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# Forest on the edge: Seasonal cloud forest in Oman creates its own ecological niche

Anke Hildebrandt[1,2] and Elfatih A. B. Eltahir[1]

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[1] Cloud forests usually grow in the moist tropics where water is not a limiting factor to plant growth. Here, for the first time, we describe the hydrology of a water limited seasonal cloud forest in the Dhofar mountains of Oman. This ecosystem is under significant stress from camels feeding on tree canopies. The Dhofar forests are the remnants of a moist vegetation belt, which once spread across the Arabian Peninsula. According to our investigation the process of cloud immersion during the summer season creates within this desert a niche for moist woodland vegetation. Woodland vegetation survives in this ecosystem, sustained through enhanced capture of cloud water by their canopies (horizontal precipitation). Degraded land lacks this additional water source, which inhibits re-establishment of trees. Our modeling results suggest that cattle feeding may lead to irreversible destruction of one of the most diverse ecosystems in Arabia. **Citation:** Hildebrandt, A., and E. A. B. Eltahir (2006), Forest on the edge: Seasonal cloud forest in Oman creates its own ecological niche, *Geophys. Res. Lett.*, *33*, L11401, doi:10.1029/2006GL026022.

## 1. Introduction

[2] Cloud forests are hotspots of endemism worldwide [*Bruijnzeel and Hamilton*, 2000; *Gentry*, 1992]. They are ecosystems with distinct features caused by frequent, persistent or seasonal cloud immersion [*Hamilton et al.*, 1995]. Persistent fog creates an exceptional micro-climate; a cool and humid environment that leads to moist soils and low transpiration rates [*Bruijnzeel*, 2002; *Bruijnzeel and Veneklaas*, 1998]. Moreover, cloud forests often draw from an additional water source besides rain by collecting cloud water on their canopies (horizontal precipitation). Because of their dependence on specific atmospheric conditions, cloud forests already have been considered particularly threatened by those anthropogenic processes that change cloud prevalence [*Foster*, 2001; *Lawton and Dryer*, 1980; *Still et al.*, 1999]. Most of these usually evergreen forests are located in the moist tropics, with high annual rainfall, therefore little consideration has been given to the role of cloud cover and horizontal precipitation for survival of those cloud forests located in semiarid environments, where water limits plant growth [e.g., *Gioda et al.*, 1995; *Hursh and Pereira*, 1953; *Hutley et al.*, 1997]. Here we present an example of a deciduous and water-limited cloud forest in Oman. Using experimental data and a numerical model we show that the forest depends for survival on clouds prevalence, but additionally also on its own canopy structure, which captures valuable cloud water. Compared to moist cloud forests, the threat to these water-limited cloud forests is increased: not only changes in cloud immersion but also canopy degradation may lead to extinction. By enhancing its own water supply through horizontal precipitation, the forest is involved in creating its own ecological niche. According to our results, the ecological niche, or refugium, in which the cloud forests in Oman thrive today may disappear when the forests degrade to grassland. These results suggest an increased threat from tree removal to this fragile ecosystem, and may apply to semiarid cloud forests elsewhere in the world.

## 2. Field Site and Experimental Setup

[3] Our study site is located in a coastal mountain range, covered with drought deciduous broadleaf Anogeissus forest [*Kurschner et al.*, 2004; *Miller and Morris*, 1988] typical for the Cloud Oasis of the Dhofar Governorate in the Sultanate of Oman (Figure 1a). The site is at 500 m above sea level and about 20 km away from the coast. Precipitation and temperature at the coast are 114 mm and 26°C (20 m elevation), while they are 252 mm and 21°C near the mountain crest (880 m elevation). The wet season (locally called khareef) is in summer, mid-June through mid- September (3 months). During this period moist air from the Indian ocean is pushed against the coastal mountain range, leading to orographic clouds and drizzle (Figure 1b). During the rest of the year desert climate prevails. Besides khareef rain, precipitation is rare and erratic, mainly from cyclones occurring about once in three years [*Brook and Shen*, 2000; *Miller and Morris*, 1988]. The measurement campaign started in August 2003 and is ongoing. Meteorological data and rainfall were measured 2.5 m above the canopy. From meteorological data, potential evaporation was calculated using the Penman-Monteith equation assuming zero stomatal resistance. Cloudiness was calculated from incoming shortwave radiation [*Henderson-Sellers et al.*, 1987]. Additionally, below the canopy throughfall, sap flow [*Granier*, 1985] and soil moisture were measured. Throughfall was measured with 4 gauges at random locations in 2003 and with 1 gauge in 2004. Comparison of the results of the throughfall measurement using 4 tipping buckets with data collected from a 1.8 m × 2.4 m large plastic sheet showed that spatial variability was captured well. They correlated with $r^2 = 0.81$ at 1h intervals over 6 days (n = 144). During the same time the throughfall measured with the single tipping bucket available in 2004 correlated well with the throughfall deduced from the entire array ($r^2 = 0.88$, n = 144). Soil moisture was measured using a capacitance probe. Since

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[1] Department for Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

[2] Now at UFZ Centre for Environmental Research, Leipzig, Germany.

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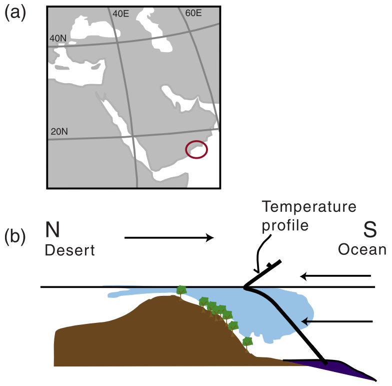

**Figure 1.** Geography of the Dhofar Cloud Oasis. (a) Location (circle), (b) North South cross section (about 20 km, not to scale) through the coastal plain and mountains together with the typical metrological situation during the khareef in summer.

calibration of the capacitance measurement was not feasible at the site, soil moisture is expressed as a relative value, derived by normalizing the readings over the observed range during the entire campaign, yielding values between 0 and 1.

## 3. Experimental Results and Discussion

[4] Figures 2a–2e give an overview of the observed climate in 2004. Net precipitation (total amount of water arriving below the canopy at ground level) during the representative wet season of 2004 was estimated to be about 300 mm. Net precipitation (consisting at this site of approximately 70% throughfall and 30% stemflow) exceeded the rainfall that was measured above the canopy. Throughfall alone was about double the rainfall, during times when both were measured simultaneously (summer 2003). Overall, net precipitation was estimated to be three times as high as rainfall, suggesting that water gain from cloud droplet interception (horizontal precipitation) is a substantial water source for the cloud oasis in this environment.

[5] In spite of the contribution of horizontal precipitation, net precipitation was surprisingly small. The observed amount is rather characteristic of a sparsely vegetated semi-desert not a forest biome [*Holdridge*, 1947]. How does a relatively moist biome like deciduous broadleaf forest survive in such a dry environment?

[6] Indeed, although precipitation occurs almost continuously during the khareef season, the amounts are small, such that the infiltration front progresses slowly and only reaches a depth of 60 cm after three weeks from the beginning of the khareef season (Figure 2d). However, the cloud cover allows for effective re-distribution of the available water from the wet to the dry season, which roughly doubles the length of the growing season. In 2004 the growing season started simultaneously with the khareef in June. During the khareef the atmospheric water demand was low, which suppresses transpiration as confirmed by sap flow measurements (Figure 2e). By the end of the khareef, three months into the growing season, almost all water received was stored in the soil and was still available for use. Soil moisture measurements confirm that the storage is filled beyond 60 cm depth, and remains at high saturation throughout the wet season (Figure 2d). The soil saturation only drops after the end of the khareef, when clouds disappear and sap flow (transpiration) increases as a result of high evaporative demand (Figure 2b). In total the growing season lasts six months (June to December). Considering the small precipitation received, the six month long growing season can only be explained by the low evaporative demand during the wet season, caused by the persistent cloud cover.

[7] It is worthwhile noting the influence of a cyclone, which occurred on September 30 2004, and brought 64 mm of throughfall in one night. Those events are erratic and occur about once in 3 years, in spring or fall. Following the event, in the shallow layers soil moisture reached maximum values, comparable to the khareef time. However, in the deeper soil layers the influence of the cyclone was small, compared to the relatively large amount of precipitation: at 60 cm depth the saturation only increased to values from two weeks earlier, less than during the khareef. Therefore, although cyclones bring a lot of precipitation when they occur, they seem to contribute little to maintaining the woodland vegetation in this region.

## 4. Modeling Study

[8] Simulations with the dynamic vegetation model IBIS [*Foley et al.*, 1996; *Kucharik et al.*, 2000] also suggest that the decrease of available energy for evapotranspiration during the cloudy season plays a vital role in extending the length of the growing season and opens a niche for a forest biome. This model captures the processes essential for simulating the local water and energy balance, and models the competition between grass and tree Plant Functional Types. The model was forced with measured climate

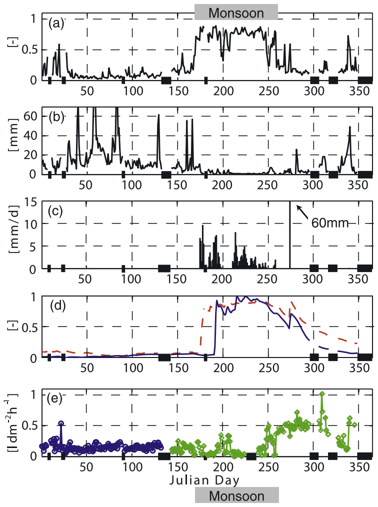

**Figure 2.** Climate as observed at the field site (a) cloudiness; (b) potential evaporation; (c) net precipitation; (d) referenced soil saturation, measured at 10 cm (red) and 60 cm (blue) depth; and (e) sap velocity, sensor 1 (blue) (operational August 2003 to May 2004, sensor 2 (green) (operational since June 2004). The black bar on the time-axis signifies times of missing data, and the grey box case marks the khareef season.

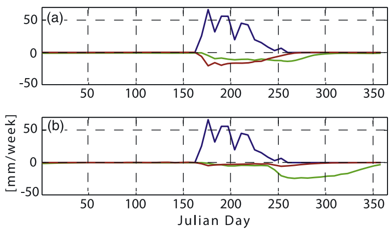

**Figure 3.** Modeled water budget at vegetation equilibrium, weekly averages: net precipitation forcing (blue), transpiration (green), soil evaporation red), interception loss and surface runoff (both not shown) were zero in both simulation. (a) Simulations with climate as observed at the field site (100% cloud cover during the khareef); and (b) same as Figure 3a but 0% cloud cover during the khareef.

data for 2004, which were repeated for 500 years. Data gaps in the measurement record were filled with the data of the immediately preceding period. Enhanced infiltration around the stems was accounted for by multiplying the estimated area-average precipitation with 1.33 (which corresponds at this site to infiltration of stemflow within 0.5 m around the stem [e.g., *Pressland*, 1976]). The cyclone was omitted, in order to model a representative year. Vegetation evolved according to resource distribution among different competing vegetation types, and had reached equilibrium at the end of each 500 year modeling period.

[9] Figure 3a shows the modeled seasonal water budget for an IBIS simulation forced with measured meteorological data and assuming 100% cloud cover during the khareef. Modeled transpiration (Figure 3a) and measured sap flow (Figure 2e) show the same pattern and timing, and the dominant vegetation type is deciduous broadleaf forest, as is the Anogeissus forest at the field site. The growing season lasts six months. On the other hand, the seasonal water balance and vegetation state are dramatically changed, when the experiment is repeated with the same meteorological input (including high relative humidity, low temperature during the khareef), but with clear sky all year round (Figure 3b). The clear sky condition causes an increase in available energy for evapotranspiration during the wet season. The result is a khareef with higher evaporative demand, enough to transpire and evaporate most water away from the soil storage before the end of the khareef. As a result, at the end of the wet season little water is left in soil storage for transpiration, and the growing season ends soon after. Therefore, the growing season, the period of carbon assimilation, is three months shorter, and allows for less biomass production. The modeled vegetation type is therefore grassland. These model results show that given the same annual net precipitation, the radiative shield of the cloud cover allows for higher biomass production, and therefore a biome with taller and denser vegetation. They also show that the forests in Dhofar thrive thanks to the cloud cover in a climate that is at most marginally suited for them. Clouds are therefore a necessary factor creating the ecological niche for the Dhofar cloud oasis. Are they the only necessary factor?

[10] As shown by our field measurements, another important process maintaining the vegetation in this dry environment is horizontal precipitation. Horizontal precipitation is a process, where cloud droplets are mixed into the canopy from aloft due to turbulence [*Shuttleworth*, 1977]. Tall vegetation induces more turbulence than low vegetation, and consequently tall trees receive more horizontal precipitation than shrubs and grass. The vegetation in Dhofar may therefore rely on a positive feedback process for its own water gain, since vegetation height depends on the biomass production of the ecosystem, which is itself a function of available water. The forest vegetation in Dhofar is assumed to have been established as far back as during the Oligocene, which was also a wetter period [*Kurschner et al.*, 2004]. When the climate turned drier, the described feedback might have worked to benefit and maintain tall vegetation. On the other hand, when trees die as a result of camel feeding on young leaves, the same feedback might trigger further degradation.

[11] To investigate the influence of this feedback on vegetation, we added to IBIS a horizontal precipitation module [*Slinn*, 1982; *Zhang et al.*, 2001]. Using cloud properties (droplet radius and cloud liquid water content) as well as the parameters of turbulent flow that IBIS derives from the current state of the vegetation, the model solves at each time step for water gain from horizontal precipitation. In order to reflect in-homogeneities and edges of tree clusters Slinn's deposition velocity was enhanced by a factor $c = 2\star h_c/R_c + 1$, where $h_c$ is the tree height and $R_c$ the cluster size (assumed to 30 m). Time series of cloud liquid water content (LWC) and droplet radius were estimated by inverting Slinn's model, using measured net precipitation and wind speed as input and using a relationship developed for remote sensing applications [*McFarquhar and Heymsfield*, 2001]. Additionally, we assumed three pairs of time constant LWC and droplet radius such that the cumulative of the modeled horizontal precipitation for 2004 plus rainfall was equal to the cumulative measured net precipitation in 2004. We used the derived cloud properties, and repeated two model simulations, one where initial vegetation was broadleaf forest, as observed in Dhofar, the other where the initial vegetation was grassland (representing here a degraded landscape).

[12] Figure 4 shows the development of the modeled leaf area index (LAI) over two simulations with the same forcing, but different initial conditions, one for forest (Figure 4a), the other for grassland (Figure 4b). When the model was initialized with forest, the dominant vegetation at

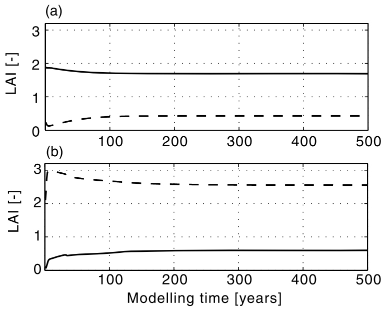

**Figure 4.** Modeled vegetation for different initial conditions. (a) Leaf area index (LAI) of trees (solid) and grassland (dashed) over the course of a simulation initialised with forest, (b) LAI of trees (solid) and grassland (dashed) over the course of a simulation initialised with grassland.

equilibrium was forest. At the same time, the vegetation remained grassland when the initial vegetation was grassland. We found the same result for most of the assumed cloud properties (5 out of 6 experiments). The modeled horizontal precipitation for grassland (85–140 mm) was only about half the amount simulated for forest (165–246 mm), where the range is explained by use of different cloud properties as input. As assumed, forest receives more water than grassland, and can therefore survive, whereas grassland receives less water and remains a sparse ecosystem. For the forest equilibrium the modeled vegetation height compared well with typical values for Dhofar: Tree height was between 7.5–9.5 m somewhat taller than observed at the field site (6.5 m), but within the range observed elsewhere in Dhofar (up to 12 m) [*Miller and Morris*, 1988]. In a control experiment, where net precipitation was assumed independent of vegetation height (as is the case in most ecosystems), the assumed initial vegetation had no influence on the vegetation at equilibrium, as expected.

[13] The field site and most of the forests in Dhofar are located on slopes. However, our model assumes a simple logarithmic wind profile, which is based among others on the assumption of flat terrain. In complex terrain the wind field may assume substantially different forms, with associated changes in cloud droplet deposition. Nevertheless, our investigation shows that change of vegetation height can modify horizontal precipitation significantly in Dhofar and to such an extent that the increased water limitation following tree removal may inhibit re-emergence of forest.

## 5. Conclusion

[14] If they hold, our model results suggest that in this region, with high contribution of horizontal precipitation and under strongly water limiting conditions, the current vegetation determines the destiny of the tree biome. Vegetation state and horizontal precipitation seem in a dynamic equilibrium that can have multiple stable states, determined by the initial condition and the cloud properties. As a consequence this ecosystem might be particularly fragile; when trees are removed, the system could be pushed into a drier and equally stable equilibrium. These results support the previously raised concern that degraded lands might not recover in Dhofar [*Kurschner et al.*, 2004; *Miller*, 1994]. The ongoing overexploitation of this ecosystem, which is one the most unique and diverse within the Arabian Peninsula [*Fisher et al.*, 1998] is alarming and calls for immediate steps for conservation.

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E. A. B. Eltahir, Department for Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.

A. Hildebrandt, UFZ Centre for Environmental Research, Leipzig-Halle, Permoserstrasse 15, D-04318 Leipzig, Germany. (hildebra@alum.mit.edu)