Improving the Initialization of Soil Moisture in Numerical Weather Prediction – Phase 2

FINAL REPORT

for the

Korea Institute For Atmospheric Prediction Systems

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1. Preface

The Institute of Global Environment and Society, Inc. (IGES, a non-profit, tax exempt institute, incorporated in the State of Maryland, USA) seeks to improve understanding and prediction of the variations of the Earth's climate through scientific research on its variability and predictability, and to share both the results of, and the tools necessary to conduct, this research with society as a whole. Toward this goal, IGES has established the Center for Ocean-Land-Atmosphere Studies (COLA). COLA has become a national center of excellence for research on climate variability and predictability.

The goal of COLA research is to explore, establish and quantify the predictability of intra-seasonal to inter-decadal variability of the present climate through the use of state-of-the-art dynamical coupled ocean-atmosphere general circulation models and the development of new techniques for analysis of observational and model data. COLA continues its multi-decade service as a unique institution that enables Earth scientists from several disciplines to work closely together on interdisciplinary basic and applied research related to variability and predictability of Earth's climate on intra-seasonal to inter-decadal time scales. The main scientific premise for research at COLA is that, while the chaotic nature of the global atmosphere imposes a limit on climate predictability at a given instant, there is predictability on longer time scales due to low-frequency fluctuations and the interactions between atmosphere and ocean and atmosphere and land. This makes possible accurate and useful climate forecasts with lead times longer than the inherent limit of instantaneous deterministic predictability.

Scientists at COLA use computer models of the Earth’s global atmosphere, world oceans and land surface in numerical predictability experiments and experimental predictions, and they develop and use advanced techniques for analysis of observational and model data. By seeking to always use a suite of the best available climate models, COLA scientists remain at the forefront of research advancements. Close coordination of the predictability research and experimental predictions is a high priority.

This proposal seeks funding to continue the collaboration with the Korea Institute For Atmospheric Prediction Systems (KIAPS) that was initiated in 2012 to develop a more robust and accurate weather and climate prediction system.

2. Introduction

The importance of land surface variability in modulating and contributing to climate predictability on weather, intra-seasonal and longer time scales has long been recognized. In particular, the role that soil moisture anomalies play in enhancing predictability has been the focus of a great many numerical experiments that COLA has helped lead (Shukla and Mintz, 1982; Dirmeyer et al. 2009), including the multi-model Global Land-Atmosphere Circulation Experiment (GLACE; Koster et al. 2006) that evaluated the sensitivity of climate to soil moisture anomalies, and the second generation of GLACE (GLACE-2; Koster et al. 2010) that examined the impact of antecedent soil moisture anomalies on climate prediction skill.

Based on the hypothesis that the land surface state, particularly the soil moisture and vegetation, has a large impact on the weather, numerical weather forecasts, subseasonal and seasonal predictions require the state of the atmosphere and land to be initialized from the most realistic conditions at the start of the forecasts (Shukla and Kinter 2006). This ensures a realistic evolution of the forecast from its start. Atmospheric initialization is an old problem with many decades in the development of data assimilation and procedures to perturb initial states to produce ensemble forecasts that sample the likely range of evolution of weather and shirt-term climate. Similar treatments for the land surface are relatively new, and a variety of methods have been proposed whose strengths and weaknesses remain to be evaluated.

3. Background

3.1 Motivation for better land surface initialization

Results from the second phase of the Global Land-Atmosphere Coupling Experiment (GLACE-2; Koster et al. 2010, 2011) quantified, with a suite of long-range forecast systems, the degree to which realistic land surface initialization contributes to the skill of subseasonal precipitation and air temperature forecasts. Significant contributions to temperature prediction skill out to two months were found across large portions of the North American continent, as well as other parts of the globe. For precipitation forecasts, contributions to skill are weaker but are still significant out to 45 days in some locations.

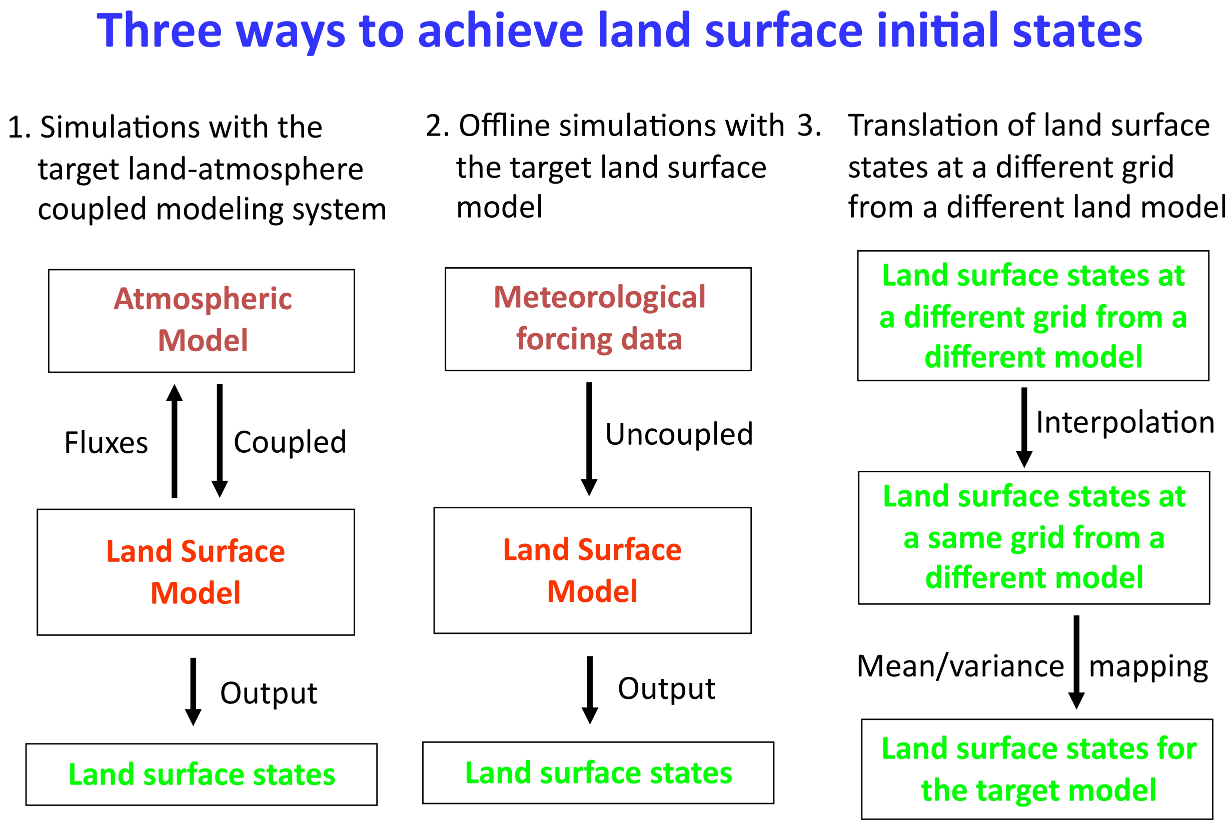
The GLACE-2 models show modest but significant skill especially where the rain gauge network is dense (Koster et al. 2011). Given that precipitation is the chief driver of soil moisture, and thereby assuming that rain gauge density is a reasonable proxy for the adequacy of the observational network contributing to soil moisture initialization, this result indeed highlights the potential contribution of enhanced observations to prediction. Land-derived precipitation forecast skill is much weaker than that for air temperature. The skill for predicting air temperature, and to some extent precipitation, increases with the magnitude of the initial soil moisture anomaly.

Skill improvements for surface air temperature forecasts are tied to the sensitivity of surface fluxes to soil moisture, which are optimum in a middle range between wet and very dry conditions. Thus, humid regions have more predictability and skill realized during relatively dry conditions for the area, while arid regions experience more skill when conditions are wetter than normal.

Another factor that can be exploited to improve forecasts during spring in mid-latitudes is an apparent rebound in predictability from soil moisture states (Guo et al. 2011, 2012). The sensitivity of forecasts to the initial soil moisture state emerges over much of the United States in late May, with realistic land initialization leading to much more predictability. Predictability is stored in the soil moisture states, and is released to the atmosphere only after the coupling between the two has been established, late in spring.

Recent assessment of the operational forecast model from the U.S. National Centers for Environmental Prediction (NCEP) shows that forecast skill for precipitation on subseasonal time scales, including the deterministic range for weather forecasts (the first 7 days of the forecasts), is also sensitive to the initial soil moisture state (Dirmeyer 2013). There is considerably more skill over much of the globe when the initial soil moisture state is in the wettest or driest fifth of its range than for all forecasts taken as a whole. There is a strong ling between extreme soil moisture states and subsequent precipitation.

3.2 *Methods of land surface initialization*



As shown in the diagram above, three methods can be used to initialize the land surface states in the numerical weather prediction (NWP) system: 1. Snap output of land surface states from the land-atmosphere coupled modeling system; 2. Snap output of land surface states from the offline land surface simulations, where the uncoupled land surface model is forced with the meteorological forcing data; 3. Translation of an existing set of land surface states from either a coupled or offline simulation generated by a land surface model, which is not necessarily the same as the one used in the NWP system. Also, the grid may be different from the atmospheric model grid. Since the land surface model used in the target NWP system is under consideration, and was not available at the time of this project, the last method becomes the only choice.

3.3 *Consistency of initial states*

To provide initial land surface states for a weather forecast model with minimal shock or spin-up, the climatological statistics of the initial states should match those of the forecast model. The optimum way to ensure this consistency is to take the initial states from a version of the same land surface model as is coupled to the atmospheric model, on the same grid, at the same resolution with the same distribution of land surface properties (soil properties, vegetation, albedo, etc.). This is the rationale behind the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) approach to model initialization.

GLDAS drives offline land surface models (not coupled to the atmosphere) with observation-based data, and executes globally at spatial and temporal resolutions useful for both weather and climate prediction. More information is available at the Land Data Assimilation Systems (LDAS) and Land Information System (LIS) websites.

Because the climate of atmospheric models is biased relative to that of nature in terms of both the mean and variance, land surface states generated offline need to be transformed before they are used to initialize GCM forecasts. The value of a variable produced with the offline system can be converted to a standard normal deviate for the date in question (i.e., an anomaly expressed in units of standard deviations), and this standardized value combined with the corresponding mean and standard deviation of the host atmospheric model to produce the proper initialization value (Koster et al., 2009). A climatology of the host GCM forecasts is needed to perform this scaling step.

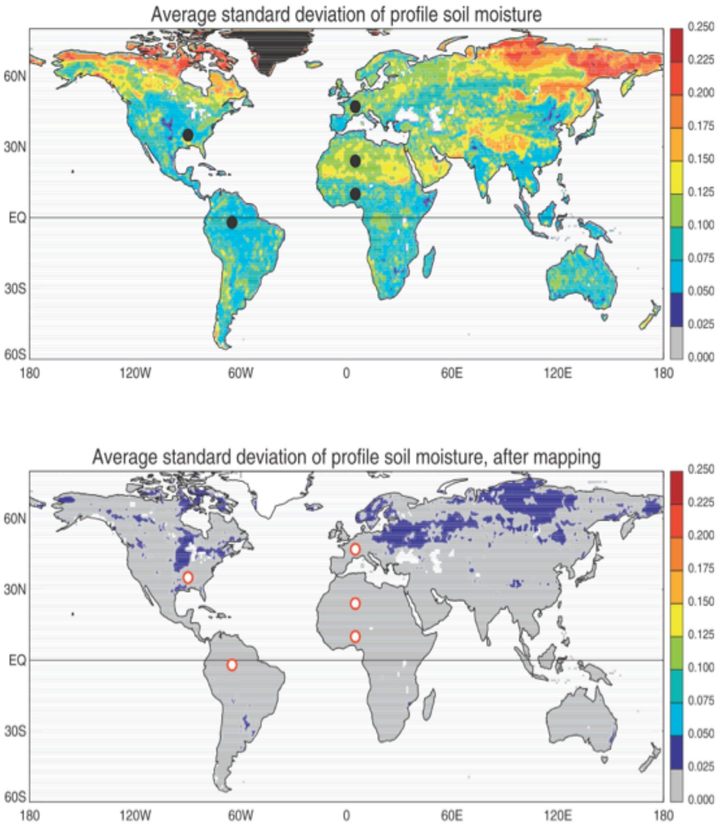


Figure 1 Impact of renormalization on the inter-model standard deviation of soil moisture in GSWP-2.

3.4 *Cross-model consistency*

This same issue of consistency in the first two statistical moments applies to taking data from a different land surface model, or even from observations, and using it in the host land model. The result of renormalization by the method of standard normal deviates is shown in Fig 1 (from Koster et al. 2009). Variation among the simulations of soil moisture for participating land models in the Second Global Soil Wetness Project (GSWP-2 Dirmeyer et al. 2006) is shown as the standard deviation in the top panel. After each model was mapped to a common framework, expressing soil moisture as standardized deviations from each model's mean at each point for the same 10-year period, the inter-model differences are one to two orders of magnitude smaller.

Failure to renormalize degrades forecast skill. Figure 2 shows that skill when soil moisture from one land model is applied without renormalization to initialize another model, the skill worse than forecasts with either model initialized consistently.

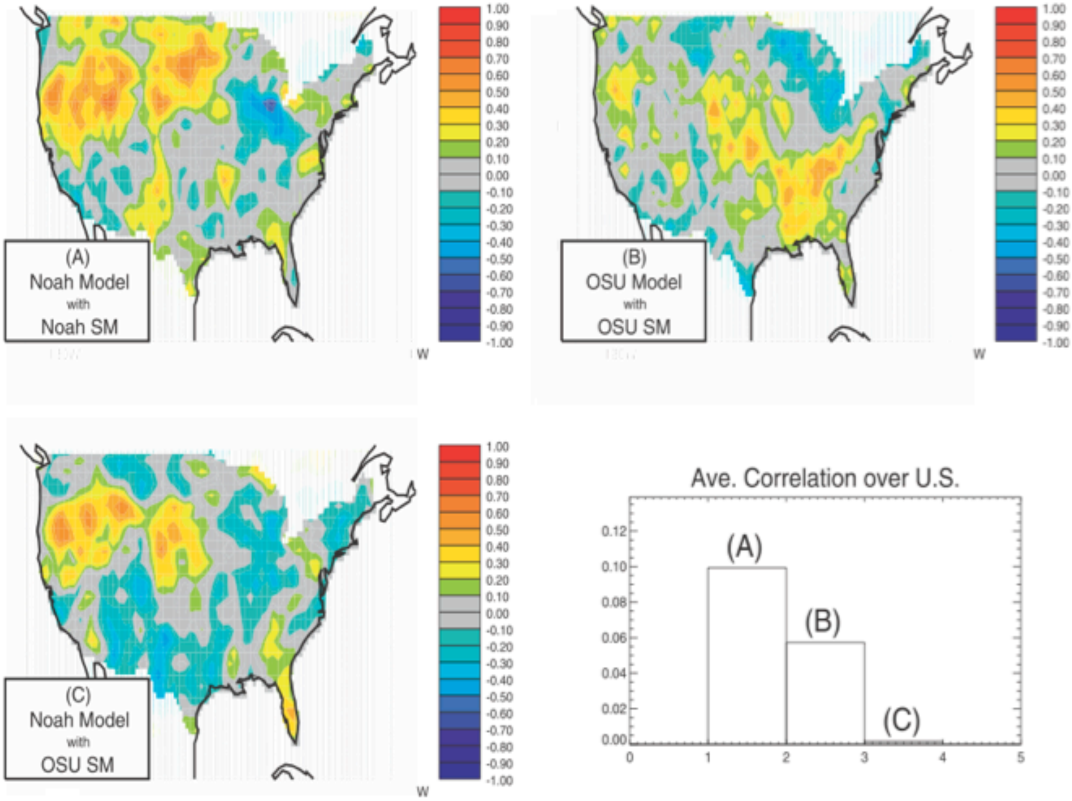


Figure 2: Impact of inconsistent soil moisture initialization on forecast skill.

3.5 *Multi-model initialization*

While initialization with data from the same model provides the most consistent initialization (Sec 2.2), the loss in consistency may be rather small when appropriate renormalization is applied (Sec 2.3). Therefore, it may be more advantageous to use a multi-model analysis as the basis for initialization of forecasts. This is because multi-model analyses have been shown to have smaller soil moisture errors relative to *in situ* observations than the products of individual models (Gao and Dirmeyer 2006). This fact was used as motivation for the production of a multi-model analysis for GSWP-2.

Figure 3 shows the error in the GSWP-2 multi-model analysis relative to the errors from each of the input models to the analysis, several independent land model analyses, and several reanalysis products. Validation is against soil moisture measurements accumulated across Asia, Europe and North America. The multi-model analysis performs consistently better than products based on a single model.

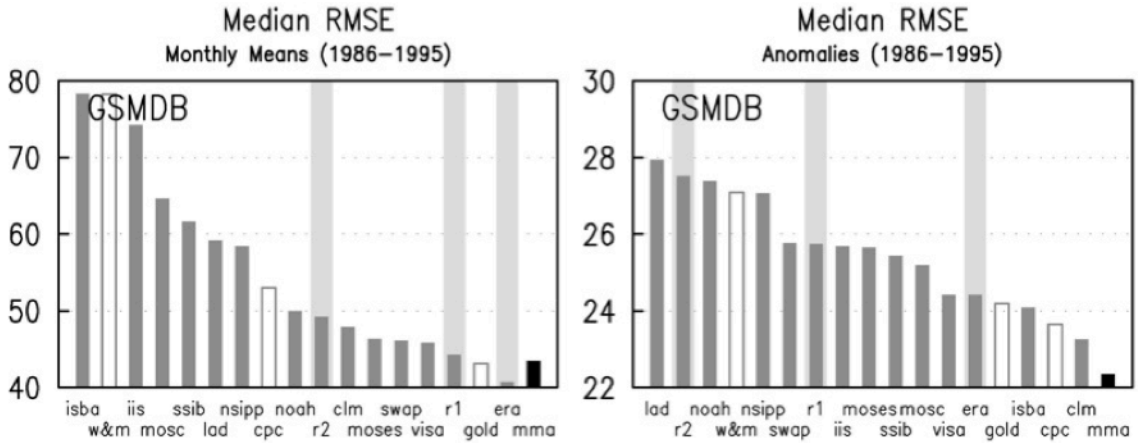


Figure 3: Performance of GSWP-2 multi-model analysis (black bar) versus the individual input models (grey), independent one-model analyses (white) and three reanalyses (light grey background stripe).

4. Work Performed

4.1 Accomplishments

The following tasks were accomplished in the course of this project.

1. Meteorological forcing data for the offline run with NOAH at NE30NP4 grids
   The Princeton three-hourly meteorological forcing data (global 1x1 degree resolution, 1948-2010) have been interpolated to the NE30NP4 cubed-sphere grids. The variables include: downward long-wave radiation, downward shortwave radiation, precipitation rate, near-surface air temperature, air specific humidity, air pressure, wind speed.

2. Fixed fields for the offline run with NOAH at NE30NP4 grids
   All parameters and the fixed fields for the offline run with NOAH have been prepared at NE30NP4 grids. They include: modified IGBP/MODIS vegetation type, USGS vegetation type, STATSGO/FAO soil type, bottom soil temperature, maximum volumetric soil

moisture, soil moisture wilting point, monthly greenness fraction, annual maximum greenness fraction, annual minimum greenness fraction, background surface albedo.

3. NOAH land surface schemes
   NOAH versions 2.7.1, 3.4.1, and MP1.1 have been successfully configured for its run at NE30NP4 grids.

4. NOAH offline simulations at NE30NP4 grids
   Both the NOAH version 2.7.1 and 3.4.1 have been run at the NE30NP4 grids for the years from 1948-2010. The daily restart files and outputs have been archived.

5. CLM Version 4.5 offline simulations at NE30NP4 grids
   CLM version 4.5 has been run at the NE30NP4 grids for the years from 1948-2012. Daily outputs have been archived, but only the monthly outputs have been transferred back to COLA due to its huge data volume.

6. GLDAS datasets
   All GLDAS datasets (1-degree version 1, quarter degree version 1, and 1-degree version) have been regularly updated.

4.2 Deliverables

Datasets and model source codes have been developed that are available to KIAPS researchers in the COLA computer system:

1. Meteorological forcing data for the offline run with NOAH at NE30NP4 grids
   /project/kiaps/NE30NP4_FORCING

2. Fixed fields for the offline run with NOAH at NE30NP4 grids
   /project/kiaps/KIAPS_SRC/NOAH2.7.1/NOAH_NE30NP4_FIXED.nc

3. Source codes for the NOAH land surface schemes
   /project/kiaps/KIAPS_SRC

4. NOAH version 2.7.1 offline simulations at NE30NP4 grids
   /project/kiaps/KIAPS_NOAH2.7.1

5. NOAH version 3.4.1 offline simulations at NE30NP4 grids
   /project/kiaps/KIAPS_NOAH3.4.1

6. CLM version offline simulations at NE30NP4 grids
   /project/kiaps/KIAPS_CLM4.5.0

7. GLDAS datasets:
   One-degree GLDAS-V1 datasets: /project/kiaps/GLDAS_NC_10
   Quarter-degree GLDAS-V1 datasets: /project/kiaps/GLDAS_NC_025
   One-degree GLDAS-V2 datasets: /project/kiaps/GLDAS_NC_10V2

4.3 Land Surface Modeling Workshop

As part of the project, COLA/GMU hosted a Workshop on Land Surface Modeling in Support of NWP and Sub-Seasonal Climate Prediction, during 5-6 December 2013, which brought together experts in land surface, weather and climate modeling and evaluation from around the world to discuss issues pertinent to the improvement of forecasts through improved initialization of the land surface state and the representation of coupled land-atmosphere processes in numerical forecast models.

Variations in land surface state can have a profound influence on weather and short-term climate. Land surface models are representations of the processes involving fluxes of energy, water and momentum between the atmosphere and the land surface, as well as land states like soil moisture, snow cover, heat content and vegetation. Land surface modeling (LSM) is, therefore, a critical component for both NWP and sub-seasonal climate prediction (SSCP). COLA and KIAPS are collaborating in this project to develop a set of codes for LSM and NWP that may be interesting and useful to a wider audience. The workshop addressed the needs for LSM in the context of real-time NWP and SSCP, with emphasis on the following questions:

- What is the role and importance of the representation of interactions among different spatial scales, including those unresolved by the atmospheric model? Do LSMs need to include scale-aware parameterizations for incorporation in both NWP and SSCP systems?
- What is the role and importance of interactions between the land surface and the planetary boundary layer during the course of the diurnal cycle? How do these interactions manifest on sub-seasonal time scales?
- What is the role and importance of land surface memory (persistence of anomalies) and land-atmosphere feedbacks in the transition between NWP time scales and (sub-seasonal) climate time scales?

The 1.5-day workshop was attended by 45 scientists and program managers from nine countries. An agenda, complete set of abstracts, copies of the presentations and list of participants is available at: http://www.iges.org/lsm/

The workshop will result in a white paper in 2014 that will serve as a guide to accelerating improvements in our representation and initialization of the land surface in operational weather and climate forecast models.

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