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

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

## Students

Two students have been fully supported on this grant.

Holly Norton will defend her Ph.D. dissertation titled, "Soil Moisture Memory of Karst and Non-Karst Soils" and is scheduled to graduate in Fall 2018. 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 (Norton and Dirmeyer 2018). Soil moisture memory estimated from SMAP data has been found to correlate with a number of surface properties including soil and vegetation, but most notably with the distribution of karst – regions with high variability in karst coverage have significantly higher spatial variability in soil moisture memory than other regions (Dirmeyer and Norton 2018). Two other papers are in preparation. Norton's committee consists of myself, Dr. Daniel Doctor (USGS), Prof. Kathleen Pegion (GMU) and Prof. Celso Ferreira (GMU).

Jiexia Wu will defend her Ph.D. dissertation titled, "A new framework for attributing causes of drought demise over CONUS" and is scheduled to graduate in Fall 2018. Wu's topic focuses on attribution of drought demise and the specific role of land-atmosphere interactions relative to other factors in nature and models (Wu and Dirmeyer 2018). 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. Two additional papers are in preparation. Wu's 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.

Students Akiko Elders and Liang Yu were also supported partially for Spring 2018 as part of a reciprocation within the Department of Atmospheric, Oceanic and Earth Sciences and the Center for Ocean-Land-Atmosphere Studies.

## SUMMARY OF RESEARCH

### LoCo and Coupling metrics

The "cheat sheet" of land-atmosphere coupling metrics is hosted online at http://tiny.cc/l-a-metrics 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-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.

Co-Is Santanello, Dirmeyer and Ek are among authors of a recent overview paper in BAMS (Santanello et al. 2018) describing the Local Coupled (LoCo) perspective on land-atmosphere interactions as developed within the GEWEX Global Land-Atmosphere System Study (GLASS), with much of the current theory and understanding involving work within this project. This work is informed the annual US Climate Modeling Summit in April 2018, which held an accompanying workshop on land-atmosphere interactions, leading to a call for proposals for "Land Climate Process Teams" from NOAA and DOE.

Co-I Santanello has also been leading efforts to promote improved observations of the PBL from space, including white papers submitted to the Decadal Survey (Santanello w/Co-Is Dirmeyer and Ek). These efforts have resulted in a high prioritization of PBL measurements in the new 2018 Decadal Survey, which will be critical for advancing the science and application of LoCo metrics throughout the community.

The Land-Atmosphere Feedback Experiment (LAFE; PI: Volker Wulfmeyer; Co-I: Santanello) has been conducting a field campaign with 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 SGP region (Wulfmeyer et al. 2018). The LoCo group is taking part in analyzing the data and assessing their utility for L-A metrics and studies.

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.

**Model evaluation**

For Phase 1 of the workplan, validation of several reanalyses including CFSR and MERRA against the thorough observational data during a 17-year period from the DOE Southern Great Plains (SGP) in situ measurement facilities has been conducted (Santanello et al. 2015). A range of diagnostics exploring the links between soil moisture, evaporation, PBL height, temperature, humidity, and precipitation have been applied to the summertime monthly mean diurnal cycles of the North American Regional Reanalysis (NARR) as well as MERRA and CFSR. Results show that CFSR is the driest and MERRA the wettest of the three reanalyses in terms of overall surface-PBL coupling. CFSR and NARR are most similar in terms of PBL dynamics and response to dry and wet extreme years, while MERRA is more constrained in terms of evaporation and PBL variability. When compared against observations, CFSR has a significant dry bias that impacts all components of the land-PBL system, and the results are put into context of community investigations into drought assessment and predictability over SGP. The implications for moist processes is also discussed, and warrants further investigation into the potential downstream impacts of land-PBL coupling on the diurnal cycle of clouds, convection, and precipitation. Overall, caution should be used when treating RAs as truth, as the coupled water and energy cycle representation in each can vary considerably.

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 National Weather Service forecast model (Dirmeyer and Halder 2016, 2017). 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 (Tawfik et al. 2015a,b).

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.*).

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. Lack of energy conservation in the observational data was not found to be responsible for the results (Haughton et al. 2016); 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.

(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. Observations were first analyzed for error characteristics and representation of spatial and temporal variability. Some networks have multiple stations within an area comparable to model grid boxes; for those it is found that aggregation of stations before calculation of statistics has little effect on estimates of variance, but soil moisture memory is sensitive to aggregation. Buried sensors appear to have less random error than near-field remote sensing techniques, and heat-dissipation sensors show less temporal variability than other types. Model soil moistures were then evaluated using three metrics: standard deviation in time, temporal correlation (memory), and spatial correlation (length scale). Models do relatively well in capturing large-scale variability of metrics across climate regimes, but they poorly reproduce observed patterns at scales of ~*O*(100km) and smaller. Uncoupled land models do no better than coupled model configurations, nor do reanalyses outperform free-running models. Spatial decorrelation scales are found to be difficult to diagnose. Using data for model validation, calibration, or data assimilation from multiple soil moisture networks with different types of sensors and measurement techniques requires great caution. Data from models and observations should be put on the same spatial and temporal scales before comparison.

The 4x3 model analysis paradigm was then extended to terrestrial coupling metrics with the 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. 2018). The main result is that models clearly under-represent the feedback of surface fluxes on boundary layer properties (atmospheric leg of land-atmosphere coupling), while possibly over-representing the connection between soil moisture and surface fluxes (terrestrial leg). All models bias high in near-surface humidity and downward shortwave radiation, struggle to represent precipitation accurately, and show serious problems in reproducing surface albedos. These errors create challenges for models to partition surface energy properly, and errors are traceable through the surface energy and water cycles. The study also showed how error propagation along the process chains described by (Santanello et al. 2018) can be traced as a means to determine where process representation fails in coupled land-atmosphere models.

**<u>Relevant Journal Publications</u>:**


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: HCF AS A CONVECTIVE TRIGGER IN THE CFSv2. *Journal of Advances in Modeling Earth Systems*, **8**, 1310–1329, doi:10.1002/2016MS000668.

**Dirmeyer, P. A.**, and S. Halder, 2016: Sensitivity of Numerical Weather Forecasts to Initial Soil Moisture Variations in CFSv2. *Weather and Forecasting*, **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, Version 2 (CFSv2). *Journal of Hydrometeorology*, **18**, 85–108, doi:10.1175/JHM-D-16-0064.1.

**Dirmeyer, P. A.**, and H. E. Norton, 2018: Indications of Surface and Sub-Surface Hydrologic Properties from SMAP Soil Moisture Retrievals. *Hydrology*, **5**, 36, doi:10.3390/hydrology5030036.

**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. *Journal of Hydrometeorology*, **17**, 1049–1067, doi:10.1175/JHM-D-15-0196.1.

**Dirmeyer, P. A.**, L. Chen, **J. Wu**, C.-S. Shin, B. Huang, B. Cash, **M. Bosilovich**, S. Mahanama, R. D. Koster, **J. A. Santanello Jr., M. B. Ek**, G. Balsamo, E. Dutra and D. M. Lawrence, 2018: Verification of Land–Atmosphere Coupling in Forecast Models, Reanalyses, and Land Surface Models Using Flux Site Observations. *Journal of Hydrometeorology*, **19**, 375–392, doi:10.1175/JHM-D-17-0152.1.

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: Is Poor Performance a Result of Methodology or Data Quality? *Journal of Hydrometeorology*, **17**, 1705–1723, doi:10.1175/JHM-D-15-0171.1.

**Norton, H. E.**, and **P. A. Dirmeyer**, 2018: Soil moisture memory in karst and non-karst terrains. *Geophysical Research Letters*, (in review).

**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. *Journal of 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, 2018: Land-Atmosphere Interactions: The LoCo Perspective. *Bulletin of the American Meteorological Society*, **99**, 1253–1272, doi:10.1175/BAMS-D-17-0001.1.

Tawfik, A. B., **P. A. Dirmeyer**, and **J. A. Santanello**, 2015a: The Heated Condensation Framework. Part I: Description and Southern Great Plains Case Study. *Journal of Hydrometeorology*, **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 Conterminous United States. *Journal of Hydrometeorology*, **16**, 1946–1961, doi:10.1175/JHM-D-14-0118.1.

**Wu, J.**, and **P. A. Dirmeyer**, 2018a: Drought demise quantification and attribution using the Community Earth System Model Large Ensemble (CESM-LE). *Journal of Geophysical Research*, (in review).

**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).

Wulfmeyer, V., and Coauthors, 2018: A New Research Approach for Observing and Characterizing Land-Atmosphere Feedback. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-17-0009.1. https://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-17-0009.1 (Accessed August 17, 2018).

## <u>Book Chapters</u>:

**Dirmeyer, P. A**., P. Gentine, **M. B. Ek** and G. Balsamo, 2018: 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 (accepted).

**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, (also available in French and Spanish).

**Dirmeyer, P. A.,** K. L. Findell, and **J. A. Santanello Jr**., 2018: Metrics of Land-Atmosphere Coupling. [Chapter 18 in: Land-Atmosphere Interactions: Coupling Between The Energy, Water And Carbon Cycles], Common Ground, (submitted).

## <u>Conference and Workshop Presentations</u>:

**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.

**Dirmeyer, P. A**. and S. Halder, 2017: On the harvest of predictability from land surface states. American Geophysical Union Fall Meeting, New Orleans, LA, USA, H42B-04.

**Dirmeyer, P. A**., 2018: Confronting forecast models, reanalyses and land surface models with global remote sensing estimates of land-atmosphere coupling. 8th GEWEX Open Science Conference, Canmore, AB, Canada.

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.

**Norton, H. E., P. A. Dirmeyer, M. B. Ek**, H. Wei and Y. Xia, 2017: Parameterizing subsurface karst geology within the Noah Land Surface Model (LSM). American Geophysical Union Fall Meeting, New Orleans, LA, USA, H43N-08.

**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.

**Wu, J.,** and **P. A. Dirmeyer**, 2018: A new framework for determining causes of drought demise over CONUS. 8th GEWEX Open Science Conference, Canmore, AB, Canada.

## 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.