Impacts of High-Resolution Land Surface Initialization on Regional Sensible Weather Forecasts from the WRF Model

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ABSTRACT

This manuscript presents an assessment of daily regional simulations of the Weather Research and Forecasting (WRF) numerical weather prediction (NWP) model initialized with high-resolution land surface data from the NASA Land Information System (LIS) software versus a control WRF configuration that uses land surface data from the National Centers for Environmental Prediction (NCEP) Eta Model. The goal of this study is to investigate the potential benefits of using the LIS software to improve land surface initialization for regional NWP. Fifty-eight individual nested simulations were integrated for 24 h for both the control and experimental (LISWRF) configurations during May 2004 over Florida and the surrounding areas: 29 initialized at 0000 UTC and 29 initialized at 1200 UTC. The land surface initial conditions for the LISWRF runs came from an offline integration of the Noah land surface model (LSM) within LIS for two years prior to the beginning of the month-long study on an identical grid domain to the subsequent WRF simulations. Atmospheric variables used to force the offline Noah LSM integration were provided by the North American Land Data Assimilation System and Global Data Assimilation System gridded analyses.

The LISWRF soil states were generally cooler and drier than the NCEP Eta Model soil states during May 2004. Comparisons between the control and LISWRF runs for one event suggested that the LIS land surface initial conditions led to an improvement in the timing and evolution of a sea-breeze circulation over portions of northwestern Florida. Surface verification statistics for the entire month indicated that the LISWRF runs produced a more enhanced and accurate diurnal range in 2-m temperatures compared to the control as a result of the overall drier initial soil states, which resulted from a reduction in the nocturnal warm bias in conjunction with a reduction in the daytime cold bias. Daytime LISWRF 2-m dewpoints were correspondingly drier than the control dewpoints, again a manifestation of the drier initial soil states in LISWRF. The positive results of the LISWRF experiments help to illustrate the importance of initializing regional NWP models with high-quality land surface data generated at the same grid resolution.

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1. Introduction

The exchange of energy and moisture between the earth’s surface and the atmospheric boundary layer plays a critical role in many hydrometeorological processes. This exchange is parameterized in numerical weather prediction (NWP) models using land surface models (LSMs) [e.g., Noah (Ek et al. 2003) or the Common Land Model (CLM; Dai et al. 2003)]. Accurate and high-resolution representations of surface properties such as vegetation, soil temperature and moisture, and sea surface temperature (SST) are necessary to better understand earth–atmosphere interactions and to improve numerical predictions of weather and climate phenomena.

The hypothesis for this paper is that improved land surface states obtained through an offline land surface model spin-up at higher resolution and with better atmospheric forcing will lead to more accurate short-term forecasts of regional sensible weather elements (e.g., 2-m temperatures and dewpoints) in a mesoscale NWP model. Many previous modeling-based studies have examined the interactions between the land surface and the atmosphere and the sensitivities as a result of variations in the initial land surface properties. Smith et al. (1994) demonstrated the feasibility of obtaining realistic initial soil moisture fields for regional mesoscale model runs of the fifth generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) by running a 1D hydrologic model offline for 4.5 months, forced by conventional meteorological observations. Using the MM5 model in conjunction with the Simulator for Hydrology and Energy Exchange at the Land Surface, Santanello and Carlson (2001) examined rapid soil moisture decoupling/drying and its sensitivity to soil type and fractional vegetation cover. Weaver (2004a,b) found that land surface heterogeneities over the U.S. southern Great Plains under a quiescent synoptic regime can lead to strong mesoscale circulations in the lower troposphere on diurnal time scales. These studies illustrated the importance of properly initializing land surface variables for atmospheric simulations.

Other works have focused on the links between initial land surface states and precipitation. With the aid of the Weather Research and Forecasting (WRF) model, Sutton et al. (2006) concluded that forecast differences on a high-resolution grid as a result of changes in initial soil moisture were comparable to forecast differences that arose from running the model with an alternative convective parameterization scheme on a coarser-resolution grid. Holt et al. (2006) and Chen et al. (2001) have shown the impact of high-resolution soil moisture and temperature initial conditions on convective initiation for midcontinental case studies in the southern Great Plains and Rockies. In studies conducted over the Florida peninsula (which is the current domain of interest), Baker et al. (2001) concluded through idealized simulations that areas of pre-existing wet soils favored the focus of heavy precipitation as a result of an increase in convective available potential energy.

Recent modeling efforts at the National Aeronautics and Space Administration (NASA) Short-term Prediction Research and Transition (SPoRT) Center have demonstrated the positive impacts of high-resolution SST initial conditions derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on WRF-simulated clouds and mesoscale circulations in the Florida coastal zone (LaCasse et al. 2008). For the current study, the SPoRT Center seeks to extend the work of LaCasse et al. (2008) to the land surface by investigating the potential benefits of using the WRF model in conjunction with the NASA Goddard Space Flight Center (GSFC) Land Information System (LIS; Kumar et al. 2006, 2007) to improve land surface initialization and subsequent land–atmosphere interactions. The objective of this project is to evaluate the influence of high-resolution lower boundary data on short-term NWP (0–24 h) to determine how a configuration of LIS within WRF could improve local-to-regional NWP at the National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service (NWS) forecast offices. The ultimate goal of this and other SPoRT Center projects is to accelerate the infusion of NASA Earth Science observations, data assimilation, and modeling research into NWS operations and decision making at the regional and local levels.

This paper presents an evaluation of a configuration of the Advanced Research WRF (ARW; Skamarock et al. 2005) model initialized with high-resolution land surface data provided by LIS for a month-long period over a domain centered on Florida. The study involves an evaluation of output fields from LIS-initialized WRF simulations versus control simulations that initialize land surface variables by a simple interpolation off of a larger-scale NWP model, in the same manner that many local modeling initiatives currently initialize the land surface. This manuscript focuses on the first-order influences of the high-resolution LIS land surface data on predictions of sensible weather elements near the surface. Once the influence on these primary elements is quantified, subsequent studies will examine more complex problems such as the influence of land surface initial conditions on convective initiation and quantitative precipitation forecasts.
The remainder of the paper is organized as follows. Section 2 describes the LIS software and the interface to WRF. Section 3 presents the experiment design for comparing LIS-initialized WRF runs to control simulations. Results and composite verification statistics are presented in section 4. Finally, section 5 summarizes the results and discusses possible follow-up research.

2. The Land Information System

LIS is a software framework that integrates satellite-derived datasets, ground-based observations, and model reanalyses to force a variety of LSMs. By using scalable, high-performance computing and data management technologies, LIS can run LSMs offline globally with a grid spacing as fine as 1 km to characterize land surface states and fluxes. The software infrastructure enables LIS to ingest high-resolution datasets such as leaf area index and vegetation fraction derived from the MODIS instruments on the Terra and Aqua satellites. LIS has been used to demonstrate land surface modeling capability at 1-km grid spacing over urban areas (Peters-Lidard et al. 2004) and also has the ability to assimilate land surface observations using techniques such as ensemble Kalman filtering (Kumar et al. 2008).

To predict water and energy processes, LSMs require (1) initial conditions, (2) boundary conditions from the atmosphere (i.e., forcings such as temperature, precipitation, radiation, wind, among others) and lower soil states, and (3) parameters describing the soil, vegetation, topography, and other surface properties. Using these inputs, LSMs solve the governing equations of the soil–vegetation–snowpack medium and predict surface fluxes and soil states to provide a realistic representation of the transfer of mass, energy, and momentum between the land surface and the atmosphere (Kumar et al. 2006).

By itself, LIS runs in an uncoupled, offline mode using a variety of atmospheric forcings [e.g. the Global Data Assimilation System (GDAS; Derber et al. 1991), the North American Land Data Assimilation System (NLDAS; Mitchell et al. 2004), supplemental precipitation data, among others] to drive one of several community LSMs: the Noah LSM, the CLM, the Variable Infiltration Capacity (VIC) model (Liang et al. 1994, 1996), the Mosaic model (Koster and Suarez 1996), and the Simple Biosphere Model (SiB) with hydrology (Sellers et al. 1986; Sud and Mocko 1999). In addition to running offline, LIS can also be run in a coupled mode with WRF to integrate surface and soil quantities using the LSMs available in LIS. The LIS has been coupled to version 2.1.2 of the ARW, giving users the ability to run an ensemble system of LSMs within the ARW dynamical core (Kumar et al. 2007). First, the atmospheric forcing variables provided by WRF are imported into LIS. Then, the coupled version of LIS is called to run the user-selected LSM within LIS. The LSM output from LIS is then exported back to the WRF code in the form of soil temperature, moisture, surface fluxes, etc. Diagnostic variables (e.g., 2-m temperature and dewpoint) are handled within the WRF code following the call to LIS. This setup allows users to continue running the same LSM configuration in the WRF simulation as it was designed in the offline LIS run.

The benefits of running LIS with WRF for regional modeling are numerous. First, LIS provides the capability to conduct long-term offline integrations or “spinups” to allow the surface and soil profiles to reach thermodynamic equilibrium, using bias-adjusted meteorological inputs or “forcings.” Producing high-resolution spinups is not currently possible using the standard WRF version, and therefore most users initialize surface and soil fields by interpolating from a coarse-resolution analysis/forecast system such as GDAS or the North American Mesoscale model. However, recent studies by Chen et al. (2007) and Rodell et al. (2005) have shown that changing soil types from a coarse-resolution analysis system to a finescale regional forecast grid may require spinup times in excess of two years, particularly for high latitude or high elevation areas. Second, offline LIS output is generated at the same resolution as the local/regional grids (i.e., for each nest) and is then used directly as input into the WRF simulation, eliminating the need for horizontal spatial interpolation. Third, users can run WRF with the LSMs available in LIS, whereas only the Noah, Rapid Update Cycle’s LSM, or thermal diffusion scheme can be run within the standard ARW. Finally, the LIS provides a plug-in framework through which users can introduce new high-resolution land datasets, LSMs, or land surface observations into WRF.

3. Experiment design

The basis of our experimental design is to run two identical WRF configurations with the only difference being the initial land surface conditions. The experiment consists of evaluating a set of control WRF simulations (control) using land surface data interpolated from a large-scale operational model versus WRF simulations initialized with land surface data provided by an offline spin-up run of LIS conducted on the exact WRF grids (LISWRF). Details of the period of record, model configuration, and offline LIS run are provided in the subsections that follow.
a. Period of record

Experiments were conducted to measure the potential benefits of using the LISWRF system versus a control configuration over the Florida peninsula during May 2004. This region was chosen to determine the influence of land surface initialization on the resulting mesoscale circulations (e.g., sea breezes) in a coastal environment and as an extension of the WRF/SST study by LaCasse et al. (2008). During this month, there was minimal precipitation over the region of interest, which enabled us to focus on the local and mesoscale influences of the high-resolution, spun-up soil and surface initial conditions on predictions of 2-m air temperatures and dewpoint temperatures, 10-m winds, as well as surface energy fluxes. The small precipitation totals during this month allowed for an extended dry down of the soil, which is critical to capturing the soil moisture dynamics and hence the influence of soil initialization.

A cold front crossed the Florida peninsula early in the month (3–4 May), followed by several days of dry, calm conditions. A sustained period of east-southeast flow occurred from 9–19 May, accompanied by occasional periods of scattered shower activity propagating from the Atlantic waters, especially on 15, 17, and 19 May. The weather regime transitioned from the predominant easterly flow to a light/variable low-level flow as high pressure controlled the Florida region from 20–25 May. The axis of high pressure then moved south of Florida for the remainder of the month, leading to a westerly low-level flow from 26–31 May along with increasingly hot conditions. The approach of a front and upper-level trough on 31 May led to increased coverage of thunderstorms in southern Georgia and northern Florida later that day.

b. Domain and model configuration

The simulation domain (depicted in Fig. 1) consists of two grids with 9- and 3-km horizontal grid spacing, respectively. Both grids contain 43 sigma-pressure vertical levels from near the surface to a domain top at 75 mb, with a minimum vertical spacing of approximately 65 m near the surface.

For both the control and LISWRF simulations, the ARW physics options consist of the rapid radiative transfer model (Mlawer et al. 1997) and the Dudhia scheme (Dudhia 1989) for longwave and shortwave radiation, respectively. The WRF single-moment 6-class microphysics scheme (WSM6; Hong and Lim 2006; Skamarock et al. 2005) is used in conjunction with the modified Kain–Fritsch convective parameterization scheme (Kain 2004) on the 9-km grid and without any convective parameterization on the 3-km inner nested grid. The planetary boundary layer and turbulence processes are parameterized by the Mellor–Yamada–Janjić scheme (Janjić 1990, 1996, 2002). Surface layer calculations of friction velocities and exchange coefficients needed for the determination of sensible and latent fluxes in the LSM are provided by the National Centers for Environmental Prediction (NCEP) Eta similarity theory scheme (Janjić 1996, 2002). Horizontal diffusion is handled by the two-dimensional Smagorinsky first-order closure scheme (Smagorinsky et al. 1965). All WRF runs use the Noah LSM as configured in version 2.1.2 of the ARW.

c. Offline LIS spin-up simulation

For the offline simulation, version 2.6 of the Noah LSM was run in LIS version 4.3 on the exact horizontal grid configuration of Fig. 1. The inner 3-km grid on which all evaluations were conducted used the State Soil Geographic (STATSGO; Miller and White 1998) database, only valid over the continental United States (CONUS). The STATSGO soil texture database contains 19 classes of soil characteristics and is the same database that was used in the ARW. Because of the geographical
limitations of the STATSGO database, the outer 9-km grid used the Zobler nine-class global soil scheme (Zobler 1986), which employs the global soil database from the United Nation’s Food and Agriculture Organization within the Noah LSM. This global nine-class soil database is merged with the STATSGO CONUS dataset for use in the WRF model.

Additional required parameters that were used in the offline LIS runs include quarterly climatologies of albedo (Briegleb et al. 1986) and maximum snow-free albedo (Robinson and Kukla 1985), monthly climatologies of greenness fraction data derived from the AVHRR satellite (Gutman and Ignatov 1998), and a deep soil temperature climatology (serving as a lower boundary condition for the soil layers) at 3 m below ground, derived from 6 yr of GDAS 3-hourly averaged 2-m air temperatures using the method described in Chen and Dudhia (2001).

In LIS, all parameters are sampled from their native datasets. Categorical variables such as land cover and soil texture are sampled based on the dominant type for the upscaled grid box. Continuous variables such as leaf area index and sand/silt/clay fractions are computed as aggregated averages (more details are found in Kumar et al. 2006).

Atmospheric forcings for the LIS run were provided by NLDAS analyses over the CONUS and GDAS analyses outside of the NLDAS coverage region over the southern portions of the 9-km grid. The NLDAS consists of hourly atmospheric analysis data over North America at 0.125° (~14 km) horizontal resolution. The GDAS has global coverage but with only 3-hourly data at a coarser horizontal resolution of 0.469° (~52 km). The forcing fields are downscaled to the running resolution in LIS using bilinear or conservative (for precipitation) interpolation approaches. In the case of downward shortwave radiation, an additional zenith angle–based temporal disaggregation is applied. The forcing fields of downward-directed longwave radiation, pressure, 2-m air temperature and 2-m relative humidity are further topographically corrected via lapse rate and hypsometric adjustments using the elevation data differences between the LIS grid and the native forcing grid [refer to Cosgrove et al. (2003) for more details].

The offline LIS was run for 2 yr and 1 month from 1 May 2002 to 1 June 2004, using a time step of 30 min for integrating the Noah LSM. Output from the offline LIS run was used to initialize the land surface fields in the LISWRF runs at 0000 UTC and 1200 UTC every day during May 2004. The process of determining an appropriate offline simulation length for achieving soil state equilibrium for this experiment is described in Case et al. (2007). Based on offline simulation results of the Noah LSM using LIS configured for a domain similar to the 3-km nest in Fig. 1, the authors found that a 9-month integration length was adequate for bringing the LSM into equilibrium for most of the domain. This integration time is relatively short compared to that required for other domains because of the extent of the nested grid configuration and for the purposes of optimizing initial land surface conditions in LISWRF, we increased the offline integration of the Noah LSM in LIS to 2 yr prior to initializing the land surface variables in LISWRF. The Noah LSM within LIS was run this long to ensure convergence to a soil state equilibrium, particularly on the outer 9-km grid. The outer grid contains many different soil types besides sand, thereby requiring a longer integration time frame to reach an equilibrium soil state compared to that found in Case et al. (2007) for the Florida peninsula.

d. Control versus LISWRF

The experiment involved running 24-h simulations of the control and the LISWRF configurations daily for the entire month of May 2004, except for the 24th and 28th when archived atmospheric boundary condition data were missing. Simulations were initialized at 0000 UTC and 1200 UTC to examine differences that might occur between an evening versus an early morning model initialization and to determine which initialization time may have the most positive influence from LIS land surface data. The control and LISWRF simulations used the ARW dynamical core from the same software version (2.1.2). Soil initial conditions in the control runs were obtained through a typical interpolation of the soil temperature and moisture values from the NCEP Eta Model data (projected onto a 40-km grid) to the 9- and 3-km grids, using the WRF standard initialization utilities. All atmospheric data for initial and boundary conditions for the control and LISWRF runs initialized at 0000 UTC and 1200 UTC came from 0–24-h forecasts from the 0000 UTC and 1200 UTC forecast cycles of the NCEP Eta Model on the 40-km grid, respectively. The Eta Model provided boundary conditions to the 9-km grid every 3 h, whereas the 9-km simulation grid provided boundary conditions every model time step to the 3-km grid in a one-way nested mode.
In the LISWRF runs, the LIS software was called in the first model time step to initialize the land surface variables with the LIS output. For the remainder of the integration, the Noah LSM within the standard ARW was called. Therefore, the only differences between the control and LISWRF simulations are those that result from differences in the land/soil conditions in the first model time step. Land surface data interpolated from the 40-km Eta grids initialized the control runs, while the spun-up LIS data on the exact simulation grids were used to initialize the LISWRF runs. All evaluations of the control and LISWRF systems were done only on the inner 3-km grid where the same static soil and vegetation parameters were used for the offline LIS and all the WRF simulations. The common land surface parameters of the 3-km grid combined with the short integration time (24 h, thereby minimizing boundary condition influences from the outer 9-km grid) ensured a clean comparison between the control and LISWRF simulations.

e. Surface verification

Hourly model verification statistics were calculated for both the control and LISWRF simulations at 80 surface observations locations (Fig. 2), consisting of 53 standard aviation routine weather reports (METAR) and 27 mesonet sites from the Florida Automated Weather Network (FAWN, available online at http://fawn.ifas.ufl.edu/). Verification variables include 2-m air temperature, 2-m dewpoint, and 10-m winds at all 80 stations, mean sea level pressure at the 53 METAR sites, and 10-cm soil temperatures at the 27 FAWN sites. The surface and 2- and 10-m forecast grids were horizontally interpolated to the station locations using the Unidata General Meteorological Package (GEMPAK) software utilities. To obtain forecast soil temperatures representative of the observed 10-cm measurements at the FAWN sites, a linear weight was applied to the simulated soil temperatures in the 0–10 (\(T_{0-10}\)) and 10–40 cm (\(T_{10-40}\)) layers as depicted in Eq. (1):

\[
T_{10} = 0.75T_{0-10} + 0.25T_{10-40}.
\]

This representation of the forecast 10-cm soil temperature may incur interpolation errors when the vertical profile of soil temperatures deviates from a linear relationship, especially during the midday hours when the top layer heats up more rapidly in response to intense solar heating.

The point error statistics were calculated at every forecast hour and consist of the root-mean-square error (RMSE) and bias of 2-m air temperature and dewpoint, 10-m wind speed and \(u\) and \(v\) wind components, mean sea level pressure, and 10-cm soil temperature. The bias is the mean difference between modeled and observed quantities and represents the systematic portion of the error. The RMSE represents the total model error consisting of the systematic and nonsystematic (random) components of the error.

Error statistics were calculated for the entire month of May 2004 at all stations collectively and at each individual station. The error statistics at individual stations were also objectively analyzed using the Barnes (1964) analysis scheme within GEMPAK and plotted as a function of forecast hour and variable to visualize the spatial distribution of the errors and note any favored geographical patterns that may occur. In addition, errors were plotted at each individual station as a function of forecast hour to understand the temporal distribution of errors at specific sites as necessary. Finally, forecast fields were examined to identify and compare possible changes in predicted mesoscale phenomena such as sea and lake breezes as well as to quantify differences in predicted sensible, latent, and ground heat fluxes.

4. Results

The following subsections highlight the differences in the LISWRF and control land surface initializations and the impacts on the subsequent simulations. First,
the differences between the initial soil moisture and soil temperature fields in the LISWRF versus the control are examined. The impact of the different soil moisture initialization on a sea-breeze forecast from 6 May is then presented. The section concludes with an analysis of the surface verification statistics.

a. Evaluation of land surface initial conditions on the 3-km grid

To quantify the domain-wide differences on the 3-km inner nested grid, the means of the volumetric soil moisture and temperature were calculated over all land grid points every 12 h during May 2004 for both the Eta (control) and LIS (LISWRF). The soil fields in the LISWRF are consistently ~2%–5% lower than the control in all layers of Noah during May 2004, with a general drying trend seen throughout the month (Fig. 3). Layer 1 mean soil moisture at 0000 UTC and 1200 UTC (0–10 cm in Figs. 3a and 3b) decreases from ~20%–25% in the first several days to less than 10% by day 31 in the LISWRF. Layer 4 exhibits a gradual drying trend with little day-to-day variability (100–200 cm in Figs. 3c and 3d). The largest difference between the control and LISWRF initial grid-averaged soil moisture occurred in the 100–200-cm layer, where the LISWRF was consistently drier by about 5% during the entire month.

The 12-hourly domain-averaged soil temperatures in Noah layer 1 and layer 4 initializing the 0000 UTC and 1200 UTC forecasts are given in Fig. 4. The 0000 UTC shallow (0–10 cm) and deep (100–200 cm) LIS soil temperatures as well as the 1200 UTC deep LIS soil temperatures are consistently cooler than the Eta/control by about 1°–3°C during the month (Figs. 4a, 4c, and 4d), whereas the 1200 UTC shallow LIS soil temperatures are nearly identical to the control (Fig. 4b).

These differences between the control and LIS soil moisture and temperature are directly attributed to the differences in atmospheric forcing used by the operational Eta Model (control) and the NLDAS forcing used solely for the offline LIS runs on the 3-km domain. During May 2004, the operational NCEP Eta Model initial land states were provided by the Eta Data Assimilation System (EDAS) running the Noah LSM (Ek et al. 2003). In the EDAS, the land surface states cycled on themselves in response to land surface forcing and the Noah LSM physics. Except for precipitation, the land surface forcing in the EDAS came from the lowest model level analysis fields of the EDAS atmospheric data assimilation component. For precipitation over the CONUS, the forcing consisted of hourly 4-km precipitation analyses produced operationally by the U.S. River Forecast Centers, primarily anchored by radar precipitation estimates from the Weather Surveillance

In the NLDAS analyses, all the atmospheric forcing variables except for downward-directed shortwave radiation and precipitation were provided by the Eta/EDAS fields described above. Whereas, the downward-directed shortwave radiation forcing was provided by Geostationary Operational Environmental Satellite (GOES) data, which have been documented to have a low bias of $\sim5\%$ compared to a high bias of $\sim10\%$ in the EDAS (Betts et al. 1997; Cosgrove et al. 2003). The NLDAS precipitation forcing is anchored by the daily gauge-only precipitation analysis produced by the NCEP Climate Prediction Center (CPC), which is disaggregated to an hourly time interval using the aforementioned hourly radar analyses. Despite the coarser resolution of the CPC precipitation analyses in NLDAS ($0.125^\circ$) compared to the primarily radar-based estimates (4 km), the CPC product contains less bias and has a much greater density of rain gauges over the CONUS (Cosgrove et al. 2003). An examination of the accumulated Stage IV precipitation (a composite of the 4-km radar-based product) and NLDAS precipitation forcing patterns for the 7-day period from 1200 UTC 29 April to 1200 UTC 6 May 2004 (not shown) closely corresponds to the different 0–10 cm soil moisture patterns depicted in Fig. 5. The impact of this soil moisture initialization difference on the simulated sea breeze is highlighted in the next subsection.

Therefore, the combination of a reduction in downward-directed shortwave radiation forcing and the use of the CPC gauge-only versus mostly radar-based precipitation forcing explains the cooler and drier LIS soil temperature and moisture fields seen in Figs. 3 and 4 relative to the interpolated Eta Model soil fields in the control. The reduced downward shortwave radiation forcing especially manifests itself in the 0000 UTC initialized runs as all the soil layers depicted a cooler soil temperature, whereas the 1200 UTC initialized runs have nearly identical shallow (0–10 cm) soil temperatures but cooler LIS temperatures in the deeper soil layers. These differences in the land surface initialization (particularly the soil moisture fields) modulated the surface heating rates and subsequent sensible weather elements, which will be seen in the following subsections.

b. Improvement in sea-breeze prediction on 6 May 2004

On 6 May a dry, stable air mass controlled Florida’s weather following the passage of a cool front on 4 May. Very few clouds occurred on this day, mainly consisting of a few high cirrus (not shown). Therefore, this day was ideal for comparing the development and evolution of the sea-breeze front in the LISWRF versus the control simulations based solely on the differences in the land surface initial conditions.

The initial 0–10-cm volumetric soil moisture in the control and LISWRF at 1200 UTC 6 May is given in Fig. 5 along with the difference between the two fields. The initial soil moisture in the control is generally between 10% and 24% across much of the domain with a swath of 24%–30% over parts of north Florida and
southwestern Georgia (Fig. 5a). The more detailed LIS initial 0–10-cm soil moisture has a qualitatively similar pattern except for considerably drier values over parts of north Florida and southwestern Georgia as well as slightly more moist values over south Florida (Fig. 5b). The difference field (LISWRF minus control) in Fig. 5c indicates that LIS is drier than the Eta by more than 10% over parts of north Florida, southwestern Georgia, and the Bahamas, with a smaller magnitude of drying over a large portion of the Florida peninsula. LIS is more moist by 2%–8% over southeastern Georgia and extreme south Florida near the Everglades. These soil moisture differences closely follow the pattern of soil texture across the domain (not shown) because the drying of the soils is largely controlled by soil type and corresponding hydraulic properties (Chen et al. 2007).

The drier initial LIS soil fields over north Florida had a noticeable impact on the evolution of the simulated sea-breeze fronts on 6 May. Figure 6 shows the 10-m divergence fields, which depict the evolution of the simulated sea-breeze fronts from the 1200 UTC 6 May control and the LISWRF 9–12-h forecasts along with the difference in predicted 2-m temperatures. At the 9-h forecast (Fig. 6a), the Gulf of Mexico LISWRF sea-breeze front (color shading) over northwest Florida has begun to penetrate farther inland than the control sea-breeze front (gray shading) between Perry (40J) and Cross City, Florida (CTY, locations highlighted in Fig. 6g). This inland penetration difference is consistent with the increased land–sea temperature contrast that can be inferred from the LISWRF run on the basis of the 1°–3°C positive differences in predicted 2-m temperatures over a large portion of north Florida (Fig. 6b). The narrow band of negative differences in predicted 2-m air temperatures close to the coast indicates the greater penetration of post-sea-breeze marine air in the LISWRF run relative to the control simulation.

At 10 h, the LISWRF sea-breeze front has reached 40J and passed by CTY, whereas the control sea-breeze front has approached but not yet passed these two stations (Fig. 6c). The corresponding 2-m temperature difference in Fig. 6d continues to show a widespread area of warmer inland temperatures in LISWRF and an ex-
FIG. 6. Sequence of the 1200 UTC 6 May 2004 forecast cycle 10-m divergence (color is LISWRF convergence and gray shading is control convergence) for forecast hours (a) 9, valid at 2100 UTC; (c) 10, valid at 2200 UTC; (e) 11, valid at 2300 UTC; and (g) 12, valid at 0000 UTC 7 May. Corresponding sequence of 2-m temperature differences (°C) for forecast hours (b) 9, (d) 10, (f) 11, and (h) 12. Plots are from the 3-km grid zoomed into north Florida and south Georgia. Locations 40J and CTY (discussed in Figs. 7 and 8) are labeled in (g).
Expanding area of cooler marine air advancing inland behind the accelerating LISWRF sea-breeze front. Figures 6e and 6g show that the separation between the LISWRF and Control sea-breeze fronts continues to increase in the 11-h and 12-h forecasts near stations 40J and CTY. By 12 h, sea-breeze fronts have completely crossed these two stations in both model runs. The corresponding 2-m temperature differences depict a shrinking area of positive differences as the Gulf of Mexico and Atlantic sea-breeze fronts move farther inland (Fig. 6f and 6h).

Comparisons between the control, LISWRF, and observed hourly meteorological conditions at 40J and CTY are given in Figs. 7 and 8. At 40J, the LISWRF daytime forecast 2-m temperatures began about the same as in the control run but warmed more quickly compared to the control and stayed at least a few degrees warmer through 2200 UTC (Fig. 7, top). In addition, the LISWRF 2-m dewpoints were several degrees lower than the control 2-m dewpoints between 1300 UTC and 2100 UTC, almost exactly the same as the observed 2-m dewpoints during those hours (second panel in Fig. 7). With these results, it can be inferred that the lower LISWRF soil moisture near 40J (north Florida and south Georgia in Fig. 5c) is more representative as a result of the improved 2-m dewpoint forecasts during much of the daylight hours.

A noteworthy feature at 40J is the improved timing of the sea-breeze passage in LISWRF compared to the control. The sea-breeze passage is accompanied by an increase in 2-m dewpoints and 10-m wind speed and a shift to a southwesterly wind direction. According to

Fig. 7. A meteogram plot at 40J, of temperature (°C), dewpoint (°C), wind speed (m s⁻¹), and wind direction (°). The graphs compare hourly forecasts interpolated to the station location from the control simulation (solid bold line) and LISWRF run (solid line with labels) to observations (dashed line).
the observed traces (dashed lines), the sea-breeze passage occurred at about 2100 UTC (Fig. 7). Meanwhile, both the control and LISWRF simulated the sea-breeze frontal passage too late at 40J. However, the sea-breeze onset occurred 1 h earlier in the LISWRF (2200 UTC) run relative to the control run (2300 UTC), closer to the observed timing at 2100 UTC.

A similar improvement in the timing of the sea-breeze passage is found at station CTY, southeast of 40J (Fig. 8). The sea-breeze front is observed at 2100 UTC based on the increase in 2-m dewpoint and 10-m wind speed and a shift to a southwesterly wind direction. Similar to 40J, the control sea-breeze frontal passage at CTY occurred at about 2300 UTC, whereas the LISWRF sea-breeze passage moved through an hour earlier at 2200 UTC.

The 6 May case helps to illustrate the influence of the drier initial soil moisture over north Florida and south Georgia in the LISWRF simulation. The pattern of warmer LISWRF 2-m temperatures in Fig. 6 correlates closely with the pattern of drier 0–10-cm soil moisture in Fig. 5c. Consequently, a larger land–sea temperature contrast exists across the portion of north Florida, where the LISWRF sea breeze is seen to penetrate inland more rapidly than in the control simulation. This example of improved sea-breeze timing indicates that the higher-resolution land surface initial conditions of LISWRF can have a favorable influence on sensible weather features in a coastal region experiencing a quiescent environment. Future work will include sea-breeze verification for additional cases and surface stations to validate the net improvement in sea-breeze prediction that may result from using the high-resolution land surface initial conditions. Improved sea-breeze prediction in coastal zones also has an influence on potential improvements to predictions of summer-
time convective initiation over these regions, which could be a follow-up phase of this current study.

c. Surface verification for May 2004

The 80 surface verification sites (Fig. 2) consist of 68 stations in Florida (41 METAR and 27 FAWN), 11 stations in southern Georgia, and 1 station in southeastern Alabama. With 29 forecasts interpolated to 80 sites, there are as many as 2320 pairs of data for each verification hour and variable in both the 0000 UTC and 1200 UTC forecast cycles (except for mean sea level pressure and 10-cm soil temperature). This represents a statistically robust sample size for interpreting the significance of the error differences between the control and LISWRF statistics. A Student’s t test and a Mann–Whitney nonparametric rank test were computed for each verification variable and forecast hour to determine the level of statistical significance of the bias and RMSE differences, respectively.

With the hourly 2-m temperature errors (Fig. 9a), the LISWRF clearly improves upon the control predictions. The LISWRF RMSE is a few tenths of a degree Celsius smaller than the control at nearly all forecast hours, primarily as a result of a reduction of the nocturnal warm bias from hour 0 to hour 11 and a reduction in the daytime cool bias from hour 16 to hour 23. This improved diurnal range in predicted 2-m temperatures can be attributed to the lower soil moisture initial conditions in the LISWRF compared to the control, resulting in a greater partitioning of sensible heat flux in the overall energy budget. The temperature improvement was the most significant of all verified variables, with significant bias improvement found at 99.5% confidence for all forecast hours except hour 14 and hour 24. The RMSE improvement was significant (95% confidence) at all forecast hours except hours 13, 14, and 24.

Despite the improvements seen in the simulated 2-m temperatures, very little overall improvement occurs in the 2-m dewpoint errors (Fig. 9b). Between hour 0 and hour 15, the RMSE and biases are quite similar. Thereafter, the biases drift apart with the control becoming slightly too moist by hour 20, whereas the LISWRF retains a small dry bias (from −0.2°C to −0.5°C) from hour 15 to hour 20 and then realizes a nearly unbiased 2-m dewpoint from hour 21 to hour 24 (Fig. 9b). Significant reduction (at 95% confidence) was found only during forecast hours 8–11.

The wind speed errors indicate that LISWRF improved slightly over the control during the nighttime hours (Fig. 9c). Between forecast hour 0 and hour 12, the RMSE is lower by a few tenths of a meter per second during most hours. Once again, the total error reduction can be attributed to a reduction in the bias. Both the control and LISWRF experience a positive bias in the wind speed during all forecast hours; however, during the nocturnal hours, the LISWRF improves upon the control bias until forecast hour 11. Between hour 21 and hour 24, the LISWRF has a slightly higher positive wind speed bias, possibly as a result of stronger post-sea-breeze winds at numerous coastal locations, given the larger land–sea temperature

![Figure 9](image.png)

**Fig. 9.** Hourly verification statistics of the 80 surface stations shown in Fig. 2 for the 29 individual 24-h forecasts during May 2004 (excluding the 24th and 28th), each initialized at 0000 UTC. Statistics are shown for (a) 2-m temperature, (b) 2-m dewpoint, (c) 10-m wind speed, and (d) 10-cm soil temperature at 20 selected FAWN sites (7 stations were eliminated during a manual quality control). Statistics include the control bias, control RMSE, LISWRF bias, and LISWRF RMSE, according to the legend in (a).
contrast of LISWRF. Only forecast hours 0–5 experienced statistically significant improvements in the LISWRF wind speed forecasts.

The 10-cm soil temperature forecasts tend to be too cold relative to the FAWN sites during most forecast hours in both the control and LISWRF (Fig. 9d). The LISWRF is even colder on average than the control by as much as 1.5°C during the nighttime hours, as noted by the differences in biases from hour 0 to hour 11. This cooler LISWRF result due to the differences in downward-directed shortwave radiation forcing, as described in section 4a. During the daytime hours (12–24), the control and LISWRF biases converge to −2°C by hour 24. As a result of the increase in the negative bias, the magnitude of the LISWRF RMSE exceeds the control during most forecast hours.

An examination of the spatial pattern of daytime biases and bias differences for the 0000 UTC forecast cycle (computed at individual stations for both 2-m temperatures and dewpoints and then objectively analyzed) reveals a noticeable correlation to the initial soil moisture differences, which resulted in improvements in LISWRF over favored regions. The contoured control biases of the 18-h forecast 2-m temperatures depict the nearly domain-wide cold daytime bias (generally 1°–3°C in magnitude) except for parts of southeast Georgia, where a slight warm bias exists (Fig. 10a). In the control 2-m dewpoint bias field at hour 18, a wet bias approaching 2°C is found over northwestern Florida and parts of south Georgia, whereas a dry bias of 1°–2°C occurs over south Florida (Fig. 10b).

The LISWRF improves upon the cold 2-m temperature bias across much of the domain, while also improving upon the slight warm bias over southeastern Georgia (Fig. 10c). Meanwhile, the moist bias in 2-m dewpoints over northwest Florida–south Georgia and small, dry biases over south Florida and portions of the East Coast are both correctly adjusted by LISWRF (Fig. 10d). Some portions of southwestern Florida, however, experience too much drying in LISWRF compared to the control. The greatest bias differences over north Florida and southwestern Georgia correspond to the area where LISWRF is much drier than the control 0–10 cm soil moisture. The LISWRF 2-m temperatures are 1.0°–1.5°C (or more) warmer, whereas the LISWRF dewpoints are 0.5°–1.5°C drier in these areas (Figs. 10c and 10d, respectively). Slightly warmer and drier conditions prevail across much of the peninsula except for south Florida, parts of Florida’s east coast, and eastern Georgia. The 1.0°–1.5°C warmer LISWRF 2-m temperatures correspond to −50–100 + W m−2 reduction in the monthly-mean sensible heat flux (depicted in Fig. 11a, averaged over all 0000 UTC 18-h forecasts). In a similar fashion, the 0.5°–1.5°C drier LISWRF 2-m dewpoints correspond to −50–100 + W m−2 reduction in the monthly-mean latent heat flux (Fig. 11b).

The qualitative patterns of both the monthly temperature–dewpoint bias differences and monthly-mean sensible/latent heat flux differences are quite similar to the pattern of 0–10 cm soil moisture differences from 1200 UTC 6 May (from Fig. 5c). It should be noted that the soil moisture difference pattern from 6 May is similar to most other days during May 2004 (not shown), given the relatively dry conditions that prevailed during the month. This evidence helps to emphasize the importance of providing a regional model with an accurate soil moisture initialization in the shallow soil layer and its influence on the overall surface energy budget and quality of short-term forecasts in the first 24 h during a summer regime.

Finally, the 1200 UTC forecast cycle errors are shown in Fig. 12, which show similar results as in the 0000 UTC error statistics. Similarities include a reduction in the daytime cold temperature bias, a daytime drying tendency in the dewpoint, and overall cold soil temperature bias and positive wind speed bias. The primary differences between the 0000 UTC and 1200 UTC cycles is that the LISWRF 1200 UTC diagnosed 2-m temperatures at 0 h have a larger warm bias than the control (Fig. 12a; the opposite is true of the 0000 UTC diagnosed 2-m temperatures at 0 h in Fig. 9a), the 1200 UTC 2-m temperatures do not exhibit a nocturnal warm bias, no improvement is seen in the 1200 UTC LISWRF wind speed errors compared to the control (Fig. 12c), and the control and LISWRF 10-cm soil temperature errors are more similar in the 1200 UTC cycle (Fig. 12d) compared to the 0000 UTC cycle (Fig. 9d). The disparity between the EDAS and NLDAS shortwave radiation forcing best explains the different behavior of the 0000 UTC and 1200 UTC cycle 10-cm soil temperature errors in the control versus LISWRF. The offline LIS run used to initialize the LISWRF land surface variables was forced by the NLDAS GOES-based shortwave radiation, which reduced a high bias in the EDAS as described earlier in this section. Therefore, the 0000 UTC (evening) LISWRF 10-cm soil temperatures are lower than the control (Fig. 9d), whereas little difference is found in the 1200 UTC (morning) soil temperatures (Fig. 12d).

5. Summary and future work

This manuscript describes an experimental design for evaluating the differences between daily regional simulations of a control configuration initialized with interpolated land surface data from the NCEP Eta Model versus the same model setup initialized with high-
resolution land surface data from the NASA LIS. Fifty-eight individual daily simulations were generated for both the control and LISWRF experimental configurations during May 2004 over Florida and the surrounding areas: 29 initialized at 0000 UTC and 29 initialized at 1200 UTC. The initial soil conditions in the LISWRF simulations came from an offline run of the Noah LSM within the LIS software for 2 yr prior to the beginning of the month-long period of study. Atmospheric variables used for forcing the Noah LSM during the offline integration were provided by a combination of NLDAS and GDAS gridded analyses.

The high-resolution LIS initial conditions were on average cooler and drier than the NCEP Eta Model data. During May 2004, there was an overall warming and drying trend in all four layers of the Noah LSM, especially in the top two layers. Comparisons between the control and LISWRF runs from 6 May 2004 suggested that the high-resolution soil initial conditions provided by LIS improved the timing and evolution of

![Fig. 10. Contour plots of the 0000 UTC forecast cycle 18-h control bias [plotted values (×10°C)] for (a) 2-m temperature, and (b) 2-m dewpoint as well as the bias differences (LISWRF – control) for (c) 2-m temperature, and (d) 2-m dewpoint. Biases at each individual verification station were objectively analyzed to contour the geographical distribution of errors.](image-url)
a sea-breeze circulation over portions of northwestern Florida compared to the control simulation. The LISWRF model run produced an area of warmer simulated 2-m temperatures over parts of northern Florida and southern Georgia, which resulted in an enhanced land–sea temperature contrast and correspondingly stronger and faster-moving sea-breeze front. The faster sea-breeze solution in LISWRF verified more favorably than the control at Perry and Cross City, Florida.

The LISWRF runs produced a more amplified diurnal range in 2-m temperatures compared to the control as a result of the drier initial soil states. This increased diurnal temperature range in LISWRF came from a reduction in the nocturnal warm bias in conjunction with a reduction in the daytime cold bias, and was more consistent with observations. Daytime LISWRF dewpoints were correspondingly drier than the control dewpoints, again a manifestation of the drier initial soil state provided by LIS. Most other verified quantities indicated little improvement compared to the control.
simulations. The predicted 10-cm soil temperatures were cooler in the 0000 UTC LISWRF runs as a result of the smaller GOES-based shortwave radiation forcing of NLDAS compared to the high-biased shortwave radiation of EDAS in the control runs.

A natural extension to this project involves fusing the work of LaCasse et al. (2008) that examined the influence of high-resolution MODIS SST composites (Haines et al. 2007) on model simulations over the Florida coastal waters with the current LISWRF work to provide high-resolution lower boundary initialization data everywhere in the coastal domain. Follow-up experiments could also examine the potential utility of high-resolution initial land surface data from LIS to more complex weather scenarios such as convective initiation (e.g., Trier et al. 2004).

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