Ecohydrology of a seasonal cloud forest in Dhofar: 1. Field experiment

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[1] We describe the ecohydrology of a unique semiarid broadleaf deciduous forest in Dhofar (Oman). The forest is surrounded by desert and is confined to a coastal area, where the summer wet season is characterized by a persistent dense cloud immersion. Using field observations, we show how clouds render the ecosystem particularly water conserving and therefore create a niche for a moist forest biome in a semiarid area in three ways. First, horizontal precipitation (collection of cloud droplets on tree canopies) added valuable water, such that about two times as much water was received below the canopy (net precipitation) compared to above (rainfall). Second, high stemflow, of about 30% to net precipitation, led to concentrated water input around the stems. Third, transpiration was suppressed during the cloudy summer season, which allowed for storage of the received water. It was only used after the end of the wet season and lasted for the following 3 months, which roughly doubled the length of the growing season. Our results demonstrate that cloud immersion may shape ecosystem hydrology in significant ways, particularly in semiarid environments.

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1. Introduction

[2] The vastness of the Arabian Desert is striking, even when seen from space. Less noticeable is a small area at its southern border on the Indian Ocean. Unexpectedly, a narrow band of lush vegetation spreads along the coastal mountains from western Oman further into Yemen. These are the Dhofar Cloud Oases, a remnant of a former moist vegetation belt of paleo-African origin [*Kurschner et al.*, 2004; *Meister et al.*, 2005]. When the climate on the Arabian Peninsula turned dry, most of the previously moist vegetation gave way to the desert. Under the present arid climate, forests occur only at the southern coast of the Arabian Peninsula, where the desert climate gets interrupted in summer by a foggy moist season that immerses the coastal mountains in clouds.

[3] Today, the cloud oases are among the most diverse ecosystems of the Arabian Peninsula [*Fisher et al.*, 1998] and the lush vegetation gives the impression of a relatively moist climate. However, despite a moist season in summer, the climate is overall only semiarid (120–250 mm annual rainfall at 21°C average annual temperature) and rather characteristic for a semidesert biome, not forest. In fact, most climate-vegetation charts indicate that in a climate with annual temperature of 21°–26°C, and a short 3 month long moist season, forest vegetation would only be expected at annual precipitation of the order of 1000 mm (e.g., charts by *Bonan* [2002] and *Huggert* [1995]), roughly four times the rainfall reported from climate stations in Dhofar. It appears that the fog during the moist season does more than add water to this region.

[4] Ecosystems that depend on persistent seasonal or annual fog are called cloud forests [*Bubb et al.*, 2004]. Cloud forests have received increased attention in recent years because of their high biodiversity, exceptional hydrology and their sensitivity to environmental change that makes them particularly vulnerable [*Bruijnzeel and Hamilton*, 2000; *Ray et al.*, 2006; *Still et al.*, 1999]. They are usually described as dense evergreen ecosystems, receiving abundant precipitation. However, investigations indicate that their hydrology is favorable for low water use, as incoming radiation and transpiration rates are suppressed [*Bruijnzeel and Veneklaas*, 1998]. Moreover, during fog, trees gain additional water from intercepting cloud droplets with their canopies, a phenomenon known as horizontal precipitation. Most of the cloud forests, where hydrologic investigations have already been carried out, are located in the moist tropics, where annual rainfall is high, i.e., greater than 2000 mm [*Bruijnzeel*, 2001]. In these environments, the low transpiration and additional water from horizontal precipitation does not influence water availability for plants significantly. In moist cloud forests, the cloud immersion impacts tree morphology (i.e., stunted trees; see reviews by *Bruijnzeel and Hamilton* [2000] and *Foster* [2001]), abundance of epiphytes [*Sugden and Robins*, 1979] and leads possibly to enhanced recharge of underlying aquifer and

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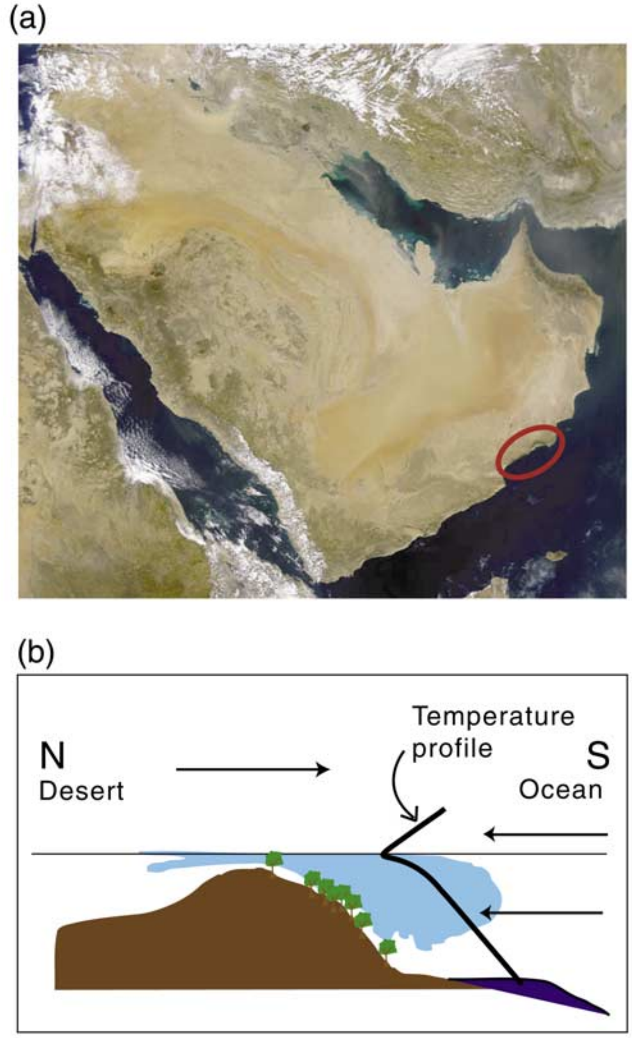

Figure 1. Geography of the area of interest. (a) Satellite image of the Arabian Peninsula. The region of interest is circled in red; note the half-moon shape of the coastal mountain range. Picture provided by the SeaWiFS Project, NASA Goddard Space Flight Center, and ORBIMAGE, http://visibleearth.nasa.gov. (b) Meteorological situation in Dhofar during the khareef.

river flow [*Zadroga*, 1981]. In a semiarid environment, on the other hand, where water is the primary limiting factor to vegetation growth, horizontal precipitation and low transpiration demand might have a significant impact on plant available water, and thus shape the vegetation more significantly. While still only a limited number of studies on cloud forest hydrology have been conducted, those located in water-limited environments are particularly rare. Known examples include rain forests in Australia [*Hutley et al.*, 1997], forests in Africa [*Hursh and Pereira*, 1953], Hawaii [*Juvik and Nullet*, 1995] and Chile [i.e., *del-Val et al.*, 2006]. In these studies, researchers pointed out the important role of cloud cover for maintaining vegetation that was characteristic for moister conditions.

[5] In Dhofar, the zone of influence of the seasonal cloud cover and fog limits the extension of the forests [*Miller and Morris*, 1988]. However, up to now, no scientific investigation has been carried out on the role of clouds for maintaining plants. Also, no information exists about the amount of water that is actually available for the vegetation. Following an increase in the local livestock population the extent of the forest has progressively diminished. Efforts for protection and reforestation are under way, but for those to be efficient, first the question has to be answered how the forest maintains itself. A government study during the 1980s, conducted using artificial collectors, suggested that horizontal precipitation adds two to four times as much water as rainfall to a typical site. This number has since been referred to as the expected amount of horizontal precipitation gained from vegetation [i.e., *Miller*, 1994]. In the following we use field observations to draw a picture of the annual cycle of water fluxes, and water storage to shed light on the question of how lush vegetation and trees survive in this comparatively dry environment.

[6] This paper is the first in a series of two papers investigating the role of cloud cover for forest survival over Dhofar (Oman). Both papers attempt to improve understanding of the mechanistic interactions and the hydrological processes by which cloud cover enables and favors growth of trees under semiarid climate conditions. This paper presents the results of a field experiment, while the second paper [*Hildebrandt and Eltahir*, 2007], uses a numerical model to study the same processes. An independent follow-up paper (A. Hildebrandt and E. A. B. Eltahir, A feedback process between atmospheric cloud deposition and vegetation height, manuscript in preparation, 2007) will deal with a feedback between horizontal precipitation and vegetation height, which highlights the fragility of water-limited cloud forests. A summary of these results has already been published [*Hildebrandt and Eltahir*, 2006]. Our research helps to explain how the environment in this region presents an ecological niche for tree cover, although the low rainfall and high annual temperature suggest that the vegetation should be thinner and more xeric.

2. Geography of the Area

[7] The area of interest are the forests on the seaward pointing slopes of a coastal mountain range in the southwest of the Sultanate of Oman, extending west toward Yemen. It is about 200 km long and at the maximum 20 km wide, the highest elevation of the mountain range is about 1500 m. This ecosystem is surrounded by desert. Figure 1a shows a satellite image of the Arabian Peninsula, the area of interest is marked with a red circle. During the moist season in summer, locally called the khareef, moist air from the ocean pushes against the mountains, resulting in orographic cloud formation and drizzle along the mountain range. The vertical extent of the cloud cover is limited by an overlaying inversion (Figure 1b). The areal extent of the summer cloud cover also defines the lush vegetation belt in the coastal mountain range and the coastal plain [*Miller and Morris*, 1988]. With some annual variation the khareef season usually lasts from mid-June to mid-September (3 months), and is the most reliable source of precipitation. Additionally, rainfall from strong cyclones occurs, but those events are rare (one in three to four years [*Brook and Shen*, 2000]). Recorded annual rainfall is about 100 and 250 mm, measured at climate stations at the coast and mountain crest,

Figure 2. Picture of the field site Gogub. The deciduous *Anogeissus dhofarica* trees surround the tower with mounted meteorological sensors at 9 m height.

respectively. Most of the annual rainfall is provided during the khareef (55 and 220 mm, respectively).

3. Study Site

[8] The field experiment was set up in the Jabel al Qara, in a forest patch at about 17.12°N, 54.6°E approximately 450 m above sea level and 20 km away from the coast. Figure 2 shows a picture of the site. The patch stretches along the hillslope for some 100 m, and also includes larger openings. Since the site is located near the village called Gogub, it will be referred to in the rest of this work by this name. The site is sloped between 0°–10° southward (170° from magnetic north), which is also the prevailing wind direction during the monsoon season. The tree cover consists of one species (*Anogeissus dhofarica*), a perennial broadleaf drought deciduous tree, which is endemic in this region [*Miller and Morris*, 1988]. The growing season of *Anogeissus dhofarica* starts with the first rains (usually in mid-June) and the last leaves are shed in December, 3 months after the last rainfall. The site was set up under closed canopy, adjacent to a small opening in the West (lee side). The experimental plot has an area of 86 m^2, and supports 24 trees. A second vegetation layer below the trees is composed of annual herbs and grasses. The height of the upper canopy is about 6.5 m. The conditions at the site are representative of those up to 60 m downslope (south), 30 m upslope (north), and 20 m to the East.

4. Methods

4.1. Meteorological Data

[9] Temperature and relative humidity (HMP45C, Vaisala, Inc., Woburn (MA), USA), incoming shortwave radiation (LI200x, Li-Cor, Inc, Lincoln (NE), USA), wind direction and wind speed (03001-5 Wind Sentry Set, R.M. Young Company, Traverse City (Mi), USA) were measured every 30 s and averaged over 15 min periods. Rainfall was measured using a horizontal tipping bucket rain gauge (TE525, Texas Electronics Inc., Dallas (TX) USA) and aggregated over 15 min periods. The sensors for the meteorological measurements were mounted at 2.5 m (wind speed/direction, incoming shortwave radiation, rain) and 2 m (relative humidity/temperature) above the canopy top (at 8.5 and 9 m above ground respectively).

4.2. Rainfall Correction

[10] The rainfall measurement was corrected for wind-induced loss and for slope and aspect. A rain gauge acts as an obstacle in the wind field, thus causing turbulence around it. This turbulence might lead to deviation of some raindroplets away from the rain gauge orifice. This wind induced loss leads to underestimation of rainfall. Following *Førland et al.* [1996], we corrected the rainfall measurement for wind induced loss by multiplying with a correction factor f_w:

$$R_O = f_w \cdot \hat{R}, \quad (1)$$

where R_O (mm/h) and $\hat{R}$ (mm/h) represent the corrected and gauge-measured rainfall intensity respectively. The factor f_w is calculated from $\hat{R}$ and wind speed $\hat{u}$ (m/s) as follows,

$$f_w = \exp\left(-0.001 \cdot \ln\left(\hat{R}\right) - 0.0122 \cdot \hat{u} \cdot \ln\left(\hat{R}\right) + 0.034 \cdot \hat{u} + 0.0077\right). \quad (2)$$

Furthermore, the rainfall received on an inclined surface differs from the rainfall received by the projected horizontal area. Therefore rainfall measurements using a horizontal rain gauge do not reflect the amount of water received by the sloping ground. The difference depends on the slope, the aspect of the slope and the inclination of the incident precipitation. Measurements from a conventional horizontal rain gauge can be corrected to represent the amount received at the sloping ground using a trigonometrical model as shown by *Sharon* [1980]:

$$R = R_O \cdot f_S \quad (3)$$

$$f_S = 1 + \tan(\alpha)\tan(\tau)\cos(z_a - z_b), \quad (4)$$

where f_S is the slope correction factor, α refers to the slope of the hill (10°), τ (degrees) is the inclination of the rainfall vector, z_a is the direction of the slope (170°), and z_b (degrees) is the prevailing wind direction during the interval. We calculated τ from its two components:

horizontal wind speed $\hat{u}$ and terminal fall velocity of the raindrop v_g (m/s)

$$\tan(\beta) = \frac{\hat{u}}{v_g}. \quad (5)$$

Terminal fall velocity was approximated from droplet diameter D (mm) using a fitted curve on the experimental data obtained by *Gunn and Kinzer* [1949]:

$$v_g(D) = 3.464 \cdot \ln(D) + 4.142, \quad (6)$$

which gives an excellent fit ($r^2 = 0.997$) for the droplet size range of interest (D = 0.5 to 4.0 mm). The droplet diameter was calculated from the wind-corrected rainfall intensity R_O using the relationship from *Laws and Parsons* [1943]

$$D = 2.23(0.03937 \cdot R_O)^{0.102}. \quad (7)$$

The correction was applied to one hour cumulated time series, using the average wind speed and prevailing wind direction during the same interval.

4.3. Throughfall

[11] Throughfall was measured using two techniques: (1) throughfall from four fixed tipping bucket rain gauges (same as rainfall and connected to a SDM-SW8A Switch Closure Module, Campbell Scientific, Logan (UT), USA), which were installed at random points below the canopy, and (2) for a limited time (7 days, 1 September to 7 September 2003) throughfall measured using an inclined plastic sheet (1.8 × 2.4 m), which was spanned below the canopy, such that the received water was collected by a tipping bucket rain gauge. In both cases the measurements were summed over 15 min periods.

4.4. Spatial Variability of Throughfall

[12] Bootstrap analysis was used to determine variability of throughfall. For each period of interest, we created sets of four throughfall measurements, by sampling with replacement from the original measurements of the four buckets. We calculated the mean of each of those sets of four. By repeating this procedure 10.000 times we created an empirical probability density function (edf) of the throughfall average. We indicate the 0.05 and 0.95 percentiles as the confidence interval.

[13] In addition, we tested whether the bucket average captured spatial variability at the level of the size of the sheet. Because the sheet covered a large enough area to average out some of the spatial variability of throughfall, it was used as a reference of the "true spatial average throughfall." We tested two null hypotheses: (1) the mean of the two throughfall time series, i.e., measured using the sheet and the average of a given combination of throughfall gauges, are the same; (2) the ratio of variances of the two time series is not different from 1. We performed a bootstrap analysis to estimate the edf of the bucket data. We sampled with replacement from the bucket measurements at each time step of a three hour aggregated time series then calculated the mean and variance of the new time series. The procedure was repeated 10.000 times, thus creating an edf of means and variances of the time series. We rejected the null hypothesis if the control value fell outside the 0.05 or 0.95 percentile (double sided test). If either or both null hypotheses were rejected we concluded that the measurement of the sheet and the throughfall buckets were different. We performed the analysis on different combinations of throughfall gauges: on all possible combinations of pairs (6 pairs), on all possible combinations of triplets (4 triplets), and on all four gauges.

4.5. Estimation of Throughfall for 2004

[14] After December 2003 only one (TF_5) of the four throughfall gauges was operational as a result of broken signal cables, so for summer 2004 only measurements of one throughfall gauge were available. The spatial average throughfall measured with four fixed throughfall buckets and the throughfall from the single bucket TF_5 correlate well ($r^2 = 0.88$), and the regression line has a slope of 1.26. Thus, at its location, TF_5 underestimates the spatial average throughfall in a consistent fashion, and we therefore use the relation $TF = 1.26 * TF_5$ to estimate actual throughfall after December 2003 (see also section 6).

4.6. Stemflow

[15] Stemflow was measured using collar type flanges (PVC) slung around 6 stems of various sizes. A PVC tube leads from the collar to the collection container, which had a volume of 6 L until 26 June 2004, and 22 L thereafter. The collected amount was measured at every field visit (about once per week in 2003 and every 2–5 days in 2004). Collected stemflow volume was independent of tree size class (data not shown). Therefore the equivalent precipitation height contributed by stemflow was calculated from the volume average collected from the six sampled stems, which was then multiplied by the tree density (number of stems per square meter) in Gogub, 0.28 per m^2.

4.7. Estimation of Stemflow Variability

[16] We estimated the variability of stemflow around the calculated mean similarly as for throughfall, from an edf created using bootstrap analysis. We indicate the values at the 0.05 and 0.95 percentiles respectively as the upper and lower limits of the confidence interval.

4.8. Soil Water Status

[17] Soil water status was measured using capacitance probes (C probes) manufactured by Sentek Pty Ltd (Australia) at four locations around the tower. One profile was sampled automatically every two hours using an enviroSMART probe (Sentek Pty Ltd, Stepney, Australia, connected to the data logger) with six individual capacitance sensors stacked inside a plastic access tube at depths of 5 cm to 65 cm and spaced 10 cm. The other three locations were sampled manually during field visits (about once per week) using a mobile capacitance sensor (Diviner, Sentek Pty Ltd, Stepney, Australia), which was moved up and down in preinstalled plastic access tubes. The maximum measurement depth of the three access tubes was 40, 50 and 60 cm, respectively. The depth increment between measurements was 10 cm.

[18] Calibration of the sensor would usually yield an equation by which the volumetric soil water content can be calculated from the capacitance measurement. However, loose stones created gaps of varying size between access tube and soil during installation, thus making a gravimetric calibration impossible. We therefore defined an alternative

value (SM^*) that references the measured signal over the observed range and allows for qualitative assessment of the change of soil water storage:

$$SM^* = \frac{F_n - F_{\min}}{F_{\max} - F_{\min}}, \tag{8}$$

where SM^* is defined here as a referenced soil saturation at a given tube and soil depth, F_n is the observed (raw) signal at time n, $F_{\max}$ and $F_{\min}$ are respectively the maximum and minimum signal reading observed during the whole measurement campaign at a certain point. SM^* ranges between 0 and 1 encompassing the lowest and highest observed water content respectively. If the two known readings were "completely dry" and "completely saturated," SM^* would be a good proxy for the actual soil saturation. An SM^* value of 0 is associated with very low soil saturation. Prior to the onset of the monsoon in 2003 a test hole was augured, to a depth of 170 cm. Despite a strong monsoon in 2002, from visual inspection the soil appeared as dry at all depths. Our spring measurements reflect these dry conditions. On the other hand, we have no indication about what water content $SM^* = 1$ corresponds to. It is thus important to note that because $SM^* = 1$ reflects different volumetric soil water contents at different measurement points, SM^* is strictly specific to a single location (defined both by access tube and measurement depth). Nevertheless, SM^* allows tracking of soil moisture at a certain place as a function of time and is a reliable indicator for the arrival of wetting fronts and the emptying of soil water storage.

4.9. Sap Velocity

[19] Sap velocity was measured using the heat dissipation method first proposed by *Granier* [1987]. Installation was done during foggy weather. Pairs of 3 cm long needles were inserted into predrilled holes in a trunk one above the other, approximately 10 cm apart. During drilling the color of the drilled wood was checked to ensure that the dark colored heartwood was not reached. Both needles were equipped with a Copper-Constantan thermocouple, which returned a voltage signal to the data logger. The upper needle was heated by supplying a heater coil with 0.17 W, using a constant voltage supply. Heating was discontinuous with a 20 min long heating cycle and 20 min pause between each heating period. Observation of the raw signal indicated that the sap flow head reached equilibrium after about 16 min. The voltage difference was recorded every two minutes. We used altogether three sap flow sensors installed at about breast height on two different trees, with 7.5 cm (one sensor) and 21 cm diameter (two sensors) diameter at breast height respectively. The sensor in the smaller tree was introduced only to 1.5 cm, in the thicker tree to 3 cm. All sensors point toward a similar direction. The sensor ends were sealed with silicone to prevent cooling from water running down the stem, and were covered with reflecting sheets and plastic to prevent wetting and differential heating of the stem. The sap velocity J_u ($m^3\ m^{-2}\ s^{-1}$) was derived from the calibration of *Granier* [1987],

$$J_u = 119 \cdot 10^{-6} \cdot \left(\frac{\Delta T_o - \Delta T}{\Delta T}\right)^{1.231}, \tag{9}$$

where ΔT (°C) refers to the temperature difference between the upper and the lower needle after 20 min heating, and ΔT_o (°C) to the (maximum) temperature difference between upper and lower needle, i.e., at zero sap flow. We chose the maximum temperature difference during a 1 month period to reflect zero sap flow and therefore ΔT_o.

4.10. Cloudiness

[20] Using daily values of measured incoming shortwave radiation $\hat{S}$ (in W/m^2) and theoretical incident shortwave radiation on top of the atmosphere S_a (W/m^2), we calculated cloudiness, β, according to *Henderson-Sellers et al.* [1987]:

$$\beta = \frac{S_{clear} - \hat{S}}{S_{clear}} \tag{10}$$

$$S_{clear} = t_a \cdot S_a, \tag{11}$$

where t_a is the transmissivity of the atmosphere under clear conditions. We assumed a constant $t_a = 0.75$ and found that the resulting S_{clear} fit well with the maxima of measured daily incoming shortwave radiation throughout the measurement period.

4.11. Potential Evaporation

[21] Potential evaporation was calculated from the meteorological data using the Penmann-Monteith equation for a completely wet canopy (i.e., stomatal resistance is zero):

$$\lambda E = \frac{R_n \Delta + \frac{\rho_a c_p}{r_a}\left(e_{sat}\left(\hat{T}_a\right) - e\right)}{\Delta + \gamma}, \tag{12}$$

where R_n (W/m^2) is net radiation, Δ (Pa/K) is the slope of the saturation vapor pressure versus temperature curve, c_p (J/kgK) the specific heat of air, ρ_a (kg/m^3) is the density of air, e_{sat} (Pa) and e (Pa) are the saturated and ambient vapor pressure at measured ambient temperature $\hat{T}_a$ (K), γ (Pa/K) is the psychometric constant, and r_a (s/m) is the aerodynamic resistance. We estimated R_n according to the component approach as described by *Burman and Pochop* [1994]:

$$R_n = \hat{S}(1 - \alpha) + C_{cloud}\left(L_{d,clear} - L_u\right), \tag{13}$$

where C_{cloud} (−) is a parameter depending on cloudiness, $L_{d,clear}$ (W/m^2) the estimated clear sky downward longwave radiation, L_u (W/m^2) the estimated upward longwave radiation. The albedo α (−) depends on vegetation type. Values for deciduous broadleaf forest range around $\alpha = 0.2$ (i.e., 0.15–0.25 [*Brutsaert*, 1982] and 0.18–0.22, [*Bras*, 1990]. The cloudiness factor C_{cloud} in equation (13) is calculated as (*Weiss* [1982], cited by *Burman and Pochop* [1994]):

$$C_{cloud} = \left(0.4 + 0.6\frac{S_{clear}}{\hat{S}}\right). \tag{14}$$

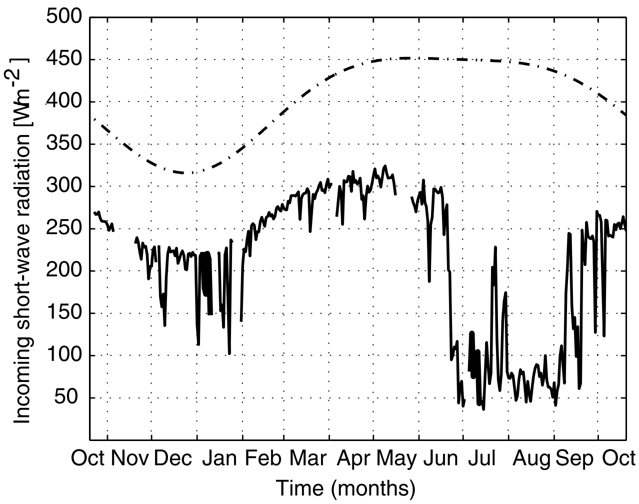

Figure 3. Daily mean incoming shortwave radiation for 19 October 2003 to 19 October 2004 measured at the climate station in Gogub (solid line) and theoretical on top of the atmosphere (dash-dotted line).

The upward surface longwave radiation is calculated as radiation from a grey body

$$L_u = (T_S)^4 \cdot \varepsilon_s \cdot \sigma, \tag{15}$$

where T_s (K) is equivalent to the surface or canopy temperature. Because the canopy temperature was not measured, we make the assumption that the temperature measured two meters above the canopy is a good estimate for canopy temperature; thus $T_s \approx \hat{T}_a$. The surface emissivity ε_s is assumed with $\varepsilon_s = 0.97$ for vegetated surfaces [*Brutsaert*, 1982]. The clear sky downward longwave radiation $L_{d,clear}$ was similarly estimated as

$$L_{d,clear} = \left(\hat{T}_a\right)^4 \cdot \varepsilon_a \cdot \sigma, \tag{16}$$

where ε_a stands for the atmospheric emissivity, and ε_a is estimated as [*Brutsaert*, 1982]

$$\varepsilon_a = 1.24 \cdot \left(\frac{0.01 \cdot e}{\hat{T}_a}\right)^{1/7}. \tag{17}$$

5. Results

[22] The collected data cover almost two growing seasons, which were different in character. While the khareef in 2004 was usual, the monsoon in 2003 was very short and dry. The median of khareef rainfall is 154 mm near the mountain crest (Quairoon Hairitti, from 13 years of data) and 54 mm near the coast (Salalah, from 20 years of data). During the short monsoon in 2003 the khareef rainfall was only 69 mm at the mountain crest and 29mm at the coast respectively, which compares to 130 mm and 43 mm during the somewhat drier than normal monsoon in 2004.

5.1. Seasonality of Cloud Cover

[23] The incoming shortwave radiation (Figure 3) gives a good picture of the annual pattern of cloudiness (plotted in Figure 4), which is roughly bimodal: cloudiness is close to 0% outside the monsoon season (the sky is almost always clear), while cloudiness is 80–90% during the monsoon. Daily maxima of incoming shortwave radiation were much lower during monsoon (median 328 W/m^2) than outside of the monsoon (median 900 W/m^2) and most frequently occurred in the hours around noon time (data from 2004, not shown) throughout the year. According to personal observation during many years, cloudiness occurs usually as fog and immerses vegetation during the monsoon. Fog was also frequently observed during field visits. For example, during the khareef of 2004, light or dense fog were observed (visual observation) during most of the field visits (20 of 26) between the first (23 June) and last recorded throughfall (16 September).

[24] Figure 5 shows the impact of the annual cloudiness pattern on the temperature at the field site. Plotted are daily mean, maximum and minimum temperature as measured in Gogub from mid-October 2003 to mid-October 2004. Outside the monsoon the mean temperature followed the seasonal cycle of solar insolation on top of the atmosphere (Figure 3) and temperature differences between day and night are large (up to 15°C). With the start of the cloudy monsoon season the mean daily temperature dropped (from an average of 28°C during the first half of June to an average 24°C second half of June) and kept decreasing throughout the monsoon. Toward the end of the monsoon daily averages reached values comparable to the winter, although insolation on top of the atmosphere was at its annual maximum. Also during this time, daily temperature variation was suppressed, usually varying by less than 3°C between day and night.

5.2. Rainfall

[25] Rainfall during the khareef 2003 was frequent, but of low intensity. Between the beginning of the measurement campaign (3 August 2003) and the last rain of the monsoon (13 September 2003) rainfall was detected on 33 of 42 days.

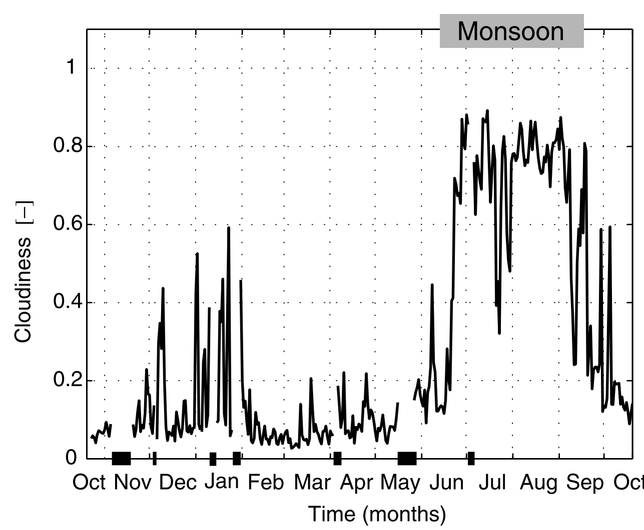

Figure 4. Cloudiness parameter β (as defined in equation (10)) for 19 October 2003 to 19 October 2004, based on daily averages of incoming radiation; the black bars on the x axis denote periods of missing data, and the gray bar shows the period of the monsoon season.

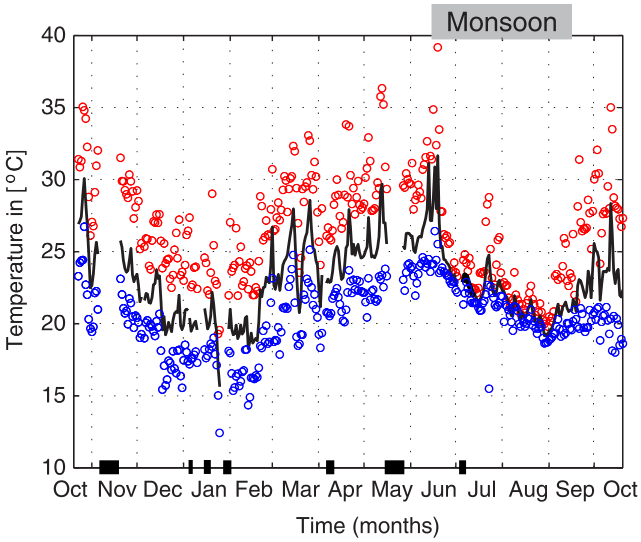

Figure 5. Temperatures at the climate station in Gogub for 19 October 2003 to 19 October 2004 showing daily mean (black line), daily maximum (red circles), and daily minimum (blue circles). The black bars on the x axis denote periods of missing data, and the gray bar shows the period of the monsoon season.

However, intensities were low, with 21 of 33 days receiving less than 1 mm rainfall per day. Maximum daily rainfall during the cloudy period was 6.2 mm. The measurement campaign started shortly after the late monsoon onset and during the following August and September 2003 cumulated rainfall was only 37 mm. Between the end of the monsoon and the end of the calendar year rainfall occurred on two more days (27 September and 3 October 2003), yielding cumulated rainfall 4.1 mm and 1.4 mm, respectively.

5.3. Throughfall

[26] Throughfall received between 3 August and 13 September 2003 was 50 mm. Maximum daily throughfall was 9.7 mm. Throughfall occurred on 35 of 42 days, on 4 days throughfall was registered in the absence of rainfall, and on 2 days no throughfall occurred although rainfall was detected. During the moister khareef of 2004 (24 June to 16 September 2004) accumulated throughfall was 145 mm (n = 71) with 14 days of missing data. On 61 of 71 days throughfall was detected. Maximum daily throughfall in 2004 was 9.6 mm similar as in 2003, but days with elevated throughfall were more common in 2004 then 2003. For example, of all days during khareef when throughfall was detected at all, it was greater than 1 mm on 74% of days in 2004, and only on 42% of days in 2003. Throughfall during the rain events outside the khareef was 2.4 mm and less than 0.1 mm for the rain events on 27 September and 3 October 2003. Additionally, on 30 September 2004, a cyclone contributed 64 mm of throughfall in one night.

[27] Spatial variability of throughfall was apparent from the difference of the throughfall measurements from individual gauges. Accumulated over the entire khareef 2003 the minimum and maximum measurement differ by 15 mm (thus by 30% of the mean). In order to test whether spatial variability was captured by the average of the buckets, we applied a bootstrap analysis for comparing the bucket to the sheet measurement. Daily throughfall during a 7-day comparison period ranged between 0.8 and 2.8 mm, representative of 35% of the throughfall days in khareef 2003. Sheet data showed that events lasted between 12 hours and almost 2 days. The analysis showed that the 3-hour cumulated time series of the sheet measurement was not different at the 15% level from the equivalent time series of throughfall estimated from the average of the four tipping buckets. This applies to both the mean and the ratio of the variances. The difference between the measurement methods (using a sheet compared to the average from a limited number of buckets) only becomes apparent when buckets are removed from our original sample size of four. When averages of only three buckets were used for the bootstrap analysis, one (out of four possible) combination(s) was different from the sheet measurement at the 5% level. When using only two buckets, four (out of six possible) combinations were different from the sheet measurement.

5.4. Stemflow

[28] In Table 1 stemflow (mean and confidence interval) is listed together with the cumulated throughfall collected during the same period. Stemflow is indicated as a fraction of net precipitation (total amount of water received on the ground). This is because the influence of horizontal precipitation makes net precipitation a better reference value for incident precipitation than rainfall (which is usually used). In order to give an impression of the considerable contribution of stemflow, Table 1 also includes periods where stemflow collectors overflowed. However, for computation of stemflow contribution these periods were omitted. Contribution of stemflow to the overall water received below the canopy (net precipitation) was on the average 34% (26–40%) in 2004. Contribution of stemflow was variable in time (±7%), but independent of absolute values of rain, throughfall or stemflow.

5.5. Above and Below Canopy Precipitation

[29] Figure 6 shows daily rainfall, throughfall and the difference, as measured during the khareef 2003. Total above canopy precipitation (rainfall) was 37 mm, while throughfall was 50 mm, thus higher than rainfall. Generally, on days with low rainfall, throughfall tended to be smaller than rainfall. Of the days with rainfall less than 1mm, throughfall was greater than rainfall only 43% of the time, while on days with more than 1 mm of rainfall, throughfall was greater than rainfall 83% of the time.

[30] Throughfall does not account for all water received below the canopy; stemflow also needs to be considered. Stemflow measurements were unreliable in 2003, when both rainfall and throughfall were measured. Measurements from 2004 indicated that stemflow accounted for about 50% of throughfall (34% of net precipitation) for most periods of the khareef. We can only roughly estimate net precipitation in 2003 by presuming the same stemflow fraction applies as in 2004. Under this assumption, total net precipitation for the 2003 khareef would have been somewhat less than twice the rainfall (67 mm and 37 mm, respectively). For the time series of rainfall and net precipitation similar fractions apply. For example, at the daily level, estimated net precipitation was on the average 203% of rainfall, and for the 8 hour time series the average contribution was 195%. In both cases, in about 75% of the considered intervals (24 hour

Table 1. Listing of 2003 and 2004 Measured Throughfall, Stemflow Mean ($\overline{X}$), and Confidence Interval for the Mean (0.05 Percentile ($X_{0.05}$) and 0.95 Percentile ($X_{0.95}$)) and Corresponding Stemflow Fraction of Net Precipitation[a]

Date	Year	Number of Days	Number of Overflown Buckets	Bucket Size, L	Throughfall, mm	Stemflow, mm			Stemflow as Fraction of Net Precipitation, %		
						$\overline{X}$	$X_{0.05}$	$X_{0.95}$	$\overline{X}$	$X_{0.05}$	$X_{0.95}$
9 Aug to 16 Aug	**2003**	**7**	**4/6**	**6**	**11.9**	**1.3**					
3 Aug to 9 Aug	**2003**	**7**	**4/6**	**6**	**21.3**	**1.2**					
2 Sep to 6 Sep	**2003**	**4**	**4/6**	**6**	**6.9**	**1.2**					
30 Aug to 2 Sep	**2003**	**3**	**2/6**	**6**	**1.3**	**0.7**					
16 Aug to 23 Aug	**2003**	**7**	**2/6**	**6**	**3.4**	**0.7**					
6 Sep to 9 Sep	2003	3	-	6	2.6	0.4	0.1	0.7	13	4	21
23 Aug to 27 Aug	2003	4	-	6	1.7	0.2	0.0	0.5	9	0	23
27 Aug to 30 Aug	2003	3	-	6	0.7	0.0	0.0	0.1	6	0	13
Total from not overflowing periods	2003				5.0	0.6	0.1	1.3	9	1	19
8 Jul to 10 Jul	**2004**	**2**	**5/6**	**22**	**13.1**	**5.7**					
10 Jul to 12 Jul	**2004**	**2**	**4/6**	**22**	**15.7**	**5.3**					
31 Jul to 2 Aug	**2004**	**2**	**4/6**	**22**	**13.1**	**5.1**					
30 Jun to 5 Jul	**2004**	**5**	**3/6**	**22**	**11.2**	**4.7**					
5 Jul to 8 Jul	**2004**	**3**	**2/6**	**22**	**6.1**	**4.5**					
9 Aug to 11 Aug	2004	2	-	22	7.7	4.2	3.2	5.3	35	29	41
21 Aug to 28 Aug	2004	7	-	22	6.7	3.9	3.1	4.6	37	32	41
18 Aug to 21 Aug	2004	3	-	22	5.8	3.6	2.8	4.4	38	33	43
11 Aug to 15 Aug	2004	4	-	22	9.3	3.5	2.9	4.2	27	24	31
12 Jul to 14 Jul	2004	2	-	22	5.8	2.9	2.0	3.8	33	26	40
7 Aug to 9 Aug	2004	2	-	22	5.4	2.7	2.1	3.4	33	28	38
3 Aug to 7 Aug	2004	4	-	22	6.1	2.5	1.8	3.2	29	23	34
28 Jul to 31 Jul	2004	3	-	22	4.2	2.1	1.4	2.7	34	25	39
2 Aug to 3 Aug	2004	1	-	22	3.8	2.1	1.6	2.5	35	29	39
23 Jun to 26 Jun	**2004**	**3**	**6/6**	**6**	**14.7**						
15 Aug to 18 Aug	2004	3	-	22	2.6	1.2	0.8	1.6	32	24	38
14 Jul to 18 Jul	2004	4	-	22	1.9	1.0	0.6	1.9	34	24	50
19 Jun to 23 Jun	2004	4	-	6	1.2	0.6	0.3	1.1	33	20	48
Total from not overflowing periods	2004				60.4	30.3	22.6	38.7	34	26	40
1 Sep to 15 Sep	2004	15	-	22	10.2	0					

[a]Marked in bold are periods with overflowing stemflow collectors. Net precipitation used in the last three columns is the sum of stemflow and throughfall for a given period. For the totals, periods with overflowing collectors were omitted.

and 8 hour intervals), estimated net precipitation was larger than rainfall, in 52%, and 37% of the intervals (24 hour sand 8 hours, respectively) estimated net precipitation was more than twice, and in 22% of the intervals (both 24 hours and 8 hours) more than 3 times higher than rainfall.

[31] During the 2004 khareef, estimated daily net precipitation was about 3 mm. The total net precipitation received during khareef can be estimated to be 246 to 295 mm when replacing missing periods (14 days) with the seasonal average (3 mm per day) and measurements from the directly preceding period, respectively. The latter better reflects the moister conditions at the beginning of the monsoon, when the data loss occurred.

5.6. Annual Dynamics of Water Demand, Water Storage, and Transpiration

[32] We used a number of proxies to draw a picture of the seasonal dynamics in the ecohydrology of this cloud forest: cloud cover (β), atmospheric water demand (ETP), water availability (net precipitation), and change in soil water storage (SM*). Figure 7 summarizes the data. Figures 7c and 7h illustrate the continuous and small precipitation during the khareef (mid-June to mid-September), coincident with the period of high cloudiness (Figures 7a and 7f). At the same time potential evapotranspiration (Figures 7b and 7g) is low during the khareef (about 1.5–2 mm per day) compared to the following period (15–20 mm per day), and later in the year (30–40 mm per day). The extremes of potential evaporation are associated with strong northerly winds, bringing hot and extremely dry air (relative humidity of 10% and less) to the site (data not shown).

[33] Owed to the small precipitation intensities, soil moisture (Figures 7d and 7i) penetrated the soil slowly at the beginning of the monsoon. In 2004 it took as long as 14 days from the first rain until the wetting front passed the lowest sampled layer at 60 cm, but afterward the high moisture was maintained. Only at the end of the monsoon, when throughfall ceased and cloudiness decreased, soil moisture decreased. Comparison of soil moisture between the years 2003 and 2004 shows the impact of the weak monsoon in 2003 on soil moisture. Although the measurement began only in August, long after the usual beginning of the khareef, which is expected in mid-June, progression of the wetting front was still in an early stage; the lowest layer had not been reached yet. The wetting front reached the lowest layer on 3 August in 2003, as compared to 10 July in 2004. Consequently, at the end of the monsoon the soil

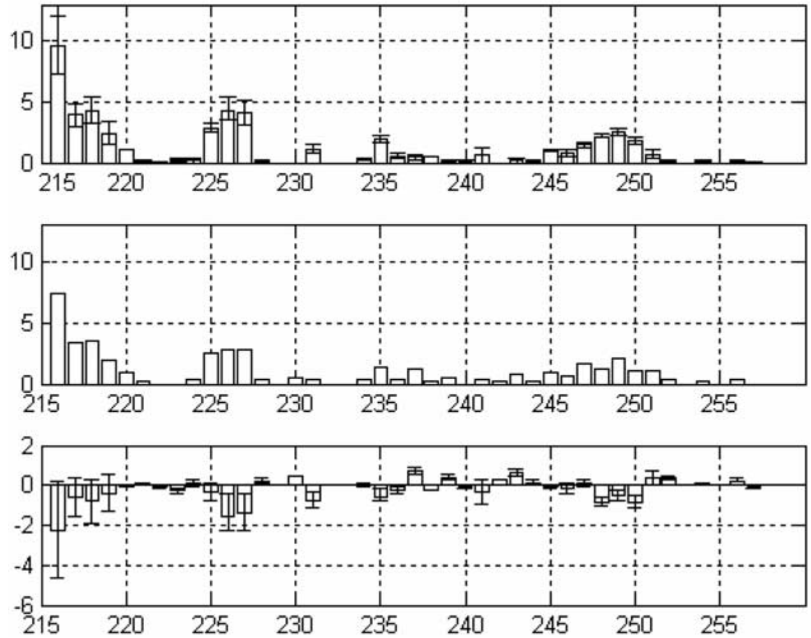

Figure 6. (top) Daily throughfall, (middle) rainfall, and (bottom) the difference between rainfall and throughfall from 3 August to 17 September 2003. The error bars indicate the confidence interval (0.05, 0.95 percentile) found from bootstrap analysis.

contained less water in 2003 than in 2004: at the end of September, the referenced saturation is between 0.3 and 0.55 in 2003 and between 0.45 and 0.6 in 2004.

[34] During the time of continuously closed cloud cover, both sap flow and potential evaporation were low. When potential evaporation increased at the end of the monsoon in 2004, sap flow responded proportionally, while soil moisture started decreasing steadily. Sap flow remained at fairly constant levels (and responding readily to extremes in evaporation demand) until about early November. Afterward, sap flow decreased although the evaporative demand of the atmosphere kept increasing. In contrast, in 2003, after the short monsoon sap flow started decreasing soon after the monsoon had ended, starting mid-October.

[35] Figure 7 also allows a comparison of the impact of rare but heavy cyclone rain with low-intensity khareef precipitation. A cyclone brought on the order of 40% (64 mm) of the total 2004 monsoon throughfall (184 mm) on the night of 30 September 2004. While this event had great impact on the upper most soil layers, it did not saturate the layers below 30 cm to the extent that they had reached earlier during the khareef. For the sampled soil layers (up to 60 cm depth) the soil moisture increased to values from two weeks earlier, but the impact was less in deeper soil.

6. Discussion

6.1. Water Fluxes

[36] Our observations indicate that the amount of water received below the canopy was substantially larger than the amount of water received above. Several assumptions and approximations went into this estimation.

[37] Rainfall was corrected with regard to wind induced loss and slope aspect and inclination, using almost the same procedure as *Holwerda et al.* [2006a]. The correction factor for wind induced loss ranged between f_w = 1.1.3 depending on wind speed. The fractions calculated using *Førland et al.*'s [1996] method agree well with wind induced error found from numerical simulations by *Nespor and Sevruk* [1998] for orographic rain and drizzle, and comparable wind speed. A trigonometrical model was used to correct for aspect and slope, the correction factor was f_S = 0.95. 1.15 depending on the wind speed.

[38] Throughfall was estimated for 2003 on the basis of measurements from a limited number of fixed tipping buckets, four in 2003 and only one in 2004. On the basis of research about spatial variability of throughfall, scientists have recommended using a large number of gauges (30 and more gauges), which should also be moved frequently [*Holwerda et al.*, 2006b; *Kimmins*, 1973; *Lloyd and Marques*, 1988]. The spatial variability of throughfall depends on forest structure, canopy density and canopy closure. On our field site, the canopy is thin but closed at 6.5 m height, consists of only one tree species (*Anogeissus dhofarica*), and carries no epiphytes or moss. Thus throughfall is likely less variable spatially than in taller and more heterogeneous canopies investigated by *Kimmins* [1973], *Lloyd and Marques* [1988], or *Holwerda et al.* [2006b]. Comparison of throughfall measurements obtained using throughfall buckets and a sheet indicated that spatial variability was likely captured, at least on the order of the size of the sheet (4.3 m^2). However, some uncertainty remains, since dripping points might not have been sampled by either of the methods used. Dripping points are points where throughfall is concentrated and enhanced [*Shuttleworth*, 1989], possibly because of peculiarities of the canopy, and they might contribute substantial proportions of overall throughfall [*Lloyd and Marques*, 1988]. Missing dripping points might have led to an underestimation of throughfall, and thus net precipitation.

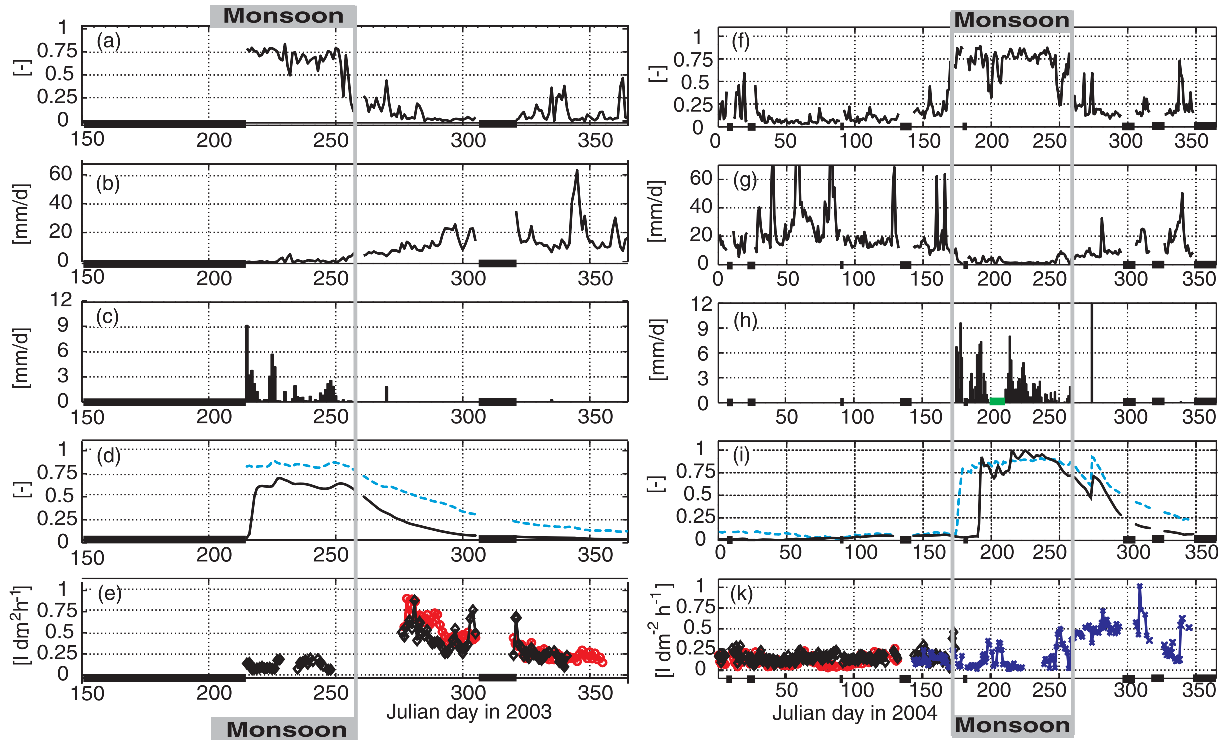

Figure 7. Selected climate variables as measured during the field campaign. Daily values for the year 2003 of (a) cloudiness; (b) potential evaporation; (c) throughfall; (d) referenced soil saturation at 10 cm depth (dashed, blue) and 60 cm depth (solid, black); and (e) sap velocity from sensor 1 (circles, red) and sensor 2 (diamonds, black). Daily values for the year 2004 of (f) cloudiness; (g) potential evaporation; (h) throughfall; (i) referenced soil saturation at 10 cm depth (dashed, blue) and 60 cm depth (solid, black); and (j) sap velocity from sensor 1 (circles, red), sensor 2 (diamonds, black), and sensor 3 (crosses blue). The black bar on the time axis signifies times when data logger file got lost or before the measurement campaign started; data loss from broken signal cables is indicated with a green bar in Figure 7h, while in Figures 7e and 7k, broken signal cables are reflected through gaps in the record and are not explicitly indicated. The gray bars give a rough indication of the monsoon time, with a mark at the last measured rain during fog. Note that the beginning of the monsoon in 2003 was shortly before the start of the measurement campaign and is therefore not explicitly marked.

[39] After December 2003, only one single throughfall gauge (TF_5) was operational, and we therefore chose to estimate average throughfall from the regression of TF_5 with average of the four tipping buckets. The regression line explains a great deal of variance (88%) of the average throughfall in 2003 and the gauge was not moved. By applying this procedure we imply that spatial variability is constant in time, an assumption made by previous researchers [e.g., *Lloyd and Marques*, 1988]. Given the comparatively homogenous and thin canopy, the estimate based on TF_5 likely captures the order of throughfall in 2004, but distributed measurements are necessary to confirm the results.

[40] On average, throughfall exceeded rainfall by 0.3 mm/d during the khareef in 2003. This compares well with data found in the literature for cloud forests elsewhere that were similarly deduced from rain and throughfall measurements, and which found water gains of 0.3–1.33 mm/d obtained from annual averages (review by *Bruijnzeel* [2001]). However, this difference is not equivalent to horizontal precipitation because (1) dripping points might not have been captured (see above) and (2) stemflow and interception loss are not considered. Regarding the latter, stemflow fraction was substantial, on the order of 30% (on the basis of measurements in 2004).

[41] Stemflow was estimated from sampling six trunks. Given that this is a quarter of the total number of trunks (24) on the site, the sampled number seems adequate. However, whatever uncertainty is contained in the estimation of throughfall for 2004, is also reflected in the estimate of contribution of stemflow to net precipitation. Nevertheless, even if throughfall was substantially underestimated (say, by an unlikely factor of two), the contribution of stemflow to net precipitation would still be comparatively large, on the order of 20% [e.g., *Levia and Frost*, 2003]. The high stemflow proportion might be explained by several factors. The fog during khareef leads to moist canopy and stems. Wet stems can provide for a preferential flow path along the stem [*Levia and Frost*, 2003], thus increasing stemflow. In addition, stemflow proportion usually increases with decreasing rainfall intensity and small droplet size, both characteristic for drizzle. However, investigations in cloud forests elsewhere found relatively smaller contributions of stemflow [*Bruijnzeel*, 2001; *Bruijnzeel and Proctor*, 1995], although conditions there should be equally conducive for stemflow. One exception is a cloud affected ecosystem in

Jamaica where stemflow was estimated as 13 and 18% of rainfall (3060 mm/yr). The authors attributed the high values to tree stature [*Bruijnzeel*, 2001; *Hafkenscheid et al.*, 2002]. The general disagreement remains, but may mainly be related to the fact that stemflow is typically reported as a percentage of incident precipitation. While observations of absolute values of stemflow may be similar, the indicated percentage value can vary greatly. As mentioned above, most cloud forest studies have been conducted in moister regions. Furthermore, on an event basis stemflow increases with increasing rainfall intensities until a certain point and then remains constant; this is most likely the point when canopy storage is filled up. Therefore, when precipitation is high, it is natural that the stemflow fraction decreases, and vice versa. Finally, stemflow depends on the anatomy of the plants. It has been observed that desert shrubs have an anatomy that helps to channel rainfall water quickly to the ground [*Levia and Frost*, 2003; *Mauchamp and Janeau*, 1993]. The trees at our field site (*Annogeissus dhofarica*) have steep branch angles, which might have contributed to increasing stemflow.

[42] Because stemflow represents a concentrated water input around the stem, large stemflow fractions may lead to considerable heterogeneity of infiltration and soil moisture [*Pressland*, 1976]. At our field site, the arrival of the moisture front at different locations also suggests heterogeneity of infiltration, related to the distance to the next trunk, and thus the potential importance of stemflow. At the beginning of both the 2003 and 2004 khareef seasons, the wetting front arrived earlier at a given depth in those soil moisture measurement tubes that were located near tree trunks. For example, in 2003, at tubes close to the next standing tree (1.0 m and 1.2 m away) the wetting front had already reached 40 cm depth on 2 August, while further away (1.7 m and 3.5 m), it was only detected during the next field visit on 9 August. In 2004, the pattern was similar. Thus high stemflow might have lead to heterogeneity of infiltration, by channeling water closer to the trees.

[43] For some purposes it is desirable to have a rule of thumb indicating how much water to expect below the canopy (net precipitation) compared to above (rain). Our investigations suggest roughly a factor of two larger for the time average; in other words, the contribution of rainfall and horizontal precipitation to plant available water are about the same. While it seems safe to conclude that horizontal precipitation adds a substantial amount of water to this ecosystem, the exact number should be used carefully. We likely underestimated both rainfall and throughfall with our setup, and used average stemflow fractions from 2004 in the water budget of 2003. Also, the monsoon in 2003, for which the fractions were calculated, was drier than usual. Net precipitation tended to be higher than rainfall on days with overall high net precipitation, and those days were less frequent in the unusual monsoon of 2003 than in the more normal monsoon of 2004. Therefore net precipitation might overall tend to be somewhat higher than double the rainfall.

6.2. Annual Dynamics of Water Demand, Water Storage, and Transpiration

[44] We used a number of proxies to draw a qualitative picture of the annual cycle of water fluxes and water storage, and relate them to the time of cloud cover. In doing so, we used sap velocity to assess changes of transpiration over time. Sap velocity was purposefully not used to calculate water use of the entire tree, since the number of sensors is too small to allow for a reliable estimation. Sap flow can change along the radius and circumference of the tree. In particular, when water becomes limiting the profiles may change in an unpredictable manner [*Lu et al.*, 2000]. On the other hand, researchers have observed that in the absence of water stress sap flux at different depths in the stem is correlated over time [*Lu et al.*, 2000], such that a limited number of sensors is appropriate for deducing the change of overall transpiration over time. However, during times of water stress, the measurement from few sensors is less reliable because of unpredictable changes in sap flow profiles, and a point measurement of sap flow no longer correlates with overall transpiration. Nevertheless, sap velocity in Gogub shows an overall decreasing trend, when soil moisture arrives at lower levels. The seasonal change of transpiration, particularly the change between low sap velocity during *khareef* and the increase during the months afterward (time of unstressed transpiration), should be reliably reflected even by our limited number of sap velocity measurements.

[45] The decrease of sap flow under foggy conditions is in agreement with data collected by *Santiago et al.* [2000], and cloud forests are generally thought of as ecosystems with low water use [*Bruijnzeel*, 2001]. Other researchers have pointed out that the decrease in atmospheric water demand might contribute to alleviating water stress during dry periods [*Burgess and Dawson*, 2004; *Hutley et al.*, 1997], and providing for a biome, which is only marginally suited for the dry climate [*Hutley et al.*, 1997]. At the site in Dhofar the situation seems to differ in one aspect: clouds are present during the moist season, which not only alleviates water stress, but also allows for filling of the soil storage. It appears that plants benefit from the low atmospheric water demand during fog mainly because the cloud cover allows for effective storage of water, thus making it available for use in the later part of the growing season.

[46] In this system the growing season seems to be partitioned into three periods. During the first period (the khareef), incoming radiation is low, relative humidity is high and both potential evaporation and transpiration are small. The soil storage is filled, while only little water is removed. The growing season continues after the end of the monsoon with a second period, where relative humidity is low and both incoming radiation and evaporation demand are high. Transpiration readily follows the evaporation demand, while soil moisture does not appear to be limiting. The following third period is marked by stressed transpiration: sap velocity shows a clear decreasing trend, and does not anymore follow the evaporative demand as in the second period. The end of the third period is reached when all leaves are shed.

7. Summary and Conclusion

[47] Our field study is the first comprehensive hydrological investigation within forest in Dhofar. It expands the understanding of the hydrology of the deciduous forest ecosystem in Dhofar. This system is marked by surprisingly low water availability. We estimated net precipitation in Gogub during the relatively normal khareef of 2004 to only 246–295 mm. This includes stemflow estimates and com-

pensation for the days of missing data by the daily average and the corresponding preceding periods of precipitation, respectively. The khareef of 2004 can be considered a relatively normal monsoon on the basis of the rainfall data recorded at nearby climate stations, therefore the amount of water received can be considered as representative. While many assumptions went into the estimation of total available water in 2004, the final number is much smaller than the expected water demand of forest, according to common climate-vegetation charts that are based on annual averages of climate variables [e.g., *Bonan*, 2002; *Lieth and Whittaker*, 1975].

[48] Judging from the observations made in Gogub, several factors facilitate tree growth in spite of exceptionally small amounts of available water:

[49] 1. Given the small precipitation amounts, horizontal precipitation is a substantial additional source of water. Net precipitation was estimated to be about twice the rainfall in Gogub.

[50] 2. Water losses are minimized during the presence of clouds (low evaporative demand and moist canopies coinciding with the moist season), which allows for effective filling of soil storage. The soil storage facilitates prolonging the growing season far beyond the end of the wet season.

[51] 3. Stemflow contributed about 30% of total incident precipitation to the water budget on the Gogub field site during the monsoon. Soil moisture measurements suggest that stemflow enhanced infiltration around the stem. The length of the growing season seems to be limited by soil storage, therefore increased soil storage around the stems clearly would prolong the growing season. As will be shown in more detail in the companion paper [*Hildebrandt and Eltahir*, 2006], infiltration depth plays a crucial role for the performance of trees in Dhofar. Therefore the relatively high amounts of stemflow may be an essential factor for tree survival.

[52] 4. Precipitation intensities are low, implying that little water is lost to surface runoff during the khareef.

[53] Our results suggest that the contribution of horizontal precipitation might have been overestimated in the past [*Miller*, 1994] on the basis of previous observation using artificial devices, and possibly judging from the abundant lush vegetation. However, the more realistic measurements under the natural forest canopy showed that the contribution of horizontal precipitation was smaller than expected and therefore other factors, like low evaporative demand during khareef, need to be considered when explaining the lush vegetation. Our observation and analysis show that the forests in Dhofar gain additional water from horizontal precipitation, but more importantly the water requirement seems to be low.

[54] The forests of Dhofar thrive in a well-defined niche that is strictly linked to cloud presence. Therefore, although it is water limited, and deciduous rather than evergreen, it completely fulfills the definition of a cloud forest as stated in the UNEP Cloud Forest Agenda [*Bubb et al.*, 2004]. We believe the forests of Dhofar add a new ecosystem to the global map of cloud forests: a seasonal semiarid cloud forest with deciduous phenology.

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