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APPLICATION OF A LAND SURFACE MODEL THAT INCLUDES FOG DEPOSITION OVER A TREE HEATH-LAUREL FOREST IN GARAJONAY NATIONAL PARK (LA GOMERA, SPAIN)

Genki Katata[1], Carlos M. Regalado[2], Axel Ritter[2] and Haruyasu Nagai[1]

1: Japan Atomic Energy Agency
2-4 Shirakata-shirane, Tokai
Ibaraki 319-1195 Japan
e-mail: katata.genki@jaea.go.jp

2: Instituto Canario de Investigaciones Agrarias (ICIA)
Dep. Suelos y Riegos
Apdo. 60 La Laguna
38200 Tenerife
e-mail: cregalad@icia.es, aritter@icia.es, web: http://www.icia.es

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RESUMEN. *Se aplicó un modelo unidimensional multicapa atmósfera-suelo-vegetación (SOLVEG) que incluye deposición de agua atmosférica (niebla). El modelo permitió cuantificar la distribución del contenido de humedad en la zona no saturada y la cantidad de niebla interceptada que llega a la superficie del suelo de una cuenca de laurisilva en el Parque Nacional de Garajonay (La Gomera, España). El modelo permite dar cuenta tanto de la deposición de agua atmosférica sobre hojas lanceoladas, como la captación de niebla por hojas aciculadas en un bosque mixto de fayal-brezal. El modelo se evaluó comparando medidas de contenido de agua en el horizonte superficial del suelo y de transpiración con las predicciones del modelo SOLVEG obtenidas a partir de registros de variables micrometeorológicas y de captura artificial de niebla. El aporte anual de agua de niebla al suelo se estima en 110 mm, lo que equivale a un 18% de la precipitación. Es necesario, sin embargo, seguir investigando para reducir la incertidumbre de los parámetros del modelo y estimar así con mayor fiabilidad la contribución del agua de niebla al bosque de laurisilva.*

ABSTRACT. *A one-dimensional multilayer atmosphere-soil-vegetation model (SOLVEG) that includes cloud water (fog) deposition onto vegetation was used to quantify the distribution of water content in the vadose zone and the amount of intercepted fog reaching the ground in a 'laurisilva' watershed of the Garajonay National Park (La Gomera, Spain). The model allows both fog water deposition onto broad laurel-type leaves and fog collection by needle-like leaves in a mixed tree heath-laurel forest to be included. Measurements made of both the soil water content in the top soil layers and the transpiration rate were compared with SOLVEG predictions, which were made using micrometeorological and artificial fog water capture records. The annual fog deposition on the forest soil was estimated to be 110 mm, which corresponds to 18% of annual precipitation. Further studies are necessary to reduce the uncertainties in the simulation parameters, and in order to obtain better estimates of fog water deposition and its impact on water resources in the laurel forest.*

1. INTRODUCTION

The tree heath-laurel 'laurisilva' relict forests of the Canary Islands (Spain) are comprised of both broad and needle-like leaved endemic tree species that are influenced by fog (Pérez de Paz, 1990). However, the role of the fog, although long acknowledged to be important in the survival of the 'laurisilva' forests, has only recently been identified (Ritter et al., 2008; 2009a). The studies indicate that the fog may reduce the transpiration of the 'laurisilva' tree species because of the accompanying decrease in temperature and radiation attenuation that take place during cloud immersion (Ritter et al., 2009a). Furthermore, Ritter et al. (2008; 2009b) concluded that, although the turbulent deposition of fog droplets onto plant elements and subsequent gravitational precipitation to the ground may represent an additional soil water source, this may be only relevant in well-exposed windy areas. The conclusions, however, were obtained using a simple particle impaction model that included several assumptions made regarding the fog collection process, and thus require further validation. For example, based on standard theories of aerosol impaction dynamics (Friedlander, 2000), Ritter et al. (2008) assumed the amount of fog collected by broad leaf laurel-like 'laurisilva' species to be negligible. In addition, for the sake of simplicity wind speed and fog Liquid Water Content (LWC) were assumed to be constant with decreasing tree height within the canopy. Their model predictions were also not compared with data on soil water content or transpiration measurements obtained using, for example, sap flow sensors. In general direct comparison of measurements with previous fog models estimates, such as those of the multilayer model of Lovett (1984) for atmosphere-vegetation interaction, are rather scarce (Klemm et al., 2005). Hence further studies dealing with these issues are necessary. In general the hydrological processes (evapotranspiration, precipitation, soil water transport, etc) within a forest are fairly complex, and thus benefit from the application of process-based models that are capable of simultaneously handling all the interconnected hydrological variables. A detailed description of such hydrological processes is also necessary because of the low volumes of fog water typically collected by cloud forest species, with daily mean values ranging from 0.65-2.15 mm day^{-1} (Bruijnzeel et al., 2005) and a reported maximum of 5 mm day^{-1} (Bruijnzeel, 2001).

A detailed one-dimensional multi-layer model for atmosphere-vegetation-soil interactions named SOLVEG was developed by Yamazawa and Nagai (1997) and Nagai and Yamazawa (1999), which was then verified in various vegetative (such as crop, woodland, and closed cloud forest) and non-vegetative areas with both humid and arid environments (Nagai, 2002; 2003; 2005; Katata et al., 2007; 2008). The model is unique in that it can be used to solve equations on detailed water, energy, and CO_2 exchange processes that take place between the atmosphere and the surface of the land. Moreover, fog water deposition onto vegetation has recently been incorporated into the model (Katata et al., 2008). The objective of this work was to apply the SOLVEG model in estimating the amount of fog deposition on the laurel forests of Garajonay National Park (La Gomera, Canary Islands). The role of fog deposition as an additional source of water to the soil was also investigated in numerical experiments.

2. MATERIALS AND METHODS

2.1. Site description and observational variables

The study area was a small representative watershed (43.7 ha) within the Garajonay National Park located between 1090 and 1300 m a.s.l. The vegetation is comprised of wax myrtle-tree heath ('fayal-brezal') dominated by *Erica arborea* L. coniferous trees 7-12 m tall with abundant epiphytic moss and lichen. Broad-leaf tree species, such as *Laurus azorica* (Seub.) Franco and *Myrica faya* Ait., are also present in the area (Golubic, 2001). A botanical inventory of the plot rendered the following tree species density: 21% (*M. faya*), 37% (*E. arborea*), and 42% (*L. azorica*).

An instrument equipped scaffolding tower located 1270 m a.s.l. in an upper exposed plot within the watershed was used to monitor wind velocity (mean and max) and direction, global radiation, air temperature and humidity, and rainfall at 15 min. intervals (Figure 1). The SOLVEG model requires, as part of its input, both the downward short- and long-wave radiation. The latter was estimated using measured global radiation, air humidity and temperature data, after Brutsaert (1975) and Crawford and Duchon (1999), and a cloudiness factor computed from Allen et al. (1998). The precipitation data used as input in SOLVEG was corrected to account for wind induced loss and inclined rainfall falling on sloping terrain after Sharon (1980) and Førland et al. (1996), as described by Ritter et al. (2008). Additionally, an artificial fog catcher (QFC) comprised of a 0.5×0.5 m screen with a single layer of polypropylene Raschel-type mesh, with a 65% shade coefficient, connected to a rain gauge was used to measure the fog water that gathered on top of the scaffolding tower. The fog LWC was estimated using the QFC measured fog water, wind speed and direction data (refer to Demoz et al. (1996) and Ritter et al. (2008) for more details). The transpiration rate was derived from the tree sap flow rate (g s^{-1}) obtained using Granier's heat dissipation technique (Granier, 1985) in different tree individuals from March through to December 2003 (see Ritter et al., 2009a). The water content of the soil θ (m^{3}m^{-3}) was measured with Time

Domain Reflectometry (TDR) probes with two 0.16 m rods (Trime-EZ, Imko GmbH, Ettlingen, Germany) installed horizontally at depths of 0.15 and 0.30 m. The soil was volcanic ash-derived and could be classified (Soil Survey Staff, 1999) as Aluandic Andosol (Fulvudand). To account for the volcanic origin of the organic soil present in the watershed a specific TDR calibration was carried out, as described in Regalado et al. (2003; 2006), which yielded the following log dependence of θ on the soil permittivity, ε (r^2=0.947): $\theta=0.2518\ ln(\varepsilon) - 0.3165$, $\theta < 0.65 m^3m^{-3}$. Soil parameters were measured using standard methods (Dane and Topp, 2002): the apparent soil texture was loamy sand (8.1% clay, 22.8% silt, 69.1% sand), the soil water saturation =0.665 m^3m^{-3}, a field capacity (soil water content at 33 kPa) = 0.354 m^3m^{-3}, and a wilting point = 0.216 m^3m^{-3}. The Brooks-Corey parameters were air entry pressure value ψ=17.3 cm and λ=0.2924. The van Genuchten parameters were α=0.0265 cm^{-1}, n=1.499, and m=1-1/n. The saturated hydraulic conductivity, K_s, determined using a laboratory constant head parameter, ranged from 10^{-3} to 10^{-5} m s^{-1} in the study area. The 1.2 m depth soil profile, including root distribution, was further described by Thissen (2001). The LAI was taken to be 4.2 from Golubic (2001), and the assumption of a vertical leaf area density Gaussian-like distribution derived for laurel forest tree species made by Morales et al. (1996) used.

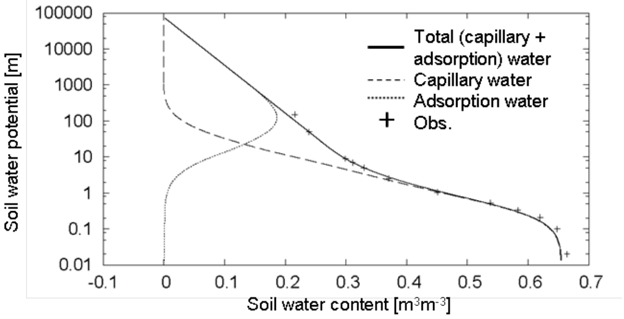
Figure 1. Micrometeorological instrumentation in the tree heath-laurel forest at the experimental site.

2.2. SOLVEG model and simulation conditions

The simulation using SOLVEG was carried out from 14:00 on February 7th 2003 to 23:45 on January 31th 2004. SOLVEG consists of one-dimensional multilayer sub-models for the atmosphere near the surface, soil, and vegetation interactions with a radiation transfer scheme for calculating the transmission of solar and long-wave radiation fluxes in the canopy layers. The atmosphere and vegetation components of SOLVEG were modified to deal with the fog deposition process onto vegetation more precisely (Katata et al., 2008). Details of the model have been described by Nagai (2004) and Katata (2009). The hourly input and output data used in SOLVEG are summarized in Table 1.

In order to determine the SOLVEG upper and lower boundary conditions hourly meteorological data was used, as described in Section 2.1. A soil water retention curve (Figure 2a) and root fraction distribution (Figure 2b) were determined using the parameters given in Section 2.1. Other simulation settings are summarized in Table 1.

(a) Water retention curve



(b) Root fraction

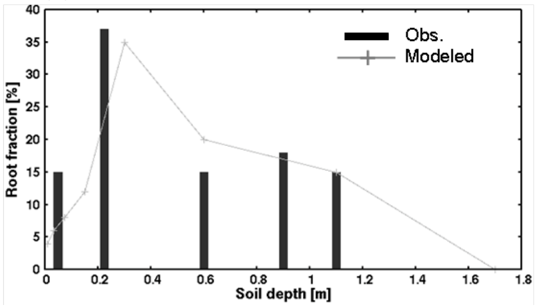


Figure 2 Modeled and observed (a) soil water retention curve (total water) and (b) root fraction distribution in the study area. Modeled water retention curve can be separated into capillary and adsorption water, as provided in (a).

Table 1. Simulation settings, input and output data used in the SOLVEG model.

Item	Description
Input meteorological data	Wind speed, air temperature and humidity, downward short- and long-wave radiations, precipitation, fog LWC, and CO_2 concentration (set to a constant value of 370 ppm. in the present study)
Output data	Surface heat fluxes, fog deposition, surface runoff, evaporation from the soil, wet canopy evaporation, transpiration, soil water content
Calculation period	Feb. 7 2003 - Jan. 31 2004
Vegetation species	Tree heath-laurel `fayal-brezal´
Leaf shape and diameter	Needle-like (cylindrical element), ∅=0.25±0.02 mm
Boundary of soil layers	0.02, 0.05, 0.1, 0.2, 0.4, 0.8, and 1.2 m soil depth
Canopy height and layers	From 1 to 12 m height in 1 m increments
Root fraction function	4, 6, 8, 12, 35, 20, 5, and 0% of total roots at each soil layer
Numerical solution time step	6 seconds
Soil bottom temperature	12 ºC
Initial soil water content	0.6 m^3 m^{-3} for all soil layers
Other parameters	Given by Katata et al. (2008)

3. RESULTS AND DISCUSSION

Due to the large uncertainty in saturated hydraulic conductivity (K_s), which would consequently affect the soil water content predictions for the plot, with coefficients of variation typically > 100%, three K_s cases: K_s = 4.0×10^{-4}, 4.0×10^{-5}, and 4.0×10^{-6} m s^{-1}, were considered in order to investigate how sensitive the model was to that parameter. The above values all fall within the range of previous published K_s values of volcanic soils (Regalado et al., 2005), but are typically larger than those expected from their apparent loamy sand texture (i.e. 10^{-5}–10^{-6} m s^{-1}; Carsel and Parrish, 1988).

3.1. Soil water content

The time series of the calculated and observed soil water contents at 0.15 m and 0.30 m depths are plotted in Figure 3. Predicted soil water content at 0.15 m and 0.30 were derived by averaging the simulated water content at 0.10 and 0.20 m, and at 0.20 and 0.40 m, respectively. The lowest soil water content was observed from day 120 to 240 (named the dry period), as a consequence of the absence of rainfall. The effect of rainfall on the investigated upper soil layer can be illustrated by causing sharp increases in the soil water content (rainy period). The model performance in reproducing the measured θ was fairly good in the case where the smallest K_s value (4.0×10^{-6} m s^{-1}) was used (Figure 3). However, when using $K_s > 4.0\times10^{-6}$ m s^{-1}, model predictions of soil water content did not succeed, yielding higher soil water content during the dry period. This would imply that the capillarity movement of water from deeper to topsoil layers is faster than the root water uptake. This indicated that the soil parameters, such as K_s, affect the dynamics of soil water content significantly. Thus, in order to evaluate the effect of fog deposition and transpiration on the surface water balance, the uncertainty in soil parameters should be reduced using e.g. inverse methods (Ritter et al., 2003).

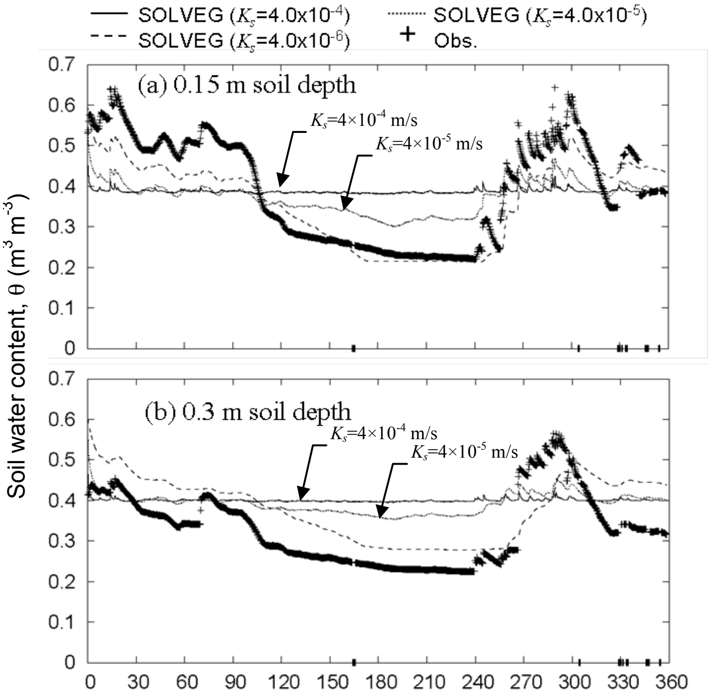


Figure 3. Temporal changes of soil water content measurements and SOLVEG calculations at soil depths of (a) 0.15 m and (b) 0.3 m.

3.2. Surface water balance

Despite the uncertainty in the above soil parameters the cumulative fog deposition onto vegetation (P_r), throughfall plus drip onto the soil surface of intercepted rain and fog water (canopy drip, C_{drip}), transpiration (E_{trans}), and wet canopy evaporation (E_{leaf}) (Figure 4) were estimated using $K_s = 4.0\times10^{-6}$ m s^{-1} that did reproduce the change in observed soil water content, as revealed in Figure 3. It should be noted that no surface runoff occurred during the simulation period. At the end of the simulation period (at day 364), the cumulative fog deposition on the laurel forest was estimated to be 110 mm, representing approximately 18.3 % of cumulative precipitation. This value is more than two times smaller than the potential amounts of 251-281 mm reported by Ritter et al. (2008) using a fog impaction model. One possible reason for that may well be that, in contrast with SOLVEG, their fog water collection calculations did not take into account the reduction with height in the reduced wind speed that occurs within the canopy. This is similar situation to results obtained in a numerical study carried out in a German forest, in which it was revealed that fog deposition calculated with a simple model, although rather more sophisticated than the one used by Ritter et al. (2008), significantly overestimated the measured fog deposition flux by 1.75 times, while the fog deposition estimates rendered by SOLVEG had a better agreement with the actual measurements (Katata et al., 2008).

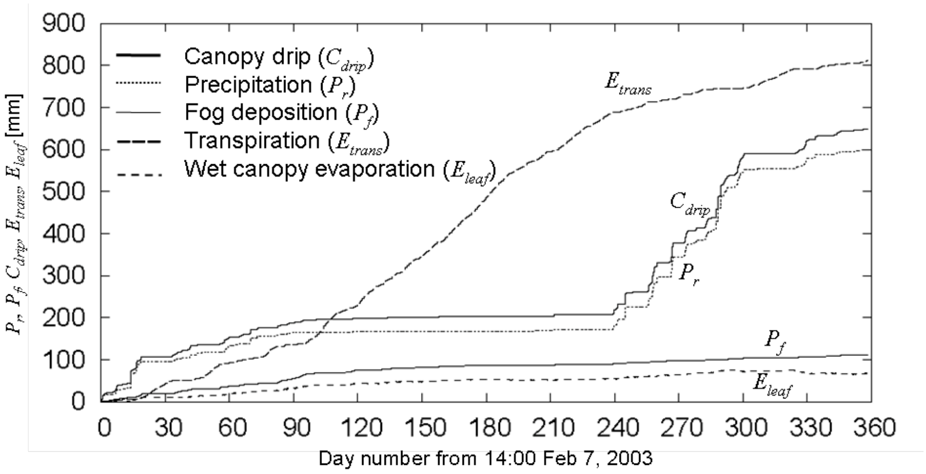


Figure 4. Temporal changes in SOLVEG estimates of cumulative canopy drip (C_{drip}), precipitation (P_r), fog deposition (P_f), transpiration (E_{trans}), and wet canopy evaporation (E_{leaf}) with $K_s = 4.0\times10^{-6}$ m s^{-1}.

While the total amount of simulated transpiration reached 800 mm, the soil water input supplied by canopy drip was only 650 mm. Transpiration, however, is sensitive to plant water stress, i.e., changes in soil water content. In fact, comparing the cases with $K_s = 4.0\times10^{-5}$ and 4.0×10^{-6} m s^{-1}, the cumulative E_{trans} value obtained at the end of the simulation using $K_s = 4.0\times10^{-5}$ m s^{-1} proved to be 100 mm more than when $K_s = 4.0\times10^{-6}$ m s^{-1} was used (not shown). These results point towards the need of further investigation about errors arising as a consequence of the uncertainty in the soil hydrological parameters used in the model. In addition, the difference between transpiration and canopy drip could well be explained by the enhancement of fog deposition caused by edge effects, which is often observed in montane forests standing in environments that include escarpments, steep slopes, and canopy gaps. It can yield additional disturbances from the site of the canopy in addition to turbulent deposition from above. Prior studies have suggested that high elevation forest edges receive in the order of 1.5-3 times more fog deposition than the interior of a forest (Weathers et al., 1995). The edge effect could not be taken into account here as SOLVEG is a one-dimensional model. The limitations of the one-dimensional vertical model used therefore, and its suitability for extrapolating the results obtained to the whole forest stand, should thus be kept in mind.

3.3. Transpiration rate

Figure 5 plots the temporal changes in measurements and SOLVEG calculations of a half-hourly transpiration rate. It should be noted that the observations represent the average values of transpiration expressed as sap flow (g s^{-1}) obtained from four coniferous trees of differing vegetative structure, such as canopy height and trunk diameter. Since SOLVEG calculates a representative transpiration value for the entire forest the measured transpiration rate should not be directly compared with the simulated values (E_{trans}). However, the trends over the simulated and observed time series can be explored. The general trend of the calculated transpiration rate was similar to that exhibited by the measurements. For instance, relatively low transpiration rates could be seen in both the calculations and the observations during the dry season (Figure 5). In addition to that kind of seasonal change, hourly or daily changes in transpiration due to weather conditions were also reproducible using the calculations. This therefore indicates that, after further verification of the simulation model using data scaled up from individual trees to the forest stands, SOLVEG will be capable of being used in investigating the effect of fog deposition on the actual water demands in tree survival (i.e., transpiration) and water use efficiency of photosynthesis.

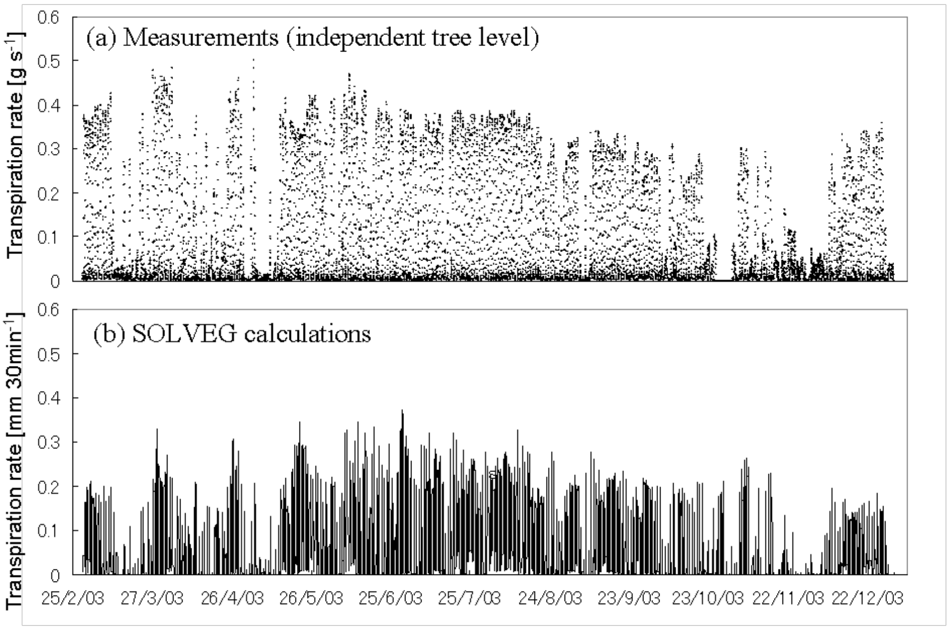


Figure 5. Time series of (a) measurements and (b) SOLVEG calculations in half-hourly transpiration rate (g s^{-1}) with $K_s = 4.0 \times 10^{-6}$ m s^{-1}.

4. CONCLUSIONS

This study addressed the impact of fog deposition on the laurel forests of the Canary Islands using a detailed land surface simulation model. Fog deposition on coniferous trees ('fayal-brezal') in a laurel forest was estimated using meteorological data and the liquid water content of the fog derived from fog water collected in an artificial fog catcher (QFC). The annual fog deposition over the laurel forest was estimated to be 110 mm, which corresponds to 18% of annual precipitation, more than two times smaller than the potential amounts reported in a previous study. After the optimized soil hydraulic conductivity was derived via a trial-and-error procedure, SOLVEG was able to reproduce the general trends of the observed soil water content and transpiration rate. Further studies to evaluate the affect of the forest edge on fog deposition and minimize uncertainties in the soil parameters used in the model will be necessary to ensure estimations of fog deposition over the forest and its impact as a water source in the laurel forest are as accurate as possible.

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