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/m²/day in the southern locations, in contrast to 2.0 l/m²/day collected at one site in a northern location. The highest summer fog water yield was 4.6 l/m²/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.

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...
Mediterranean Sea to the mountain ranges near the coast. There are other situations in which isolated summits are repeatedly covered by clouds, causing the formation of orographic fog. On the other hand, radiation fog is of little interest in this study due to its poor collection efficiency by means of passive collectors. In addition, it normally occurs under calm conditions and on lowlands.

The present study aims to quantify and relate fog water collection to the geographic and meteorological conditions at several mountain locations on the east coast of the Iberian Peninsula. It was decided to use passive fog water collectors since they are simple, economic and reliable. Among the passive devices, a cylindrical string collector, based on the work of Falconer and Falconer (1980), was selected instead of the flat-panel standard fog collector (SFC) described in Schemenauer and Cereceda (1994b). This was due to the fact that cylindrical fog collectors act as omnidirectional devices, i.e., being independent of the orientation they have a uniform exposure to winds from all directions. SFCs also collect fog with winds from all directions but their efficiency is decreased when the wind is parallel to the panel surface. A discussion on the advantages and disadvantages of SFCs versus cylindrical fog collectors can be found in Juvik and Nullet (1995) and Schemenauer and Cereceda (1995). SFCs are more appropriate for locations where the prevailing winds carrying fog are already documented or can be ascertained by means of certain terrain features. This study analyses the prevailing winds and how they relate to fog water collection without concern to sensor orientation.

2. Background: geographical and meteorological settings

The Valencia region is located on the east coast of the Iberian Peninsula, and constitutes the western boundary of the Mediterranean basin (Fig. 1). It is characterised by a very complex orography, with narrow coastal plains especially in its northern and southern sections. Most of the high terrain ends at the coastal plains and forms pronounced slopes and ridges, in some cases exceeding 500 m difference in height. Of note is the mountain range in the south—east, which stretches out to the sea and ends at the Cape of San Antonio. The highest peak inland is Peñagolosa at 1815 m a.s.l., located in the northern part of the Valencia region 40 km from the coastline. The

Fig. 1. The Valencia region, some of its geographic features and the four pilot sites.
second highest peak (Aitana, 1558 m a.s.l.) is situated in the southern part 15 km from the coast.

The Valencia region is known for its fine and warm weather that prevails most of the year. Mean winter temperatures are between 4 and 11 °C, with a positive gradient from north to south and from the inland to the coast. Mean summer temperatures are between 20 and 26 °C, with the warmest areas being the inland lowlands (Diago and Recatalá, 1994). The climate of the region is semi-arid with an average annual precipitation between 300 and 500 mm. The extreme southern part, with its coastline-facing the south–east, is the most arid part of the region with an annual precipitation below 300 mm (Peñarrocha, 1990, 1994). There are two wet areas with precipitation above 800 mm: one extends south of the city of Valencia to the mountain range in the south–east, and the other is located at the northwestern edge of the territory. Precipitation in the Valencia region can be described on the basis of its meteorological origin (Millán et al., 2005). Atlantic depressions normally yield low precipitation at the coast. Convective summer storms are generated by sea breeze/upslope winds in the presence of colder air aloft; they leave significant precipitation amounts on the east side of the coastal mountains. Finally, torrential rainfall due to Mediterranean cyclogenesis can occur in late summer and autumn. Mixed situations of the above precipitation sources are also present.

3. Data and methods

3.1. Pilot sites and instrumentation

Bearing in mind the above climatic considerations, four different mountainous locations were selected in the Valencia region on the basis of their north-to-south geographical distribution and their coastal or inland situation (see Fig. 1):

- Mt. Bartolo, the northernmost site with an altitude of 736 m a.s.l., is a ridge with a long crest line and is only 6 km from the coastline.
- Mt. Moduver, in the south-central part, is an isolated and almost pyramidal mountain 843 m high and only 7 km inland from the coast.
- Mt. Montgo, the southernmost site with an altitude of 670 m a.s.l., stands alone as a massive rock in the vicinity of the Cape of San Antonio 4 km from the nearest coastline.
- Mt. Peñarroya, the interior site at 1193 m a.s.l. and 50 km inland, is a distinctive cliff that drops approximately 400 m within 4 km, constituting the apex of a valley that leads perpendicularly to the coastline.

Fog water volumes were sampled using a handmade cylindrical fog collector that was based on Falconer and Falconer (1980), and particularly on the ASRC (Atmospheric Science Research Center, State University of New York) string collector (Fig. 2). It consists of a cylinder, 26 cm in diameter and 46 cm in height, strung with five concentric rows of 0.8 mm thick nylon line. In all, 1000 vertically oriented and closely spaced strings were arranged on a cylindrical polyamide frame, resulting in an effective collection surface of 0.12 m² (diameter times height). Collection efficiency does not depend on the wind direction because of the cylindrical design of the device. Additionally, a round polypropylene tray of approximately 60 cm in diameter acted as a rain shield on top of the collector. To prevent disruption of the fog water collection, rain water was drained from the shield through a central hole connected to a hose. It must be said that the prevention of rain water reaching fog water volume samples is not perfect. Rain drop trajectories are wind-driven, hence the greater the wind speed, the more likely that rain drops can enter the fog collector.

The fog water collection process of the above device is simple. Fog droplets carried by the wind are intercepted on the vertical nylon strings, form larger drops and then run down the strings. Water accumulates onto a collector base that is shaped like a funnel and then drains through six concentric holes into silicone tubing. This tubing connects the drainage holes to an enclosure containing a tipping bucket raingauge for water volume sampling (see Fig. 2). The collected fog water volume per unit area (l/m²) comes from dividing the collected volume by the effective collection surface of the collector. The cylindrical collector is mounted on top of a 3-m galvanised steel mast that is properly fixed to the ground at its base. Three additional steel cables anchor the ensemble to the ground.

More meteorological instruments were also appended to the erected mast at different heights; a Davis Instruments integrated vane–anemometer (Model 7914) at 3 m, two Davis Instruments magnetic-reed-switch tipping bucket rainfall gauges (Model 7856, 0.2 mm resolution)—one used for precipitation measurements and the other for fog sampling—, four Campbell wetness-sensing flat grids (Model 237F), and finally a Vaisala temperature and relative humidity probe (Model 50Y) at 2 m. Automatic data acquisition was done by a Campbell CR510 data logger. The stored data was transmitted by a GMS communication modem once a day. Sensor sampling was performed at 6-s intervals in the case of the wind sensor and the tipping buckets, and at 1-min intervals for the other instruments. Data were recorded as
10-min averages of the sampling measurements and sent to a central receiving station.

3.2. Data measurements

Results presented here correspond to a 1-year period (2004), so they should be considered provisional; more data will be gathered and processed in subsequent years. Data from the meteorological instruments greatly complemented the fog water samples. Some of the data could be validated by comparing responses from different sensors. Also, calibration of the tipping bucket raingauges used for rainfall and fog measurements was carried out by the authors, thus providing quality data on the yielded volumes.

As indicated by Schemenauer and Cereceda (1994c, 1995), simultaneous fog and rainfall values are very hard to separate, especially if a passive collector is being used. In the data set presented here, a large number of fog events also showed the presence of rainfall. This vertical precipitation could be in the form of rain with differing intensities, or just drizzle, and it could be present during, after and/or before the fog event. Schemenauer and Cereceda (1995) suggest that the best approach is to make use of a simple, even unshielded, passive collector and concurrently measure the presence of rainfall by means of a raingauge. This approach then provides horizontal precipitation volumes as collected by a passive collector in comparison with recorded rainfall volumes. In some studies, collected fog volumes are defined more narrowly to minimise contamination by rainfall by means of corrected ratios or some kind of data filtering that uses rainfall values (Juvik, 1998; Olivier and Rautenbach, 2002). In this study, horizontal precipitation volumes as directly collected by the passive collector are simply referred to as cloud water yields since their origin comes from clouds containing both fog and rain. Despite the above limitations, a technique was also developed here to try to remove the rain component that may be included in the fog samples. The technique, explained below, was then assumed as a data reduction routine for fog measurements and provided an estimated fog yield without the rain water contribution. Obviously, if no rainfall was recorded, fog data reduction was unnecessary since all the water collected originated from fog alone. Therefore, rectified water volumes are referred to hereafter simply as fog water yields, since they represent only the contribution from fog in a passive

Fig. 2. Integrated system for fog water collection and meteorological measurements.
collector. Both cloud water and fog water yields were computed, rainfall yields, and daily and seasonal values were calculated.

3.3. A fog data-reduction technique: removal of the rainfall component

This technique is aimed at removing the rain water component that may eventually enter the collector. The reduction technique was established from data that were known to come from rainfall episodes alone, thus rendering false fog samples. Samples of this kind were particularly observed in the Mt. Peñaroya data set when the wind blew from the north–west, a well-known condition at this specific location for the Atlantic frontal depressions that produce rainfall alone. If fog and rainfall samples are plotted versus wind velocity, a distinctive pattern can be seen for points under this particular condition (see Fig. 3). Fig. 3 represents a two-dimensional plot with velocity on the horizontal axis and an index that combines fog and rainfall samples on the vertical axis. This index can be called a normalised volume index, NVI, and can be defined by the following expression:

\[
\text{NVI} = \frac{F - r}{F + r} \tag{1}
\]

where \(F\) is the fog water volume as sampled by the fog collector, and \(r\) is the rainfall water volume collected by the raingauge.

The NVI index will take a value for each of the events where both rainfall and fog measurements were registered simultaneously, ranging from \(-1\) to \(+1\). Rainwater volume that enters the passive collector must be a function of rainfall and wind velocity. The following proposed relation was assumed:

\[
r' = r \times g(V) \tag{2}
\]

where \(r'\) is the rainwater contribution volume, i.e., the amount of rainfall that enters the passive collector, \(r\) is the rainfall water volume collected by the raingauge, and \(g(V)\) is a function to be determined, which depends on wind velocity \(V\).

Therefore, subtracting the rainwater contribution volume, \(r'\), from the fog water sample, \(F\), will yield the actual fog water volume, \(f\), i.e., the fog water yield. This is the data reduction technique for fog measurements that was applied in the study:

\[
f = F - r' = F - r \times g(V) \tag{3}
\]

The question is how function \(g(V)\) can be determined. Working out the value of \(F\) from Eq. (1), we obtain:

\[
F = \frac{1 + \text{NVI}}{1 - \text{NVI}} \times r \tag{4}
\]

For the specific events in which only rainfall is present, the rainwater contribution volume, if any, must coincide with the sampled fog water volume, thus:

\[
F_0 = r' \tag{5}
\]

where \(F_0\) is the sampled fog water volume when only rainfall is present, i.e., \(f=0\).

Fig. 3. Normalised volume indexes for the Mt. Peñaroya data set. Triangle icons represent the indexes for the rain-alone data. The line is the regression curve fitted to those particular indexes.
The assumption in the last equation is that the rainwater contribution volume does not depend on the amount of fog that is present; thus, it follows that the same applies when rainfall occurs with no fog. Substituting the left part of Eq. (5) with Eq. (4) and the right part with Eq. (2), and finally removing redundant factors, an expression is obtained for the function \(g(V)\):

\[
g(V) = \frac{1 + NVI_0}{1 - NVI_0}
\]

where \(NVI_0\) is the normalised volume index when only rainfall is present, i.e., \(f=0\).

A curve regression of \(NVI_0\) versus wind velocity, \(V\) (m/s), leads to the following expression (see Fig. 3):

\[
NVI_0 = 0.52 - \frac{4.65}{V}
\]

The root mean square (rms) error obtained for the above equation was 0.2. The function \(g(V)\) can now be obtained by a simple substitution of Eq. (7) into Eq. (6). Using Eq. (3), data reduction can be performed on all fog samples thus rendering an estimation of the fog water yields. If the datum reduction generates a negative number, the fog water yield is considered to be zero.

The importance of this fog data-reduction technique becomes clear if a comparison is made between recorded rainfall levels and horizontal precipitation, i.e. cloud water yields. In this case, knowing the contribution of the wind-blown rain in the collector to ascertain rectified fog water yields is always interesting. The reduction technique is based on a parameterisation that is specific for the instrument ensemble presented in the study. The methodology for its retrieval can be widely exportable to other similar configurations featuring a cylindrical passive collector with a circular rain shield on top; nevertheless, direct application of the parameterisation values found is not advised unless the configurations are identical. The rain water contribution in the initial fog sample is assumed to be given by Eq. (2). Due to the limited number of fitting data, function \(g(V)\) was supposed to depend only on wind velocity. However, it is obvious that small rain drops would increase this contribution as well. In fact, the fit data dispersion in Fig. 3 may be explained by this effect. Nevertheless, all the dispersion is included as an error associated with the parameterisation found here. A more refined technique could take into account this raindrop size dependence and therefore reduce the associated errors.

4. Results

4.1. Seasonal water volume yields

Table 1 shows the seasonal rates obtained as the ratio of total water collection volumes to the length in days of each of the periods. No data were available for the Mt. Peñaroya site during winter since the station was not operative in that period. Total annual rainfall volumes for the Mt. Bartolo (643 mm), Mt. Monduver (1046 mm) and Mt. Montgo (1146 mm) sites were contrasted with data from neighbouring meteorological stations located in lowlands. In spite of the difference in height, the agreement between neighbouring locations was reasonable, with differences no greater than 25%.

The comparison in Table 1 between fog and cloud water yields shows larger differences between them for spring and autumn than for winter or summer. As the smallest values for rainfall are observed during winter

<table>
<thead>
<tr>
<th>Station</th>
<th>Yield type</th>
<th>Autumn</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Bartolo</td>
<td>Rainfall (mm/day)</td>
<td>1.0</td>
<td>0.9</td>
<td>4.5</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Cloud water (l/m²/day)</td>
<td>1.3</td>
<td>1.9</td>
<td>5.3</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Fog water (l/m²/day)</td>
<td>1.1 (0.1)</td>
<td>1.7 (0.1)</td>
<td>3.8 (0.9)</td>
<td>1.4 (0.0)</td>
<td>2.0 (0.3)</td>
</tr>
<tr>
<td>Mt. Monduver</td>
<td>Rainfall (mm/day)</td>
<td>3.6</td>
<td>1.9</td>
<td>5.5</td>
<td>0.4</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Cloud water (l/m²/day)</td>
<td>13.0</td>
<td>7.5</td>
<td>13.9</td>
<td>1.6</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>Fog water (l/m²/day)</td>
<td>10.3 (1.3)</td>
<td>6.6 (0.5)</td>
<td>10.8 (1.5)</td>
<td>1.6 (0.0)</td>
<td>7.3 (0.8)</td>
</tr>
<tr>
<td>Mt. Montgo</td>
<td>Rainfall (mm/day)</td>
<td>5.5</td>
<td>1.1</td>
<td>5.7</td>
<td>0.2</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Cloud water (l/m²/day)</td>
<td>11.0</td>
<td>7.5</td>
<td>11.9</td>
<td>4.7</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>Fog water (l/m²/day)</td>
<td>7.7 (1.4)</td>
<td>7.0 (0.2)</td>
<td>8.9 (1.5)</td>
<td>4.6 (0.1)</td>
<td>7.9 (0.8)</td>
</tr>
<tr>
<td>Mt. Peñaroya</td>
<td>Rainfall (mm/day)</td>
<td>1.3</td>
<td>–</td>
<td>4.6</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Cloud water (l/m²/day)</td>
<td>3.0</td>
<td>–</td>
<td>7.7</td>
<td>3.1</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Fog water (l/m²/day)</td>
<td>2.2 (0.2)</td>
<td>–</td>
<td>3.8 (0.8)</td>
<td>2.5 (0.2)</td>
<td>2.9 (0.4)</td>
</tr>
</tbody>
</table>

Water volume rates correspond to rainfall, cloud water yield and fog water yield according to the description in Section 3.2. Values in parenthesis are the absolute errors given by the uncertainties associated to the fog data-reduction technique.
and summer, cloud water yields for these periods must come mostly from fog contribution, with the rain water contribution representing only a small amount. Conversely, clouds intercepted during autumn and spring, which come basically from frontal systems, generate a significant amount of both rainfall and fog. Thus our

Fig. 4. Percentage of days for which there was at least one event of fog alone, rainfall and fog, or rainfall alone that led to water collection. Numbers at right of each bar indicate the seasonal rates of fog water yield (l/m²/day) split into two separate values on the basis of fog alone and rainfall-and-fog.

Fig. 5. Time lengths in hours and associated collection rates in l/m²/h for each of the fog episodes that delivered a continuous fog water yield. The scales are logarithmic.
The proposed data-reduction technique works selectively without any major problems for each of the seasonal periods that feature distinctive fog and rainfall patterns.

Based on the magnitude of the values shown in Table 1, a site classification can be made: a northern segment consisting of Mt. Bartolo and Mt. Peñaroya, and a southern segment formed by Mt. Monduver and Mt. Montgo. Rainfall shows values of the same order in both segments, although the smallest amounts correspond to the north. Nevertheless, there is a large difference in the cloud water and fog water yields between the two groups. With regard to the southern segment, spring and then autumn are the annual periods with the largest cloud water and fog water yields. In particular, Mt. Montgo always shows relatively high amounts of fog water yield for all four annual seasons. In the summer period, Mt. Montgo has the largest fog water yield of the four sites, contrasting with its rainfall rate for the same period, which is the lowest.

### 4.2. Seasonal percentage of days with water collection

Fig. 4 shows seasonal frequencies of water collecting days for the four pilot sites in the study. The four categories in the graph represent the seasonal percentage of days that presented at least one episode of fog alone, rainfall and fog, rainfall alone or no water collection at all. The numbers at the right of each bar indicate the seasonal rates of the fog water yields collected for each of the two types of fog occurrence: fog alone or rainfall and fog. Explicitly, each pair of numbers on each of the bars correspond to the splitting of the seasonal fog water yields in Table 1 into the separate episodes of fog alone and rainfall and fog. For instance, in autumn at Mt. Peñaroya, Fig. 4 indicates that 23% of the days yielded fog water collection alone, 27% of the days presented both fog and rainfall collection that could be concurrent or not, only 5% of the days delivered rain water alone and the rest (45%) of the days did not provide any kind of water collection. Fog water yields were 0.4 l/m²/day for the number of days with fog collection alone and 1.9 l/m²/day for the number of days with collection of both rainfall and fog.

As Fig. 4 shows, the seasonal frequency of fog alone is dominated by summer with a day percentage of 30% at the four pilot sites, except for Mt. Bartolo where it is 40%. Fog water yields in this period were also the annual highest when fog was present alone, with values being around 0.6 l/m²/day, except for Mt. Montgo where they reached the annual fog alone geographical maximum (1.1 l/m²/day). On the other hand, the seasonal frequency of rainfall and fog is dominated by spring and/or autumn depending on the site, with values around 30 to 40%. Spring is the period with the largest seasonal fog water yields. It appears that it is during winter when the smallest seasonal frequencies of days with fog collection occur. With regard to days with episodes of rainfall alone, their seasonal frequencies are minimal, except for autumn at Mt. Montgo, which was probably due to the isolated malfunctioning of the fog tipping bucket observed in that particular period.

Summing up, the fog events with the highest fog water yields mostly correspond to the days with rainfall episodes. Nevertheless, days with only fog episodes are not rare and show seasonal frequencies of around 10 to 20%; their associated fog water yields are minimal though in comparison with the former. It is during summer that this tendency is broken, as the values for fog water yield that are obtained during days with fog alone and days with rainfall and fog are more comparable. Some kind of fog water collection occurs on at least 30% of the days in the worst case and around 60% at best.

### 4.3. Quantifying fog episodes

Time lengths of the individual fog events generating water yields were obtained for the entire data set.
irrespective of any possible rainfall episode. Their associated fog water collection rates, in l/m²/h, were also calculated, as the ratio of the fog water yields to the time duration in hours. Fig. 5 shows time length against collection rate for each of the individual fog episodes at each of the four pilot sites. The resulting cluster of points roughly indicates that the higher the time length of a fog episode, the larger the fog water collection rate will be. It contains all fog data available in the study but grouped into their respective fog events, i.e. the periods of continuous fog water collection. A logarithmic scale is needed to allow each of the different events with their particular characteristics to be represented.

Typically, as Fig. 5 shows, a fog episode may last for 2–4 h yielding between 0.3 and 0.9 l/m²/h. For each of the points in Fig. 5, multiplying time duration by collection rate gives the total water yield associated with a particular fog event. In this manner, the longest fog episode, which corresponds to Mt. Montgo, persisted for 92 consecutive hours and delivered a total fog water amount of 140 l/m². Additionally, the most effective fog episode occurred at Mt. Monduver; it lasted only 19 consecutive hours but yielded a water volume of 140 l/m², at a rate of 7.4 l/m²/h. If the data set on fog episodes is averaged separately for each pilot site, mean time lengths as well as mean fog water collection rates increase as one goes southwards. On average, Mt. Bartolo displays the shortest fog events (only 2 h) with the lowest water rates (0.47 l/m²/h). In contrast, Mt. Montgo is the site with the highest mean values for fog event duration (3.7 h) and fog water collection rate (0.84 l/m²/h).

4.4. Daily fog collection occurrence

Daily one-hour periods delivering any amount of fog water were counted irrespective of any concurrent rainfall episode. Hourly frequencies of fog collection were then calculated as the daily percentage of these 1-h periods over the entire year or over one season. Fig. 6 shows hourly frequencies at the four pilot sites obtained for the annual and summer periods. A daily cycle can be observed for each of the sites; this daily cycle is slight during the annual period but prominent during the summer. Mt. Bartolo shows no fluctuation in the hourly frequency of fog collection during the annual period. However, in summer, fog is collected on 20% of the days at 06:00 and on only 5% of the days at 12:00. The other three sites show slightly larger fluctuations during the annual period, with maximum-to-minimum differences of about 10%, except for Mt. Peñaroya with a value around 20%.

In summer, the fluctuations increase, with maximum-to-minimum differences of as much as 40% for Mt. Peñaroya or around 20% for Mt. Bartolo and Mt. Monduver. At all four sites, minimum values occur for about 3 h at noon. On the other hand, maximum values develop from 01:00 to 07:00 for the coastal sites but at 19:00 for the inland site. These daily fluctuations in the hourly frequency must be due to the development and dissipation of orographic fog since they are associated with the daily changes in air temperature. When the temperature decreases, the water vapor contained in the ascending air can condense and produce fog. Conversely, when the air temperature increases at noon, there may not be enough cooling in the ascending air for the water vapor to condense, and therefore fog formation is inhibited.

4.5. Wind dependence

Annual wind statistics for each of the pilot sites are given in Fig. 7A and B according to a 16-direction scale and the Beaufort wind velocity scale. Wind calms are considered for wind velocities below 1.7 km/h. The wind roses at the top were derived from the entire set of 10 min wind data, those in the middle use only the 10 min wind data that had simultaneous fog occurrence, while those at the bottom give the percentage of fog water over the total annual volume that was collected at a certain wind direction and velocity. The calculations involved for the bottom wind roses follow a similar procedure to those in the middle but weigh each fog collection occurrence by its yielded water volume. Wind roses in the middle show the occurrence percentage of fog collection when wind blows from a particular direction and at a certain velocity for the total of events with fog water collection. For instance, for wind direction 22.5° wide centred at SE, Mt. Monduver shows a wind frequency of 7%, a fog collection frequency of 9% and a fog water volume percentage of 14% over the annual total. The frequencies associated with each of the wind velocity ranges in this SE direction are diverse: 2%, 3%, 1% and 1%, respectively, for the first four ranges of the Beaufort scale in the case of the wind statistics, 1%.
Fig. 7 (continued).
4%, 2%, 1% and 1% for the first five wind velocity ranges in the case of the fog collection occurrence statistics, and 0%, 2%, 2%, 3%, 4% and 3% for the first six wind velocity ranges in the case of the fog water volume distribution.

All of the top wind roses present distinct annual frequent wind directions. Most of the frequent directions are distributed into two main components, except for Mt. Monduver where there is a wide range in frequent winds with a predominant WSW. At Mt. Bartolo, the two principal directions are aligned to the transverse direction to the mountain ridge line, while in the case of Mt. Peñaroya, they are arranged according to the valley, which is perpendicular to the coastline. With regard to Mt. Montgo, the two most frequent wind directions are from the S and the NW.

The mid wind roses show wider distribution patterns, normally spread over an angle sector or quadrant, except for Mt. Bartolo where the frequent directions are limited to a pair of narrow angles (N and S). Mt. Monduver shows the broadest range of wind directions, corresponding to almost all possible maritime components. At Mt. Montgo, approximately 40% of the fog occurs when wind blows from the quadrant S-SE, while all the fog episodes at Mt. Peñaroya come from the quadrant SSE-ENE. Wind velocity rarely exceeds 30 km/h when fog is present, although the two stations that are the most exposed because of their altitude (Mt. Monduver and Mt. Peñaroya) registered regular winds of up to 50 km/h for some specific directions. Moreover, wind calms commonly show low amounts, which can be explained by the fact that wind is needed for a passive string collector to collect fog water.

The bottom wind roses show similar distribution patterns to the ones in the middle. Frequent winds are stronger since they deliver fog water amounts at a higher rate than from lighter winds. For this reason, calms are almost nil and winds lighter than 10 km/h contribute poorly. At Mt. Bartolo, the greatest percentage of the total fog water volume can be collected when the wind blows from N. In the case of Mt. Monduver, winds from the N-ENE sector deliver approximately 45% of the total volume while another 40% can be attributed to winds from the SSW-ENE sector. Wind patterns for Mt. Montgo show a manifest southern component, although other thin components can be observed. At Mt. Peñaroya, winds greater than 30 km/h from the ENE-E sector deliver so much fog water that they prominently enlarge this component in their corresponding wind rose. The analysis of these wind patterns may be useful for the correct deployment of large flat collectors where orientation is important to achieve the best possible efficiency. Although not shown in Fig. 7A and B, for the summer period all wind patterns show a clear southern component, with the exception of Mt. Monduver with a principal component from ENE.

5. Conclusions

This study demonstrates that fog water can be obtained from advected and orographic clouds in the Valencia region by using passive fog water collectors exposed to the wind at several mountainous locations. This alternative water resource can be obtained based on good site selection and wind exposure. Even though the four selected sites shared some geographic conditions such as altitude, good exposure to prevailing winds or proximity to the coastline (only one site was inland), the annual collected fog water yields distinguished two types of sites: northern sites and southern sites. Fog water yields at the southern sites compare well with the best values shown by other studies either in the Canary Islands, Spain, or in other locations abroad (Marzol, 2002; Cereceda et al., 2002; Larrain et al., 2002). On the other hand, the northern sites recorded lower annual yields in comparison with results from other studies at relatively modest locations (Olivier and Rautenbach, 2002; Osses et al., 2004). In particular, during a one-year pilot study in the Canary Islands, Marzol (2005) used several cylindrical string collectors at a mountain location with an altitude of 1400 m a.s.l. Marzol built different passive devices, the most efficient of which was a collector made of vertically oriented teflon strings. The annual cloud water rate collected by this type of fog collector was 9 l/m2/day, with the rainfall rate for that period around 2 l/m2/day. These values compare well with the results obtained at Mt. Monduver and Mt. Montgo. Similarly, at a 2600 m high location in Hawaii, Juvik et al. (1993) also registered fog collection by means of two cylindrical passive devices made of louvered aluminium screens. This study lasted for 12 consecutive months, which were unusually dry since the recorded rainfall rate was 0.7 l/m2/day and the fog rate was even smaller, around 0.6 l/m2/day. Values for Mt. Bartolo and Mt. Peñaroya are larger than those registered in Hawaii.

In this preliminary study, the duration of fog episodes and their associated fog collection rates increase as one goes southwards. Therefore, there seems to be a North-to-South positive gradient in the fog water collection potential. Fog episodes are more frequent and deliver higher water volumes at southern mountain locations than at northern locations. At all four sites, summer is the season with the lowest fog water yields. As low as such
yields are, however, they are still important when compared with the sometimes negligible amounts of summer rainfall. Except for the summer period, rainfall is always present on the same day as fog events with important water yields. The hourly frequencies of fog water collection show a characteristic daily cycle, which is prominent during the summer period but weak for the rest of the year. This cycle must indicate how the orographic component of fog dominates the advected part during the summer.

Annual wind roses reveal the most frequent wind directions and speeds occurring at each of the sites. When considering the entire set of wind data, the majority of wind patterns are distributed into two main directions. However, if only the winds that deliver any amount of fog water are considered, the wind patterns show other frequent directions or stress one of the former. The wind analysis can be further improved if winds carrying fog are evaluated in terms of their corresponding fog water collection rates. The resulting frequent directions and speeds show which winds deliver the largest amounts of fog water. Considering wind velocity, light winds delivered low amounts of fog water in contrast to stronger winds (up to 50 km/h), which provided the biggest part of the annual total volume. As compared with the sometimes negligible amounts of rainfall, they yielded only 25% of the total annual fog water volume. These values demonstrate the importance of wind when collecting fog with passive devices. Considering wind direction, the principal components came from the direction of the inland valleys that lead to the sea in the case of Mt. Pañaroya, from the coastline-facing side in the case of Mt. Monduver, or from different preferred directions that point directly to the sea in the case of the remaining stations. In contrast, one of the principal wind directions at Mt. Bartolo corresponded to a northern direction, which may be explained by the influence of inland frontal systems on the development of fog events at this location. These principal direction components may be useful for the appropriate alignment of any kind of passive collector, such as the widely-used flat-panel collector, in order to increase efficiency. Most of the preferred directions for fog water collection come from the coast although a southern component is also common at all of the sites, and is more prominent in summer.

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References


Schemenauer, R.S., Cereceda, P., 1994c. The role of wind in rainwater catchment and fog collection. Water Int. 19, 70–76.