Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model

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[1] We present the impact tests that preceded the most recent operational upgrades to the land surface model used in the National Centers for Environmental Prediction (NCEP) mesoscale Eta model, whose operational domain includes North America. These improvements consist of changes to the "Noah" land surface model (LSM) physics, most notable in the area of cold season processes. Results indicate improved performance in forecasting low-level temperature and humidity, with improvements to (or without affecting) the overall performance of the Eta model quantitative precipitation scores and upper air verification statistics. Remaining issues that directly affect the Noah LSM performance in the Eta model include physical parameterizations of radiation and clouds, which affect the amount of available energy at the surface, and stable boundary layer and surface layer processes, which affect surface turbulent heat fluxes and ultimately the surface energy budget. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; *KEYWORDS:* coupled modeling, Eta model, land surface model

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1. Introduction

[2] During the past two decades, a number of advances in land surface models (LSMs) have been made in simulating surface energy and water fluxes and the surface energy and water budgets in response to near-surface atmospheric forcing. The companion evolution of soil moisture, soil temperature, and snowpack are important to the surface energy and water budgets on short-term (e.g., daily) to long-term (e.g., seasonal to annual) timescales, and they in turn depend on surface conditions (such as vegetation state and soil texture). Increasingly then, the parameterizations of land surface processes have become more physically based because of heightened multidisciplinary cooperation and increased knowledge in the fields of meteorology, hydrology, and plant and soil physics.

[3] Surface fluxes provide the necessary lower boundary conditions for numerical weather prediction (NWP) and climate models. These weather and climate models are computationally intensive and as such the LSMs utilized must be efficient in their representation of land surface processes. At the onset of the 1990s, the National Centers for Environmental Prediction (NCEP) started testing the efficient LSM developed for use in NWP at Oregon State University (OSU) beginning in the middle 1980s [*Mahrt and Pan*, 1984; *Pan and Mahrt*, 1987]. The original OSU LSM consisted of two soil layers with thermal conduction equations for soil temperature and a form of Richardson's equation for soil moisture. The effect of stomatal control by plants was represented via a constant "plant coefficient" (fractional, 0 to 1) to account for atmospheric influences, multiplied by the soil moisture availability (fractional, 0 to 1) to account for the soil moisture influence, finally multiplied by the potential evaporation [*Mahrt and Ek*, 1984]. Later, a variable plant coefficient that accounted for stomatal control was related to a canopy conductance formulation using the common "big leaf" approach [*Jarvis*, 1976; *Noilhan and Planton*, 1989], reported by *Holtslag and Ek* [1996], where canopy conductance is modeled as a function of soil moisture availability and atmospheric conditions (solar insolation, temperature, and humidity).

[4] During the 1990s, NCEP greatly expanded its land surface modeling collaborations via several components of the Global Energy and Water Cycle Experiment (GEWEX), most notably, the GEWEX Continental-Scale International Project (GCIP) and the Project for Intercomparison of Land-

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Table 1. Timeline of Noah Land Surface Model (LSM) Evolution, With References to Relevant Model Physics and/or Land Surface Fields Implemented in the NCEP Operational Mesoscale Eta Model

Date	Description	Reference(s)
	Original OSU LSM (Prior to NCEP Era)	
	potential evaporation	*Mahrt and Ek* [1984]
	surface fluxes, soil hydraulics,	*Mahrt and Pan* [1984]
	and soil thermodynamics	and *Pan and Mahrt* [1987]
	Noah LSM Implementation in Eta Model at NCEP	
31 Jan. 1996	OSU LSM introduced into Eta model	*Chen et al.* [1996]
	(GFS initial soil moisture and temperature)	
	surface runoff and infiltration	*Schaake et al.* [1996]
24 July 1996	ISLSCP vegetation greenness changes	
18 Feb. 1997	NESDIS vegetation greenness	*Gutman and Ignatov* [1998]
	bare soil evaporation changes	*Betts et al.* [1997][a]
	snow melt changes	*Betts et al.* [1997][a]
	thermal roughness length changes	*F. Chen et al.* [1997][a]
9 Feb. 1998	increase from 2 to 4 soil layers	
3 June 1998	self-cycling Eta-EDAS soil moisture and temp.	
	NESDIS daily snow cover and sea ice analysis	*Ramsay* [1998]
	Noah LSM Upgrades (With Assessment in Eta Model) Described in This Study	
21 July 2001	frozen soil physics	*Koren et al.* [1999]
	snowpack physics upgrade	*Koren et al.* [1999]
	maximum snow albedo climatology	*Robinson and Kukla* [1985]
	shallow snow thermal conductivity	*Lunardini* [1981]
	bare soil evaporation refinement	
	bare soil thermal conductivity changes	*Peters-Lidard et al.* [1998]
	vegetation-reduced soil thermal conductivity	*Peters-Lidard et al.* [1997]
	transpiration refinements	
26 Feb. 2002	patchy shallow snow thermal conductivity	

[a]Assessed in an Eta model study.

surface Parameterization Schemes (PILPS). These collaborations included the Office of Hydrological Development (OHD) of the National Weather Service, National Environmental Satellite Data and Information Service (NESDIS), NASA, National Center for Atmospheric Research (NCAR), the U.S. Air Force, and OSU and other university partners. As an outgrowth of these collaborations and their broad scope of LSM testing in both uncoupled and coupled mode over a wide range of space scales and timescales (see citations below), NCEP substantially enhanced the OSU LSM, now renamed the Noah LSM in recognition of the broad partnership above.

[5] The mesoscale model forecast suite at NCEP is the Eta model [*Janjić*, 1990, 1994; *Black*, 1994; *Mesinger*, 2000] and its Eta Data Assimilation System (EDAS) [*Rogers et al.*, 1996], now run operationally at 12-km resolution with 60 layers. NCEP generally first implements the Noah LSM enhancements in the Eta-EDAS suite, followed later by implementation in the NCEP Global Forecast System (GFS). Before introducing the latest Noah LSM enhancements and tests that are the subject of this paper, we first briefly review the highlights of the earlier Noah LSM upgrades that have taken place in the Eta-EDAS suite at NCEP over the past seven years. These included an increase from two to four soil layers, modifications to the canopy conductance formulation [*Chen et al.*, 1996], bare soil evaporation and vegetation phenology [*Betts et al.*, 1997], surface runoff and infiltration [*Schaake et al.*, 1996], and thermal roughness length treatment in the surface layer exchange coefficients [*F. Chen et al.*, 1997]. A key companion advance was the implementation of fully continuous self-cycling of soil moisture and temperature in the EDAS (without soil moisture nudging) in June 1998. Since then the Eta model initial soil moisture and temperature are sole products of the EDAS (namely, the coupled Noah-Eta model and the land surface forcing internal to the EDAS) without undue drift in soil moisture and temperatures.

[6] The above forerunner Noah LSM advances have yielded improved model performance, both in an offline mode (that is, atmospheric-forced LSM-only runs for specific sites or in two-dimensional horizontal land surface domains), as well as coupled in the fully three-dimensional operational mesoscale Eta analysis and forecast system. Offline testing of the Noah LSM has involved several PILPS and related or similar projects [e.g., *Chen et al.*, 1996; *T. H. Chen et al.*, 1997; *Qu et al.*, 1998; *Wood et al.*, 1998; *Chen and Mitchell*, 1999; *Koren et al.*, 1999; *Schlosser et al.*, 2000; *Slater et al.*, 2001; *Boone et al.*, 2001; *Bowling et al.*, 2003]. Coupled evaluation has addressed performance of the Noah LSM in an NWP setting with focus on land surface processes from local to continental scales [e.g., *Berbery et al.*, 1996, 1999, 2003; *F. Chen et al.*, 1997; *Betts et al.*, 1997; *Yucel et al.*, 1998; *Hinkelman et al.*, 1999; *Angevine and Mitchell*, 2001; *Berbery*, 2001; *Marshall et al.*, 2003].

[7] Given the significant role GCIP has played in supporting land surface model development at NCEP, it is appropriate to review the Noah LSM in this special GCIP issue. In describing the various model advances and when they occurred (see Table 1), this paper reviews upgrades to the physical parameterizations and land surface fields used in and by the Noah LSM along with the companion impact tests in the coupled Noah/Eta-EDAS suite, for the cold season (section 2) and the warm season (section 3). This latest phase of Noah LSM advances described here embodies a "generational" Noah LSM upgrade including

the addition of frozen soil physics and major advances in snowpack-related physics [*Koren et al.*, 1999], significant improvements to bare soil evaporation, soil heat flux enhancements for bare soil, snow-covered and vegetated conditions, and some modest changes to canopy conductance. These Noah LSM upgrades address Eta model forecast biases in near-surface air temperature and relative humidity thought to be due in part to deficiencies in Noah LSM physics evident in uncoupled testing (described above).

[8] This paper presents the follow-on testing to confirm in coupled mode the improvement anticipated from our uncoupled (offline) testing. The model testing and assessment includes regional verification of realtime parallel executions in winter, early spring, and summer, as well as individual case studies (under conditions of minimal large-scale forcing) in order to demonstrate model bias reductions. The most recent Noah LSM upgrades were tested in the NCEP mesoscale Eta model and then implemented in the Eta-EDAS suite operationally in July 2001, with an additional change in February 2002. We summarize our findings and suggest further Noah LSM improvements and future direction in section 4.

2. Cold Season Processes

[9] Cold season processes are important in the evolution of the land surface for a large fraction of the earth during many cold season months. In the presence of snow cover, albedo increases, surface roughness is often reduced, and the exchange of heat and moisture between land surface and atmosphere is diminished, while subsurface freezing reduces the movement of heat and moisture within the soil. All of these processes affect the surface energy budget and thus the surface fluxes, so it is necessary to include these effects in LSMs used in weather and climate models. These processes are included in the Noah LSM upgrades demonstrated herein, as well as other land surface models [e.g., *Viterbo et al.*, 1999; *Smirnova et al.*, 2000; *Boone et al.*, 2000; *Boone and Etchevers*, 2001]. The improvements to the Noah LSM in the area of cold season processes were first made and tested in an offline mode by *Koren et al.* [1999] and during the PILPS 2d exercise [*Schlosser et al.*, 2000; *Slater et al.*, 2001], and then in a coupled mode within the NCEP mesoscale Eta model as presented here.

2.1. Patchy Snow Cover and Frozen Soil

[10] The cold season processes that have been added or improved are described by *Koren et al.* [1999] and include the effect of latent heat release during soil water freezing in winter, which ameliorates the typical underestimation (when frozen soil processes are ignored) of soil temperature (and thus surface and air temperatures) during soil freezing periods, and overestimation of temperatures during thawing periods. The frozen soil moisture content depends on the soil temperature, volumetric soil moisture, and characteristics dependent on soil texture. Additionally, a treatment of patchy (fractional) snow cover is introduced, which allows the surface temperature to exceed freezing. The previous formulation in the Noah LSM used all incoming energy to melt and sublimate the snowpack (which was considered uniform across a gridbox) until complete ablation. This bounded the surface skin temperature at 0°C (in the solution of the single surface energy budget), resulting in the daytime low-level air temperature holding near freezing. The new Noah LSM formulation allows for patchy snow cover if the snow depth is below some threshold, and hence allows exposed ground, a lower albedo, more energy absorption, and the aggregate (gridbox) surface skin temperature (still corresponding to a single surface energy budget) to rise above 0°C. As such the surface sensible heat flux increases with a corresponding increase in low-level air temperature. The subgrid patchiness is related to the depth of the snow and surface characteristics; for example, for a "smoother" surface such as a grassland, a smaller snow depth threshold is required for 100% snow cover compared to a forest (Figure 1).

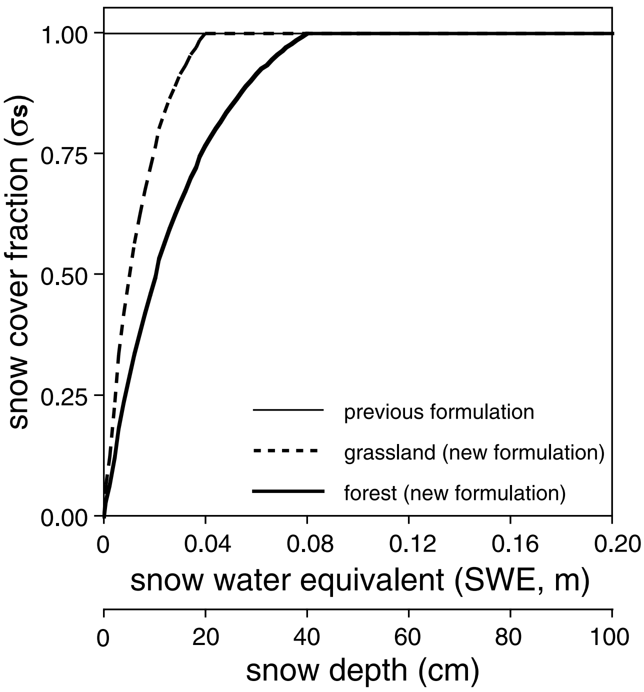

Figure 1. Snow cover fraction (σ_s) as a function of snow water equivalent (SWE, and snow depth assuming a snow density ratio of 5:1) for the previous Noah LSM formulation (thin line, $\sigma_s = 0$ for SWE = 0, and $\sigma_s = 1$ for SWE >0), and for the new Noah LSM formulation for forest (thick solid line) and grassland (thick dashed line) vegetation classes.

[11] Moreover, the evolution of the snowpack density is added as a new snowpack state, and is governed via a time-dependent snow compaction algorithm, which includes the effect of new snowfall. Previously the snow depth was assumed to have a "typical" 5:1 ratio, usually too low for new snowfall, but perhaps too high for an older snowpack. The snow density then affects the thermal conductivity through snow (previously assumed to be constant), which is important in determining the exchange of heat between the land surface and atmosphere. Also, in the presence of frozen soil moisture, the moisture infiltration (i.e., of snowmelt water and precipitation) is reduced. These parameterizations have been adopted in the current version of the Noah LSM with some modifications; for example, the computational efficiency of snow density formulation and frozen soil numerics have been greatly improved.

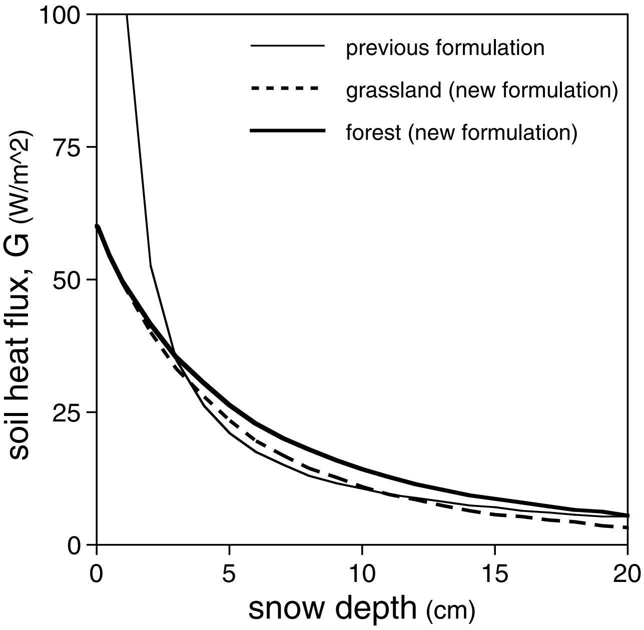

Figure 2. Soil heat flux (G) through patchy snow cover as a function of snow depth for the previous Noah LSM formulation (thin line), and the new Noah LSM formulation for forest (thick solid line) and grassland (thick dashed line) vegetation classes. Here we have assumed a temperature gradient of 3 K (old formulation: equation (1); new formulation: equation (4)), and, for the new formulation, an upper soil layer volumetric soil moisture content of 0.29 (yields soil thermal conductivity of 1.0 W m^{-1} K^{-1} for Noah LSM soil texture class No. 2, silty clay loam) and snow density ratio of 5:1 (yields snow thermal conductivity of 0.108 W m^{-1} K^{-1}).

[12] Below, we describe our further extensions to the Noah LSM in terms of cold season processes beyond those presented by *Koren et al.* [1999].

2.2. Soil Heat Flux Under Snow

[13] As the snowpack becomes very thin, it is difficult to estimate the large near-surface temperature gradients in the snow and upper soil layer, which sometimes leads to unrealistic spikes in the modeled values of the soil heat flux (G) through the snow and upper soil layer (e.g., as seen in the study by *Hinkelman et al.* [1999]). The original formulation for G in the Noah LSM assumed a constant value for the snow thermal conductivity (0.35 W m^{-1} K^{-1}) with heat flux through the soil and snow determined as

$$G = K_s(T_s - T_{s1})/\Delta Z_s \tag{1}$$

where K_s is the snow thermal conductivity, T_s and T_{s1} are the surface (snow) skin and upper soil layer (midpoint) temperatures, respectively (with the restriction that $T_s \leq 273.15$), and ΔZ_s is the snow depth, assumed to be 10 × SWE, where SWE is the snow water equivalent (so a snow density ratio of 10:1). The solution for G was then bounded by ±100 W m^{-2} for numerical stability because with a vanishing snowpack ($\Delta Z_s \rightarrow 0$), G could spike with large positive or negative values, depending on the gradient of T_s-T_{s1} (Figure 2).

[14] Therefore the soil heat flux formulation in the Noah LSM has been modified to include the effect of heat flow through thin patchy snow cover. This is done by considering the thermal conductivity of a snowpack-plus-upper-soil-layer following a method described by *Lunardini* [1981], where heat flow can be in parallel, in series, or intermediate between the two. Here parallel heat flow through the snowpack-plus-upper-soil-layer is assumed, which yields a larger thermal conductivity (than say, series), implicitly accounting for the nonuniform nature of snowpack cover. The effective thermal conductivity for the surface is then determined via a linear weighting between the snow-covered and non-snow-covered fractions (of a model gridbox), where

$$K_T = \Delta Z_s K_s + \Delta Z_{s1} K_{s1} \tag{2}$$

$$K_{eff} = \sigma_s K_T + (1 - \sigma_s) K_{s1} \tag{3}$$

where K_{s1}, K_T, K_{eff} are the thermal conductivities of the upper soil layer, snow-plus-upper-soil-layer, and patchy snow-covered surface (Figure 3), respectively, ΔZ_{s1} is the upper soil layer depth, and σ_s is the snow cover fraction ($0 \leq \sigma_s \leq 1$). The soil heat flux through the patchy snow-covered surface is then formulated as

$$G = \frac{K_{eff}(T_s - T_{s1})}{\Delta Z_s + \Delta Z_{s1}} \tag{4}$$

In this formulation the thermal conductivity remains robustly defined even in the extremes of vanishing snow cover ($\Delta Z_s = 0$, $\sigma_s = 0$, $K_{eff} = K_{s1}$), or for a very deep

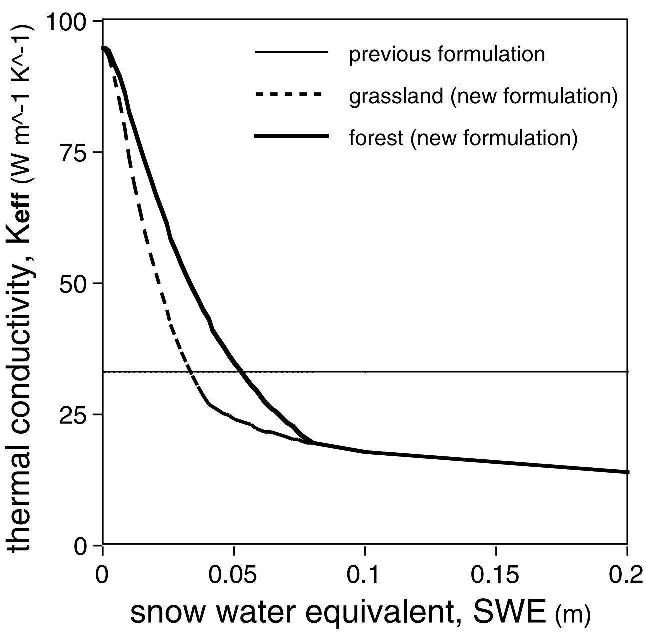

Figure 3. Thermal conductivity (K_{eff}) through patchy snow cover versus snow water equivalent (SWE) for the previous Noah LSM formulation (thin line, $K_{eff} = K_s$ = const. = 0.35 W m^{-1} K^{-1}), and new Noah LSM formulation for forest (thick solid line) and grassland (thick dashed line) vegetation classes, with the same patchiness corresponding to Figure 1, and soil and snow conditions as in Figure 2.

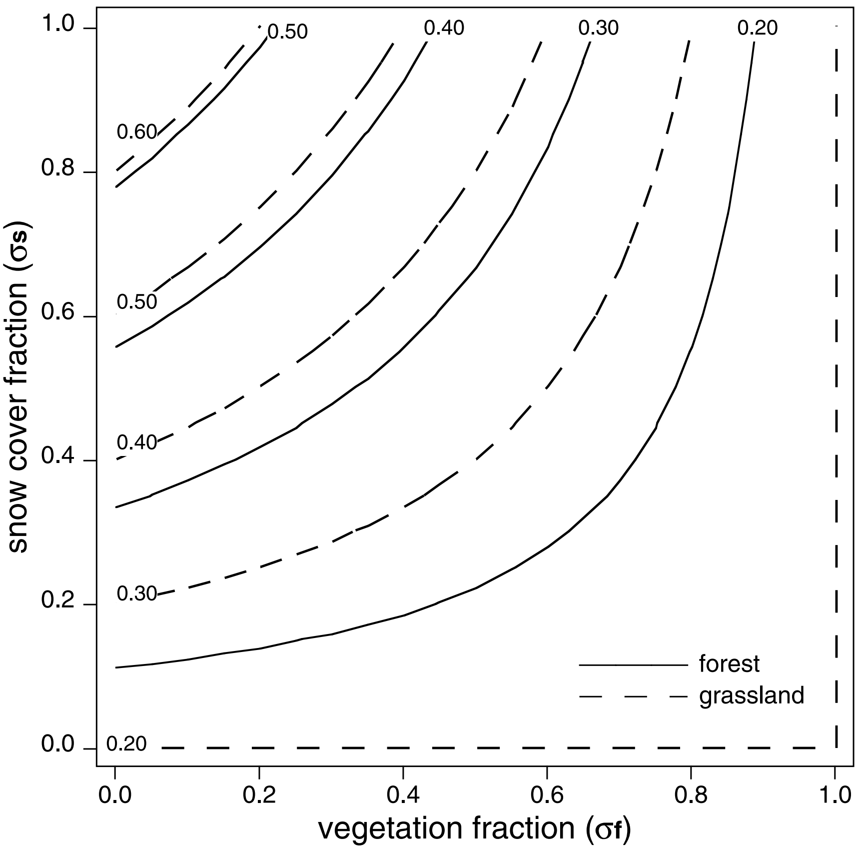

Figure 4. Surface albedo contours as a function of snow cover fraction versus green vegetation fraction with "typical" forest (grassland) values for snow-free albedo, $\alpha_0 = 0.15$ ($\alpha_0 = 0.20$) and maximum snow albedo, $\alpha_s = 0.60$ ($\alpha_s = 0.70$).

snowpack ($\Delta Z_s \gg \Delta Z_{s1}$, $\sigma_s = 1$, $K_{eff} \rightarrow K_s$), which is quite important for numerical stability. *Chang et al.* [1999] describe a similar thermal conductivity formulation (derived independently) adopted in another version of the OSU LSM, which accounts for a vanishing snowpack depth, although they did not account for patchy snow cover (equivalent to setting $K_{eff} = K_T$). Patchy snow cover must be accounted for since it increases the heat flux between the surface and atmosphere (especially at smaller snow cover fractions) because of the typically larger thermal conductivity of soil compared to snow.

2.3. Albedo Over Snow

[15] In the presence of snow cover, the surface albedo may be markedly increased because of the high albedo of snow (depending on vegetation cover). However, in conditions of shallow snowpack when snow first accumulates at the start of snowfall or diminishes because of snow sublimation or snow melt, there will be patchy areas that are not snow covered, e.g., in a model gridbox. To account for this patchiness effect, we formulate the surface albedo as a composite of a snow-covered and non-snow-covered surface as

$$\alpha = \alpha_0 + (1 - \sigma_f)\sigma_s(\alpha_s - \alpha_0) \tag{5}$$

where α, α_0, and α_s are the actual, snow-free, and maximum snow surface albedo, respectively, σ_f is the green vegetation fraction ($0 \leq \sigma_f \leq 1$), and σ_s is the snow cover fraction (defined earlier), as illustrated in Figure 4. As snow depth becomes zero, the albedo becomes the snow-free albedo ($\alpha = \alpha_0$). When the snow depth exceeds a threshold value (dependent on land surface classification, e.g., vegetation type), snow cover is complete ($\sigma_s = 1$) and $\alpha = \alpha_s$, the maximum snow albedo (described below).

[16] Over deep snow, the albedo of the surface is higher and in LSMs is often set to some uniformly large value, e.g., 0.55 previously in the Eta model. However, this can vary greatly depending on the surface character. For example, a conifer forest may have a lower albedo because of darker treetops sticking through a brighter (deep) snowpack, compared with a higher albedo for a completely snow-covered grassland. However, rather than use a maximum snow albedo simply as a function of the vegetation class or surface type (e.g., as in the ECMWF land surface model [*van den Hurk et al.*, 2000]), we use an annual maximum snow albedo climatology data set that extends the work of *Robinson and Kukla* [1985]. Their original data set covered the area north of 25°N at 1° × 1° resolution, so for each 1° × 1° cell, the maximum snow albedo implicitly includes the effect of variable vegetation density (subgrid variability) within the same vegetation class. Note the differences between the North American boreal forests with lower maximum snow albedos due to more shading of the snowpack under the canopy, compared to the Great Plains grasslands with higher maximum snow albedos due to more open ground and exposed snow cover (Figure 5).

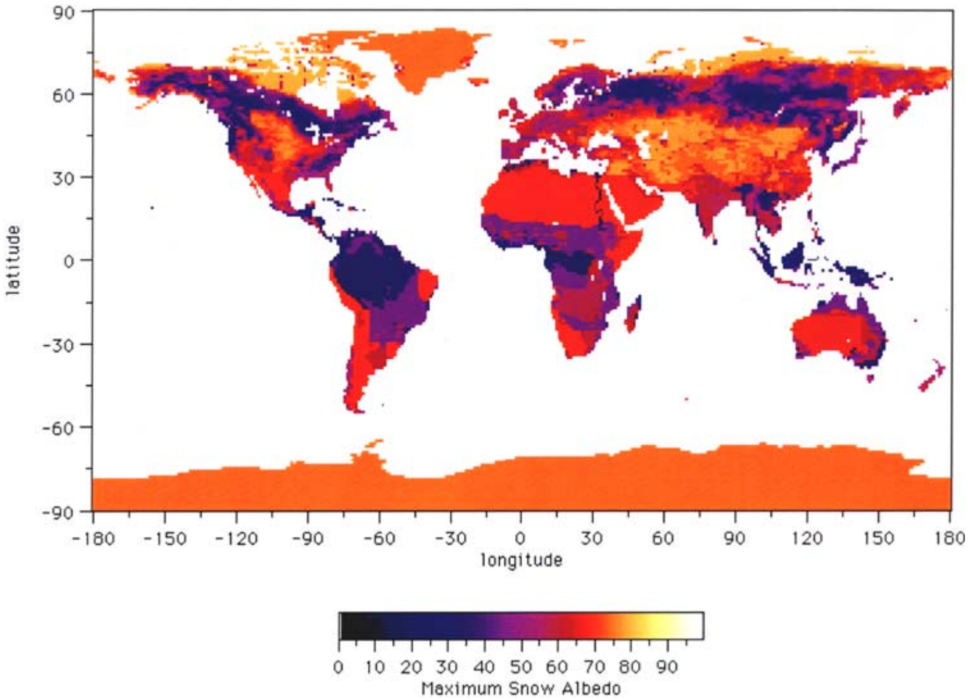

Figure 5. Maximum snow albedo based on *Robinson and Kukla* [1985].

[17] To populate a global 1° × 1° database, the maximum snow albedos from the original database were correlated with the SiB vegetation class [*Dorman and Sellers*, 1989] over this region to determine any pattern by "binning" the maximum snow albedo for a given vegetation class, then averaging and noting ranges. Indeed, the analysis showed a lower maximum snow albedo over forests than over short vegetation (i.e., grasslands, tundra). The average maximum snow albedo for a given vegetation class was then applied to the region south of 25°N, hence the more homogeneous "look" of the database in this "filled" region. Since there were no maximum snow albedo values for the tropical forest regions in the original database, the maximum snow albedo for this vegetation type was nominally set to the *Matthews* [1983] snow-free albedo for the vegetation type in these regions.

2.4. Snowpack Initialization

[18] Before showing model impact studies, we review how the snowpack is initialized in the Eta model since snow cover and snow depth are important initial conditions for LSMs during winter months in many regions. Previously, only the daily 47-km U.S. Air Force snow depth and sea-ice analysis was used in initializing snow and sea-ice in Eta model forecasts. While not an upgrade in the context of the study here, a 23-km northern hemisphere snow and ice chart (Figure 6) prepared operationally on a daily basis year-round by the Satellite Analysis Branch of the Satellite Services Division of NESDIS [*Ramsay*, 1998] is being used operationally for the Noah LSM in the Eta-EDAS forecast system. This product provides superior information on the areal coverage of the snow and ice using visible imagery of the polar and geostationary (GOES) orbiting satellites as the primary tools for the analysis of this snow and ice cover, and relies on the human-interactive scrutiny of a trained satellite imagery analyst. Low-resolution visible data are used, augmented whenever possible by the visible high-resolution imagery and visible GOES, GMS, and Meteosat data. In addition, ground weather observations and various DMSP microwave products are incorporated into this daily snow and ice chart.

[19] The Eta model initialization interpolates the most recent 47-km U.S. Air Force (USAF) global snow depth analysis [*Kopp and Kiess*, 1996] and the NESDIS snow

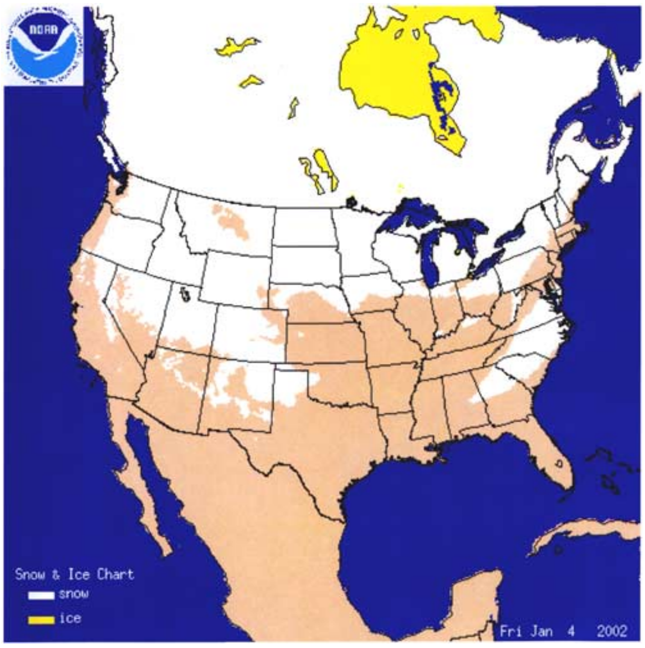

Figure 6. Snow cover over North America based on NESDIS snow cover analysis for 4 January 2002.

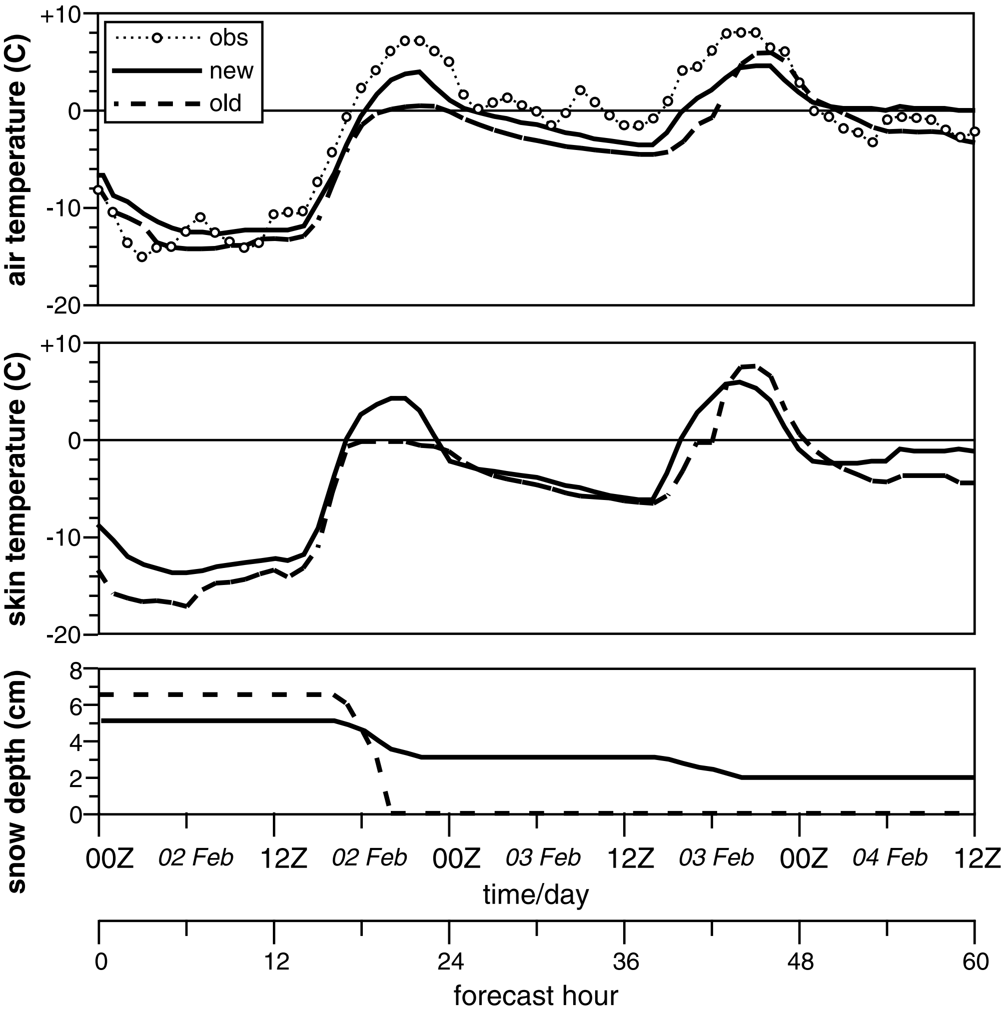

Figure 7. Observed (circles-dotted line) versus modeled (top) 2-m air temperature, (middle) surface skin temperature, and (bottom) snow depth for original (dashed lines) and new (solid lines) Noah LSM formulation for snow cover, at North Platte, Nebraska (60-hour Eta model forecast from 00Z, 2 February 2001). The slight difference in the initial snow depths in the original versus new models reflects the different snowpack evolutions during the prior 24-hr model assimilation and analysis period.

cover analysis to create an initial snow cover and (actual) snow depth analysis for use by the Noah LSM, e.g., in Eta model runs. Snow water equivalent (SWE) is determined from the snow depth assuming a snow density ratio of 5:1. The NESDIS snow cover analysis is used as a quality control for the USAF snow depth analysis; that is, if NESDIS indicates snow cover, the USAF snow depth is used, unless the USAF analysis indicates no snow depth, in which case a minimal value is assigned to the model gridbox (2.5 cm snow depth, which yields 0.5 cm SWE); if NESDIS indicates no snow cover, this is assumed to be the case and any USAF snow depth is ignored.

2.5. Results From Late Winter Snowmelt Case

[20] To assess the performance of the various modifications made to the Noah LSM in a coupled mode, we make several sets of model runs using the NCEP mesoscale Eta analysis and forecast system, that is, model runs made each day for both the 00Z and 12Z cycles, run out beyond 48 hours. These sets consist of Eta model runs made over a period of several weeks to over a month for different times of the year with the results then compared to the operational (control) runs and observations. Additionally, a number of events episodic in nature (case studies) are examined during the periods described above where model output is compared with observations for specific forecast cycles using individual station time series and (horizontal) geographical plots showing Eta model performance.

[21] Under conditions of southerly warm advection over a daytime melting shallow snowpack, surface skin temperature was held at 0°C in the previous formulation in the Noah LSM, resulting in the 2-m air temperature holding near freezing, a condition noted by many NWS field offices and others. In the new Noah LSM formulation with patchy snow cover (section 2.1), the surface skin temperature may rise above 0°C, allowing the daytime 2-m air temperature to rise further above freezing. This is the case for 2 February 2001 at North Platte, Nebraska, in the central United States, where the forecast 2-m air temper-

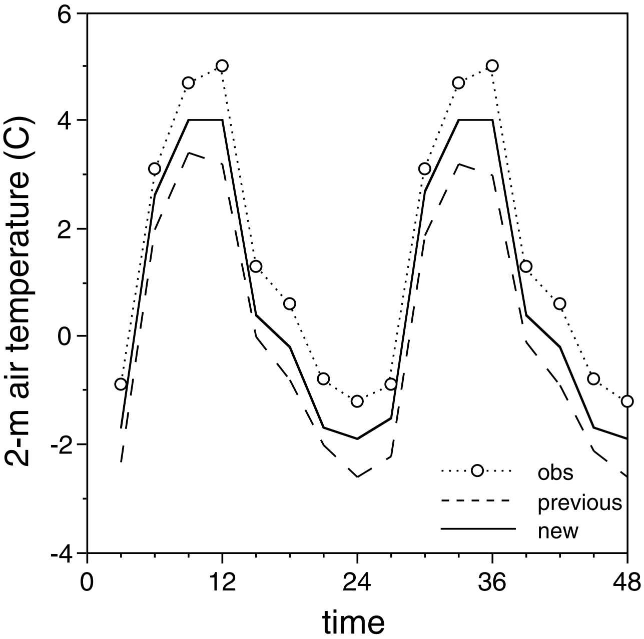

Figure 8. February 2001 monthly composite of 2-m air temperature, observations (circles-dotted line), and previous (dashed line) and new (solid line) Noah LSM for the eastern United States (Eta 12Z cycle).

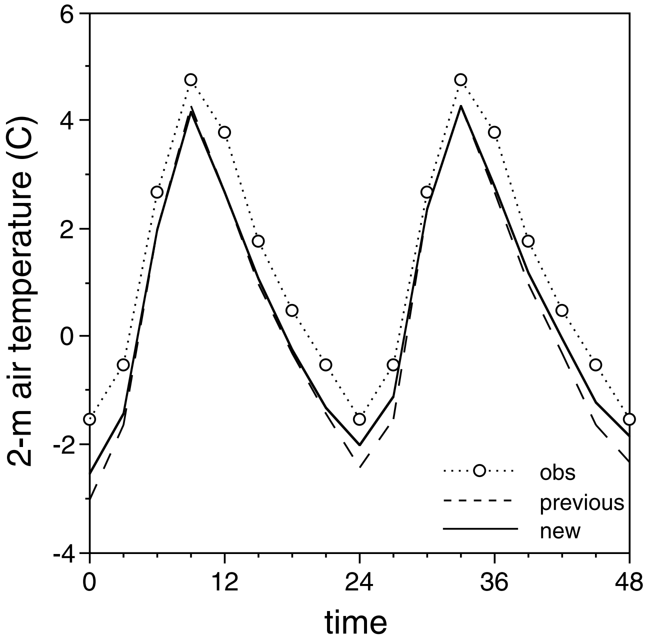

Figure 10. Monthly composite (during January through February 2002) of 2-m air temperature, observations (circles-dotted line), and previous (dashed line) and new (solid line) Noah LSM for the western United States (Eta 12Z cycle).

ature is closer to the observed using the new Noah LSM formulation (Figure 7). So less energy goes toward melting the shallow snowpack (it lasts longer), and more energy goes toward surface sensible heating resulting in warmer 2-m air temperatures and hence a substantial reduction in the daytime cold bias. This also shows up in the closer agreement between forecast and observed midday 2-m air temperatures across this region of shallow melting snowpack (not shown).

[22] In order to assess model performance for longer periods (i.e., monthly) on a regional basis, we utilize the NCEP forecast verification system, which provides statistics on near-surface verification of 2-m air temperature and relative humidity from the operational and test versions of the Eta model. These statistics are generated for 22 different regions covering the Eta model domain, e.g., continental United States and Alaska, and include monthly diurnal time series composites of the 00-hour through 48-hour forecast compared with observations. Monthly compositing allows smoothing of the transient nature of day-to-day variability in weather, so that patterns emerge that help evaluate and understand the diurnal nature of model forecasts related to the Noah LSM. As such, we can see a reduced cold bias with the new Noah LSM reflected in the composite plot of

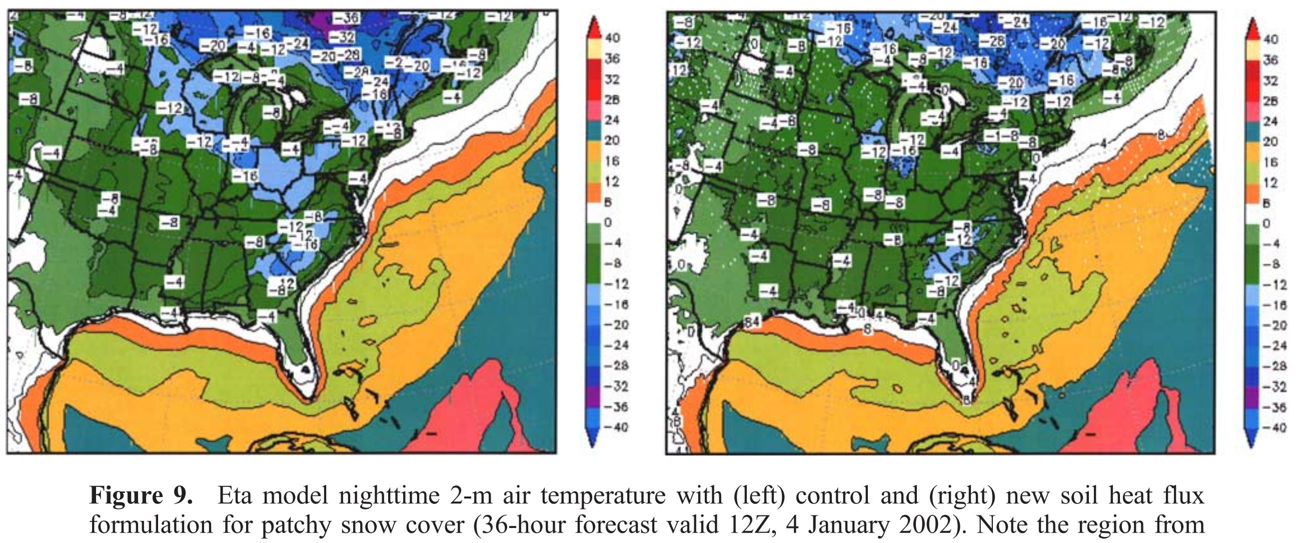

Figure 9. Eta model nighttime 2-m air temperature with (left) control and (right) new soil heat flux formulation for patchy snow cover (36-hour forecast valid 12Z, 4 January 2002). Note the region from northeast Georgia through south central Virginia, and along the "snow line" in the U.S. upper midwest and upper Ohio Valley as seen in Figure 6.

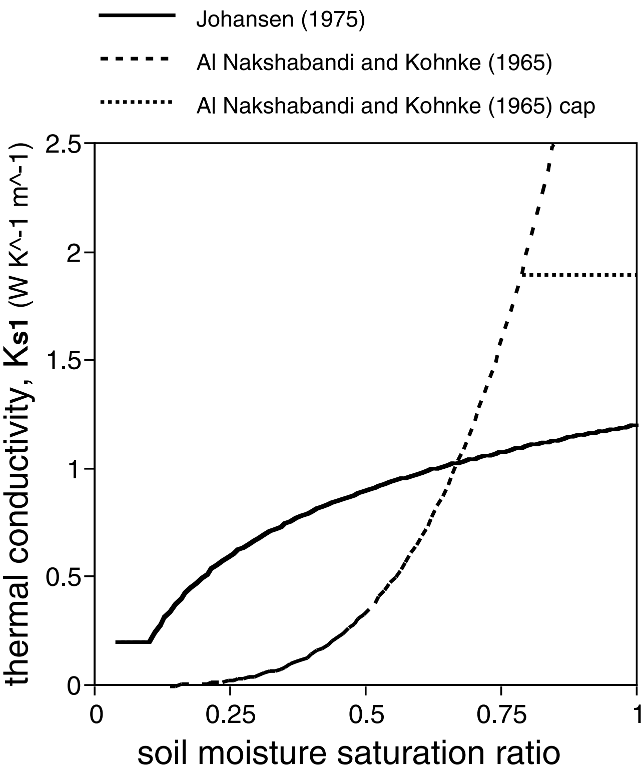

Figure 11. Soil thermal conductivity (K_{s1}) as a function of fractional soil moisture saturation, for the previous Noah LSM formulation following *Al Nakshabandi and Kohnke* [1965] (dashed line) versus the new formulation following *Johansen* [1975] (solid line) for silty clay loam (Noah LSM soil texture class No. 2). The horizontal short-dashed line (at K_{s1} = 1.9 W m^{-1} K^{-1}) represents an earlier attempt to limit (cap) the larger thermal conductivity values via Al Nakshabandi and Kohnke at higher soil moisture conditions.

the diurnal cycles of the 2-m air temperature from the Eta model forecasts for the month of February 2001 in the eastern United States (Figure 8), a region more likely to have patchy snow cover conditions.

2.6. Results From Midwinter Nighttime Cold Bias Case

[23] During early January 2002 a snow event occurred in the southern Appalachian mountains from northeastern Georgia, through South Carolina, and into North Carolina and Virginia (Figure 6). Prompted by reports from NWS field offices, Eta model output was examined and showed a overly-strong temperature drop with a severe cold bias (5–10°C) in near-surface Eta model temperatures across this region after the appearance of snow cover. Using the modified thermal conductivity through the soil and snowpack, which accounts for patchy snow cover (section 2.2), this results in more ''communication'' with the warmer soil below. This gives greater soil heat flux from below at night, partly offsetting the strong nighttime radiative cooling over the new snow cover, resulting in warmer nighttime temperatures (Figure 9). The reduced nighttime cold bias with the new Noah LSM is reflected in the composite plot of the diurnal cycles of the 2-m air temperature from the Eta model forecasts for a month-long period during January through February 2002 in the western United States (Figure 10), a region with more persistent snowpack. The remaining cold bias may be due to too little downward sensible heat flux in the stable boundary layer; underforecast low-level cloud cover and the associated downward longwave radiation may also play a role.

3. Warm Season Processes

[24] While snowpack processes (e.g., snow sublimation) often dominate surface fluxes during the cold season, during the warm season a key component in the surface moisture flux is evapotranspiration via bare soil evaporation and plant transpiration. In the Noah LSM, evapotranspiration is modeled as the sum of transpiration from the plant canopy, direct (''bare soil'') evaporation of soil water from the uppermost soil layer, and direct evaporation of canopy-intercepted water. These quantities come from an evaluation of a single surface energy budget for a given model gridbox. For complete details on plant transpiration and canopy conductance, and canopy evaporation, see *Chen et al.* [1996, section 3.1.2]. The updated bare soil evaporation formulation is discussed in more detail in the next section.

3.1. Bare Soil Evaporation

[25] Direct soil evaporation (E_{dir}) is moisture flux from the nonvegetated (that is, the nongreen portion, or ''bare soil'' for shorthand) fraction of a model gridbox ($1 - \sigma_f$), and originally followed an explicit soil diffusivity formulation for moisture transport at the (bare soil) surface [*Mahrt and Pan*, 1984]. However, modeling experience showed that this formulation results in evaporation that falls off too rapidly as soil moisture declines

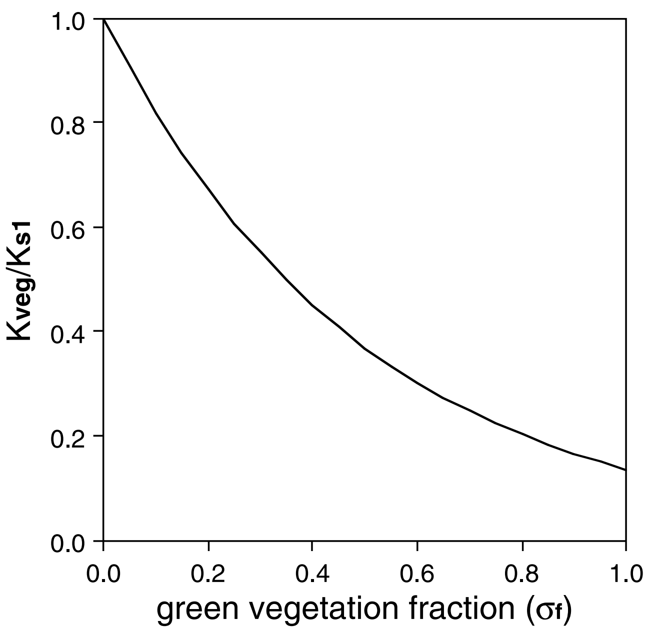

Figure 12. Ratio of soil thermal conductivity under vegetation to ''bare soil'' soil thermal conductivity (K_{veg}/K_{s1}) as a function of green vegetation fraction.

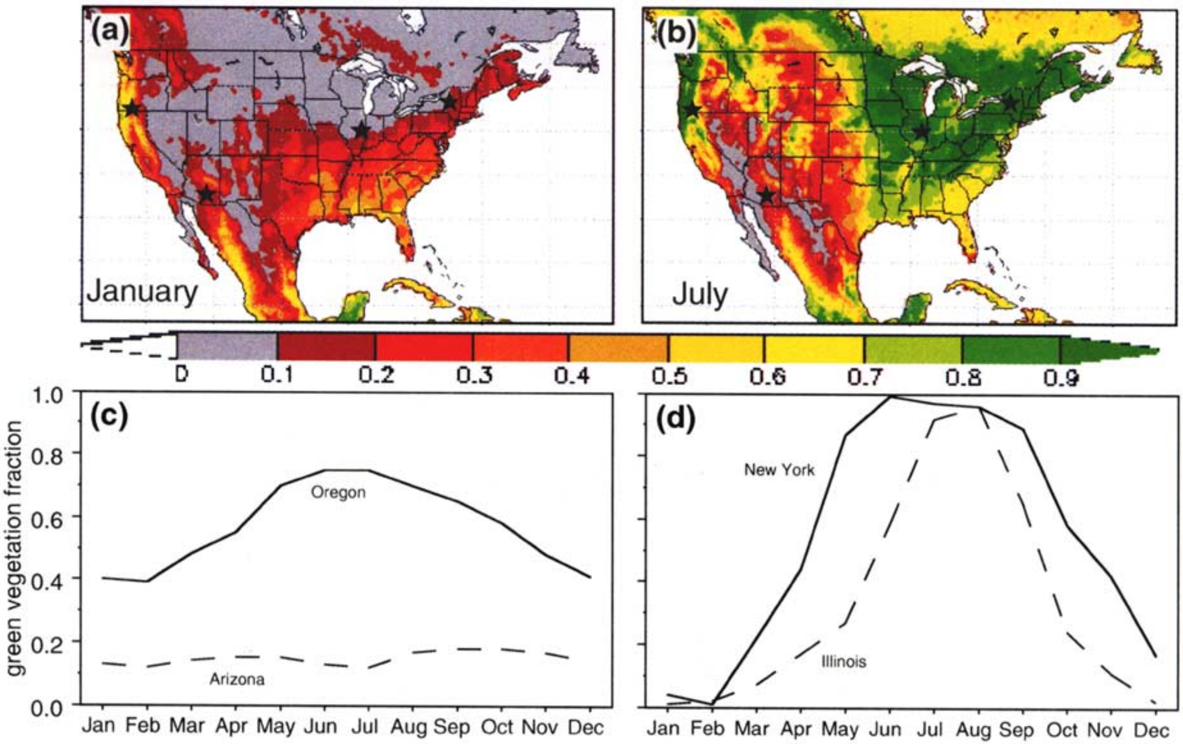

Figure 13. Green vegetation fraction based on NESDIS NDVI-based 15-km, 5-year climatology data set for the United States in (a) January and (b) June, and annual cycle of green vegetation fraction near (c) Medford, Oregon (42.2N,122.6W), and Tucson, Arizona, (32.2N,111.0W), and near (d) Ithaca, New York (43.0N,75.1W), and Champaign, Illinois (40.0N,88.4W).

(reported by *Betts et al.* [1997]); a better alternative is formulated as

$$FX = (\Theta_1 - \Theta_{dry})/(\Theta_{sat} - \Theta_{dry}) \quad (6)$$

$$E_{dir} = (1 - \sigma_f)(FX)^{fx} E_p \quad (7)$$

where FX is the fraction of soil moisture saturation in the upper soil layer, Θ_1, Θ_{dry}, and Θ_{sat} are the soil moisture in the upper soil layer, air dry (minimum), and the saturation (porosity) values, respectively, and fx is an empirical coefficient. Nominally, fx = 1 yielding a linear function (i.e., *Betts et al.* [1997], following *Mahfouf and Noilhan* [1991]), though we have now modified it to be a nonlinear function in order to more properly account for the large gradients in soil moisture near the surface. So with fx = 2, bare soil evaporation falls off more rapidly (in a quadratic manner) as the near-surface soil dries. This nonlinear function then compensates for using the soil moisture content at the typically moister midpoint level of the upper soil layer where FX is evaluated, rather than the more appropriate (and most often drier) soil moisture content at the surface. This then more properly reflects the real process whereby as bare soil dries, the top few millimeters of the soil become significantly drier than the several centimeters below and thus act as a capping evaporative "crust" barrier at the upper boundary of the topmost soil layer.

3.2. Soil Thermal Conductivity Changes

[26] The soil thermal conductivity, including that of the upper soil layer (K_{s1}) used in the calculation of soil heat

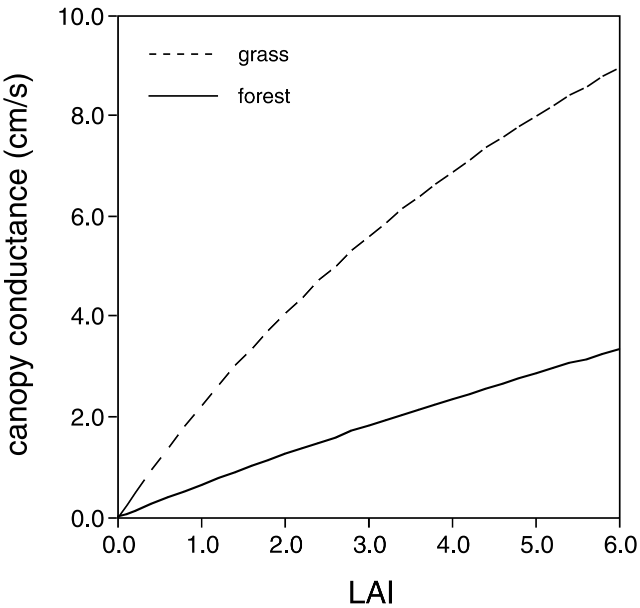

Figure 14. Canopy conductance as a function of LAI for forest (solid line) and grassland (dashed line) vegetation classes, with incoming solar radiation of 800 W m^{-2}, and nonlimiting (no reduction of canopy conductance) effects of air temperature, atmospheric vapor pressure deficit, and soil moisture availability.

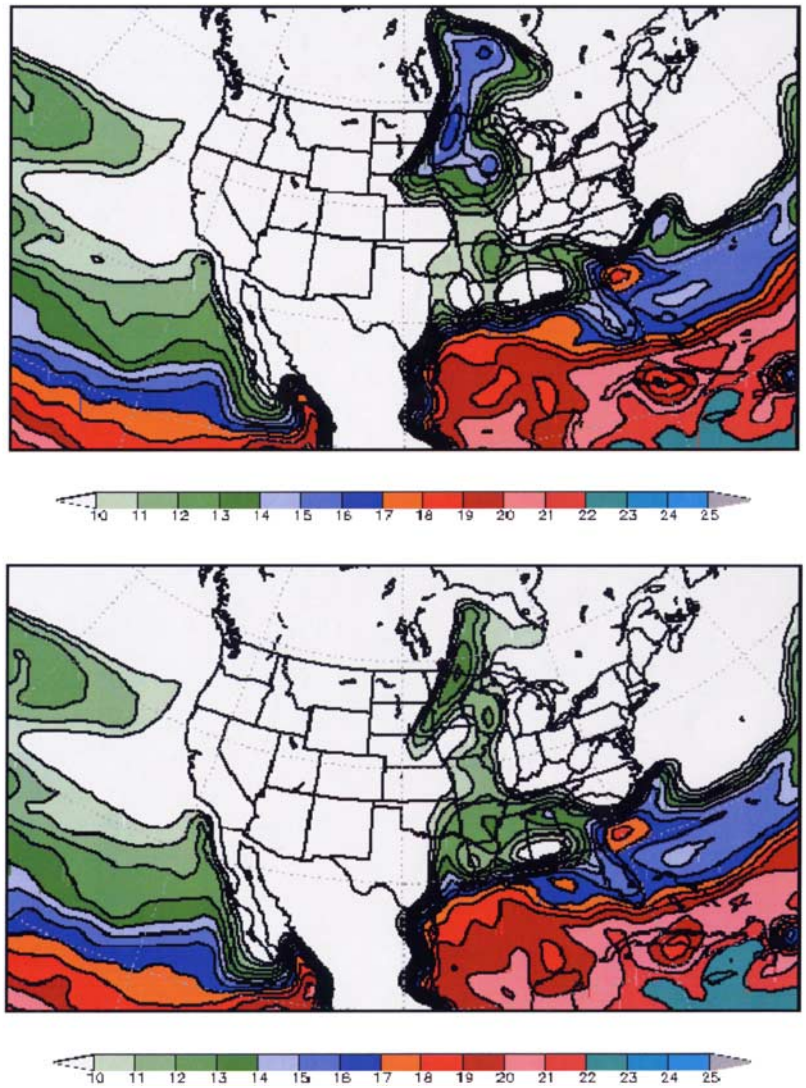

Figure 15. Dew point temperatures for the lowest 30 mb layer (nominally 300 m) above the surface with the (top) old and (bottom) new Noah LSM (60-hour Eta model forecast valid 00Z, 30 April 2001). Note the reduced region of high dew point temperatures using the new Noah LSM over the sparsely vegetated wet soil regions in the U.S. upper midwest and into south central Canada at this time of year.

flux, is a function of soil texture and increases with increasing soil moisture content (equation (4), with $\Delta Z_s = 0$ and $K_{eff} = K_{s1}$). The nonlinear formulation by *Al Nakshabandi and Kohnke* [1965] (described by *McCumber and Pielke* [1981]) has been commonly used in land surface modeling for calculating thermal conductivity, but a less nonlinear function following *Johansen* [1975] has been adopted for use in the Noah LSM (Figure 11). The advantage of *Johansen* [1975] is described in detail by *Peters-Lidard et al.* [1998], and when compared to Al Nakshabandi and Kohnke, the Johansen formulation appropriately yields more (less) thermal conductivity for drier (moister) soils, and thus greater (lesser) soil heat flux, which in turn leads to a more damped (amplified) diurnal signal in the surface skin and near-surface (e.g., 2-m) air temperatures.

[27] In the presence of a vegetation layer, soil heat flux is reduced because of lowered heat conductivity through vegetation. This effect of vegetation may be accounted for explicitly, such as by using the leaf area index (LAI) as in BATS [*Yang et al.*, 1999], or implicitly, such as using a fixed thermal conductivity "coefficient" dependent on surface classification (e.g., sparse vegetation, forest, etc. as in the ECMWF land surface model [*van den Hurk et al.*, 2000]). We adapt the explicit approach applied by *Peters-Lidard et al.* [1997] wherein the soil thermal conductivity under vegetation (K_{veg}) is reduced from the "bare soil" value (K_{s1}) by an exponential function of LAI. Here we adopt a similar alternate formulation using the vegetation fraction (σ_f) instead, where

$$K_{veg} = K_{s1}\exp(-\beta_{veg}\sigma_f), \tag{8}$$

where β_{veg} is an empirical coefficient, nominally equal to 2.0 following tests with the offline Noah LSM (Figure 12). So K_{veg} then replaces K_{s1} in the soil heat flux calculation (again, equation (4), with $\Delta Z_s = 0$, and $K_{eff} = K_{veg}$). We use

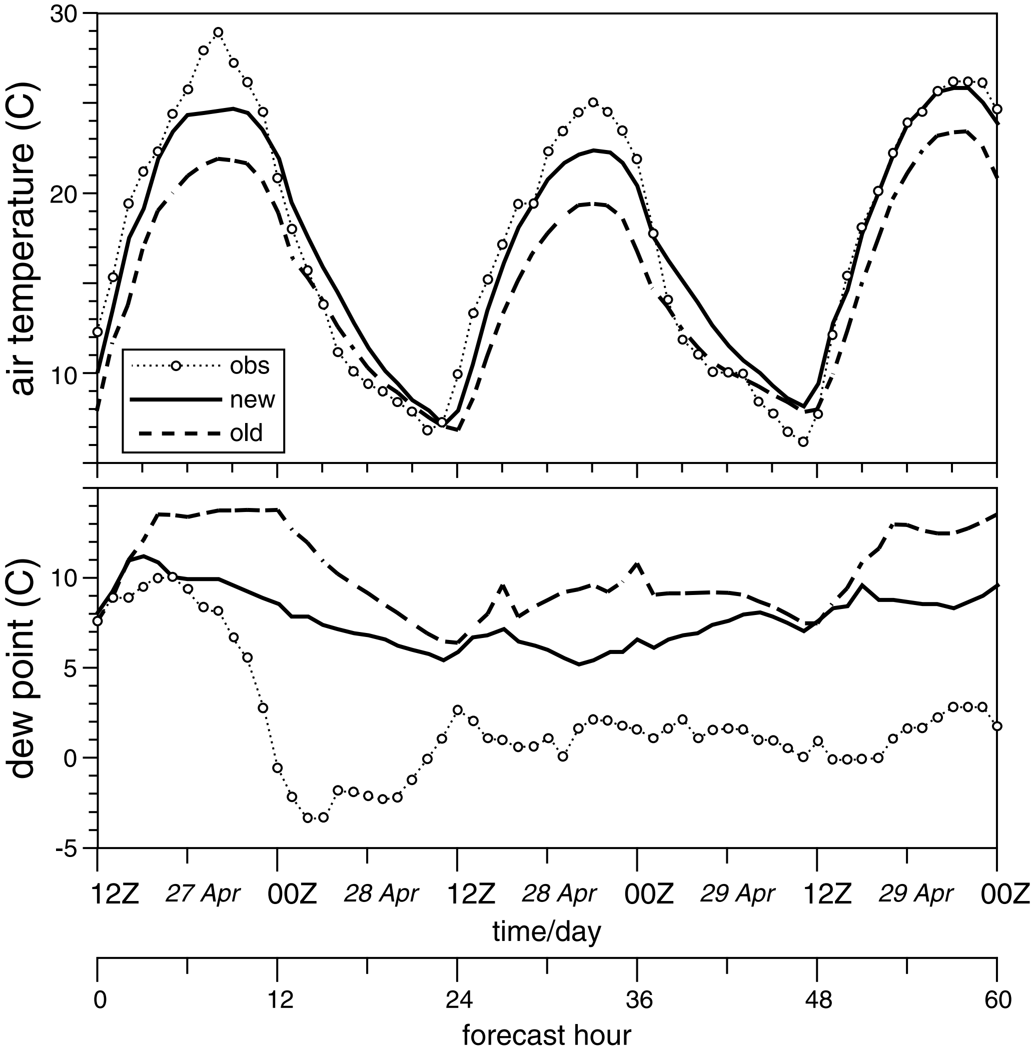

Figure 16. Observed (circles-dotted line) versus modeled (top) 2-m air temperature and (bottom) 2-m dew point for old (dashed lines) and new (solid lines) Noah LSM formulation, at Champaign, Illinois (60-hour Eta model forecast from 12Z, 27 April 2001).

σ_f to account for the seasonal changes in vegetation rather than LAI (see section 3.3).

3.3. Transpiration Refinements

[28] Plant transpiration can provide a dominant source of surface moisture flux especially in regions with large vegetation coverage during the warm season, using energy that might otherwise heat the surface. As such the explicit effects of vegetation have been incorporated into many LSMs used in NWP models, including the Noah LSM. Given a good physical parameterization for plant transpiration, land surface models still require information on the vegetation class, and spatial coverage and seasonal greenness phenology of this vegetation for proper representation of the surface fluxes. Previously, the ISLSCP 1° × 1° monthly green vegetation data set was used [*Sellers et al.*, 1995]; however, experience showed that this data set had a low bias in greenness resulting in a low evaporation bias [*Betts et al.*, 1997]. While not an upgrade in the context of the study here (as with the snow cover and depth analysis described in section 2.4), the monthly NESDIS NDVI-based 15-km, 5-year climatology data set [*Gutman and Ignatov*, 1998] is being used operationally for the Noah LSM in the Eta-EDAS, providing monthly-varying green vegetation fraction for each model gridbox (Figure 13).

[29] The Noah LSM uses the spatially and temporally varying green vegetation fraction (σ_f) to represent the seasonality of vegetation (described above), and treats the vegetation density through the leaf area index (LAI) as a constant for reasons outlined by *Gutman and Ignatov* [1998]. Essentially, in creating their green vegetation fraction data set, *Gutman and Ignatov* [1998] had limited degrees of freedom, such that for a monthly-varying σ_f, LAI had to be fixed with a value on the order of 1–6. This is not entirely surprising since as the greenness fraction within a particular gridbox increases, the LAI under that area (σ_f) does not vary as markedly. Though a modest change, because of a noted underprediction of transpiration in the Noah LSM, we increase the LAI from 1 to 4, which increases the canopy conductance (Figure 14), and thus increases transpiration and decreases surface sensible heat flux.

[30] Additionally, we change the number of root layers (out of 4 total soil layers in the Noah LSM) for a particular vegetation class to more properly reflect the depth of root penetration, and thus the ability to extract water for transpiration. Previously, the number of root layers was fixed (at 3) for all vegetation classes, but is now increased for forests (to 4), though reduced for tundra (to 2). Additionally, the "glacial" vegetation class uses the same rooting depth as tundra since any vegetation greenness in a glacial region is assumed to be due to tundra.

3.4. Results From Early Spring Case With Sparsely Vegetated, Wet Soil

[31] Over wet soils with sparse green vegetation common during early spring, bare soil evaporation dominates the surface moisture flux; soil heat flux is more directly coupled with the atmosphere (because of less green vegetation cover) so the thermal conductivity for bare soil is more important. Under such conditions, previous Eta model testing showed that low-level humidity and temperature were too moist and cool, which resulted in a dampened diurnal temperature cycle because of excess bare soil evaporation, and excess soil heat flux because of too much heat going into (coming out of) the soil during daytime (nighttime).

[32] This deficiency lead to the introduction of more optimal formulations for bare soil evaporation and soil thermal conductivity in the Noah LSM (sections 3.1 and 3.2). Now there is less bare soil evaporation because of a more nonlinear decrease in evaporation as wet soils dry slightly, and less soil heat flux because of reduced thermal conductivity in moist soils. We see that during spring 2001 parallel Eta model testing, in the upper midwest with wet soils and sparse vegetation coverage during this time of year (annual cover that has not yet gone through "green-up"), the previous (new) Noah LSM formulation yields higher (lower) near-surface dew points in the U.S. upper midwest (Figure 15). With reduced surface evaporation and decreased soil heat flux (into the soil) under wet soil conditions, the low-level (e.g., 2-m) air temperature (dew point) is warmer (lower) and compares more favorably with observations (Figure 16). The reduced moist bias with the new Noah LSM is also reflected in the composite plot of the diurnal cycles of the relative humidity from the Eta model forecasts for the month of April 2001 in the U.S. northern midwest region (Figure 17).

[33] In the opposite conditions of dry soil moisture, *Marshall* [1998] and *Marshall et al.* [2003] show that the new Noah LSM soil thermal conductivity formulation yields more soil heat flux for dry soils (refer to section 3.2) during Oklahoma summertime such that an amplified diurnal temperature cycle is reduced, and is closer to the observations.

3.5. Results From Midsummer Case With Large Green Vegetation Fraction

[34] During summer months with large green vegetation fractions, plant transpiration dominates the surface moisture flux; soil heat flux is less directly coupled with the atmosphere (because of more green vegetation cover) so the effect of vegetation on soil thermal conductivity is important. A warm bias in the Eta model is noted in these regions because the Noah LSM produces a canopy conductance that is too low so transpiration is underpredicted, giving more available energy to surface heating (and thus temperatures), which can carry over into the nighttime and next day. This bias is addressed (modestly) via an increase in LAI in the new Noah LSM (section 3.3). This increases the canopy conductance and thus surface moisture flux, reducing sensible heat flux and decreasing the bias in low-level (e.g., 2-m) air temperature (Figure 18). We also note a small reduction in the warm bias with the new Noah LSM in the composite plot of the diurnal cycles of the air temperature from the Eta model forecasts for a month-long period during August and September 2000 in the U.S. northern midwest region (Figure 19).

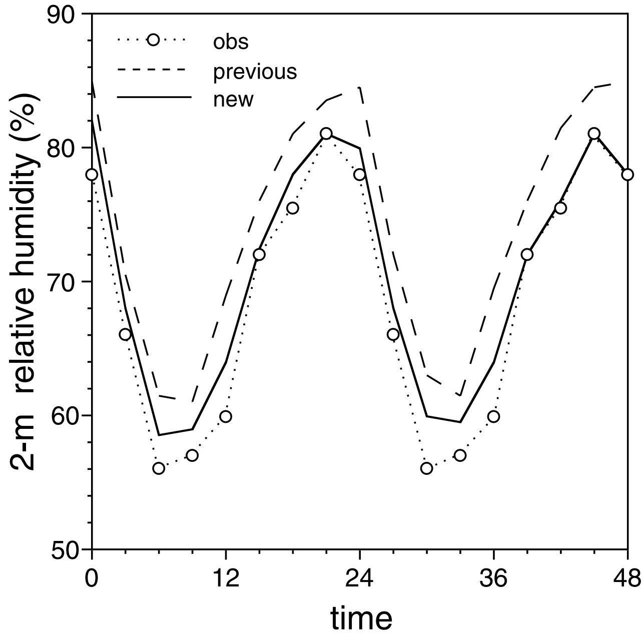

Figure 17. April 2001 monthly composite of 2-m relative humidity, observations (circles-dotted line), and previous (dashed line) and new (solid line) Noah LSM for the U.S. upper midwest (Eta 12Z cycle).

4. Summary and Future Direction

[35] Various upgrades to the Noah land surface model (LSM) have been made to address different biases in the NCEP mesoscale Eta model. We described analyses of various operational and retrospective runs of the Eta model using previous and upgraded versions of the Noah LSM. These analyses included individual case studies, as well as regional monthly composite plots of the diurnal cycles of observations versus Eta model output, which helped us evaluate and understand the diurnal nature of model forecasts related to the Noah LSM.

[36] From these the following conclusions may be drawn:

[37] Upgrading snowpack and adding frozen soil physics are crucial in representing wintertime conditions. The previous cold biases in the wintertime low-level temperatures have been partially mitigated by including patchy snow cover that allows greater surface heating and increased soil heat flux.

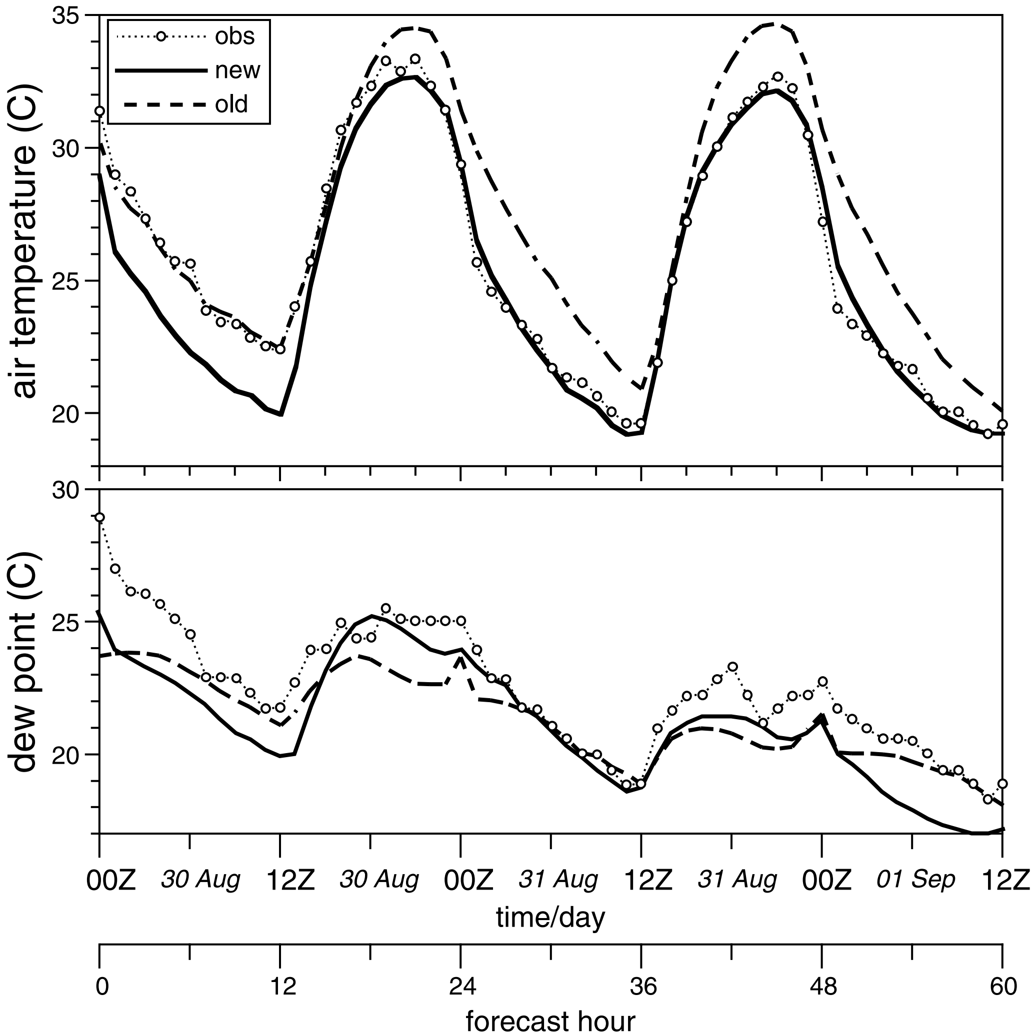

Figure 18. Observed (circles-dotted line) versus modeled (top) 2-m air temperature and (bottom) 2-m dew point for old (dashed lines) and new (solid lines) Noah LSM formulation, at Champaign, Illinois (60-hour Eta model forecast from 00Z, 30 August 2000).

[38] Modifying the bare soil evaporation and soil thermal conductivity formulations is important for typical early spring conditions with wet soils and sparse green vegetation cover. The bare soil evaporation now falls off more rapidly as the upper layer of the soil dries, with reduced soil heat flux, such that previous excess humidity conditions are abated, and a damped diurnal temperature cycle is ameliorated. Leaf area index and rooting depth changes modestly increase transpiration, reduce sensible heat flux and near-surface air temperature, partially addressing the low-level warm bias in the Eta model during the warm season.

[39] The changes to the Noah LSM described in this study have not completely eliminated Eta model biases thought to be attributable to land surface processes. As always, several issues remain to be considered in future work: further cold season modifications to the Noah LSM will be necessary to address the remaining cold season bias. The remaining warm season low-level warm bias in the operational Eta model may be related to the underprediction of the plant transpiration by the Noah LSM as noted in offline studies.

[40] The parameterization of surface layer physics should be re-examined to address the uncertainty in surface fluxes and the effect on low-level temperatures. Of particular interest is a low-level cold bias that may be due to overly-weak downward sensible heat flux, common under night-time clear-sky, weak wind conditions especially over snow cover, and a persistent problem in stable boundary layer parameterization. This cold bias may also be affected by the under-forecast of clouds and the associated downward longwave radiation.

[41] Higher-resolution surface characteristics, such as soil and land-use classes (e.g., as described by *Mitchell et al.* [2003]) and albedo [*Csiszar and Gutman*, 1999] will be tested. Compared to the current vegetation "climatology" used by the Noah LSM in the Eta model, a realtime weekly green vegetation fraction analysis now operational at NESDIS provides a more realistic surface state, and has shown a positive impact on low-level air temperature forecasts in Eta model tests [*Kurkowski et al.*, 2003].

[42] Finally, as a step toward unifying land surface parameterization at NCEP, plans include testing the Noah LSM in

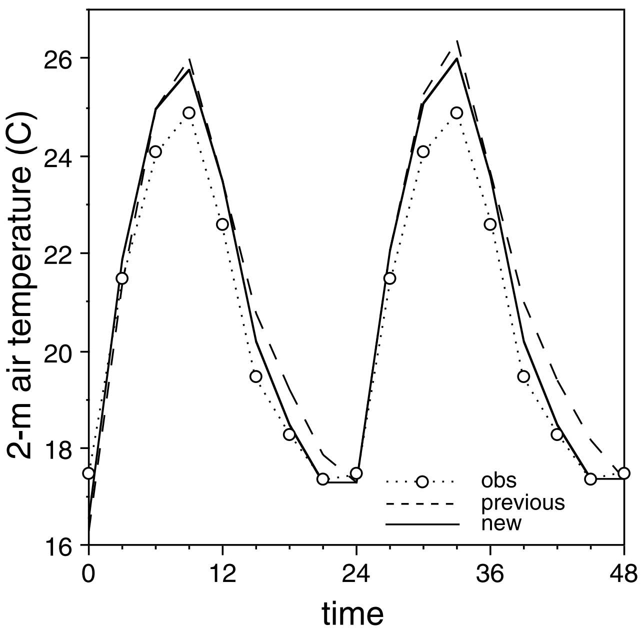

Figure 19. A 12 August to 12 September 2000 month-long composite of 2-m air temperature, observations (circles-dotted line), and previous (dashed line) and new (solid line) Noah LSM for the U.S. upper midwest (Eta 12Z cycle).

all NCEP/EMC weather and climate models. For example, in addition to the Eta model, the latest operational Noah LSM is currently being used in the NCEP 25-year Regional Reanalysis project [*Mesinger et al.*, 2003], tested in the Global Forecast System, and will soon be the default option in the mesoscale Weather Research and Forecasting (WRF) model, to be implemented operationally at NCEP in the future. Such unification allows land surface states, surface characteristics, and model physics parameters to be more easily and appropriately "exchanged" between the various modeling systems at NCEP, and elsewhere using the Noah LSM.

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