Fuenzalida et al

5.3

METEOROLOGICAL ASPECTS OF WATER COLLECTION FROM STRATOCUMULI IN NORTHERN CHILE.

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1. INTRODUCTION

The arid coast of northern Chile is under the permanent influence of the subtropical anticyclone of the South East Pacific Ocean. Its climate, although extremely dry, is characterized by a persistent stratocumulus cloud deck topped by the trade wind inversion. This cloud never rains but frequently intersects the coastal topography producing dense fogs locally known as "camanchacas". The stratocumulus layer develops in the upper part of a well mixed atmospheric boundary layer, between the mixing condensation level, at about 400 m, and the base of the trade wind inversion, typically between 700 and 800 m. Mixing of the boundary layer produces almost constant vertical profiles of potential temperature in the subcloud layer, with values within a one degree interval most of the time (Figs. 4 and 5 below). Because of the cold sea underneath, moderate winds and absence of higher cloud decks, the turbulence must be due to the cloud-top radiative cooling. This kind of marine boundary layers have been studied by several authors, Lilly (1968), Deardorff (1976 and 1980), Randall (1980), Nicholls (1984) among others.

Since November 1987, a project aimed to trap the liquid water content of the cloud is under way. This is the most recent of several attempts made in northern Chile in the last thirty years. Their results have summarized by Schemenauer et al. (1988). The final objective of the project is to supply with potable water a small fishing village, Chungungo, where 500 people live and are presently supplied by truck once or twice a week. The fog liquid water content is being trapped using 50 massive collectors each of which presents 48 m2 of mesh to the air flow. A more detailed description of the collectors together with information on their efficiency and water production is given in a poster presentation, Fuenzalida, Schemenauer and Cereceda (1989). The complete project by its natural complexity includes topics as diverse as microphysics of the fog, geographical, oceanographic and meteorological aspects. In this article only the meteorological part of the project is considered.

Project activities include continuous measurement of surface meteorological variables in the collection site using two automatic stations together with field experiments with intensive data gathering. Two experiments have been done so far in November 1987 and November 1988. On both opprotunities failures in the radiosonde system did not allowed to obtain moisture vertical profiles making impossible to evaluate moist conservative variables.

The site chosen for the experiment is an old iron mine, El Tofo (29°26'S; 71°15'W and 780 m above sea level), located at the top of a coastal range, distant 6 km from the shore, extending in a north-south direction with 1000 m summits at both ends. On the range east side there is a closed basin that communicates with the sea on its northern side trough a narrow creek. The regional rainfall is due to few frontal passages that occur during the cold season (from May to August) and on the average amounts to about 100 mm a year. Global solar radiation at ground level on clear days varies between a maximum over 1140 w/m2 in December to a minimum around 650 w/m2 in June. Most of the temperature variance is due to random changes in the surrounding air mass originated in vertical displacements of the trade wind inversion. These might be as large as 10 C in a few hours. Wind variation are mostly due to the sea breeze regime with strong westerly flow in the afternoon, typical summer values are 6 m/s between 17 and 19 local time decreasing to 2 m/s in the cold season. Nocturnal flows are weak easterlies, less than 2 m/s, that tend to be more persistent in winter.

From a meteorological point of view the basic problem is to understand the processes that control the presence and variability of the cloudiness along the coast in a regional and local scale and to asses the influence of other atmospheric variables on the water collection.

The presence of fog around the collectors depends on the height of the cloud, base and top, relative to the site altitude. The cloud top is dependant on the trade wind inversion height which in turn is determined by a balance between the entrainment of free air into the boundary layer and the large scale subsident motion. This balance is modified by mesoscale processes such as frontal passages, coastal lows and land-sea breezes. Away from the coast, the cloud base corresponds to the mixing condensation level in the marine boundary layer but close to the site is affected by the terrain to some extent. When the inversion base gets below the mixing condensation level the coast is clear and cloudiness, if any, can exist only around the terrain slopes.

When the cloud is present around a given collector, the water trapping depends on its liquid water content, the droplet size and the wind flow across the mesh. According to results reported in Nicholls (1984) the number of droplets in stratocumulus is almost independent of altitude but the liquid water content increases almost linearly with height up to almost the cloud top. This implies that the size of the droplets must increase in the same fashion as the liquid water content. From this point of view, water collection is favored by a thick cloud layer and a collector located somewhat under the cloud top.

Observations have shown that two major factors determining the water collection, although not the only ones, are the inversion base height and the wind speed perpendicular to the mesh. Both aspects will be considered in some detail according to the evidence gathered during the field experiments.

2. CLOUD TOP AND SYNOPTIC PHENOMENA

Both experiments were performed in the month of November. Therefore all results refer to springtime and cannot be considered as representative of the average annual conditions. Furthermore, November 1987 differ significantly from November 1988 in the region of interest. The first was substantially more baroclinic than the second. This can be seen by comparing the 500 hPa temperature between Antofagasta (24°S) and Quintero (33°S). Fig. 1 shows their variations along the first half of November 1987 and November 1988, respectively.

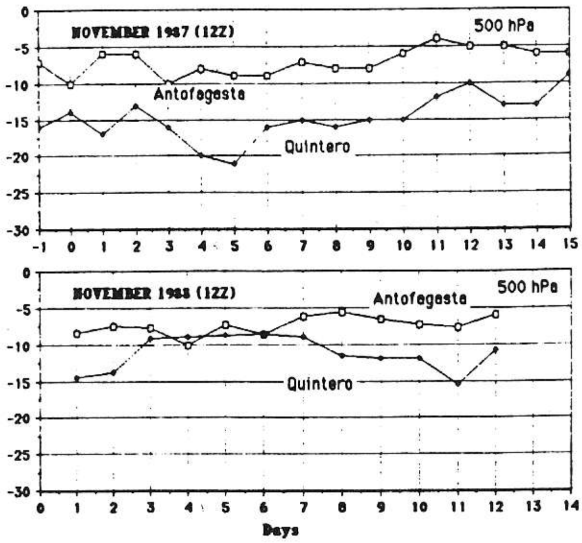

Fig. 1. Temperature in deg. C at 500 hPa for Quintero and Antofagasta: Nov. 1987 (upper) and Nov. 1988 (lower).

The cloud top follows closely variations of the base of the trade wind inversion. The importance of the height of the inversion base can be appreciated from Fig. 2 where its day to day variations are presented together with the daily total of collected water. The upper part corresponds to measurements at 09 and 15 local time over Chungungo during the first field experiment. The lower part portrays the observations done at the same local time 50 km offshore in the second experiment. In both cases the temperature profiles were determined with an airborne thermometer. In both opportunities significant collected volumes are obtained when the inversion height exceeds the site altitude (indicated by a horizontal line). Another feature to be noted is the asymmetry in the water collection for the importants events, the largest volumes are obtained in the first day with a high inversion, decreasing slowly afterwards. When the inversion is appreciably below the site altitude little if any water is trapped and when both altitudes are similar small amounts are recorded.

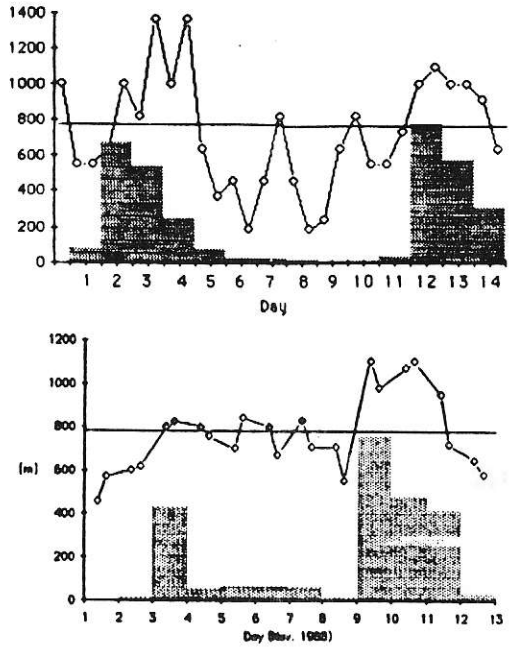

Fig. 2. Water yield in l/d from a 48 m2 collector and inversion height in m for Nov. 1987 (upper) and Nov. 1988 (lower).

Because the height of the trade wind inversion is determined by large scale and mesoscale systems, its behavior must be considered in relation to the synoptic conditions. For the second field experiment synoptic analysis for the low troposphere every six hours were graciously provided by the Numerical Meteorological Center, Washington, makin possible better control of the synoptic evolution.

According to Fig. 2 in each experiment there were two episodes when the inversion was lifted beyond El Tofo altitude producing significant water trapping. Two of these were associated with frontal conditions in the vicinity of the site: 2nd to 4th of November 1987 and 9th to 11th of November 1988. The other two episodes, 12th to 14th of November 1987 and 3rd of November 1988, were related to the northwest side of coastal depressions.

Properly speaking cold fronts are not observed in the region of El Tofo (30°S) in November. Surface observations immersed in the cold marine boundary layer do not show evidence of their passage, but temperatures measured at

1000 m or higher reveal a sudden thickening in the cold marine boundary layer. This is illustrated by Fig. 3 where the evolution of the potential temperature at 500, 1000, 1500 and 1800 m are presented for the first experiment. During the 2nd of November there is a fall in potential temperature that affects levels 1000, 1500 and 1800 m but not 500 m; afterwards the temperature recovers slowly.

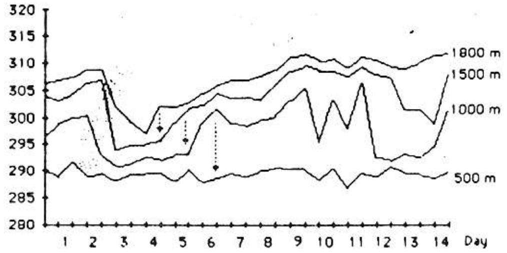

Fig. 3. Potential temperature variations at selected heights over Chungungo in Nov. 198

Fig. 4 shows a time-height cross section for potential temperatures during the second field work in November 1988. The isolines indicate a cooling between the 9th and the 11th day that affected a layer above 700. The warming occurs between the 11th and the 12th at about the same rate as the cooling. The NMC analysis indicate that this behavior was related to a cut-off low that approached the coast from the west, with its center at 40°S, between the 6th and the 9th. The northern side jet stream, that reached latitude 31°S, disappeared on the 11th with a subsequent collapse of the cold dome on the 12th.

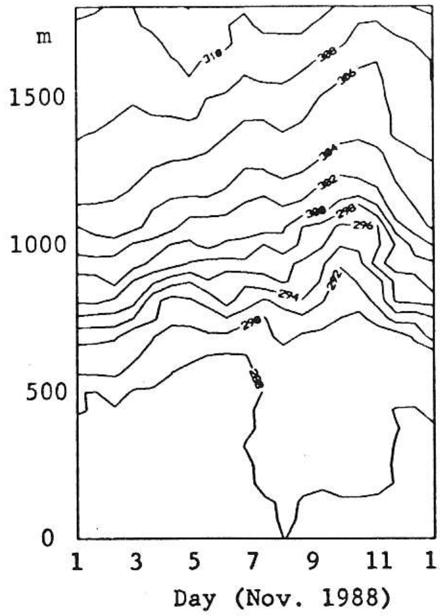

Fig. 4. Potential temperature variations 50 km offshore of Chungungo in Nov. 1988.

The second process that lifts the trade wind inversion is associated with coastal depressions. This kind of phenomena have been described by Gill (1977) for the South African coast, Rutllant (1983) for central Chile and Maas and Albright (1988) for the west coast of North America. As far as the inversion height is concerned the southward propagation of a coastal low first brings the inversion closer to the ground, on its southern side, and later, on its northern side, it lifts the inversion beyond its original altitude.

During the first field experiment a coastal depression passed over the site on the 9th of November,1987, (see Fig. 2). Between the 11th and the 12th the inversion was lifted beyond El Tofo altitude starting a three day episode of water collection. The 1988 field work started after a coastal low had crossed the site between the 31st of October and the 1st of November with the arrival of a warm ridge to the coast. Consequently the measurements begun with the inversion in the process of rising. On the 3rd it surpassed El Tofo altitude producing a one day event (Fig. 2). The following days, until the cold air mass mentioned above arrived on the 9th, the inversion base remained close to the site altitude with a very wide and ill defined ridge at 500 hPa.

Because along the coast of Chile, cold fronts propagate northwards and coastal lows do it in the opposite direction, further evidence discriminating between both mechanisms to lift the inversion at El Tofo (29.5°S) can be obtained from the radiosondes released at Antofagasta (24°S) and Quintero (33°S), located north and south of the site, respectively.

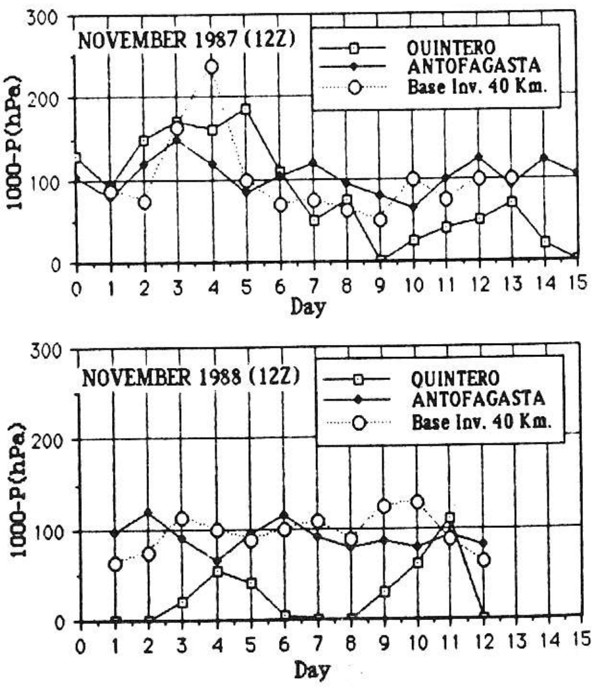

Fig. 5. Pressure variations of the inversion base at Quintero, Antofagasta and 50 km offshore of Chungungo for Nov. 1987 (upper) and Nov. 1988 (lower).

In Fig. 5 the pressure level for inversion base at Antofagasta, Quintero and 50 km offshore of El Tofo at 12 GMT are shown. The upper part refers to the first field experiment and the lower to the second. In the period comprised between the 1st and 7th of November, 1987, corresponding to a frontal passage, the inversion maximum height occurs first over Antofagasta (Nov. 3), next over El Tofo (Nov. 4) and then over Quintero (Nov. 5). The second frontal case occurred in November 1988, from the 9th to the 12th. In this case the frontal boundary was weaker and did not reach Antofagasta; the inversion rises almost simultaneously at Quintero and El Tofo and start descending at El Tofo one day before than at Quintero when the cold dome begun to subside. The case associated with a coastal depression in 1987, occurred in the last part of the field experiment, from the 9th to the 14th. The maximum height is reached on the 12th over Antofagasta and one day later over Quintero. At El Tofo the maximum height is attained the 12th in the afternoon, according to Fig. 2. The coastal depression occurring in the second experiment between the 1st and the 6th. The inversion peaks on the 2nd at Antofagasta, the 3rd over El Tofo and the 4th over Quintero.

Therefore, according to the evidence collected in the field experiments the occurrence of water collection episodes are determined by the frequency of cold air masses outbreaks and the passage of coastal depressions.

3. CLOUD BASE AND SEA SURFACE TEMPERATURE

Cloud base height offshore corresponds to the mixing condensation level and should be related to moisture and temperature conditions in the atmospheric boundary layer. These conditions are determined by turbulent fluxes of heat and moisture both at the surface and top of the boundary layer. These measurement requires instrumentation that was not available. The only related variable measured from the aircraft was the sea surface temperature. Therefore there was little control on processes determining the cloud base.

Fig. 6 shows the variations in the cloud top and base as determined from the flights 50 km offshore. The upper part corresponds to the first field experiment when observations were done once a day at 9 local time. The lower part belongs to the second experiment with determinations at 9 AM and 3 PM. Near the coast the cloud base can be quite different to that offshore, some days being at higher levels on others being lower. In the morning on unperturbed days, the cloud base was located around 400 m above sea level in the first experiment, while during most of the days in the second it was 100 to 200 m lower. In general, the cloud base was lifted from morning to the afternoon.

Part of the flights tracks were flown 100 m above the sea level measuring the sea surface temperature by means of a radiation thermometer (PRT-4) up to 50 km offshore. However, no clear correlation was found between the sea surface temperature and the cloud base height, probably due to the smallness of the area covered in the flights.

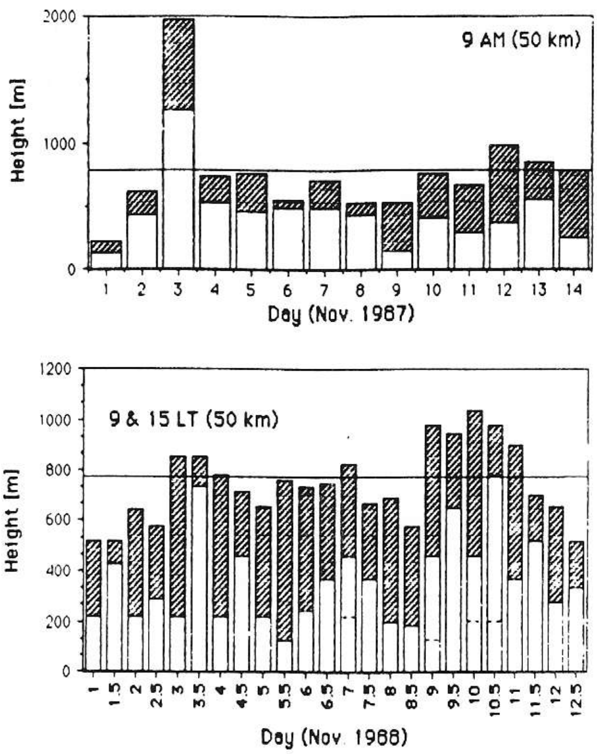

Fig. 6. Cloud layer variations for Nov. 1987 (upper) and Nov. 1988 (lower).

4. WATER COLLECTION AND WIND SPEED

In a local scale, once the cloud has set in, water collection must increase with the air flow across the mesh. The wind component normal to the collector presents a well defined diurnal cycle, Fig. 7, with a maximum at about 17 local time. However, water collection in the high sun season exhibits two maxima around this time of the day, Fig. 8.

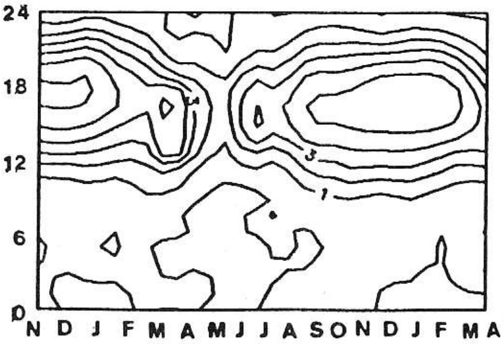

Fig. 7. Average daily variation of wind speed across the collector from Nov. 1987 to April 1989 in m/s.

When the water flow is correlated with wind speed a linear relation is clear up to 5 m/s, but not for stronger winds. A detailed study of this behavior was done selecting several days with strong winds.

Fig. 8. Average daily variation of water flow from a 48 m2 collector from Nov. 1987 to Apr. 1989 in cc/s.

Fig. 9 shows normalized curves for solar radiation, water flow and wind speed across the collector for a selected case (Dec. 26, 1987). Note that this day remained overcast but water collection was almost nil from 9 AM to 2 PM except for a short time around noon. Winds are from the west from 9 Am to midnight with a maximum speed of 8 m/s recorded around 4 PM. During the night there are weak east winds. In the early morning, when east winds prevailed, there was a good correlation between water flow and wind speed. A similar behavior occurred in the evening, after 18 local time, with west winds. However, between 9 AM and 6 PM, when the sea breeze blows strongly, the correlation does not exist. these variations can be interpreted as a consequence of the relatively strong radiation that by heating of the ground and the air decreases the size of the droplets and the liquid water content of the cloud beyond the values where the mesh is an effective trap. A similar effect can be produced by changes in the upstream cloud thickness by the sea breeze system bringing the top of the cloud closer to the collector.

An interesting feature also shown in Fig. 9 is the nocturnal variations of the wind and the water collection. In the first place, water collection was not expected to be significant with east winds. Instantaneous values are not large, but because of frequent occurrence on the monthly average it amounts to 20% of the daily maximum. Secondly, both variables show very regular oscillations before the sunrise with a periodicity of about 47 min. This value is similar to the period of transverse seiches in the basin to the east of the site. Therefore, it seems that during the night the basin is filled with the cool humid air from the marine boundary layer up to the inversion base height. Visual verification of this is given by the frequent early morning overcast conditions in the basin. The cloud over the basin disappears a few hours after sunrise. By night, katabatic drainage from the east slopes might excite the basin seiches that will approach El Tofo with regular time intervals.

4. FINAL REMARKS

According to the small sample obtained during the field experiments, at the experimental site, cloud cover variations are controlled mainly by coastal depressions and cold outbreaks. The latter lift the inversion. Coastal depressions bring clear skies in their souther flank, as they approach the inversion to the ground, followed by overcast conditions in their northern side when the inversion is lifted beyond its normal altitude. Faster variations of cloud behavior demand further research, for instance cloud base variations that can be very wide within a day. However, this fast changes must depend on turbulent fluxes which study need sophisticated instruments.

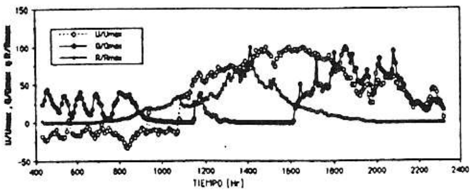

Fig. 9. Normalized wind speed U, water flow Q and solar radiation R for Dec. 26, 1987, between 4 AM and midnight.

5. ACKNOWLEDGMENTS

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