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Impact of High Resolution Land Surface Initialization on Convection along the Sierra Madre Occidental

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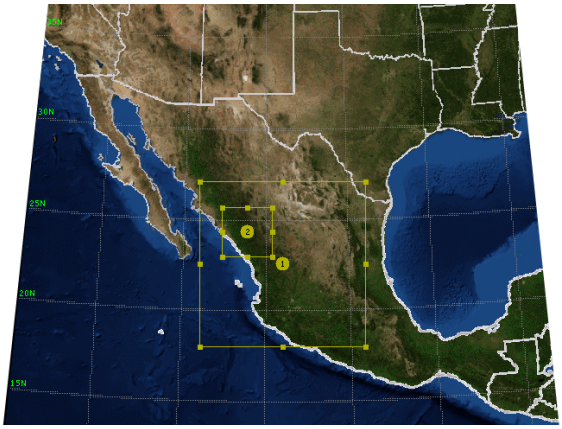

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1. Abstract

Convection within the North American Monsoon (NAM) is characterized by a marked diurnal cycle of precipitation. While identified, the nature of the diurnal convective cycle and its environmental forcing mechanisms are not fully understood, and current climate and weather models fail to represent timing, location, and amounts of precipitation associated with this cycle accurately. This study seeks to utilize a recently developed tool, the NASA Land Information System (LIS), coupled with the Weather Research and Forecasting (WRF) numerical weather prediction model, to examine the role of land-atmosphere interactions such as heat and moisture fluxes on the cycle of precipitation on a diurnal timescale.

Satellite and radar-based observations have provided evidence for a theoretical model of the convective cycle. Shallow convection tends to initiate in higher terrain of the Sierra Madre Occidental (SMO) early in the day, deepening as storms drift westward and encounter increasing moisture and correspondingly higher values of convective available potential energy (CAPE). Subsidence and residual moisture over higher terrain facilitates development of stratus and fog overnight, reducing radiational cooling and enhancing boundary layer moisture, therefore creating a more conducive environment for initiation of convection the following day. Land surface features such as vegetation and soil may alter moisture and energy fluxes enough to play a crucial role in this cycle. Additional moisture from vegetation and soil could aid development of the nocturnal stratus layer, as well as enhance moisture and modulate latent versus sensible heat fluxes over the coastal plain and foothills west of the SMO in support of deep convection.

To investigate these feedbacks, LIS and WRF are set up to run in a coupled manner. LIS is first tested with single-site data, then is run off-line to generate high resolution initial conditions of land surface features. Initial tests of LIS alone show that land surface properties such as soil moisture and soil temperature are highly sensitive to, and dependent upon, the choice of data used for input to the LSM. For the period of a 48-hour case study over August 2-4 2004, LIS and WRF are set up to run in a coupled manner using nested grids with resolution of 1 km on the innermost grid. Future comparisons of LISWRF runs versus runs of WRF alone will allow us to quantify and evaluate the role of moisture and energy fluxes between the land surface and atmosphere within the diurnal convective cycle of the NAM.

2. Introduction

2.1 Purpose of this study

The North American monsoon (NAM) provides life-sustaining seasonal rainfall to typically arid and semi-arid regions of western Mexico and the southwestern United States from May through September. Gochis et al. (2006) has shown that a mountainous subset of this area known as the Sierra Madre Occidental (SMO) receives 50-80% of its annual water resource from precipitation associated with the NAM. Deep convection that develops along the slopes of the SMO is an important part of monsoon precipitation, and has been observed to occur in a daily pattern that may be dependent on smaller-scale features such as orography, land cover, sea breezes, and local moisture transport. It is hypothesized that smaller-scale spatial and temporal features interact with regional and larger-scale dynamical forcings in a way that models are unable to represent well, because the underlying mechanisms and physical processes controlling this cycle of convection are not sufficiently understood (Higgins et al. 2006).

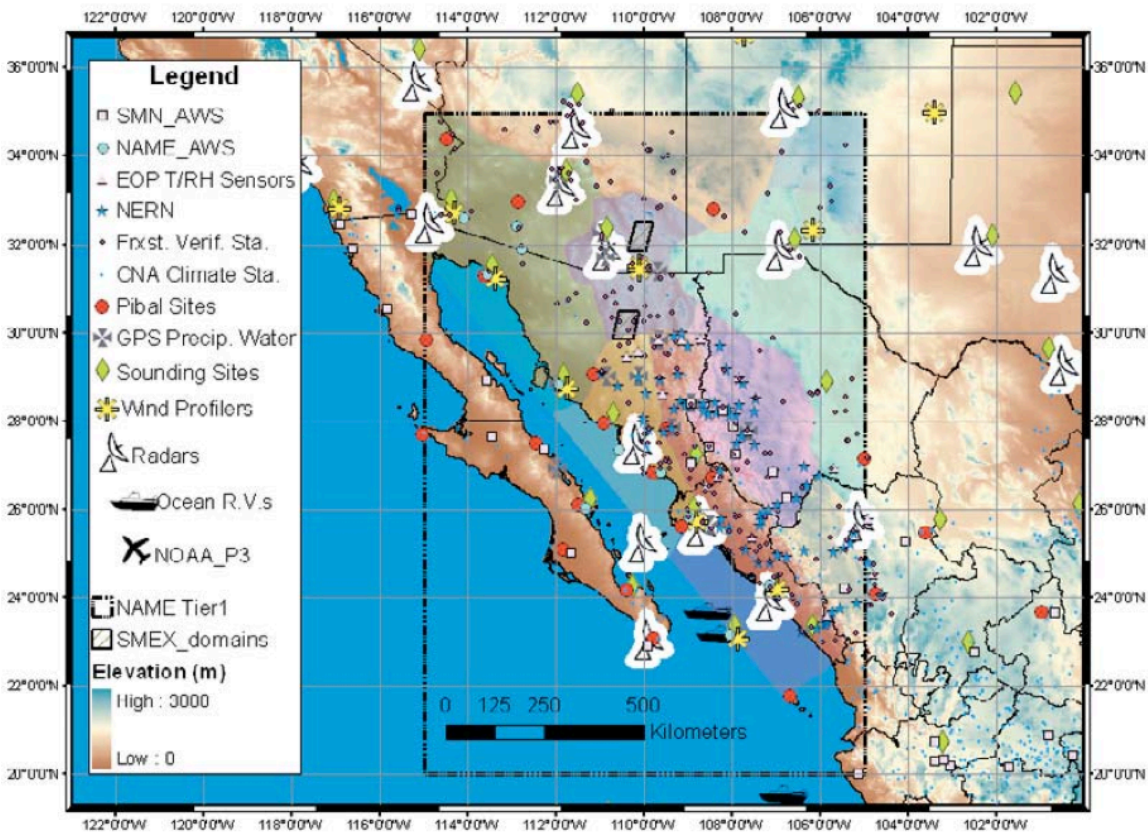


Figure 1. Additional terrestrial-based instrumentation and observing system enhancements used in the North American Monsoon Experiment 2004. From Higgins et al. (2006).

The current thinking on the NAM diurnal convective cycle has emerged from analysis of radar, ground-based, and satellite data obtained as part of the North American Monsoon Experiment (NAME, Higgins et al. 2006). Siting of radar and ground-based instrumentation used in NAME, as well as the area of interest (referred to hereafter as the

NAME region) can be seen in Fig. 1. A summary of the hypothesized meteorological scenario follows, and is explained in more detail by Nesbitt et al. (2008), Ciesielski and Johnson (2008), and Hong (2007).

During the NAM, convective systems tend to initiate in higher terrain of the SMO of northwestern Mexico around 1100-1200 local time (LT) primarily due to more efficient insolation in higher elevations. These convective systems are initially relatively shallow, most likely because of a lack of moisture and therefore lower convective available potential energy (CAPE). Though shallow, they produce precipitation in higher terrain, mostly via warm-rain processes. Storms are steered westward by prevailing winds and intensify as they encounter increasingly available moisture at lower levels, in part from transpiration of vegetation. These deep convective systems initiate around 1500 LT and result in a secondary, more intense, precipitation maximum over the foothills. Occasionally, convection evolves into mesoscale convective systems (MCSs) which propagate north or northwestward into the night. Larger-scale circulations induced by MCSs result in weak subsidence over high elevations of the SMO overnight, facilitating development of stratus and fog (Fig. 2). Nesbitt et al. (2008) proposes that the presence of stratus and fog will reduce surface radiational cooling as well as enhance boundary layer moisture, making foothills and higher slopes of the SMO a more conducive environment for assisting convection the following day. In this way, daily MCS generation could be functioning as a partially self-sustaining process.

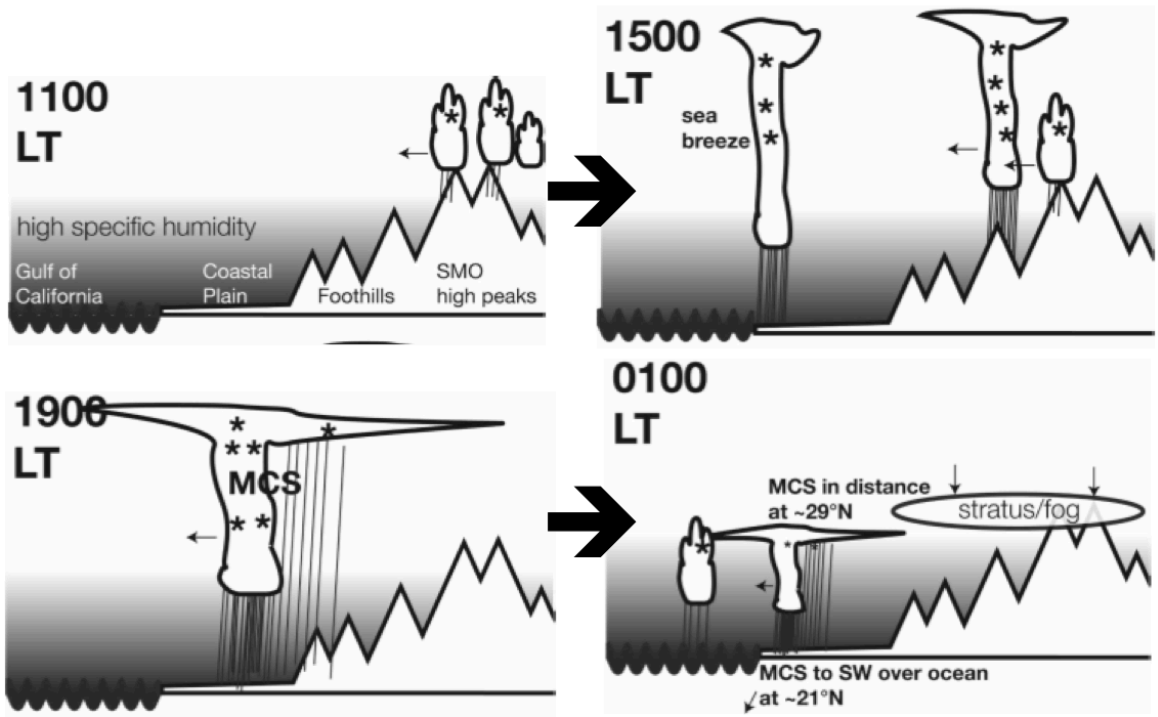


Figure 2. Conceptual diagram of thunderstorm evolution in the North American Monsoon, including diurnal mechanisms, along the Sierra Madre Occidental at 25N. Asterisks indicate mixed-phase microphysical processes, and density of vertical lines indicate locations and relative intensities of precipitation. Adapted from Nesbitt et al. (2008).

Regional and climate models are notoriously poor at resolving the diurnal convection cycle in the NAM (Gutzler et al. 2005). One of the overarching hypotheses of the North American Monsoon Experiment (NAME) is that gaining a better understanding of smaller spatial and temporal scale features, such as the diurnal cycle of convection, will lead to more accurate representation of these features and their interaction with larger-scale dynamical processes in models. Directions for model improvements associated with NAME are guided toward developing better-tuned convective parameterizations and coupling of ocean-atmosphere regional models (Gutzler et al. 2005), leaving the potential for using land surface-atmosphere coupled models unexplored. This is a little surprising due to the nature of the problem. Initiation of these diurnal convective systems is strongly dependent upon temperature and moisture gradients within complex terrain.

One of the well established controls on convection in the NAME region is the prevalence of atmospheric moisture. Not so well established, however, are the sources of moisture, particularly at lower levels. On the synoptic scale (~2000 km), higher-level moisture originates from the Gulf of Mexico, transported westward (and vertically upward) over Mexico, then north/northwestward into the NAME region (Adams and Comrie 1997). Evaporation from the eastern Pacific Ocean and Gulf of California are more significant sources of low level moisture (Berbery 2001). This moisture is transported primarily by to a nocturnal low level jet that occasionally forms over the Gulf of California.

Local moisture sources within the SMO include evaporation from water contained within soils and evapotranspiration from plants. The onset of the monsoon is marked by an abrupt increase in rainfall, and with the rain comes a dramatic proliferation of vegetation. As vegetation coverage and soil moisture increase, exchanges of energy and moisture between the land and atmosphere are altered. Koster et al. (2004) used a suite of GCMs to identify regions across the globe of high seasonal "coupling strength," where atmospheric conditions were strongly influenced by anomalous soil moisture conditions. One of these regions over North America extended from the central US south and westward into Mexico to include the NAME region. Dominguez et al. (2008) targeted the NAME region and surrounding areas in assessing the contribution of "recycled" precipitation to total precipitation in monsoon season. A significant portion (15-25%) of rainfall here is "recycled" by re-entrance to the atmosphere through evaporation from soils and evaportranspiration from plants. Other recently-published literature (Ciesielski and Johnson 2008, Nesbitt et al. 2008) has indicated that examining the role of land surface-atmosphere moisture and radiative fluxes in the diurnal convective cycle of the North American Monsoon (NAM) is a worthy topic for further investigation.

In order to simulate complex interactions on different scales (local, mesoscale, synoptic) and across multiple scientific disciplines, models must be capable of representing the involved dynamical processes adequately. Datasets representing the land surface features must also be as up-to-date and accurate as possible. Unfortunately, high-resolution land surface datasets and meteorological observations are not available for the NAME region. Additional instrumentation and observing system enhancements during NAME 2004 provide a more well-rounded meteorological dataset to judge model

performance by, however. By using a coupled land surface and atmospheric modeling system with existing databases of land surface parameters, we can infer potential influences of differing land surface characteristics on the diurnal convective cycle.

2.2 Coupled Land-Surface and Meteorological Models: LISWRF

The recently coupled Land Information System (LIS) and Weather Research and Forecasting (WRF) model, known jointly as LISWRF (Kumar et al., 2008), is a model system capable of representing land-surface and atmospheric interactions in an interactive manner. Case et al. (2008) indicate that strengths of the LISWRF lie in its ability to represent terrain and land surface data at high resolution, which improves temperature and dewpoint forecasts as well as timing and location of sea-breeze fronts on a diurnal timescale, as demonstrated in a case study over northern Florida. Case studies of the NAM over the SMO are therefore a timely and worthy challenge to test the strengths of the LISWRF, as well as the diurnal convection cycle hypothesis. Through LISWRF, we will be able to utilize the most current surface datasets at resolutions of up to 1 km to assess the importance of proper initializations of the land surface, in particular, soil moisture, on convection in the SMO. Information regarding energy and moisture fluxes as simulated by the LISWRF will help us better understand these diurnal cycles.

3. Methodology

3.1 Experimental Design

In order to become familiarized with LIS, year-long model runs focused on two climatologically differing sites in the United States. One site was Bondville, Illinois, situated in cropland with silt-loam soil which experiences a moist, humid climate, and the second site was Walnut Gulch, Arizona, situated in desert-like terrain with coarse-loam soil which experiences a dry climate – more representative of the NAME region. Initial year-long tests were run using data from 2003 in order to judge sensitivities of LIS and the chosen Land Surface Model (LSM) to various types of meteorological forcing data. After these initial tests were run, LIS and WRF were set up with the same grid size and domain for a case of cyclic diurnal convection in early August 2004 over the SMO (Nesbitt et al. 2008). LIS was first run alone in order to "spin up" land surface initial conditions to be used with the WRF, then WRF was run for a 48-hour period without initial conditions from LIS. The LIS "spin-up" initial conditions were compared to the initial conditions standard to WRF. In future work, more in-depth comparisons will be made on different varieties of land-surface initialization, and LIS and WRF will be run coupled mode in order to compare and contrast evolution in convection.

3.2 Meteorological Model: WRF

The Advanced Research WRF (WRF-ARW; Michalakes et al. 2001, Skamarock et al. 2005) is a state-of-the-art mesoscale numerical weather prediction model. This model uses an Eulerian mass dynamical core, and is set up to be highly customizable by the user with an assortment of radiation, microphysics, and boundary layer schemes to choose

from. WRF also allows for 1-way and 2-way nesting with multiple nested domains. This study utilizes WRF version 2.1.2, which has been linked with LIS to allow users to run a variety of LSMs with the WRF (Kumar et al. 2008).

Initialization of land cover when WRF is run alone typically comes from an interpolation of a coarse dataset such as the Global Data Assimilation System (GDAS; Derber et al. 1991). A major benefit to using LIS with WRF will be the direct translation and usage of datasets produced by LIS and WRF separately. Calculated land surface conditions will be on the same grid as the meteorological model, allowing WRF to use this data directly for calculations.

3.3 LIS and Land Surface Model

LIS (Kumar et al. 2006, Peters-Lidard et al. 2007, Kumar et al. 2008), developed at the NASA Goddard Space Flight Center, is a land surface modeling framework designed to streamline the task of processing and using data in one-dimensional land surface models (LSMs). Standards according to the Assistance for Land-surface Modeling Activities (ALMA, 2002) are used to ensure consistency of variables and sign convention in land-surface models. Land surface models use parameter datasets of soil and vegetation, and meteorological forcing datasets to compute transfers of mass, energy, and momentum between the land surface and atmosphere. Eight LMSs are included in the most recent publicly available version of LIS, LISv5.0, however this study was constrained to use only the Noah LSM (Ek et al. 2003) due to it being the sole LSM mutually used by both LIS and WRF.

LSMs dictate where energy and water (from meteorological forcing input) go upon intercepting the land surface. Noah v2.7.1, otherwise known as the operational Noah LSM (Ek et al. 2003), solves moisture and heat transport through four soil layers. Soil type and vegetation type are designated through the use of look-up tables, while parameter datasets of quarterly albedo, monthly greenness, maximum snow albedo, and bottom temperature (without elevation correction) are used. Noah requires near-surface air temperature and specific humidity, incident short-wave and long-wave radiation, eastward and northward wind components, surface pressure, and precipitation rate as inputs. When these inputs are provided either from a model-generated forcing dataset or from meteorological observations, Noah outputs variables such as soil moisture and soil temperature for all four layers, sensible heat flux, latent heat flux, and ground heat flux. The Noah LSM is used in this study for running in synchronization with WRF through LISWRF, and also for spin-up.

Spin-up is a term for priming a land surface before a coupled run with meteorology. The purpose of a spin-up is to allow a land surface to run “offline,” or uncoupled, for many years with meteorological forcing data until a thermodynamic equilibrium is reached. This is necessary because features of the land surface, such as soil moisture, have “memory” that is on significantly longer timescales than meteorology, and can influence local meteorology. Rodell et al. (2005) recommends that spin-ups be done for a period as long as possible prior to initialization of the meteorological model. Further,

Rodell et al. (2005) notes that arid regions are particularly slow to adjust after an anomalously wet or dry initialization. This will likely be important for the arid and semi-arid conditions present in the NAME region, so a preferable spin-up period for this study would likely be at least 10 years, with a dataset at high spatial resolution.

3.4 Test Case Setup

3.4.1 Meteorological Setup

Test cases were run using only LIS with the Noah LSM. Meteorological forcing used in test cases came from model-assisted datasets as well as direct observations from flux towers at Bondville, IL and Walnut Gulch, AZ. LIS with Noah was run independently for the entire year of 2003 at both sites varying only the meteorological forcing data in order to observe differences in output, such as soil moisture and sensible and latent heat fluxes, for meteorologically important variables.

NCEP's Global Data Assimilation System (GDAS; Derber et al. 1991) is a model-derived meteorlogical forcing dataset with a spatial resolution of 0.313 degrees and temporal resolution is every 6 hours, reduced to 3 hours for use with LIS. This dataset contains all variables necessary for running LIS (see Table 1) and has global coverage, however, is used at the expense of its rather coarse resolution. GDAS data from January – December 2003 was obtained from NASA.

Bondville, IL, situated in cropland, is the site of a Coordinated Energy and water cycle Observations Project (CEOP) flux tower. Data was provided by NCAR/EOL under sponsorship of the National Science Foundation (http://data.eol.ucar.edu) and was obtained online (http://www.eol.ucar.edu/projects/ceop/dm/). Station pressure, air temperature, dew point, relative humidity, specific humidity, wind speed and direction, precpitation, snow depth, incoming and outgoing shortwave radiation, incoming and outgoing longwave radiation, net radiation, skin temperature, and incoming and output photosynthetically active radiation (PAR) are recorded according to local and UTC time. Not all of these variables are necessary for LIS, however (Table 1). LISv5.0 was set up to read in data according to the format set up during CEOP-EOP 1 in 2001. During the 2003 CEOP-EOP 3, the format was changed with data collected at 30 minute intervals instead of only on the hour, and datasets included flags that indicated quality of data. Some manipulation of the EOP-3 dataset was required in order to conform to the type of input LIS expected, which was performed with a FORTRAN program.

Walnut Gulch, AZ, situated in a desert environment, is the site of a Soil Climate Analysis Network (SCAN) flux tower and measurement site. Data is available courtesy of the United States Department of Agriculture Natural Resources Conservation Service (www.wcc.nrcs.usda.gov) and data used in this study was obtained online (http://www.wcc.nrcs.usda.gov/scan/). Precipitation, air temperature, relative humidity, wind speed and direction, solar radiation, barometric pressure, snow water content, snow depth, soil moisture, and soil temperature are recorded according to local time. A

FORTRAN program was written in this case as well to convert parameters in the dataset in order to conform to the LIS expected input format.

LIS Forcing Variables	Noah	Bondville	Walnut Gulch	GDAS
Near-Surface Air Temp	x	x	x	x
Near-Surface Specific Hum	x	x	x (convert)	x
Incident SW Radiation	x	x	x	x
Incident LW Radiation	x	x		x
Eastward Wind	(wind speed)	x	x (convert)	x
Northward Wind	(wind speed)	x	x (convert)	x
Surface Pressure	x	x	x (convert)	x
Rainfall Rate	x	x	x (convert)	x
Snowfall Rate				x
Convective Rainfall Rate				x

Table 1. Forcing variables required for LIS and Noah, as compared with what variables are present in the Bondville CEOP site observations, the Walnut Gulch SCAN site observations, and GDAS dataset. X's represent requirement of data for LSMs and presence of data in datasets.

3.4.2 LIS Setup

For the test cases, LIS was run at 1km resolution over individual sites for the year of 2003 on 3x3 domains, centered on either Bondville, IL or Walnut Gulch, AZ. Both sites used the same soil tables and vegetation tables, as well as parameter datasets. Soil properties in Noah are assigned according to the Food and Agriculture Organization (FAO) dataset, which is constructed from 5-minute soils datasets of uniform sand, silt, and clay percentages (Reynolds et al. 1999). For land cover, a 24-class USGS 1 km dataset assembled by the University of Maryland (Masson et al. 2003) is used. The global vegetation static 1 km parameter dataset also was assembled by the University of Maryland. Monthly greenness vegetation fraction data was derived from the Gutman and Ignatov (1998) AVHRR global monthly 5 year climatology, at 0.1444 degree resolution. The coarseness of this dataset, with resolution ~15 km, may have a significant effect on the resolution of LIS and LISWRF model run results. Deep soil temperature (used as a lower bound for soil layers) was derived by Chen and Dudhia (2001) from six years of GDAS 2 m temperature data, averaged in 3 hr intervals. Quarterly snow-free albedo (Briegleb et al. 1986) and maximum snow-free albedo (Robinson and Kukla 1985) are also required by Noah.

3.5 LISWRF Setup

3.5.1 Meteorological Setup

Nested WRF simulations were performed with 2-way interaction for the 48-hour period of 00 UTC August 2 – 00 UTC August 4 when a cycle of convection and stratus were observed over the SMO by Nesbitt et al. (2008). The outer domain has a resolution of 5 km centered over western Mexico and the NAME region, and the inner domain has

horizontal resolution of 1 km, centered on the specific region of the SMO of interest in Nesbitt et al. (2008). 41 vertical levels were used in order to directly coincide with the vertical levels in the NARR data. No convective parameterization was used for either domain. Timesteps used for advection were 30 seconds for the outer 5 km domain, and 6 seconds for the inner 1 km domain. The WSM-6 microphysics scheme, longwave Rapid Radiative Transfer Model scheme, shortwave Dudhia scheme, Monin-Obukhov surface-layer physics scheme, and Mellor-Yamada-Janjic (Eta) turbulent kinetic eddy scheme were implemented as well. Boundary conditions were assigned by the North American Regional Analysis (NARR; Mesinger et al. 2006). NARR has a 32km horizontal resolution, with 41 vertical levels and 6-hourly data, and was obtained through the National Climatic Data Center (NCDC) online portal.

The default land surface initialization in WRF is the USGS 24 category dataset, which is derived from 1 km AVHRR data collected 1992-1993 (Eidenshink and Faundeen, 1994). A more recent MODIS 20-category land use dataset is available for use only with the Noah LSM, but was not used in this study. Future work will incorporate this more up-to-date MODIS dataset.

3.5.2 LIS Setup

Due to time constraints, a coupled run of LISWRF was not possible within the time of the 10-week program. Future plans for this project include using the GDAS forcing dataset and LIS-Noah with nested grids to spin up initial conditions for use with WRF. Using meteorological forcing data from NARR is also a possibility, but a specific reader would have to be developed for LIS to use this dataset. For purposes of comparing a hypothetical LIS spin-up initialization to a standard WRF initialization of land surface features, a short spin-up of Noah was performed with GDAS data from January 2004-August 2004 at 1 km resolution. The same parameter datasets for LIS and Noah were used as detailed in section 3.4.2.

4. Results and Discussion

4.1 Test Cases

A suite of tests were run at 1 km resolution to examine sensitivities to meteorological forcing datasets at Bondville, IL, and Walnut Gulch, AZ. LIS was run for the full year of 2003 at each site with forcing data only (one run with GDAS, one run with GDAS plus the local observational dataset), and then with forcing data and the Noah LSM (one run with GDAS and Noah, one run with GDAS and the local observational dataset with Noah). Test runs with forcing data only (no LSM) had limited use, as the data was processed through LIS no calculations took place so the forcing data was regurgitated. Test runs with the LSMs were more useful.

At both sites, significant inconsistencies were seen in the rainfall data. This was not too surprising, as GDAS data at a resolution of over 30 km cannot be expected to accurately represent precipitation at a point within a gridbox. When calculating the

difference between GDAS precipitation and gauge precipitation at Bondville, it became clear that GDAS data is consistently overestimating rainfall (Fig. 3, left). In fact, slight but nearly continuous overestimations in rainfall on the range of approximately 3 mm resulted in a significant bias in soil moisture at all levels, but most notably in the top soil layer (Fig. 3, right). Similar results were seen at Walnut Gulch, AZ (not shown).

The consistent light precipitation in the GDAS data is reason enough to suspect other parameters that will be affected. If GDAS is producing precipitation, it is most likely cloudy in that model gridbox, altering shortwave and longwave radiative fluxes, temperature, and more. Erroneously high soil moisture values would likely result in higher moisture fluxes from the surface, which might increase instability within lower levels of the atmosphere. Therefore, it is of primary importance for studies on convective initiation to use the best precipitation forcing datasets available.

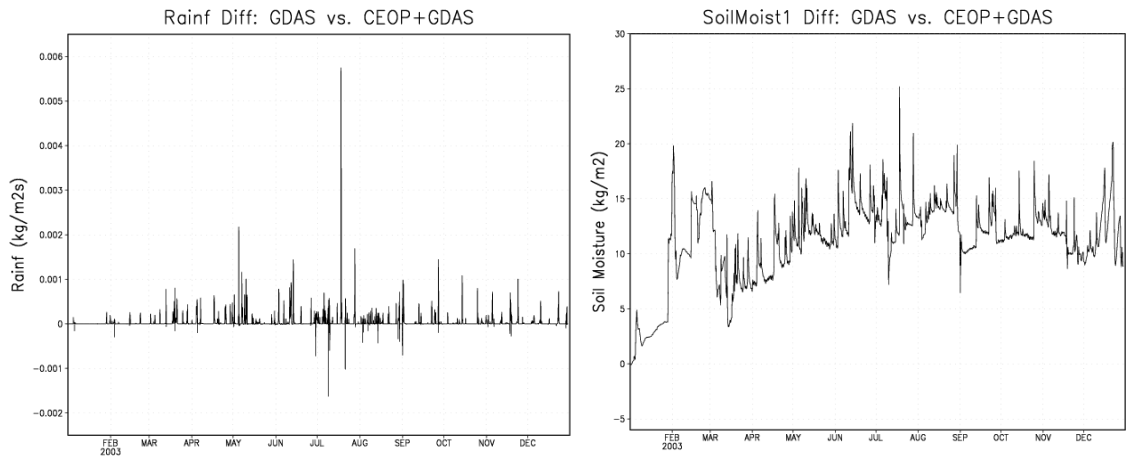


Figure 3. Year-long LIS runs at Bondville, IL. In the left panel, the difference between rainfall forcing datasets is shown: rainfall from the GDAS meteorological forcing dataset and rainfall from the observations taken at Bondvillle CEOP site. In the right panel, the difference between the topmost soil layer moisture as output by LIS/Noah is shown.

Seasonal site-to-site comparisons were performed with GDAS data in order to contrast the two sites' climatological energy and moisture fluxes. Output from June, July and August 2003 were averaged on an hourly basis and viewed from a diurnal timescale. This seasonal analysis was only performed for the summer season because the phenomena of interest occurs in summer. In general, the "signatures" in latent heat, sensible heat, and ground heat fluxes that were seen were appropriate representations of their respective climatic and vegetation conditions.

In Bondville, the dominant energy flux is latent heat, which experiences a sharp increase after sunrise and rises to an afternoon maximum (Fig. 4). Sensible heat flux exhibits a similar pattern but is slightly lower in magnitude. This type of diurnal heating profile can be expected from moist climatic regions with vegetation or crops (Stensrud 2007). The partition of latent and sensible heat is even more dramatic at Walnut Gulch, where sensible heat is the dominant energy flux in the daytime. The vegetation coverage (or lack thereof) and soil type again plays a major role in determining how energy is retransmitted from Earth's surface.

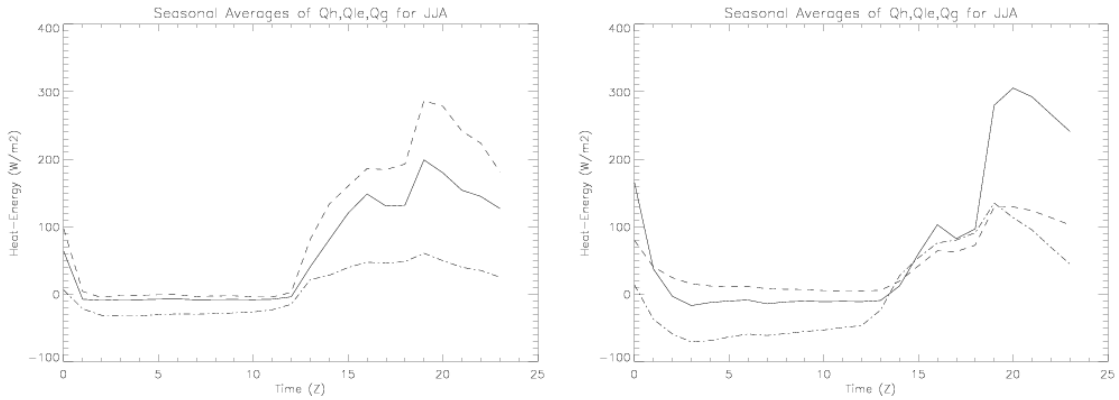


Figure 4. Hourly comparison of seasonally averaged (JJA) sensible heat flux (Qh, solid line), latent heat flux (Qle, long dashed line), and ground heat flux (Qg, short dashed line) for Bondville, IL (left), and Walnut Gulch, AZ (right).

Notable in the seasonal averages in Fig. 4 at both sites is an anomalous dip near 18 UTC. This deviation from the otherwise smooth fluxes is certainly in error, and may be due to the small domain size used, or the extrapolation of GDAS data from 6 hours to 3 hours (Hiroko Beaudoing, personal communication). This anomalous dip did not appear when using CEOP or SCAN data.

Another way of visualizing the relative contributions to energy from latent and sensible heat fluxes is through the Bowen Ratio. This value is typically more significant during daytime hours, or after 12 UTC as shown in Fig. 5. Simply defined as a ratio of the sensible heat flux to latent heat flux, its value can be as high as 5 in semi-arid regions, and near 0.2 over irrigated orchards or grass (Stensrud 2007). The Bowen ratio for Walnut Gulch exceeds 2 in the afternoon, even with overestimated soil moisture values due to excessive light rain seen in GDAS forcing data earlier. Bondville's Bowen ratio is near, but slightly below 1, indicative that latent heat flux plays more of a role.

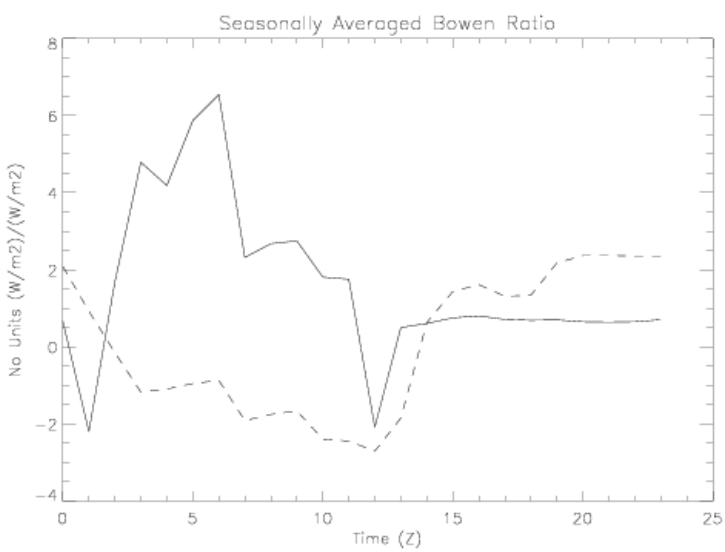


Figure 5. Hourly comparison of seasonally averaged (JJA) Bowen Ratio at Walnut Gulch, AZ (dashed line) and Bondville, AZ (solid line).

4.2 Comparison of LIS and WRF Initial Conditions

Due to time constraints, a coupled run of LISWRF was not possible. However, LIS was run for January 2004-August 2004 and 1 km resolution initial conditions were compared between LIS and default initial conditions for WRF. Four variables are compared in Fig. 6.

The first pair of panels in Fig. 6 show differences between downward longwave flux. This variable is highly sensitive to cloud cover and elevation. Ridges (blues and purples) and valleys (oranges and reds) are prominently displayed at high detail, due in part to the higher resolution inputs of elevation, vegetation, and soil properties. It is important to note that though the LIS data appears to be of superior quality, that with lack of high-resolution observations in this area there is no way currently to quantify this assumption.

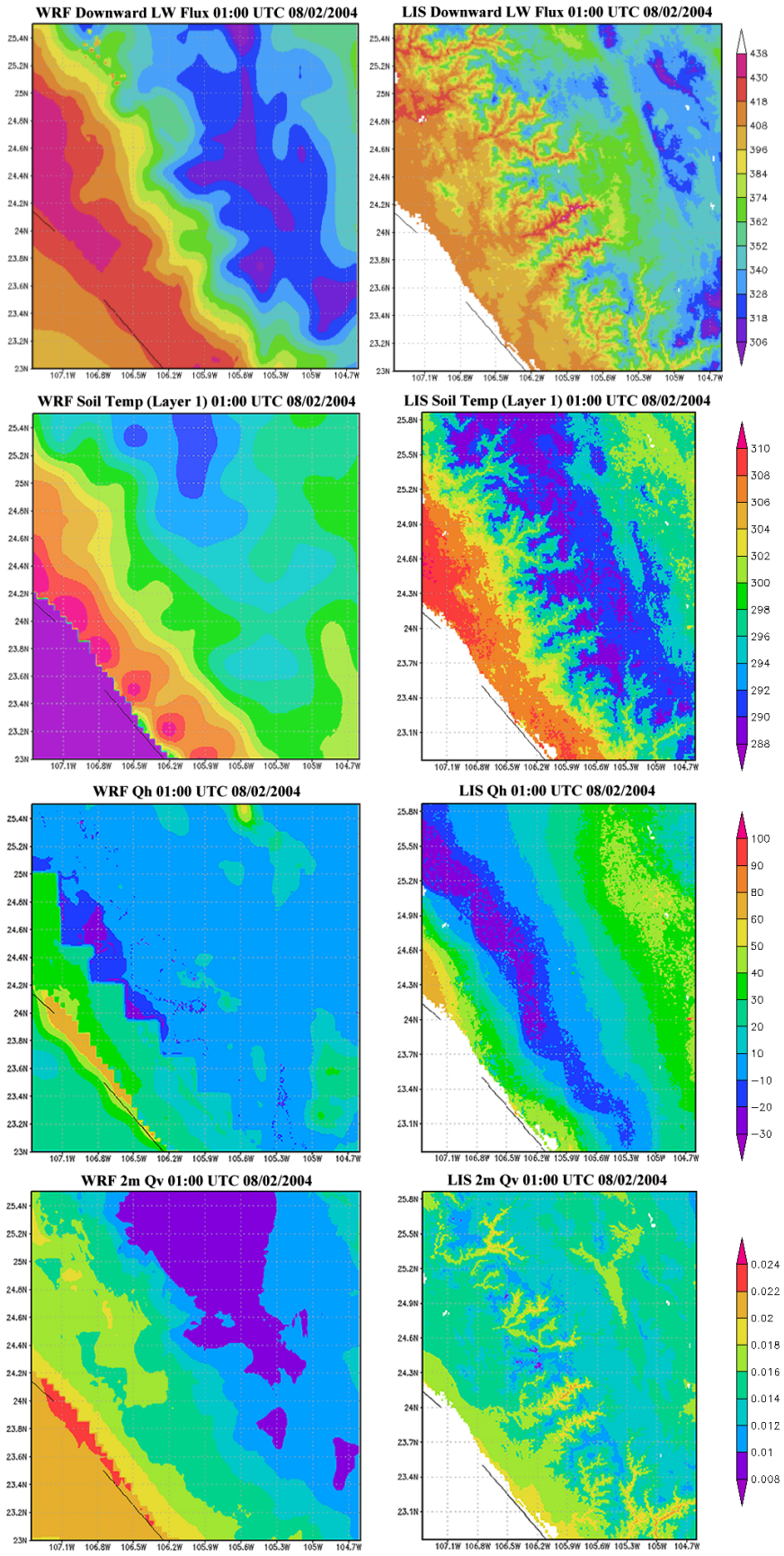
Soil Temperature within the first layer as defined by the Noah LSM is compared in the second set of panels in Fig. 6. Soil temperatures in LIS are seen to be highest near the coast, and follow dendritic valley pathways into the higher terrain inland. WRF initialization certainly captures the major features, but it easy to see that in this region of complex terrain that the gradients in soil temperature are not being adequately represented, and this has effects on the thermodynamic environment.

Sensible heat fluxes are featured in the third set of panels in Fig. 6. Latent heat fluxes were also analyzed but were clearly at the mercy of the vegetation and soil type datasets used in LIS and WRF, which are at a rather coarse resolution. Where the LIS output shows negative heat fluxes, clouds and precipitation are in the vicinity. WRF resolved several individual clusters of storms, while LIS and GDAS may have had more widespread precipitation features.

The last set of panels in Fig. 6 show 2 meter specific humidity. WRF shows a much higher range, perhaps due to a higher quality meteorological forcing dataset in the NARR, and its ability to resolve small convective features. The LIS spinup indicates that gradients of water vapor are present on a much smaller scale, especially in valleys and ridges of the SMO.

The nested grid simulations with WRF alone, at resolutions of 5 km and 1 km using the Noah LSM were able to initiate convection along the high terrain of the SMO in the afternoon and showed low clouds over these same areas in the late overnight/early morning hours. This is promising because if WRF is showing itself to be capable of representing convection on these scales, testing sensitivity to land surface initialization is a logical next step.

Figure 6. (Next page) A suite of meteorologically significant parameters output shortly after WRF initialization. From top to bottom, these are downwelling long wave radiation (W m^{-2}), soil temperature of the uppermost soil layer (K), sensible heat flux from the surface (W m^{-2}), and 2 meter mixing ratio (kg/kg). Values from WRF-only runs are on the left; from LIS after a year-long spinup on the right.


WRF Downward LW Flux 01:00 UTC 08/02/2004
LIS Downward LW Flux 01:00 UTC 08/02/2004
438 430 418 408 396 384 374 362 352 340 328 318 306
WRF Soil Temp (Layer 1) 01:00 UTC 08/02/2004
LIS Soil Temp (Layer 1) 01:00 UTC 08/02/2004
310 308 306 304 302 300 298 296 294 292 290 288
WRF Qh 01:00 UTC 08/02/2004
LIS Qh 01:00 UTC 08/02/2004
100 90 80 60 50 40 30 20 10 −10 −20 −30
WRF 2m Qv 01:00 UTC 08/02/2004
LIS 2m Qv 01:00 UTC 08/02/2004
0.024 0.022 0.02 0.018 0.016 0.014 0.012 0.01 0.008

5. Conclusions and Future Work

Experimentation with LIS alone (point-runs) revealed many intricacies within the realm of land surface modeling, especially in choice of meteorological forcing datasets, and soil and vegetation types. Most significant perhaps was the precipitation component of the forcing datasets. For example, use of relatively coarse-resolution GDAS data resulted in consistently erroneously high precipitation, and therefore soil moisture values, in both test sites. It is likely that increased soil moisture would lead to higher latent heat fluxes, and therefore higher moisture content in the lower levels of the atmosphere. Because this would act to destabilize the atmosphere, misrepresentations of soil moisture would have significant ramifications in studies involving convective processes, particularly convective initiation.

While LISWRF was not run in a coupled manner in the end, the comparisons of spun-up LIS land surface conditions to the WRF initialization were quite promising. LIS is able to generate a much higher resolution dataset than observations can provide, and WRF is able to resolve convection at these same scales. The foundation has been laid, and this study will continue over the next few months.

There are many new pathways for research within the NAME region (and beyond) opened by this study. Through the course of this project, the author learned of a new dataset that incorporates satellite and high-resolution rain gauge data collected during NAME that could potentially be used in a LIS spinup, with a little work. Also within the realm of possibility is writing code within LIS to process NARR meteorological forcing data, which is available for a longer period of time, at a higher resolution, and of better quality than GDAS data. The Noah LSM as implemented in LIS and WRF currently does not include any consideration of slope or aspect in radiation calculations. A region of complex terrain such as NAME would benefit from inclusion of slope or aspect within meteorological simulations. Another exciting prospect is the potential use of MODIS sea surface temperature over the Gulf of California. This setup is possible, as shown by LaCasse et al. (2008), and could be of high importance to simulations of diurnal convection in the NAM.

In conclusion, extreme care must be taken in simulation of complex processes. Scientists using dynamical models to represent physical processes mathematically must endeavor to do their best at understanding the assumptions and possible biases in parameterizations and schemes in the models themselves, as well as the parameter datasets and forcing data. With this in mind, LISWRF can be an incredibly valuable tool for regions where a paucity of observations and surface data had previously prevented any type of concrete analysis to be done.

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7. References

Adams, D. K., and A. C. Comrie, 1997: The North American Monsoon. *Bull. Amer. Meteor. Soc*., **78**, 2197-2213.

ALMA, 2002. Assistance for Land Modeling Activities, Version 3. http://web.lmd.jussieu.fr/~polcher/ALMA/

Berbery, E. H., 2001: Mesoscale Moisture Analysis of the North American Monsoon. *J.Climate,* **14**, 121-137.

Briegleb, B. P., P. Minnis, V. Ramanathan, and E. Harrison, 1986: Comparison of Regional Clear-sky Albedos Inferred from Satellite Observations and Model Computations. *J. Climate Appl. Meteor.,* **25**, 214-226.

Case, J. L., W. L. Crosson, S. V. Kumar, W. M. Lapenta, and C. D. Peters-Lidard, 2008: Impacts of High-Resolution Land Surface Initialization on Regional Sensible Weather Forecasts from the WRF Model. *J.Hydrometeorol.,* **9**, 1249-1266.

Ciesielski, P. E., R. H. Johnson, 2008: Diurnal Cycle of Surface Flows during 2004 NAME and Comparison to Model Reanalysis. *J.Climate,* **21**, 3890-3913.

Dominguez, F., P. Kumar, and E. R. Vivoni, 2008: Precipitation Recycling and Ecoclimatological Stability – A Study Using NARR Data. Part II: North American Monsoon Region. *J.Climate,* **21**, 5187-5203.

Eidenshink, J. C., and J. L. Faundeen, 1994: 1-km AVHRR Global Land Dataset: First Stages in Implementation. *International Journal of Remote Sensing*, **15**, 3443-3462.

Ek, M. B., K. E. Mitchell, L. Yin, P. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah Land-Surface Model Advances in NCEP Operational Mesoscale Eta Model. J. Geophys. Res., 108, (D22), 296, doi:10.1029/2002JD003.

Derber, J. C., D. F. Parrish, and S. J. Lord, 1991: The New Global Operational Analysis System at the National Meteorological Center. *Wea. Forecasting*, **6**, 538-547.

Gochis, D. J., L. Brito-Castillo, and W. J. Shuttleworth, 2006: Hydroclimatology of the North American monsoon region in northwest Mexico. *J. Hydrol*., **316**, 53-70.

Gutman, G. and A. Ignatov, 1998: The derivation of the green vegetation fraction from NOAA/AVHRR for use in numerical weather prediction models. *International Journal of Remote Sensing*, **19**, 1533-1543.

Gutzler, D. S., H. K. Kim, R. W. Higgins, H. M. H. Juang, M. Kanamitsu, K. Mitchell, K. Mo, P. Pegion, E. Ritchie, and J. K. Schemm, 2005: The North American Monsoon Model Assessment Project: Integrating Numerical Modeling into a Field-based Process Study. *Bull.Am.Meteorol.Soc.,* **86**, 1423-1429.

Higgins, W., D. Ahijevych, J. Amador, A. Barros, E. H. Berbery, E. Caetano, R. Carbone, P. Ciesielski, R. Cifelli, and M. Cortez-Vazquez, 2006: The NAME 2004 Field Campaign and Modeling Strategy. *Bull.Am.Meteorol.Soc.,* **87**, 79-94.

Hong, Y., D. Gochis, J. Cheng, K. Hsu, and S. Sorooshian, 2007: Evaluation of PERSIANN-CCS Rainfall Measurement Using the NAME Event Rain Gauge

Network. *J.Hydrometeorol.,* **8**, 469-482.

Koster, R., and Coauthors, 2004: Regions of Strong Coupling between Soil Moisture and Precipitation. *Science*, **305**, 1138-1140.

Kumar, S. V., C. D. Peters-Lidard, J. L. Eastman and W.-K. Tao, 2008: An integrated high-resolution hydrometeorological modeling testbed using LIS and WRF. *Environ. Model. Softw*., **23**, 169-181.

Kumar, S. V., C. D. Peters-Lidard, Y. Tian, P. R. Houser, J. Geiger, S. Olden, L. Lighty, J. L. Eastman, B. Doty, P. Dirmeyer, J. Adams, K. Mitchell, E. F. Wood and J. Sheffield, 2006: Land Information System - An Interoperable Framework for High Resolution Land Surface Modeling. *Environ. Model. Softw*., **21,** 1402-1415.

Kumar, S. V., C. Peters-Lidard, Y. Tian, R. H. Reichle, C. Alonge, J. Geiger, J. Eylander, and P. Houser, 2008: An integrated hydrologic modeling and data assimilation framework enabled by the Land Information System (LIS). *IEEE Comput.*, **41**, 52-59.

Kumar, S. V., R. H. Reichle, C. D. Peters-Lidard, R. D. Koster, X. Zhan, W. T. Crow, J. B. Eylander, and P. R. Houser, 2008: A Land Surface Data Assimilation Framework using the Land Information System: Description and Applications. *Adv. Water Res.,* **31**, 1419-1432, doi:10.1016/j.advwatres.2008.01.013.

LaCasse, K. M., M. E. Splitt, S. M. Lazarus, and W. M. Lapenta, 2008: The Impact of High-Resolution Sea Surface Temperatures on the Simulated Nocturnal Florida Marine Boundary Layer. *Mon. Wea. Rev*., **136**, 1349-1372.

Masson, V., J.L. Champeaux, F. Chauvin, C. Meriguet, and R. Lacaze, 2003: A Global Database of Land Surface Parameters at 1-km Resolution in Meteorological and Climate Models. *J. Climate*, **16**, 1261–1282.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.,* **87**, 343-360.

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, and W. Skamarock, 2001: Development of a next generation regional weather research and forecast model. *Developments in Teracomputing: Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology,* W. Zwieflhofer and N. Kreitz, Eds., World Scientific, 269-276.

Nesbitt, S. W., D. J. Gochis, and T. J. Lang, 2008: The Diurnal Cycle of Clouds and Precipitation along the Sierra Madre Occidental Observed during NAME-2004: Implications for Warm Season Precipitation Estimation in Complex Terrain. *J.Hydrometeorol.,* **9**, 728-743.

Peters-Lidard, C. D., P. R. Houser, Y. Tian, S. V. Kumar, J. Geiger, S. Olden, L. Lighty, B. Doty, P. Dirmeyer, J. Adams, K. Mitchell, E. F. Wood and J. Sheffield, 2007: High-performance Earth system modeling with NASA/GSFC's Land Information System. *Innovations in Syst. Softw. Eng*. **3**, 157-165.

Reynolds, C. A., T. J. Jackson, and W. J. Rawls, 1999: Estimating Available Water Content by Linking the FAO Soil Map of the World with Global Soil Profile Database and Pedo-transfer Functions. In American Geophysical Union Fall

Meeting, EOS Transactions, 80.

Robinson, D. A., and G. Kukla, 1985: Maximum Surface Albedo of Seasonally Snow-covered Lands in the Northern Hemisphere. *J. Climate Appl. Meteor*., **24**, 402-411.

Rodell, M., P. R. Houser, A. A. Berg, and J. S. Famiglietti, 2005: Evaluation of 10 Methods for Initializing a Land Surface Model. *J.Hydrometeorol.,* **6**, 146-155.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005:A Description of the Adanced Research WRF Version 2. NCAR Tech Note NCAR/TN-468 + STR, 88 pp.

Stensrud, D. J., 2007: *Parameterization Schemes: Keys to Understanding Numerical Weather Prediction Models.* Cambridge University Press, 459 pp.