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The use of satellite-derived temperature for soil moisture initialization in the Penn State/ NCAR mesoscale model (MM5)

Jeffrey S. Tilley and Jing Zhang

Geophysical Institute, University of Alaska-Fairbanks, Fairbanks, AK

1. Introduction

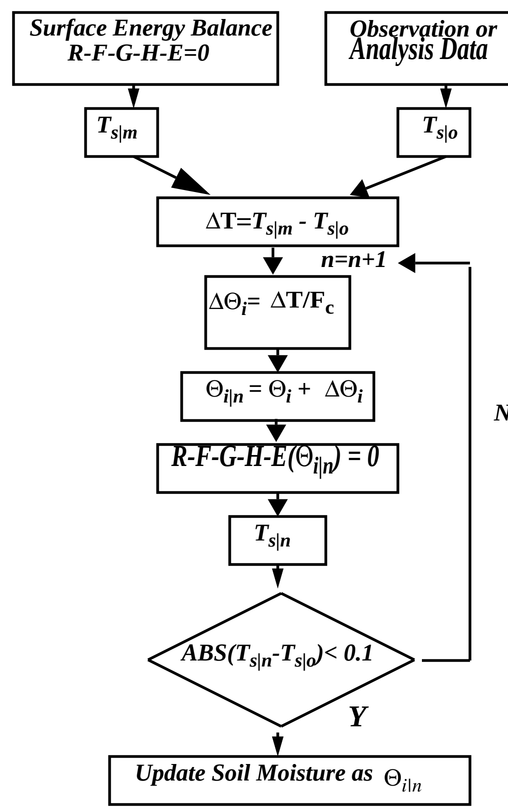
Previous numerical modeling studies of the influence of soil moisture on simulated atmosphere circulation (e.g., Shukla and Mintz 1982; Sellers et. al 1988; Betts et. al 1996) have demonstrated that soil moisture has a relatively long temporal ‘memory’ compared to the atmosphere and thus a relatively slow temporal variation in the simulated climate. Thus, the initial soil moisture is very important for obtaining an appropriate depiction of atmosphere-surface exchanges in numerical weather prediction and climate models. But due to a lack of in situ observation data in high latitudes, the initial soil moisture in these areas is often specified poorly in current models.

We have incorporated a satellite data assimilation method (hereafter referred to as the Heating Rate Retrieval method) following the work of Jones et al.(1998) into version 3 of the Penn State/NCAR MM5 modeling system (Chen and Dudhia 2000) to retrieve soil moisture. As earlier studies showed that the surface temperature is most sensitive to the soil moisture (relative to other surface factors) during the mid-morning hours (e.g, Wetzel et. al 1984; Carlson 1986), this method is based on the assumption that the difference between simulated and observed skin temperatures can be minimized by adjustments to the soil moisture, especially during this mid- morning period.

In this paper, we present a brief description of the method as well as a sample of results from case study simulation experiments using our implementation of the Heating Rate Retrieval method over high latitudes. By conducting experiments over an otherwise data sparse region, we hope to not only demonstrate the technique but its potential utility over such data sparse regions of significant hydrologic and climatic importance.

2. Summary of the Heating Rate Retrieval Method

The core assumption of this approach is that the differences between the observed and simulated skin temperature heating rate arise from differences between the actual and simulated latent heat fluxes (Jones et al., 1998). Under the same atmospheric conditions, such differences in the heat flux can be due only to differences in available soil moisture. The key to the method, then, is to use the difference in observed and simulated skin temperatures to adjust the model's energy balance (primarily the latent heat fluxes), which in turn is used to derive physically consistent values of soil moisture.



***Where:** R = total atmospheric radiation*
***F** = sfc. longwave radiation*
***G** = soil heat flux*
***H** = sensible heat flux*
***E** = latent heat flux*
***T_s**= skin temp.(m: modeled; o: observed), and*
***q_i**= soil moisture for the ith layer*

Figure 1. Flow chart depicting Heating Rate Method

Figure 1 shows a flow chart summarizing the procedure used in our implementation. The modeled skin temperature is obtained via a surface energy balance computation, while the observed skin temperature is

.*Corresponding Author Address:*
Dr. Jeffrey S. Tilley,Geophysical Institute,
University of Alaska-Fairbanks
903 Koyukuk Dr,. P.O. Box 757320
Fairbanks, AK 99775-7320 email: jeff@gi.alaska.edu

derived from either available observations or an analysis. An initial skin temperature difference is computed and then an iterative loop is entered. In this loop an adjustment is first made to the simulated soil moisture based on the skin temperature difference and a complex function F_c whose form is not presented here for brevity (see Tilley and Zhang 2001 for details.) The adjusted soil moisture is then used to compute a new latent heat flux, which in turn enters a new surface energy balance computation with the result an adjusted simulated skin temperature which is compared with the observed value. If the new skin temperature difference is less than 0.1K, the method stops and the soil moisture is set to its most recent value. Otherwise, the loop repeats.

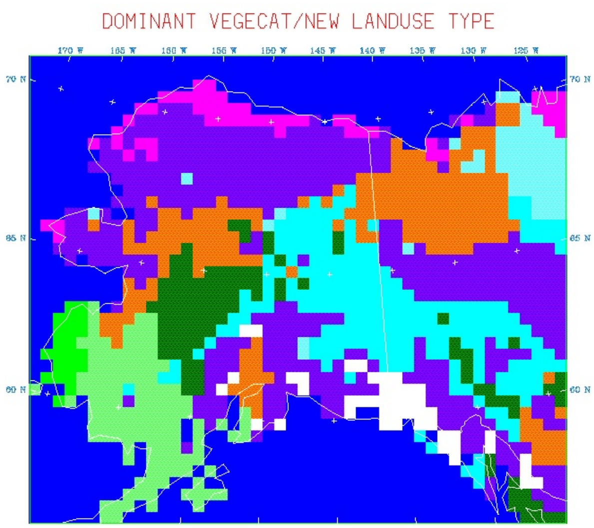


Figure 2. Domain and vegetation depiction used in the modeling experiments. The vegetation classes follow the USGS classification scheme. Darker colors indicate tundra types, lighter colors indicate forests or mixed tundra/forest vegetation, white indicates glacial ice.

3. Experiment Design

The Heating Rate Retrieval Method, as we have implemented it within MM5V3, can be applied not only to actual satellite-derived skin temperatures but also to surrogate datasets such as from a skin temperature analysis. For our initial tests of the method over Alaska and the Western Arctic, an area deemed fairly representative of the high latitude environment, we have adopted such an approach and utilized NCEP/NCAR Reanalysis data in the experiments. This approach actually has two advantages w/r/t initial experimentation with the scheme. First, there is ample contemporaneous skin temperature data from the Reanalysis data over the entire domain of interest (Figure 2), something which can generally not be achieved from polar orbiting satellite data since the satellite data swath width is limited to a maximum of 2700km and is only periodically scanning at an optimal angle for domain-wide contempaneous measurements. Second, this approach allows us to determine the robustness of the scheme irrespective of satellite data quality issues; we may perturb the initial soil moisture values from the Reanalysis and evaluate how well the method can retrieve an appropriate distribution in the course of the simulation.

The model grid used in all experiments, shown in Figure 2, has a horizontal resolution of 45 km with a computational grid of 41 x47 x 23 vertical levels. A model timestep of 150 seconds is used. In all experiments, we utilized the following physical parameterizations, all of which are standard options in MM5V3: the Dudhia (1989) simple ice microphysics scheme; the Grell (1993) cumulus scheme, the MRF planetary boundary layer scheme (Hong and Pan 1996) and the Benjamin (1983)cloud radiative cooling scheme. NCEP/NCAR reanalysis data are used to provide initial and boundary conditions to the atmospheric model as well as to the Chen and Dudhia (2000) MM5 Land Surface Model (LSM) derived from the Oregon State University model of Mahrt and Ek (1984).

We consider a mid-summer period, 4-7 July 1999. During this period there was only scattered light precipitation at a few locations; most of the domain shown in Figure 2 experienced no precipitation at all. Such a case was selected in order to avoid complications that precipitation would introduce into the latent heat flux adjustments as well as violate the basic assumptions underlying the scheme (see Jones et. al 1998 for details).

The following experiments, all for a 72 hour simulation period beginning at 00 UTC 4 July 1999, were conducted for this case study:

- a Control Run which does not utilize the Heating Rate Retrieval method; initial soil moisture from the NCAR/NCEP analysis is applied
- a Dry Run where the initial soil moisture is reduced 10% volumetrically from the NCAR/NCEP analysis but the Heating Rate Method is still not applied. This run effectively represents the potential errors that can result from a poor soil moisture initialization.
- a Skin Temperature Run where the initial soil moisture is as in the Dry Run but the Heating Rate Method is applied at 10 am local time on the first simulation day. This run measures, effectively, the degree to which application of the Heating Rate method can mitigate the errors that would result from the poor soil initialization in the Dry Run.
- for comparison with other techniques, a Nudging Run where a technique foll following Hu et. al (1999) is applied during the first simulation day. We will not present detailed results from this simulation here

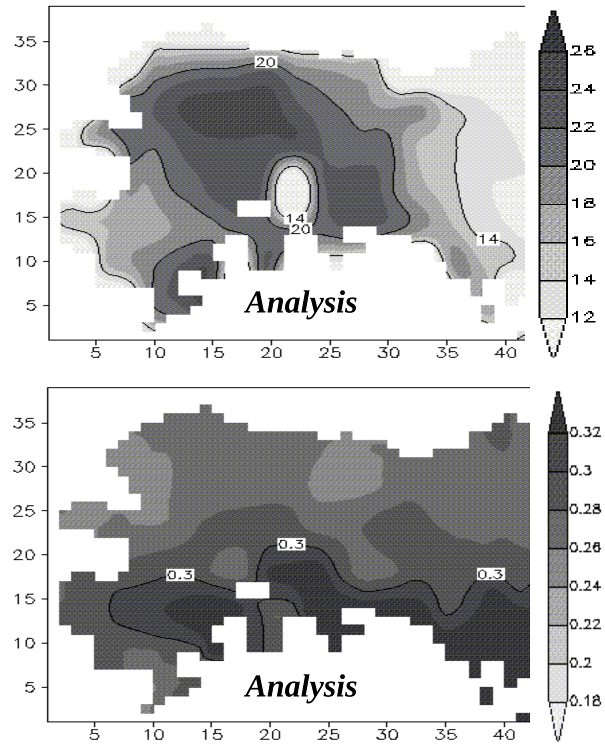


Figure 3. NCAR/NCEP Reanalysis fields at the initial simulation time (00 UTC 4 July 1999) for the Skin Temperature (^oC;upper panel) and Upper Layer (0-10cm) Soil Moisture (volumetric; lower panel).

but instead refer the reader to Tilley and Zhang (2001) for details.

4. Results:

Figure 3 shows the NCAR/NCEP Reanalysis fields for skin temperature and upper 10cm soil moisture over the domain at the initial time of the simulation (00 UTC 4 July 1999). The skin temperature field shows a maximum in Interior Alaska and the Brooks Range while the soil moisture indicates a sharp drop northward from the Gulf of Alaska coastline into Interior Alaska, followed by a more gradual decline to the North Slope region. These conditions are fairly typical for the warm season in Alaska, reflecting the influences of the maritime environment near the Gulf of Alaska and the more continental climate experienced in interior sections.

Figure 4 depicts the simulated values for skin temperature and upper layer soil moisture in the Control, Dry and Skin Temperature Runs at 00 UTC 5 July (24 hrs into the forecast). As would be anticipated, the Control Run results are not dissimilar to the analysis from the previous day. There is strong continuity of the upper layer soil moisture field; The main differences in the skin temperature field reflect differences in cloudcover and prevailing wind direction (offshore rather than onshore flow along the North Slope) associated with changes in the synoptic flow pattern (not shown) over the 24 hour period.

The Dry Run results clearly reflect the effects of

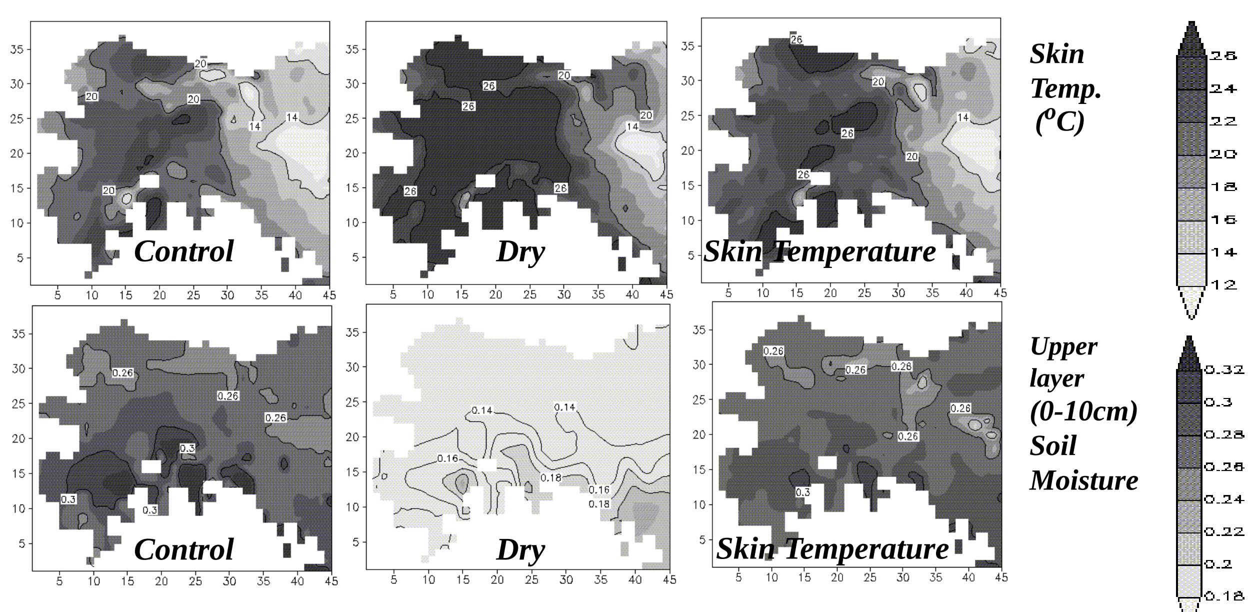


Figure 4. Skin Temperature (^oC; upper panels) and Upper layer volumetric soil moisture (lower panels) at 00 UTC 5 July for the Control (left), Dry (center) and Skin Temperature (right) simulations

the 10% initial reduction in soil moisture from the analysis values. Skin temperature values are 4-8 ^oC higher over interior and northern Alaska, consistent (from an energy balance perspective) with soil moisture values that have remained essentially unchanged at the reduced initial values.

The key test of the scheme is found in the results for the Skin Temperature Run. The values of both skin temperature and upper layer soil moisture at 24 hours into the simulation are reasonably close to those of the Control Run. This close correspondence of the Skin Temperature run with both the Control Run and the Reanalysis soil moisture fields continues for most of the entire 72 hour simulation (figures not shown), even though the Heating Rate Method is only applied once.

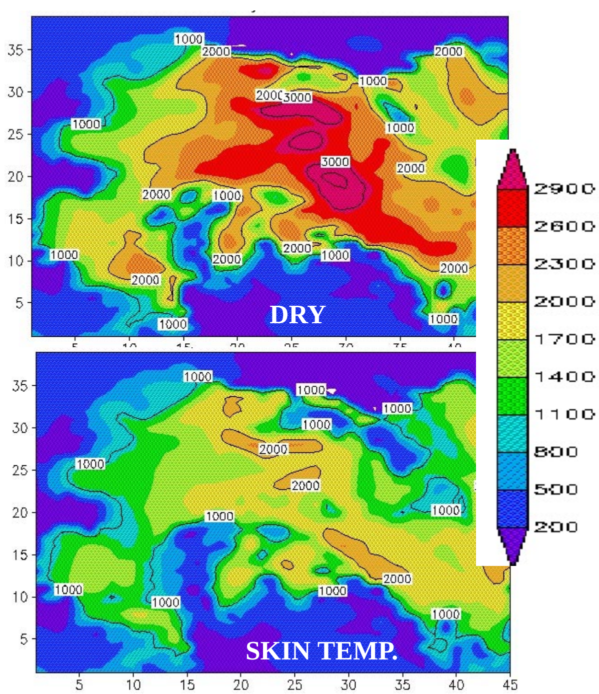


Figure 5. Planetary boundary layer height (m) at 00 UTC 6 July for the (top) Dry and (bottom) Skin Temperature Runs.

Improvements in soil moisture and temperature structure from application of the scheme extend to boundary layer fluxes and structure as well. Figure 5 shows plots of planetary boundary layer (PBL) height at 00 UTC 6 July for both the Dry Run and the Skin Temperature Run. Differences of up to 1000 m in PBL height occur over Interior Alaska, the Brooks Range and the Yukon Territory, even though it is 42 hours after application of the scheme. Comparison with the Control Run results (not shown) show much closer agreement with the Skin Temperature Run results. This further implies, considering the otherwise good agreement between the Control Run and Reanalysis, that the PBL heights in the Dry Run are too high and that the Skin Temperature run provides a better simulation of boundary layer properties.

Tests were conducted to test the sensitivity of the scheme to time of application, precipitation during the simulation period and the presence of snow cover. Those results will be reported on at a future date, as will the results of tests utilizing direct satellite information.

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