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); Trent W. Ford (Southern Illinois University;
Report Year: 1 July 2018 – 30 June 2019 (Year 3)
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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 heat waves and land-atmosphere coupling 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 3:

The third year research foci have been on all three objectives. For objective 1, we have continued to collect and analyze model hindcasts at various lead times from the S2S climate modeling community, and have adopted a variety of gridded observation-based temperature and atmospheric reanalysis datasets for model validation. We have developed a verification framework to assess the fidelity of forecasts and hindcasts seamlessly across S2S timescales. The development of this verification methodology and results from multiple SubX models are summarized in Ford *et al.* (2018) and Dirmeyer and Ford (in review).

In addition, we have further verified SubX model temperature hindcasts, and related model performance to land surface conditions. 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. We have adopted a number of atmospheric reanalysis, model, *in situ*, and satellite-based products for this comparison, including ERA-Interim, NLDAS-2, FluxNet, SMAP, and GLEAM. We have found consistent model overestimation of heat wave occurrence, corresponding with overly persistent daily maximum air temperature, as compared with observations. This occurs primarily in the upper Midwest, co-located with underestimation (overestimation) of latent heat (sensible heat). This is consistent with the thermodynamics underlying soil moisture-temperature coupling that could lead to over-forecasted extreme heat. We will soon submit an article for publication based on these results in *J. Geophysical Research-Atmospheres*.

So far, the results of this project have been disseminated through a scientific article published in *NPJ Climate & Atmospheric Science* (Ford *et al.* 2018), an article published in *U.S. CLIVAR Variations*, and presentations in the S2S Prediction Task Force Kickoff Meeting in December 2016, the American Geophysical Union Fall Meetings in December, 2016, 2017, and 2018, the 8th GEWEX Open Science Conference in 2018, the 2nd International Conference on S2S Prediction in 2018, and the 2019 Workshop on Predictability, Dynamics and Applications Research using the TIGGE and S2S ensembles. Additionally, we have one article in review (Dirmeyer and Ford, in review) and two articles in preparation.

Significant Results:

To date, the major findings of this project are:

(1) A versatile weighting methodology has been developed that can be used to seamlessly transition from deterministic to time-mean forecasts, and can be applied to subseasonal forecasts, including probabilistic forecasts and forecasts predicated on skill scores from ensemble statistics

(2) All 5 SubX models validated so far over-predict maximum temperature heat waves over the upper Midwest

(3) Model heat wave hindcast fidelity is related to the soil moisture conditions and surface heat flux partitioning over the Midwest

Key Outcomes

To date, this project has resulted in a manuscript published, 1 manuscript in review, and 2 in process. In addition, the project has resulted in 7 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 conferred in Summer 2017); this student has continued on to pursue his Ph.D. at George Mason beginning in the 2017-2018 academic year. The student's dissertation research is related to his work on this project. In addition, the project has benefited from the thesis research by a Masters student at Southern Illinois University over the 2017-2018 and 2018-2019 academic years. One undergraduate student researcher at Southern Illinois

University has also been working on the project, focusing on the role of land cover on heat wave characteristics and the models' abilities to capture these effects.

4. Highlights of Accomplishments

- Developed a framework for validating model forecasts and hindcasts seamlessly across S2S timescales
- Comprehensively verified heat wave hindcasts from 5 SubX models
- 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 multiple workshops/conferences, developed 3 manuscripts, augmented the thesis work of 2 MS-level graduate students, 1 PhD-level graduate student, and provided a research opportunity for 1 undergraduate student

5. Transitions to Applications

N/A at this time.

6. Publications from the Project

Conference Papers & Presentations:

Ford, T.W., Dirmeyer, P.A., and D. Benson (2017) "Evaluation of Heat Wave Forecasts Seamlessly Across S2S Time Scales: Skill Attribution and the Role of Land-Atmosphere Interactions.

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.

Publications:

Dirmeyer, P. A., T. W. Ford and D. O. Benson, 2018: Evaluation of Heat Wave Forecasts Seamlessly Across Subseasonal Time Scales. *npj Climate & Atmos. Sci.*, 1, 20.

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., and T.W. Ford, 2019: A technique for seamless forecast validation from weather to monthly time scales. *Mon. Wea. Rev.*, (in review).

Ford, T.W., P.A. Dirmeyer, D.O. Benson, and C. Wong, 2019: Land-Atmosphere interactions and subsesaonal heat wave forecasts from a suite of climate forecast models. *J. Geophys. Res.*, (in prep.).

Benson, D.O. and P.A. Dirmeyer, 2019: A diagnosis of heatwaves and associated land-atmosphere interactions over the U.S. from reanalyses, (in prep.).

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8. Budget for Coming Year

A no-cost extension has been requested to complete the proposed work.

9. Future Work

I am requesting a no cost extension, during which the focus of research activities will include the following:

(1) Finalized verification of SubX models

Over the last year, we have made significant progress in designing and implementing a methodology for verifying S2S model heat wave hindcasts. We have applied this framework to extensively evaluate heat wave forecasts from 5 models in the SubX program. We will finalize verification of the other 2 SubX models and summarize verification results in a journal article.

(2) Finalized 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. In particular, all 5 SubX models assessed so far systematically overestimate maximum temperature heat waves over the upper Midwest, attributable to overly persistent daily maximum temperature. The models all tend to underestimate soil moisture availability and latent heat flux in the same region, suggesting a land surface imprint in the overly persistent maximum temperature. Some S2S models have updated output to include soil moisture, necessary for estimating land-atmosphere feedbacks on heatwaves, and will be re-evaluated. We will continue to use a variety of verification datasets to diagnose the source of model hindcast error, and better understand the role model land surface conditions and surface-atmosphere interactions in modulating or exacerbating these errors. These results will be summarized in two journal articles.

(3) Graduate student support

The supported PhD student at GMU, David Benson, came onto the project late – as a result there is particularly graduate student support remaining on the grant. To ensure completion of the tasks, we plan to support a second student on the project for the next year to help complete work described above.