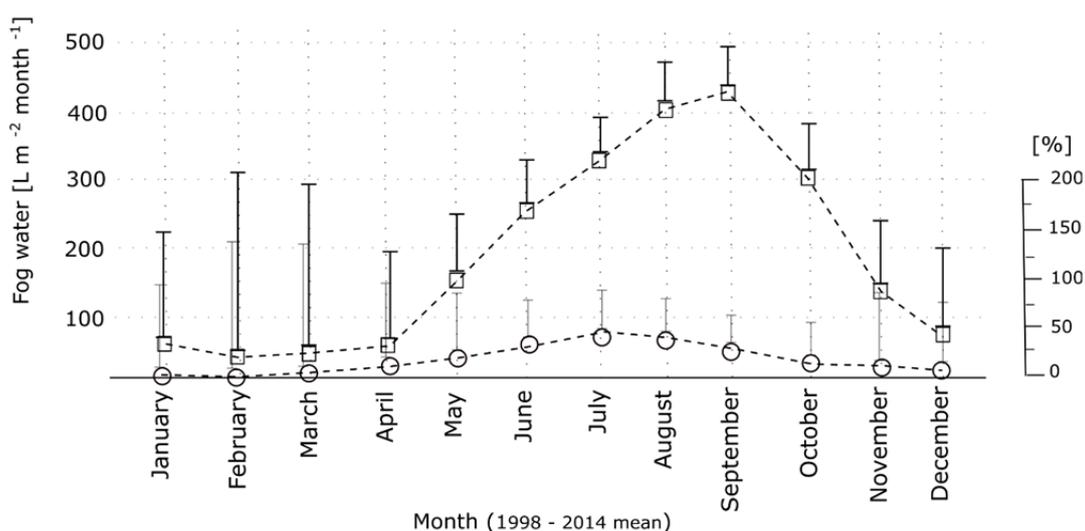


Fig. 3. Monthly means of fog water yields collected by standard fog collectors (SFC) at Alto Patache (squares) and Cerro Guatalaya (circles) for the period 1998–2014. Bars represent standard error expressed as percentage (dark grey for Alto Patache and light grey for Cerro Guatalaya, respectively; see scale to the right). Higher variability is present in summer months in both SFCs, opposite during winter months.

At inter-annual and inter-decadal temporal scales, ENSO and the Pacific Decadal Oscillation (PDO) (Mantua *et al.*, 1997) are known to exert control on the SEP climate (Garreaud *et al.*, 2008b). In the case of ENSO, while El Niño years bring precipitation, La Niña years produce enhanced arid conditions in the Atacama (Ortlieb, 1995). Garreaud *et al.* (2008a) explored direct correlations between ENSO and the presence of coastal Sc and advective fog in the semiarid regions of Chile (~30°S) during spring. They concluded that while La Niña conditions produce an increase in the presence of fog, the opposite occurs during El Niño years. Interestingly, they hypothesized that north of 25°S the effect of ENSO is opposite, with an apparent asymmetry in the fog response to ENSO between hyper-arid and semiarid regions within the Atacama. Our study area is centered at 20°S, and therefore suitably located to test this hypothesis. At inter-decadal time scales, recent studies, limited to the current cold PDO phase, have shown that Sc cloud cover has not changed between 1981–2013 (Muñoz *et al.*, 2016), although (del Río *et al.*, 2016) found a weak nighttime positive trend and a compensating daytime negative trend during the period 1995–2015.

MATERIAL AND METHODS

We present fog water data obtained by standard fog collectors (SFCs) at two sites (see Fig. 1(b)) separated latitudinally by 75 km. The first site (Fig. 1(c)), Alto Patache, is located on the summit of the Coastal Cordillera (850 m a.s.l.) about 3.5 km lineal distance from the coastline on a peninsula oriented opposite the coastal SW wind direction. These prevailing winds generate increased upwelling and colder SSTs, which in turn produces better conditions for fog cloud coverage (Cereceda *et al.*, 2002; Farías *et al.*, 2005). The second site is located at the top of Cerro Guatalaya, 1050 m a.s.l. and about 12 km lineal distance from the coastline.

Systematic monthly measurements have been taken at both SFCs from January 1998 until present, with only six months of omitted data. Here, we present data from 1998 to 2014. Each SFC collects water by channelization in a closed conduit to a sealed hard-plastic 200 L container; therefore losses (e.g., by evaporation) are minimized. Manual measurements were performed monthly (or in some cases more frequently) using mL graded lab jars. For seasonal analysis, based on data from Alto Patache fog water yields, we analyzed data by season: austral summer (January, February, March [JFM]), austral fall (April, May, June [APJ]), austral winter and early spring (July, August, September [JAS]), and austral spring (October, November, December [OND]).

We assessed the link between fog and SEP atmospheric and oceanographic components, by analyzing multi-scale (local, meso and regional) atmospheric and oceanic indices. These indicators are listed in Table 1 and shown in Fig. 2. The selected atmospheric indicators related to cloud cover include local- and meso-scale data. At a local scale, we used oktas cloud cover data. Oktas are systematic measurements taken hourly by the Dirección Meteorológica de Chile by watching and recording sky conditions at the Iquique airport (20°32'S–70°10'W; 50 m a.s.l., ~3 km from the Coastal Cordillera and 1 km from the coastline, 32 km north of Alto Patache SFC and 40 km SW of Cerro Guatalaya SFC); values range from 0 to 8, with 0 indicating no cloud cover and 8 indicating 100% cloud cover. In order to convert the oktas hourly data into daily data, we calculated for the days with presence of Sc cloud, the arithmetic mean of the 12:00 and 24:00 UTC (08:00 and 20:00 local time) measurements; these daily values were then used to calculated monthly means. This methodology follows that of Schulz *et al.* (2011), with the exception that we did not include 18:00 UTC measurements, due to low fog presence at this time of day at our study sites (Cereceda *et al.*, 2008a). Meso-scale data was based on Low Cloud Amount

Table 1. Multi-scale oceanic and atmospheric indicators analyzed in this study.

Variable	Indicator	Scale	Coordinates (point or area)	Source	Available Data	Data Used	Original Measurements interval	Measurement interval analyzed
Fog water	$L m^{-2} day^{-1}$	Local	20°49'S–70°09'W (Alto Patache)	Centro del Desierto de Atacama UC	1998–Present	1998–2014	Monthly	Monthly
Cloud cover	$L m^{-2} day^{-1}$	Local	20°12'S–70°00'W (Cerro Guatalaya)	Centro del Desierto de Atacama UC	1998–2013	1998–2014	Monthly	Monthly
	Okta	Local	20°32'12"S– 70°10'41"W	Dirección Meteorológica de Chile (DMC)	1981–Present	1998–2014	Hourly	Monthly
	Low Cloud Amount (LCA)	Meso	19°S–21°30'S; 72°– 70°W	NASA – ISCCP	1983–2009	1998–2009	Monthly	Monthly
Sea Surface Temperature (SST)	Sc cloud Presence/ absence	Meso	19°S–21°50'S; 71°– 69°W	GOES-8 Satellite: NASA - NOAA	1994–Present	July 1997 and 1999–January 1998 and 2000	30 minutes	Monthly
	SST Iquique	Local	20°12'16"S– 70°08'52"W	Servicio Hidrológico y Oceanográfico de la Armada, Chile (SHOA)	1984–Present	1998–2014	Daily	Monthly
SST Atacama	SST Atacama	Meso	19°S–21°30'S; 72°– 70°W	NOAA - Optimum Interpolation (OI) SST V2 Data	1989–Present	1998–2013	Monthly	Monthly
	SST ENSO 1+2	Regional	0°–10°S; 90°–80°W	NOAA/ National Weather Service	1950–Present	1998–2014	Monthly	Monthly
SST ENSO 3.4	SST ENSO 3.4	Regional	5°N–5°S; 120°W– 170°W	NOAA/ National Weather Service	1950–Present	1998–2014	Monthly	Monthly

(LCA) estimates and GOES-8 satellite images. The LCA is based on monthly averages obtained from the International Satellite Cloud Climatology Project (Schiffer and Rossow, 1983). LCA data was assumed to be representative of the offshore cloud cover conditions for the coastal Atacama Desert. We used satellite images for spatiotemporal Sc cloud and fog presence estimates.

Indicators of oceanic SST used here include: (1) at a local scale, Iquique SST data based on measurements taken by the Servicio Hidrográfico y Oceanográfico de la Armada; (2) at the meso-scale, Atacama SST data obtained from Optimum Interpolation Sea Surface Temperature (OI.v2 SST) maps developed by the National Oceanic and Atmospheric Administration (NOAA); and (3) at a regional scale, we used the SST 3.4 (monthly SST area average), the Oceanic Niño Index (ONI) (a 3-month running mean of SST anomaly in zone 3.4), and the SST 1 + 2 (monthly SST zone average) (see Fig. 2).

In order to contrast Sc cloud coverage and fog variability during extreme ENSO years, we processed GOES satellite images. We analyzed seasonal spatiotemporal differences in Sc cover during July (El Niño 1997 and La Niña 1999) and January (El Niño 1998 and La Niña 2000), obtaining monthly frequencies of Sc presence for the months when the ENSO index had the most disparate values. We used 2 images per day, taken at 03:39 and 07:39 UTC (23:39 and 03:39 local time), which correspond to the times of maximum fog presence (Fariás *et al.*, 2005; Cereceda *et al.*, 2008a). Identification of low clouds was based on a widely used metric: the difference between short (3.8 μm) and long (10.9 μm) thermal infrared wavelengths (Eyre *et al.*, 1984; Ellrod, 1995; Lee *et al.*, 1997; Anthis and Cracknell, 1999; Bendix, 2002; Underwood *et al.*, 2004). Change detection techniques were used to discriminate between low clouds and salt flats erroneously classified as fog based on thermal differences. We excluded images containing high clouds from the final estimations and finally analyzed between 20 and 28 images per month. Ground truth methodologies, based on Osses *et al.* (2005), were applied to validate satellite image results. Field visits were conducted in 2015, during which over 30 observations of Sc/fog presence were recorded at the two study locations. Comparisons with satellite data showed > 93% agreement.

The time period analyzed in this study (1998–2014) includes some very strong El Niño years (1997–1998, 2007), as well as some strong La Niña years (e.g., 1999–2000 and 2010–2011). This allowed us to analyze fog water yields and cloud cover under opposite extreme ENSO oceanic-atmospheric conditions. We carried out linear regressions that helped us assess fog water variability. All the correlations shown here are significant at $\geq 95\%$ confidence levels. We also carried out periodic analyses to assess potential causal links between analyzed variables (e.g., ENSO versus fog water yield).

RESULTS

Fog Water Yields

Our measurements reveal an annual average of nearly 7

$\text{L m}^{-2} \text{ day}^{-1}$ and $< 1 \text{ L m}^{-2} \text{ day}^{-1}$ at the Alto Patache and Cerro Guatalaya SFCs, respectively. Fig. 3 illustrates seasonal differences at both sites, with significantly higher yields during the austral winter (here defined as JAS) and spring (here defined as OND) when compared to the summer (here defined as JFM) and autumn (here defined as AMJ). The highest annual yields at Alto Patache were recorded from June to October and concentrate > 75% of the amount of water collected annually. In JAS the mean values at Alto Patache reach their maximum, $> 13 \text{ L m}^{-2} \text{ day}^{-1}$, corresponding to an average accumulation of nearly $400 \text{ L m}^{-2} \text{ month}^{-1}$ during this time period. These values contrast with the $< 40 \text{ L m}^{-2} \text{ month}^{-1}$ collected at Alto Patache during JFM. Maximum values at Cerro Guatalaya also occurred in JAS, reaching $\sim 2 \text{ L m}^{-2} \text{ day}^{-1}$, resulting in a monthly average of nearly $55 \text{ L m}^{-2} \text{ month}^{-1}$. Minimum accumulation occurs during JFM, when accumulation averages values are barely over $0 \text{ L m}^{-2} \text{ day}^{-1}$, resulting in a mean of $\sim 1 \text{ L m}^{-2} \text{ month}^{-1}$. At Cerro Guatalaya, 77% of the annual yield accumulates from June to October; however, yields here are significantly lower than at Alto Patache. Despite differences in fog water yields, both SFCs maintain similar monthly, seasonal and inter-annual trends, which are reflected in a positive correlation between the two sites ($r = +0.68$). However, peak fog water accumulation occurs slightly earlier at Cerro Guatalaya than Alto Patache. The differences in fog water yields and timing of max water content between the two sites can be explained by their contrasting geographical location within the coastal realm. Compared to Cerro Guatalaya, Alto Patache is closer to the coastline and at a lower altitude, as is presented in Fig. 1(b) and described in Section 2. These geographic factors would imply that (1) the Cerro Guatalaya site is near the inversion layer limit and, (2) ground temperature together with a drier air prompt a greater influence on fog evaporation in Cerro Guatalaya compared to Alto Patache.

Fig. 3 shows the mean monthly variability in fog yields at the two sites for the period 1998–2014, expressed as percentage. The maximum relative variability in yields at both SFCs occurs during summer (in February). In comparison, winter and early spring (September) are more stable both in Alto Patache and Cerro Guatalaya (see Fig. 4).

There is a marked inter-annual variability in fog water yields at both SFCs (see Fig. 5). The monthly mean and associated standard deviation of the total water collected during the period 1998–2014 is $185 \pm 98 \text{ L m}^{-2} \text{ month}^{-1}$ at Alto Patache and $25 \pm 10 \text{ L m}^{-2} \text{ month}^{-1}$ at Cerro Guatalaya. Mean water yields at Alto Patache are $388 \pm 156 \text{ L m}^{-2} \text{ month}^{-1}$ during JAS and $38 \pm 54 \text{ L m}^{-2} \text{ month}^{-1}$ during JFM. The maximum inter-annual variability occurs during summer, regardless of whether data from 1998 (with extreme El Niño conditions and high fog water yields, Fig. 4) is included.

The linear trend lines for fog water yields at both SFCs (dashed lines in Fig. 5) indicate a weak negative trend over the time period studied, although at Alto Patache the downward trend is more pronounced (slope = -0.36) than at Cerro Guatalaya (slope = -0.01).

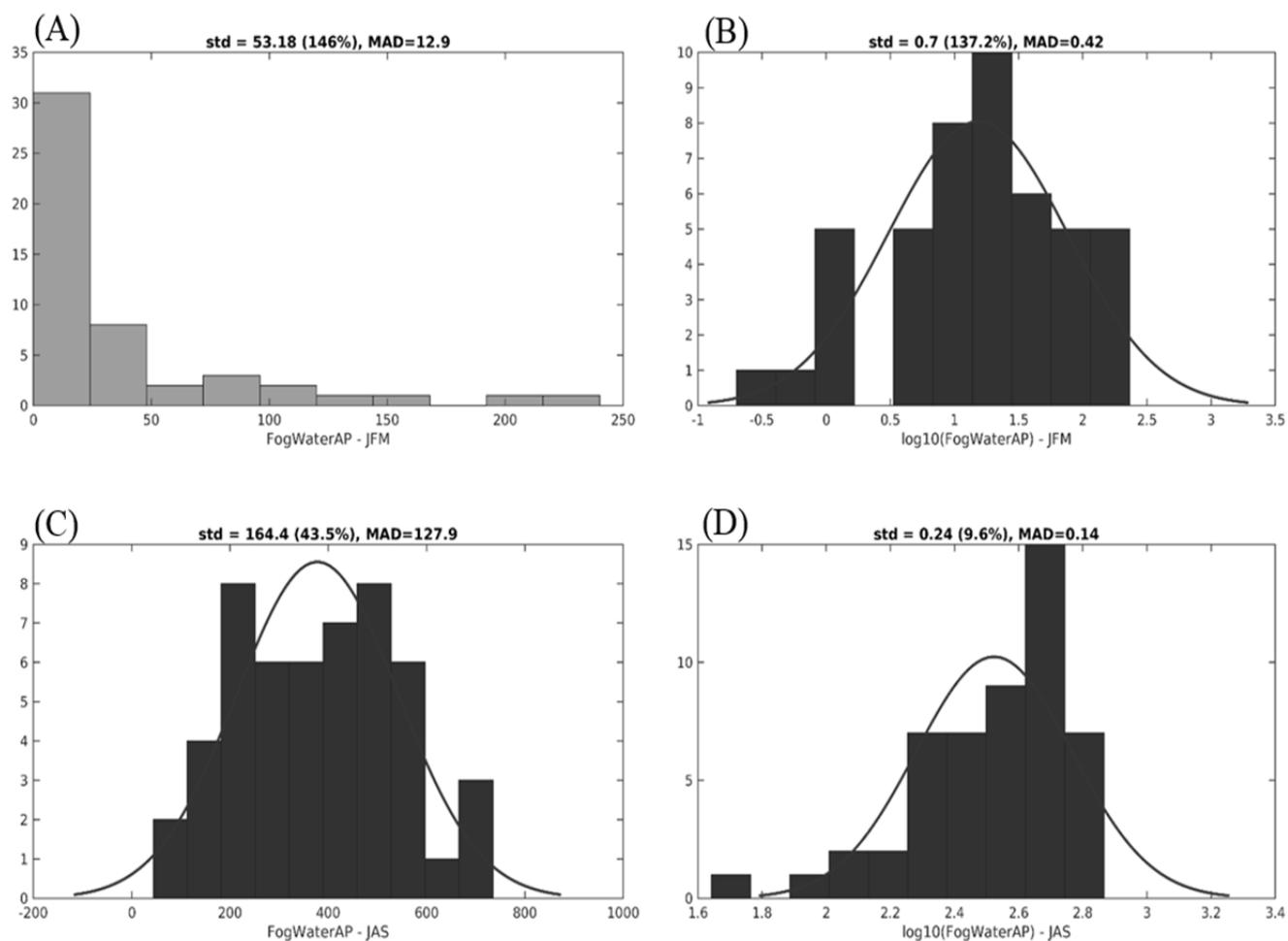


Fig. 4. Dispersion analysis of fog water yields at Alto Patache in summer (JFM) and winter (JAS). Due to the very low values during summer, the summer and winter fog water yield histograms show two very distinct distributions and make it difficult to compare dispersion between the two (left column). The logarithms of the data (right column) show more similar distributions. For both the linear and logarithmic histograms we compare the standard deviation (in brackets the relative std from the mean), as well as the non-parametric Median Absolute Deviation (MAD). Both suggest a higher relative variability during summer than during winter.

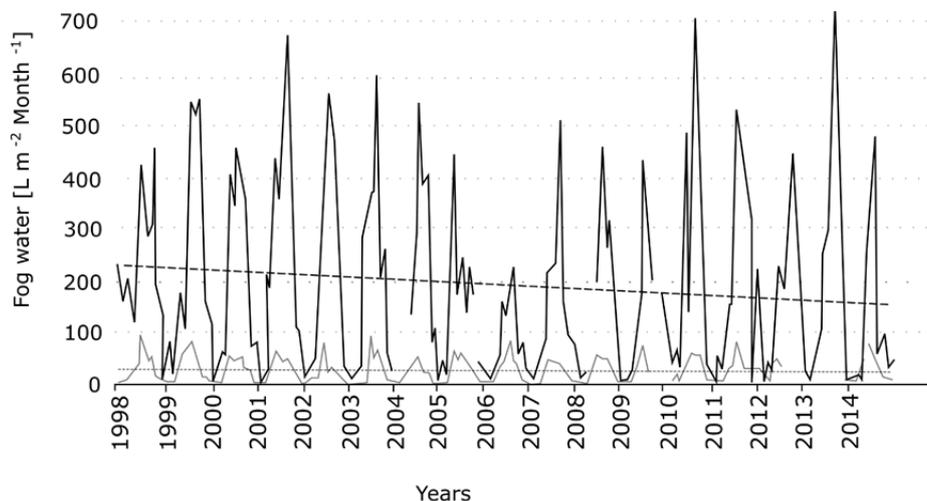


Fig. 5. Inter-annual variability in fog water yields at Alto Patache (AP) (dark grey line) and Cerro Guatalaya (light grey line) for the period 1998–2014. Dotted lines indicate the trend for the period. Note the marked annual cycle of collected fog water and the slight negative trend (dashed lines), particularly at AP. Discontinuity in lines correspond to times with no data.

Cloud Cover

Cloud cover was analyzed using the oktas and the LCA indices, at a local and meso-scale, respectively. Both indices show a positive correlation ($r = +0.67$). They indicate seasonal changes in cloud cover offshore and in the coastal Atacama, with higher cloud cover during the winter and spring, and lower cover during the summer and early autumn. The oktas seasonal maximum and minimum are consistent with the observed fog water collected variability. The winter/spring maximum varied between 6 and 7 oktas, but can be higher (e.g., August 2007 and 2011 it was > 7 oktas). In turn, the lowest summer Sc cloud cover varied from 1.5 oktas in 2008 and 2012 to 3.8 oktas in 1998. The LCA winter maximum values reach 90% of cloud presence, with a seasonal mean of 75%; the minimum summer LCA cloud cover varied from 35% to 40% with a mean of 55% of cloud presence. The LCA during winter and early spring was more stable ($\text{std} = 5\%$) than during the summer ($\text{std} = 9\%$), implying more variation in cloud cover during JFM.

Fog water yields at Alto Patache and Cerro Guatalaya are positively correlated with the oktas ($r = +0.60$ and $r = +0.68$, respectively) and with LCA ($r = +0.62$ and $r = +0.57$, respectively) measurements. This confirms that Sc clouds are the main source of moisture in the Coastal Cordillera, here

typified as advective marine fog, and the link between offshore cloud conditions and coastal fog liquid water content (LWC), with higher (lower) offshore LCA occurring together with higher (lower) fog-cloud cover and fog-water collection at our two sites. Despite these significant correlations, the presence of orographic fog and its contribution to fog water measurements should be taken into consideration, particularly at Alto Patache due to its location close to the coastline, altitude and essentially its topographic configuration, which promotes local cloud formation.

The oktas data from Iquique show no obvious trend over the period studied (see Fig. 6(a)). Seasonal mean cloud cover indices (oktas and LCA) are shown in Figs. 6(c) and 6(d) and reveal slightly divergent trends. While winter and autumn show a neutral or weak positive trend, summer reveals a weak negative trend for the 1998–2014 period. Similarly, Muñoz *et al.* (2016), based on hourly oktas data from Iquique, found no trends for the period 1981–2013. Using nighttime satellite images, del Río *et al.* (2016) found weak positive trends in Sc cloud cover for the 1995–2015 period in the study area. Additionally, Muñoz *et al.* (2016) revealed a decrease in the inversion layer elevation ($100 \text{ m decade}^{-1}$) for the period 1981–2013 at coastal Atacama. This decrease in the inversion layer altitude may be

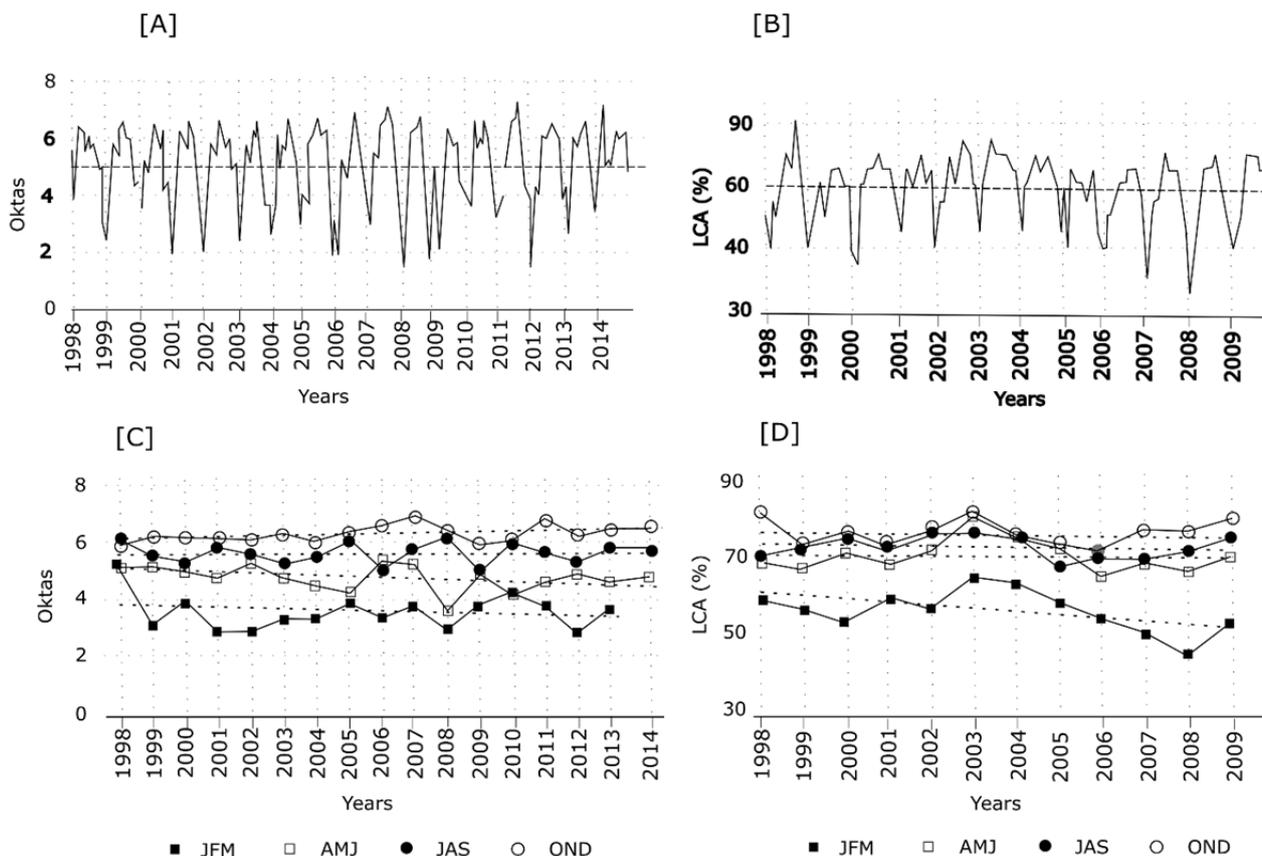


Fig. 6. Yearly and seasonal variability and trends in cloud cover. (A) Oktas monthly data for the period 1998–2014; (B) Low cloud amount (LCA) monthly data for the period 1998–2009; (C) Oktas seasonal trends; (D) LCA seasonal trends. Yearly, both indices, Oktas and LCA, show no inter-annual trend within the studied period. Seasonally, summer months (January, February and March), show a negative trend for both indices within the studied period. JFM: January, February, March; APJ: April, May, June; JAS: July, August, September; OND: October, November, December.

conditioning the presence of fog at upper elevation, which may be related to the decrease in the amount of fog water collected at both SFCs during 1998–2014. In this manner, the decrease in fog water yields at Alto Patache could be related to a negative trend in the thermal inversion layer elevation, leaving the fog collector in a position closer the cloud top where the LWC is lower.

Sea Surface Temperature

SST was analyzed using a multi-scale approach, including the Iquique SST (local), the SST offshore Atacama (meso-scale) and the SST at 1 + 2 and 3.4 ENSO zones (regional-scale) (Fig. 2). The Iquique SST presents a seasonal cycle with higher temperatures during summer (JFM average = 16.8°C) and lower in winter (JAS average = 14.3°C), with a mean of 15.7°C. Temperatures for the entire period (1998–2014) oscillated between 14°C and 18°C, except during summer of 1998 when temperatures reached a maximum of > 22°C (5.2°C above the 1998–2014 JFM mean). There is a negative correlation between fog water and the Iquique SST ($r = -0.40$ at Alto Patache and $r = -0.42$ at Cerro Guatalaya).

As expected, offshore Atacama SSTs also shows significant seasonal variability, with maximum temperatures during the summer (> 21°C) and lower temperatures (14–17°C) during the winter. Higher offshore SST compared to coastal waters is explained by decreased deep-water upwelling and a stronger Humboldt cold current (Garreaud *et al.*, 2001, 2007). Offshore SSTs are negatively correlated with the LCA ($r = -0.77$), as the presence of lower (higher) SST increases (decreases) the condensation of moisture present in the MBL, for instance in winter and early spring.

Offshore SSTs also correlated with local Iquique SSTs ($r = +0.68$). We found a significant negative correlation between offshore SST and fog water yields ($r = -0.73$ at Alto Patache and Cerro Guatalaya). This correlation is stronger than the correlation between fog water yields and local Iquique SSTs. At the same time, variations in ENSO zone 1 + 2 SST are strongly negatively correlated with fog water yields ($r = -0.66$ at Alto Patache and $r = -0.57$ at Cerro Guatalaya; both at 99% confidence level; Fig. 7). SSTs in zone 1 + 2 are also significantly correlated (at 99% confidence level) with local SSTs in Iquique ($r = +0.66$), offshore SSTs in Tarapacá ($r = +0.88$), LCA from Atacama ($r = -0.66$) and oktas data ($r = -0.48$). Finally, SSTs in ENSO zone 1 + 2 are positively correlated with SSTs in ENSO zone 3 + 4 ($r = 0.3$). Therefore, our data suggests that fog water yields may be linked to ocean SST conditions beyond the coastline (farther offshore).

The multi-scale approach carried out in this paper suggests that the atmospheric and oceanographic variables may act as an integrated system controlling fog water production along the coast of the Atacama Desert. Fog water yields are positively correlated with onshore and offshore cloud cover and negatively correlated with SST, whether at the local, meso or regional scale (Iquique, Atacama and ENSO 1 + 2). This is exemplified during the special year of 2006, winter SST at ENSO 1 + 2 reached about 1°C above the annual mean (20.6°C). At this time, the SFC at Alto Patache had the lowest fog water yield during the studied period (46% lower than the winter average) (see Fig. 7). This unusually warm winter SST may have caused the anomaly in fog water yields at Alto Patache. A

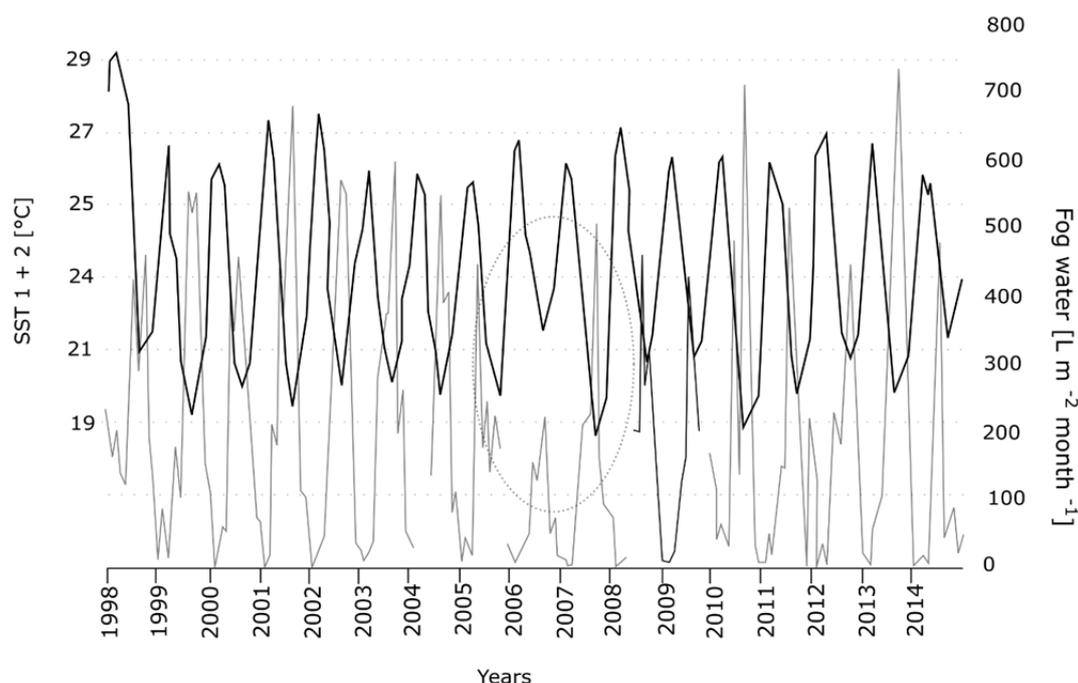


Fig. 7. Comparison between sea surface temperature at ENSO zone 1 + 2 (dark grey line) and Alto Patache (AP) fog water yields (light grey line). Note the relatively higher winter SST temperatures and lower fog water yields at AP during 2006, which tentatively we relate to concurrent positive SST anomalies at the SEP. Gaps in AP fog water corresponds to times with no data.

possible causal link could include high overall air temperatures at the MBL that did not allow air humidity to reach condensation levels. The implication is that the tropical Southeast Pacific works as a united system where ocean and atmospheric process and dynamics are intimately linked. Fig. 8 highlights the dominating role of seasonality in the variability of all variables in that region, from central Pacific SSTs to Atacama fog water yields. However, there appears to be more that only seasonal correlation between the central Pacific and the coastal Atacama. Fig. 9 show the inter-annual correlations between ENSO Zone 1 + 2, cloud cover and fog water yield in Alto Patache for OND (spring season). The first 6 years feature very low variability in all variables. Starting in 2006, though, a higher variability in ENSO 1 + 2 zone SST appears to provoke a similar response in coastal Atacama cloud cover and fog water yield. This regional to local sequence may be indicative of a potential causal link between the various regions, and a possible influence of ENSO on fog along the Atacama that goes beyond the yearly cycle.

When considering all months together, the SST in the Pacific Ocean ENSO zone 3.4 (see Fig. 2) does not

correlate with any of the variables. The equatorial 3.4 zone present a lower and less clear seasonality demonstrating a disconnection with the Atacama meso and local scale, at least for the seasonal cycle. However, when considering only summers, we observe a positive significant correlation between Alto Patache fog water yields and SST ENSO 3.4 ($r = +0.38$) and with ONI ($r = +0.44$) (Fig. 11). This correlation points to ENSO positive phase (El Niño conditions) being linked to higher fog water yields during summer at an inter-annual scale scenario.

DISCUSSION

Inter-Annual Fog Variability and ENSO

Seasonal variability in fog water yields in the coastal Atacama Desert demonstrate that local fog conditions and fog water yield respond at least partially to the regional climatic realm prevailing in the SEP and beyond into the ENSO realm. The significant and strong correlations between monthly fog water and ocean and atmospheric indices are due for the most part to the annual cycle beat. However, focusing our analysis on specific seasons we can extract

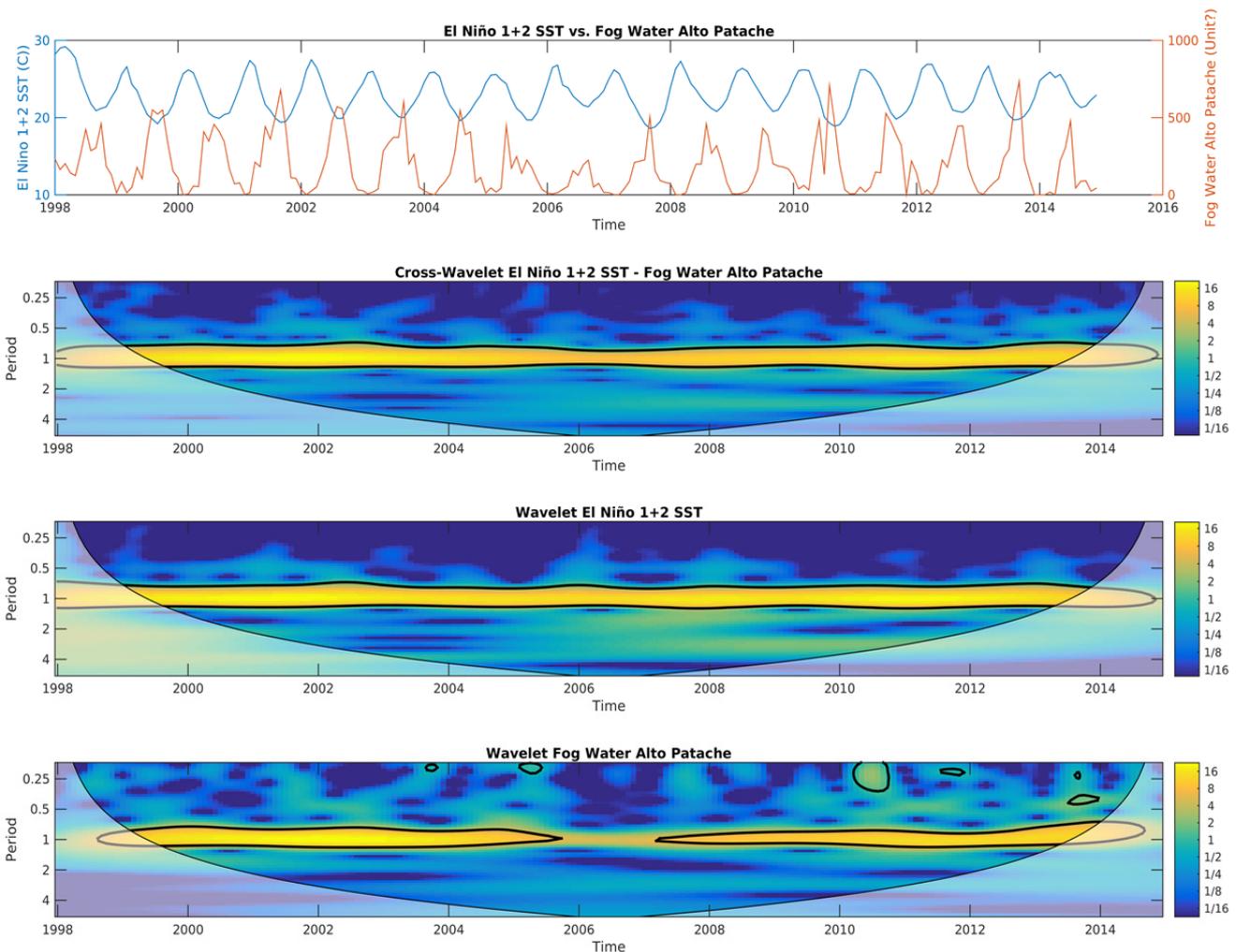


Fig. 8. Cross-wavelet analysis (Grinsted *et al.*, 2004) of ENSO zone 1 + 2 SSTs and fog water yield at Alto Patache. The three wavelet panels highlight the strength of the seasonal cycle in all the region.

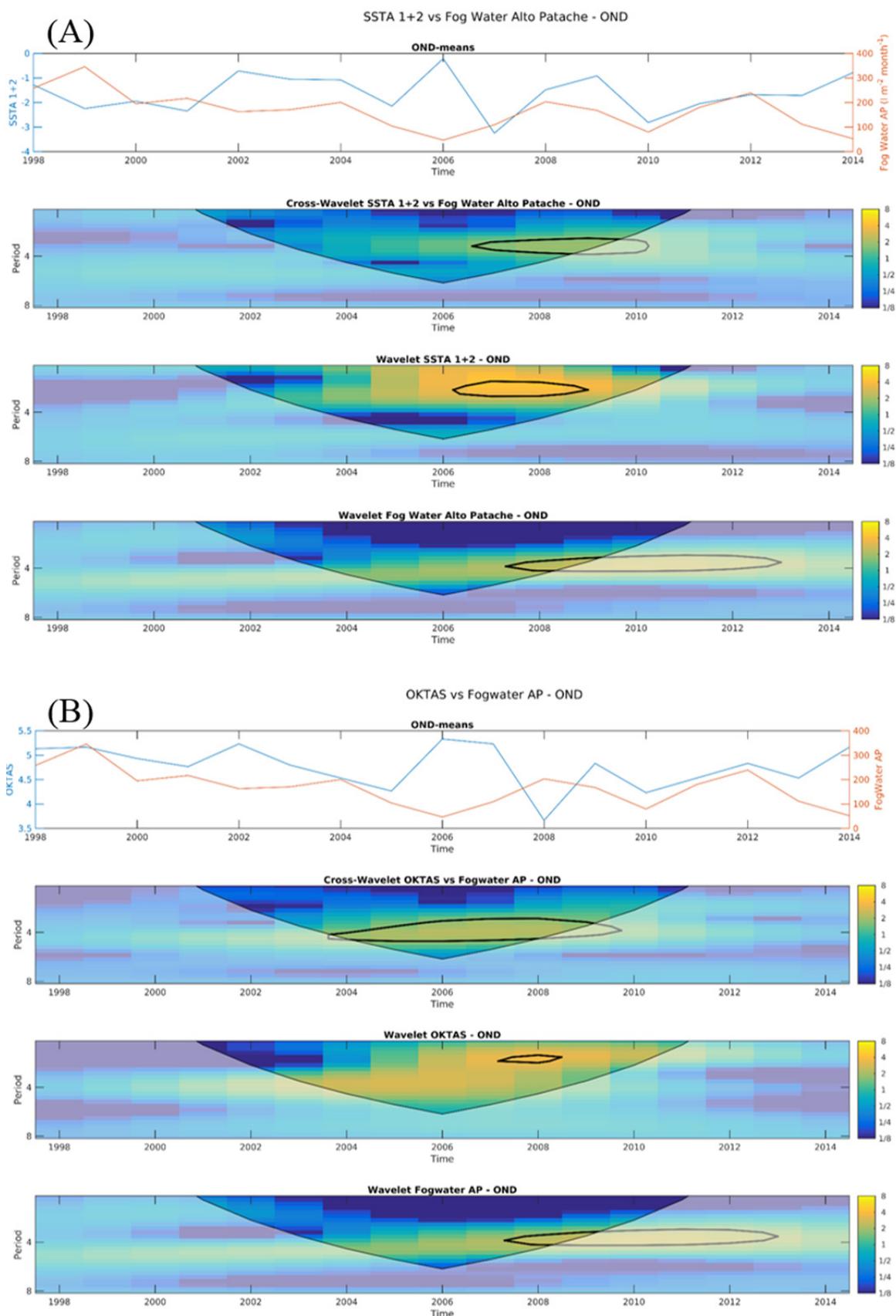


Fig. 9. Spring (OND) cross-wavelet analysis (Grinsted *et al.*, 2004), of (A) ENSO zone 1 + 2 SSTs and fog water yield at Alto Patache; and (B) Oktas and fog water yield at Alto Patache. The regional to local sequence showed may be exposing a potential causal link and the influence of ENSO in fog along the Atacama.

more detailed information. We have shown that ENSO 3.4 SST inter-annual variability correlates with fog water yields during the summer ($r = 0.38$) but not during the rest of the year. A possible causal link is suggested by the successive correlations between ENSO zones 3 + 4 and 1 + 2, the offshore and local SSTs, and finally the cloud cover

and fog water yield. In order to further test this relationship, we analyzed GOES satellite images at the regional level that capture low cloud conditions during opposite ENSO extreme years: 1997–1998 (very strong El Niño) and 1999–2000 (strong La Niña). Fig. 10 reveals significantly higher presence of Sc and fog cloud cover during ENSO (+) (El

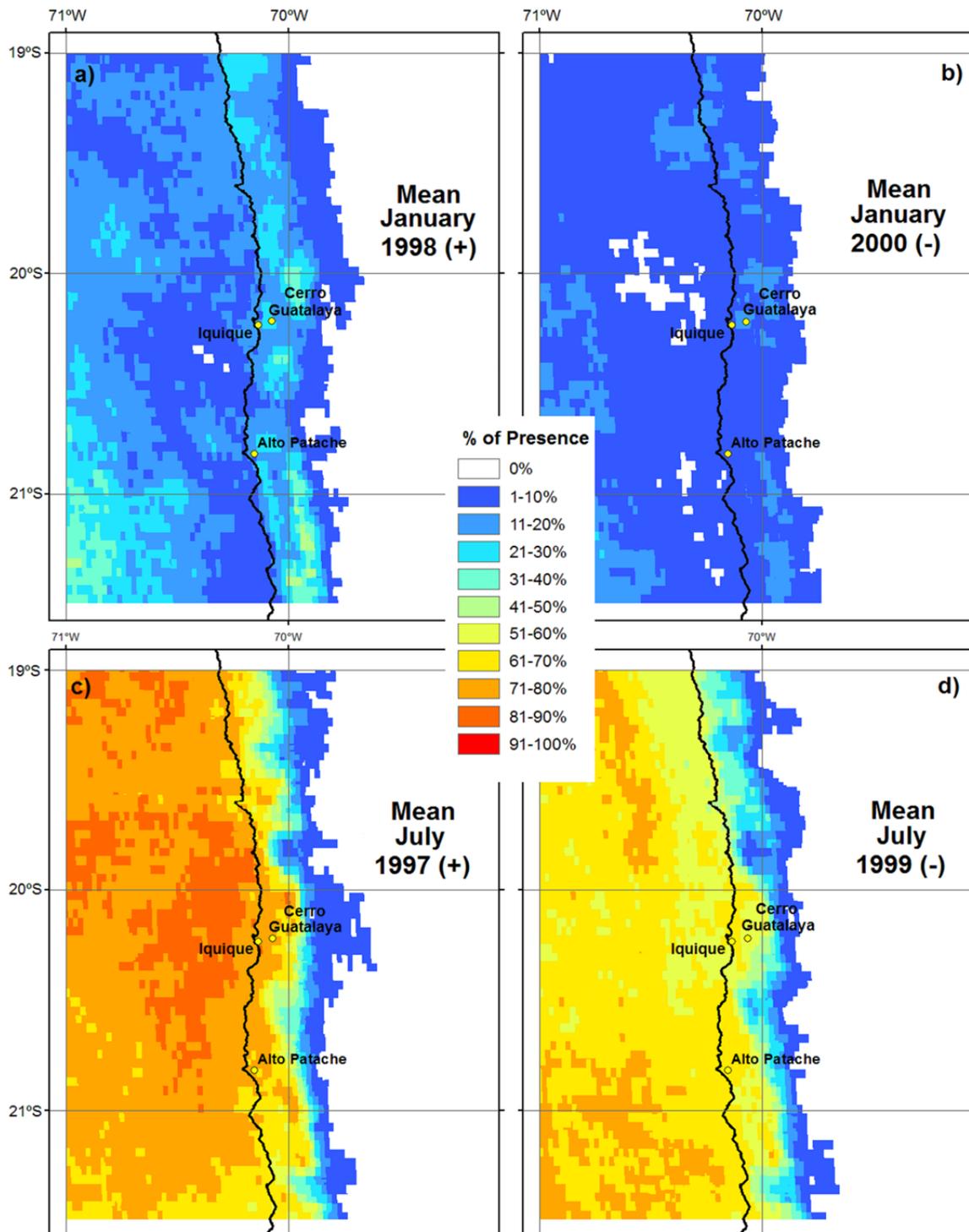


Fig. 10. GOES satellite Images showing Sc cover presence (%) for (a) January 1998; (b) January 2000; (c) July 1997 and (d) July 1999. Note higher presence values during ENSO (+) years. (-): ENSO negative (La Niña), (+): ENSO positive (El Niño).

Niño) when compared to ENSO (–) (La Niña) years during both summer and winter. In fact, some areas, such as the coastal cliff area, have twice the Sc presence during ENSO (+) as compared to ENSO (–) years studied in this paper. Over the nearby Pacific Ocean, Sc cloud presence in ENSO (+) January and July (1997–98) reached 50% and 10% over ENSO (–) January and July (1999–00), respectively. Similarly, the ENSO (+) presence of fog over the continental area was 55% and 30% higher during January and July, respectively, than the same months in ENSO (–) conditions. This straightforward spatiotemporal analysis supports the idea that inter-annual fog-water variability observed during the summer is linked to ENSO, which exerts its highest influence to the region during summer months.

The apparent link between ENSO 3.4 zone and coastal Atacama emerges also when summer fog water yields are analyzed, particularly during an ENSO positive (+) and strong summer phase, but is obscure or inexistent during other seasons of the year (Fig. 12). The seasonal variability in fog water yields and the prevailing ENSO conditions, as described by the ONI, are shown in Table 2. During summer (JFM), the ONI is mostly in an active (+ or –) phase indicating that it is during this season that ENSO exhibits its highest intensity within the annual cycle. Throughout JFM, the two maximum fog-water yields from our 17-year record corresponded to the El Niño phases of 1998 and 2010. The ENSO (+) phase during these two years was very strong (1998) and moderate (2010). Fig. 11 shows the inter-annual variability in fog water yields at Alto Patache compared to SSTA, oktas, LCA and the SST at Iquique during JFM. Years 1998 and 2010 denote the positive relationship among these variables. In 1998 the complete SEP is under an extreme warm condition, showing values considerably above average in fog water yields, cloud cover presence and SSTs. A similar situation is observed

in 2010 but with less intensity (see Fig. 11). A quadratic regression was fitted to all data points belonging to the positive ENSO phase that were above the threshold of $SSTA > 1^{\circ}\text{C}$ (Fig. 12). The regression indicates that above this threshold, SSTAs explain 79% of the variance in Alto Patache fog water yields during summer. This strong relationship suggests a link between very strong ENSO (+) phases and coastal Atacama summer fog cover and water content. Conversely, during winter months (JAS) fog-water yields do not follow a straightforward pattern. During austral winter, the ONI is usually in a neutral phase (i.e., does not exert mayor influence), an aspect that can help explaining the relatively low inter-annual variability in fog water yields during this season (Table 2).

Garreaud *et al.* (2008a) using springtime data (SON) hypothesized that at latitudes north of $\sim 25^{\circ}\text{S}$ in the coastal Atacama, El Niño (La Niña) conditions should result in more (less) fog cover presence. The opposite should be true south of $\sim 25^{\circ}\text{S}$, into the semiarid realm of northern Chile ($\sim 32\text{--}27^{\circ}\text{S}$). In this scenario, the coastal Atacama should exhibit an asymmetry in fog cloud cover centered at $\sim 25^{\circ}\text{S}$ and inter-annual variability controlled, at least partially, by ENSO. Our results show greater Sc cloud coverage during strong El Niño years at $19\text{--}21^{\circ}\text{S}$ particularly during summer, which is consistent with this hypothesis. Fig. 13 shows the general oceanic-atmospheric interchange north of 25°S for Sc cloud formation (or not) under ENSO neutral or ENSO (+) summer conditions. During ENSO neutral years (Fig. 13(a)), there is a decoupling within the MBL, turbulences are not strong enough to raise the moisture and condensate. In addition, the weak inversion layer allows interaction between the MBL and the free atmosphere and hinders the Sc cloud formation (Garreaud *et al.*, 2007). The increased summer cloud cover during ENSO (+) years (Fig. 13(b)) in northern Atacama can then

Table 2. Seasonal variability in fog water yields at Alto Patache and their relation with the Oceanic Niño Index (ONI).

Year	Patache JFM L m ⁻² Month ⁻¹				ONI	Patache JAS L m ⁻² Month ⁻¹				ONI
	Max	Min	Mean	S.D.		JFM	Max	Min	Mean	
1998	230	164	200	34.2	(+) Very strong	424	285	338	74.7	(–) Weak
1999	86	12	37	42.3	(–) Moderate	550	357	477	104.3	(–) Moderate
2000	109	0.8	39	61.2	(–) Strong	457	347	405	55	(–) Weak
2001	78	1	31	41.1	(–) Weak	680	360	517	159.6	Neutral
2002	34	0.8	20	17	(+) Moderate	570	474	534	52.3	(+) Weak
2003	27	0.5	17	10.3	(+) Weak	602	372	449	132.9	Neutral
2004	26	0	13	18.5	Neutral	547	281	406	133.6	(+) Weak
2005	45	11	24	18.2	Neutral	248	139	204	57.3	Neutral
2006	14	6	11	4.2	(–) Weak	225	126	182	50.4	Neutral
2007	15	1	6	7.3	Neutral	505	218	316	163.6	(–) Weak
2008	73	0.2	25	41.4	(–) Moderate	460	199	309	135.1	Neutral
2009	11	5	8	3	(–) Weak	431	201	339	121.5	(+) Weak
2010	119	38	73	41.7	(+) Moderate	708	132	435	289.6	(–) Moderate
2011	50	7	25	22.3	(–) Moderate	528	392	463	68.6	Neutral
2012	140	0	58	73.6	(–) Weak	445	178	311	133.3	Neutral
2013	44	4	21	20.2	(–) Weak	735	294	530	222.4	Neutral
2014	18	0	6	10.3	(–) Weak	478	44	203	238.6	Neutral

Max: maximum; Min: minimum; S.D.: standard deviation.

JFM: January, February March; JAS: July, August September.

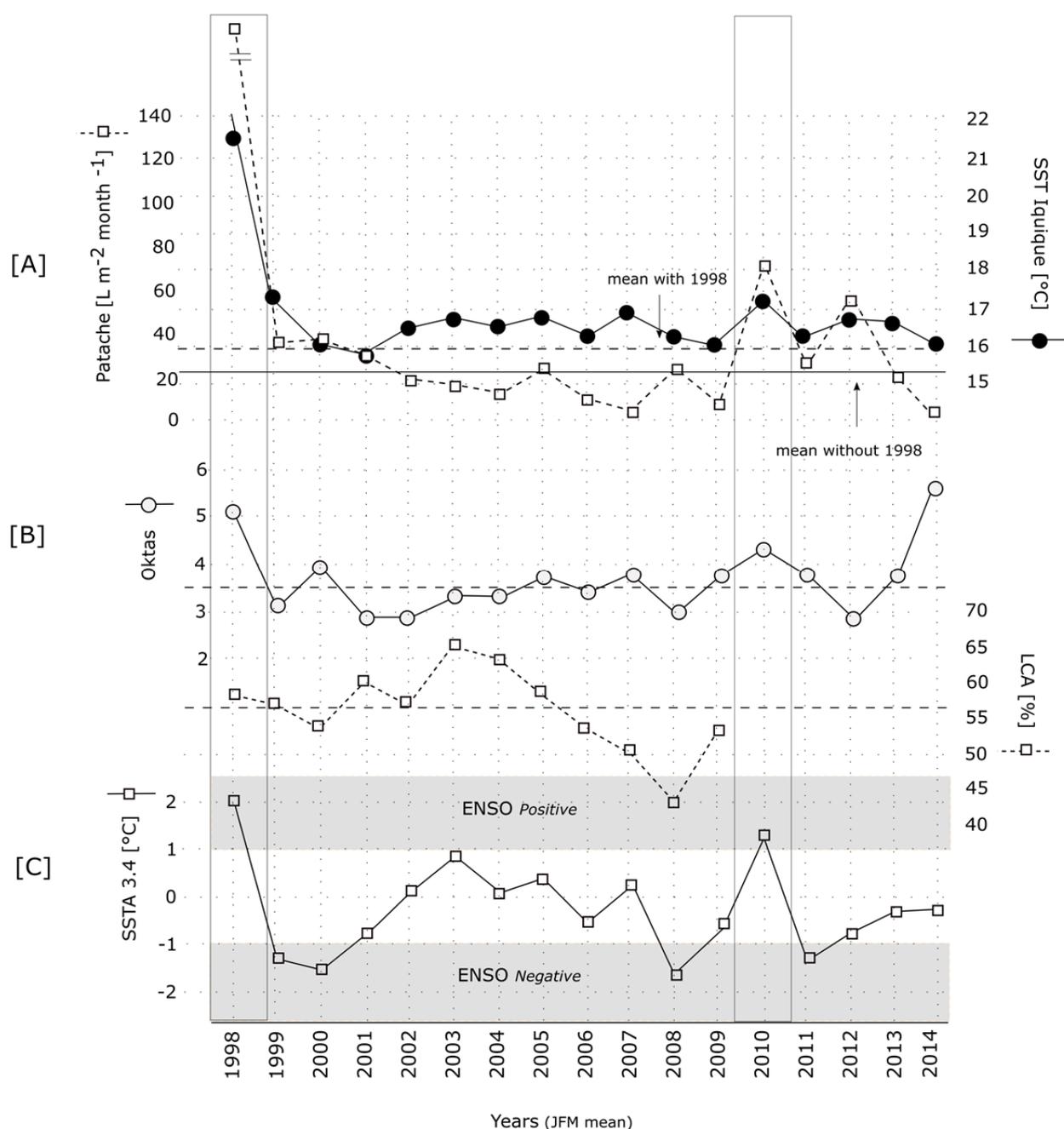


Fig. 11. Summer (January, February and March) inter-annual variability of oceanographic and atmospheric indices for the period 1998–2014. (A) Fog water yields at Alto Patache and Iquique SST. Dotted lines indicate the summer mean in the period 1998–2014. Continuous line indicates the mean for the years 1999–2014; (B) Cloud cover (Oktas and Low cloud amount, LCA); and (C) Sea surface temperature (SST) anomaly at ENSO 3.4 zone. Vertical grayish bars denote ENSO (+) years when linked oceanographic and atmospheric realms between SST, cloud cover and fog water yield in the Atacama are obvious during $\text{SSTA} > 1^{\circ}\text{C}$. Also, note the similar behavior between the Sc (expressed as LCA) and the SSTA 3.4, suggesting the direct link between both variables at summer.

be explained by a significant increase in SSTs (around 2°C over the average) and in air temperatures above the thermal inversion layer. These conditions are accompanied by an upward amplification of the air potential temperature together with an enhanced air stability and thermal inversion, resulting in relatively extensive summer Sc formation (Garreaud *et al.*, 2008a).

Fog Temporal Trend

The air temperature and the SST in coastal and offshore northern Chile reveal cooling trends in the last decades (Boisier and Aceituno, 2006; Falvey and Garreaud, 2009; Schulz *et al.*, 2011; Vuille *et al.*, 2015; Muñoz *et al.*, 2016), which could be linked to cold PDO phase (La Niña-Like). The air temperature rate of change is $-0.2^{\circ}\text{C}/\text{decade}$ for the

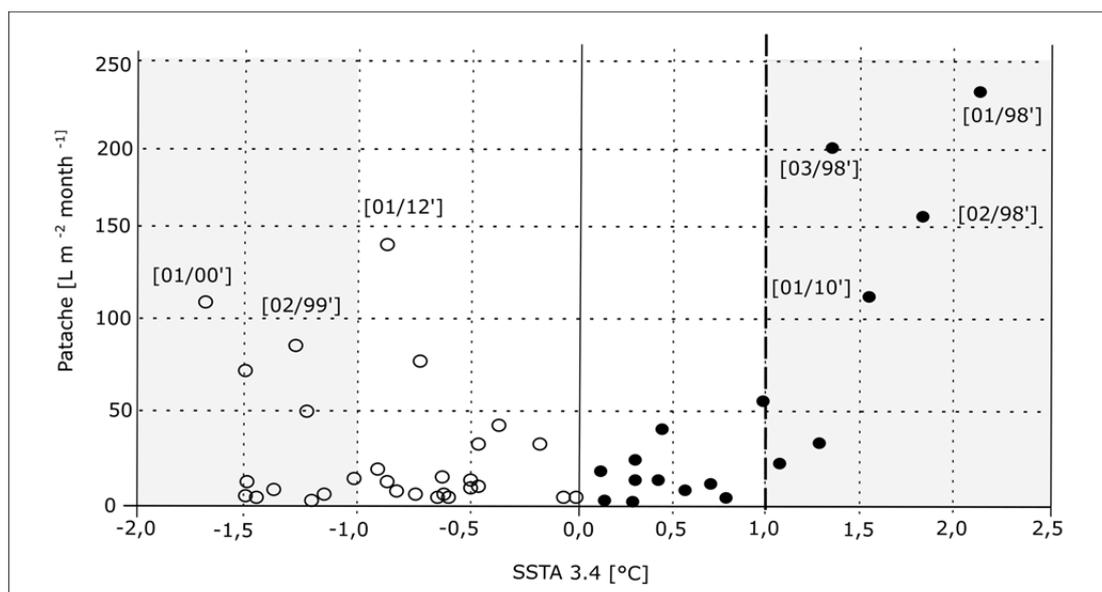


Fig. 12. Scatter plot of austral summer (January, February and March) fog water yields at Alto Patache versus sea surface temperature anomalies (SSTAs). SSTAs $< -1^{\circ}\text{C}$, corresponding to moderate to strong La Niña ENSO phase; SSTAs $> 1^{\circ}\text{C}$, corresponding to moderate to very strong El Niño ENSO phase. The dark vertical line indicate the summer SSTA threshold for a direct influence of ENSO 3.4 on local fog water yield.

period 1979–2006 (Falvey and Garreaud, 2009). Concurrent Sc cover observations indicate a contrasting trend; weak positive trends during wintertime and weak negative trends during summertime (Fig. 6). This conclusion is consistent with the intensification of the Southeast Pacific Anticyclone and the reduced MBL during a cold PDO phase. We do not see a clear response of fog water yields that we can link to the mentioned trends. Fog water has been slightly decreasing over time, particularly in Alto Patache. If we consider that most of the water collected at this site occurs during winter and early spring we should expect then a gradual increase in total water budgets. However, we see the opposite. We believe this can be explained by the change in elevation of the MBL. The demonstrated decrease in the inversion layer altitude within the study period (100 m decade^{-1} ; Muñoz *et al.*, 2016) is causing the Alto Patache SFC located at 850 m a.s.l. to be exposed to clouds containing less water closer to their top. If near future oceanic-atmospheric conditions continue on this cooling trend, associated to the intensification of the Southeast Pacific Anticyclone and a reduced MBL, we expect to see decreasing water yields in Alto Patache but possibly increasing ones at lower elevations.

CONCLUSIONS

- 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 hyper-arid Atacama Desert is closely related to the local and meso-scale sea surface temperature (SST) and low cloud cover inside the SEP realm. At a regional scale, there is a possible causal link between El Niño Southern Oscillation (ENSO) zone 1 + 2 SST, coastal Atacama SST, Atacama

cloud cover, and fog water yields.

- The Oceanic Niño Index (ONI) is correlated with Sc cloud cover and fog along the coast of the hyper-arid Atacama Desert during summer time when ENSO reaches its maximum intensity. If ENSO (+) conditions in zone 3.4 overcome the threshold of 1°C above average temperatures, this produces abnormally high fog water yields and extensive cloud presence during the summer season. Under ENSO neutral or (–) conditions, fog water yields and low cloud presence reveal random variability.
- Because $> 75\%$ of the fog water is collected in winter-spring, when the Sc presence is persistent in the SEP, we do not expect significant mean annual water yield changes into the future. In this scenario, the use of fog as a fresh water resource is sustainable over time, despite the prevailing ENSO or Pacific Decadal Oscillation (PDO) phases. This suggests that Sc cloud and associated Atacama coastal fog, despite subtle changes over time, are stable components of the SEP. Nonetheless, changes in the fog distribution and fog water content are expected to happen at different elevations at the Coastal Cordillera with climate change.

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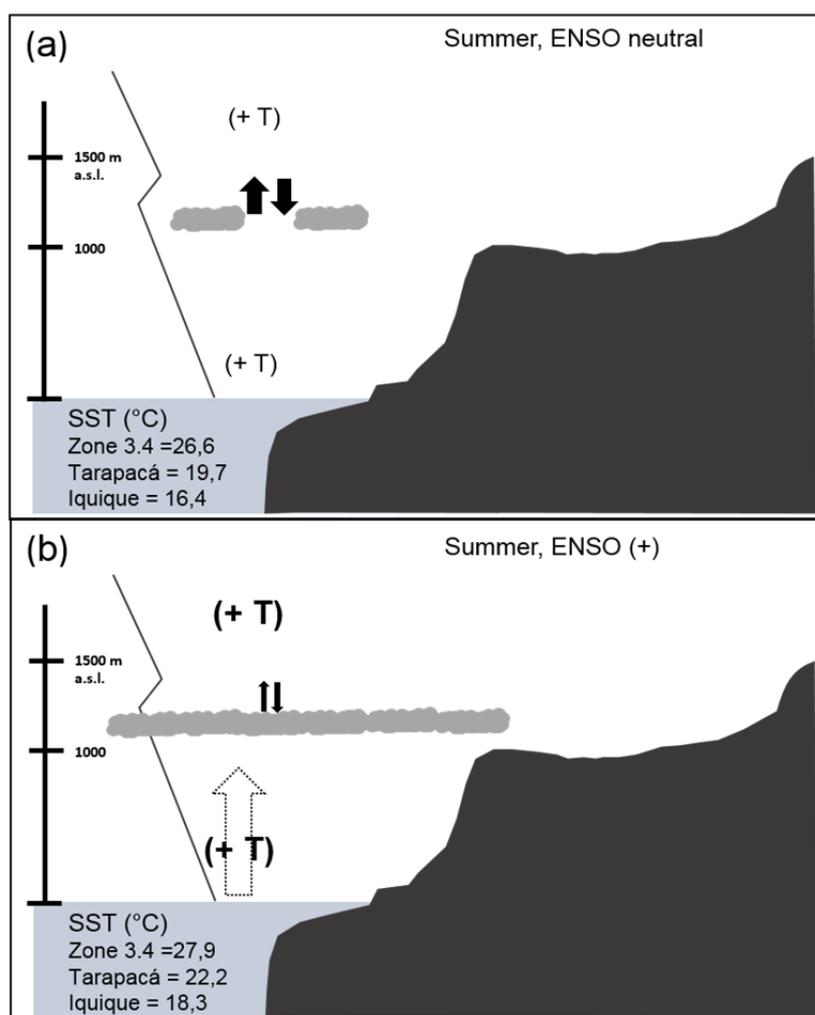


Fig. 13. Schematic Sc cloud formation during summer at the coastal Atacama. (a) ENSO neutral conditions, where warm sea surface temperatures (SST) and warm air temperatures in the free atmosphere produce a weak inversion layer and consequently energy interchange (wide black arrows) between the marine boundary layer (MBL) and dry air mass above, then reducing the Sc cloud formation; (b) ENSO (+) conditions, when significant warmer SST and air temperatures in the free atmosphere occurs. The air potential temperature signal amplifies upward (dashed arrow) (Garreaud *et al.*, 2008a), generating an intensification of the thermal inversion layer (thin black arrows) and consequently better conditions for Sc cloud formation. (+ T): Temperature increase, SST is the average of JFM for neutral (a) or positive (b) ENSO phases within the studied period (1998–2014).

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