Title: Enhancement of high resolution hydrological modeling on the CONUS HRAP grid using operational NOAA NCEP and NOAA OHD models

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This MAPP-funded project centers on supporting NOAA/NCEP/EMC's and NOAA/NWS/OHD's operational hydrological and land surface modeling missions, as well as furthering their support of the *National Integrated Drought Information System (NIDIS*), NOAA Hydrology Test Bed, and the NOAA Climate Test Bed. New capabilities resulting from this joint NOAA EMC/OHD/CPC effort allowed for the execution of enhanced Noah and Sacramento Heat Transfer (SAC-HTET) models on the 4km HRAP grid over the Continental United States (CONUS) over a 33-year period using NLDAS2 forcing data. Enhancements impacted all stages of modeling operations and included improved downscaled forcing data, spin-up strategies, data assimilator modules, model physics, and model validation procedures.

Results and Accomplishments:

The high resolution land surface modeling study had three main components which together provided a comprehensive suite of modeling-related improvements that enabled both improved OHD and NCEP hydrological and land surface forecasts and analyses, as well as investigations into land-atmosphere interactions:

1. Model Support-Related Improvements
    1.1 Improved downscaling of 1/8th degree NLDAS forcing to 4km HRAP grid
    1.2 Enhanced spin-up strategies for the initialization of retrospective simulations
2. Model Component Improvements
3. Model Output and Evaluation

Project work closely followed the deliverables schedule included in the proposal, and we summarize below the project's results and accomplishments.

1. Model Support-Related Improvements

1.1 Improved downscaling of 1/8th degree NLDAS forcing to 4km HRAP grid

One thrust of high spatial resolution land surface and hydrological modeling is to accurately downscale the current coarse resolution atmospheric forcing data to better match the land surface complexity. Toward this aim, we have demonstrated a linear relationship between the surface lapse rate and temperature. The statistical linear regression equation is spatially and temporally independent, with air temperature as the only input variable. The approach is thus well-suited for producing time- and space-varying lapse rates, and would require minimal resources to implement in the downscaling software which typically support land surface and hydrologic modeling activities.

An elevation adjustment has been applied to update the NLDAS daily mean air temperature from the NLDAS pixel height to the high spatial resolution (4km) pixel height. Statistics have been calculated for all 1981 in-situ sites (SNOTEL, USHCN, and RAWS) in each month from 1991 to 2011 and for the monthly climatology over the 21-year period. Although the NLDAS forcing generation process does feature an elevation adjustment (albeit with a constant lapse rate) and the NLDAS temperatures show high accuracy when validated against in-situ air temperature, the updated NLDAS temperatures generated via the varying lapse rates show further improvement from March to October, with large improvements in the spring and summertime. Please refer to FY12 and FY13 Progress Reports for further detail.

1.2 Enhanced spin-up strategies for the initialization of retrospective simulations

The process of a model adjusting to its forcing (model spinup) can severely bias land surface simulations, and result in questionable land surface model output during the spinup process. We have designed and undertaken numerical experiments to evaluate the production and evolution of model ICs through model spin-up methods. Comparison of the four designed spinup strategies suggest that use of one-year of recursive forcing is an effective and efficient spin-up strategy for obtaining an optimal initial condition, and for quantifying the spin-up time needed for land surface modeling. Please refer to the FY13 Progress Report for further details.

The difference in spin-up time may result from different atmospheric forcing regimes. The required spin-up time was found to be less than one year in the study region with annual precipitation over 1000mm, 4-5 years for the region with precipitation between 500-1000mm, and nearly 10 years for the dry region with annual precipitation below 500mm. This project-developed spinup strategy has been applied to the Climate Forecast System Reanalysis (CFSR) to good effect. CFSR ran with six simultaneous “streams” (separate runs) over the 32-year period (1979-2010) which gave rise to challenging temporal land surface discontinuities. Application of the newly developed spinup process to each stream improved simulation continuity (Figure 1, "GLDAS version 2").

Figure 1. Comparison of total soil moisture anomaly between the original Climate Forecast System Reanalysis (CFSR), simulation with enhanced spinup (GLDAS version 2), and NLDAS continuous simulations for the selected region in the southwest US.

2 Model Component Improvements

Many of NCEP’s operational numerical weather prediction (NWP) models utilize the Noah land surface model (LSM) as their land surface component. The Noah land surface model was developed and has been continuously upgraded with substantial collaborative effort between NCEP and external partners from the land hydrology community over the last decade. The Community Noah Land-Surface Model is used operationally in NCEP models as follows: (1) Version 2.7.1 is currently in the GFS, CFS; (2) Version 2.8 is in NLDAS; and (3) Version 3.0 is in the NAM.

Noah LSM version 3.2 features upgrades over Noah LSM version 2.7.1 including (1) Updated roughness length and snow albedo over snow-covered surfaces. (2) Updated soil moisture availability. (3) Addition of the exchange of heat required to change the temperature of falling precipitation from the air to the skin temperature. (4) Calculation of roughness and emissivity dependent on vegetation fraction. (5) Addition of the capability to use MODIS land-use dataset for vegetation categories. (6) Addition of the option to use 2-D LAI. (7) Significant changes to the treatment of glacial ice. (8) Inclusion of multi-layer urban impacts. (9) Cold-start initialization with soil moisture initialized at 0.2 and soil temperature initialized at 290K. Building on these enhancements, Noah LSM version 3.3 features further upgrades including the activation of time-varying roughness lengths and fixes to the underground runoff module. GFS cold/wet biases occur mainly during late fall and winter. Two types of GFS biases occur in the late afternoon including 1) rapid temperature dropoff and 2) snow-related biases, while a cold bias is present in the NAM over snow, particularly in the parallel NAM. To address these issues, as part of this project, the EMC land team investigated various tunings of model parameters, and also integrated and tested the snow shading effect published by our collaborator from University of Arizona in offline GFS.

NASA's Land Information System (LIS) integrates NOAA NCEP's operational and research land surface models (Noah versions 2.7.1, 3.2, 3.3), high-resolution satellite and observational data, and land data assimilation (DA) tools. The LIS EnKF-based DA tool is used to assimilate land surface states, such as soil moisture, snow cover area, and snow depth products. LIS contains all versions of the Noah model including those run operationally by NOAA/NCEP. Thus, it is important to note that the recent community LIS-based Noah LSM model upgrades, test results and code improvements are easily transferable and applicable to the operational versions used by forecasters.

As an example, Noah LSM version 3.3 in LIS was configured and executed at a 4km high resolution for the whole North America Mesoscale Modeling (NAM) domain using forcing extracted from the Production NAM NDAS. The project-developed spinup strategy discussed above was applied in this high resolution LIS Noah simulation experiment (Figure 2).

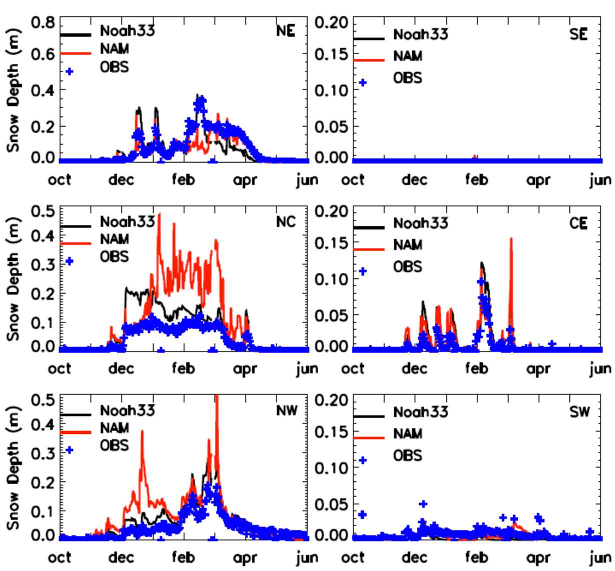

Figure 2. Comparison of snow depth between Noah version 3.3 in LIS (labeled as Noah33) and Noah version 3.0 in Production NAM NDAS (labeled as NAM) versus in-situ measurements (OBS) using U.S. Daily Snowfall and Snow Depth Data for six selected regions over Continental US (CONUS). NE-Northeast; SE-Southeast; NC-North Central; CE-Central East; NW-Northwest; and SW-Southwest.

Snow depth from the upgraded Noah LSM (version 3.3) agrees closely with observations in all six regions. Snow depth from the Production NAM NDAS with an earlier version of Noah (version 3.0) is also in close agreement with observations in the NE, but is overestimated in the NC and NW regions. Snow assimilation used in the Production NAM NDAS has a positive impact in the NE, but a detrimental impact in the NC and NW. The simple direct replacement using satellite snow data did not consider the relative uncertainty of satellite snow retrievals. Therefore, the use of an advanced EnKF method in LIS will be explored in the operational NAM system to examine the impact of assimilating satellite product on NAM forecasts.

Understanding and quantifying satellite-based remotely-sensed snow cover errors are critical for the successful utilization of snow products. In order to attain an optimal estimate of the snow pack state, it is essential that the assimilation scheme accounts for the relative uncertainty of both model predictions and satellite observations. As part of this project, Dong et al. (2014) demonstrated that MODIS snow cover retrieval errors can be quantitatively predicted by air temperature from model- or in-situ-based daily mean air temperature measurements. The study in Dong et al. (2014) also represents a preview of the MODIS Collection-6 (C6) data set that should be valuable to other researchers after MODIS C6 data becomes available. As a further part of this project, we tested the bisection method over California’s Sierra-Nevada basin using MODIS-based daily fractional snow cover data for the NOAA/NWS Distributed Model Intercomparison Project (DMIP) II, and demonstrated improved simulation of SCA and SWE. The bisection method automatically determines the optimal snow water equivalent so that the generated fractional snow cover is closest to the MODIS fractional snow cover observations.

3. Model Evaluation and Transition to Operation

PALS (Protocol for the Analysis of Land Surface models) is a web application for evaluating land surface models and the data sets used to test them. It provides driving and evaluation data for particular modeling experiments as well as a wide range of diagnostic performance measures once model output created using these data is uploaded. PALS is a useful tool for benchmarking both individual studies and community experiments. The PALS Land sUrface Model Benchmarking Evaluation pRoject (PLUMBER) was designed to be the first international land surface model (LSM) benchmarking intercomparison. Three Noah models under LIS together with other nine land surface models joined the PLUMBER project (Figure 3), and it can be seen that Noah version 3.3 exhibits slightly better performance than Noah version 2.7.1 for simulations of both Q_H and Q_E.

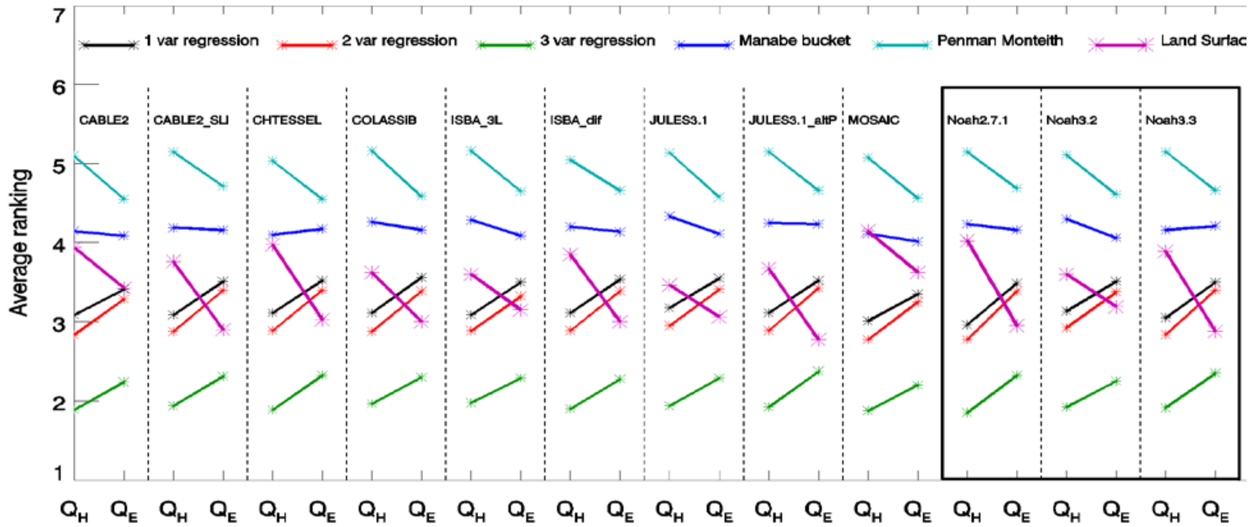

Figure 3: *Ranking of benchmarks and each model for the standard statistics across all 20 sites. A ranking of one corresponds to the best performance. The points are linked between the fluxes purely to aid the reader's interpretation of the data. Comparison of three Noah models is shown in the right three columns. The definition of the five benchmarks can be found in the FY13 Progress Report.*

For the purpose of transitioning existing land model upgrades and data assimilation capabilities in LIS into operations to support NCEP's land surface assimilation of satellite-based soil moisture and snow observations (Figure 4), we have performed additional upgrades to the current version of LIS. First, the Gaussian grid implementation has been upgraded within LIS to support current and future GFS/CFS grid definitions. This effort will reduce model errors and computing costs by avoiding grid mismatches. The interfaces between the LIS-based GFS/CFS-LDAS and GFS/CFS have been improved via (1) Upgrading the forcing reader to enable reading of all GFS resolutions, (2) Implementing satellite data readers and interpolation procedures into GFS Gaussian grids, and (3) Enabling direct initial condition exchanges between the LIS-based GFS/CFS-LDAS and GFS/CFS cores.

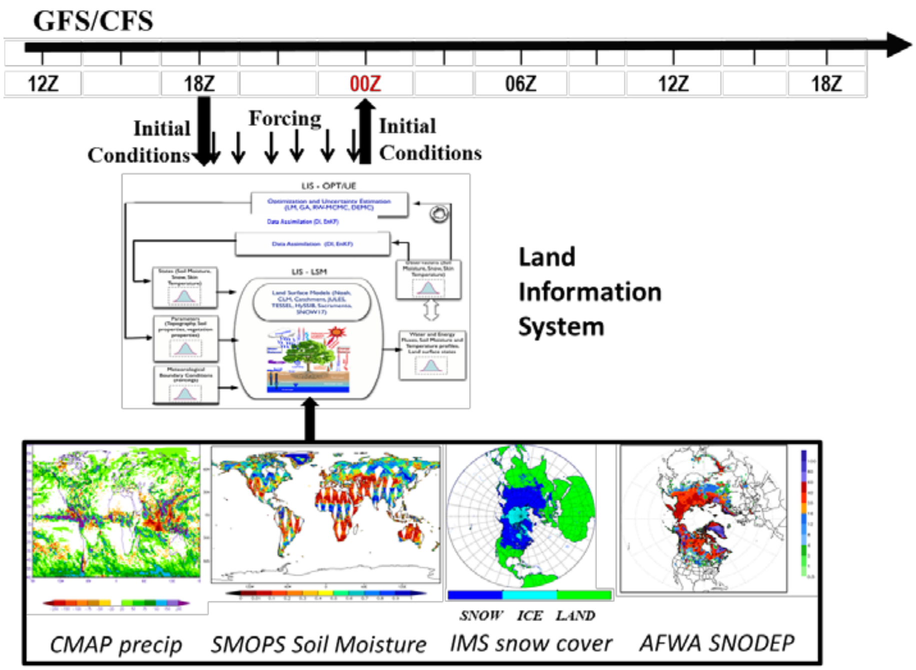

Figure 4: *Schematic of the coupled LIS and GFS/CFS*

Highlights of Accomplishments:

- Enhanced spin-up strategies were studied and tested for both NLDAS retrospective runs and CFS Reanalysis simulations.
- A high resolution downscaling technique for NLDAS temperature data has been created and verified.
- NLDAS-based 4km air temperature and precipitation data have been generated and post-processed into XMRG binary format for CONUS and RFC domains, and delivered to NWS/OHD for use in testing their SAC-HTET model.
- NASA's newly developed MODIS snow cover fraction product has been validated and verified, and the error in the MODIS product can be quantitatively estimated from temperature using a cumulative double exponential distribution equation. Through this effort, the EnKF ensemble spread will be evaluated in our snow DA experiments.
- Noah upgrades including the snow shading effects from the University of Arizona approach has been tested.
- The NAM NDAS forcing reader has been implemented into LIS7 and applied in the spin-up and real-time test runs.
- Production NAM NDAS forcing from 2012-present has been processed and used to drive LIS Noah LSM version 3.3 for spin-up studies, real-time NAM simulation practice and data assimilation applications.
- The Gaussian grid has been implemented into LIS version 7 to support current and future LSM upgrades in the GFS/CFS. The interfaces between LIS-based GFS/CFS-LDAS and GFS/CFS has been tested.

- The GLDAS has been upgraded (to GLDAS version 2) to include LIS version 7 with newly tested parameters and advanced DA modules.
- NOAA OHD's SAC-HTET and Snow17 models have been implemented into LIS version 7.
- The IMS snow cover product from July 2013-present has been processed and the IMS reader in LIS7 has been implemented and tested.
- Daily snowfall and snow depth observations collected at National Weather Service (NWS) Cooperative Observer stations and NWS First Order stations from July 2005-present have been downloaded and processed for verification of NAM NDAS products and LIS LSM runs.
- PALS tests have been conducted to evaluate the model performance of several Noah versions at 20 benchmark sites all over the world.

Publications from the Project:

Publications and Manuscripts:

Dong, J., M. B. Ek, D. Hall, C. Peters-Lidard, B. Cosgrove, J. Miller, G. Riggs and Y. Xia (2014): Using Temperature to Quantitatively Predict the MODIS Fractional Snow Cover Retrieval Errors over CONUS, *J. Hydrometeor*, 15, 551–562. doi: http://dx.doi.org/10.1175/JHM-D-13-060.1

Xia, Y., M. B. Ek, D. Mocko, C. D. Peters-Lidard, J. Sheffield, J. Dong, and E. F. Wood (2014), Uncertainties, Correlations, and Optimal Blends of Drought Indices from the NLDAS Multi Land Surface Model Ensemble, *J. Hydrometeor*, 15, 1636-1650.

Xia, Y., J. Sheffield, M. B. Ek, J. Dong, N. Chaney, H. Wei, J. Meng, and E.F. Wood (2014): Evaluation of Multi-Model Simulated Soil Moisture in NLDAS-2. *J. Hydrology*, 512, 107-125.

Dong, J., B. Cosgrove, M. B. Ek, and K. Mo (2013): The relationship between 2-meter air temperature and lapse rate in the western U.S., in revision.

Best, M.J., G. Abramowitz, H.R. Johnson, A.J. Pitman, G. Balsamo, A. Boone, M. Cuntz, B. Decharme, P.A. Dirmeyer, J. Dong, M. Ek, Z. Guo, V. Haverd, B.J.J van den Hurk, G.S. Nearing, B. Pak, C. Peters-Lidard, J.A. Santanello Jr., L. Stevens, N. Vuichard (2014), The plumbing of land surface models, *J. Hydrometeor*, Submitted.

Presentations:

Jiarui Dong, Mike Ek, Brian Cosgrove, Kingtse Mo (2013): Temperature Downscaling in High Spatial Resolution Land Surface Modeling in Support of US Drought Monitoring Efforts, *Climate Diagnostics and Prediction Workshop (CDPW)*, College Park, Maryland, October 21-24.

Jiarui Dong, Mike Ek, Dorothy Hall, Christa Peters-Lidard, Brian Cosgrove, Miller, George Riggs, and Youlong Xia (2013): Quantify the MODIS Fractional Snow Cover Retrieval Errors over CONUS and Assimilation Experiments, *6th WMO Symposium on Data Assimilation*, College Park, Maryland, October 7-11.

Mike Ek and Jiarui Dong (2013): NCEP/EMC land modeling and data assimilation, *VIIS Snow and Ice Product Provisional Maturity Review* at NCWCP on 14 November.

Jiarui Dong, Mike Ek, Dorothy Hall, Christa Peters-Lidard, Brian Cosgrove, Miller, George Riggs, and Youlong Xia (2014): Quantify the MODIS Fractional Snow Cover Retrieval Errors over CONUS and Evaluation of Assimilation Experiments in Production NAM/NDAS, *12th JCSDA Annual meeting*, College Park, Maryland, may 21-23.

Jiarui Dong, Mike Ek (2014): Evaluation and Verification of Snow Depth and Snowfall from NAM Production NDAS and Noah 3.3 in LIS, *15th Annual WRF User's Workshop*, Boulder, Colorado, June 23-27.

Jiarui Dong, Mike Ek, Eric Rogers, Brian Cosgrove, Sean Helfrich, George Gayno, Kingtse Mo (2014), Evaluation of assimilation efforts using IMS Fractional Snow Cover in the NOAA/NCEP's NAM operational product, *1st International Satellite Snow Products Intercomparison workshop (ISSPI)*, College Park, Maryland, July 21-23.

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