18 Tropical montane cloud forest: a unique hydrological case[1]

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INTRODUCTION

The paper by Zadroga (1981) on the hydrological significance of tropical montane cloud forests (TMCF) in northern Costa Rica probably marks the start of the enhanced interest in these remarkable forests although the importance of fog deposition on vegetation surfaces as an extra source of moisture has been acknowledged for a long time (see Kerfoot's 1968 review of early literature).

Arguably, this increased interest is in no small measure due to the unstinting efforts of one man, Professor Lawrence S. Hamilton, who recognised the far-reaching implications of Zadroga's preliminary work and who kept stressing the hydrological and ecological importance of TMCF on numerous occasions. Hamilton's efforts culminated in the organisation of the First International Symposium on Tropical Montane Cloud Forests, held in San Juan, Puerto Rico, from 31 May until 5 June 1993 (Hamilton, Juvik and Scatena, 1995), and the launching of *'A Campaign for Cloud Forests'* by the World Conservation Union (IUCN) in 1995 (Hamilton, 1995a). The hydrological and biogeochemical evidence on TMCF was reviewed in detail at the Puerto Rico Symposium by Bruijnzeel and Proctor (1995). These authors stressed how little is actually known about the hydrological functioning of different types of montane forests exposed to varying degrees of cloud impaction; the role of epiphytes in cloud water interception and retention; cloud forest carbon dynamics and the factors limiting their growth; and, above all, the uncertainty surrounding the water use of different types of TMCF and the effect of their conversion to pasture or vegetable cropping on downstream water yield. Bruijnzeel and Proctor (1995) also called for the establishment of a pan-tropical network linking the more data-rich TMCF research sites where these important questions could be addressed in an integrated manner.

The nomenclature of montane forests, including TMCF, is confusing. Stadtmüller (1987) listed at least 35 different names that have been used to typify 'cloud forest'. Therefore, before reviewing the results of hydrological research in TMCF (with emphasis on post-1993 work, i.e. published or initiated after the Puerto Rico Symposium), a simple classification of TMCF types is proposed to allow for hydrological distinctions between the different forest types. In addition, background information is provided on the chief controls governing TMCF occurrence. Finally, the chapter identifies the chief remaining research questions with suggestions for where and how these might be addressed.

TROPICAL MONTANE CLOUD FORESTS: DEFINITIONS AND OCCURRENCE

With increasing elevation on wet tropical mountains, distinct changes occur in forest appearance and structure. At first, these changes are gradual. The tall and often buttressed trees of the multi-storeyed *lowland rainforest* (main canopy height 25–45 m, with emergents up to 60 m), gradually give way to *lower montane forest*. With a mean canopy height of up to 35 m in the lower part of the montane zone and emergent trees as high as 45 m, lower montane forest can still be quite impressive. Yet, with two rather than three main canopy layers, the structure of lower montane forest is simpler than that of lowland forest. Also, the large buttresses and climbers that are so abundant in the lowland forest all but disappear while epiphytes (orchids, ferns, bromeliads) become more numerous on branches and stems with increasing elevation (Whitmore, 1998). The change from lowland to lower montane forest seems to be controlled largely by temperature as it is normally observed at the elevation where the average minimum temperature drops below 18 °C. At this threshold many lowland tree species are displaced by a floristically different assemblage of montane species (Kitayama, 1992). On large equatorial inland mountains this transition usually occurs at an altitude of

1 Largely based on Bruijnzeel (2001/2002a) and updated in April 2003.

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1200–1500 m but it may occur at much lower elevations on small outlying island mountains and away from the Equator (see also below). As elevation increases further, the trees not only become gradually smaller but also more 'mossy' (changing from *c*. 10% to 25–50% moss cover on the stems). There is usually a very clear change from relatively tall (15–35 m) lower montane forest to distinctly shorter-statured (2–20 m) and much more mossy (70–80% bryophytic cover) *upper montane forest* (Frahm and Gradstein, 1991). Although at this point the two forest types are not separated by a distinct thermal threshold, there can be little doubt that the transition from lower to upper montane forest coincides with the level where cloud condensation becomes most persistent (Grubb and Whitmore, 1966). On large mountains in equatorial regions away from the ocean this typically occurs at elevations of 2000–3000 m but incipient and intermittent cloud formation is often observed from *c*. 1200 m upwards, *i.e*. roughly at the bottom end of the lower montane zone. On small oceanic island mountains, however, the change from lower to upper montane-looking forest may occur at much lower altitudes (down to less than 500 m above sea level) (Van Steenis, 1972). Mosses also start to cover rocks and fallen trunks on the soil surface in the upper montane forest zone. With increasing elevation and exposure to wind-driven fog and rain, tree stems become increasingly crooked and gnarled, and bamboos often replace palms as dominant undergrowth species (Kappelle, 1995). The eerie impression of this tangled mass, wet with fog and glistening in the morning sun, has given rise to names like 'elfin' forest or 'fairy' forest for the more dwarfed forms of these upper montane forests (Stadtmüller, 1987).

A third major change in vegetation composition and structure typically occurs at the elevation where the average maximum temperature falls below 10 °C . Here the upper montane forest gives way to still smaller-statured (1.5–9 m) and more species-poor *subalpine forest* (or scrub) (Kitayama, 1992). This forest type is characterised not only by its low stature and gnarled appearance but also by even tinier leaves, and a comparative absence of epiphytes. Mosses usually remain abundant, however, confirming that cloud incidence is still a paramount feature (Frahm and Gradstein, 1991). On large equatorial mountains the transition to subalpine forest is generally observed at elevations between 2800 and 3200 m. As such, this type of forest is encountered only on the highest mountains, mostly in Latin America and Papua New Guinea, where it may extend to *c*. 3900 m (Whitmore, 1998).

It follows from the preceding descriptions that most lower montane, and all upper montane and subalpine forests, are subject to various degrees of cloud incidence. As indicated earlier, definitions, names and classification of the respective vegetation complexes are myriad, as well as overlapping and, at times, contradictory (Stadtmüller, 1987). Bruijnzeel and Hamilton (2000) proposed to distinguish the following forest types that become increasingly mossy with elevation:

- lower montane forest (tall forest little affected by low cloud but rich in epiphytes, particularly in the upper reaches of the zone);
- lower montane cloud forest (25–50% moss cover on stems);
- upper montane cloud forest (70–80% epiphyte cover on stems); and
- subalpine cloud forest.

In doing so, the widely adopted broad definition of cloud forests as 'forests that are frequently covered in cloud or mist' (Stadtmüller, 1987; Hamilton *et al.*, 1995) is included whilst at the same time recognising the important influence of temperature and humidity on montane forest zonation. However, a fifth and more or less 'a-zonal' cloud forest type should be added, low-elevation dwarf (or 'elfin') cloud forest (see below).

The large variation in elevation at which one forest formation may replace another is caused by several factors. For example, the transition from lower to upper montane forest is mainly governed by the level of persistent cloud condensation (Grubb and Whitmore, 1966). Cloud formation, in turn, is determined by the moisture content and temperature of the atmosphere. Naturally, the more humid the air, the sooner it will condense upon being cooled during uplift. With increasing distance from the ocean the air tends to be drier. As such, it will take longer to cool to its condensation point and the associated cloud base will be higher. Likewise, for a given moisture content, the condensation point is reached more rapidly for cool air than for warm air. Thus, at greater distance from the Equator, the average temperature, and thus the altitude at which condensation occurs, will be lower (Nullet and Juvik, 1994). Superimposed on these global atmospheric moisture and temperature gradients are the more local effects of sea surface temperatures and currents, the size of a mountain and its orientation and exposure to the prevailing winds, as well as local topographic factors (Stadtmüller, 1987). It goes almost without saying that sea surface temperatures influence the temperature of the air overhead and thus the 'starting point' for cooling. Also, where warm, humid ocean air is blown over a comparatively cold sea surface, a low-lying layer of persistent coastal fog tends to develop. Well-known examples are the fog-ridden west coast of California where tall redwood forests thrive in an otherwise sub-humid climate (Dawson, 1998), and the coastal hills of Chile and Perú, where, under conditions approaching zero rainfall, forest groves are able to survive solely on water stripped from the fog by the trees themselves (Aravena, Suzuki and Pollastri, 1989).

The occurrence of low-statured mossy, upper montane-looking forest at low elevations on small, isolated coastal mountains has

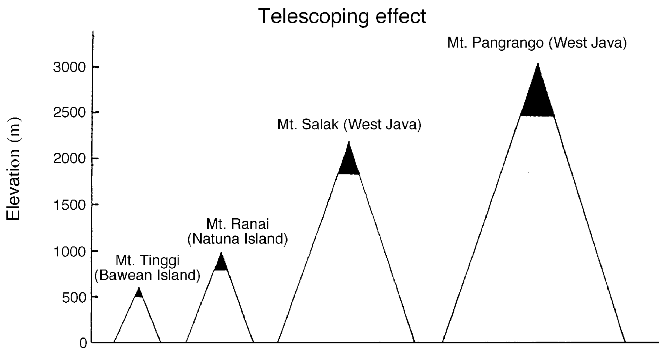

Figure 18.1 The telescoping effect of vegetation zonation on differently sized mountains. (After Van Steenis, 1972.)

puzzled scientists for a long time. This phenomenon is commonly referred to as the 'mass elevation' or 'telescoping' effect (Van Steenis, 1972; Whitmore, 1998) (Figure 18.1). The sheer mass of large mountains exposed to intense radiation during cloudless periods is believed to raise the temperature of the overlying air, thus enabling plants to extend their altitudinal range. Whilst this may be true for the largest mountain ranges it is not a probable explanation for mountains of intermediate size on which the effect is also observed. Instead, the contraction of vegetation zones on many small coastal mountains must be ascribed to the high humidity of the oceanic air promoting cloud formation at (very) low elevations rather than to a steeper temperature lapse rate with elevation associated with small mountains. Further support for this comes from the observation that the effect is most pronounced in areas with high rainfall and thus high atmospheric humidity (Van Steenis, 1972; Bruijnzeel *et al.*, 1993).

Whilst the cloud base on small islands is often observed at an elevation of 600–800 m, dwarf cloud forests reach their lowermost occurrence on coastal slopes exposed to both high rainfall and persistent wind-driven cloud. Examples from the equatorial zone include Mount Payung near the western tip of Java and Mount Finkol on Kosrae island (Micronesia) where dwarf forests are found as low as 400–500 m (Hommel, 1987; Merlin and Juvik, 1995). An even more extreme case comes from the island of Gau in the Fiji archipelago where the combination of high precipitation and strong winds has led to the occurrence of a wind-pruned dwarf cloud forest at an altitude of only 300–600 m above sea level (Watling and Gillison, 1995).

These examples illustrate the importance of site exposure. Generally, the lower limits of mossy forest of any kind (upper montane, subalpine, or dwarf cloud forest at low elevation) on drier and more protected leeward slopes lie well above those on windward slopes. In extreme cases, such as in the Colombian Andes, the difference in elevation may be as much as 600 m (Stadtmüller, 1987). Also, leeward forests tend to be better developed than their more exposed windward counterparts at the same elevation. For example, in the Monteverde Cloud Forest Preserve, northern Costa Rica, the trees of 'leeward cloud forest' are 25–30 m tall *v.* 15–20 m in nearby floristically similar 'windward cloud forest'. Moreover, towards the exposed crests of the windward slopes the height of the vegetation decreases further to 3–10 m along an altitudinal gradient of only 30–50 m (Lawton and Dryer, 1980; cf. Weaver (1995) for similar contrasts in Puerto Rico).

Although the stunted appearance of low-elevation dwarf cloud forests resembles that of the transition from high-elevation upper montane to subalpine cloud forests at first sight, the two differ in several important respects. At low elevations, the leaves are much larger and the floristic composition is very different (Grubb, 1974). Also, the degree of moss cover on the ground (but not the vegetation) is generally much less pronounced at lower altitudes (Frahm and Gradstein, 1991). Lastly, the temperatures and thus overall evaporative demand to which the forests are exposed are (much) higher at lower elevations (Nullet and Juvik, 1994). The soils of upper montane and dwarf cloud forests (regardless of elevation) are typically very wet and, in extreme cases, persistently close to saturation. As a result, decomposition of organic matter is slow and topsoils become peaty and acid (Bruijnzeel and Proctor, 1995). Recent work in the Blue Mountains of Jamaica suggests that the most stunted upper montane cloud forests suffer from toxic levels of aluminium in their soils which, in turn, affect nutrient uptake by the trees and a host of other forest ecological processes (see Hafkenscheid (2000) for details). At the other end of the scale, the very tall (up to 50 m) montane oak forests found at high elevations (up to 3000 m) on the large inland mountain massifs of Latin America (Kappelle, 1995) and Papua New Guinea (Hyndman and Menzies, 1990) more than likely reflect a fortunate combination of slightly warmer and drier air (due to the 'mass elevation' effect, distance to the sea and topographic protection) and the presence of well-drained soils in which the toxic conditions described by Hafkenscheid (2000) for the wettest localities do not easily develop.

So far, the focus has been on the climatic gradients and other factors governing the elevation of the cloud *base*. Another climatological phenomenon, which influences the vertical temperature profile of the air and the *top level* of cloud formation, is the so-called 'trade wind inversion'. As part of a large-scale atmospheric circulation pattern (the Hadley cell), heated air rises to great elevation in the equatorial zone, flowing poleward and eastward at upper atmospheric levels and descending in a broad belt in the outer tropics and subtropics from where it returns to the Equator. This subsidence reaches its maximum expression at the oceanic subtropical high-pressure centres and along the eastern margins of the oceanic basins. As the air descends and warms up again, it forms a temperature inversion that separates the moist layer of surface air (that is being cooled while rising) from the drier descending air above. The inversion forms a tilted

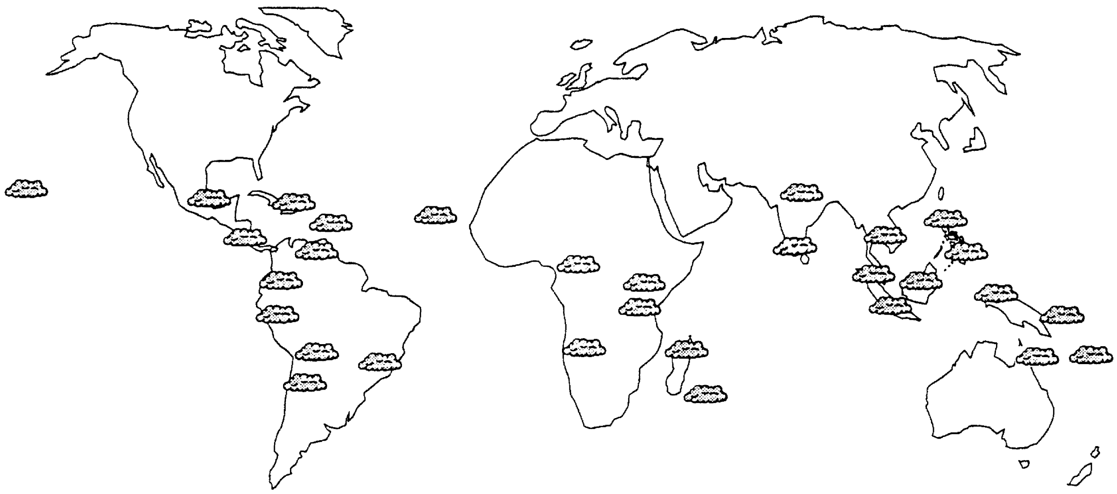

Figure 18.2 Generalized occurrence of montane cloud forests in the (sub)tropics. (Adapted from Hamilton *et al.*, 1995.)

three-dimensional surface, generally rising towards the Equator and from east to west across the oceans. Over the eastern Pacific Ocean, the inversion is found at only a few hundred metres above sea level, e.g. off the coast of southern California, rising to about 2000 m near Hawai'i and dissipating in the equatorial western Pacific (Nullet and Juvik, 1994). The low elevations at which the inversion occurs on mountains situated away from the Equator may well be another reason why the vegetation zonation tends to become compressed on smaller mountains (Stadtmüller, 1987). The consequences of the trade wind inversion for the occurrence of the upper boundary of montane cloud forest are profound. For instance, at 1900–2000 m on the extremely wet windward slopes on islands in the Hawai'ian archipelago, the montane cloud forest suddenly gives way to dry sub-alpine scrub because the clouds (which generally deliver more than 6000 mm of rain per year below the inversion layer) are prevented from moving upward by the presence of the temperature inversion (Kitayama and Müller-Dombois, 1992). One of the best-known examples of the trade wind inversion and its effect on vegetation zonation comes from the Canary Islands. Situated between 27 and 29 degrees north, a daily 'sea of clouds' develops between 750 m and 1500 m which sustains evergreen Canarian laurel forests in an otherwise rather arid environment (Ohsawa, Wildpret and del Arco, 1999).

As a result of the various climatic and topographic gradients described in the previous paragraphs, concentrations of montane cloud forests in the tropical and subtropical parts of the world occur approximately as shown on the generalised map in Figure 18.2. Further details on TMCF distribution can be found in Hamilton *et al.* (1995) and a draft directory of TMCF sites has been published by Aldrich *et al.* (WCMC, 1997).

HYDROLOGICAL PROCESSES IN TROPICAL MONTANE CLOUD FORESTS

Rainfall and cloud interception

One of the most important aspects in which cloud forests differ from montane forests that are not affected much by fog (low cloud) concerns the deposition of cloud water onto the vegetation. Whilst the hydrological and ecological importance of this extra input of moisture is widely recognised, its quantification is notoriously difficult (Kerfoot, 1968). Two approaches are usually followed: (i) the use of 'fog' gauges, of which there are many types, and (ii) a comparison of amounts of canopy drip as measured inside the forest with amounts of rainfall measured in the open. Both methods are fraught with difficulties of measurement and interpretation of the results. Therefore, before presenting recent research results obtained with either method, the chief limitations of the two approaches are discussed below.

Fog gauges

The inherent problem of fog gauges is that no gauge, whether of the 'wire mesh cylinder' (Grünow) type (Russell, 1984), the 'wire harp' type (Goodman, 1985), the 'louvered-screen' type (Juvik and Ekern, 1978), or the more recently proposed poly-propylene 'standard' fog collector of Schemenauer and Cereceda (1994), can mimic the complexities of a forest canopy. Also, each forest represents a more or less unique situation that defies standardisation. Therefore, fog gauges can only be used as comparative instruments (e.g. for site climatic characterisation) and, provided they are protected against direct rainfall and equipped with a recording mechanism, for the evaluation of the timing and frequency of occurrence of fog. Where concurrent information on wind speed is available as well, the liquid water content of the fog may also be evaluated from measured volumes of fog water (Padilla *et al.*, 1996). However, apart from its intrinsic trapping efficiency, the catch of a fog gauge is highly dependent on its position with respect to the ground and nearby obstacles. It has been recommended to install gauges at a 'standard' height of 2 m (Schemenauer and Cereceda, 1994) or 3 m (Juvik and Ekern, 1978). Often, however, studies using fog gauges in the tropics have not specified gauge height or position, rendering interpretation of the results more difficult, even more so when placed above an aerodynamically rough surface such as a forest canopy (Bruijnzeel and Proctor, 1995).

A major problem of interpretation associated with most fog gauges concerns the distinction between cloud water and wind-driven rain (Hafkenscheid, 2000; Cavelier, Solis and Jamarillo, 1996). Adding a protective cover to keep out vertical rain may further complicate things as different amounts of wind-driven rain will be included in the catch depending on wind speeds and the inclination of the rain drops (Sharon, 1980; cf. Juvik and Nullet, 1995a). For particularly windy and exposed conditions, Daube *et al.* (1987) proposed the use of a wire harp collector enclosed in a rain-proof box in which air flow is restricted by two baffles. The front baffle causes the passing air to accelerate and project heavy raindrops against the rear baffle where they are drained away. The lighter fog particles continue on and impact against the collecting harp. This type of fog collector has been used successfully above a fog-ridden lower montane forest in southern Queensland, Australia, by Hutley *et al.* (1997). Elsewhere in Queensland, Herwitz and Slye (1992) used a more theoretical approach to evaluate the angle of wind-driven rain as a function of wind speed and drop size (based in turn on rainfall intensity; Sharon, 1980).

There has been some debate as to what is the most suitable type of fog gauge under the windy and rainy conditions that prevail on many tropical mountains (Juvik and Nullet, 1995a; Schemenauer and Cereceda, 1995). Metal louvered screen collectors have been shown to drain their catch (both rain and cloud water) more efficiently than wire mesh screens (Juvik and Ekern, 1978), whereas cylindrical designs are considered superior to two-dimensional screens in terms of presenting the same silhouette and catchment surface configuration regardless of wind direction (Juvik and Nullet, 1995a). On the other hand, the catching surface of cylindrical gauges is generally much smaller than that of a large screen such as that proposed by Schemenauer and Cereceda (1994). The latter may thus generate measurable deposition rates when fog liquid water contents are low or winds are light (Schemenauer and Cereceda, 1995). There is a need to test the relative performance of the various gauge types under typical cloud forest conditions against concurrent measurements of visibility or cloud liquid water content (Burkard *et al.*, 2002). Therefore, the results of two such ongoing comparative experiments at East Peak in the Luquillo Mountains of Puerto Rico and in the windy Tilarán range near Monteverde, Costa Rica (F. Holwerda and K. F. A. Frumau, pers. comm.) are awaited with interest.

Measurement of net precipitation

Subtracting amounts of throughfall (T_f) plus stemflow (S_f) (together making up net rainfall) as measured below the forest canopy from gross rainfall measured above the forest or in a nearby clearing (P_g), gives the amount of precipitation intercepted by the canopy and evaporated back to the atmosphere during and shortly after the event. This process is usually referred to as rainfall interception (E_i) or wet canopy evaporation and implies a *net loss of water* to the forest:

$$E_i = P_g - (T_f + S_f) \tag{18.1}$$

where the terms are as defined above and expressed in mm of water per time period. Where fog or cloud only is present, a similar process of cloud interception (CW) may be expressed as:

$$\mathrm{CW} = E_{i_{cw}} + T_f + S_f \tag{18.2}$$

However, because neither the actual amounts of cloud interception (CW) nor those evaporated from the wetted vegetation ($E_{i_{cw}}$) are easily quantifiable in a direct manner, a more practical approach is to measure net precipitation and equate the amount to *net* cloud interception CW_{net}:

$$\mathrm{CW}_{net} = T_f + S_f \tag{18.3}$$

where the term 'cloud interception' implies a *net gain of water* to the ecosystem. In the more complex case of rainfall plus cloud incidence, separate knowledge of the total evaporation from the vegetation wetted by both rain and fog (ΣE_i) would be required to solve the wet canopy water budget equation for CW:

$$P_g + \mathrm{CW} = \Sigma E_i + T_f + S_f \tag{18.4}$$

Solving Eqn (18.4) under the climatic conditions prevailing at many cloud forest sites is not easy for a number of reasons. Firstly, depending on wind speeds and rainfall intensities, P_g can be severely underestimated because of unaccounted wind-driven rain missed by a standard rain gauge. Although various corrections have been proposed for this phenomenon (e.g. Sharon, 1980; Yang *et al.*, 1998) there is the added complication afforded by live forest canopies in which emergent trees sticking out of the main canopy tend to catch inclined rainfall (and CW) more efficiently than their more sheltered neighbours, thereby increasing the overall catch to a level that exceeds amounts of conventionally measured rainfall in the open (Herwitz and Slye, 1992). Thirdly, because net precipitation under these conditions often exceeds P_g, it is not possible to estimate ΣEi in a manner analogous to Eqn 18.1. Some investigators have therefore used the wet canopy version of the Penman-Monteith equation to approximate ΣEi although this may result in an underestimation due to problems with advected energy (see discussion in Roberts *et al.,* this volume). Furthermore, for the proper quantification of net precipitation ($T_f + S_f$) large numbers of throughfall gauges (>20–30) are usually needed to account for the high spatial variability of rainforest canopies. In addition, it is advisable to apply a 'roving' gauge technique that is considered to include 'drip' points (where rain or fog drip becomes concentrated because of peculiarities in the configuration of the trees) in a more representative manner than a fixed gauge arrangement would do. Although amounts of throughfall sampled in this way in lowland rainforest have been shown to be significantly higher than when a fixed gauge network is used (Lloyd and Marques, 1988), the roving gauge technique has been little used so far in TMCF (Bruijnzeel and Proctor, 1995) and published results may therefore represent underestimates (cf. Hafkenscheid *et al.*, 2002). On the other hand, regularly relocating one's throughfall gauges easily causes major disturbance to the often fragile soils of TMCF, particularly on steep slopes. As such, the use of a large number of gauges in a fixed spatial arrangement has been preferred by some investigators, particularly under seasonal conditions in which the assumption of a temporally non-variant canopy that underlies the roving approach no longer holds (Köhler, 2002; cf. Brouwer, 1996). Given the very high stemflow proportions generated in the more stunted cloud forest types with their multiple-stemmed and crooked trees, adequate attention should also be paid to the stemflow sampling design.

The classic approach to evaluate contributions by cloud water to forests by simply comparing amounts of net and gross precipitation for events with and without fog ignores potential contrasts in rates of wet canopy evaporation under the respective conditions (Kashiyama, 1956; Harr, 1982). Furthermore, given the high spatial variability in net precipitation already referred to, this method only works well if cloud water contributions are substantial and temporally well-defined or if the confidence intervals for the net precipitation estimates are narrow through the use of a sufficiently large number of throughfall and stemflow gauges. For example, both Hafkenscheid (2000) and Schellekens *et al.* (1998) reported that regression equations linking gross and net precipitation in TMCF in Jamaica and Puerto Rico, respectively, did not differ significantly for events with and without fog, thus rendering the approach meaningless from the statistical point of view in these particular cases, possibly because an insufficient number of (roving) gauges was used (10–12); (Table 18.2).

ALTERNATIVE APPROACHES

In view of the above-mentioned difficulties with the more traditional approaches various alternative methods have been advanced but these too have met with variable success. Exploiting the fact that concentrations of sodium and chloride in cloud water are generally much higher than in rainfall (Asbury *et al.*, 1994; Clark *et al.*, 1998), Hafkenscheid, Bruijnzeel and De Jeu (1998) attempted to evaluate the contribution of cloud water to net precipitation in two upper montane cloud forests in Jamaica of varying exposure using a *sodium mass balance approach*:

$$(P_g \times C_{P_g}) + (\mathrm{CW} \times C_{\mathrm{cw}}) = (T_f \times C_{T_f}) + (S_f \times C_{S_f}) \quad (18.5)$$

in which C denotes the concentration of Na (or any other suitable constituent) in the respective components. Whilst a reasonable estimate was obtained for the most exposed forest, an unexpectedly high cloud water input was derived for the less exposed forest, suggesting that application of the chemical mass balance approach may be less than straightforward in complex mountainous terrain, possibly due to spatial variations in dry deposition. A similar approach makes use of the difference in isotopic composition of rain and fog water (fog often being enriched in the heavier isotopes ^{2}H and ^{18}O relative to rainfall in the same region; Ingraham and Matthews, 1988, 1990; Scholl *et al.*, 2002). Dawson (1998) and Te Linde *et al.* (2001) applied this *isotope mass balance technique* to quantify contributions by CW to the water budgets of a redwood forest in California and elfin cloud forest in Puerto Rico, respectively. In the latter case, Eqn 18.4 was then used to derive a plausible estimate for ΣE_i (4.4% of P_g) where the simple subtraction of net precipitation from gross rainfall had previously yielded a negative value of 7.5%.

Of late, various studies have attempted to measure fog deposition onto forest canopies in the temperate zone directly through the use of a so-called eddy covariance set-up in which a three-dimensional sonic anemometer (measuring turbulence) is combined with an active high speed cloud particle spectrometer (measuring fog liquid water content) (Kowalski *et al.*, 1997; Eugster *et al.*, 2001; Burkard *et al.*, 2002). Although promising, the technique is not without problems, among others because of flux divergences related to uncertainties in the magnitude of advected air streams and what has been termed the 'local net source and sink term' (i.e. condensation and evaporation of fog droplets; Burkard *et al.*, 2002). The first application of the eddy covariance technique in a tropical montane cloud forest setting (Puerto Rico) suggested contributions by CW to be much smaller than those by wind-driven rain (F. Holwerda, pers. comm.).[2]

An alternative experimental process-based approach to the evaluation of CW has been followed by M. Mulligan and A. J. Jarvis (pers. comm., February 2000) who *monitored the changes in weight of a known mass of living mossy epiphytes* suspended below the canopy of a TMCF in Colombia over an extended period

2 A similar experiment was initiated by the University of Bern and the Vrije Universiteit Amsterdam in windward lower montane cloud forest in the Tilarán range of northern Costa Rica in February 2003 (R. Burkard and K. F. A. Frumau, pers. comm.).

(weeks). Their alternative ‘cloud trap’ was protected against rainfall and extended over the first 5 m above the forest floor. No fog drip was recorded from this device, suggesting that either most of the intercepted cloud water was evaporated again or that absorbed amounts were too low to generate drip. Rates of both processes were comparable. A different result might have been obtained if the interceptor had been allowed to be wetted by throughfall or if it had been placed at a more exposed position higher up in the canopy. Chang, Lai and Wu (2002) followed a similar approach in a montane coniferous forest at a particularly foggy location in Taiwan using much smaller moss samples in a series of wetting and drying experiments under field conditions. By multiplying the average rate of fog absorption for various mosses times the estimated epiphytic biomass a stand-scale deposition rate of 0.17 mm h^{-1} (mosses only) was derived. Although the fog stripping capacity of individual conifer leaves was about half that of the mosses (0.30 vs. 0.63 g H_2O g^{-1} dry weight h^{-1}) the corresponding leaf biomass was about 20 times larger. As such, the fog stripping capacity of the canopy as a whole was considered to be closer to *c*. 2 mm h^{-1}. Unexpectedly, little change in weight occurred during moss exposure on a sunny day. With average daily fog durations of 4.7–11 h (depending on the time of year) overall fog deposition at this site can be expected to be considerable, therefore (Chang *et al.*, 2002). Köhler (2002), on the other hand, reported a distinct seasonal variation in moss and epiphyte water content in an upper montane forest in Costa Rica subject to comparatively little fog, indicating that evaporation may be important under certain conditions. Values ranged from *c*. 405% at the height of the wet season to less than 25% in the dry season. D. Hölscher *et al.* (2004) were able to reproduce this seasonal variation in epiphyte water contents using a simple running water balance model linked to an adapted analytical model of rainfall interception (Van Dijk and Bruijnzeel, 2001). Out of a total annual interception of 28%, 6% was predicted to be contributed by the epiphytes (D. Hölscher *et al.*, unpublished).

Finally, considerable progress has also been made during the last decade in the estimation of cloud water deposition in complex terrain using *physically-based models* (Joslin, Mueller and Wolfe, 1990; Mueller, 1991; Mueller, Joslin and Wolfe, 1991; Walmsley, Schemenauer and Bridgman, 1996; Walmsley, Burrows and Schemenauer, 1999). Such models include assumptions about the shape and spacing of the trees, their fog water collection efficiency, the frequency of fog, and the vertical rate of change of the liquid water content within ground-based clouds. Topographical data are used as a forcing function in wind flow models to derive a spatially explicit representation of the wind field. Although the application of such advanced models has given promising results for the estimation of cloud water deposition onto montane coniferous forest in Canada (Walmsley *et al.*, 1999), virtually none of the required input data is presently available for TMCF environments. Clearly, the application of physically-based models to remote tropical mountain sites remains a major challenge for some years to come. In the meantime, a ‘hybrid’ approach in which (some) physical modelling is combined with empirically derived estimates of fog characteristics, such as employed successfully to evaluate fog water contributions to catchment water budgets in the Maritime Provinces of Canada by Yin and Arp (1994), may constitute a suitable alternative that is worth exploring in a tropical montane context.

Results of post-1993 rainfall and cloud interception studies in TMCF

Measurements made with various types of fog gauges in areas with TMCF as reviewed by Bruijnzeel and Proctor (1995) suggested typical cloud water deposition rates of 1–2 mm/day (range 0.2–4.0 mm/day), with a tendency towards lower values during the dry season and with increasing distance to the ocean. Several studies employing fog gauges or measuring net precipitation in TMCF environments have been published since 1993, the results of which are summarised in Tables 18.1 (cloud interception data) and Table 18.2 (overall interception data).

At 0.3–2.43 mm d^{-1}, the majority of the post-1993 results for cloud water interception fall within the previously established range. Minimum values of *c*. 0.3 mm d^{-1} have been derived for forests in Honduras and Venezuela during rather dry periods whereas a maximum of 6.3 mm d^{-1} (or 2300 mm $year^{-1}$) has been claimed for an exposed site at 1100 m on the Pacific-Caribbean water divide as part of a transect study in western Panama (Cavelier *et al.*, 1996). There are strong indications that the latter figure is unrealistically high. Firstly, it is based on measurements with uncovered Grünow-type fog gauges, the poor performance of which has been hinted at already. Secondly, the rainfall at this windy site is reported as only 1495 mm $year^{-1}$ whereas annual totals at similar elevations on either side of the main divide were consistently above 3600 mm (Cavelier *et al.*, 1996), suggesting severe underestimation of rainfall and thus overestimation of the fog input at this site. Finally, Cavelier *et al.* (1997) obtained a rather low throughfall fraction (63% or *c*. 2200 mm $year^{-1}$) for lower montane rainforest at a similar elevation (1200 m) in the same area (Table 18.2). Adding the 2300 mm of allegedly intercepted cloud water to the 3500 mm of rain received annually by this forest would suggest a total precipitation input of *c*. 5800 mm, of which *c*. 3600 mm (5800 minus 2200 mm of throughfall) would then be required to have been lost through evaporation from the wet canopy (‘rainfall interception’). As will be shown below, reported *total* evaporative losses (i.e. both wet and dry canopy evaporation) from lower montane rainforests do not exceed 1380 mm $year^{-1}$. Nevertheless, although the claim of excessively large cloud water inputs in western Panama by Cavelier *et al.* (1996)

Table 18.1. *Post-1993 studies of cloud water interception (CW) in tropical montane environments; figures represent annual averages unless indicated otherwise*

Location	Elevation (m)	Forest type[a]	Mean annual precipitation (mm)	Cloud water interception mm d^{-1}	Cloud water interception percent[b]	Remarks	Reference
Australia	1000	LMCF	1350	0.94	35	CW equal to 'excess' T_F	Hutley *et al.* (1997)
Costa Rica	1500	LMCF	2520	2.43	28	Artificial foliage collector 1410 cm^2 at 17 m height	Clark *et al.* (1998)
Costa Rica	1500	LMCF	3300	0.53	6	CW equal to 'excess' T_F[c]	Fallas (2002)
		fragment LMCF		1.25	14		
		secondary LMCF		0.70	8		
Guatemala	2400	UMCF	2500	0.72	13	CW equal to 'excess' T_F	Brown *et al.* (1996)
	2750	UMCF		1.65d	281d	Dry season (Jan–March)	
Guatemala	2550	UMCF	2500	0.64	8	Dry season (Jan–March)	Holder (1998)
				1.30d	53d	Dry season (Nov–March)	
Hawai'i	2600	SA(C)F	<500	0.61[d]	38	Louvered fog gauge (3m)	Juvik and Nullet (1995b)
Honduras	900–1400	LMCF	4200	0.3d	6d	CW equal to 'excess' *TF*; Dry season (Jan–May)	Brown *et al.* (1996)
	1500	LMCF	2500	0.37d	12d	Dry season (Jan–March)	
Jamaica	1850	UMCF	2850	1.84	22	Grünow fog gauge above	Hafkenscheid (2000)
	1825			1.0	12	forest canopy	
	1850			0.53	6	Covered gauge in clearing	
	1810			0.53	6	Net precipitation method[e]	
Panama	1100	LMF	>3600[f]	6.30[f]	154	Grünow fog gauges	Cavelier *et al.* (1996)
	1250	LMF	5700	1.23	8		
Puerto Rico	1015	ECF	4500	1.33	7	Net precipitation method[a]	Schellekens *et al.* (1998)
Venezuela	2300	LMCF	3000	0.29	7	'Standard' collector (5m); 7 months (rather dry)	Ataroff (1998)

[a] LM(C)F, lower montane (cloud) forest; UMCF, upper montane cloud forest; SA(C)F, (dry) subalpine (cloud) forest; ECF, low-elevation dwarf cloud forest.
[b] Expressed as percentage of associated rainfall.
[c] Adding the 320 mm yr^{-1} of rainfall intercepted by a nearby LMF only seasonally affected by cloud (Fallas, 2002), would raise these values to: 1.40, 2.13 and 1.58 mm d^{-1}, and 15%, 23% and 17%, respectively.
[d] Expressed as mm/event (0.27 mm per calendar day).
[e] Minimum value due to exclusion of fog deposition during and shortly after rain (Hafkenscheid, 2002).
[f] See text for explanation of this excessively high value.

must thus be ascribed to instrumental error and misinterpretation of the data and is more likely to represent wind-driven rain, substantial (short-term) additions of cloud water (up to 5 mm d^{-1}) have been observed occasionally on rainless days at the highest elevations in the Sierra de las Minas, Guatemala (Brown *et al.*, 1996; Holder, 1998) (Figure 18.3c below).

Typical ranges of net precipitation determined for the respective types of montane forests as reviewed by Bruijnzeel and Proctor (1995) were: (i) 67–81% (average 75%; $n = 9$) for lower montane forest not affected much by cloud; (ii) 80–101% (average 88%; $n = 4$) for lower montane cloud forest; and (iii) 81–179% (average 112%; $n = 10$) for upper montane and low-elevation dwarf cloud forests. These averages for the respective forest types do not change much after incorporating the results of post-1993 studies (Table 18.2). The extent of the change, however, sometimes depends on the forest type to which each 'new' study is assigned and this presents difficulties in several cases. For example, throughfall fractions obtained for 'leeward' lower montane cloud forests in Costa Rica and, especially, Venezuela are so low (65% and 55%, respectively) (Table 18.2) that these forests effectively behave like LMRF not affected by cloud. This is partly a result of the protected location of the two sites but possibly also reflects their high epiphyte loading (Clark *et al.*, 1998; Ataroff, 1998; cf. Cavelier *et al.*, 1997). Epiphytes, especially

Table 18.2. *Post-1993 studies of throughfall* (T_f)*, stemflow* (S_f) *and apparent rainfall interception* (E_i) *fractions in tropical montane environments*

Location	Elevation (m)	Forest type[a]	T_f	S_f (% of P)	E_i[b]	Remarks	Reference
Australia	1000	LMCF	90	2	8	25 fixed troughs; 10–21 day sampling interval	Hutley *et al.* (1997)
Costa Rica	1500	LMCF	65	–	35	20 fixed standard gauges; 1–3 day sampling interval	Clark *et al.* (1998)
Costa Rica	1500	LM(C)F	90/131d[c]	–	10	10 fixed troughs; daily	Fallas (2002)
		LMCF	106/175d	–	−6		
		Remnant LMCF	114/174d	–	−14	4 fixed troughs, daily	
		Secondary LMCF	108/135d	–	−8		
Ecuador	1900–2300	LMCF	57	1	42	10 fixed gauges	Wilcke *et al.* (2001a)
Guatemala	2200	LM(C)F	81	<1	18	3–6 fixed gauges with	Brown *et al.* (1996)
	2400	L/UMCF	113	1–2	−15	large (52 cm dia) funnels; 4–7 day intervals	
	2750	UMCF	281d	2	−183		
Guatemala	2550	UMCF	108	–	−8	58 fixed gauges, weekly;	Holder (1998)
			100w	–	(0)	Rainy season (April–Oct)	
			153d	–	−53	Dry season (Nov–March)	
Hawai'i	2600	SA(C)F	75	–	25	2 fixed recording troughs;	Juvik and Nullet (1995b)
Honduras	900–1400	LMCF	95	–	5	3–6 fixed large diameter	Brown *et al.* (1996)
	idem		106d[d]	–	−6	gauges; 4–7 day intervals	
	1500	LMCF	111d[e]	–	−11		
Jamaica	1810	UMCF	73	12	14	1 recording trough + 12	Hafkenscheid (2000)
	1825	UMCF	60[f]	18	22	roving gauges (3–4 days)	
Panama	1200	LMRF	63	<1	37	50 fixed troughs; daily	Cavelier *et al.* (1997)
Puerto Rico	1015	ECF	89	(5)[g]	6	3 recording gutters + 10 roving gauges (1–3 days)	Schellekens *et al.* (1998)
Venezuela	2300	LMCF[h]	55	<<1	45	6 fixed trough gauges; weekly sampling	Ataroff (1998), Ataroff and Rada (2000)

[a] LM(C)F, lower montane (cloud) forest; UMCF, upper montane cloud forest; SA(C)F, (dry) sub alpine forest; LMRF, lower montane rainforest not affected significantly by cloud; ECF, low-elevation dwarf cloud forest.
[b] $E_i = P - (T_f + S_f)$, apparent interception, including ungauged contributions by cloud water.
[c] Dry season: December–April.
[d] Dry season: January–May.
[e] Dry season: January–March.
[f] Underestimate due to insufficient number of gauges (see Hafkenscheid *et al.* (2002) for details).
[g] Based on data from Weaver (1972).
[h] Transitional to UMCF (Ataroff and Rada, 2000).

'tank' bromeliads and moss 'balls', are known to have very high *potential* moisture storage capacities and to release their water rather slowly (Pócs, 1980; Nadkarni, 1984; Veneklaas *et al.*, 1990; Richardson *et al.*, 2000). On the other hand, *effective* storage capacities will depend strongly on actual water contents which are known to vary rapidly depending on variations in precipitation and evaporation (Köhler, 2002). More work is needed along the lines indicated by Chang *et al.* (2002), Köhler (2002) and Hölscher *et al.* (2004) to solve this question.

The remaining new studies in undisturbed lower montane cloud forests listed in Table 18.2 ($n = 4$; i.e. leaving the two transitional Guatemalan forests at 2200 and 2400 m aside as they rather resemble LMRF and UMCF, respectively) produced results that are in agreement with previously established values for this type of forest. Adding these new results to the existing dataset for LMCF raised the average net precipitation fraction slightly from 88% to 92% ($n = 8$). Instead, incorporating the 'anomalous' results for the Costa Rican and Venezuelan sites as well would not only lower the 'old' average value from 88% to 85% but particularly extend the bottom end of the reported range for LMCF (from 80% to 55%). Alternatively, assigning these two studies plus the Guatemalan forest at 2200 m and the Panamanian forest to the class of LMRF not affected much by low cloud would bring the associated average value down from 75% to 71%. Adding the new results obtained for upper montane and elfin cloud forests in Guatemala, Jamaica and Puerto Rico ($n = 5$) also lowers the associated average value of net precipitation slightly (from 112% to 109%). However, this is entirely due to the inclusion of the rather low throughfall figure obtained for the forest at 1810 m in Jamaica (Table 18.2).[3] The very high stemflow fractions obtained for the two Jamaican forests are noteworthy and were ascribed to the presence of multiple-stemmed and crooked trees (Hafkenscheid *et al.*, 2002). Similarly high values have been reported for stemflow in 10–15 year-old leeward secondary montane forest in Costa Rica which showed both a very high stem density and a high frequency of multiple-stemmed trees (Köhler, 2002).

Given the rapid conversion of TMCF to other land uses (mostly pasture; Bruijnzeel and Hamilton, 2000), the finding of enhanced net precipitation in small primary and secondary forest fragments compared to nearby tall undisturbed windward lower montane cloud forest in northern Costa Rica (Fallas, 2002; study no. 3 in Table 18.2) is potentially of great interest. More work is needed to confirm these preliminary (because based on few, fixed gauges) results.[4]

Summarising, the extended dataset for net precipitation in tropical montane forests suggests a steady increase in average values from lower montane forest (*c*. 70%), through lower montane cloud forest (*c*. 90%) to upper montane and low-elevation dwarf cloud forests (*c*. 110%). More work is needed to elucidate the precise role of epiphytes in the interception process, as evidenced by the very low throughfall fractions obtained for some cloud forests despite considerable inputs of cloud water (e.g. as in Costa Rica and Venezuela, Tables 18.1 and 18.2). Future work could profitably combine several of the approaches outlined in the previous sections, notably the use of stable isotopes, electronic field monitoring of epiphytic water content, and interception modelling. Furthermore, amounts of net precipitation generated in cloud forest fragments deserve more study as well.

Most of the data collated in Tables 18.1 and 18.2 concern annual averages. However, in many areas (e.g. Central America) cloud interception is a highly seasonal process that assumes its greatest importance during the dry season. As such, a cloud forest with an overall net precipitation figure well below 100% may still experience a much higher value during particular times of the year. A case in point is the Sierra de las Minas, Guatemala, where in the LMCF zone at 2200 m average throughfall is 81% (Table 18.2). At the height of the rainy season (August, September) relative throughfall drops to about 65% but during the dry season (January–March) it exceeds incident rainfall (Figure 18.3a). At 2400 m (transition zone to UMCF), cloud interception is important year-round but again reaches its peak during the dry season (Figure 18.3b; cf. the seasonal contrast observed by study no. 6 in the same area; Tables 18.1 and 18.2). Cloud interception is still more pronounced at 2750 m (UMCF zone). In the period January–March 1996, throughfall exceeded rainfall by 147 mm (181%; study no. 5 in Table 18.2), with the excess reaching maximum values of as much as 40–50 mm over 3–4 day periods (Figure 18.3c). Such findings contradict the suggestion by Vogelmann (1973) that absolute amounts of fog incidence in eastern Mexico decreased with elevation within the cloud belt and during the dry season compared to the rainy season. However, Vogelmann's contention was based on measurements made with cylindrical wire-mesh fog gauges, the limitations of which have been stressed already. It is more than likely therefore that these early measurements at least partly reflect effects of wind-driven rain, notably during the rainy season (cf. Cavelier *et al.*, 1996). More importantly, the findings from Guatemala underline the importance of TMCF for sustained dry season flows (cf. Zadroga, 1981). We will come back to this important point in the section on TMCF and water yield.

There is a need for additional studies like that of Brown *et al.* (1996) to document the changes in net precipitation with elevation, slope aspect and season in different regions.

Transpiration and total forest water use

In their review of pre-1993 work on TMCF water use (both total evapotranspiration, E_T and transpiration, E_t), Bruijnzeel and Proctor (1995) had to draw mostly on catchment and site water balance studies. In addition, in the absence of direct estimates of E_t, only approximate values – obtained by subtracting apparent interception totals E_i from E_T – could be presented. Apart from the general limitations of the water budget technique for the evaluation of E_T (see Bruijnzeel (1990) for a discussion in a tropical context) there is the added complication in the case of TMCF that unmeasured inputs via the interception of cloud water and wind-driven rain will lead to correspondingly lower values of E_T. As such, the estimates of E_T for cloud-affected forests cited below represent *apparent* values only and care should be taken when comparing them with values derived by non-water budget based methods.

3 The results for the nearby forest at 1825 m are excluded from the present analysis because these are considered underestimates due to the use of an insufficient number of throughfall gauges.

4 Recent ongoing work in the same area seems to confirm the findings of Fallas (2002) (K. F. A. Frumau, pers. comm.).

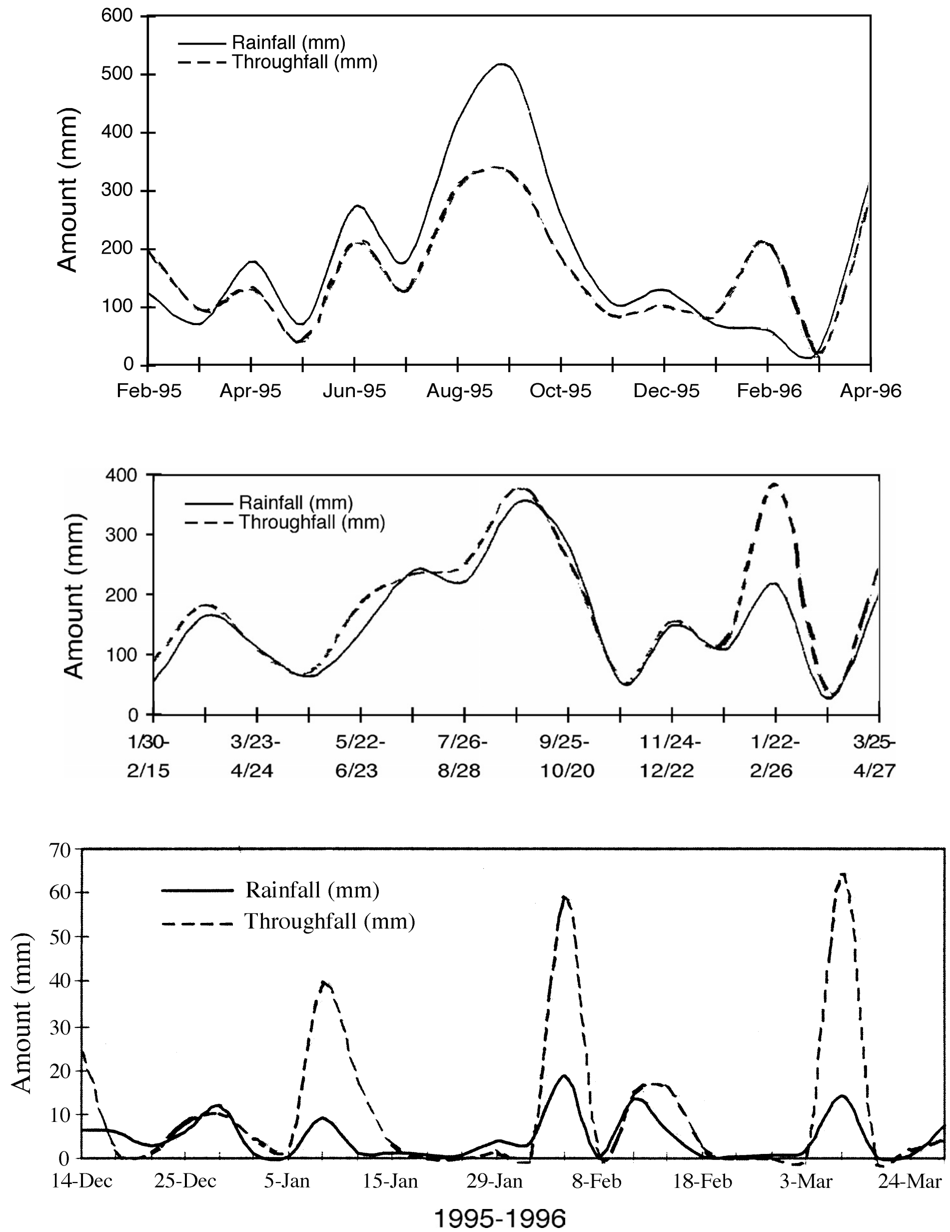

Figure 18.3 Seasonal rainfall and throughfall patterns with elevation in the Sierra de las Minas, Guatemala. (a) 2200 m, lower montane cloud forests; (b) 2400 m, transition from lower to upper montane cloud forest; (c) 2750 m, upper montane cloud forest, dry season only (after Brown *et al.*, 1996).

The pre-1993 dataset on E_T for tropical montane forests can be summarised as follows: (i) equatorial lower montane forest with negligible fog incidence: 1155–1380 mm year^{-1} (average 1265 mm year^{-1}; $n = 7$); (ii) lower montane cloud forest with moderate fog incidence: 980 mm year^{-1} ($n = 1$); upper montane cloud forest with high fog incidence: 310–390 mm year^{-1} ($n = 3$). Corresponding 'guesstimates' for E_t are: (i) 510–830 mm year^{-1}; (ii) 675 mm year^{-1}; and (iii) 250–285 mm year^{-1}, respectively (see Bruijnzeel and Proctor (1995) for details). Thus, whilst information on total water use (E_T) of cloud forests of any type is admittedly scarce, the data for upper montane cloud forest seem at least consistent. Conversely, there is considerable uncertainty about the water use of lower montane cloud forest. The only estimate available (980 mm year^{-1} for a tall forest at 2300 m in Venezuela) is based on energy budget calculations which involved numerous assumptions (Steinhardt, 1979). Bruijnzeel *et al.* (1993) derived

Table 18.3. *Post-1993 water budget studies in tropical montane cloud forest environments (values rounded off to the nearest 5 mm)*

Location	Elevation (m)	Forest type[a]	Mean annual precipitation	E_T (mm yr^{-1})	E_t	Reference
Australia[b]	1000	LM(C)F	1350	1260	845	Hutley *et al.* (1997)
Jamaica[c]	1810	UMCF[h]	2850	1050	620	Hafkenscheid *et al.* (2002)
	1825	UMCF*		890[j]	510	
Venezuela[d]	2350	L/UMCF[h]	3125	2310	560	Ataroff and Rada (2000)
Puerto Rico[e]	780	UMCF[h]	4450	1045	–	Van der Molen (2002)
	1015	ECF[i]	4450	705	–	
Puerto Rico[f]	1015	ECF[i]	4450	1145	–	Garciá-Martino *et al.* (1996)
Puerto Rico[g]	1015	ECF[i]	4450	435	170	Holwerda (1997), Schellekens *et al.* (1998)

[a] LMCF, lower montane cloud forest; UMCF, upper montane cloud forest; ECF, low-elevation dwarf cloud forest.
[b] E_t evaluated from soil water budget (net precipitation vs. change in soil water storage); $E_T = E_i + E_t$,
[c] E_t estimated via energy-balance temperature fluctuation (EBTF) method for nearby secondary forest; scaling up to forest plots according to relative values of leaf area index; values must be considered approximate; $E_T = E_t + E_i$.
[d] E_t via portable gas exchange measurements; $E_T = E_t + E_i$.
[e] E_T estimated with Bowen ratio energy balance method; no distinction made between wet and dry canopy conditions, and therefore no separate estimate for E_t.
[f] E_T evaluated as the difference between average rainfall (with 10% cloud water added) and runoff, both estimated from regression equations against elevation.
[g] E_t via EBTF method; $E_T = E_t + E_i$, with $E_i = 6\%$.
[h] Relatively tall-statured forest.
[i] Stunted ridge top forest.
[j] Value lowered by 300 mm by the present writer to account for underestimation of throughfall and corresponding overestimation of E_i (Hafkenscheid *et al.*, 2002).

an E_T of 695 mm year^{-1} for a 'stunted lower montane cloud forest' at 870 m on a coastal mountain in East Malaysia. However, their estimate was based on short-term site water budget calculations for a particularly dry period and is therefore not included in the present analysis.

Despite the great need for additional information on TMCF water use signalled at the 1993 Puerto Rico Symposium, comparatively little new evidence has become available since then. The results of several recent studies in three different types of cloud forest are summarised in Table 18.3.

Table 18.3 shows that all new estimates are considerably higher than those derived previously for the respective forest types. For example, at 1260 mm, the annual E_T of a tall lower montane forest subject to 'frequent, low intensity rainfall associated with low cloud' in Queensland, Australia is very close to the average value of E_T for lower montane forests *not* affected by fog and low cloud cited earlier (1265 mm year^{-1}). Similarly, E_t for this forest (845 mm year^{-1}) approximates the maximum value inferred by Bruijnzeel (1990) for non-cloud forests (830 mm). However, the investigators stressed that their evaporation estimates should be seen as maximum values because the observations concerned a small plot dominated by a single emergent tree. If a larger plot had been monitored, with additional species, openings in the canopy and individuals with less exposed crowns, the result might well have been lower (Hutley *et al.*, 1997). At first sight, the E_T values estimated for two upper montane cloud forests of contrasting stature in the Blue Mountains of Jamaica (1050 and 890 mm year^{-1}, Hafkenscheid *et al.*, 2002) also seem to be closer to the single value reported earlier for tall *lower* montane cloud forest (980 mm year^{-1}; Steinhardt, 1979) rather than to the 310–390 mm year^{-1} derived by Bruijnzeel and Proctor (1995) for upper montane cloud forests proper. However, the latter water budget based estimates would need to be raised by the corresponding amounts of *CW* to be directly comparable with the present micro-meteorological estimates. In the absence of measured values for *CW* for these other sites, Bruijnzeel (1990) tentatively added amounts measured at comparable nearby locations, obtaining approximate E_T values of 570–775 mm year^{-1}. These are more in line with the presently found estimates but still lower. The cloud water incidence experienced by the Jamaican forests is relatively low, however (Table 18.1), which may go some way towards explaining their somewhat higher E_t. Further support for the Jamaican values comes from soil water depletion patterns measured at the same sites (Hafkenscheid *et al.*, 2002) as well as from the almost identical value derived for a comparable forest type in Puerto Rico (Van der Molen, 2002). Albedoes (0.11–0.14) and net radiation fractions of incoming short-wave radiation for these forests were comparable to values derived for lowland forest (Hafkenscheid, 2000; Van der Molen, 2002; Shuttleworth, 1988), suggesting that any contrasts in cloud forest water uptake should rather reflect differences in stomatal behaviour or leaf area index (see below). The estimated total evaporation from a tall cloud forest in the transitional zone from lower to upper montane forest in Venezuela reported by Ataroff and Rada (2000) is excessively high. Although based on comparatively short-term measurements of gas exchange, the estimate for *Et* seems plausible at 560 mm year^{-1}. The very high value for total E_T is largely due to the comparatively even higher wet canopy evaporation component (1750 mm year^{-1}) to which the authors added a further 215 mm of litter evaporation, thereby bringing the total annual evapotranspiration figure to as much as 2525 mm. Since available radiation totals in this otherwise 'very humid and cloudy environment' almost certainly will not be sufficient to sustain such high rates of evaporation it cannot be excluded that the author's throughfall sampling design (Table 18.2) is in need of intensification (cf. Hafkenscheid *et al.*, 2002).

The three estimates for E_T of low-elevation dwarf cloud forest in Puerto Rico that have become available in recent years are very different at 435–1145 mm year^{-1} (Table 18.3). The highest of these estimates must be considered suspect for two reasons. Firstly, it is based on the subtraction of an average runoff figure from an average rainfall figure (though corrected for unmeasured cloud water inputs), both of which were estimated from regressions linking rainfall/runoff to elevation (Garciá-Martino *et al.*, 1996). Secondly, it is much higher than the value established by Holwerda (1997) for the reference open-water evaporation total for the dwarf forest zone (670 mm year^{-1}). Because inclusion of ungauged additions to the water budget by wind-driven rain would have increased estimated E_T even more, it is more than likely that this excessively high value is caused by catchment leakage problems. Assuming the contribution to overall E_T by wet canopy evaporation from the elfin forest to be $5 \pm 1\%$ of the rainfall (Schellekens *et al.*, 1998; Te Linde *et al.*, 2001), suggests the average transpiration rate to vary between 0.47 (Holwerda, 1997) and 1.2 mm d^{-1} (Van der Molen, 2002). Given these rather contrasting findings, the results of an ongoing study in the same forest by F. Holwerda using more sophisticated equipment are awaited with interest.

Despite these recent additions to the literature on TMCF water use, it must be concluded that our knowledge remains fragmentary and at times contradictory. Further work is urgently needed (see also the next section). Nevertheless, it can also be concluded that differences in actual water use by lower and upper

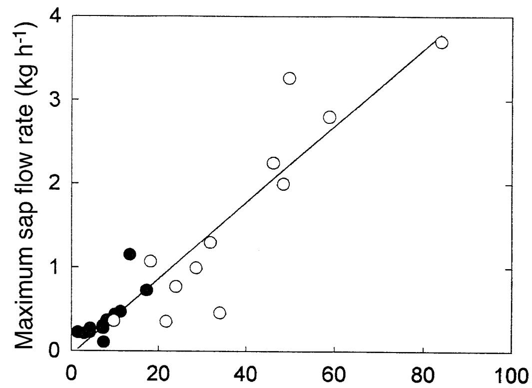

Figure 18.4 Relationship between maximum sapflow rate and total leaf area from level, waterlogged sites (closed circles) and from sloped, better drained sites (open circles) in TMCF in Hawai'i. (After Santiago *et al.* (2000); reproduced with permission.)

montane cloud forests are much smaller than inferred initially from catchment- or site water budget calculations. In theory, future studies of cloud forest water uptake could make use of a variety of plant physiological techniques (cf. Dawson, 1998; Smith and Allen, 1996; Wulschleger, Meinzer and Vertessy, 1998). A recent study that employed sapflow gauges to study transpiration in montane cloud forest in Hawai'í is that reported by Santiago *et al.* (2000). Their measurements demonstrated a clear dependence of (maximum) instantaneous transpiration rates on tree leaf surface areas that, in turn, were governed by site drainage conditions. Stand leaf area index, and therefore E_t, was much lower on waterlogged, level sites compared to better drained, sloping sites (Figure 18.4). However, transpiration rates were often too low for monitoring by the sapflow method. Similar problems were encountered in Jamaican cloud forest (R. L. L. J. Hafkenscheid, pers. comm.). It would seem, therefore, that there may be scope for alternative approaches, such as the use of stable isotopes (Dawson, 1998).

TROPICAL MONTANE CLOUD FORESTS AND WATER YIELD

Due to the combination of added moisture inputs from cloud water interception (Tables 18.1 and 18.2) and somewhat lower water use (Table 18.3), water yields for a given amount of rainfall from cloud forested headwater areas tend to be higher than those emanating from montane forests not affected by fog and low cloud. Similarly, flows from cloud forest areas tend to be more stable during extended periods of low rainfall. Therefore, fears have been expressed that the conversion of TMCF to other land uses could result in significant declines in overall and dry season flows (Zadroga, 1981; Brown *et al.*, 1996).

The original extent of TMCF worldwide was given as about 50 million ha (Persson, 1974). Although this estimate was probably somewhat higher than reality (Hamilton, 1995b) and no accurate information is available as to how much might now remain, there can be little doubt that cloud forests are disappearing rapidly. In Central America and the Caribbean, LaBastille and Pool (1978) considered as early as the 1970s that cloud forests were declining faster than any other forest type. Similarly, it has been estimated that some 90% of the cloud forests of the northern Andes of Colombia has been lost, mostly to pastures and agricultural fields (Doumenge *et al.*, 1995). The causes of cloud forest disappearance and degradation are myriad but worldwide the greatest loss comes from its conversion to grazing land, especially in seasonally dry climates. Other, regionally important causes include conversion to temperate vegetable cropping and harvesting of wood for charcoal production, timber harvesting, mining, unsustainable harvesting levels of non-wood products (e.g. orchids and bromeliads), recreation and eco-tourism, introduction of alien species, and the establishment of an ever increasing number of telecommunication installations on cloud forested mountain tops (Doumenge *et al.*, 1995; Hamilton, 1995b; Bruijnzeel and Hamilton, 2000). Finally, as discussed more fully below, there is increasing evidence that TMCFs are also threatened by global warming.

Where tropical forests of any kind are replaced by annual cropping or grazing there are bound to be profound changes in the area's hydrology (Bruijnzeel, 1990). The beneficial effects on soil aggregate stability and water intake capacity afforded by the high organic matter content and abundant faunal activity of forest soils may linger for a year or two after clearing. However, exposure of the soil surface to the elements generally leads to a rapid decline thereafter, particularly if fire was used during the clearing operation (Lal, 1987). An additional aspect in densely populated agricultural steep lands is that considerable areas may become permanently occupied by compacted surfaces, such as houses, yards, trails and roads (Ziegler and Giambelluca, 1997). In areas with heavy grazing pressure, soil infiltration capacities suffer further from compaction by trampling cattle (Gilmour, Bonell and Cassells, 1987). As a result, conversion of forest to annual cropping or grazing is almost inevitably followed by increases in amounts of surface runoff (Bruijnzeel, 1990; cf. Grip *et al.*, this volume).

A second consequence of forest clearing relates to the associated changes in net rainfall – no longer are there trees to intercept rainfall or fog. Neither, of course, are (low) levels of forest water use (transpiration) maintained. Whilst annual crops and grass also intercept rainfall and cloud water, and take up water from the soil, the associated amounts are (much) smaller than for forest due to the generally larger total leaf surface area and deeper root systems of forests compared to crops or grass (Calder, 1998). Thus, the clearing of a montane forest that does not experience appreciable inputs of cloud water (i.e. LMRF) will result in an increase in the total volume of streamflow, typically by 100–400 mm year^{-1} (depending on rainfall; Bruijnzeel, 1990). In theory, the extra amount of moisture available in the soil due to the reduction in E_i and E_t after converting (non-cloud) forest should permit an increase in baseflow levels – *as long as soil infiltration capacity is maintained*. In practice, however, the degeneration of the soil's infiltration capacity after forest removal is often such that the potential gain in soil water afforded by the reduced water use after clearing is more than offset by increases in overland flow and peak runoff during the wet season, with diminished streamflow during the dry season as the result (Bruijnzeel, 1989, 2004).

The risk of reduced dry season flows following forest clearance becomes even more serious in the case of clearing TMCF. The extra inputs of water to the forest ecosystem afforded by cloud interception during the dry season can be substantial, particularly at exposed locations (Tables 18.1 and 18.2). Also, such extra additions assume particular importance during periods of low rainfall (Figure 18.3c). Whilst the cloud stripping ability of solitary or groups of trees that have been left standing remains more or less intact and could even be enhanced due to greater exposure to passing fog (cf. study no. 3 in Table 18.2; Fallas, 2002; Weathers *et al.*, 1995), it would surely disappear altogether in the case of a wholesale conversion to vegetable cropping or grazing (Zadroga, 1981). The eventual effect on streamflow will depend on the relative proportions of the catchment that were occupied by the respective types of cloud forest. For example, exposed ridge top forests may intercept large amounts of cloud water but their spatial extent is limited (Brown *et al.*, 1996).

In recent years, diminished dry season flows have been reported for various parts of the tropics that experienced a considerable reduction in montane forest cover, including Costa Rica's Monteverde area (Pounds, Fogden and Campbell, 1999), Honduras' Cusuco National Park and Guatemala's Sierra de las Minas (Brown *et al.*, 1996), eastern Mexico (I. Garciá, pers. comm.) and (possibly) Flores, eastern Indonesia (Patthanayak and Kramer, 2004). However, it is not clear to what extent these reductions in flow are primarily the result of the loss of the fog stripping capacity of the former forest, or of diminished rainfall related to larger-scale climatic fluctuations (cf. Mahé *et al.*, this volume), reduced infiltration and water retention capacities of the soil due to erosion after forest clearance or, in some cases, increased diversions for irrigation. For instance, the two catchment pairs in Honduras and Guatemala for which Brown *et al.* (1996) derived a

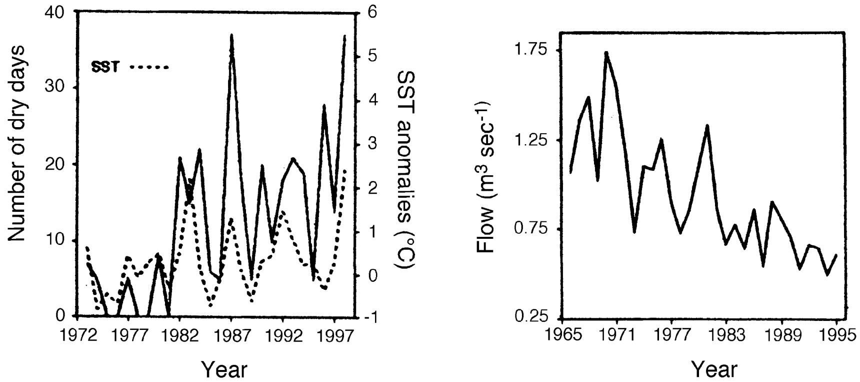

Figure 18.5 Trends for (a) sea surface temperature anomalies and number of rainless days, and (b) minimum streamflows in north-west Costa Rica since the 1970s. (Adapted from Pounds *et al.*, 1999.)

50% reduction in dry season flow after conversion to vegetable cropping, were rather different in size and elevational range, and therefore in their exposure to fog and rainfall (Table 18.1). A more convincing, albeit non-tropical, case was provided by Ingwersen (1985) who observed a (modest) decline in summer flows after a 25% patch clearcut operation in the same catchment in the Pacific Northwest region of the US for which Harr (1982) had inferred an annual contribution by fog of *c*. 880 mm. The effect disappeared after five to six years. Because forest cutting in the Pacific Northwest is normally associated with strong increases in water yield (Harr, 1983), this anomalous result was ascribed to an initial loss of fog stripping upon timber harvesting, followed by a gradual recovery during regrowth. Interestingly, the effect was less pronounced in an adjacent (but more sheltered) catchment and it could not be excluded that some of the condensation not realised in the more exposed catchment was ‘passed on’ to the other catchment (Ingwersen, 1985; cf. Fallas, 2002). Little is known of the soil physical changes accompanying cloud forest conversion to pasture. Duisberg-Waldenberg (1980) did not detect consistent changes in infiltration capacity in grazing land in northern Costa Rica some five to seven years after forest clearance. More recently, however, substantial reductions were observed in 30-year-old pasture in the same area, with the degree of the reduction being commensurate with the frequency of cattle passing. Infiltration-excess overland flow was observed regularly on hillslope contour cattle trails which were estimated to make up at least 15% of the total area (C. Tobón, pers. comm.). Such findings suggest that it may take a number of years before soil degradation reaches a critical level and surface hydrological processes are altered sufficiently to affect streamflow regimes (cf. Sandström, 1998). Identifying the precise cause(s) of the observed decreases in dry season flows and finding ways of restoring them should be given very high research priority in the years to come (cf. Scott *et al.*, this volume; Bruijnzeel, 2004).

On a related note, there is increasing evidence that TMCFs are also threatened by regional and global warming of the atmosphere. The latter tends to raise the average level of the cloud condensation level (Scatena 1998; Still, Foster and Schneider, 1999; Lawton *et al.*, 2001). Apart from adverse hydrological consequences such as diminished opportunities for cloud water interception, a lifting of the cloud base is bound to produce important ecological changes as well. The organisms living in TMCFs are finely attuned to the rather extreme climatic and soil conditions prevailing in these already stressed ecosystems (Benzing, 1998; Pounds *et al.*, 1999; Hafkenscheid, 2000). One of the best-documented cases in this respect is provided by the Monteverde Cloud Forest Preserve in northern Costa Rica (Pounds *et al.*, 1999). Here, a decrease in fog frequency since the mid 1970s has been inferred using the number of days with no measurable precipitation as an index of fog frequency. The most extreme decreases within an overall downward trend occurred in 1983, 1987, 1994 and 1998, which appeared to be correlated with higher sea surface temperatures (Figure 18.5a). Anoline lizard populations in the area have declined in association with this pattern, with major population crashes in 1987, 1994 and 1998. Currently, 20 out of 50 species of frogs and toads, including the spectacular and locally endemic golden toad, have disappeared. At the same time, species from drier, lower elevations are invading and becoming residents (Pounds *et al.*, 1999).

The evidence presented in Figure 18.5 suggests a worrying relationship between global warming and drying of the air on the one hand, and reduced streamflows on the other in the case of north-west Costa Rica (Fleming, 1986). It could be argued that these data pertain to an area that is rather protected from the moisture-bearing trade winds coming from the Caribbean and that one should therefore be careful not to generalise such findings to ‘all’ cloud forest situations. For example, simulation studies of the effects of global warming on rainfall patterns predict a distinct rise in some cloud

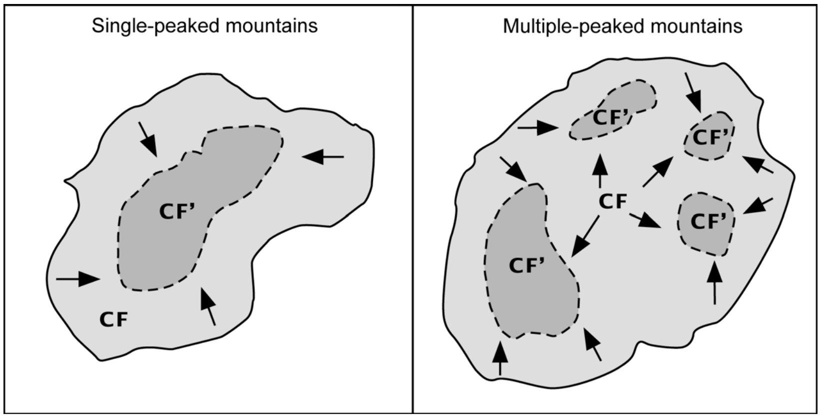

Figure 18.6 Possible changes in spatial cloud forest distribution in response to a rise in the cloud condensation level on (a) a single peak and (b) a mountain with several peaks. (After Sperling (2000); reproduced with permission.)

forest areas, such as the Pacific slopes of the Andes in southwest Colombia (Mulligan, 2000). Nevertheless, recent observational evidence reported by Lawton *et al.* (2001) suggests that widespread deforestation in the Atlantic lowlands of northern Costa Rica does indeed reduce cloud formation during the dry season, with possible consequences for cloud water interception in the adjacent uplands. The authors were able to reproduce the observed differences in cloud formation using a meso-scale atmospheric circulation model although values applied to parameterise soil water status below forest and pasture have been subject to criticism (Bruijnzeel, 2004). The current measurements of variations in surface climate, soil water content and the height of the cloud base by Lawton and collaborators (pers. comm.) in the area should resolve the issue before too long, however (see also Foster, 2001). Further evidence of the importance of land cover in the lowlands on the height of the cloud base comes from Puerto Rico. Here, the average cloud condensation level was lifted temporarily by several hundred metres after Hurricane Hugo had effectively defoliated the forests on the lower slopes of the Luquillo Mountains in September 1989. The resulting drop in forest water use caused a significant rise in the temperature of the overlying air and thus in the average position of the cloud base. Interestingly, the effect disappeared in a few months after the leaves had grown back again (Scatena and Larsen, 1991; see also photographs in Bruijnzeel and Hamilton, 2000). In the same area, Scatena (1998) interpreted the presence of isolated stands of large and very old (>600 years) Colorado trees (*Cyrilla racemiflora*) at elevations well below the current cloud base that experience relatively low rainfall (<3000 mm year^{-1}) as evidence of a gradual upward shift in vegetation zonation over the past several centuries. *Cyrilla* is currently a dominant tree in areas above the cloud base (> 600 m) and is most common where mean annual rainfall exceeds 4000 mm. Similarly, Brown *et al.* (1996) reported the occurrence of pockets of mossy cloud forest below the current average cloud base in Honduras. There is a need for more systematic research linking such empirical evidence to records of current and sub-recent climatic change (cf. Scatena, 1998).

On single mountains, a lifting of the average cloud condensation level will result in the gradual shrinking of the cloud-affected zone (Figure 18.6a). On multiple-peaked mountains, however, the effect may be not only that, but one of increased habitat fragmentation as well (Figure 18.6b), adding a further difficulty to the chances of survival of the remaining species (Sperling, 2000). Much more research is needed to confirm and extend the results obtained so far at Monteverde (Pounds *et al.*, 1999) and, to a lesser extent, Puerto Rico (Scatena, 1998). Apart from amphibians (Pounds *et al.*, 1999), the epiphyte communities living in the more exposed parts of TMCF canopies might prove equally suited to detecting changes in climatic conditions, rainfall and cloud water chemistry, and possibly enhanced ozone and UV-B levels (Lugo and Scatena, 1992; Benzing, 1998; cf. Gordon, Herrera and Hutchinson, 1994).

PUTTING CLOUD FORESTS ON THE HYDROLOGICAL RESEARCH AGENDA

Having reviewed the post-1993 evidence on the hydrological functioning of TMCF, what are the primary remaining gaps in knowledge? Arguably, the most urgent research questions in relation to the perceived 'added' hydrological value of TMCF over other montane forests are:

- Does conversion of TMCF to vegetable cropping or pasture indeed lead to reductions in dry season flows, or even total water yield? And if so, is this mainly because of the loss of the cloud interception function, or does the reduction in dry season flow rather reflect a deterioration in infiltration opportunities after deforestation?

- Do changes in (dry season) flow after forest clearance differ for the respective types of montane forest (i.e. LMRF, LMCF, and UMCF) and thus local climatology (e.g. distance to the ocean, exposure)?
- To what extent does global warming or the clearing of forests *below* the cloud belts affect the regional hydrological function of TMCF through raising the average level of cloud condensation? What are the associated changes in fog stripping opportunities, forest water use and, ultimately, streamflow?

Furthermore, most hydrological studies in TMCF have concentrated on quantifying net precipitation (crown drip). Whilst these have indicated important differences between contrasting forest types and topographic situations, published results differ widely in their reliability and comparisons between sites and forests are, therefore, rather difficult to make (Bruijnzeel and Proctor, 1995) (cf. Tables 18.1 and 18.2). There is a distinct need for more systematic observations of cloud water interception and net precipitation along elevational gradients according to an internationally accepted (standard) measuring protocol. This would require the adoption of a robust standard cloud water collection device that may be used for comparative purposes (site characterisation; cf. Schemenauer and Cereceda, 1994, 1995; Juvik and Nullet, 1995a; Daube *et al.*, 1987). Net precipitation measurements should involve the use of a sufficient number of roving throughfall gauges to allow for an adequate representation of 'drip points' (cf. Lloyd and Marques, 1988; Hafkenscheid *et al.*, 2002). In addition, the potential contrast in concentrations of stable isotopes in rain and cloud water to evaluate cloud water contributions to overall net precipitation totals (cf. Dawson, 1998) deserves further exploration in a TMCF context. The same holds for the further development and testing of physically-based cloud water deposition models on tropical mountains (cf. Joslin *et al.*, 1990; Mueller, 1991; Yin and Arp, 1994; Walmsley *et al.*, 1996).

Finally, before a sound understanding can be obtained of the influence of TMCF on streamflow amounts, reliable information is urgently needed on the water uptake rates (transpiration) of these forests. Such information is lacking almost entirely at present (Table 18.3; Bruijnzeel and Proctor, 1995). There are no published studies that have combined hydrological process work (rainfall and cloud interception, water uptake) and streamflow dynamics in any TMCF environment, although such work was recently initiated by a consortium led by the Vrije Universiteit Amsterdam in northern Costa Rica (Bruijnzeel, 2002).

Having defined the chief hydrological research needs in TMCF in the previous sections, where could these be addressed best? Arguably, the most cost-effective approach would be to identify sites with ongoing work (hydrological and/or ecological) and plan additional observations and experiments as part of a network that covers the range of environmental conditions encountered in the pan-tropical cloud forest belt (Figure 18.2). A preliminary inventory of current climatological and hydrological research efforts in TMCF (Bruijnzeel and Proctor, 1995; this chapter) establishes: (i) A notable lack of work in African, and to a lesser extent, Asian TMCF; and (ii) an almost total absence of studies linking streamflow dynamics with hydrological process work or land use change (see also Bonell, *in press*).

On the basis of previously executed or ongoing work, representativity of site geology and climate, as well as logistical considerations, the sites listed in Table 18.4 may be considered to be the most promising for inclusion in such a pan-tropical TMCF research network. To answer the questions raised earlier with respect to the effect on water yield of converting TMCF to other land uses would ideally require setting up a paired catchment experiment in which flows from a forested control catchment are compared against flows from a cleared catchment *after initial intercalibration of the two areas in the undisturbed state* (Hewlett and Fortson, 1983). 'Direct' comparisons of streamflow emanating from forested and cleared catchments may easily give biased results due to potential differences in ungauged, subterranean water transfers into or out of the catchments, especially in the kind of volcanic terrain prevailing at almost all of the sites listed in Table 18.4 (cf. Bruijnzeel, 1990; Brown *et al.*, 1996; Garciá-Martino *et al.*, 1996). However, because much of the remaining forest in these areas is officially protected, experimental clearing within the context of a paired catchment is almost certainly not feasible. The other option then is to compare streamflows from catchments with contrasting land uses whilst accounting for differences in deep leakage and within-basin processes (interception of rainfall and cloud, transpiration, soil water depletion, deep drainage). It goes without saying that any inferences for streamflow made on the basis of (short-term) measurements of forest and pasture water use will reflect the quality of such measurements. For example, based on rather short-term measurements of gas exchange Ataroff and Rada (2000) claimed an increase in soil water uptake of as much as 1510 mm year^{-1} after converting cloud forest in the transition zone from lower to upper montane forest to pasture. Even though their grassland was said to exhibit active growth, the cited value seems excessively high. Adding the interception loss of 625 mm brings the total evaporation to the very high value of 2690 mm year^{-1}. Further work seems necessary which could usefully employ energy budget or lysimetric measurements to back up the plant physiological observations.

Some of the more suitable sites for such an experiment include Mt Kinabalu, Malaysia, and Sierra de las Minas, Guatemala (forest clearance for vegetable cropping); and Monteverde, Costa Rica and the Cauca area, Colombia (conversion to pasture). The effects of timber harvesting (oaks and *Podocarpus*) and forest clearing for orchards or grassland under somewhat drier climatic conditions

Table 18.4. *Key research sites in tropical montane cloud forests*

Site	Elevation range (m)	Mean annual precipitation (mm)	Forest types[a]	Reference
'Maritime' tropics				
Mt Kinabalu, Sabah, Malaysia	600–3400	2600–4100	LRF – SACF	Kitayama (1992), Frahm (1990a, 1990b)
Hawai'i islands	500–3200	<7000	LMRF-SACF	Kitayama and Mueller-Dombois (1992), Juvik and Ekern (1978), Juvik and Nullet (1995b), Santiago *et al.* (2000), Nullet and Juvik (1997)
Luquillo Mnts, Puerto Rico	600–1050	<4500	LMCF-ECF	Weaver (1972, 1995), Schellekens *et al.* (1998), Baynton (1968, 1969), Van der Molen (2002), Scatena (1998), Vugts and Bruijnzeel (1999)
Blue Mnts, Jamaica	1500–2265	2600–4000	LMRF-UMCF	Tanner (1977), Kapos and Tanner (1985), Hafkenscheid (2000); Hafkenscheid *et al.* (2002)
'Continental' tropics				
Cauca, Southwest Colombia	1375–2895	>5000	LMCF-UMCF	M. Mulligan and collaborators (http://www.kcl.ac.uk/herb)
San Francisco, South Ecuador	1900–2300	2200	LM(C)F	Wilcke *et al.* (2001a, 2001b), Bussmann (2001), Schrumpf *et al.* (2001)
Merida, Venezuela	2200–3000	<2950	LMCF-UMCF	Ataroff (1998), Ataroff and Rada (2000)
Monteverde, Costa Rica	1200–1850	2500	LMCF	Lawton and Dryer (1980), Zadroga (1981), Clark *et al.* (1998), Nadkarni (1984), Fallas (2002), Still *et al.* (1999), Pounds *et al.* (1999), Lawton *et al.* (2001), Bruijnzeel (2002)
Talamanca, Costa Rica	2000–3300	<6300	LMCF-UMCF	Kappelle (1995), Hölscher *et al.* (2002, 2004), Köhler (2002), Dohrenwend (1979)
Sierra de las Minas, Guatemala	1400–2700	2500	LMRF-UMCF	Brown *et al.* (1996), Holder (1998)

[a] LM(C)F, lower montane (cloud) forest; UMCF, upper montane cloud forest; SA(C)F, (dry) sub alpine forest; LMRF, lower montane rainforest not affected significantly by cloud; ECF, low-elevation dwarf cloud forest.

may be studied in the Talamanca area, Costa Rica (Kappelle, 1995) or in the Merida area, Venezuela (Ataroff and Rada, 2000).

In view of the ongoing monitoring of amphibian and bird populations (Pounds *et al.*, 1999), bryophyte communities (cf. Nadkarni, 1984), and climate change modelling efforts (Still *et al.*, 1999; Lawton *et al.*, 2001) in the Monteverde area, this site must rank as the prime location for continued long-term observations of ecological changes due to climate change. In addition, it was recently chosen as the site for a process-based evaluation of the hydrological impacts of cloud forest conversion to pasture[5].

At several of the sites listed in Table 18.4 (e.g. Malaysia, Hawai'i, Puerto Rico), observations of climatic variables along the elevational gradient have been made whereas in others (e.g. Guatemala, Puerto Rico) preliminary estimates of net precipitation vs. elevation are available as well. It would be of great interest to both regional water resource planning and TMCF conservation efforts to also initiate gradient studies of forest water and energy budgets (including transpiration) at key sites. We seem to have reached a crucial point where additional hydrological information is required if true progress in the promotion of the water values of TMCF – and therefore their chances of being afforded adequate protection – is to be made. This, together with the rapid disappearance of TMCF in many areas (Doumenge *et al.*, 1995) is why it is 'decision time' for cloud forests (Bruijnzeel and Hamilton, 2000).

It is encouraging to note, therefore, that in 1999 IUCN, WWF International, the World Conservation Monitoring Centre (Cambridge, UK) and UNESCO-IHP joined hands to form the

5 See Bruijnzeel (2002) for details.

'Tropical Montane Cloud Forest Initiative'. The objectives of the Initiative include: 'the building and strengthening of networks of TMCF conservation and research organisations around the globe' and 'to increase recognition and resources for cloud forest conservation around the world, emphasizing their role in maintaining water catchments and biodiversity'. For further details, see: http://www.unep-wcmc.org/forest/cloudforest/english/homepage.htm. The Steering Committee of the Initiative brings together representatives from the founding organisations, scientists actively working in TMCF, and NGO representatives from Asia, Latin America and Africa. In June 2000, a 40-page document entitled: '*Decision time for cloud forests*' (Bruijnzeel and Hamilton, 2000) was published by the Initiative to help raise awareness among a non-scientific audience.[6]

A concerted effort is needed now to put tropical montane cloud forests firmly on the agendas of tropical hydrologists, conservationists, resource managers, donor agencies and policy makers. The chances of achieving this have never been better than today but time is running out in some areas. One can only hope that the recently initiated 'payment for environmental services' schemes installed in some Latin American countries and considered by others (Calvo, 2000; see Aylward, this volume, for details) will help to turn the tide. At the same time policy-makers would do well to remember that such schemes need to be based on sound hydrological information. Otherwise they may well suffer loss of credibility with lowlanders being charged for environmental services (such as a reliable supply of good quality water) that cannot be met in practice.

References

Aravena, R., Suzuki, O., and A. Pollastri, A., 1989. Coastal fog and its relation to ground-water in the IV region of northern Chile. *Chemical Geology* 79: 83–91.

Asbury, C. E., McDowell, W. H., Trinidad-Pizarro, R., and R. Berrios, 1994. Solute deposition from cloud water to the canopy of a Puerto Rican montane forest. *Atmospheric Environment* 28: 1773–1780.

Ataroff, M., 1998. Importance of cloud water in Venezuelan Andean cloud forest water dynamics. In: *First International Conference on Fog and Fog Collection*, Schemenauer, R. S. and H. A. Bridgman (eds). ICRC, Ottawa, pp. 25–28.

Ataroff, M. and Rada, F., 2000. Deforestation impact on water dynamics in a Venezuelean Andean cloud forest. *Ambio* 29: 440–444.

Baynton, H. W., 1968. The ecology of an elfin forest in Puerto Rico, 2. The microclimate of Pico del Oeste. *Journal of the Arnold Arboretum* 49: 419–430.

Baynton, H. W., 1969. The ecology of an elfin forest in Puerto Rico, 3. Hilltop and forest influences on the microclimate of Pico del Oeste. *Journal of the Arnold Arboretum* 50: 80–92.

Benzing, D. H., 1998. Vulnerabilities of tropical forests to climate change: the significance of resident epiphytes. *Climatic Change* 39: 519–540.

Bonell, M. (in press). Selected issues in mountain hydrology of the humid tropics. In *Water: Forestry and Land Use Perspectives*. *UNESCO Technical Documents in Hydrology* No. 5x. Paris: UNESCO.

Brouwer, L. C., 1996. Nutrient Cycling in Pristine and Logged Tropical Rain Forest. Tropenbos-Guyana Series, 1, Tropenbos-Guyana Programme, Georgetown, Guyana. 224 p.

Brown, M. B., de la Roca, I., Vallejo, A., Ford, G., Casey, J., Aguilar, B. and R. Haacker, 1996). *A Valuation analysis of the Role of Cloud Forests in Watershed Protection. Sierra de las Minas Biosphere Reserve, Guatemala and Cusuco N.P., Honduras*. RARE Center for Tropical Conservation, Philadelphia, USA

Bruijnzeel, L. A., 1989. (De)forestation and dry season flow in the humid tropics: a closer look. *Journal of Tropical Forest Science* 1: 229–243.

Bruijnzeel, L. A., 1990. *Hydrology of Moist Tropical Forests and Effects* converting tropical montane cloud forest to pasture, with initial *of Conversion: a State of Knowledge Review*. IHP-UNESCO Humid Tropical Programme, Paris, 224 pp.

Bruijnzeel, L. A., 2001. Hydrology of tropical montane cloud forests: a reassessment. *Land Use and Water Resources Research* 1: 1.1–1.18. [Also published under the same title as: Bruijnzeel (2002a) in *Hydrology and Water Management in the Humid Tropics*, (ed). J. S. Gladwell, pp. 353–383. *UNESCO Technical Documents in Hydrology* No. 5x. Paris: UNESCO.

Bruijnzeel, L. A., 2002. Hydrological impacts of reference to northern Costa Rica. Project Memorandum Form R7991, Forestry Research Programme, Natural Resources International, Aylesford, UK, 60 pp.

Bruijnzeel, L. A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment* doi: 10.1016/j.agee.2004.011.015.

Bruijnzeel, L. A. and L. S. Hamilton, 2000. Decision Time for Cloud Forests. *IHP Humid Tropics Programme Series* no. 13, IHP-UNESCO, Paris, IUCN-NL, Amsterdam and WWF International, Gland, 44 pp.

Bruijnzeel. L. A. and J. Proctor, 1995. Hydrology and biogeochemistry of tropical montane cloud forests: what do we really know? In: *Tropical Montane Cloud Forests. Ecological Studies* 110, Hamilton, L. S., Juvik, J. O. and F. N. Scatena (eds). Springer Verlag, New York, pp. 38–78.

Bruijnzeel, L. A., Waterloo, M. J., Proctor, J., Kuiters, A. T. and B. Kotterink, 1993. Hydrological observations in montane rainforests on Gunung Silam, Sabah, Malaysia, with special reference to the '*Massenerhebung*' effect. *Journal of Ecology* 81: 145–167.

Burkard, R., Eugster, W., Wrezinsky, T. and Klemm, O., (2002). Vertical divergence of fogwater fluxes above a spruce forest. *Atmospheric Research* 64: 133–145.

Bussmann, R. W., 2001. The montane forests of Reserva Biológica San Francisco (Zamora-Chinchipe), Ecuador. *Die Erde* 132: 9–25.

Calder, I. R., 1998. Water use by forests: limits and controls. *Tree Physiology* 18: 625–631.

Calvo, J. C., 1986. An evaluation of Thornthwaite's water balance technique in predicting stream runoff in Costa Rica. *Hydrological Sciences Journal* 31: 51–60.

Calvo, J. C. (2000). Case study: payments for watershed services in Costa Rica. In: M. F. Price and N. Butt (Eds.), *Forests in Sustainable Mountain Development. A State-of-Knowledge Report for 2000*, pp. 428–429, CABI, Wallingford, UK.

Cavelier, J., Jaramillo, M., Solis, D. and D. De Leon, 1997. Water balance and nutrient inputs in bulk precipitation in tropical montane cloud forest in Panama. *Journal of Hydrology* 193: 83–96.

Cavelier, J., Solis, D. and M. A. Jaramillo, 1996. Fog interception in montane forests across the Central Cordillera of Panama. *Journal of Tropical Ecology* 12: 357–369.

Chang, S. C., Lai, I. L., and Wu, J. T. (2002). Estimation of fog deposition on epiphytic bryophytes in a subtropical montane forest ecosystem in northeastern Taiwan. *Atmospheric Research* 64: 159–167.

Clark, K. L., Nadkarni, N. M., Schaeffer, D. and H. L. Gholz, 1998. Atmospheric deposition and net retention of ions by the canopy in a tropical montane forest, Monteverde, Costa Rica. *Journal of Tropical Ecology* 14: 27–45.

Daube, B., Kimball, K. D., Lamar, P. A. and K. C. Weathers, 1987. Two new ground-level cloud water sampler designs which reduce rain contamination. *Atmospheric Environment* 21: 893–900.

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

Dohrenwend, R. E., 1979. Hydrologic behavior at the top of a tropical mountain. *Michigan Technological University Forestry Center Research Note no. 29*, 14 pp.

6 A Spanish translation appeared in 2001. Both documents are freely available as long as stocks last from the Humid Tropics Programme, UNESCO-IHP, Paris, or from the author.

Doumenge, C., Gilmour, D. A., Ruiz Perez, M. and J. Blockhus, 1995. Tropical montane cloud forests: conservation status and management issues. In:. *Tropical Montane Cloud Forests. Ecological Studies* 110, L. S. Hamilton, J. O. Juvik, J. O. and F. N. Scatena (eds). Springer Verlag, New York, pp. 24–37.

Duisberg-Waldenberg, P. (1980). Erosion y conservacion de suelos. In: Centro Cientifico Tropical. *Estudio Ecológico Integral de las Zonas de Afectación del Proyecto Arenal.* Centro Cientifico Tropical, San José, Costa Rica, pp. 2-1–2-65.

Eugster, W., Burkard, R., Klemm, O. and Wrezinsky, T. (2001). Fog deposition measurements with the eddy covariance method. In: *Second International Conference on Fog and Fog Collection*, R. S. Schemenauer and H. Puxbaum (eds). ICRC, Ottawa, pp. 193–196.

Fallas, J., 2002. Net precipitation patterns in undisturd and fragmented Costa Rican cloud forests. In: J. S. Gladwell (Ed.), *Proceedings of the Second International Colloquium on Hydrology and Water Management*. CATHALAC, Panamá City, Panamá, pp. 389–398.

Fleming, T. H., 1986. Secular changes in Costa Rican rainfall: correlation with elevation. *Journal of Tropical Ecology* 2: 87–91.

Foster, P., 2001. The potential negative impacts of global climate change on ropical montane cloud forests. *Earth-Science Review* 55: 73–106.

Frahm, J. P., 1990a. The ecology of epiphytic bryophytes on M. Kinabalu, Sabah (Malaysia). *Nova Hedwigia* 51: 121–132.

Frahm, J. P., 1990b. The altitudinal zonation of bryophytes on M. Kinabalu. *Nova Hedwigia* 51: 133–149.

Frahm, J. P. and S. R. Gradstein, 1991. An altitudinal zonation of tropical rainforests using bryophytes. *Journal of Biogeography* 18: 669–676.

Garciá-Martino, A. R., Warner, G. S., Scatena, F. N. and D. L. Civco, 1996. Rainfall, runoff and elevation relationships in the Luquillo Mountains of Puerto Rico. *Caribbean Journal of Science* 32: 413–424.

Gilmour, D. A., Bonell, M. and D. S. Cassells, 1987. The effects of forestation on soil hydraulic properties in the Middle Hills of Nepal: A preliminary assessment. *Mountain Research and Development* 7: 239–249.

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

Gordon, C. A., Herrera, R. and T. C. Hutchinson, 1994. Studies of fog events at two cloud forests near Caracas, Venezuela-II. Chemistry of fog. *Atmospheric Environment* 28: 323–337.

Grubb, P. J., 1974. Factors controlling the distribution of forest types on tropical mountains; new facts and a new perspective. In:. Altitudinal Zonation in Malesia, J. R. Flenley (ed). *University of Hull, Department of Geography Miscellaneous Series* no. 16, 1–25.

Grubb, P. J. and T. C. Whitmore, 1966. A comparison of montane and low land rainforest in Ecua dor. II. The climate and its effects on the distribution and physiognomy of the forests. *Journal of Ecology* 54: 303–333.

Hafkenscheid, R. L. L. J., 2000. *Hydrology and Biogeochemistry of Montane Rain Forests of Contrasting Stature in the Blue Mountains of Jamaica*. PhD thesis, Vrije Universiteit, Amsterdam.

Hafkenscheid, R. L. L. J., Bruijnzeel, L. A. and R. A. M. De Jeu, 1998. Estimates of fog interception by montane rainforest in the Blue mountains of Jamaica. In: *First International Conference on Fog and Fog Collection,* Schemenauer, R. S. and H. A. Bridgman (eds). ICRC, Ottawa, pp. 33–36.

Hafkenscheid, R. L. L. J., Bruijnzeel, L. A., R. A. M. De Jeu and N. J. Bink (2002). Water budgets of two upper montane rainforests of contrasting stature in the Blue mountains, Jamaica. In: J. S. Gladwell (Ed.), *Proceedings of the Second International Colloquium on Hydrology and Water Management*. CATHALAC, Panamá City, Panamá, pp. 399–424.

Herwitz, S. R., and Slye, R. E. (1992). Spatial variability in the interception of inclined rainfall by a tropical rainforest canopy. *Selbyana* 13: 62–71.

Hewlett, J. D. and J. C. Fortson, 1983. The paired catchment experiment. In: *Forest Water Quality*, J. D. Hewlett (ed). University of Georgia, School of Forest Resources, Athens, Ga., pp. 11–14 (77).

Hommel, P. F. M., 1987. *Landscape Ecology of Ujung Kulon (West Java, Indonesia)*. PhD Thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Hamilton, L. S., 1995a. *A Campaign for Cloud Forests*. International Union for the Conservation of Nature, Gland, Switzerland.

Hamilton, L. S., 1995b. Montane cloud forest conservation and research: a synopsis. *Mountain Research and Development* 15: 259–266.

Hamilton, L. S., Juvik, J. O. and F. N. Scatena (eds), 1995. *Tropical Montane Cloud Forests. Ecological Studies* 110, Springer Verlag, New York, 407 pp.

Harr, R. D., 1982. Fog drip in the Bull Run municipal watershed, Oregon. *Water Resources Bulletin* 18: 785–789.

Harr, R. D., 1983. Potential for augmenting water yield through forest practices in western Washington and western Oregon. *Water Resources Bulletin* 19: 383–393.

Holder, C. D., 1998. Fog precipitation in the Sierra de las Minas Biosphere Reserve, Guatemala. In: *First International Conference on Fog and Fog Collection*, Schemenauer, R. S. and H. A. Bridgman (eds). ICRC, Ottawa, pp. 101–103.

(2003). Fog precipitiation in the Sierra de las Minas Reserve, Guatemala. *Hydrological Processes*, 17, 2001–2010.

Hölscher, D., Köhler, L., Leuschner, C. and Kappelle, M. (2002). Nutrient fluxes in stemflow and throughfall in three successional stages of an upper montane rainforest in Costa Rica. *Journal of Tropical Ecology* 19: 557–565.

Hölscher, D., Köhler, L., van Dijk, A. I. J. M., and Bruijnzeel, L. A. 2004 The importance of epiphytes to total rainfall interception by a tropical montane rainforest in Costa Rica. *Journal of Hydrology*, 292, 308–322.

Holwerda, F., 1997. A Study of Evaporation from Lowland and Montane Tropical Rain Forest in the Luquillo Mountains, Puerto Rico. MSc Thesis, Vrije Universiteit, Amsterdam.

Hutley, L. B., Doley, D., Yates, D. J. and A. Boonsaner, 1997. Water balance of an Australian subtropical rainforest at altitude: the ecological and physiological significance of intercepted cloud and fog. *Australian Journal of Botany* 45: 311–329.

Hyndman, D. C. and J. I. Menzies, 1990. Rainforests of the Ok Tedi headwaters, New Guinea: an ecological analysis. *Journal of Biogeography* 17: 241–273.

Ingraham, N. L. and R. A. Matthews, 1988. Fog drip as a source of groundwater recharge in northern Kenya. *Water Resources Research* 24: 1406–1410.

Ingraham, N. L. and R. A. Matthews, 1990. A stable isotopic study of fog: the Point Reyes Peninsula, California, USA *Chemical Geology* 80: 281–290.

Ingwersen, J. B., 1985. Fog drip, water yield, and timber harvesting in the Bull Run municipal watershed, Oregon. *Water Resources Bulletin* 21: 469–473.

Joslin, J. D., Mueller, S. F. and M. H. Wolfe, 1990. Tests of models of cloudwater deposition to forest canopies using artificial and living collectors. *Atmospheric Environment* 24A: 3007–3019.

Juvik, J. O. and P. C. Ekern, 1978. *A Climatology of Mountain Fog on Mauna Loa, Hawai'i Island. Technical Report* no. 118, Water Resources Research Center, Honolulu, Hawai'i, 63 pp.

Juvik, J. O. and D. Nullet, 1995a. Comments on 'a proposed standard fog collector for use in high elevation regions'. *Journal of Applied Meteorology* 34: 2108–2110.

Juvik, J. O. and D. Nullet, 1995b. Relationships between rainfall, cloudwater interception and canopy throughfall in a Hawaiian montane forest. In: *Tropical Montane Cloud Forests. Ecological Studies* 110, Hamilton, L. S., Juvik, J. O. and F. N. Scatena (eds). Springer Verlag, New York, pp. 165–182.

Kapos, V. and E. V. J. Tanner, 1985. Water relations of Jamaican upper montane rainforest trees. *Ecology* 66: 241–250.

Kappelle, M., 1995. *Ecology of Mature and Recovering Talamancan Montane Quercus Forests, Costa Rica*. PhD thesis, University of Amsterdam, Amsterdam.

Kashiyama, T., 1956. Decrease of sea-fog density by a model shelterbelt. *Proceedings of the 12th Congress of the International Union of Forestry Research Organizations Oxford*, November 1956.

Kerfoot, O., 1968. Mist precipitation on vegetation. *Forestry Abstracts* 29: 8–20.

Kitayama, K., 1992. An altitudinal transect study of the vegetation on Mount Kinabalu, Borneo. *Vegetatio* 102: 149–171.

Kitayama, K. and D. Müller-Dombois, 1992. Vegetation of the wet windward slope of Haleakala, Maui, Hawai'i. *Pacific Science* 46: 197–220.

Köhler, L. (2002). Die Bedeutung der Epiphyten im ökosystemaren Wasser- und Nährstoffumsatz verschiedener Altersstadien eines Bergregenwaldes in Costa Rica. PhD thesis, University of Göttingen, Göttingen, Germany, 131 pp.

Kowalski, A. S., Anthoni, P. M., Vong, R. J., Delany, A. C. and MacLean, G. D. (1997). Deployment and evaluation of a system for ground-based measurement of cloud liquid water turbulent fluxes. *Journal of Atmospheric and Oceanic Technology* 14: 468–479.

Lal, R., 1987. *Tropical Ecology and Physical Edaphology*. Wiley and Sons, New York.

Lawton, R. and V. Dryer, 1980. The vegetation of the Monteverde cloud forest reserve. *Brenesia* 18: 101–116.

Lawton, R. O., Nair, U. S., Pielke Sr., R. A. and Welch, R. M. (2001). Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science* 294: 584–587.

Lloyd, C. R. and A. de O. F. Marques, 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. *Forest and Agricultural Meteorology* 42: 63–73.

Lugo, A. E. and F. N. Scatena, 1992. Epiphytes and climate change research in the Caribbean: a proposal. *Selbyana* 13: 123–130.

Merlin, M. D. and J. O. Juvik, 1995. Montane cloud forests in the tropical Pacific: Some aspects of their floristics, biogeography, ecology and conservation. In: *Tropical Montane Cloud Forests. Ecological Studies* 110, Hamilton, L. S., Juvik, J. O. and F. N. Scatena (eds). Springer Verlag, New York, pp. 234–253.

Mueller, S. F., 1991. Estimating cloud water deposition to subalpine spruce-fir forests. I. Modifications to an existing model. *Atmospheric Environment* 25A: 1093–104.

Mueller, S. F., Joslin, J. D. and M. H. Wolfe, 1991. Estimating cloud water deposition to subalpine spruce-fir forests. II. Model testing. *Atmospheric Environment* 25A: 1105–1122.

Mulligan, M., 2000. Downscaled climate cyhange scenaria for Colombia and their hydrological consequences *Advances in Environmental Monitoring and Modelling* 1, 3–40.

Nadkarni, N. M., 1984. Epiphyte biomass and nutrient capital of a neotropical elfin forest. *Biotropica* 16: 249–256.

Nullet, D. A. and J. O. Juvik, 1994. Generalised mountain evaporation profiles for tropical and subtropical latitudes. *Singapore Journal of Tropical Geography* 15: 17–24.

Nullet, D. and J. O. Juvik, 1997. Measured altitudinal profiles of UV-B irradiance in Hawai'i. *Physical Geography* 18: 335–345.

Ohsawa, M., Wildpret, W. and M. del Arco, 1999. *Anaga Cloud Forest: A Com-parative Study on Evergreen Broad-leaved Forests and Trees of the Canary Islands and Japan*. Laboratory of Ecology, Chiba University, Chiba, Japan.

Padilla, H., Belmont, R., Torres, M. C., Garcia, R. and A. Baez, 1996. A field comparison of cloud water collectors in a mountainous region under low wind speed conditions in eastern Mexico. *Atmosfera* 9: 189–199.

Pattanayak, S. and R. Kramer, 2004. Valuing watershed services: concepts and empirics from South East Asia. *Agriculture, Ecosystems and Environment* (in press).

Persson, R., 1974. *World Forest Resources*. Royal College of Forestry, Stockholm, Sweden.

Pócs, T., 1980. The epiphytic biomass and its effect on the water balance of two rainforest types in the uluguru Mountains (Tanzania, East Africa). *Acta Botanica Academia Scientifica Hungarica* 26: 143–167.

Pounds, J. A., Fogden, M. P. A. and J. H. Campbell, 1999. Biological response to climate change on a tropical mountain. *Nature* 398: 611–615.

Richardson, B. A., Richardson, M. J., Scatena, F. N. and W. H. McDowell, 2000. Effects of nutrient availability and other elevational changes on bromeliad populations and their invertebrate communities in a humid tropical forest in Puerto Rico. *Journal of Tropical Ecology* 16: 167–188.

Russell, S., 1984. Measurement of mist precipitation. *Techniques Notebook, The Bryological Times* 25: 4.

Sandström, K. (1998). Can forests 'provide' water: widespread myth or scientific reality? *Ambio* 27, 132–138.

Santiago, L. S., Goldstein, G., Meinzer, F. C., Fownes, J. H. and D. Müller-Dombois, 2000. Transpiration and forest structure in relation to soil waterlogging in a Hawaiian montane cloud forest. *Tree Physiology* 20: 673–681.

Scatena, F. N., 1998. An assessment of climatic change in the Luquillo Mountains of Puerto Rico. In: *Third International Symposium on Water Resources*, American Water Resources Association, pp. 193–198.

Scatena, F. N. and M. Larsen, 1991. Physical aspects of hurricane Hugo in Puerto Rico. *Biotropica* 23: 317–323.

Schellekens, J., Bruijnzeel, L. A., Wickel, A. J., Scatena, F. N. and W. L. Silver, 1998. Interception of horizontal precipitation by elfin cloud forest in the Luquillo Mountains, eastern Puerto Rico. In: R. S. Schemenauer and H. A. Bridgman, eds., *First International Conference on Fog and Fog Collection*, ICRC, Ottawa, pp. 29–32.

Schemenauer, R. S. and P. Cereceda, 1994. A proposed standard fog collector for use in high elevation regions. *Journal of Applied Meteorology* 33: 1313–1322.

Schemenauer, R. S. and P. Cereceda, 1995. Reply to comments by Juvik and Nullet (1995). *Journal of Applied Meteorology* 34: 2111–2112.

Schol, M. A., Gingerich, S. A., and Tribble, G. W., 2002. The influence of microclimates and fog on interpretation of regional hydrology using δ^{18}O and δD: East Maui, Hawaii. *Journal of Hydrology* 264: 170–184.

Schrumpf, M., Guggenberger, G., Valarezo, C. and Zech, W., 2001. Tropical montane rainforest soils. Development and nutrient status along an altitudinal gradient in the south Ecuadorian Andes. *Die Erde* 132: 43–59.

Sharon, D. (1980). The distribution of hydrologically effective rainfall incident on sloping ground. *Journal of Hydrology* 46: 165–188.

Smith, D. M. and S. J. Allen, 1996. Measurement of sap flow in plant stems. *Journal of Experimental Botany* 47: 183–1844.

Sperling, F., 2000. Tropical montane cloud forests – Ecosystems under the threat of climate change. Unpublished report, World Conservation Monitoring Centre, Cambridge, UK, 10 pp.

Stadtmüller, T., 1987. *Cloud Forests in the Humid Tropics. A Bibliographic Review*. The United Nations University, Tokyo and Centro Agronomico Tropical de Investigacion y Ensenanza, Turrialba, Costa Rica, 81 pp.

Steinhardt, U., 1979. Untersuchungen über den Wasser- und Nährstoffhaushalt eines andinen Wolkenwaldes in Venezuela. *Göttinger Bodenkundliche Berichte* 56: 1–185.

Still, C. J., Foster, P. N. and S. H. Schneider, 1999. Simulating the effects of climate change on tropical montane cloud forests. *Nature* 398: 608–610.

Tanner, E. V. J., 1977. Four montane rainforests of Jamaica: a quantitative characterization of the floristics, the soils and the foliar mineral levels, and a discussion of the interrelations. *Journal of Ecology* 65: 883–918.

Te Linde, A. H., Bruijnzeel, L. A., Groen, J., Scatena, F. N., and Meijer, H. A. J. (2001). Stable isotopes in rainfall and fog in the Luquillo Mountains, eastern Puerto Rico: a preliminary study. In: *Second International Conference on Fog and Fog Collection*, R. S. Schemenauer and H. Puxbaum (eds). ICRC, Ottawa, pp. 181–184.

Van der Molen, M. K. (2002). Meteorological impacts of land use change in the maritime tropics. PhD thesis, Vrije Universiteit, amsterdam, The Netherlands, 262 pp.

Van Dijk, A. I. J. M. and Bruijnzeel, L. A. (2001). Modelling rainfall interception by vegetation of variable density using an adapted analytical model. 1. Model description. *Journal of Hydrology* 247: 230–238.

Van Steenis, C. G. G. J., 1972. *The Mountain Flora of Java*. E. J. Brill, Leiden, The Netherlands.

Veneklaas, E. J., Zagt, R. J., Van Leerdam, A., Van Ek, R., Broekhoven, A. J. and M. Van Genderen, 1990. Hydrological properties of the epiphyte mass of a montane tropical rainforest. *Vegetatio* 89: 183–192.

Vogelmann, H. W., 1973. Fog precipitation in the cloud forests of Eastern Mexico. *BioScience* 23: 96–100.

Walmsley, J. L., Burrows, W. R. and R. S. Schemenauer, 1999. The use of routine observations to calculate liquid water content in summertime high-elevation fog. *Journal of Applied Meteorology*, 38: 369–384.

Walmsley, J. L., Schemenauer, R. S. and H. A. Bridgman, 1996. A method for Estimating the hydrologic input from fog in mountainous terrain. *Journal of Applied Meteorology* 35: 2237–2249.

Watling, D. and A. N. Gillison, 1995. Endangered species in low elevation cloud forest on Gau island, Fiji. In: *Tropical Montane Cloud Forests. Ecological Studies* 110, Hamilton, L. S., Juvik, J. O. and F. N. Scatena (eds). Springer Verlag, New York, pp. 333–342.

Weathers, K. C., Lovett, G. M. and Likens, G. E., 1995. Cloud deposition to a spruce forest edge. *Atmospheric Environment* 29: 665–672.

Weaver, P. L., 1972. Cloud moisture interception in the Luquillo Mountains of Puerto Rico. *Caribbean Journal of Science* 12: 129–144.

Weaver, P. L., 1995. The Colorado and dwarf forests of Puerto Rico's Luquillo Mountains. In: *Tropical Forests: Management and Ecology*, Lugo, A. E. and C. Lowe (eds). *Springer Ecological Studies* 112, pp. 109–141.

Whitmore, T. C., 1998. *An Introduction to Tropical Rain Forests (2nd Edition)*. Clarendon Press, Oxford.

Wilcke, W., Yasin, S., Valarezo, C. and Zech, W., 2001a. Changes in water quality during the passage through a tropical montane rainforest in Ecuador. *Biogeochemistry* 55: 45–72.

Wilcke, W., Yasin, S., Valarezo, C. and Zech, W., 2001b. Nutrient budget of three microcatchments under tropical montane rainforest in Ecuador – preliminary results. *Die Erde* 132: 61–74.

World Conservation Monitoring Centre, 1997. *A Global Directory of Tropical Montane Cloud Forests (draft)*. M. Aldrich *et al.* (eds). WCMC, Cambridge, UK

Yang, D., Goodison, B. E., Ishida, S. and Benson, C. S. (1998). Adjustment of daily precipitation data at 10 climate stations in Alaska: Application of World Meteorological Organization intercomparison results. *Water Resources Research* 34: 241–256.

Yin, X. W. and P. A. Arp, 1994. Fog contributions to the water budget of forested watersheds in the Canadian Maritime Provinces: a generalized algorithm for low elevations. *Atmosphere-Ocean* 32: 553–566.

Zadroga, F., 1981. The hydrological importance of a montane cloud forest area of Costa Rica. In: *Tropical Agricultural Hydrology*, Lal, R. and E. W. Russell (eds). J. Wiley, New York, pp. 59–73.

Ziegler, A. D. and T. W. Giambelluca, 1997. Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand. *Journal of Hydrology* 196: 204–229.