Improving the Initialization of Soil Moisture in Numerical Weather Prediction

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 report describes the collaborative work initiated with the Korea Institute For Atmospheric Prediction Systems (KIAPS) 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 a central theme of COLA research. 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, 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. 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.

We have completed a feasibility study for the Korea Institute For Atmospheric Prediction Systems (KIAPS) to evaluate the efficacy of and further develop a method of initialization of the land surface in numerical weather prediction (NWP) models. The primary purpose of this project has been to develop and implement a land initialization procedure for NWP that will significantly enhance the prediction capability of the model(s) under consideration for use in NWP by KIAPS.

3. Motivation

Numerical weather forecasts, subseasonal and seasonal predictions need atmospheric and land surface initialization — the specification of atmospheric pressure, temperature, wind, humidity, soil moisture, soil temperature, and snow (especially SWE, Snow Water Equivalent) at the beginning of the forecast. Numerous studies show that the forecast skill relies heavily on accurate atmospheric initialization and 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 much weaker but are still significant out to 45 days in some locations.

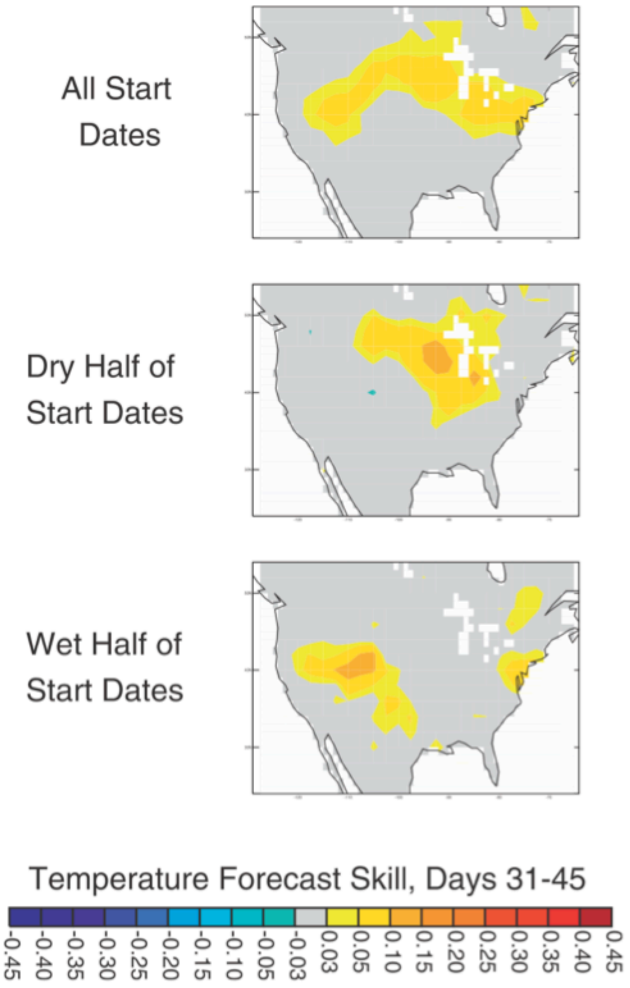

Figure 1.

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 assuming that rain gauge density is a reasonable proxy for the adequacy of the observational network contributing to soil moisture initialization, this result highlights the potential contribution of enhanced observations to prediction. Landderived 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.

Figure 1 shows the increase in skill realized for surface air temperature forecasts over North America in GLACE-2. Air temperature forecast skill (r^2 against observations for realistically initialized vs. uninitialized land states) for the 30-day lead (days 31–45). (Top) All start dates. (Middle) Start dates for which the local initial soil moisture lies in the driest half of all values realized there. (Bottom) Start dates for which the local initial soil moisture lies in the wettest half of all values realized there. The improvements 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 is an apparent rebound in predictability from soil moisture states (Guo et al. 2011, 2012). Figure 2

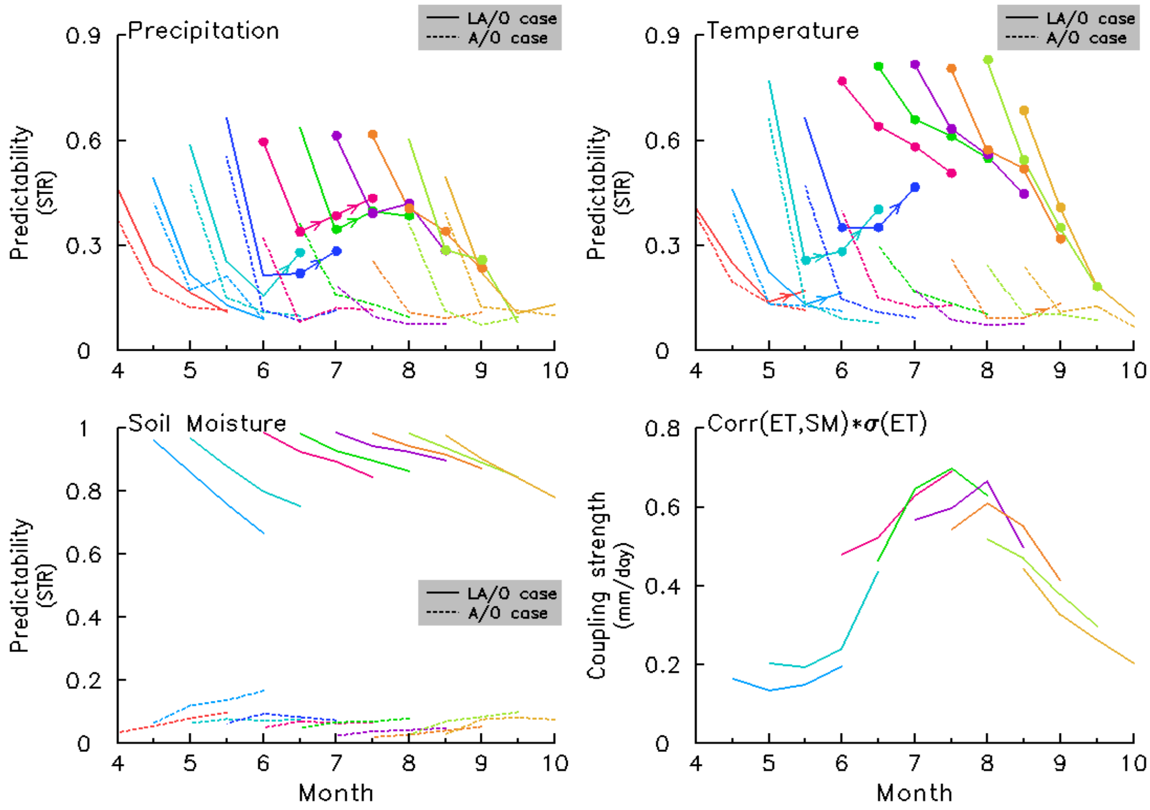

Figure 2

shows the evolution of predictability (signal to total ratio of variances) of temperature and precipitation over the continental United States for forecasts initialized every half-month from April through August, as well as for soil moisture and correlation between soil moisture and surface evapotranspiration (a measure of the strength of coupling of the atmosphere to the state of the land surface). Dotted lines are for the suites of forecasts with random land surface initialization, sold lines for realistic land surface initialization. Beginning in late May, the curves for the two initialization strategies begin to diverge, with realistic land initialization leading to much more predictability. Predictability significantly increases for certain time intervals (arrows), in apparent violation of the notion that predictability must always decrease over time (analogous to the second law of thermodynamics that requires entropy to increase monotonically with time). In fact, for the entire system, the predictability does decrease. What occurs is that 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. The dots in Fig. 2 show times when the predictability is significantly different between forecasts with initialized and uninitialized land surface states.

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, 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. Figure 3 shows the difference in the correlation between initial soil moisture states and subsequent forecast precipitation (left) and observed precipitation (right). The preponderance of red in all panels suggests a strong link between extreme soil moisture states and subsequent precipitation.

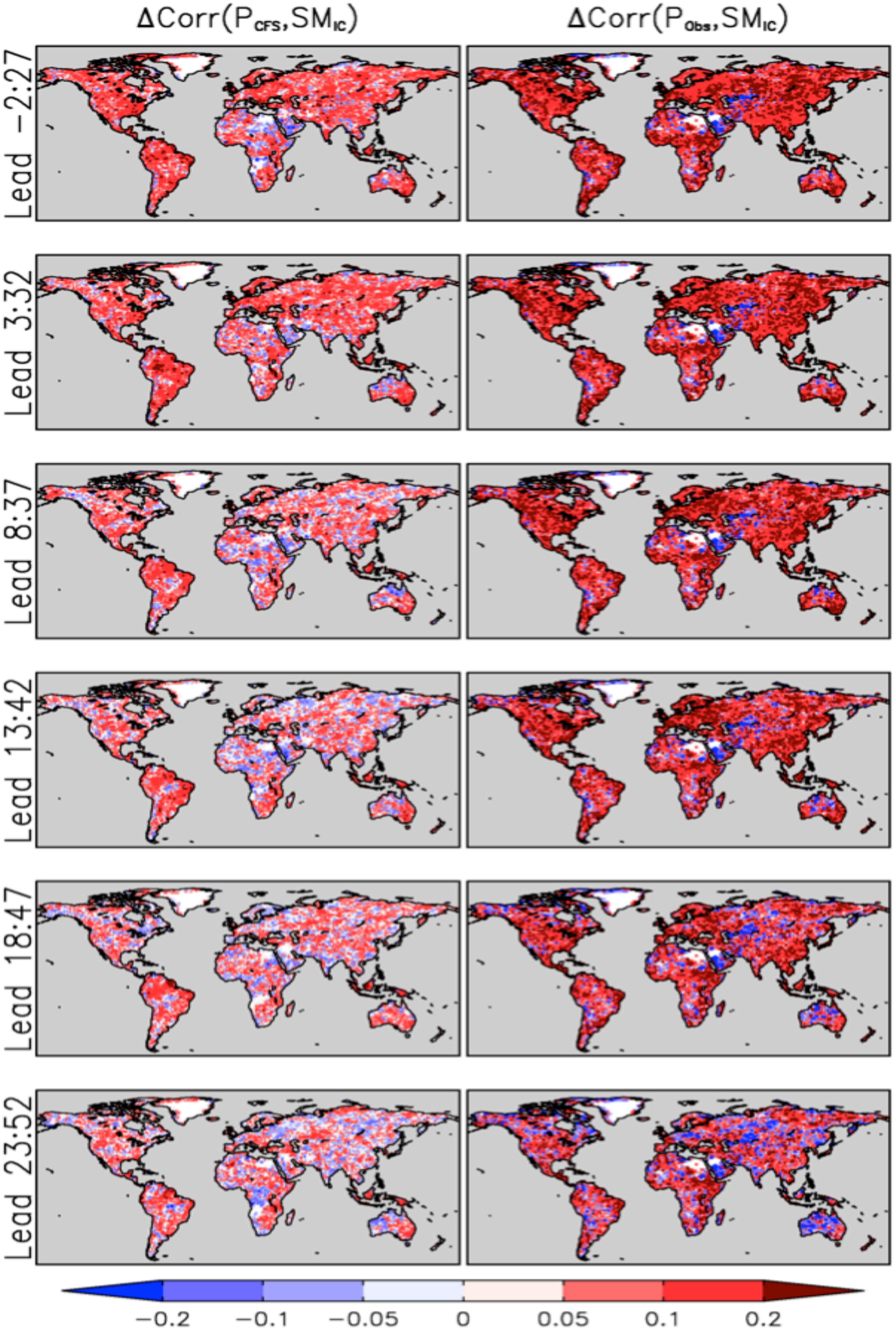
ΔCorr(P_CFS,SM_IC)
ΔCorr(P_Obs,SM_IC)
Lead −2:27
Lead 3:32
Lead 8:37
Lead 13:42
Lead 18:47
Lead 23:52
−0.2
−0.1
−0.05
0
0.05
0.1
0.2

Figure 3

4. Work Performed

We have applied a standard method of generating initial soil wetness to develop a method for initializing the land surface in potential KIAPS NWP systems. In this method, sets of realistic global land initial conditions are created by driving a land surface model (LSM) offline (i.e., disconnected from the host atmospheric general circulation model or GCM) with realistic fields of precipitation, radiation, and other meteorological forcings. This approach has been used retrospectively in the Global Soil Wetness Project (GSWP; Dirmeyer et al., 2006), and in near-real-time by the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004).

In this project, we have applied this approach, using the forcing data from GLDAS to establish the history of land surface states in the Noah LSM, originally developed by NCEP (Ek et al. 2003). The approach can easily be applied to other LSMs, e.g., the Simplified Simple Interactive Biosphere (SSiB; Xue et al. 1991).

This analysis can be extended with forcing from near-real-time re-analyses or operational analyses to provide land surface initial conditions for NWP. This approach helps to ensure maximum consistency of state variables with the land surface model, since the definitions and physical means of states such as soil moisture are not consistent across models (Koster and Milly, 1997). The Second Global Land-Atmosphere Coupling Experiment (GLACE-2) has used such an approach in a multi-model setting to demonstrate the impact of realistic land surface initialization on sub-seasonal to seasonal climate forecasts (Koster et al., 2010).

Because the climate of atmospheric models is biased relative to that of nature in terms of both the mean and variance, the land surface states generated offline will 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.

At the time of this project, a long simulation of the target NWP model was not available. In lieu of this data set, a simpler procedure that interpolates the land surface state on a given date from the GLDAS soil moisture analysis, suitably interpolated and weighted for use on the Unified Model grid, was used to develop an initial condition suitable for use with the KIAPS NWP model.

The research results were communicated to KIAPS personnel (E. Jin, K.-M. Cho and K. Seol) at COLA on 13 February 2013. Copies of the presentations from that meeting are attached to this report. In addition, several data sets and computer codes were delivered to KIAPS personnel on 14 February 2013 (see section 6).

5. Description of Land Surface Analysis, Initialization and Models

a. Land surface initialization

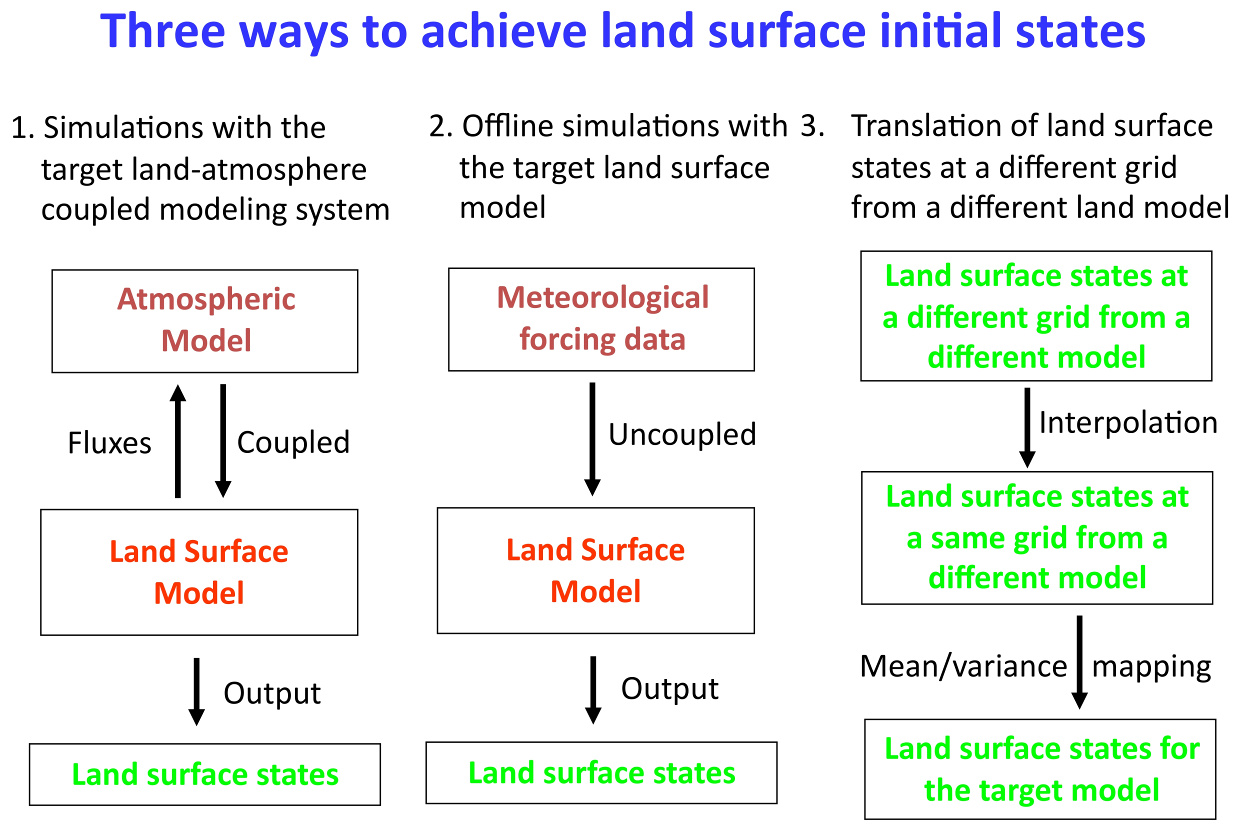

Figure 4

As shown in the diagram above, three methods could 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 Unified Model (UM) 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. Among various land surface datasets, the data from the operational systems GLDAS serves the purpose of land surface initialization best as it is closer to near-real-time, and it provides flexibility of model choices since it is a multi-model product.

b. GLDAS

The Global Land Data Assimilation System (GLDAS) drives multiple, offline (not coupled to the atmosphere) land surface models, integrates a huge quantity of observation based data, and executes globally at high resolutions (2.5° to 1 km), enabled by the Land Information System (LIS) (Kumar et al., 2006). Currently, GLDAS drives four land surface models (LSMs): Mosaic, Noah, the Community Land Model (CLM), and the Variable Infiltration Capacity (VIC). More information is available at the Land Data Assimilation Systems (LDAS) and Land Information System (LIS) websites.

The temporal resolution for the GLDAS products is 3-hourly. Monthly products are also generated through temporal averaging of the 3-hourly products. Output files from these four models are briefly described here. Table 1 lists some basic characteristics of the GLDAS data.

Table 1. Basic characteristics of the GLDAS data.

Contents	Water and energy budget components, forcing data
Latitude extent	-60° to 90°
Longitude extent	-180° to 180°
Spatial resolution	0.25°, 1.0°
Temporal resolution	3-hourly or monthly
Temporal coverage	January 1, 1979 to present for the 1.0° data February 24, 2000 to present for the 0.25° data
Dimension	360 (lon) x 150 (lat) for the 1.0° data 1440 (lon) x 600 (lat) for the 0.25° data
Origin (1st grid center)	(179.5°W, 59.5°S) for the 1.0° data (179.875°W, 59.875°S) for the 0.25° data
Land surface models	CLM 2.0, GLDAS/CLM experiment 691 (1.0°) MOSAIC, GLDAS/MOSAIC experiment 691 (1.0°) NOAH 2.7, GLDAS/NOAH experiment 691 (1.0°) VIC water balance, GLDAS/VIC experiment 692 (1.0°) NOAH 2.7, GLDAS/NOAH experiment 881 (0.25°)

c. Land surface initialization with soil moisture translated from land surface analysis products

Since soil moisture, as a relatively slow varying component of the land-atmosphere system, is one of the most important variables of the land surface initialization, it is chosen as the primary variable for LSM initialization to evaluate the efficacy of developing a method, although a similar procedure could be applied to other variables. Soil moisture is a highly model-depend quantity. It varies widely from one land surface model to another. Thus, the transformation of soil moisture among land surface models requires caution, involving the vertical structure of the LSM (number of soil layers and layer depths), local soil parameters such as wilting point and soil capacity, as well as mean and variance adjustments. Among the various GLDAS datasets, output from the NOAH land surface model (four vertical layers with layer depths of 0.1, 0.3, 0.6, and 1.0 m from the top to the bottom, respectively) has a vertical structure similar to that of the U.K. Met Office Unified Model (UM) LSM (four vertical layers with layer depth 0.1, 0.25, 0.65, and 2.0 m from the top to the bottom, respectively). In order to reduce biases, which could be introduced by vertical interpolation and extrapolation, the GLDAS-NOAH dataset is used as the source land surface product, and the soil moisture data are directly matched for each soil layer. Since the model grid and soil properties in GLDAS-NOAH are different from their counterparts in UM, soil moisture is converted to soil wetness with the soil properties in the source model before the procedures of horizontal interpolation are performed, and the soil wetness is convert back to soil moisture with the soil properties in the target model after the interpolation. The conservative area average approach is used for the horizontal interpolation of fields between grids while the bilinear interpolation is available as another option. One sample of initial soil moisture for April 1, 2012 generated from the GLDAS-NOAH is shown in Fig. 5.

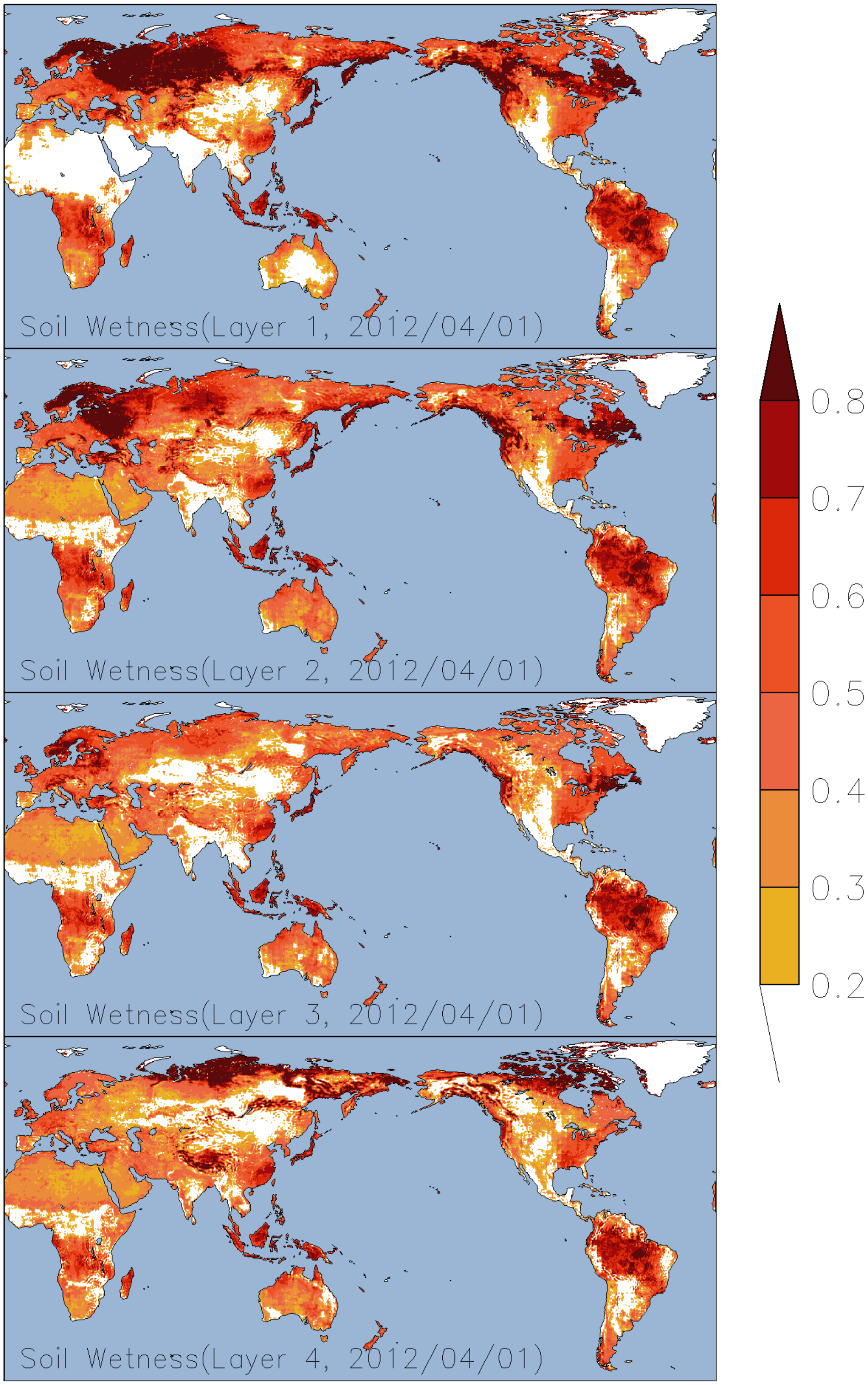
Soil Wetness(Layer 1, 2012/04/01)
Soil Wetness(Layer 2, 2012/04/01)
Soil Wetness(Layer 3, 2012/04/01)
Soil Wetness(Layer 4, 2012/04/01)
0.8
0.7
0.6
0.5
0.4
0.3
0.2

Figure 5

d. SSiB model

The Simplified Simple Biosphere (SSiB) model is a biophysically based model of land-surface-atmosphere interaction designed for coupling to an atmospheric GCM, to provide lower boundary states and fluxes over land. It is a second-generation land surface scheme, meaning that it represents the complete surface water and energy balances, and the controls of vegetation on the transpiration component of surface water and latent heat flux to the atmosphere, but does not model the carbon cycle or photosynthetic processes directly. The updated version of SSiB, has been improved over the previous version of SSiB: the number of soil layers has increased from three to six; a three-layer snow model (*Stieglitz et al.*, 2001) is coupled to SSiB to replace the original simple snow parameterization; and the CLM schemes (*Oleson et al.*, 2004) are used for calculating soil thermal conductivity and soil temperature. Preliminary results show that the new version has corrected a dry bias over much of the globe when coupled with the COLA AGCM, and the snow cover is better simulated. Full documentation of SSiB can be found in the following references: Sellers et al. (1986), Sellers and Dorman (1987), Dorman and Sellers (1989), Sato et al. (1989), Xue et al. (1991, 1996), Fennessy and Xue (1997), Dirmeyer and Zeng (1997, 1999), and Misra et al. (2002).

e. Noah Model

Noah is a stand-alone, one-dimensional column model of the land surface, which can be executed in either coupled or uncoupled mode. The model applies finite-difference spatial discretization methods and a Crank-Nicholson time-integration scheme to numerically integrate the governing equations of the physical processes of the soil-vegetation-snowpack medium. Noah is a second-generation land surface scheme that has been used operationally in NCEP models since 1996, and it continues to benefit from a steady progression of improvements.

Beginning in 1990, and accelerating after 1993, under sponsorship from the GEWEX/GCIP/GAPP then GEWEX/GAPP Program Office of NOAA/OGP via collaboration with numerous GCIP/GAPP/GAPP Principal Investigators (PIs), the Environmental Modeling Center (EMC) of NCEP joined with the NWS Office of

Hydrology (OH) and the NESDIS Office of Research and Applications (ORA) to pursue and refine a modern-era LSM suitable for use in NCEP operational weather and climate prediction models. NCEP adopted the Oregon State University (OSU) LSM (known as the Coupled Atmospheric boundary layer - Plant – Soil, CAPS, model land-surface scheme in some PILPS studies) for further refinement and implementation in NCEP regional and global coupled weather and climate models (and their companion data assimilation systems). The results of initial EMC refinements to the OSU LSM were reported in Chen et al. (1996).

At the beginning of the EMC LSM effort in 1990, the OSU LSM already had a 10-year history. Its initial development was carried out by OSU in a series of three papers (Mahrt and Ek, 1984; Mahrt and Pan, 1984; and Pan and Mahrt, 1987). A series of NCEP extensions to the OSU LSM were (a) added by EMC and its GCIP/GAPP and other collaborators and (b) tested and validated in both uncoupled and coupled studies (see review of these in Ek et al. 2003). At NCEP, the LSM was first coupled to the operational NCEP mesoscale Eta model on 31 Jan 1996, with significant subsequent Eta LSM refinements. In 1999, with a) the new addition and testing of frozen soil and patchy snow cover physics in the uncoupled LSM used for the NCEP-OH submission to PILPS-2d (Valdai, Russia), and b) the growing number of external user requests for access to and use of the NCEP LSM (e.g. GCIP/GAPP PIs), we decided the NCEP LSM had advanced to a stage appropriate for formal public release (first in March 1999).

In 2000, given a) the advent of the "New Millenium", b) a strong desire by EMC to better recognize its LSM collaborators, and c) a new NCEP goal to more strongly pursue and offer "Community Models", EMC decided to coin the new name "NOAH" for the LSM that had emerged at NCEP during the 1990s:

N: National Centers for Environmental Prediction (NCEP)

O: Oregon State University (Dept of Atmospheric Sciences)

A: Air Force (both AFWA and AFRL - formerly AFGL, PL)

H: Hydrologic Research Lab - NWS (now Office of Hydrologic Dev -- OHD)

The NOAH model reflects these changes and collaborations remain strong.

6. Deliverable Datasets and Codes

i. 1-degree daily GLDAS dataset in NETCDF format; (3-hourly dataset in GRIB format is available)

/project/kiaps/GLDAS_NC_10

ii. 0.25-degree daily GLDAS dataset in NETCDF format; (3-hourly dataset in GRIB format is available)

/project/kiaps/GLDAS_NC_025

iii. Fortran codes and C-shell scripts which generate the initial fields of soil moisture on the UM grids from 0.25-degree GLDAS

/project/kiaps/SM_INIT_025

iv. Fortran codes and C-shell scripts which generate the initial fields of soil moisture on the UM grids from 1-degree GLDAS

/project/kiaps/SM_INIT_10

v. SSiB codes

/project/kiaps/SSiB/

vi. Noah codes

/project/kiaps/NOAH/

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