Impact of Soil Moisture Assimilation on Land Surface Model Spinup and Coupled Land–Atmosphere Prediction

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ABSTRACT

Advances in satellite monitoring of the terrestrial water cycle have led to a concerted effort to assimilate soil moisture observations from various platforms into offline land surface models (LSMs). One principal but still open question is that of the ability of land data assimilation (LDA) to improve LSM initial conditions for coupled short-term weather prediction. In this study, the impact of assimilating Advanced Microwave Scanning Radiometer for EOS (AMSR-E) soil moisture retrievals on coupled WRF Model forecasts is examined during the summers of dry (2006) and wet (2007) surface conditions in the southern Great Plains. LDA is carried out using NASA’s Land Information System (LIS) and the Noah LSM through an ensemble Kalman filter (EnKF) approach. The impacts of LDA on the 1) soil moisture and soil temperature initial conditions for WRF, 2) land–atmosphere coupling characteristics, and 3) ambient weather of the coupled LIS–WRF simulations are then assessed. Results show that impacts of soil moisture LDA during the spinup can significantly modify LSM states and fluxes, depending on regime and season. Results also indicate that the use of seasonal cumulative distribution functions (CDFs) is more advantageous compared to the traditional annual CDF bias correction strategies. LDA performs consistently regardless of atmospheric forcing applied, with greater improvements seen when using coarser, global forcing products. Downstream impacts on coupled simulations vary according to the strength of the LDA impact at the initialization, where significant modifications to the soil moisture flux–PBL–ambient weather process chain are observed. Overall, this study demonstrates potential for future, higher-resolution soil moisture assimilation applications in weather and climate research.

1. Introduction

Advances in satellite remote sensing of Earth’s hydrological cycle have led to the development of various model–data fusion approaches to ingesting retrieved products such as soil moisture, groundwater, snow, surface temperature, and precipitation into land surface models (LSMs). By providing spatially distributed and timely information on the condition of the land surface at regional to global scales, satellite data are a particularly attractive option to improve LSMs that are typically limited by insufficiencies in parameterizations and input data (Lahoz and De Lannoy 2014). Two such model–data fusion approaches to utilizing these data in this fashion are calibration (parameter estimation) and land data assimilation (LDA).

Model calibration, while often applied in offline LSMs over limited time and space scales (e.g., Santanello et al. 2014),
Atmosphere System Study (GLASS; van den Hurk et al. 2007; Hogue et al. 2005), focuses on modifying large parameter sets to improve predictions and effectively changes the model itself while providing “tuned” parameters. The observations are often of high quality (e.g., in situ) but with limited spatial extents. The modification of the parameters of the model is often tricky, as it not only changes the climatological behavior of the model, but also could deteriorate model skill for outputs that are not well constrained in parameter estimation. LDA, on the other hand, is a state estimation method, which attempts to blend observed and modeled states while leaving the remainder of the LSM intact. This is typically performed over large, distributed spatial domains using satellite data, which have larger uncertainty (compared to in situ datasets) but whose error characteristics can be incorporated through the LDA approach itself.

One of the advantages of LDA is that the model states themselves can be directly improved by adjusting their values to be closer to observations. Hence, there has been a push for satellite missions to retrieve near-surface soil moisture at increasing spatial and temporal resolutions from a variety of active and passive sensors (Xu et al. 2014). For example, between 2002 and 2011, the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) on board NASA’s Aqua satellite has provided soil moisture retrievals globally at ~45-km resolution and at daily time scales. The record length of AMSR-E makes it desirable for long-term studies of the impacts of LDA on hydrological prediction, on which much work has been done in recent years (Kumar et al. 2014; Sahoo et al. 2013; Maggioni et al. 2013; Draper et al. 2012; Liu et al. 2011; Reichle et al. 2007).

One still unaddressed aspect in the community is that of the potential improvement in coupled land–atmosphere (LA) prediction as a result of LDA being performed during an offline LSM spinup. As coupled initialization relies on accurate soil moisture and temperature representation, LDA of soil moisture in particular has strong potential to improve the initial state generated by the LSM with expected downstream (in time and space) impacts felt throughout the forecast (Santanello et al. 2013a,b; Case et al. 2008, 2011; Kumar et al. 2008). In fact, this idea has been in place and in situ for over a decade, but has remained largely unexplored. Most offline Land Data Assimilation Systems (LDASs; e.g., Mitchell et al. 2004; Rodell et al. 2004) to date do not include actual LDA during simulations for offline applications [e.g., drought monitoring; North American Land Data Assimilation System (NLDAS)] or for coupled initialization. More recent efforts have attempted to bridge this gap by transitioning the assimilation of soil moisture (Kumar et al. 2014), snow (Kumar et al. 2015a), and terrestrial water storage (Kumar et al. 2015c, manuscript submitted to Water Resour. Res.) in NLDAS.

In this paper, the potential for soil moisture assimilation to improve offline LSM spinup for coupled prediction is investigated for the first time. The experimental design, case studies, and results follow those of Santanello et al. (2013a), who explored the impacts of model calibration on LSM spinup and subsequent weather forecasts. Specifically, NASA’s Land Information System (LIS; Kumar et al. 2006), new LDA module, and ensemble Kalman filter (EnKF; Reichle et al. 2002a,b) are used to assimilate AMSR-E soil moisture products in the Noah LSM, version 3.3 (Ek et al. 2003), during a multi-year spinup. Selected case studies during dry and wet extreme periods over the southern Great Plains (SGP) are then performed with the NASA Unified WRF Model (NU-WRF; Peters-Lidard et al. 2015) using the assimilated LIS–Noah soil states as initial conditions. Analyses of both offline and coupled LA forecasts are performed for each case study with the focus on diurnal and short-term prediction impacts, utilizing diagnostics that assess the land–PBL coupling as a whole in terms of water and energy cycling.

Section 2 of this paper provides a brief review of recent LDA studies focused on AMSR-E and soil moisture as well as the LA coupling diagnostics used to assess the coupled forecasts. The NU-WRF system, LIS and LDA approach, and experimental design are described in section 3. Results are presented in section 4, with conclusions and a discussion of the current status and issues involved with LDA for coupled prediction in section 5.

2. Background

a. LSM spinup and calibration

The importance of an accurate, high-resolution LSM spinup for coupled prediction has been highlighted in previous studies ranging from impacts on land surface states and fluxes (Lawston et al. 2015) to ambient weather and precipitation on short-term (Chen et al. 2007; Kumar et al. 2008; Case et al. 2008, 2011; Wen et al. 2012) to seasonal (Hirsch et al. 2014) scales. Initial soil states generated from large-scale atmospheric initialization (e.g., via reanalyses) of WRF Model forecasts are typically limited by coarse spatial resolution and lack of heterogeneous or observation-based land surface conditions. Substantial improvement can therefore be obtained by simply performing an offline LSM spinup, with
even further accuracy obtained when observations are brought into the spinup (e.g., via calibration; Santanello et al. 2013a).

A flexible yet consistent modeling framework is required to conduct spinups using the same LSM and resolution as the coupled simulations. Hence, the coupling of LIS to NU-WRF was designed to facilitate the multyear spinup of LSMS prior to WRF initialization while at the same time allowing for the model–data fusion components of LIS to be employed throughout. Santanello et al. (2013a) demonstrated this end-to-end capability of LIS and NU-WRF by calibrating the Noah LSM to observed surface fluxes during spinup and showing resultant improvements in LA coupling and ambient weather forecasts in WRF.

Santanello et al. (2013a) also focused on issues such as what, when, and how to calibrate an LSM in the context of improving hydrometeorological forecasts. In their approach, a surface flux network was used to calibrate the full set of Noah LSM parameters. In practice, such dense and long-term networks (~20 sites over a regional domain) are quite rare, which limits the broader applicability of the calibrated spinup approach until more reliable, spatially distributed satellite flux measurements become available. In addition, their results represented a “best case” scenario in terms of maximum impact on coupled forecasts, as the fluxes themselves are what are most directly tied to WRF and influential on the planetary boundary layer. The reader is referred to Santanello et al. (2013a) for more details.

b. Soil moisture data assimilation

LDA offers a practical and robust approach to improving LSM-based initial conditions by employing the global and routine coverage of satellite data. Soil moisture assimilation has been performed for various applications using diverse models and techniques and is the most mature of the LDA disciplines with efforts that are commensurate with the large number of soil moisture missions supported by various agencies. More details on the LDA approach used in this study are presented in section 3, but some recent studies using AMSR-E are relevant to offline LSM spinup and will be discussed here.

To date, most soil moisture LDA studies have focused on continental scales and hydrological applications (e.g., streamflow and drought) over long periods of integration (e.g., Wanders et al. 2014; Xu et al. 2014). More recently, Kumar et al. (2014) assimilated AMSR-E soil moisture into the offline Noah LSM over the continental United States (CONUS). Overall, the statistical improvement seen in soil moisture and surface fluxes was shown to be marginal at best, with sometimes neutral or degrading effects of performing assimilation. The increments from AMSR-E assimilation in this case acted to primarily dry the soil from the default (open loop) Noah simulation, particularly in the summer months when impacts from LDA were largest. Note that these results were compiled over many years (2003–11) and regions, which likely averaged out the local, diurnal, seasonal, and anomalous regime impacts that may have been present.

Similarly, Liu et al. (2011) incorporated AMSR-E soil moisture into the offline catchment LSM via an EnKF approach and evaluated soil moisture impacts over the 2002–09 period. They found that moderate yet comparable improvements in near-surface and root-zone soil moisture skill could be obtained by simply using better (i.e., observed) precipitation forcing as opposed to performing LDA. Also of note was the rather low correlation of AMSR-E soil moisture retrievals themselves to that of in situ soil moisture network measurements [also shown by Reichle et al. (2007)], which suggests that there are potential limitations of the satellite data before ingestion into the LSM.

The studies above focus solely on soil moisture impacts from data assimilation. For weather and climate applications, it is actually the surface turbulent fluxes that the atmospheric model responds directly to, and thus the translation of soil moisture to fluxes in the LSM remains a critical moderator of the ultimate impacts felt downstream in the coupled prediction. To this end, Peters-Lidard et al. (2011) focused on the impacts of LDA on evapotranspiration (ET) over CONUS while assessing two retrievals of soil moisture from AMSR-E during 2002–08. Results generally showed that LDA tends to produce drier soils in the Noah LSM over the central United States during summer months, which occasionally correlates at certain times and locations with statistically significant impacts and improvements in latent heat fluxes. However, the majority of the results are mixed, with the highest sensitivity in ET seen because of the type of AMSR-E retrieval and evaluation data (e.g., ET estimates from satellite) employed, each of which have large uncertainties that preclude broader conclusions from being made.

c. Land–atmosphere coupling

Land–atmosphere interactions have been the focus of many investigations, projects, and working groups over the past decade, led principally by the GEWEX GLASS (van den Hurk et al. 2011) community. Varying definitions of LA coupling metrics have been developed and range from global climate model (GCM) applications such as the Global Land–Atmosphere Coupling Experiment (GLACE; Koster et al. 2004) to diurnal process-level understanding within the local LA coupling
(LoCo; Santanello et al. 2011a) initiative. These studies have demonstrated the potential for the land (and in particular soil moisture) to modulate atmospheric and PBL water and energy cycling in the support of hydrological extremes such as flood and drought (e.g., Koster et al. 2010; Santanello et al. 2013b).

In terms of short-term forecast implications, LoCo diagnostics are most appropriate because of their ability to quantify the diurnal evolution and coupled land–PBL process that translate soil state and flux impacts through the atmosphere. The series of interactions and feedbacks (i.e., links in the chain) between soil moisture and precipitation can be summarized in terms of the soil moisture–evaporation, evaporation–PBL height, and entrainment–evaporation relationships and their collective impact on clouds and precipitation (Santanello et al. 2011b). Each of these can be quantified in both models and observations using a series of LoCo metrics, as has been demonstrated using LIS and NU-WRF as test beds over the SGP region (Santanello et al. 2009, 2011b, 2013b). A thorough review of LoCo research can be found in these publications, and the relevant diagnostics employed in this study are outlined briefly in section 3.

3. Experimental design

a. LIS and NU-WRF

NASA’s Land Information System (Kumar et al. 2006; Peters-Lidard et al. 2007) supports a suite of LSMs under the same software framework and provides a high-resolution and flexible representation of land surface physics and states. LIS can be run offline for multiyear spinups (Rodell et al. 2005; Kato et al. 2007) and then directly coupled to an atmospheric model. The latest version [LIS, version 7.0 (LISv7.0); lis.gsfc.nasa.gov] includes a data assimilation (DA) subsystem (LIS-DA; Kumar et al. 2008) that allows for LDA algorithms to be applied to a range of LSM variables and/or radiances computed from the LIS Radiative Transfer Model (LIS-RTM) subsystem.

The Community ARW is widely used for atmospheric research and operational prediction utilizing high-resolution (e.g., 1–10 km) regional simulations on the order of 1–14 days. Recently, unique NASA assets such as LIS have been integrated into the NU-WRF system at NASA’s Goddard Space Flight Center (GSFC). Built on the ARW Model, NU-WRF incorporates LIS, the chemistry component of the WRF Model (WRF-Chem) enabled version of the Goddard Chemistry Aerosol Radiation and Transport (GOCART; Chin et al. 2000) model, GSFC radiation and microphysics schemes, and the Goddard Satellite Data Simulation Unit (SDSU; Matsui et al. 2009) into a single modeling framework.

Land–atmosphere interaction studies are a component of NU-WRF and have been facilitated by the coupling of LIS and WRF by Kumar et al. (2008). The specific versions of NU-WRF used here include LIS, version 7.0, and ARW, version 3.5.1. The advantages of coupling LIS and WRF include the ability to spin up land surface conditions on a common grid from which to initialize and run the coupled model, flexible and high-resolution (satellite based) soil and vegetation representation, and direct access in WRF to the LIS subsystems (including LIS-DA). The LoCo studies cited in section 2 have demonstrated NU-WRF as a test bed for LA interaction studies because of its land–PBL scheme flexibility and diurnal and process-level resolution. Hereafter, we refer to NU-WRF as the coupled prediction system that includes the LIS–WRF coupling for these experiments.

Model specification and setup are identical to those in Santanello et al. (2013a), with the LIS and NU-WRF experiments run on a single 500 × 500 domain at 1-km spatial resolution using a 3-s time step, GSFC microphysics, long- and shortwave radiation, Mellor–Yamada–Nakanishi–Niino (MYNN) PBL scheme, and Monin–Obukhov surface layer scheme. Likewise, the North American Regional Reanalysis (NARR; Mesinger et al. 2006) data were used for atmospheric initialization and lateral boundary conditions using 3-hourly nudging, and the vertical resolution of NU-WRF was specified as 61 vertical levels, with the lowest model level ~24 m above the surface.

The LSM employed in LIS for this study is the Noah LSM, version 3.3 (Ek et al. 2003), and it is identical to the version of Noah packaged in the community version of the ARW, version 3.3, release. Internal LIS–Noah testing has shown very minimal impacts of recent (3.x) versions on spinup results, particularly those not focused on cold process or snow events. Noah is used in operational and research modes by a number of institutions, and as such is a well-supported, developed, and utilized LSM for both offline and coupled weather prediction applications. As is the common and advantageous practice of using LIS–WRF, the spun-up soil moisture and temperature profiles from LIS–Noah are then used to initialize (and overwrite the coarser NARR initial soil conditions) for all NU-WRF case studies.

b. LIS-DA and AMSR-E soil moisture

For this study, we employ assimilation of soil moisture retrieval products via the EnKF approach in LIS-DA using the Noah LSM, version 3.3 (Ek et al. 2003). The one-dimensional EnKF algorithm is adopted from Reichle...
reduce the statistical artifacts from lumped CDF matching, seasonal differences in the model and observations. To (2005), the bias differences are also often influenced by seasons (called “lumped”). As noted by Drusch et al. that encompasses the soil moisture dynamics across all et al. 2012, 2014) use a single CDF (at each grid point) to use methods such as cumulative distribution function (CDF) matching (Reichle and Koster 2004) to scale the observations into the LSM climatology as a bias-mitigation strategy. The CDFs are derived separately from the soil moisture retrievals and the LSM at each grid point during the time period of 2002–11. Using these CDFs, the observations are rescaled at each grid point before employing them in the assimilation system. Most soil moisture data assimilation studies (Crow et al. 2005; Reichle et al. 2007; Kumar et al. 2009; Liu et al. 2011; Draper et al. 2011; Hain et al. 2012; Kumar et al. 2012, 2014) use a single CDF (at each grid point) that encompasses the soil moisture dynamics across all seasons (called “lumped”). As noted by Drusch et al. (2005), the bias differences are also often influenced by seasonal differences in the model and observations. To reduce the statistical artifacts from lumped CDF matching, temporally stratified CDFs can be used if the sampling density of the data archive is sufficient. In this study, we examine the impact of both lumped and seasonal CDF-matching approaches. The seasonal stratification in the CDFs is derived at a monthly time scale (i.e., the CDFs are derived separately for each calendar month by considering data across all available years).

The LPRM data from Vrije Universiteit (VU) Amsterdam used in this study include data layers for soil moisture retrievals expressed in degrees of saturation (dimensionless) as well as in volumetric soil moisture (m$^3$m$^{-3}$). The volumetric soil moisture fields are derived by CDF matching the retrievals in degree of saturation units to a reference climatology of the Noah LSM–based GLDAS outputs. We employ both these fields in the assimilation integrations. The soil moisture fields in degrees of saturation and volumetric units are referred to as “raw” and “scaled,” respectively. The input observation error standard deviation for the raw and scaled retrievals is set at 0.08 and 0.04 m$^3$m$^{-3}$, respectively. An ensemble size of 12 is used in the assimilation integrations, and perturbations are applied to both forcing and soil moisture prognostic states to simulate uncertainty in the model estimates, using the same perturbation parameters employed in Kumar et al. (2014).

c. Case studies

LIS and NU-WRF have been employed for a host of studies centered over the SGP, effectively serving as a test bed for LoCo diagnostics, LSM calibration, and coupled forecasting. It is a region of strong LA coupling (Koster et al. 2004) that exhibits both dry and wet seasonal and interannual extremes. In addition, the SGP contains a wealth of continuous (from 1996 to present) and spatially distributed (~20 sites) soil, flux, and PBL measurements, available from the Atmospheric Radiation Measurement Southern Great Plains test bed (ARM-SGP), that encompass many such dry and wet extremes as well as the full AMSR-E period of record. Following Santanello et al. (2013a,b), the contrasting dry and wet regimes of 2006 and 2007 (respectively) are of primary interest for this study and coupled case studies performed here.
As the goal of this study is the impact assessment of LDA on spinup and coupled forecasts, the case studies from each year were chosen accordingly. First, the 14 July 2006 “golden day” that is the focus of Santanello et al. (2013a, b) represents a well-understood case during a lengthy drydown period where local LA interactions were a primary driver of the diurnal land–PBL evolution. The second case study (26–27 July 2007) was chosen more specifically based on when maximum impact from assimilation increments could be expected (as will be shown in section 4) during a wet regime characterized by frequent precipitation.

LIS–Noah was first run offline beginning on 1 January from 2002 through 2010, thus producing a ~4.5–5.5-yr spinup prior to the start time of the 2006 and 2007 case studies. This is slightly longer than the recommended spinup length for this region and corresponds to the AMSR-E LPRM product availability. Atmospheric forcing data from phase 2 of the NLDAS (NLDAS-2; Xia et al. 2012) and the Global Data Assimilation System (GDAS; http://www.emc.ncep.noaa.gov/gmb/gdas/) were used to drive the spinups. A series of offline simulations was then performed with the NLDAS-2 forcing composed of a default [hereafter referred to as open loop (OL)] run, and AMSR-E assimilation runs using raw data and monthly CDF matching (RM), raw data and lumped CDF matching (RL), scaled data and monthly CDF matching (SM), and scaled data and lumped CDF matching (SL). This was then repeated with GDAS forcing for the open loop and raw, monthly permutations (GOL and GRM). These runs are summarized in Table 1, a subset of which (OL vs RM; GOL vs GRM) serve as the basis for evaluation and intercomparison in section 4.

To examine the impact of LDA spinups on coupled forecasts, these spinups were then used as initial conditions (0000 UTC; 1800 LST) for the NU-WRF case studies. Note that LDA was performed during offline spinup only and not during coupled NU-WRF simulations. Online LDA remains a challenging and untested...
approach both computationally and scientifically (e.g., Mahfouf 2010; Dharssi et al. 2012), and understanding of offline LDA impacts will provide guidance on future work in this regard.

d. Evaluation data

The evaluation of the surface components of offline and coupled experiments is performed using the Land Surface Verification Toolkit (LVT; Kumar et al. 2012), which provides an intercomparison platform combined with a range of statistical and benchmarking approaches. ARM-SGP provides a long-standing record of quality-controlled surface flux, meteorological, and hydrological observations along with atmospheric profiles for a network of sites across Oklahoma and Kansas. This includes collocated soil moisture, net radiation, sensible, latent, and soil heat fluxes, along with collocated surface meteorology data. Typical error ranges for latent and sensible heat fluxes (Qle and Qh, respectively) are ~10% for an Energy Balance Bowen Ratio Station (EBBR) with perfect closure (by definition) and ~5%–6% for an Eddy Correlation Flux Measurement System (ECOR) with 75%–90% closure (http://www.arm.gov/instruments/ecor; Wilson et al. 2002). The processing of ARM-SGP best-estimate data is now included in LVT as well, comprising surface fluxes, soil moisture and temperature, and meteorology data.

<table>
<thead>
<tr>
<th>TABLE 2. Anomaly correlation and RMSE for 3-hourly, 0–10-cm soil moisture from the NLDAS-2 forced OL, DA (RM), and GDAS forced OL (GOL) and DA (GRM) simulations evaluated at the three SCAN sites over the 2002–10 period shown in Figs. 1 and 6.</th>
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</thead>
<tbody>
<tr>
<td>OL</td>
</tr>
<tr>
<td>---</td>
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<tr>
<td>Anomaly correlation</td>
</tr>
<tr>
<td>Anomaly RMSE (m$^3$ m$^{-3}$)</td>
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Fig. 2. As in Fig. 1, but for the difference in DA (RM) − OL in 0–10-cm soil moisture (m$^3$ m$^{-3}$).
LoCo diagnostics were computed outside of LVT using collocated surface meteorology, flux towers, and radiosonde profile (i.e., PBL) data. The suite of diagnostics includes mixing diagrams, evaporative fraction versus PBL height (PBLH; Santanello et al. 2009), and lifting condensation level deficit (LCLdef; Santanello et al. 2011b). Note that the “atmospheric response vector” approach of Santanello et al. (2013a) and Lawston et al. (2015) has been followed here as well, which better represents the components of advection and entrainment as well as the 2-m assumption. Last, the ambient weather (temperature, humidity, and wind) evaluation

<table>
<thead>
<tr>
<th>Year</th>
<th>OL RMSE (W m⁻²)</th>
<th>RM</th>
<th>RL</th>
<th>SM</th>
<th>SL</th>
<th>GOL</th>
<th>GRM</th>
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<tbody>
<tr>
<td>2006</td>
<td>67.8</td>
<td>70.5</td>
<td>69.6</td>
<td>70.7</td>
<td>69.0</td>
<td>84.5</td>
<td>69.7</td>
</tr>
<tr>
<td></td>
<td>Qle bias (W m⁻²)</td>
<td>-6.7</td>
<td>1.2</td>
<td>-15.6</td>
<td>-0.4</td>
<td>-16.1</td>
<td>-15.4</td>
</tr>
<tr>
<td></td>
<td>Qh RMSE (W m⁻²)</td>
<td>68.1</td>
<td>67.6</td>
<td>73.9</td>
<td>67.9</td>
<td>73.0</td>
<td>90.3</td>
</tr>
<tr>
<td></td>
<td>Qh bias (W m⁻²)</td>
<td>12.7</td>
<td>5.2</td>
<td>20.0</td>
<td>6.7</td>
<td>20.5</td>
<td>27.2</td>
</tr>
<tr>
<td>2007</td>
<td>Qle RMSE (W m⁻²)</td>
<td>83.9</td>
<td>79.3</td>
<td>79.7</td>
<td>80.0</td>
<td>78.3</td>
<td>85.3</td>
</tr>
<tr>
<td></td>
<td>Qle bias (W m⁻²)</td>
<td>32.8</td>
<td>14.0</td>
<td>11.0</td>
<td>19.2</td>
<td>9.6</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>Qh RMSE (W m⁻²)</td>
<td>62.8</td>
<td>63.7</td>
<td>69.9</td>
<td>64.5</td>
<td>69.8</td>
<td>66.8</td>
</tr>
<tr>
<td></td>
<td>Qh bias (W m⁻²)</td>
<td>-10.1</td>
<td>1.7</td>
<td>8.6</td>
<td>1.5</td>
<td>14.9</td>
<td>4.0</td>
</tr>
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</table>

Fig. 3. The difference in DA – OL in surface Qle and Qh (W m⁻²) simulated at the (a) 2022, (b) 2023, and (c) 2092 SCAN sites during July 2006 from NLDAS-2 driven runs.
was performed using the Model Evaluation Tools statistical software package [MET; developed by the National Center for Atmospheric Research (NCAR) and incorporates NCEP Automated Data Processing (ADP) atmospheric and surface data], which is based on a large number of site observations at 6-hourly intervals on the case study dates.

4. Results

The impacts of assimilation on the offline spinups are considered first, including that of the scaling in remote sensing retrievals, bias correction strategies in LDA, and forcing permutations. This is followed by the downstream impacts on the coupled case studies and LoCo diagnostics.

a. Offline spinup results

1) Soil moisture and fluxes

The full time series of top-layer soil moisture from the OL and RM simulations are shown in Fig. 1 for three U.S. Department of Agriculture (USDA) Soil Climate Analysis Network (SCAN) sites located in the domain (see Fig. 10, described in greater detail below, for locations). Overall, the dynamic and annual range of soil moisture is similar between the two simulations (as expected because of bias correction) and across the sites, generally ranging from 0.10 to 0.40 m$^3$m$^{-3}$. Also evident are the dry (2006) and wet (2007) years relative to the remainder of the period. The differences between the assimilation and open-loop runs (defined as DA $-$ OL) in Fig. 2 show somewhat distinct patterns across the three sites. Site 2022 shows the overall largest impacts due to DA, with differences from $-0.10$ to $-0.15$ m$^3$m$^{-3}$ (negative indicating that LDA acts to dry the soil) during the wet 2007–08 regime. These changes are $\sim$25%–50% of the soil moisture dynamic range shown in Fig. 1 and suggest that the model has a high bias in soil moisture during wet regimes. Site 2023 shows smaller LDA impacts (generally $\pm 0.05$ m$^3$m$^{-3}$), but also shows a prolonged drying signal from LDA during the 2007–08 period. Site 2092 shows a more consistent annual cycle of LDA increments.

Fig. 4. As in Fig. 3, but for July 2007.
through the period, with a general wetting in winter and drying in summer (also seen at times in 2022 and 2023).

When compared with near-surface soil moisture observations across the SCAN sites (Table 2), the anomaly correlation and root-mean-square error (RMSE) statistics show quite minimal positive impacts of assimilation (RM vs OL). The statistical significance levels (at the 95% level) in the anomaly correlation $R$ (based on the Fisher $Z$ transform) and anomaly RMSE values (based on a Student’s $t$ test) are approximately 0.02 and 0.01, respectively. The marginal impacts from LDT shown in Table 2 are not uncommon in the LDA literature to date. However, these are 8-yr averages over the period and the three sites, and thus the impacts at any given time (such as those seen in Figs. 1 and 2) would be expected to be more significant. In addition, soil moisture is a more slowly varying component of the model on diurnal time scales compared to surface fluxes, which ultimately the coupled model responds to more directly.

To assess the more practical coupled impacts, 3-hourly surface $Q_{le}$ and $Q_h$ were evaluated across eight ARM-SGP flux sites during the May–September 2006 and 2007 summertime periods (Table 3), corresponding to the coupled case study periods. Results (RM vs OL) show only a small reduction in $Q_{le}$ and $Q_h$ biases in 2006 and even less improvement in RMSE. These minor impacts correspond with the smaller LDA increments seen in the summer 2006 period (Fig. 2). In contrast, the 2007 period shows more substantial bias reduction due to LDA than in 2006. The $Q_{le}$ high bias and $Q_h$ low bias are both reduced, thus raising the Bowen ratio closer to what is observed. This is consistent with the LDA acting to lower the soil moisture during the wet regime as discussed above. Also note that the larger RMSE and bias impacts are seen in $Q_h$ in the dry year and $Q_{le}$ in the wet year, as they are the dominant fluxes during each regime [consistent with the larger impacts of calibration during dry vs wet periods shown by Santanello et al. (2013a)].

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**FIG. 5.** As in Fig. 2, but for the differences in (a) SM − OL at site 2022, (b) SL − OL at site 2023, and (c) SL − OL at site 2092.
A closer look at the diurnal cycle of flux impacts for July 2006 and 2007 are shown in Figs. 3 and 4 for the SCAN sites. As expected from the small increments seen in Fig. 2 during July 2006, only small changes in surface fluxes ($<50 \text{ W m}^{-2}$) are seen with an increase in $Q_h$ and decrease in $Q_{le}$ due to slight drying of the soil from assimilation. July 2007 shows much larger impacts on surface fluxes (up to $\sim 150 \text{ W m}^{-2}$) that correspond to the 0.10–0.15 m$^3$ m$^{-2}$ drying during this wet regime. These magnitudes are quite large, and thus soil moisture LDA has potential to significantly impact land–PBL coupling on diurnal time scales through surface fluxes, depending on the regime and time period considered.

2) SCALING AND BIAS CORRECTION IMPACTS

While the analysis above focuses on the raw, monthly LDA simulation, there is information to be gained from the remainder of the combinations of scaling and CDF-matching approaches. Figure 5a shows the LDA impacts from the scaled, monthly (SM - OL) simulation at site 2022, and compared to Fig. 2a it shows a slightly more muted response with a slightly smaller range of increments, but similar overall patterns and signs of the increments. The difference between Figs. 5a and 2a is that the former uses AMSR-E soil moisture retrievals that are already scaled to the Noah LSM (through GLDAS), so these results are not all that unexpected.

Figure 5b shows the LDA impact of using a scaled, lumped (full annual CDF matching) approach (SL - OL) at site 2023. It is evident that the impacts are reduced considerably in this case compared to Fig. 2b, often approaching zero, and, more importantly, never resulting in positive increments (i.e., wetter soil due to LDA). As it is highly unlikely that the LSM is always wetter than the AMSR-E observations in reality, this result is an artifact of the lumped CDF approach for this particular site as opposed to the monthly (Fig. 2b). Matching to an annual cycle has indeed been
shown to improve LDA results during certain periods, but in turn to balance out the CDF must generate artificially high (low in this case) values during other extended periods.

Interestingly, the SL approach at site 2092 (Fig. 5c) produces impacts that are nearly opposite those at site 2022, with high-amplitude annual cycles shown that are larger than those in the original RM simulation (Fig. 2c). This too is an artifact of the lumped CDF-matching approach, where the seasonal signal dominates and implicitly generates unrealistic increments that are the same in winter (positive) and summer (negative) regardless of the actual conditions. Statistics in Tables 2 and 3 also support that RM performs better than the other permutations, and in particular the simulations using the lumped CDF approach consistently have the highest biases. Ultimately, the real-time information from AMSR-E is lost in the lumped approach, and RL – OL results (not shown) support similar conclusions.

3) FORCING SENSITIVITY

A key component of an offline LDA system that is often overlooked is that of the atmospheric forcing. In particular, the precipitation applied to the LSM has a direct impact on the simulated soil moisture, and thus better precipitation produces more accurate simulations. To explore the sensitivity to forcing, a series of runs was produced using GDAS forcing (GRM and GOL), which is a much coarser resolution than NLDAS-2 and does not have bias or gauge-corrected precipitation. GDAS also represents the typical modeling scenario at most regions of the world where high-quality precipitation products such as NLDAS-2 are not available.

The overall impacts of LDA in GDAS versus NLDAS-2 forced simulations are shown in Figs. 6 and 7. LDA increments (GRM – GOL) are much larger, variable, and often of opposite sign to those from the NLDAS-2 runs (RM – OL). This is likely because
of the lower precipitation accuracy of GDAS, creating a model state that needs more severe correction based on the AMSR-E observations. Figures 8 and 9 show the surface flux differences (GRM – GOL) at the three SCAN sites for the July 2006 and 2007 periods (similar to Figs. 3 and 4). In 2006, there is a marked increase in flux impacts over that seen in the NLDAS-2 runs, often approaching or exceeding 200 W m$^{-2}$. The impacts are more variable in time as well, including varying signs of increments throughout the period and across the three sites. Flux impacts are more consistent with NLDAS-2 in 2007 in magnitude and sign (drying due to LDA).

Statistics in Table 2 support that the soil moisture simulated by GOL is much poorer than that from OL, leading to considerable improvements in GRM that are on par with that of RM. This is also the case in terms of fluxes, whereby the large 2006 RMSE and bias value in GOL are reduced in GRM (and approximately match those of RM). The year 2007 sees more marginal results, and it should be noted that both OL and GOL perform similarly with only little improvement due to LDA.

b. Coupled results

1) Spatial impacts

The impacts of LDA on NU-WRF simulations are felt solely through the soil moisture initial conditions generated by the offline LIS spinup runs. The domainwide initial conditions differences from the NLDAS-2 (RM – OL) and GDAS (GRM – OL) simulations for the 14 July 2006 case study can be seen in Figs. 10a and 10b. Overall, the magnitudes are similar across much of the domain ($\pm 0.05$ m$^3$ m$^{-2}$), with a mix of small drying (negative) and wetting (positive) due to LDA. However, the GDAS runs show larger magnitude ($>0.10$ m$^3$ m$^{-2}$) and more positive increments across much of the southern and southeastern portion of the domain.

The midday evaporative fraction [EF; defined as Qle/(Qle + Qh)] as an indicator of the surface energy...
balance is shown in Figs. 10c and 10d. EF traces rather consistently in space and sign with that of the initial soil moisture increments. In particular, the NLDAS-2 runs show higher EF where the LDA acted to increase the soil moisture in the northeastern portion of the domain. Minor impacts are seen elsewhere. In contrast, the GDAS results show very large EF impacts (more than $\pm 0.15$), aligning closely with the regions of soil moisture increments. These flux impacts are what the atmospheric and PBL components of NU-WRF respond to directly. Thus, the midday PBL height (Figs. 10e,f) impacts correspond closely to both the EF and soil moisture increments, with wetter soil leading to higher EF and lower PBL growth. In 2007, PBL impacts on the order of $\pm 500$ m over much of the domain. The fully integrated impact of the land–PBL system can then be represented by the 2-m temperatures ($T_2$), as shown in Figs. 10j and 10k. Impacts are up to 3 K in either direction and again correspond to the sign of the soil moisture increment as modulated by the EF and PBL growth. The positive feedback of PBL growth and warm (dry) air entrainment on higher 2-m temperature [2-m humidity ($Q_2$); not shown] can also be seen in the larger swath of positive $T_2$ values in 2007 relative to the regions of PBL depression.

Figure 11 shows the corresponding plots for the 26 July 2007 wet regime case study. What is most noticeable is the overall negative (drier) increments applied across the domains in both NLDAS-2 and GDAS, consistent with the offline analysis of this period. Drier soils lead to lower EF, as expected, with some similar spatial patterns across the simulations. This leads to generally larger PBL growth, especially in the northern half of the domain, and a wash of a 0–2-K increase in $T_2$ over much of the domain in each. Overall, compared to 2006, the differences in NLDAS-2 and GDAS and magnitudes of coupled impacts are smaller during the wet regime, once again supporting that the LSM has a strong wet bias in that year that the LDA consistently corrects.
FIG. 10. Differences in RM−OL and GRM−GOL in (a),(b) 0–10-cm soil moisture (m³ m⁻³) at the initial time and (c),(d) EF; (e),(f) PBLH (m); and (g),(h) T2 (K) at the 2100 UTC 14 Jul 2006 NU-WRF simulations.
FIG. 11. As in Fig. 10, but for the 26 Jul 2007 simulations.
FIG. 12. Mixing diagrams for the OL, RM, GOL, and GRM simulations and observations at the ARM-SGP E4 site for the (a) 14 Jul 2006 and (b) 26 Jul 2007 case studies. The surface and atmospheric Bowen ratios ($\beta_{\text{bsfc}}$, $\beta_{\text{atm}}$) and latent and sensible heat flux ratios ($A_{\text{Qle}}$, $A_{\text{Qh}}$) are also shown as defined in Santanello et al. (2013b).
make things slightly drier again in this case (away from observed), and thus the statistics confirm that the OL and GOL runs perform better than RM and GRM. The LCLdef (not shown) impacts from LDA are also consistent with a drier surface, producing a higher LCL change relative to PBLH, thus increasing LCLdef and taking the coupled state farther from saturation. This has implications downstream in terms of reducing support for clouds and precipitation. Overall, impacts at this single site are mixed but demonstrate the variable nature of LDA impacts as different scales and locations are considered.

3) AMBIENT WEATHER

A more robust measure of whether the LDA is making an overall positive impact on the land–PBL coupling in NU-WRF can be found through analysis of T2 and Q2 at a network of sites across the domain. Figures 14 and 15 show the hourly T2 and Q2 RMSE and bias statistics across ~50 sites distributed throughout the domain. As shown earlier, T2 and Q2 represented the fully integrated impacts of the soil moisture increments through the fluxes, PBL, and onto ambient weather.

Focusing on the daytime period (12–24 h), it is immediately evident that the GOL simulation is the poorest, showing a warm, dry bias throughout. The impact of LDA (GRM) is to improve these statistics across the board, particularly in late afternoon when the land–PBL feedbacks are at their strongest. OL and RM are very similar throughout, with some small improvement of a warm, dry bias seen in T2 and Q2 in late afternoon as well. It should be noted that overall, the Noah LSM, regardless of forcing or LDA, has a significant warm (5 K) and dry (3–4 g kg\(^{-1}\)) bias during the daytime versus the open-loop runs. As evident from the offline analysis, the LDA acts to dry the soil during the wet regime, which indicated the model may have a wet bias initially, but these results suggest that the uncertainty and bias may lie also in the satellite retrievals themselves during this period.

The impacts of LDA on wind components and precipitation (not shown) were also quantified in similar fashion against observations. Overall, there is very little change in wind (zonal \(U\) and meridional \(V\)) components.
in terms of RMSE or bias, and no consistent signal of LDA improvement or degradation with respect to wind in any of the case studies. Likewise, there was very little precipitation observed over the domain in the 26–27 July 2007 period. While all four simulations tend to produce slightly higher and more widespread precipitation than observed, there was only a slight decrease in precipitation amounts due to LDA, which is consistent with the small drying increments observed in RM and GRM of Fig. 12b.

5. Discussion and conclusions

LDA techniques that exploit satellite-based soil moisture observations continue to be developed and implemented in increasingly complex offline and coupled
modeling systems. Here, a practical assessment has been made of the potential impacts of soil moisture LDA on offline spinups and initialization of short-term forecasts. This includes sensitivities to variants of traditional scaling and bias correction approaches as well as atmospheric forcing, the impacts of which are quantified over a range of scales from diurnal to interannual, and local to regional.

Results from the offline experiments show that large soil moisture increments (up to 50% of the dynamic range) from LDA are common across the domain and 8-yr period. While impacts can vary significantly from site to site and year to year, extreme regimes (such as that in 2007) produce increments that are larger and more spatially consistent. Traditional metrics such as anomaly correlation and RMSE tend to mask the larger, potential short-term and local impacts of LDA, which can be demonstrated through seasonal and diurnal cycle analyses.

Quantifying surface flux impacts is also critical, as they represent the direct link between the LSM and coupled model (through the PBL). To this end, there are large impacts (over 200 W m\(^{-2}\)) on sensible and latent heat fluxes on diurnal scales, thus supporting the idea that LDA can have a significant impact on LA coupled processes. LoCo analyses show domainwide impacts on the process-chain connecting soil moisture to surface fluxes to PBL growth to ambient weather.

A key result found here is that there are major implications for the choice of atmospheric forcing used in LDA experiments. High accuracy forcing (such as NLDAS-2) generates a much different open-loop model climatology than does a coarser, global model–based forcing (GDAS). As a result, LDA increments can vary greatly between the two simulations both in sign, magnitude, and response to extreme conditions. The end
result (i.e., soil moisture analyses) of LDA in each case is nearly identical and produces very similar statistics, surface fluxes, and coupled impacts. Ultimately, LDA has greater potential for improving simulations when only lower resolution and accuracy forcing is available, which is common over most of the globe and outside of the United States.

When stratifying by regimes, bulk statistics show that dry-to-moderate soil moisture conditions (2006) see more potential improvement due to LDA, particularly when GDAS forcing is used. During the wet regime, LDA impacts are more limited in terms of offline and coupled statistics, indicating that there is less divergence in the results because of quality of forcing. In the wet year, there is frequent and widespread precipitation keeping soil moisture values high throughout. In the dry year, precipitation is much more nonuniform and soil drying is more heterogeneous. As a result, the quality of precipitation forcing makes a larger impact in 2006 and, in turn, there is larger potential benefit from LDA when using GDAS forcing [consistent with Liu et al. (2011)]. Individual site impacts also vary in both years, and examples are shown where the LDA increments act to dry the soil and coupled system in both cases away from observations (i.e., LSM has a dry bias at this site, and LDA increases that bias).

In terms of technical LDA aspects, using raw AMSR-E data and monthly CDF matching (RM) produces the most physically meaningful results, retaining the true observable value of the AMSR-E measurements without introducing modeled or statistical artifacts in the LDA system. In contrast, larger errors are introduced by using a lumped CDF matching (RL and SL) that can generate an unrealistic annual cycle of LDA increments,

![Graphs showing T2 RMSE and Bias](image-url)
consistent with recent work by Kumar et al. (2015b). These errors can also result in larger biases in down-
stream (e.g., surface flux) components of the system. Using raw observations is also recommended when the
scaled versions are tied to a particular LSM climatology
(such as the Noah LSM in GLDAS in the case of AMSR-
E). Overall, the impacts of these various approaches are
particularly important for the LDA community to rec-
ognize, particularly as a de facto approach such as lumped
CDF matching may produce inferior results that can be
missed when only evaluating over large domains through
cumulative anomaly statistics.

Last, the results here are promising for the potential
use of satellite soil moisture to improve LSM spinup and
coupled prediction. Even considering the limitations of
AMSR-E in terms of spatial resolution and accuracy
relative to a high-resolution modeling system such as LIS,
there is still considerable improvement possible
though LDA, particularly where high-resolution pre-
cipitation data are unavailable. Results also stress that a
more holistic approach should be considered when
evaluating the impacts of LDA, as there will be locations,
periods, and metrics when LDA impacts are positive
(domainwide improvement in ambient weather) and
others where they are confounding (e.g., LoCo analysis at
E4). That the EnKF approach works consistently to
produce similar results regardless of the open-loop state is
an important result, supporting the robustness of the al-
gorithm and bias correction applied. Current and future
sensors (e.g., SMOS and SMAP) will be able to provide
even finer-resolution soil moisture information that will
be on par with that of even the best forcing data available
(e.g., SMAP at 9 km vs NLDAS-2 at 12 km), at which
time the importance and impacts of LDA will become
even larger for LSM and NWP applications.

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