DIAGNOSIS AND VALIDATION OF LAND-ATMOSPHERE FEEDBACKS IN TWO GLOBAL MODELS

Year 4 Progress Report
16 Aug 2016 – 15 Aug 2017

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NASA Grant: **NNX13AQ21G**

Project website: http://cola.gmu.edu/dirmeyer/nasa_map_12.html

Students

Ph.D. student Holly Norton defended her dissertation research proposal in January and is on target to graduate in Spring 2018 with a dissertation titled, "Soil Moisture Memory of Karst and Non-Karst Soils." Norton's dissertation topic focuses on the modulation of soil moisture memory by underlying geology, namely the presence or absence of permeable substrates like karst, which may significantly affect land-atmosphere interactions through the hydrologic cycle. Her committee consists of myself, Dr. Daniel Doctor (USGS), Prof. Kathleen Pegion (GMU) and Prof. Celso Ferreira (GMU).

Furthermore, Ms. Norton is a recipient of a 2017 NCEP Student Internship supported by NOAA. She will be working at the Environmental Modeling Center in College Park, MD under the supervision of Dr. Michael Ek, co-PI on this project. This represents a fantastic opportunity to advance the parameterization development portion of her study and accelerate implementation of model changes to account for variations subsurface geology and their effects on soil hydrology and the surface water balance.

Jiexia Wu will be defending her dissertation research proposal in June. Ms. Wu is interested in drought demise and the role of land-atmosphere interactions relative to other factors in nature and models. This is a novel topic, as nearly all attention on the topic of droughts has centered on the conditions and prediction of their initiation, not termination. Her committee consists of myself, Dr. Randal Koster (NASA/GSFC) and Prof. David Straus (GMU) and Prof. Kathleen Pegion (GMU).

Both Wu and Norton have already contributed essential analysis of observational and model data described below.

Coupling metrics

Co-I Santanello and his NPP and LoCo working group member, Joshua Roundy, have for the first time applied LoCo metrics such as the Coupling Drought Index (CDI) to satellite

data and compared it to those derived from reanalysis products such as CFSR and MERRA (Roundy and Santanello, 2017). Metrics derived solely from satellite (AMSR-E soil moisture, AIRS temperature and humidity) can be derived globally and correspond well with those from reanalysis products. In addition, the trends in wet and dry coupling (via the CDI) can be derived over the Aqua period of record and compared to the longer-term trends from the reanalysis products.

The "cheat sheet" of land-atmosphere coupling metrics is hosted online at http://cola.gmu.edu/dirmeyer/Coupling_metrics.html and has become a major resource in the GEWEX community and beyond. It brings together the theory, formulations and references for various published metrics of land-atmosphere feedbacks over the past 20 years in one place, with strengths and weaknesses of each listed. It is periodically updated with new metrics and information to stay current and useful as a community resource. Two of the metrics representing terrestrial and atmospheric legs of land-atmosphere coupling have been calculated from three reanalyses and blended to produce an animation of the mean seasonal cycle of land-atmosphere interactions: http://cola.gmu.edu/dirmeyer/animation.gif.

Co-Is Santanello and Ek are working towards implementing the suite of LoCo metrics (mixing diagrams, EF vs. PBLH, and LCL deficit) in the GEWEX sponsored Diurnal Cycle Experiment (DICE; Best et al. 2013; *GEWEX News*), with a paper to follow. The DICE results include 3-phases of land-PBL sensitivity experiments with a suite of ~20 single-column models contributed by the international community. LoCo metrics offer a valuable perspective on the integrated coupling between the various LSMs and PBL schemes.

The Land-Atmosphere Feedback Experiment (LAFE; PI: Volker Wulfmeyer; Co-I: Santanello) was selected by DOE-ARM to be conducted in August 2017 over the SGP, and will include state-of-the-art PBL sounding instrumentation and synergy in order to capture PBL fluxes such as entrainment and characterize the full land-PBL coupling over the region. The LoCo group will take part in analyzing the data and assessing their utility for L-A metrics and studies.

Model evaluation

Dirmeyer et al. (2016) evaluated four models (NASA/GMAO, NCEP, NCAR and ECMWF) in three configurations (stand-alone land surface model, coupled land-atmosphere, and reanalysis) regarding their simulation of the temporal and spatial variability of soil moisture over the US versus a multitude of *in situ* observational networks. We have completed analyses for the next phase of model evaluation work on terrestrial coupling metrics with the recently released FLUXNET2015 dataset (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/), which contains soil moisture, surface flux and meteorological information from 166 sites around the globe and 1242 site-years of data (Dirmeyer et al. 2017). The main result is that models clearly under-represent the feedback of surface fluxes on boundary layer properties (atmospheric leg of land-atmosphere coupling), and may over-represent the connection between soil moisture and surface fluxes (terrestrial leg). Fig 1 shows distinguishes positive values of two coupling metrics, which indicate the existence of feedbacks from land to atmosphere, from negative (no feedbacks) by coloring the four quadrants according to their coupling

regimes: red = both legs present and a full coupling pathway; green = the land leg is present, the atmospheric leg is missing; blue = that atmospheric leg is present, the land is missing; grey = neither leg present. The white dots show where the FLUXNET2015 sites fall in this two-dimensional metric space. The colored dots are each model's rendering of the metrics for the grid boxes containing the FLUXNET2015 sites, with the color indicating the quadrant according to the FLUXNET measurements. Thus, the more colored dots that fall in the quadrant with the matching color, the better the model is reproducing the global pattern of coupling regimes.

For Phase 2a of the project, we have leveraged computing resources from a National Monsoon Mission supported project at COLA to produce a large suite of CFSv2 simulations to examine the role of land-atmosphere feedbacks/coupling in the operational

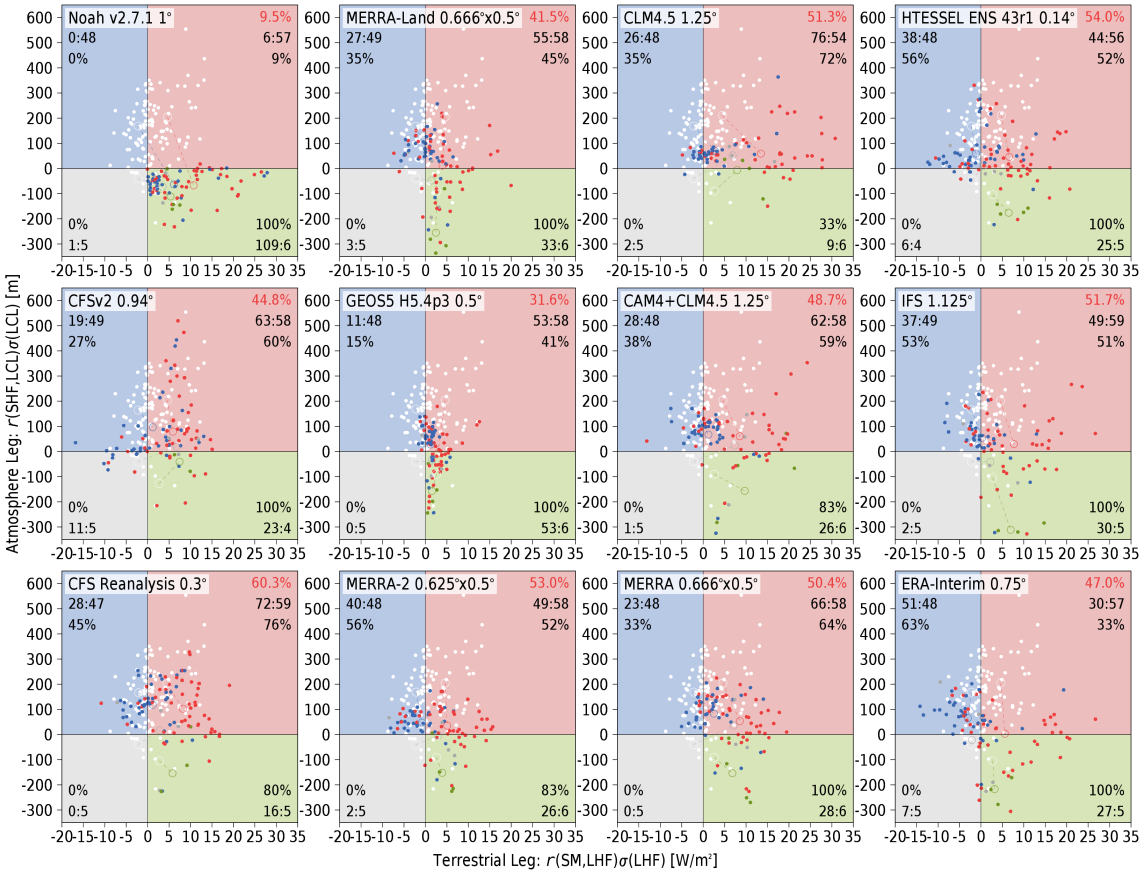

Figure 1. Distribution of coupling indices for the terrestrial (x-axis) and atmospheric (y-axis) legs for the warmest consecutive 3 months of the annual cycle for FLUXNET2015 sites (white dots; identical in each panel) and for each model as indicated. Colors of dots indicate in which quadrant that FLUXNET2015 site lies: red = both indices positive; green = terrestrial positive, atmospheric negative; blue = atmospheric positive, terrestrial negative; grey = both negative. The white circle indicates the centroid of all FLUXNET2015 stations that are in that quadrant, connected by a colored dotted line to a colored circle that is the centroid of the same stations' corresponding grid boxes as simulated by the model. Numbers in the corners of each quadrant show the number of points in that quadrant according to the model and FLUXNET2015 data, separated by a colon, and the percentage of the FLUXNET2015 sites within that quadrant that the model placed in the same quadrant. The percentage in red at the upper right of each panel is the overall percentage of sites where model and FLUXNET2015 agree on the quadrant. [from Dirmeyer et al. 2017]

National Weather Service forecast model (Dirmeyer and Halder 2016a,b). Results indicate the widespread nature of land surface impact on surface fluxes, near surface meteorological states and even boundary layer development in the model, but a profound lack of sensitivity of precipitation that hampers forecast skill improvements and suggests possible problems in the response of the convective parameterization to surface states. Bombardi et al. (2016) has pursued this issue by implementing a convective trigger based on the Heated Condensation Framework theory of Tawfik, Dirmeyer and Santanello (2015a,b). Co-I Ek and Youlong Xia of NOAA/NCEP/EMC are now pursuing this issue in the operational setting.

For Phase 2b of the project, Co-Is Santanello and Bosilovich have extended the work of Santanello et al. (2015), which examined the L-A coupling in reanalysis products (MERRA, CFSR, NARR), to that of MERRA-2. Results indicate significant improvement (reduction) in the dry (specific humidity) bias over the SGP in MERRA-2 as compared to MERRA. In addition the PBL height climatology from MERRA-2 is much more aligned with observations from radiosonde and from the other reanalysis products, presumably as a result of tweaking of the GEOS-5 PBL scheme in MERRA-2 (Molod; *pers. comm.*).

Additionally, the WRF Single Column Model (SCM) has been coupled to NASA's Land Information System (LIS) and is now included (as LIS-SCM) as part of the NASA Unified WRF software package. This tool will enable ensemble (calibration, assimilation) experiments to be conducted in coupled mode and allow more focused and expansive land-atmosphere coupling assessment and metric development in future projects/proposals.

Initial LSM evaluation from the Protocol for the Analysis of Land Surface Models (PALS) Land Surface Model Benchmarking Evaluation Project (PLUMBER), which challenged models to outperform statistically-based benchmarks in simulating surface fluxes, has been extended to explain the causes of poor model performance. Haughton et al. (2016) find that lack of energy conservation in the observational data is not responsible for the results; the partitioning between sensible and latent heat fluxes in LSMs, rather than the calculation of available energy, is the cause of the original findings. The nature of this partitioning problem is likely shared among all contributing LSMs.

Lo-Co related

Co-I Santanello has been working to implement the suite of locally coupled (LoCo) metrics (mixing diagrams, EF vs. PBLH, and LCL deficit) to the GEWEX-GLASS sponsored DIurnal Cycle Experiment (DICE; Best et al. 5/2013; *GEWEX News*), which will be submitted as part of a special collection to *J. Hydrometeor*. The DICE results include 3-phases of land-PBL sensitivity experiments with a suite of ~20 single-column models contributed by the international community. LoCo metrics offer a valuable perspective on the integrated coupling between the various LSMs and PBL schemes.

We have also submitted a review paper to the Bulletin of the American Meteorological Society on the topic of local land-atmosphere interactions, describing the state of the science and future goals (Santanello et al. 2017).

The Land-Atmosphere Feedback Experiment (LAFE; PI: Volker Wulfmeyer; Co-I: Santanello) was selected by DOE-ARM to be conducted in August 2017 over the SGP, and will include state-of-the-art PBL sounding instrumentation and synergy in order to capture PBL fluxes such as entrainment and characterize the full land-PBL coupling over the region. The LoCo group will take part in analyzing the data and assessing their utility for L-A metrics and studies.

Relevant Journal Publications:

Bombardi, R. J., A. B. Tawfik, J. V. Manganello, L. Marx, C.-S. Shin, E. K. Schneider, **P. A. Dirmeyer**, and J. L. Kinter III, 2016: The Heated Condensation Framework as a convective trigger in the NCEP Climate Forecast System version 2. *J. Adv. Mod. Earth Sys.*, **8**, doi: 10.1002/2016MS000668.

Dirmeyer, P. A., **J. Wu, H. E. Norton**, W. A. Dorigo, S. M. Quiring, T. W. Ford, **J. A. Santanello Jr.**, **M. G. Bosilovich, M. B. Ek**, R. D. Koster, G. Balsamo, and D. M. Lawrence, 2016: Confronting weather and climate models with observational data from soil moisture networks over the United States. *J. Hydrometeor.*, **17**, 1049-1067, doi: 10.1175/JHM-D-15-0196.1.

Dirmeyer, P. A., and S. Halder, 2016: Sensitivity of surface fluxes and atmospheric boundary layer properties to initial soil moisture variations in CFSv2. *Wea. Fcst.* **31**, 1973-1983, doi: 10.1175/WAF-D-16-0049.1.

Dirmeyer, P. A., and S. Halder, 2017: Application of the land-atmosphere coupling paradigm to the operational Coupled Forecast System (CFSv2). *J. Hydrometeor.* **18**, 85-108, doi: 10.1175/JHM-D-16-0064.1.

Dirmeyer, P. A., L. Chen, J. Wu, C.-S. Shin, B. Huang, B. Cash, **M. Bosilovich**, S. Mahanama, R. Koster, **J. A. Santanello Jr.**, **M. B. Ek**, G. Balsamo, and D. M. Lawrence, 2017: Verification of land-atmosphere coupling in forecast models, reanalyses and land surface models using flux site observations. *J. Hydrometeor.*, (submitted).

Haughton, N., G. Abramowitz, A. J. Pitman, D. Or, M. J. Best, H. R. Johnson, G. Balsamo, A. Boone, M. Cuntz, B. Decharme, **P. A. Dirmeyer**, J. Dong, M. Ek, Z. Guo, V. Haverd, B. J. van den Hurk, G. S. Nearing, B. Pak, C. Peters-Lidard, **J. A. Santanello** Jr., L. Stevens and N. Vuichard, 2016: The plumbing of land surface models: why are models performing so poorly? *J. Hydrometeor.*, (early online release), doi: JHM-D-15-0171.1.

Koster, R. D., A. K. Betts, **P. A. Dirmeyer**., M. Bierkens, K. E. Bennett, S. J. Déry, J. Evans, R. Fu, F. Hernandez, L. R. Leung, X. Liang, M. Masood, H. Savenije, G. Wang, and X. Yuan, 2017: Hydroclimatic variability and predictability: A survey of recent research. *Hydrol. Earth Sys. Sci. Discuss.*, doi: 10.5194/hess-2017-122.

Kumar, S. V., **P. A. Dirmeyer**, C. D. Peters-Lidard, and R. Bindlish, 2017: Information theoretic evaluation of satellite soil moisture retrievals. Remote Sens. Env., (submitted).

Norton, H. E., and **P. A. Dirmeyer**, 2017: The impact of subsurface karst formations on surface fluxes and land-atmosphere interactions. (in prep).

Norton, H. E., **P. A. Dirmeyer** and D. Doctor, 2017a: Subsurface controls on surface soil moisture: the role of karst. (in prep).

Norton, H. E., **M. B. Ek**, and **P. A. Dirmeyer**, 2017b: A parameterization of enhanced baseflow for soils underlain by fractured and porous bedrock (in prep).

Roundy, J. K., and **J. A. Santanello**, 2017: Utility of satellite remote sensing for land–atmosphere coupling and drought metrics. *J. Hydrometeor*., **18**, 863-877, doi: 10.1175/JHM-D-16-0171.1.

Santanello, J. A., J. Roundy, and **P. A. Dirmeyer**, 2015: Quantifying the land-atmosphere coupling behavior in modern reanalysis products over the U.S. Southern Great Plains. *J. Climate*, **28**, 5813-5829, doi: 10.1175/JCLI-D-14-00680.1.

Santanello, J. A., **P. A. Dirmeyer**, C. R. Ferguson, K. L. Findell, A. B. Tawfik, A. Berg, **M. B. Ek**, P. Gentine, B. Guillod, C. van Heerwaarden, J. Roundy, and V. Wulfmeyer, 2017: Land-atmosphere interactions: The LoCo perspective. *Bull. Amer. Meteor. Soc*., (submitted).

Tawfik, A. B., **P. A. Dirmeyer**, and **J. A. Santanello**, 2015a: The heated condensation framework. Part I: Description and Southern Great Plains case study. *J. Hydrometeor*., **16**, 1929–1945, doi: 10.1175/JHM-D-14-0117.1.

Tawfik, A. B., **P. A. Dirmeyer**, and **J. A. Santanello**, 2015b: The heated condensation framework. Part II: Climatological behavior of convective initiation and land-atmosphere coupling over the continental United States. *J. Hydrometeor*., 16, 1946–1961, doi: 10.1175/JHM-D-14-0118.1.

Tawfik, A. B., D. M. Lawrence, and **P. A. Dirmeyer, 2017**: Representing sub-grid convective initiation in the Community Earth System Model. J. Adv. Mod. Earth Sys., (in revision).

Wu, J. and **P. A. Dirmeyer**, 2017a: An objective quantification of drought demise (in prep).

Wu, J. and **P. A. Dirmeyer**, 2017b: Attribution of drought demise to local and non-local causes – a climatology for the United States. (in prep).

Wu, J. and **P. A. Dirmeyer**, 2017c: The capacity of weather and climate models to reproduce the causes of drought demise (in prep).

Book Chapters:

Dirmeyer, P. A., C. Peters-Lidard, and G. Balsamo, 2015: Land-Atmosphere Interactions and the Water Cycle. [Chapter 8 in: Seamless Prediction of the Earth System: from Minutes to Months, (G Brunet, S Jones, PM Ruti Eds.)], World Meteorological Organization (WMO-No. 1156), Geneva.

Dirmeyer, P. A., K. L. Findell, and **J. A. Santanello Jr**., 2017: Metrics of Land-Atmosphere Coupling. [Chapter 18 in: Land-Atmosphere Interactions: Coupling Between The Energy, Water And Carbon Cycles], Common Ground, (submitted).

Dirmeyer, P. A., P. Gentine, **M. B. Ek** and G. Balsamo, 2017: Land surface processes relevant to S2S prediction. [Chapter 8 in: The Gap Between Weather And Climate Forecasting: Sub-Seasonal To Seasonal Prediction (A. W. Robertson and F. Vitart eds.)], Elsevier (submitted).

Presentations:

Dirmeyer, P. A., 2015 Invited talk: "Metrics as Tools for Assessing Land-Climate Feedback in Observations and Models". American Geophysical Union Fall Meeting, San Francisco, CA, USA, GC24B-01.

Dirmeyer, P. A., 2015 Invited talk: The Land Surface as a Source of Predictability on Sub-Seasonal Time Scales (Invited). American Geophysical Union Fall Meeting, San Francisco, CA, USA, A43K-05.

Dirmeyer, P. A., 2015 Invited lecture: "Land surface processes and interactions with the atmosphere" ECMWF Annual Seminar, Reading, UK, 1-4 September 2015.

Dirmeyer, P. A., 2016 Invited lecture: "The Land-Atmosphere Coupling Paradigm in the Operational NWS Forecast Model: Consequences for Hydrologic Predictability." Observations and Modeling Across Scales: Symposium in Honor of Eric Wood, Princeton, New Jersey, USA.

Dirmeyer, P. A., 2016 Invited Senior Leonardo Lecture: "What water vapor back-trajectory analysis can tell us about climate variability", From Evaporation to Precipitation: The Atmospheric Moisture Transport, 2016 EGU Leonardo Conference, Ourense, Spain, 25-27 October 2016.

Dirmeyer, P. A., 2016 Invited lecture: "Land-atmosphere feedbacks" ICTP-IITM-COLA Targeted Training Activity (TTA): Towards Improved Monsoon Simulations, International Centre for Theoretical Physics, Trieste, Italy, 13-17 June 2016.

Dirmeyer, P. A., 2017 Invited talk: "Land-atmosphere interactions in models and observations" NASA Goddard Space Flight Center, Global Modeling and Data Assimilation Office, 23 May 2017.

Dirmeyer, P. A., and **M. B. Ek** 2016: Modeling Land-Surface – Atmosphere. Water Availability Grand Challenge for North America Workshop, Columbia, Maryland, USA.

Dirmeyer, P. A., and L. Chen, 2016: Judging the Dance Contest – Metrics of Land–Atmosphere Feedbacks. 2016 International Land Model Benchmarking (ILAMB) Workshop, Washington, DC, USA.

Dirmeyer, P. A., L. Chen and **J. Wu**, 2016: Extending the confrontation of weather and climate models from soil moisture to surface flux data. American Geophysical Union Fall Meeting, San Francisco, CA, USA, NG13A-1692.

Kumar, S., I, Suhr, **P. A. Dirmeyer**, and C. D. Peters-Lidard, 2017: Evaluating and improving the information content of satellite soil moisture measurements. American Meteorological Society 31st Conference on Hydrology, Seattle, WA, USA, 5.3.

Sobocinski-Norton, H. E. and **P. A. Dirmeyer**, 2016: Soil moisture memory in karst and non-karst landscapes. American Geophysical Union Fall Meeting, San Francisco, CA, USA, H31I-02.

Tawfik, A. B., D. M. Lawrence and **P. A. Dirmeyer**, 2017: Dynamic scale awareness: Switching parameterized convection on at the right time. American Meteorological Society 29th Conference on Climate Variability and Change, Seattle, WA, USA, 4A.4.

Wu, J. and **P. A. Dirmeyer**, 2016: Understanding the causes of drought demise over CONUS. American Geophysical Union Fall Meeting, San Francisco, CA, USA, H21D-1434.

White Papers:

Santanello, J. A., A. Boone, **P. A. Dirmeyer, M. Ek**, C. R. Ferguson, P. Gentine, B. P. Guillod, Z. Li, B. R. Linter, D. D. Turner, C. C. van Heerwaarden, D. Wu, V. Wulfmeyer, and Y. Zhang, 2015: The Importance of Routine Planetary Boundary Layer Measurements over Land from Space. White Paper in response to the Earth Sciences Decadal Survey Request for Information (RFI) from the National Academy of Sciences Space Studies Board, 5pp.