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Modeling of soil surface temperature and heat flux during pre-monsoon season at two tropical stations

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ABSTRACT

A pilot experiment was conducted in pre-monsoon months of 2007 at Kharagpur (22°30′ N, 87°20′ E) under STORM (Severe Thunderstorms: Observations and Regional Modeling) programme, during which measurements of soil surface temperature and heat flux are absent. An attempt has been made to estimate these parameters using *in situ* soil temperature and moisture measurements at varied depths employing one-dimensional soil temperature rate model that includes both thermal conduction and heat transfer by water flux. One of the limitations of the model is that the soil–vegetation interactions are not considered. Validation of the methodology has been carried out using data sets obtained from the Land Surface Processes Experiment (LASPEX) at Anand (22°35′ N, 72°55′ E). The estimated surface and sub-surface soil temperatures have captured the variation with depth in terms of phase and amplitude as noticed *in situ* observations at both the sites but with $\frac{1}{2}$ h lag at Anand and about 1 h lag at Kharagpur. Successful validation of the methodology using LASPEX data reveals the estimation of soil surface temperature and heat flux at Kharagpur obtained is reasonable.

1. Introduction

Soil temperature is a primary factor in determining the rates and directions of soil physical processes and of energy and mass exchanges with the atmosphere. Soil temperature varies in response to changes in radiant, thermal, and latent energy exchanges taking place primarily through the soil surface. The soil temperature gets affected by the soil's changing thermal properties such as heat capacity, thermal conductivity as it wets and dries and variation of these properties with depth. It also depends on the geographical location, vegetative cover and human management (Oke, 1978). Modeling of soil surface temperature has been a challenging task for researchers since a long time. The simplest way to approximate soil temperature is assuming model equation on the fact that it varies as a sinusoidal function of time around an average value. Since nature's actual variations are not so orderly, this model equation may not follow actual observation at some times. Assumption for this model could be that temperature is following one-dimensional heat conduction equation in the soil (Kirkham and Powers, 1972; Hillel, 2004). Bhumralker (1975) used the simple solution of one-dimensional heat conduction equation following Force-Restore method to estimate soil temperature in general circulation model. Rao (1995) has followed almost similar approach in estimating soil temperature using Monsoon Trough Boundary Layer Experiment (MONTBLEX) data at various sites in India. Soil temperature estimation by extension of Force-Restore method has been done by Hirota et al. (2002) and tendency of current models in overestimating (underestimate) of soil temperature during daytime (nighttime) has been demonstrated by Gao et al. (2004) and Kahan et al. (2006). Further research resulted in improving the estimation of soil surface temperature by incorporating intra-porous convective processes to the heat conduction equation (Passerat de Silans et al., 1996, Gao et al., 2003, Gao et al., 2007). Droulia et al. (2009) have estimated ground temperature using empirical and semi-empirical methods. Variation of surface and sub-surface heat fluxes of radiation and heat at various sites in India have been studied (e.g. Nagar et al., 2002, Padmanabhamurty et al., 1998, Chacko and Renuka, 2002). Gao (2005) has estimated soil heat flux in a Tibetan short-grass prairie. Liebethal and Foken (2007) have evaluated various parameterization schemes to estimate soil heat flux and found that the simple method using *in situ* soil measurement yielded good results.

Energy exchange processes from the surface to the overlying atmosphere plays an important role in initiating the convective activity. The Gangetic West Bengal region of India experiences high convective activity during the pre-monsoon months (March–May) every year resulting in occurrence of severe thunderstorms, locally known as 'Kalbaishakhi'. Due to lack of mesoscale observations considerable research was not done in understanding the genesis, development and propagation of severe thunderstorms and in development of an operational forecast

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system for its prediction. To fill this gap, Department of Science and Technology (DST), Government of India had initiated a multi-intuitional experiment known as Severe Thunderstorm – Observational and Regional Modeling (STORM) over Gangetic West Bengal and NE India (for more details refer STORM Science Plan, 2005). Under the field phase of this programme, a pilot experiment was conducted over Kharagpur.

During the pilot experiment at Kharagpur, the surface soil temperature and soil heat flux measurements are absent. In the Science Plan it is broadly planned to obtain soil temperature and soil moisture at few sites in meso-net domain for land surface processes studies. At Kharagpur during the pilot experiment sub-surface temperature and moisture observations are only taken. The present study fills the data gap (obtaining surface soil temperature and surface soil heat flux) and it is useful in understanding the land surface processes interaction (surface energy transport) and feed back mechanism during pre-monsoon thunderstorm activity.

To estimate the surface energy balance information of soil surface temperature is very crucial to estimate the soil heat flux. In the present paper, an attempt has been made to estimate soil surface temperature and the soil heat flux at Kharagpur using the available sub-surface temperatures and soil moisture measurements by employing the new approach suggested by Gao et al. (2003, 2007; henceforth referred at Model 2) in addition to the Bhumralkar (1975; henceforth referred as Model 1) method. In general both models are same except for the inclusion of soil water convection processes in Model 2 and soil–vegetation interactions are not considered. The main objective of the present study is to estimate surface soil temperature and soil heat flux at Kharagpur. Validation of these methods are conducted using observed values of soil temperatures and soil heat flux at Anand, having similar soil type and site characteristics as that of Kharagpur, using LASPEX data sets.

2. Site description

The study domain of the present investigation comprises of an agriculture farm at Indian Institute of Technology, Kharagpur, Kharagpur (22°30′ N, 87°20′ E), region of west Midnapore, Gangetic West Bengal, India. This site consists of sandy loam soil, which is a mixture of sand (64.1%), silt (20.1%), and clay (15.8%) with a bulk density 1.65 Mg m^{-3}, volumetric heat capacity 2.960×10^{6} J m^{-2} K^{-1}, field capacity 26.7% and wilting point 9.3% (Panigrahi and Panda, 2003; Roy, 2006) and the mean sea level height of the station is 39 m. Topographically the site is flat and grassy. A 50 m micrometeorological tower has been erected at this site, as a part of a research project under Department of Science and Technology (DST), Government of India sponsored STORM programme (refer STORM Science Plan, 2005), intended to measure all basic meteorological parameters to study Nor'westers during the pre-monsoon season. Another study area is located at Anand (22°35′ N, 72°55′ E), Gujarat in India at which an experiment was conducted namely Land Surface Processes Experiment (LASPEX) during 1997–1998. The mean sea level height of the site is 45.1 m. The soil type at Anand is sandy loam, which represents 80.67% sand, 8.73% clay and 6.93% silt with a bulk density 1.55 Mg m^{-3}, volumetric heat capacity 1.858×10^{6} J m^{-2} K^{-1}, field capacity 17% and wilting point 5% (Nagar et al., 2002). The meteorological tower at Anand was located in the midst of an agricultural farm. This region is a flat river basin area situated in the semi-arid/arid zone in the western part of India, nearly homogeneous terrain. Low-level crops were present during the experimental period. No significant weather activity was noticed and no precipitation occurred during the study period (Satyanarayana et al., 2000, 2003; Vernekar et al., 2003).

3. Observational data

The data sets used in present study are during the pilot experiment of STORM programme for the pre-monsoon months (April –May) of 2007 at Kharagpur. Eight days are chosen for the present study (16–19, 24 April; 3, 4, 6 May, 2007). These days were chosen because of clear sky conditions. Kharagpur data comprises of air temperature (K), relative humidity (%), wind speed (ms^{-1}) and wind direction (degrees) at six different levels (viz. 2, 4, 8, 16, 32 and 50 m) obtained from the 50 m micrometeorological tower. At 10 m level a Sonic Anemometer (Make: RM Young) has been installed to measure the turbulent components of wind and temperature with 10 Hz frequency. Soil temperature was measured at three different depths (0.10, 0.20, and 0.50 m) using soil temperature sensor (Make and Model: Campbell Scientific 107B). Soil moisture at these three depths was measured by using water content Reflectometer (Make and Model: Campbell Scientific CS616-L). Net radiation (W m^{-2}) was measured at 10 m level using a net radiometer (Make and Model: Kepp and Zonnen NRLITE). A tipping rain gauge is installed to measure the rainfall rates near the tower site. For the present study, the slow response data averaged for 30 min are used.

For the site at Anand, data sets from LASPEX during 1–7 April, 1997 are used in this study. This data comprises of soil surface as well as sub-surface temperature, soil moisture at different depths of 0.05, 0.10, 0.20, 0.40 and 1 m soil heat flux at 0.05 m depth (averaged at every 10 min), radiation and sonic anemometer measurements. The meteorological parameters such as air temperature (K), relative humidity (%), wind speed (ms^{-1}) and wind direction (degrees) are available at four levels (1, 2, 4 and 8 m) obtained from an 8 m mast (for more details of experiment, data acquisition, quality control, refer Ref. Vernekar et al. 2003). The details of sensors, their model, accuracy, and measurement range used in the field experiments at both the sites are given in Table 1.

4. Methodology

4.1. Soil temperature estimation

Assuming that temperature is governed by the one-dimensional heat conduction equation in the soil, the fundamental equation (Kirkham and Powers, 1972, Bhumralker, 1975) is

$$\partial T/\partial t = k(\partial^2 T/\partial z^2) \quad (1)$$

Using the boundary condition: $T|_{Z=Z_L} = \overline{T}_1 + A_1 Sin(\omega t - \phi_1)$, ($t \geq 0$), the following is a solution to Eq. (1) given by Gao et al. (2007), which can be used to predict the soil temperature at depth z_1

$$T(z_1, t) = \overline{T}_1 + A_2 \exp[-(z_1 - z_2)\alpha] Sin[\omega t - \phi_2 - (z_1 - z_2)\alpha] \quad (2)$$

where A_1, A_2 and ϕ_1, ϕ_2 are amplitude and phase values at two depths z_1 and z_2, respectively, ω is the rotation of earth, $\overline{T_1}$ is the mean temperature at depth z_1, $\alpha = \sqrt{\omega/2k}$, k is thermal diffusivity and α^{-1} is the damping depth of the diurnal temperature wave.

Gao et al. (2003) and Gao (2005) incorporated convection process along with the heat conduction and proposed the following Eq.:

$$\partial T/\partial t = k(\partial^2 T/\partial z^2) + W(\partial T/\partial z) \quad (3)$$

where W is water flux density.