North American Heat Wave Predictability: Assessing the Role of Land Surface Initialization on S2S and NMME Model Forecasts -- *Progress Report*

1. General Information

Project Title: North American Heat Wave Predictability: Assessing the Role of Land Surface Initialization on S2S and NMME Model Forecasts
PI/co-PI names and institutions: Paul A. Dirmeyer (George Mason University
Report Year: 1 July 2016 – 30 June 2017 (Year 1)
Grant #: NA16OAR4310095

2. Main goals of the project, as outlined in the funded proposal

(1) Evaluate the ability of numerical forecast models included in the Sub-seasonal to Seasonal (S2S) Prediction and North American Multi-Model Ensemble (NMME) Phase II (SubX) projects to predict heat waves following drought events in the United States
(2) Relate model forecast performance to parameterization of land surface variables, coupled land-atmosphere metrics and initialization of land surface conditions
(3) Assess how more realistic land surface initialization in forecast models influences their ability to predict and simulate heat wave events in the United States

3. Results and accomplishments

The research goal of this project is to enhance our understanding of the connection between droughts and heat waves in the United States, as well as evaluating the ability of a suite of climate forecast models to predict heat wave occurrence. This goal is achieved by addressing the three objectives listed above:

Major Activities:

Research Activities in Year 1:

The first-year research focus has been on Objective 1: ***Evaluation the ability of numerical forecast models in the Sub-seasonal to Seasonal (S2S) Prediction and North American Multi-Model Ensemble (NMME) Phase II projects to predict heat waves following drought events in the United States.***

To this end, we have collected and begun to analyze model hindcasts at various lead times from the S2S and SubX climate modeling communities as well as atmospheric reanalysis datasets by which the hindcasts are verified. We have developed methods for identifying heat waves and droughts over the historical (1979 – 2014) period in MERRA-2 and ERA-I reanalysis datasets, and have developed an extensive heat wave climatology based on these datasets. Additionally we have developed methodology for verifying model hindcasts of minimum and maximum temperature heat waves using the reanalysis datasets. We have begun assessing the ability of the NCEP forecast model to predict heat wave occurrence and quantify the influence of pre-existing moisture conditions on the model's hindcast fidelity. We are summarizing the results of this analysis, and will soon submit an article invited for publication in a special S2S issue of *npj Climate & Atmos. Sci.*.

In addition, we have begun evaluating the statistical relationship between land surface moisture and subsequent maximum temperatures in the MERRA-2 and ERA-I reanalysis datasets. In particular we have evaluated the influence of antecedent moisture conditions on the likelihood of extreme heat, as well as the intensity and duration of extreme heat events. The thermodynamics connecting the land surface with air temperature anomalies in the MERRA-2 and ERA-I systems will be compared to the internal soil moisture – temperature coupling in the NCEP forecast model, and the results could help explain the model's performance in predicting heat wave occurrence. We are summarizing the results of this analysis, and will soon submit an article for publication in *J. Hydrometeor*. or similar journal.

So far the results of this project have been disseminated through an article published in *U.S. CLIVAR Variations*, as well as with presentations in the S2S Prediction Task Force Kickoff Meeting in December, 2016 and the American Geophysical Union Fall Meeting in December, 2016.

Significant Results:

To date, the major findings of this project are:

(1) The NCEP Model does not well predict Heat Waves in the Contiguous United States

Our verification of NCEP temperature hindcasts has demonstrated that the model cannot outperform a climatology forecast beyond about a 5-day lead time over much of the United States. These results are consistent over deterministic and probabilistic forecast verification measures, including the Kullback-Leibler Divergence (a.k.a. Relative Entropy), the Heidke Skill Score, and the Equitable Threat Score. The model tends to perform better in the inter-mountain West relative to chance, potentially related to the low interannual variability of heat wave occurrence in this region. But because of the short heat wave season over that same region, the NCEP model struggles to beat climatology there, showing greater skill relative to a climatological forecast at longer leads over the Southeast US.

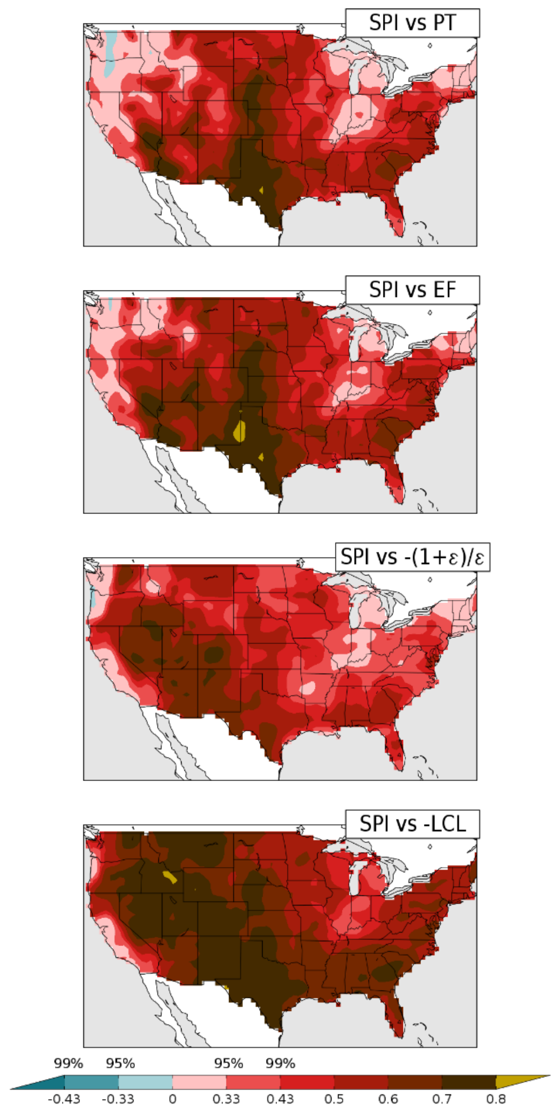

Figure 1. Correlation of MERRA-2 summer (JJA) standardized precipitation index (SPI) with Priestley-Taylor ratio (top), SPI with evaporative fraction term (second), SPI with the vapor pressure slope term (third), and SPI with lifting condensation level height (bottom).

(2) Soil moisture is statistically related to air temperature through multiple coupled pathways between land and atmosphere.

GMU MS student David Benson has been investigating, as part of his thesis, an array of coupling metrics from MERRA-2 reanalyses (chosen for its generally high quality and complete independence from any participating S2S forecast/hindcast models). This analysis is revealing the seasonal evolution of land-atmosphere coupling processes relevant to the pre-conditioning and amplification of heat waves over CONUS (Figure 1).

Benson is calculating the same metrics for the NCEP S2S set of hindcasts to determine how closely this model, in forecast mode, matches the MERRA-2 proxy for observed behavior and how differences may evolve as a function of forecast lead time.

(3) Poisson Averaging in time can help bridge the gap between deterministic hindcast verifications at short (typical weather forecast) lead-times and probabilistic hindcast verifications at longer lead-times

We verify NCEP model hindcasts at lead times ranging from 1 to 30 days. It is therefore less than ideal to directly compare the model's ability to predict heat waves on day n+1 with the heat wave prediction on day n+30. Ideally the shorter lead-time hindcasts would be validated deterministically at a single point in time while the longer lead-time hindcasts would be validated probabilistically for averages over days to weeks. We have developed a Poisson weighting method for bridging the gap between short- and long-lead time verification. The method uses a Poisson distribution to weight the model heat wave forecasts and validation data over multiple days surrounding the target day. The "window" of days included in the final weighted hindcast prediction lengthens as the lead time increases, thereby smoothly transitioning from deterministic to probabilistic verification. This also allows us to verify model hindcasts with a range of measures including a traditionally deterministic measure (Equitable Threat Score) at all lead times.

(4) The relationship between soil moisture and temperature extremes varies significantly by geographic region

We have used quantile regression with antecedent moisture conditions and maximum temperatures to identify regions where the 90th percentile of maximum temperature relates most strongly to antecedent precipitation and moisture. We found that although an ordinary least-squares regression model suggests a soil moisture-temperature "hot spot" in the Southern Great Plains, the extreme right tail of daily maximum temperature is most strongly related with antecedent moisture in an extensive region between the central Great Plains and Midwest. This analysis provides insights on the geographic regions where we could expect significant relationships between antecedent moisture and heat wave onset, motivating Objectives 2 and 3 (Figure 2).

Key Outcomes

To date, this project has resulted in 2 manuscripts in process. In addition, the project has resulted in 2 conference presentations, and was the basis for an article in the U.S. CLIVAR *Variations* publication. This article summarizes the state-of-the science and recent research on land-atmosphere interactions and their role in subseasonal-to-seasonal forecasting. The project has benefitted from thesis research by a Masters student at George Mason University over the 2016-2017 academic year (M.S. degree to be conferred in Summer 2017), and will employ 1 Ph.D. student each at George Mason University and Southern Illinois University beginning with Fall term of 2017.

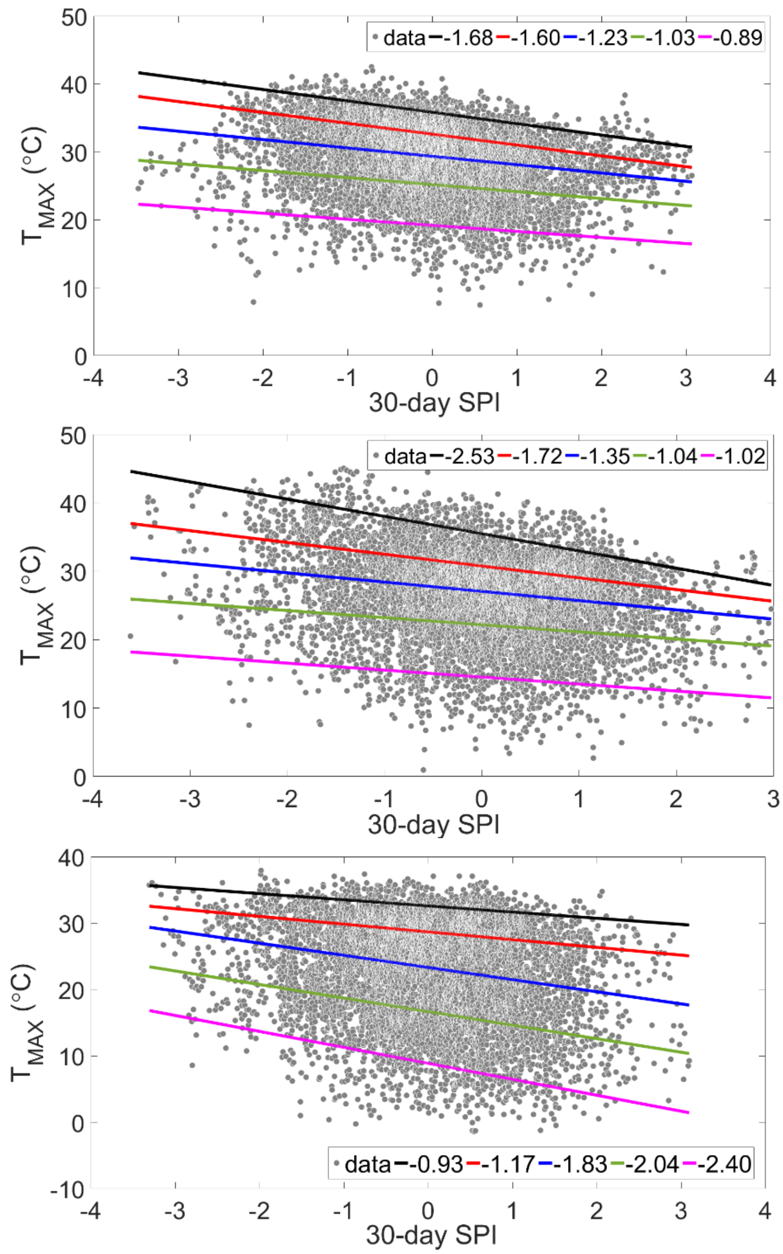

Figure 2. Regression of 30-day SPI and maximum temperature at (black) 95th, (red) 75th, (blue) 50th, (green) 25th, and (magenta) 5th percentiles. The slope of each regression is reported in the legend.

4. Highlights of Accomplishments

- Developed a framework for validating S2S model heat wave forecasts at a variety of lead times
- Decomposed the statistical coupling between soil moisture and air temperature relevant to heat wave occurrence
- Established a climatology of heat waves and assessed heat wave characteristics within multiple atmospheric reanalysis datasets
- Determined the spatial variability of soil moisture – temperature interactions
- Presented findings at 2 workshops/conferences, developed 2 manuscripts, and augmented the thesis work of 1 MS-level graduate student

5. Transitions to Applications

N/A at this time.

6. Publications from the Project

Conference Papers & Presentations:

Dirmeyer, P.A., Ford, T.W., and D. Benson (2016) "Predictability of Heat Waves Following Drought Events in the United States in S2S Models". NOAA Sub-seasonal to Seasonal Extremes Workshop. December 7, 2016. Palisades, New York.

Ford, T.W., Dirmeyer, P.A., and D. Benson (2016) "Land-Atmosphere Interactions and Subseasonal-to-Seasonal Forecasting of Extreme Heat in the United States". CLIVAR *Variations* Webinar Series. December 8, 2016.

Ford, T.W., Dirmeyer, P.A., and D. Benson (2016) "Evaluation of the Ability of S2S and NMME Models to Predict Heat Waves Following Drought Events in the United States". American Geophysical Union Fall Meeting. December 15, 2016. San Francisco, California.

Published Articles:

Ford, T. W. and P. A. Dirmeyer, 2016: Land-atmosphere interactions and subseasonal-to-seasonal forecasting of extreme heat in the United States. *US CLIVAR Variations*, **14**(4), 30-35.

Dirmeyer, P. A., T. W. Ford and D. O. Benson, 2017: Seamless evaluation of heat wave forecasts across subseasonal time scales: Skill attribution and the role of land-atmosphere interactions. *npj Climate & Atmos. Sci.*, (in prep).

Ford, T. W., P. A. Dirmeyer, and D. O. Benson, 2017: Soil moisture-temperature interactions in the context of extreme heat. *J. Hydrometeorol.* (in prep).

7. PI Contact Information

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8. Budget for Coming Year

Incremental amount: $116,558 for Y2 period (through 30 June 2018)

9. Future Work

The focus of our research activities during the next year will include the following:

(1) Continued verification of S2S model heat wave forecasts

Over the last year, we have made significant progress in designing and implementing a methodology for verifying S2S model heat wave forecasts. We are completing extensive analysis to this end using the NCEP forecast model, and will extend this analysis to additional forecast models that are part of the S2S and SubX groups.

(2) Continued analysis of soil moisture – atmosphere coupling relevant for heat wave processes

The initial results from the land-atmosphere coupling analysis suggest the dynamic and thermodynamic processes connecting soil moisture to boundary layer conditions relevant for heat wave onset are important components for heat wave prediction. These results necessitate further analysis to determine the specific processes that couple the land surface and atmosphere, and how these processes act to initiate extreme heat conditions.

(3) Initial validation of S2S model soil moisture conditions

As part of objective 2, we will begin collecting and processing *in situ* and gridded soil moisture datasets with which to validate soil moisture conditions in S2S models. The process of *in situ* soil moisture data collection and processing is time-consuming, but will be valuable for evaluating the models' respective abilities to accurately initialize soil moisture conditions, and for assessing how the initialization integrity relates to model heat wave forecast accuracy. We may also bring to bear FLUXNET data where and when available as means to assess the coupling links, through surface fluxes, that may act as process pathways for soil moisture to modulate heat waves.