P1.24

ASSIMILATION OF SOIL MOISTURE FROM SATELLITE-DERIVED SKIN TEMPERATURE WITHIN THE PENN STATE/NCAR MESOSCALE MODEL MM5

Jing Zhang and Jeffrey S. Tilley

Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775-7320

1.Introduction

Studies of the influence of soil moisture on atmospheric circulation over a wide range of spatio-temporal scales have been performed by many investigators (e.g., Shukla and Mintz 1982; Sellers et. al 1988; Betts et. al 1996). The results demonstrated that an accurate initialization and evolution of soil moisture is essential for obtaining an appropriate depiction of atmosphere-surface interactions and the associated impacts on weather and climate. Due to a lack of observation data, especially in high latitudes, the initial soil moisture is specified poorly in current models.

In this study, we incorporate a satellite data assimilation method following 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 have indicated that the surface temperature is most sensitive to the soil moisture (relative to other factors) during the mid-morning hours (e.g, Wetzel et. al 1984; Carlson 1986), we assume that the difference between simulated skin temperature and the observed one in mid-morning can be minimized by adjustments to the soil moisture. Thus the observed skin temperature is the key for this soil moisture initialization scheme.

Several methods of estimating surface temperature using thermal satellite data from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA polar-orbiting platforms have been developed (e.g, Becker and Li 1990; Gutman 1994; Key et al 1997). In this study, we choose to employ the retrieval algorithm for clear-sky surface-temperature from Key et al (1997) which is developed specifically for high latitudes. In this algorithm, two 'split-window' infrared channels at approximately 11 µm and 12 µm from AVHRR are used.

In this paper, first we briefly introduce Key's algorithm for retrieving skin temperature from thermal satellite data. Then we present a description of our soil moisture assimilation scheme. In the last part of the paper, we give the results from case study simulation experiments using our implementation of the soil moisture assimilation scheme 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. Brief Description of the Retrieval Algorithm for Skin Temperature

The retrieval of land surface skin temperature (LST) is much more complicated than for sea surface temperature (SST) because of the high spatial and temporal variability of surface emissivity and difficulties in detecting clouds over land surfaces. The basic approach of LST retrieval algorithms is to use the split window channels (4&5) of NOAA-AVHRR to develop relationships between surface temperature, split-window radiances and surface emissivity with radiative transfer model. The derivation scheme we adopted here is from Key et al (1997) (hereafter denoted the Key scheme). The Key scheme considers almost all the existing polar orbiting satellites (NOAA-7,9,11,12,14) and is optimized for high latitude surface temperature estimation, with spectrally dependent emissivity.

The relationship between surface temperature, infrared channel 4 & 5 brightness temperature and surface emissivity in the Key scheme is as follows:

$$T_s = a + b \times T_4 + c \times T_5 + d \times emiss4 + e \times emiss5$$

where a~e are coefficients as a function of temperature range and satellite number. T_4, T_5 are channel 4 & 5 brightness temperature. $emiss4$ (0.985), $emiss5$ (0.975) are surface emissivity in channel 4 and 5 respectively.

For NOAA-12 and 14 satellites when T_4 > 260K, the coefficients are:

<u>NOAA-12</u>:	<u>NOAA-14</u>:
a=46.9049	a=45.9367
b=3.6529	b=3.3803
c=-2.6470	c=-2.3725
d=-181.5388	d=-166.7875
e=132.7192	e=118.6037

The scheme is applied only for clear sky condition; clouds are filtered out with the aid of both visible and IR channels following Czajkowski et al (1997). The satellite retrieval skin temperature is then assimilated into the model to retrieve soil moisture as described in the following section.

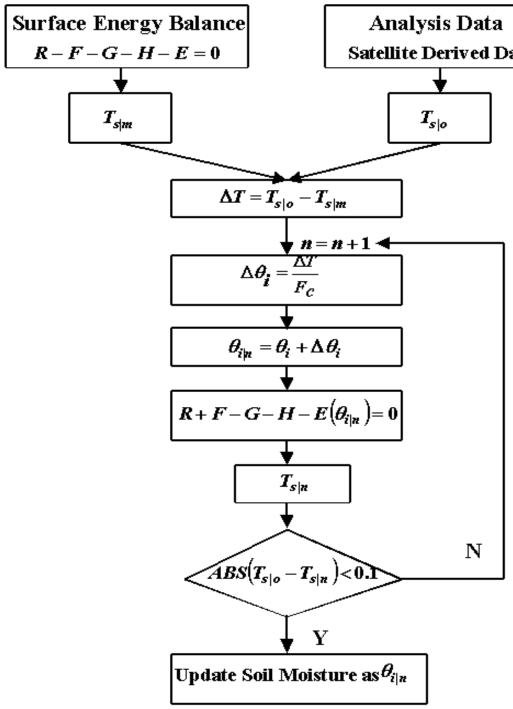
3. Summary of the Soil Moisture Assimilation Scheme

The core assumption of the assimilation approach is that the differences between the observed and simulated skin temperature arise from differences

---

Corresponding Author : Jing Zhang, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Dr. P.O.Box 757320 Fairbanks, AK 99775-7320
email:jing@rathlin.iarc.uaf.edu

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 assimilation 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 derived from either available observations or satellite data or 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. The result is an adjusted simulated skin temperature which is then 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.

4. Experiment Design

The soil moisture assimilation 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 tests of the method over Alaska and the Western Arctic, an area deemed fairly representative of the high latitude environment, we utilized both satellite derived skin temperature and NCEP/NCAR Reanalysis data in the experiments and compared their results. The use of reanalysis data has two advantages. 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 AVHRR swath width is a maximum of 2700km and the satellite only periodically scans at an optimal angle for domain-wide contemporaneous measurements. Second, analysis data allow 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.

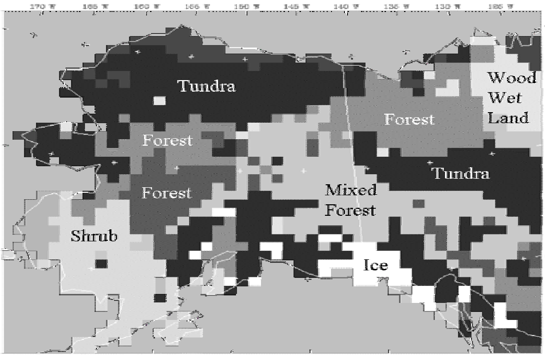


Figure 2. Domain and vegetation depiction used in the modeling experiments. The vegetation classes follow the USGS classification scheme. There are tundra, forest, wetland, shrub and glacial ice within this domain.

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 time step 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 assimilation scheme; initial soil moisture from the NCAR/NCEP analysis is applied

b) Dry Run where the initial soil moisture is reduced 10% volumetrically from the NCAR/NCEP analysis but the assimilation scheme is still not applied. This run effectively represents the potential errors that can result from a poor soil moisture initialization.

c) Assimilation Run 1 where the initial soil moisture is as in the Dry Run but the assimilation scheme with analysis skin temperature is applied at 10 am local time on the first simulation day.

d) Assimilation Run 2 which is same as Assimilation Run 1 except that the satellite derived skin temperature is used in the assimilation scheme.

The assimilation runs measure, effectively, the degree to which application of the assimilation scheme can mitigate the errors that would result from the poor soil initialization in the Dry Run.

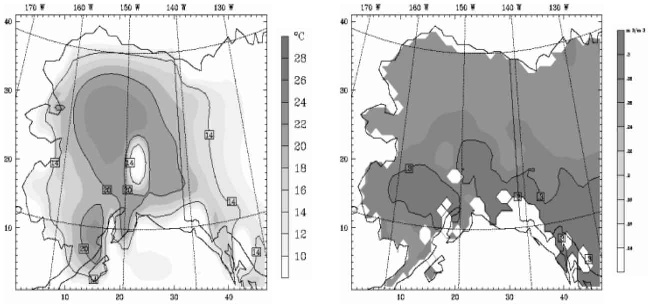


Figure 3. NCAR/NCEP Reanalysis fields at the initial simulation time (00 UTC 4 July 1999) for the Skin Temperature (°C; left panel) and Upper Layer (0-10cm) Soil Moisture (volumetric; right panel).

5. Results

Figure 3 shows the NCAR/NCEP Reanalysis fields for skin temperature and upper 10 cm 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.

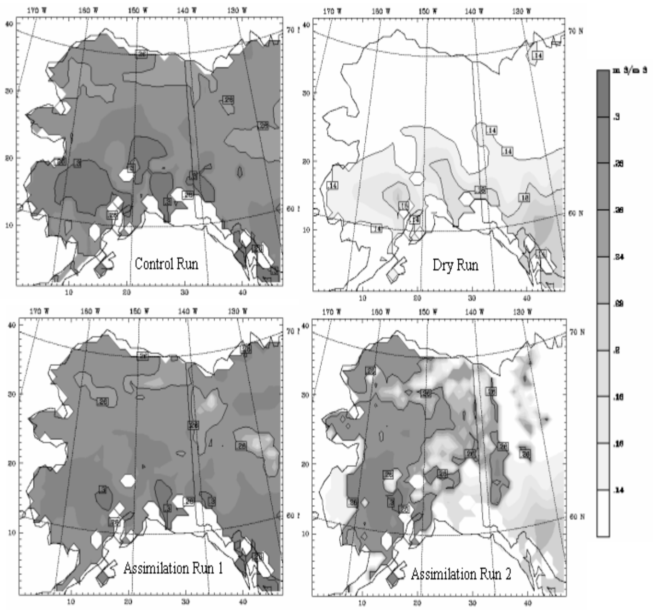


Figure 4. Upper layer volumetric soil moisture at 00 UTC 5 July for the Control, Dry and Assimilation Run 1 & 2 simulations.

Figure 4 depicts the simulated values for upper layer soil moisture in the Control, Dry and Assimilation 1&2 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 Dry Run results clearly reflect the effects of the 10% initial reduction in soil moisture from the analysis values. Skin temperature values (not shown) are 4-8°C 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 results from Assimilation Run 1 show that the values of both skin temperature (not shown) 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 Assimilation 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 assimilation scheme is only applied once.

Soil moisture from the Assimilation Run 2 is retrieved reasonably over the part of the domain where there is no significant cloud cover (not shown). Recall that the Key scheme can only retrieve skin temperature from AVHRR satellite data under clear sky conditions for the assimilation scheme. Comparing the Assimilation Runs 1 & 2, the resultant soil moistures are very similar under the clear sky conditions.

Improvements in soil moisture from application of the assimilation 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 the Dry Run and the Assimilation Runs 1 & 2. 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 Assimilation Run 1 & 2 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 Assimilation Run provides a better simulation of boundary layer properties.

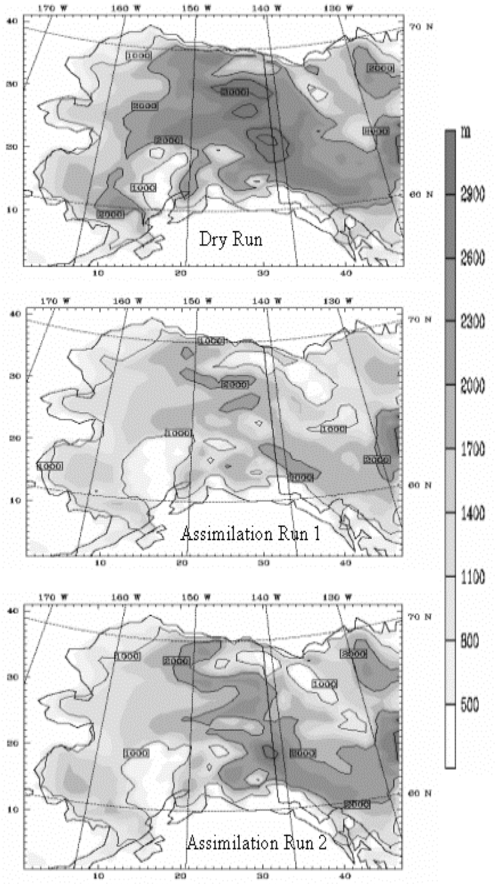


Figure 5. Planetary boundary layer height (m) at 00 UTC 6 July for the Dry Assimilation1&2 Runs.

6. References

Benjamin, S. G., 1983: Some effects of surface heating and topography on the regional severe storm environment. Ph.D. Thesis, Department of Mete-orology, The Pennsylvania State University, 265 pp.

Betts,A.K., J. B. Ball, A.C.M.Neljaars, M.J.Miller, and P.A. Viterbo, 1996:The land surface-atmosphere interaction: A review based on observation and global modeling perspectives. J.Geophys.Res., 101, 7209-7225.

Becker, F., and Z.-L. Li, 1990: Towards a local split window mehod over land surface. Int. J. Remote Sens., 11, 369-393.

Carlson, T.N., 1986: Regional scale estimates of surface moisture availability and thermal inertia using remote thermal measurements. Remote Sens. Rev., 1, 197-246.

Chen, F. and J. Dudhia, 2001: coupling an advanced land-surface hydrology model with the PSU/NCAR MM5 modeling system. Part I: Model description and implementation, Mon. Wea. Rev., 129, 569-585.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. J. Atmos. Sci., 46, 3077-3107.

Grell, G., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. Mon. Wea. Rev., 121, 764-787.

Gutman, G. G., 1994: Global data on land surface parameters from NOAA AVHRR for use in numberical climate models. J. Clim., 7,669-680.

Hong, S. Y. and H-L. Pan 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev., 124, 2322-2339.

Jones, A. S., I. C. Guch and T. H. Vonder Haar, 1998: Data assimilation of satellite diurnal heating rates as proxy surface wetness data into a regional atmospheric mesoscale model, Part I: Methodology. Mon. Wea. Rev., 126, 634- 645.

Key, J. R., J. B. Collins, C. Fowler and R. S. Stone, 1997: High-latitude surface temperature estimates from thermal satellite data. Remote Sens. Environ., 61,302-309.

Mahrt, L., and K. Ek, 1984: The influence of atmospheric stability on potential evaporation. J. Clim. Appl. Meteor., 23, 222-234.

Sellers,P.J., F.G.Hall, G.Asrar, D.E. Strebel, and R.E.Murphy, 1988: The first ISLSCP Field Experi-ment (FIFE). Bull. Amer. Meteor. Soc., 69, 22-27.

Shukla,J., and Y. Mintz, 1982: Influence of land-surface evapotranspiration on the earth's climate. Science, 215, 1498-1501.

Tilley, J. S. and J. Zhang, 2000: Testing methodologies for high latitude soil moisture initialization in the Penn State/NCAR MM5 Mesoscale Model. AGU Fall Meeting, San Francisco, 2000.

Wetzel, P.J., D.Atlas, and R.H.Woodward, 1984: Determining soil moisture from geosynchronous satellite infrared data: A feasibility study. J.Climate Appl. Meteor., 23, 375-391.

Acknowledgments:

The authors gratefully acknowledge Dr. Andrew Jones of Center for Geosciences, CSU for his helpful discussions. The work was sponsored by grants from the Dept. of Defense and Johns Hopkins University under the University Partnering for Operational Support Initiative**.**