Forecasting risk of seasonal temperature extremes with the North American Multi-Model Ensemble (NMME)
Progress Report

1. General Information

Project Title: Forecasting risk of seasonal temperature extremes with the North American Multi-Model Ensemble

PI/co-PI names and institutions: Krakauer, City College of New York (CCNY), City University of New York Research Foundation (RF-CUNY)

Report Year (Progress Report Fiscal Year or Final Report): August 2015-January 2018

Grant # (if available -- "NA…"): NA15OAR4310080

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

Apply and extend methods (including trend extrapolation, quantification of forecast information gain and over- or under-confidence, and different approaches to probability distribution estimation and model weighting) for quantifying and improving seasonal forecast skill with NMME, to provide usable probability forecasts and with diagnostic outputs for model improvement. Key work plan elements included:

- Optimal trend estimation
- Optimal combination of models and ensemble members
- Construction of probability forecasts from ensembles
- Algorithms for probabilistic prediction.

3. Results and accomplishments

Results and accomplishments have included:
1) Published a paper on development and evaluation of probabilistic temperature forecasts using CFS-v2 hindcasts, where we focused on the ability of regression-based methods to better account for warming trends and to correct ensemble under-dispersion [1].
2) Published a paper in the *Climate Dynamics* NMME special issue [2] evaluating the skill of NMME-based probabilistic monthly temperature forecasts using different processing schemes to correct for biases and misrepresented trends. Special attention was paid to conditional skill under extreme temperatures. It was found that mean skill of NMME-based forecasts for future months was modest over most land areas, but conditional skill was much better for extreme conditions, particularly in warmer seasons and climates. This suggests that NMME could be valuable in providing early warning of heightened risk for damaging extremes.
3) Published a peer-reviewed software meta-paper [3] on the open-source SeFo collection of scripts developed to produce and verify seasonal forecasts from NMME output. Since this publication, SeFo has been extended in its repository [4] to include routines for transforming

non-normally distributed variables such as precipitation and generating forecasts of the transformed quantities, as well as implementing additional diagnostics such as an analytic expression for the continuous rank probability skill score of forecast *t* distributions.
4) An application of the developed forecast methods to probabilistic forecasts of record exceedances was presented at the NMME/SubX Science Meeting held at the NOAA Center for Weather and Climate Prediction on September 2017.
5) Optimal trend estimation methods were applied for evaluation of trends in annual minimum temperatures, with implications to agronomy and invasion biology [5].
6) The renewal of the CREST Cooperative Institute [6] at CCNY includes follow-up work on drought prediction to be led by the PI as a component of the science plan. Hydrological prediction for a basin in Nepal will also take place as part of a new High Mountain Asia award to CCNY by NASA ROSES. Grant applications to MAPP for evaluating machine learning methods for improved probabilistic prediction of drought indices and monsoon predictions were submitted and turned down.
7) Work was conducted on variability and potential seasonal predictability of energy supply and demand (particularly wind and solar resources) as a way of potentially applying processed NMME outputs to a growing economic sector, with a presentation at the SOLAR 2016 conference as well as a published case study on "wind drought" [7] and a global-scale study [8].
8) Other related work included assessment of climate model simulation of trends due to irrigation forcing [9], studies of historic and projected precipitation change patterns and simulated implications for reservoir reliability [10, 11] and streamflow probability distribution [12], and evaluation of machine learning for estimating the water table depth field and its dependence on climate from sparse measurements [13, 14].

[1] H Aizenman, MD Grossberg, NY Krakauer, I Gladkova (2016) Ensemble forecasts: probabilistic seasonal forecasts based on a model ensemble, *Climate*, 4(2): 19, doi: 10.3390/cli4020019
[2] NY Krakauer (2017), Temperature trends and prediction skill in NMME seasonal forecasts, *Climate Dynamics*, doi: 10.1007/s00382-017-3657-2
[3] NY Krakauer (2016), SeFo: A Package for Generating Probabilistic Forecasts from NMME Predictive Ensembles, *Journal of Open Research Software*, 4(1): e19, doi: 10.5334/jors.112
[4] https://bitbucket.org/niryk/sefo
[5] NY Krakauer (2018), Shifting hardiness zones: trends in annual minimum temperature, *Climate*, 6(1): 15, doi: 10.3390/cli6010015
[6] http://noaacrest.org/
[7] D Rife, NY Krakauer, DS Cohan, JC Collier (2016), A new kind of drought: U.S. record low windiness in 2015, *Earthzine*
[8] NY Krakauer, DS Cohan (2017), Interannual variability and seasonal predictability of wind and solar resources. *Resources*, 6(3): 29, doi: 10.3390/resources6030029

[9] NY Krakauer, MJ Puma, BI Cook, P Gentine, L Nazarenko (2016), Ocean-atmosphere interactions modulate irrigation's climate impacts, *Earth System Dynamics*, doi: 10.5194/esd-7-863-2016

[10] B Asadieh, NY Krakauer, BM Fekete (2016), Historical trends in mean and extreme runoff and streamflow based on observations and climate models, *Water*, 8(5): 189, doi: 10.3390/w8050189
[11] B Asadieh, NY Krakauer (2016), Impacts of changes in precipitation amount and distribution on water resources studied using a model rainwater harvesting system, *Journal of the American Water Resources Association*, doi: 10.1111/1752-1688.12472
[12] B Asadieh, NY Krakauer (2017), Global change in streamflow extremes under climate change over the 21st century, *Hydrology and Earth System Sciences*, 21(11): 5863-5874, doi: 10.5194/hess-21-5863-2017
[13] IC Pérez Hoyos, NY Krakauer, R Khanbilvardi, RA Armstrong (2016) A review of advances in the identification and characterization of groundwater dependent ecosystems using geospatial technologies, *Geosciences*, 6(2): 17, doi: 10.3390/geosciences6020017
[14] IC Pérez Hoyos, NY Krakauer, R Khanbilvardi (2016) Estimating the probability of vegetation to be groundwater dependent based on the evaluation of tree models, *Environments*, 3(2): 9, doi: 10.3390/environments3020009

4. Highlights of Accomplishments

- A paper in the *Climate Dynamics* NMME special issue evaluated the skill of NMME-based probabilistic monthly temperature forecasts using different processing schemes to correct for biases and misrepresented trends. It was found that mean skill of NMME-based forecasts for future months was modest over most land areas, but conditional skill was much better for extreme and record conditions, particularly in warmer seasons and climates. This suggests that NMME could be valuable in providing early warning of heightened risk for damaging extremes.
- A peer-reviewed software meta-paper described the developed open-source SeFo collection of scripts developed to produce and verify seasonal forecasts from NMME output. SeFo is freely available on BitBucket, and has been extended to include routines for transforming non-normally distributed variables such as precipitation and generating forecasts of the transformed quantities, as well as implementing additional diagnostics such as an analytic expression for the continuous rank probability skill score of forecast t distributions.
- Funding was obtained for future applications of the developed methods for seasonal forecasts for drought prediction in the USA and hydrological forecasting in the Himalayas.

5. Transitions to Applications

None.

6. Publications from the Project

H Aizenman, MD Grossberg, NY Krakauer, I Gladkova (2016) Ensemble forecasts: probabilistic seasonal forecasts based on a model ensemble, *Climate*, 4(2): 19, doi: 10.3390/cli4020019
NY Krakauer (2016), SeFo: A Package for Generating Probabilistic Forecasts from NMME Predictive Ensembles, *Journal of Open Research Software*, 4(1): e19, doi: 10.5334/jors.112
D Rife, NY Krakauer, DS Cohan, JC Collier (2016), A new kind of drought: U.S. record low windiness in 2015, *Earthzine*
NY Krakauer (2017), Temperature trends and prediction skill in NMME seasonal forecasts, *Climate Dynamics*, doi: 10.1007/s00382-017-3657-2
NY Krakauer, DS Cohan (2017), Interannual variability and seasonal predictability of wind and solar resources. *Resources*, 6(3): 29, doi: 10.3390/resources6030029

7. PI Contact Information

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8. Budget for Coming Year

N/A

9. Future Work

Follow-on work under other projects will include extending the software and methodology developed to probabilistic forecasting of other variables (such as precipitation and windspeed) and potentially to various operational settings. Opportunities will be sought to conduct comparisons of the developed forecast methods with operational NCEP forecasts and to work with NOAA scientists to transition the advances made to operational applications.