Next Phase of the NCEP Unified Land Data Assimilation System (NULDAS): Vision, Requirements, and Implementation

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Executive Summary

This white paper summarizes two operational land systems jointly developed by NOAA, NASA, and several universities: the North American (NLDAS) and Global (GLDAS) Land Data Assimilation Systems. It highlights several key development stages and milestones for the NLDAS and GLDAS systems over the next several years. To meet various public requirements and scientific advances, NLDAS will be transitioned from a near-real-time to a truly real-time system, use the latest upgraded land-surface models, add data assimilation of remotely-sensed states, and extend the spatial domain and increase spatial resolution. These additions to NLDAS are to enhance application capacity and product accuracy. In addition to NLDAS, GLDAS will become a standalone system in order to efficiently adapt new research from the community to this system to enable R2O and O2R tasks. The two systems will use the NASA-developed Land Information System (LIS) software framework. To reduce the complexity of the NCEP modeling suite, especially the number of overall models, the ultimate goal is that the two LDAS systems will be unified to become a single NCEP Unified LDAS system (NULDAS). The NULDAS will be largely embodied in the NOAA Next General Global Prediction System initiative (NGGPS). A global system with a nested high resolution NLDAS domain will efficiently support various public users and provide the capability for global land-surface initialization for weather and climate prediction models. This white paper provides details of these additions as well as of expected timelines for their operational implementation.

Contents

1. Introduction

The National Centers for Environmental Prediction (NCEP) has implemented two operational Land Data Assimilation Systems (LDAS): North American LDAS (NLDAS, implemented in 2014) and Climate Forecast System (CFSv2) based Global LDAS (GLDAS, implemented in 2011). The purpose of NLDAS (*Mitchell et al., 2004; Xia et al., 2012*) is to support numerous research and operational applications in the land modeling and water resources management communities, including U.S. Drought Monitor and related operational drought monitoring and prediction tasks (*Ek et al., 2011*). The objective of GLDAS (*Meng et al., 2012*) is to provide land initial conditions to NCEP CFSv2 and Reanalysis (CFSR) to improve global climate simulation and prediction and generate new hydrometeorological reanalysis products to support users. Recently, GLDAS is moving towards supporting NCEP's Global Forecast System (GFS), Next Generation Global Prediction System (NGGPS), and Global Integrated Drought Information System (GIDIS). To merge these two LDAS systems into a unique NCEP Unified LDAS (NULDAS) system, NLDAS can be nested within GLDAS to simplify the NCEP product suite. In addition, NLDAS/GLDAS and NULDAS will use the Land Information System software framework (LIS, *Kumar et al., 2006; Peters-Lidard et al., 2007*) recommended by NCEP and NASA scientists.

The NLDAS system is a joint system between NOAA/NCEP and NASA/GSFC. The GLDAS system described in this white paper is led by NOAA/NCEP, with some support from NASA/GSFC. There is a completely separate GLDAS project (Rodell et al., 2000) that is led by separate personnel at NASA/GSFC. For more information, please see:

NOAA/NCEP NLDAS website: http://www.emc.ncep.noaa.gov/mmb/nldas/
NASA/GSFC NLDAS website: https://ldas.gsfc.nasa.gov/nldas/
NASA/GSFC GLDAS website: https://ldas.gsfc.nasa.gov/gldas/

There is not a separate GLDAS website at NOAA/NCEP.

2. NLDAS

2.1. Background and Status

The North American Land Data Assimilation (NLDAS) is a multi-institutional collaborative project that has comprised two major phases so far. Phase 1 (NLDAS-1) was initiated in 1999 with the purpose of establishing a land data assimilation framework for the continental United States, southern part of Canada, and northern part of Mexico that includes several land-surface models (LSMs), high-quality meteorological forcing, soil and vegetation parameters, and validation datasets. Phase 2 (NLDAS-2) is an extension of the Phase 1 with the key purpose of producing quality-controlled long-term and near real-time products to support the national operational drought monitoring, prediction, and water resource information needs of various government agencies, academia, and enterprises. To provide timely and stable products to all users, NLDAS-2 became part of the NCEP operational production suite in August 2014.

However, there are several major issues with the current operational NLDAS-2 that have opportunities for improvement towards the development of the next phase on NLDAS. These issues raised by both NLDAS participants and product end-users are listed below:

1. NLDAS-2 currently has a 3.5-day latency behind real-time; this latency is a result of the high-quality surface meteorological forcing used to drive the NLDAS LSMs. This issue was first raised by the U.S. Drought Monitor (USDM) author group, a major user of the NLDAS Drought Monitor maps/products. The USDM authors produce a weekly-based/updated drought map; however, during this 7-day period, the 3.5-day latency of NLDAS-2 results in the authors missing 3.5 days of information from NLDAS. In addition, many users who use NLDAS-2 datasets for their operational purposes have complained about this drawback.
2. The current NLDAS-2 LSMs are legacy code versions and do not contain the latest model developments. For example, none of the current LSMs include the concept of groundwater, dynamic phenology, or representation of biogeochemical cycles.
3. NLDAS has lacked the capability to assimilate numerous historical and operational remotely-sensed satellite-based land-surface products. The limitation must be addressed to realize the "DA" part of NLDAS. Ensemble data assimilation algorithms have been demonstrated in the NLDAS configurations to enable the assimilation of soil moisture, snow, snow cover, and terrestrial water storage retrievals from various remote sensing platforms.
4. The domain and spatial resolution of the current NLDAS-2 datasets is limited. The NLDAS-2 spatial resolution is 0.125-deg (~12.5km) and only covers from 25^{o}N to 53^{o}N. Many users have requested an expanded domain and finer spatial resolution.
5. The quality of the surface meteorological and boundary condition datasets used in NLDAS as input to the LSMs needs to be improved. Since the development of NLDAS-2, numerous higher-quality datasets such as new land soil and vegetation parameters, and other land surface characteristics datasets have been produced that can improve the next phase of NLDAS. Furthermore, several issues with the NLDAS-2 forcing datasets have been identified, particularly with the near real-time updates, and are detailed at the NASA/GSFC NLDAS website.

To solve these problems, personnel from NOAA and NASA are developing the next phase of the NLDAS system. The following section contains the next phase vision and requirements.

2.2. Next Phase Vision and Requirements

The vision of the next phase of NLDAS is to provide quality-controlled and spatially/temporally consistent land-surface model (LSM) datasets from the best-available observations and model output to support modeling activities. Specifically, the next phase is intended to reduce the errors and address the aforementioned issues in the NLDAS products for use by both the operational and research communities. This vision includes two fundamental goals for the next phase of NLDAS. The first is to provide high-quality real-time drought monitor maps and datasets. The second is to provide the best-possible land-surface states for initialization of operational numerical weather prediction (NWP) models.

The requirements of the next phase of NLDAS system are:

1) Reduce the 3.5-day latency to real-time, to allow the operational use of NLDAS;
2) Upgrade the LSMs to use the latest model physics and ensure consistency with versions within various operational and research models and corresponding land-surface data sets, e.g., land-use type, soil type, near-realtime greenness, upgrading to newer higher-resolution data sets, etc.;
3) Enable observational constraints through the assimilation of terrestrial hydrological remote sensing measurements;
4) Expand the domain to all of North America – including Alaska, Hawaii, and Puerto Rico – and increase the spatial resolution to match that of an operational NWP model; and
5) Use the highest-quality surface meteorological and boundary condition datasets.

Based on maturity of research and workload, the first three requirements will be set as the first priority. The last two requirements will be implemented at later phases.

2.3. Next Phase Status and Plans

To implement the next phase of NLDAS, the NOAA and NASA teams are planning for two stages of development. The first stage focuses on upgrading the current operational NLDAS-2 system to reach actual real-time, thereby meeting the first requirement above. We will denote this as NLDAS-2.5. The second stage will include the real-time upgrade, and add upgraded and newly-added LSMs as well as the use of data assimilation of remotely-sensed hydrologic states. This stage will be denoted NLDAS-3.0, and will satisfy requirements 1-3. NLDAS-3.0 will use NASA's Land Information System (LIS) software framework to enable these upgrades. The use of LIS will allow a common software driver for all LSMs and include advanced data assimilation processes to assimilate remotely-sensed snowpack, snow cover, soil moisture, terrestrial water storage, and irrigation intensity for the next phase of NLDAS. The LIS software is mature and is supported by a revision control system, thus allowing NLDAS-based code modifications to be updated with the latest versions of LIS.

2.3.1. NLDAS-2.5

The purpose of NLDAS-2.5 is to close the 3.5-day latency and to extend the current operational NLDAS-2 into a real-time system. To achieve this goal, the NLDAS team will use the newly-upgraded NAMv4 (North American Mesoscale forecast system version 4) and its associated analysis component, which runs at an hourly cadence, as the meteorological forcing backbone to NLDAS-2.5. In addition to the analysis component, NLDAS-2.5 will also leverage the 13-36 hour forecast products from the previous day's 00Z NAMv4. 0-12 hour forecast products from the 12Z current day NAMv4 are not used due to spin-up issues. The CPC unified 0.125-degree gauge-based daily precipitation, the NCEP stage II hourly precipitation, and the NAMv4 analysis and forecast products are used to generate the real-time hourly NLDAS surface meteorological forcing data. Figure 1 shows that the different products are used to fill in the 3-5 day latency. Each day by soon after 20Z, the NLDAS-2.5 products (forcing, models, and streamflow) are updated to the end (23Z) of the current day. The current operational NLDAS-2 forcing, using

CPC daily precipitation and the R-CDAS reanalysis, is used up to 3.5 days before the end of the current day. From 3.5 to 1.5 days before the end of the current day, the CPC daily precipitation is still used, but the NAMv4 reanalysis is instead used for the near-surface meteorology due to that there is no R-CDAS ready for that period. As with the NLDAS-2 forcing, Stage II hourly precipitation estimates are used in this period to temporally disaggregate the CPC daily precipitation to hourly, while keeping the CPC daily total precipitation amounts. From 1.5 to 0.5 days before the end of the current day, the NAMv4 reanalysis is still used, but the Stage II hourly precipitation estimates are directly used as the NLDAS-2.5 hourly precipitation amounts as there is no CPC gauge precipitation ready. From 0.5 to 0.0 days before the end of the current day (from 13Z to 23Z of the current day), the NAMv4 hourly forecast (13-24 hour) precipitation and near-surface meteorology is used as either gauge-based, or radar-based, or reanalysis data do not exist. To summarize for precipitation, the 3.5-1.5 day period will use CPC daily gauge data disaggregated with the hourly Stage II product, the 1.5-0.5 day period will use the hourly Stage II product only, and the 0.5-0.0 day product will use the 13+ hour NAMv4 forecasts. For the near-surface variables of 2-m air temperature and specific humidity, 10-m wind speed, surface pressure, and downward shortwave and longwave radiation, the NAMv4 analysis is used for the 3.5-0.5 day period and the 13+ hour NAMv4 forecast product is used for the 0.5-0.0 day period. Figure 1 also details the approximate times during the day for the NLDAS-2.5 data production and availability.

NLDAS-2.5 will produce a most-recent 5-day product for users; the first 1.5 days will be the same as the current operational NLDAS-2 system. The quality of the other 3.5 days of the real-time product as compared to the lagged operational NLDAS-2 products will vary based on the availability and quality of the observed/forecast datasets. A preliminary assessment including forcing and model outputs will be delivered to the user community so that they can decide how to use these data. The current NLDAS-2 forcing and LSMs will continue to be updated daily with a 3.5-day latency, to provide continuity and a consistent set of forcing inputs and model outputs with the existing Jan 1979 to present archive of the NLDAS-2 datasets. The most recent NLDAS-2.5 products will always start with initial states from most-recent daily update of the NLDAS-2 system. As the required datasets for the generation of NLDAS-2.5 forcings are not available for the retrospective period, an archive of NLDAS-2.5 datasets will not be available going back to Jan 1979. The NLDAS-2.5 real-time data products will only be made available starting on the date of its operational implementation.

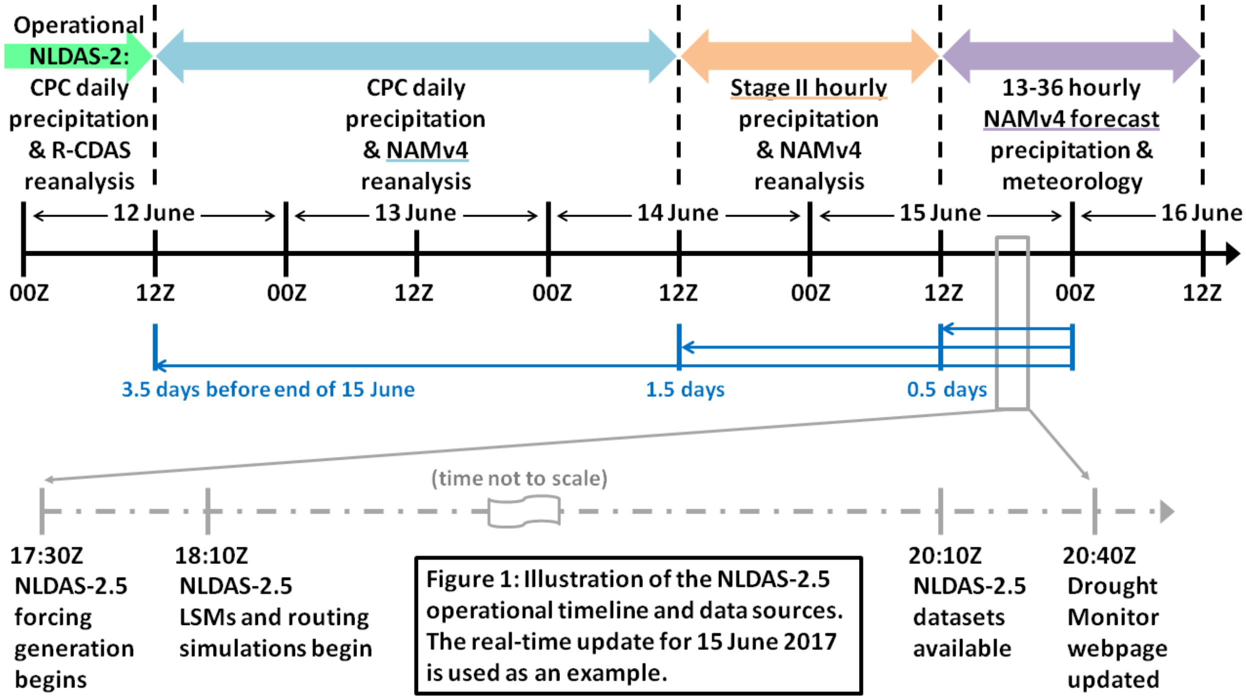

Figure 1: Schematic diagram shows the datasets used for forcing for the real-time NLDAS-2.5 product (top) and the approximate times of data generation and availability (bottom).

2.3.2. NLDAS-3.0

The purpose of NLDAS-3.0 is to incorporate the new NLDAS features jointly developed by NASA and NOAA scientists through grants supported by the NOAA/CPO/MAPP program. The LIS software framework will be used for all LSMs and future upgrades for NLDAS-3.0. The LIS framework is also planned to be used for FV3/NEMS at NCEP.

- The Noah-2.8 and VIC-4.0.3 LSMs currently in NLDAS-2.0 will be upgraded to later versions. Noah (as maintained by NCAR) will be upgraded to Noah-3.6 or later. The plan is to use the same version of Noah in NLDAS-3.0 as used in FV3/ NEMS, and other NCEP offline and coupled models.
- VIC (as developed/maintained by the Univ. of Washington and by Princeton Univ.) will be upgraded to VIC-4.1.2.l or later.
- The NLDAS-2 SAC model has recently undergone several upgrades to be renamed SAC-HTET; however, the necessary parameters for SAC-HTET are not easy to obtain, and it is not clear what future this LSM has for operational or research usage. Therefore, the NLDAS team is recommending discontinuing the use of the SAC LSM for NLDAS-3.0.
- To replace SAC, the team plans to add the Noah-MP (Multi-Physics) next-generation LSM. Noah-MP is the LSM of the National Water Model (NWM) at NOAA/NWS. Noah-MP (as maintained by NCAR) will be upgraded to Noah-MP-3.6 or later, with the goal of having the same version as used in the NWC to ensure compatibility.
- The NLDAS-2 Mosaic LSM is no longer used or supported by NASA/GMAO. Therefore, the NLDAS team plans to use the Catchment LSM, which is descended from the Mosaic LSM. Catchment LSM (as maintained by NASA/GMAO, and the land

component of the NASA GEOS-5 GCM) will be upgraded to CLSM-F2.5 or later. Noah-MP and CLSM-F2.5 also include a representation of groundwater, which will provide enhanced products to the NLDAS Drought Monitor.

In addition to the advanced LSMs, NLDAS-3.0 under the LIS framework will also include advanced data assimilation of remotely-sensed satellite-based soil moisture, snow, and terrestrial water storage (TWS) products to improve the states and fluxes simulated by the LSMs. Some of the products that will be used for the historical period include: 1) for soil moisture, the ESA CCI product and LPRM (AMSR-E); ASCAT, SMOS, and SMAP retrievals; 2) for snow depth, SMMR, SMM/I, AMSR-E, and AMSR2; 3) for snow cover, IMS, MODIS, and VIIRS; and 4) for TWS anomalies, GRACE. For the operational real-time period, products to be used include: 1) for soil moisture, ASCAT, SMOS, and SMAP retrievals from SMOPS; 2) for snow depth, AFWA SNODEP; and 3) for snow cover, IMS.

In this stage, the NASA and NOAA NLDAS teams will maintain a close collaboration with NCAR and NWC model development and implementation teams. We will use the same version Noah-MP as implemented in the next version of the NWM system. It should be noted that the primary focus of the NWM is to provide hourly to monthly streamflow forecasts, as opposed to drought monitoring, which is the primary focus of NLDAS-2, -2.5, and NLDAS-3.0.

Two other new features included within the LIS software framework will also be part of NLDAS-3.0. The HyMAP streamflow router will replace the NLDAS streamflow router, which is no longer maintained and is tied to the current 0.125-degree NLDAS grid. HyMAP is a physically-based river routing scheme capable of simulating surface water dynamics, providing streamflow, water depth, flow velocity, and water storage in both rivers and floodplains. The HyMAP version currently available in the public LIS version uses the kinematic wave equation. Early evaluations have found that the advanced representation of physical processes in HyMAP results in improved daily correlation of simulated streamflow over the NLDAS router. Improvements in HyMAP's physics using the local inertia formulation, accounting for backwater effects, are currently being evaluated over the U.S., West Africa, and the Amazon basin. Reservoir operation is another feature currently being implemented in HyMAP, and a refined river geometry parameterization at higher spatial resolution will be developed to improve its parameterization and upscaling scheme. The other LIS feature to be included is a demand-based irrigation scheme based on MODIS-derived irrigated areas. Therefore, the final NLDAS-3.0 will be a real-time system featuring new models, advanced data assimilation processes, an improved streamflow router, and a representation of irrigation.

The NLDAS team recognizes that discontinuing Mosaic and SAC and adding CLSM-F2.5 and Noah-MP will definitely affect current operational NLDAS product users. To help their operational works smoothly transition from the current NLDAS-2 system to the NLDAS-3.0 system, 38-year (1979-2017) retrospective products including meteorological forcing and model outputs completed by the NASA NLDAS team will be first released to the public before the real-time NLDAS-3.0 operational transition. During the transition period, the users can compute new climatologies and test their operational processes with these new test NLDAS-3.0 retrospective products. During the transition period, the NCEP NLDAS team will also run an experimental system on WCOSS, provide real-time products to the users, and allow them to test their processes. In addition, during the 30-day NCO pre-implementation period, the users can further test their processes by using these products. Furthermore, an overlap period of the operational production of NLDAS-2 and NLDAS-2.5 products and the new NLDAS-3.0 products will be performed to assist NLDAS product users to transition to NLDAS-3.0. While operational products can change due to computational and funding concerns, the NLDAS team targets an overlap period of six months to one year.

2.3.3. NLDAS-3.5 and Beyond

As noted in the previous discussion, NLDAS-3 will satisfy requirements 1-3, but not 4 and 5. Therefore, a future version of NLDAS (NLDAS-3.5) will target domain expansion and forcing data improvements. In addition, we will closely watch development of other regional LDASs such as Africa, Asia, Europe, Mid-East, and South America. Their successful experiences will be considered in developing this next phase of NLDAS. The key objectives for NLDAS-3.5 are:

- Expand the NLDAS domain to include the entire North America (including Alaska, Hawaii, and Puerto Rico) and increase the spatial resolution to 1-3km.
- Use fine spatial resolution datasets such as PRISM daily precipitation and temperature, Stage II/IV hourly precipitation, and other forcing observations. The newly produced forcing data will be compressively evaluated using cross-validation or independent observed data.
- The forcing products will be updated to include the best available datasets. The available downscaling methodologies within LIS will be used to disaggregate coarser data products to the fine model grid. The use of forcing ensembles will also be targeted for enabling probabilistic model predictions.

Further, there are a number of enhancements that are ongoing and will be targeted for inclusion in NLDAS in future phases, starting with NLDAS-3.5. They include:

- The NLDAS team is also integrating the Community Land Model (as maintained by NCAR) version 4.5 (CLM-4.5) into LIS. CLM-4.5 may be added to NLDAS-3.5, depending on progress and evaluation. Other LSMs that have been considered for future inclusion in later phases of NLDAS include RUC, CABLE, JULES, PRMS, LM4, and SUMMA.
- Advancements in data assimilation: The multivariate data assimilation capabilities will be expanded to include a larger suite of sensors and variables and extended to multiple LSMs. For example, thermal remote sensing measurements (land surface temperature, evaporative stress) will be incorporated into the data assimilation environment. To constrain surface water storage estimation, inclusion of remotely altimetry measurements will be targeted. The availability of dynamic phenology within models such as Noah-MP will be used to enable the assimilation of remotely sensed vegetation data (LAI/GVF/NDVI).
- The DA system for operational NLDAS will be updated with advanced observation operators either based on machine learning or calibrated radiative transfer models to enable the direct use of radiance measurements. This will also reduce the latency in the incorporation of remote sensing data in the assimilation system.

3. NCEP Global LDAS (GLDAS)

3.1. Background and Status

Current operational GLDAS (version 2, GLDAS2.0) is a single model LDAS system that is used to provide land initial conditions to NCEP CFSv2 and Reanalysis (CFSR). It currently uses coarse soil texture (Zobler, 1986) and vegetation parameters (UMD, Loveland et al. 2000). One of the high-priority objectives for the next version is to upgrade the land surface datasets to the same as used in FV3/NEMS. The higher-resolution databases include 1-km STATSGO-FAO soil texture, 1-km IGBP-MODIS vegetation type, 5-km MODIS maximum snow albedo and snow-free albedo, monthly/weekly 1-km NESDIS greenness vegetation fraction (Friedl et al., 2002). The current version of GLDAS utilizes an old (and no longer supported) version of the LIS software. Therefore, upgrading to the newly released LIS 7.1 infrastructure and Noah version (version 3.4) with a 0.125-0.25 degree resolution are also high priorities. Recently, GLDAS is moving towards supporting NCEP's Global Forecast System (GFS), Next Generation Global Prediction System (NGGPS), and Global Integrated Drought Information System (GIDIS). The current system does not contain any data assimilation capabilities, and therefore, another high priority area for future development is to enable the LIS EnKF data assimilation module to assimilate snowpack and soil moisture globally, which is an important task for NGGPS development.

NCEP GLDAS team will maintain a close collaboration with the scientists from other operational centers such as Environment and Climate Change Canada and European Center for Mid-term Weather Forecast (ECMWF). In particular, some successful DA experiences from CaLDAS (Canadian LDAS) and ECMWF LDAS systems will be adapted to NCEP GLDAS development.

3.2. Next Phase Vision and Requirements

The vision of the next phase GLDAS is very similar to the next phase NLDAS except for the global domain and some differences in priorities. Specifically, the next phase is intended to reduce the land state errors and address the aforementioned issues in the GLDAS products to focus on support of NCEP global prediction systems development and improvement. Therefore, the first priority is to provide the best-possible land-surface states for initialization of operational global prediction systems including CFS, GFS, and the future NGGPS. The second is to provide high-quality real-time drought monitor maps and datasets to support GIDIS.

The requirements of the next phase of GLDAS system are:

1) Upgrade soil texture, vegetation parameter, and albedo data;
2) Use NEMS and LIS infrastructure, upgraded Noah model (from version 2.7.1 to 3.x), new CPC 0.25 degree operational precipitation, and finer spatial resolution to match next phase GFS resolution;
3) Enable observational constraints through the assimilation of remote sensing measurements (e.g., soil moisture and snowpack data);

4) Add more land surface models tested in NLDAS to GLDAS including Noah-MP; and
5) Extend high spatial resolution (e.g., 4 km) globally to serve joint LDAS testbed and NULDAS.

3.3. Next Phase Status and Plans

To implement the next phase of GLDAS, the NOAA team is planning for three stages of development. The first stage focuses on upgrading the current operational GLDAS2.0 system to NASA's Land Information System (LIS) software and NOAA NEMS framework including using the upgraded Noah model and new soil texture and vegetation parameters without data assimilation, thereby meeting the first two requirements above. We will denote this as GLDAS2.2. The use of LIS and NEMS will meet EMC numerical model system requirements and allow a common software driver for all LSMs with advanced data assimilation processes to assimilate remotely-sensed snowpack, snow cover, and soil moisture for the next phase of GLDAS (e.g., GLDAS3.0). The LIS software is mature and is supported by a revision control system, thus allowing GLDAS-based code modifications to be updated with the latest versions of LIS. The second stage will include upgraded Noah model and soil moisture and snowpack assimilation, increase the spatial resolution and use improved surface meteorological and boundary conditions datasets and real-time vegetation parameters (e.g., LAI, GVF). This stage will be denoted GLDAS3.0, and will satisfy requirements 1-3. GLDAS3.5 and beyond will move forward to NULDAS with multiple models and high spatial resolution globally and will use NASA's Land Information System (LIS) software framework to enable these upgrades. In this stage, NLDAS will be nested in the GLDAS system to end its operational task.

3.3.1. GLDAS2.2

GLDAS2.0 is not a standalone component of CFSv2. Therefore, the CFSv2 design limits GLDAS development and improvement to quickly transition research to operations. The purpose of GLDAS2.2 is to setup is a global standalone LDAS system, while also improving land parameters, precipitation forcing and upgrading the land model physics. To achieve this goal, the GLDAS team will use LIS and NEMS infrastructure, STATSGO soil texture, MODIS vegetation and albedo parameter, newly released 0.25 degree CPC daily gauge precipitation blended with remote sensing products, and Noah3.4 LSM to produce 1979-present global water and energy fluxes and state variables with a 0.25 degree spatial resolution.

3.3.2. GLDAS3.0

The GLDAS3.0 is an extension of GLDAS2.2, where we will take advantage of LIS EnKF data assimilation system and increase the spatial resolution to match the operational GFS (~13 km) and NGGPS. Due to the use of LIS and NEMS infrastructure, it is very flexible to add LSMs and select spatial resolutions to meet the requirements of EMC operational model system upgrades. In GLDAS3.0, we propose to transition existing land data assimilation capabilities in LIS to NCEP to support assimilation of satellite-based snow depth and soil moisture products, specifically the AFWA SNODEP and NESDIS soil moisture. The NOAA/NESDIS SMOPS has been in operations since 2013 and will be used in the proposed soil moisture assimilation tests, and the AFWA SNODEP estimated daily by merging satellite-derived snow cover data with daily snow depth reports from ground stations will be used in the snow depth assimilation tests.

3.3.3. GLDAS3.5 and beyond

As noted in the previous discussion, GLDAS3.0 will satisfy requirements 1-3, but not 4 and 5. Therefore, a future version of GLDAS (GLDAS-3.5) will target model addition and higher resolution.

- Increase spatial resolution from 0.125 degree in GLDAS3.0 to 3-4 km
- Add 2-3 extra LSMs with best performance in NLDAS system

The purpose of the GLDAS3.5 is to establish a 3-4 km multi-model GLDAS system. This system will be used to provide optimal initial conditions to operational weather and climate forecast systems and support GIDIS and other water resource management tasks. It will be a major component of the joint LDAS science testbed described in the next section.

3.4. Joint LDAS Science Testbed

The NASA and NCEP NLDAS teams have jointly developed the NLDAS Science Testbed. The current operational NLDAS system is used as a benchmark. The purpose is to quickly test improved model physics, improved surface forcing data, and new model parameters so that the NULDAS system can be intermediately upgraded. The in-situ, remotely-sensed, and reanalyzed data have been well established and validation/verification tool (LIS-based Land Verification Toolkit -LVT) has been developed. This will provide a very useful way to transition the new research work to NCEP operations. The NLDAS science testbed will be extended to the Joint LDAS testbed including regional and global domains with different spatial resolutions. The purpose is to motivate NULDAS system development and updates, support NCEP regional and global system forecasts, and accelerate NGGPS development including preliminary assessment of various operational and research land surface models from a standalone point. It is an essential step to efficiently transition research to NCEP operational systems. NLDAS testbed focuses on continental United States as data quality is relatively high including forcing data (e.g., precipitation) and evaluation data (e.g., in situ soil moisture, snow water equivalent, land skin temperature, AmeriFlux data, USGS streamflow, soil temperature, snowpack etc.). As an example, NLDAS can help to select candidate LSMs to consider in the joint LDAS testbed to further evaluate for all continents over the globe using observations, remotely-sensed data, and reanalysis products. Through this two-step offline selection process, 2-3 candidate LSMs can be selected to perform further tests for regional and global coupled forecast systems. This will enhance the performance and skills for both NCEP offline and coupled systems.

We also recognize that NCEP and NOAA have together established 12 formally recognized testbeds, such as the Climate Test Bed (CTB), Hazardous Weather Testbed (HWT), Aviation Weather Testbed (AWT), Coastal and Ocean Modeling Testbed, UCAR Development Testbed Center (DTC). The latter is more focused on NWP forecast evaluations with high quality near-real-time observations. However, due to the lack of near-real-time land product observations, our testbed will mainly focus on long-term historical data evaluations against both observations and other LDASs from different operational centers and academia over the U.S. and globe. The joint LDAS testbed is characterized by uncoupled land modeling and 1-D column coupled modeling, such as in the GEWEX/GLASS Local Coupling (LoCo) project can be part of the NOAA Testbed and Proving Grounds Portfolio in the future.

4. Unification of two LDAS systems

These activities will be efficiently coordinated between NCEP and NASA LDAS teams. The NLDAS system will be nested in GLDAS framework as soon as possible. At the same time, the GLDAS system will be expanded from single model system to multi-model system to support GIDIS drought monitoring and prediction task. Eventually, a NCEP Unified LDAS (NULDAS) system will be developed at NCEP to provide initials for numerical models and to support operational drought monitoring and prediction task as well as water resource management. This will be completed in summer 2020.

5. Awareness and Survey

Since the operational implementation of the NLDAS-2 system in August 2014, many users have been using these operational products. Before the NLDAS team discontinues the Mosaic and SAC LSMs from the next phase of NLDAS, a survey will be conducted (using the NASA GES DISC ldas-users and NLDAS telecon email lists) to see how big of an effect this will have on the NLDAS user community. This feedback will be circulated and discussed during the monthly NLDAS telecons as well as a future MAPP webinar. Updates will be provided on progress and challenges with the development of the next phases. The NLDAS team pledges to work together with NLDAS product users to minimize any negative effects of NLDAS-3.0 updates and to ensure a smooth upgrade and implementation of NLDAS-3.0.

6. Tentative Implementation Plan

a. NLDAS-2.5 is expected for operational implementation at NCEP in spring of 2018.
b. NLDAS-3.0 is expected for operational implementation at NCEP in spring of 2019.
c. NLDAS-3.5 is expected for operational implementation at NCEP in spring of 2020.
d. GLDAS2.2 is expected for operational implementation at NCEP in fall 2017.
e. GLDAS3.0 is expected for operational implementation at NCEP in spring 2019.
f. NULDAS1.0 is expected for operational implementation at NCEP in summer 2020.

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List of Acronyms

AFWA Air Force Weather Agency
AMSR Advanced Microwave Scanning Radiometer
AMSR-E AMSR for Earth Observing System
ASCAT Advanced SCATterometer
AWT Aviation Weather Testbed
CABLE Community Atmosphere Biosphere Land Exchange
CCI Climate Change Initiative
CFSR Climate Forecast System Reanalysis
CFSv2 Climate Forecast System Version 2
CLM Community Land Model
CLSM Catchment Land Surface Lodel
CPC Climate Prediction Center
CPO Climate Program Office
CTB Climate Testbed
DA Data Assimilation
DISC Data Information Services Center

DTC	Development Testbed Center
EnKF	Ensemble Kalman Filter
EMC	Environmental Modeling Center
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
FV3	The GFDL Finite Volume Cubed-Sphere Dynamical Core
GAMO	Global Modeling and Assimilation Office
GES	Goddard Earth System
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
GIDIS	Global Integrated Drought Information System
GLASS	Global Land/Atmosphere System Study
GLDAS	Global Land Data Assimilation System
GMAO	Global Modeling and Assimilation Office
GRACE	Gravity Recovery And Climate Experiment
GSFC	Goddard Space Flight Center
GVF	Greenness Vegetation Fraction
HWT	Hazardous Weather Testbed
HyMAP	Hydrological Modeling And Analysis Platform
IGBP	International Geosphere-Biosphere Pragramme
IMS	Ice Mapping System
JULES	Joint UK Land Environment Simulator
LAI	Leaf Area Index
LDAS	Land Data Assimilation System
LIS	Land Information System
LM4	Land Model version 4
LPRM	Land Parameter Retrieval Model
LSMs	Land Surface Models
LVT	Land Verification Toolkit
MAPP	Modeling, analyses, prediction and projection
MD	Maryland
MODIS	Moderate Resolution Imaging Spectroradiometer
NAMv4	North American Model Version 4
NAMRR	NAM Regional Reanalysis
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Modeling
NDVI	Normalized Difference Vegetation Index
NEMS	NOAA Environmental Modeling System
NESDIS	National Environmental Satellite, Data, and Information Service
NGGPS	Next Generation Global Prediction System
NLDAS	North American LDAS
NLDAS-1	NLDAS Phase 1
NLDAS-2	NLDAS Phase 2
NLDAS-3	NLDAS Phase 3

NOAA	National Oceanic and Atmospheric Administration
Noah	**N**CEP, **O**regon State University, Air Force, and Hydrologic Research Laboratory
Noah-MP	Noah Multiple Physics
NULDAS	NCEP Unified LDAS
NWP	Numerical Weather Prediction
NWC	National Water Center
NWM	National Water Model
NWS	National Weather Service
PRMS	Precipitation Runoff Modeling System
RUC	Rapid Update Cycle
SAC	SACramento Hydrological Model
SAC-HTET	SAC Heat Transfer and Evapotranspiration
SMAP	Soil Moisture Active Passive
SMM/I	Special Sensor Microwave/Imager
SMMR	Scanning Multichannel Microwave Radiometer
SMOPS	Soil Moisture Operational Product System
SMOS	Soil Moisture and Oceanic Salinity
SNODEP	Snow Depth
STATSCO	State Soil Geographic dataset
SUMMA	Structure for Unifying Multiple Modeling Alternatives
TWS	Terrestrial Water Storage
UCAR	University Corporation for Atmospheric Research
UMD	University of Maryland
USDM	US Drought Monitor
VIC	Variable Infiltration Capacity model
VIIRS	Visible Infrared Imaging Radiometer Suite