Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

Cloud water interception in the temperate laurel forest of Madeira Island

Celso Figueira , Miguel Menezes de Sequeira , Rita Vasconcelos & Susana Prada

To cite this article: Celso Figueira , Miguel Menezes de Sequeira , Rita Vasconcelos & Susana Prada (2013) Cloud water interception in the temperate laurel forest of Madeira Island, Hydrological Sciences Journal, 58:1, 152-161, DOI: 10.1080/02626667.2012.742952

To link to this article: https://doi.org/10.1080/02626667.2012.742952

Hydrological Sciences Journal – Journal des Sciences Hydrologiques, 58 (1) 2013
http://dx.doi.org/10.1080/02626667.2012.742952

Cloud water interception in the temperate laurel forest of Madeira Island

Celso Figueira[1], Miguel Menezes de Sequeira[2], Rita Vasconcelos[1,4] and Susana Prada[1,4]

[1]*Centro de Ciências Exactas e da Engenharia, Universidade da Madeira, Campus Universitário da Penteada, 9000-390 Funchal – Madeira, Portugal*

[2]*Centro de Ciências da Vida, Universidade da Madeira, Campus Universitário da Penteada, 9000-390 Funchal – Madeira, Portugal*

[3]*Centro de Estatística e Aplicações da Universidade de Lisboa, Bloco C6, Piso 4, Campo Grande, 1749-016 Lisboa, Portugal*

[4]*Centro de Vulcanologia e Avaliação de Riscos Geológicos, Universidade dos Açores, Ed. Complexo Científico, 3 Piso, Ala Sul, 9501-801 Ponta Delgada – Açores, Portugal*
susana@uma.pt

Received 3 February 2011; accepted 9 May 2012; open for discussion until 1 July 2013

Editor Z.W. Kundzewicz

Citation Figueira, C., Menezes de Sequeira, M., Vasconcelos, R., and Prada, S., 2013. Cloud water interception in the temperate laurel forest of Madeira Island. *Hydrological Sciences Journal*, 58 (1), 152–161.

Abstract A cloud belt frequently forms on the windward side of Madeira Island, between 800 and 1600 m a.s.l., as a result of adiabatic cooling of the northeastern trade winds that are forced upward. Temperate laurel forest is the most common vegetation inside that cloud belt altitudinal range. Cloud water interception was estimated by comparing precipitation and throughfall during a hydrological year. It totalled 200 mm (8% of rainfall) during 65 days (3 mm d^{-1}) and seems to constitute a larger fraction of water input during drier months. Multiple linear regression between gauge standard deviation and throughfall throughout rain events shows that cloud interception is common before the onset of rainfall. Its role in the ecohydrology of laurel forest and in the island's hydrology should be acknowledged. Further studies on this issue should be a priority in order to better understand these dynamics and provide tools for the correct management of this protected forest and the island's groundwater resources.

Key words cloud water interception; Madeira Island; temperate laurel forest; groundwater recharge

L'interception de l'eau des nuages dans la forêt tempérée de lauriers de l'Ile de Madère

Résumé Une ceinture de nuages se forme fréquemment sur le côté au vent de l'île de Madère, entre 800 et 1600 m d'altitude, à la suite du refroidissement adiabatique des alizés de Nord-Est qui sont poussés en altitude. La forêt tempérée de lauriers est la végétation la plus courante dans cette fourchette d'altitude de la ceinture de nuages. L'interception de l'eau des nuages a été estimée en comparant les précipitations et le pluviolessivat au cours d'une année hydrologique. Ce dernier s'élève à 200 mm (8% des précipitations) pendant 65 jours (3 mm $jour^{-1}$) et semble constituer une partie importante de l'apport d'eau pendant les mois les plus secs. La régression linéaire multiple entre l'écart-type des précipitations et le pluviolessivat pendant les épisodes de pluie montre que l'interception de l'eau des nuages est fréquente avant le début des pluies. Son rôle dans l'écohydrologie du laurier et sur l'hydrologie de l'île devrait être reconnu. La poursuite des études sur cette question devrait être une priorité afin de mieux comprendre cette dynamique, et de pouvoir fournir des outils pour une bonne gestion de cette forêt protégée et des ressources en eau souterraine de l'île.

Mots clefs interception de l'eau des nuages; Ile de Madère; forêt tempérée, laurier; recharge des eaux souterraines

1 INTRODUCTION

Cloud water interception occurs in windy and foggy environments, when cloud droplets (essentially fog droplets of various sizes and sometimes drizzle) coalesce on plant surfaces, as the cloud base passes through the canopy, and drip to the forest floor (Twomey 1957, Ekern 1964, Bruijnzeel 2001, Holder 2003, 2004, 2006, Bruijnzeel *et al.* 2005, Prada *et al.* 2009, 2010a, Brauman *et al.* 2010, Holwerda *et al.* 2010). In the absence of vegetation, this cloud water would not precipitate on the soil in significant quantities (Cunha 1964, Davis and DeWiest 1991). Different local factors influence the amount of cloud water intercepted. Among these are climatic factors like wind speed and direction, length of cloud immersion, cloud liquid water content, mean cloud droplet diameter, air temperature and relative humidity (Lovett *et al.* 1982, Lovett 1984, Schemenauer *et al.* 1987, Schemenauer and Cereceda 1991, Bruijnzeel *et al.* 2005). Topographical factors, such as the hill slope orientation, and site location, such as crest lines or positions just slightly upwind, are favourable to its occurrence (Schemenauer *et al.* 1987). Vegetation features, such as canopy height and architecture, foliar surface type, leaf area index and foliage density, are also important (Kittredge 1948, Parsons 1960, Shuttleworth 1977, Goodman 1985).

Madeira Island is situated at about 900 km southwest of mainland Portugal, and about 600 km from North Africa, in the North Atlantic. It is a volcanic island originating about six million years ago from the activity of an oceanic hot-spot in the African Plate (Ech-Chakrouni 2004). It has a total area of 737 km^2, and reaches a maximum altitude of 1861 m a.s.l. The island forms an east–west oriented mountain range that results in a barrier to the prevailing northeasterly trade winds. This frequently forms a windward cloud belt, between 800–1600 m a.s.l., on the northern slope. Events of thick, very moist and turbulent ground fog, which can last for several days, are common inside the cloud belt and are a result of the adiabatic cooling of the humid trade winds that are pushed up the northern slopes of the island. An area of about 125 km^2, characterized by steep slopes and mostly covered by indigenous plant communities, is directly exposed to north-northeast winds (Prada *et al.* 2008).

Madeira's actual vegetation cover is the result of 600 years of human disturbance of native vegetation. Temperate laurel forest (hereafter TL) is an evergreen Lauraceae dominated forest, endemic to the island (Capelo *et al.* 2004). It is distributed between 800–1450 m a.s.l. on the southern slope and 300–1400 m a.s.l. on the northern slope. This area is characterized by a temperate macrobioclimate, an infratemperate to mesotemperate thermotype and an upper sub-humid to lower humid ombrotype (Mesquita *et al.* 2004). Because its occurrence is almost simultaneous with the cloud belt, it can be considered a montane cloud forest (Bruijnzeel 2001). Nowadays, the temperate evergreen laurel forest is mainly present in the more remote and inaccessible northern areas, and it corresponds to the most widespread and iconic of all forest communities described for Madeira Island (Capelo *et al.* 2004). It has been recognized by UNESCO in 1999 as a World Heritage Site, meeting the (ix) and (x) criteria ("to be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, freshwater, coastal and marine ecosystems and communities of plants and animals" and "to contain the most important and significant natural habitats for *in situ* conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation", respectively – UNESCO 2008).

Previous studies have shown that, in Madeira, cloud water interception (or fog drip) is a significant water source, especially during the dry season, when it can represent as much as 33% of the total water input (Prada *et al.* 2009). Fog also reduces significantly the evapotranspiration rates due to air saturation and decreased insolation (Santiago *et al.* 2000, Burgess and Dawson 2004, Sperling *et al.* 2004, Ritter *et al.* 2008, 2009). Madeira's cloud belt could thus play a large role in the sustenance of TL, especially during the drier summer months.

In this study, we analyse a new and more representative throughfall data set obtained in a temperate laurel forest area, during a year-long experiment. The objective was to evaluate cloud water interception in Madeira's TL and compare it with the values obtained in Prada *et al.* (2009). We also analysed statistically the behaviour between gauge standard deviation and total throughfall throughout rainstorms. We aimed to detect if the canopy was already wet before the onset of rainfall, thus providing indirect evidence of the occurrence of cloud water interception. Lastly, we make a rough estimate of cloud water input to the ecosystem and discuss its relationship with the island's water resources and vegetation.

2 MATERIALS AND METHODS

2.1 Study area

The study was conducted on the northern slope of "Paul da Serra" (Fig. 1), the largest plateau and the most important groundwater recharge area in Madeira (Prada 2000). The area is largely covered by natural vegetation (TL or its successional stages). A 100 m^2

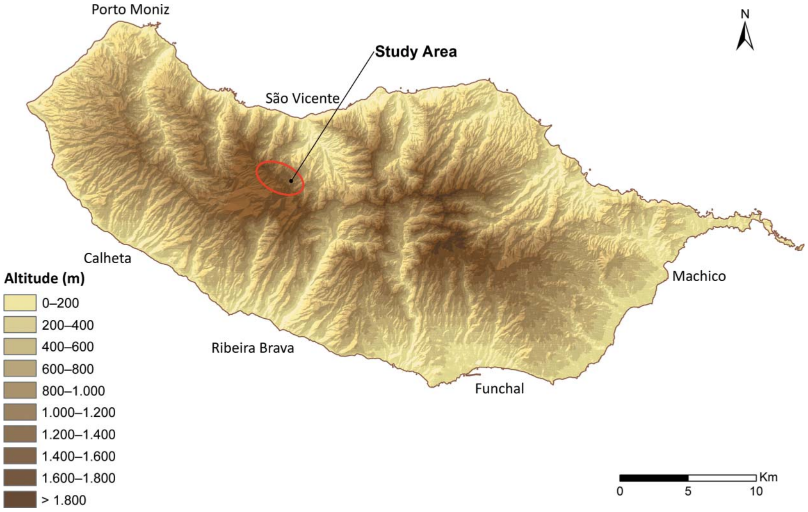

Fig. 1 Madeira Island: the study area is marked by the red elipse in the northern slope of Paul da Serra massif.

plot was set inside a relatively homogenous old-growth TL stand at 32°45′N and 17°02′W, at an altitude of 1025 m a.s.l (Fig. 2), on a 15° slope oriented north–northeast. The macrobioclimate in the area is temperate, the thermotype is inferior mesotemperate and the ombrotype is inferior hyperhumid (Capelo *et al.* 2004, Mesquita *et al.* 2004). Several endemic and relictual taxa are present and the dominant tree species are the stink laurel (*Ocotea foetens*)*,* the Macaronesian laurel (*Laurus novocanariensis*) and the lily-of-the-valley tree (*Clethra arborea*), which are covered by a large epiphyte community of mosses, lichen and ferns with hyperhumid characteristics (e.g. *Trichomanes speciosum, Hymenophyllum tunbringense, Davallia canariensis*). A very rich nemoral understory of ferns, shrubs and herbs was also present. The soils are andosols with a deep profile (at least 2 m) and have high organic matter content (Ricardo *et al.* 1992). A thick superficial humus and leaf-litter layer and an A-horizon more than 50 cm deep are also present.

2.2 Rainfall, throughfall and cloud water interception measurements

Intercepted cloud water values were calculated by comparing the amounts of water collected under the canopy and in the open (Holder 2003, 2004, Prada *et al.* 2009). A raingauge in the open normally receives a larger quantity of water (gross precipitation or rainfall) than a gauge under a forest canopy (net precipitation or throughfall). As such, the interception of water by the canopy has a positive value. However, when net precipitation is higher than gross precipitation (negative value), the additional water is considered to come from the cloud droplets intercepted by the canopy.

Rainfall was measured in a nearby raingauge located about 1 km to the east, at 950 m a.s.l. It stood in a flat clearing, approximately 30 m wide and surrounded by old-growth TL. This location provided shelter to the gauge from the wind, thus minimizing rainfall underestimation due to wind blow (Førland *et al*. 1996). Throughfall was measured between

Fig. 2 Temperate laurel forest in the study site.

October 2008 and September 2009, with five gauges placed under the vegetation, using a "roving gauge technique", where the gauges were randomly relocated every month within the 100 m^2 plot (Lloyd and Marques 1988). As the number of throughfall gauges was small, in order to obtain a more representative sample size, they were equipped with a metal ring that doubled their total collecting area to 0.5 m^2. Throughfall values were calculated as an arithmetic average of all gauges.

Cloud water values were determined by using the apparent canopy interception formula (Crockford and Richardson 2000). Stemflow was not determined. Throughfall was considered equal to net precipitation according to equation (1) (Bruijnzeel 2001), in which I is apparent canopy interception, P_{gross} is gross precipitation, and P_{net} is net precipitation:

$$I = P_{gross} - P_{net} \tag{1}$$

Whenever apparent canopy interception is negative, cloud interception is considered to have occurred and its value equalled the absolute value of I. By using the absolute apparent canopy interception when the values were negative, the input of cloud water interception to the ecosystem can be inferred, by equation (2), in which CWI is cloud water interception:

$$\text{CWI} = \sum |I \text{ value in the days when it is negative}| \tag{2}$$

2.3 Indirect evidence of cloud water interception

Cloud water intercepted by the vegetation is not equal to the difference between net and gross precipitation (when the first exceeds the second). This is due to the fact that evaporation and canopy storage of cloud water during interception is not taken into account. Thus, cloud water is usually underestimated, because its contribution to throughfall is only quantified whenever net precipitation is higher than gross precipitation. Cloud water that may have been captured when canopy interception is positive is ignored, as well as the volume that compensates for rain water intercepted by vegetation in the days when the canopy interception value is negative (Holder 2004). In an area subjected to frequent cloud immersion, interpretation of canopy interception can be particularly difficult, as it can be diminished by the presence of additional cloud water. Due to this, in places where cloud interception occurs, what is measured is not the real value of canopy interception (the volume of rain that does not reach the ground), but apparent canopy interception, the volume of rain that does not reach the ground plus the intercepted cloud water (Holwerda *et al.* 2010).

Although it is extremely difficult to accurately quantify what water portion comes from rain or cloud interception, it is possible to identify the presence of cloud water in the canopy before rain events. Due to the forest canopy's heterogeneous structure, its capacity to store water is not uniform. Before the canopy becomes saturated, rainfall is differentially intercepted and stored, making the standard deviation between several throughfall gauges under the canopy to be high. However, when the storage capacity is exceeded, rainfall, even if displaced, will reach the ground and standard deviation between throughfall gauges will become smaller throughout time and stabilize as the canopy becomes wet. As a result, throughfall under a saturated canopy is more predictable and a more spatially uniform fraction of rainfall than under an unsaturated canopy (Brauman *et al.* 2010). These authors state that variability among the gauges during a storm should be evident, and that throughfall variability between gauges decreases as a storm progresses and the canopy becomes saturated. This can be observed if the standard deviation between gauges is higher during the first hour than during the following hours. However, the absence of such a pattern is a sign that the canopy was already saturated or near-saturation when the storm began. This can be considered indirect evidence of the occurrence of cloud water interception, at least before the onset of a rain storm (Brauman *et al.* 2010).

In the studied area, we identified the rain events that occurred throughout the sampling period. Different events had to have at least a 2-hour interval between them. Storm events were divided into three periods (Hour 1, Hour 2 and Following Hours). Standard deviation among the throughfall gauges was plotted as a function of mean measured throughfall in each period. Then, a multiple linear regression was performed between standard deviation (dependent variable) and the independent variables, mean throughfall and time periods (we created three dummy variables for each hour). The objective of this test was to determine whether or not there was a significant difference in the relationships between standard deviation and mean throughfall during rainfall events. If there was no statistical difference in the relationships between the standard deviation and mean throughfall during the three time frames, then it was assumed that the canopy was saturated, or near saturation, before the beginning of the storm (Brauman *et al.* 2010).

3 RESULTS

Total rainfall during the studied period was 2484 mm, and 71% of total rainfall occurred between October and March. The rainfall pattern was similar to the 1960–1990 normals, with the exception of April and June. The driest months coincided with the warmer months (between April and September), when cloud water represented a larger proportion of total water input (Fig. 3).

Total throughfall was 2087 mm (84% of annual rainfall). Canopy interception was negative for 65 days (18% of the studied period). Cloud water totalled 200 mm (CWI – the sum of excess water volume in the days when throughfall was higher than rainfall), which represents 8% of annual rainfall (Table 1).

Figure 4(a) shows the value of standard deviation between the gauges plotted against the mean throughfall volume for all rainfall events, while Fig. 4(b) is a zoomed view of the lighter rain events

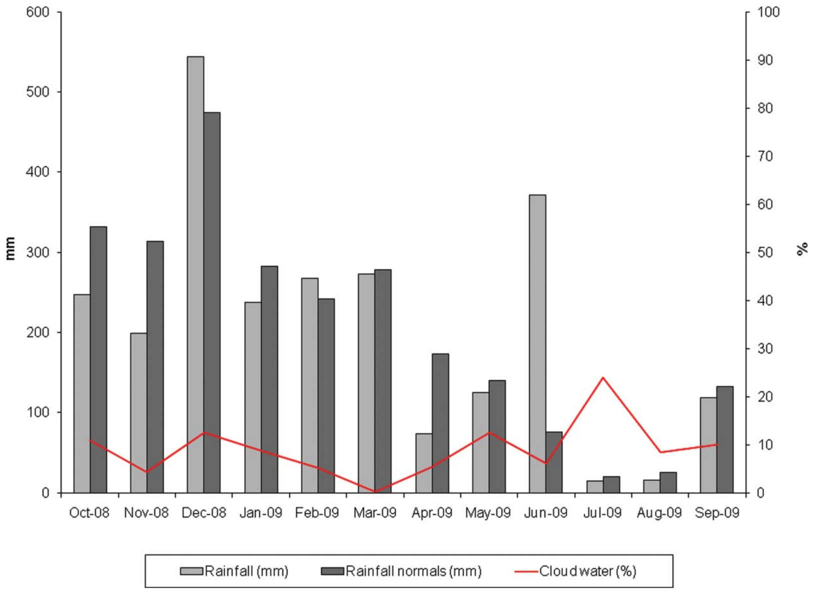

Fig. 3 Comparison between rainfall normals and rainfall values during the study period. The line shows the percentage of cloud water in rainfall.

Table 1 Precipitation and throughfall monthly measurements over the study period, October 2008–September 2009.

Date	Sampled days	Days with cloud interception	Rainfall normals (mm)	Rainfall (mm)	Throughfall* (mm)	Cloud water interception		Cloud water input	Apparent canopy interception	
						(mm)	(mm d^{-1})	(%)	(mm)	(%)
Oct-08	31	6	332	247	180 ± 49 SD	27	4.5	11	67	27
Nov-08	30	5	314	199	129 ± 38 SD	9	1.8	5	70	35
Dec-08	31	8	475	544	489 ± 170 SD	68	8.5	13	55	10
Jan-09	31	11	283	237	225 ± 92 SD	21	1.9	9	12	5
Feb-09	28	4	242	267	258 ± 72 SD	14	3.5	5	9	3
Mar-09	31	2	278	273	170 ± 44 SD	1	0.5	0	103	38
Apr-09	30	5	173	73	58 ± 26 SD	4	0.8	5	15	21
May-09	31	4	140	125	129 ± 30 SD	16	4.0	13	−4	−3
Jun-09	30	5	76	371	321 ± 81 SD	23	4.6	6	50	13
Jul-09	31	5	20	14	11 ± 5 SD	4	0.8	29	3	21
Aug-09	31	5	25	16	6 ± 4 SD	1	0.2	6	10	63
Sep-09	30	5	133	118	111 ± 22 SD	12	2.4	10	7	6
Total	365	65	2491	2484	2087 ± 751 SD	200	3	8	397	16

*SD: standard deviation.

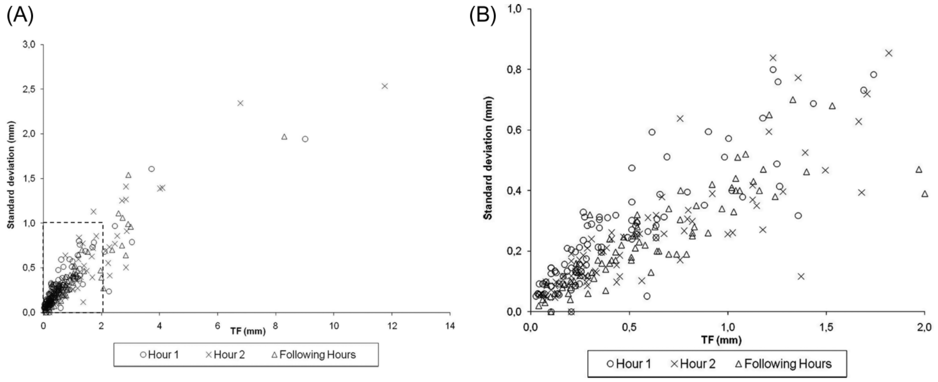

Fig. 4 Standard deviation as a function of mean measured throughfall for Hour 1, Hour 2 and Following Hours (a) all events; and (b) zoom of the smaller events (dashed box in Fig. 4(a)).

(dashed box in Fig. 4(a), for a better view). Standard deviation is plotted as a function of mean throughfall (measured in the gauges) during the first, second and following hours. A multiple linear regression analysis showed that there was no significant difference between standard deviation and mean throughfall in Hour 1, Hour 2 and Following Hours. The relationship between the dependent variable (standard deviation) and the independent variable (mean throughfall) is the same, independent of the hour ($p < 0.001$). The lack of statistical difference is an indicator that, before the onset of the storm, the canopy was generally already saturated or near saturation. Assuming that there was no rain before the onset of a storm event, the water must have come from the interception of cloud water.

4 DISCUSSION

During this study, monthly rainfall was similar to the monthly normals in the area, except for April and June (IM 2009). Apparent canopy interception was 16% of incident rainfall, a lower fraction than that obtained previously by Prada *et al.* (2009) for the same type of vegetation at the same altitude. This was perhaps due to the fact that the period sampled by those authors was exceptionally dry and measurements took place only during two short periods (*vs* a complete year in this study). Besides, the small number (2) of throughfall gauges used by Prada *et al.* (2009) may have influenced their results, as the canopy heterogeneity was probably misrepresented.

Even though the stemflow was not measured, it is expected to be negligible. Previous studies in a forest with similar tree species in the Canaries showed that stemflow was approximately 2.5% of throughfall (García-Santos *et al.* 2004). Such a low value can be explained because Macaronesian laurel forests usually develop in areas affected by high-intensity rain events, are formed by big trees with branches parallel to the ground and have high leaf area indexes. These factors favour throughfall instead of stemflow (Crockford and Richardson 2000). Even when subjected to low-intensity rainfalls, the presence of large communities of epiphytes is responsible for diverting and clogging the water drainage paths away from the trunks, increasing throughfall. Since TL is characterized by all of the above characteristics, it is expected that stemflow will be only a very small portion of total water input. Nevertheless, future studies should include the measurement of this parameter in order to maximize the reliability of the results.

Overall cloud water input was similar to that obtained by Prada *et al.* (2009) for the winter period (11%). Although the input percentage usually decreases in wetter months, the total input in volume is higher than in the drier months. Total amounts of cloud water are higher during wetter months, when storms, frontal systems and strong winds affect the island. However, cloud water seems to represent a larger fraction of the water budget during the drier months, when even a small amount can be proportionately high when compared with a low rainfall value, as in July (Fig. 3). Prada *et al.* (2009) suggested that, during a dry year, cloud water interception tends to play a more important role in the water budget (summer – 33%; winter – 11%).

A multiple linear regression test shows no significant difference between standard deviation and mean throughfall over time ($p < 0.001$). The relationships between standard deviation of the gauges and their average measured throughfall were not significantly different during Hour 1, Hour 2 and Following Hours after the beginning of the storm (Fig. 4). This indicates that the canopy was already saturated when it began to rain. In fact, if the canopy was not saturated, standard deviation among the throughfall gauges would be higher at the beginning of the event and it would gradually decrease and stabilize as the canopy became saturated (Brauman *et al.* 2010). This variation would be detected as a significant difference in the slopes of the regression lines between standard deviation and mean throughfall for the three different temporal periods. The multiple linear regression shows that the slopes are similar, so the canopy conditions between the three different periods must also have been similar. If they were different, it would mean that the canopy changed its conditions throughout the rain event, a fact that happens when it is dry and it starts to rain. Because they are not different, it means that it is already saturated or near saturation before the onset of a rain event. Although this did not happen during all events, the statistical test showed that this is a regular phenomenon throughout the year. *In situ* observation showed that most of the time, when it started to rain, the forest was wet and dripping water due to the presence of fog, while nearby clearings and rocks were still dry. Because the canopy is already wet when it starts to rain, the entrance of rain water inside the forest is also facilitated (García-Santos 2007, Brauman *et al.* 2010).

4.1 Cloud water as a water resource in Madeira

Temperate laurel forest is the most widespread type of native forest on the island, even though it covers only a small fraction of its original area. The area that it currently occupies is still not completely measured. Nevertheless, its potential area of occurrence (in which it would develop and occupy if human disturbance was not present) is already established in Madeira's potential vegetation model (Capelo *et al.* 2004, Mesquita *et al.* 2004). About 43 km^2 of TL potential area have similar climatic and physical characteristics to our study plot (S. Mesquita, personal communication, January 2011). They stand inside the cloud belt, between 800 and 1400 m a.s.l., and have steep slopes exposed to the NNE winds (Fig. 5). As such, it is possible to make a rough estimation of the volume of cloud water that could have been captured by Madeira's TL during the experiment, if the forest indeed occupied that area. The TL can be divided into two types, old-growth forest on one hand, and its successive stages from herbaceous plants to shrubs, on the other. It is reasonable to assume that only 75% of the total area would be naturally covered with old-growth, climatic forest, while the remaining 25% would correspond to a mosaic of younger secondary plant communities that occupy clearings inside the old-growth forest. These would be formed by natural disturbance, such as landslides and debris-flows. This secondary vegetation also has the ability to intercept cloud water, as stated by Prada *et al.* (2009). However, because the different vegetation communities that compose it are morphologically very varied and different from old-growth laurel forest, in order to simplify the estimation, we assumed that this mosaic did not contribute to cloud water interception.

We consider that an area of approximately 32 km^2 of the island is subject to climatic and geographical conditions similar to our study plot and was originally occupied by old-growth TL (75% of the

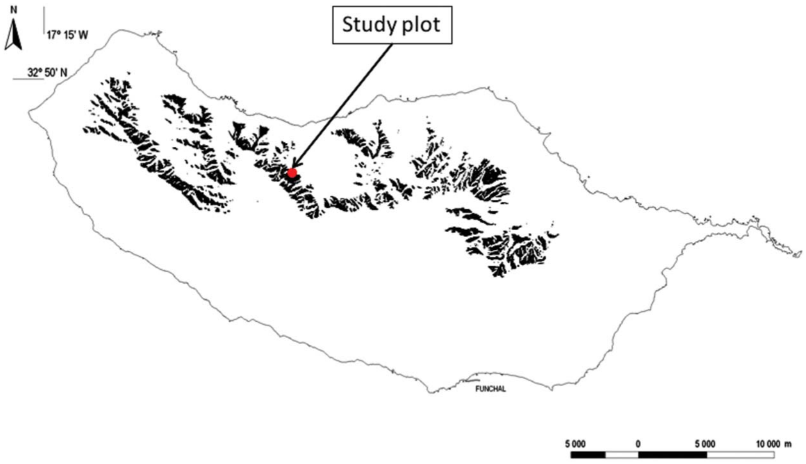

Fig. 5 Potential area of occurrence of TL that we consider to have similar conditions to the study plot (800–1400 m a.s.l. and north-northeast slope based on data from Mesquita *et al.* (2004)).

original 43 km^2). If we assume that inside the whole area, cloud water interception was similar to that on our plot (200 mm), cloud water could have contributed over 6 300 000 m^3 to the hydrological input of the area during the studied period. However, this extrapolation from the study plot to the entire forest should be interpreted cautiously. Although TL is a relatively uniform forest, there is structural variability as a consequence of small-scale canopy irregularities (tree architecture, understory shrubs, epiphyte cover, etc.) and small-scale topographic features that may interfere with cloud interception. Rugged terrain is responsible for the occurrence of microclimates that can shelter or expose forest patches. The slope inclination is also important. A steeper slope will be more exposed to a wind-driven cloud than a gentler one, consequently increasing cloud interception and *vice versa*. The cloud liquid water content should also be taken into account, as it varies with altitude, ranging from 0.01 g m^{-3} in the cloud base to 0.25 g m^{-3} in the middle and to 0.1 g m^{-3} in the cloud top (Frisch *et al.* 1994).

Even though the study plot corresponded to a typical old-growth TL (Costa *et al.* 2004) and stands in the windward margin of a wide valley, the extrapolation can only be used as a rough estimate. Nevertheless, it shows that even small cloud water volumes can, when summed up, represent a large input to the system, and that cloud water interception may play a key role for local ecosystems and groundwater resources.

Besides the direct input of water, the presence of orographic clouds and fog increase relative humidity and decrease insolation and temperature, thus decreasing evapotranspiration and water use by plants (Jímenez *et al.* 1996, García-Santos 2007, Ritter *et al.* 2008, 2009). This has important implications in the ecohydrology of TL, and its occurrence may be closely related to the frequency and altitudinal range of the cloud belt. This multistratified and complex forest needs high volumes of available water to be sustained. It does not withstand large periods of drought, especially when associated with hot summer months (Capelo *et al.* 2004). Typical TL trees, such as *L. novocanariensis*, transpire large quantities of water throughout the year, especially because the climate conditions in these latitudes permit a year-round growing season (Jímenez *et al.* 1996). In the desert of Central Chile, it was discovered that the vegetation that lives in fog-occurring areas is highly dependent on fog water (Aravena *et al.* 1989). It is also known that coast redwoods (*Sequoia sempervirens*) in California use this type of water, especially during the drier months (Dawson 1998). There are currently no data regarding this subject for Madeira's vegetation, but it is plausible that such a complex multistratified forest as the TL, riddled with bryophytes, lichens and ferns that need high levels of humidity to live and prosper (e.g. *Trichomanes speciosum*, *Hymenophyllum tunbringense*, etc.), uses water from cloud interception, especially during the drier periods, when rainfall is scarce and high levels of humidity results from the interaction with the cloud belt.

Cloud water interception also plays an important role in Madeira's groundwater, the island's major water supply source and the only one during summer (Prada 2000, Prada *et al.* 2005). There is evidence that groundwater is partly recharged by cloud water. The isotopic composition of groundwater (^{18}O and ^{2}H), especially in high-altitude springs associated with perched aquifers, is a mixture of rain and intercepted water from the clouds (Prada *et al.* 2010b). The rich humus soil layer that is formed under TL forests (Ricardo *et al.* 1992) acts like a sponge by retaining water and then releasing it slowly into the deeper ground layers, preventing surface runoff (Ward and Trimble 2004). In addition, the diminished evapotranspiration that results from the occurrence of frequent fog events and consequent diminished temperature and water use by plants (Ritter *et al.* 2009), favours infiltration and groundwater recharge.

Although legally protected, TL is threatened by a series of factors. Invasive species, especially *Acacia* sp., *Cytisus scoparius* and *Pittosporum undulatum*, have become a major threat to the forest (Jardim *et al.* 2007). In places where the vegetation cover was lost, due to human activity or natural phenomena, these species overlap the natural regenerative species and impede the development of TL (Jardim *et al.* 2007).

Climate change may also pose a threat. In the nearby Canary Islands, it is expected that the cloud belt will decrease in altitude and reduce the potential area of occurrence of laurel forests on the islands in more human pressured zones, where they may become even more scarce (Sperling *et al.* 2004). In Madeira, a climate change study by Santos and Aguiar (2006) admitted the possibility that TL would increase its upper altitudinal range to areas where it is not present today. However, this prediction is based only on the altitudinal temperature increase and does not take into account the interaction between the cloud belt and the vegetation. As the altitude of Madeira's cloud belt tends to decrease during warmer periods (McInnes 1981, Prada 2000), it can be expected, in our opinion, that in a future warmer climate, it will also decrease, in much the same way as in the Canary Islands (Sperling *et al.* 2004). Thus, it is doubtful that TL will increase its altitudinal range only due to warmer conditions at higher altitudes. Instead, it will probably follow the cloud belt, thus decreasing its entire altitudinal range towards more human pressed areas (A. Figueiredo, personal communication, February 2011), leading to the same problems as projected for the Canary Islands by Sperling *et al.* (2004). An effort to model this particular ecosystem is increasingly relevant in order to protect and manage it correctly.

5 CONCLUSIONS

Cloud water was 8% of TL's water budget during the studied period. Cloud water seems to have a larger role during drier periods. Similar observations were made during previous studies in the same type of vegetation, where, during a dry year, cloud interception was proportionally higher than that observed in this study (Prada *et al.* 2009).

The TL may play an important role in Madeira's water cycle. As a tall forest, it can capture water from the clouds that form on the windward island slope. In the absence of vegetation, this water would not be captured. However, the cloud belt is responsible for maintaining high relative humidity levels during rainless periods, and for diminishing evapotranspiration due to decreased insolation and temperature. This helps to sustain complex multistratified vegetation, especially during the dry months. The kind of soil on which TL develops also helps to retain water during both intense and light rain events. The high organic content of the soil makes it act like a sponge, absorbing great quantities of water and then releasing it slowly. This also helps to prevent peak volumes of superficial runoff during heavy showers, thus protecting Madeira's steep slopes from landslides and soil erosion and, at the same time, maintaining high levels of humidity in the ecosystem (Ward and Trimble 2004).

Besides its importance in terms of biodiversity, rarity and economy (tourism), TL occurs where the largest part of Madeira's water supply is collected. Regarding these factors, the forest should be given special attention. Nowadays, almost all the remaining areas of old-growth TL are within Madeira's Natural Park boundaries, where it remains relatively protected. However, menaces such as the advance of invasive species and climate change may pose a real threat to the biggest and most important area of laurel forest in the world. A comprehensive plan in which all the different aspects of this complex ecosystem are considered is necessary to correctly manage it.

Acknowledgements Special thanks to Investimentos e Gestão da Água (IGA, S.A.) and to INTERREG III B "AQUAMAC" project. We would also like to thank Arq. Sandra Mesquita for providing Figure 5 from her research data, Dr Nuno Aguiar and Dr Ana Pontes.

REFERENCES

Aravena, R., Suzuki, O., and Pollastri, A., 1989. Coastal fog and its relation to groundwater in the IV region of northern Chile. *Chemical Geology: Isotope Geoscience Section*, 79 (1), 83–91.

Brauman, K.A., Freyberg, D., and Daily, G., 2010. Forest structure influences on rainfall partitioning and cloud interception: A comparison of native forest sites in Kona, Hawai'i. *Agricultural and Forest Meteorology*, 150 (2), 265–275.

Bruijnzeel, L.A., 2001. Hydrology of tropical montane cloud forests: A Reassessment. *Land Use and Water Resources Research*, 1, 1.1–1.18.

Bruijnzeel, L.A., Eugster, W., and Burkard, R., 2005. Fog as a hydrologic input. *In*: Anderson, M. and McDonnell, J., eds. *Encyclopedia of Hydrological Sciences*. Chichester: John Wiley and Sons, 559–582.

Burgess, S.S. and Dawson, T., 2004. The contribution of fog to the water relations of *Sequoia sempervirens* (D. Don): foliar uptake and prevention of dehydration. *Plant, Cell and Environment*, 27 (8), 1023–1034.

Capelo, J., *et al*., 2004. Guia da excursão geobotânica dos V Encontros ALFA 2004 à ilha da Madeira. *In*: J. Capelo, ed. *A paisagem vegetal da ilha da Madeira – Quercetea 6*. Lisboa, Portugal: ALFA, 5–45.

Costa, J.C., *et al*., 2004. Catálogo sintaxonómico e florístico das comunidades vegetais da Madeira e Porto Santo. *In*: Capelo, J., eds. *A paisagem vegetal da ilha da Madeira – Quercetea 6*. Lisboa, Portugal: ALFA, 187–200.

Crockford, R.H. and Richardson, D., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes*, 14 (16–17), 2903–2920.

Cunha, F., 1964. O problema da captação da água do nevoeiro em Cabo Verde. *Garcia de Orta*, 12, 719–756

Davis, S.N. and DeWiest, R., 1991 *Hydrogeology*. Malabar, FL, USA: Krieger Publishing Company

Dawson, T.E., 1998. Fog in the redwood forest: ecosystem inputs and use by plants. *Oecologia*, 117 (4), 476–485.

Ech-Chakrouni, S., 2004. *Géochronologie et paléomagnétism de l'île de Madère et dês îles Desertas. Une contribution à la volcanostratigraphie et à l'évolution de l'archipel de Madère, et à l'échelle de polarité du champ magnétique*. Thesis (Ph.D). Vrije Universiteit Brussels.

Ekern, P.C., 1964. Direct interception of cloud water on Lanaihale, Hawaii. *Soil Science Society of America Journal*, 28 (3), 419–421.

Førland, E.J., *et al*., 1996. *Manual for Operational Correction of Nordic Precipitation Data*. Oslo, Norway: Norwegian Meteorological Institute.

Frisch, A.S., Fairall, C., and Snider, J., 1994. Measurement of stratus cloud and drizzle parameters in ASTEX with a

K_α-band doppler radar and a microwave radiometer. *Journal of Atmospheric Science*, 52 (16), 2788–2799.

García-Santos, G., 2007. *An ecohydrological and soils study in a montane cloud forest in the National Park of Garajonay, La Gomera (Canary Islands, Spain)*. Thesis (Ph.D), Vrije Universiteit, Amsterdam.

García-Santos, G., Marzol, M., and Aschan, G., 2004. Water dynamics in a laurel montane cloud forest in the Garajonay National Park (Canary Islands, Spain). *Hydrology and Earth System Sciences*, 8 (6), 1065–1075.

Goodman, J., 1985. The collection of fog drip. *Water Resources Research*, 21 (3), 392–394.

Holder, C.D., 2003. Fog precipitation in the Sierra de las Minas Biosphere Reserve, Guatemala. *Hydrological Processes*, 17 (10), 2001–2010.

Holder, C.D., 2004. Rainfall interception and fog precipitation in a tropical montane cloud forest of Guatemala. *Forest Ecology and Management*, 190 (2–3), 373–384.

Holder, C.D., 2006. The hydrological significance of cloud forests in the Sierra de las Minas Biosphere Reserve, Guatemala. *Geoforum*, 37 (1), 82–93.

Holwerda, F., *et al*., 2010. Rainfall and cloud water interception in mature and secondary lower montane cloud forests of central Veracruz, Mexico. *Journal of Hydrology*, 384 (1–2), 84–96.

IM (Instituto de Meteorologia), 2009. *Normais climatológicas 1961-90*. Lisboa, Portugal: Centro de Documentação Prof. Doutor J. Pinto Peixoto.

Jardim, R., Menezes de Sequeira, M., and Capelo, J., 2007. Madeira. *In*: J. Silva, ed. *Árvores e florestas de Portugal 6. Açores e Madeira. A Floresta das Ilhas*. Lisboa, Portugal: Público, Comunicação Social and Fundação Luso-Americana para o Desenvolvimento, 255–298.

Jímenez, M.S., *et al*., 1996. Laurel forests in Tenerife, Canary Islands the annual course of sap flow in *Laurus* trees and stand. *Journal of Hydrology*, 183 (3–4), 307–321.

Kittredge, J., 1948. *Forest influences*. New York, NY: McGraw-Hill.

Lloyd, C.R. and Marques, A., 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. *Agricultural and Forest Meteorology*, 42 (1), 63–73.

Lovett, G.M., 1984. Rates and mechanisms of cloud water deposition to a subalpine balsam fir forests. *Atmospheric Environment*, 18 (2), 361–371.

Lovett, G.M., Reiners, W., and Olson, R., 1982. Cloud droplet deposition in a subalpine balsam fir forests: hydrological and chemical inputs. *Science*, 218 (4579), 1302–1303.

McInnes, B., 1981. Site testing in Hawaii, Madeira and the Canary Islands. *Quarterly Journal of the Royal Astronomical Society*, 22, 266–271.

Mesquita, S., Capelo J., and Sousa, J., 2004. Bioclimatologia da Ilha da Madeira – Abordagem numérica. *In*: J. Capelo, ed. *A paisagem vegetal da ilha da Madeira – Quercetea 6*. Lisboa, Portugal: ALFA, 47–60.

Parsons, J.J., 1960. Fog drip from coast stratus, with special reference to California. *Weather*, XV, 58–62.

Prada, S.N., 2000. *Geologia e recursos hídricos subterrâneos da Ilha da Madeira*. Thesis (PhD), Universidade da Madeira.

Prada, S., Silva, M., and Cruz, J., 2005. Groundwater behaviour in Madeira, volcanic island (Portugal). *Hydrogeology Journal*, 13 (5–6), 800–812.

Prada, S., *et al*., 2008. Avaliação preliminar do contributo global da precipitação oculta para os recursos hídricos da ilha da Madeira. In: *Livro de resumos e CD-ROM das comunicações do 9° Congresso da Água*. 2–4 April 2008, Cascais – Portugal. Associação Portuguesa de Recursos Hídricos, 21.

Prada, S., *et al*., 2009. Fog precipitation and rainfall interception in the natural forests of Madeira Island (Portugal). *Agricultural and Forest Meteorology*, 149 (6–7), 1179–1187.

Prada, S., *et al*., 2010a. Response to "Comment on fog precipitation and rainfall interception in the natural forests of Madeira Island (Portugal)". *Agricultural and Forest Meteorology*, 150 (7–8), 1154–1157.

Prada, S., *et al*., 2010b. Contribution of cloud water to the groundwater recharge in Madeira Island: preliminary isotopic data. In: *Proceedings of the Fifth International Conference on Fog, Fog Collection and Dew*, 25–30 July 2010, Münster, Germany: Copernicus Meetings and University of Münster, Institute for Landscape Ecology Climatology.

Ricardo, R.P., Câmara, E., and Ferreira, M., 1992. *Carta dos solos da Ilha da Madeira. Região Autónoma da Madeira*. Lisboa, Portugal: Governo Regional da Madeira, Secretaria Regional da Economia and Direcção Regional de Agricultura.

Ritter, A., Regalado, C., and Aschan, G., 2008. Fog water collection in a subtropical elfin laurel forest of the Garajonay National Park (Canary Islands): a combined approach using artificial fog catchers and a physically based model. *Journal of Hydrometeorology*, 9 (5), 920–935.

Ritter, A., Regalado, C., and Aschan, G., 2009. Fog reduces transpiration in tree species of the Canarian relict heath-laurel forest (Garajonay National Park, Spain). *Tree Physiology*, 29 (4), 517–528.

Santiago, L.S., *et al*., 2000. Transpiration and forest structure in relation to soil waterlogging in a Hawaiian montane cloud forest. *Tree Physiology*, 20 (10), 673–681

Santos, F.D. and Aguiar, R. (eds.), 2006. *Impactos e medidas de adaptação às alterações climáticas no Arquipélago da Madeira – Projecto CLIMAAT II*. Funchal, Portugal: Direcção Regional do Ambiente da Madeira.

Schemenauer, R. and Cereceda P., 1991. Fog-water collection in arid coastal locations. *Ambio*, 20 (7), 303–308.

Schemenauer, R., Cereceda P., and Carvajal, N., 1987. Measurements of fog water deposition and their relationships to terrain features. *Journal of Climate and Applied Meteorology*, 26 (9), 1285–1291.

Shuttleworth, W.J., 1977. The exchange of wind-driven fog and mist between vegetation and the atmosphere. *Boundary-Layer Meteorology*, 12 (4), 463–489.

Sperling, F.N., Washington, R., and Whittaker, R., 2004. Future climate change of the subtropical North Atlantic: implications for the cloud forests of Tenerife. *Climatic Change*, 65 (1–2), 103–123.

Twomey, S., 1957. Precipitation by direct interception of cloud water. *Weather*, 12, 120–122.

UNESCO, 2008. *The criteria for selection* [online]. UNESCO World Heritage Centre 1992–2012. Available from: http://whc.unesco.org/en/criteria/ [Accessed 16 March 2012].

Ward, A.D. and Trimble, S., 2004. *Environmental hydrology*. 2nd ed. Boca Raton, FL: Lewis Publishers.