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Relating the X-band opacity of a tropical tree canopy to sapflow, rain interception and dew formation

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ABSTRACT

During summer and autumn 2007, a 11 GHz microwave radiometer was deployed in an experimental tree plantation in Sardinilla, Panama. The opacity of the tree canopy was derived from incoming brightness temperatures received on the ground. A collocated eddy-covariance flux tower measured water vapor fluxes and meteorological variables above the canopy. In addition, xylem sapflow of trees was measured within the flux tower footprint. We observed considerable diurnal differences between measured canopy opacities and modeled theoretical opacities that were closely linked to xylem sapflow. It is speculated that dielectric changes in the leaves induced by the sapflow are causing the observed diurnal changes. In addition, canopy intercepted rain and dew formation also modulated the diurnal opacity cycle. With an enhanced canopy opacity model accounting for water deposited on the leaves, we quantified the influence of canopy stored water (i.e. intercepted water and dew) on the opacity. A time series of dew formation and rain interception was directly monitored during a period of two weeks. We found that during light rainfall up to 60% of the rain amount is intercepted by the canopy whereas during periods of intense rainfall only 4% were intercepted. On average, 0.17 mm of dew was formed during the night. Dew evaporation contributed 5% to the total water vapor flux measured above the canopy.

1. Introduction

1.1. Rain interception and dew formation

Tropical rain forests play a dominant role in the earth's water balance. An important fraction of the hydrological cycle amounts to rain water interception and its subsequent re-evaporation. According to Lawrence et al. (2007), transpiration is the dominant process of evapotranspiration with a contribution of 58%, followed by interception evaporation (33%) and soil evaporation (9%).

Rain interception is rather difficult to measure accurately. The most frequently used technique is the measurement of throughfall by setting up several rain-gages below the canopy and one or more above the canopy. The difference of the collected water is assumed to be withheld by the canopy. There are some major drawbacks to this method: Due to the complex structure of a forest canopy, the spatial variability of the throughfall is very large, hence numerous rain gages are needed in order to achieve representative and accurate sampling (Kimmins, 1973). Direct evaporation of intercepted rain water is another effect that cannot be tackled with the throughfall method, wherefore reliable measurements can only be conducted during night time.

A promising technique is the attenuation measurement of a 10 GHz signal over a horizontal path through a Douglas fir stand as reported in Bouten et al. (1991). They observed a distinct linear relation of the attenuated signal to intercepted rain. The authors then employed this attenuation method in several upcoming studies as a monitoring tool for water interception in forest canopies (Bouten et al., 1996; Vrugt et al., 2003). Czikowsky and Fitzjarrald (2009) reported on a new interception estimation technique that estimates the excess evaporation following rain events with eddy covariance flux measurements.

Recently, a global assessment of canopy interception from satellite data was published in Miralles et al. (2010). The authors used an analytical interception model (Valente et al., 1997) and fed it with satellite data of precipitation, lightning frequency and canopy fraction. It was found that the interception loss is sensitive to the rainfall volume, rain intensity and the forest cover. Some of these findings will be confirmed in the article at hand.

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Compared to intercepted rain, very little is known about the importance of dew formation and dew evaporation, most likely because no established measurement technique is available so far to measure the dew amount in a forest canopy. It is although known that dew not only promotes diseases of plant crops and is therefore an important parameter in agriculture (for tropical conditions see e.g. Holliday, 1980), according to Kabela et al. (2009), dew “also may contaminate remotely sensed measurements of important ecosystem variables such as soil moisture, land surface temperature, and vegetation biomass”. Dew duration is relatively easy to measure by using electrical devices that change their resistance or capacity when becoming wet (Kidron et al., 1965; Noffsinger, 1965). However, methods for measuring dew amounts (e.g. weighing dew gages, weighing lysimeters) are limited and solely used for measurements close to the ground (Agam & Berliner, 2006).

1.2. Microwave properties of forest canopies

Microwave properties of tree canopies have been investigated for many years and good overviews over this research topic are given in Chukhlantsev (2006) and Pampaloni (2004). In contrast to the wealth of available information on radiometric forest properties like the emissivity of forests (e.g., Della Vecchia et al., 2007; Ferrazoli & Guerriero, 1996; Santi et al., 2009), canopy scattering (e.g., Karam et al., 1995) and canopy attenuation (e.g., Kurum et al., 2009), reports on measurements of diurnal variations in tree opacities as well as observations of tree opacities focusing on intercepted water are sparse. McDonald et al. (2002) reported on diurnal variations in the dielectric constant of the xylem and hypothesized a relation to the ascent of sap in the xylem. Satake and Hanado (2004) studied diurnal changes of the radar backscatter of tropical trees with the Ku-Band Radar of the TRMM satellite and concluded that the signal has a relation to dew formation. A large experiment on diurnal changes in the optical and microwave frequency range was reported in Way et al. (2004), although no evident conclusions on diurnal variations could be derived from their measurements at X-band frequencies.

With the launch of the SMOS satellite in November 2009, L-band attenuation through tree canopies is recently attracting interest and therefore several studies are being performed with L-band radiometers. A recent study by Guglielmetti et al. (2007) measured the L-band and X-band transmissivities of a deciduous forest site during a 4 month defoliation period. The main focus of this work was not on diurnal changes but they found out that leaves contribute more to the transmissivity at X-band than at L-band frequencies, leading to a stronger response to the defoliation of the canopy. In addition, it was shown that the transmissivity at both frequencies is related to the rain intensity. A similar experiment was conducted by Mätzler (1994b), who observed an individual beech tree during two years with several microwave radiometers that covered a frequency range from 1 to 100 GHz. A pronounced seasonal cycle caused by the foliation and defoliation of the tree was registered during this experiment.

In our study, the downwelling brightness temperature of a tropical tree canopy was measured with a ground deployed 11.4 GHz microwave radiometer that was looking up through the canopy. The objectives of these measurements were to test if the opacity of the tree canopy underlies a diurnal cycle and to relate the microwave signal to the amount of water deposited on the leaves. In Section 2, the microwave radiometer and the other instruments are described. Section 3 treats the different radiative transfer models that allow 1. to calculate the canopy opacity, 2. to model the effect of the temperature on the opacity and 3. to account for the radiative effect of wet leaves in the canopy. Furthermore, we also relate the sapflow in the tree to opacity of the tree. These findings were then applied to opacity time series in Section 4 and they allowed us to quantify the water amount of intercepted rain and dew formation in the canopy. Finally, in Section 5 we summarize and conclude on our findings.

2. Instruments and study site

2.1. Microwave radiometer

For this experiment, a single polarization microwave radiometer operating at a frequency of 11.4 GHz has been developed. The frequency selection was based on the availability of high-quality but still inexpensive receivers. From the point of view of the application there is nothing against this selection. For our purpose and in order to be deployed in a tropical environment, the instrument had to fulfill certain requirements. First of all, an instrument with automated internal calibration was needed, since tipping-calibration (Han & Westwater, 2000) is not possible below the canopy and manual calibration with hot/cold black-body loads not desirable. To achieve this, the instrument was equipped with a waveguide switch, switching every 5 s to an ambient load (internal termination load enclosed in a copper block). Every minute, additional 80 K noise from a solid state noise source was coupled in over a 20 dB cross coupler. Second, the instrument needed protection against tropical heat, high relative humidity, rain and insects. This was achieved by installing the radiometer together with the horn antenna in a sealed solid aluminum box. The radiation entered the box through a microwave transparent Styrofoam window. The Schottky diode detectors and the noise source, being the most temperature critical components, were enclosed in a solid aluminum block and attached to a Peltier element, capable of heating and cooling. The temperature of this block was stabilized to 26 °C such that the Peltier element had to cool during the day and to heat during the night, when we had high relative humidity. Finally, our system had built-in data acquisition and storage and was capable of unattended operation over several days. Data were taken every 100 ms and averaged over one full calibration cycle of 1 min.

The radiometer has two channels, both measuring at the same center frequency but one with 50 MHz and the other with 500 MHz bandwidth. The 50 MHz channel was built in the radiometer in order to mitigate possible radio frequency interferences (RFI) that are more likely for a wider bandwidth. Since the antenna could be adjusted to a position where no RFI was detected, the wider bandwidth was employed for all the measurements, resulting in an improved signal-to-noise ratio. The antenna we used is a rectangular horn with a beam width of about 15°. In addition to the microwave part, a thermal infrared radiometer (Everest 4000.5 GL) was installed in the box. More technical details on the radiometer system are found in Schneebeli et al. (2008).

The microwave radiometer was placed on the ground, looking upwards through the canopy under an elevation angle of 40°, measuring in horizontal polarization. A tarp, set-up above the instrument without interfering with the radiometer's line-of-sight, protected the antenna from becoming wet and therefore enabled us to conduct measurements during rain as well. Data were gathered from July to October 2007. Fig. 1 shows the instrument operating at the field site in Sardinilla.

2.2. Sapflow measurements

Continuous measurements of xylem sapflow were performed within the flux tower footprint using the thermal dissipation method by Granier (1985). The sapflow sensors consisted of two cylindrical probes that were embedded into the tree stem (0–20 mm below cambium) with a vertical distance of 10–15 cm between both probes. Two sensors were installed on each of the 5 trees measured, at 130 cm height (DBH) on the southern and northern side of the trees. A Styrofoam box combined with reflective foil and a plastic cover reduced thermal influences and provided rain shelter. Voltage output of the thermocouple were measured every 30 s and 15 min averages were stored on CR800 and CR1000 data loggers, and AM16/32 and AM416 multiplexer (Campbell Scientific, Logan, USA). Sap flux