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Development of a simple forest evapotranspiration model using a process-oriented model as a reference to parameterize data from a wide range of environmental conditions

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ABSTRACT

It is essential to know the spatial distribution of water resources to maintain sustainable water use. We present a method for developing a simple model of forest evapotranspiration, an essential component of the water budget because it controls water loss from the land surface, that uses a process-oriented model as a reference to parameterize data from a wide range of environmental conditions instead of observed data. Our model considers two major forest evapotranspiration processes, dry-canopy evapotranspiration and wet-canopy evaporation. Dry-canopy evapotranspiration was calculated based on the Priestley–Taylor equation. Wet-canopy evaporation assumed a constant interception ratio. The accuracy of the model performance was determined in two steps. First, we compared the new model with a reference model using meteorological data other than those used in model parameterization. Then, we compared evapotranspiration data based on the annual water budget method for 25 forest sites with data based on the short-term water budget method for eight forest sites in Japan. The model successfully reproduced both the geographical and seasonal patterns of forest evapotranspiration over Japan. The model has a simple structure and requires few meteorological inputs compared with process-oriented models, and it is therefore considered suitable for regional-scale application. The model has the potential to be incorporated into other monthly forest ecosystem models.

1. Introduction

Water is one of most essential resources on the globe, and proper water resource management is required to match human needs with available water resources. Evapotranspiration, defined as the total water loss to the atmosphere from vegetated ecosystems, is an essential component in the water budget used to estimate the potential water yield from vegetated ecosystems. The distribution of land evapotranspiration plays a key role in large-scale water resource assessments in hydrological models (Graham et al., 2007; Olesen et al., 2007; Bergstrom et al., 2001; Hanasaki et al., 2008; Deckers et al., 2010).

Although forest area is decreasing globally due to deforestation, forests are still one of the world's major vegetated ecosystems (Lindquist et al., 2012). Evapotranspiration from both native forest and plantations is higher than that from other ecosystems such as pastures and crops (Holmes and Sinclair, 1986; Zhang et al., 2001; Vertessy, 2001). Thus, estimating the spatial distribution of forest evaporation is fundamental to determining the distribution of forest water resources and managing sustainable water use.

Simple models are effective tools for large-scale applications, but the reliability of simple models is limited by the data used for model parameterization (Hashimoto et al., 2011). Usually, simple models are strongly dependent on the dataset used for model parameterization because the parameters are measured directly from observed data without considering the detailed processes. However, simple models have the advantage of being easy to handle because they have a simple structure and require few meteorological inputs. Therefore, many simple models that estimate forest evapotranspiration have been proposed based on resource-limiting theory and the concept of potential evaporation and/or on the relationship between observed evapotranspiration and meteorological

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factors (Thornthwaite, 1948; Hamon, 1961; Zhang et al., 2001; Komatsu et al., 2008a,b, 2010, 2012; Sun et al., 2011).

The reliability of model estimation is improved when the model parameters are determined using data from a wide range of environments (Hashimoto et al., 2011). Forest evapotranspiration is forced by meteorological factors, such as solar radiation input, vapor pressure deficit, and temperature, as well as by forest properties such as stand age and leaf area. The relationships among meteorological factors vary within a region. When the model is applied at a regional scale, parameterization should be conducted using a wide range of data for more reliable model estimation.

Another key to building simple models that are suitable for large-scale application is to represent the principle processes of the subject matter being modeling. Forest evapotranspiration has two major components: dry-canopy evapotranspiration (transpiration from the forest canopy and forest floor evaporation) and wet-canopy evaporation (interception loss from the forest canopy). These processes occur under different meteorological conditions. The forest canopy is well coupled to atmospheric conditions during transpiration. However, wet-canopy evaporation is not limited by stomatal control (McNaughton and Jarvis, 1983; Komatsu, 2003; Monteith and Unsworth, 2008). The proportion of total evapotranspiration accounted for by these two processes may differ depending on the spatial and temporal variability in precipitation. Shuttleworth and Calder (1979) reported that model performance was improved when they estimated dry-canopy evapotranspiration and interception separately over three consecutive years with different precipitation conditions. A simple model consisting of the major forest evapotranspiration components would be applicable to a wide range of environmental conditions.

A process-oriented model could be a useful tool to confirm the performance of a simple model. A process-oriented model strictly evaluates the processes influencing forest evapotranspiration based on detailed climate and environmental data. Simple model parameters can be fixed to fit the outputs of a process-oriented model. Generally, a simple model tends to combine various effects within the model parameters. Hence, we should consider data from a wide range of environmental conditions to determine the simple model parameters using a process-oriented model. In addition, the quality of observed data varies depending on the environmental conditions at each individual observation site. In this study, we propose a model parameterization method using a process-oriented model to obtain data for the major components of forest evapotranspiration from a wide range of environmental conditions.

Various levels of structural complexity of process-oriented models have been proposed for the evaluation of energy, water, and mass cycles in forested areas (e.g. Running and Coughlan, 1988; Watanabe, 1994; Kondo et al., 1992a; Granier et al., 1999; Tanaka, 2002; Kumagai et al., 2006; Toda et al., 2010). The number of meteorological variables input to a model and the model parameters depend on the complexity of the model structure. High-complexity models require data for various meteorological components at short time intervals. Models with a medium degree of structural complexity can be operated using a meteorological dataset with a time resolution longer than a daily because they reduce the model processes and input data based on experimental and/or empirical relationships (e.g., Running and Coughlan, 1988; Kondo et al., 1992a; Granier et al., 1999). If meteorological data from a routine weather station network can be used as the input for a process-based model, the model can then be used to estimate forest evapotranspiration under a wide range of environmental conditions and to fix simple model parameters instead of using observed forest evapotranspiration data.

The aims of this study were to construct a simple forest evapotranspiration model for large-scale application using a process-oriented model to obtain multi-site forest evapotranspiration data instead of observed evapotranspiration data, and to evaluate the reliability of model estimations compared with process-oriented models (which are used to determine the model parameters) and observed forest evapotranspiration data. We applied this approach to Japan because of the wide range of climatic conditions, the substantial variation in elevation and topography, and the availability of a quality-controlled meteorological dataset.

2. Materials and methods

2.1. Concept and execution of the study

After construction of the simple model to estimate forest evapotranspiration, we determined the model parameters by comparing and fitting the computational result with a simulation produced by another process-oriented model, which had previously succeeded in reproducing actual evapotranspiration. We avoided direct comparison with actual evapotranspiration data at this stage because we required that our simple model correspond with the fundamental characteristics of the process-oriented model. We then examined the applicability of our simple model to a large-scale domain by comparing it again with the process-oriented model simulation and also with observed data.

The procedures followed in this study are shown in Fig. 1. We used a model proposed by Kondo et al. (1992a) as the reference model because its applicability has been validated in Japan. A Japan Meteorological Agency (JMA) data set from established weather stations was obtained for the model parameterization and validation. High-resolution gridded meteorological data and evapotranspiration data from forest experimental watersheds were collected across Japan for the model validation as the large-scale application. More detailed information regarding our model, the reference model, and the various data used in this study is provided in the following sections.

2.2. The simple model proposed in this study

2.2.1. Model structure

We developed a simple forest evapotranspiration model that was driven by monthly meteorological inputs. In this model, dry-canopy evapotranspiration and wet-canopy evaporation are described separately using following equation:

$$E = E_d + E_w \quad (1)$$

where E is evapotranspiration from a forested area, E_d is dry-canopy evapotranspiration, and E_w is wet-canopy evaporation. We used the same model structure as Shuttleworth and Calder (1979), which consisted of dry-canopy evapotranspiration determined by the Priestley–Taylor equation and wet-canopy evaporation determined using the interception loss ratio. In the Shuttleworth and Calder (1979) model, water intercepted by the forest canopy evaporated after rainfall ended. In our study, we did not take into account the effect of evaporation from a wet canopy after rainfall ended because it is difficult to detect the magnitude of the effect on the large-scale simulation of evapotranspiration using only monthly meteorological inputs.

2.2.2. Dry-canopy evapotranspiration E_d

Priestley and Taylor (1972) simplified the Penman equation, which estimates evaporation at the land surface using meteorological conditions, by redefining potential evaporation E_p as