

Water and Ion Fluxes to a Tropical Montane Cloud Forest Ecosystem in Costa Rica

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In every cloud there is a silver lining
(Proverb)

Dedicated to my grandmother Gertrud

Abstract

To determine the hydrological importance of cloud forests, it is essential to know the exact amount of fog water deposited to cloud forest ecosystems. In many studies, fog water inputs were determined with the water balance method. This method trusts in correct rainfall, throughfall, stemflow, and wet-canopy evaporation measurements. Errors in these measurements lead to wrong fog water deposition estimates which might bias the discussion about the hydrological importance of cloud forests. During a field campaign between February and May 2003 in Monteverde, Costa Rica, a sophisticated set-up was employed to directly measure fog water deposition to a cloud forest ecosystem. In order to quantify the hydrological and chemical importance of fog and rain water inputs, we measured in addition to fog water deposition precipitation, throughfall, and stemflow, and their respective inorganic ion loads and isotopic concentrations of ^{18}O and ^2H . Wet-canopy evaporation was calculated by the Penman-Monteith equation and rainfall amounts were corrected by a trigonometric model. The direct fog and rainfall measurements were compared to a set of indirect methods such as the water balance technique, and the isotope and chloride compartmental model. The amount of deposited fog water measured or calculated was heavily depending on the method used. The most reasonable results were obtained by the direct measurement (4% of rainfall), and by the isotope compartmental model (12% of rainfall). For 11 days, the results of the isotope compartmental model correlated well with the directly measured amounts ($r = 0.70$, $p = 0.0148$). Due to rainfall undersampling, the water balance method most likely strongly overestimated the fog water inputs. The chloride compartmental model delivered unreasonable results. Rainfall amounts were underestimated by the conventional rain gauge, especially for events with high wind speeds that caused wind-driven precipitation. For 13 days, the calculated amounts by the isotope compartmental model correlated very well with the measured rainfall amounts ($r = 0.94$, $p < 0.0001$). Concentrations in rain and fog water were very low and showed a clear maritime signal (dominant concentrations: Na^+ and Cl^-). Net canopy retention was positive for nitrogen, and negative for

IV

all other ions. Especially a large amount of potassium leached from the canopy. Occult deposition added a significant share of nutrients to wet deposition (43% of NH_4^+ -N and 23% of $\text{NO}_3^- (+\text{NO}_2^-)$ -N, with wet deposition regarded as 100%). The calculated annual deposition of chemical compounds was controlled by large rainfall amounts. The total annual nitrogen deposition (wet and occult) of $28.8 \text{ kg ha}^{-1} \text{ yr}^{-1}$ constitutes one of the highest amounts reported for a tropical montane cloud forest site and lies in the middle range of reported amounts for European sites.

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Chapter 1

Introduction

In the past two decades, cloud forests received increasing attention because of their possible hydrological key role in tropical areas with dry periods (Bruijnzeel 2001). It is believed that cloud forests add water in significant amounts to a watershed by catching fog water from the clouds (Zadroga 1981; Stadtmüller 1987; Bruijnzeel 2001). When the forests are immersed in clouds, fog droplets adhere to the branches and leaves. This water drips to the forest floor and constitutes an additional input to streams beside common precipitation. This process is especially important during dry periods with very little rainfall (Bruijnzeel and Hamilton 2001). The hydrological importance of cloud forests was first mentioned by Zadroga (1981). Since then, many studies have focused on the open question of the hydrological importance of cloud forests and its key topic: How much cloud water is captured by different cloud forest ecosystems? Bruijnzeel (2001) gives an excellent overview of the research of the past ten years. In cloud forest areas, fog water input was mostly measured with different types of fog gauges and water or ion balance techniques (Bruijnzeel 2001). Operating with fog gauges leads to the problem of translating the measured amounts of fog water to a deposited amount per square meter. Applying water or ion balance techniques to obtain fog water inputs, it is crucial to measure canopy drip and rainfall amounts exactly, which is still difficult. Several years ago, the eddy covariance technique had been presented as a new method to directly measure fog water inputs to an ecosystem. This micrometeorological method combines the measurements of a 3-dimensional ultrasonic anemometer with those of a high speed cloud droplet spectrometer (Burkard 2003). Having been applied for several years already to measure CO₂, trace gas, energy, and momentum fluxes, the eddy covariance technique was for the first time ever used to measure the fog water

deposition to cloud forests in summer 2002 in Puerto Rico (Luquillo Experimental Forest site) (Burkard 2003; Holwerda et al. 2004).

Occult deposition plays an important role in many ecosystems in temperate zones in terms of deposition of nutrients and pollutants (Burkard et al. 2002; Thalmann et al. 2002). For regions with human activities, the ion loading of fog water may be remarkably high, which compensates for the — comparative to rain — small fog water inputs (Burkard et al. 2003). Because of the frequent immersion in clouds, tropical montane cloud forests receive a greater portion of deposited ions than lower elevation forests, where occult deposition is not important (Clark et al. 1998). Still, studies from more remote sites in the tropics and especially from cloud forests are rare (Clark et al. 1998; Asbury et al. 1994). Conversion of forests to pasture and the seasonal biomass burning activities, as well as other land use changes, have generally increased rates of ion loading in the tropics (Clark et al. 1998). Clark et al. (1998) concluded in their study, that increased, long-term N deposition may constitute a problem for cloud forest ecosystems. They also mentioned that deposition of nutrients should be higher to forests on windward slopes, like the one studied in this thesis.

1.1 Objectives of this thesis

This thesis is closely related to the Swiss project “The Role of Cloud and Fog Water Inputs in the Hydrological Budget of a Tropical Cloud Forest Ecosystem in Costa Rica”, hereafter denoted as FITMCF, led by PD. Dr. W. Eugster and Dr. R. Burkard. The aim of this project was to perform direct fog water flux measurements in a tropical montane cloud forest ecosystem (TMCF) using the eddy covariance method. The project was designed as a one-year add-on to the international “Impacts of Cloud Forest Conversion” project, hereafter denoted as FIESTA, guided by Prof. Dr. L. A. Bruijnzeel (Vrije Universiteit Amsterdam). The aim of this international team is to quantify the impact of cloud forest conversion to pasture on streamflow in the Tilarán Range of northern Costa Rica.

The main objectives of this work were (i) to compare different methods to measure water inputs to a cloud forest ecosystem, (ii) to estimate the deposition of selected ions by fog and rain water to a cloud forest ecosystem and to calculate their net retention by the canopy. These two main aims lead to the following research goals:

1. Direct measurements of the fog water deposition

How large is the fog water deposition measured directly with an eddy covariance set-up? How well do the eddy covariance data agree with the fog water deposition amounts obtained by other methods, namely the isotope and chloride compartmental model, and the water balance method? Is it possible to calibrate a low-cost fog water measurement equipment with the eddy covariance system?

2. Direct measurements of horizontal and vertical precipitation

What amounts yield different rain gauges with vertical and horizontal orifices? Can these amounts be translated to mm? Are conventional rain gauges suitable for measurements in cloud forest areas?

3. Applying the ion and isotope compartmental models

What share of fog and rain water in throughfall and stemflow water is obtained with these methods? Can the results be compared to the eddy covariance and rain gauge data?

4. Compute the wet-canopy water balance

Is there an agreement between the measured or calculated inputs to the forest canopy (fog and rain water deposition) and the output from the canopy (throughfall and stemflow)? Where might possible mismatches originate from?

5. Analysing the chemistry of rain, fog, throughfall, and stemflow

What differences can be found between these four water types? How big is the input of nutrients to the forest canopy and how much is retained by the latter? How important is fog water for the ecosystem?

6. Comparison with a previous study by Clark et al. (1998)

Comparison of the deposition of chemical compounds and their net retention with the results obtained by Clark et al. (1998). How large is the difference between the windward and the leeward field sites in terms of deposition of chemical compounds?

1.2 Background information on this thesis

Because of the high costs of the field campaign and the sophisticated equipment, this master's thesis would never have been possible without the close connection to the

FITMCF project. The data basis presented in the FITMCF project report and in this thesis is the same and was obtained in a four months lasting field campaign and during several months in the lab. Reto Burkard, working as a Postdoc for the FITMCF project, performed the analyses of the eddy covariance and meteorological data presented in Chapter 3. There was also an intense collaboration with the FIESTA team which provided meteorological and hydrological data and helped with calculations and discussions. In the context of this thesis, the data sets of the chemistry and isotopic data were generated and the data sets containing general meteorological data, precipitation, throughfall and stemflow data obtained from the FIESTA team were adapted for our needs. Furthermore, the interpretation of the chemistry data were performed and the eddy covariance data were put in the superordinate context of the water balance studies. Because the isotopic data could only be analysed in the very last moment, they were just used in this thesis to calculate the isotope fractions in throughfall. To get nevertheless an overview over the data, they are presented in the appendix.

1.3 The cloud forest ecosystem

In general, cloud forests are defined as *forests that are frequently covered in cloud or mist* (Stadtmüller 1987). In the tropics, they are mostly located on high mountains between 1,500 and 3,000 m a.s.l, where cloud belts are originated by moist ascending airmasses (Zadroga 1981). The lower limit of the cloud base and thus of cloud forests is given by the condensation level of the airmasses. In the tropics, the upper limit is mostly defined by the trade wind inversion, where the descent of warm airmasses from the equator stops the ascent of the clouds. The lowermost occurrence of low-statured cloud forest (300–600 m) is reported from specific locations like small islands, where the cloud base may be very low and the coastal slopes are exposed to both, high rainfall and persistent wind-driven clouds (Bruijnzeel 2001). Average annual rainfall in cloud forests is usually above 2500 mm and the daily temperature range is generally between 12 and 21 °C, depending upon factors such as latitude, altitude, aspect, and exposure. No frosts occur (Zadroga 1981). In Figure 1.1 an overview of the worldwide distribution of cloud forests is given. The frequent bathing in clouds leaves its traces. The cloud cover reduces incoming radiation which means cooler temperatures and less energy available for photosynthesis. Humidity is almost permanently near the saturation point. Thus, cloud forests look in many ways different than common rain forests: Trees are smaller and have smaller and tougher leaves. The forest canopies are laden with

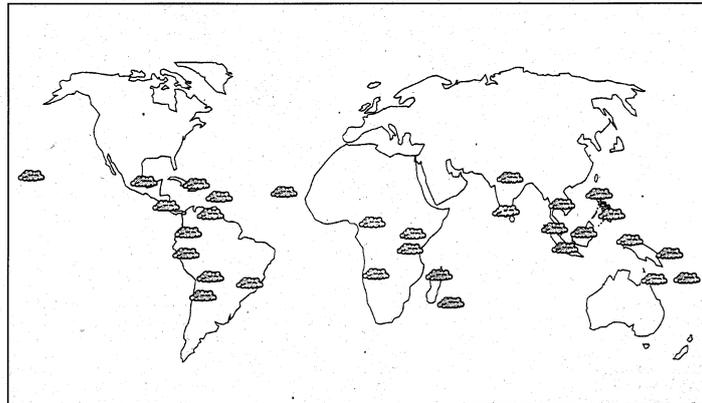


Figure 1.1: Generalized occurrence of tropical montane cloud forests (Bruijnzeel and Hamilton 2001).

epiphytes, i.e. plants, which get support but not nutrients from their host trees, such as ferns, orchids, mosses, and bromeliads. Stems, fallen trees, and rocks are covered with mosses. Where the forests are exposed to high wind speeds, trees are often gnarled and only some meters high – so called ‘dwarf cloud forests’ (Bruijnzeel 2001). In terms of biodiversity, cloud forests are of global importance, especially because of high endemism (the occurrence of species confined only to the area of concern and found nowhere else). A significant proportion of this diversity is found in the canopy: Epiphytes, making up a substantial part of rain forest canopies, reach their greatest abundance and diversity in cloud forests (Bruijnzeel and Hamilton 2001).

Figure 1.2 shows the hydrological cycle for a cloud forest. The forests receive their water input by vertical or wind-driven precipitation and by fog or cloud water. The distinction between vertical and wind-driven precipitation is made in this thesis because of the different measuring techniques required for each of this rainfall type: Vertical precipitation is being measured by conventional rain gauges with a horizontal orifice. It originates mostly from cumulus or cumulonimbus clouds with mean horizontal wind speeds below 2 m/s (Clark et al. 2000). Wind-driven precipitation originates mostly from stratus or stratocumulus clouds with wind speeds over 2 m/s (Clark et al. 2000). It can be measured by tilted gauges (Sharon 1980) or by gauges with a vertical orifice. One of these gauges is the so called Juvik gauge (Fig. 2.7). The water amount caught by this gauge cannot be separated into fog and rain water. For this reason, the combination of fog water deposition and wind-driven precipitation is called horizontal precipitation in this thesis.

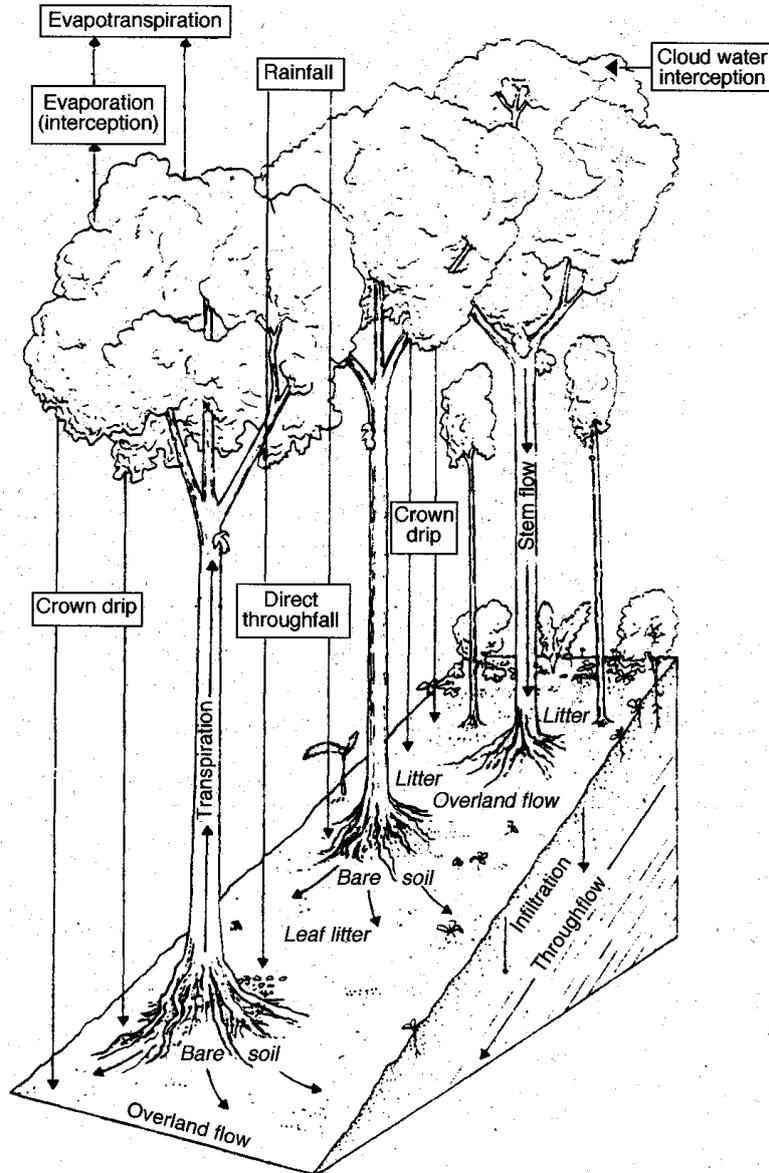


Figure 1.2: *The hydrological cycle for a cloud forest (Bruijnzeel and Hamilton 2001).*

Because of the definition of fog as *a cloud in contact with the ground and a visibility below 1000 m* (Glickman 2000) cloud and fog water are used as synonyms in this work. If a cloud moves over a canopy, the roughness of the vegetation causes turbulence. Because of this turbulence, cloud droplets penetrate into the canopy. The second process causing fog droplets to enter a canopy is the gravitational settling of heavier fog water droplets. Having entered the canopy, these droplets collide with and adhere to leaves, branches,



Figure 1.3: *Cloud forest impressions at Monteverde, Costa Rica at 1460 m a.s.l.*

and the epiphyte vegetation. In this thesis, these processes are summarized as cloud or fog water deposition.

Rain and fog water wets the canopy vegetation which acts like a sponge and retains water until the mosses and other plants are saturated. This process is called canopy storage. Part of the stored water is evaporated back to the atmosphere. This is called rainfall, respectively fog water interception loss, or wet-canopy evaporation. The water which cannot be stored in the canopy reaches the forest floor by two paths: either dripping from the leaves which is called throughfall, or flowing down the stems, termed stemflow. The water which reaches the forest floor by stemflow and throughfall is called net precipitation. All these processes are summarized in the wet-canopy water balance:

$$P + F = TF + SF + \Delta CS + E_i, \quad (1.1)$$

where P is rainfall, F fog water deposition, TF throughfall, SF stemflow, ΔCS is the change in canopy storage and E_i the evaporation from a wet canopy.

Besides scientific curiosity there are other reasons to measure rain and fog water deposition to a cloud forest. The hydrological importance of cloud forests is of high relevance to politicians, conservancy and development organizations. This importance depends among others on the cloud stripping efficiency of these forests. If the fog water input indeed adds a significant share to the water balance, this were an additional watertight argument not to cut down these forests. Because of the much larger droplet sizes, rain water is less influenced by turbulence than fog and thus will be deposited independent of the surface cover. If a cloud forest is cut down, there will be the same amount of rain water deposited as before. This is not the case for cloud water deposition. Because of the rougher and greater surface area, forests strip more cloud water than, for example, pasture. Therefore it is crucial to distinguish between fog and rain water inputs. In comparison to fog water deposition measurements or calculations, rain water input and net precipitation are rather easy to measure. Therefore, fog water inputs were quantified in many studies as the remaining term of the calculation $(TF + SF + \Delta CS + E_i) - P$ (Bruijnzeel 2001). This method trusts in correct rainfall, throughfall, stemflow, and wet-canopy evaporation measurements. Errors in these measurements lead to over- or underestimations of the fog water deposition and the resulting answer to the question of the hydrological importance of cloud forests might be wrong. For this reason it is essential to measure the fog water deposition independently from other measurements.

1.4 Structure of this thesis

In the following chapter a description of the site and its climatology, and the vegetation of Monteverde is presented. The instruments and the underlying methods which were used to measure the amounts as well as the ionic and isotopic concentrations of fog, rain, throughfall and stemflow water, and to calculate the wet-canopy evaporation are described. In the third chapter, an overview over the meteorological situation during the field campaign is being given, and the data quality of the eddy covariance measurements and the chemical data are presented. Furthermore, the results of the direct measurements of fog, rainfall, throughfall, and stemflow are showed together with the results of the calculations of the wet-canopy evaporation and the rain and fog water inputs. The last section of Chapter 3 summarizes the results of the chemical analyses of fog, rain, throughfall and stemflow water. In Chapter 4, the directly measured rain and fog water inputs are compared to results of other studies in similar environments. Also, these measured amounts are compared to the calculated amounts by indirect methods. The

calculated wet-canopy evaporation is compared with results from earlier studies. The wet-canopy water balance is computed and the mismatches between the single parts are discussed. Furthermore, a model to estimate fog water inputs without an eddy covariance system is presented. In the last section of Chapter 4, the chemical composition of all involved water types and the ion deposition and net retention of ions by the canopy is discussed. In Chapter 5 the conclusions of this work are summarized, and improvements for future measurements of the components of the wet-canopy water balance are proposed in order to be able to close this budget in the future.

Chapter 2

Experimental

2.1 Site

Hydrological and micrometeorological measurements were performed at 1460 m above sea level near the Monteverde Cloud Forest Biological Preserve, Tilarán Range, NW Costa Rica (10°18' N, 84°48' W) in a small catchment within the Caño Negro drainage basin, located 7 km NE of the town of Santa Elena (San Gerardo farm; national grid coordinates: ²58 – ²62, Tilarán topo sheet). Meteorological measurements were made on a 24 m high meteorological tower situated on a 30 degree slope facing approximately 80 degree, about 200 meters below a ridge. This ridge is part of the continental divide between the Pacific and the Atlantic coasts of Costa Rica. Hydrological measurements were performed within the same catchment, on a slope opposite to the one where the meteorological tower was standing, with a 30 degree inclination and an aspect of about 340 degree.

2.1.1 Climate and weather

Average rainfall reported for cloud forests above 1,300 m on the Atlantic side of the Monteverde area is 2,500–3,500 mm (Haber 2000). For the nearby but leeward Monteverde site, a mean annual temperature and precipitation of 18.8 °C and 2,519 mm respectively were reported (Clark et al. 2000). The annual variations in temperature and precipitation for the Monteverde site are shown in Fig. 2.1. The migration of the ITCZ controls the seasonality of precipitation in the Monteverde region. Roughly, there are three seasons recognized. (i) The wet season (May – October), when the ITCZ is directly over

and north of Costa Rica. This season is characterized by cumulus cloud formation and convective precipitation. As a result of tropical low-pressure systems in the Caribbean basin during the hurricane season (August – October), “temporales del Pacífico” occur in Monteverde. Reversed surface winds bring warm and moist air, and thus clouds and precipitation from the Pacific Ocean to Monteverde (Fig. 2.2a). When the ITCZ moves to the south of Costa Rica, the (ii) transition season starts (November – January), and the area is exposed to northeasterly trade winds. The transition season is characterized by strong northeastern trade winds, stratus, and stratocumulus clouds, and horizontal precipitation and fog water deposition during day and night. A frequent weather system in this season in Monteverde is called “temporales del norte”. These storms are the result of outbreaks of cold, dry, polar air from the North Pacific which pass over the Gulf of Mexico and eventually bring intense horizontal precipitation and fog water deposition to Monteverde (Fig. 2.2b). With the ITCZ moving north again, the (iii) dry season starts (February to April), which is characterized by moderate trade winds, stratus clouds, or clear sky conditions, with horizontal precipitation and fog water deposition particularly during the night (Fig. 2.2b) (Clark et al. 2000). At the San Gerardo field site, fog was formed by clouds advected mostly with eastern winds, so called orographic fog (Wanner 1979). According to (Clark et al. 2000), cloud immersion at the upper ridges of the continental divide is 25% in the dry season, and the cloud base at a height of 1,400–1,700 m a.s.l.. During this field campaign, fog events were mainly short (one to several hours). The longest duration of a continuous visibility below 1000 m was 30 hours. There was no clear daily cloud immersion pattern visible. In many cases, the early afternoon hours were not foggy and clouds started to move in after 16.00 o’clock. Many of these fog events stopped between midnight and 4 o’clock.

2.1.2 Vegetation

The vegetation at the San Gerardo site is of the cloud forest type, found in the Monteverde area above 1,300–1,400 m on the Atlantic slopes. The cloud forest in this area is an evergreen forest which usually remains wet throughout the year because of the frequent mist and cloud cover in the dry season. Canopy height varies from 20 to 40 m at the sheltered sites and from 5 to 10 m at more exposed sites. The forest is characterized by a diverse and abundant epiphyte community, an uneven canopy top, and a dense understory of shrubs, treelets and large herbs (Haber 2000). After the Holdridge life zone classification system, the cloud forest areas of Monteverde include the lower

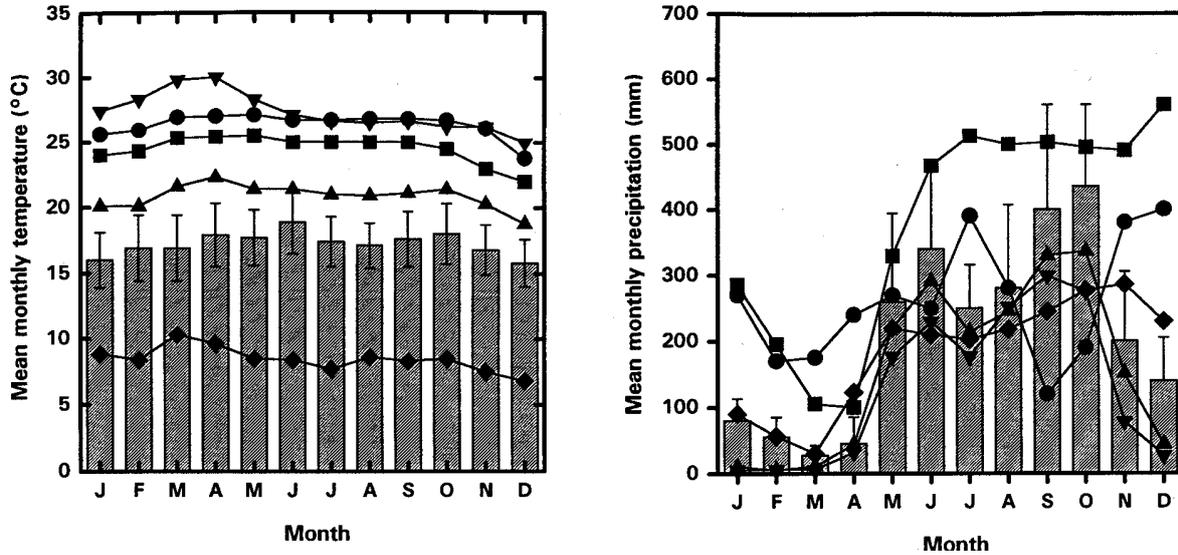


Figure 2.1: *Left: Mean monthly temperature [°C] at 1460 m at Monteverde (bars; mean \pm monthly minimum and maximum values), Limón (○), Ciudad Quesada (□), Irazú (◇), San José (△) and Puntarenas (▽). Right: Mean monthly precipitation depth [mm] at 1460 m at Monteverde (bars; mean \pm 1 S.D.), Limón (○), Ciudad Quesada (□), Irazú (◇), San José (△) and Puntarenas (▽) (Clark et al. 2000).*

montane wet forest and the lower montane rain forest life zones (Holdridge 1966; Tosi 1969; Bolanos and Watson 1993).

2.2 Methods and instrumentation

In this section, the methods are presented to measure or calculate the components of the wet-canopy water balance:

$$P + F = TF + SF + \Delta CS + E_i, \quad (2.1)$$

where P is the deposition of rain, F the fog water deposition caused by turbulence and gravitational settling, TF the throughfall, SF the stemflow, ΔCS the difference in canopy storage and E_i the evaporation from a wet canopy, all given in [mm]. P , F , TF and SF were measured directly with different gauges and installations, and the eddy covariance method. E_i was calculated with the Penman-Monteith method. The difference in canopy storage was not considered because under permanent wet circumstances it might be neglected.

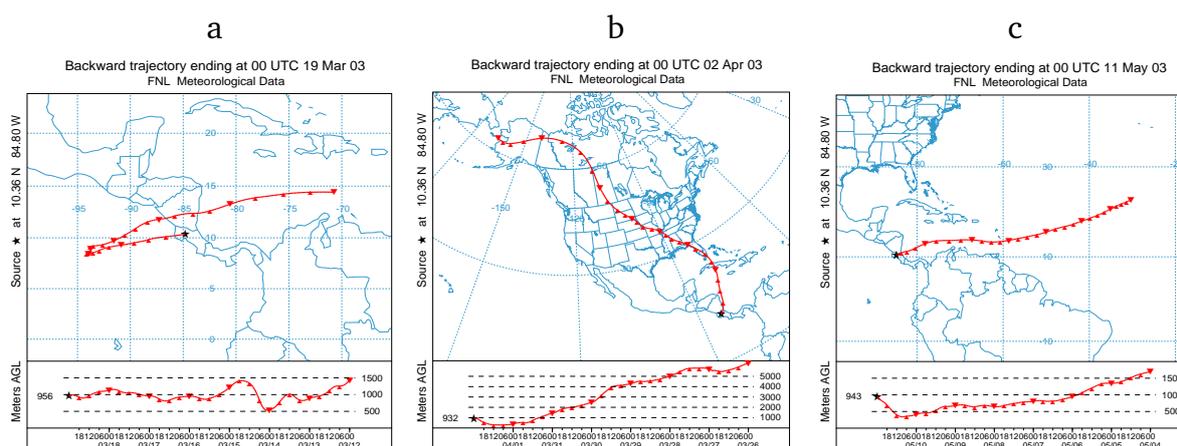


Figure 2.2: 168-hour backward trajectories of 19th of March 2003 (a), 2nd of April (b), and 11th of May 2003 (c), ending at 2443 m a.s.l. (<http://www.arl.noaa.gov/ready.html>). Symbols are placed along the trajectories at 6 hour intervals.

2.2.1 Meteorological measurements

Meteorological measurements were performed by employing a data logger (Campbell Scientific, Inc., model CR10X), which stored average data (measuring interval was 10 sec.) every 10 minutes: Global radiation, reflected short-wave radiation, incoming and outgoing long-wave radiation. These measurements were done using a Kipp & Zonen CNR1 net radiometer (Fig. 2.3). The photosynthetic active radiation (PAR) was measured using a Skye SKP215 PAR quantum sensor. The radiation measurements were performed at a height of 24 m a.g.l.. Air temperature and relative humidity were measured by using a Rotronic Thermo-Hygrometer MP100A (with radiation protection shield; 24 m a.g.l.). Air pressure was measured using a Vaisala PTB101B analog barometer. The wind speed (A100R Switching Anemometer, Vector Instruments, UK) and the wind direction (W200P Potentiometer Windvane, Vector Instruments, UK) were measured at a height of 26 m a.g.l.. To detect the presence or absence and the density of fog, and to control the fog water collector, a present weather detector (PWD11 manufactured by Vaisala, FI) which measures the visibility, the rainfall amount, and the rainfall intensity, was mounted at 24 m height of the tower (Fig. 2.4).



Figure 2.3: Kipp & Zonen CNR1 net radiometer and PAR sensor (Skye SKP215 PAR quantum sensor).

2.2.2 Measurements performed by the FIESTA core team

During the entire FIESTA project many different (micro-) meteorological measurements were performed at several locations. Especially at the tower site a lot of additional profile data were provided by performing wind speed-, wind direction-, temperature-, humidity-, visibility-, and radiation measurements. In order to quantify and assess the role of the different water inputs in the hydrological budget, rainfall and fog water amounts were measured at different heights by employing a tipping bucket rain gauge, a standard rain gauge (both connected to a data logger by Campbell Scientific), different types of totalizing rain buckets (Fig. 2.5) and fog water sampling systems (Juvik Fog Gauge, Standard Wireharp Fog Water Sampler by Schemenauer. See Bruijnzeel 2001). Throughfall and stemflow measurements presented in this thesis were performed by the FIESTA team.

2.2.3 Rain water input (P)

Precipitation was measured by several devices: Vertical rainfall was measured by two manual gauges which were emptied once a day and by an automatic gauge, measuring tips of 2 ml (Fig. 2.5). Furthermore, horizontal precipitation, i.e., fog and horizontal rainfall, was measured by a home-made, rotating collector with a vertical orifice (called



Figure 2.4: *Present weather detector (PWD11 manufactured by Vaisala, FI).*



Figure 2.5: *One automatic (white) and two totalizing rain gauges at the top platform of the meteorological tower.*

UFO, Fig. 2.6) and by a passive, modified Juvik-type precipitation gauge (Bruijnzeel 2001). This sampler was provided with two tipping bucket systems: One measured horizontal precipitation, i.e., precipitation caught by the vertical surface of the cylinder, and the other one measured vertical precipitation, i.e., precipitation falling into a funnel which was placed at the top of the cylinder. At the same time the funnel acted as a cap to prevent vertical rain from falling into the tipping bucket system for horizontal rain (Fig. 2.7).



Figure 2.6: *Self constructed vertical-orifice-gauge for wind-driven rain at the top platform of the meteorological tower (UFO).*

2.2.3.1 Correction of precipitation

After Sharon (1980), effective hydrological rainfall, i.e., the rain amount intercepted by a given surface, can exceed rainfall amounts measured with conventional horizontal gauges by more than 100%, depending on slope and rainfall inclination and direction. In this campaign, conventional rain gauges were installed horizontally on the meteorological tower which was placed on a 30° slope. Rain fell at a considerable angle during most rain events. Therefore, it is most likely that rain amounts measured by the rain gauges do not represent the effective hydrological rainfall, i.e., throughfall and stemflow. To correct for this effect, the following trigonometric model was applied (Sharon 1980):



Figure 2.7: Modified Juvik horizontal precipitation gauge mounted at the meteorological tower (24 m height)(photo by Arnoud Frumau).

$$P_a = P_0[1 + \tan(a) \cdot \tan(b) \cdot \cos(z_a - z_b)] , \quad (2.2)$$

where P_a is the effective hydrological rainfall [mm], P_0 the conventionally measured rainfall [mm], a the inclination of the slope [degrees], b the rainfall inclination angle from the vertical [degrees], z_a the aspect of the slope and z_b the azimuth from which rain is falling, i.e., the clockwise angular distance of the horizontal projection of the rainfall vector and the south, which is equal to the wind direction [degrees]. In order to close the water balance, the correction of the rain amount was not done for the slope, where the meteorological tower equipped with the rain gauges was standing, but for the slope where throughfall measurements were performed. Therefore, the angle and aspect of the opposite slope was taken (z_b : 30° and z_a : 260°). The angle of rainfall was calculated as follows (Herwitz and Slye 1995):

$$\tan(b) = W/U_v , \quad (2.3)$$

where b is the angle of rainfall in degrees from the vertical [degrees], W is the horizontal

wind speed [m s^{-1}] and U_v is the terminal fall velocity [m s^{-1}]. Terminal fall velocity was calculated after Herwitz and Slye (1995):

$$U_v = [3.378 \cdot \ln(D)] + 4.213 , \quad (2.4)$$

where U_v is the terminal fall velocity [m s^{-1}] and D is the raindrop diameter [mm]. Raindrop diameter was computed on the basis of rainfall intensity (Herwitz and Slye 1995):

$$D = 2.23 \cdot (0.03937P)^{0.102} , \quad (2.5)$$

where D is the raindrop diameter [mm] and P is the rainfall intensity [mm h^{-1}].

2.2.4 Fog water deposition (F)

The deposition of fog water to a forest canopy is dominated by two main processes: The most important one is the turbulent diffusion of smaller droplets, followed by their impaction on vegetation. The other process is the gravitational settling of larger droplets (Burkard et al. 2003). The gravitational settling was determined using the Stokes settling velocity as described in Beswick et al. (1991). The turbulent flux was calculated by means of the eddy covariance method. This method is based on the assumptions that turbulent fluxes in the atmosphere are driven by the short-term fluctuations of the wind vector, i.e. the turbulence. Gases, small-sized particles, and water droplets contained in an air parcel follow the turbulent motions of the air. The turbulent flux in the vertical direction can therefore be expressed by the covariance of vertical wind speed w and liquid water content (LWC). Further details on the measurement method of liquid water fluxes are given in Burkard et al. (2002, 2003). In summary, the total fog water deposition is the sum of the turbulent liquid water flux plus the gravitational liquid water flux.

The eddy covariance measurements were performed with a three-dimensional ultrasonic anemometer (model 1199 HSE with a builtin inclinometer, Gill Ltd., Solent, UK) and an active high-speed FM-100 cloud particle spectrometer (Droplet Measurement Technologies, Inc., Boulder, CO, USA).

Its principle of operation is described in detail in Burkard et al. (2002) (Fig. 2.9).

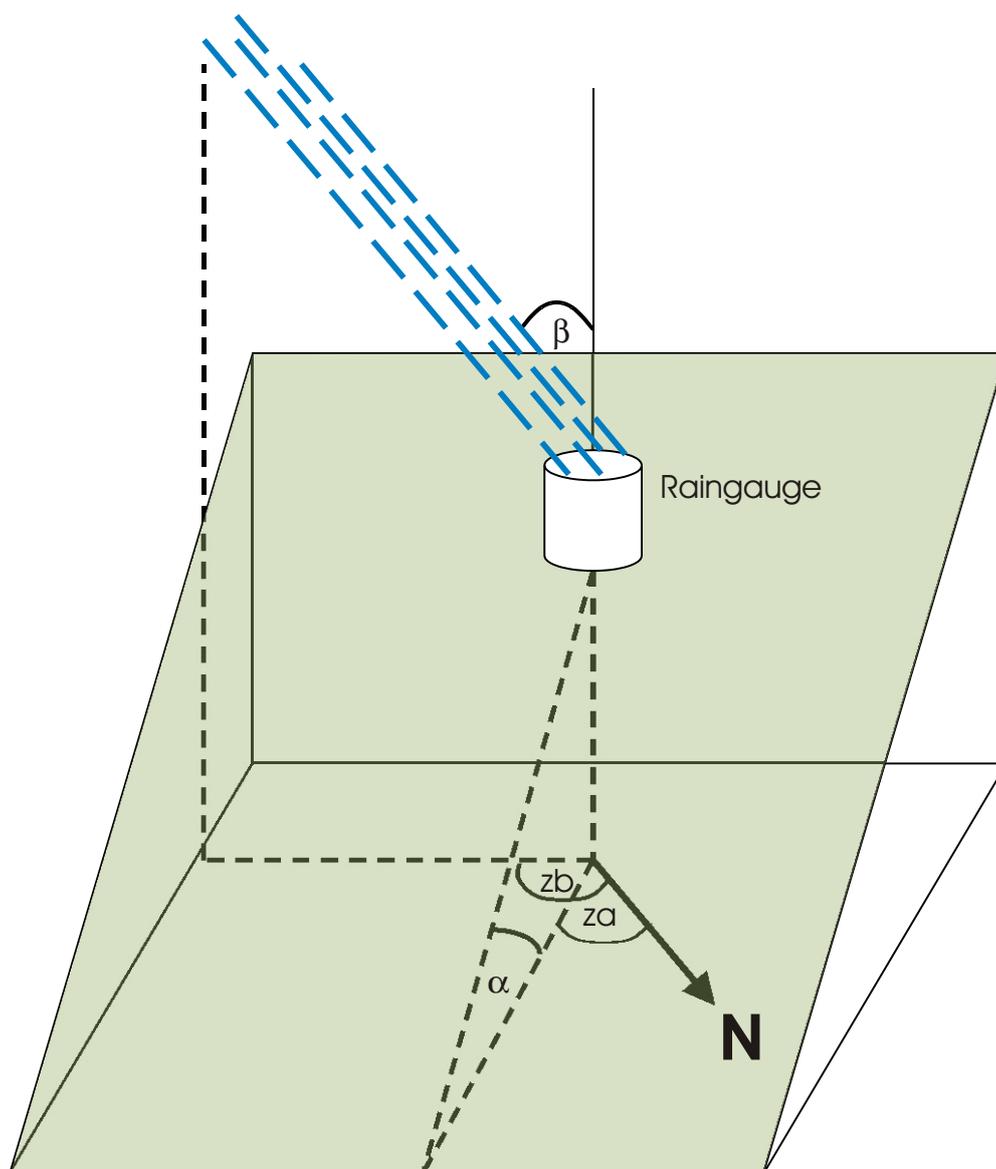


Figure 2.8: *The angles used in the Sharon correction model.*

Fog droplets within the diameter range of 2 and 50 μm were categorized into 40 size bins. The anemometer and the FM-100 were operated at a sampling rate of 12.5 Hz in order to resolve most of the frequency spectrum of turbulent motion. The fog water flux equipment was connected via digital serial data lines (RS422) to a laptop. The data was finally transferred to a workstation for evaluating and processing by the in-house software CONVERTALL version 11.08. The main functions of this software are the



Figure 2.9: *The eddy covariance measurement set-up: Ultrasonic anemometer (horizontally) and an active high-speed FM-100 cloud particle spectrometer (bottom part, funnel visible at the right side).*

calculation and averaging of the liquid water fluxes from the raw eddy covariance data over half hour periods. A detailed description of the basic concepts of this software can be found in Eugster (1994).

2.2.5 Throughfall (TF)

Throughfall and stemflow measurements were performed some hundred meters away from the tower site at the opposite slope. Throughfall was measured by two different methods in order to have representative measurements: By the roving sampling technique where 60 totalizing rainbuckets were placed by randomly selecting 20 from 80 possible sampling points along a transect line to obtain throughfall water samples. The course of the transect line was chosen with the intent to take the variation in the vegetation cover into account as much as possible (Lloyd and Marques 1988). Once a day, the throughfall volume of every single rainbucket was measured by a measuring cylinder. The values were then averaged to the representative throughfall amount for this specific sampling interval. The other approach was to measure the occurrence and the intensity of the throughfall continuously by using fixed installed steel gutters which were equipped with a tipping bucket and a logger system. Studies by Lloyd and Marques (1988) and Holwerda et al. (2005) showed that the amounts of throughfall measured by random re-

location of totalizers is more representative for the spatial variability of the forest canopy than when throughfall is measured by fixed position totalizers.



Figure 2.10: *Throughfall gauge at the forest floor.*

2.2.6 Stemflow (SF)

Stemflow was measured at 30 representative trees (e.g. varying diameter of the stem, different crown shapes, height etc.). The water was sampled by a polypropylene funnel, which was wrapped around the base of the stem. The junctions were sealed with silica gel. The sampled water was then drained in bottles, which were regularly cleaned with deionized water. Once a day, the volume of the collected stemflow water was determined manually by a measuring cylinder.

2.2.7 Wet-canopy evaporation (E_i)

The reduced Penman-Monteith equation (Monteith 1965) was used to calculate evaporation from a wet canopy:



Figure 2.11: *Stemflow measuring installation.*

$$\lambda E = \frac{\Delta(R_n - G) + p_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma}, \quad (2.6)$$

where λE is the latent heat of vaporization [W m^{-2}], R_n is the net radiation [W m^{-2}], G is the soil heat flux [W m^{-2}], $(e_s - e_a)$ represents the vapor pressure deficit of the air [mb], p_a is the mean air density at constant pressure [kg m^{-3}], c_p it the specific heat of the air [$\text{J kg}^{-1} \text{K}^{-1}$], Δ represents the slope of the saturation vapor pressure temperature relationship [hPa K^{-1}], γ is the psychrometric constant [hPa K^{-1}] and r_a is the aerodynamic resistance [s m^{-1}]. r_a was calculated after Thom (1975):

$$r_a = \frac{\left(\ln \frac{z-d}{z_0}\right)^2}{k^2 u(z)}, \quad (2.7)$$

where r_a is the aerodynamic resistance [s m^{-1}], z is the measurement height above the ground surface [m], d the zero plane displacement height [m], z_0 the roughness length [m], k the von Karman constant [0.40] and $u(z)$ the wind speed at height z [m s^{-1}]. d and z_0 were assumed to be 0.6 and 0.1 times the mean forest height of 20 meters (Allen

et al. 1998). Because the soil heat flux was not measured, it was estimated to be 0.1 times net radiation. Interception loss was then calculated after Gash (1979):

$$E_i = \sum_{j=1}^n E_{w,j} , \quad (2.8)$$

where E_i is total interception loss [mm], n is the total number of half-hourly periods that the canopy was considered completely wet, $E_{w,j}$ is the wet canopy evaporation [mm] over a half hourly period j obtained by the Penman-Monteith equation. The canopy was considered wet when there was a signal from one of the rain gauges (horizontal or vertical gauge) plus a time lag of two hours (Schellekens and Bruijnzeel 2000).

2.2.8 The compartmental model

To obtain an additional estimation of the fog water deposition, we calculated the fraction of fog and rain water in throughfall, applying the compartmental model described by (Brunel et al. 1995):

$$f = (C_{TF} - C_F)/(C_P - C_F) , \quad (2.9)$$

where f is the fraction of throughfall water originating from rain and the various subscripts of C denote the respective concentrations of either δ^2H , $\delta^{18}O$ or Cl^- in throughfall (TF), fog (F) and rain water (P). Because we did not know the fraction of fog and rain water in evaporated water and because the stemflow concentrations seemed to be too much influenced by evaporation, we assumed the same fraction of fog and rain water in stemflow and evaporated water as in throughfall water. For those days where there were either isotopic or chemical samples available from all water types (throughfall, rainfall, fog water), we calculated the fractions on a daily basis. Fractions outside the range 0–1 were excluded from the calculations. To obtain either rain or fog amounts (the equation was rearranged to obtain the fraction of fog water), the fraction was multiplied with the respective throughfall, stemflow and wet-canopy evaporation amount. Because we additionally wanted to estimate the fog and rain water amounts for the time period of the whole measuring campaign, the compartmental model was applied using the volume weighted means of each water type and the total throughfall, stemflow, and E_i amounts.

2.2.9 Water sampling

For the determination of the ionic and isotopic composition of fog, rain, throughfall, and stemflow, water samples were taken once a day. All water collecting devices were cleaned once a week with deionized water to prevent accumulation of dust and organic matter.

Fog water was sampled for both, chemical and isotopic analyses, by a modified Caltech Active Strand Cloudwater Collector (CASCC; for details see Demoz et al. 1996; Daube et al. 1987), which was mounted at a height of 24 m a.g.l. (Fig. 2.12). Air containing fog droplets was drawn by a fan through a conduit of the CASCC where the droplets were collected by impaction on six rows of Teflon strands. The fog water was then drawn down to the lower ends of the strands, where they dropped in a teflon channel before they were diverted in a sample bottle for collection. To avoid the sampling of rain water, the intake of the CASCC was covered with a rain protection shield. During the field campaign, the CASCC was triggered by the visibility measurements of a present weather detector. Whenever the visibility was below 500 m the fog water collector was switched on, at visibility values higher than 500 m it was switched off. For cleaning, the running collector was sprayed with deionized water. The CASCC was switched back to normal operation 10 minutes later in order to prevent the collection of fog water from dilution by the deionized water.

Additionally, two CASCC owned by the group of Jeff Colett (Colorado State University) were continuously running at 16 m a.g.l. (in the vegetation canopy) and at 20 m a.g.l. (at the top of the vegetation canopy). These collectors were installed to sample the fog water at different heights for providing a profile of the chemical compounds and the isotopic concentrations in the fog water depending on

- the measuring height above ground, and
- on the position within or above the forest canopy.

Rain water was sampled at a height of 24 m a.g.l.. The samples for chemical analyses were taken from a wet-only sampler which was developed at the University of Bern. It was equipped with a device for automatically collecting successive rain water samples. The rain droplet detection sensor consists of an array of conductive laminae over a



Figure 2.12: *Caltech Active Strand Cloudwater Collector.*

camshaft which removes rain droplets from the gaps between the laminae by vibration. As soon as this sensor registers a rain event, it opens the lid until 7 minutes after the last rain drop has fallen. A detailed description can be found in Eugster (1999). Samples of bulk precipitation were taken from the normal rain gauges at the same height. For isotope analyses, a sampler was built after a description found in IAEA (2002). The hose connected to the funnel goes down to the bottom of the bottle so that the first precipitation prevents further contact of the sampled water with the atmosphere. The hose connections are well sealed in order to avoid air exchange through the cap. The external hose is needed for pressure equilibration and has to be long enough to avoid atmospheric air exchange (see Figure 2.13).

For throughfall and stemflow samples, the volume of all the respective gauges was collected in one bottle, was mixed and a representative subsample was taken for isotopic and chemical analysis.

2.2.10 Water analyses

Conductivity was measured directly after the samples were brought to the field laboratory. Measurements of the conductivity of a randomly chosen subset of all samples in the laboratory in Switzerland showed no major systematic deviations from the conductivity



Figure 2.13: Rainwater sampler for isotopic analysis. The hose connected to the funnel goes down to the bottom of the bottle so that the first precipitation prevents further contact of the sampled water with the atmosphere.

measured in Costa Rica. For chemical analyses, fog, rain, stemflow, and throughfall water samples were stored in precleaned polyethylene bottles in the freezer. At the end of the campaign, they were sent in cooling boxes — in order to avoid evaporation processes during the transport — to the Institute of Geography (GIUB) in Bern, Switzerland, where the analyses were carried out. The chemical analysis included the measurements of the pH, specific electrical conductivity, and the concentrations of major ions (F^- , Cl^- , NO_2^- , PO_4^{3-} , NO_3^- , SO_4^{2-} , Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+}). The pH was measured using an electrode (Single Pore pH Electrodes, manufactured by Hamilton, CH) with automatic temperature correction. The electrical conductivity was determined by an electrode (Standard conductivity cell, TetraCon manufactured by WTW, D). After filtration ($0.45 \mu m$ nylon filter) all water samples were analyzed by ion chromatography using a Dionex DX120 with autosampler. During the field campaign, several blank samples were collected in order to estimate the contamination of the fog collectors due to the collector or sample handling. The samples were taken before and after cleaning the collectors.

For isotope analysis, fog, rain, throughfall, and stemflow water samples were filtered with a $0.45 \mu m$ nylon filter and filled in crimp cap glass vials (manufactured by Infocroma, CH). They were stored in the refrigerator until they were brought to the Paul Scherrer Institute in Villigen, Switzerland, for isotope analyses. The isotope analyses of

2H and ^{18}O were done with an isotope ratio mass-spectrometer (Delta plus XL, Finnigan MAT). Detailed information about the procedure can be found in Saurer et al. (1998).

2.2.11 Calculation of the deposition of chemical compounds

Deposition of chemical compounds was calculated by multiplying the measured ionic concentration of a water sample z collected during time period x with the deposited amount of the water type z during period x . Wet deposition was calculated by multiplying the Sharon corrected rain amounts with the ionic concentrations found in bulk precipitation. Occult deposition was calculated by multiplying the directly measured fog water amounts with the concentrations found in fog water sampled by the Caltech Active Strand Cloudwater Collector. The transport of nutrients from the canopy was estimated by multiplying throughfall and stemflow amounts with the respective ionic concentration. Annual deposition rates were estimated by multiplying total amounts of rain and fog water deposition of the year 2003 with the volume weighted means of the ion loading obtained between the 20th of February and the 15th of May 2003.

Chapter 3

Results

In this chapter, the results from the measurements and calculations are presented. The field campaign lasted from the 10th of February to the 13th of May 2003. During several days, the eddy covariance equipment was switched off due to the lack of fog. For the computation of the water balance, we selected a time period of 65 days (9th of March 2003 – 13th of May 2003) where there are uninterrupted data sets available from all measurements.

3.1 Meteorological situation during the campaign

3.1.1 Temperature and wind

Figure 3.1 gives an overview of the meteorological conditions during the entire campaign. As mentioned in the caption to Figure 3.1, the entire set-up was switched off in the period between the 28th and the 31st of March (day of year 87–90) because of clear weather conditions without fog. The mean temperature was 17.7 °C with a maximum of 23.3 and a minimum of 13.0 °C. Except for the end of the stormy weather period the median wind speed shows low variation. The mean wind speed during the entire campaign was 2.6 m s⁻¹ and a median value of 2.3 m s⁻¹, respectively. During 56% of the time with wind speed >1 m s⁻¹ the wind direction was from northwest to northeast (337.5° to 67.5°), where the sector from southeast to south (112.5° to 202.5°) represents a second maximum (Fig. 3.2, left panel). The wind directions during low wind speeds <1 m s⁻¹ were not taken into consideration. During foggy weather conditions (Figure 3.2, right

panel) the dominance of the northern winds is even more pronounced with an obvious increase of the low wind speeds ($<1 \text{ m s}^{-1}$) during which the wind directions have been measured with low accuracy due to the design of the wind vanes.

3.1.2 Fog occurrence

The bottom panel in Figure 3.1 shows the temporal variation of the median visibility in meters, measured by the present weather detector (see Chapter 2.2.1). It will be used as a measure for the occurrence and frequency of fog at the field site. It is obvious that days with dense fog during 50% of the time of the day are rare. During the entire field campaign of 2,013.5 hours, the fog water flux equipment was running 83% of the time (1,677 hours). During the remaining hours the equipment was switched off because there was no fog. This stopping of the equipment was introduced during the first few weeks with a weak occurrence of fog at the field site to save gasoline. The characterization of fog at the field site was done by employing the visibility measurements, which were available during 97% of the time when the system was running. About 26% of the entire field campaign in Costa Rica, fog was detected by the present weather detector (Table 3.1). Clear conditions without fog indicated by a visibility of 2,000 m (and more), occurred for 60% of the entire campaign. There exist some uncertainties concerning these percentages because of the lack of visibility data from the period where all the equipment was switched off (see above).

Table 3.1: *Characteristics of fog at the field site in Costa Rica: Duration of foggy conditions, liquid water content (LWC), liquid water flux (LWF), and Volume weighted Mean Droplet Diameter (VMD). The Characterization is based on the visibility measurements by the present weather detector.*

Visibility [m]	Duration [h]	Percentage for total field campaign [%]	LWC [mg m^{-3}]	LWF [$\text{mg m}^{-2} \text{ s}^{-1}$]	VMD [μm]
< 100 m	206.0	10.5	270.1	-18.2	12.3
100–250 m	154.0	7.8	196.9	-10.9	11.5
251–500 m	67.5	3.4	102.9	-5.2	9.9
501–1000 m	94.5	4.8	65.7	-1.9	9.0
1001–2000 m	238.5	12.1	12.5	-0.5	7.0
no fog	1203.5	61.3	0.0	0.0	3.8

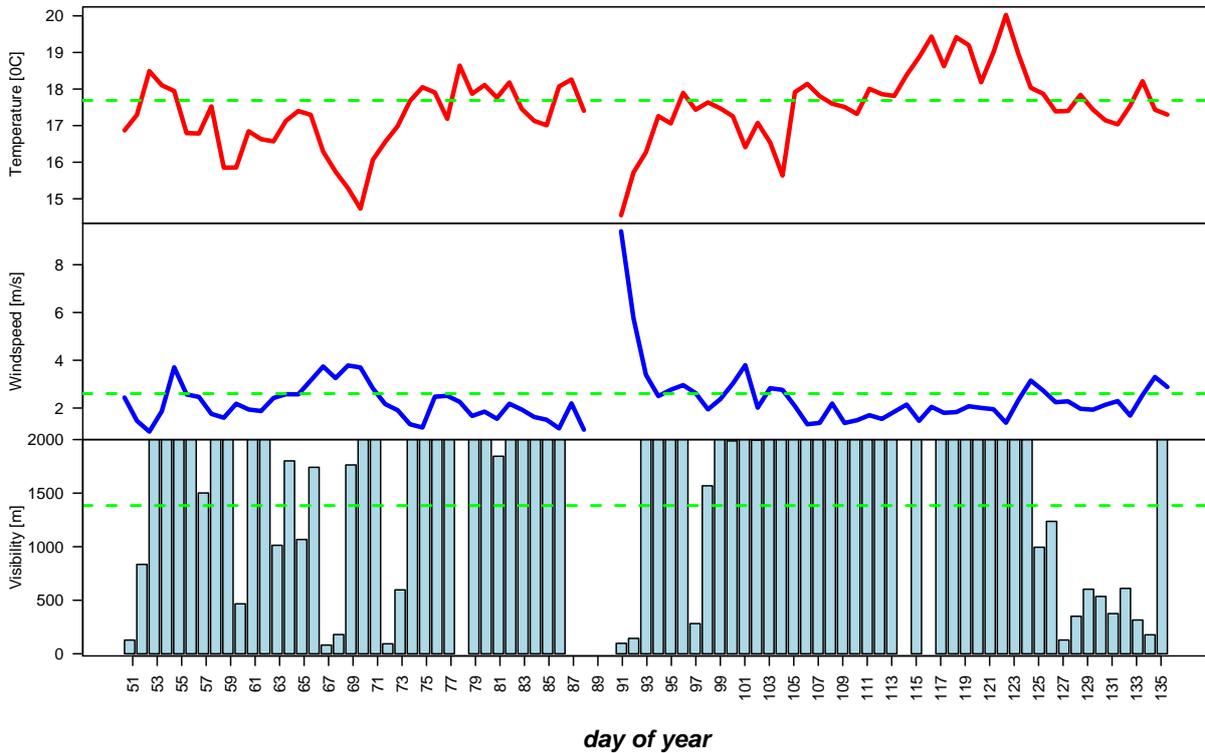


Figure 3.1: Meteorological conditions during the entire field campaign in Costa Rica. Daily median temperature (top panel), median daily wind speed (center panel), and median daily visibility (bottom panel). The dashed green lines represent the mean values of the shown variable during the entire campaign. Between the 28th and the 31st of March (day of year 87–90), all the devices were switched off due to the lack of fog.

3.2 Data quality

3.2.1 Data quality of the eddy covariance measurements

Due to the fact that the original sonic anemometer belonging to the fog water flux equipment was broken during the transportation to Costa Rica, we were forced to measure with an older device of the same type (see Section 2.2.4). The only difference was that this older device has not been upgraded by GILL Ltd. with the newest probe design and with the newest release of the internal software, which should improve the functioning of the sonic anemometer during heavy rain conditions (as they can occur in the tropics during strong convective weather situations). Due to the lack of this upgrade we had several problems such as short data interruptions during stormy

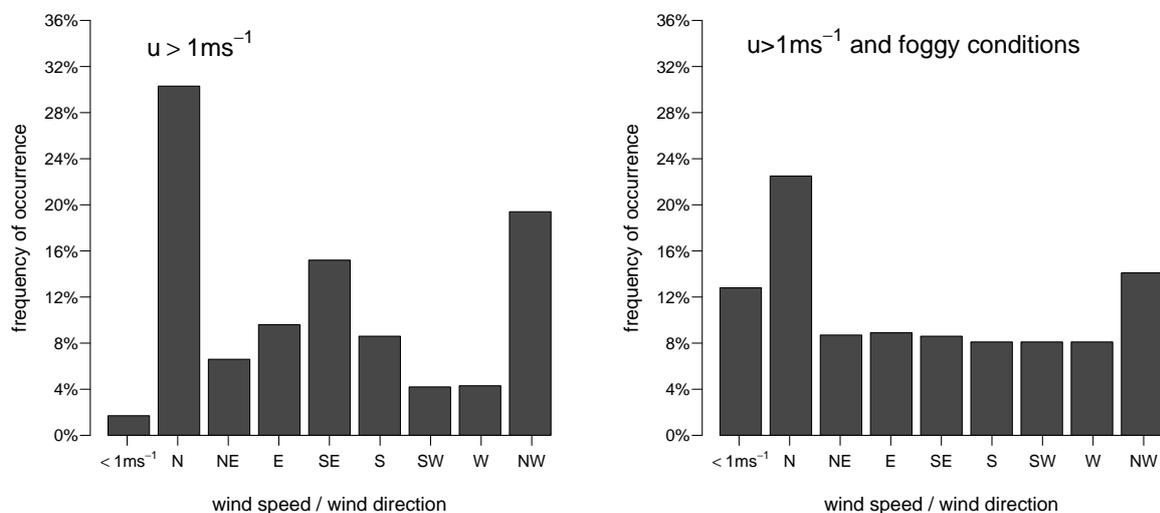


Figure 3.2: Left: Frequency of the occurrence of wind speeds $> 1 \text{ m s}^{-1}$ with respect to wind direction during the entire campaign. Right: Frequency of the occurrence of wind speeds $> 1 \text{ m s}^{-1}$ with respect to wind direction during foggy weather conditions.

weather conditions (low cloud base, heavy rain, high wind speeds), which could not be fixed during the campaign. Finally, we missed about 8% (132 hours) of the fog water flux data, due to the use of the older sonic anemometer. Because the weather conditions during these periods were often foggy, we reconstructed the missing data on the basis of the 1-, 5- and 10-minute averages. Half-hour fog water flux data were calculated by merging these short-time averages. The same way of calculating half-hour fog water flux averages out of short-time data was also performed during periods when the sonic anemometer was running properly. The comparison of the reconstructed and the original flux data did not reveal any major differences.

Additionally, several statistical approaches to test the quality of the reconstructed fog water fluxes confirmed the suitability of our approach. For the further analysis of the fog water deposition in this study we used the combination of the original and reconstructed flux data. For the period when the sonic anemometer was running properly the following first-order quality check was performed: the two time series of the FM-100 and of the sonic anemometer were averaged over 1-minute periods. The distributions of these averages did not show any indications for bad data quality such as outliers. Moreover,

spectral analysis of wind (u , v , and w) and the FM-100 (LWC) data showed very good agreement with the theoretical spectra by Kaimal et al. (1972) in the high-frequency range, indicating high quality of the wind and FM-100 measurements during the whole field campaign.

3.2.2 Data quality of the chemical analyses

The quality of the chemical data was examined by considering the ion balances (Fig. 3.3) of the chemical samples and by comparing the measured electrical conductivity with the calculated electrical conductivity. The quality of the fog samples was further analysed by checking the concentrations found in the blank samples. For all fog and rain water samples the ion balances show a reasonable agreement between the sum of anions and the sum of cations. The samples which plotted outside the 25% threshold (anions as 100%) were rejected. For deposition calculations, the rejected samples were replaced by the volume weighted mean of the respective ions over the whole period. The ion balance of the throughfall and stemflow data show an under-representation of anions, especially for lower concentrations. This is most likely due to unmeasured weak organic acids such as carbonate and acetate. Similar ion balances of throughfall were found in a previous study performed in a mixed forest at the Lägeren research site in Switzerland (Burkard et al. 2003). Thus, no throughfall or stemflow sample was rejected. The samples of deionized water sprayed through the fog water collectors showed no contamination of the fog water sampler at the top platform. But there were several blank samples taken from the two collectors located at 20 and at 16 m a.g.l. which showed a pollution of these two samplers, especially after dry periods. For technical reasons, these two samplers could not be cleaned as often as the one at the top platform. Because they were running continuously, the contamination of these two samplers originate mainly from dry deposition accumulated during periods without fog. Because the blank samples taken after cleaning showed no pollution anymore and the natural variability of the concentrations in the fog water samples was much higher than the concentrations found in the blank samples, the chemical data was used nevertheless for comparisons within the fog events.

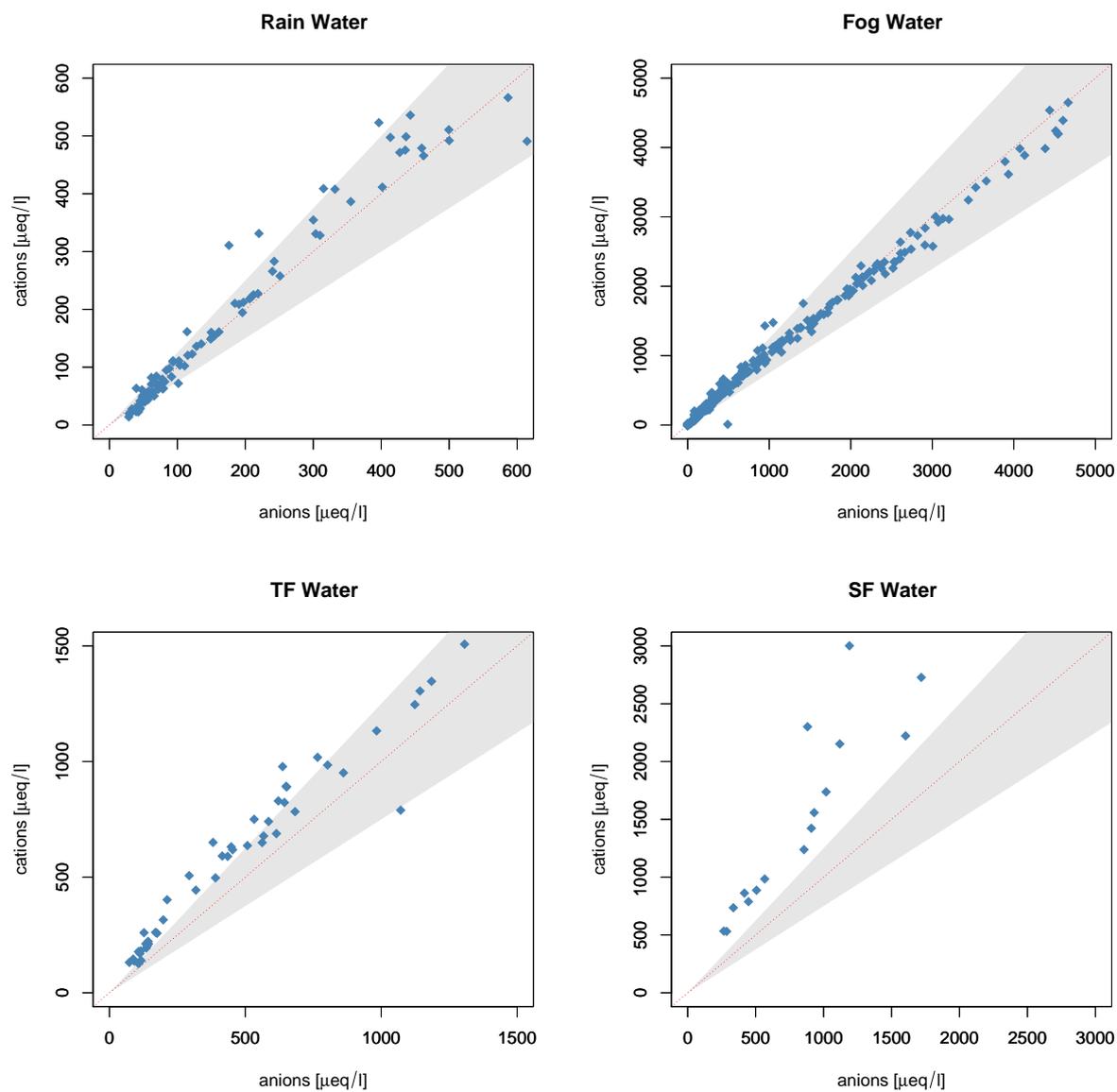


Figure 3.3: The ion balances of rain, fog, throughfall, and stemflow. The grey-shaded area shows the $\pm 25\%$ deviation range from the 1:1 line.

3.3 Rainwater input (R)

Between the 9th of March and the 13th of May, the two conventional rain gauges measured 390.6 (totalizing gauge) and 381.1 mm (tipping bucket gauge) of vertical rainfall. Because of the higher time resolution of the tipping bucket rain measurements, the Sharon correction was performed on these data. The Juvik gauge measured 773.0 mm and the UFO 508.8 mm of horizontal precipitation. Rainfall angles for the period between the 9th of March and the 13th of May ranged between 1.4 and 66.3 degrees from the vertical, with a mean of 31.3 degrees. The corrected rainfall amount for the 65-day period is 449.0 mm. This is 15% more than the conventionally measured amount (381.1 mm).

Table 3.2: *Rainfall amounts measured by different devices for a period of 65 days (9th of March 2003 – 13th of May 2003)*

Device	measurement height [m]	rainfall amount [mm]
precipitation tipping bucket gauge	22	381.1
precipitation totalizing gauge	24	390.6
Sharon corrected precipitation	22	449.0
horizontal precipitation UFO	24	508.8
horizontal precipitation Juvik	22	773.0

3.4 Fog water input (F)

During the entire campaign, the total fog water deposition measured by the eddy covariance system was 26.9 mm. This is the sum of the turbulent (23.6 mm) and the gravitational fog water input (3.3 mm, gravitational input accounts for 12% of total fog water input). During the selected period (9th of March 2003 – 13th of May 2003), the total fog water input (turbulent and gravitational fluxes) was 19.0 mm. The mean deposition rate for the periods with a visibility below 1,000 m was 1.2 mm d^{-1} . 58% of all fog water was deposited while the visibility was below 100 m or during 10.5% of the whole campaign (Fig. 3.4).

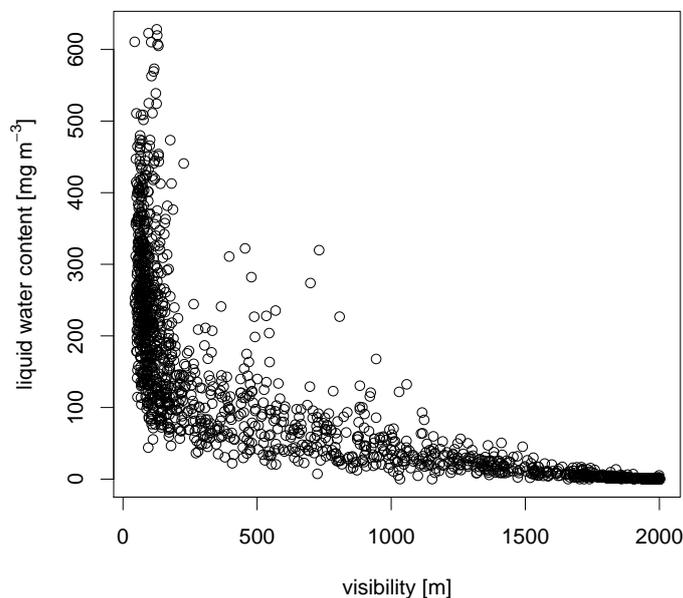


Figure 3.4: *Visibility versus liquid water content.*

3.5 Throughfall (TF) and stemflow (SF)

Total amount of throughfall measured in the period between the 9th of March 2003 and the 13th of May 2003 was 497.1 mm. This is 127% of uncorrected vertical rainfall. Stemflow data are available from the 3rd of April 2003 onwards. The stemflow water collected between the 3rd of April and the 13th of May was 11,016 ml. To convert these values to millimeters, the projected crown area is needed (Tobón-Marín et al. 2000). Because this value is not yet estimated, the conversion can not be done at this moment. For this reason an expert's best guess value of 2% of net precipitation is used (C. Tobón Marín, personal communication, August 2003). Thus, for the period between the 9th of March and the 2nd of May stemflow accounts for 9.9 mm.

3.6 Wet-canopy evaporation (E_i)

The total wet-canopy evaporation between the 9th of March and the 13th of May was calculated to be 49.1 mm, with a mean of 0.094 mm h⁻¹ or 2.3 mm d⁻¹. The

interception loss was 12.5% of uncorrected, 11% of corrected, and 10.5% of corrected precipitation plus fog water input (449.0 mm plus 19.0 mm).

3.7 Results of the compartmental model

3.7.1 Calculations on a daily basis

The fraction of fog and rain water in throughfall was calculated after equation 2.9 with three different tracers: δ^2H , $\delta^{18}O$, and Cl^- . Isotope tracer data were available from all needed water types (TF , P and F) for 21 days. Calculating with δ^2H values, the obtained fraction was for 7 events outside the range of 0–1. These events were excluded from the comparison with the directly measured amounts. For 2 events the calculated fog water amounts exceeded 4 mm day^{-1} which is unrealistically high. These events were excluded as well from the comparison. The comparison with the directly measured amounts revealed a good correlation between measured and calculated rain amounts ($r = 0.9$, $p < 0.0045$) and no significant correlation between the measured and calculated fog amounts ($r = 0.47$, $p = 0.4266$). The calculated rain amounts constituted 77% of the directly measured and uncorrected amounts and the calculated fog amounts constituted 236% of the directly measured ones.

The correlations obtained by the $\delta^{18}O$ tracer is shown in Fig. 3.5. 8 events were excluded because the obtained fraction lied outside the range of 0–1. 2 calculated fog amounts exceeded 4 mm day^{-1} and were not included in the comparison with the directly measured amounts. The correlation between the calculated and the measured rain amounts was excellent ($r = 0.94$, $p < 0.0001$) and rather good for the calculated and measured fog amounts ($r = 0.70$, $p = 0.0148$). The calculated rain amounts constituted 86% of the directly measured ones and the calculated fog amounts constituted 150% of the measured ones. Because of the better correlation between measured and calculated fog amounts and the more reasonable calculated amounts during these selected days, we decided to perform the estimation of the fog water fraction in throughfall for the whole duration of the field campaign on the basis of $\delta^{18}O$ values.

Chemical samples from all water types were available during 11 days. For 9 events the calculated fraction lied outside the range of 0–1. One of the two calculated fog water amounts should have been excluded from the comparison with the directly measured amounts because the calculated daily deposition rate is greater than 4 mm day^{-1} . However, in Fig. 3.5 both calculated fog water deposition values are compared to the measured ones. The rain amount was in one case underestimated by the calculation. The two calculated fog water amounts were both higher than the measured ones.

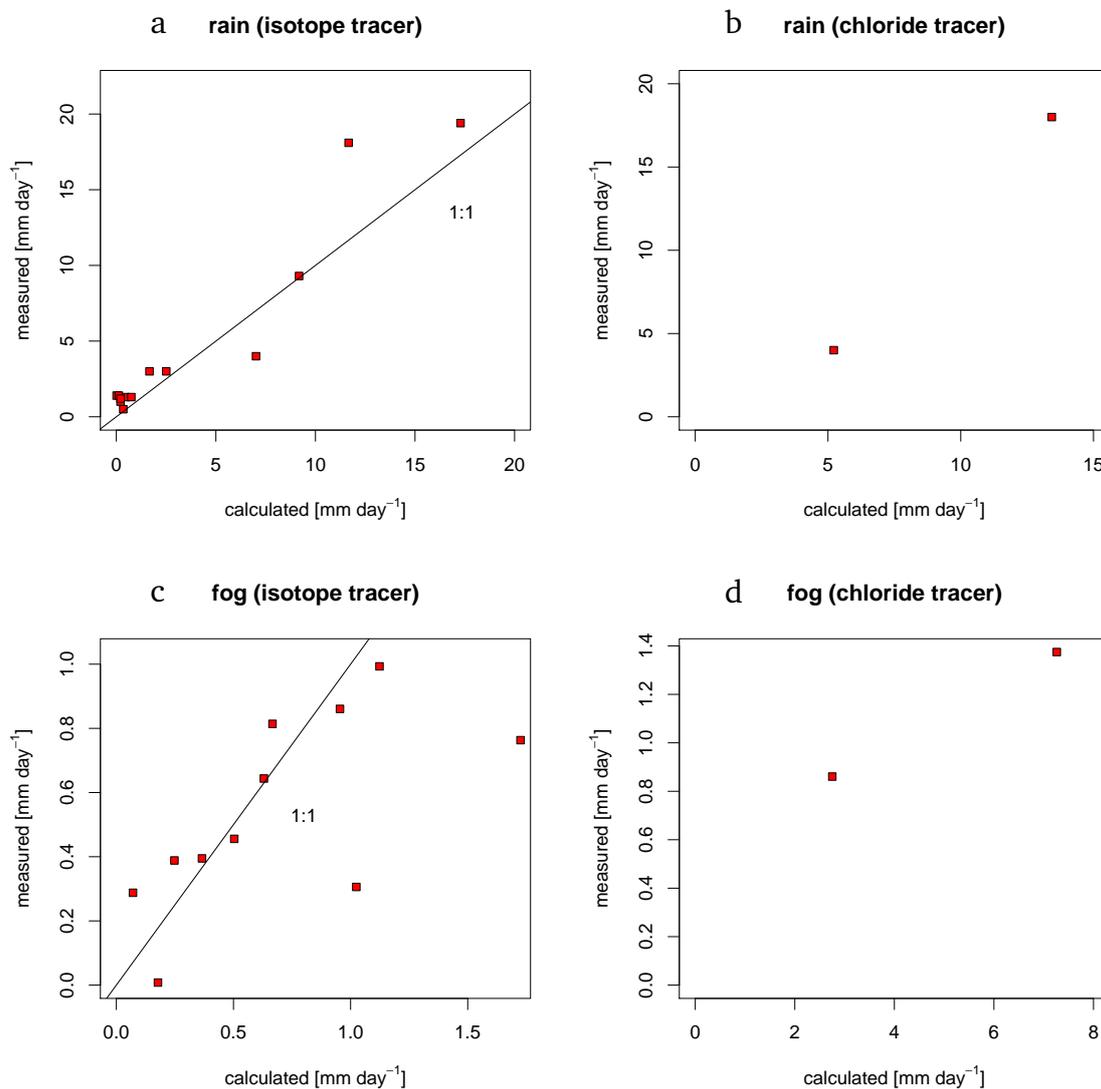


Figure 3.5: Calculated rain and fog amounts versus measured amounts. Rain amounts measured with a conventional gauge versus the calculated amounts by the isotope compartmental model (a), conventionally measured rain amounts versus the calculated amounts by the chloride compartmental model (b), fog amounts measured directly with the eddy covariance set-up versus the calculated fog water deposition by the isotope compartmental model (c), and directly measured fog water deposition versus calculated fog water deposition by the chloride compartmental model (d).

3.7.2 Calculations for 65 days

Because there were no isotope samples available for all days during the field campaign from all respective water types, the average fraction of fog and rain water in throughfall water was estimated for each tracer with the respective volume weighted mean of each water type (Table 3.3). An average share of fog water in throughfall water of 11% was obtained with the $\delta^{18}O$ tracer and an average share of 23% with the chloride tracer. Assuming that the share of fog water was the same in stemflow and in the evaporated water, the total amount of fog water between the 9th of March and the 16th of May would be 61.2 mm or 127.9 mm respectively.

Table 3.3: Volume weighted means of $\delta^{18}O$ and Cl^- in TF , P and F .

Sample	$\delta^{18}O$	Cl^-
Rain	-3.6 ± 0.5	53.2 ± 29.5
Fog	-1.8 ± 0.3	209.9 ± 45.0
Throughfall	-3.4 ± 0.4	89.5 ± 41.2

Table 3.4: Calculated rain and fog amounts and percentage of directly measured amounts.

Method	Rain	Fog
Isotope compartmental model ^a	495.0 (127%)	61.2 (322%)
Chloride compartmental model ^b	428.2 (110%)	127.9 (673%)

^aResulting fraction: 11% (fog) respectively 89% (rain) in TF . These fractions were multiplied with the total amount of TF (497.1 mm), SF (9.9 mm) and E_i (49.1 mm)

^bResulting fraction: 23% (fog) respectively 77% (rain) in TF . These fractions were multiplied with the total amount of TF (497.1 mm), SF (9.9 mm) and E_i (49.1 mm)

3.8 The chemistry of R , F , TF , and SF water

Table 3.5 shows the volume weighted mean solute concentrations in fog water (F_z ; sampled at different heights z), rain water (P ; bulk rain water samples from the manual rain gauge), throughfall water (TF), and stemflow water (SF) of the most relevant ions. In addition, the mean pH and the mean conductivity (Lf in μS) as a measure of total ion loading of a water sample are presented.

The concentrations found in *P*, *F*, *TF* and *SF* differ greatly from event to event. The ionic composition of all samples was dominated by sodium, chloride, and sulphate.

The ion loading of the fog and rain water was very low, with an average of $62.4 \mu S$ for fog sampled at the top platform and $16.3 \mu S$ for rain water. The vertical profile of fog water chemistry shows a significant difference in conductivity between the water sampled at the different heights. The relative shares of the water from the two lower samplers are almost identical, but show some differences to the water sampled at the top platform: The proportion of ammonium and sulphate is smaller whereas the proportion of sodium and chloride is greater (see also Fig. 4.6).

Table 3.5: Volume-weighted mean solute concentrations [$\mu\text{eq l}^{-1}$], pH , and conductivity (Lf , [μS]) in fog water at different heights ($F_{24\ m}$, $F_{20\ m}$, $F_{16\ m}$), rain (P), throughfall (TF), and stemflow (SF).

Ion	$F_{24\ m}$	$F_{20\ m}$	$F_{16\ m}$	P	TF	SF
H^+	19.8 ± 4.6	4.9 ± 6.6	3.0 ± 1.5	11.1 ± 1.8	0.3 ± 0.6	0.2 ± 0.0
SO_4^{2-}	129.1 ± 21.4	155.7 ± 54.0	211.0 ± 37.0	34.4 ± 6.7	48.9 ± 8.5	91.9 ± 22.4
NO_3^-	51.9 ± 10.2	114.7 ± 56.3	166.7 ± 51.0	11.3 ± 4.0	5.5 ± 4.6	7.2 ± 1.3
NH_4^+	120.8 ± 16.9	109.3 ± 34.0	140.8 ± 20.7	17.1 ± 5.0	6.9 ± 8.7	52.1 ± 49.6
Cl^-	209.9 ± 45.0	408.6 ± 151.9	609.4 ± 153.9	53.2 ± 29.5	89.5 ± 41.2	377.4 ± 79.2
Na^+	204.5 ± 39.0	396.6 ± 136.4	630.4 ± 131.7	50.6 ± 25.2	99.2 ± 28.3	221.9 ± 32.3
K^+	14.6 ± 2.5	34.0 ± 6.1	58.7 ± 5.4	4.6 ± 1.3	51.9 ± 14.1	417.1 ± 236.5
Ca^{2+}	23.7 ± 4.4	53.4 ± 22.4	69.9 ± 21.5	8.8 ± 2.9	21.6 ± 7.5	150.8 ± 37.5
Mg^{2+}	48.2 ± 10.5	98.2 ± 38.0	148.2 ± 37.0	10.3 ± 5.7	16.9 ± 6.7	97.2 ± 96.0
pH	5.0	5.8	6.2	5.2	6.6	6.9
Lf	63.7	88.9	138.3	16.0	24.3	119.3

Chapter 4

Discussion

In this chapter, the measured and calculated components of the wet-canopy water balance are discussed and the different methods are compared to each other. The chemical analyses are compared to previous studies in same environments.

4.1 Rain water input

In the dry season, rainfall at the leeward side of Monteverde varied from 1956 to 1995 between 50–100 mm per month (Clark et al. 2000). During this campaign, the monthly average between the 9th of March and the 1st of May (start of the rainy season) was 158 mm of vertical, uncorrected rainfall. Despite the fact that after the local population the dry season of 2003 was a very dry one, the higher amount measured on the windward side seems reasonable. It often occurred that the field site was immersed in clouds and received considerable amounts of rainfall, mostly in form of drizzle, whereas the town of Monteverde was sunny. To compute the water balance, the Sharon corrected precipitation values were taken. Because rain fell at a considerable angle most of the time we assumed that the hydrologically effective rainfall was higher than conventionally measured. Thus, we took the Sharon corrected precipitation values to compute the water balance in Section 4.4.

Isotope tracers The rain water input calculated by the isotope compartmental model was 27% higher than measured with the conventional gauge. As will be shown in the next section, the amount obtained by this method represents the lowest estimation be-

Table 4.1: Rain amounts measured or calculated by different methods for the period between the 9th of March 2003 and the 13th of May 2003 and the percentage of the measured amount by a conventional rain gauge.

Method	Rain amount [mm]	% of conventionally measured amount
conventional rain gauge ^a	390.6	100
Sharon corrected precipitation ^b	449.0	115
horizontal precipitation UFO ^c	508.8	130
horizontal precipitation Juvik ^d	773.0	198
calculated rain amount ^e	428.2	110
calculated rain amount ^f	495.0	127

^aSection 3.3

^bSection 2.2.3

^cSection 3.3

^dSection 3.3

^echloride compartmental model: 77% of $(TF + SF + E_i)$ (Section 3.7.2)

^fisotope compartmental model: 89% of $(TF + SF + E_i)$ (Section 3.7.2)

cause the fraction of precipitation in throughfall was fixed during the whole time. During 16 days there were isotopic samples available from all water types (P , F , TF). The calculated amounts obtained during these days correlate very well with the conventionally measured amounts ($r = 0.94$, $p < 0.0001$, Section 3.7). This method thus seems to be suitable to estimate the rain water inputs provided that there is a significant difference between the isotope concentrations of fog and rain water. This difference was more pronounced for the δ^2H than for the $\delta^{18}O$ concentrations. Nevertheless there were better results obtained by using $\delta^{18}O$ as tracer.

Chloride tracer The rain water inputs calculated with the chloride tracer were rather small and too small in comparison to fog water and throughfall (Sections 4.2 and 4.4). Furthermore the calculated rain water inputs for seven days do not correlate with the measured amounts and would exceed them many fold. The reason for the failure of this method can be explained by the frequent dry periods between the rain events. We assume that water on the leaves evaporated, leaving residua of chloride on the leaf surfaces. The following rain event washed these residua down and caused higher concentrations in throughfall than measured in precipitation for this rain event. Also,

there might have been considerable amounts of dry deposition enhancing chloride concentrations in throughfall. Because it is assumed that the ionic concentrations of the water do not change whilst travelling down from the forest canopy to the floor (which is normally the case for so called conservative elements, such as chloride), higher ionic concentrations in throughfall bias the calculations by the compartmental model.

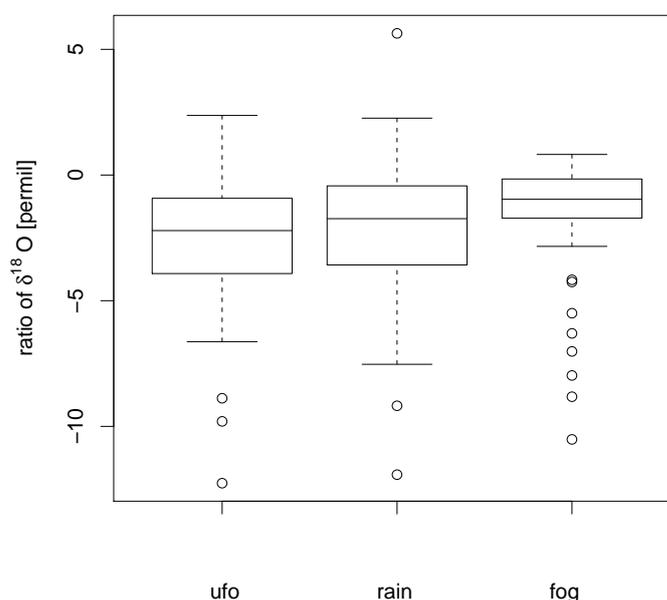


Figure 4.1: Ratios of $\delta^{18}\text{O}$ in ufo, rain and fog water. Each box indicates the 25 and the 75 percentile and the whiskers indicate the 1.5 interquartile range from the box.

Horizontal precipitation The gauges which measured horizontal precipitation with a vertical orifice measured an amount of 508.8 mm (UFO) and 773.0 mm (Juvik gauge) horizontal precipitation. From the UFO gauge water we took isotopic samples. The comparisons of the isotopic values from the UFO water with isotopic concentrations of fog and rain water showed clearly, that the water caught by the UFO gauge was rain water (Fig. 4.1). From the Juvik gauge we did not take isotopic samples, but it is most likely that this gauge did catch fog water because of the mesh surface and the different aerodynamic properties (Fig. 2.7 and 2.6). Most reasonably the Juvik gauge was also more efficient in sampling rain water in comparison to the UFO, because the latter was not wind permeable. This might have caused winds carrying rain water to flow around

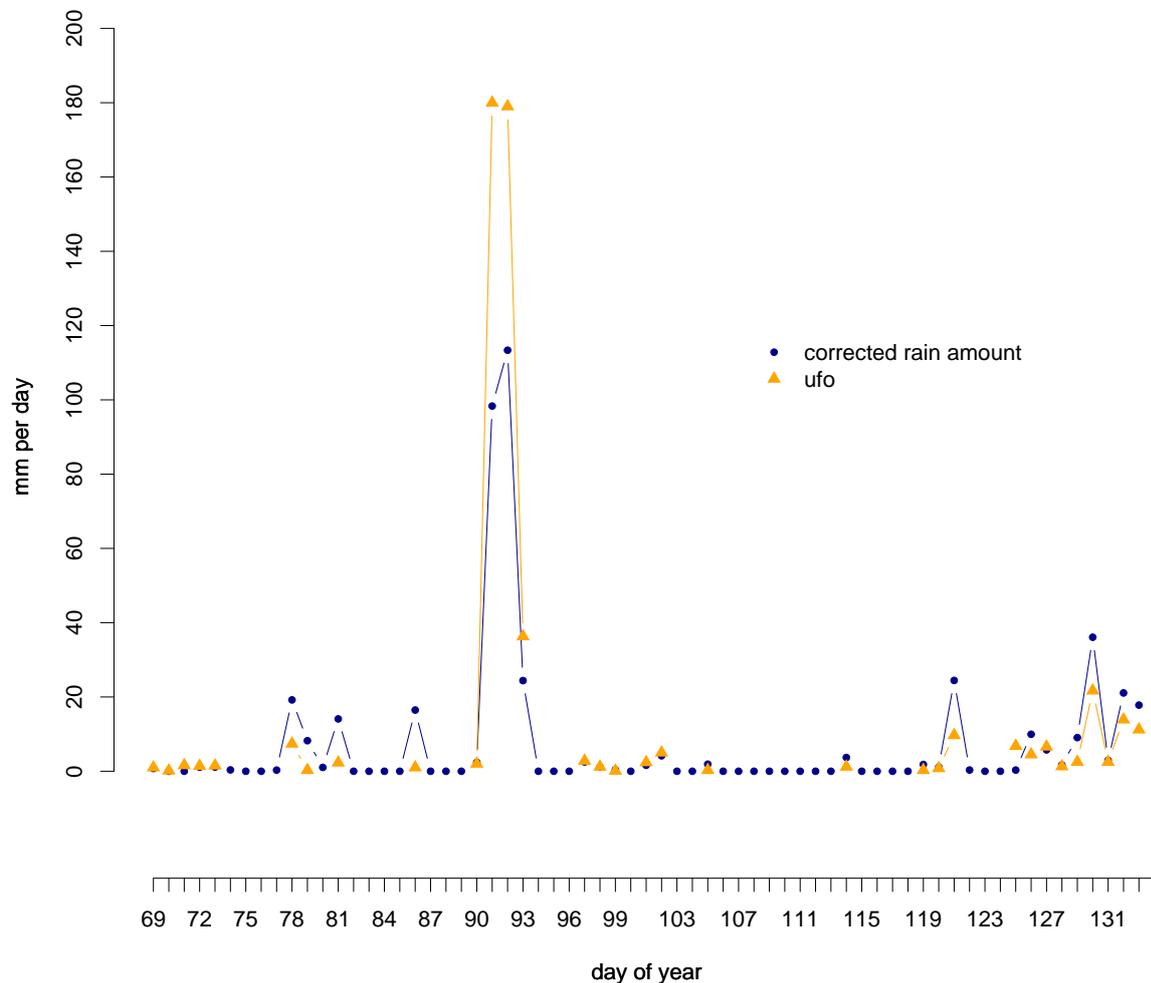


Figure 4.2: Temporal distribution of rain water input measured by a conventional (corrected rain amount) and by a vertical orifice (ufo) gauge .

the UFO gauge. These two reasons could explain the differences and the higher amounts sampled by the Juvik gauge.

Fig. 4.2 shows the temporal distribution of the measured amounts by the conventional gauge and the UFO gauge. For events with high wind speeds (e.g. between 1st and 2nd of April), the vertical surfaces caught more water than the horizontal ones. For events with low wind speeds it is the opposite pattern. Because rain fell always at a certain angle and never completely horizontally (during these days between $1 - 60^\circ$), there is

an overlapping of the measurements of these two gauges. It is therefore not possible to add the two amounts. However, the vertical surface gauges gave us the information that there was a big portion of wind-driven precipitation which is not or only insufficiently measured with the conventional rain gauge. For a more detailed discussion of the rain amounts and possible errors in precipitation measurements, it was necessary to compare them with net precipitation amounts, which will be done in Section 4.4.

4.2 Fog water deposition

Average fog water deposition measured by the eddy covariance system for a visibility below 1000 m was $0.05 \text{ mm m}^{-2} \text{ h}^{-1}$ or $14.2 \text{ mg m}^{-2} \text{ s}^{-1}$. This amount is similar to the fog water deposition measured with an eddy covariance system in a cloud forest ecosystem in Puerto Rico ($0.04 \text{ mm m}^{-2} \text{ h}^{-1}$ or $10.2 \text{ mg m}^{-2} \text{ s}^{-1}$) (Holwerda et al. 2004) and lies within the range of reported values measured outside the tropics (Beswick et al. 1991; Gallagher et al. 1992; Vong and Kowalski 1995; Vermeulen et al. 1997; Kowalski and Vong 1999; Thalmann et al. 2002; Burkard et al. 2003). The daily deposition rate of 1.2 mm d^{-1} lies within the range of $0.27\text{--}6.3 \text{ mm d}^{-1}$ of reported cloud water interception rates in tropical montane areas obtained by different methods (Bruijnzeel 2001). Fog water deposition expressed as percentage of rainfall (4%) was at the lower end of the scale reported by Bruijnzeel (2001) (2–281% of associated rainfall). While the daily deposition rates are reasonable values, the share of fog water in total water input is very small. According to the direct measurements, fog water did not add a significant portion of water to the water balance of this ecosystem during this field campaign. This can be explained by the low fog frequency during the field campaign. In addition to a high cloud base, the lack of fog was caused by the weather pattern “temporales del pacifico” (Section 2.1.1). During several days, the field site was in the lee of the continental divide due to western winds caused by this pattern. Usually, these type of weather systems occur in the hurricane season (August–October) and their occurrence in March might have caused an unrepresentative dry season. However, Clark et al. (2000) report an average cloud immersion of the upper slopes and ridges along the continental divide in the area of Monteverde during the dry season of 20–25%. This percentage compares well to the 26% of fog detected in this campaign (Section 3.1.2) and therefore the share of 4% of fog water deposition in precipitation seems to be normal for the dry period.

Table 4.2: Fog water deposition measured or calculated by different methods for the period between the 9th of March 2003 and the 13th of May 2003, percentage of the directly measured amount and the mean daily flux [mm d^{-1}].

Method	fog water input [mm]	%	[mm d^{-1}]	% of rain
directly measured ^a	19.0	100	1.5	4
calculated: isotope tracer ^b	61.2	322	4.1	12
calculated: chloride tracer ^c	127.9	673	8.9	30
calculated: water balance ^d	107.1	564	7.4	24

^aeddy covariance method (Section 2.2.4)

^bisotope compartmental model: $F = 11\%$ of $(TF + SF + E_i)$ (Section 3.7.2)

^cchloride compartmental model: $F = 23\%$ of $(TF + SF + E_i)$ (Section 3.7.2)

^dwater balance method: $F = (TF + SF + E_i) - P$ (Section 1.3)

The daily deposition rate calculated by the isotope compartmental model was 4.1 mm d^{-1} (61.2 mm during 348 hours where the visibility was below 1,000 m). This value lies as well in the range of daily deposition rates reported for tropical montane areas by Bruijnzeel (2001), but at the very high end of the scale. There are indications that the calculated fog water depositions by means of the volume weighted means instead of daily concentrations are too high: As will be shown in Section 4.4, the fraction of fog water in throughfall water is very variable and gets smaller, the higher the amount of throughfall is. For 12 selected days, the mean fraction of fog water in throughfall was very high (50%) but the resulting fog water amounts were only 35% of the throughfall amounts. With a fixed fraction of 11% over the whole period, the fog water amount is likely to be overestimated because of the events with high throughfall amounts, where the fraction of fog water in throughfall would be smaller. An overestimation of fog water inputs calculated by the volume weighted means is as well supported by the finding that the calculated fog water amounts for these 12 days were 61% higher than the eddy covariance amounts. With the fixed fraction over the whole time period, the calculated fog water amount exceeds the directly measured ones by more than 220%. Another reason for a too high estimation of fog water inputs by the isotope compartmental model is the effect of evaporation. Evaporation influences the isotopic concentrations of throughfall water such that the concentration of the heavier isotopes (^2H and ^{18}O) increase with respect to the lighter isotopes (^1H and ^{16}O) which evaporate more easily. Mixing rain water with “heavier” fog water has the same effect. Thus, fog water inputs might be overestimated with this method due to evaporation.

In comparison to Bruijnzeel (2001), the chloride compartmental model and the water balance method both yielded unreasonably high daily fog water deposition rates (8.9 and 7.4 mm d⁻¹, respectively). For seven selected days, the resulting daily amounts calculated by the chloride fraction technique did not correlate with the directly measured amounts by the eddy covariance set-up. The fog water deposition calculated by the water balance method might have been overestimated due to rainfall measuring errors. This possibility will be discussed in Section 4.4.

4.3 Wet-canopy evaporation

The mean wet-canopy evaporation rate of 0.094 mm h⁻¹ compares well with the rate reported in other studies (Schellekens and Bruijnzeel 2000; Hafkenscheid 2000). The 49.1 mm wet-canopy evaporation calculated for the selected time period highly depend on the definition of a wet canopy. In this thesis, it was assumed that the canopy was wet during a rain event plus two hours after a rain event. These two hours refer to the time that crown drip is recorded by throughfall gauges after rainfall stopped. This time lag has been used by Schellekens and Bruijnzeel (2000) and Hafkenscheid (2000). However, the stopping of crown drip does not necessarily mean that the evaporation stops as well — especially in forests with many moss balls like the one at the Monteverde site, which can store water for a long time. In addition, Schellekens and Bruijnzeel (2000) and Hafkenscheid (2000) worked under near coastal conditions where wet-canopy evaporation was higher because of advected heat from the ocean and thus the drying time was shorter than it might have been at the San Gerardo field site. Thus, the value of 49.1 mm represents a rather conservative estimate of wet-canopy evaporation during these 65 days.

4.4 The wet-canopy water balance

The components of the wet-canopy water budget should balance, if measured and calculated correctly. The following computation shows the measurements and calculations for the period between the 9th of March and the 16th of May:

$$449.0_{P(\text{Sharon cor.})} + 19.0_{F(e.c.)} < 497.1_{TF} + 9.9_{SF} + 49.1_{E_i} . \quad (4.1)$$

The unexplained amount is 88.1 mm. Thus, the budget remains unbalanced. A closer look at the water balance on a daily basis shows where the greatest deviation originates from (Fig. 4.4).

The key event seems to be the storm between day 91 and 92 (1st and 2nd of April 2003). During these days, the greatest deviation from the balanced conditions occurred. For these two days only, there is an unexplained amount of 91 mm. We assume that the error in throughfall measurements, which constituted the greatest portion of the output component during these two days (299 mm, 97% of $TF + SF + E_i$), was small due to the roving gauge technique (Lloyd and Marques 1988; Holwerda et al. 2004). In comparison, the input components (i.e., rainfall and fog water deposition) were measured at one point only. Therefore, it is more likely that the unexplained amount during these days represents an unmeasured amount of input water rather than an overestimation of the output. It is also improbable that the larger proportion of this missing water should be attributed to unmeasured fog water deposition. This would require a daily deposition rate of more than 18 mm day⁻¹ which, in turn, is not in the range of possible deposition rates (Section 4.2). Fig. 4.3 shows the fraction of fog water in throughfall calculated by the isotope compartmental model for 12 selected days. The fraction of fog water in throughfall water decreased from 100% for a daily throughfall amount of 0.9 mm down to 5% for a daily throughfall amount of 9.7 mm. The daily throughfall amount for the 1st and 2nd of April was 165 and 134 mm, respectively. Unfortunately, there are no isotope samples available from this storm event. However, it is likely that the fraction of fog water in throughfall was even smaller than the 5% for a daily deposition rate of 9.7 mm. This would indicate that fog water deposition was below 15 mm during these two days (the eddy covariance system measured an amount of 5.5 mm). We conclude that most probably rainfall was not measured correctly during this storm event. This assumption is supported by the following observations:

- Wind speeds during these two days were the highest of the whole measuring campaign with a maximum of 10 m s⁻¹. It is known that rainfall measurements by raised gauges underestimate precipitation because of the distorted wind field above the gauge orifice. This error lies between 2 to 10 percent of rainfall, depending on wind speed and rain droplet size (Holwerda et al. 2004). The precipitation data however were not corrected for wind induced loss.

- The high wind speeds and small droplet sizes resulted in slanted rainfall with angles reaching a maximum of 60° from the vertical. This wind-driven precipitation was measured by the UFO gauge, which sampled amounts of 180 and 179 mm of rainfall per day during this storm event (not mixed with fog water, see Section 4.2). This is 70% more than the Sharon corrected precipitation (211 mm for both days). The amount measured by the UFO is higher than throughfall because it represents the amount of precipitation caught by a vertical surface and not by the sloping ground. The true precipitation thus was smaller, but the UFO gauge shows clearly that there indeed was more rainfall than measured by the horizontal gauge. A tilted gauge (i.e. a gauge with an orifice parallel to the slope) might deliver the best measurements under such circumstances.

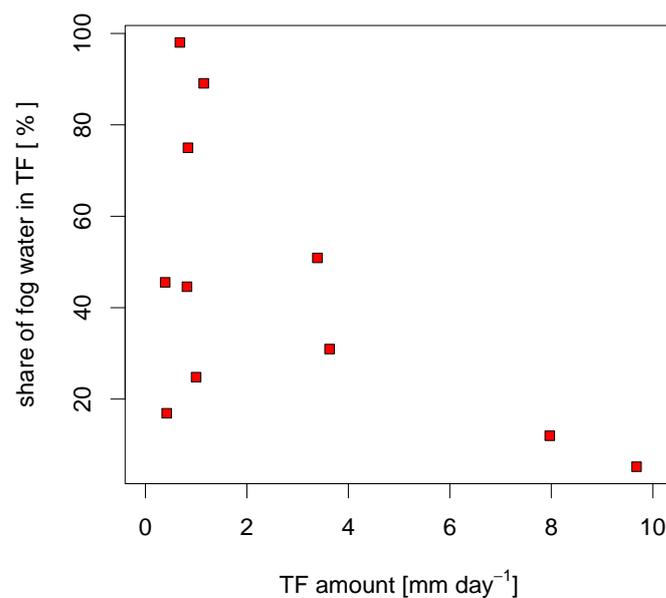


Figure 4.3: Fraction of calculated fog water deposition (isotope compartmental model) in TF as a function of throughfall amount.

Fig. 4.4 illustrates that the wet-canopy water balance shows small deviations apart from this storm event in the beginning of April. For many days, the measured amounts were very small and the uneven daily balances might just reflect the inaccuracies of the mea-

surement methods. However, some discrepancies between input and output could be explained as follows:

- First, there might be an error created by the measuring setup: throughfall was measured at a slope opposite to the slope where the meteorological tower was standing (Section 2.1). Arazi et al. (1997) state, that small scale topographical inhomogeneities substantially influence the rainfall distribution. Therefore, an uneven rainfall distribution in the catchment area could explain different rain amounts where throughfall was measured in comparison to the area where fog and rain water inputs were measured.
- Second, there might be mismatches because of the extrapolation of the input measurements to a larger area. Fog and rain measurements were performed in one spot and represent the deposition to this location. Because of spatial differences in precipitation (Arazi et al. 1997) and fog water deposition, the extrapolation of the point-measurements to a greater area (i.e., the area where throughfall and stemflow are measured) might lead to under- or overestimation of the input to this area. Spatial differences are also reported for stemflow and throughfall (Lloyd and Marques 1988) and are taken into consideration with the application of the roving gauge technique. For precipitation measurements it could be worth working with several gauges spread over the whole catchment, because a roving gauge technique is hardly possible above the canopy.
- Third, there might have been a difference between the fog water inputs measured at the tower site and the amount of fog water that entered the throughfall plots. The fog water deposition measured by the eddy covariance method is representative for a footprint area several hundreds of meters upwind, depending on measurement height, wind speed and atmospheric stability (Holwerda et al. 2004). Often, the throughfall plots did not lie in this footprint area. Because of a decoupled atmospheric system in the small catchment and unstable atmospheric conditions, high spatial differences of fog water depositions are reasonable. For the footprint area, the eddy covariance measurements are of good quality, but it is critical to extrapolate the measurements to a larger area.
- Fourth, the change in canopy storage was not considered. It was assumed that the conditions in the forest were permanently wet, which was not always the case. A drying up of the canopy between rain events would explain the situations where the balance was negative, i.e. more input than output.

- Fifth, the Sharon correction of the rain amount might have introduced new errors.
- Sixth, stemflow was only estimated for this work. For precise computations of the wet-canopy water balance it is necessary to know the exact stemflow amount.

The water balance method trusts in correct rainfall, throughfall, stemflow, and wet-canopy evaporation measurements. If precipitation is underestimated – like it was in this study – the fog water input is overestimated and thus the hydrological importance of cloud forests. The water balance method can be a good method for periods without rainfall (Holwerda et al. 2004). For situations with a combination of fog and rainfall – especially in form of drizzle or wind-driven rainfall – this method should not be applied unless the rainfall measurements are improved. The eddy covariance method and the isotope compartmental model on a daily basis give both reasonable results. The eddy covariance method measures rather conservative net amounts (that is, the net difference between true surface deposition and the concurrent formation of fog from water vapor via condensation) whereas the isotope compartmental model might overestimate fog water deposition because of evaporation. Thus, the fog water input to this cloud forest during this field campaign lied between 4 and 12%. We therefore conclude that precipitation was undermeasured by 15 to 37%. Fog water inputs might not be of very large hydrological importance if only the additional water amount is considered. Fig. 4.3 shows that fog water fraction in throughfall is very high for small throughfall amounts. Thus, fog water maintains a minimal water flow when there is no rainfall, keeps the canopy wet and reduces the evaporation rate. These factors are especially important for the existence of epiphytes.

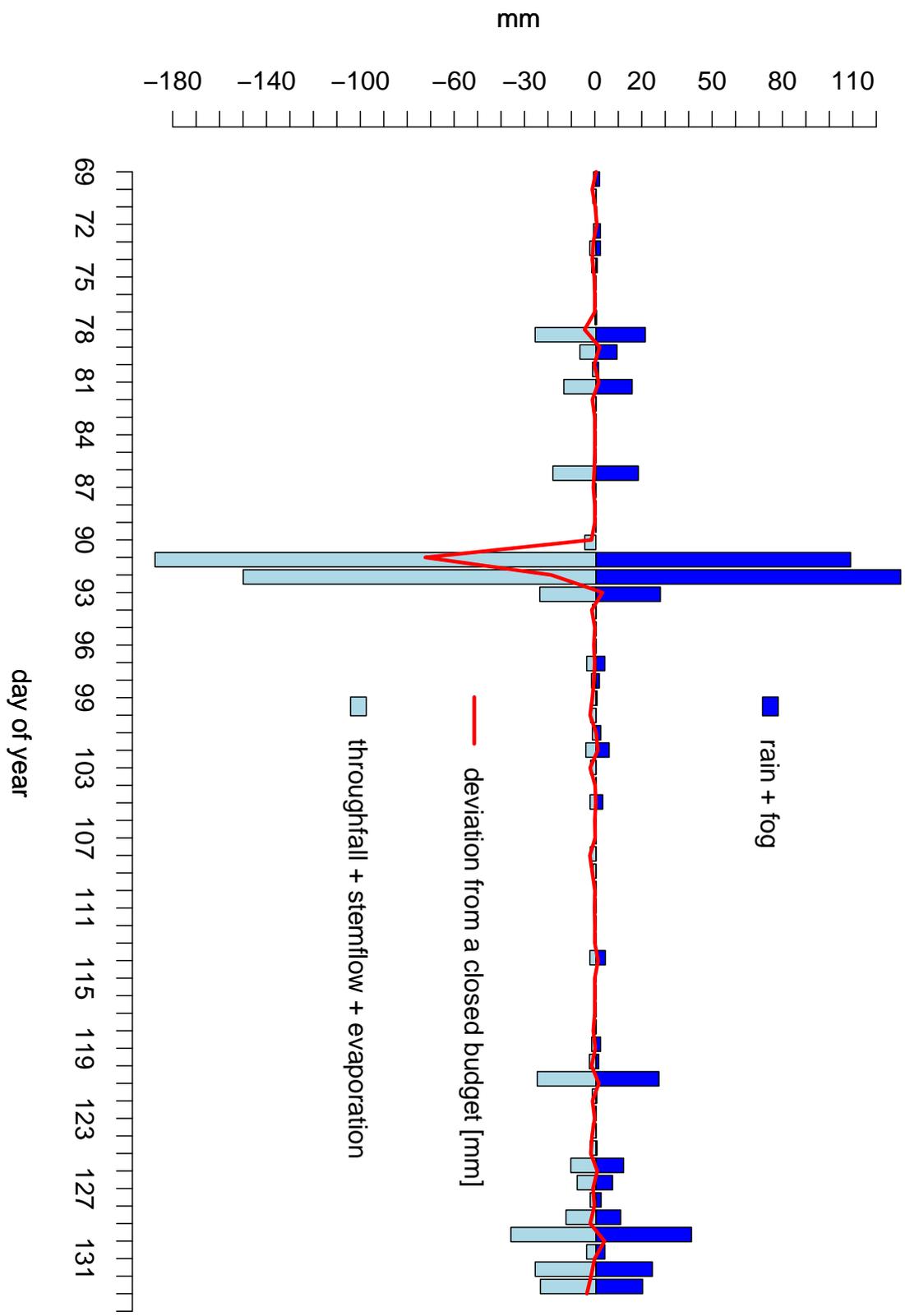


Figure 4.4: All measured components of the water budget (fog: eddy covariance method; rain: conventional gauge, amounts Sharon corrected; throughfall: roving gauge method; stemflow: 2% of throughfall; evaporation: wet-canopy evaporation after Penman-Monteith), and the deviation from a closed budget: (rain + fog) – (throughfall + stemflow + evaporation), all in mm.

4.5 Estimation of the annual fog deposition

One aim of this work was to calibrate a low-cost fog water deposition equipment with the eddy covariance measurements to estimate the eddy covariance fog water deposition rates at the same site without the system running anymore. In addition, an estimation of the annual fog water input was needed to calculate the annual occult ionic deposition. Because there are no accurate measurements of visibility nor liquid water content available from this site for a whole year, the estimations were made on the basis of a model obtained by the correlation of the eddy covariance measurements with horizontal and vertical rain amounts and wind speeds. As discussed in the previous section, the eddy covariance method gave a very conservative amount of fog water deposited to the forest. As such, the value obtained by the following model has to be considered as a minimum estimate and likewise the annual occult ion deposition presented in Section 4.7.

During the 3 months lasting field campaign, two different systems were running in parallel to estimate additional water inputs to the conventionally measured rain amount: Fog water deposition was measured with an eddy covariance setup, and horizontal precipitation was measured with a Juvik-gauge (see Section 3.3).

Between the 9th of March 2003 and the 13th of May 2003, the eddy covariance measurements yielded an amount of 19.0 mm, whereas the Juvik gauge sampled an amount of 773.0 mm. As described in Section 4.1, this gauge sampled both, wind-driven precipitation and fog water deposition. Because fog and wind-driven precipitation occurred during almost all events of this field campaign together, we correlated the liquid water content and the fog water deposition measured by the eddy covariance system with the amounts obtained by the Juvik gauge. The correlation was moderate between the liquid water content and the Juvik gauge ($r = 0.50$, $p < 0.0001$) and good for the correlation between the eddy covariance fog water deposition and the Juvik gauge ($r = 0.73$, $p < 0.0001$). The highest correlation was obtained between the eddy covariance deposition amounts and the amounts obtained by the following model ($R^2 = 0.76$):

$$F_E = 0.026 + 0.002 \cdot F_J / P \cdot W , \quad (4.2)$$

where F_E [mm h^{-1}] is the fog water deposition measured by the eddy covariance

system, F_J [mm h^{-1}] is the horizontal precipitation amount sampled by the Juvik gauge, P [mm h^{-1}] is precipitation measured with a horizontal orifice and W [m s^{-1}] is wind speed (Fig. 4.5).

The resulting amount of fog water deposition for the year 2003 with this method is 275.5 mm, which is 5% of total water input (Sharon corrected rain water input of the year 2003: 5496.5 mm).

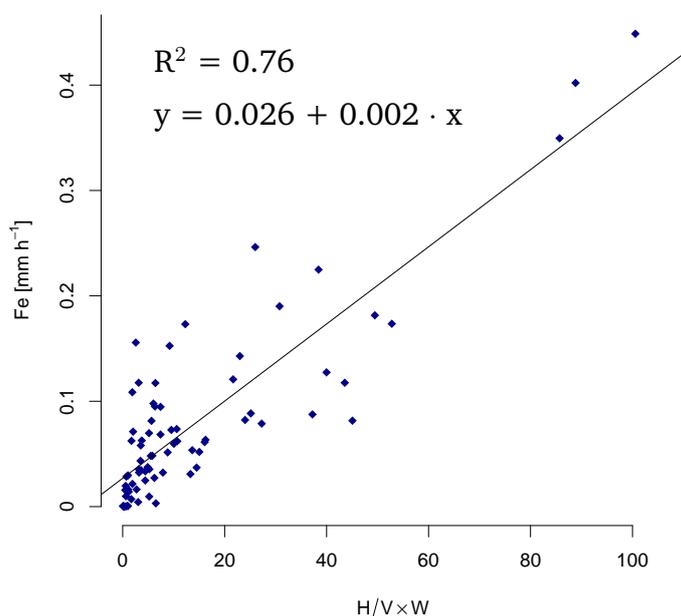


Figure 4.5: Fog water deposition measured by the eddy covariance method as a function of the fog water deposition calculated by a model including horizontal and vertical precipitation measurements and wind speed (Eq. 4.2).

4.6 Chemical composition of *R*, *F*, *TF*, and *SF* water

Comparisons with studies at continental sites (Thalmann et al. 2002; Burkard et al. 2003) revealed that the ion loading of the fog and rain water in Monteverde was very low, with an average of $63.7 \mu S$ for fog and $16.0 \mu S$ for rain water. The concentrations found in *P*, *F*, *TF*, and *SF* varied greatly from event to event. This is in accordance with other studies performed in tropical cloud forests (Asbury et al. 1994; Burkard 2003).

Generally, there is a good agreement between the fog water concentrations from this study compared to Clark et al. (1998) (Fig. 4.3). The dominance of Na^+ , Cl^- , and SO_4^{2-} was explained by the long distance transport of the marine ions with the trade winds from the Caribbean Sea. In addition, there could be a volcanic influence on the SO_4^{2-} , NO_3^- , and NH_4^+ concentrations because the Arenal volcano is in short distance from the site (about 25 km) in the direction facing the prevailing winds. Heath and Huebert (1999) reported an enrichment of NO_3^- concentrations in cloud water associated with thermal fixation of atmospheric N at the hot lava surface. Unfortunately, we could not compare the changes of ionic concentrations in rain and fog water to the volcanic activity, because we could not get any information about the volcanic activity. Finally the higher fog water concentrations of NH_4^+ and NO_3^- compared to the ones found by Clark et al. (1998) could be attributed to intensified fertilizing in the lowlands or an increased burning of organic material during the dry period (Clark et al. 1998). No influence of air mass origin on fog chemistry could be found after analysis of the 160-hours backward trajectories computed with the Hysplit4 model (NOAA 1997). In one case, air masses travelled from Alaska over the North-American continent to Costa Rica. No higher ionic concentrations were found in fog water although the air masses could have been enriched anthropogenic. We suggest therefore that the ionic concentrations are regionally influenced and not by large-scale transport.

Compared to studies in central Europe, the ionic concentration in fog water found in this study was rather low (Thalmann et al. 2002; Burkard et al. 2003): the fog water ionic concentrations in Europe were 4 to 10 times higher than in Costa Rica. This observation can be explained, on the one hand, with the atmospheric background concentrations that are much higher in central Europe compared to Costa Rica due to intense human activities. On the other hand, fog water concentrations at the Costa Rican site are

Table 4.3: Volume-weighted mean solute concentrations [$\mu\text{eq l}^{-1}$], pH and conductivity (Lf , [μS]) in fog (F) and rain water (P) of this study (Monteverde, windward side of Continental divide), in comparison to Clark et al. (1998) (Monteverde, leeward side of Continental divide). The ratios show the accumulation of ions in fog water compared to rain water.

Ion	$F_{\text{this study}}$	$F_{\text{Clark(1998)}}$	$P_{\text{this study}}$	$P_{\text{Clark(1998)}}$	$\approx F/P$ (this study)
H^+	19.8	47.5	11.1	9.9	2
SO_4^{2-}	129.1	–	34.4	–	4
NO_3^-	51.9	33.6	11.3	3.6	4.5
NH_4^+	120.8	35.0	17.1	3.6	7
Cl^-	209.9	–	53.2	–	4
Na^+	204.5	249.3	50.6	27.4	4
K^+	14.6	15.9	4.6	2.3	3
Ca^{2+}	23.7	33.4	8.8	9.0	3
Mg^{2+}	48.2	73.2	10.3	5.8	5
pH	5.0	4.3	5.2	5.0	
Lf	63.7	–	16.0	–	

influenced by “clean” trade winds. Furthermore, the trajectory analysis showed that the air masses never travelled over highly polluted areas such as the Costa Rican capital San Jose.

Rain water concentrations of almost all ions were in the same range as found by Clark et al. (1998) (Fig. 4.3). They are also comparable to the results of studies performed in central Europe (Thalmann et al. 2002; Burkard et al. 2003), except with a clearer signal from the ocean visible in higher Na^+ and Cl^- concentrations. We found higher concentrations of NO_3^- and NH_4^+ in precipitation than Clark et al. (1998) which might be explained by the same reasons as for the higher NO_3^- and NH_4^+ found in fog water: volcanic influence, fertilizing in the lowlands and burning of organic material.

As deposited solutes flow through forest canopies, nutrient concentrations change due to leaching and uptake of ions by the canopy and due to the enrichment of ions by dry deposition and evaporative concentration (Asbury et al. 1994; Parker 1983). In

this study, we found higher or similar volume weighted mean ionic concentrations in throughfall water compared to cloud water. Concentrations in stemflow were in the same range or up to ten times higher than throughfall concentrations. The changes of the relative shares of dissolved ions in the solution while flowing down the forest canopy is shown in Figure 4.6. Volume-weighted mean pH-values of the deposited solutions changed during the passage through the canopy from 5.2 (rain water) and 5.0 (fog water sampled at 24 m) to 5.8 (fog water at 20 m), 6.2 (fog water at 16 m), 6.6 (throughfall water) and 6.9 (stemflow water). This shows the high buffering capacity of the canopy (Schaefer et al. 1992).

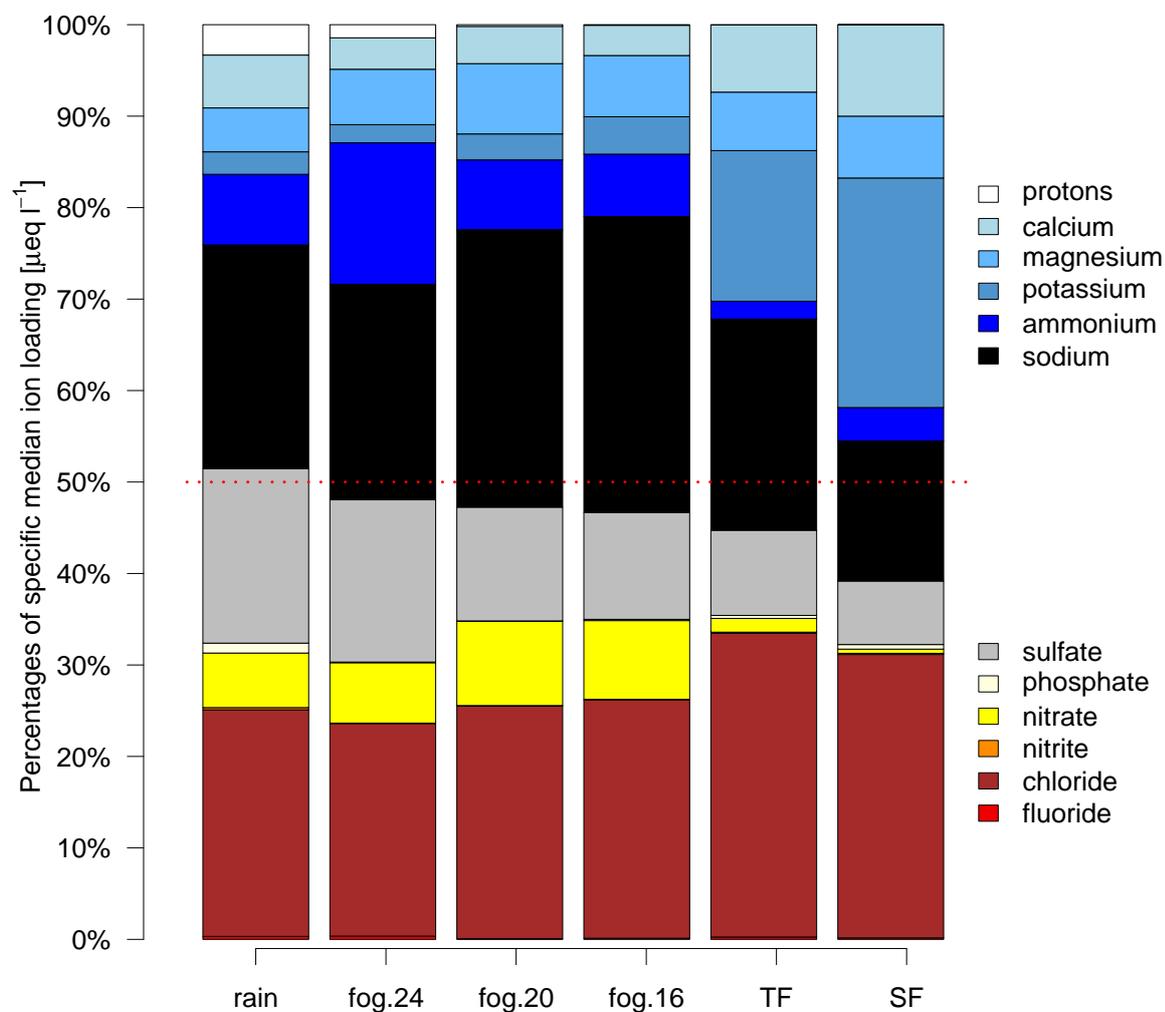


Figure 4.6: Relative shares (medians) of the different ions in precipitation (rain), in fog water sampled at different heights (fog.XX) and in throughfall (TF) and stemflow (SF) water. The red dotted line corresponds to the equilibrium (ideal) ion balance.

4.7 Ion deposition and net canopy retention

Table 4.4 shows the deposition of ions by fog and rain water and the export from canopy by throughfall and stemflow water. Deposition was mainly controlled by the larger rainfall amounts. Na^+ , Cl^- and SO_4^{2-} constitute the biggest portion of the total deposition. For almost all ions, the transport by throughfall was significantly higher than the incoming amount by rain and fog water (Table 4.4). The transport of K^+ from the canopy is explained by foliar leaching and high values have been often reported (Katzensteiner 2000; Cavelier et al. 1997; Parker 1983; Clark et al. 1998). High transport rates of Na^+ and Cl^- are contributed to dry deposition, which is plausible because of some long and frequent shorter dry periods. There was a significant net retention of NO_3^- and NH_4^+ by the canopy which is in accordance with many studies (Clark et al. 1998; Parker 1983; Hietz et al. 2002; Katzensteiner 2000; Lovett 1992). Clark et al. (1998) suggested that 80% of the inorganic N retained by the canopy was withheld by epiphytic bryophytes (mosses and liverworts) and assemblages of epiphytic bryophytes, vascular epiphytes, litter and humus. Regarding the vertical profile we found lower concentrations of NH_4^+ and higher concentrations of NO_3^- in the fog water sampled in the canopy compared to the fog water sampled above the canopy. Because the collector within the canopy was running constantly, the higher concentrations of NO_3^- might reflect high concentrations of HNO_3 and particles containing NO_3^- in dry deposition. The change in concentrations might also show a nitrification process while fog water is travelling downwards and gets in contact with the vegetation. Furthermore, the lower concentrations of NH_4^+ might indicate an uptake of this ion by leaves and epiphytes. Many authors suggested that leaves and epiphytes retain nutrients directly from fog water (Katzensteiner 2000; Lovett 1992; Clark et al. 1998).

For further analyses, we focused on the deposition of nutrients. Especially nitrogen is of special interest, because NO_3^- and NH_4^+ depositions are believed to be responsible for excessive nutrient inputs and acidification in forests in the temperate zones (Burkard et al. 2003). The additional input of nitrogen and sulphur by fog is shown in Fig. 4.7. Occult deposition added a significant portion of NH_4^+ -N (43%) and smaller portions of NO_3^- (+ NO_2^-)-N (23%) and SO_4^{2-} -S (17%) to wet deposition (with wet deposition regarded as 100%).

Table 4.4: Ion deposition from fog (F), rain (P) and transport in throughfall (TF) and stemflow (SF) [mg m^{-2}] during the whole campaign (20 Feb – 15 May 2003). Net retention is calculated as the difference between the sum of bulk deposition ($P + F$) and the sum of transport from the canopy ($TF + SF$).

Substance	F	P	share of F in total input [%]	TF	SF	Net retention
Na ⁺	141.3 ± 1.1	677.3 ± 5.0	17	1465.4 ± 9.5	63.5 ± 0.4	-710.2
K ⁺	16.5 ± 0.1	94.7 ± 0.6	15	1427.4 ± 21.4	179.1 ± 0.8	-1495.3
Mg ²⁺	17.7 ± 0.2	71.0 ± 0.5	20	148.1 ± 0.9	13.6 ± 0.1	-73.0
Ca ²⁺	13.3 ± 0.1	91.0 ± 0.5	13	324.7 ± 2.3	36.5 ± 0.2	-256.8
Cl ⁻	226.5 ± 1.9	1094.7 ± 7.5	17	2313.3 ± 26.6	157.1 ± 0.8	-1149.1
SO ₄ ²⁻ -S	51.8 ± 0.1	308.4 ± 2.4	14	452.6 ± 1.6	17.6 ± 0.1	-110.1
NO ₃ ⁻ -N	18.7 ± 0.0	69.1 ± 0.3	21	55.0 ± 0.2	1.4 ± 0.0	31.3
NH ₄ ⁺ -N	42.6 ± 0.1	100.2 ± 0.5	30	106.0 ± 0.4	8.3 ± 0.0	28.5

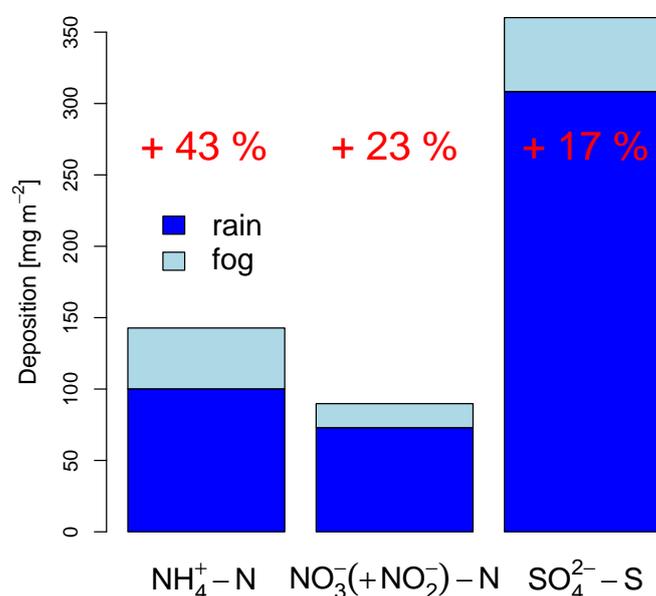


Figure 4.7: Wet and occult reduced/oxidized nitrogen and sulphur input [mg m^{-2}] during the entire field campaign (20 Feb – 15 May 2003). The numbers are based on wet-only deposition as 100%.

The estimated annual deposition rates are shown in Table 4.5. They were obtained by multiplying the water inputs of 2003 (5497 mm of rainfall and 276 mm of fog water deposition) with the volume weighted mean ionic concentrations measured during the field campaign. We calculated a total deposition (wet and occult deposition) of $28.8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. This is one of the highest amounts reported for a tropical montane cloud forest sites (Table 4.7). In comparison to European sites, the N deposition would range in the middle of reported amounts of annual N deposition (wet & occult & dry) by MacDonald et al. (2002), which ranged between $1 \text{ kg ha}^{-1} \text{ yr}^{-1}$ to more than $60 \text{ kg ha}^{-1} \text{ yr}^{-1}$. The total amount of deposited N might be even higher at our site, considering the fact that Weathers et al. (2000) reported very high organic N concentrations in fog water. 66% of total N deposited from cloud water was of organic origin.

Clark et al. (1998) suggested, that tropical montane forests are more resistant to increased N inputs because epiphytes initially retain inorganic N and may buffer ‘pulses’ of inorganic N before they reach the forest floor. They concluded, that the effects of increased long-term N deposition to tropical montane forests and particularly those on

Table 4.5: Estimates of annual ion deposition rates [$\text{kg ha}^{-1} \text{yr}^{-1}$] from occult and wet deposition found in this study compared to the amounts calculated by Clark et al. (1998).

Substance	This study			Clark et al. (1998)		
	occult	wet	ratio	occult	wet	ratio
Na^+	13.5	64.5	0.2	22.9	20.9	1.9
K^+	1.6	10.1	0.2	2.2	3.0	0.7
Mg^{2+}	1.7	7.2	0.2	3.2	2.4	1.3
Ca^{2+}	1.4	11.3	0.1	2.4	5.8	0.4
Cl^-	21.5	104.1	0.2	–	–	–
SO_4^{2-} -S	5.7	30.8	0.2	–	–	–
NO_3^- -N	2.1	8.8	0.3	1.7	1.7	1.0
NH_4^+ -N	4.8	13.1	0.4	1.7	1.7	1.0
Σ -N	6.9	21.9	0.2	3.4	3.4	1.0

windward slopes and ridges (like the one in this study) are unknown. The canopy in their study retained 80% of NO_3^- and 61% of NH_4^+ . In this study, the canopy retained only 35% of NO_3^- and 20% of NH_4^+ . This might indicate, that the canopy reached its buffering capacity and if the N input further increases, there might be some severe changes awaiting this ecosystem. Eugster (1999) for example suggested that excessive nitrogen inputs to an ecosystem might result in a loss of species diversity or in shifts in the species composition.

Table 4.6: Comparison of annual inorganic nitrogen deposition (wet & occult) to tropical forests between this study and studies from other tropical remote sites [$\text{kg ha}^{-1} \text{yr}^{-1}$].

Location	N
Santa Elena, Costa Rica (this study)	28.8
Monte Verde, Costa Rica (Clark et al. 1998)	6.8
Volcano National Park, Hawaii (Heath and Huebert 1999)	15.6
Pico del Este, Puerto Rico (Asbury et al. 1994)	18.3

However, the estimates of the annual deposition have to be used with caution. The concentrations were measured during the dry period. This period does not represent the mean annual conditions in respect to meteorology and chemical composition of the atmosphere. There may be for example higher atmospheric concentrations of HNO_3 and NH_3 due to biomass burning activities (Clark et al. 1998). The annual estimates are also very high because of the high Sharon-corrected rainfall amount of the year 2003 (5496.5 mm). The high deposition of N in comparison to Clark et al. (1998) does not necessarily mean that there was an increase of N deposition during the last five years due to human activities. It might be also possible that there was a stronger volcanic activity during our measuring campaign which might enrich the concentrations of NO_3^- in cloud water because of thermal fixation of atmospheric N (Heath and Huebert 1999).

Chapter 5

Conclusions and Outlook

During an 83-day field campaign in Costa Rica we measured and calculated the components of the wet-canopy water balance technique. Rain water inputs were measured by means of different gauges with horizontal and vertical orifices and calculated by the isotope and chloride compartmental model. Vertical rainfall was corrected for the effects of sloping ground after a trigonometric model by Sharon (1980). Fog water deposition was measured directly by an eddy covariance set-up and calculated by the isotope and chloride fraction and by the water balance method. Wet-canopy evaporation was calculated after the Penman-Monteith equation. Throughfall was measured by the roving gauge technique and stemflow below 30 representative trees.

Rainfall amounts were most probably underestimated by the conventional rain gauge. The Sharon correction yielded a precipitation amount 15% higher than the uncorrected amount. During a 2-day storm event, the vertical-orifice-gauges, throughfall and fog measurements indicate an underestimation of the rain amount by the conventional gauge of at least 36%. Therefore we conclude that the rain amount which entered the forest falls between the Sharon corrected amount (+15% of conventionally measured precipitation) and the resulting amount of $(TF + SF + E_i) - F_{Eddy}$ (+37% of conventionally measured precipitation).

The eddy covariance system yielded a reasonable fog water deposition rate of 1.2 mm d⁻¹ for a cloud forest ecosystem in comparison to Bruijnzeel (2001). When expressed as a percentage of precipitation, the low amount of fog water deposition (4%) can be explained by the low fog occurrence (26%). Clark et al. (2000) reported an average

cloud immersion of the ridges of Monteverde during the dry period of 25%. This finding supports our conclusion that the low percentage of fog water in total input was not abnormal. However, eddy covariance measurements are critical in complex terrain. Because a high spatial variability of fog water deposition in a small catchment is reasonable, the eddy covariance measurements might not be representative for a larger area. Therefore, a higher fog water input at the throughfall plots – as indicated by the isotope compartmental model – can be reasonable. Also the fact, that the eddy covariance represent net fluxes, not including concurrent condensation effects, suggest a higher fog water deposition at the canopy height level. We arrive to the conclusion that the fog water deposition to this forest ecosystem lied between 4% of the Sharon corrected precipitation to 12% of the calculated precipitation by the isotope fraction.

The comparison of the measured amounts of fog and rain water inputs with the results of the isotope compartmental model showed that this method can be a good tool to estimate the fraction of fog and rain water in throughfall water using $\delta^{18}O$ as tracer. For 13 respectively 11 days, there was a good correlation between calculated and measured rain and fog amounts ($r = 0.94$ and 0.70). For eleven days when chemical samples were available, the same method was applied with chloride as alternative tracer. Only for two events, the obtained fraction lied between the range of 0-1 and the calculated amounts were nonrealistic results in comparison to the directly measured amounts. We assume that dry deposition and evaporation were responsible for the malfunctioning of the compartmental model with chloride as a tracer. The fog water input would have been overestimated tremendously with the water balance method (daily deposition rates of over 7 mm which do not appear realistic). The reason for this was most likely the error in rainfall measurements, especially during the storm event during the 1st and 2nd of April 2003. We conclude that this method is not suitable for events when rain and fog water deposition occur together.

Occult deposition added a significant part of nutrients to wet deposition (43% of NH_4^+ -N and 23% of $NO_3^- (+NO_2^-)$ -N, with wet deposition regarded as 100%). The calculated annual deposition of chemical compounds was controlled by large rainfall amounts. The total annual nitrogen deposition (wet and occult) of $28.8 \text{ kg ha}^{-1} \text{ yr}^{-1}$ constitutes one of the highest amounts reported for a tropical montane cloud forest site and lies in the middle range of reported amounts for European sites. It is not clear whether the source of this high input rate is mainly natural (e.g., volcanic activity) or human

made (e.g., biomass burning activities). It remains unclear as well whether the high input rate increased in the last years, for example because of intense cultivation of the Costa Rican lowlands. Comparisons with a study performed by Clark et al. (1998) at Monteverde several years ago suggest an increase of nitrogen inputs. However, this comparison is difficult because Clark et al. (1998) did measure at the leeward side of the continental divide which received less water inputs than our windward site. Therefore we recommend further measurements of chemical inputs at the windward side of the continental divide of Monteverde. Also, correlations between nitrogen concentrations and the activity of the Arenal volcano would be very interesting.

During this measuring campaign, fog water input did not contribute as much to the hydrological budget of this cloud forest ecosystem as previously expected. However, there were small events with a high fraction of fog water in throughfall. This shows that fog water inputs might be important to maintain a minimal stable flow of water when there is no rainfall. Considering the ecosystem, fog is especially important for epiphytes. The existence of these plants depends on a frequent fog immersion which provides the epiphytes with nutrients, additional water and protects them from drying out. For trees, however, fog rather constitutes a stressing element which reduces radiation, lowers transpiration to a minimum and brings the leaves in contact with high ionic concentrations. Further ecological studies would be interesting focusing on fog as a stress factor.

The computation of the water balance showed that the measured components did not balance entirely. For future measurements we therefore propose the following improvements:

- Rainfall measurements should be improved. Preferably, rain amounts should be measured with tilted gauges additional to conventional gauges and vertical-orifice-gauges. Also, rainfall should be measured with more gauges to account for the spatial variation in precipitation.
- If eddy covariance measurements are performed, they should be carried out on an even slope and not in the complex terrain of small catchments such as the ones that are preferred for hydrological measurements. For combined hydrological and meteorological studies, a compromise has to be found between the optimal terrain for each discipline.

- Throughfall and stemflow measurements should be carried out at the same slope where the water input is measured to reduce the mismatch between input and output. For eddy covariance measurements it has to be assured that the net precipitation measurement plots lie within the footprint area of the fog water deposition measurements.
- More comparisons between directly measured and calculated amounts with the isotope balance technique are needed to further test this method. This method might be a good alternative to replace the very expensive eddy covariance set-up.

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Bibliography

- Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998). Crop evapotranspiration - Guidelines for computing crop water requirements. *FAO Irrigation and drainage paper* **56**.
- Arazi, A., D. Sharon, A. Khain, A. Huss, and Y. Mahrer (1997). The windfield and rainfall distribution induced within a small valley: field observations and 2-D numerical modelling. *Boundary-Layer Meteorology* **83**, 349–374.
- Asbury, C. E., W. H. McDowell, R. Trinidad-Pizarro, and S. Berrios (1994). Solute Deposition from Cloud Water to the Canopy of a Puerto Rican Montane Forest. *Atmospheric Environment* **28** (10), 1773–1780.
- Beswick, K. M., K. J. Hargreaves, M. W. Gallagher, T. Choularton, and D. Fowler (1991). Size-resolved measurements of cloud droplet deposition velocity to a forest canopy using an eddy correlation technique. *Quarterly Journal of the Royal Meteorological Society* **117**, 623–645.
- Bolanos, R. A. and V. Watson (1993). *Mapa ecológico de Costa Rica*. San José, Costa Rica: Centro Científico Tropical.
- Bruijnzeel, L. A. (2001). Hydrology of tropical montane cloud forests: A Reassessment. *Land Use and Water Resources Research* **1**, 1–18.
- Bruijnzeel, L. A. and L. S. Hamilton (2001). Decision Time for Cloud Forests. *UNESCO Humid Tropics Programme Series* **13**. 40 pp.
- Brunel, J.-P., G. K. Walker, and A. K. Kenneth-Smith (1995). Field validation of isotopic procedures for determining sources of water used by plants in a semi-arid environment. *Journal of Hydrology* **167**, 351–368.
- Burkard, R. (2003). *Fogwater Flux Measurements Above Different Vegetation Canopies*.

- Ph. D. thesis, University of Bern.
- Burkard, R., P. Bützberger, and W. Eugster (2003). Vertical fogwater flux measurement above an elevated forest canopy at the Lägeren research site, Switzerland. *Atmospheric Environment* **37**, 2979–2990.
- Burkard, R., W. Eugster, T. Wrzesinsky, and O. Klemm (2002). Vertical Divergence of Fogwater Fluxes Above a Spruce Forest. *Atmospheric Research* **64**, 133–145.
- Cavelier, J., M. Jaramillo, D. Solis, and D. de León (1997). Water balance and nutrient inputs in bulk precipitation in a tropical montane cloud forest in Panama. *Journal of Hydrology* **193**, 83–96.
- Clark, K. L., R. O. Lawton, and P. R. Butler (2000). The Physical Environment. In N. M. Nadkarni and N. T. Wheelwright (eds.), *Monteverde. Ecology and Conservation of a Tropical Cloud Forest*, pp. 15–34. New York Oxford: Oxford University Press.
- Clark, K. L., N. M. Nadkarni, D. Schaefer, and H. L. Gholz (1998). Cloud water and Precipitation Chemistry in a Tropical Montane Forest, Monteverde, Costa Rica. *Atmospheric Environment* **32** (9), 1595–1603.
- Daube, B., R. Flagan, and M. Hoffmann (1987). Active cloudwater collector. *United States Patent No. 4697462*.
- Demoz, B. B., J. L. Collett, and B. C. Daube (1996). On the Caltech Active Strand Cloudwater Collectors. *Atmospheric Research* **41**, 47–62.
- Eugster, W. (1994). *Mikrometeorologische Bestimmung des NO₂-Flusses an der Grenzfläche Boden/Luft*. Ph. D. thesis, University of Bern.
- Eugster, W. (1999). *Atmospheric Deposition of Nitrogen to the Swiss Seeland Region*. Bern: Swiss Agency for the Environment, Forests and Landscape (SAEFL). 122 pp.
- Gallagher, M. W., K. M. Beswick, and T. W. Choularton (1992). Measurement and Modelling of Cloudwater Deposition to a Snow-Covered Forest Canopy. *Atmospheric Environment* **26A** (16), 2893–2903.
- Gash, J. H. C. (1979). An analytical model of rainfall interception loss by forests. *Quarterly Journal of the Royal Meteorological Society* **105**, 43–55.
- Glickman, T. S. (2000). *Glossary of Meteorology (2 ed.)*. Boston, MA: American Meteorological Society.

- Haber, W. A. (2000). Plants and Vegetation. In N. M. Nadkarni and N. T. Wheelwright (eds.), *Monteverde. Ecology and Conservation of a Tropical Cloud Forest*, pp. 15–34. New York Oxford: Oxford University Press.
- Hafkenscheid, R. L. L. J. (2000). *Hydrology and Biogeochemistry of Montane Rain Forests of Contrasting Stature in the Blue Mountains of Jamaica*. Ph. D. thesis.
- Heath, J. A. and B. J. Huebert (1999). Cloudwater deposition as a source of fixed nitrogen in a Hawaiian montane forest. *Biogeochemistry* **44**, 119–134.
- Herwitz, S. R. and R. E. Slye (1995). Three-dimensional modeling of canopy tree interception of wind-driven rainfall. *Journal of Hydrology* **168**, 205–226.
- Hietz, P., W. Wanek, R. Wania, and N. M. Nadkarni (2002). Nitrogen-15 natural abundance in a montane cloud forest canopy as an indicator of nitrogen cycling and epiphyte nutrition. *Oecologia* **131**, 350–355.
- Holdridge, L. R. (1966). The life zone system. *Adansonia* **6**, 199–203.
- Holwerda, F., R. Burkard, W. Eugster, F. N. Scatena, A. G. C. A. Meesters, and L. A. Bruijnzeel (2004). Estimating fog deposition at a Puerto Rican elfin cloud forest site: comparison of the water-budget and eddy covariance methods. *Hydrological Processes*, submitted.
- Holwerda, F., F. Scatena, and L. A. Bruijnzeel (2005 (?)). Throughfall Measurements in Puerto Rican Tropical Rainforest: a Comparison of Sampling Strategies. To be submitted.
- IAEA (2002). Special issue on the global network of isotopes in precipitation. *Water & Environment Newsletter* **16**, 5.
- Kaimal, J. C., J. C. Wyngaard, Y. Izumi, and O. R. Coté (1972). Spectral Characteristics of Surface Layer Turbulence. *Quarterly Journal of the Royal Meteorological Society* **98**, 563–589.
- Katzensteiner, K. (2000). *Wasser- und Stoffhaushalt von Waldökosystemen in den Nördlichen Kalkalpen*. Wien: Österreichische Gesellschaft für Waldökosystemforschung und experimentelle Baumforschung an der Universität für Bodenkultur. 159 pp.
- Kowalski, A. S. and R. J. Vong (1999). Near-surface fluxes of cloud water evolve

- vertically. *Quarterly Journal of the Royal Meteorological Society* **125**, 2663–2684.
- Lloyd, C. R. and A. O. Marques (1988). Spatial Variability of Throughfall and Stemflow Measurements in Amazonian Rain Forest. *Agriculture and Forest Meteorology* **43**, 277–294.
- Lovett, G. M. (1992). Atmospheric deposition and canopy interactions of nitrogen. In Johnson and Lindberg (eds.), *Atmospheric Deposition and Forest Nutrient Cycling*, pp. 152–166.
- MacDonald, J. A., N. B. Dise, E. Matzner, M. Armbruster, P. Gundersen, and M. Forstner (2002). Nitrogen input together with ecosystem nitrogen enrichment predict nitrate leaching from European forests. *Global Change Biology* **8**, 1028–1033.
- Monteith, J. L. (1965). Evaporation and the environment. *Symposium of the Society for Experimental Biology* **19**, 205–234.
- NOAA (1997). HYSPLIT4 (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model. Web address: <http://www.arl.noaa.gov/ready/hysplit4.html>. NOAA Air Resources Laboratory, Silver Spring, MD.
- Parker, G. (1983). Throughfall and stemflow in the forest nutrient cycle. In A. Macfarlane and E. D. Ford (eds.), *Advances in Ecological Research*, pp. 58–120. London: Academic Press.
- Saurer, M., I. Robertson, R. Siegwolf, and M. Leuenberger (1998). Oxygen isotope analysis of cellulose: An interlaboratory comparison. *Analytical Chemistry* **70** (10).
- Schaefer, D. A., P. Conklin, K. Knoerr, S. E. Lindberg, and G. M. Lovett (1992). Atmospheric deposition of acids and canopy interactions. In Johnson and Lindberg (eds.), *Atmospheric Deposition and Forest Nutrient Cycling*, pp. 427–450.
- Schellekens, J. and L. A. Bruijnzeel (2000). Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico. *Journal of Hydrology* **36**, 2183–2196.
- Sharon, D. (1980). The Distribution of Hydrologically Effective Rainfall Incident on Sloping Ground. *Journal of Hydrology* **46**, 165–188.
- Stadtmüller, T. (1987). *Cloud Forests in the Humid Tropics. A Bibliographic Review*. Turrialba: United Nations University, Tokyo and Centro Agronomico Tropical de

Investigacion y Ensenanza.

- Thalmann, E., R. Burkard, T. Wrzesinsky, W. Eugster, and O. Klemm (2002). Ion fluxes from fog and rain to an agricultural and a forest ecosystem in Europe. *Atmospheric Research* **64**, 147–158.
- Thom, A. S. (1975). Momentum, mass and heat exchange of plant communities. In J. L. Monteith (ed.), *Vegetation and the Atmosphere*, pp. 57–109. San Diego, CA: Academic Press.
- Tobón-Marin, C., W. Bouten, and J. Sevink (2000). Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazonia. *Journal of Hydrology* **237**, 40–57.
- Tosi, J. A. (1969). *Mapa ecológico de Costa Rica*. San José, Costa Rica: Tropical Science Center.
- Vermeulen, A. T., G. P. Wyers, F. G. Römer, N. F. M. V. Leeuwen, G. P. Draaijers, and J. W. Erisman (1997). Fog Deposition on a coniferous forest in the Netherlands. *Atmospheric Environment* **31** (3), 375–386.
- Vong, R. J. and A. S. Kowalski (1995). Eddy correlation measurements of size-dependent cloud droplet turbulent fluxes to complex terrain. *Tellus* **47B** (3), 331–352.
- Wanner, H. (1979). *Zur Bildung, Verteilung und Vorhersage winterlicher Nebel im Querschnitt Jura-Alpen*. Geographica Bernensia. Vol. G7, 240 pp.
- Weathers, K. C., G. M. Lovett, G. E. Likens, and N. F. Caraco (2000). Cloudwater Inputs of Nitrogen to Forest Ecosystems in Southern Chile: Forms, Fluxes, and Sources. *Ecosystems* **3**, 590–595.
- Zadroga, F. (1981). The Hydrological Importance of a Mountain Cloud Forest Area of Costa Rica. In R. Lal and W. Russell (eds.), *Tropical Agricultural Hydrology*, pp. 59–73. New York: John Wiley & Sons Ltd.