Estimating Evapotranspiration with Land Data Assimilation Systems

C. D. Peters-Lidard*1, S. V. Kumar2,1, D. M. Mocko2,1, and Y. Tian3,1

1*NASA, Goddard Space Flight Center, Hydrological Sciences Branch, Code 614.3, Greenbelt, MD
2Science Applications International Corporation, Beltsville, MD
3Earth System Science Interdisciplinary Center, College Park, MD.

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* Corresponding Author: Dr. Christa D. Peters-Lidard, NASA/Goddard Space Flight Center, Hydrological Sciences Branch, Code 614.3, Greenbelt, MD 20771 Phone: 301-614-5811; Fax: 301-614-5808; E-mail: christa.peters@nasa.gov; URL: http://lis.gsfc.nasa.gov.
Abstract
Advancements in both land surface models (LSM) and land surface data assimilation, especially over the last decade, have substantially advanced the ability of land data assimilation systems (LDAS) to estimate evapotranspiration (ET). This article provides a historical perspective on international LSM intercomparison efforts and the development of LDAS systems, both of which have improved LSM ET skill. In addition, an assessment of ET estimates for current LDAS systems is provided along with current research that demonstrates improvement in LSM ET estimates due to assimilating satellite-based soil moisture products. Using the Ensemble Kalman Filter in the Land Information System, we assimilate both NASA and Land Parameter Retrieval Model (LPRM) soil moisture products into the Noah LSM Version 3.2 with the North American LDAS phase 2 (NLDAS-2) forcing to mimic the NLDAS-2 configuration. Through comparisons with two global reference ET products, one based on interpolated flux tower data and one from a new satellite ET algorithm, over the NLDAS2 domain, we demonstrate improvement in ET estimates only when assimilating the LPRM soil moisture product.

Keywords
Land surface modeling, land data assimilation systems, evapotranspiration, soil moisture assimilation
INTRODUCTION

Land surface models predict terrestrial water, energy, momentum, and in some cases, biogeochemical exchange processes by solving the governing equations of the soil-vegetation-snowpack medium based on atmospheric boundary conditions including precipitation, radiation, wind, temperature, humidity and pressure. By constraining land surface models with observed atmospheric boundary conditions and land surface states, land surface data assimilation improves our ability to understand and predict terrestrial water and energy fluxes and states, including evapotranspiration. The ability to predict evapotranspiration is critical for applications in weather and climate prediction, agricultural forecasting, water resources management, and hazard mitigation (e.g., NRC, 2010; 2011). Until recently, global or continental land surface modeling at horizontal scales of 1 km or finer was infeasible due to limits in computational and observational resources.

Land Data Assimilation Systems (LDAS, Figure 1), are typically run “uncoupled” (or “offline”) to estimate water and energy fluxes and states using observationally-based precipitation, radiation and meteorological inputs. However, they may also be run “coupled” to an atmospheric model for weather forecasts.

This paper reviews current and developing capabilities for estimating evapotranspiration (ET) using land surface models (LSMs) as part of an LDAS. First, we present a survey of land surface modeling for ET estimation, including recent intercomparison studies and LDAS efforts. Next, we compare LSM ET estimates from current LDAS systems to global gridded tower-based and remote sensing-based flux estimates. Finally, we present the results from simulations that
employ data assimilation (DA) of remotely sensed soil moisture measurements to improve LSM ET estimates.

**BACKGROUND**

The ability of LSMs or soil-vegetation-atmosphere transfer schemes (SVATS) to predict evapotranspiration has advanced significantly since the original bucket (Manabe, 1969), Simple Biosphere (SiB; Sellers et al., 1986) and Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al., 1986) models pioneered at the National Oceanic and Atmospheric Administration’s Geophysical Fluid Dynamics Laboratory (NOAA/GFDL), National Aeronautics and Space Administration’s Goddard Space Flight Center (NASA/GSFC) and the National Center for Atmospheric Research (NCAR), respectively. Numerous advancements in second-generation LSMs have brought additional focus to snow physics and hydrology, such as the community Noah (Ek et al., 2003; Barlage et al., 2010; Livneh et al., 2010) and the Variable Infiltration Capacity (VIC; Liang et al., 1996; Bowling and Lettenmaier, 2010). So-called “third generation” LSMs include dynamic phenology and carbon stores, such as the Community Land Model (CLM; Bonan et al., 2002; Lawrence et al., 2011). To a large extent, this advancement has come as the result of three key community activities: first, the Global Land Atmosphere System Study (GLASS) intercomparison studies, second, the North American and Global LDAS projects, and third, the recent LandFlux initiatives. Below, we provide background on these efforts, including their major findings related to evapotranspiration estimation from LSMs.

**GLASS Intercomparison Studies: PILPS, Rhone-AGG, and GSWP**

The international GLASS panel, as part of the Global Energy and Water Cycle Experiment (GEWEX), has spearheaded three major intercomparison projects designed to evaluate the skill
of land surface models for predicting water and energy fluxes and states. The first was the Project to Intercompare Land-Surface Parameterization Schemes (PILPS; Henderson-Sellers et al., 1995; Pitman and Henderson-Sellers 1998). This project focused on a series of evaluations conducted in phases using specified atmospheric boundary conditions and parameters at points or regions. One of the key findings in this project is the documentation of the systematic improvements in LSIs from first-generation (bucket) to second-generation (e.g., SiB, BATS, Noah, VIC) through third generation (e.g., CLM). Another major finding from PILPS is the synthesis work by Koster and Milly (1997), in which it was shown that the interplay between the evaporation and runoff formulations in any LSM, could be expressed via two model-independent quantities: 1) the soil-depth-integrated evaporation sink efficiency and 2) the runoff-generation fraction over this integrated evaporation sink. A third major finding was that hydrologically-oriented models such as VIC were shown to be more skillful for continental scale water budgets.

The second major GLASS intercomparison projects, which represented a global-scale follow-on to PILPS, were the Global Soil Wetness Projects (GSWPs, Dirmeyer, 2011). GSWP-1 (Dirmeyer et. al, 1999) focused on the International Satellite Land-Surface Climatology Project (ISLSCP) Initiative I forcing data for the period 1987-88, and produced the first ever global, offline, multimodel land analysis based on “best possible” meteorological forcings. In addition, GSWP-1 served as a pathfinder for the NLDAS and GLDAS efforts described below. GSWP-2 (Dirmeyer et al., 2006) built on the foundation of GSWP-1, and produced 1 degree global multi-model fluxes and states for the ISLSCP II period from 1986-95 and showed that, in the absence of robust in-situ and/or remotely sensed soil moisture to provide constraints, the best estimate of soil wetness from multiple model products is a simple average. In addition to this finding,
GSWP-2 also derived multi-model soil wetness values normalized to the LSM dynamic range controlling the ET-runoff interplay, as described above in the PILPS analyses by Koster and Milly (1997). With respect to ET, GSWP-2 showed that ET has the smallest interannual variability of any water budget variable, and that global average transpiration is about one-third larger than direct evaporation from the soil. For the GSWP-2 period, latent heat flux exceeded sensible heat flux by about 20%, although that may reflect an absence of soil moisture limitations in later periods as observed by Jung et al. (2010) and discussed further below.

The third major intercomparison project, which occurred between GSWP-1 and GSWP-2, is known as Rhone-AGG (Boone et al., 2004). Rhone-AGG significantly advanced the community’s ability to observationally diagnose deficiencies in LSM hydrological cycles by looking at spatial scaling of water and energy balance processes finer than GSWP (8km vs. 1°), particularly the interplay of high-elevation snow accumulation/melt and lower-elevation streamflow. Techniques for evaluating and diagnosing physical processes with simulated hydrographs helped advance LSM’s ability to simulate the daily hydrological cycles at multiple scales, most notably by implementing subgrid runoff formulations and elevation-based tiling for snow pack modeling. Rhone-AGG and GSWP-2 occurred in parallel with and greatly benefitted the development of NLDAS and GLDAS, as described in the following sections.

The North American Land Data Assimilation System

The primary goal of the North American Land Data Assimilation System (NLDAS; Mitchell et al., 2004; http://ldas.gsfc.nasa.gov/nldas/; http://www.emc.ncep.noaa.gov/mmb/nldas/) is to construct quality-controlled, and spatially- and temporally-consistent, land-surface model (LSM) datasets from the best available observations and model outputs. NLDAS is a collaboration project among several groups: NOAA/NCEP's Environmental Modeling Center (EMC), NASA's...
Goddard Space Flight Center (GSFC), Princeton University, the University of Washington, the NOAA/NWS Office of Hydrological Development (OHD), and the NOAA/NCEP Climate Prediction Center (CPC). The NLDAS project produces a LSM forcing dataset from a daily gauge-based precipitation analysis (temporally disaggregated using hourly radar data, satellite estimates, or other sources), bias-corrected shortwave radiation, and surface meteorology reanalyses. This forcing is used to drive four separate LSMs to generate hourly model outputs of surface fluxes, soil moisture, snow cover, and runoff. The current operational version of NLDAS uses the following LSMs: Noah – from NOAA/NCEP, Mosaic – from GSFC, VIC – from Princeton University, and SAC – from NOAA/OHD. Datasets and simulations from NLDAS Phase 2 (NLDAS-2) extend back to January 1979 and continue to be produced in near real-time on a 1/8th-degree grid over central North America (from 25 to 53N and 125 to 67W). NLDAS individual and ensemble-mean LSMs are also used for drought monitoring and as part of an experimental drought forecast system. The ensemble-mean on the drought monitor is a simple type of a multi-model analysis of LSMs, which have been shown to improve the depiction of simulated states in many ways (e.g., Guo et al., 2007, for GSWP-2 datasets). NLDAS data products are distributed at EMC as well as at the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC; http://disc.gsfc.nasa.gov/hydrology/).

The first incarnation of the project, Phase 1 (NLDAS-1), comprised data since October 1996 and consisted of a somewhat-similar yet different LSM forcing dataset (Cosgrove et al., 2003). Earlier versions of the same four LSMs (Noah, SAC, VIC, and Mosaic) were used in NLDAS-1 as well. NLDAS-1 datasets were extensively evaluated and validated against available observations in numerous studies, including examinations of the forcing (Luo et al., 2003) and of
the LSM output (Robock et al., 2003). Robock et al. evaluated the LSM-simulated soil
moistures and temperatures against observations from the Oklahoma Mesonet, and also
evaluated surface latent, sensible, and ground fluxes using ARM/CART stations. They found
that the Noah LSM was closest to the observations of the latent heat flux in this region over a
two-year period. Lohmann et al. (2003) intercompared water balance and streamflow between
the LSMs and found regional differences up to a factor of 4 in the simulated mean annual runoff
and up to a factor of 2 in the mean annual evapotranspiration, with monthly differences even
greater. Other land parameters evaluated from NLDAS-1 included soil moisture (Schaake et al.,
2004), snow cover extent (Sheffield et al., 2003), and snow water equivalent (Pan et al., 2003).
Many of these studies from NLDAS-1 also tested the effects of LSM physics and parameter
changes on the evaluation results.

The NLDAS-2 forcing dataset corrects the daily gauge precipitation analysis using a PRISM
(Parameter-elevation Regressions on Independent Slopes; Daly et al., 1994) method which
considers the topographic effect on precipitation. The precipitation is temporally disaggregated
to hourly, primarily using Stage II radar data. In locations/times when the radar data is not
available, satellite retrievals, a coarser-scale hourly gauge analysis, or reanalysis data is used.
The non-precipitation land-surface forcing fields for NLDAS-2 are derived from the analysis
fields of the NCEP North American Regional Reanalysis (NARR, Mesinger et al., 2006).
Surface pressure, surface downward longwave radiation, and near-surface temperature and
humidity fields are vertically adjusted to the terrain on the NLDAS grid. The surface downward
shortwave radiation is bias-corrected using GOES satellite observations. NLDAS-2 also
contains numerous improvements to the equations of the LSMs as well as their calibration. The
snow physics in the Noah LSM was upgraded (Livneh et al., 2010), VIC model parameters were calibrated using streamflow observations (Troy et al., 2008), SAC used an updated potential evaporation dataset (Xia et al., 2011b), and Mosaic used updated model parameters (for details, see Robock et al., 2003). Xia et al. (2011a) analyzed water and energy fluxes in the upgraded NLDAS-2 LSMs, including their ensemble-mean and model spread. In a separate study, Xia et al. (2011c) examined the spatial distribution of the correlation between monthly-mean precipitation and evapotranspiration (ET) the four LSMs; they found that the two soil vegetation atmosphere transfer (SVAT) LSMs (Noah and Mosaic) had a stronger correlation, while the two hydrological LSMs (VIC and SAC) had a stronger correlation between the precipitation and runoff. Wei et al. (2011) evaluated improvements of the Noah LSM related to warm season simulation in NLDAS by adding a seasonally- and spatially-varying LAI as well as modifications to Noah’s treatment of the vertical profile of root density, the minimum stomatal resistance parameters, the diurnal variation of surface albedo, the roughness length for heat, and the vapor-pressure and soil moisture deficit terms. This study compared the NLDAS-2 version of Noah to ARM/CART latent heat flux observations and found reduced biases, which also helped improve the simulation of the mean annual water balance. Mo et al. (2011) compared ET from three NLDAS-2 LSMs against Ameriflux observations and found that Noah and VIC tended to exhibit low ET biases in the winter, with slight high ET biases in the summer, despite no apparent biases in NLDAS-2 net radiation. Mosaic generally had higher ET than the observations as well as from Noah and VIC, with a three-member ensemble-mean performing the best, consistent with the findings of GSWP discussed in the previous section. Kovalskyy et al. (2011) estimated evapotranspiration using a scheme that combines a water balance model with an event-driven phenology model, driven with NLDAS-2 forcing; they compared these
estimates against ET from the MODerate Resolution Imaging Spectroradiometer (MODIS) instrument (Mu et al., 2007) as well as from the NLDAS-2 Mosaic LSM, and showed better agreement to the MODIS-derived ET at the 5-km scale of the study.

The Global Land Data Assimilation System

The Global Land Data Assimilation System (GLDAS) led at NASA/GSFC (Rodell et al., 2004a) also uses satellite- and ground-based observations to construct a forcing dataset to drive four LSMs. The four LSMs in GLDAS are Noah, Mosaic, VIC, and CLM, and GLDAS data extends globally from January 1979 at both 1.0-degrees (all LSMs) and 0.25-degrees (Noah only). In addition to extending an NLDAS-style framework to the global scale, GLDAS was one of the first LDASs to routinely assimilate satellite-based surface states to improve simulated water and energy fluxes and states. GLDAS has included data assimilation of MODIS snow cover to constrain the modeled SWE (after Rodell and Houser, 2004), and has also studied the effects of assimilating remotely-sensed skin temperatures and soil moistures. While considering ET produced by GLDAS, Rodell et al. (2004b) compared basin-scale estimates of evapotranspiration produced by GLDAS/Noah and other models against a water balance approach using the Gravity Recovery And Climate Experiment (GRACE) satellites, and found that the GRACE estimates were generally within the range of the model results, and the biases were consistent and the uncertainty on the same order as GRACE. Kato et al. (2007) examined the choice of LSM, land cover, soils, elevation, and forcings using GLDAS on the simulated latent and sensible heat fluxes and soil moisture compared to CEOP in situ observations. They found that the LSM choice had the biggest effect on the simulated output (including ET), and that ET was most sensitive first to precipitation, then land cover, and then radiation. Syed et al. (2008) compared variations in terrestrial water storage from GRACE compared to GLDAS
simulations and found that ET was most effective in dissipating terrestrial water storage in the mid-latitudes. Despite all these detailed studies, however, none have directly evaluated both GLDAS and NLDAS using observations over CONUS. One study that did compare early versions of both systems (Jambor et al., 2002) demonstrated the benefit of satellite-based precipitation used in conjunction with model precipitation in GLDAS while using the gauge-based precipitation in NLDAS as the evaluation dataset. Overall, GLDAS’s advancements in land data assimilation and GRACE-based ET estimation significantly advanced the ability of LSMs to estimate ET, subject to observational constraints.

The LandFlux Initiative and Reference ET Products

The LandFlux initiative has been coordinated by the GEWEX Radiation Panel to develop and evaluate consistent and high-quality global ET datasets for climate studies. Recently developed capabilities for global ET estimation using LSMs (as discussed above) as well as techniques for synthesizing satellite data, flux tower data, and atmospheric reanalyses provide the opportunity to produce global ET products using different approaches. The LandFlux-EVAL project (Mueller et al., 2011; Jiménez et al., 2011) is currently evaluating multiple global ET products produced using four different categories of techniques: 1) Observations-based diagnostic datasets; 2) observationally-driven “offline” LSM products (e.g., GSWP, GLDAS); 3) atmospheric reanalyses; and 4) IPCC AR4 simulations from 11 GCMs. In Mueller et al., 41 global land ET datasets were evaluated along with IPCC AR4 GCM simulations for the 1989–1995 time period. An interesting finding of a cluster analysis conducted as part of this study is that the GLDAS-Noah and CLM products were closely related to two different reference ET products, including the Jung et al., 2009 product described further below.
Jiménez et al. (2011) evaluated 12 monthly mean land surface ET and other flux products for the period 1993–1995 and found that the 12-product global annual mean latent heat flux (Qle) was approximately 45 Wm$^{-2}$ with a spread of approximately 20 Wm$^{-2}$. Similar spreads were found for sensible (Qh) and net radiative (Rn) fluxes, with larger spreads for tropical rainforest year-round and grassland or crop in the dry season. Analysis for large river basins indicated large spreads for the Danube, Congo, Volga, and Nile basins, with smaller spreads for other basins, including the Mississippi.

One of the key reference datasets for the LandFlux-EVAL effort, also used as one of the reference datasets in our LDAS analysis described in subsequent sections, is the Max Planck Institute (MPI) flux dataset from Jung et al., (2009), which was created by synthesizing FLUXNET (Baldocchi et al., 2001) tower data with meteorological forcings and vegetation information from interpolated station and satellite data to produce a global, monthly, 1/2 degree resolution estimate of land ET from 1982 to 2008. Jung et al. (2010) found that global annual ET has been increasing by approximately 7 mm per year per decade during the period 1982-1997, with moisture limitation eliminating this trend during the period 1998-2008. Another ET product used as a reference dataset in this study is the global 1km ET estimates based on MODIS satellite data (Mu et al., 2011). In this dataset, ET estimates are derived using Mu et al. (2011)’s algorithm, which is improved relative to the previous Mu et al. (2007) work. The ET algorithm is primarily based on the Penman-Monteith equation and considers the surface energy partitioning and environmental constraints to derive ET. In this study, we employ the monthly averaged MOD16 ET datasets.
Although the LandFlux-EVAL effort has compared model-based GLDAS and GSWP flux estimates to observationally-based MOD16 and MPI reference flux estimates, a key question not previously addressed by LandFlux-EVAL is the extent to which assimilating observed soil moisture can reduce the differences between the model-based and observationally-based flux estimates. Addressing this question is one of the primary motivations of the current work.

EXPERIMENTAL SETUP
To illustrate the current capability of the current LDAS systems to simulate evapotranspiration at continental scales, we compare estimates from GLDAS, and two NLDAS-equivalent simulations over the NLDAS-domain with two reference datasets: (1) the gridded FLUXNET dataset from Jung et al. (2009) and (2) the MOD16 dataset developed by Mu et al. (2011). Further, we also present estimates from the NLDAS-equivalent simulations that employ the assimilation of satellite surface soil moisture retrievals. Because the NLDAS uses only a single version of the Noah LSM, we chose to produce our NLDAS-equivalent products using the Land Information System (LIS; Kumar et al., 2006, Peters-Lidard et al., 2007) with Noah versions 2.7.1 and 3.2 so that we can examine the impacts of recent physics changes in Noah on ET estimation. The experiments employ the same domain configuration used in the NLDAS project (from 25-53°N and 125-67°W at 1/8°-degree resolution) and are designed in a manner as similar as possible to the NLDAS-2 Noah model simulations. While the forcings and NLDAS-equivalent simulations are at a 1/8 degree horizontal resolution, we average the outputs to ½ degree resolution prior to comparisons with the FLUXNET and MOD16 datasets. The GLDAS Noah datasets are similarly averaged from ¼-degree to the ½ degree resolution. The forcing for the NLDAS-equivalent runs is the NLDAS-2 described above. The simulations are run with a 15
minute timestep, and the models are spun up by running from 1979 to 1985 and then reinitializing the model from 1979 to generate outputs from 1979-2010.

In the data assimilation integrations, we employ surface soil moisture data derived from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) sensor aboard the Aqua satellite. Two different AMSR-E retrieval products are employed in the data assimilation simulations; (1) the NASA Level-3, “AE_Land3” product (version 6, Njoku et al., 2003) and (2) AMSR-E Land Parameter Retrieval Model (LPRM) product developed at NASA GSFC and VU Amsterdam (Owe et al., 2008). The NASA product is primarily based on X-band brightness temperatures, whereas both X-band and C-band brightness temperature-based retrievals are used in the LPRM product. Measurements from both ascending and descending overpasses are used in these products. A number of quality control measures are applied to the soil moisture retrievals prior to data assimilation, similar to the approaches followed in Reichle et al. (2007) and Liu et al. (2011). In the soil moisture products, retrievals flagged for dense vegetation, precipitation, snow cover, frozen ground, and Radio Frequency Interference (RFI) are excluded in the assimilation system. Further, additional quality control is applied based on the information from the land surface model, where the retrievals are excluded when the land surface model indicated active precipitation, non-zero snow cover, frozen soil or dense vegetation (when green vegetation fraction > 0.7).

The assimilation integrations employ a one-dimensional Ensemble Kalman Filter (EnKF) algorithm, which is a widely used technique for soil moisture data assimilation (Reichle et al., 2002, Crow and Wood, 2003, Reichle et al., 2007, Kumar et al., 2008, Kumar et al., 2009). An
ensemble size of 12 is used in these simulations (Kumar et al., 2008), with perturbations applied to both the meteorological fields and model prognostic fields to simulate uncertainty in the soil moisture fields. The parameters used for these perturbations are listed in Table 1, which are based on earlier data assimilation studies (Kumar et al., 2009). As algorithms such as EnKF are designed to correct random, zero-mean errors and assume the use of unbiased observations relative to the model generated background, it is often a common practice to scale the observations prior to data assimilation to match the model’s climatology (Reichle and Koster, 2004, Drusch et al., 2005, Reichle et al., 2007, Kumar et al., 2009). Here we employ the Cumulative Distribution Function (CDF)-scaling approach of Reichle and Koster (2004), where the observations (roughly corresponding to a maximum depth of 2cm) are rescaled to the model’s 10cm surface soil moisture climatology by matching the CDF of the observations to the CDF of the model soil moisture. The model CDF and observation CDF are computed using 7 years of data (2002-2008), separately for each grid point.

As the soil moisture retrievals are available only from 2002 onwards, the NLDAS-equivalent simulations with data assimilation are conducted during the period of 2002-2008. During this period, we update not only the surface (10cm) soil moisture in Noah, but also the layer 2 through layer 4 soil moisture, following the parameters in Table 1. The comparisons presented in next section are limited to the data assimilation period (2002-2008).

**CURRENT RESEARCH FINDINGS AND FUTURE WORK**

The results presented in this section focus first on the evaluation of the LDAS ET estimates that do not employ data assimilation. This is followed by the description of the impact of soil moisture data assimilation on ET estimation.
Table 2 presents the domain-averaged root mean square and bias errors and the associated 95% confidence intervals, for latent (Qle) and sensible (Qh) heat flux estimates from the three LDAS simulations compared against the gridded FLUXNET and MOD16 datasets. This table also shows results from the data assimilation experiments to be discussed in the next section. Overall, the NLDAS-like simulation using the Noah 2.7.1 model provides better estimates of Qle (RMSE of 19.3 Wm\(^{-2}\) against FLUXNET and 21.5 Wm\(^{-2}\) against MOD16) relative to other products. Average seasonal cycles of these error metrics stratified monthly are presented in Figure 2. In both sets of comparisons, the largest differences between the LDAS simulations are observed during the spring and fall months, with NLDAS-like simulations with Noah 2.7.1 providing the better estimates. Qle estimates from GLDAS show underestimation in the late summer and fall months and an overestimation in the spring and early summer months, relative to both reference datasets. Comparatively, NLDAS-like integration with Noah 2.7.1 indicates lower biases most months, but the biases are consistently positive. Though Noah 3.2 is a newer version of the Noah model, the flux estimates appear to be degraded overall relative to Noah 2.7.1, with the comparison against FLUXNET data indicating more severe degradations relative to the MOD16. This may reflect uncertainty in the reference flux datasets during the springtime, in particular. During the fall months, bias estimates in Noah 3.2 are improved relative to Noah 2.7.1 (in the comparisons against FLUXNET), but during spring and summer months, biases in Noah 3.2 ET increase compared to that of Noah 2.7.1. It can be noted that these trends in RMSE and bias errors are highly statistically significant, as indicated by the 95% confidence interval values given for each error estimate. Note that any spatial auto-correlation of RMSE and Bias values across the domain is ignored in computing these confidence intervals. The tight intervals
reported in Table 2 are likely to increase if allowances for spatial autocorrelation of errors are included in the confidence interval computations. The trend of increased flux error estimates in Noah 3.2 relative to Noah 2.7.1 is likely a result of the changes in model parameters (such as LAI) along with other changes to Noah’s warm season physics as described in Wei et al. (2011).

As discussed in the Background section, Wei et al. (2011) showed improvement of these physics changes when compared to ARM/CART flux datasets, whereas our analysis uses gridded data (FLUXNET and MOD16) over the entire NLDAS domain, including many different vegetation types and climate regimes. Other studies (also presented in the Background section) showed Noah 3.2’s improved simulation of streamflow, snow, and other hydrologic variables relative to Noah 2.7.1.

Figure 3 provides an intercomparison of the seasonally-averaged Qle computed using estimates from three consecutive months (DJF represents December-January-February, MAM represents March-April-May, JJA represents June-July-August and SON represents September-October-November) from the three LDAS integrations and the two reference datasets, the gridded FLUXNET and MOD16 product. Relative to FLUXNET, all three LDAS datasets show higher ET in the spring MAM months in the Southeast and Lower Mississippi River Basin. During JJA, however, GLDAS compares much better than the NLDAS-like Noah simulations. Interestingly, the Noah 2.7.1 and Noah 3.2 results for JJA are generally similar except over highly vegetated crop regions in the upper Midwest and the irrigated growing areas along the Mississippi River. Neither reference dataset seems to reflect irrigated areas (see, for example Table 4 in Mu et al., 2011), and the differences in Noah2.7.1 and Noah3.2 do not include irrigation effects, so these differences for crops are likely due to changes in the aerodynamic
conductance formulation in Noah, implemented primarily for improved snowmelt modeling. Here, the Noah 3.2 JJA Qle is much higher, indicating that the parameter values used for the vegetation type(s) in these regions may need refinement. A closer look during MAM also shows this same pattern with higher Qle in Noah 3.2 relative to Noah 2.7.1. It can be noted that except MOD16, all other datasets show an artifact of lower Qle in California and West Coast regions. Interestingly, the higher Qle areas for MOD16 do not seem to correspond to known irrigated areas. During the fall SON months, the Qle from GLDAS is low compared to FLUXNET, particularly over the Upper Plains and Southeast; the Noah simulations show a pattern overall much closer to FLUXNET, but with too high Qle magnitudes right along the Gulf Coast. MOD16, on the other hand, indicates lower Qle over the High plains consistent with GLDAS, and higher Qle over the Southeast, consistent with the NLDAS-based estimates.

**Impact of soil moisture data assimilation on ET estimates**

Figure 4 provides a comparison of the average seasonal cycles of RMSE and Bias in Qle estimates (again, relative to the two reference datasets) from the NLDAS-like simulation without any data assimilation (termed as the "open loop" (OL) simulation) and the two integrations that employ the assimilation of surface soil moisture retrievals from NASA and LPRM products (NASA-DA and LPRM-DA, respectively). In this comparison, all three model integrations employ Noah 3.2. It can first be observed that the assimilation of soil moisture retrievals impact the Qle estimates, primarily during the summer and fall months. The Qle estimates from the open loop simulation are systematically improved by the assimilation of LPRM soil moisture retrievals, whereas the assimilation of NASA retrievals shows degradation. Compared to FLUXNET, the domain averaged RMSE of the open loop integration is 27.6 Wm$^{-2}$ and it increases to 29.4 Wm$^{-2}$ in the NASA-DA integration (Table 2). The improvements shown in
Figure 4 from LPRM-DA translates to a domain averaged RMSE of 25.6 Wm\(^{-2}\) when compared to FLUXNET. The trends in RMSE and Bias are similar in the comparisons against MOD16. The RMSE of the open loop integration is 22.7 Wm\(^{-2}\) and it improves to 21.9 Wm\(^{-2}\) with the assimilation of LPRM soil moisture retrievals. The assimilation of NASA soil moisture retrievals degrades the ET estimates, with a domain averaged RMSE of 24.5 Wm\(^{-2}\).

To quantify the spatial improvements due to assimilation, we define an "improvement metric" as difference between the RMSE of the integration with data assimilation and the RMSE of the open loop integration (RMSE (DA) – RMSE (OL)). If data assimilation improves the flux estimates (i.e., reduces the RMSE), then the improvement metric will be negative. On the other hand, the improvement metric will be positive if the assimilation simulation degrades the flux estimates. Figures 5 and 6 present a comparison of the improvement metric stratified seasonally, from both assimilation integrations, as compared to both reference ET datasets. Figure 5 represents the improvement metric when using the NASA AMSR-E product and Figure 6 shows the corresponding comparisons when using the LPRM product. In both sets of comparisons, the LPRM-based assimilation provides more systematic improvements in the flux estimates, whereas the NASA-based integration indicates degradations over several regions. For example, during MAM months, the flux estimates from NASA-DA show degradation over the Southern Great Plains, with improvements observed over Illinois, Indiana, Ohio and areas along the Mississippi river; these are the same areas discussed earlier in Figure 3 where Noah 3.2 had higher simulated ET. The LPRM-integration on the other hand, shows improvements over large areas of Midwest, and South-central U.S during MAM, with no significant degradations observed as a result of soil moisture assimilation. During JJA, the NASA-DA shows degradations in most
regions interspersed with improvements over a few regions near North Dakota, Illinois, Eastern
Texas and the West coast, in the comparisons using the FLUXNET data. The MOD16-based
comparisons show similar results, with small regions of improvements over the Central and
Eastern US with degradations over most of the domain. In contrast, the JJA comparisons for
LPRM-DA show degradations in a few regions only, with improvements observed over large
areas of the Midwest U.S. During the SON months, similar trends are seen, with degradations
over Mexico and regions near Ohio and Illinois (when compared to FLUXNET) and Mississippi
river basin areas (when compared to MOD16). The LPRM-DA based simulations show
improvements over Midwest and Central US in the comparisons against MOD16 and no
significant degradations in the comparisons against FLUXNET.

Further analysis of the differences shown in Figures 5 and 6 reveals that the magnitudes of
the differences are strongly related to landcover type. Based on further analysis (not shown),
stratifying the Qle RMSE improvements due to DA with respect to landcover type, we found that
the most significant improvements occur in croplands for both soil moisture datasets and both
reference datasets. Grassland was also found to have significant changes in Qle RMSE with both
datasets, and more so with respect to the MOD16 reference data. In general, DA does not occur
over heavily vegetated regions, due to masking out high-vegetation water content areas which
make soil moisture retrievals difficult. Nonetheless, our results suggest modest changes over
evergreen needleleaf forests and woodlands, especially for the NASA product.

In order to relate the improvements and degradations in latent heat flux estimates to changes
in soil moisture resulting from data assimilation, we present a comparison of the surface soil
moisture difference maps in Figure 7. The difference maps represent the mean surface soil
moisture of the data assimilation integration subtracted by the mean surface soil moisture of the open loop integration. In other words, the difference maps represent the changes in soil moisture values introduced by data assimilation, averaged seasonally. A negative difference indicates that the soil moisture is drier due to assimilation and a positive difference indicates that the soil moisture is wetter from assimilation. By comparing Figures 5 and 6 against Figure 7, it can be observed that the spatial patterns of the improvement metric correlates well with those of the soil moisture difference maps. For example, during MAM, both the NASA-DA and the NASA-LPRM (with a smaller magnitude) soil moisture difference maps indicate drier patterns over Illinois, Indiana, Ohio and areas along the Mississippi river that leads to corresponding improvements in latent flux estimates (Figure 5) over these same regions. During JJA, the soil moisture changes due to assimilation of NASA and LPRM are generally of opposite sign, and seem to show a mix of improvements and degradations in the fluxes, depending on landcover. During SON, assimilation of NASA retrievals dries the soil moisture over Lower Texas and Mexico (relative to OL) and it leads to a corresponding degradation in the flux estimates over these regions when compared to FLUXNET (Figure 5, panel for SON). Similar patterns of tight correlation between the soil moisture difference patterns and the flux improvement patterns can be observed in the LPRM-DA integration. During JJA, over the Midwest US, the LPRM-DA causes the soil moisture simulations to be drier than the open loop simulation leading to improvements in the latent heat flux estimates over the same areas.

It is important to note that the CDF-scaling approach for data assimilation used here (and described previously) is intended to preserve the soil moisture climatology of the LSM, while taking advantage of observed anomalies. Therefore, the results suggest that the
improvements/degradations in Qle due to soil moisture assimilation are a direct result of improved/degraded soil moisture stress responses in the stomatal resistance formulation of the Noah 3.2 LSM. This sort of non-linear feedback is likely due to the ability of LPRM-DA to redistribute water in a seasonal cycle that corresponds to Noah’s biases in soil moisture and ET.

By design, and verified by us (not shown) the soil moisture increments from both NASA-DA and LPRM-DA do not change the mean surface soil moisture relative to the open loop. However, as most easily explained via the bias time series in Figure 4, significant seasonal changes in soil moisture, translate into varying ET responses. In winter, the change in ET from the OL to the DA is nominal (since Rnet, and therefore Qle is small). In spring, LPRM tends to reduce soil moisture relative to the open loop and therefore Qle bias while NASA-DA increases soil moisture and Qle bias. In the summer, the open loop skill is higher, and both products further compensate for errors, with LPRM tending to overdry and NASA tending too wet. Overall, the net effect is a domain-averaged increase of 2 Wm$^{-2}$ in total Qle for the LPRM-DA, and a 3 Wm$^{-2}$ reduction in Qle for NASA-DA.

Evaluation of the surface energy partition from LDAS simulations

The surface energy partition consists of two key components, the latent heat and the sensible heat fluxes. Though the primary focus of this article is to evaluate the latent heat estimates, we also evaluated the sensible heat flux (Qh) estimates from the LDAS simulations using FLUXNET data to examine if the trends seen in the Qle estimates are consistent for both energy partition terms. Trends in error metrics similar to those seen with latent heat flux estimates are found in the sensible heat estimates. As shown in Table 2, Qh estimates from GLDAS has a domain averaged RMSE of 23.4 Wm$^{-2}$ whereas the NLDAS-like simulations with Noah 2.7.1 and Noah 3.2 have domain averaged RMSEs of 21.1 and 32.5 Wm$^{-2}$, respectively. The
assimilation with LPRM data improves the domain averaged RMSE to 30.4 Wm\(^{-2}\) (over that of
the open loop integration NLDAS-like simulation with Noah 3.2), whereas the assimilation of
NASA retrievals degrades the sensible heat flux estimates with a domain averaged RMSE of
34.5 Wm\(^{-2}\). Spatial patterns of improvements and degradations similar to that seen in Figures 5
and 6 are observed for sensible heat fluxes as well (not shown; for FLUXNET only, as Qh is not
available from MOD16). Again, these trends are statistically significant, as seen from the
confidence interval values presented in Table 2.

**SUMMARY**

This article provides a description of the capabilities of Land Data Assimilation Systems (LDAS)
for generating ET estimates and presents a quantitative evaluation of ET estimates, expressed as
latent heat flux (Qle), from a number of LDAS simulations. The simulated ET values from
GLDAS and LSM simulations conducted over the NLDAS-domain using two different versions
of the Noah land surface model (Noah version 2.7.1 and version 3.2) are compared against two
reference ET datasets: the gridded tower-based estimates from the FLUXNET measurements and
ET estimates based on MODIS satellite data, known as the MOD16 product. The article also
presents an evaluation of the impact of soil moisture data assimilation in ET estimation. The data
assimilation integrations employ two different retrievals of the AMSR-E soil moisture
measurements; the NASA Level-3 product and the AMSR-E Land Parameter Retrieval Model
product from VU Amsterdam.

The evaluation of ET fields indicate that the simulation using NLDAS forcing with Noah
2.7.1 provides slightly better estimates among the LDAS simulations without data assimilation,
although all Noah simulations suffer from significant high biases relative to the two reference
This could be due to a combination of parameter and structural errors in addition to errors in the reference data themselves. The three LDAS simulations differ most during the spring and fall months. Comparison of the seasonally averaged ET fluxes show overestimations during MAM in all three LDAS products over the Southeast and Lower Mississippi River basin. During JJA, the differences between the two Noah model-based simulations are more prominent over vegetated crop regions in the upper Midwest and irrigated areas along the Mississippi river. GLDAS product shows underestimation in ET during the SON months, whereas the NLDAS-forced Noah simulations show better agreement with both FLUXNET and MOD16 estimates during this period.

The assimilation of surface soil moisture impacts the ET estimates, particularly during the spring (MAM) and summer (JJA) months, which is when the expected impacts would be largest due to increasing soil moisture stress, insolation, and vegetation fraction conditions. The assimilation of LPRM retrievals demonstrates systematic, statistically significant but modest improvements in ET estimates relative to the Noah model simulation without data assimilation. The assimilation of NASA retrievals, on the other hand, provides mixed results, with improvements in a few regions of the NLDAS-domain. Overall, the integration using the NASA soil moisture retrievals indicates degradation of the open loop ET estimates. The results also indicate strong correlations between the improvements/degradations of ET estimates and the changes in soil moisture fields introduced by soil moisture assimilation. Finally, the analysis of the sensible heat flux estimates indicates consistent trends in both surface energy partition terms (latent and sensible estimates).
Acknowledgements

We gratefully acknowledge the financial support from the NASA Earth Science Technology Office (ESTO) (Advanced Information System Technology program award AIST-08-077), the NASA Energy and Water Cycle Study (NEWS), the Air Force Weather Agency, and NOAA’s Climate Program Office. The efforts of NLDAS participants in generating the surface forcing is greatly appreciated. Some of the data used in this effort were acquired as part of the activities of NASA’s Science Mission Directorate, and are archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). Computing was supported by the resources at the NASA Center for Climate Simulation.
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<table>
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<tr>
<th>Variable</th>
<th>Perturbation Type</th>
<th>Standard Deviation</th>
<th>Cross Correlations with perturbations in</th>
<th>Sm1</th>
<th>Sm2</th>
<th>Sm3</th>
<th>Sm4</th>
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<td>Downward Shortwave</td>
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<td>0.4</td>
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<td>1.0</td>
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<table>
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<th>FLUXNET</th>
<th>MOD16</th>
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<td>Bias (Wm⁻²)</td>
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<td>Qle</td>
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<td>NLDAS (Noah v3.2)+LPRM DA</td>
<td>25.6 ± 0.3</td>
<td>10.9 ± 0.3</td>
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<tr>
<td>Qh</td>
<td></td>
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<tr>
<td>GLDAS</td>
<td>23.4 ± 0.2</td>
<td>-5.6 ± 0.4</td>
</tr>
<tr>
<td>NLDAS (Noah v2.7.1)</td>
<td>21.1 ± 0.3</td>
<td>-7.0 ± 0.4</td>
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<tr>
<td>NLDAS (Noah v3.2)</td>
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<td>-9.2 ± 0.4</td>
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<td>NLDAS (Noah v3.2)+NASA DA</td>
<td>34.5 ± 0.3</td>
<td>-12.2 ± 0.4</td>
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<tr>
<td>NLDAS (Noah v3.2)+LPRM DA</td>
<td>30.4 ± 0.3</td>
<td>-7.3 ± 0.4</td>
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Figure 2: Comparison of the average seasonal cycles of RMSE and Bias for latent heat flux (Qle) estimates from the three LDAS simulations: GLDAS Noah, NLDAS-like simulations with Noah 2.7.1 (NLDAS-N271) and Noah 3.2 (NLDAS-N32) compared against the gridded FLUXNET data (left column) and MOD16 data (right column). All units are in Wm\(^{-2}\).

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Figure 5: Comparison of the latent heat flux improvement metric (RMSE (DA) – RMSE (OL)) from the data assimilation integrations using the NASA AMSR-E soil moisture retrievals (NASA-DA). The two columns represent the reference datasets used in the RMSE computations: FLUXNET (left column) and MOD16 (right column). The red and blue shades indicate improvements and degradations as a result of data assimilation, respectively. All units are in Wm\(^{2}\).

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