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Validation of CFSv2 Model Behavior – Land-Atmosphere Interactions and the Hydrologic Cycle

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1. Introduction

Recent multi-model results from the second Global Land-Atmosphere System Study (GLACE-2; Koster *et al.* 2010, 2011; Guo *et al.* 2011, 2012) suggest that realistic initialization of land surface states (namely soil moisture) in subseasonal-seasonal climate forecasts can improve the skill of temperature and precipitation predictions over some parts of the globe. However, not all models show this improvement. While there is theory to suggest the locations of the world where the effects should be largest correspond to "hotspots" of land atmosphere coupling (*e.g.*, Koster et al. 2004, Guo *et al.* 2006, Dirmeyer *et al.* 2009), some models seem to lack critical aspects of the feedback loop. The NCEP CFSv2 appears to be such a model (Dirmeyer 2013).

In this study, operational forecasts and retrospective forecasts from NCEP CFSv2 as well as Global Land Data Assimilation System (GLDAS; Rodell et al. 2004) output from the land surface component (Noah v2.7.1) are assessed with regard to metrics of land atmosphere coupling to gauge model behavior, with particular emphasis on the simulation of the water cycle.

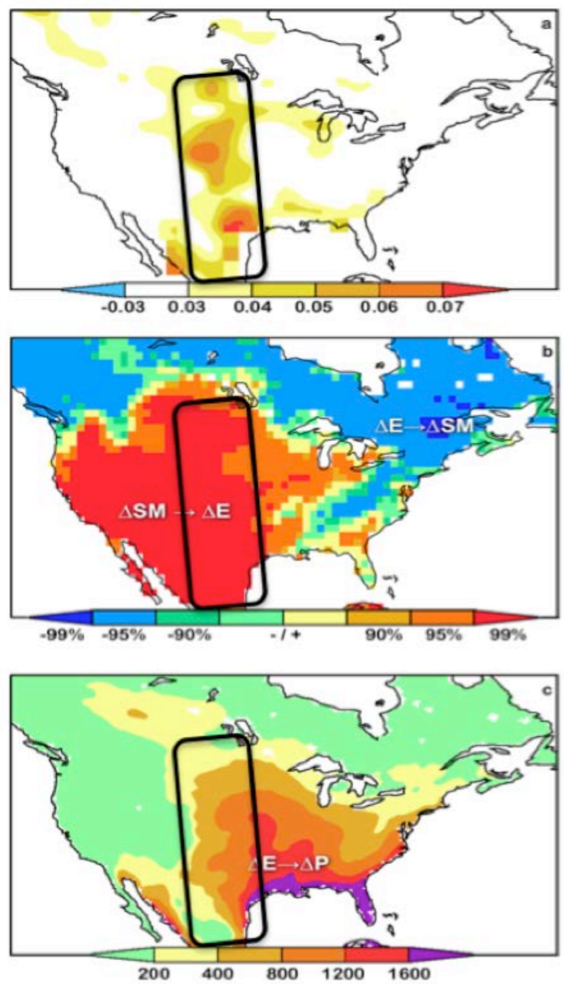

Fig. 1 Multi-model coupling strength from GLACE (top); correlation significance between soil moisture and evaporation from GSWP (middle) and mean CAPE from NARR (J/kg, bottom). All data are for the JJA season.

2. Models and Data

The current CFSv2 model is described by Saha *et al.* (2013). Saha *et al.* (2010) describe the CFSv2 reforecasts in detail. The Noah land surface model is described by Ek *et al.* (2003). Operational data come from the four-times-a-day four-member operational ensemble forecast six-hourly output from 2013, aggregated to daily means. Reforecast data are monthly from 1982-2008. GLDAS-2 data from Noah run offline are from the same period as the CFSv2 reforecast and used at both daily and monthly time scales for comparison to the coupled products, as the time interval affects certain calculations such as

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variances and correlations, but not seasonal means.

3. Theory

Variations at the land surface are translated into atmospheric responses through numerous interconnected non-linear pathways (*e.g.*, van Heerwaarden *et al.* 2010). These land-atmosphere connections can be divided into two segments, a terrestrial and an atmospheric component (Dirmeyer *et al.* 2012). The terrestrial segment describes the sensitivity of surface energy fluxes to changes in the land surface state (Dirmeyer 2011). When surface fluxes respond to soil moisture, the terrestrial segment provides a necessary but not a sufficient condition for the land surface to exert control on the properties of the atmospheric boundary layer. These may be brought to bear through the water or energy cycles.

The atmospheric segment relates the sensitivity of boundary layer development, cloud formation and precipitation to surface fluxes such as evapotranspiration or sensible heat flux (*e.g.*, Betts et al. 1996, Ek and Holtslag 2004). When both segments are operating, feedbacks occur.

Predictability in the physical climate system on time scales beyond those of deterministic weather phenomena can be greatly aided by knowledge of the surface state, precisely because it is a slow manifold compared to the atmosphere (Shukla 1998). This is, of course, predicated on properly representing the mechanisms involved in land-climate interactions. Soil moisture, in particular, has been shown to have a "memory" based on lagged autocorrelations on the order of months (*e.g.*, Schlosser and Milly 2002) and observationally-based land surface initialization extends the predictability of sub-seasonal to seasonal climate in global models (Koster *et al.* 2011, Guo *et al.* 2012).

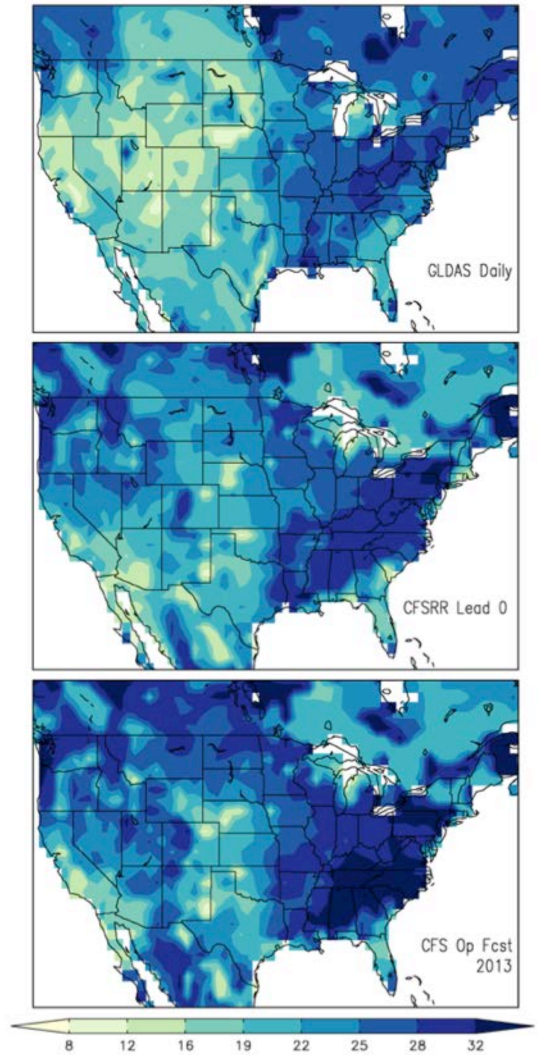

Fig. 2 10-40cm soil wetness (%) for JJA from the indicated sources.

Much of this land surface-driven predictability is associated with "hot spots" of land-atmosphere coupling around the globe (Koster *et al.* 2004) where both terrestrial and atmospheric segments show the proper relationships and adequate strength to complete the feedback loop (Guo *et al.* 2006). The sensitivity of surface fluxes to soil moisture, most readily indicated by a positive correlation between anomalies of soil moisture and evaporation on daily to monthly time scales, is most prevalent in arid and semi-arid regions. On the other hand, the sensitivity of precipitation to variations in surface fluxes skews towards more humid areas, where the atmosphere is typically in a state of conditional instability. Hotspots appear around the transitions between arid and humid zones, where both terrestrial and atmospheric segments exhibit some strength. Figure 1 illustrates this relationship over North America combining three independent data sets (Guo *et al.* 2006, Dirmeyer *et al.* 2006, Mesinger *et al.* 2006).

4. Results

The ability of CFSv2 to simulate climate sensitivity to soil moisture states over the Great Plains of North America has been shown to be weak (Zhang *et al.* 2011), and appears to be the result of several factors. First of all, the model exhibits a somewhat peculiar pattern of mean soil moisture over the central and western parts of the continent. Fig 2 shows the mean JJA soil moisture from the Noah land surface model driven offline by observationally constrained meteoro¬logical forcing, and in the coupled reforecasts at a lead forecast of 0-months (initialization ranging from 30 days prior to 7 days into the forecast month). In GLDAS, the driest soil is not over the desert Southwest but rather areas of the inter-mountain west and the Great Plains. In CFSv2 reforecasts, the western and southwestern regions are even wetter, and the driest zone is over the central and southern High Plains. The irregularity is even stronger in the operational forecasts (7-10 days lead shown). As a result, the Great Plains area is insensitive to drought because conditions are already so dry.

Figure 3 shows the pattern of latent and sensible heat fluxes for JJA in the CFSv2 operational forecasts, with superposed circles showing observed values from a distribution of FLUXNET sites across the United States (Baldocchi *et al.* 2001). There is a distinct negative bias in Bowen ratio over most areas.

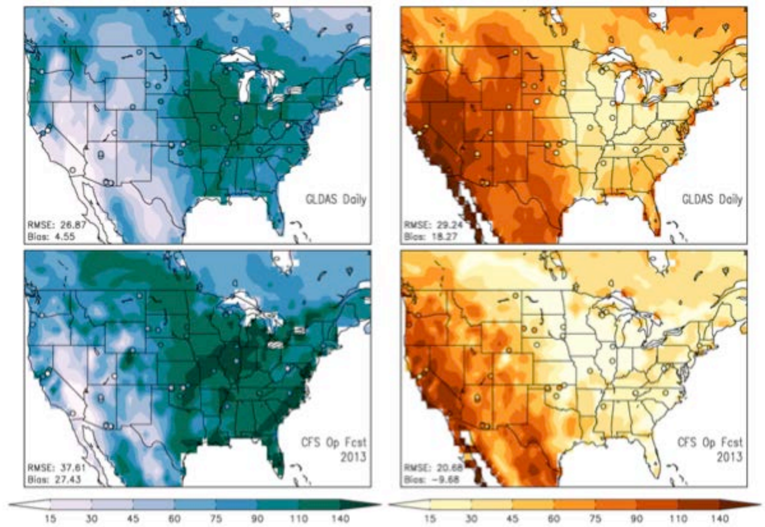

Fig. 3 JJA mean latent (left) and sensible (right) heat flux (Wm^{-2}) from the indicated sources. Dots are values from FLUXNET sites.

The positive bias in latent heat flux (LHF) is over 27 Wm-2 across the flux sites for the operational CFSv2 model, but only +4 Wm^{-2} for Noah in GLDAS. Meanwhile there is nearly a 10 Wm^{-2} deficit in sensible heat flux (SHF) in CFSv2, indicating not only a problem in partitioning net energy, but also an excess of net radiation at the surface in the coupled model. This led to a positive temperature bias in CFSRR, which was addressed by extending the root depth in Noah to tap soil moisture in all four model layers (M. Ek, pers. comm.). This reduced temperature biases through increased evaporation, but exacerbated other problems. The bias is particularly strong over the agricultural areas, with the lowest Bowen ratios outlining clearly the crop vegetation types over the eastern and northern Great Plains well into southern Canada. This profligate evaporation renders the remainder of the GLACE hot spot immune to soil moisture variations. Thus, a combination of atmospheric and land surface model errors and biases appear to compound, weakening land-atmosphere coupling strength.

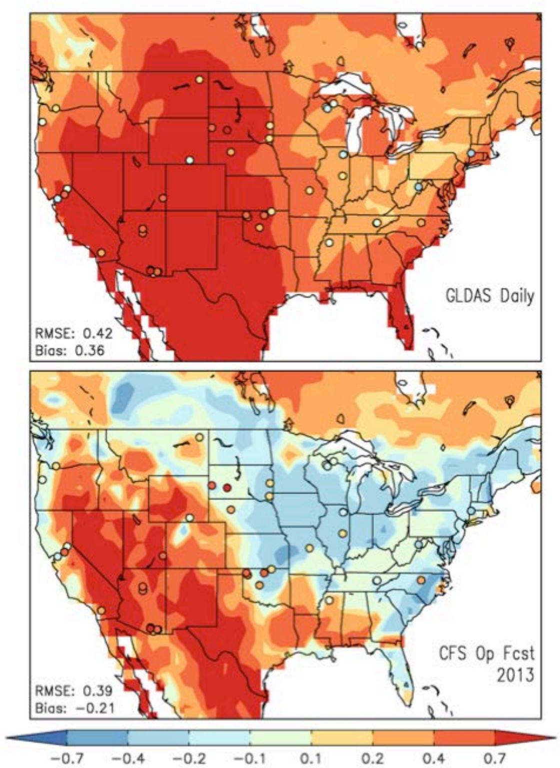

Fig. 4 Correlation between daily soil moisture and latent heat flux during JJA from the indicated sources.

The degree to which coupling intensifies these problems can be seen in Fig 4. Correlation of surface fluxes with soil moisture in GLDAS is seen to have a pattern consistent with Fig 1, but somewhat too strong compared with in situ observations. This excessive strength is characteristic of offline land model simulations and is not in itself an indicator of a problem with Noah. However, this strength is completely eradicated over the Great Plains in the coupled CFSv2, where positive correlations between latent heat fluxes and soil moisture are lost.

This also severely affects the development of the daytime atmospheric boundary layer and the height of the lifting condensation level (LCL) over the central and northern Great Plains. Cloud bases in this area are much too low, and day-to-day variability is nearly zero (not shown). As a result, both the terrestrial and atmospheric segments of the coupled feedback loop are absent over all but the extreme southern Great Plains. Figure 5 shows coupling indices – the terrestrial coupling index (top) is the standard deviation of daily LHF (Wm^{-2}) times the correlation between LHF and soil moisture. For the atmosphere, it's the standard deviation of the height of the LCL (m) times the correlation between SHF and LCL.

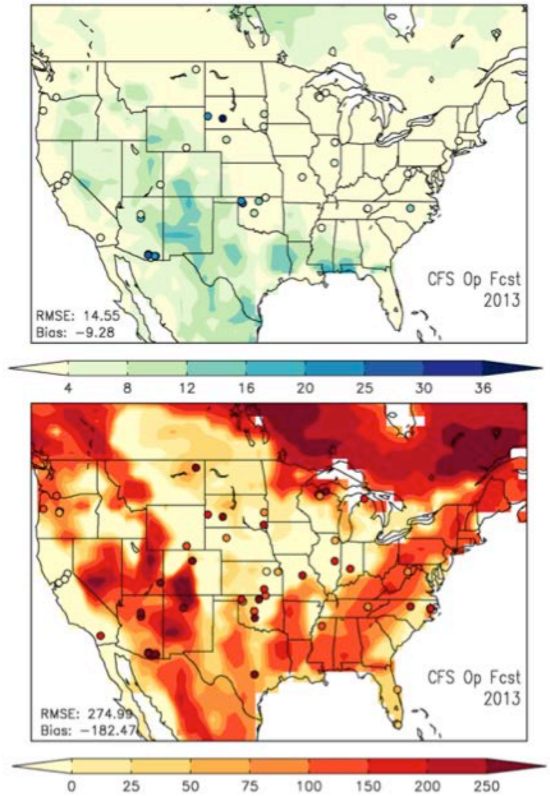

Fig. 5 Terrestrial (top; Wm^{-2}) and atmospheric (bottom; m) coupling indices for CFSv2 operational forecasts during JJA. See text for full description.

5. Conclusions and discussion

A variety of metrics based on state variables and fluxes indicated the behavior of the coupled land-atmosphere system in CFSv2 is considerably different than for the land surface model (Noah) alone driven by observed meteorology, or metrics based on FLUXNET stations. All biases trend toward excessive weakness in land surface feedbacks on the atmosphere, weakening the potential predictability and prediction skill to be gained by the operational NCEP forecast model from realistic land surface initialization (namely for soil moisture). Experiments with other models from GLACE-2 indicate that some models can benefit from realistic land initial states – and these models possess stronger coupling. Thus, this should be a correctable problem if addressed as a coupled land-atmosphere model development effort, resulting in potential increases in forecast skill over the Great Plains, and possibly neighboring areas, during the warm season. Such gains may be extendable to other "hot spot" regions as well, such as the Sahel region of Africa, Eastern Europe to central Asia, western India and Pakistan, much of South America and Australia.

References

Baldocchi, D., and coauthors, 2001: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bull. Amer. Meteor. Soc.*, **82**, 2415-2434.

Betts, A. K., J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. A. Viterbo, 1996: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives. *J. Geophys. Res.*, **101**, 7209-7225.

Dirmeyer, P. A., X. Gao, M. Zhao, Z. Guo, T. Oki and N. Hanasaki, 2006: The Second Global Soil Wetness Project (GSWP-2): Multi-model analysis and implications for our perception of the land surface. *Bull. Amer. Meteor. Soc.*, **87**, 1381-1397, doi: 10.1175/BAMS-87-10-1381.

Dirmeyer, P. A., C. A. Schlosser, and K. L. Brubaker, 2009: Precipitation, recycling and land memory: An integrated analysis. *J. Hydrometeor.*, **10**, 278–288, doi: 10.1175/2008JHM1016.1.

Dirmeyer, P. A., 2011: The terrestrial segment of soil moisture-climate coupling. *Geophys. Res. Lett.*, **38**, L16702, doi: 10.1029/2011GL048268.

Dirmeyer, P. A., and coauthors, 2012: Evidence for enhanced land-atmosphere feedback in a warming climate. *J. Hydrometeor.*, **13**, 981-995, doi: 10.1175/JHM-D-11-0104.1.

Dirmeyer, P. A., 2013: Characteristics of the water cycle and land-atmosphere interactions from a comprehensive reforecast and reanalysis data set: CFSv2. *Climate Dyn.*, **41**, 1083-1097, doi: 10.1007/s00382-013-1866-x.

Ek, M., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta model. *J. Geophys. Res.*, **108**, 8851, doi:10.1029/2002JD003296.

Ek, M. B., and A. A. M. Holtslag, 2004: Influence of soil moisture on boundary layer cloud development. *J. Hydrometeor.*, **5**, 86-99.

Guo, Z., and coauthors, 2006: GLACE: The Global Land-Atmosphere Coupling Experiment. 2. Analysis. *J. Hydrometeor.*, **7**, 611-625, doi: 10.1175/JHM511.1.

Guo, Z., P. A. Dirmeyer, and T. DelSole, 2011: Land surface impacts on subseasonal and seasonal predictability. *Geophys. Res. Lett.*, **38**, L24812, doi:10.1029/2011GL049945.

Guo, Z., P. A. Dirmeyer, and T. DelSole, and R. D. Koster, 2012: Rebound in atmospheric predictability and the role of the land surface. *J. Climate*, **25**, 4744-4749, doi: 10.1175/JCLI-D-11-00651.1.

Koster, R. D., and coauthors, 2004: Regions of strong coupling between soil moisture and precipitation. *Science*, **305**, 1138-1140.

Koster, R., and coauthors, 2010: The contribution of land surface initialization to subseasonal forecast skill: first results from the GLACE-2 project. *Geophys. Res. Lett.*, **37**, L02402, doi:10.1029/2009GL041677.

Koster, R. D., and coauthors, 2011: The second phase of the Global Land-Atmosphere Coupling Experiment: Soil moisture contributions to subseasonal forecast skill. *J. Hydrometeor.*, **12**, 805–822, doi: 10.1175/2011JHM1365.1.

Mesinger, F., and 18 co-authors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.*, **87**, 343-360.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, C. Lohmann, and D. Toll, 2004: The global land data assimilation system. *Bull. Amer. Meteor. Soc.*, **85**, 381-394.

Saha, S., and coauthors, 2010: The NCEP Climate Forecast System reanalysis. *Bull. Amer. Meteor. Soc.*, **91**, 1015–1057, doi: 10.1175/2010BAMS3001.1.

Saha, S., and coauthors, 2013: The NCEP Climate Forecast System version 2. *J. Climate*, **27**, (early release), doi: JCLI-D-12-00823.1.

Schlosser, C. A., and P. C. D. Milly, 2002: A model-based investigation of soil moisture predictability and associated climate predictability. *J. Hydrometeor.*, **3**, 483-501.

Shukla, J., 1998: Predictability in the midst of chaos: A scientific basis for climate forecasting. *Science*, **282**, 728-731.

van Heerwaarden, C. C., J. Vilà-Guerau de Arellano, A. Gounou, F. Guichard, and F. Couvreux, 2010: Understanding the Daily Cycle of Evapotranspiration: A Method to Quantify the Influence of Forcings and Feedbacks, *J. Hydrometeorol.*, **11(6)**, 1405–1422, doi:10.1175/2010JHM1272.1.

Zhang, L., P. A. Dirmeyer, J. Wei, Z. Guo, and C.-H. Lu, 2011: Land-atmosphere coupling strength in the Global Forecast System. *J. Hydrometeor.*, **12**, 147-156, doi: 10.1175/2010JHM1319.1.