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Land Ice Sea Surface Model: Short Description and Verification

A. Vukovic\textsuperscript{a}, B. Rajkovic\textsuperscript{b}, Z. Janjic\textsuperscript{c}

\textsuperscript{a}Faculty of Agriculture, University of Belgrade, Belgrade, Serbia (pazisadana@yahoo.com)
\textsuperscript{b}Faculty of Physics, University of Belgrade, Belgrade, Serbia
\textsuperscript{c}NCEP 5200 Auth Rd., Camp Springs, MD 20746, USA

Abstract: Land Ice Sea Surface model (LISS) is a new model for prediction of soil temperature and soil moisture. It is a part of the Non-hydrostatic Multi-scale Model on B-grid (NMM-B). The skin temperature, that represents the temperature of the interface between ground and air, is calculated from surface energy balance. It includes total influence of the soil processes and vegetation cover. Evapotranspiration is parameterized with $\beta$ parameter that takes into account evaporation from the bare soil, evaporation from interception reservoir and transpiration of the plants. Model has four layers and one or more layers for snow, depending on its amount. Soil temperatures are calculated using Fourier diffusion law and water content using Darcy law. LISS has been tested using two different data sets (Caumont, France 1986; Bondville, USA 1998) as well as against NOAH-LSM simulations. Annual balance of energy and water showed numerical stability. The annual diurnal variation of surface temperature is close to the observed value. RMSE for the surface temperature is 1.9°C for Bonville site. Surface fluxes in 36-hour period of snow growth simulations for Bondville are close to the observed values.

Keywords: land surface model; surface parameterization; soil temperature; soil moisture

1. INTRODUCTION

Processes in the atmosphere can be described by a system of partial differential equations. Integration of these equations over time gives us future values for meteorological variables. For solving this system initial and boundary conditions are needed. Lower boundary for atmosphere is land surface (soil with or without vegetation, snow, ice, water). In numerical weather prediction models this boundary is presented with models for surface processes. In mathematical sense, these models calculate lower boundary condition for solving the equation system of atmospheric part of the numerical weather prediction model. In physical sense, models for surface processes make communication between atmosphere and land in exchanging energy, mass and momentum.

In this paper we will present new model for surface processes, LISS (Land Ice Sea Surface) model, which is a part of the new model NMM-B (Non-hydrostatic Multi-scale Model on B grid; Janjic 2005). LISS is one-dimensional multilayer model with prognostic equations for soil temperature, soil moisture, amount of melted snow and water in interception reservoir. Based on given initial values of the prognostic variables, boundary conditions and morphological, physiological and physical characteristics of soil and vegetation, model calculates future values for prognostic and diagnostic variables. Important diagnostic variables are surface temperature and fluxes of the surface energy balance. They represent bottom boundary condition for the atmosphere.

LISS is tested offline on one-year data sets at two sites (Caumont, France 1986; Bondville, Illinois, USA, 1998). Model was forced with observed values of atmospheric variables and verified with observed values of surface fluxes, soil temperature and soil moisture. Also, numerical validation was done. For the same data sets NOAH-LSM (National Centers for Environmental Prediction-NCEP, Oregon State University, Air Force Weather Agency-
AFGWC, Air Force Research Lab-AFGL, Hydrologic Research Lab NWS - Land Surface Model; Ek 2005) simulations were performed. This model is believed to perform very well and it is in operational use as a part of most numerical weather prediction models. Comparing LISS with NOAH-LSM results and observed values gives a better picture of precision of the LISS results. Since measured values for some processes that are important for model to simulate well (evapotranspiration, runoff, etc.) are not available, results obtained with NOAH-LSM are used as reference values. After extensive experiments and verifications LISS performed very well. It follows laws of mass and energy conservation. In other words, model is numerically correct. That is very important for long term simulations. In this paper is presented only a small part of the performed experiments which lead us to general conclusion that LISS model is very good for surface processes simulations and could be trusted for operational use in numerical weather prediction model.

2. MODEL DESCRIPTION

Most of the parameterizations used in the LISS model are similar to the parameterizations in the TESSEL model (Tiled ECMWF Scheme for Surface Exchanges over Land; ECMWF 2004, IFS Documentation CY25r1, IV Physics). Model is divided into three subroutines. The first prepares parameters for selected soil and vegetation type. Second and third subroutines calculate soil temperature and soil moisture, respectively.

2.1 Soil Temperature

Surface temperature (skin temperature) is a diagnostic variable and represents value for which surface energy balance is satisfied. It is the temperature of the interface between ground and air (temperature of the layer with no thickness) and is explicitly calculated from linearized surface energy balance equation:

\[ S_w + L_{sw} - L_{sw} + H + E = G \]  

where \( S_w \) is shortwave radiation absorbed by surface \( S_w = (1 - alb)S_{w, inc} \), \( alb \) is surface albedo and \( S_{w, inc} \) is incoming shortwave radiation. \( L_{sw} \) is a longwave radiation that reaches the surface, \( L_{sw} \) is a longwave radiation emitted by the surface, obtained from Stefan-Boltzmann law. \( H \) and \( E \) are turbulent fluxes of sensible and latent heat that surface exchanges with atmosphere, respectively, under assumption that thin air layer near surface has the same temperature as the surface. Latent heat flux is parameterized as potential evaporation flux multiplied with \( \beta \) parameter.

Total latent heat flux \( E \) includes contribution of evaporation from bare soil, evaporation of water in interception reservoir and evapotranspiration. Each of these components have \( \beta \) parameter that shows the ratio between latent heat flux obtained from that process and latent heat flux in case of potential evaporation. \( \beta \) parameter for evaporation from interception reservoir is a fraction of the reservoir filled with water. \( \beta \) parameters for evaporation from bare soil and for evapotranspiration are derived from resistant parameterization according to Jarvis [1976]. Permanent wilting point is a threshold value of soil moisture under which transpiration and evaporation from bare soil stop. Field capacity is a threshold value of soil moisture above which these processes have constant values. They depend on soil type. \( \beta \) parameter for latent heat flux in surface energy balance is sum of these three beta coefficients and have value between 0 (no evaporation) and 1 (equals to potential evaporation). When snow covers the soil surface evaporation equals the potential evaporation from frozen surface.

Soil temperature \( T \) for other model layers is calculated with equation (2), derived from Fourier law of diffusion

\[
\left[ (\rho c)_{wli} - L_f \rho_w W \right] \frac{\partial T}{\partial t} - \frac{\partial}{\partial z} \left( K_z \frac{\partial T}{\partial z} \right)
\]  

(2)
where \((pc)_{out}\) is a heat capacity and contains contributions of soil, liquid water and frozen water. Second part on the left side of the equation represents effect of the soil water phase change on the temperature. As it is seen from the equation, it can be represented as additional soil heat capacity. \(L_f\) is latent heat of the freezing/melting, \(\rho_w\) water density and \(f_f\) is the frozen water fraction according to Williams and Smith [1989]. \(W\) represents total volumetric soil moisture content in model layer. Right side of the equation is vertical gradient of the heat flux. Heat conductivity \(K_t\) is parameterized according to Peters-Lidard et al. [1998]. Time variable is \(t\) and \(z\) is a vertical coordinate. Upper boundary condition for solving this equation is skin temperature. For bottom boundary condition model has two options. If depth of the last layer is deep enough, bottom boundary condition could be no heat flux between deepest model layer and underlying ground. In other case, boundary condition is a fixed soil temperature under deepest model layer and flux exchange is allowed.

### 2.2 Snow

In case there is a snow on top of the surface, skin temperature is also calculated from surface energy balance equation. Model has option to divide snow cover in multiple layers. The number of the layers and their depth depend on height of the snow cover. When snow melts, skin temperature is fixed at 0°C and temperature of the snow layers below are calculated the same way as for soil layers, but using the parameter values for snow. Amount of melted snow is calculated from surface energy balance with added term for latent heat flux of frozen-liquid phase change

\[
\rho_w L_f \frac{S_{melt}}{\Delta t} = S_w + L_{w0} - L_{wy} + H + E - G
\]

where \(S_{melt}\) is the amount of melted snow for \(\Delta t\) model time step.

### 2.3 Soil Moisture

Volumetric soil moisture \(W_i\) is calculated according to equation (4), derived from Darcy law

\[
\frac{\partial W_i}{\partial t} = \frac{\partial}{\partial z} \left[ K_w \frac{\partial W_i}{\partial z} + \gamma_w \right] + R_{ex}
\]

where the last term represents root extraction. The first term represents the effect of water fluxes through layer boundaries on the moisture content (Stensrud 2007, Hillel 1980). Hydraulic conductivity \(\gamma_w\) and diffusivity \(K_w\) are parameterized according to Clapp and Hornberger [1978]. Upper boundary condition for solving this equation is calculated with taking into account interception of precipitation, surface runoff, water infiltration and evaporation from the surface. Bottom boundary condition is gravitational drainage from deepest model layer into the underlying ground.

### 3. MODEL VERIFICATION

Data for these kind of experiments, when observations of atmospheric variables and soil variables for the whole year are needed, are very rare and difficult to find. For LISS model verification annual data sets for two sites were used (Caumont, south France 1986; Bondville, Illinois, USA, 1998). Data for Caumont site are part of the HAPEX-MOBILHY (Hydrologic Atmospheric Experiment – Modélisation du Bilan Hydrique). This data set is used for verification of large number of surface models (Shao and Henderson-Sellers 1996). Information of measuring accuracy is available, from which can be concluded that measurements are relatively high-quality and consistant. Data for Bondville are part of the FLUXNET project, that includes global network of meteorological stations and data can be
found at ORNL-DAAC (Oak Ridge National Laboratory-Distributed Active Archive Center). For this data set information about their quality is not available. During the work, that includes this data, some inconsistency in measured values were discovered. Since the simulations are done for the whole year it is assumed that results could be used, in hope that values with large errors would not have significant impact on final conclusions. This is one more reason for necessity of having one model that is used as reference. Data available for these sites together with results obtained with NOAH-LSM were used for large number of experiments. Here are presented a few selected results.

3.1 Caumont site

Caumont is in south France (part of the SAMER network, no.3; 43°41’N and 0°06’W, altitude 113 m, Goutrobe et al. 1989, Goutrobe 1991, Gouterbe and Tarrieu 1991). Observations were performed during 1986. Along the atmospheric variables (time step 30min) this data set contains soil moisture observations (time step 7 days) and observed values for surface fluxes (time step 30min) in the IOP (IOP – Intensive Observation Period: May 28th - July 3rd, Mahfouf 1990). Soil type is loam and vegetation type cropland. Vegetation is present in the period May 1st - September 30th (120-273 day). There was no snow during the whole year. Time step for both models was 10min and depth of the model layers 0.1m, 0.3m, 0.6m, 1.0m (increasing with depth). Results obtained with LISS and observed values for soil moisture are presented in Figure 1. First four graphs are values for volumetric soil moisture content in m³ m⁻³, at the middle of the each model layer. The bottom graph is the sum of soil moisture content in mm for the 1.6m depth. Model performed very well. When vegetation starts to develop, soil moisture decreases. Model results follow observations and in the period after show peaks that are coincided with rain events. Over the whole year model gave good results that convinced us that water in model is well balanced.

![Figure 1: Volumetric soil moisture content (m³ m⁻³) at the middle of the LISS model layers and observed values (top four graphs); soil moisture content (mm) in 1.6m depth obtained with LISS model and from observations (bottom graph)](image)

It is very important how model divides water in processes at the surface. Measurements for this kind of test do not exist, so NOAH-LSM simulations serve as reference. In Figure 2 are presented cummulative values for components of water balance: precipitation, total evaporation, surface and bottom runoff for LISS and NOAH-LSM. Annual precipitation amount is equal to the sum of annual total evaporation and runoff. This confirms that model
conserves mass. Also, we can conclude that LISS made a good partition of water between these three processes, similarly to reference model NOAH-LSM.

Verification of spin-up time was done. Initial soil moisture value in all layers was equal to permanent wilting point (0.06 m$^3$ m$^{-3}$). Resulting spin-up time was three years, same as for NOAH-LSM.

Mean daily values for surface fluxes in the IOP for both models and observed values are presented in Figure 3. Values for ground flux ($G$) and net radiation flux ($RN$) are very close to observations. LISS sensible heat flux ($H$) follows observations very well and in most days is closer to observations than NOAH-LSM. LISS results for latent heat flux ($E$) are close to observations and noticeably better than NOAH-LSM.
Diurnal change of surface fluxes is rapid and intense. That could present a problem for model to simulate, so it is necessary to verify flux change during the day. Results are compared with observations for every available data (on 30 min). In Table 1 are presented RMSE values for $H$ and $E$ flux for both models. Again we use NOAH-LSM as reference model. During the day values of $H$ are up to $\sim 300 \text{ Wm}^{-2}$ and for $E$ $\sim 600 \text{ Wm}^{-2}$, therefore RMSE values for LISS for the IOP are $\sim 20\%$. This are very good results considering the intensivity of flux change during the summer. Also accuracy of the flux measurements is $\sim 15\%$ at short time scales, therefore LISS RMSE is not large. Similar RMSE is obtained for NOAH-LSM, which additionally confirms that LISS simulates surface processes very well.

### 3.1 Bondville site

Bondville is in Illinois, USA ($40.01\text{N i 88.37W}$, altitude $219 \text{ m}$). Observations were performed during 1998. Atmospheric variables are given on every 30 min. Available data for model verification are soil temperature (at levels 0.00, 0.02, 0.04, 0.08, 0.16, 0.32, 0.64 m), soil moisture and surface fluxes. All data are given on 30 min. Soil type is silty clay loam and vegetation type cropland. Snow cover appeared in the last three days of the year. Model setup is the same as in previous case.

Since the soil moisture verification is already discussed, these results will not be presented here. For this data set are available soil temperature measurements, even for soil surface. It is of great importance to verify model soil temperature because atmospheric part of the weather forecast models use skin temperature as lower boundary condition. It represents a product of all processes discussed above. In Figure 4 is presented a mean annual diurnal change of the soil temperature. On the upper graph are values for LISS and NOAH-LSM skin temperature with observed surface temperature and 0.02 m temperature. Midday is the most critical part of the day for surface temperature simulation, because surface temperature could change rapidly. This effect is especially significant during the summer period, when shortwave radiation is the most intense. Soil surface absorbs it and changes temperature very fast. When cloud appears it blocks some of the shortwave radiation from reaching the land surface and surface temperature decreases quickly. Land surface models should be able to simulate these rapid changes. As it can be seen from Figure 4 LISS results are very similar to the observations (difference $\sim 0.5^\circ \text{C}$), better than NOAH-LSM. In the afternoon hours difference is $\sim 1.0^\circ \text{C}$. This could be the consequence of the turbulent coefficients calculation in the stable regime, which are input values outside land surface model. Lower graph presents the same values but for the soil temperature at the middle of the first model layer (0.05 m) with observed values at 0.04 m and 0.08 m. Observed values show that amplitude is significant and LISS results demonstrate that, but with some delay. This has no negative effect on skin temperature, therefore it can be tolerated. On the other hand, NOAH-LSM results are much flatter with the same delay, which could be the reason why NOAH-LSM skin temperature has lower values than LISS and $\sim 1.0^\circ \text{C}$ lower than observations in midday.

As in surface fluxes verification, results for skin temperature on every 30 min over the whole year are verified. Observations have low quality over some days or periods but, as discussed before, detailed information about measurement accuracy for this site was not available. In monthly or annual average this is masked, but on every 30 min this could seriously damage the verification. Therefore, following results should be taken with reserve. On Figure 5 is presented LISS model RMSE derived from data on every hour over the whole year (diurnal change of RMSE). RMSE values are between $\sim 1.5^\circ \text{C}$ (midnight) and $\sim 2.5^\circ \text{C}$ (midday). Annual RMSE for LISS is $1.9^\circ \text{C}$. Taking into account all that is discussed above, these results are satisfying. For reference model NOAH-LSM, RMSE is $1.5^\circ \text{C}$, which confirms that LISS performed well in skin temperature simulation.

<table>
<thead>
<tr>
<th></th>
<th>RMSE-H</th>
<th>RMSE-E</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISS</td>
<td>64.6</td>
<td>119.6</td>
</tr>
<tr>
<td>NOAH-LSM</td>
<td>61.4</td>
<td>124.1</td>
</tr>
</tbody>
</table>
Figure 4: Mean annual diurnal change of the skin and near surface temperature obtained with LISS model and NOAH-LSM and observed values

Figure 5: Diurnal change of RMSE obtained from LISS and observed values for each hour over the whole year

In Figure 6 are presented values of snow water equivalent, surface temperature and surface fluxes at the end of the year (last three days) when snow cover appeared. Since temperature observations are not reliable and there is no data for snow water equivalent, only results of two models are showed. LISS follows the values of reference model. Surface fluxes are similar to observed values.

Figure 6: Snow water equivalent (m) for LISS and NOAH-LSM (top left); surface temperature for LISS and NOAH-LSM (bottom left); surface fluxes for LISS, NOAH-LSM and observed values (right), for the last three days of the year
4. CONCLUSIONS

LISS model needs only information about soil and vegetation type for simulation, therefore it is prepared for operational use in weather forecast models. Basic tests for verification of mass and energy conservation are performed and model has shown that it is numerically correct. Soil moisture forecast is very good in each model layer and distribution of water in model between processes that are components of water balance are similar as in reference model NOAH-LSM. Parameterization of surface fluxes in LISS performed very well and it could simulate rapid and intense diurnal changes. Most complex is parameterization for latent heat flux, because through $\beta$ parameter are included complicated processes of vegetation coverage. It came out as very successful parameterization. Skin temperature depends on surface fluxes and therefore LISS also showed that it is able to catch rapid and intense temperature change. For mean annual values LISS gave excellent results, which is important for long range simulations. LISS verification for snow case could not be fully performed because data were not available. But, for presented three-day period LISS showed promising results. From all discussed above it can be concluded that LISS is a reliable model, can be used for operative runs and will perform very well.

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