Final Report:
Advancing Probabilistic Drought Monitoring with the North American Land Data Assimilation System (NLDAS) through Multisensor Ensemble Data Assimilation

1. General Information

Project Title: Advancing Probabilistic Drought Monitoring with the North American Land Data Assimilation System (NLDAS) through Multisensor Ensemble Data Assimilation
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2. Main goals of the project, as outlined in the funded proposal

- Add land-surface modeling improvements and capabilities to the NLDAS system through the Land Information System (LIS) software framework.
- Assimilate GRACE terrestrial water storage and SMAP surface soil moisture products, as well as include the effects of irrigation using maps derived from MODIS, into the NLDAS system for better diagnosis of drought and improvement of initial land conditions.
- Evaluate and compare the upgraded LSMs and assimilation capabilities using LVT and NLDAS evaluation tools to the existing operational NLDAS LSMs.
- Perform probabilistic and ensemble drought analysis to both advance our understanding of drought and also to provide a measure of drought uncertainty.

3. Results and accomplishments

The three main tasks over the entire project are to: 1) Make land-surface modeling improvements and add capabilities into NLDAS using the Land Information System (LIS); 2) Assimilate various water products into the LIS-NLDAS system; and 3) Perform probabilistic and ensemble drought analysis and monitoring. As is detailed in the proposal, the focus of the first year's effort was on the first task, with some complementary work also on the third task; the second year was focused on the assimilation of the water products; and the focus of the third year was on model configuration/validation and the probabilistic and ensemble drought analysis. The following sections provide further details of the progress and accomplishments by individual proposal Task.

First Task: Land-surface Model Improvements and Capabilities

The first task was to add land-surface model improvements and capabilities for the next phase of NLDAS using the NASA LIS software framework. This task included integrating two new LSMs into LIS for NLDAS, as well as making improvements to the NLDAS forcing and parameters. Work performed during the second year of this project (Nearing et al., 2016; Figure 1) showed that models, forcing, and parameters all contribute to uncertainty in the simulations of soil moisture and evaporation. Thus, the overall goal of this task was to make improvements to all three sources of this uncertainty in the NLDAS system.

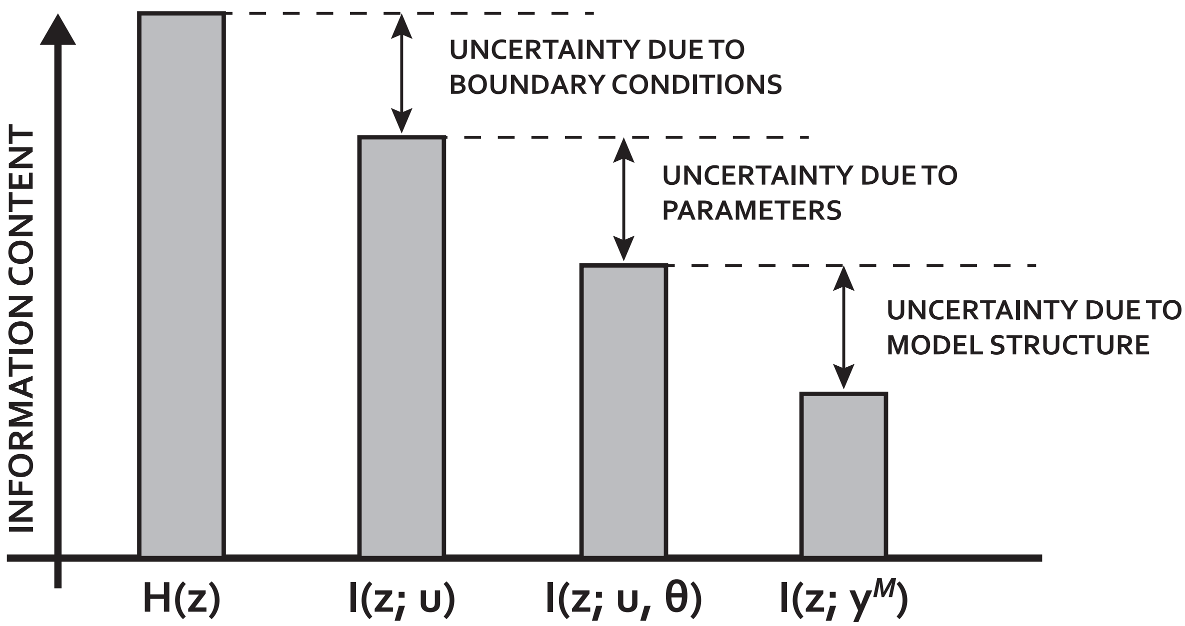

Figure 1: A conceptual diagram of uncertainty decomposition using Shannon information following Nearing et al., (2016). The term H(z) represents the total uncertainty (entropy) in the benchmark observations, and I(z; u) represents the amount of information about the benchmark observations that is available from the forcing data. Uncertainty due to forcing data is the difference between the total entropy and the information available in the forcing data. The information in the parameters plus forcing data is I(z; u), and I(z; u, θ)<I(z; u) because of errors in the parameters. The term I(z; yM) is the total information available from the model, and I(z; yM)<I(z; u, θ) because of model structural error. Figure from Peters-Lidard et al., 2017, Fig 3.

The first two sub-tasks were to add the Noah-MP LSM and the CLM LSM into NLDAS. The Noah-MP LSM was added in Year 1 of the project, and version 3.6 of Noah-MP was part of the public open source LIS 7.1 release in March 2016. A newer version of CLM, version 4.5, was integrated into the LIS software framework during this period. The LIS pre-processor – the Land Data Toolkit (LDT) – was also modified to produce CLM model parameters, including plant functional types. Benchmarking of CLM-4.5 for NLDAS and comparison to other LSMs is currently in development.

A major development of this project is the NLDAS Science Testbed. The Testbed is a framework for the systematic evaluation of new/updated LSMs for the next phase of NLDAS, including Noah-3.6, Noah-MP-3.6, CLSM-F2.5, VIC-4.1.2.l, etc. The Testbed consists of simulations run at GSFC with detailed/documented spin-up and evaluation procedures. The current operational NLDAS Phase 2 LSMs (Noah-2.8, VIC-4.0.3, Mosaic, and SAC) are also included in the Testbed. All LSM outputs are evaluated against the same set of observations using NASA's Land surface Verification Toolkit (LVT) software (Kumar et al., 2012). The goal of the Testbed is to quantify performance changes from new/updated LSMs within LIS, in addition to various configurations/parameters within each LSM. For example, multiple Testbed simulations for the Noah-MP-3.6 LSM were performed, testing options for dynamic vegetation, groundwater, and other configurations. Computational performance metrics are also compared as part of the Testbed.

Evaluations were made using routed streamflow from NLDAS runoff compared to USGS observations in small river basins. 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 soil moisture against quality-controlled in situ observations from the USDA's SCAN network as well as 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). The groundwater modules in the new LSMs were evaluated against USGS well depth observations. Testbed results were presented at the AMS Annual Meeting in Jan 2016 as well as during monthly NLDAS telecons. Figure 2 shows some example figures from the NLDAS Science Testbed. The left panel shows the anomaly correlation of the surface soil moisture modeled by the current NLDAS Phase 2 operational LSMs (left of the gray dashed line) as well as the new LSMs within LIS. The anomaly correlation is calculated for 2002-2012 against 117 SCAN soil moisture observations. The right panel shows the same period and LSMs of the anomaly correlation against USGS streamflow observations for 572 small, unregulated basins. The LSM output was routed into streamflow using the NLDAS router for the NLDAS-2 LSMs and using the new HyMAP router in LIS for the new LSMs. From the results, the simulated soil moisture has improved in newer versions of the Noah and Noah-MP LSMs.

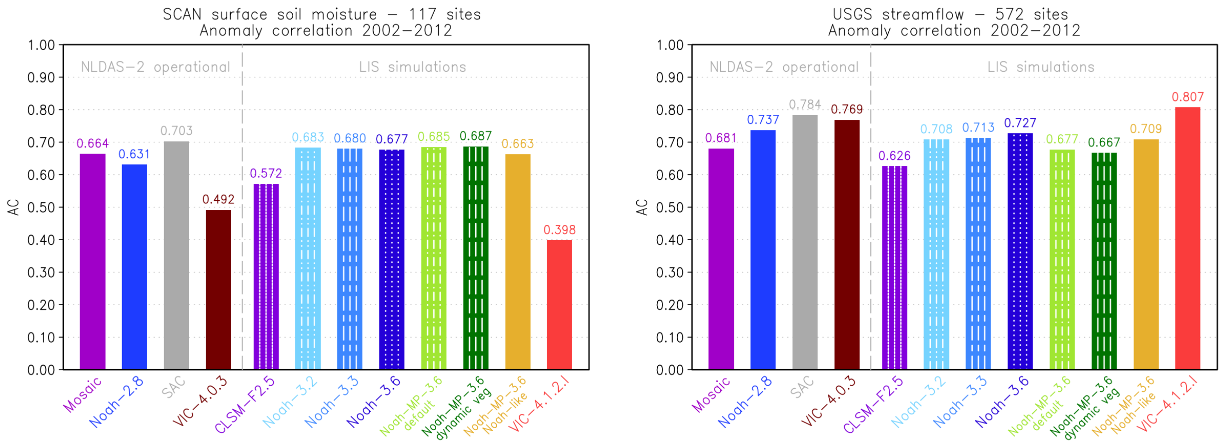

Figure 2: Anomaly correlation of the NLDAS-2 operational LSMs and new LSMs within LIS as part of the NLDAS Science Testbed evaluated against: Left) 117 SCAN surface soil moisture observations, and Right) 572 USGS streamflow observations.

During the entire project, numerous simulations were made to test various Noah-MP (Multi-Physics) options, including to dynamic vegetation, runoff/groundwater, resistances/drag, etc. These simulations were performed to obtain the best-possible set of configuration options for NLDAS. Comparisons of various terrestrial water storage components were made between the new NLDAS LSMs with groundwater physics – Noah-MP-3.6, CLSM-F2.5, and CLM-4.0. Xia et al. (2017) found that the new LSMs reasonably captured the monthly and interannual variability and magnitudes of the terrestrial water storages. Figure 3 shows anomalies of terrestrial water storage compared to that measured by the GRACE satellites; each panel is for a different NWS River Forecast Center. Other variables of the water and energy budgets in the NLDAS operational and research systems were presented in Xia et al. (2016a and 2016b).

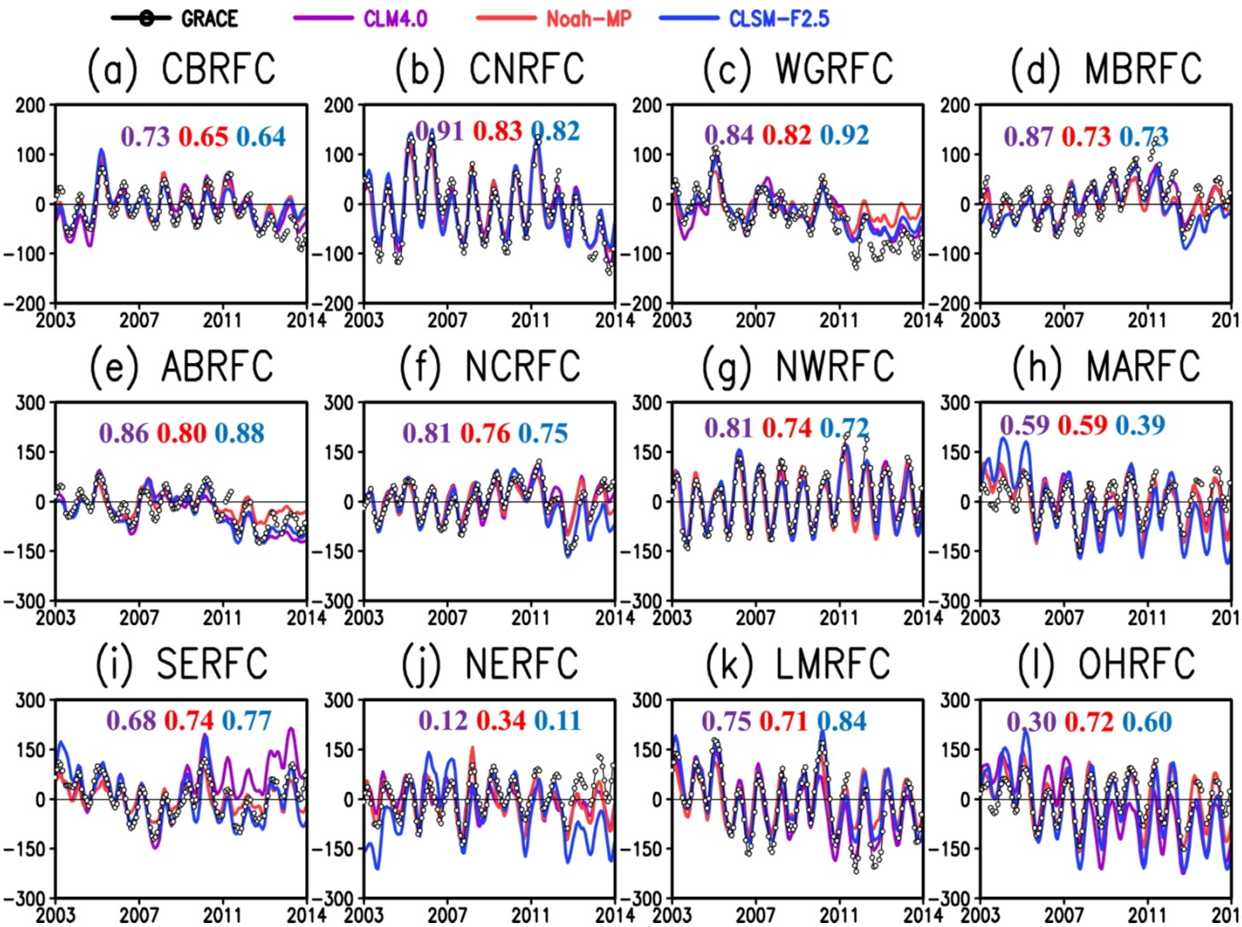

Figure 3: Comparison of terrestrial water storage anomalies [mm] from GRACE (black line with open circles) to the Noah-MP-3.6 (red), CLSM-F2.5 (blue), and CLM-4.0 (purple) LSMs, by NWS River Forecast Center (RFC). The numbers are the anomaly correlation compared to GRACE for each LSM within that RFC. Figure from Xia et al. (2017; Fig. 4).

The third sub-task was to improve the NLDAS forcing and parameters. New forcings for the next phase of NLDAS were identified, and plans for going to a finer spatial resolution and an expanded domain were developed and detailed. It is planned that the next phase of NLDAS will go from the current ~12.5-km down to ~3.125-km, and the domain will expand to include all of North America, including Hawaii, Alaska, and Puerto Rico. Preliminary results, including its implementation in LDT, were shared via the NLDAS inter-agency telecons. Additionally, work was done to reduce the ~3.5-day latency gap of the current operational product to make NLDAS a truly real-time operational product. Other forcing data sources are used to close this gap, while the current system will continue run ~3.5-days behind the current time, to provide the higher-quality climatology consistent with the long-term NLDAS record. Results found that the real-time product was of sufficient quality to provide NLDAS users with timelier drought monitoring and as input to other operational systems. Data streams, scripts, and results are mature, and the proposed operational implementation is currently undergoing external evaluation in advance of operational implementation expected to take place by Q3 FY18. Details on the new NLDAS versions, including timelines for their implementation, can be found in a white paper (Ek et al., 2017) written by proposal participants on operational land data assimilation development at

NOAA/EMC, including for the next phase(s) of NLDAS. This white paper was shared with the NLDAS community, discussed in a public telecons, and is available from the NLDAS websites.

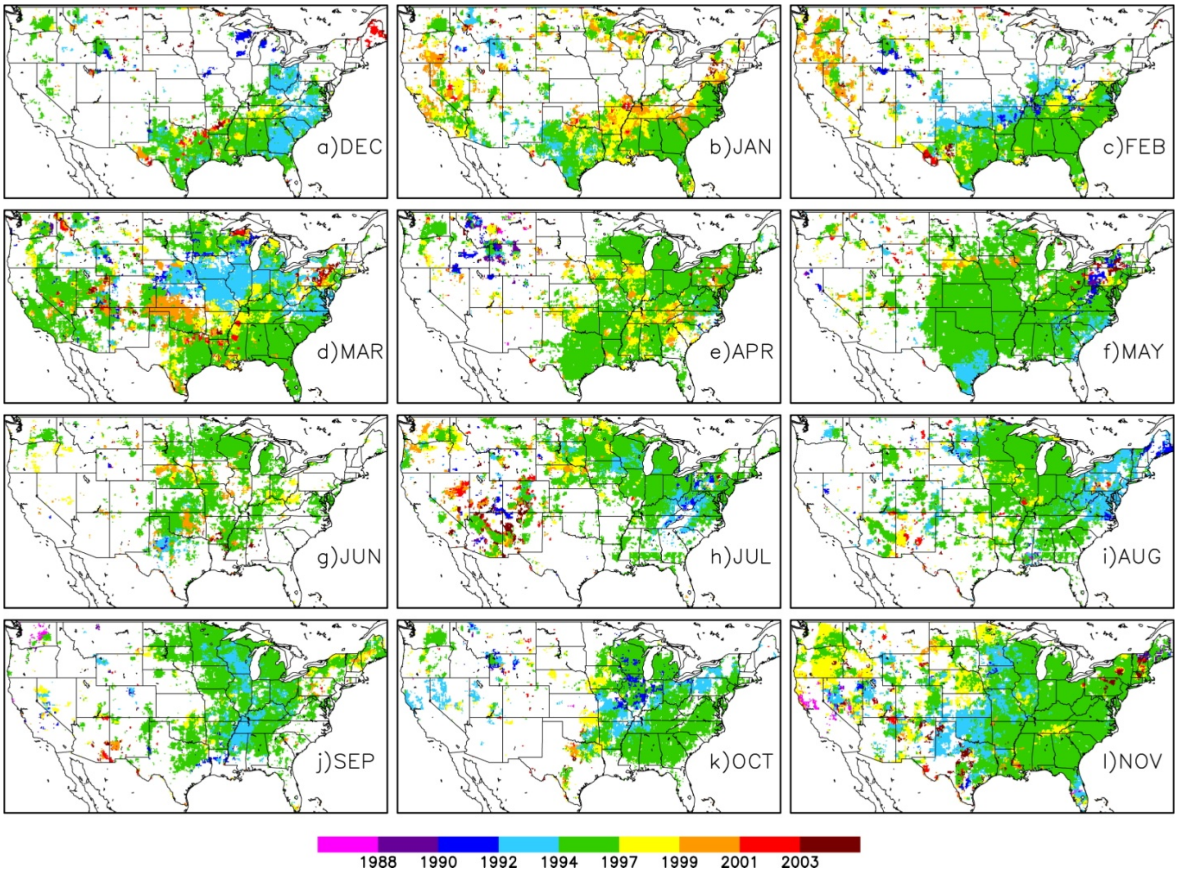

Figure 4: Years with a Pettitt field significant break at the 0.05 level for 12-17 daylight saving time for the frequency of NLDAS-2 precipitation. The most common period with a change to the afternoon precipitation frequency (shown in green) was found to be the years 1994-1997, shown to be associated with the use of Stage II Doppler radar data for temporal disaggregation of daily precipitation. Figure from Ferguson and Mocko (2017; Fig. 6).

As part of the process to improve the NLDAS forcing, studies were performed with the current Phase 2 forcing, to highlight issues that can be addressed in the next phase forcing. Ferguson and Mocko (2017) found changes in the diurnal cycle of NLDAS-2 precipitation associated with the use of Stage II Doppler radar data for temporal disaggregation of daily precipitation. Stage II was available starting around 1996, as the new radars were installed. Figure 4 shows that there is a significant change for many regions in the NLDAS-2 afternoon precipitation around 1996.

Further investigation with our NLDAS partners into the role of forcing uncertainty on potential snow data assimilation (Kumar et al., 2017a) led to the finding that hybrid forcing ensembles are critical for proper characterization of errors in snow data assimilation. This leads to the conclusion that the next phase of NLDAS should consider hybrid forcing ensembles to support data assimilation.

Second Task: Assimilate GRACE TWS, SMAP, and irrigated area

The second project task was to assimilate various water products into the LIS-NLDAS system. These products are terrestrial water storage (TWS) anomalies from the GRACE satellites as well as a surface soil moisture product from the SMAP satellite. Additionally, the effects of irrigation are to be included, using maps of irrigated area derived by MODIS.

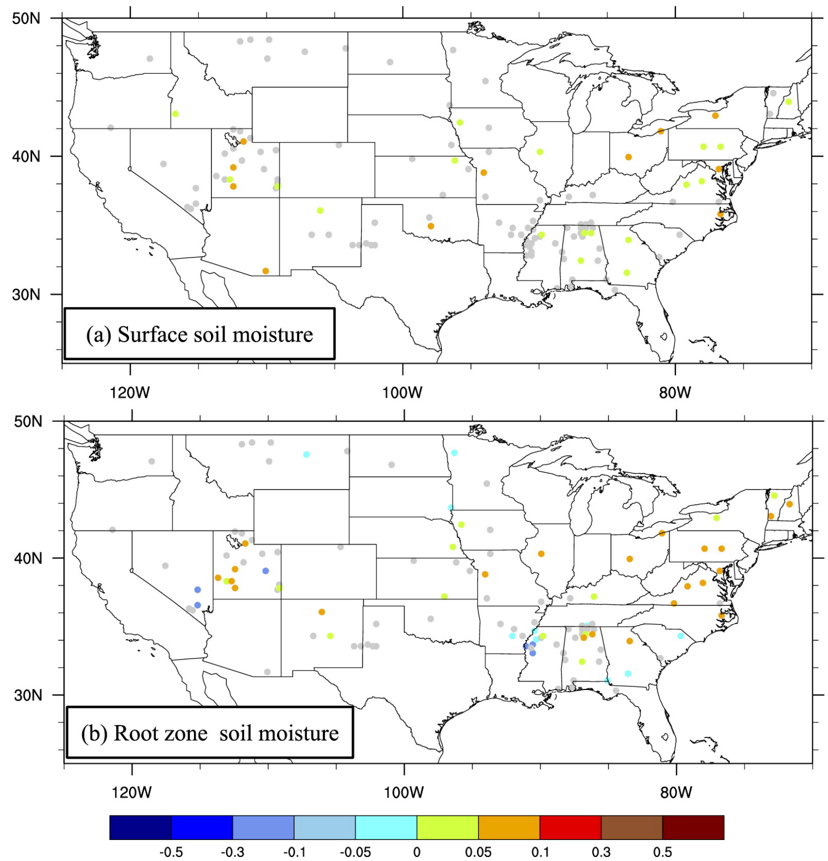

Figure 5: Anomaly R differences of (a) surface and (b) root zone soil moisture fields from DA-TWS relative to the OL integration. Warm colors indicate locations of improvement and cool colors indicate locations of degradation (Figure 5 in Kumar et al., 2016).

The first sub-task was to assimilate terrestrial water storage (TWS) from GRACE. TWS includes all storages, including water in the soil, on the ground/vegetation (including snow), and in deep storage, such as groundwater. Only LSMs that include a concept of groundwater through their physics can truly replicate the TWS such as measured by GRACE. None of the current operational NLDAS-2 LSMs have groundwater, while the Noah-MP-3.6, CLSM-F2.5, and CLM-4.5 LSMs include parameterizations for shallow groundwater. GRACE TWS anomalies have been assimilated into CLSM-F2.5 using an Ensemble Kalman Smoother (EnKS) using LIS. Kumar et al. (2016) found improvements to the simulation of groundwater and of soil moisture through the use of GRACE data assimilation, as shown in Figure 5. Noah-MP-3.6 LSM GRACE data assimilation is currently undergoing testing.

The second sub-task was to assimilate surface soil moisture from SMAP. This capability was added into LIS during this period for several new LSMs. Both the SMAP layer of the real-time SMOPS product from NESDIS as well as the NASA SMAP Level 3 product can be assimilated into LIS. In addition, multi-variate assimilation of multiple remotely-sensed products, including numerous snow and soil moisture products, was tested and evaluated in the NLDAS domain. Furthermore, a new capability to calculate the innovations on the observation grid instead of on the model domain grid was added into LIS. These updated features were included in the Spring 2017 LIS 7.2 code release towards operational transition to NOAA/EMC.

The third sub-task was to incorporate the effects of irrigation into the LSMs. This capability has been integrated into LIS, and uses maps of irrigated area derived from MODIS. The irrigation was also tested and evaluated in the NLDAS domain during this period. As part of the evaluation of irrigated areas, Kumar et al., (2015) found that remotely sensed soil moisture products from ASCAT are more skillful than SMOS and AMSR-2 at detecting soil moisture changes due to irrigation. Although not part of this project, a detailed assessment of the irrigation physics was carried out by Lawston et al., 2017.

Third Task: Probabilistic and Ensemble Drought Analysis and Monitoring

The third project task was to perform probabilistic and ensemble drought analysis and monitoring. This task also includes configuration and validation of the new system, as well as transfer of the new system to NOAA/EMC towards implementation into operations.

The first sub-task was to configure and evaluate the new LIS-NLDAS system for the next phase of NLDAS. This included comparing the new LSMs and the effects of data assimilation and irrigation against observations as well as their ability to represent drought. As many of the new LSMs have a representation of groundwater, long looping spin-ups are required to equilibrate the model states. A new capability of calculating climatological average states was added to LDT and used for initialization of the post spin-up simulations. LVT was used to compare model-simulated outputs of evapotranspiration, soil moisture, snow, groundwater, and runoff/streamflow against in situ observations and gridded reference products. The same evaluations were also performed for the operational NLDAS-2 LSMs, to assess changes as NLDAS moves to the next phase.

The second sub-task was to perform probabilistic and ensemble drought analyses, including looking at drought case studies. Comparisons were made to historical drought extents and severity from the U.S. Drought Monitor. Ensemble means from the four operational NLDAS-2 LSMs and four of the new LIS-NLDAS LSMs were also compared. The effects of different options (such as dynamic vegetation in Noah-MP-3.6 LSM) were also examined for changes in drought characterization, especially for severe drought case studies. In addition, a similarity analysis was performed of outputs of the current and new LSMs. Kumar et al. (2017b)

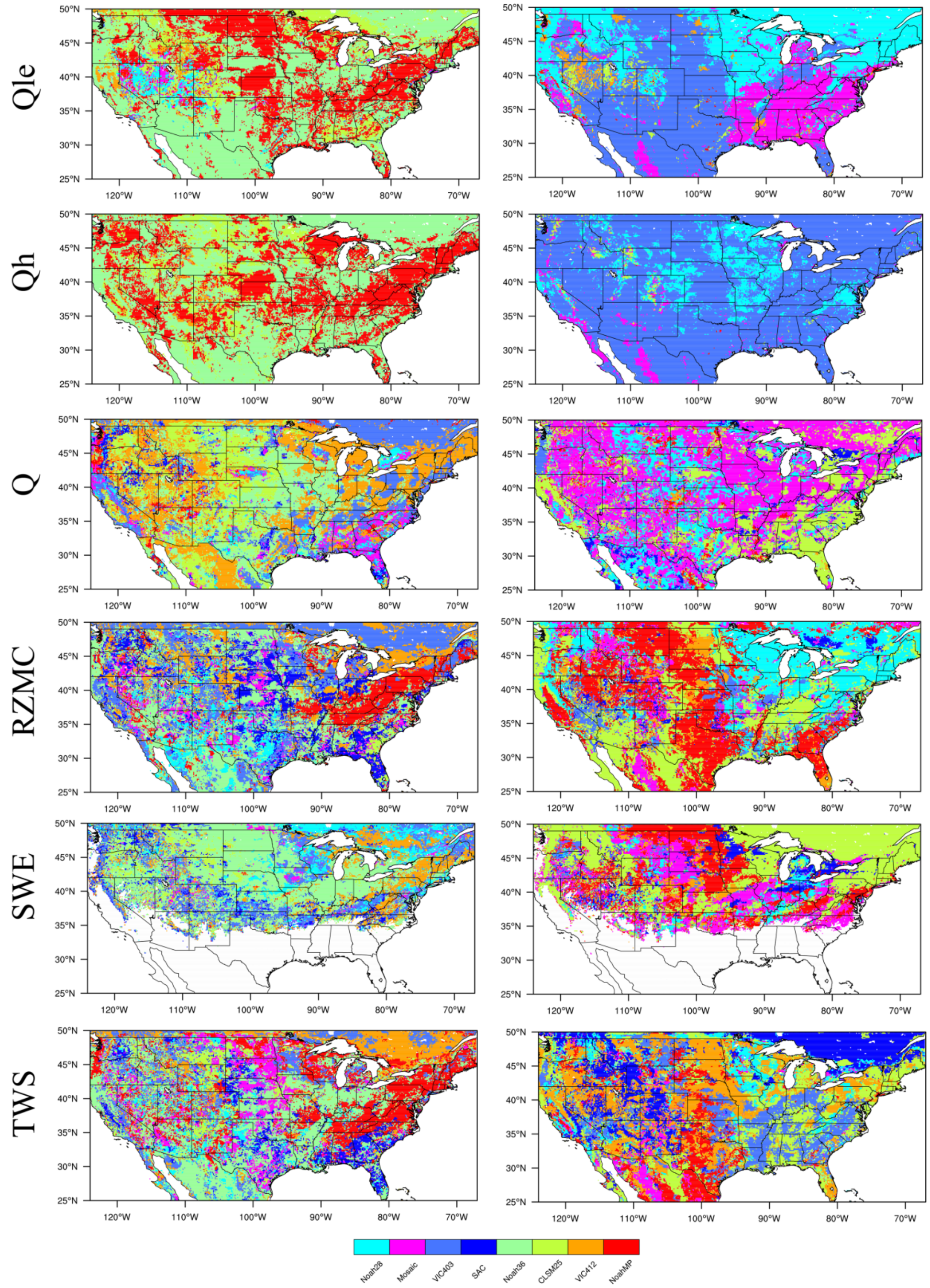

Figure 6: Map of LSM most similar (left column) and dissimilar (right column) to the common factor, for Qle (latent heat flux), Qh (sensible heat flux), Q (total runoff), RZMC (root zone soil moisture), SWE (snow water equivalent, or mass of snow on the ground), and TWS (terrestrial water storage). Figure from Kumar et al. (2017, Fig. 10).

performed a confirmatory factor analysis on the current/new NLDAS LSMs to assess the information added from individual LSMs to the multi-model ensemble. Figure 6 shows an example from this study, of the most similar (left column) and most dissimilar (right column) LSM compared to the common factor of all eight LSMs in the study (four NLDAS-2 and four new LIS-NLDAS LSMs). Shown are results for several important water/energy variables relevant to drought: fluxes, soil moisture, runoff, and snow. The study also examined the LSMs' similarity versus accuracy compared to observational reference datasets. Further analysis in work towards a follow-on paper has examined the similarity of these LSMs to depict drought percentiles and other drought-based indices.

The third sub-task was to transfer the updated LIS-NLDAS system to NOAA/EMC. LIS version 7.2 was released in Spring 2017 and contains many of these new capabilities. The code was configured to run on the NOAA "Gaea" supercomputer, using similar libraries as on WCOSS towards eventual operational implementation. Code maintenance through subversion was also established between "Gaea" and the LIS code repository. As detailed in the First Task, a white paper was written by NOAA/EMC and NASA/GSFC personnel on this project that provides information on the next phase(s) of NLDAS and their operational implementation.

Outreach, Collaboration, and Data Sharing/Management

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 are available from 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/parameter sub-setting, online figure generation, GRIB to NetCDF conversion, a GrADS Data Server (GDS), quick long-record time series access through "Data Rods", and Giovanni and Mirador services. From the NASA GES DISC alone, for the calendar year 2017, there were over 5,200 distinct users and more than 56 million files downloaded. Operational NLDAS products are used in the operational QuickDRI (Quick Drought Response Index) drought index. QuickDRI is a project led by the National Drought Mitigation Center to be used as another tool for the U.S. Drought Monitor authors, and its operational visualization webpage will be launched by USGS/EROS in late spring 2017. Operational NLDAS Phase 2 forcing and four LSMs were also maintained and distributed to users from NCEP/EMC, and the NLDAS Drought Monitor was updated in near real-time. Monthly NLDAS inter-agency teleconferences were held for collaboration amongst current NLDAS partners and new participants. Results and updates on NLDAS were also presented at the AMS Annual Meeting, the AGU Fall Meeting, and other smaller workshops/meetings. A NASA LIS Twitter feed (@NASA_LIS) and a LIS blog (https://lis.gsfc.nasa.gov/blog) were established and include posts on NLDAS datasets and studies.

4. Highlights of Accomplishments

- A major development of this project is the NLDAS Science Testbed. The Testbed is a framework for the systematic evaluation of current and new/updated LSMs for the next phase of NLDAS, including Noah-3.6, Noah-MP-3.6, CLSM-F2.5, VIC-4.1.2.l, etc. The goal of the Testbed is to quantify performance changes from new/updated LSMs within LIS, in addition to various configurations/parameters within each LSM.
- The Noah-MP-3.6 and CLM-4.5 LSMs were integrated into the LIS software framework and the Land Data Toolkit (LDT) pre-processor for generating model parameters. Noah-MP has been released publicly in both LIS7.1 and 7.2. Benchmarking of CLM-4.5 for NLDAS and comparison with other LSMs is underway.
- Data assimilation of GRACE terrestrial water storage and of SMAP surface soil moisture, along with the effects of irrigation, was performed and evaluated in LSMs in the NLDAS configuration.
- Ensemble drought analysis was conducted, including examinations of model similarity, including both the NLDAS-2 LSMs and the new LSMs.
- A white paper was written on the vision, requirements, and implementation of land data assimilation at NOAA/NCEP, which includes details on the plan and operational timelines of the next phase of NLDAS. This white paper was shared with the NLDAS community, including a recent meeting with NOAA/CPC, for additional feedback, and has been made publicly available.

5. Transitions to Operations

In process. WCOSS accounts have been obtained for NASA/GSFC LIS team members and testing of LIS7.2 for NLDAS Phase 3 is ongoing in conjunction with our CTB project.

6. Publications from the Project

Ek, M.B., C.D. Peters-Lidard, Y. Xia, D.M. Mocko, J. Meng, S.V. Kumar, H. Wei, J. Dong, A. Getirana, and S. Wang, 2017: Next Phase of the NCEP Unified Land Data Assimilation System (NULDAS): Vision, Requirements, and Implementation. Available from the NLDAS websites.

Ferguson, C.R., and D.M. Mocko, 2017: Diagnosing an artificial trend in NLDAS-2 afternoon precipitation. *J. Hydrometeor.*, **18**(4), 1051-1070, doi:10.1175/jhm-d-16-0251.1

Kumar, S.V., B.F. Zaitchik, C.D. Peters-Lidard, M. Rodell, R.H. Reichle, B. Li, M.F. Jasinski, D.M. Mocko, A. Getirana, G.J. De Lannoy, M.H. Cosh, C.R. Hain, M. Anderson, K.R. Arsenault, Y. Xia, and M. Ek, 2016: Assimilation of gridded GRACE terrestrial water storage estimates in the North American Land Data Assimilation System. *J. Hydrometeor.*, **17**(7), 1951-1972, doi:10.1175/jhm-d-15-0157.1

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Kumar, S.V., C.D. Peters-Lidard, J.A. Santanello, R.H. Reichle, C.S. Draper, R.D. Koster, G. Nearing, and M.F. Jasinski, 2015: Evaluating the utility of satellite soil moisture retrievals over irrigated areas and the ability of land data assimilation methods to correct for unmodeled processes. Hydrol. Earth Syst. Sci., 19, 4463-4478, doi:10.5194/hess-19-4463-2015.

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Kumar, S.V., S. Wang, D.M. Mocko, C.D. Peters-Lidard, and Y. Xia, 2017b: Similarity assessment of land surface model outputs in the North American Land Data Assimilation System (NLDAS). *Water Resour. Res.*, 53, 8941-8965, doi:10.1002/2017WR020635

Nearing, G.S., D.M. Mocko, C.D. Peters-Lidard, S.V. Kumar, and Y. Xia, 2016: Benchmarking NLDAS-2 soil moisture and evapotranspiration to separate uncertainty contributions. *J. Hydrometeor.*, **17**(3), 745-759, doi:10.1175/jhm-d-15-0063.1

Peters-Lidard, C.D., M. Clark, L. Samaniego, N.E.C. Verhoest, T. van Emmerik, R. Uijlenhoet, K. Achieng, T.E. Franz, and R. Woods, 2017: Scaling, similarity, and the fourth paradigm for hydrology. *Hydrol. Earth Syst. Sci.*, 21, 3701-3713, doi:10.5194/hess-21-3701-2017

Xia, Y., B.A. Cosgrove, K.E. Mitchell, C.D. Peters-Lidard, M.B. Ek, S.V. Kumar, D.M. Mocko, and H. Wei, 2016a: Basin-scale assessment of the land surface energy budget in the National Centers for Environmental Prediction operational and research NLDAS-2 systems. *J. Geophys. Res. Atmos.*, **121**(1), 196-220, doi:10.1002/2015jd023889

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Xia, Y., D.M. Mocko, M. Huang, B. Li, M. Rodell, K.E. Mitchell, X. Cai, and M.B. Ek, 2017: Comparison and assessment of three advanced land surface models in simulating terrestrial water storage components over the United States. *J. Hydrometeor.*, **18**(3), 625-649, doi:10.1175/jhm-d-16-0112.1

7. Related Publications

Lawston, P.M., J.A. Santanello, T.E. Franz, and M. Rodell, 2017: Assessment of irrigation physics in a land surface modeling framework using non-traditional and human-practice datasets. *Hydrol. Earth Syst. Sci.*, 21, 2953-2966, doi:10.5194/hess-21-2953-2017

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