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Theoretical and methodological aspects of cloud water interception

Revisão dos aspectos teóricos e metodológicos da interceptação da condensação atmosférica

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Abstract

Cloud water interception (CWI) occurs when water contained in fog and wind-driven rain collides with vegetation, merges into larger droplets, and precipitates to the ground. CWI has an important function as an additional source of water and its relationships with tropical cloud forests have often been emphasized. Despite its importance, there is no standardization of measurement methods, nor of the terms that designate the process in Portuguese. Therefore, a systematic analysis of research on CWI is necessary. To this end, the present study carried out a review of the theoretical and methodological aspects of CWI through description and analysis of terminology; history and chronology of studies on the topic; survey of the environmental conditions necessary for the CWI process to occur; analysis of methodological aspects relating to the measurement of CWI; and synthesis and discussion of magnitudes described in scientific literature. As a result, of the 31 publications reviewed, 14 different words were found, the most common being "Cloud Water Interception" (19.4%) and "Fog Drip" (16.1%). In general, CWI is more common in places such as continental edges and islands that are constantly subject to sea breezes. In most cases, the below-canopy measurement approach can be considered more accurate than those obtained by fog collectors. CWI is on average responsible for 42% of effective precipitation (n:41). The values listed show a large variation, between 0.5% and 462%, probably due to the different environmental characteristics of the sampled locations as well as variations in sample sizes.

Keywords:
Hydrological monitoring, Tropical Cloud Forests, Stemflow.

Resumo

A interceptação da condensação atmosférica (ICA) ocorre quando a água contida em nevoeiros e precipitações movidas pelo vento, colide com a vegetação, se funde em gotas maiores, e precipita no solo. A ICA tem importante função como fonte adicional de água e suas relações com a florestas nebulares tropicais foram muitas vezes enfatizadas. Apesar de sua importância, não há

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padronização dos métodos de medição, nem dos termos que designam o processo. Fazendo-se assim necessária uma análise sistemática das pesquisas sobre ICA. Para isso, o presente estudo realizou uma revisão dos aspectos teóricos e metodológicos da ICA por meio da: descrição e análise sobre a terminologia; histórico e cronologia dos estudos sobre o tema; levantamento das condições ambientais necessárias para a ocorrência do processo de ICA; análise dos aspectos metodológicos relativos à medição da ICA; síntese e discussão das magnitudes descritas na literatura científica. Como resultado: das 31 publicações revisadas foram encontrados 14 diferentes vocábulos. Sendo os mais comuns "Cloud Water Interception" (19,4%) e "Fog drip" (16,1%); em geral a ICA é mais frequente em locais como bordas continentais e ilhas constantemente sujeitas a brisas marítimas; na maioria dos casos, a abordagem para a medição abaixo do dossel, pode ser considerada mais precisa que as obtidas por coletores de nevoeiros; a ICA é em média responsável por 42% da precipitação efetiva (n:41). Os valores listados apresentam grande variação, entre 0,5 % e 462%, provavelmente decorrente das distintas características ambientais dos locais amostrados assim como das variações nos tamanhos das amostras.
Palavras-chave:
Monitoramento hidrológico, Florestas nebulares tropicais, Escoamento de tronco.

I. INTRODUÇÃO

The cloud water interception - CWI (Interceptação da Condensação Atmosférica in Portuguese) occurs predominantly in mountainous regions, where atmospheric water contained in fog and wind-driven precipitation collides with vegetation in its path. The small droplets land on canopy leaves, merging into larger droplets that drip onto the forest floor. This additional water input is normally ignored, as conventional rain gauges are not capable of collecting these small drops (CAVALIERE *et al.,* 1996; FRUMAU *et al.,* 2010; HOLWERDA et al., 2010; BRUIJNZEEL; MULLIGAN; SCATENA, 2011), and are installed in open areas, rather than under the forest canopy (ZHAN *et al.,* 2020).

Tropical montane cloud forests (TMCFs) are often immersed in clouds and occupy only 0.26% of the earth's surface (BUBB *et al.,* 2004). Despite their restricted distribution, they host great biodiversity and provide important ecosystem services (SCHEER; CURCIO; RODERJAN, 2012, 2013; ELLER *et al.,* 2020). Bruijnzeel and Hamilton (2000) reported that in TMCFs, because of CWI by vegetation, total net precipitation can increase between 15-20% and can reach up to 50-60% in conditions more exposed to fog (BRUIJNZEEL; MULLIGAN; SCATENA, 2011). These ecosystems are recognized as important for supplying adjacent plains and their hydrological balance is largely determined by the effect of fog in reducing evapotranspiration rates (TEIXEIRA *et al.,* 2021).

The role of CWI as an additional source of water and its relationships with TMCFs has often been emphasized (BRUIJNZEEL; PROCTOR, 1995; CAVALIERE *et al.,* 1996; RITTER; REGALADO; ASCHAN, 2008;

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BRUIJNZEEL; MULLIGAN; SCATENA, 2011; FIGUEIRA *et al.,* 2013; DOMINGUEZ, 2017; BITTENCOURT *et al.,* 2019). However, there are a variety of terms that designate the process, different measurement methods and specific geographic characteristics of each location studied. Therefore, an updated systematic review of research on CWI is necessary to understand the trajectory of scientific production on the topic, the relationship between the magnitudes obtained by research and the environmental aspects involved and the possibilities for improving research.

To this end, this study proposes a review of the theoretical and methodological aspects of CWI through 1) description and analysis of the terminology, history and chronology of studies on the topic; 2) survey of the environmental conditions necessary for the CWI process to occur; 3) analysis of methodological aspects relating to the measurement of CWI; and 4) synthesis and discussion of magnitudes described in scientific literature.

II. Materiais e Métodos

The method for preparing this work followed the structured review system proposed by Paul and Criado (2020). According to the authors, this system seeks, based on widely used methods and theories, to construct tables and figures that facilitate researchers to understand the volume of related research, the distinction between the methods used, advances made by previous studies, and based on the information compiled, carry out a synthesis and identify research gaps.

The criteria for selecting articles were as follows: 1) articles that contained the terms fog drip, Cloud Water Interception, Occult Precipitation, Horizontal Precipitation, Fog Deposition, Wind Driven Rain and Cloud Moisture Input, *Interceptación* Horizontal, *Interceptación Negativa*, *Interceptación de Humedad de Nubes*, *Precipitación de la Neblina, Lluvia Horizontal or "Precipitación Indireta"* - from Spanish, and "*Precipitação Oculta*"- from Brazilian Portuguese in the titles and/or key words; and 2) articles using values obtained exclusively by fog dripping below the tree canopy (values obtained only by fog collectors were discarded). The bibliometric databases were consulted using the Google Scholar and Periódicos Capes portals.

Studies on CWI generally rely on fog collectors (CAVELIER *et al.,* 1996; JUVIK; NULLET, 1995; SCHEMENAUER; CERECEDA, 1994) to evaluate precipitation rates not collected by conventional rain gauges. However, the ability of these collectors to simulate precipitation capture by the vegetation canopy is questionable. Each forest has a distinct set of characteristics, making it difficult to reproduce them by a fog collector (BRUIJNZEEL, 2001; MACJANNET; WALLACE; REDDELL 2007).

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Therefore, in most cases, the approach for measuring below the canopy can be considered more accurate than those obtained by fog collectors (MACJANNET; WALLACE; REDDELL, 2007; BRUIJNZEEL; MULLIGAN; SCATENA, 2011). This can be due to the simple difference between throughfall (measured by gutters and vegetation drip collectors) and external precipitation (measured without the interference of terrain obstacles) (HARR, 1982; RITTER; REGALADO; ASCHAN, 2010), or these take into account the amount of water intercepted and evaporated from the wet canopy (HAFKENSCHEID *et al.,* 1998; GIAMBELLUCA; DELAY; NULLET, 2010; TAKAHASHI *et al.,* 2011).

Initially, 112 articles were found and after applying the criteria mentioned above, the number was reduced to 31 publications. These articles were evaluated individually to answer a set of initial questions: 1) what are the most common terms used to define and describe the process; 2) what measurement method did they use; and 3) what are the geographical characteristics of the occurrence sites (average annual precipitation, type of vegetation, latitude and longitude, distance from the sea and altitude).

III. RESULTADOS E DISCUSSÃO

Terminology, history, and chronology of studies on the topic

Fog is defined as water droplets or ice crystals with a diameter smaller than 100 µm (FRUMAU *et al.,* 2010) or between 1 and 40 µm (PRADA; SILVA, 2001). According to Bruijnzeel, Eugster and Burkard (2005), fog consists of droplets of liquid water, condensed water vapor, remains of marine spray or evaporated raindrops.

The Clausius-Clapeyron relationship between air temperature and the amount of gaseous water the air can contain is typically used to determine when fog occurs (i.e., when relative humidity reaches 100%) and the temperature drops below the dew point. These small droplets that comprise fog do not precipitate into the air unless they encounter the surface of solid objects, as their rate of vertical stabilization is very slow. Plant canopies are quite permeable to air flow and have a large surface area and are therefore ideal interceptors (KERFOOT, 1968; DAWSON; BURGESS, 2004). In the absence of condensation nuclei, the relative humidity may exceed 100% before spontaneous condensation can occur. However, this situation only occurs in areas with minimal pollution (BRUIJNZEEL; EUGSTER; BURKARD, 2005).

Meteorologically, fog is defined as a cloud that touches the ground and reduces horizontal visibility to less than 1000 m (FRUMAU *et al.,* 2010). Fog is often also referred to by its place of occurrence (coastal, valley or mountain fog). Under continental conditions, fog contributions are generally more modest, except on mountain ridges and peaks exposed to strong wind currents (BRUIJNZEEL; EUGSTER; BURKARD, 2005).

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Therefore, there are no fundamental differences between fog and cloud in terms of physical properties. As the clouds considered in this study occur close to the ground (stratiform), there will be no distinction between cloud and fog and their unique formation processes.

Fog is associated with a number of terrestrial ecosystems, including mountainous coastal regions where the rise of moisture through orography produces adiabatic cooling, condensation, and fog formation (BURGESS; DAWSON, 2004). Cold ocean currents in contact with warm air also cause fog by advection before reaching the coast. Orographic or advection fogs depend on the wind to move and cool (OBERLANDER, 1956). Often both processes are present in mountainous regions. The third process for the formation of fog occurs when the heat caused by radiation cools below the dew point while in contact with the soil surface. This case tends to occur in environments where atmospheric conditions remain practically static and during the night (BURGESS; DAWSON, 2004).

Wind-Driven Rain (WDR) is precipitation that receives a horizontal velocity component and precipitates obliquely. It is important in several areas of study, including earth sciences, meteorology, and building science. WDR over uneven terrain, such as mountains or valleys, results in a redistribution of raindrops, due to deformations of the wind flow, which can cause large variations in precipitation. Due to these wind flow deflections, WDR is responsible for errors in precipitation measurements by individual rain gauges close to the ground (HOLWERDA *et al.,* 2006; MACJANNET; WALLACE; REDDELL, 2007). WDR can also play an important role in rain interception by tree canopies (HERWITZ; SLYE, 1995).

Fog and WDR are two sources of precipitation that are difficult to measure separately, and the volumes reported as fog (*fog*) usually concern the two phenomena combined (FRUMAU *et al.,* 2010). Furthermore, the sum of the two phenomena is called in the literature: 1) cloud water (SCHOLL *et al.,* 2007; BRUIJNZEEL; MULLIGAN; SCATENA, 2011); 2) horizontal precipitation (BRUIJNZEEL *et al.,* 2005; FRUMAU *et al.,* 2010); 3) occult precipitation (ELIAS; TESAR; BUCHETE, 1995; BURGESS; DAWSON, 2004; CARDENAS *et al.,* 2017); and 4) fog drip (FISCHER *et al.,* 2016; INGRAHAN; MATTHEWS, 1988), among others. All of these terms are used to refer to precipitation that cannot be measured by conventional rain gauges, but rather by fog collectors or by collectors below the tree canopy (HOLWERDA *et al.,* 2010; MUÑOZ-VILLERS *et al.,* 2012). As shown in Table 1, the most frequent terms are Cloud Water Interception and Fog Drip (in that order). However, there are a number of other terms to refer to the process. This terminological variety can complicate the use of electronic research portals and dialogue between researchers.

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In Brazilian Portuguese, the works already published used fog collectors as a method, and *Precipitação Oculta* (ARCOVA *et al.,* 2019) as a term, however the conceptually more appropriate term would be *Interceptação da condensação Atmosférica* (ICA). Therefore, at the Brazilian level, there is still little research carried out and it is suggested to standardize the term for ICA.

Table 1 – List of terms referring to the CWI process used in research that carried out measurements below the canopy, with location and proportion of occurrence.

Term	Country	Source	(%)
Cloud water interception	USA/Hawaii, Portugal/Madeira, Germany	Juvik; Zero, 1995; Giambelluca *et al.,* 2011; Juvik *et al.,* 2011; Takahashi *et al.,* 2011; Prada *et al.,* 2012; Köhler *et al.,* 2014	19.4
Fog drip	USA, China	Vogel, 1973; Dawson, 1998; Liu et al., 2004; Keppeler, 2007; Sawake *et al.,* 2015	16.1
Fog precipitation	USA/Hawaii, Australia	Azevedo; Morgan, 1974; Holder, 2003; Krecek *et al.,* 2017	9.7
Fog interception	USA, Guatemala, Czech Republic	Hafkenscheid *et al.,* 1998; Garcia-Santos et al., 2004; González-Martinez *et al.,* 2018	9.7
Horizontal Precipitation/Precipitación horizontal/Lluvia horizontal	China, El Salvador, Honduras	Jia *et al.,* 2019; Rodríguez., 2011; Agudelo *et al.,* 2012	9. 7
Cloud interception	Jamaica, Spain/Canaries, Mexico	MacJannet *et al.,* 2007; Braumam *et al.,* 2010	6.5
Fog water interception	Reunion, USA	Gabriel; Jauze, 2008; Potter, 2016	6.5
Fog water	China	Chung *et al.,* 2017	3.2
Cloud moisture input	Honduras	Stadtmuller; Agudelo, 1990	3.2
Mist and Fog Interception	Venezuela/ Colombia	Cavelier; Goldstein, 1989	3.2
Fog water input	Brazil	Bittencourt *et al.,* 2019	3.2
Fog water deposition	Germany	Lange *et al.,* 2003	3.2
Fog deposition	Australia	Hutley et al., 1997	3.2
Interceptación horizontal	Costa Rica	Moreno, 1981	3.2

Use: (%) Proportion in relation to other articles (selected according to criteria described in the METHODS section). Prepared by the authors, (2022).

The occurrence of fog is related to particular environments such as tropical mountain cloud forests or *Tropical Montane Cloud Forests* (TMCF) that generally appear from 800 a.s.l. (BRUIJNZEEL; MULLIGAN; SCATENA, 2011). The term TMCF is widely used in research to designate areas subject to frequent occurrence of fog and their vegetation presents unique environmental characteristics (APARECIDO et al., 2018). Its importance comes not only from the hydrological and ecological aspect, but also from the emphasis on research and conservation of these areas in relation to other tropical forests (BRUIJNZEEL; SCATENA; HAMILTON, 2010).

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In the present work the term TMCF will be used to refer to tropical and subtropical montane and upper montane forests frequently exposed to fog.

Originally, Cannon (1901) described the role of fog in maintaining forests on the west coast of the USA; later studies carried out by Cooper (1911), Ekern (1964) and Kerfoot (1968) documented rates of precipitation and soil water recharge induced by the dripping of fog and its importance as an extra source of water.

Stadtmuller (1987) carried out pioneering work in which he compiled the main differences between the physiognomies of vegetation in areas where fog occurs, which has dozens of classifications. The author indicated the close relationship between fog on vegetation and the need to conserve TMCFs. Stadtmuller (1987) highlights three components of the greatest importance in evaluating the effects of TMCFs on hydrology: 1) increase in effective precipitation; 2) reduction in evapotranspiration rates; and 3) regulation of the hydrological regime, particularly during dry periods. Their research found results indicating that ICA can vary from 7% to 158% of precipitation.

As a result of monitoring carried out on the coast of California (USA), for a period of three years, Dawson (1998) found that 34% of the water input into the annual water balance was a result of CWI by the redwood forest (*Sequoia sempervirens*), demonstrating that trees can significantly influence the magnitude of water input to ecosystems. For Burgess and Dawson (2004), the occurrence of CWI is essential for the coastal vegetation of California (USA), because a fraction of the water intercepted can be absorbed directly by the leaves.

According to Bruijnzeel, Mulligan and Scatena (2011), at the beginning of the 1990s, TMCFs were at the top of the list of the most threatened ecosystems, as in the previous decade they had been affected by vegetation suppression above the estimated average (1.1% versus 0.8%). This generated attention from the scientific community to gather information to understand, manage and protect these unique and vulnerable ecosystems. In response to this demand, in 1993, the International Symposium on TMCFs was held in Puerto Rico, which resulted in the creation of a book on TMCFs on an international scale (HAMILTON *et al.,* 1995). The chapters cover topics on hydrology, nutrient dynamics, the importance of threatened endemic species, as well as guidelines for management and conservation. In 1995, the "*A Campaign for Cloud Forests*" by the *International Union for the Conservation of Nature* (IUCN) was published with an emphasis on understanding the relationship between these forests and exposure to fog. In this context, Bruijnzeel and Proctor (1995) suggested the creation of a pantropical network linking research centers on TMCF where issues could be addressed in an integrated way. In this work, the authors were able to list only eight studies on CWI in TMCF environments and six studies on evapotranspiration losses in these same forests.

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In 2004, the *Symposium on Science for the Conservation and Management o*f TMCFs was held, where around 25 presentations reported hydrometeorological and vegetation physiological work of TMCF conducted since 1993. Furthermore, ten presentations indicated the effects of converting TMCFs into pastures on climate variations (BRUIJNZEEL *et al.,* 2011).

Bubb et al. (2004) presented the Cloud Forest Schedule in partnership with several institutions including *United Nations Environment Program* (UNEP), World *Conservation Monitoring* Center (WCMC), *United Nations Educational*, *Scientific and Cultural Organization* (UNESCO), among others. In that document, governments, non-governmental organizations and the private sector were invited to develop goals for the conservation of TMCFs and deepen research to understand the hydrological processes that regulate the quantity and quality of water in these environments.

Efforts to analyze scientific advances on hydrology in regions of TMCFs were carried out by Bruijnzeel (2001) and Bruijnzeel, Mulligan and Scatena (2011). In this first article (BRUIJNZEEL, 2001) results obtained in forests located mainly in Latin America and the Caribbean were described. In Bruijnzeel, Mulligan and Scatena (2011), regional fog interception modeling maps are presented, both in terms of absolute values and percentages of total water input. The annual CWI interception values, listed by Bruijnzeel, Mulligan and Scatena (2011), determined with the *wet-canopy water budget method* (WCWB) (described in the THEORETICAL-METHODOLOGICAL ADVANCES section RELATING TO THE CWI PROCESS) showed great variation between the sampled areas (between 22 and 1990 mm/year), probably due to the spatial heterogeneity of the sampled points and their distinct geographic characteristics.

Studies on CWI have developed in some areas of TMCFs, such as the Canary Islands (GARCIA-SANTOS; BRUIJNZEEL, 2011; RITTER; REGALADO; ASCHAN, 2008); Puerto Rico (EUGSTER *et al.,* 2006; HOLWERDA *et al.,* 2006); Hawaii (JUVIK; DELAY, 2011); Colombia (CARDENAS *et al.,* 2017); Brazil (BITTENCOURT et al., 2019); among others. However, according to Bruijnzeel *et al.,* (2005) and Bittencourt *et al.,* (2019) there is still a lack of comparative information on climatological spatial variations and typical CWI interception rates for different types of forest.

In the year 2022, the United Nations General Assembly declared the International Year of Sustainable Mountain Development. One of the main initiatives was the establishment of an Open Scientific Committee (OESC) and the production of several policy briefs for sustainable mountain development. Among them is the collection and sharing of in situ data on climate change and mountain ecosystem dynamics. The OESC points

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out a deficiency in the global coverage of recording hydrological data series and the importance of sharing these data for the conservation and recovery of mountain environments (GEO MOUNTAINS, 2022).

Of the 31 publications selected in this work, using the criteria described in section II (Materials & Methods), it is noted that the first publications date back to the 1970s. Since the 1990s, with the increase in interest in the topic, and the creation of the International Symposium on TMCF in Puerto Rico, the number of publications has doubled (Figure 1) (HAMILTON *et al.,* 1995).

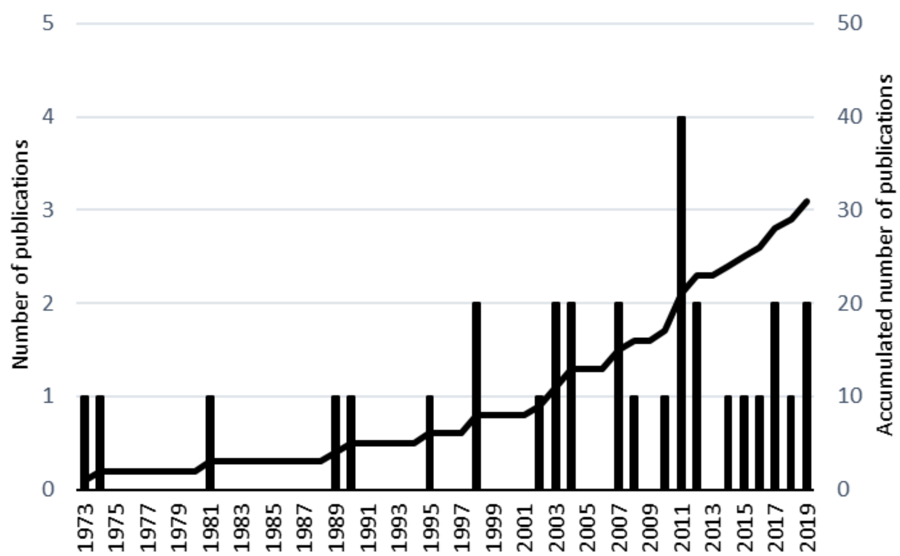

Figure 1- Number of articles referring to CWI based on measurements below the canopy and year of publication. Prepared by the authors (2023).

Survey of scientific literature on the conditions for the occurrence of CWI

The amount of water produced by CWI is highly dependent on location and partially on vegetation properties, climatic aspects and terrain characteristics. Location aspects mainly refer to distance from the sea, elevation, and degree of exposure of the land to fog (slope orientation) (FREYBERG; SAWASKE, 2015). Vegetation properties include canopy height, size and structure; arrangement and shape of leaves and trunks; location of trees and population density; and presence and morphology of epiphytes. Climatic aspects mainly refer to temperature; reduced light intensity; wind speed and direction; fog frequency; and fog properties (particularly the size distribution of water droplets) (BRUIJNZEEL; PROCTOR, 1995; RITTER; REGALADO; ASCHAN, 2008).

As seen in Figure 2, the vast majority of research on CWI, which met the selection criteria stipulated in this article, is located in the USA/Hawaii and Central America. Also notable is the number of countries with extensive coastal and/or mountainous areas that have a lack of data or a reduced number of studies on CWI.

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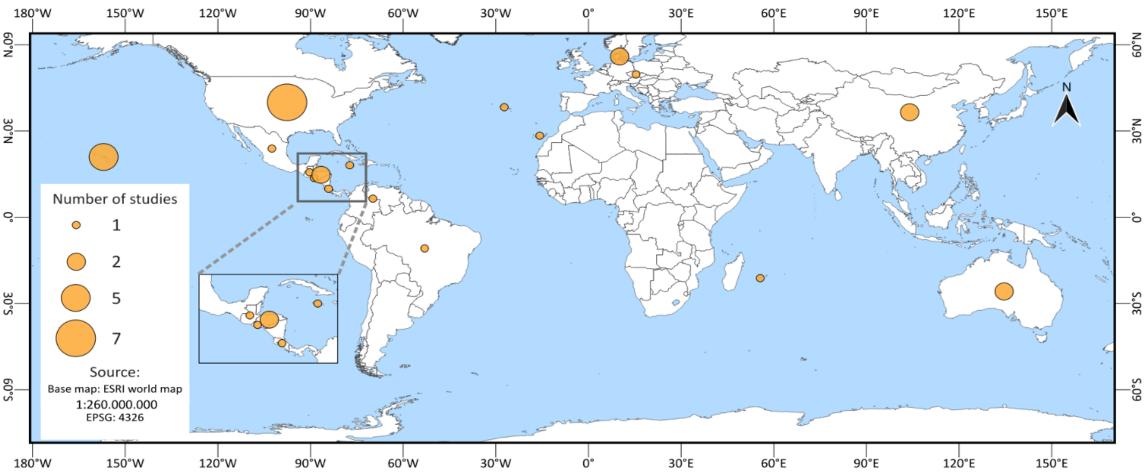

Figure 2 – Number of research on CWI using measurements below the canopy, by country. Prepared by the authors (2023).

By observing the well-defined bases of the clouds next to the TMCFs, it is possible to identify the altimetric level at which the condensation of vapor in the air occurs (HAMILTON, 1995) and also relate it to the type of vegetation associated with these climatic conditions (BRUIJNZEEL; MULLIGAN; SCATENA, 2011).

TMCFs generally occur between the altimetric limits of 800 to 3500 a.s.l. depending mainly on the size of the mountain and its distance from the coast. As altitude increases, combined with geomorphological and pedological changes, distinct alterations occur in the appearance and structure of the vegetation in TMCFs. Initially these changes are gradual and at higher levels they become more abrupt. Therefore, the exact elevations where certain forest formations are found vary greatly and can occur within a wide range of altitudes and climatic regimes (HAMILTON *et al.,* 1995; BRUIJNZEEL; HAMILTON, 2000; BRUIJNZEEL, 2001). Generally speaking, five forest classes can be distinguished: *lower montane rainforest* (LMRF), below the fog belt; *lower montane cloud forest* (LMCF); *upper montane cloud forest* (UMCF), *intermediate height*; *sub-alpine cloud forest* (SACF); and *elfin cloud forest* (EFC). In addition to contrasts in precipitation rates, these typologies can also be distinguished by vegetation structure, degree of epiphyte coverage, and temperature (BRUIJNZEEL; MULLIGAN; SCATENA, 2011).

For the Brazilian scope, this research adopted the classification used by Struminski (2001) as a nomenclature corresponding to the international classification described in the previous paragraph. Based on the IBGE classification (1992) and field observations, the author presented the following topology for Brazilian mountain forests: Floresta *Ombrófila Densa Montana*, analogous to LMCF (from 600 to 900/1000 a.s.l.); *Floresta Ombrófila Densa Altomontana*, analogous to UMCF (900/1000 to 1400 a.s.l.); *Refúgios Vegetacionais*

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Altomontanos herbáceo or campos de altitude (above 1300 a.s.l*.); Refúgios Vegetacional Altomontano herbáceo ou vegetação rupestre*, occupying the rocky outcrops. However, classifications like these, although they fulfill their role, are generalist. The forest types in Brazilian mountainous regions are directly related to pedological and geomorphological aspects and intervals between elevations (SCHEER; CURCIO; RODERJAN, 2013).

Vegetation aspects of tropical cloud forests

According to Bruijnzeel, Mulligan and Scatena (2011), the height of the canopy in LMCF (montane forest) can vary between 15 and 33 m and the occurrence of bryophytes occupies between 25% and 50% of the trunks. In areas where the UMCF (altomontana forest) is present, the canopy height varies approximately between 2 and 18 m and the coverage of the trunks by bryophytes ranges from 70 to 80%. Although there is no well-defined temperature separation between the two typologies, there is consensus among research that the transition between LMCF and UMCF coincides with the beginning of the occurrence of fog and its altimetric variations present differences between the distribution of TMCFs around the planet. SACF is characterized by trees with canopy heights and leaves smaller than those previously described, and the absence of epiphytes, but bryophytes can occur frequently. This last class occupies mountains of high elevations, as its transition is observed at elevations between 2,800 and 3,200 a.s.l.; ECF has a similar floristic structure but can occur at a wide range of elevations. This shrubby physiognomy generally occurs in the transition between forest and high-altitude highland fields.

For Scheer, Curcio, and Roderjan (2013) and Eller et al. (2020), the distribution of tropical cloud forests is best explained by soils that derive from geomorphology. Therefore, it is the geopedological factor that gains strength with the increase in altitude and dictates the physiognomy, height, and floristics, differentiating these forests.

In particular, the UMCF, or Altomontana Dense Ombrophylous Forest in Brazilian nomenclature, has unique aspects due to its frequent exposure to fog and associated soils. The UMCF is characterized by an abundance of mosses, epiphytes and a low canopy (less than 6 meters in height) (SCHEER; CURCIO; RODERJAN, 2011). The trees are twisted and stunted, the leaves are thick and resistant, with branches pointing in the opposite direction to the prevailing wind (STADTMULLER, 1987; CAVALIER *et al.*, 1997). Plants under these conditions (continuous humidification of the leaf surface) develop strategies to repel water, favoring dripping into the soil (RITTER; REGALADO; ASCHAN, 2008).

The abundance of epiphytic plants (mosses, ferns, bromeliads) is an important element in the hydrology and ecology of TMCFs. Up to a quarter of all species present in these forests may be epiphytes. These vegetables

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capture water directly from fog and their water storage can vary between 3,000 and 50,000 L.ha-1 (BUBB *et al.,* 2004).

The structure of the trees present in UMCFs includes proportionally thicker trunks and large root systems that increase the mechanical stability of the trees for their fixation on steep slopes (BRUIJNZEEL; PROCTOR, 1995). The increase in the frequency of immersion by fog, at higher altitudes and associated geopedological conditions (SCHEER; CURCIO; RODERJAN, 2013), progressively produces shorter vegetation, smaller leaves and trunks covered in epiphytes. This change in vegetation structure is accompanied by changes in floristic composition (ELLER, *et al.,* 2020).

The unique hydroclimatic conditions in TMCFs select for a plant community distinct from most found in tropical forests. The functional composition of TMCFs can be interpreted as the result of many interacting and overlapping environmental filters. These filters impose restrictions on the establishment of taller and faster-growing species, common to lower altitude and flatter areas, through hydraulic and mechanical systems together with temperature and pedological conditions. The TMCF community also has a proportionally large root system with a high density of fine roots, which reflects a large investment in nutrient acquisition (ELLER *et al.,* 2020).

Climate and distribution of tropical cloud forests

In general, the distributions of TMCFs depend on the upper and lower limits of the cloud stratum and global, regional and local environmental factors that influence their formation. The transition from LMCF to UMCF, as well as cloud thickness, are governed mainly by the level of persistent cloud condensation (BRUIJNZEEL; EUGSTER; BURKARD, 2005). This in turn is determined by the moisture content and temperature of the atmosphere. As the air moves away from the ocean, it tends to be less humid and requires lower temperatures, and therefore higher elevations, to achieve condensation (KITAYAMA, 1995). Above the UMCF, wet vegetation gives way to dry subalpine vegetation. The lower limits of the cloud belt covering the TMCF can vary from 800 to 2200 a.s.l. and can reach their upper limit of up to 3500 a.s.l. (BRUIJNZEEL; MULLIGAN; SCATENA, 2011).

In addition to the elevation of the base of the cloud stratum, the TMCF range is also governed by its upper limit, which is influenced by global-scale atmospheric circulation such as the Hadley cell. In this process, the heated air reaches high elevations in the equatorial zone and moves towards the poles and east in the upper part of the atmosphere where it cools. The cold, dry air descends in a wide band in the tropics and subtropics where it returns to the equator. As the air descends and warms, it forms a temperature inversion that separates

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the moist layer of surface air from the drier descending air above. This phenomenon is called trade wind reversal (Trade Wind Inversion -TWI) (CAO *et al.,* 2007). The effect of TWI on the upper limits of the TMCF is decisive. Over the eastern Pacific Ocean (e.g. coast of southern California) the TWI occurs only a few hundred meters above sea level and rises to about 2200 m near Hawaii. Consequently, some windward slopes in the Hawaiian archipelago receive more than 6,000 mm of rain per year below the layer inversion (BRUIJNZEEL; MULLIGAN; SCATENA, 2011).

Superimposed on a global scale, local humidity and temperature are controlled by rising air columns. These in turn are influenced by sea surface temperatures, interactions with the coast, size, orientation, and exposure of mountains to prevailing winds (STADTMÜULLER, 1987; KEPELLER, 2007; BRUIJNZEEL; MULLIGAN; SCATENA, 2011).

Due to the interaction of environmental factors responsible for the occurrence of TMCF, mapping its global distribution has been a challenge. National forest surveys tend to be inconsistent and use their own categories for classification (STADTMÜULLER, 1987; BUPP *et al.,* 2004). Approaches that use indices of altitude, temperature, precipitation, fog incidence and soil conditions were used for direct surveys and modeling (BUPP *et al.,* 2004; SCATENA *et al.,* 2010; BRUIJNZEEL; MULLIGAN; SCATENA, 2011). Scatena *et al.* (2010) combined data on vegetation cover and altitude limits of TMCF and estimated the potential area of TMCF in the order of 380,000 km², or 2.5% of the planet's tropical forests. The real area was approximately 215,000 km² or 1.4% of the world's tropical forests. Surveys on the distribution of the TMCF area were also carried out combining data on the frequency of fog occurrence and satellite observations (MULLIGAN, 2010). For Bruijnzeel, Mulligan and Scatena (2011), the results were more relevant than those obtained using altimetric quotas and the coverage values were more expressive than previous estimates (14.2% of the entire tropical forest).

Authors such as Harr (1982), Kepeller (2007), Goldesmith et al. (2012) and Sawake and Freyberg (2015) sought to identify relationships between fog drip volumes and geographic indices, such as wind-terrain interactions, in an effort to better understand the factors that condition the spatial heterogeneity of ICA. For the authors, the degree of exposure (HARR, 1982; KEPELLER, 2007; SAWAKE; FREYBERG, 2015), wind speed (OBERLANDER, 1956; INGRAHAM; MATTHEWS, 1988) and fog frequency (INGRAHAM; MATTHEWS, 1988; SAWAKE; FREYBERG, 2015) are the main controls in CWI production. The orientation of the mountainside relative to the prevailing wind direction determines the site's exposure to atmospheric moisture. Consequently, elevated locations to the windward side and close to the ridge line are the most favorable for the production of fog drips.

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Theoretical-methodological advances related to the CWI process.

The interception process in forests in tropical and temperate environments is traditionally studied by measuring or estimating the *Rf* (rainfall), *Tf* (throughfall), *Sf* (stemflow) and *I* (losses due to interception or volume of water that is retained by vegetation and returns to the atmosphere through evapotranspiration). Normally the values of *Tf* and *Sf* are lower than *Rf*. In contrast, in some mountain regions where atmospheric humidity is very high, the water that reaches the forest floor, or the net precipitation (*Tf* + *Sf*), may be greater than P (RITTER; REGALADO; ASCHAN, 2010) (Figure 3). This demonstrates that in mountain environments the condensation of atmospheric moisture is an important additional input of water, as it can considerably alter the water balance of these forests. This process has been associated with a reduction in evapotranspiration (FIGUEIRA *et al.,* 2013; DOMINGUEZ *et al.,* 2017). This appears to be associated with a reduction in solar radiation and an increase in atmospheric humidity (BRUIJNZEEL; MULLIGAN; SCATENA, 2011). Schellekens *et al.* (1998) found a 50% reduction in potential evaporation in cloud forests in Puerto Rico.

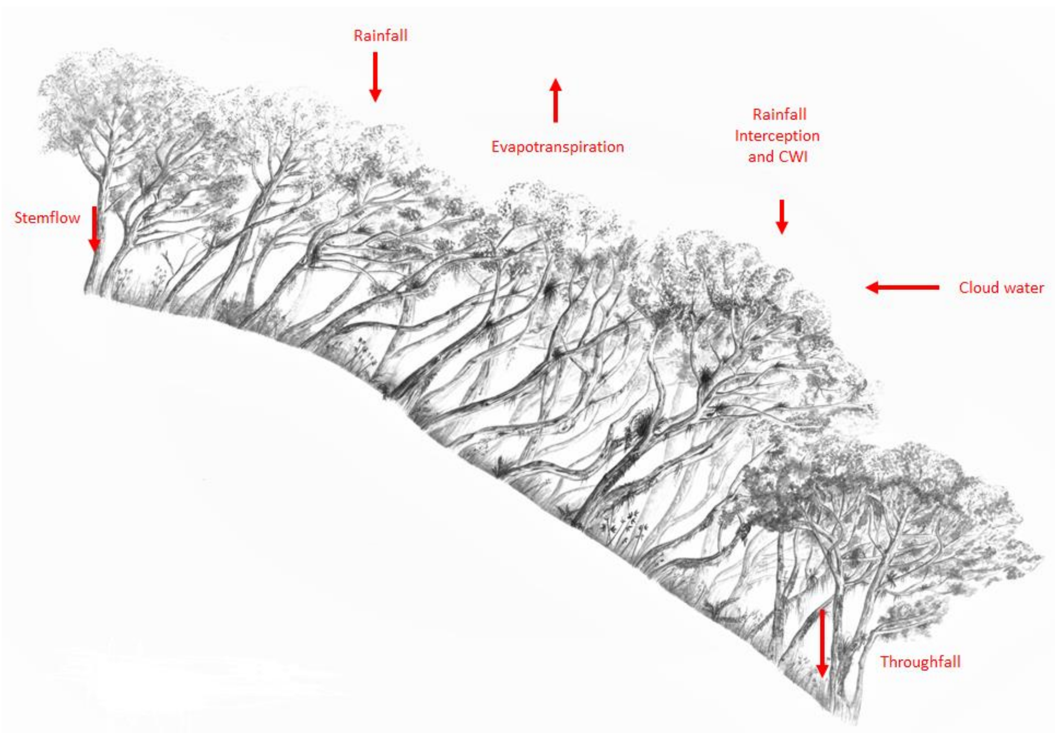

Figure 3 – Schematic profile of a section of transitional forest (LMCF-UMCF) and components of the Cloud Water Interception process. Adapted from: STOCCO (2023).

According to Bruijnzeel (2001), although the importance of CWI as an additional input of water is widely recognized, its quantification is difficult. Traditionally, two basic methods have been established to measure CWI: fog collectors and comparisons between *Tf* and *Rf.*

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Artificial fog collectors provide an indication of the frequency and amount of fog that can potentially be captured. The problem with using this type of equipment is that each forest canopy represents a unique situation that cannot be fully characterized with a mist water harvester (MACJANNET; WALLACE; REDDELL, 2007). Although fog meters are practical to install, they provide estimates related to their ability to capture fog and not that of vegetation. Therefore, they provide results that depend on the design of each collector. Still, its capture is highly dependent on its position on the ground and nearby obstacles (BRUIJNZEEL, 2001).

Among the fog meters used to characterize the occurrence of fog, the most used models are the harp (BERRONES, *et al.*, 2021), cylindrical screen (JUVIK; EKERN, 1978), panel (SCHEMENAUER; CERECEDA, 1994; JUVIK; NULLET, 1995) and electronic visibilimeters (BITTENCURT *et al.,* 2019). The amount of water captured by passive fog collectors is expressed as horizontal cloud flow or horizontal cloud water fluxes (CWF; mm/hour) (FRUMAU *et al.,* 2010). These rates can be used to infer the occurrence of CWI, compare measurement points, and be used as an input parameter for hydrological models.

CWI measurements can also occur using the canopy water balance approach or *wet-canopy water budget method* (WCWB) which is, in most cases, a more appropriate method because it measures the relationship between the amount of water dripping below the canopy, stem runoff, and total rainfall, and establishes linear regressions between its components in order to separate the two inputs of distinct water sources (rainfall and CWI) (HARR, 1982; SIGMOND *et al.,* 1989; MACJANNET; WALLACE; REDDELL, 2007; RITTER; REGALADO; ASCHAN, 2010; DOMINGUEZ *et al.,* 2017).

The CWI estimate in the absence of rainfall, that is, only with the occurrence of fog, can be expressed as:

$$CWI=E+Tf+Sf \tag{1}$$

Where CWI is the cloud water interception, E is the evaporation from wet canopy, *Tf* throughfall and *Sf* trunk flow. The sum of *Tf* and *Sf* is called effective rainfall (Net Precipitation).

As *E* is difficult to determine and is normally disregarded, resulting in an underestimated CWI value, it is called net CWI (BRUIJNZEEL; EUGSTER; BURKARD, 2005).

For periods in which there is a combination of fog and concomitant rain, the hydrological process can be expressed as the following:

$$Rf+CWI=\Sigma E+Tf+Sf \tag{2}$$

In which Rf is the total rainfall and ΣE It is the evaporation of water from fog plus rain. As in the previous case, the evaporation value is disregarded.

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To apply the previous equations (1 and 2), it is necessary to measure the *Rf* in an open place (without the influence of obstacles) and separate events with and without fog.

In some cases, the canopy water balance method also considers evaporation from the canopy as well as the variation in the volume of water retained by it (HAFKENSCHEID *et al.,* 1998; GIAMBELLUCA; DELAY; NULLET, 2011; TAKAHASHI *et al.,* 2011; GONZÁLEZ -MARTÍNEZ; HOLWEDA, 2018). To estimate canopy evaporation, the Penman-Monteith method is normally used (ALLEN *et al.,* 1998).

According to Bruijnzeel (2001) and MacJannet, Wallace and Reddell (2006), the canopy water balance methodology works well when there are significant differences between days with and without cloud interception. In places where fog interception is limited, regressions between *Rf* and net precipitation (*Tf+Sf*) may not be significantly different, making the approach invalid from a statistical point of view. This method also has a limitation, as fog dripping presents high spatial heterogeneity, and to estimate this process sampling is necessary using several collectors, or collectors with representative collection areas, or even as presented in some research (SCHELLEKENS *et al.,* 1998; HAFKENSCHEID; BRUIJNZEEL; RICHARD, 1998) collectors that are positioned at different points during monitoring.

A series of methods are still applied to infer the behavior of CWI, such as concentration of sodium and chloride present in fog (CLARK *et al.,* 1998; HAFKENSCHEID; BRUIJNZEEL; RICHARD, 1998); isotopic tracers (INGRAHAM; MATTHEWS, 1995; LIU *et al.,* 2007); mathematical models (RITTER; REGALADO; ASCHAN, 2008; DOMINGUEZ, 2017); changes in the weight of epiphytes (MULLIGAN; JARVIS, 2010) and electronic visibilimeters (BITTENCOURT *et al.,* 2019).

Cavalier and Mejia (1990) (GOES satellite), Goldsmith et al. (2013) (TERRA and AQUA satellites) and Sawake, Freyberg (2015) (satellites *MODIS* for daytime periods and *Aqua* for night periods) used spatial images with the purpose of mapping the distribution and occurrence of fog and its relationship to CWI and water supply for vegetation. From the data obtained, they concluded that fog coverage reduces daytime air flow, temperature and evapotranspiration. It also favors water supply during dry periods of the year mainly due to the increase in water content in the soil.

Magnitude and seasonality of the phenomenon in previous studies

Using spatial data, Jarvis and Mulligan (2011) made observations about the climate in 477 locations occupied by forests subject to fog. The TMCFs were considered the wettest (average of 184 mm/year) and coldest (average of 4.2 °C) in relation to other tropical forests. These are also the ones closest to the ocean and with the highest altitudes.

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Bruijnzeel, Mulligan and Scatena (2011) created a table relating rainfall data, throughfall and leaf area index for the different TMCF classes based on 60 studies. From meta-analyses, the following results were obtained: the average effective rainfall rates increase from 0.72 mm in the LMRF (n = 15) to 0.81 mm in the LMCF (n = 23), from 1.0 mm in the UMCF (n = 18) and to 1.04 mm in SACF/EFC (n = 8); and mean IAF values decreased from 5.54 mm in LMRF to 4.67 mm in LMCF, and from 3.96 mm in UMCF to 3.10 mm in SACF-ECF.

According to Bruijnzeel, Mulligan and Scatena (2011), statistical comparisons between total rainfall and effective rainfall for different measurement locations are limited by unequal sample sizes and methodological differences in sampling. However, comparisons of means and medians using t-test, Mann-Whitney sum test and ANOVA obtained significant differences between forest categories (p=0.05) for Foot versus P between UMCF and LMCF. Comparison between graph slopes Foot versus P also indicated that Foot exceeds P at SACF-ECF locations while the two lines are close at UMCF locations.

Regarding trunk flow (*Et*), Bruijnzeel, Mulligan and Scatena (2011) showed that in most of the studies analyzed the component was not measured, but the values observed in LMRF and LMCF are typically very low (<1-2% in relation to effective rainfall). However, fractions of Sf obtained for UMCF varied widely (0.1 – 30.5%), possibly reflecting variations in trunk density and degree of coverage by epiphytes, with a general average of 10% of rainfall (median 3%). The corresponding for SACF-EFC was 3-18% and 6.7% respectively.

The high rates of Foot obtained for UMCF and SACF-ECF should partially reflect the effect of CWI, as it is pertinent to note that wind speeds at UMCF and SACF-EFC sites tend to be higher than at lower, sheltered slope sites (LMCF and LMRF) (HOLWERDA *et al.,* 2006). Therefore, the amount of rainfall measured in locations exposed to wind tends to be underestimated and requires correction for losses around collectors (HOLWERDA *et al.,* 2006; MACJANNET; WALLACE; REDDELL, 2007; GIAMBELLUCA; DELAY; NULLET, 2011). According to Bruijnzeel *et al.* (2011), the magnitude of the correction can be substantial in some locations (>20%).

Another hydrological aspect related to the presence of fog in the TMCFs regions concerns not the entry of water into the system, but losses due to evaporative processes (LIU *et al.,* 2007). The results obtained show lower evapotranspiration values in the TMCF than in other tropical biomes. While TMCFs have annual evapotranspiration rates between 700 and 1000 mm, depending on the altitude and degree of cloudiness, in other forests the totals are between 1150 and 1350 mm. For the water balance, the reduced evapotranspiration in these locations implies greater water flow in the river basin (BRUIJNZEEL; HAMILTON, 2001).

Based on topography, Sawake and Freyberg (2015) distributed 77 throughfall meters, for five months, in an area of 40 km². The measuring instruments were positioned at the ridge, slope and valley floor locations in

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the Santa Cruz Mountains, California, USA. CWI rates (total, seasonal and event-based) varied substantially between different sampling points (between 0 and 375 mm/month). However, the vast majority of meters collected drip rates between 1 and 60 mm/month, with a median value close to 10 mm/month. In relation to topography, the values of the average monthly rates (mm/month) were 0.1 for the valley bottom, 1.8 for the slope and 71 for the ridge.

Although there are many other factors involved, this simple qualitative classification demonstrates that the location of experiments is likely a primary determinant of relative fog drip rates. The location aspect involves topographic control related to frequency and exposure to fog and wind patterns, as well as individual tree dimensions (SAWAKE; FREYBERG, 2015).

Table 1 includes the values of P, Foot, Et and percentage of CWI obtained exclusively by measurements of canopy drip, for different types of forests, and which met the set of requirements described in the methods section. From the values listed, a large variation can be observed between the intercepted volumes. The CWI varied between 0.3 and 362 mm/month (n = 47). The average was 59.12 mm/month and the median was 30 mm/month. The standard deviation was 81.59 and the coefficient of variation was around 138%. CWI is on average responsible for 48% of effective rainfall (n = 41). The values vary greatly, between 0.5% and 462%.

These statistics demonstrate the presence of atypical values (outliers) and, therefore, asymmetry in the data set. This fact may be due, as observed by Bruijnzeel, Mulligan and Scatena (2011), to unequal sample sizes and methodological differences in sampling, and may also be due to differences in the environmental characteristics of the study sites (HARR, 1982; KEPELLER, 2007; GOLDESMITH *et al.,* 2012; SAWAKE; FREYBERG, 2015).

Table 1- Relationship of studies with measurements of cloud water interception (CWI) below the canopy.

	Caracterização do sítio			Resultado experimental				
	País	P média (mm/ano)	Vegetação	Período (dias)	P	ICA	ICA (%)	Fonte
Continentes	EUA	1170	Redwood	1095	1266 (mm ano-1)	36,7 (mm mês-1)	34	Dawson, 1998
		1651-2032	Douglas fir, redwood	46		84 (mm mês-1)		Azevedo; Morgan, 1974
		1170	Douglas fir, redwood	457		9,6 (mm mês-1)		Keppeler, 2007
		1000	Douglas fir, coyote brush	450		10-30 (mm ano-1)		Chung *et al.,* 2017
		800-1400	Mature conifers	148		10 (mm mês-1)		Sawake *et al.,* 2015

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Caracterização do sítio			Resultado experimental				
País	**P média (mm/ano)**	**Vegetação**	**Período (dias)**	**P**	**ICA**	**ICA (%)**	**Fonte**
	400-1500	Shrub - (Baccharis pilularis e Rhamnus californica)	304	1290	1561 (mm período-1)	121	Potter, 2016
	681	Knobcone pine	135		40,8 (mm mês-1)		Vogl, 1973
MX		Cloud forest	360	1788	1,9 (mm mês-1)	8	González-Martinez *et al.*, 2018
GT	5000	LMRF	308	2559	23,4 (mm período-1)	1	Holder, 2003
		UMRF			203,4 (mm período-1)	7,4	
SV	2000-3500	Pinares	167	290	5 (mm período-1)	1,77	Rodríguez, 2011
		Bosque nublado		294	24 (mm período-1)	8,2	
				346	62 (mm período-1)	17.9	
HN	2000-4000	Bosque nublado	365	1468	59,6 (mm mês-1)	48,71	Stadtmuller; Agudelo, 1990
	2360	Bosque nublado	1825		1382(mm ano-1)	141	Agudelo *et al.*, 2012
CR	2512	Bosque úmido prémontano	182	2305	352,9 (mm período-1)	15.3	Moreno, 1981
VE/ CO	1000	Elfin cloud forest	365	853	796 (mm ano-1)	93,3	Cavelier; Goldstein, 1989
				1630	518 (mm ano-1)	31,2	
				4461	480 (mm ano-1)	10,8	
BR		TMCF	360	2517	251 (mm ano-1)	10,7	Bittencourt *et al.*, 2019

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	Caracterização do sítio			Resultado experimental				
	País	P média (mm/ano)	Vegetação	Período (dias)	P	ICA	ICA (%)	Fonte
			Picea pungense ENGELM e Picea abies L.	210	303.3	0,07 (mm h-1)	25	Lange *et al.*, 2003
	DE	582-1814	Norway spruce [Picea abies (L.) Karst.]	187	427	2 (mm período-1)	0,5	Köhler *et al.*, 2014
					656	10 (mm período-1)	1,5	
					699	65 (mm período-1)	9,3	
					671	195 (mm período-1)	29	
					750	162 (mm período-1)	21,6	
	CZ	1290-1400	Norway spruce (Picea abies)	519	630	27 (mm período-1)	4,3	Krecek *et al.*, 2017
					683	120 (mm período-1)	17,6	
	CN	1487	Menglun Forest	1440	1718	89,4 (mm ano-1)	5	Liu *et al.*, 2004
		630	Pinus tabulaeformis, Quercus variabilis, and Platycladus orientalis	720		33 (mm ano-1)	4,61	Jia *et al.*, 2019
	AU	3952	Complex Notophyll Vine Forest	657	2983 (mm ano-1)	563 (mm ano-1)	19	MacJannet *et al.*, 2007
			Simple Notophyll Vine Forest	533	3040 (mm ano-1)	207(mm ano-1)	7	
			Simple Microphyll Vine Fern Thicket	391	7471 (mm ano-1)	2168 (mm ano-1)	29	
		968	Floresta subtropical	912		309 (mm mês-1)	40	Hutley *et al.*, 1997
Ilhas	EUA/HI	1011	Shrubs	751	962 (mm ano-1)	116 (mm ano-1)	12,1	Giambelluca *et al.*, 2011*
		2702	Hawaiian cloud forests	564	2389 (mm ano-1)	1212 (mm ano-1)	50,7	
		1500	Floresta nativa norte	568	1217	0,1 (mm dia-1)	12	Brauman *et al.*, 2010
			Floresta nativa sul		993	0,3 (mm dia-1)	27	

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Caracterização do sítio			Resultado experimental				
País	P média (mm/ano)	Vegetação	Período (dias)	P	ICA	ICA (%)	Fonte
	625	Cook Pine (Araucaria columnaris)	292	457	7,9 (mm dia-1)	146	Juvik *et al.,* 2011
	1099		115	349	4,4 (mm dia-1)	462	
		Floresta nativa	510	3233 (mm ano-1)	1188 (mm ano-1)	37	Takahashi *et al.,* 2011
		Floresta invasora		3735 (mm ano-1)	733 (mm ano-1)	20	
	4400	Elfin cloud forest	100	336	606 (mm período-1)	180	Juvik; Nullet, 1995
PT/ AÇ	2966	Erica arborea L. (nativa)	688	4487,5	8337,9 (mm período-1)	186	Prada *et al.,* 2012
ES/ CAN	760	Laurel forest	360	770	670 (mm ano-1)	87	García-Santos *et al.,* 2004
JM	2850	TMCF ridge top forest	496	4880	244 (mm período-1)	5	Hafkenscheid et al., 1998
FR/ RE	3000	Upper montane forest (ericaceous shrubs, S. denudata)	240	948	232 (mm período-1)	25	Gabriel; Jauze, 2008

Use: Data without units described in column P refer to (mm period-1) USA - United States of America, MX- Mexico, GT- Guatemala, SV- El Salvador, HN- Honduras, CR- Costa Rica, VN- Venezuela, CO - Colombia, BR- Brazil, DE- Denmark, CZ- Czech Republic, CN- China, AU- Australia, HI- Hawaii, PT- Portugal, AÇ-Açores, ES- Spain, CN- Canaries, JM- Jamaica, FR- France, RE- Reunion Islands. Authors' production (2023).

As seen in Table 1, there are different nomenclatures and types of vegetation associated with fog. This variety of terms was observed by Stadtmuller and Agudelo (1990) who reported dozens of designations used to describe forests subject to fog.

Some research in Table 1 was carried out at altitudes below 600 a.s.l. and, therefore, not in mountain cloud forests as was the case of the Redwood forests located on the northern coast of California in the USA (< 50 km) (AZEVEDO; MORGAN, 1974; DAWSON, 1998; KEPPELER, 2007; SAWAKE *et al.,* 2015; CHUNG *et al.,* 2017), confirming that the proximity to the coast favors the occurrence of stratus clouds and the consequent occurrence of CWI as reported in the literature (BRUIJNZEEL; PROCTOR, 1995; RITTER; REGALADO; ASCHAN, 2008).

Of the 31 studies listed in Table 1, only five of them collected stem flow data (16%) (MORENO, 1981; HAFKENSCHEID *et al.,* 1998; MACJANNET; WALLACE; REDDELL, 2007; KRECEK *et al.,* 2017; BITTENCOURT *et al.,* 2019). The values for Sf, described by the authors mentioned above, varied between 0.42% and 21% of the total

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effective rainfall (n=6) and the average was 7.79%. Thus, it demonstrates the great variability of this component, as shown in Figure 4.

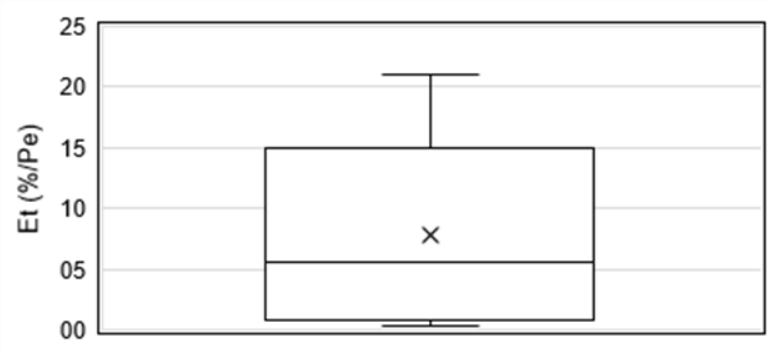

Figure 4 – variation in the percentage of stemflow (Et) over effective rainfall. Authors' production (2023).

According to Hafkenscheid et al. (1998), the high Et value obtained in their research (21%), when compared to others found in the literature, may be a result of the high proportion of trunk regrowth in sloped environments. Slopes with a high gradient make it difficult to fix the roots and favor the inclination of the trunks. In turn, there is a profusion of regrowth, giving rise to new canopies that will form the canopy arrangement (ELLER *et al.,* 2020). It can also be attributed to the high degree of coverage of bryophytes and epiphytes that favor water retention in the trunks (BRUIJNZEEL; MULLIGAM; SCATENA, 2011; SCHEER; MOCOCHINSKI; RODERJAN, 2011).

The measurement of the *Sf* requires the installation of slip rings around the trunks and periodic readings of the heights obtained. Therefore, it is a component that is difficult to obtain and, therefore, often overlooked. Studies on stem flow rates are few and heterogeneous and, therefore, insufficient for generalizations. This means that, in some cases, interception rates are overestimated. In this way, the possibilities of inferring about the relationships between the components of the process are reduced. This indicates a gap in the understanding of forest interference in the redistribution of rainfall and CWI (KOBIYAMA; GIGLIO, 2013; LANGE; SANTOS, submitted for publication).

Figure 5, drawn from data presented in Table 1, indicates that the contribution of CWI in relation to rainfall is proportional. This can represent almost all the rainfall, demonstrating that saturation promotes greater efficiency of atmospheric condensation that reaches the ground and, therefore, the importance of the phenomenon.

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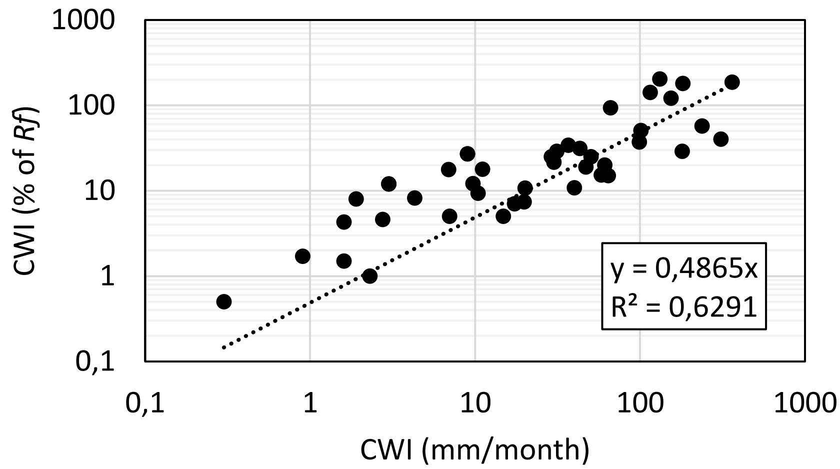

Figure 5 – Correlation between the proportion of CWI over total rainfall (%) and CWI (mm/month). Authors' production (2023).

Geographic data, such as distance from the coast and altimetry, were collected in the 31 articles selected by this research, as an attempt to establish relationships between environmental conditions and CWI magnitudes. From regressions carried out between the CWI (mm/month) and the values of distance from the coast (km) and elevation (m) represented in Figures (6 and 7) a weak correlation can be seen, with R=0.298 and R=0.028 respectively. According to statements by Ritter et al. (2008) and Bruijnzeel and Proctor (1995), location aspects such as distance from the coast and elevation are the main conditions for the occurrence of the CWI process. However, they are not sufficient to explain the CWI heights of the research listed here. The location of measurement experiments may be related to more local scales, such as position on the ground and consequent degree of exposure to fog (HARR, 1982; KEPELLER, 2007; SAWAKE; FREYBERG, 2015) and fog frequency (INGRAHAM; MATTHEWS, 1988; SAWAKE; FREYBERG, 2015).

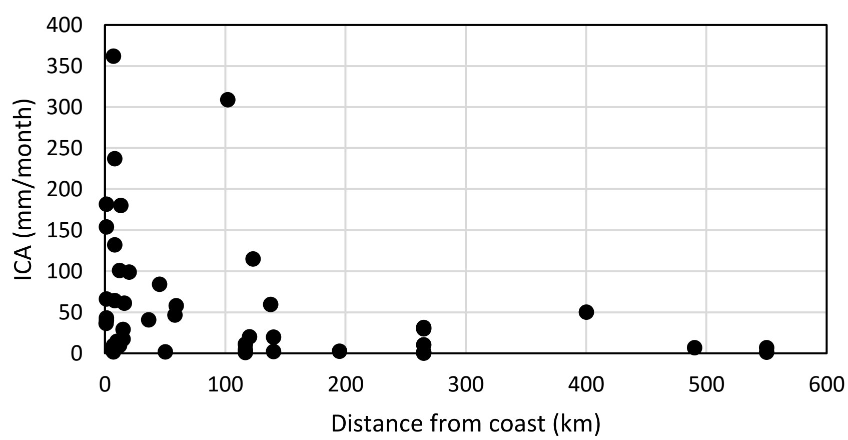

Figure 6 – Correlation between the distance from the coast over the CWI (mm/month). Authors' production (2023).

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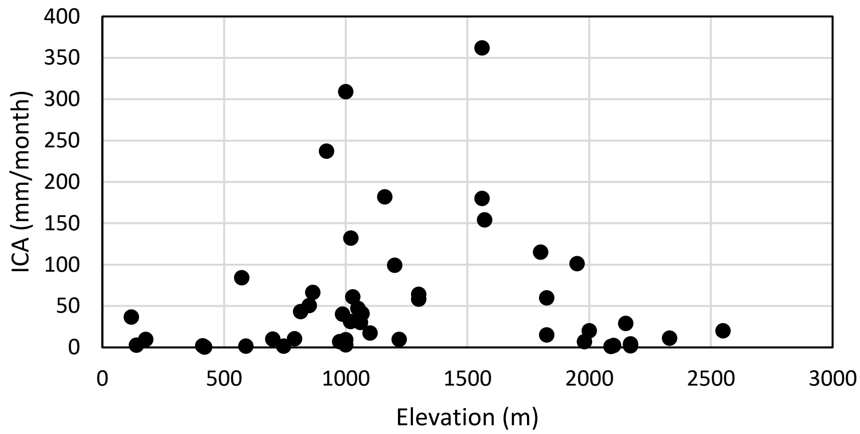

Figure 7– Correlation between the elevation over the CWI (mm/month). Authors' production (2023).

When CWI data is individualized according to location, between islands and continents, a great distinction can be seen between CWI heights (Figure 8). On continents there was a variation in CWI between 0.3 and 309 mm/month (n=34), with an average of 36.31 mm/month, median 19.95 mm/month, standard deviation 36.31 mm/month and coefficient of variation 83.69% mm/month. For measurements carried out on islands, the average was 100.28 mm/month (n=13), median was 64.20 mm/month, standard deviation was 106.48 mm/month and coefficient of variation was 106.19% mm/month.

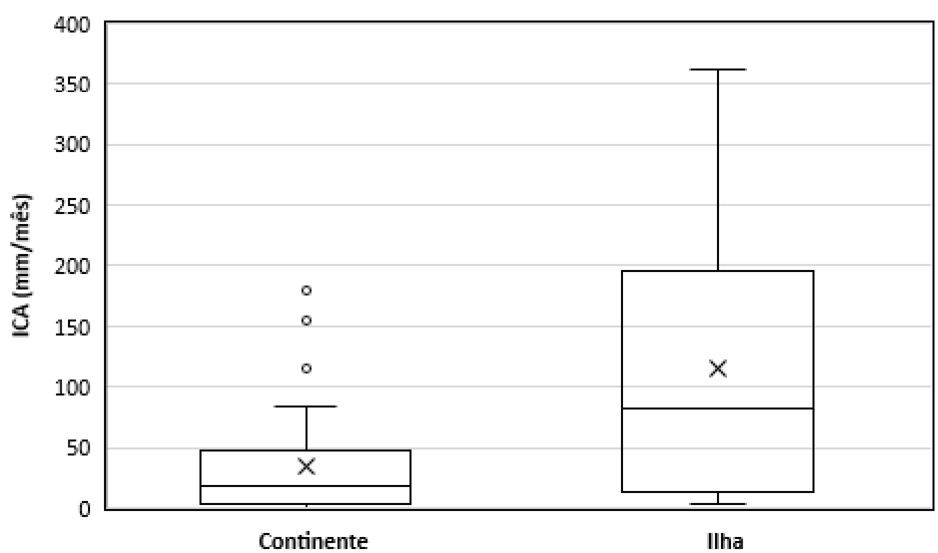

Figure 8 – CWI volumes on islands and continents. Authors' production (2023).

Despite the difference between the size of the samples, continents (n=34) and islands (n=13), the largest volumes of CWI for island environments are notable, possibly because of the action of sea breezes.

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IV. Conclusões

CWI is recognized as providing an important contribution to the water balance and as an effect on the maintenance of associated ecosystems. Based on research, which used the canopy water balance method, CWI is on average responsible for 42% of effective rainfall (n:41). The values listed show a large variation, between 0.5% and 203%, probably due to the different environmental characteristics of the sampled locations as well as variations in sample sizes.

In general, CWI is more common in places such as continental edges and islands that are constantly subject to atmospheric currents and sea breezes. The vegetation present in these locations is fundamental in regulating the water supply to rivers and other water flows in the soil.

The literature consulted presented a wide variety of terms to designate CWI. Of the 31 publications selected, 14 different words were found. The most common were "Cloud Water Interception" (19.4%) and "fog drip" (16.1%). Various nomenclatures were also verified to refer to mountain forests frequently exposed to fog and favorable to the occurrence of CWI. Thus, there is a lack of standardization of vocabulary regarding the topic, which facilitates dialogue between researchers, governments, and society for future research. In Brazilian Portuguese, the works found used the term Precipitação Oculta, however the conceptually more appropriate would be Interceptação da Condensação Atmosférica (ICA).

Studies on CWI began in the first decade of the 20th century and from the 1990s onwards they intensified due to the increased degradation of mountain environments. Since then, several initiatives have been carried out through scientific meetings. More recently, the UN declared 2022 the International Year of Sustainable Mountain Development.

As noted, research that uses measurements of canopy drip and trunk runoff, made by gutters and/or collection containers, are more efficient as they consider the ability of the canopy arrangement to intercept atmospheric condensation. For future studies, it is recommended to use the canopy water balance method that includes measurements of stemflow, a component normally disregarded.

Despite the significant contribution of CWI to the hydrological balance of certain regions, studies on the subject are still scarce in the world and especially in the southern hemisphere. Thus, the importance of obtaining data to understand hydrological processes in mountain environments, necessary for the conservation and use of environmental resources in a rational manner, arises. It must also be considered that the frequency and intensity of the CWI phenomenon may be changing due to climate change.

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