

hunt  
 found  
 unions  
 he  
 ed

# Fog precipitation on the Island of Madeira (Portugal)

Susana Nascimento Prada · Manuel Oliveira da Silva

**Abstract** An important aspect of the Madeira Island's climate is its persistent nebulose covering mainly of orographic origin, which normally exists between the 600–800- to 1,600-m altitude. The object of this study is to quantify the amount of water that can be gathered by direct interception from clouds. The first results at the end of 2 years were higher than expected. The daily rates of the 'standard fog collector' ranged between 6.0 to 21.3 l/m<sup>2</sup> of vertical collecting surface. The water collected by the rain gauges beneath *Erica arborea* L., ranged between 33.3 to 56.4 mm of water per day (l/m<sup>2</sup> per day). Depending on wind direction and speed, which is normally north-east, the highest fog water production can be 250 mm/day. Fog drip under the vegetation was three and a half times greater than the annual precipitation.

**Keywords** *Erica arborea* L. · Fog precipitation · Madeira Island · Standard fog collector

## Introduction

Madeira is in the eastern region of the Atlantic Ocean, between the meridians 16°39' and 17°16'W and the parallels

Received: 6 December 2000 / Accepted: 25 June 2001  
 Published online: 25 September 2001  
 © Springer-Verlag 2001

S.N. Prada (✉)  
 Departamento de Biologia e Centro  
 de Investigação em Ciências  
 Agrárias da Universidade da Madeira,  
 Campus Universitário, Penteada – 9000,  
 Funchal, Madeira  
 E-mail: susana@uma.pt  
 Tel.: +291-705380  
 Fax: +291-705399

M.O. da Silva  
 Departamento e Centro de Geologia da FCUL,  
 Edifício C2-5 piso, Campo Grande – 1700,  
 Lisboa, Portugal

32°38' and 32°52'N. The island rises above a vast underwater plain in the midst of the African Plate, forming a volcanic massif about 5.5 km high, of which only a third is above water.

Madeira's volcanic activity took place before the late Miocene, the oldest rock is 5.2 Ma (Prada and Serralheiro 2000), and continued into the Holocene with the last eruption occurring 6,000–7,000 years B.P. (Geldmacher and others 2000). The island grew through the accumulation of explosive and effusive volcanic materials. Madeira has an area of 737 km<sup>2</sup>, and is 58 km long and 23 km wide. It has a maximum altitude of 1,861 m, consisting of an enormous east–west-oriented mass that is cut by deep valleys. The relief is the result of different local climates because of its perpendicular position in relation to predominant winds, which results in different temperatures and precipitation rates on the different slopes (Prada 2000).

Madeira's climate is influenced by the subtropical anticyclone from the Azores. The predominant winds are north-east (trade winds; Ferreira 1955). Precipitation increases with altitude, and is higher on the northern slopes than on the southern slopes at the same altitude. The highest rates of precipitation are at Bica da Cana, at an altitude of 1,560 m, with a maximum of 2,966.5 mm/year, which decreases above this altitude.

The island fogs are almost exclusively of orographic origin, and normally remain between 600–800 and 1,600 m altitude, in certain areas, during 234.8 days/year.

The phenomenon to be quantified has been variously called occult precipitation, horizontal precipitation, fog drip, fog precipitation, fog-water and precipitation by direct interception of cloud water. The latter best expresses the process, for it suggests that without interception there is no significant deposition.

Fog droplets have diameters from about 1 to 40 µm, and fall velocities from less than 1 to ~5 cm/s. These fall speeds are so low that, even in very light winds, the drops will travel almost horizontally. This means that the appropriate collector for fog droplets is a vertical, or near vertical surface (Schemenauer and Cereceda 1994a). Trees can be good fog collectors because of the continuous movement of leaves and branches by the action of the wind, with the consequent decrease in turbulence around them (Cunha 1964). Fog drip is the coalescence of fog droplets on foliage from blowing fog, which produces large drops that rain to the ground. The amount of fog drip that

can be produced is related to the duration of fog, to the type, density and cross sectional area of the collecting vegetation, and to the prevalence of wind (Ingraham and Matthews 1988).

## Selection of the experimental site

The choice of the experimental site of Bica da Cana in the Massif of Paul da Serra to install the equipment for the measurement of the fog precipitation was made according to the analysis of the existing atmospheric conditions and the proximity of the meteorological stations (Prada and Silva 1998). Equipment was installed at Chão das Feiteiras, which did not offer as good conditions as at Bica da Cana.

### Bica da Cana station

Bica da Cana is near the northeast edge of the plateau of Paul da Serra, at 32°45'N and 17°03'W, 1,560 m altitude. It is on a plain with gentle slopes SW, (Nascimento 1990), marked by the presence of a partially destroyed volcanic neck. The fields are carpeted by low-growing gramineous and other herbaceous species. Cover of soil is irregular, with a more or less continuous layer of fern, tufts of *Erica* spp. and tree-like shrubs of *Erica arborea* L. The area is exposed to northeast prevailing winds, dominant throughout the year, with an average frequency of 36%, and an average velocity of 20 km/h. The annual precipitation was 2,966.5 mm, reaching its maximum rate in January with a total of 448.4 mm and minimum in July with a total of 25.4 mm. The average rate of air humidity is greater than 75% during 10 months of the year, reaching a maximum rate of 88% in November and decreasing to 63% during July and August.

Fogs average 234.8 days/year and the area is frequently in a stratocumulus layer.

### Chão das Feiteiras station

Chão das Feiteiras is in a small plain area near Ribeiro Frio that slightly slopes north, at 32°42'N and 16°53'W, of 1,183 m altitude. The area experiences some incidence of fogs and is exposed to north and northeast winds with velocities of 20.1 and 22.4 km/h, respectively (values registered at the nearest meteorological station, Areeiro Station at 1,610 m altitude). The air humidity ranges between 75 and 79% and the annual precipitation is between 2,000 and 2,400 mm.

## Equipment and methodology used

Fog drip of Madeira's typical vegetation was measured to determine its contribution to the groundwater supply and to evaluate the potential of this water resource as an available complement to traditional sources of water supply in the island. Several types of measurements were made.

First, direct measurement by placing rain gauges under trees at higher altitudes was carried out. The vegetation at these altitudes (1,200–1,600 m) is mainly composed of *Erica arborea*, *Erica scoparia* and *Vaccinium padifolium* (*Polysticho falcinnelli-Ericetum arboreae*; Capelo and others 1999). Below 1,400 m, Laurisilva is a completely developed forest, with all the vegetation layers being present (Valente and Silva 1990). The tree layer is impressive and includes *Laurus azorica*, *Clethra arborea*, *Ocotea foetens*, *Picconia excelsa*, *Persea indica*, *Ardisia excelsa* and *Apollonias barbujana* (*Clethro arboreae-Ocoteetum foc-tentis* and *Semele androgynae-Apollonietum barbujanae*; Capelo and others 1999) as the main species. Some species have become rare, almost extinct, such as *Pittosporum coriaceum*, *Juniperus cedrus* and *Taxus baccata*. Under the top of these great trees shrubs are abundant, *Erica arborea*, *Vaccinium padifolium*, *Erica scoparia*, *Ilex perado*, *Ilex canariensis*, *Teline maderiensis*, *Isoplexis sceptrum*, *Echium candicans*, *Sonchus fruticosus* and, *Argyranthemum pinnatifidum*. On the soil the vegetation is luxuriant, including a continuous thick and wet cloak of hepatics, fungus and bryophytes, chiefly in places with permanent water supply. Many endemic species to Madeira can be found here.

The existence of constant fogs from the northern coast during much of the year has a decisive influence on the existence and development of this humid subtropical forest, which covers mainly the island's northern slope and now has a total area of over 150 km<sup>2</sup>, of which 120 km<sup>2</sup> are above 400 m (Neves and others 1996).

The occurrence of vegetation in strong condensation rate areas plays an important role in fog interception, allowing for extra water gain. Because of the slow and frequent way it reaches the ground this water is an important source of groundwater recharge.

This study began by measuring fog precipitation in the giant heathers, *Erica arborea* L., which are a constant presence in all of the island's northern slope, and is more frequent at higher altitudes. These heathers possess thousands of kilometres of needle-like leaves, a shape ideal for collection of fog water droplets (Went 1955).

A second measurement was the use of a man-made collector to intercept fog droplets. Our choice was a structure by Schemenauer and Cerceda (1994a), called a standard fog collector (SFC). It is simple, easy to construct and inexpensive and is a widely known and successful piece of equipment that allows comparative analysis between the data collected in Madeira and in other parts of the world (Fig. 2).

The SFC consists of a square metal frame (galvanised) that measures 1×1 m on the inside and 1 cm in diameter covered with a polypropylene mesh and placed 2 m above the ground. The material chosen for use was a double layer polypropylene mesh. The fibre is about 1 mm wide and the mesh is woven in a triangular pattern with a 1.3-cm spacing between the horizontal lines.

The double layer of mesh covers about 60% of the surface area of the collector, which leaves 40% of the area open for the wind to pass through. Below the frame is a collection

trough, measuring 1.04 m long and 15 cm wide, square in cross section. The depth of the trough is 10 cm and it is placed asymmetrically, 2 cm in the same direction as the predominant winds and 12 cm behind the frame to collect any drops carried by strong winds. The amount of water collected by the trough is led through a tube to a rain gauge placed in a closed shelter so as to prevent the direct entrance of rain water, thus registering only the fog and the rain water collected by the panel. Its major limitation is that it is a fixed structure and, therefore, does not follow the variation of wind direction. Although it is fixed perpendicular to the direction of the predominant winds, when they change their course there is a lower collection rate.

The Bica da Cana Station is composed of the following equipment:

1. A rain gauge installed in an open area to measure only rain water.
2. Two rain gauges installed under two *Erica arborea* L., about 3 m high, placed in different positions in relation to the prevailing winds so as to register the amount of water collected by that type of vegetation (Fig. 1).
3. The SFC placed perpendicularly to the direction of the prevailing winds (NE), to measure the amount of water collected by a square metre of vertical area (Fig. 2).

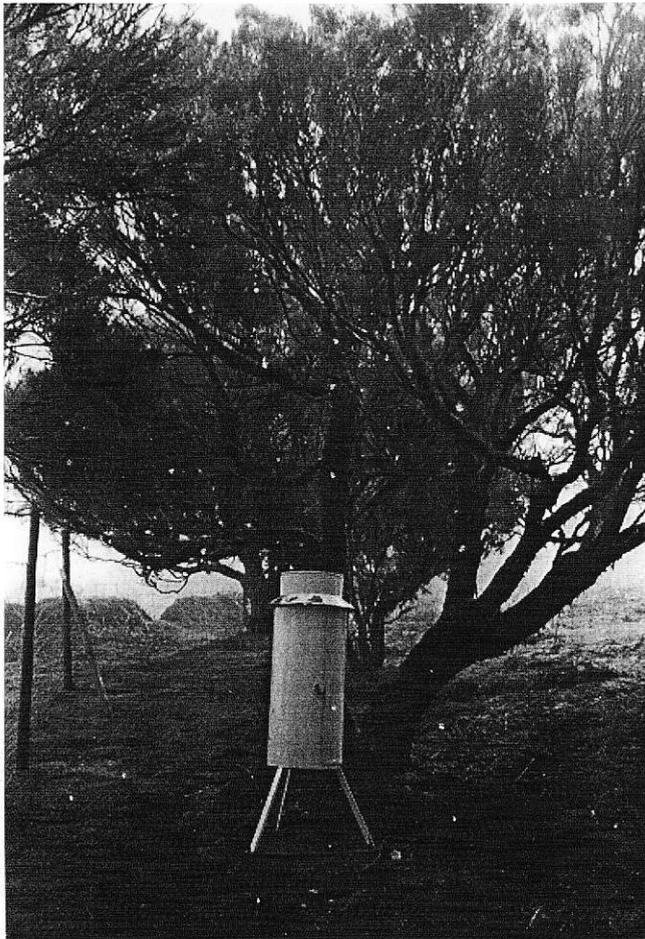


Fig. 1

Rain gauge placed under an *Erica arborea* L. at Bica da Cana

The Chão das Feiteiras Station consists of only one rain gauge installed in an open space to measure the rain precipitation and a SFC placed perpendicularly to the direction of the prevailing winds.

## Results

Measurement of Madeira's fog precipitation began in September 1996 and continued until July 1998. Because of the high rates of air humidity registered, especially at Bica da Cana, the rain gauges had severe malfunctions, thus provoking some failures in observation.

### Results of the standard fog collector

The SFC installed at Bica da Cana in September 1996 fell twice because of the force of the winds, especially from the SW, perpendicular to the structure, which can blow to speeds of 86 km/h. The values registered are represented in Fig. 3.

When it rains the SFC collects fog water and rain. To determine the fog water collected we chose to subtract the total amount of rain from the total rate registered by the SFC rain gauge, which corresponds both to the fog and the rain water. This way, we believe that we can obtain a value that safely corresponds to the rate of fog precipitation

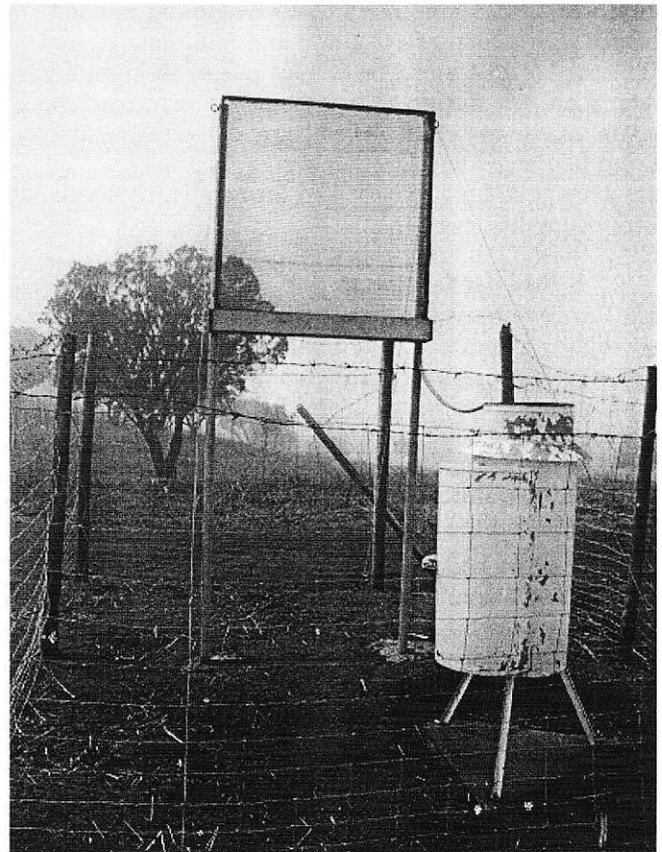


Fig. 2

Standard Fog Collector' protected by a metallic fence at Bica da Cana

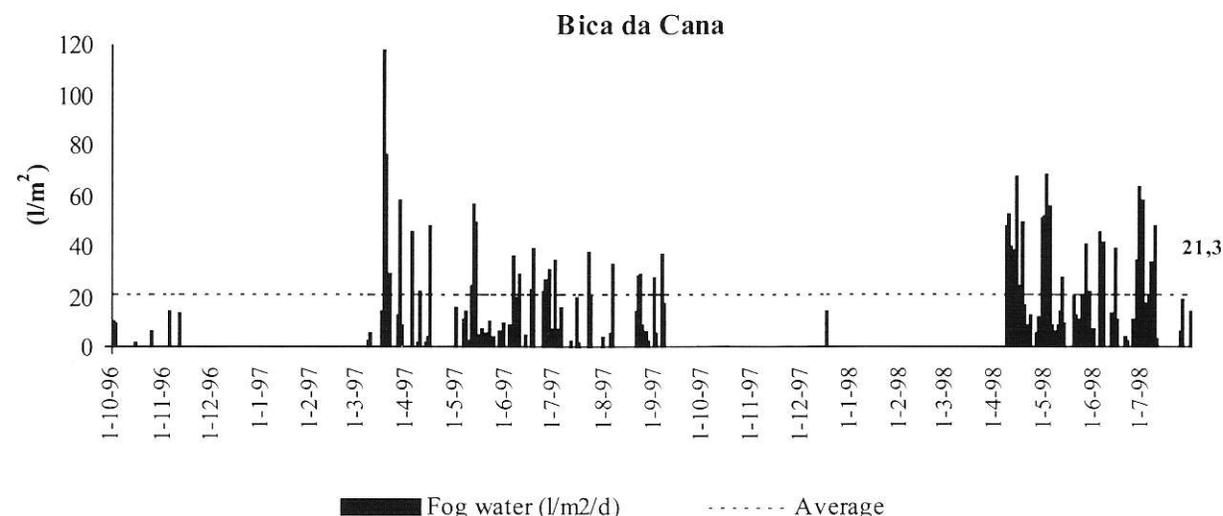


Fig. 3

Variation of fog collection rates at Bica da Cana

Table 1

Fog water production and length of fog season at four sites. (Schemenauer and Cereceda 1994b)\*

Sites	Average production ( $l\ m^{-2}\ year^{-1}$ )	Days per year	Annual production ( $l\ m^{-2}\ year^{-1}$ )
Chile*	3.0	365.0	1,095
Peru*	9.0	210.0	1,890
Oman*	30.0	75.0	2,250
Madeira (Bica da Cana)	21.3	234.8	5,001

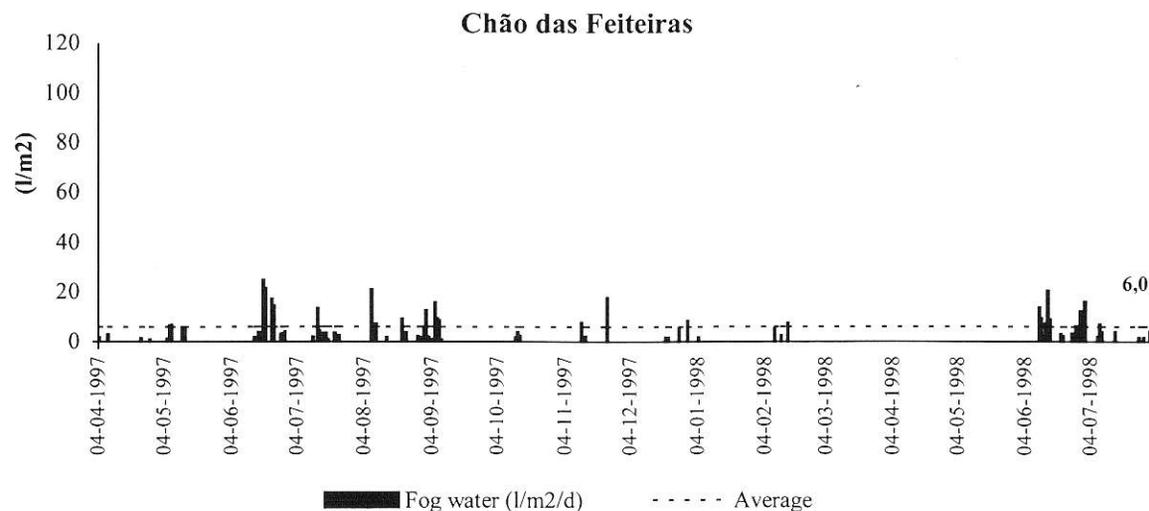


Fig. 4

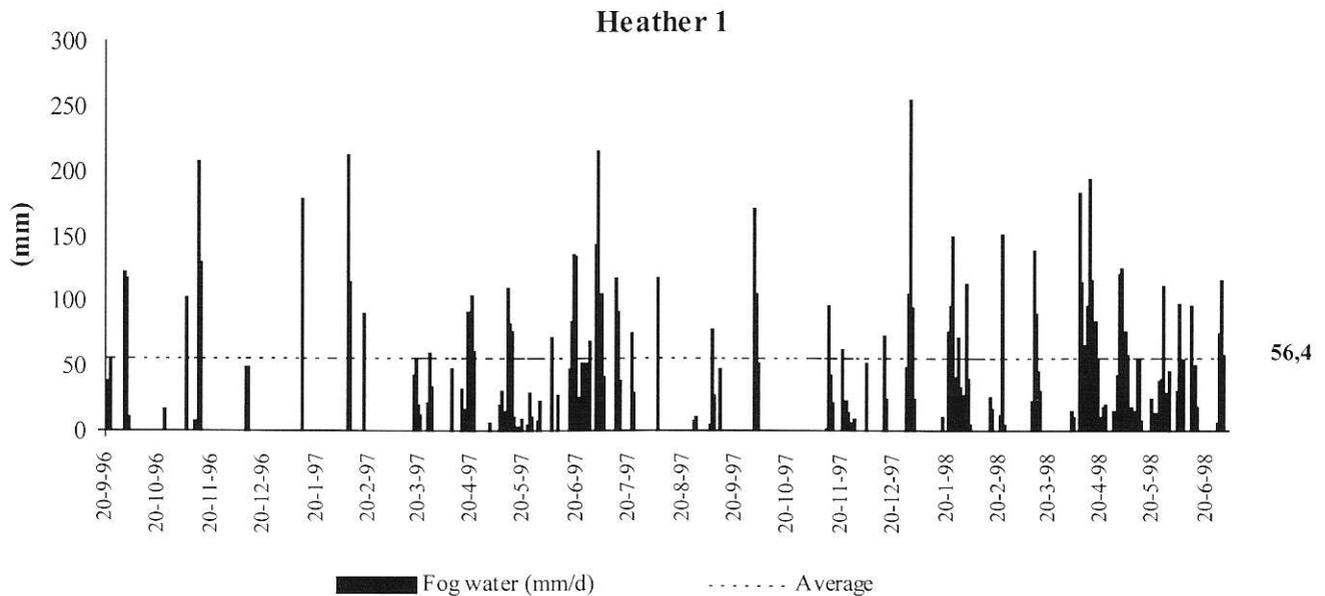
Variation of fog collection rates at Chão das Feiteiras

because the water captured by the vertical mesh is always inferior to or equal to the water that falls inside the rain gauge destined to measure the rain water. As was predicted, the values registered by the SFC at Bica da Cana were substantially greater than the ones registered with a similar device at Chão das Feiteiras.

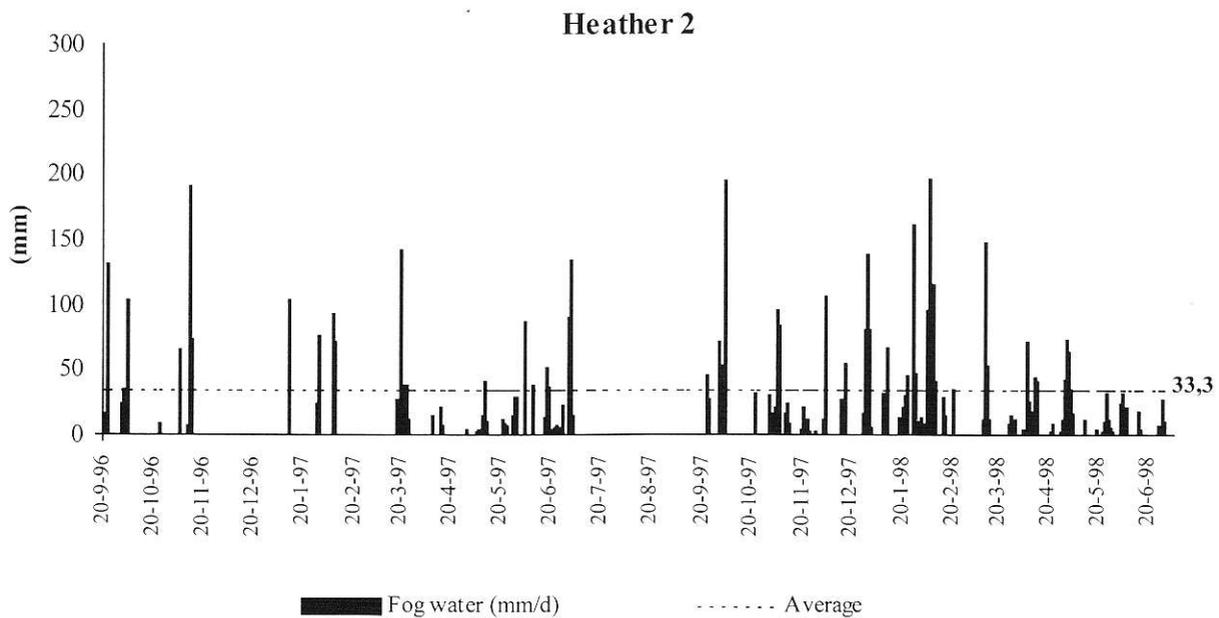
At Bica da Cana, average values of 21.3  $l/m^2$  of vertical collecting surface per day were registered; moreover, a

value of 118  $l/m^2$  was obtained in only one day. This value exceeds the theoretical maximum, which was set at 104  $l/m^2$  per day calculated for a vertical collecting surface of 1  $m^2$  (only 60% of the surface is able to intercept the droplets), crossed by NE winds at an average speed of 8 m/s and carrying fog for 24 h with a liquid water content of 0.25  $g/m^3$  (Frisch and others 1994). These values can be explained by higher wind velocities than those determined by Spenk (1990).

By comparing the rates obtained with the SFC at Bica da Cana with those obtained in other locations using the same



**Fig. 5**  
Fog water collected by heather 1 at Bica da Cana



**Fig. 6**  
Fog water collected by heather 2 at Bica da Cana

device it can be concluded that the annual fog water production at Bica da Cana can surpass 5,000 mm/year because of elevated daily production values and a higher rate of foggy days per year (Table 1).

At Chão das Feiteiras, the SFC was installed in May 1997 and the values registered are represented in Fig. 4. The average rates per day did not exceed 6 l/m<sup>2</sup> of vertical collecting surface. The highest value was 25 l/day. Although lower than the rates registered at Bica da Cana, these values are close to the ones obtained in Chile and Oman by Schem-

mauer and Cereceda (1994a), which vary from 1 to 10 l/m<sup>2</sup> per day and, in special cases, reach 30 to 40 l m<sup>-2</sup> day<sup>-1</sup>.

#### Results obtained from the vegetation

The measurement of fog precipitation from the vegetation was started with heathers (*Erica arborea* L.) because of their great number in the area and their leaf characteristics, which are favourable for the collection of fog droplets. The tree heath located windward of the prevailing NW winds was heather 1. Heather 2 is to the leeward. The values obtained are represented in Figs. 5 and 6.

It was concluded that heather 1 was more productive than heather 2 with average values of about 56.4 and 33.3, respectively, with the different exposures to the prevailing

winds. Heather 1, located windward, registered a maximum value of 250 mm/day. It was observed that when the wind direction changed to the SE, heather 2 was more productive, although this did not happen frequently. These rates greatly exceed the those predicted by Silva (1984), of 20 to 40 mm/day.

A comparison of the annual average precipitation rate at Bica da Cana, which is about 3,000 mm, with the average fog precipitation rate, shows that the latter is three-and-a-half times greater.

## Conclusions

In spite of the difficulty with the SFC, which made it impossible to obtain a daily continuous record, it is believed that a sufficient number of observations were made to determine, with some accuracy, the daily average rate of fog precipitation by a vertical unit of area during the 2 years the equipment was installed.

The daily average fog precipitation was  $\sim 21/\text{m}^2$ , which is similar to results obtained at other locations using the same device. The annual fog precipitation in Madeira, however, was greater because fog at high altitude is very frequent (235 days/year).

Fog precipitation rates, measured with the SFC ( $5,001 \text{ l m}^{-2} \text{ year}^{-1}$ ) and under vegetation (three-and-a-half times more than the annual average precipitation rate in the area) illustrates the importance of this kind of precipitation at high altitudes as a complement to traditional supply sources or as a source of groundwater recharge.

## References

- Capelo J, Costa JC, Louia M, Fontinha S, Jardim R, Sequeira M, Rivas-Martinez S (1999) Vegetação da Madeira: aproximação à tipologia fitossociológica. *Silva Lusitana* 7(2):257–286
- Cunha F (1964) O problema da captação da água do nevoeiro em Cabo Verde. *Garcia Horta* 12(4):719–756
- Ferreira A (1955) O clima de Portugal. Açores e Madeira, Fascículo VIII, INMG, Lisboa
- Frisch AS, Lenschow DH, Fairall CW, Snider JB (1994) Stratus cloud liquid water and turbulence profiles using a Ka-band Doppler radar and a microwave radiometer. Second International Conference on Air–Sea Interaction and on Meteorology and Oceanography of the Coastal Zone, vol XXIX, 309, Sponsored by American Meteorological Society and Instituto de Oceanografia da Universidade de Lisboa. American Meteorological Society, Boston, pp 58–59
- Geldmacher J, van den Bogaard P, Hoernle K, Schmincke H-U (2000) Ar age dating of the Madeira Archipelago and hotspot track (eastern North Atlantic). *Geochem Geophys Geosyst* 1, paper no 1999GC000018
- Ingraham NL, Matthews RA (1988) Fog drip as a source of ground water recharge in northern Kenya. *Water Resour Res* 24:1406–1410
- Nascimento S (1990) Estudo Hidrogeológico do Paul da Serra. Dissertação de Mestrado, FCUL
- Neves, Valente, Faria, Silva, Marques, Gouveia, Silva, Oliveira (1996) Laurisilva da Madeira, caracterização quantitativa e qualitativa. Parque Natural da Madeira. Secretaria Regional de Agricultura Florestas e Pescas, Governo Regional da Madeira
- Prada SN (2000) Geologia e Recursos Hídricos Subterrâneos da Ilha da Madeira. Dissertação para obtenção do Grau de Doutor em Geologia. Universidade da Madeira
- Prada SN, Serralheiro A (2000) Stratigraphy and evolutionary model of Madeira Island. *Bocagiana* no 200, Maio, 2000. Museu Municipal Funchal, Madeira
- Prada SN, Silva MO (1998) Contribuição da Precipitação Oculta para os Recursos Hídricos Subterrâneos da Ilha da Madeira. *Comun. Inst Geol Min* 84(2):118–121
- Schemenauer R, Cereceda P (1991) Fog-water collection in arid coastal locations. *Ambio* 20(7):303–308
- Schemenauer R, Cereceda P (1994a) A proposed standard fog collector for use in high-elevation regions. *Am Meteorol Soc* 33:1313–1322
- Schemenauer R, Cereceda P (1994b) Fog collection's role in water planning for developing countries. *Natur Resour Forum* 18(2):91–100
- Silva CG (1984) O Regime Hídrico da Madeira – a vaca madeirense. *Diário de Notícias* de 1 de Novembro de 1984, Funchal
- Spenk G (1990) Possibilidades de aproveitamento da energia eólica na Madeira – Estudo de Viabilidade. IBEK, Bremen
- Valente A, Silva P (1990) Laurisilva, water and soil, communication presented to the meeting 'Evolution and conservation in the North Atlantic islands', Manchester University
- Went FW (1955) Fog, mist, dew, and other sources of water. In: *Yearbook of agriculture*. US Dept of Agriculture. Washington, DC, pp 103–109