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Advective, orographic and radiation fog in the Tarapacá region, Chile

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Abstract

A project in northern Chile was undertaken to determine the origin and behaviour of fog in the coastal and inland locations of the Tarapacá Region. In the Pampa del Tamarugal, 50 km from the sea, conditions exist for the formation of radiation fog. Advective fog has been studied on the coast and orographic fog was observed at a few coastal sites near mountain ranges with elevations above 1000 m. Fog water collected by two standard fog collectors (SFC) for 3 1/2 years showed an average flux of $8.5\ \mathrm{l\ m^{-2}\ day^{-1}}$ on the coast and $1.1\ \mathrm{l\ m^{-2}\ day^{-1}}$ inland 12 km from the coastline. On only a few days in 10 months was water collected at the inland site of Pampa del Tamarugal. GOES satellite images are shown to illustrate the pattern of formation of the stratocumuli cloud over the sea, its approach to the coastline, the entrance of fog by corridors through the coastal range and the presence of radiation fog inland. The results are important for the understanding of fog formation and dissipation along the coastal mountain range and for the recognition of potential sites for the installation of fog water collectors, which can be used as a water source in the Atacama Desert. The results also provide vital information for use in the preservation of the unique ecosystems of the most arid desert of the world.

Keywords: Fog; Marine stratocumulus; Fog water; Atacama desert; Remote sensing

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1. Introduction

Fog has been widely studied in Chile, especially as a water resource for human consumption (Schemenauer and Cereceda, 1994a; Cereceda and Schemenauer, 1998). At present, there are at least seven sites with operational or scientific projects in the country. Science and technology are important in these types of research. The understanding of cloud physics and chemistry as well as the behaviour of fog are crucial, as is the technology to use fog water as a managed water resource.

In the coastal area of the Atacama Desert, there are four types of ecosystems (fog oasis) with a predominance of cacti, shrub formation, *Bromeliaceas* and annual plants. These formations are the result of fog and the occasional rains that occur mainly during the El Niño phenomenon. Probably, cacti are relic plants of past wetter periods and sustain themselves due to fog. In a similar situation are the shrub formations that live off the combination of rain and fog. The *Bromeliaceas*, called here "tillandsias", live almost only on fog. The annual plants survive principally on rain. Understanding fog and rain is vital for the comprehension of these fragile ecosystems whose protection is important for the preservation of the biodiversity of this arid environment.

In the last 4 years, a geographical study has been done in the Tarapacá Region in northern Chile, in the Atacama, the "most arid desert of the world" (Weischet, 1974). One focus of the investigation carried out has been the understanding of the factors that determine the origin and behaviour of fog. Radiation fog in inland locations and advective and orographic fog along the coasts have their causes based on the planetary atmospheric circulation and the local geographical features.

Presently, there is a group of scientists studying the geophysics of the southeastern Pacific stratus decks and their interactions with weather systems through the program VEPIC, the VAMOS East Pacific Investigation of Climate. In this paper, the regional and local scales of the stratocumulus cloud and fog are examined and the planetary scale is only discussed in so far as it relates to the origin of the air mass that are involved in the formation of fog on the continent.

2. The study area and methodology

The study area is located in the First Region of Tarapacá (Fig. 1) from Junín to the Loa River (19°40′ S-21°30′ S–70°10′ W-69°40′ W). The length of the coastline is approximately 200 km and the width toward the interior is an average of 50 km. The total area is about 10,000 km^2. From west to east, the relief is formed by a narrow coastal plain (average 5 km); a cliff of 400–1000 m; a mountain range, Cordillera de la Costa, with peaks of 1500–2000 m (width of 50–70 km); and a tectonic basin of an average width of 100 km called Pampa del Tamarugal. The study area reaches the piedmont of the Cordillera de los Andes (Osses et al., 1998a).

The work presented here was done during the years 1997–2001. Initially, cartographic and GIS analyses were undertaken to find the places where the topographical features would be favourable for the formation of fog. Osses et al. (1998b) has reported that critical

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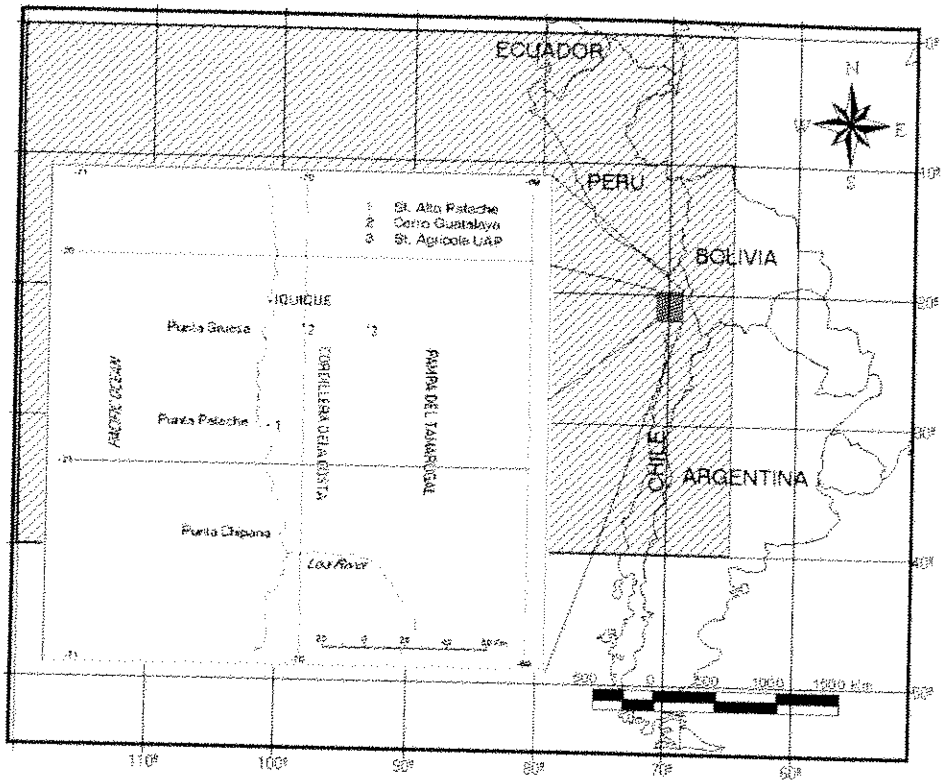

Fig. 1. The study area.

aspects such as mountain ranges, terrain altitude, transverse valleys, coastline shape and distance to the coast are important.

Two standard fog collectors (SFC) (Schemenauer and Cereceda, 1994b) were installed at the coastal location of Alto Patache (20°49′ S; 70°09′ W-850 m) and in Station Tillandsias (20′ 12′ S; 70°W-1050 m) located in Cerro Guatalaya 12 km from the coast. The SFC collects fog droplets and allows the flux of fog water over the terrain to be measured. The data were collected on a weekly basis from July 1997 until March 2001. Forty-five kilometres inland, in Pampa del Tamarugal, in Estación Agrícola Universidad Arturo Prat (20°20′ S; 69°43′ W-950 m), an SFC was installed in May 1999 and data were collected until March 2000. Since in a light fog it is difficult to collect water in an SFC, daily observations on the presence or absence of fog were recorded. Surveys in four field campaigns of 15 days were done during the winter of 1997, the summer and winter of 1998 and in the summer of 1999, at different sites, with standard fog collectors and with manual instruments to measure temperature, humidity and wind parameters at different hours of the day and night. To recognise the presence of orographic fog, a study of vegetation in the fog oases was done using the literature and field surveys.

In 2001, a project funded by the National Commission of Science and Technology of Chile (Fondecyt # 1010801) began to understand the relationship between the ecosystems and fog. GOES and NOAA satellite images are being used. The spatial and temporal behaviour of the stratocumulus clouds will be analysed using GOES images, and NOAA images, with a better spatial resolution, will be used for the study of the influence of relief on the penetration of fog into the continent. In this paper, the emphasis is on the theoretical discussion of fog behaviour, as well as the data acquired in field experiments. Some examples of the GOES images are given to illustrate the phenomenon.

3. Results and discussion

3.1. Stratocumulus cloud

The typical stratocumulus cloud of northern Chile is formed hundreds of kilometres from the coast in the southeastern Pacific Ocean. It is frequent to find in the scientific literature that the Peruvian fog in the "Lomas" area, and the Chilean coastal fog, locally called "camanchaca", are due to the effect of the cold Humboldt Current. Nevertheless, the satellite images show a different reality. Effectively, in the initial examination of the GOES satellite images done during the months of May, June, July and August 2001, the results show a large mass of stratocumuli clouds that was always present during the period. Examples of this phenomenon are given in Fig. 2, showing high and low magnifications of the low cloud as a compact mass.

The South Pacific Anticyclone produces a strong subsidence that generates a thermal inversion layer along the coast, defined by Espejo (2001) at Cerro Moreno as being between 483 and 1543 m. This inversion does not permit the evolution of the typical tropical clouds of these latitudes, allowing only the formation of stratus and stratocumuli. On the northern and central Chilean coast, the Humboldt Current intensifies the presence of advective fog at the above-mentioned altitudes (Weischet, 1974; Schemenauer et al., 1988). The associated cold water upwellings, frequent in the study area, are probably partly responsible for the orographic clouds and the more frequent advective fogs in certain areas of the coast, as will be seen below.

3.2. Advective fog

The massive cloud that originates over the Pacific Ocean expands toward the continent and is intercepted by the mountain ranges of the Chilean coast, forming persistent advection fog. It reaches the coastal cliff between altitudes of 400 and 1100 m. In research done in Perú and Chile, the thickness of this cloud has been measured at being around 300 and 400 m (Espejo, 2001; Cereceda et al., 1997, 1998). Presently, the data collected in 3 months (June–September) of 2001, with six SFCs located in a vertical line, from 350 to 850 m, shows that in this winter period, fog in Alto Patache has been more frequent at higher altitudes, indicating that the cloud base in the area was around 750 m.

The horizontal fog flux varies with altitude. From August to December of 1997, SFCs were installed on the cliff of Alto Patache at 750 and 850 m. The lower SFC had a yield of

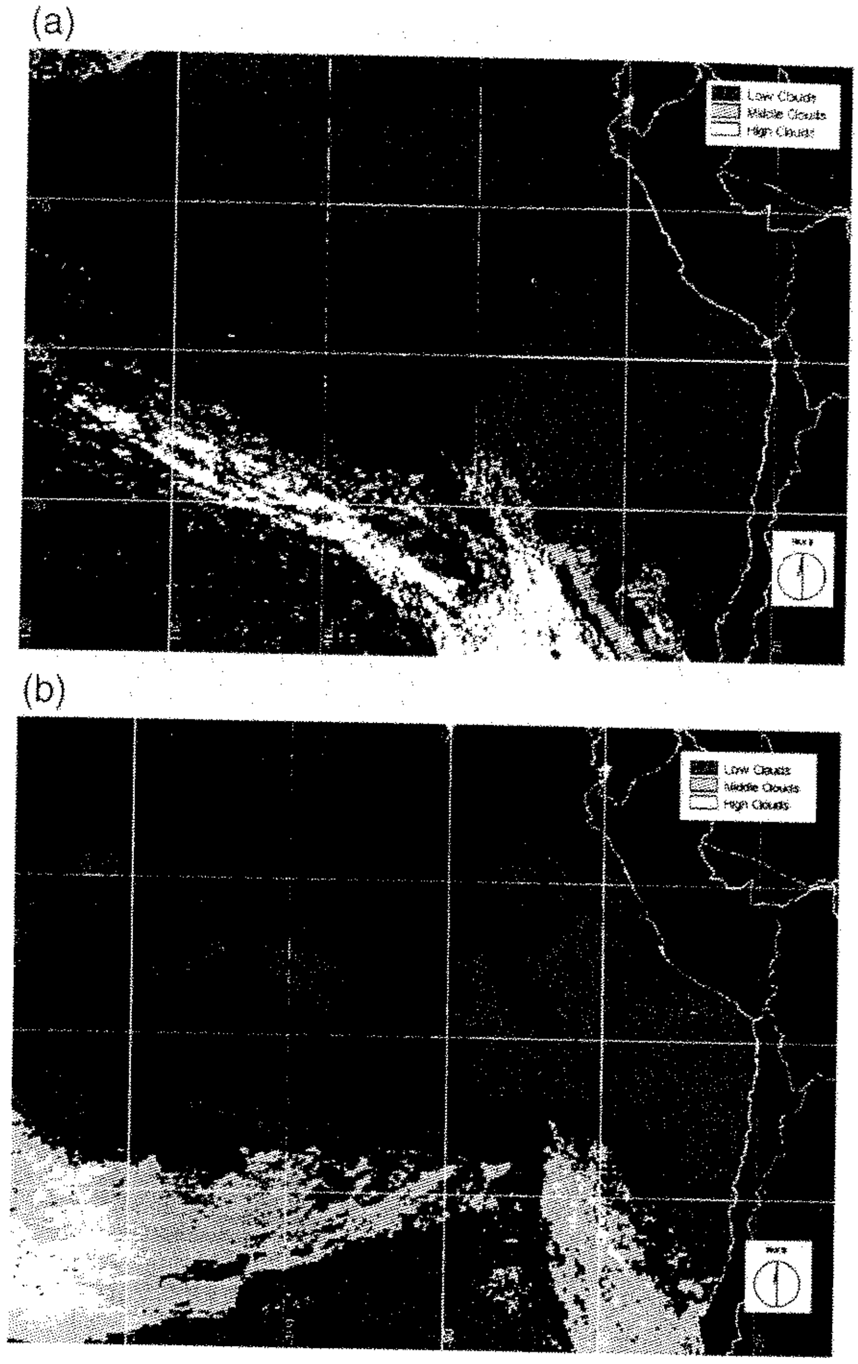

Fig. 2. (a) GOES image: high magnification, 1445 GMT, 26 June 2001. (b) GOES image: low magnification, 1445, 24 May 2001.

less than half of the higher one, which registered an average of 17.0 l m^{-2} day^{-1}. In Mejía, Perú (17°S–71°59′ W), 430 km from Patache, the best potential site for fog water collection was also found at 850 m (Osses et al., 1998b). Espejo (2001) has found in Cerro Moreno, Antofagasta the best collection of fog water at 1150 m.

Advective fog enters the Pampa and intermontane basins through saddles and corridors or paths formed between the high mountains of the Cordillera de la Costa. It persists until the heat of the land evaporates the fog droplets. Fog water collection is much higher on the coast than inland. The distance that fog can penetrate depends on the characteristics of the atmosphere: temperature, humidity and wind speed.

The fog flux data of Alto Patache and Tillandsias in Cerro Guatalaya show that on the coast, the average from July 1997 to December 2000 was 8.5 l m^{-2} day^{-1}, while in the interior, it was only 1.1 l m^{-2} day^{-1}. Both locations have the same yearly and seasonal variations and respond to El Niño and La Niña phenomena in a similar way. The El Niño of 1997–1998 had the highest water collection (17 l m^{-2} day^{-1}) in Alto Patache. In this same location, the average of years 1998–2000 was 7.4 l m^{-2} day^{-1} (Fig. 3a and b).

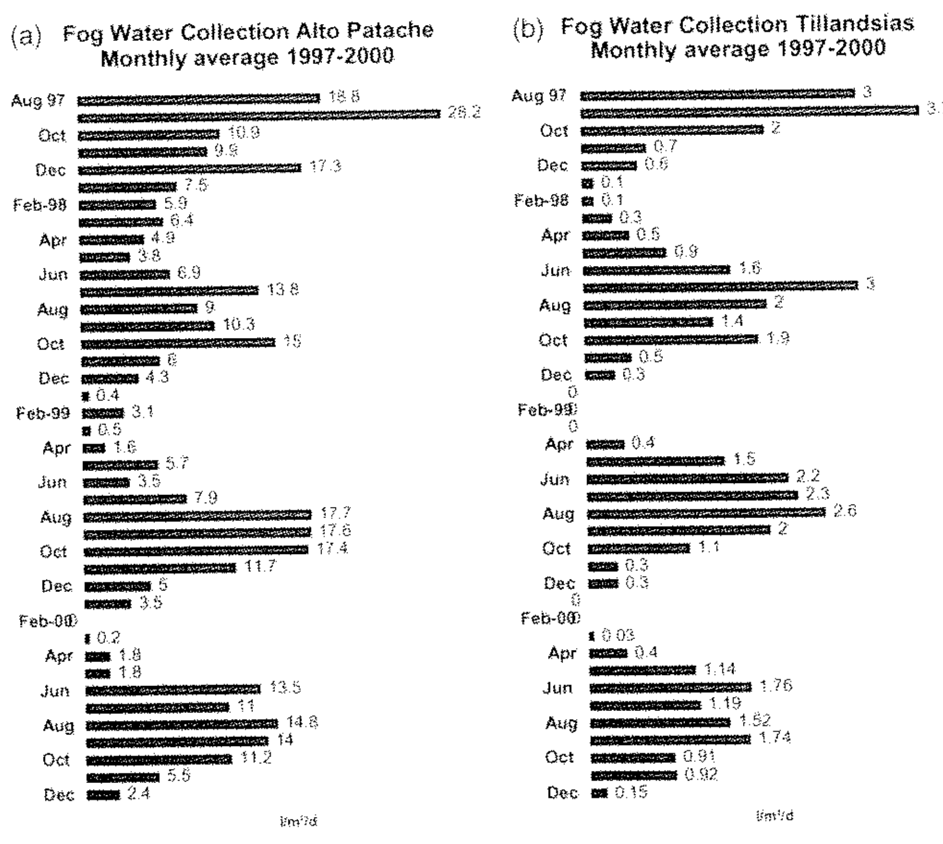

Fig. 3. (a) Fog water collection at Alto Patache. (b) Fog water collection in tillandsias, Cerro Guatalaya.

In the Pampa del Tamarugal (45 km from the coast), from May 1999 to March 2000, on only 10 days between June and August fog was observed. On only four of them were water collected in the SFC.

It is well established that in all locations, winter and spring are the most productive for fog water collection and from July until September, fog water collection rates are the highest. Summer and autumn include the months with the lowest yields, bringing down the yearly average.

With respect to the atmospheric parameters that control the shift of fog along the Cordillera de la Costa toward Pampa del Tamarugal, in the few days where fog water was collected inland, the following pattern was seen. During the field campaign of August 4–12, 1998, in Alto Patache and in Salar de Llamara in the southern part of Pampa del Tamarugal, 30 observations every 4 h of the day and night were done on five consecutive days when fog was present.

The SFC of Alto Patache on the coast collected 21 l in 16 registration periods and 1.5 l of water was collected in nine events in Llamara. Fog was recorded inland during the nights and in the mornings at 0200, 0600 and 1000; on the coast, it was more erratic, but still predominant in the same hours. In six of the nine events observed in Llamara, fog was present on the coast in the last 4-h period. There was almost a permanent calm inland and the light gusts were from 210° to 240° (SSW–SW); on the coast, wind was generally from the south and with higher speeds, the maximum speed measured was 5.5 $m\ s^{-1}$. During the entire period, temperatures in the Pampa oscillated from 2 to 27 °C; during fog events, it was between 2 and 12 °C inland and between 8 and 10 °C on the coast.

These data may indicate that either fog was present all the way from the coast to the Pampa and connected by the corridor, or that the fog dissipated and the humid air mass that arrived at the Pampa condensed and formed the fog as a result of the nocturnal winter cold. The other possibility is that the humidity of the atmosphere over the Pampa is derived from evaporation during the day from the salt flats present in the area, which have abundant underground water. The low temperatures and the calms or light winds are typical of radiation fog.

During these field campaigns, only two heavy fog events were surveyed along the corridors and in the Pampa. Probably the best way to monitor these fogs is with remote sensing. Examples of the preliminary study are given below (Fig. 4).

In the above four cases, the images show the penetration inland of the marine stratocumulus cloud. Where the relief intercepts this low cloud, fog is formed. In Fig. 4A and B, the cloud covers the coastal plain, the cliff and the Cordillera de la Costa, reaching the Pampa del Tamarugal, leaving only the highest mountains clear. In Fig. 4C and D, the dissipation process is seen beginning in the mountain range while the stratus over the Pampa remains for a longer time. If the stratocumulus cloud is low enough to generate fog, it is necessary to determine if the presence of it is due to radiation processes or if it is only a remainder of the advection fog. It may be that the cooler surface of the area reinforces the conditions for fog formation, so a combined process determines the permanence of this situation in the Pampa. In deciding on which parameters can be used to define this phenomenon, the analysis should center on the origin of the water vapour that forms the radiation fog.

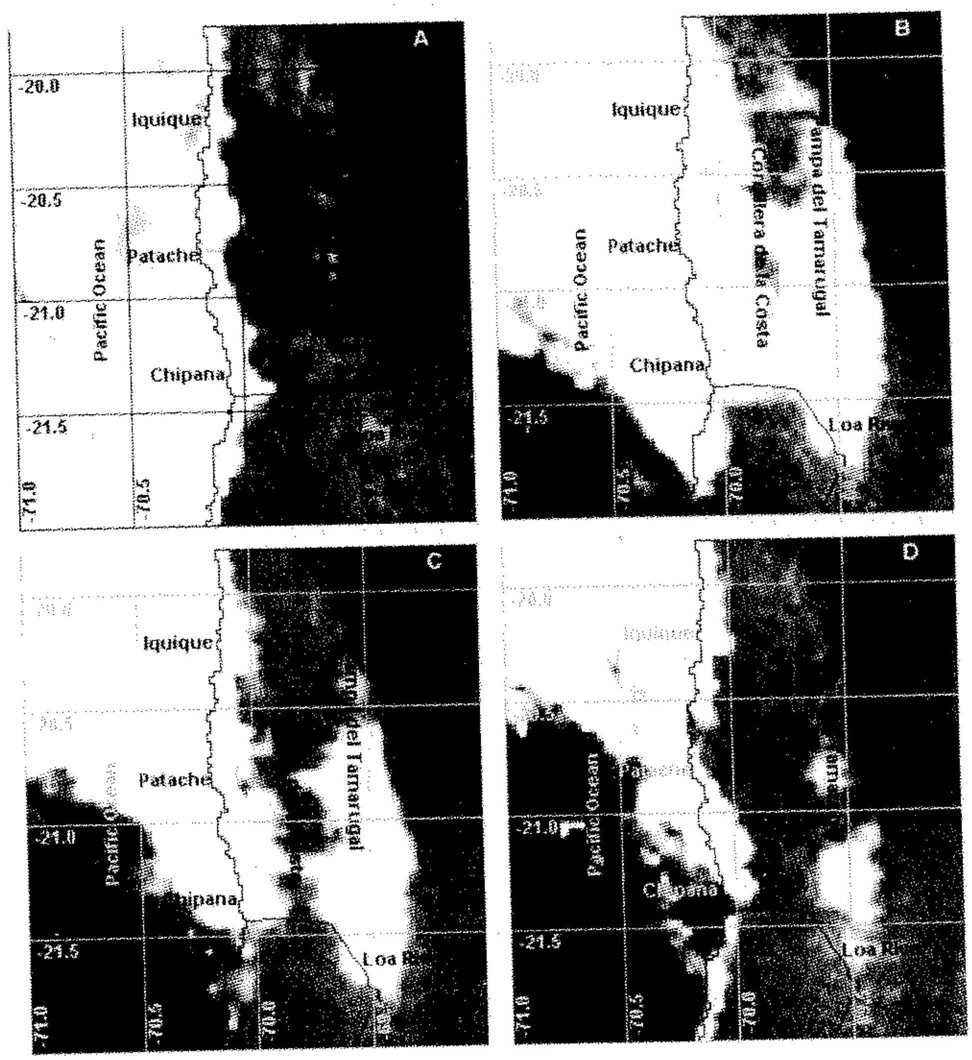

Fig. 4. GOES images: fog penetration (in white) in the Tarapacá Region.

3.3. Orographic fog

Many days during the field work, fog was observed on the coastal cliff on certain summits, while the rest of the area was clear and sunny. The sites were stated by local residents as being typically covered by clouds. This suggests the presence of orographic fog, which is influenced by factors such as upwellings in the sea, isolated mountains, altitude, form of the relief and the shape of the coastline. According to a survey of fog oases done by Muñoz et al. (2001), there are seven vegetated areas in the zone. On this occasion, they were identified and studied from the geographical point of view.

Table 1
Fog oases and associated geographical features

Fog oasis	Point	Bay size	Mountain	Mountain altitude
Junin	Punta Junin	small	Junin	1096
Ballena	Punta Ballena	medium	no name	945
P. Gruesa	Punta Gruesa	medium-irregular	Oyarbide	1469
A. Patache	Punta Patache	big	Cerro Rojo	1161
Pabellón Pica	Punta Colina	medium	Carrasco	1592
P. Blanca	Punta Blanca	big	Chipana	1300
P. Chipana	Punta Chipana	big	Quebradillas	1196

In general, all of the fog oases are located near the same coastal features, they are located on headlands and have wide bays on their southern edge. They are located at altitudes near 800 m.a.s.l. and have a mountain that is outstanding to the south, which has a summit from 945 to 1592 m.a.s.l. These higher mountains are the obstacles that oblige the incoming air mass to ascend and cool by expansion, condense the water vapour and form the fog. Also, they divert the air mass inland due to the predominant winds from the south and the southwest (Table 1).

In Fig. 5, the GOES images show two cases, one where the cloud is formed only in the above-mentioned areas (no stratocumulus cloud in the nearby sea), and in the other case, it may be the first manifestation of the advective process on the coastal range as shown by the mass of cloud near the coast.

Researchers on fog on the US West Coast distinguish between West Coast fog and the frequent sea fogs saying that the first one is unique and the major factors are the great strength of the low inversion and the presence of cool upwelled water along the coast. He refers also to air, water and topographic conditions.

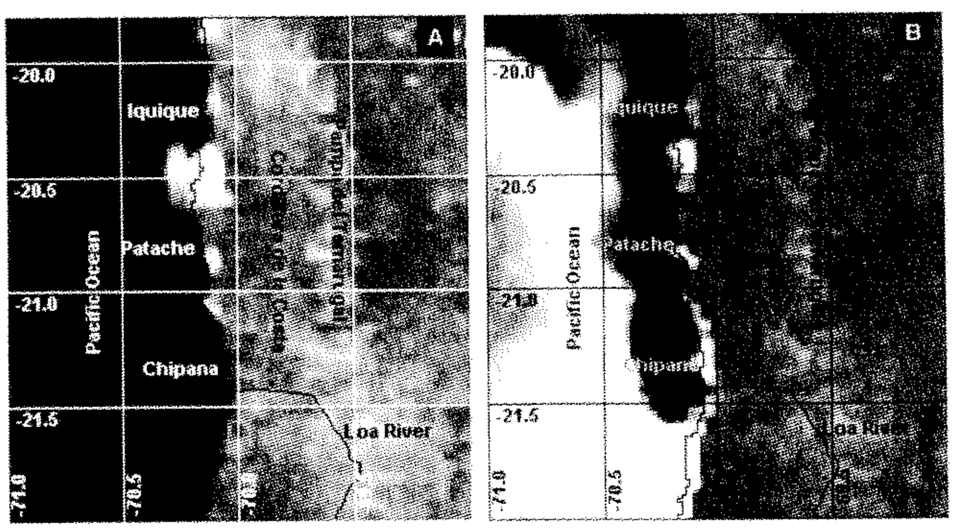

Fig. 5. GOES image: orographic clouds (in white) along the coast.

During episodes of advective fog, the influence of the orographic component results in a higher fog flux in the air mass and more potential for water collection.

4. Conclusions

In this project in the Atacama Desert of Chile, at least two types of fog were observed in a very narrow area, no more than 50 km wide. Advective fog results from clouds generated over the ocean far from the continent, which are transported by the wind to the coast. Depending on the relief, the advective fog can enter the continent through corridors in the coastal mountain range of the area. Orographic fog is formed in situ on the first windward slope facing the sea. It is local and related to high mountains or special forms of the relief and coastline. A third type, radiation fog, has been noted in the discussion since all the factors for its formation are present in the Pampa del Tamarugal.

The flux of fog water over the terrain is very dependent on the proximity to the coast. The 3 1/2 years of measurements with standard fog collectors showed an average flux of 8.5 $l\ m^{-2}\ day^{-1}$ on the coast and 1.1 $l\ m^{-2}\ day^{-1}$ 12 km inland.

The area of interest for fog investigations in northern Chile is vast, of the order of 100,000 km^2. The studies presented here show that the fluxes of fog water over the surface can be measured; however, the measurements are severely limited both in time and spatial scales. Conversely, satellite studies can look at the presence of fog and low cloud over large spatial scales and for long periods of time. The fluxes cannot be measured from satellite data but areas with the probable presence of fog can be identified from GOES images and other properties such as visibility and fog liquid water content may be possible to determine (Bendix, 2001). A true understanding of the fog phenomenon requires the application of the best of both technologies as has been initiated in this study.

Acknowledgements

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