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Cloud water interception in the high altitude tree heath forest (*Erica arborea* L.) of *Paul da Serra* Massif (Madeira, Portugal)

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Abstract:

Cloud water interception (CWI) occurs when cloud droplets are blown against the forest canopy, where they are retained on the vegetation surface, forming larger water droplets that drip into the forest floor. CWI was measured from 1 October 1997 to 30 September 1999, on a first-line tree heath (*Erica arborea*), at *Bica da Cana*, Madeira Island. Rainfall was corrected for wind-loss effect and compared with throughfall and other climatological normals. The CWI depletion rate along a forest stand transect was also analysed during three distinct fog events in 2008. Cloud water was 28 mm day^{-1}, corresponding to 68% of total throughfall and 190% of the gross precipitation. Cloud water correlates directly with monthly normals of fog days and wind speed and correlates inversely with the monthly air temperature normal. CWI has an exponential correlation with monthly relative humidity normal. Cloud water capture depletion along the stand shows a logarithmic decrease. Although a forest stand does not directly relate to a first-line tree heath, this study shows that CWI is a frequent phenomenon in the *Paul da Serra* massif. Restoration and protection of high altitude ecosystems in Madeira should be a priority, not only for biodiversity, ecological and economical purposes but also for its role in regional water resources. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS cloud water interception; throughfall; water resources; *Erica arborea*; Madeira Island; depletion rate

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INTRODUCTION

Cloud water interception (CWI) is a phenomenon that occurs when cloud droplets are retained on foliar and woody surfaces as the cloud base passes through the vegetation (Holder, 2003, 2004). When wind and a ground touching cloud base persists long enough for cloud droplets to coalesce on vegetation surfaces, the canopy becomes saturated and drips to the forest floor. Several studies have shown that fog and cloud water, in addition to reducing evapotranspiration losses from soil and vegetation, enhance the water yield and contribute with significant quantities of water to the hydrological cycle in foggy ecosystems (Byers, 1953; Oberlander, 1956; Twomey, 1957; Parsons, 1960; Ekern, 1964; Vogelmann *et al*., 1968; Azevedo and Morgan, 1974; Harr, 1982; Goodman, 1985; Ingraham and Matthews, 1988, 1995; Aravena *et al*., 1989; Marzol *et al*., 1996; Dawson, 1998; Bruijnzeel, 2001; Holder, 2003, 2004; García-Santos *et al*., 2004; Liu *et al*., 2004; Scholl *et al*., 2007; Prada *et al*., 2009; Brauman *et al*., 2010; Holwerda *et al*., 2010 etc). Madeira Island forms an EW-oriented barrier, almost perpendicular to the prevailing north-eastern trade winds. Its northern slope is usually covered by a thick (*ca* 800 m) orographic cloud belt, locally named '*mar de nuvens*' (sea of clouds), that forms when the moist wind-driven air masses are pushed up by the mountain range and adiabatically cool down, thus condensing their moisture and originating clouds that form a layer between 800 and 1600 m a.s.l. (Prada *et al*., 2005). These clouds normally envelop the ground and originate thick fogs and orographic precipitation which occurs along two thirds of the time during most of the year (Instituto de Meteorologia—IM). This phenomenon is also common in other oceanic islands, such as the Canaries and Hawaii (Marzol *et al*., 1996; Marzol, 2003; García-Santos *et al*., 2004; Scholl *et al*., 2007), where it has an important role in local ecohydrology.

The small water droplets that comprise cloud water (fog and, occasionally, drizzle) do not readily precipitate out of air unless they encounter the surface of solid objects, as the vertical settling rate is too slow (Cunha, 1964; Davis and De Wiest, 1991). As a consequence, cloud water rarely registers on a typical rain gauge and is therefore termed occult (hidden) precipitation. Precipitation of cloud water droplets mostly occurs by horizontal interception in vertical or near vertical surfaces (Schemenauer and Cereceda, 1994). According to Kerfoot (1968), plant canopies, which are fairly permeable

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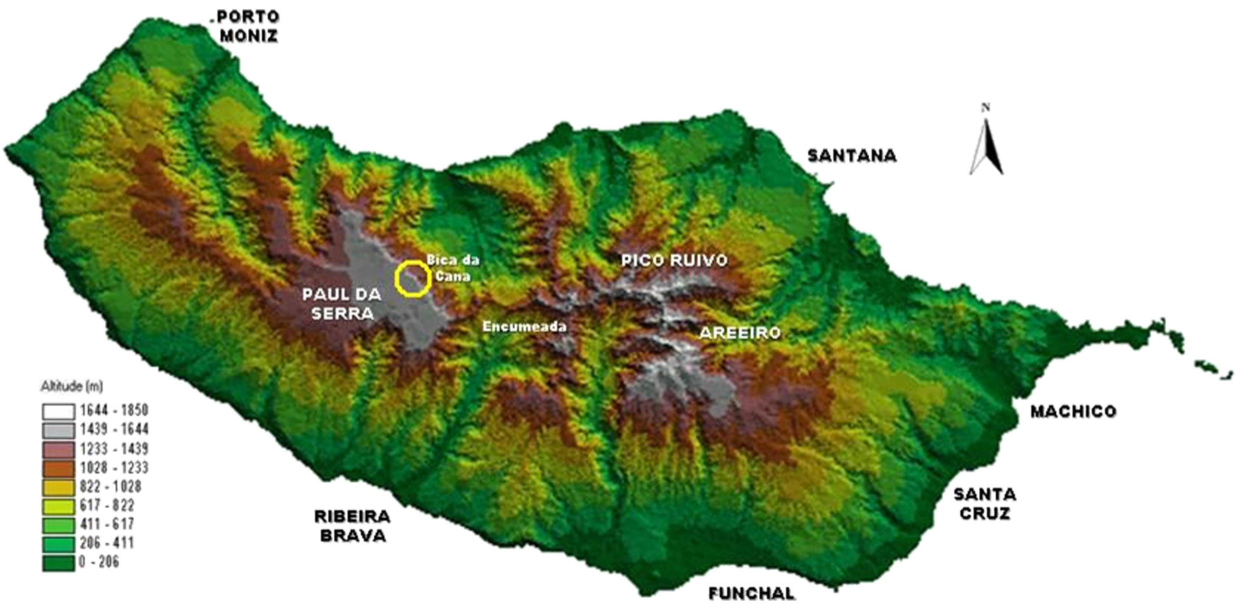

Figure 1. Location of the study area—*Bica da Cana*, at *Paul da Serra* massif

to the through-flow of air and have a large surface area, are ideal cloud water collectors.

The amount of fog precipitation (or CWI) in the different natural forests that occur inside Madeira's cloud belt was recently published (Prada *et al*., 2009, 2010a). Among them, the high altitude tree heath forest (*Polystichum falcinelli–Ericetum arboreae* association, hereafter *TH*) showed an ability to capture significantly more cloud water than the other forest associations. *TH* is the potential climax vegetation between 1400 and 1650 m a.s.l. (Mesquita *et al*., 2004). This forest is dominated by tree heaths (*Erica arborea* L.), a native species in the archipelago. It is thought that this community was originally co-dominated by *Juniperus cedrus maderensis* (Madeira island's juniper), but, in the present, due to overexploitation, it is extremely rare in the wild (Capelo *et al*., 2004). Since the twenty-fifth century, *TH* has been subjected to severe human impact by fire, wood cutting for charcoal and overgrazing (Menezes de Sequeira *et al*., 2007), leading to a critical conservation status. Nowadays, only a few small woods persist (less than 1% of the *TH* potential area of occurrence).

In this study, CWI under a mature tree heath (*E. arborea*) in the first line (windward side) of a high altitude tree heath forest in Madeira Island is analysed. For that purpose, the data obtained in Prada *et al*. (2009) and corrected for rainfall wind loss (Førland *et al*., 1996; Prada *et al*., 2010a) were used. The objectives were to analyse the interaction between cloud interception, throughfall and gross precipitation and how cloud interception relates to the local climatological normals [relative humidity, temperature, fog days and wind speed (WS)]. The depletion rate of CWI along a 400-m transect across the tree heath forest, from the well-exposed windward side to the more protected leeward side, is also analysed.

MATERIAL AND METHODS

Study site

Situated between 32°38′ and 32°52′N and 16°39′ and 17°16′W, Madeira is an intraplate volcanic island, approximately 600-km northwest of the Western African coast. It has a 737-km^2 surface, 58-km by 23-km and a maximum altitude of 1861 m a.s.l. (*Pico ruivo*). The island forms an EW-oriented barrier, concave in the north and cut by deep valleys and vertical cliffs.

As the island forms a barrier almost perpendicular (EW) to the prevailing north-eastern trade winds, temperature and rainfall vary remarkably between the northern and southern slopes. The northern slope is more humid than the southern one at the same height and rainfall increases with altitude on both slopes (Prada *et al*., 2003, 2005). The study site was located in a small tree heath forest at *Bica da Cana* (1580 m a.s.l.), in the north-eastern tip of *Paul da Serra* plateau (Figure 1, circled area). This place was selected because it has a relatively well-preserved tree heath forest cover, is exposed to all wind directions and is frequently covered by fog (average of 235 days of fog per year during 1961–1990—IM).

This high-altitude tree heath forest (5·6 ha) has a mostly homogenous height stand of about 5 m with some sporadic clearings and is mainly composed of young adult tree heaths with some scattered old-growth individuals, especially at the borders (Figure 2). According to Mesquita *et al*. (2004), the area is characterized by a temperate macrobioclimate, superior mesotemperate termotype and ultrahyperhumid ombroclimate, exposed to winds from all directions, with prevailing north-eastern direction (31% of the time). The WS average is 4·1 m s^{-1} (about 15 km h^{-1}) and average annual air temperature is 9·3 °C (Prada, 2000).

Madeira old-growth *E. arborea* specimens are imposing trees that can reach up to 8-m high and have trunk diameters up to 1 m. However, the larger individuals

Figure 2. First-line tree heath (old-growth *Erica arborea*—left) and high altitude tree heath forest at *Bica da Cana* (right)

are currently very rare. Mature individuals show distal branching and well-defined trunk, apical part of the branches dropping, leaves 3–4 × 1 mm linear with revolute margins (McClintock, 1994; Jardim *et al.*, 2007). The first-line tree heath (32°45′23″N; 17°03′25″W) was 7-m high and had a diameter of 30 cm at 40-cm height. Above this height, it branched into two large stems that remained undivided up to 180 cm. It had a near elliptical canopy and a projected area of 69·5 m^2 (major axis 5·75 m, minor axis 3·85 m). It was heavily covered by epiphytical mosses and lichens. Some branches doubled their diameter due to this thick cover. All the above characteristics are typical of an old-growth adult tree (Figure 2). The neighbouring heaths were similar to this one and the trunks were separated by at least 3 m. However, their branches were intertwined and formed a continuous canopy.

First-line tree heath

Throughfall was measured in the first-line tree between October 1997 and September 1999. Two fixed rain gauges (0·357-m diameter) were placed under the tree. To obtain a better representation of cloud water drip under the canopy, one gauge was positioned on the leeward of the tree and the other on the windward. Data correspond to the arithmetic average of the values registered by the two fixed rain gauges. Rainfall was measured with an identical gauge at the same altitude. Because *Bica da Cana* is a windy mountainous area, rainfall values were corrected for wind losses in the gauge. A simple model correction was used (Førland *et al.*, 1996), as there was no instant wind and rain intensity data for the studied period (Prada *et al.*, 2010a). A class 4 correction factor ($k = 1{\cdot}166$) was applied, because the raingauge was installed in a small depression near a forest stand that provides some protection against the wind. Correction due to slope effects was not necessary, as the area has a very gentle slope (García-Santos, 2007).

Because of the low number of throughfall gauges, the CWI values were checked for consistency using three large diameter gauges (0·28 m^2 each) in a 'roving gauge arrangement' (Lloyd and Marques, 1988). They were used during intense fog periods without rain and the cloud water volumes that they measured were consistent with the ones captured by the fixed throughfall gauges (Prada *et al.*, 2010a). Monthly normals (1961–1990) of air temperature, WS and direction, relative humidity and number of fog days were registered by a Portuguese Meteorological Institute's (IM) weather station at *Bica da Cana*.

CWI values were obtained from the canopy interception Equation (1) (Crockford and Richardson, 2000; Bruijnzeel, 2001; Holder, 2003, 2004).

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

where I is the interception, P_{gross} the gross precipitation and P_{net} the net precipitation.

Stemflow was not measured and throughfall was considered equal to the net precipitation (Bruijnzeel, 2001; Bruijnzeel *et al.*, 2005).

Whenever canopy interception is negative, CWI is considered to have occurred and its value equalled the absolute value of I. Using the absolute canopy interception average values in the days in which cloud drip is considered to have occurred, the input of CWI in the ecosystem can be inferred [Equation (2)—CWI is cloud water interception (mm day^{-1})]:

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

The real volume of CWI is not, however, equal to the difference between net and gross precipitation (when the first exceeds the second), since evaporation and storage of fog water during canopy interception was not taken into consideration (Bruijnzeel, 2001; Holder, 2003, 2004). Cloud interception is often underestimated, because its contribution to throughfall is only quantified whenever net precipitation is higher than gross precipitation. Cloud water volume present in the days when canopy interception is positive was ignored as well as cloud water volume that compensates for rain water intercepted by vegetation in the days when the canopy interception value is negative. However, because it is very difficult to equate the different water source proportions in the throughfall, in this article, CWI is considered to only have occurred when throughfall exceeded rainfall.

CWI depletion along a forest transect

When a cloud passes through a forest in a gentle or inexistent slope, it experiments depletion in the CWI rate (Barry and Chorley, 2003). This is due to a decrease in wind velocity and cloud liquid water content. Forests prevent both the lateral and the vertical movement of the air, so, as the wind penetrates the stand, it rapidly decreases its velocity until it becomes negligible, depending on its original speed. Also, as cloud droplets are collected in the more exposed parts of the stand, the more sheltered parts collect fewer ones. As such, CWI conditions are best in the most exposed part of the forest stand (first-line or windward), decreasing beyond this point (Barry and Chorley, 2003). As it stands in the *Paul da Serra* plateau, the heath tree forest at *Bica da Cana* lays in an almost horizontal slope.

The CWI depletion along the forest stand was measured during three fog periods in 2008. All periods were characterized by intense fog (less than 2- to 3-m visibility) with no rainfall detected in the rain gauge at least 2 h before the beginning of the experiment. The wind blew steadily from northeast during these three periods. A 400-m transect in the *Bica da Cana* tree heath stand was set. It was oriented in a NE-SW direction and was divided into eight 100-m^2 plots that were disposed 50 m apart from each other along the transect, from the windward to the leeward side. The vegetation in each plot was very similar and homogenous between each other. Tree species composition was identical (only *E. arborea* was present) and their height (about 4 m), structure, epiphytic cover and tree density (128 ± 12·2 trees/plot) was essentially the same. The similar characteristics among the plots indicate a similar age for the most part of the stand. Ten collecting gauges, with an area of 0·045 m^2, were randomly placed in each plot under the canopy and left to capture throughfall for about 5 h each. After that, the throughfall volume was measured with a volumetric recipient and an arithmetic mean was calculated for each plot.

RESULTS

First-line tree heath

Results are presented as monthly totals. Table I and Figure 3 show the results obtained over the 24-month period (October 1997–September 1999) and indicate

Table I. Measurements during the study period

Date	Days	Precipitation (mm)	Throughfall (mm)	Cloud water interception (mm)	Canopy interception (mm)
Oct-97	24	481·6	959·7	501·3	−478·1
Nov-97	30	335·1	451·9	226·0	−116·8
Dec-97	26	319·7	829·5	526·1	−509·8
Jan-98	31	543·0	1027·2	501·8	−484·2
Feb-98	28	386·3	1002·0	616·4	−615·7
Mar-98	29	127·4	394·8	272·7	−267·3
Apr-98	30	169·1	1166·7	998·7	−997·6
May-98	31	187·1	698·6	538·8	−511·5
Jun-98	30	105·2	469·0	373·1	−363·8
Jul-98	31	19·2	156·1	141·1	−136·9
Aug-98	31	4·2	89·0	85·5	−84·8
Sep-98	30	85·4	39·2	16·8	46·2
Oct-98	31	38·2	140·3	112·7	−102·1
Nov-98	30	304·1	606·3	427·2	−302·2
Dec-98	23	221·7	692·9	471·2	−471·2
Jan-99	29	527·8	1081·5	704·4	−553·7
Feb-99	23	125·9	466·6	366·8	−340·7
Mar-99	28	29·1	782·4	567·5	−753·3
Apr-99	30	110·3	349·9	257·6	−239·6
May-99	31	86·4	123·7	54·2	−37·3
Jun-99	25	19·6	42·6	27·9	−23·0
Jul-99	31	11·8	88·7	79·4	−76·9
Aug-99	26	40·5	105·8	72·8	−65·3
Sep-99	30	208·8	597·6	397·9	−388·8
Total	688	4487·5	12362	8337·9	−7874·4

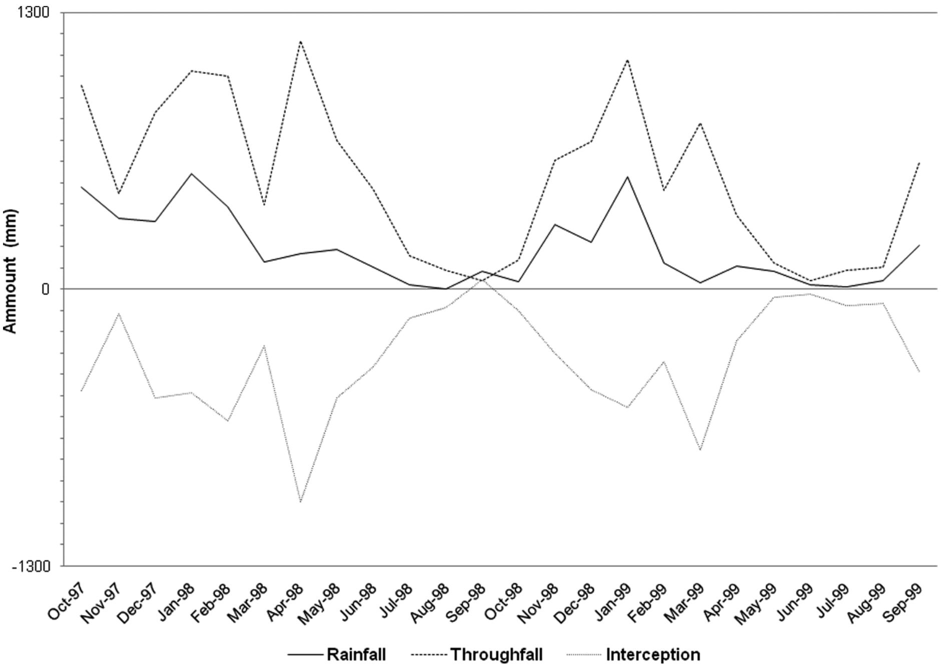

Figure 3. Rainfall, throughfall and interception patterns during the sampled period

the monthly number of sampled days, precipitation, throughfall, CWI and canopy interception totals for them.

Monthly throughfall always exceeded rainfall except for September 1998, and lower differences were attained during summer. Canopy interception was always negative, as expected, except for September 1998, providing evidence of a water source other than rainfall (positive canopy interception values indicate the presence of water from cloud interception).

Throughfall correlates with precipitation ($R^2 = 0{\cdot}64$—Figure 4) and throughfall is linearly correlated with CWI ($R = 0{\cdot}95$—Figure 5).

CWI monthly average (based on the two sampled years) was plotted against the monthly WS normal as well as against the average number of fog days in *Bica da Cana*. Figure 6 shows that in months with lower average WSs (such as in summer), CWI totals are also lower. The opposite occurs during the windier winter months. CWI is strongly correlated with WS ($R^2 = 0{\cdot}82$—Figure 6).

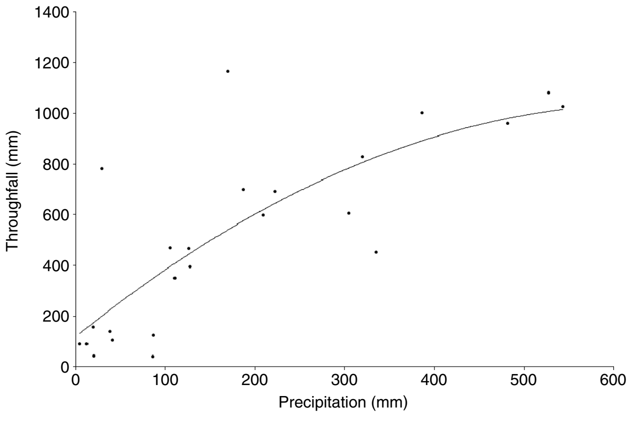

Figure 4. The relationship between throughfall and gross precipitation ($P_{\text{net}} = -0{\cdot}0022 \times P_{\text{gross}}{}^2 + 2{\cdot}86 \times P_{\text{gross}} + 118{\cdot}92$; $R^2 = 0{\cdot}64$)

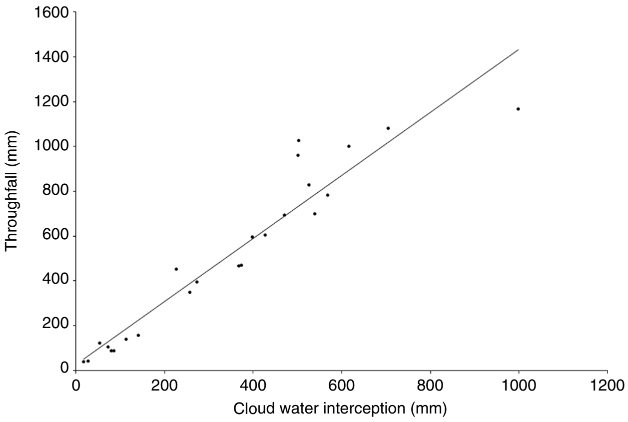

Figure 5. The relationship between throughfall and cloud water interception ($P_{\text{net}} = 27 + 1{\cdot}41 \times \text{CWI}$; $R = 0{\cdot}95$)

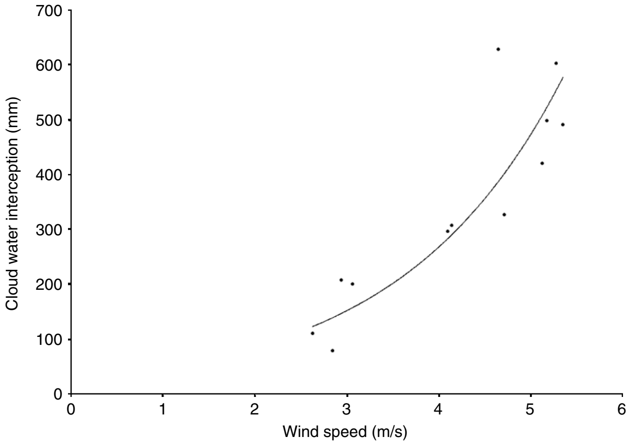

Figure 6. The relationship between monthly average of cloud water interception and wind speed ($\text{CWI} = 27{\cdot}52e^{0{\cdot}569\times \text{Ws}}$; $R^2 = 0{\cdot}82$)

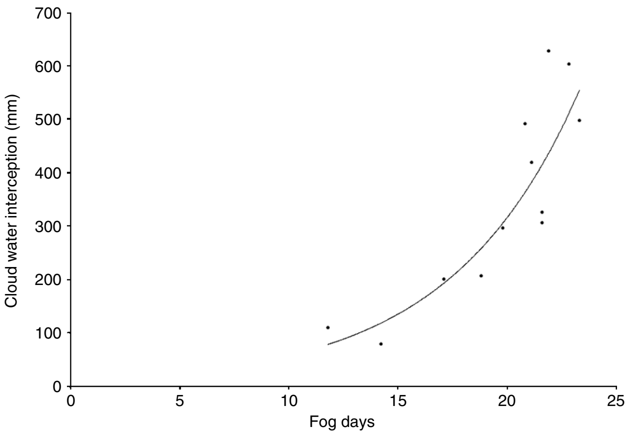

Figure 7. The relationship between monthly average of cloud water interception and monthly normal of fog days ($CWI = 10{\cdot}579e^{0{\cdot}17Fd}$; $R^2 = 0{\cdot}84$)

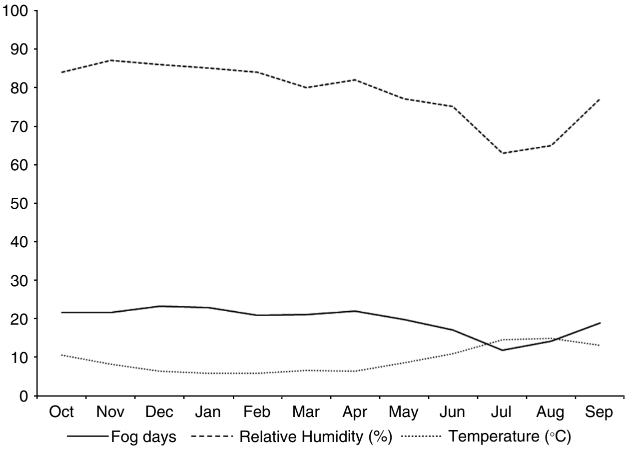

Figure 8. Relative humidity, number of fog days and air temperature monthly normals at *Bica da Cana* (1961–1990)

There is also a strong exponential correlation between CWI and the monthly normal of fog days ($R^2 = 0{\cdot}84$—Figure 7).

Figure 8 shows the relationship between fog days, relative humidity and air temperature normals. The number of fog days is, as expected, negatively correlated with air temperature ($R = -0{\cdot}87$) and has a strong positive correlation with relative humidity ($R = 0{\cdot}97$).

Monthly CWI has a strong negative correlation with the monthly air temperature normal ($R = -0{\cdot}92$—Figure 9) and an exponential correlation with relative humidity ($R^2 = 0{\cdot}79$—Figure 10). Monthly CWI also has an exponential correlation with relative humidity ($R^2 = 0{\cdot}79$—Figure 10).

Results obtained under the first-line tree heath at *Bica da Cana* correspond to a 688-day timeframe, between October 1997 and September 1999 (Table II). In the days when it was registered, CWI was, on average, 28 mm day^{-1}. This value corresponds to an average of 4169 mm of cloud water and 148 productive days per year. CWI was much higher than the average precipitation value of 2243·7 mm that occurred during the study (1961–1990 normal for this site is 2966 mm—IM). Our results are similar to the ones obtained by Kittredge (1948) that states that fog drip may fold rainfall values by two or three times. The average canopy interception was −201%, while CWI adds 68% to the throughfall or 190% to the gross precipitation to the hydrologic input in this first-line heath tree.

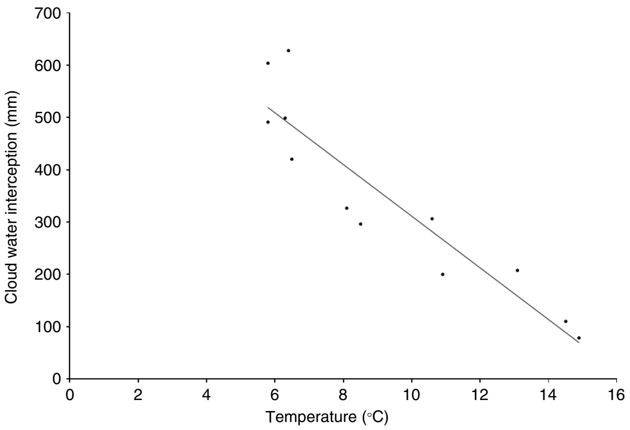

Figure 9. The relationship between monthly average of cloud water interception and monthly temperature normal ($CWI = 805{\cdot}4 - 49{\cdot}34 \times T$; $R = -0{\cdot}92$)

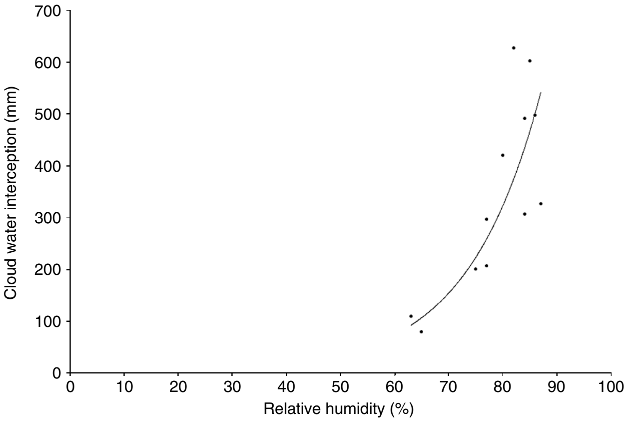

Figure 10. The relationship between cloud water interception monthly average and relative humidity monthly normal ($CWI = 0{\cdot}875e^{0{\cdot}0739RH}$; $R^2 = 0{\cdot}79$)

CWI depletion along the forest

CWI depletion was sampled during three distinct events of 5-h each. Figure 11 shows the complete forest transect, from the windward side to the leeward (10-gauge average). The values in the last strip are signalled because of possible drift effects that could have influenced cloud interception.

The correlation between plots for each event is strongly logarithmic. It shows a rapid decrease in CWI from the first line towards the interior where it tends to stabilize. It is also possible to see that the leeward plot of the stand (350) appears to yield more water than its immediate predecessor (300). This makes the correlations between plots weaker than when the last plot values are removed. Table III summarizes the results obtained, including the average CWI from the stand.

Table II. Results summary

	97/98	98/99	97/99
Sampled days	351	337	688
Productive days	155	141	296
Productive days (%)	44	42	43
Gross precipitation (mm)	2763·3	1724·2	2243·7
Throughfall (mm)	7283·7	5078·3	6181
Canopy interception (mm)	−4520·3	−3354·1	−3937·2
Canopy interception (%)	−207	−195	−201
Cloud water interception (mm)	4798·3	3539·6	4169
Cloud water interception (mm/day)	31	25	28
Cloud water interception input (% of throughfall)	66	70	68
Cloud water interception input (% of gross precipitation)	174	205	189·5

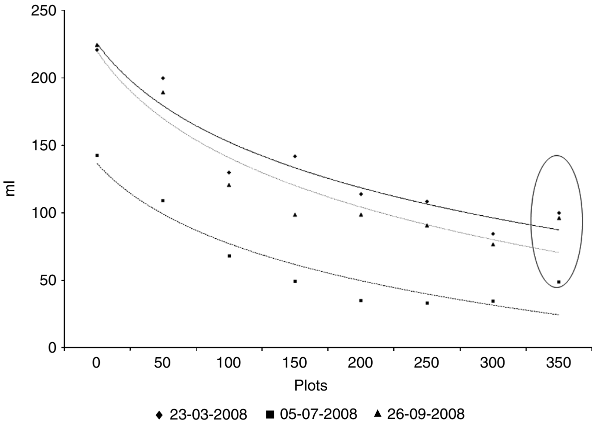

Figure 11. Throughfall captured along the tree heath stand. '0' corresponds to the first line, in the windward position. The leeward border plot (circled) shows an increase in collected throughfall

DISCUSSION

First-line tree heath

The correlation between throughfall and gross precipitation ($R^2 = 0\cdot64$) is not as strong as the correlation between throughfall and CWI ($R = 0\cdot95$). The observed deviations in the first correlation are not completely random, showing heavy influence of cloud water in throughfall.

Reliable data for rainfall, throughfall and stemflow are essential to interception estimation (Crockford and Richardson, 2000). Because stemflow was not measured, canopy interception may be overestimated. Empirical observations of local tree heaths seem to point that stemflow may represent a significant portion of the water that reaches the forest ground (Prada *et al.*, 2010a). Bruijnzeel (2001) refers that in certain upper montane cloud forests, similar to the heath tree forest, stemflow can reach 18% of total rainfall. However, because this first-line tree heath crown morphology is similar to a broad-leafed one (horizontal stems and twigs and round shaped), it is expected that stemflow in here is not as high as in those trees mentioned by the author.

The low number of throughfall gauges may have introduced some uncertainty in our results. Bruijnzeel (2001) and Bruijnzeel *et al.* (2005) state that a large number of gauges (usually more than 20) should be used for a proper quantification of net precipitation amounts to account for the spatial variability of rain forest canopies. However, the same author refers to a number of similar experiments that used a variable number of gauges (from only 2 to 58). The high volumes of cloud water were also confirmed by three 0·28-m^2 gauges used during rainless fog periods (average value was 8·2 mm h^{-1}, ranging between 7 and 9·5 mm h^{-1}; Prada *et al.*, 2010a). They show that it is plausible that in a full intensive fog day, frequent at Madeira's northern slope, the total amount of CWI can reach, in the first line, values as high as 200 mm day^{-1} (Prada *et al.*, 2010a).

According to Schemenauer (1986), key factors affecting the rate and amount of fog deposition include WS, cloud liquid water content, collecting surface area and geometry (including height) of the vegetation and the event-length. The high cloud water volumes obtained can be explained by several factors that can be divided in vegetation type and plant morphology as well as climatic

Table III. Results summary

Plot	23-03-2008 (ml)	05-07-2008 (ml)	26-09-2008 (ml)
0	221	142·5	224·5
50	200	109	189·5
100	130	68	121
150	142	49·5	99
200	114	35	99
250	108·5	33·5	91
300	84·5	34·5	77
350	100	49	96·5
Mean stand cloud water interception (mm h^{-1})	0·61	0·29	0·56
All plots' depletion equations	$y = -66\cdot3\ \ln(x) + 225\cdot4$ $R^2 = 0\cdot92$	$y = -53\cdot8\ \ln(x) + 136\cdot5$ $R^2 = 0\cdot89$	$y = -71\cdot6\ \ln(x) + 219\cdot6$ $R^2 = 0\cdot90$
All but last plot depletion equations	$y = -70\cdot1\ \ln(x) + 228\cdot2$ $R^2 = 0\cdot93$	$y = -61\cdot3\ \ln(x) + 142\cdot1$ $R^2 = 0\cdot96$	$y = -79\cdot5\ \ln(x) + 225\cdot5$ $R^2 = 0\cdot95$

factors (González, 2000). Among the first group are the following:

- Optimum morphology and architecture, characteristics of a mature tree heath. Went (1955) verified that very small needle-like leaf surfaces are much more efficient in capturing fog water. The sampled *E. arborea* tree is a tall plant, with distal branching, a well-defined trunk, characteristic of an old-growth individual, apical part of the branches dropping and short and dense linear leaves (with revolute margins), 3–4 × 1 mm. This originates a large capture surface and facilitates cloud droplets impaction and capture (Shuttleworth, 1977).
- A very abundant epiphytical cover of mosses and lichens contributes not only to the increase in capture area but also to the increase in dropping effect. In fact, the pendent structure of both mosses and lichens facilitate the dropping of water to the soil and diminishes stemflow (Crockford and Richardson, 2000).

The climatic factors favouring CWI are

- Optimum location in the first line of the stand, near the crest line just slightly upwind as referred by Schemenauer and Cereceda (1994) for an ideal location.
- High fog frequency at 1580 m (Figure 9, distribution over the year—average 235 fog days per year) as compared with other studied sites (Schemenauer and Cereceda, 1994; Zimmermann and Zimmermann, 2002). The criterion 'fog day' describes fog intensity only in a very limited way, since it is defined by the presence of a single daily event, when the horizontal visibility ranges below 1 km and does not consider fog density, persistance or droplet size. Nevertheless, it is the only available long-term climatological fog characterization for the area and the correlation with CWI is strong ($R^2 = 0{\cdot}84$). This shows that cloud water capture occurs normally during fog events. The exponential relation is related to the cumulative effect of continuous fog events. Longer fog periods contribute much more than isolated fog events and available data of 'number of fog days' reflect the monthly number of fog days normal. Although this is a rough estimate of continuity, it nevertheless expresses the 'lag' effect of water being captured by the trees and dripping to the soil. Water dripping depends on the saturation of epiphytes such as mosses, so the presence of epiphytes increases the lag effect mentioned above.
- High average WSs at 1580 m (4·1 m s^{-1}, about 15 km h^{-1}) contribute to high potential rates of cloud droplet capture (Lovett *et al.*, 1982; Schemenauer *et al.*, 1988; Cameron *et al.*, 1997; Chang *et al.*, 2006). The strong correlation ($R^2 = 0{\cdot}82$) found between average WS and CWI is similar to the results by other authors such as Lovett (1984) and shows a clear strong positive correlation between WS and water flux and the capital importance of wind in fog water capture. Higher WSs result in a higher volume of clouds passing through a collection surface, which increases cloud droplet interception and captured cloud water.
- High cloud liquid water content at 1580 m (0·17 g m^{-3}, Frisch *et al.*, 1994) and large water droplets (about 40 μm, Frisch *et al.*, 1994) strongly contribute to increased water capture efficiency (Shuttleworth, 1977; Lovett, 1984; Schemenauer and Cereceda, 1994; Cameron *et al.*, 1997).
- Relative humidity is usually high (mean daily values of 100% are frequent—IM) with monthly normal values over 85% from October to April, and normal values of about 70% only attained in July and August. According to Lovett (1984), the evaporation rate decreases as relative humidity increases. In fact, the number of fog days is strongly correlated with relative humidity ($R = 0{\cdot}97$). High relative humidity values are an indication that fog and, consequently, CWI are frequent in the area. When present, fog also significantly reduces evaporation (Bruijnzeel, 2001; Bruijnzeel *et al.*, 2005; Ritter *et al.*, 2008). This reduction may increase the throughfall yield. Nevertheless, Lovett (1984) refers that CWI is more sensitive to WS, cloud liquid water content and droplet size than to relative humidity and net radiation.
- Temperature varies, as expected, inversely with relative humidity and number of fog days. The summer high temperatures lead to the reduction in relative humidity. The higher temperatures are found in July and August and they further enhance the evaporation of water captured during short cloud interception events. CWI has, as expected, a strong negative correlation with air temperature ($R = -0{\cdot}92$).

CWI depletion along the forest transect

Results show that the first plot had the highest cloud interception values. This was expected as it represents the first line of trees. Collected throughfall values follow a logarithmic path. The leeward plot ('350') showed an increase in throughfall values due, possibly, to a drift effect, similar to the snowdrift observed during snowstorms (Whiteman, 2000). As the wind passes above a barrier, it must come back down to surface in its lee side, as the barrier ends. Since this descent is not immediate, the lee areas nearer to the obstacle are sheltered from the airflow passing above. In this area, eddies are frequent, though they are usually characterized by low wind velocities. However, despite the average low velocity, these eddies tend to be gusty and turbulent, thus promoting the deposition of cloud droplets in the vegetation (Whiteman, 2000; Barry and Chorley, 2003; Barry, 2008). Due to this, the depletion equations correlate better when the last plot is not included. This depletion was expected, since both wind velocity and cloud water content decrease along the stand. The smoother decrease in the CWI towards the interior may be explained by the entrance in the stand of small parts of the air mass passing above the canopy, due to the occurrence of turbulence and small eddies originating in small variations in stand height (González, 2000; Barry and Chorley, 2003).

The proportional difference between the first and the last line ('300' plot) is higher when there is a smaller amount of CWI. On 5 July, the difference was 3 : 1, whereas on the other 2 days, it was only 2·25 : 1. Lower wind velocities and/or cloud liquid water content may be a reason for this. It appears to demonstrate that the less water captured in the first line, the faster is the depletion rate towards the interior.

The sampled events were few and should be used carefully, because they may not represent the real processes that occur inside this type of forest. However, the fact that the plots were very similar between each other (tree density, height, leaf area index (LAI), moss cover and slope inclination) makes us suppose that this depletion follows a logarithmic decrease. Similar measurements in the future would be useful to provide enough data to determine a general equation for cloud water depletion along tree heath forest in a flat or almost flat area. The plateau is under a reforestation program and this information may be useful to future water balance, ecological modelling and environmental management and restoration of the area.

CONCLUSIONS

CWI was conservatively estimated in the sampled first-line tree, since it was only measured when throughfall exceeded rainfall. Due to this, cloud water contribution to the annual water budget may be greater than 68% of the throughfall (Prada *et al.*, 2009, 2010a). Cloud water is also underestimated because stemflow was not measured so, although the proportion of cloud water in stemflow is unknown, it could likely produce larger daily amounts of CWI. Nevertheless, similar heath forests may have stemflow rates of 2·8% of gross rainfall (García-Santos *et al.*, 2004). The low number of gauges located below the canopy could also have introduced uncertainty in the results. However, other short event measurements with three additional large area (0·28 m^2) throughfall gauges, in a roving arrangement, shows that these results, although extreme, are possible (Prada *et al.*, 2010a).

Although the fact that a forest stand does not directly relate to a first-line tree, as demonstrated during the cloud water depletion experiment, this study shows that the *Paul da Serra* massif has favourable climatic conditions to the occurrence of frequent fog and that the local forest vegetation has morphological characteristics that facilitate water capture from it.

The results show that, even though CWI decreases towards the interior of the forest, this depletion seems to stabilize following a logarithmic relation. Nowadays, the tree heath vegetation in the *Paul da Serra* plateau is reduced to *Bica da Cana*'s forest, so extrapolating the depletion rate to a flat plateau fully covered by heath trees forming a much wider and continuous stand is not straightforward. However, small eddies and associated turbulence due to surface roughness and small isolated reliefs may bring fog from the air mass passing above, into the canopy, thus providing some cloud water input. This effect probably occurred in a once fully forested *Paul da Serra* plateau where, even in the middle of a thick and wide tree heath stand, it might have contributed to the occurrence, even if in small quantities, of CWI. The name *Paul da Serra* translates from the Portuguese as 'mountain marsh', suggesting that when the early settlers set foot in this part of the island, a wetland environment was probably present.

It is expectable that rainfall in Madeira will decrease (between 20 and 40% until 2099) and temperature will rise (between 1·4 and 3·2 °C until 2099) due to climate change (Santos and Aguiar, 2006). Since groundwater is the major source of water supply in Madeira, and *Paul da Serra* is the most important groundwater recharge site, ecological restoration of the plateau and other similar high altitude areas, naturally and artificially, should be a priority. Nowadays, tree heath forests are reduced to a very small fraction of its potential area, only about 2 km^2 (Figueira *et al.*, 2010). A strong investment in reforestation practices and protection from natural and man-induced hazards is advisable, not only for biodiversity, environmental and touristic purposes but also due to its impact in regional water resources. Recent isotopic studies seem to provide evidence that cloud water contributes to groundwater recharge in the island (Prada *et al.*, 2010b). As stated by Holder (2003, 2006), a deforested cloud forest area will have an impact on the hydrological input, thus reducing the available water in a given area. Besides incrementing the volume of intercepted cloud water, reforested areas facilitate the infiltration of rainwater and decrease the evaporation and superficial runoff (Buttle, 2011), also preventing soil erosion and landslides, especially in steep places such as in Madeira Island.

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