**Global Land Data Assimilation System (GLDAS) of the Water and Energy Simulations and Prediction (WESP) Working Group**

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**Project Starting Date:** September 2000
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**URL:** http://ldas.gsfc.nasa.gov/
**Chair and Dates of Terms:** Matt Rodell, 2006 – present

**Overview**

Accurate simulation and prediction of the global energy and water cycles demands the synthesis of data products from multiple sources, including ground and satellite based systems. The goal of GLDAS is to integrate these products using advanced land surface modeling and assimilation techniques, in order to generate a physically consistent and realistic, global representation of terrestrial processes. The Land Information System (LIS) has provided a highly sophisticated and efficient software infrastructure for GLDAS. LIS was a high performance computing initiative based on the GLDAS heritage, which in turn had roots in the multi-institution North American Land Data Assimilation Systems (NLDAS) project. The massive GLDAS archive of land surface and meteorological data continues to be maintained and augmented, and it provides the foundation for the project.

**Objectives**

Our hypothesis is that global land surface energy and water cycles cannot be skillfully represented and described without a comprehensive approach, which integrates the best observation based hydrometeorological products as data for forcing, constraining, and evaluating sophisticated LSMs. Our primary objectives are to incorporate mature data assimilation techniques, datasets, and other advancements into the LIS global land surface modeling and assimilation system, and to assess their impacts on the simulation of high resolution fields of land surface states and fluxes.

**Status**

*Systematic Simulations and Data Distribution*

We have completed four long term simulations, each of which was initialized on 1 January 1979 and continues to near present. Three of these were run on a 1° global grid (60°S to 90°N), with the Noah v.2.7.1, CLM2, and Mosaic land surface models (LSMs). The fourth simulation was run on a 0.25° resolution global grid with the Noah LSM. Output fields from all of these simulations have been made available through our anonymous FTP site. The output is currently being highlighted as a Featured GEWEX Data Product. At present, there are 50 known, distinct user groups. For simplicity, we continue to call the simulated results "GLDAS output" in this report.

*Snow Assimilation*

The Rodell and Houser (J. Hydromet., 2004) MODIS snow cover assimilation algorithm, which was originally designed for Mosaic, was modified and implemented in LIS/Noah v. 2.7.1. A simulation has been executed using this new option. It was initialized in 2001 from the long term Noah 0.25° simulation described above, and continues to present. Preliminary evaluation of the results has begun. The experiment is described in the latest issue of the CEOP Newsletter.

*Sensitivity Study*

In order to compare the impacts of the choice of LSM, land cover, soil, and elevation information, and precipitation and downward radiation forcing datasets on simulated evapotranspiration (ET), sensible heat flux (Qh), and top layer soil moisture (SM), a set of experiments was designed which made use of high quality, physically coherent, 1-year datasets from four CEOP reference sites. We describe the results in a manuscript submitted to the Journal of the Meteorological Society of Japan's special issue on CEOP. Rather than assessing sensitivity to a theoretical but unlikely range of inputs, our study focused on model responses to real differences in land properties and forcing from some of the best available global datasets, which is more relevant to the decisions that modelers face. The primary objectives of the study were to discover the relative importance of the input options and to determine whether observed values of

ET, Qh, and SM were within the range of outputs that could reasonably be expected from three state-of-the-art LSMs. As in previous studies, it was shown that the LSM itself is generally the most important factor governing output. Beyond that, evapotranspiration seems to be most sensitive to precipitation, land cover, and radiation (in that order); sensible heat flux is most sensitive to radiation, precipitation, and land cover; and soil moisture is most sensitive to precipitation, soil, and land cover. Various seasonal and model specific dependencies and other caveats exist. Output fields were also compared with observations in order to test whether the LSMs are capable of simulating an observed reality given a plausible set of inputs. In many cases, they are not. In general, that potential was fair for evapotranspiration, good for sensible heat flux but problematic given its strong sensitivity to the inputs, and poor for soil moisture. The results emphasize that improving the LSMs themselves through development of more sophisticated physical parameterizations, identification of oversimplifications which lead to large errors, and parameter optimization will be essential if we hope to model land surface water and energy processes accurately. Towards this goal, the effectiveness of improving model inputs alone is limited.

*Simulating Irrigation*

We performed a preliminary study of the impact of irrigation on modeled states and fluxes in the continental US. We collaborated with Dr. Mutlu Ozdogan, who is a post doctoral associate in NASA/GSFC's Hydrological Sciences Branch. Using maps of irrigated area derived from MODIS observations by Dr. Ozdogan, we applied irrigation in the LIS/Noah LSM based on crop water demands, which were estimated in a preprocessing step. The spatial resolution was 0.125° and the run spanned the year 2003. The applied irrigation totals were consistent with estimates from state and national agencies. It was shown that in parts of the US where irrigation is intensive, it significantly affects soil moisture, evapotranspiration, and sensible heat flux. Indirect effects include adjustment of daily maximum surface temperatures.

*Analysis of Output*

We have begun to assess and compare the output from the long term simulations described above. In particular, we are looking for trends in the output water storage fields. Because the GLDAS forcing sources change throughout the 27 years due to availability and the types of observations which contributed, it is important to determine whether anomalies and trends in the output are potentially real or simply artifacts of the forcing changes.

*GRACE Related Studies*

GLDAS output continues to be the primary hydrological data source for studies of the potential of the Gravity Recovery and Climate Experiment (GRACE) to measure changes in terrestrial water storage. At least 18 user groups in the GRACE community have downloaded GLDAS output. Among others, our group completed a study of the potential for estimating groundwater storage changes in the Mississippi River basin by subtracting GLDAS modeled soil moisture and snow water storage changes from GRACE derived total terrestrial water storage changes. That paper (currently available online) will appear in Hydrogeology Journal's special issue on remote sensing in March 2007.

**New Directions**

The early objectives of this project are to install capabilities in LIS which will allow us to integrate data from multiple sources in a physically meaningful way, and to continually generate new output datasets to support scientific studies – both our own and those of WESP and the larger hydrometeorological community. We have accomplished some of these objectives and have targeted others for the next year (section 7.4). Secondary objectives involve describing the individual and combined impacts of the new capabilities and the data in particular. Results of this research will set the course for future investigations of energy and water cycle functioning and change. Impacts will be judged using sensitivity analyses and error assessments, with an eye toward improving our understanding of the value of each data product, dataset compatibility, and the uncertainty in the assimilated fields that result.

As previously mentioned, the mechanisms for data integration will be parameterization, forcing, constraint (via data assimilation), and evaluation of multiple, sophisticated LSMs, including Noah, the Community Land Model, and the Variable Infiltration Capacity model, within the LIS framework. The assimilated output fields, impact assessments, and error analyses that result will support WESP related studies and hence provide the basis for improving understanding and skill at predicting energy and water cycle phenomena. Specific future objectives which may or may not be targeted in the next year include:

- Implementing mature assimilation schemes for assimilating Advanced Microwave Scanning Radiometer for EOS (AMSR-E) based soil moisture (e.g., Zhan et al., 2004) and snow water equivalent (e.g., Sun et al., 2004), and geostationary satellite infrared based surface temperature (e.g., Bosilovich et al., 2004; Radakovich et al., 2001);
- Incorporating root zone depth maps;
- Installing a runoff routing scheme;
- Simulating sub-grid precipitation variability;
- Enabling sub-grid lake modeling;
- Coupling a simple groundwater module;
- Producing multiple output datasets and using these to characterize regional, seasonal to interannual variability in the stocks and fluxes of the water and energy cycles.

**Future: Next Year**

*Improvements to MODIS Snow Cover Assimilation Algorithm*
The architecture of LIS is being redesigned to make the data assimilation routines more generic (for multiple models), modular, and efficient, and the MODIS snow cover assimilation algorithm must be adapted to it. Thus our first sub-objective is to modify the current algorithm so that the various components are separated into a set of subroutines dictated by the new LIS architecture. Ultimately this exercise will simplify implementation of snow cover assimilation with multiple LSMs.

Following that redesign and testing, we intend to assess a more sophisticated snow cover assimilation algorithm. New techniques will minimize the impact of assimilation on the water budget while producing output that is more consistent among variables and in time.

*Precipitation Forcing Alternatives*
We will install, as necessary, and test several precipitation forcing alternatives. These will include global products from NASA/GSFC, GPCP, and PERSIANN. We will also assess the value of overlaying various precipitation products, for example, Stage 4 Doppler based precipitation from the NLDAS project, over the GSFC "3B42" 0.25° 50°N-50°S satellite and gauge based product, over the GLDAS spatially and temporally disaggregated CMAP forcing.

*Land Cover and Irrigation Improvements and Testing*
We are now extending the irrigation study described above. The first step is to merge a global 5 arc minute resolution database of 17 crop types with the current LIS land cover dataset (13 classes and water), which was derived by the University of Maryland (UMD) based on AVHRR observations. The UMD dataset includes only a single "crop" land cover class, so the new land cover map will have 29 classes. We will then test the effect of the new land cover dataset. Next, we will incorporate the approach for computing demand based irrigation amounts into LIS (this was a preprocessing step in the original experiment), and repeat our test of this simple approach. If the results are positive, we will attempt to implement the algorithm globally and for at least three (Noah, CLM, and Mosaic/VIC) of the LIS LSMs. Furthermore, Drs. Ozdogan and Rodell have submitted a proposal to NOAA's CPPA program to design and assess more sophisticated approaches for applying irrigation in LIS LSMs. These approaches would incorporate additional information about the timing, rates, methods, and efficiencies of irrigation in different agricultural regions around the world.

*Other Objectives*

It is likely that we will also begin installing and testing one or more of the following previously mentioned capabilities in LIS during the next year: surface temperature assimilation; AMSR derived snow water equivalent assimilation; sub-grid lake modeling; runoff routing; sub-grid precipitation downscaling; linked groundwater storage simulation.

**Key Results**

- Global land surface state and flux fields have been simulated by three LSMs driven by GLDAS for 1979-present, at 1° and 0.25° resolutions, and are publicly available.
- A 2001-present, 0.25° global simulation of GLDAS/Noah which includes assimilation of MODIS snow cover is also complete and available.
- A model sensitivity study was completed, driven by CEOP reference site data, which demonstrated (1) the choice of LSM itself (physics and tuning) is the dominant influence on output states and fluxes, over choices of forcing or input land surface characteristics datasets; (2) in many cases, the range of an output state and flux which can possibly be simulated given a reasonable set of input data choices does not encompass observed values of that state or flux.
- Preliminary experiments in which satellite based irrigation maps were incorporated into a GLDAS/Noah showed that irrigation significantly influences the simulated water and energy budgets.
- GLDAS supports many GRACE related studies, and has been shown to be useful for separating changes in groundwater storage from soil moisture and snow variations.

**Issues and Recommendations**

**Contributions to WCRP Strategic Framework**

Results of WESP/GLDAS have obvious implications for WCRP strategic objectives. In particular, we are synthesizing data from multiple observation systems, both ground and satellite based, using advanced land surface modeling and data assimilation techniques. The resulting fields are high resolution, global, physically consistent, and spatiotemporally continuous. Furthermore they cover the entire Earth observing satellite era, 1979-present, approaching climatic timescales. Hence they are valuable for regional to global scale studies of the water and energy cycles and climate.

**Contributions to Society and to WCRP/GEWEX Visibility**

GLDAS output supports investigations of water and energy cycle variability around the world. It has also been used for initializing short term and seasonal weather forecast models, water resources applications, and military mobility assessments. There are currently 50 known groups who use GLDAS output and certainly many more. The LDAS website (http://ldas.gsfc.nasa.gov/) gets about 5,500 non-GSFC hits per year. GLDAS output was recently selected as the Featured GEWEX Data Product.

**List of Key Publications**

Kato, H., M. Rodell, F. Beyrich, H. Cleugh, E. van Gorsel, H. Liu, and T. P. Meyers, Sensitivity of Land Surface Simulations to Model Physics, Parameters, and Forcings, at Four CEOP Sites, J. Meteor. Soc. Japan, in review, 2006.

Rodell, M., and H. Kato, GLDAS output supports CEOP studies, CEOP Newsletter, 10, 2006.

Rodell, M., J. Chen, H. Kato, J. Famiglietti, J. Nigro, and C. Wilson, Estimating ground water storage changes in the Mississippi River basin (USA) using GRACE, Hydrogeology Journal, doi:10.1007/s10040-006-0103-7, 2006.

de Goncalves, L. G. G., W. J. Shuttleworth, E. L. Burke, P. Houser, D. Toll, M. Rodell, and K. Arsenault, Toward a South America Land Data Assimilation System: Aspects of land surface model spin-up using the Simplified Simple Biosphere, J. Geophys. Res., 111, D17110, doi:10.1029/2005JD006297, 2006.

de Goncalves, L. G. G., W. J. Shuttleworth, S. C. Chou, Y. Xue, P. R. Houser, D. L. Toll, J. Marengo, and M. Rodell, Impact of different initial soil moisture fields on Eta model weather forecasts for South America, J. Geophys. Res., 111, D17102, doi:10.1029/2005JD006309, 2006.

Rodell, M., P. R. Houser, A. A. Berg, and J. S. Famiglietti, Evaluation of ten methods for initializing a land surface model, J. Hydromet., 6 (2), 146-155, 2005.

Gottschalck, J., J. Meng, M. Rodell, and P. Houser, Analysis of multiple precipitation products and preliminary assessment of their impact on Global Land Data Assimilation System (GLDAS) land surface states, J. Hydromet., 6 (5), 573-598, 2005.

Rodell, M., J. S. Famiglietti, J. Chen, S. Seneviratne, P. Viterbo, S. Holl, and C. R. Wilson, Basin scale estimates of evapotranspiration using GRACE and other observations, Geophys. Res. Lett., 31, L20504, doi:10.1029/2004GL020873, 2004.

Rodell, M., and P. R. Houser, Updating a land surface model with MODIS derived snow cover, J. Hydromet., 5 (6), 1064-1075, 2004.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll, The Global Land Data Assimilation System, Bull. Amer. Meteor. Soc., 85 (3), 381–394, 2004.

Koster, R. D., M. J. Suarez, P. Liu, U. Jambor, M. Kistler, A. Berg, R. Reichle, M. Rodell, and J. Famiglietti, Realistic initialization of land surface states: impacts on subseasonal forecast skill, J. Hydromet., 5 (6), 1049-1063, 2004.

**List of Meetings, Workshops**

- 1st Annual NASA Energy and Water Cycle Study (NEWS) PI Meeting
- GRACE Science Team Meeting
- U.S. Climate Change Science Program Workshop: Climate Science in Support of Decision Making
- American Geophysical Union Fall Meeting 2005, multiple papers from WESP/GLDAS
- American Meteorological Society Annual Meeting 2006, multiple papers
- 5th International Implementation Planning Meeting for the Coordinated Enhanced Observing Period (CEOP) and 2nd Integrated Global Observing Strategy Partners (IGOS-P) Integrated Global Water Cycle Observation Theme (IGWCO) Workshop
- American Geophysical Union Spring Meeting 2006, multiple papers
- NASA/NOAA Joint Center for Satellite Data Assimilation

**Planned Meetings, Workshops**

- 2nd Annual NASA Energy and Water Cycle Study (NEWS) PI Meeting
- 1st Pan-GEWEX Meeting
- American Geophysical Union Fall Meeting 2006, multiple papers from WESP/GLDAS
- American Meteorological Society Annual Meeting 2007, multiple papers

**Summary**

The goal of the Global Land Data Assimilation System (GLDAS) is to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states and fluxes. The software, which has been streamlined and parallelized by the Land Information System (LIS) sister project, drives multiple, offline (not coupled to the atmosphere) land surface models, integrates a huge quantity of observation based data, executes globally at high resolutions (2.5° to 1 km), and is capable of producing results in near-real time. Data assimilation techniques for incorporating satellite based hydrological products, including snow cover and water equivalent, soil moisture, surface temperature, and leaf area index, are now being implemented as part of a follow-on project funded by the NASA Energy and Water Cycle Study (NEWS)

Initiative. The high-quality, global land surface fields provided by GLDAS support several current and proposed weather and climate prediction, water resources applications, and water cycle investigations. The project has resulted in a massive archive of modeled and observed, global, surface meteorological data, parameter maps, and output which includes 1° and 0.25° resolution 1979-present simulations of the Noah, CLM, and Mosaic land surface models.

**List of members and their term dates (including changes where appropriate):**

- Matt Rodell, NASA/GSFC
- John Roads, Scripps
- Christa Peters-Lidard, NASA/GSFC
- Hiroko Kato, U. Maryland ESSIC and NASA/GSFC
- Ben Zaitchik, U. Maryland ESSIC and NASA/GSFC
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- Sujay Kumar, U. Maryland Baltimore County GEST and NASA/GSFC
- Paul Houser, Center for Research on Environment and Water
- Brian Cosgrove, SAIC and NASA/GSFC
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