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A soil moisture assimilation scheme using satellite-retrieved skin temperature in meso-scale weather forecast model

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ABSTRACT

A thermodynamically consistent soil moisture assimilation scheme for clear sky and snow free conditions has been developed for the meso-scale modeling system in the Arctic region by using satellite-derived skin temperatures. Parallel control and sensitivity modeling experiments were designed and their results demonstrated that the assimilation scheme successfully improves the soil moistures that were deliberately perturbed initially, indicating capability of the scheme to correct bias in the soil moisture initialization. Moreover, the resultant benefit of this assimilation scheme does not only lie in the improvement of soil moisture; the skin temperature also consequently exhibits improvements in a thermodynamic consistency. A real application of the assimilation scheme with satellite-retrieved skin temperature exhibited noticeable positive impacts on the modeling simulation and weather forecast; the model obviously captured meso-scale features of soil moistures as well as the skin temperatures. The warming tendency bias in original model simulations was removed to a considerable extent by this assimilation scheme.

1. Introduction

Manabe (1969) was one of the first to describe the mechanisms by which the land surface and the atmosphere interact when the underlying soil surface is wet rather than dry, through incorporation of a 'bucket' hydrology model. Since then, many other investigators (e.g., Mahrer and Pielke, 1978; Shukla and Mintz, 1982; Delworth and Manabe, 1988; Sellers et al., 1988; Betts et al., 1996; Mölders et al., 2003) have examined the significant influence of soil moisture on atmospheric circulation over seasonal to interannual time scales. Moreover, strong impacts of soil moisture on short and medium term weather forecasts have also been recognized. Miyakoda et al. (1979) indicated that realistic prescription of initial soil moisture could lead to an improvement of precipitation and evaporation forecast over two weeks in summer. Rowntree and Bolton's (1983) results showed that, because soil moisture varies slowly, atmospheric anomalies induced by an inaccurate specification of initial soil moisture could persist for several days. Therefore, accurate initialization and evolution of soil moisture is essential for obtaining correct simulations and forecasts of climate and weather, as well as the associated water cycling.

However, it is still a difficulty and a challenge to define initial soil moistures realistically in the numerical models due to a lack of good *in situ* observational data in many regions, particularly in the high latitudes. To address this problem, various efforts have been made towards a more accurate soil moisture initialization (e.g. Mahfouf and Viterbo, 1998). The principal idea in the proposed methods is to use proxy data sources to initialize soil moistures. Mahfouf (1991) suggested an optimal interpolation technique which used analyzed and observed surface temperature and humidity fields to improve soil moisture. McNider et al. (1994) and Jones et al. (1998a,b) applied retrieved infrared (IR) satellite skin temperatures to obtain upper soil heating rates and then adjusted the soil moisture through energy balance considerations. Njoku and Entekhabi (1996) and Houser et al. (1998) assimilated microwave remote sensing data into a model to generate soil moisture, while Diak and Whipple (1995) used IR skin temperatures in combination with the observed daytime

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change of the planetary boundary layer (PBL) height to evaluate soil moisture conditions. Complex variational and Kalman filter approaches were also developed to improve the land surface modeling (e.g., Margulis and Entekhabi, 2003; Reichle et al., 2002).

In particular, with the recent improvements of the quality and quantity (e.g. Aries et al., 2001; Prigent et al., 2003), the satellite-retrieved skin temperatures have been increasingly assimilated into weather and climate models to improve soil moisture initialization (e.g. Lakshmi, 2000; Van den Hurk et al., 2002; Seuffert et al., 2004) or further account for the whole model biases (e.g. Bosilovich et al., 2007). All of these attempts demonstrated positive impacts on model simulations, but most applications were for the mid-latitudes, rather than the high latitudes. In particular, along with the warming climate and increasing scientific and human activities in the Arctic region, it is imperative to improve modeling system and provide high quality weather information (e.g. Mölders, 2008).

During recent years we have applied the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) meso-scale model MM5 (Grell et al., 1994; Chen and Dudhia, 2001) for Arctic regional weather forecast and scientific research. Because of a paucity of robust soil moisture observations in the high latitudes, there is a need to develop an assimilation scheme by using proxy data to improve initialization of soil moisture in this forecast system. The aforementioned methods were successful to some degree by taking advantage of abundant proxy data from satellites and global data assimilation systems. However, many of them employed empirical relationships derived from historic data. Limited observation periods and sparse observation networks reduce the possibility of establishing such relationships in the high latitudes. Therefore, we aim to develop an assimilation scheme, which is independent of any empirical relationships, in the meso-scale weather forecast model.

We were inspired by the idea proposed by McNider et al. (1994) and Jones et al. (1998a,b) who apply the satellite-retrieved skin temperature to improve soil moisture simulation and has applied this method successfully to the short-term regional scale integrations of the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS) in the central United States. We developed an assimilation scheme in the framework of the land surface model NOAH-LSM within the meso-scale atmospheric model MM5 and applied it for routine weather forecast and scientific research. Given that the MM5 model has been widely used all over the world and NOAH-LSM has been applied to a variety of numerical models, such as the Weather Research and Forecast (WRF) model (Skamarock et al., 2005; Mölders et al., 2008) and the NCEP (National Centers for Environmental Prediction) Eta model (Ek et al., 2003), the assimilation scheme developed in this paper will apparently have broad potential applications.

2. Description of the soil moisture assimilation scheme

2.1. Land surface model NOAH-LSM

Land surface model NOAH-LSM, which is the vehicle for our soil moisture assimilation scheme development, was developed by Koren et al. (1999) and Mitchell et al. (2002) based on the land surface model LSM (Chen and Dudhia, 2001), which is a descendant of the Oregon State University land surface model OSU-LSM (e.g., Mahrt and Pan, 1984). The model is generally characterized by four soil layers and a single canopy layer. Usually a total depth of 3 m is chosen for the soil in order to reasonably simulate diurnal cycle and seasonal variation of the soil moisture and soil temperature fields. Vegetation and soil properties vary at different locations according to the categories assigned from US Geological Survey (USGS) databases (Loveland et al., 1991; Brown et al., 1993). Soil moisture and soil temperature are calculated prognostically as a solution of the soil water and energy budget equations, respectively. The surface temperature is defined as a blend of area-weighted temperatures of both the bare soil and the canopy surface within a grid cell, and is computed diagnostically from the surface energy balance equation. A detailed description of the model governing equations and the parameterizations can be found in Chen and Dudhia (2001).

2.2. Assimilation scheme of skin temperature for improve soil moisture

Earlier studies (e.g. Wetzel et al., 1984; Carlson, 1986) have shown a strong sensitivity of surface temperature to soil moisture during the mid-morning hours relative to the sensitivity to other surface variables. Note that this does not imply independence of surface air temperature from radiative forcing. It represents the situation in which, when radiative forcing is defined, soil moisture plays a crucial role in determining surface air temperature. This fact guides the development of a data assimilation scheme of skin temperature for improving soil moisture which is enabled to use under clear sky and snow free conditions. The assimilation of cloud impacts will not be considered in this paper. Under the stable clear sky, there are no cloud-induced radiative forcing on surface energy budgets and also no precipitation impact on soil moisture. Accordingly, differences between the observed and the modeled skin temperatures arise predominantly from differences between the actual and modeled latent heat flux in the surface energy balance (Jones et al., 1998a). Such differences in the latent heat flux can only be due to differences in available soil moisture, particularly in the upper soil layer, although all layers of soil contribute to the latent heat flux to a greater or lesser extent. So, the essential principal of the assimilation scheme is to use the difference between the observed and simulated skin temperatures to adjust the surface energy balance in the NOAH-LSM model, primarily through the latent heat fluxes; the soil moisture is, in turn, adjusted due to a requirement to retain thermodynamic consistency in the model.

The surface temperature in the NOAH-LSM model is computed diagnostically from the surface energy budget (Koren et al., 1999; Mitchell et al., 2002):

$$R - F - G - H - E = 0 \tag{1}$$

where R is the incoming net shortwave radiation; F the outgoing longwave radiation; G the soil heat flux; H the sensible heat flux; and E the latent heat flux. All symbols used below are listed in Appendix D.