Cloud water interception in the temperate laurel forest of Madeira Island

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Cloud water interception in the temperate laurel forest of Madeira Island

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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

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,
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 m²

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 m²
Fig. 1 Madeira Island: the study area is marked by the red ellipse 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 tunbrigense*, *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
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 m² 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 m². 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, \( P_{\text{gross}} \) is gross precipitation, and \( P_{\text{net}} \) is net precipitation:

\[
I = P_{\text{gross}} - P_{\text{net}} \tag{1}
\]

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.

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

*SD: standard deviation.
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 (Jimenez et al. 1996, Garcia-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 (Jimenez 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 tunbrinense, 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 Aguilar (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.

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