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The spatial and temporal variability of fog and its relation to fog oases in the Atacama Desert, Chile

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Abstract

Fog has been studied in the Atacama Desert of Chile for the past ten years. This paper analyzes its temporal and spatial variability, relying in part on satellite images (GOES) to analyze the frequent orographic fog and the low cloud deck (stratocumulus, Sc) that generates advective fog in the area. Fog water fluxes were measured with Standard Fog Collectors (SFC). Field trips and observers provided information on cloud top and base and the presence of fog. Vegetation in fog oases were used to confirm the results of these surveys.

The Sc moves onshore into the continent with different intensities depending on season and time of day. The maximum spatial extent occurs during winter and at night. Fog is frequent in the coastal cliffs, where fog water fluxes of 7.0 L m^{-2} day^{-1} were measured using a SFC. It is less frequent 12 km inland, where the collection rates were less than 1 L m^{-2} day^{-1}. The height of the fog collector above the ground affected the collection rate. The highest fog water fluxes were recorded at Alto Patache at altitudes of between 750 and 850 m a.s.l. The growth or thickness of the cloud is important in the collection of fog water. The information that GOES provides on the altitude of the top of low clouds is used to analyze this factor. Fog oases are described and analyzed in relation to how the geographical location of fog influences the growth of vegetation.

Keywords: Fog; Remote sensing; Desert; Fog oases; Atacama Desert

1. Introduction

Since 1997, geographical studies about fog and ecosystems have been carried out in the *Cordillera de la Costa*, a coastal range of the Atacama Desert, Chile. Fog has been investigated with respect to its origin, factors that define its variability, its potential for water collection, and the importance of low clouds (stratocumulus, Sc) in its formation (Cereceda et al., 2002; Larrain et al., 2002; Osses et al., 2005a,b). Fog oases have been surveyed in terms of geographic location, geomorphology, substrate and vegetation (Cereceda et al., 1999; Pinto et al., 2001; Larrain et al., 2002; Egaña et al., 2004), and systematic studies of insects have also been conducted (Sagredo et al., 2002). In addition,

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archaeological and historical research has been pursued (Larrain et al., 2004a,b). These studies have highlighted the importance of the meteorological variables of the climate present in the fog zone and the need to quantify fog water fluxes as the main source of water of the oases.

This paper addresses coastal fog variability in the Tarapacá region, located in the northern part of the Atacama Desert. The research was conducted by means of remote sensing techniques (GOES images), cartography, field work, and fog water collection. The findings are related to the ecosystems found in the Atacama Desert. The objectives of the investigation were to analyze the frequency of high elevation fog in the area with regard to the presence of the almost permanent stratocumulus clouds in Tarapacá, and to measure fog water fluxes as a function of: a) distance from the ocean (in a coastal and an inland site): b) altitude in the mega cliff of Tarapacá; c) collection height above the ground (2 m and 0.2 m); and d) thickness or growth of the clouds during a foggy period (10 days in July 2002). It is important to note that the fog water data in this study were collected over a period of 8 years, with the same technique being used throughout.

2. The study area

The study area (Fig. 1) is located in northern Chile, in the coastal mountain range of the Atacama Desert, between 19°48′S–22°00′S and 69°00′W–71°00′W. It covers an area of 50,755 km^2, of which 28,930 km^2 is land and 21,825 km^2 is ocean. The geomorphological features of this area are, from west to east, a narrow littoral plain, a cliff of 400 to 1000 m, a coastal range (*Cordillera de la Costa*) of about 50 km in width, and an inland plain called *Pampa del Tamarugal*. It is a very arid zone, averaging 1 mm of annual rainfall over the last 30 years in the low elevations near the coastline (12 m a.s.l.). The mean annual temperature is 18 °C, the average annual maximum is 22 °C, the average annual minimum is 16 °C, and the average relative humidity is 68%. The temperature at high elevations (515 m a.s.l.) is cooler by almost 4 °C, while the humidity exceeds 75% (Cereceda et al., 2007). Low clouds associated with the Sc and orographic causes occur frequently in the area. There is only one river that has a permanent flow and several dry rivers that flow during the rainy periods. Almost the entire study area is hyperarid, and only in the fog zone can some ecosystems with perennial plants survive.

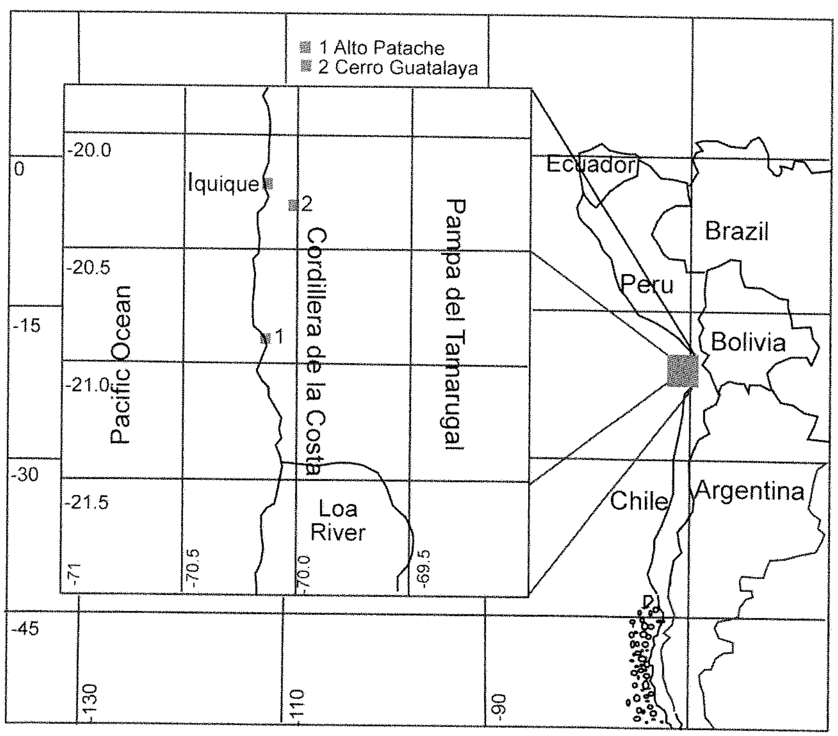

Fig. 1. The study area in the Atacama Desert, Tarapacá Region, Chile.

3. Methodology

3.1. GOES images

Around 11,500 GOES images were stored from May 2001 to April 2003. Spectral thresholds and change detection techniques were used to develop algorithms to identify low clouds. This process generates digital thematic maps every 90 min at a cartographic scale of 1:5,000,000 (Farías et al., 2005). The time tag used is UTC. Local time is 4 hours behind UCT in winter and 3 hours behind UCT in summer.

Between 17 and 26 July 2002, in an area of 6,000 km^2, a ground truth experiment was carried out to determine the efficiency of the image processing methodology. On-site observations were made 10 times per day (simultaneously with the GOES satellite) to estimate the area covered by low clouds. Observers were placed at the Cerro Carrasco site above the fog cloud (1592 m a.s.l.), within the fog/cloud at Alto Patache (800 m a.s.l.) and below the fog/cloud at Alto Patache (450 m a.s.l.), in order to register the altitudes of the fog top and base (Osses et al., 2005a,b). For this analysis, all GOES images that were affected by middle and high clouds were eliminated.

For each thematic map, the area covered by low clouds was calculated to determine the spatial and temporal (daily, weekly and monthly) variability. The daily, weekly and monthly frequency of the presence of low clouds was determined for every pixel. Two months with different low cloud characteristics, August 2001 and January 2002, were selected to show the differences between seasons. This involved the use of 456 thematic maps for August (the winter month) and 475 for January (summer).

3.2. Fog water collection

Two Standard Fog Collectors (SFCs,), of 1 m^2 as specified by Schemenauer and Cereceda (1994), were installed in July 1997. The first was erected at 850 m a.s.l. at the edge of the cliff of Alto Patache, 3.5 km from the coastline (20°49′S–70°09′W), and the second, 12 km inland at Cerro Guatalaya at 1062 m a.s.l. (20°12′S–70°00′W). They were monitored manually on a weekly basis during the fog season and every 15 to 30 days during the dry summer. Eight and a half years of data are reported on here (August 1997 to December 2005). Wind speed and wind direction were recorded at Alto Patache during the study period, with more than 300 instant observations being made during the course of this study. The months with the best information were obtained for winter and spring (from June to December), and the most frequent observation times were between 10:00 and 14:00. Even though the data for the other seasons and hours are scarce, they have been included in the analysis.

In addition, pairs of 0.25 m^2 fog collectors covered with double Raschel mesh, one installed at 2 m and another at 0.2 m above the ground, were placed at altitudes of 850 m, 750 m, 650 m, 550 m, 450 m and 350 m along the cliff at Alto Patache facing the predominant south wind. The reason for not using SFCs here was that only a smaller collector would allow safe measurements to be made once per month in this hazardous cliff environment. In order to standardize the unit of measurements in L m^{-2} day^{-1}, the water collected was multiplied by a factor of 4 and used for comparison purposes only in the Alto Patache area.

At Cerro Carrasco (located 15 km ESE), air temperature data above the cloud top were registered manually 10 times per day during the ground truth programme.

3.3. Fog oases

General information about fog oases was extracted from available literature and from biogeographical surveys carried out during the project (Egaña et al., 2004; Muñoz-Schick et al., 2001; Pinto et al., 2001; Cereceda et al., 1997; Rundel 1991; Dillon and Rundel, 1990).

Table 1
Monthly averages of cloud cover and types of events

Analysis per month	August 2001	January 2002
Monthly average per image, total area (km^2)	20,895	2846
Monthly average per image, only land area (km^2)	1934	52
Monthly average of the daily maximum, total area (km^2)	24,153	3211
Monthly average of the daily maximum, only land area (km^2)	3096	139
Monthly average of the daily minimum (km^2)	16,539	895
Monthly average of the daily minimum, only land area (km^2)	422	0
Number of advective events (inland penetration)	31	5
Maximum inland area penetrated (km^2)	12,676	2750
Number of orographic events	28	18
Number of radiation events over land	10	2

4. Results and discussion

4.1. Spatial and temporal variability of low clouds

A comparison of GOES images and ground truth observations for 33 validated cases showed a 92% similarity of results during daylight time, and 79% at night and at sunrise.

The areas covered by low clouds during August 2001 and January 2002 are very different, especially in the oceanic region (Table 1). During August 2001 there were only 3 days when some of the oceanic sectors were free of fog — and then only for a few hours. At all other times the low cloud cover was never less than 70%. The area has an almost permanent and solid cloud mass that remains very close to the coastline. There were many and deep penetrations of fog inland (advective events). In contrast, during January 2002 the solid mass of clouds over the ocean almost disappeared, with few, weak inland intrusions of fog occurring in isolated small sectors. Several days were completely free of low clouds (Table 1).

Regression analysis was done to determine the relationship between the continental area versus the total area (ocean and land) covered by low cloud. For August, the adjusted R^2 was found to be 0.89 (slope=0.3255, $p<0.001$; intercept=−4868.6, $p<0.001$). This means that 89% of the increase in low cloud cover over the land occurs simultaneously with an increase in low cloud extension over the ocean. This emphasizes the importance of advection. The remaining 11% of the variation can be attributed to the influence of orographic and radiation events. For January 2002, the adjusted R^2 was only 0.14 (slope=0.027, $p=0.088$; intercept=−15.4, $p=0.694$), which means that during summer, advection is not such an important factor in fog occurrence (only 5 events). Instead the influence of the other types dominates (20 events) (Table 1).

The average diurnal cycle of low clouds was determined using the daily spatial and temporal variability data for the winter and summer months. The seasonal patterns are shown in Fig. 2. During August 2001, the daily variation of the covered area was greater and the cycle better defined than during January 2002. During both months, the minimum area covered occurs at more or less the same time, i.e. shortly after local noon, at 17:45 UTC in winter and at 16:30 UTC in summer. The maximum area covered occurs around 07:10 UTC in both months, but this area is much more extensive in summer (20:45 to 05:45 UTC).

During August, 14,479 km² were free of low clouds, while the area increased to 21,974 km² in January (Fig. 3). August showed large sectors of the ocean where the time frequency reached an average of 85% (with a maximum of 97.9% and a minimum of 60%). The maximum value in January over the ocean was 36%, with a few sectors completely free of low clouds. Over the cliff (at the western limit of the coastal range) there is a notorious longitudinal belt with values between 60% and 85% in August. In January, this fog belt disappears. Over the Cordillera de la Costa, there were low cloud frequencies in August 2001 (between 20% and 50%),

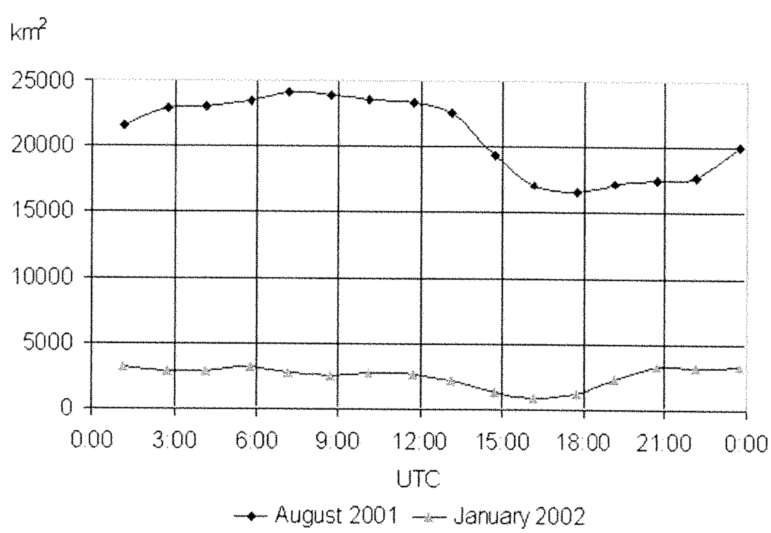

Fig. 2. Monthly average of area covered by low clouds.

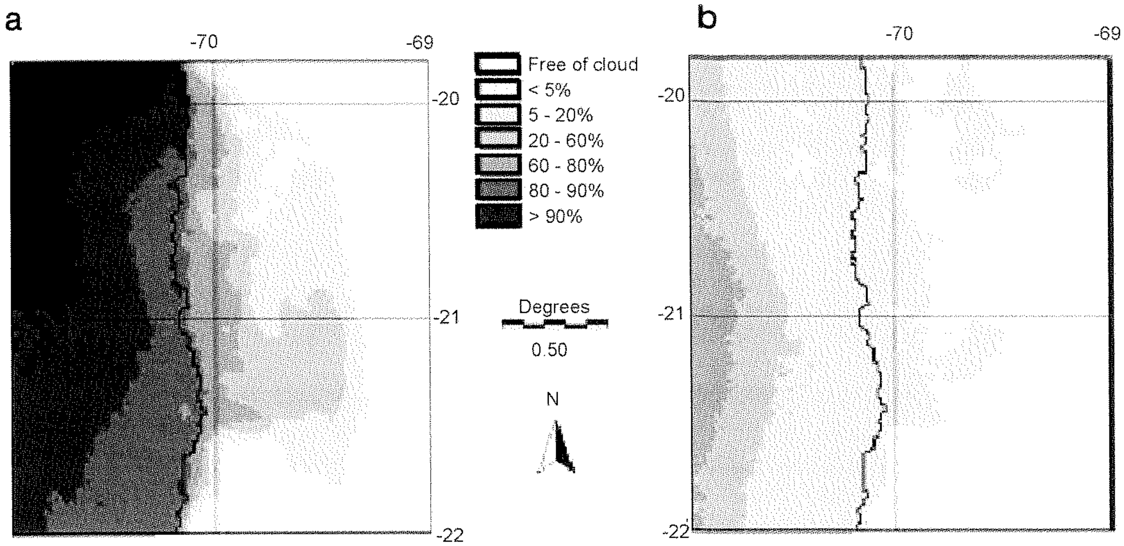

Fig. 3. Frequency of low cloud cover (a) in August 2001, and (b) in January 2002.

while in January 2002 these places show frequencies varying from 0.2% to 3.5%. Finally, 50 km inland, in Pampa del Tamarugal, there were sectors where the low cloud frequency was 15% in August whereas in January it did not reach more than 0.5%.

4.2. Spatial and temporal variation of fog water fluxes in coastal and inland sites

The site at Alto Patache has a significantly higher fog water yield than the inland site of Cerro Guatalaya. In the 1998 to 2005 period, the average annual collection rate for the coastal site was 7.0 L m^{-2} day^{-1}, while for the inland site it was 0.8 L m^{-2} day^{-1}. At Alto Patache, the annual yield varied between 8.4 and 5.3 L m^{-2} day^{-1}, and at Cerro Guatalaya it ranged between 1.1 and 0.6 L m^{-2} day^{-1} (Fig. 4). Although measurements with SFCs began in August 1997, data for that year are not included here because the first 7 months data are missing. It is, however, interesting that the best water collection rate of the entire period occurred during the winter and spring of that year, with an average of 15 L m^{-2} day^{-1} (during an

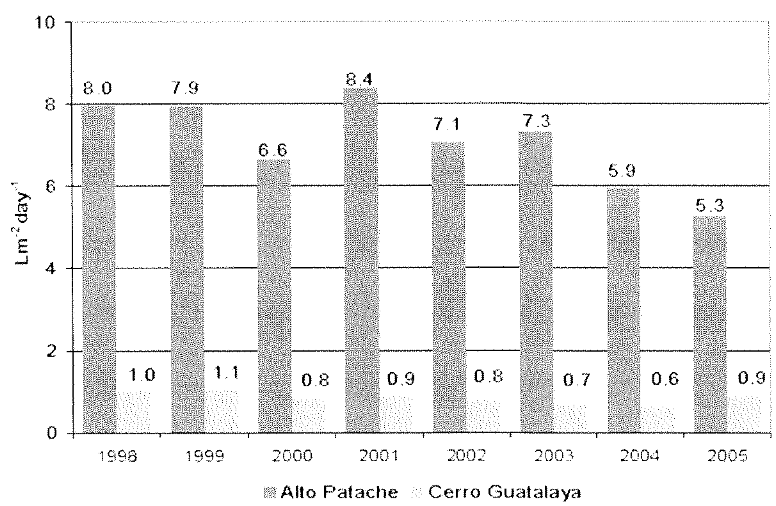

Fig. 4. Mean annual fog water yield per m^2 of collection mesh (1998–2005).

El Niño year). This regularity in fog water collection is an important aspect to consider when assessing the possibility of fulfilling the water demands of a village, afforestation, agriculture or mining, since the possibility of "dry years" is low. Ecosystems would thus receive a relatively similar amount of fog water every year, even while the precipitation of the area has large annual fluctuations, with several years in a decade not receiving any rain at all.

The seasonal variation of fog water fluxes is extreme (Fig. 5) at both sites: summer is the driest period and winter is the foggiest. This is important for ecosystems since summer (from December to March) is the period in which plants are in their most active state and need more water. For example, the ecosystems of Cerro Guatalaya may have an entire month without any fog, but in Alto Patache this very rarely happens.

Regarding the monthly average, it can be seen that the general trend is very similar at both sites. There is a gradual increase of fog water fluxes from summer to winter (Fig. 6a and b). However, it is interesting to note that the highest yield found in the coastal site occurs in September, while inland the best yield occurs in July (Fig. 7).

Both sites have in common that geographical factors affect fog water yields. Distance from the sea is a very important variable, since evaporation of the fog droplets takes place during the passage of the air mass over the continental surface. Alto Patache is only 3.5 km from the sea. The mountains intercept the stratocumulus cloud immediately, since it is the first orographic structure in the prevailing wind direction. In turn, Cerro Guatalaya lies in a fog corridor 12 km from the coastline in a mountainous area. Altitude is also important, since the position of the cloud is defined by an inversion layer that is formed by subsidence associated with the South-eastern Pacific Anticyclone. However the cloud is forced to rise in the coastal range, where the altitude increases from west to east.

4.3. Spatial and temporal variation of fog water fluxes in relation to altitude at Alto Patache

A substantial difference was found between the fog water flux averages of the fog collectors erected at different altitudes along the cliff at Alto Patache. The higher elevations (850 and 750 m a.s.l.) have the highest collection rates in the study area. The seasonal trend is also similar at all altitudes. The yields at 650 m during August and September are similar to the annual yield of Cerro Guatalaya, whereas from 450 m and below, the fog water fluxes measured are irrelevant (Figs. 8 and 9).

Since very high mountains do not occur in the immediate vicinity of the Alto Patache study area, it was not possible to collect fog water data from higher altitudes. Because of this lack of information, it is not possible to explore the altitude or the thickness of the top of the stratocumulus cloud that generates fog in the area. Since these are important variables for understanding fog water fluxes, remote sensing was used to obtain useful estimates.

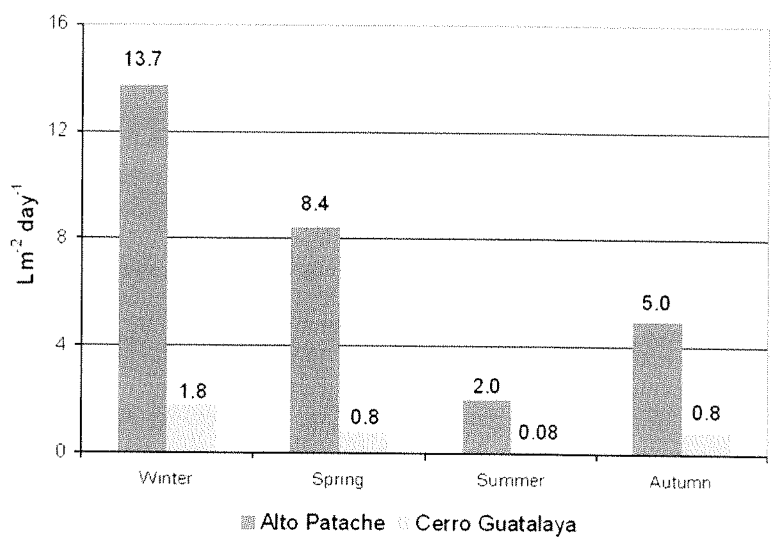

Fig. 5. Mean seasonal fog water yield per m^2 of collection mesh (1997–2005).

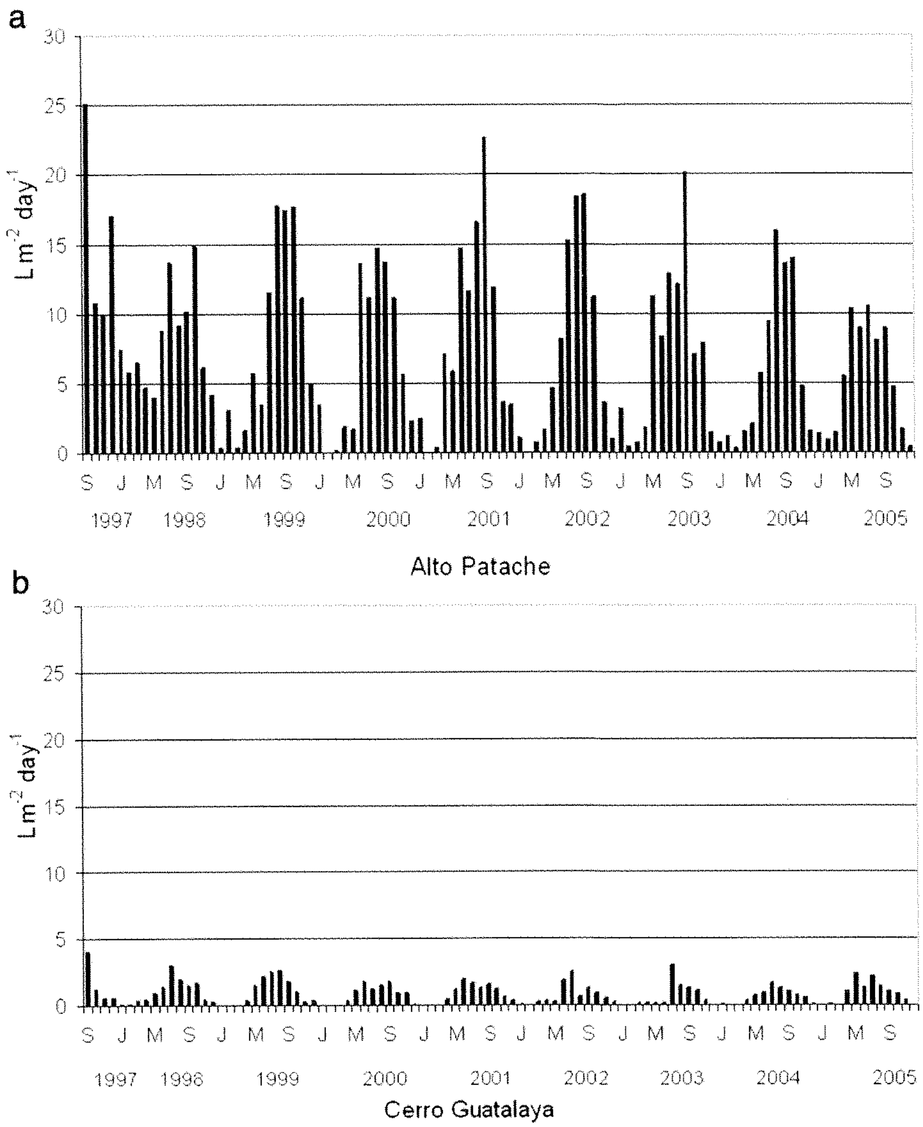

Fig. 6. Fog water collection at Alto Patache (a) and Cerro Guatalaya (b) (September 1997–July 2005).

Altitude was assessed as a factor of spatial and temporal fog variation with ground truth field work data. During a seven-day period, only one complete day was free of fog. During the other days the thickness of the stratocumulus cloud varied from 600 m to 50 m; the lowest position of the base of the cloud was 600 m a.s.l. and the highest position of the top was 1200 m a.s.l. Fig. 10 shows the change of top and base heights during one of the weeks, in a month with high fog frequency, and the fog water collected each day at 09:00 hours, local time.

A negative correlation was found between the temperature at Carrasco and the altitude of the Sc cloud cover. The correlation coefficient was -0.30; $p=0.06$. This indicates that when the temperature is lower over the top of the stratocumulus, the altitude of the cloud cover tends to be greater.

From this result and the GOES data, the interaction between the altitude of the Sc top and the area covered by the cloud can be defined in the Tarapacá study area. A regression analysis was done, where the dependent variable (y) was the area covered by the Sc and the independent variable (x) was the altitude of the top of the cloud. The result shows a clear positive relation between both variables, with an R^2 of 0.548 ($F_{1,31}=37.66$;

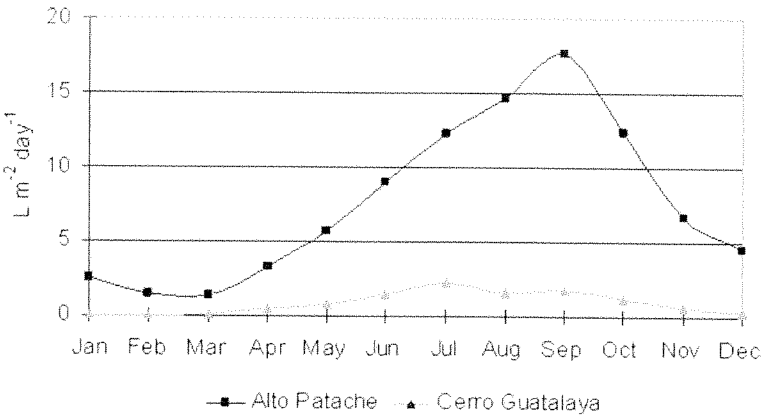

Fig. 7. Mean monthly fog water yield (1997–2005).

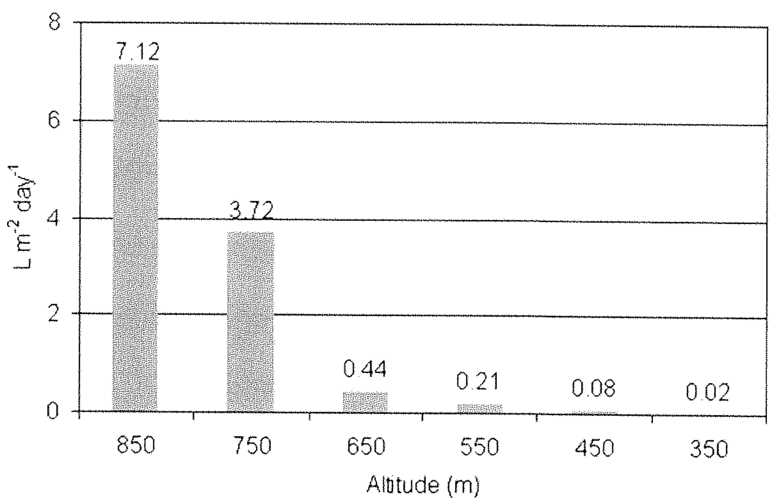

Fig. 8. Mean annual fog water yield in relation to altitude at Alto Patache (2001–2004).

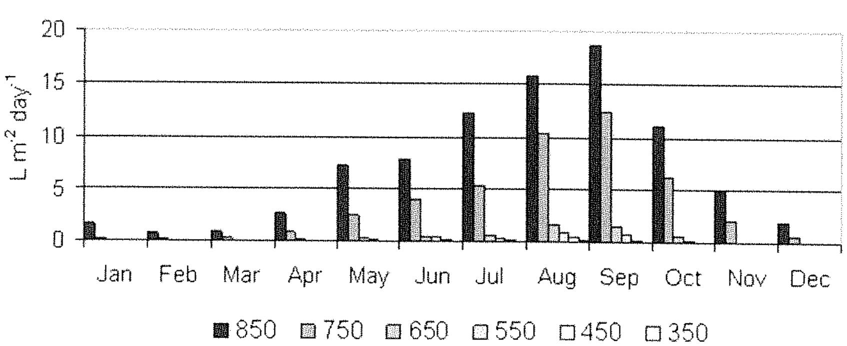

Fig. 9. Mean monthly fog water yield in relation to altitude at Alto Patache (2001–2004).

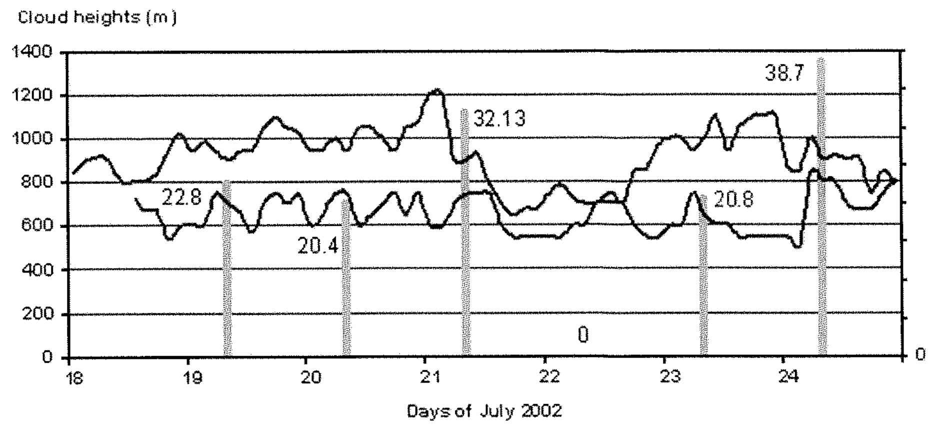

Fig. 10. Top and base heights of the stratocumulus cloud and water collected at Alto Patache.

$p<0.05$; intercept $=-3232$ [km^2]; slope $=4.75$ [km^2 m^{-1}]) (Fig. 11). The area covered by the Sc is thus larger with an increase in the altitude of its top.

When exploring the relationship between the area covered by the Sc and cloud thickness (which is difficult to obtain with GOES images), the result shows a positive and significant correlation coefficient between both variables ($R=0.70$; $p=0.05$). A regression analysis was carried out with the thickness of the cloud (d, in [m]) as the dependent variable and the area covered by the Sc (A, in [km^2]) and the altitude of the cloud top (z, in [m]) as the independent variables. The result of the multiple linear regression is significant ($d=-419+0.0526\ A+0.682\ z$; $F_{2,30}=38.8$; $p<0.01$; $R^2=0.721$). Thus it is possible to obtain the thickness of the Sc with good accuracy from the horizontal extension of the cloud and its altitude as obtained from the GOES images. The base of the cloud has a mean average altitude of 652 m a.s.l. with a standard deviation of 80 m, while the top has an average altitude of 960 m with a standard deviation of 130 m. This suggests that when the cloud top is higher, its thickness tends to be greater, primarily because of the change in the top of the cloud. The relationship between these variables can be explained in the following way. The study area is located in a mountain range, where the presence of warm air above the stratocumulus cloud top means that the inversion layer is strong. This is due to the subsidence that alters the temperature in the boundary layer, which causes the cloud top to be low in altitude. A

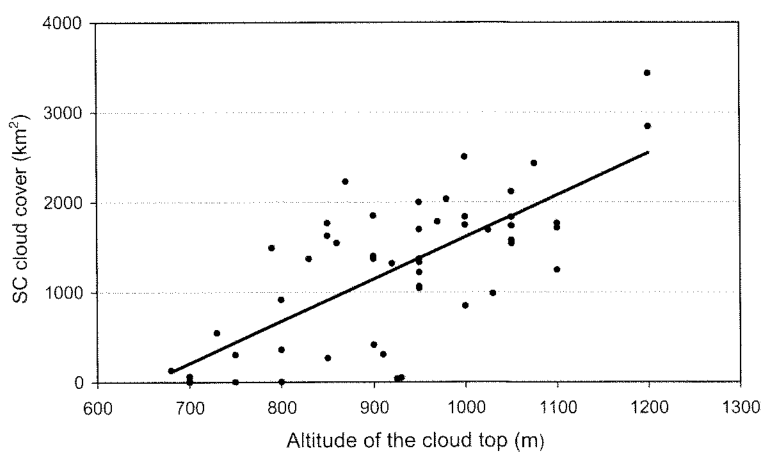

Fig. 11. Regression between stratocumulus cloud top altitude and area covered by it.

significant area of land lies above the clouds, and such high elevations areas can become an obstacle to the penetration of the cloudy mass. The opposite situation occurs when the cloud top temperature is lower. The altitude of the cloud top is thus higher, and the area covered by the cloud is larger. The data from the fog collectors in the coastal cliff of Alto Patache show that the cloud base in that area over the course of a year is between 650 and 750 m a.s.l., and that it tends to be lower in winter (August and September) only.

4.4. Fog water fluxes in relation to height above the ground

The difference in fog water collection in relation to height above the ground is important for studies of vegetation in fog oases. The amount of water that a plant can collect depends on its size and also on the fog that rolls along the terrain. A large difference was found between collection surfaces erected at heights of 2 m and 0.2 m above the ground. In the former, the annual yield at 750 m a.s.l. was 3.72 L m^{-2} day^{-1} for the period of 10 January 2003 to 13 August 2005. This is three times greater than the amount that was collected near the ground (0.92 L m^{-2} day^{-1}). The amount of water collected at 0.2 m at the lower altitudes is negligible.

4.5. Fog water fluxes and wind regimes

In addition to Sc cover, distance from the sea, altitude of the relief and height above the ground, wind also plays an important role in the amount of water collected in the SFCs.

The predominant winds at the coastal site were from the S, SSW and SW. This coincides with the information of the official Meteorological Station of Diego Aracena in the littoral plain 10 km from Alto Patache. The N, NNE and NE winds in the morning are typical breezes due to the differential warming between the sea and the continent. A similar situation occurs during autumn and winter evenings. At Alto Patache, the highest wind speeds have been measured in spring with peaks in the afternoon, light winds usually occurring in the mornings. This fact explains the high fog water collection in spring. It is interesting to note that winter, with the highest fog water yields, does not have strong winds (1 to 3.6 m s^{-1}, highest at midday). The high winter yield is probably due to the liquid water content of the cloudy mass that forms the fog in the area (Table 2).

4.6. Fog oases

Fog has been studied in the Atacama Desert for several reasons, one of which is to understand its role in the presence of vegetation in one of the world's most arid places. Annual precipitation in the area is less than 1 mm (0.8 mm in the last 30 years), yet there are many vegetated zones having different surface areas. These areas are known as fog oases or *lomas* vegetation. In general, botanists have distinguished two types according to the number of plant species found: monospecific, with one species, and plurispecific, with several species. The large high altitude fields of *Tillandsia* sp. of the Bromeliaceae family are an example of monospecific *lomas* vegetation. At Alto Patache, where plurispecific oases are present, Pinto et al. (2001, p. 295) wrote: "The great number of species, genera and families detected by us in the area of Alto Patache fully justifies the need of studying this peculiar type of coastal flora, present in very isolated and ignored spots, south of Iquique".

Table 2
Wind speed and direction at Alto Patache 850 m a.s.l. (1997–2005)

	Wind speed (m s^{-1})				Wind direction			
Time	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
09–10	0.0	1.6	1.0	3.2	NE	N–NE	NNE–S	SSW
10–11	0.9	1.3	1.6	1.9	S–SSW	S	S	S
11–12	2.3	2.0	3.6	4.4	S–SW	S	S	S
12–13	3.9	2.8	3.3	6.5	S	S	S	S
13–14	4.4	5.0	3.4	6.3	S	S	S–SSW	S
14–15	7.7	6.0	3.4	8.9	S	S	S	S
15–16	No data	0.8	2.0	10.7	S	S	S–SSW	SSW
16–17	5.0	1.2	No data	4.5	S	S	No data	S–SSW
17–18	4.3	No data	3.0	7.1	S–SSW	No data	NE	S
18–19	No data	0.3	0.0	5.3	No data	N–NE	NEE	S

For each type of oasis, there is a geographical setting that is strongly related to fog conditions. Although this correlation does not necessarily imply a causal relationship, there is some evidence that these ecosystems functionally depend on the fog water inputs and thus on the variability of the stratocumulus cloud and fog.

The *Tillandsia* sp. fields are usually found between 900 and 1200 m a.s.l., and are well developed in higher altitudes and inland locations. This suggests that the plants do not need large amounts of water to survive and that they can survive for two months with no fog water or with very small amounts of it (in summer). Cerro Guatalaya is a good example of this type of environment and vegetation (Cereceda et al., 1999). The surveys also highlighted the need to explore the role of dew in such environments.

The plurispecific oases are found in the cliffs, usually in rocky environments where fog is frequent and the cloud cover helps to maintain the humidity. According to Pinto et al. (2001) and Egaña et al. (2004), at Alto Patache the dominant vegetation found on the sandy and gravel substrates (300–700 m a.s.l.), are herb species from the Nolanaceae and Liliaceae families. They appear mainly in rainy years, typical of El Niño events. The upper section of the rocky cliff (700–800 m a.s.l.) has an abundant community of lichens, and shrubs and cacti are also present. In a plain covering several hectares east of the cliff ridge at about 800 m a. s.l, *Nolana sedifolia*, *Cristaria molinae*, *Hoffmannseggia rostrata*, *Fortunatia biflora* and *Leucocoryne appendiculata* are abundant in rainy years (Pinto et al., 2001).

A typical oasis that tends to survive in the cliffs of Tarapacá is that of *Eulychnia iquiquensis*, a Cactaceae, which is located in areas of more frequent fog (about 800 m a.s.l.) and high winds, usually on steep slopes or in deep valleys. The plants collect water by interception and the water then infiltrates the adjacent soil.

5. Conclusions

Eight years of studies in Tarapacá with GOES images, field observations, SFC measurements of fog water fluxes and other activities, have indicated that several conclusions can be drawn. The large stratocumulus cloud of the South-eastern Pacific is present year-round in the sea and moves onshore with different intensities depending on the season and time of day. Maximum spatial expansion of the Sc occurs in winter and minimum in summer. The cloud is formed over the sea and is then advected to the mountains. This leads to frequent fog along the cliffs near the coastline. Fog also penetrates inland along corridors formed in the coastal mountain range, reaching distances of up to 12 km at Cerro Guatalaya, and even further in *Pampa del Tamarugal* (50 km inland) (Cereceda et al., 2002). The thickness of the cloud ranged between 600 m and 50 m when fog was present in Alto Patache. There is a statistically significant relationship between the temperature above the inversion layer that defines the altitude of the top of the cloud, and the surface area occupied by the Sc in the coastal range which at the same time modifies the growth of the cloud.

Fog collectors have the highest yields near the sea; at Alto Patache 7.0 L m^{-2} day^{-1} is collected, and further inland in Cerro Guatalaya it decreases to 0.8 L m^{-2} day^{-1}. In the coastal cliff of Alto Patache, fog is present above 650 m a.s.l. and at Cerro Guatalaya around 1000 m a.s.l. Fog water fluxes vary from year to year, with a difference of about 3 L m^{-2} day^{-1} between the years with highest and lowest yields. Winter and spring are the best seasons for fog water collection in both places. Fog collectors mounted 2 m above the ground have substantially higher yields than those at 0.2 m.

Several oases consisting of a variety of different species of herbs, cacti and shrubs occur in the foggy areas. There are also oases consisting of only one plant species, such as *Tillandsia* sp., that cover large expanses of high altitude plains and slopes in areas where the lowest fog water flux were measured. Cacti and shrubby environments are located mainly in areas where the yields of fog water collection are the highest, such as along the cliffs of Alto Patache. There are other areas of vegetation that are not determined by the presence of fog, but which respond to heavy precipitation, for example herbal fields below 600 m that sprout during rainy years. The relationship between fog and vegetation in Tarapacá, and the effect of dew as a source of atmospheric water in these oases, are topics that require further study.

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Fog collection in the western Mediterranean basin (Valencia region, Spain)

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Abstract

Four different mountainous locations were selected in the Valencia region, East coast of the Iberian Peninsula, for fog water collection studies. Data for 2004 were obtained by means of an instrument ensemble consisting essentially of a passive cylindrical fog water collector, a raingauge, a wind direction and velocity sensor and a temperature and humidity probe. An approximate data reduction technique was also found for this specific ensemble to eliminate the simultaneous rain water component from the fog water measurements. Main results indicate that fog water collection holds significant potential in this region, and especially for southern locations. Annual rates of fog water yield can be as high as 7.0 l/m^2/day in the southern locations, in contrast to 2.0 l/m^2/day collected at one site in a northern location. The highest summer fog water yield was 4.6 l/m^2/day, a relatively large value. Except for the summer period, fog episodes delivering sizeable water volumes are inherently coupled to rainfall. Hourly frequencies of fog collection were also examined to show a distinct daily cycle in summer, denoting orographic fog formation during this period. Lastly, winds were analysed to resolve the most suitable directions for fog collector alignment.

Keywords: Passive fog collection; Valencia, Normalised volume index; Rainfall

1. Introduction

Fog water collection studies have been carried out in Spain, specifically in the Canary Islands (Marzol, 2002; Marzol and Valladares, 1998), but not within the eastern part of the Iberian Peninsula. Millán et al. (1998) discussed the main hydrological system inputs for the western Mediterranean basin: frontal precipitation, Mediterranean cyclogenesis, summer rainfall and micro-scale processes such as fog and dew. Although there is abundant information on the first three types of inputs from more than 25 years of rainfall records, little information is available on the microscale inputs that may occur at elevated orographic sites in the region.

According to Schemenauer and Cereceda (1994a), the coastal regions of eastern Spain meet most of the geographical conditions for fog occurrence and collection potential. For example, this region features mountain ranges that rise to altitudes exceeding 500 m and within 10 km distance from the coastline. At these altitudes, fog water collection can be accomplished by using simple passive collectors since they can be exposed to either advection fog or orographic fog as explained by Cereceda et al. (2002). Advection of fog is produced when certain prevailing winds bring clouds originating over the

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