An Integrated High Resolution Hydrometeorological Modeling Testbed using LIS and WRF

Popular Summary

Author: Sujay V. Kumar

Scientists have made great strides in modeling physical processes that represent various weather and climate phenomena. Many modeling systems that represent the major earth system components (the atmosphere, land surface, and ocean) have been developed over the years. However, developing advanced Earth system applications that integrates these independently developed modeling systems have remained a daunting task due to limitations in computer hardware and software. Recently, efforts such as the Earth System Modeling Framework (ESMF) and Assistance for Land Modeling Activities (ALMA) have focused on developing standards, guidelines, and computational support for coupling earth system model components. In this article, the development of a coupled land-atmosphere hydrometeorological modeling system that adopts these community interoperability standards, is described. The land component is represented by the Land Information System (LIS), developed by scientists at the NASA Goddard Space Flight Center. The Weather Research and Forecasting (WRF) model, a mesoscale numerical weather prediction system, is used as the atmospheric component.

LIS includes several community land surface models that can be executed at spatial scales as fine as 1km. The data management capabilities in LIS enable the direct use of high resolution satellite and observation data for modeling. Similarly, WRF includes several parameterizations and schemes for modeling radiation, microphysics, PBL and other processes. Thus the integrated LIS-WRF system facilitates several multi-model studies of land-atmosphere coupling that can be used to advance earth system studies.

Significant Findings

In this article, several synthetic and real simulations using the coupled LIS-WRF system are presented. The results suggest that capturing the fine scale heterogeneities associated with topography, soils, land cover, and other land surface features is important for accurate characterization of the land surface boundary. Further, the accurate representation of land surface conditions have significant impacts on the evolution of clouds and precipitation. The wealth of modeling infrastructure and tools in the LIS-WRF system is expected to enable studies to investigate the nature of interaction and feedback between land and the atmosphere.

An Integrated High Resolution Hydrometeorological Modeling Testbed using LIS and WRF *

Sujay V. Kumar [a], Christa D. Peters-Lidard [b], Joseph L. Eastman [a], Wei-Kuo Tao [c],

[a] *University of Maryland at Baltimore County, Goddard Earth Sciences and Technology Center, Baltimore, MD 21250*

[b] *Laboratory for Hydrospheric and Biospheric Processes, NASA Goddard Space Flight Center, Greenbelt, MD, 20771*

[c] *Mesoscale Atmospheric Processes Branch, NASA Goddard Space Flight Center, Greenbelt, MD, 20771*

Keywords

land atmosphere interaction, earth system modeling, hydrologic prediction, mesoscale modeling

---

Abstract

Interactions between the atmosphere and the land surface have considerable influences on weather and climate. Coupled land-atmosphere systems that can realistically represent these interactions are thus critical for improving our understanding of the atmosphere-biosphere exchanges of energy, water, and their associated feedbacks. NASA's Land Information System (LIS) is a high resolution land data assimilation system that integrates advanced land surface models, high resolution satellite and observational data, data assimilation techniques, and high performance computing tools. LIS has been coupled to the Weather Research and Forecasting (WRF) model, enabling a high-resolution land-atmosphere modeling system. These coupled Earth system model components help us to understand and predict regional and global water and energy cycles. Synthetic and realistic simulations using the coupled LIS-WRF system for a June 2002 International H2O Project (IHOP) case study illustrate the impact of accurate, high resolution land surface conditions on the evolution of clouds and precipitation.

---

* Corresponding author: S. V. Kumar. Tel. 001-301-286-8663.
Fax: 001-301-286-8624, *email: sujay@hsb.gsfc.nasa.gov*

1 Introduction

Accurate characterization of the complex dynamics governing land-atmosphere interactions is important for improving our understanding of water and energy cycles. The land surface exerts significant influences on the atmospheric processes across a number of spatial and temporal scales through the exchanges of mass and energy (Pan and Mahrt (1987); McCorcle (1988); Castelli et al. (1996)). The dependence and sensitivity of the atmospheric processes to the land surface boundary has been reported in many studies (Pielke (2001); Avissar and Pielke (1991); Chen and Avissar (1994)). For example, soil moisture, a variable that represents the amount of available water on the land surface, modulates the partitioning the surface energy into turbulent components of sensible and latent heat fluxes. The evolution of atmospheric processes such as precipitation, which supplies water to the land surface, is in turn is intimately linked to the moisture state of the surface. This interdependence has been cited as the cause of anomalous features such as drought and flood (Oglesby (1991); Koster et al. (2000)). Several past studies have shown the effects of surface heterogeneity and soil moisture gradients on the development of convection (Pielke (2001); Shaw et al. (1997); Holt et al. (2006); Trier et al. (2004)). Holt et al. (2006) further demonstrated the influence of the effects of vegetation and soil processes on convection and suggest that a detailed representation of these processes should be included in forecast models.

Though the interdependence of land surface conditions and atmospheric processes have been well-established (Betts and Ball (1995); Basara and Crawford (2002)), the initialization of mesoscale and NWP models have been limited by the lack of availability of real-time land surface states such as soil moisture, temperature, and snow pack. Traditional ground-based observation systems provide "point" measurements of soil moisture, which are inadequate for application and interpretation at varying spatial scales. Land surface initialization in regional mesoscale models is typically performed with coarser, spatially interpolated analysis from operational streams. The coarse representation of surface conditions fails to capture the fine scale heterogeneities associated with topography, soils, land cover and other land surface features. The interpretation of soil moisture and temperature profiles to the land surface model's configuration further introduces errors. The mesoscale model simulation is also constrained to use the same land surface model and the set of parameters to maintain consistency between initialization and forecasts. Uncoupled or offline land surface modeling systems have been shown to adequately capture the evolution of land surface states (Robock et al. (2003)), which in turn can be used to initialize the atmospheric models. Offline systems to generate high resolution land surface initial conditions such as High Resolution Land Data Assimilation System (HRLDAS; Chen et al. (2004)) have also been used to demonstrate the impact of fine scale soil moisture representation on forecasts of deep convection. This system, however, currently supports a single land surface model, a limited set of land surface, observational and meteorological data, and certain limited domains. NASA's Goddard Space Flight Center (GSFC) has recently developed a Land Information System (LIS; Peters-Lidard et al. (2004); Kumar et al. (2006)) capable of simulating land surface conditions at various spatial resolutions as high as 1km globally and as fine as 30m regionally. LIS is a Land Data Assimilation System (LDAS) that consists of software interfaces to execute several community land surface models using a blend of observationally-based precipitation, radiation, and other model-based sources of meteorological inputs and surface parameters. The LIS infrastructure generates spatially and temporally distributed estimates of land surface conditions using previously observed or model-derived meteorology to constrain and force the land surface models in an uncoupled manner.

LIS is a modeling system that provides both the ability to resolve and evaluate the impact of the heterogeneities in vegetation, soils, topography and other land surface states at the specified resolution, and the ability to specify custom land surface models and parameters. In this article, we describe the extension of the uncoupled LIS framework to support a coupled land-atmosphere modeling, which can employ several land surface models and can be applied over the region of interest. The flexibility provided by LIS can advance earth system science by facilitating multi-model studies of land-atmosphere coupling. The explicit characterization of the land surface at the same spatial scales as that of cloud and precipitation processes helps in accurately characterizing the land-atmosphere interaction.

An integrated system to conduct high resolution land-atmosphere simulations is enabled by coupling LIS and the Weather Research and Forecasting model (WRF; Michalakes et al. (2001)). WRF is a state of the art mesoscale numerical weather prediction system that serves both the atmospheric research and operational forecasting communities. LIS is used in an uncoupled manner to generate high resolution land surface initial conditions for a coupled simulation. Using LIS as the land surface modeling component in WRF in coupled simulations also allows for consistency across models, parameters, and computational configurations. In the sections that follow, we describe LIS, WRF and the architecture of the coupled system. A number of synthetic and real case day simulations demonstrating various modeling capabilities enabled by the coupled system are presented in section 5. Finally a summary and future extensions to the system are presented.

2 Land Information System

Land surface processes constitute significant components of the terrestrial climate system and they have profound influences on the interactions between the biosphere and atmosphere. Land surface models provide characterizations of the water and energy exchanges and biogeochemical processes of the soil-vegetation-snowpack medium. A realistic representation of these processes is critical for improving the understanding of the boundary layer and land-atmosphere interactions. The development of LIS has been motivated by the need to develop an infrastructure that combines the use of land surface simulation, available observations and the required computing tools for accurate land surface prediction. As discussed in Kumar et al. (2006), LIS integrates and extends the capabilities of Land Data Assimilation Systems (LDASs) such as the 25km Global Land Data Assimilation System (GLDAS; Rodell et al. (2004)) and the 12.5km North American Land Data Assimilation System (NLDAS; Mitchell et al. (2004)). LIS is primarily an infrastructure for operating an ensemble of land surface models with capabilities for data integration and assimilation, over user-specified regional or global domains. The new phase in LIS development is to extend its capabilities by linking with other earth system components, enabling coupled systems that can model land-atmosphere interactions more effectively.

LIS is designed using advanced software engineering principles, and features a highly modular, flexible, object oriented, component-based framework. Figure 1 shows the software architecture of LIS. The core of the system consists of structures to manage generic utilities such as time, configuration, geospatial transformations, I/O, parallel computing constructs, logging, etc. These structures provide generic, model-independent support for high performance computing, resource management, data and I/O handling, and other functions. The LIS core controls the overall program execution and manages the inclusion of user-defined extensible components through several related abstractions. These abstractions, shown in the middle layer, include generic representations of land surface models, data assimilation schemes, meteorological forcing schemes, domains, running modes etc. The specific user defined components extend these abstractions. For example, Figure 1 shows a number of land surface models (Noah, CLM, HySSIB, Catchment) implemented in LIS through the land surface model abstraction. By providing a structure that allows the reuse and community sharing of modeling tools, LIS allows rapid prototyping and development of new applications. These interoperable features in LIS has enabled the incorporation of a growing suite of community LSMs, meteorological forcing analyses, different sources of land surface parameters, and data assimilation schemes. The system also allows for the plug and play of various user-defined components and has enabled several intercomparison studies involving land surface models, parameters, and assimilation schemes (Dirmeyer et al. (1999)).

3 Weather Research and Forecasting Model

The Weather Research and Forecasting (WRF; Michalakes et al. (1998, 2001)) model is a next-generation mesoscale numerical weather prediction system that serves both operational and research communities. The system consists of multiple dynamical cores, preprocessors for producing initial and lateral boundary conditions for simulations, and a three-dimensional variational data assimilation (3DVAR) system. WRF is built using software tools to enable extensibility and efficient computational parallelism. The use of WRF system has been reported in a variety of areas including storm prediction and research, air-quality modeling, wildfire, hurricane, tropical storm prediction, and regional climate and weather prediction (Michalakes et al. (2004)).

The WRF software follows a modular structure with complex functionalities encapsulated into three main hierarchical layers. The top level corresponds to the driver layer and the lowest level corresponds to the model layer. The mediation layer provides the interface between the driver and the model layers. The driver performs the overall creation and organization of model domain data structures, control of model clock, parallel decomposition functions, processor topologies, and other aspects of parallelism. The management of I/O operations on model domains, control of forcing, feedback and nested operations are also handled in the driver layer. The mediation layer represents the instances of a particular dynamical core and its interaction with the model layer. This layer manages the invocation of interprocess communication and multithreading. The model layer encompasses the actual computational modules that constitute the model. These include advection, diffusion, physical parameterizations and representations of various other processes.

4 Design of the Integrated Coupled Land Atmosphere System

The advanced features of LIS and WRF are combined by integrating these modeling systems into a single system for coupled hydrometeorological modeling. In the coupled system, LIS and WRF represent the components of the land surface and the atmosphere, respectively. The design of the coupled system is enabled by the structure and tools provided by the Earth System Modeling Framework (ESMF; Hill et al. (2004)). ESMF is a project intended to develop standards-based, open-source software tools to enable software reuse, interoperability and performance portability in Earth Science Applications. The ESMF software primarily consists of a superstructure for coupling and exchanging data between components (e.g., atmosphere, land) and an infrastructure consisting of tools and utilities to speed up construction of components and to ensure consistent, guaranteed component behavior. A model component using ESMF is organized to perform three major functions: initialization, run, and finalization. The initialization methods typically implement the initialization of parameters, initial and boundary conditions, and any other model setup. The run method provides the model simulation methods and the finalization routine provides methods to properly complete the model operations.

As shown in Figure 1, the LIS software architecture allows LIS to be used in an analysis or uncoupled mode, where the meteorological boundary conditions are provided using existing meteorological data. In the coupled or forecast mode of operation, LIS obtains the meteorological boundary conditions from the atmospheric component such as WRF. Figure 2 illustrates the roles of LIS in the coupled LIS-WRF system: LIS is used as in an analysis mode to provide initial land surface conditions for WRF, and in the coupled mode for forecast/coupled simulations, LIS acts as the land surface component.

In the coupled mode of operation, the sequence of data exchanges between WRF and LIS are shown in Figure 3. In the LIS-WRF system, LIS and WRF are represented as two model components `lisComp` and `wrfComp`, respectively. `lis2wrfCpl` and `wrf2lisCpl` represent the coupler components that perform the actual data transformations and exchanges between the model components. The user-defined components that conform to ESMF use special objects called `ESMF_State` for inter component data exchanges. Every component accepts one or more `ESMF_States` as import states and produces one or more `ESMF_States` as export states. The data exchanged between the model components are encapsulated by `lisImport`, `lisExport`, `wrfImport`, and `wrfExport` objects that represent the import and export states from LIS and WRF. The simulation starts at `t=t0` and cycles `n` times. At the beginning of the simulation, both model components and the coupler components are created. The invocation to LIS is performed from the WRF surface driver, which is a model layer component in WRF. The export states from WRF are fed into LIS as the import states and the `lisComp` is executed. Finally the export states from LIS are fed back to WRF and the process repeats at every invocation of the surface driver.

The import and export states for the LIS model component follows the Assistance for Land Modeling Activities (ALMA (2002)) convention. ALMA is a data convention to facilitate the exchange of forcing data for land surface models and the results produced by them. In the design described above, the ALMA convention is imposed on the import and export states of LIS. The `lisImport` state consists of the atmospheric forcing variables that are specified in the ALMA data convention for forcing data. Similarly, the `lisExport` state is defined in accordance with the ALMA standard model output convention. In order for any LSM in LIS to be used in a coupled simulations, the LSM needs to provide methods to define the `lisExport` state, and methods to translate the `lisImport` state to its own variables. Thus, the two interfaces in LIS that define the import and export states of a LSM are sufficient to complete its incorporation in the coupled system.

The integration of LIS and WRF provides an enhanced system with several improved functionalities. The LIS-WRF system is designed such that LIS acts as the land modeling component, encapsulating several community land surface models, the broad set of data and land surface data assimilation tools. The data components in LIS enable the direct use of high resolution satellite and observational data streams for modeling. Similarly, WRF acts as the atmospheric component, providing a number of surface layer, Planetary Boundary Layer (PBL) schemes and parameterizations. The interaction of these two modeling systems through generic interfaces allows the plug and play of different land models, PBL and surface layer schemes. Further, the conformance to the ALMA standard and ESMF structure allows the model components of LIS and WRF to interface with other compatible earth system models.

Land surface states simulated by the LSMs typically require long-term simulations to reach thermodynamic equilibrium with the meteorology. This modification process or "spinup" of the model that adjusts for initial anomalies in soil moisture content or meteorology is important for accurate characterization of land surface conditions (Yang et al. (1995)). Further, Rodell et al. (2005) notes that the model climatologies differ from those observed in nature, and an ideal initialization of a LSM should be done with the results from a long-term simulation. Studies have shown that model biases originating from improper spinup can adversely impact the land surface simulations (Maurer and Lettenmaier (2004); Koster and Suarez (2001); Zhang and Frederiksen (2003)). LIS can be executed in an uncoupled mode, forcing the LSM with a meteorological dataset to conduct multiyear spinup simulations. The configurable features in LIS enable these simulations to be conducted at the same grid configurations using the same parameters and LSM as those used in the coupled simulations. Further, the high performance computing infrastructure in LIS allows these simulations to be conducted rapidly, with a turnaround time on the order of hours for a multi-year spinup (depending on the processor speed and availability).

WRF supports a horizontal nesting option that allows a high resolution simulation to be focused over a region of interest by introducing additional grids that are used to provide lateral boundary conditions to the inner, finer grid. In order to preserve consistency across different processes, the surface fluxes and processes also need to be represented at the same spatial scales. LIS provides options to set up regional domains in the same grid configurations as that generated by the WRF preprocessor (Standard Initialization - SI) program. LIS allows these domains to be set up anywhere in the world, and conduct longterm simulations using suitable meteorological forcing and available parameters.

5 Results

In this section, we present the results of simulations and experiments conducted using the coupled LIS-WRF system. These simulations illustrate the improvements in modeling capabilities enabled by the enhancements in computing and software of the coupled system. This section is organized into three segments: In the first segment, a set of idealized synthetic experiments to to test the land-atmosphere coupling interface is presented. Section 5.2 presents the application of the system to forecast a case day. Finally an analysis of the computational performance and scalability of the system is presented.

5.1 Synthetic Experiments

The goal of the synthetic experiments is to examine the exchange of energy and water across the land-atmosphere interface using a number of simple idealized cases. The experiments are designed using horizontally homogeneous conditions and a steady atmospheric forcing. The modeling domain is chosen over a region in the U.S. Southern Great Plains, which was also the focus of large weather field experiment called the International H2O project (IHOP-2002; Weckwerth et al. (2004)), conducted from 13 May to 25 June, 2002. The domain is chosen to be of size 100x100 grid points at 1km resolution, with 41 vertical levels. The height of the vertical levels is chosen with high resolution near the ground and progressively less resolution with increasing height. The whole domain is uniformly specified with grassland as the landcover type. The soil is uniformly specified with sandy clay loam, which is the dominant soil type of the area. The experiments are conducted with two of the land models in LIS; the community Noah LSM (Noah; Ek et al. (2003)), and the Community Land Model Version 2.0 (CLM; Dai et al. (2003)). Both these models dynamically predict water and energy fluxes and states at the land surface, although their parameterizations and/or structures representing various processes differ. For example, CLM includes 10 layers for soil temperature and soil water, with explicit treatment of liquid water and ice, whereas Noah uses four soil layers. An important difference between the two is related to the representation of vegetation and its control over transpiration: Noah assumes uniform Leaf Area Index (LAI) over the globe, with a temporally and spatially varying Green Vegetation Fraction (GVF) and a simple Jarvis-based stomatal resistance formulation controlling the maximum transpiration from vegetated grids or tiles. In contrast, CLM has a much more complex representation of the canopy, including variable LAI and coupled photosynthesis-stomatal conductance formulation.

Two sets of experiments are conducted: A DRY experiment where the coupled system is initialized with a dry, soil moisture deficient land surface, and a WET experiment with a relatively wet soil state. Atmospheric initial conditions for the modeling domain are uniformly applied from the sonde extracted from the data archive of IHOP-2002, for June 6, 2002 at 12GMT. This day is chosen since there were light winds in the PBL and the atmosphere was extremely dry leading to negligible moist development. These conditions are generally favorable to the growth of mesoscale circulations that can result from the influence of the land surface conditions as noted by Lynn et al. (2001).

Figures 4 and 5 show the domain averaged surface energy fluxes from the DRY and WET simulations, respectively. From the figures it can be observed that the LSMs generate the partitioning of radiant energy between the turbulent (latent Qle and sensible Qh) heat fluxes and the ground heat (Qg) fluxes differently. The partition of the input energy is also tightly coupled to water availability at the surface. In the DRY simulations, the plants are constrained by the lack of transpirable water, leading to stomatal closure. As a result, the surface latent fluxes in the DRY experiments are expected to be zero. The DRY experiments using both LSMs demonstrate this feature. In the WET experiments, the latent heat flux constitutes the primary component of the turbulent fluxes, due to the evaporation of water through the plant stomata. Both LSMs exhibit these trends, though the partition is done differently. Figure 6 shows the evolution of planetary boundary layer (PBL) height from the DRY and WET experiments. The PBL, the lowest portion of the atmosphere is strongly influenced by surface characteristics. This influence is demonstrated in the experiments using both LSMs. The PBL height from the DRY experiment is larger than the height from the WET experiment, indicating the direct influence of larger sensible fluxes on the PBL growth.

These simple, synthetic experiments demonstrate how the evolution of fluxes of energy and water between the land-atmosphere interface is intimately linked to the moisture state of the land surface. The atmospheric processes that supply moisture to the surface are in turn dependent on the moisture-driven fluxes from the land.

5.2 *Impact of LIS on precipitation forecast*

To demonstrate the impact of high resolution land surface conditions on the development of clouds and precipitation processes, the LIS-WRF system is applied over the IHOP-2002 region using June 12, 2002 as the case day. This date is chosen since the day was characterized by clear skies and relatively weak synoptic forcing. As a result, the land surface influence is likely to be magnified in the evolution of mesoscale circulations. The data archives of IHOP show that convection occurred between 12GMT on June 12, 2002 through 12GMT on June 13, 2002.

The chosen modeling domain is centered around the area where the convection is initiated. The model domain shown in Figure 7 consists of three nested domains, with the outermost grid (d1) with a 9-km grid spacing, and the inner grid (d2) with 3km and the innermost grid (d3) with a 1km spacing. The d1 domain consists of 399x270 grid points, the d2 domain consists of 402x402 grid points and the d3 domain consists of 504x504 points. The vertical grid consists of 41 vertical levels, with the lowest level at 10m extending upto 18km above the ground level. The 32km North American Regional Reanalysis (NARR; Mesinger et al. (2006)) data is used to initialize the meteorological conditions for all three nests. Other WRF model settings includes Lin Microphysics, RRTM longwave, and Dudhia shortwave parameterizations.

Three different simulations are conducted for the case day using initial land surface conditions generated by: (1) from a climatology, (2) from a long term spinup of the Noah land surface model in LIS, and (3) from a long term spinup of the CLM land surface model in LIS. The climatology-based soil moisture and temperature profiles are derived from the NARR data by the WRF preprocessor program, which is on a coarse, 32km grid. The soil profiles in LIS are generated from the uncoupled, long-term spinup by LIS. Using Noah and CLM LSMs, each of the three nested domains are spunup for approximately 17 years, starting from 1985, using bias-corrected atmospheric reanalysis data (Berg et al. (2003)). From 2000 onwards the inner nests are forced with the forcing data used in the NLDAS (Cosgrove et al. (2003)), which includes the radiation from the GOES satellites and the precipitation from the NCEP STAGEIV estimates (Lin and Mitchell (2005)). The spatial extent of the NLDAS forcing did not cover the d1 domain completely. As a result, the d1 domain is forced with the output from the Global Data Assimilation System (GDAS), the global operational weather forecast model of NCEP (Derber et al. (1991)). A static, 1km resolution global vegetation classification dataset produced at the University of Maryland (Hansen et al. (2000)) is used to prescribe vegetation-based parameters for both LSMs. The Noah LSM requires monthly GVF and quarterly snow-free albedo. The GVF fields in LIS are currently sampled from the global, 0.144 degree (approx. 15-km), monthly 5-year climatology derived by Gutman and Ignatov (1998) from the Advanced Very High Resolution Radiometer (AVHRR) instrument aboard the NOAA satellites. CLM requires climatologies of Leaf Area Index (LAI) and the simulation uses a 1km, 4 year average climatology derived from the MODIS Collection 4 LAI products. Soil hydraulic properties are derived using vertically uniform sand, silt and clay percentages from the 5-min global soils dataset of Reynolds et al. (1999), which is also known as the Food and Agriculture Organization (FAO) based data. This dataset is used in the outer domain d1. A finer, 1km resolution State Soil Geographic Database (STATSGO) soil parameters from Miller and White (1998), which carries 16 texture classes over 11 layers to 2-m depth, available for the continental United States is used for the inner domains d2 and d3. In the simulations using the Noah LSM, water points are treated as quasi-ocean points using redefined sea surface temperature as the skin temperature value. In CLM, however, the water points are modeled with an explicit lake model (Bonan (1996)), with lake temperatures computed based on a six-layer model.

Figures 8 and 9 show a comparison of the initial soil moisture and soil temperature fields for the d3 domain from WRF preprocessor program (which is based on the NARR data), LIS Noah spinup, and the LIS CLM spinup, at 12Z, June 12, 2002, which is the initial time of the forecast simulation. The comparison demonstrates the fine-scale features from the LIS spinups, compared to the overall more uniform NARR data-based initial conditions. Further, it can be observed that the CLM spinup demonstrates more fine scale features, compared to Noah. This can be attributed to the fact that the CLM spinup uses the 1km MODIS LAI along with other high resolution data to prescribe the input land surface parameters, whereas Noah LSM uses a rather coarse GVF data to prescribe the vegetation phenology.

The initial soil moisture and temperature profiles of 12Z June 12, 2002, used in the three simulations are evaluated by comparing them to the station data from the Oklahoma mesonet Brock et al. (1995). Table 1 shows the summary of the comparisons that includes approximately 115 stations. It can be observed that the LIS generated soil moisture and temperature initial conditions demonstrate reduced error estimates compared to the NARR-based initialization. The bias estimates for soil moisture indicates that the NARR and LIS-Noah initializations are hotter and drier, whereas the LIS-CLM initialization is wetter and colder.

The simulations using the above described initial conditions are used to conduct a 24 hour coupled LIS-WRF simulation starting at 12Z, June 12, 2002. These simulations are analyzed for their predictive skill in generating the case day convection. Table 2 shows a summary of several evaluation metrics typically applied for NWP rainfall verifications. The NARR-based simulation overpredicts the precipitation event, indicated by a high positive bias. The bias is reduced in the LIS-Noah simulation. The LIS-CLM run has a negative bias. The root mean square (RMS) errors are highest in the NARR simulation and are reduced in the LIS-based simulations, with the LIS-CLM simulation showing the lowest error estimate. Probability of Detection (POD), which measures the success of the forecast in correctly predicting the occurrence of rain events is improved with the LIS-based forecasts, with the LIS-CLM run showing the best metric. Similarly, the False Alarm Ratio (FAR), which measures the fraction of event forecasts that are actually non-events, is reduced in LIS-based simulations, the LIS-CLM run with the lowest FAR value. The simulations are also evaluated by comparing the distribution of rain rates with the STAGEIV rates, shown in Figure 10. The NARR data-based simulation underestimates the low rain rates, and overpredicts the higher rain rates. The LIS-based simulations provide estimates of rain rates closer to the observations, compared to the NARR data-based simulation.

These results demonstrate the improved skill in forecasts with the use of LIS-derived land surface initial conditions. Further, the improved estimates in skill, magnitude and distribution of the CLM forecast can be attributed to the more physically-based, process oriented parameterizations in its treatment of vegetation, soils, and water components of the land surface and the use of more high resolution land surface parameters compared to the Noah LSM.

5.3 Computational Performance

The real case simulation described above is extremely computationally demanding. The simulation is carried out using 128 processors, requiring approximately 50 gigabytes of memory. The 24 hour simulation required approximately 22 hour wall clock time. Therefore, it becomes very important that the coupled system scales well in a multiprocessor environment in order to have a realistic turnaround time.

To analyze the computational scalability of the LIS-WRF system and to examine the overhead imposed by LIS, simulations are carried out on a 100x100 domain at 1km resolution, varying the number of processors, using the LIS-WRF system and the native WRF system, using the Noah land surface model. All simulations are carried out on the HP/Compaq SC45-halem system at the NASA Goddard Space Flight Center. This supercomputing system employs standard symmetric multiprocessor (SMP) nodes that incorporates four Alpha-EV68 processors. The nodes are connected to a Single rail Quadrics QsNet network that yields peak internode bandwidth of about 280MB/s. Figure 11 shows the comparison of execution times for a 24 hour forecast for different number of processors, for both the LIS-WRF, and the native WRF systems. It can be observed that the use of multiprocessors provides significant improvement in computational performance and the execution scales efficiently in a massively parallel environment. Further, the overhead imposed by LIS is in the order of 5-7 percent and can be considered to be minimal.

6 Summary

The article describes the design of a high resolution hydrometeorological modeling system that integrates LIS and WRF using the interoperable standards and constructs provided by ESMF. This highly modular system is designed using advanced software engineering principles and practices. The wealth of user-defined extensible components in LIS and WRF enables prototyping, plug and play, and intercomparison of various model components. The use of LIS as the land surface modeling component in WRF enables not only the use of different land surface models, but also the use of high resolution data access and distribution, high performance computing, and land surface data assimilation tools.

The land surface initial conditions for the coupled LIS-WRF simulations are generated by running LIS "uncoupled" for 17 years, using observationally-based precipitation, radiation, and meteorological inputs and high resolution surface parameters. Long uncoupled simulations are necessary because deep soil moisture and temperatures require long integrations to reach dynamic equilibrium. Our case study results suggest that the soil thermodynamic profiles generated by LIS improves the coupled system estimates relative to the standard initialization using the output from an NWP model.

The integration of these two complex systems is achieved without a significant overhead in the computational scaling performance. The analysis of the coupled system simulations showed that the code scaled very well in a massively parallel environment. Though the real case day simulation described in the article is computationally intensive, near-real time performance is achieved using adequate computing resources.

In this article, the interoperability of using different LSMs is demonstrated using a number of synthetic experiments. Many studies to investigate the impact of high resolution satellite and ground observations such as those provided by MODIS can be readily investigated through the use of LIS. The data assimilation tools in LIS use state-of-the art techniques such as the ensemble kalman filter to constrain the model behavior with observations. The coupled LIS-WRF system can be used to simultaneously employ both atmospheric data assimilation through WRF and land data assimilation through LIS. Such a state-of-the-art system could improve the predictive capabilities significantly in an operational environment.

The coupling interface in the LIS-WRF system is currently implemented in an explicit manner, using the atmospheric and surface values for different time steps to compute the turbulent fluxes. The focus of this approach is to conserve energy.The fluxes fed back to the atmosphere is obtained by solving the surface energy balance. The main drawback is that the atmospheric feedback to the surface is only felt from one time step to the other. Other coupling strategies such as implicit, semi-implicit methods that focus on keeping the atmospheric profiles synchronous to the surface conditions will be explored through future enhancements to the LIS-WRF system. Thus, the LIS-WRF system will enable studies to investigate the nature of interaction and feedback between land and the atmosphere using various modeling tools and schema in LIS and WRF.

7 Acknowledgments

This work is supported by NASA ESTO/AIST NRA-02-OES-04 (PI Peters-Lidard) project. This support is gratefully acknowledged.

References

ALMA. "Assistance for Land Modeling Activities, Version 3.", 2002. Http://www.lmd.jussieu.fr/ALMA/.

Avissar, R., and R.A. Pielke. "The impact of plant stomatal control on mesoscale atmospheric circulations." *Agricultural and Forest Meteorology* 54: (1991) 353–372.

Basara, J.B., and K.C. Crawford. "Linear relationships between root-zone soil moisture and atmospheric processes in the planetary boundary layer." *Journal of Geophysical Research* 107, D15: (2002) DOI:10.1029/2001JD000,633.

Berg, A.A., J.S. Famiglietti, J.P. Walker, and P.R. Houser. "Impact of bias correction to reanalysis products of north american soil moisture and hydrological fluxes." *Journal of Geophysical Research* 108, D16: (2003) DOI:10.1029/2002JD003,334.

Betts, A.K., and J.H. Ball. "The FIFE surface diurnal cycle climate." *Journal of Geophysical Research* 101, 25: (1995) 674–693.

Bonan, G.B. "A land surface model (LSM version 1.0) for ecological, hydrological, and atmospheric studies." Technical Report NCAR/TN-417+STR, National Center for Atmospheric Studies (NCAR), 1996.

Brock, F.V., K.C. Crawford, R.L. Elliot, G.W. Cuperus, S.J. Stadler, H.L. Johnson, and M.D. Eilts. "The Oklahoma Mesonet: A Technical overview." *Journal of Atmospheric and Oceanic Technology* 12: (1995) 5–19.

Castelli, R., Rodriguez-Iturbe, and D. Entekhabi. "An analytic framework for the modeling of the spatial interaction between soil moisture and the atmosphere." *Journal of Hydrology* 184: (1996) 19–34.

Chen, F., and R. Avissar. "The impact of land-surface wetness heterogeneity on mesoscale heat fluxes." *Journal of Applied Meteorology* 33, 11: (1994) 1323–1340.

Chen, F., K.W. Manning, D.N. Yates, M. A. LeMone, S.B. Trier, R. Cuenca, and D. Niyogi. "Development of a High Resolution Land Data Assimilation System (HRLDAS)." In *Preprints, 16th Conference on Numerical Weather Prediction.* Seattle, WA.: American Meteorological Society, 2004, CDROM, 22:3.

Cosgrove, B., D. Lohmann, K.E. Mitchell, P.R. Houser, E.F. Wood, J.C. Schaake, Robock. A., C. Marshall, J. Sheffield, Q. Duan, L. Luo, R.W. Higgins, R.T. Pinker, J.D. Tarpley, and J. Meng. "Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project." *Journal of Geophysical Research* 108, D22: (2003) DOI:10.1029/2002JD003,118.

Dai, Y., X. Zeng, R.E. Dickinson, I. Baker, G.B. Bonan, M.G. Bosilovich, A.S. Denning, P.A. Dirmeyer, P.R. Houser, G. Niu, K.W. Oleson, C.A. Schlosser, and Z-L. Yang. "The Common Land Model (CLM)." *Bulletin of the American Meteorological Society* 84, 4: (2003) 1013–1023. DOI:10.1175/BAMS-84-8-1013.

Derber, J.C., D.F. Parrish, and S.J. Lord. "The new global operational analysis system at the National Meterorological Center." *Weather and Forecasting* 6: (1991) 538–547.

Dirmeyer, P.A., A.J. Dolman, and N. Sato. "The Global Soil Wetness Project: A pilot project for global land surface modeling and validation." *Bulletin of the American Meteorological Society* 80: (1999) 851–878.

Ek, M.B., K.E. Mitchell, L. Yin, P. Rogers, P. Grunmann, V. Koren, G. Gayno, and J.D. Tarpley. "Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta model." *Journal of Geophysical Research* 108, D22: (2003) DOI:10.1029/2002JD003,296.

Gutman, G., and A. Ignatov. "Derivation of green vegetation fraction from NOAA/AVHRR for use in numerical weather prediction models." *International Journal of Remote Sensing* 19: (1998) 1533.

Hansen, M.C., R.S. DeFries, J.R.G. Townshend, and R. Sohlberg. "Global land cover classification at 1km spatial resolution using a classification tree approach." *International Journal of Remote Sensing* 21, 6: (2000) 1331–1364.

Hill, C., C. DeLuca, V. Balaji, M. Suarez, and A. da Silva. "The architecture of the Earth System Modeling Framework." *Computing in Science and Engineering* 6, 1: (2004) 18–28.

Holt, T., D. Niyogi, F. Chen, M.A. LeMone, Manning. K., and A. L. Qureshi. "Effect of Land-Atmosphere Interactions on the IHOP 24-25 May 2002 Convection Case." *Monthly Weather Review* 134: (2006) 113–133.

Koster, R., M. Suarez, and M. Heiser. "Variance and predictability of precipitation at seasonal-to-interannual timescales." *Journal of Hydrometeorology* 1: (2000) 26–46.

Koster, R.D., and M.J. Suarez. "Soil moisture memory in climate models." *Journal of Hydrometeorology* 2, 6: (2001) 558–570.

Kumar, S.V., C.D. Peters-Lidard, T. 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. "Land information system: An interoperable framework for high resolution land surface modeling." *Environmental Modeling and Software* 21: (2006) 1402–1415.

Lin, Y., and K.E. Mitchell. "The NCEP Stage II/IV hourly precipitation analyses: development and applications." In *Preprints, 19th American Meteorological Society.* San Diego, CA, 2005.

Lynn, B.H., W.-K. Tao, and F. Abramopoulos. "A parameterization for triggering landscape generated moist convection, Part I:Analyses of high resolution model results." *Journal of Atmospheric Sciences* 58: (2001) 575–592.

Marguilis, S. A., and D. Entekhabi. "A coupled land surface boundary layer model and its adjoint." *Journal of Hydrometeorology* 2: (2004) 274–296.

Maurer, E.P., and D.P. Lettenmaier. "Potential effects of long-lead hydrologic predictability on Missouri river main-stem reservoirs." *Journal of Climate* 17, 1: (2004) 174–186.

McCorcle, M. D. "Simulation of surface soil moisture effects on the Great Plains low-level jet." *Monthly Weather Review* 116: (1988) 1705–1720.

Mesinger, F., G. DiMego, E. Kalnay, K.E. Mitchell, P.C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi. "North American Regional Reanalysis." *Bulletin of the American Meteorological Society* 87, 3: (2006) 343–360.

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, and W. Skamarock. "Development of a next generation regional weather research and forecast model." In *Developments in Teracomputing: Proceedings of the Ninth ECMWF Workshop on the use of high performance computing in meteorology.* Singapore, 2001, 269–276.

Michalakes, J., J. Dudhia, D. Gill, T. Henderson, J. Klemp, W. Skamarock, and W. Wang. "The Weather Research and Forecasting Model: software architecture and performance." In *11th ECMWF Workshop on the use of High Performance Computing in Meteorology*, edited by George Mozdzynski. Reading, U.K., 2004.

Michalakes, J., J. Dudhia, D. Gill, J. Klemp, and W. Skamarock. "Design of a next-generation regional weather research and forecast model." In *Eighth ECMWF workshop on the use of parallel processors in meteorology.* Reading, England: European Center for Medium Range Weather Forecasts, 1998.

Miller, D.A., and R.A. White. "A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling." *Earth Interactions* 1: (1998) paper 2.

Mitchell, K. E., D. Lohmann, P. R. Houser, J. C. Wood, E. F. Schaake, A. Robock, B. Cosgrove, J. Sheffield, Q. Duan, L. Luo, W. R. Higgins, R. T. Pinker, J. D. Tarpley, D. P. Lettenmaier, C. H. Marshall, J. K. Entin, M. Pan, W. Shi, V. Koren, J. Meng, B. H. Ramsay, and A. A. Bailey. "The multi-institution North American Land Data Assimilation System (NLDAS): utilization of multiple GCIP products and partners in a continental distributed hydrological modeling system." *Journal of Geophysical Research* 109: (2004) DOI:10.1029/2003JD003,823.

Oglesby, R.J. "Springtime soil moisture, natural climate variability, and North American drought as simulated by NCAR community climate model." *Journal of Climate* 4: (1991) 890–897.

Pan, H. L., and L. Mahrt. "Interactions between soil hydrology and boundary-layer development." *Boundary Layer Meteorology* 38: (1987) 187–202.

Peters-Lidard, C. D., S. V. Kumar, Y. Tian, J. L. Eastman, and P. R. Houser. "Global Urban-scale Land-Atmosphere Modeling with the Land Information System." In *Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, 84th AMS Annual Meeting.* Seattle, WA., 2004.

Pielke, R.A. "Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall." *Reviews of Geophysics* 39: (2001) 151–177.

Reynolds, C.A., T.J. Jackson, and W.J. Rawls. "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.* 1999, 80.

Robock, A., L. Luo, E. Wood, F. Wen, K. E. Mitchell, P. R. Houser, J. C. Schaake, D. Lohmann, B. Cosgrove, J. Sheffield, Q. Duan, R. W. Higgins, R. T. Pinker, D. Tarpley, J. B. Basara, and K. C. Crawford. "Evaluation of the North American Land Data Assimilation System over the southern Great Plains during the warm season." *Journal of Geophysical Research* 108, D22: (2003) DOI:10.1029/2002JD003,245.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng., K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll. "The Global Land Data Assimilation System." *Bulletin of the American Meteorological Society* 85, 3: (2004) 381–394.

Rodell, M., P.R. Houser, A.A. Berg, and J. S. Famiglietti. "Evaluation of 10 Methods for Initializing a Land Surface Model." *Journal of Hydrometeorology* 6, 2: (2005) 145–155.

Shaw, B.L., R.A. Pielke, and C.L. Ziegler. "A three-dimensional numerical simulation of a Great Plains dryline." *Monthly Weather Review* 125: (1997) 1489–1506.

Trier, S.B., F. Chen, and K.W. Manning. "A Study of convection initiation in a mesoscale model using high resolution land surface initial conditions." *Monthly Weather Review* 132: (2004) 2954–2976.

Weckwerth, T.M., D.B. Parsons., S.E. Koch, J.A. Moore, M.A. LeMone, B.B. Demoz, C. Flamant, B. Geerts, J. Wang, and W.F. Feltz. "An overview of the International H2O (IHOP) project and some preliminary highlights." *Bulletin of the American Meteorological Society* 85: (2004) 253–277.

Yang, Z-L, A. Dickinson, R.E. Henderson-Sellers, and A.J. Pitman. "Preliminary study of spin-up processes in land surface models with the first stage of Project for Intercomparison of land surface parameterization scheme Phase 1(a)." *Journal of Geophysical Research* 100, 16: (1995) 553–578.

Zhang, H., and C.S. Frederiksen. "Local and nonlocal impacts of soil moisture initialization on AGCM seasonal forecasts: A model sensitivity study." *Journal of Climate* 13: (2003) 2117–2137.

Table 1
Comparison of Root Mean Square (RMS) and Bias errors for the initial soil moisture and soil temperature profiles at 12ZJune 12, 2002, used for the initialization of the precipitation forecasts

	RMS			Bias		
	NARR	LIS-Noah	LIS-CLM	NARR	LIS-Noah	LIS-CLM
10 cm volumetric soil moisture (m3/m3)	0.112	0.058	0.062	-3.22E-2	-1.42E-2	4.17E-3
30 cm volumetric soil moisture (m3/m3)	0.129	0.079	0.087	-7.47E-2	-3.82E-2	5.19E-2
60 cm volumetric soil moisture (m3/m3)	0.169	0.090	0.101	-0.150	-5.29E-2	8.23E-2
10 cm soil temperature (K)	2.38	1.37	1.24	1.32	0.89	-0.62
30 cm soil temperature (K)	2.41	2.17	2.26	1.29	1.75	-1.60

Table 2
Comparative skill scores from simulations using different land surface initial conditions compared with the STAGEIV data

Metric	NARR-based	LIS-Noah	LIS-CLM
Root Mean Square Error (mm)	5.97	5.62	5.38
Bias Error (mm)	8.85E-2	2.70E-2	-8.73E-2
Probability of Detection (POD)	0.21	0.25	0.35
False Alarm Ratio (FAR)	0.61	0.56	0.32

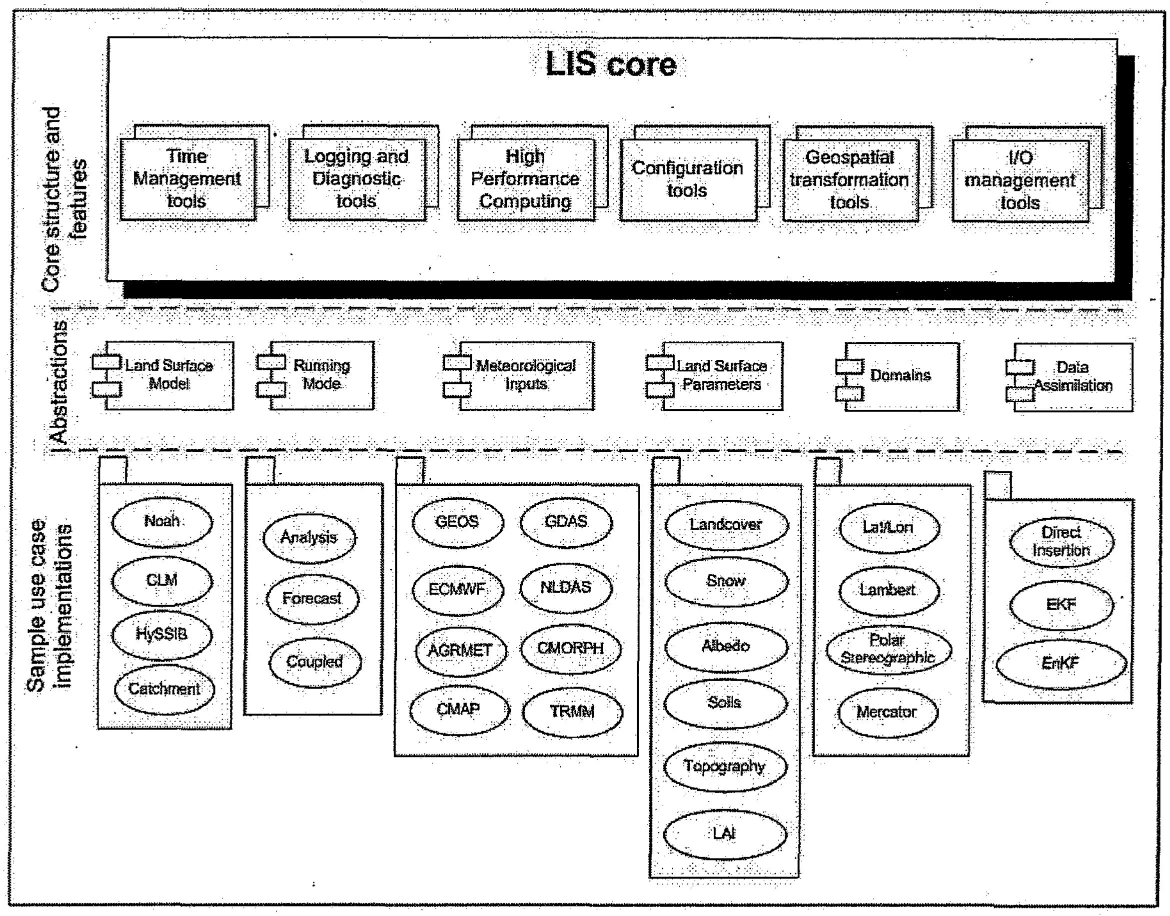

Fig. 1. Software architecture of the LIS framework

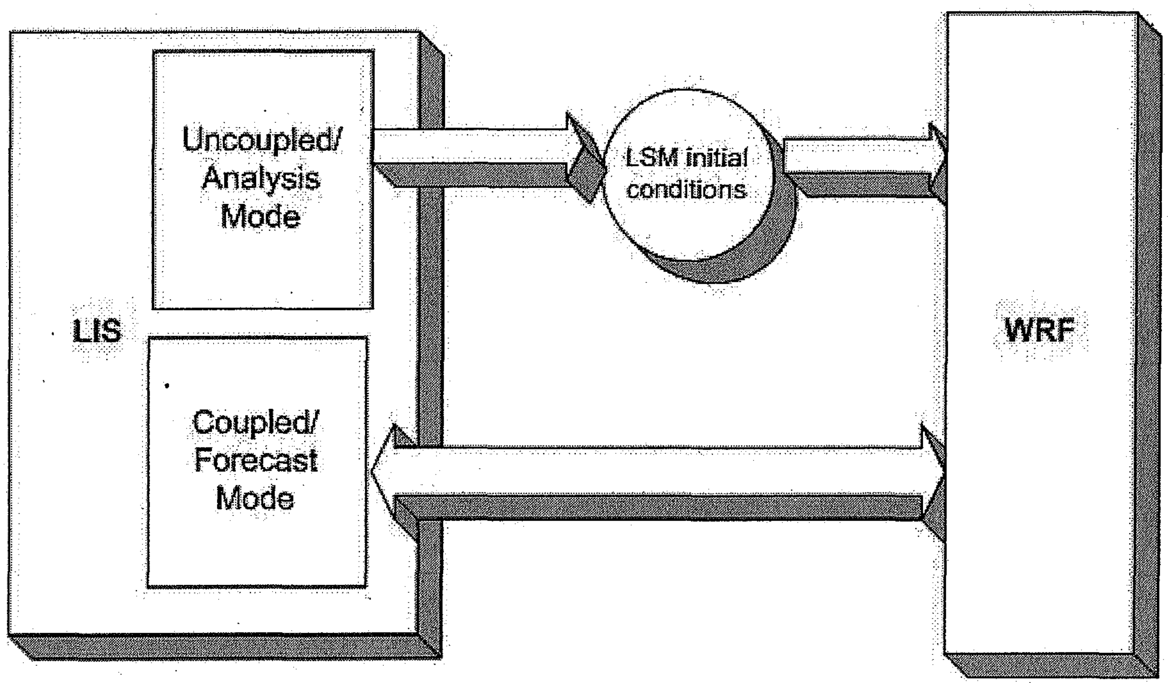

Fig. 2. Running modes of LIS in the LIS-WRF system: the uncoupled/analysis mode for initialization and the coupled/forecast mode as the land modeling component

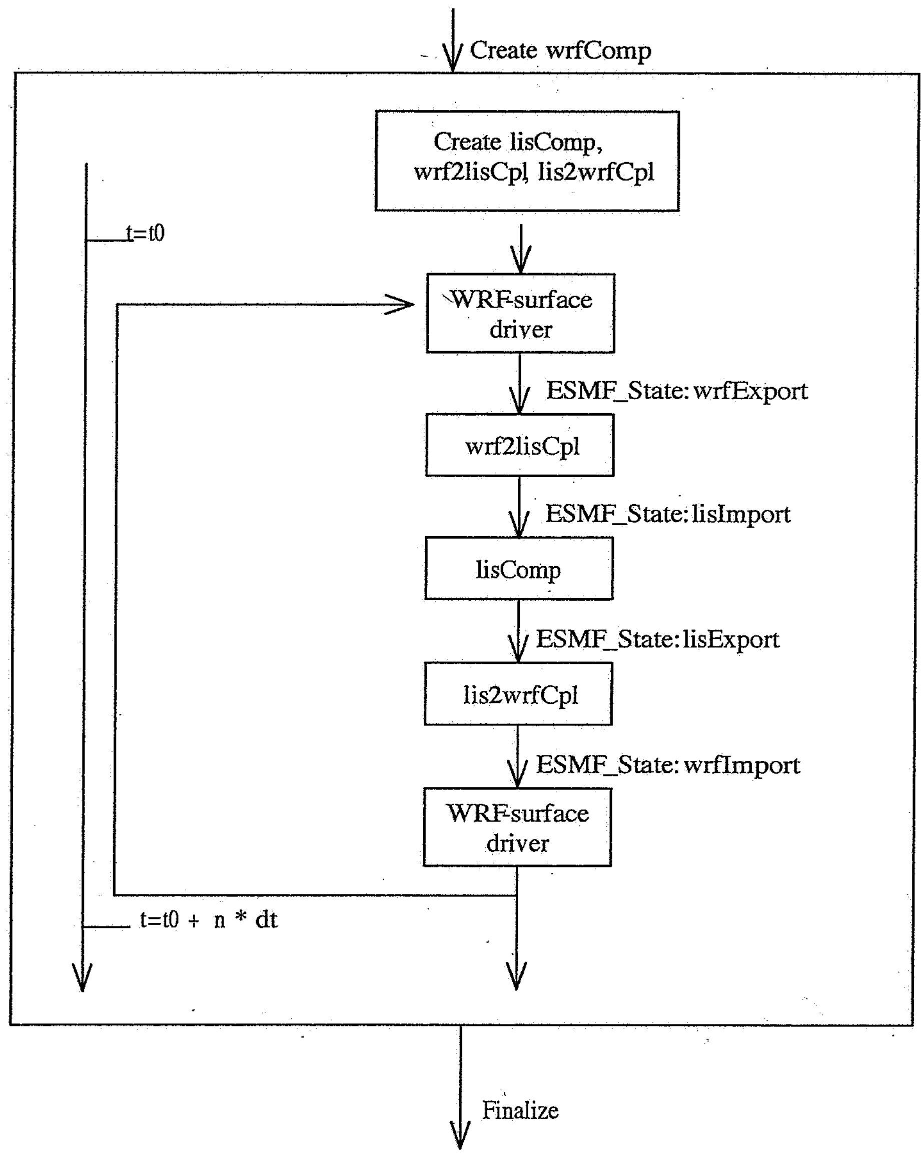

Fig. 3. Sequence of component interactions in the coupled LIS-WRF system

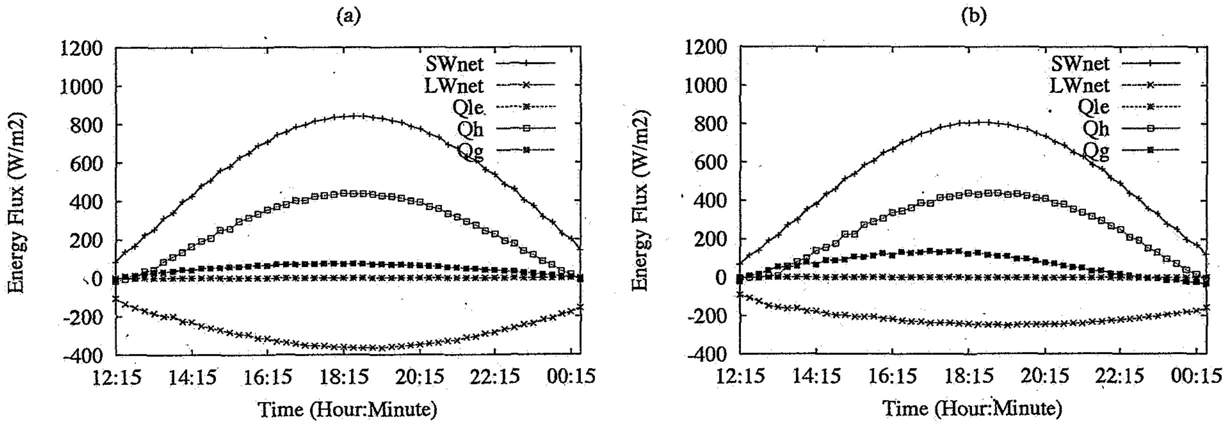

Fig. 4. Domain averaged surface energy flux terms from the DRY simulations using: (a) Noah and (b) CLM land surface models

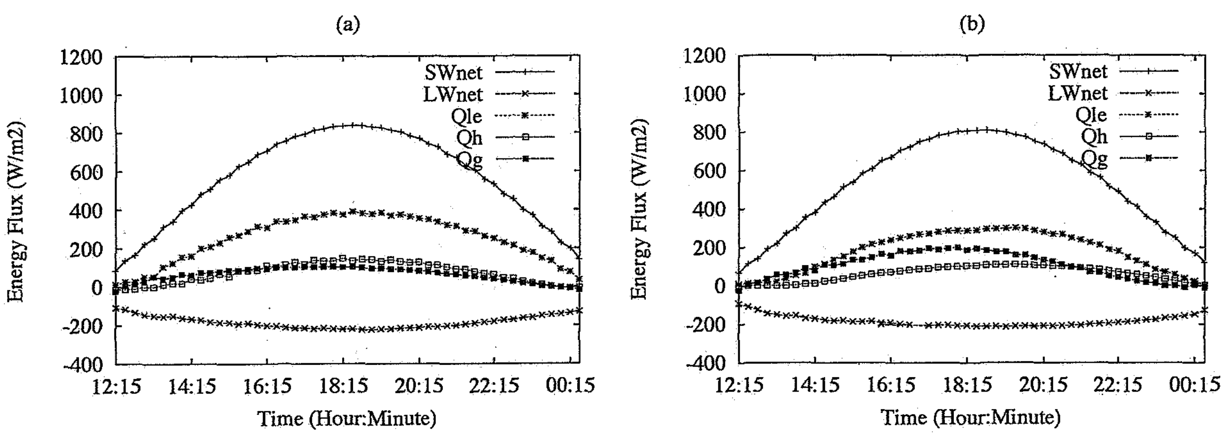

Fig. 5. Domain averaged surface energy flux terms from the WET simulations using: (a) Noah and (b) CLM land surface models

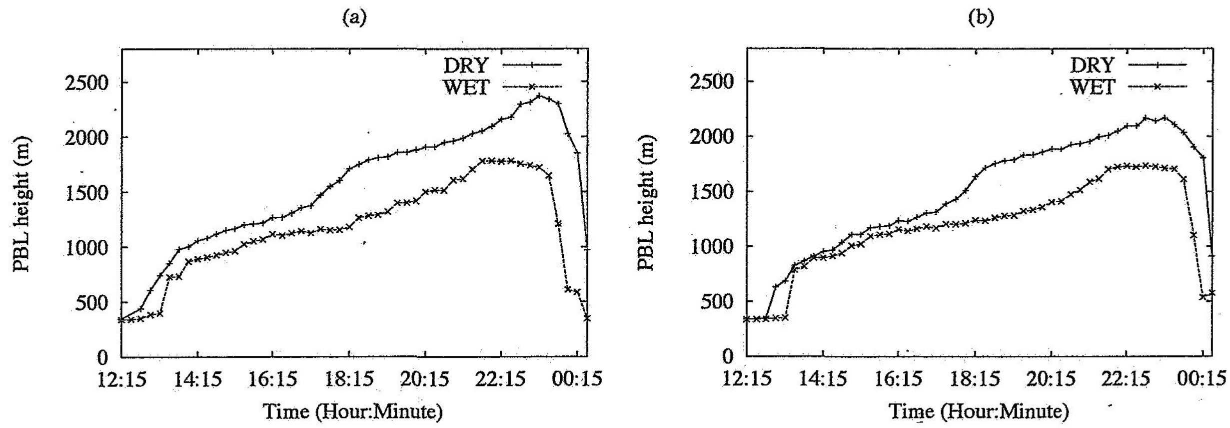

Fig. 6. Domain averaged PBL height from the DRY/WET simulations using: (a) Noah and (b) CLM land surface models

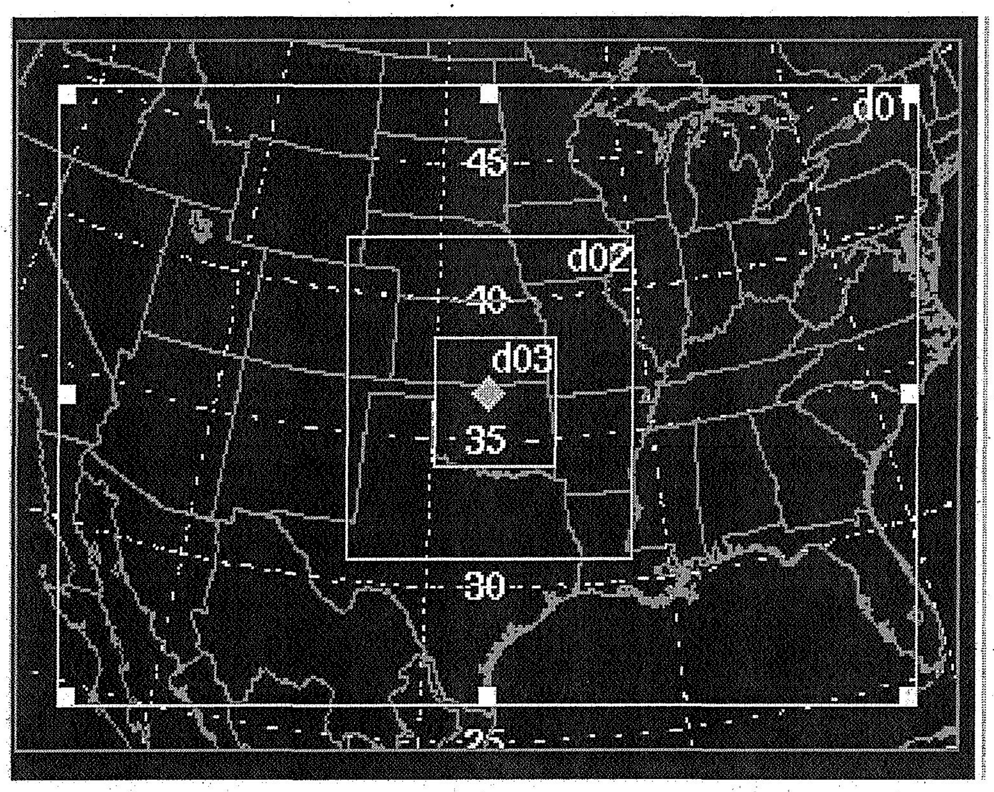

Fig. 7. Configuration of the triple nested domain used in the coupled LIS-WRF simulations for the June 12, 2002 forecast

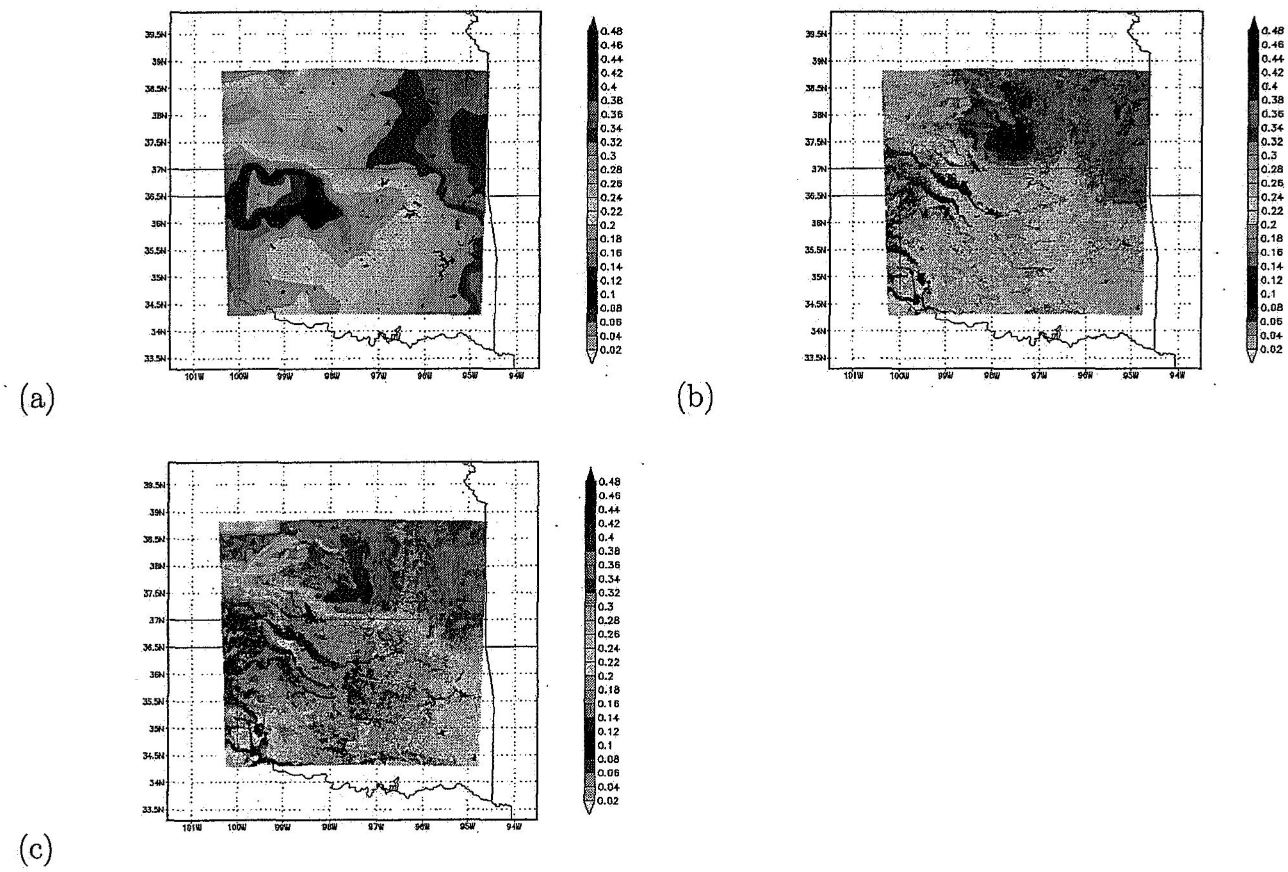

Fig. 8. Top 10cm volumetric soil moisture initial conditions at 12Z, on June 12, 2002 generated by (a) WRF preprocessor (using NARR data), (b) long term spinup of Noah by LIS, and (c) long term spinup of CLM by LIS

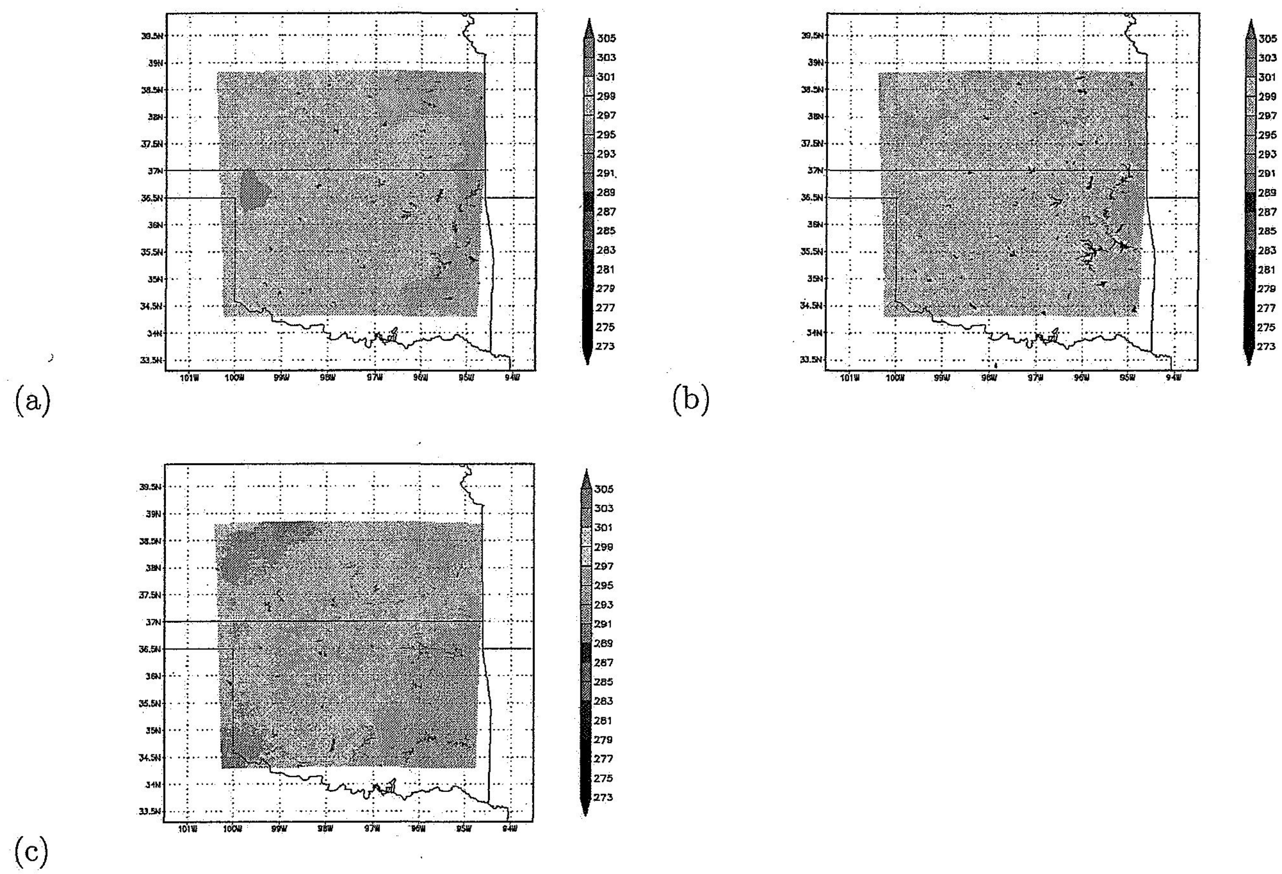

Fig. 9. Top 10cm soil temperature (K) initial conditions at 12Z, on June 12, 2002 generated by (a) WRF preprocessor (using NARR data), (b) long term spinup of Noah by LIS, and (c) long term spinup of CLM by LIS

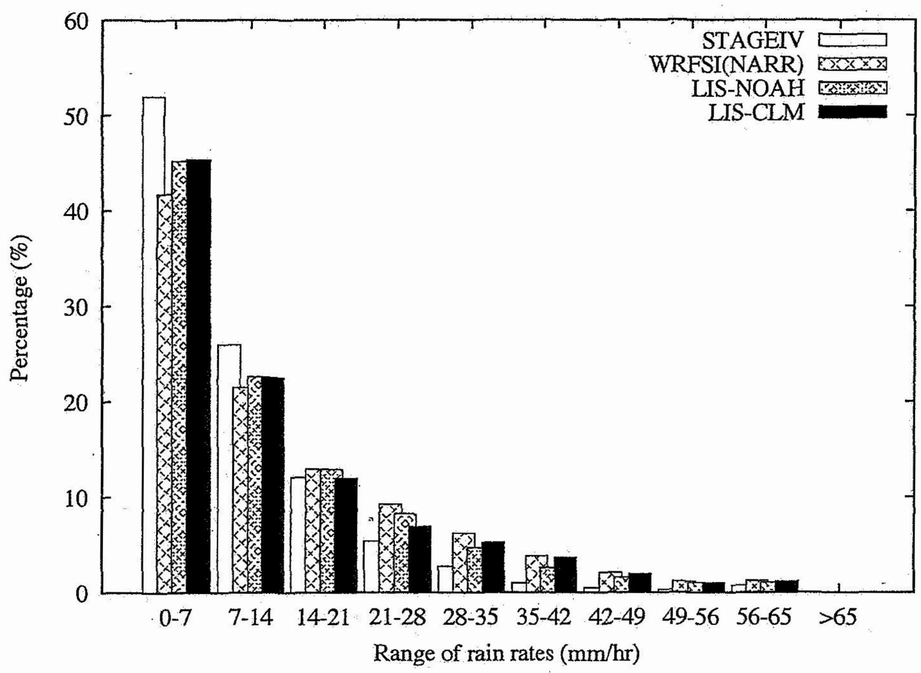

Fig. 10. Comparison of the distribution of rain rates (mm/hr) from simulations using different land surface initial conditions compared with the STAGEIV data

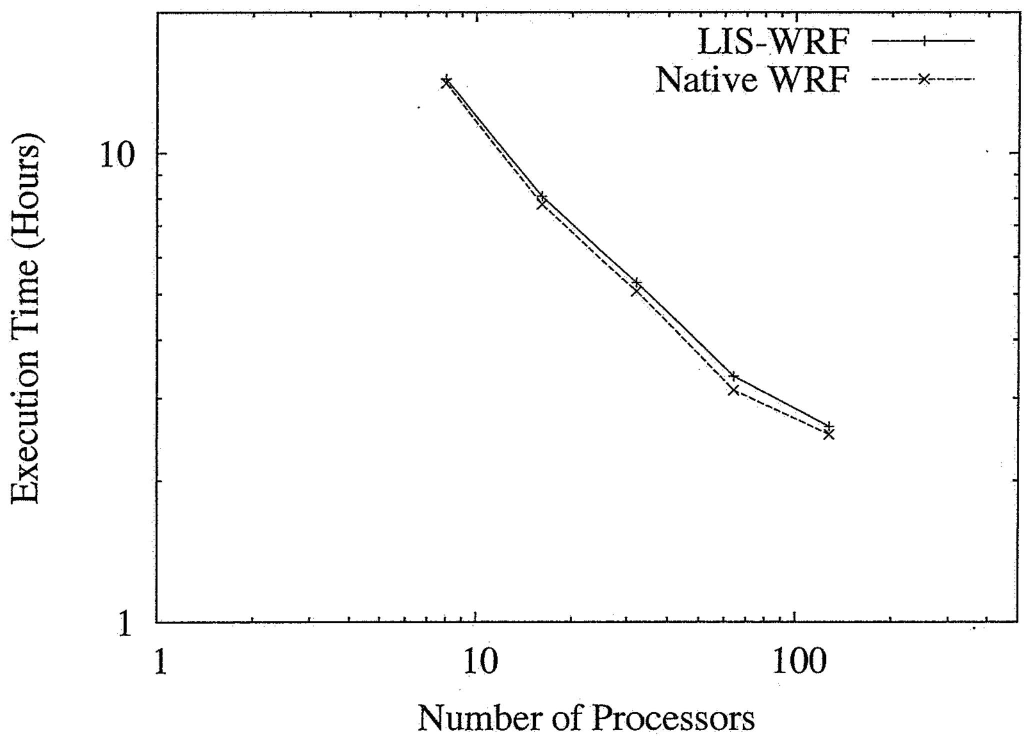

Fig. 11. Computational scaling of the LIS-WRF system, compared with the native WRF system for a domain with 100x100 grid points at 1km resolution