Fog: An Important Water Source in Arid Zones

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The Third European Conference on Sustainability, Energy & the Environment 2015
Official Conference Proceedings

Abstract
In semiarid and arid zones, fog is considered an important alternative water source. The southeast Pacific anticyclone, the cold Humboldt Current and the prominent coastal topography that characterize the north of Chile promotes the formation of low stratocumulus along the coastline. The thermally induced winds move these low clouds eastwards and, in the hills of the Coast Range higher than 600 m, persistent fog episodes can be observed.

The goal of this work was to characterize fog water collection and its relation with atmospheric variables. To achieve this, an experimental station equipped with a meteorological station and a Standard Fog Collector (SFC) was installed in El Sarco, a coastal hill located in the semiarid area of Chile known as Norte Chico. Near the station, a large fog collector of 150 m^2 designed by an engineer team in Chile was installed. The collected water was used to restore a selected area with relict vegetation.

We found that the wind regime was compatible with a land-sea circulation, where the wind speed was stronger during the day than at night. Fog water (FW) collection increased with wind speed and occurred when the wind came from the ocean, as well as when it came from the opposite direction. The shape of the diurnal cycle of the mean FW collection was dependent on the season, and on average, it had two maximum peaks at 07:00 LT and 20:00 LT. The daily average per month ranged between 1.7 l day^{-1} and 5.0 l day^{-1} and occurred in August and January, respectively.

Keywords: fog water collection, meteorology, arid zones

Introduction

Because of its influence on human life, fog has been the focus of many scientific studies. On the one hand, it represents a hazard to air, road and marine traffic with significant economic loss, but on the other hand, fog is an important hydrological resource for replenishing aquifers, for promoting reforestation and for human needs (Gultepe et al., 2007, Möller D., 2008, Klemm et al., 2012). However, the intensive study of fog, as well as its formation and dynamics, are complex processes that require further understanding.

Many studies and field experiments have demonstrated that the coast of South America exhibits geographical and topographical characteristics that make it suitable for the presence of fog most of the year. The interaction between the Humbolt current and the Southeast Pacific anticyclone favors the presence of well-formed stratocumulus clouds (Sc) that are transported inland by the trade winds and a sea-breeze circulation. When these clouds intercept the coastal topography, advection fog events can be observed. Furthermore, when air rich in humidity is forced by the wind to rise to the prominent relief of the Coast Range, the air cools and promotes the formation of orographic fogs (Garreaud et al., 2008).

Fog water (FW) is a sustainable water resource for reforestation and human needs (Domen et al., 2014). During the last century, experiments to measure FW collection have been performed in many places around the world using various prototypes of mainly different kinds of mesh. For example, in Lanai (Hawaii), several hundreds of Norfolk Pine trees were planted in the mountain summits to collect fog water and replenish aquifers (Olivier, 2004).

Chile is a pioneer in using fog to obtain fresh water for human needs. In 1992, a system of 100 large fog collectors (LFG) were installed in El Tofo, a hill of 700 m altitude located in the Coastal Range of the semi-arid Coquimbo Region in Chile. The water harvested from fog was used to provide fresh water to Chungungo, a fishing village with 300 inhabitants. During more than 8 years, fog was the only water source for this village.

This experience has been replicated in different parts of the world where water is scarce and the occurrence of fog events happen often enough to make the collection of fog water convenient (Cereceda et al., 2003; Marzol, 2008; Marzol & Sanchez, 2008; Marzol, 2010; Oliver 2004; Oliver & Rautenbach, 2002, 2007; Oliver et al., 2012; Schemenauer et al., 1987, 1988, 2004; Cereceda & Schemenauer, 1991; Schemenauer & Cereceda, 2013). Currently, Morocco and Guatemala are communities in which the only water source is from fog collected by LFC. The location of sites where fog has been or is actually used as a fresh water source can be found in Klemm et al., 2012.

Fog is defined as a cloud that touches the Earth´s surface leading to a reduction in visibility less than 1 km (Fessehaye et al., 2014). With regards to visibility, fog can be characterized as dense, thick, moderate and light which pertains to ranges of 40 - 70 m, 10 – 250 m, 250 – 500 m and 500 – 1000 m, respectively (Awan et al., 2009).

Technologies to collect fog water are simple. The working principle is to expose a mesh to a foggy environment. Water droplets carried by the wind are pushed through the mesh where they condense. With successive impacts, the droplets grow until they are large enough to fall by gravity and the water can be collected (Klemm et al., 2012).

The quantity of water that can be collected from fog is measured by a Standard Fog Collector (SFC), a square Raschel mesh with an area of 1 m^2 that is installed 2 m above ground level (agl) (Schemenauer and Cereceda, 1994). This system allows the comparison of potential FW collection in different sites.

Experiences carried out in different parts of the world show that it is possible to collect considerable quantities of water by artificial devices or Large Fog Collectors (LFC) (Schemenauer et al., 1987, 1988; Cereceda et al., 2003; Schemenauer & Cereceda, 1991; Klemm et al., 2012, Marzol et al., 2008; Marzol, 2010; Olivier et al., 2004, 2012).

The collection of FW depends not only on the presence of fog, but also on meteorological variables such as wind direction, relative humidity, dew point depression, and most importantly, wind speed (Hiatt et al., 2012, Caceres et al. 2007). Other factors that influence FW collection are the orientation of the mesh and its collection efficiency.

In this paper, we analyze the relationship between FW collected by a SFC and meteorological variables. The study was based on results obtained from an experimental station located in the Coastal range 15 km south of El Tofo where the first successful project was performed in Chile.

Study site

The study site was located on a hill called El Sarco (29.51ºS, 71.27º W and 700 m altitude) in the Coast Range of the semi-arid Coquimbo Region in Chile, 7 km from the coast, 43 km north of the city La Serena, the main city of the region (Figure 1).

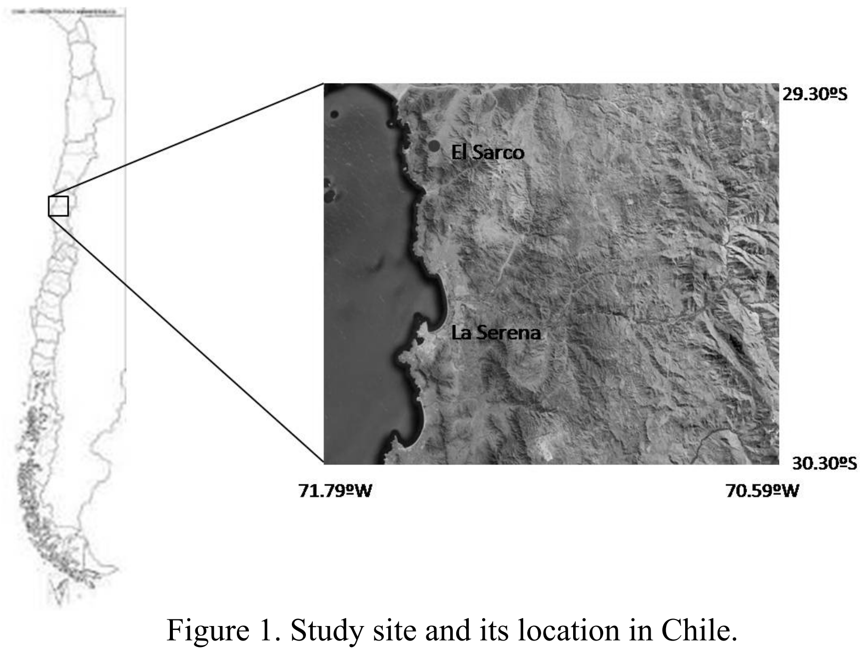

Figure 1. Study site and its location in Chile.

The climatic characteristics are influenced by the cold Humboldt Current which moves northwards along the Chilean coast and the southeast Pacific high pressure area that produces a light southerly wind. The site is a saddle point of two mountains of around 1000 m altitude forcing the moist air masses coming from the sea to converge, increasing the probability of the occurrence of fog events.

Experimental design

The experimental station, shown in figure 2, consisted of a Campbell meteorological station equipped with sensors for wind speed, wind direction, temperature and relative humidity (RH) at 2.5 m and 10 m above ground level (agl), and a rain gauge. Near the meteorological station, a SFC oriented in a SW direction (230°) was installed. The water collected by the SFC was measured by a second rain gauge. Both meteorological data and water collected were registered each 3 seconds and stored each 10 minutes.

Figure 2. Experimental station. Left: meteorological station and SFC. Right: Large Fog Collector

Near the experimental station, a LFC of 150 m^2 area designed by an engineer team in Chile was installed. The water harvested from fog was used to restore an area with relict vegetation.

The results presented in this work are from data collected for one year from June 18, 2014 until June 17, 2015. For the purposes of this article, only meteorological variables registered at 2.5 m agl were analyzed.

Results

Air temperature and humidity

Both temperature and RH experiments demonstrated important day to day variations. If fog was present, the RH achieved near saturation values and the amplitude of the diurnal cycle of temperature was small. The higher variations in temperature occurred in winter where the minimum and maximum temperatures were reached. The lowest and highest temperature at 10 minute averages were 29.6° C and 3.74° C achieved on the 17th of August at 10:30 LT and the 1st of July at 04:40 LT, respectively.

The high fluctuations in temperature in the winter time can be observed in figure 3, where the mean daily and monthly temperatures are shown. The minimum and maximum mean daily temperatures were 6.7° C and 25.6° C achieved in July and August, respectively.

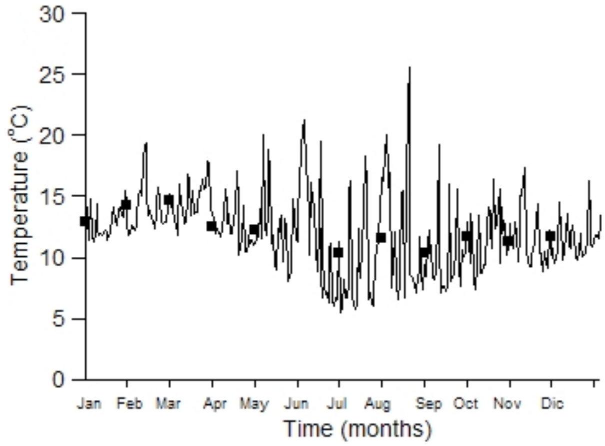

Figure 3. Daily (solid line) and monthly (squares) average temperatures.

The monthly temperature average demonstrated small variations during the year. The values ranged between 10.4° C, reached in July and September, and 11.7° C observed in October and December.
The behavior of RH was opposite to the temperature. It ranged between 5% and near saturation values. The minimum and maximum mean monthly averages were 70.6% and 92.2% obtained in August and April, respectively (not shown).

Wind speed and direction

The wind characteristics of the site were compatible with a land-sea circulation. During the day, the wind blew from the land to the sea (S-W) and at night it blew in the opposite direction (N-E). The wind direction distribution shown in figure 4 reveals that there are two predominant wind directions corresponding to the day and night winds.

The wind speed ranged between calm and 13.1 m s^{-1} stronger during the daytime than at night. The higher fluctuations in wind speed occurred during the winter months of June, July, and August (Figure 4). The monthly wind speed average exhibited small variations during the year. The minimum monthly averages was 2.9 m s^{-1} achieved in in July and August, and the maximum one was 3.9 m s^{-1} reached in December.

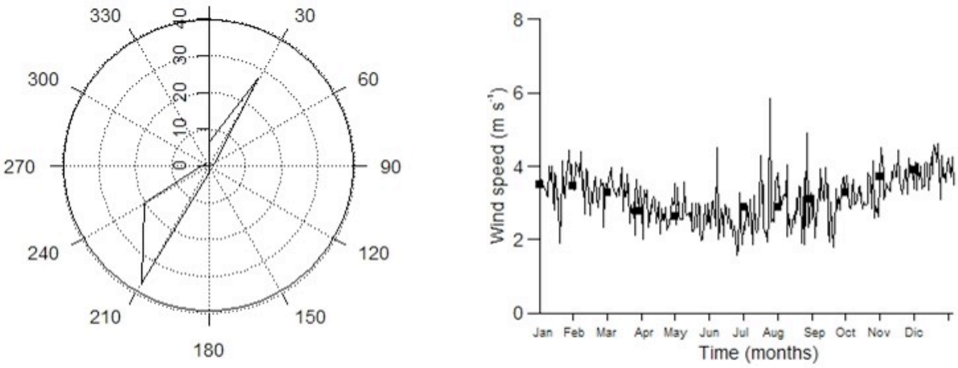

Figure 4. Left: Wind direction distribution. The labels are in degrees and indicates where the wind is blowing from. Right: daily (solid line) and monthly (squares) wind speed average.

Water collected by the SFC

In order to analyze the water collected (WC) from fog and its relation with meteorological parameters, meteorological data were averaged at 1 hour intervals. In the case of FW collected, the accumulated value in the same period was calculated.

We found that the maximum FW collection was 4.2 L m^{-2} h^{-1} and occurred on July 22 at 090:0 LT during a precipitation event. Regarding precipitations, the highest harvest of fog water was 2.6 L m^{-2} h^{-1} and occurred on September 21 at 18:00 LT.

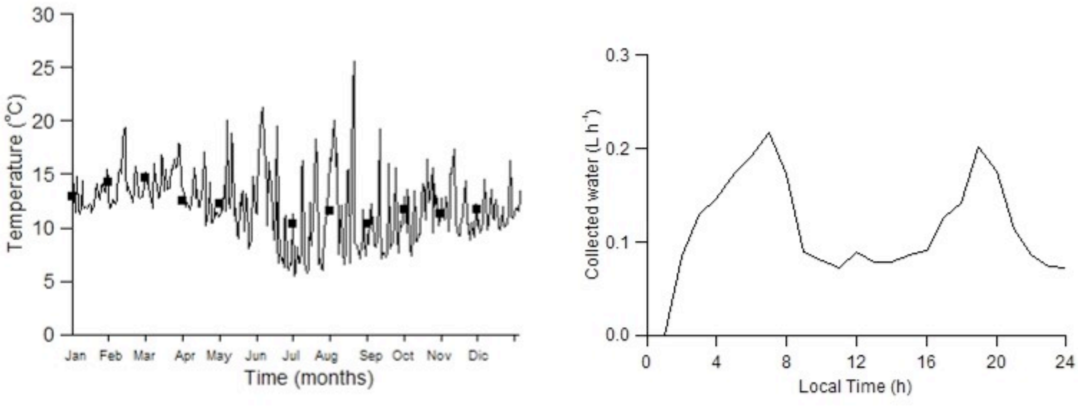

Figure 5. Water collected by the SFC. Left: one day intervals (solid line) and monthly daily average. Right: mean diurnal cycle in a one-year period.

Figure 5 displays the daily and the daily monthly average of water collected by the SFC. We found that the mean daily FW collected was 2.7 L m^{-2} day^{-1}. The maximum daily FW collected was 19.5 L m^{-2} day^{-1} on July 22 during the precipitation event mentioned above. Excluding this value, the highest collection was 16.0 L m^{-2} day^{-1} and occurred on October 8. The monthly daily FW collection was higher in the summer than in winter. The months with the lowest and highest FW collection were August and January with 1.7 L m^{-2} day^{-1} and 5.0 L day^{-1}, respectively.

The mean diurnal cycle of FW collected by the SFC showed two maximum peaks at 07:00 and 20:00 LT, with values of 0.23 L m^{-2} h^{-1} and 0.20 L m^{-2} h^{-1}, respectively (Figure 5). During 09:00 LT and 16:00, the mean water harvest from fog was approximately constant and equal to around 0.08 L m^{-2} h^{-1}.

Fog water collection and meteorological variables

Figure 6 displays the relation between FW collection and wind velocity (speed and direction). We found that the FW collection increased with wind speed, which can be explained because the liquid water flow incident on the mesh increases with wind speed. The right panel in figure 6 shows that FW collection occurred with both S-W winds, when the wind blew inland from the Pacific Ocean, and with N-E winds, when the wind blew in the opposite direction.

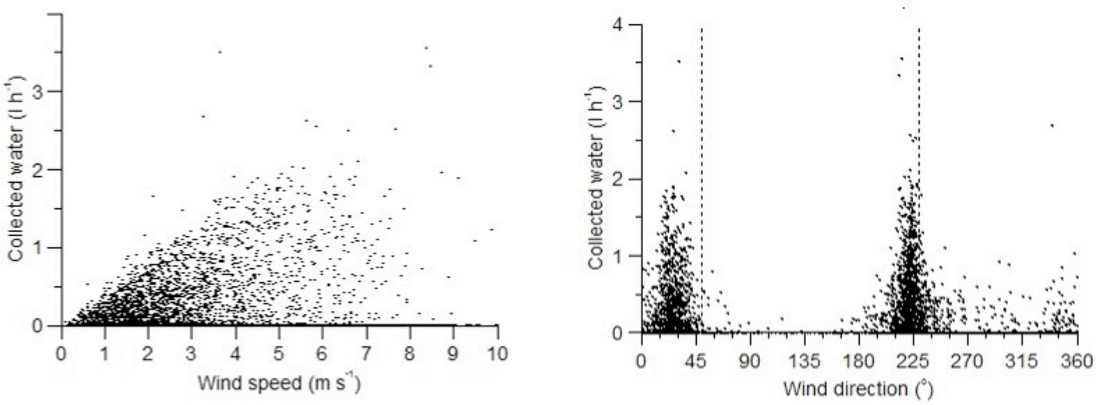

Figure 6. Relation between water collection and wind speed (left) and wind direction (right). The vertical dashed lines represent the orientation of the mesh

Summary and discussion

In this paper we analyzed FW collected by an SFC and its relation with meteorological conditions.

The principal findings were:

- There are variations in FW collection during the year. In the summer when water is normally scarcer, WC is higher than during the winter months. The daily monthly average ranged between 0.7 L m^{-2} day^{-1} and 5.0 L day^{-1} obtained in August and January, respectively. On average, the FW collection was 2.7 L m^{-2} day^{-1}.

- The highest fluctuations in temperature and RH occurred in the winter and autumn months. During fog events, the RH remained near saturation values, whereas the temperature stayed approximately constant.

- The wind behavior was compatible with land-sea circulation. During the day, the wind blew from the southwest in the direction from the ocean to inland, and during the night it blew in the opposite direction.

- FW collection increased with wind speed. This fact can be explained because more water droplets condense onto the mesh when there is more wind.

- FW collection occurred when the wind was coming from both the ocean (southwest direction) and the opposite direction (northeast).

Finally, we would like to emphasize that if the mean FW collected in El Sarco was 2.7 L m^{-2} day^{-1}, the quantity of water that could be harvested from fog using an LFC of 150 m^{-2} area similar to the one installed in our experimental site, would be almost 400 L day^{-1}. A system of several ATN would have the capacity to harvest a large quantity of water to be used for different purposes. Therefore, the results from our study confirm that fog represents a sustainable water resource.

Acknowledgments

This research was funded by Project Dominga of Andes Iron, SpA, and it is attached to the Plan de Mejoramiento Institucional en Eficiencia Energética y Sustentabilidad Ambiental ULS-1401.

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