Assimilating Soil Moisture and Snow Products for Improved Drought Monitoring with the North American Land Data Assimilation System (NLDAS)

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Highlights of Accomplishments

- The Noah-3.3 land-surface model (LSM) was implemented in the Land Information System (LIS) software framework, and run using NLDAS Phase 2 (NLDAS-2) forcing with data assimilation (DA) of remotely-sensed soil moisture, snow depth, and snow cover
- The Catchment Fortuna-2.5 (CLSM-F2.5) LSM was also implemented within LIS and run using NLDAS-2 forcing with DA of remotely-sensed soil moisture and snow, as well as terrestrial water storage (TWS) anomalies from GRACE
- New remotely-sensed products were also added into LIS for DA, including the ability to perform simultaneous (multi-sensor) water product data assimilation
- Open Loop and DA simulation outputs were evaluated against various observations/products of surface fluxes, snow, soil moisture, and USDM drought extent using NASA's Land surface Verification Toolkit (LVT)
- Routed streamflow from both the original NLDAS router and the new HyMAP router within LIS were evaluated against USGS streamflow observations using LVT
- The SAC-HTET-3.5.6/SNOW-17 LSM was configured within the LIS framework, and tested over the NLDAS domain
- The VIC-4.1.2.l LSM was also configured within the LIS framework and tested for NLDAS
- The NLDAS-2 LSMs were evaluated using LVT as part of the development of a benchmarking system to show improvements through the upgraded LSMs and the use of data assimilation
- Real-time NLDAS Phase 2 forcing and four LSM simulations were maintained and distributed to users, and the NLDAS Drought Monitor was updated in real-time
- The current NLDAS-2 system was configured and transitioned into NCEP Operations
- An objective-blend drought methodology was developed using ensemble-mean NLDAS drought indices through collaboration with NOAA/EMC, NASA, and Princeton Univ.
- NLDAS retrospective and near real-time hourly, monthly, and monthly-climatology datasets were distributed via the NASA GES DISC for all users
- Several journal articles were accepted as part of the Journal of Hydrometeorology's Special Collection on Advancing Drought Monitoring and Prediction
- Results were presented at MAPP Webinars, a Drought Task Force RtC telecon, the CDPW/ Drought Task Force Meeting, and at AMS, AGU, WRF, and GEWEX meetings
- Served as co-Lead and as members of the NOAA MAPP Drought Task Force

Results and Accomplishments

The three main tasks over the entire project lifetime were to: 1) Bring the NLDAS land-surface models (LSMs) into the latest Land Information System (LIS) architecture, including upgrading all LSMs to their latest version and implementing NASA's Catchment LSM; 2) Assimilate remotely-sensed soil moisture and snow products into NLDAS to improve the representation of the land-surface; and 3) Evaluate NLDAS output and drought monitoring skill. All three of these tasks were accomplished during the project, and are detailed below.

Task 1: Benchmark and extend NLDAS data production within the latest LIS architecture

The first task of this project was to run the latest versions of all NLDAS LSMs within the LIS framework. LIS is a software framework developed at NASA/GSFC for high-performance land-surface modeling and data assimilation. The Noah-3.3, CLSM-F2.5, SAC-HTET-3.5.6/SNOW-17, and VIC-4.1.2.l LSMs were all implemented into LIS, including benchmarks against their original drivers. NCAR/NCEP's Noah LSM is part of the WRF community forecast model; Noah is the LSM used in many NCEP applications. Noah-3.3 includes several updates and new options, including to the roughness length parameterization. NASA's Catchment (Fortuna-2.5 version – CLSM-F2.5) LSM is the land component of NASA's GEOS-5 GCM, and was also used in an offline mode by the GMAO to develop the MERRA-Land dataset. CLSM-F2.5, which includes a treatment of groundwater, will be replacing the older Mosaic LSM in the NLDAS project. NOAA/OHD's SAC-HTET (Sacramento soil moisture Accounting – Heat Transfer EvapoTranspiration) model is coupled to the SNOW-17 snow accumulation/ablation model. SAC-HTET/SNOW-17 includes a new soil temperature physics treatment, and evapotranspiration physics based on the Noah LSM. Univ. of Washington and Princeton University's VIC (Variable Infiltration Capacity) latest model is Version 4.1.2.l. VIC-4.1.2.l includes numerous updates and upgrades, including an extended computation of soil temperatures and ground fluxes. These LSMs were configured for and run over the NLDAS domain. These LSMs are also part of the latest public release of the LIS code (version 7.0) for collaborators at NOAA and other institutions. Open Loop (without any data assimilation) simulations were performed using the NLDAS-2 forcing from 1979 to 2012.

Task 2: Assimilate soil moisture and snow products into the LIS-NLDAS system

Several remotely-sensed soil moisture and snow products were assimilated into the latest versions of the LSMs within LIS. Soil moisture products from AMSR-E as well as a soil moisture data product from ESA (ECV, Essential Climate Variable, Liu et al., 2012; Wagner et al., 2012) were assimilated using an Ensemble Kalman Filter (EnKF) approach into both the LIS/Noah-3.3 and LIS/Catchment-F2.5 LSMs. Also, a snow depth (SWE) product based on AMSR-E retrievals and snow-covered area (SCA) products from IMS and MODIS were also assimilated into the simulations (Kumar et al., 2014). The CLSM-F2.5 LSM additionally allows the assimilation of terrestrial water storage (TWS) anomalies from GRACE through an Ensemble Kalman Smoother (EnKS). Simulations using the simultaneous DA of multiple water balance products (including soil moisture, snow, and TWS) were also performed, again using NLDAS-2 forcing from 1979 to 2012. Figure 1 (from Kumar et al., 2015, submitted) shows the RMSE and Bias of the simulated SWE in the Noah-3.3 LSM simulations of the Open Loop, of only SWE product assimilation, and of SWE and SCA assimilation. The figure shows that using SCA products to constrain the assimilation of the SWE products reduces the RMSE of the simulated SWE compared to the CMC product observations.

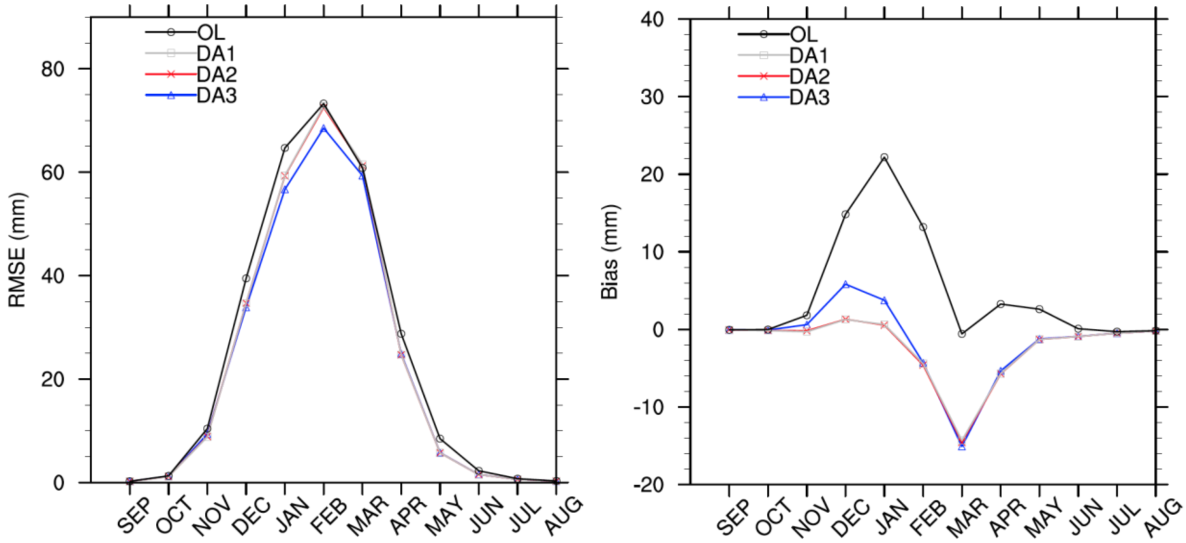

Figure 1. Average seasonal cycle of RMSE (left) and Bias (right) of simulated SWE from the Noah-3.3 LSM as compared to the CMC SWE product. The Open Loop (OL; black) simulation shows a high bias, which is greatly reduced when using data assimilation of the AMSR-E product (DA1; grey). The use of SCA products from IMS (DA2; red) and both IMS and MODIS (DA3; blue) further reduces the RMSE compared to the DA1 simulation.

Task 3: Evaluate NLDAS model (drought) performances with/without assimilation

The third task of the project was to evaluate and validate the simulations from the new LSMs (both with and without data assimilation) against the NLDAS Phase 2 outputs, using available observation-based datasets. This task includes an analysis of the model's performance against drought. These evaluations were performed using the Land-surface Verification Toolkit (LVT) developed at NASA/GSFC (Kumar et al., 2012). The soil moisture and snow simulations with and without data assimilation were all evaluated using LVT against observations and analyses of soil moisture, streamflow, snow, surface fluxes, and drought extent. LVT was also used to evaluate the current NLDAS-2 versions of the LSMs in the same framework. Evaluations were made using routed streamflow from NLDAS runoff compared to USGS observations in small river basins as well as compared to naturalized streamflow at major river basins (data described in Koster et al., 2010). The existing NLDAS router as well as a new HyMAP router (Getirana et al., 2012) were used to route simulated runoff from the LSMs into streamflow. Evaluations were also made of surface and root zone soil moisture against in situ observations from the USDA's SCAN network as well as surface soil moisture from USDA's ARS "CalVal" sites. Simulated snow depths were evaluated against Global Historical Climate Network (GHCN) observations and against the Canadian Meteorological Center (CMC) snow depth analysis. Surface heat fluxes (both latent and sensible) were evaluated against four separate monthly gridded products, FLUXNET (Jung et al., 2009), MOD-16 (Mu et al., 2011), ALEXI (Anderson et al., 2007), and UW ET (available online). Weekly U.S. Drought Monitor (USDM) historical drought area extent data was also added into LVT and used to evaluate drought extent and severity of the NLDAS products/simulations. Small but generally significant improvements were found in the new LSMs' simulated results when using data assimilation.

Examples of the performance of the new simulations with and without data assimilation (DA) are shown in Figures 2 and 3. Figure 2 shows the effects of both soil moisture and snow DA on the simulation of streamflow (through routed runoff) against USGS streamflow observations. Many locations in the central U.S. and in the Midwest show improvements in the simulation of streamflow from using DA, with a few degradations noted in North Dakota and the high elevations of the Rockies. Figure 3 shows the effects of DA on simulation drought area percentage against USDM weekly estimates. For the South region shown here, assimilating soil moisture into the LSM improves the simulation of drought several times; notably the significant drought in 2011 and 2012. These figures are adapted from Kumar et al. (2014).

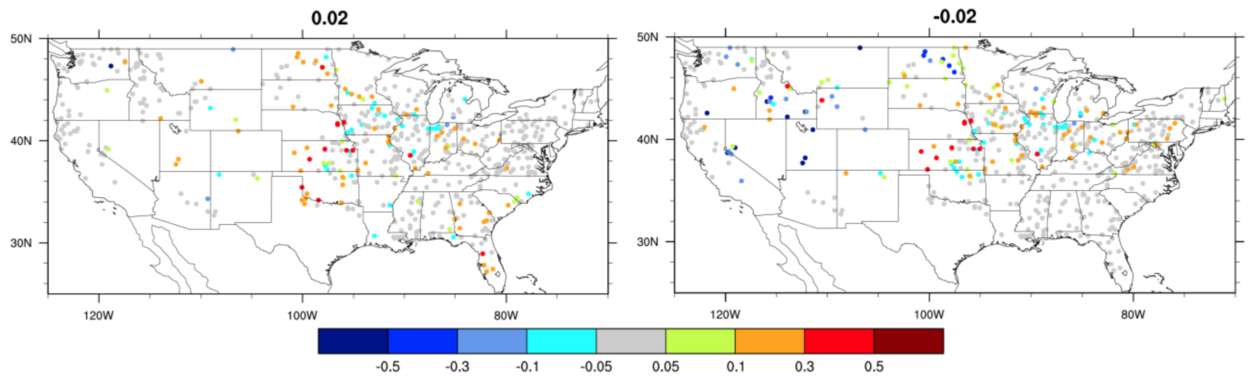

Figure 2. Streamflow NIC values for the RMSE of streamflow for soil moisture (left) and snow depth (right) data assimilation with the Noah-3.3 LSM as evaluated against 572 small unregulated USGS basins. Red colors indicate skill improvements and blue colors indicated skill degradations. The Normalized Information Contribution (NIC) quantifies the improvement or degradation due to data assimilation, and is defined as a measure of how much of the maximum potential skill improvement is realized through DA. From Kumar et al., 2014 (Figure 5).

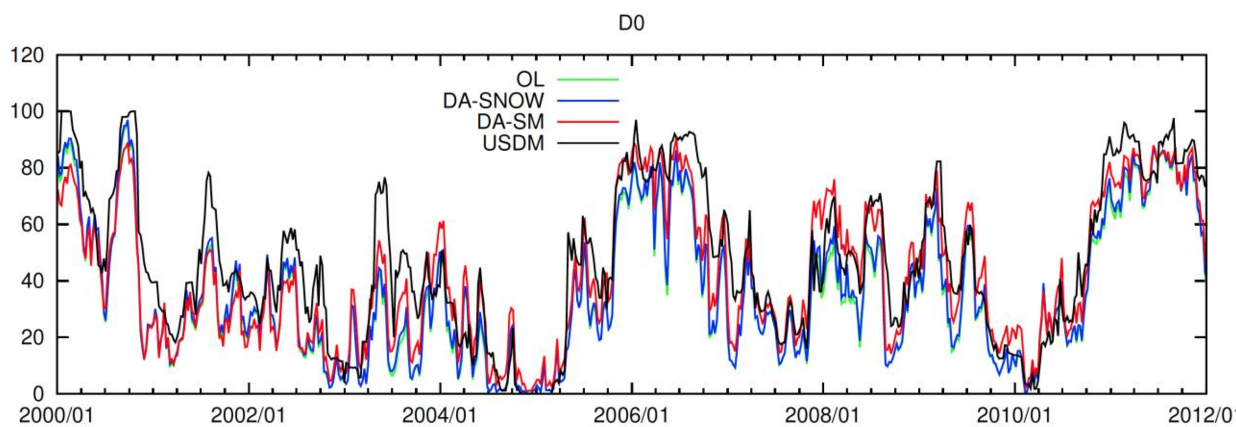

Figure 3. Time series of drought area percentage from root zone soil moisture for the South region of the U.S. Drought Monitor (USDM) for the D0 drought category. Shown are the Open Loop (no DA) simulation with the Noah-3.3 LSM (green), the snow depth DA simulation (green), the soil moisture DA simulation (red), and the USDM drought area percentage weekly estimates (black). From Kumar et al., 2014 (Figure 9).

Online and updated verification/evaluation capabilities

The NASA/GSFC NLDAS website and FAQ were continuously updated for all users (http://ldas.gsfc.nasa.gov/nldas/), complementing the NOAA/NCEP/EMC NLDAS site (http://www.emc.ncep.noaa.gov/mmb/nldas/). NLDAS datasets and documentation were added to the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC; http://disc.sci.gsfc.nasa.gov/hydrology/). Hourly, monthly, and monthly climatology datasets are available to researchers and the public. The GES DISC provides numerous data and services, including spatial and parameter sub-setting, online figure generation, GRIB to NetCDF conversion, a GrADS Data Server (GDS), and Giovanni and Mirador services. These services allow users to easily plot trends as well as anomalies in the NLDAS datasets over their lifespan from 1979 to present. As an example of the widespread usage of the NLDAS products, for the calendar year 2013 there were nearly 5,000 distinct users and over 36 million files downloaded from the NASA GES DISC alone. Datasets are also available from the NOAA/NCEP/EMC NLDAS ftp server. With the assistance of the GES DISC, NLDAS datasets have been added and improved within many online tools and models, such as CUAHSI's HydroDesktop and USGS's Geo Data Portal. The GES DISC has also continuously improved and added new "data rods" of NLDAS data products for quicker access using time series for use by hydrologists.

Engagement with the wider scientific user and stakeholder groups was also accomplished during the project lifetime. The PI served as a co-Lead for the NOAA Drought Task Force, in which the entire team participated through regular telecons. The Drought Task Force released a Special Collection on Advancing Drought Monitoring and Prediction. Numerous journal articles were published or submitted on NLDAS evaluation and improvements (*e.g.*, Kumar et al., 2014, 2015; Liu et al., 2015; Xia et al., 2013a-b, 2014a-d). Presentations were made at AMS and AGU meetings, the CDPW/Drought Task Force meeting, the WRF LSM Workshop, the GEWEX conference, as well as online meetings including MAPP webinars, Drought Task Force telecons, and Noah telecons. NLDAS datasets were provided weekly to the U.S. Drought Monitor, to the Climate Data Center (CPC) monthly drought briefing, and to the CPC seasonal drought outlook.

Collaboration with NOAA/NCEP/EMC

The success of this MAPP project, as well as the overall continued development of the NLDAS project, is due to the collaborative nature of NLDAS, as led by the co-Is within the NOAA/NCEP/EMC Land Group. Some of EMC's NLDAS-related accomplishments include: 1) maintaining the near-real-time generation of the NLDAS-2 forcing and four-model LSM output data and NLDAS Drought Monitor (http://www.emc.ncep.noaa.gov/mmb/nldas/drought/); 2) developing and evaluating an objective blend drought methodology using ensemble-mean NLDAS-2 drought indices (Xia et al., 2014c&d); 3) evaluating NLDAS-2 outputs through journal articles (Xia et al., 2013a; Xia et al., 2014b); 4) developing and evaluating NLDAS-2 Noah Interim (Xia et al., 2014a); 5) evaluating LIS/Noah-2.7.1, -3.2, and -3.3 at 20 benchmark in-situ point sites through PALS (Protocol for the Analysis of Land Surface models); 6) releasing Noah-2.8 code, post-processed NLDAS-2 SAC soil moisture data, and hourly streamflow data from the four NLDAS-2 models to the public; 7) quantifying the uncertainty in MODIS snow cover fraction for snow data assimilation applications (Dong et al., 2014); 8) studying downscaling for higher resolution modeling and implementing the B-grid into LIS, and 9) implementing the latest version of LIS on NOAA development computers. LIS version 7.0 was released in the summer of 2014, and includes numerous new upgrades for the NLDAS project, including testcases with data assimilation and routing for the various NLDAS LSMs.

The most significant accomplishment was the transition of the NLDAS-2 system into NCEP Central Operations (NCO) on 5 August 2014. NLDAS source code and scripts were modified to meet the NCO operational requirements. A 3-month parallel pre-test on a product machine, a 30-day pre-operational test, and a final evaluation from NASA, CPC, and USDA were performed during the transition to the NCO. The operational NLDAS-2 products include all products generated from the previous quasi-operational NLDAS-2 run, and the addition of hourly gridded streamflow from the four models. These operational products are available in GRIB-2 format (http://www.nco.ncep.noaa.gov/pmb/products/nldas/) from the NCEP/NCO website, and archived at the NCEP LDAS website. The NASA GES DISC is converting the NCO NLDAS-2 products from GRIB-2 to GRIB-1, to keep consistency for the users. This achievement is significant because NLDAS-2 products are now ensured to be updated daily by the NCO, increasing data reliability for the user community. Additionally, NCEP/EMC will no longer need to manage the quasi-operational system, freeing resources to begin the transition of the next version of NLDAS from NASA to NCEP. The next version will be fully LIS-based, and will include the upgraded model versions (e.g., Catchment vs. Mosaic, SAC-HTET vs. SAC, etc.), upgraded model physics (e.g., groundwater component, irrigation, multi-layer snow, etc.), improved forcing data, newly-released observed vegetation and soil data, and higher spatial resolution (e.g., 4-km) by incorporating new progresses and research results from this and other MAPP-funded NLDAS-related projects, as well as from our NLDAS collaborators.

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