10.16

OFF-LINE TESTS OF THE LAND SURFACE MODEL NOAH FOR ALASKAN SITES

Jing Zhang and Jeffrey S. Tilley
Geophysical Institute, University of Alaska Fairbanks, Fairbanks AK 99775-7320

1. Introduction

The unique features of the land surface model NOAH (e.g., Mitchell et al. 2002 and Koren et al. 1999), compared to its predecessor (called as OSU-LSM) are the inclusion of frozen soil and snowpack physical processes. Obviously, all these processes are particularly important for the Arctic and sub-Arctic continental regions in which there are permafrost, active frozen soil layers plus large snow-covered areas during the long winter season. To obtain realistic depictions of the land-atmospheric exchange processes for applications in the Arctic region, it is necessary to validate the model performance and calibrate the model parameters with *in-situ* observation data.

There are several data sets available from Alaskan field sites to evaluate the NOAH model. These data are from several projects, including the Arctic Transitions in the Land-Atmosphere System (ATLAS) project, the Caribou Poker Creeks Research Watershed (CPCRW) project and other projects conducted by the Water Environment Research Center (WERC) of the University of Alaska Fairbanks (UAF). Through a series of off-line simulation tests, forced by such field data, the NOAH model predictions will be evaluated and validated for Arctic land system simulations.

We first briefly describe the NOAH model in section 2 and introduce the observed field data we are using in section 3. In section 4 the simulation results are given and discussed.

2. Model Description

The NOAH model has been developed by Koren et al. (1999) and Mitchell et al. (2002) based on the land surface model LSM (Chen and Dudhia, 2001), which itself is a descendant of the OSU-LSM (e.g., Mahrt and Pan, 1984). The governing equations and model structures for these two models are similar. In general, the model features four soil layers and a single canopy layer. Usually a total depth of 2 meters is chosen for the soil in order to reasonably simulate daily and seasonal variation of the soil moisture and soil temperature fields. Depths of the layers are assumed to be 0.1, 0.3, 0.6 and 1 meter proceeding downward from the top layer, respectively. Vegetation and soil types are defined according to the categories assigned from U.S. Geological Survey (USGS) databases. Soil moisture and soil temperature for each soil layer are calculated prognostically from the model governing equations, which describe the soil hydraulic conductivity and heat conduction. The surface temperature is defined to reflect a linear combination of both the bare soil temperature and the canopy surface temperature fractions within a grid cell, and is computed diagnostically from surface energy balance considerations. A more detailed description of the model governing equations and the parameterizations can be found in Chen and Dudhia (2001).

The significant improvements with the NOAH model compared to its predecessors are the inclusion of winter season processes. Briefly, NOAH allows for temporal variability in snow properties as well as ice formation within the soil and the effects of soil ice on the soil water diffusivity, water potential and thermal conductivity. In particular, snow density in NOAH varies with snow temperature, snowmelt and snow accumulation. The relationship of snow density and snow temperature based on the work of Anderson (1976) is used to consider snow compaction. Whenever there is new snowfall, snow density will be calculated as a weighted value from the old snow and new snow densities. When snowmelt occurs, it is assumed that 13% of the snowmelt water stored in the snowpack is used to calculated aged snow density. Fractional snow coverage in a grid cell is allowed to account for the effect of patchy snow. With this inclusion, surface albedo becomes snow-depth dependent.

For frozen soil layers, NOAH first accounts for the energy source or sink resulting from phase transitions (liquid water to or from ice) in the soil temperature equation. Then, the frozen water is removed from the total soil water content in the soil moisture transfer equation. The soil heat capacity, thermal conductivity and water potential are then modified from their previous values with weighted values based on the fractional content of water and ice. Other details of the NOAH parameterization of snowpack and frozen soil processes can be found in Koren et al. (1999). More discussion on improvements to the ground heat flux, bare soil evaporation and other processes can be found in Mitchell et al. (2002).

3. Alaskan Field Site Description

The site data from the Arctic Transitions in the Land-Atmosphere System (ATLAS) (Hinzman, 2001, 2002) project will be utilized within the portion of the study described here. The ATLAS project is investigating how the soil moisture and surface temperature affect the surface energy balance, sub-surface thermal dynamics and vegetation distribution in Arctic regions of western Alaska. As such, the field measurements of the ATLAS project have been focused on continuous recordings (from 1999) of soil moisture and temperature, precipitation, air temperature, relative humidity, and wind speed at each field site. All of these field data, plus the radiation data observed at meteorological towers (3 meter and 10 meter) will be used to define the initial conditions and provide atmospheric forcing for the off-line simulations with NOAH. As introduced below, the vegetation types for most sites are tundra types and these are the major vegetation types for the Arctic and subarctic regions. By performing simulations forced by these sites' atmospheric data and comparing the resulting soil with the field soil data, we can then evaluate the NOAH model for Arctic applications.

Data from three sites within the ATLAS study area have been collected for the work discussed here: the Kougarok site (K2), the Council site (C2) and the Ivotuk Moss site. Site K2 is located at latitude 65°25.70'N, longitude 164°38.61'W, approximately 90 miles north of Nome on the Seward Peninsula of Alaska, at an elevation of approximate 110 meters above sea level. The slope at this location is approximately 0.057 m/m, southwest facing. The vegetation at this site is tussock tundra. Soil texture at this site in general is a fine-silty soil, but with vertical variations from peat in the 0-5 cm layer to silt loam at the 15 cm layer.

Site C2 is located at latitude 64°53.47'N, longitude 163°38.61' W, about 80 miles northeast of Nome on the Seward Peninsula of Alaska, at an elevation of approximate 140 meters above sea level. This site is representative of subarctic transitional regions where the dominant vegetation type is tundra. The slope at this location is approximately 0.113 m/m. The vegetation at this site is tussock tundra and moss. The soil texture at this site in general is loamy-skeletal soil but with vertical variation: peat as the dominant soil texture in the top layer (0-25 cm), peaty muck in the 25-30 cm layer and silt loam in the 30-100 cm layer.

The Ivotuk Moss site is located at latitude 68º 29' N, longitude 155º 45' W, on the North Slope of Alaska, in the central coastal plain north of the Brooks Range, at an elevation of approximate 570 meters above sea level. The slope at this location is flat. The vegetation at this site is tussock moss and soil texture in general is fine-loamy soil with the vertical variation: peat in the top layer (0-10 cm), peaty muck in the 10-30 cm layer and loam in the 30-70 cm layer.

4. Simulation Results

NOAH's ability to simulate melting and freezing processes are our main concerns in this study. According to the data continuity and availability at each site, we will perform the melting process simulations with data from January 3-July 28 2002 at the Ivotuk Moss site and from April 10-August 31 2001 at the C2 site; The freezing process simulations will be forced with data from July 20-December 31 2001 at the Ivotuk Moss site and from July 20-October 10 2001 at the K2 site.

Another concern is the parameterization of soil type for the simulations. The NOAH model doesn't allow for vertical variation of the soil texture. So in the following simulations, we define the soil types as silt loam for the K2 site, loam for the C2 site and clay loam for the Ivotuk Moss site. As described in the section 3, soil type in the top layer for all three sites is peat, so we will also perform sensitivity simulations with the soil type of organic materials and show the results in the presentation. The vegetation type for all three sites is set up as wood tundra.

An important point is that the parameters of soil types and vegetation types are all derived from the PSU/NCAR MM5 model's look up tables derived from USGS data. The reason we used these parameters for these uncoupled tests is to, a part, calibrate those parameters as used in the MM5/NOAH model system.

In the remaining part of this article, we will only show the results from the Ivotuk Moss site. The results from the other sites will be presented at the conference.

4.1 Melting simulation

The melting processes in NOAH include both snowmelt and melting of ice within the soil. Figure 1 compares the snow cover simulation for the Ivotuk Moss site from January 3-July 28 (i.e. Julian day 3-209) of 2002 with the observations. The simulated snow cover is clearly quite similar to the observation. Simulated zero snow depth occurred at the same time as the observation. But the simulated snow depth is generally a bit thinner than observed. Concurrently, the simulated snow water equivalent doesn't decrease before snowmelt begins (not shown). Taken together, these results suggest the snow compaction in the model is probably a bit too strong. From the results for snowmelt simulation rate (not shown), simulated snowmelt occurred mainly between Julian days 135–145 when snow-depth decreased sharply as shown in Figure 1.

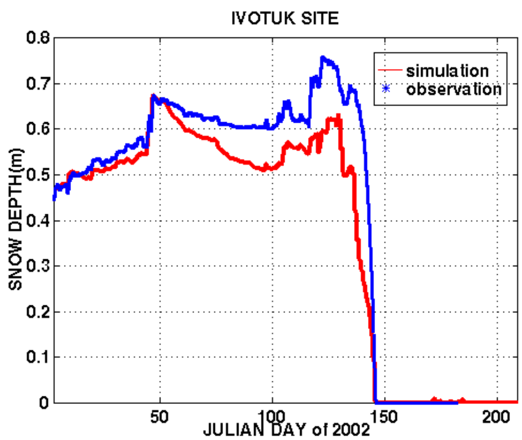

Figure 1. Simulated and observed snow cover for Julian days 3-209 of 2002 at the Ivotuk Moss site.

Figure 2 shows the simulated soil temperatures at the model soil layers of 5cm, 25cm, 70 cm and 150cm for the same period and the same site as that in Figure 1. It is evident that the soil temperatures vary slowly under snow cover. After the snow cover is removed, soil temperatures in the upper soil layers increased immediately and the soil temperature at 5cm (in red line) shows significant diurnal variation.

However, when we compare the simulated results with the observed soil temperatures as shown in Figure 3, it is clear that the simulated soil temperatures have a much larger variation than the observed soil temperatures for both snow cover and snow free situations. This result implies that the insulating effect of snow is too small and the soil heat conductivity is too large for this soil type in the model. As a result, the simulated soil temperatures in the upper soil layers (e.g., 5cm, 25cm) are colder than observed during cold season and warmer than the observed ones during warm season. Soil temperatures in the lower soil layers (e.g., 70cm, 150cm) decrease very quickly during the cold season in the simulation and are remain colder than the observations.

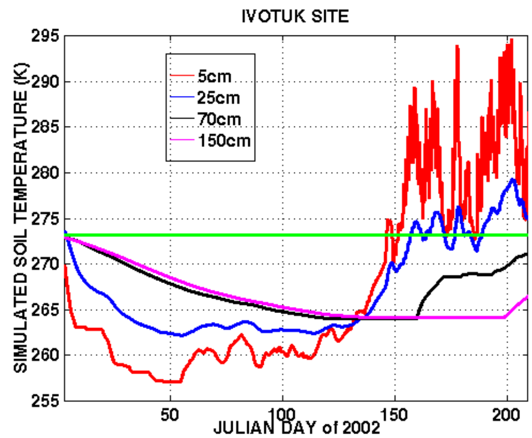

Figure 2. Simulated soil temperatures for Julian days 3-209, 2002 at the Ivotuk Moss site.

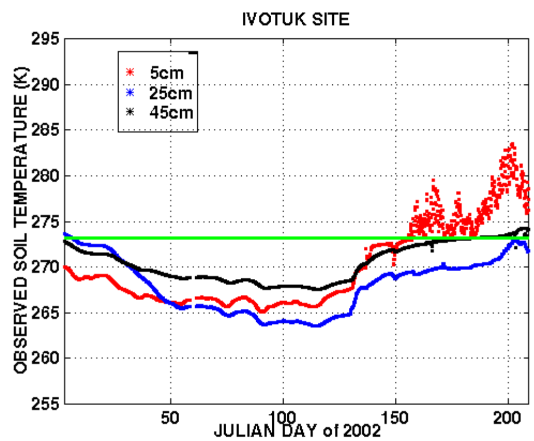

Figure 3. Observed soil temperatures forJulian days 3-209 of 2002 at the Ivotuk Moss site.

Figure 4 shows the simulated liquid soil moisture at 5cm, 25cm, 70cm and 150cm for the same period and the same site as that in Figure 1. A problem is evident in the simulation of soil moisture for the upper soil layers (5cm and 25cm): the liquid soil moisture increase even in the snow-covered frozen soil. As shown in Figure 2, the first soil layer (5cm) had the coldest temperature, which means this soil layer could gain heat from the other soil layers. When the net heat fluxes for this soil layer are larger than zero and the liquid soil moisture is smaller than the maximum allowed supercooled water (which is the function of soil texture, soil moisture and soil temperature), soil ice begins to melt. Such melting is the reason for the increase of liquid soil moisture in the 5cm layer. From the decrease of total soil moisture in the 5cm layer and the increase of total soil moisture in the 25cm layer (not shown), it seems clear that the increase of liquid soil moisture at the 25cm level results from soil water movement downward.

After snow cover is removed, the frozen soil gains energy from the warm surface and the soil ice begins to melt. Liquid soil moisture in each soil layer increases. Compared to the observed soil moisture shown in Figure 5, the simulated melting occurs earlier than observed because of rapid response of soil temperatures to the warm surface. It is also found that the upper layer soil melts and refreezes very quickly with the large diurnal variation in the simulated soil temperature. The soil moisture in the lower soil layers (70cm, 150cm) increases slowly because of the cold soil temperatures shown in Figure 2.

The simulated liquid soil moisture in the 25cm layer doesn't increase as much as in the observations even though the simulated soil temperature for this layer increases significantly after snow cover is removed. The reason is that there is no soil ice within this soil layer at any time in the simulation. The simulated total soil moisture for this layer (not shown) is exactly the same as the liquid one and the increase of soil moisture within this layer results from soil water vertical movement.

Why isn't there soil ice in this soil layer during the cold season? As shown in Figure 2 and 3, the initial soil temperature defined from the observation for the 25cm layer is greater than the freezing point. As such, the model will assume the soil isn't frozen and the initial total soil moisture is the same as the liquid one. The simulated liquid soil moisture for the 25cm layer is always smaller than the maximum allowed supercooled water for the defined soil texture in the model. As a result, there is no soil ice formation for the whole simulation period.

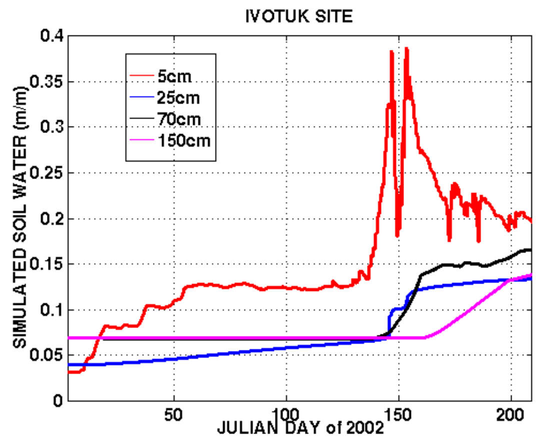

Figure 4. Simulated liquid soil moisture for Julian days 3-209 of 2002 at the Ivotuk Moss site.

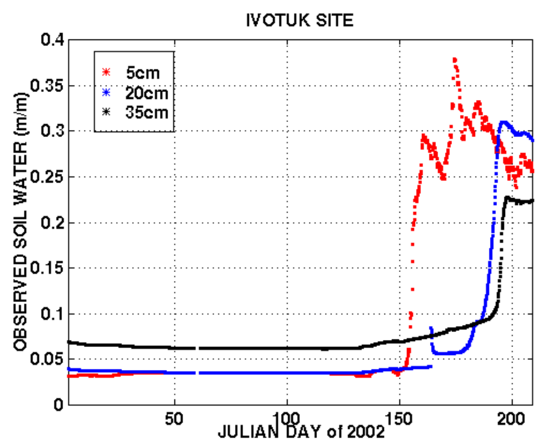

Figure 5. Observed liquid soil moisture for Julian days 3-209 of 2002 at the Ivotuk Moss site.

4.2 Freezing simulation

The freezing processes in NOAH include snow cover accumulation and soil ice formation. Figure 6 shows a comparison of the snow cover simulation and the observations for the Ivotuk site during Julian day 201-365 of 2001. The simulated snow accumulation is basically consistent with the observations except that the simulated snow depth is thinner than the observed depth. The difference becomes larger around Julian day 278 when there was a flow of warm air passing the site and the simulated skin temperature (not shown) increased abruptly, resulting in a strong compaction of snow. As noted in the preceding subsection excessive compaction of snow in NOAH contributes to a simulated snow depth simulation that is too thin.

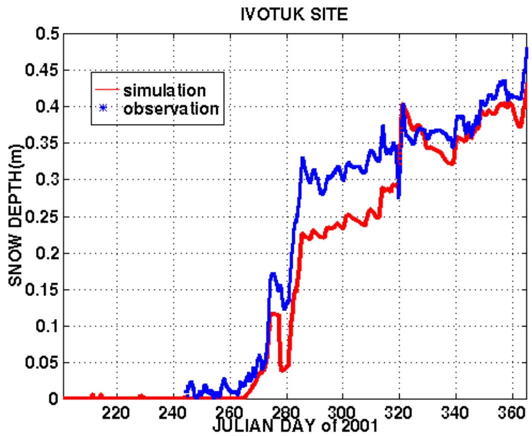

Figure 6. Simulated and observed snow cover for Julian day s 201-365, 2001 at the Ivotuk Moss site.

The simulated liquid soil moisture at the 5cm, 25cm, 70cm and 150cm levels and the comparisons with observations at the 5cm, 25cm and 35cm levels are shown in Figures 7 and 8. Before freezing began, changes in liquid soil moisture are mainly derived from evapotranspiration and the infiltration of rainfall. As shown in Figures 7 and 8, a significant increase of soil moisture occurs around Julian day 226 when there was 2 days continuous precipitation with precipitation rate reaching 3mm/hr. The consequent increase in soil moisture happens only in the upper soil layer in the observed time series (Figure 8). However, a soil moisture increase occurred in most soil layers in the simulation (Figure 7). This result implies soil water vertical movement is too strong for this soil type in the model.

At almost the same time of snow accumulation, the soil began to freeze. As shown in Figures 7 and 8, soil moisture began to decrease significantly at this time. In the observations (Figure 8) the decrease of soil moisture occurred first in the upper soil layer (5cm), followed one month later by a decrease at the 20cm level, followed still later by the 35cm level. However in the simulation, the decrease of soil moisture in the 5cm and 25cm soil layers begins at almost the same time except that the rates of decrease are different between them. From a comparison of simulated and observed soil temperatures (not shown), it is found the simulated soil temperatures are much colder than the observations because of an excessively weak insulating effect of the snow and an excessively large soil heat conductivity, as mentioned in section 4.1.

Another difference between the simulations and the observations is the supercooled water contents. When the soil freezes, the observed residual liquid soil moisture is about 0.05 m/m. However, the simulated supercooled liquid is much larger, about 0.15 m/m, and is related to the prescribed soil texture. Sensitivity tests suggest a strong sensitivity in this parameter and the subsequence evolution of the liquid. Clearly it must be prescribed carefully to achieve optional results.

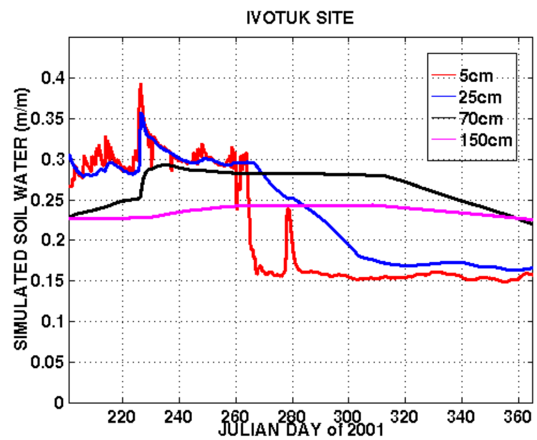

Figure 7. Simulated liquid soil moisture for Julian days 201-365, 2001 at the Ivotuk Moss site

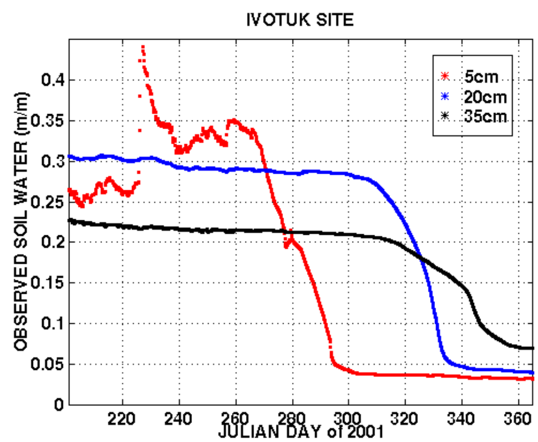

Figure 8. Observed liquid soil moisture for Julian days 201-365, 2001 at the Ivotuk Moss site

References:

Anderson, E., A point energy and mass balance model of a snow cover, *NOAA tech. Rep. NWS 19*, Natl. Oceanic and Atmos. Admin., Washingtion, D.C., 1976.

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 imple-mentation, *Mon. Wea. Rev.,* **129,** 569-585.

Hinzman, L.D., 2001, 2002: Climate data for the Arctic Transitions in the Land-Atmosphere System (ATLAS) project. URL: *http://www.uaf.edu/water/projects/atlas.* Fairbanks, Alaska.

Koren, V., J. Schaake, K. Mitchell, Q.-Y. Duan, F. Chen, and J. M. Baker, 1999: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, *J. Geophys. Res*., **104,** 19,569-19,585.

Mahrt, L., and H. L. Pan, 1984: A two-layer model of soil hydrology, *Boundary–Layer Meteorology*, 29, 1-20.

Mitchell, K., M.Ek, D.Lohmann, V.Koren, J. Schaake, Q.Duan, P.Grunmann, G.Gayno, Y. Lin, E.Rogers, D.Tarpley, and C.Peters-Liard, 2002: Reducing near-surface cool/moist biases over snowpack and early spring wet soils in NCEP ETA model forecasts via land surface model upgrades. *Preprints, 16th conference on hydrology,* AMS, Orlando, FL., Jan. 13-17, J1-J6.

Acknowledgments:

The work was sponsored by grants from Johns Hopkins University under the University Partnering for Operational Support Initiative.