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Rainfall interception modelling: Is the wet bulb approach adequate to estimate mean evaporation rate from wet/saturated canopies in all forest types?

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SUMMARY

The Penman–Monteith equation has been widely used to estimate the maximum evaporation rate (E) from wet/saturated forest canopies, regardless of canopy cover fraction. Forests are then represented as a big leaf and interception loss considered essentially as a one-dimensional process. With increasing forest sparseness the assumptions behind this big leaf approach become questionable. In sparse forests it might be better to model E and interception loss at the tree level assuming that the individual tree crowns behave as wet bulbs ("wet bulb approach"). In this study, and for five different forest types and climate conditions, interception loss measurements were compared to modelled values (Gash's interception model) based on estimates of E by the Penman–Monteith and the wet bulb approaches. Results show that the wet bulb approach is a good, and less data demanding, alternative to estimate E when the forest canopy is fully ventilated (very sparse forests with a narrow canopy depth). When the canopy is not fully ventilated, the wet bulb approach requires a reduction of leaf area index to the upper, more ventilated parts of the canopy, needing data on the vertical leaf area distribution, which is seldom-available. In such cases, the Penman–Monteith approach seems preferable. Our data also show that canopy cover does not *per se* allow us to identify if a forest canopy is fully ventilated or not. New methodologies of sensitivity analyses applied to Gash's model showed that a correct estimate of E is critical for the proper modelling of interception loss.

1. Introduction

A proportion of the rain falling on to a forest canopy is intercepted and evaporates back to the atmosphere (David et al., 2005). Several models of the process have been developed (see the review by Muzylo et al., 2009) and these have contributed to a good understanding of the underlying mechanisms of interception loss. Interception models are also important as a component of hydrological catchment models or continental-scale water balance models (e.g. Wallace et al., 2013), to assess global evaporation (e.g., Miralles et al., 2010; Zhang et al., 2016), and in the land surface schemes of Global Circulation Models (see Carlyle-Moses and Gash, 2011).

The most widely used interception models are those developed by Rutter (Rutter et al., 1972; Rutter et al., 1975) and Gash (Gash, 1979). The former was the first with a physically-based background where interception loss was explicitly driven by the rate of evaporation from the wet canopy. To calculate the dynamic water balance of the forest canopy and trunks, during each rainfall event, the Rutter model requires a continuous evaluation of the maximum evaporation rate under wet conditions. Based on the Rutter model, Gash (1979) proposed a simpler, storm-based analytical model to estimate interception loss, which needs only the average rainfall and evaporation rates ($\bar{R}$, $\bar{E}$) under fully saturated canopy conditions for the entire period of simulation.

In their original formulations, these models assume that forest canopy uniformly covers the entire ground area. Based on this assumption, they were successfully applied to closed canopy forests, but their application to sparse forests proved to be problematic, with interception loss being overestimated (Gash et al.,

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1995). To overcome this limitation, both the Rutter and Gash models have been reformulated to adapt to sparse forests (Gash et al., 1995; Valente et al., 1997) by treating the open and the covered areas separately. In these revised model versions, the rate of evaporation is partitioned between the open area, where it is considered zero, and the covered area where it is modelled as a closed forest under the same environmental conditions.

Usually, the Penman–Monteith equation is adopted to estimate the maximum evaporation rate from the wet/saturated canopy (Carlyle-Moses and Gash, 2011), setting canopy resistance to zero. With the Penman–Monteith model the tree canopy is considered as a big leaf, and evaporation is treated as a one-dimensional vertical process, with the aerodynamic conductance estimated assuming a vertical logarithmic wind profile between the canopy level and some reference height above it (van Dijk et al., 2015). However, this assumption does not take into account the possible effect of forest sparseness on the enhancement of turbulence and evaporation rate – becoming increasingly questionable as the forest becomes more and more sparse.

Pereira et al. (2009b) suggested that, for very sparse stands, an approach based on the rate of evaporation from the individual, isolated wet (non-overlapping) tree-crowns would be more appropriate. These authors showed that the saturated crowns of isolated trees behave like wet bulbs, allowing the estimation of their evaporation rate through a simple diffusion equation. Knowing the tree density, the whole-stand evaporation could then be derived in this case as the sum of the contribution of the individual trees.

Like the Penman–Monteith model, this "wet bulb approach" is also physically based but, compared to the former, requires less data to estimate the maximum evaporation rate from saturated tree canopies.

By combining this approach with the Gash analytical model, Pereira et al. (2009a) estimated the interception loss from two savanna-type Mediterranean oak woodlands with a good accuracy (normalised mean error less than ±10%).

Being simpler and less data demanding than the Penman–Monteith equation, the wet bulb approach seems an attractive option. However, the need to check whether the assumption that tree crowns behave as fully ventilated wet bulbs remains. We need to answer the question: is the wet bulb approach applicable or adaptable to more-closed forests? For instance, Roberts et al. (1990, 1993) showed that the canopy of a closed Amazonian rainforest was much better ventilated in the upper crown strata (roughly the upper half of the canopy), where wind speed was higher and air temperature relatively uniform compared to the lower canopy layers. Furthermore, the results reported by Gash et al. (1999) show that better estimates of evaporation rate from a fully wet, sparse pine forest based on use of the Penman–Monteith model were obtained when the aerodynamic conductance for vapour flux was set equal to the measured conductance to momentum flux. This may be taken as an additional indication that in saturated canopies the lower boundary of the main source of water vapour flux is located at the same height where momentum is (apparently) absorbed.

Many forest structural characteristics may affect its aerodynamic behaviour, such as the canopy cover fraction, tree density, tree height, canopy depth and forest composition (type and number of species). Our aim is to determine how these structural features may interact, trying to distinguish in which types of forests interception loss can be best modelled using a one (Penman–Monteith) or a three-dimensional (wet bulb) approach.

The present study reanalyses data from several forest types and climate conditions where the measurement and modelling of interception loss has already been done previously: a eucalyptus plantation in central Portugal, two maritime pine stands (one in Portugal and another in Les Landes, France), an agroforestry system in Kenya and an Amazonian terra firme rainforest (see Table 1 for references).

The objectives of the work were: (1) to use the micrometeorological datasets obtained in the course of previous research to derive new estimates of the maximum evaporation rate from fully wet canopies using the wet bulb approach (E_{WB}); (2) to compare interception loss measurements with modelling results using these E_{WB} estimates, attempting to check the adequacy of the wet bulb approach in forests of different sparseness; (3) to quantify the impact of the method used to estimate E (Penman–Monteith or wet bulb) on the performance of Gash's interception model.

2. Methods

2.1. Sites

Two main criteria were used to select the forest sites: (1) they should cover a wide range of forest structure; and (2) availability of the necessary datasets. Four distinct forest types at five different locations were selected: two maritime pine stands with canopy covers of 45% and 64%; a *Eucalyptus globulus* Labill. plantation with a canopy cover of 60%; an Amazonian tropical rainforest with a canopy cover of 92%; and an African agroforestry plantation consisting of a tree stratum of *Grevillea robusta* with a tree crown cover varying from 2% to 54%. Details of forest stands are given in Table 1. Besides differences in canopy cover, these forests also contrast in climate type and rainfall regime (maritime, Mediterranean, tropical wet and semi-arid/sub-humid). Total annual rainfall and potential evapotranspiration varies between sites from 600 to 2400 mm and 741 to 1396 mm, respectively, while the ratio between them varies from 0.5 (in the Portuguese and Kenya sites) to 1.8 (in the Amazonian rainforest) (Table 1).

All the listed structural parameters (namely canopy cover, leaf area index, number of species, plant density, tree height and age) are liable to influence the rainfall interception process (Llorens and Domingo, 2007), either directly or indirectly.

As with most rainfall interception modelling studies, the contribution of undergrowth or of lower vegetation strata to interception loss was not considered in the original studies. Likewise, it is not considered in this study.

2.2. Mean evaporation rate

In all sites used in this study, the version of Gash's model has previously been applied to predict interception loss, using the Penman–Monteith equation to estimate the average maximum evaporation rate ($\bar{E}_{PM}$) from the wet canopies assuming a one-dimensional representation of the forests (see Table 2). The good modelling results obtained in all cases (good fit between measured and modelled interception loss) suggest that those evaporation rates were adequately estimated.

As an alternative and for comparison purposes, the wet bulb approach suggested by Pereira et al. (2009b) is now used to estimate the average maximum evaporation rate ($\bar{E}_{WB}$). According to Pereira et al. (2009b), evaporation (E, kg m^{-2} s^{-1}) from a fully wet, isolated tree crown can be estimated as:

$$\lambda E = \frac{\rho_a c_p}{\gamma} g_{bV}[e_s(T_s) - e_a] \quad (1)$$

and the surface temperature T_s (°C) of a saturated tree crown as:

$$T_s = \frac{1}{\rho_a c_p} \frac{\gamma}{\Delta + \gamma} \frac{A}{g_{bV}} + T_w \quad (2)$$

where λ (J kg^{-1}) is the latent heat of vaporisation, ρ_a (kg m^{-3}) is air density, c_p (J kg^{-1} °C^{-1}) is air specific heat at constant pressure,