A U. S. Nation Multi-Model Ensemble

Final Report 08/01/2012 – 07/31/2015
Award Number NA12OAR4310089
PI: Benjamin Kirtman

The North American Multi-Model Ensemble (NMME; Kirtman et al. 2014) experiment is an unprecedented effort to improve intraseasonal to interannual (ISI) operational predictions based on the leading North American climate models. As a result of two Climate Test Bed (CTB) NMME workshops (February 18, and April 8, 2011) a collaborative and coordinated implementation strategy for the phase-I NMME prediction system was developed and is now fully functioning. The core activity of phase-I was to make multi-model (from the major US and Canadian modeling centers) ***seasonal*** predictions in real-time on the NOAA operational schedule. Participating models are necessarily global coupled ocean-atmosphere-land-seaice models. The NMME phase-I project was supported by the NOAA Climate Program Office (CPO) MAPP (Modeling, Analysis, Predictions and Projections) Program, and critically leverages existing seasonal prediction activities at the major US and Canadian modeling centers. The NMME Phase-II project for the period of August 2012 – July 2015 is supported by NOAA/CPO with contributions from DOE, NASA, and NSF. The phase-II objectives include:

(i) Continued real-time forecasts and incorporating updated models;
(ii) Coordinated predictability research that identifies the benefit of the multi-model approach, examines how best to combine models, and guides model development and applications;
(iii) Developing and evaluating an intraseasonal protocol;
(iv) Continued and enhanced data distribution to facilitate use of NMME data.

The entire scope and impact of NMME cannot be exhaustively described here[1]. Nevertheless, NMME made substantial progress in all of its goals, is a key asset to operational forecasters, a facility that enables predictability and prediction research, informs model development, is critical input for a host of application models and is being extensively used by the private sector. *Importantly, the NMME project has been "operationalized" as of July 2015.*

In terms of broad brush overarching accomplishments, NMME-2:

- Has introduced four new modeling systems that expands the ensemble size to well over 100 members;
- Increased the real-time monthly data to include five new variables;
- Provides real-time bias corrected monthly forecast data and over 2500 figures each month showing the forecasts from the individual models and the multi-model mean and the multi-model distribution (http://www.cpc.ncep.noaa.gov/products/NMME/);
- Produced (by the end of October 2014) the most comprehensive seasonal prediction data set (1.5 PB) that is made readily available to the entire community;

[1] Here after the NMME phase-I project will be referred to as NMME-1 and the phase-II project will be referred to as NMME-2. We note, however, that most of the NMME-1 activities continue as part of NMME-2.

- Has demonstrated that the diversity of models is enhancing the forecast skill beyond CFSv2 alone.

This final report emphasizes results directly related to efforts at the University of Miami – RSMAS. Specifically, we summarize several scientific results from our NMME efforts into two broad categories: (i) production and dissemination of retrospective and real-time forecast and (ii) advancing understanding for forecast quality and the limits of predictability.

(i) Retrospective and Real-time CCSM4 forecasts

A major component of the proposed research that has been completed is to produce a set of retrospective (1982-2009) seasonal forecasts with CCSM4 initialized every month using the agreed upon NMME protocol. These retrospective forecasts have been completed and have been uploaded by the IRI (monthly limited fields), by NCAR on the ESG server (daily expanded fields), and by CPC for operational guidance. In addition, we have filled-in the retrospective data base so that there is a complete set of retrospective forecasts from 1982-present – also published in the archives. The CCSM4 real-time forecasts have been delivered to CPC on time every time since July 2014. We have also modified the production schedule to accommodate the use of NMME in the monthly ENSO briefing. Finally, we make additional dynamic fields available in real-time to CPC for seasonal hurricane forecasts.

To highlight the contribution from CCSM4 we show a brief comparison with CCSM3. Figure 1, for example, shows the difference (CCSM4 minus CCSM3) in SSTA anomaly correlation measured by Fisher's r-to-z transform. Shading indicates transformed difference, stippling indicates where correlations are significantly different at 0.05 level of significance. In most locations CCSM4 has larger correlations. The notable exception is the deep tropical Pacific where CCSM3 is larger, but this does not pass this particular significance test. Similarly, Fig. 2 shows the difference in Fisher's r-to-z transform T2m (top panel) and precipitation (bottom panel). For T2m the correlation is generally larger for CCSM4, particularly over North America. In terms of the precipitation correlation, the results are noisy but generally positive and some notable regions where the CCSM4 has significantly larger correlation.

Another example is the initialization strategy developed for CCSM4 that was specifically designed with the NMME forecast protocols in mind. This can be seen by the fact that the ocean, land and atmospheric initial conditions are taken from CFSR (Saha et al. 2010) for both the retrospective forecast and the real-time forecasts. This is done so that CCSM4 can meet the on-time NMME protocol requirements and use state-of-the-art initial conditions. The approach has the added advantage that we can examine how using the same initial conditions with a very difference forecast tool (CFSv2 vs. CCSM4) affects the prediction. In contrast, the CCSM3 forecasts use climatological states for the land and atmosphere and an ocean-only data assimilation system for the ocean states (see Kirtman and Min 2009).

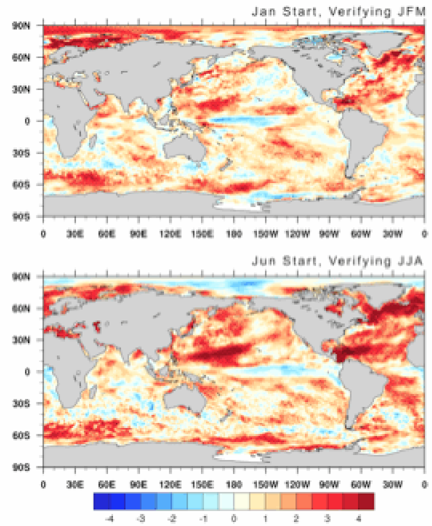

Figure 1. Difference in anomaly correlation for CCSM4 SSTA minus CCSM3 SSTA measured by Fishers r-to-z transform. Anomaly correlation is calculated versus observed SSTA where the forecasts are initialized during 1982-2010. Shading indicates transform difference, stippling indicates where correlations are significantly different at 0.05 level of significance. Red (blue) shading indicates CCSM4 anomaly correlation higher (lower) than CCSM3. January start hindcasts verifying in JFM, or a 1.5 season lead is shown in the top panel, June start hindcasts verifying in JJA (1.5 season lead) shown in the bottom panel.

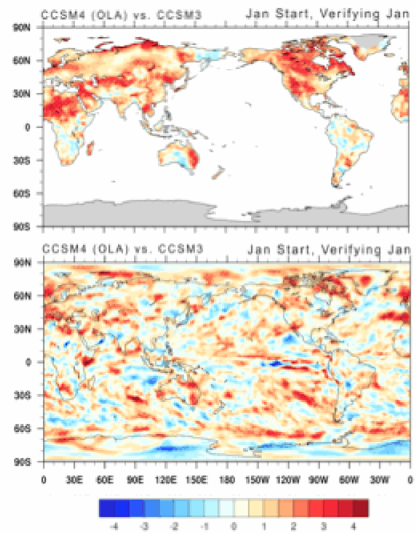

Figure 2: Difference in anomaly correlation for CCSM4 minus CCSM3 SSTA measured by Fishers r-to-z transform. Anomaly correlation is calculated versus observed T2m (top) and precipitation (bottom) where the forecasts are initialized during 1982-2010. Shading indicates transform difference, stippling indicates where correlations are significantly different at 0.05 level of significance. Red (blue) shading indicates CCSM4 anomaly correlation higher (lower) than CCSM3. Both panels show January start hindcasts verifying in January.

(ii) Assessing Forecast Quality and Predictability

The results briefly summarized below highlight how the CCSM4 NMME data and the greater NMME ensemble members have been used to assess forecast quality and the limit of predictability.

a. Southeastern US Precipitation

Infanti and Kirtman (2014) investigated the predictive skill of the North American Multi-Model Ensemble (NMME) system for intraseasonal-to-interannual (ISI) prediction with focus on southeastern U.S. precipitation. The southeastern United States is of particular interest because of the typically short-lived nature of above- and below-normal extended rainfall events allowing for focus on seasonal prediction, as well as the tendency for more predictability in the winter months. Included in this study is analysis of the forecast quality of the NMME system when predicting above- and below-normal rainfall and individual rainfall events, with particular emphasis on results from the 2007 dry period. Both deterministic and probabilistic measures of skill are utilized in order to gain a more complete understanding of how accurately the system predicts precipitation at both short and long lead times and to investigate the multi-model aspect of the system as compared to using an individual predictive model. The NMME system consistently shows low systematic error and relatively high skill in predicting precipitation, particularly in winter months as compared to individual model results.

We have plotted the NMME ensemble mean anomaly (most probable outcome) for FMA2006, ASO2006, and FMA2007 at short and long leads versus observations in Figs. 3a, 3b, and 3c, respectively. Figure 3a (FMA2006) shows similar results to previous figures, with good agreement at a short lead, and slightly dry, but mainly neutral, precipitation at a long seasonal lead. ASO2006 (Fig. 3b) accurately captures the precipitation deficit off the coast of the United States with a slight wet anomaly inland, but is mainly neutral at both leads. This season did not show good skill at either lead time, so this is expected. Finally, we find that the NMME system does not accurately resolve the precipitation anomalies in FMA2007 (Fig. 3c) at a long lead, showing a pre-dominantly wet anomaly at this lead time and very weakly dry precipitation at a short seasonal lead.

Given this large tendency for above-normal precipitation during FMA2007 at a long lead, we also looked at the SSTA hindcast during this time period, as there is potential for a linkage to tropical Pacific SSTAs during the winter seasons. In observations, we find cold SSTAs during phase 1, followed by warm SSTA in phase 2, and narrow, cold, more concentrated SSTAs in phase-3. We do not see a continual cold event in the tropical Pacific, and we find warm SSTAs in summer. We find that during FMA2006, ASO2006, and FMA2007 there is good agreement during the short-lead periods in the tropical Pacific, but during the long-lead hindcast, there are neutral SSTAs in FMA2006 and warm SSTAs in FMA2007; thus, the SSTA hindcast during these two time periods was incorrect.

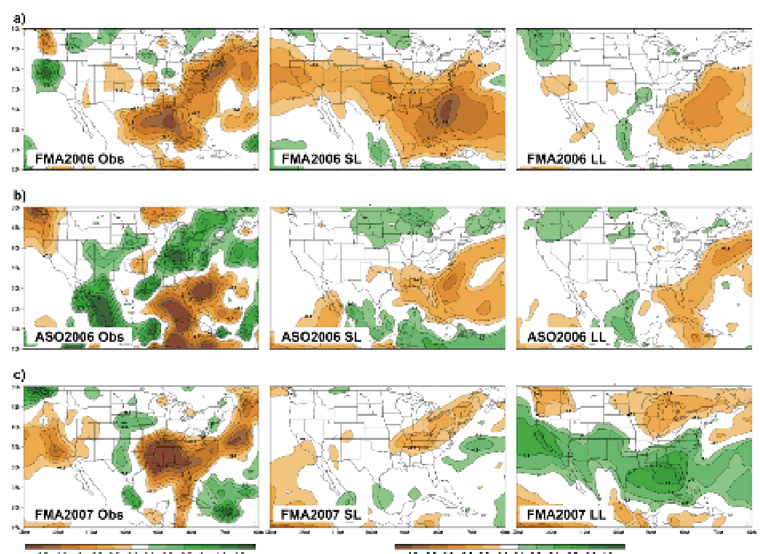

Figure 3. (left) Observed vs NMME ensemble mean precipitation anomalies for (middle) short and (right) long leads for (a) FMA2006, (b) ASO2006, and (c) FMA2007. Observed is plotted for phase 1 through phase 3 of the 2006–07 drought and has a color scale and contours ranging from 21.5 to 1.5 mm per day at intervals of 0.3, 0.5, 0.7, 1.0, 1.3, and 1.5 mm per day. NMME ensemble mean verifies in the same seasons at the short and long leads and has a color scale and contours ranging from 21 to 1 mm day21 at intervals of 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 mm per day. The y axes run from 15 to 50N in increments of 5 and the x axes run from 130W to 60W in increments of 10.

b. Pacific Meridional Mode and ENSO prediction

Although modeling and observational studies have highlighted a robust relationship between the Pacific Meridional Mode (PMM) and ENSO, namely, that the PMM is often a precursor to El Niño events, it remains unclear if this relationship has any real predictive use. Bridging the gap between theory and practical application is essential, because the potential use of the PMM precursor as a supplemental tool for ENSO prediction has been implied but not yet implemented into a realistic forecast setting. In Larson and Kirtman (2014), a suite of sea surface temperature hindcasts is utilized from the NMME prediction experiment between 1982 and 2010. The goal is to first, assess the NMME's ability to forecast the PMM precursor and second, examine the relationship between PMM and ENSO within a forecast framework. In terms of model performance, results are optimistic in that not only is PMM variability captured well by the multi-model ensemble mean, but also appears as a precursor to ENSO events in the NMME. There proves to be considerable opportunity for improvement of the PMM/ENSO relationship in the forecast models and accordingly, the predictive use of PMM for certain types of ENSO events may also see improvement.

c. North American hydroclimate prediction response to diversity of ENSO

Research has shown that there is significant diversity in the location of the maximum sea surface temperature anomaly (SSTA) associated with the El Niño Southern Oscillation (ENSO). In one extreme, warm SSTA peak near the South American coast (often referred to as Eastern Pacific of EP El Niño), and at the other extreme, warm SSTA peak in the central Pacific (Central Pacific or CP El Niño). Due to the differing tropical Pacific SSTA and precipitation structure, there are differing extratropical responses, particularly over North America. Recent work involving the North American Multi-Model Ensemble (NMME) System for Intra-Seasonal to Inter-Annual Prediction (ISI) on prediction of the differences between El Niño events found excess warming in the eastern Pacific during CP El Niño events. Infanti and Kirtman (2015) investigate the ensemble and observational agreement of the NMME system when forecasting the North American response to the diversity of ENSO, focusing on regional land-based 2-meter temperature and precipitation. NMME forecasts of North American precipitation and T2m agree with observations more often during EP events. Ensemble agreement of NMME forecasts is regional. For instance, ensemble agreement in Southeast North America demonstrates a strong connection to NINO3 precipitation and SSTA amplitude during warm ENSO events. Ensemble agreement in Northwest North America demonstrates a weak connection to NINO4 precipitation and SSTA amplitude during warm ENSO events. Still other regions do not show a strong connection between ensemble agreement and strength of warm ENSO events.

(vii) References

Infanti, Johnna M., Ben P. Kirtman, 2014: Southeastern U.S. Rainfall Prediction in the North American Multi-Model Ensemble. *J. Hydrometeor*, **15**, 529–550. doi: http://dx.doi.org/10.1175/JHM-D-13-072.1.

Infanti, J. M., and B. P. Kirtman, 2015: Uncertainty of the North American rainfall and temperature response to the diversity of ENSO in the North American Multi-Model Ensemble. Climate Dynamics (in press).

Kirtman, B. P., and co-authors, 2014: The North American Multi-Model Ensemble (NMME): Phase-1 Seasonal-to-Interannual Prediction, Phase-2 Toward Developing

Intra-Seasonal prediction. Bull. Amer. Met. Soc.,doi: http://dx.doi.org/10.1175/BAMS-D-12-00050.1.

Kirtman, B. P., and D. Min, 2009: Multi-model ensemble ENSO prediction with CCSM and CFS. *Mon. Wea. Rev*., DOI: 10.1175/2009MWR2672.1.

Larson, S. M., and B. P. Kirtman, 2014: Assessing Pacific Meridional Mode forecasts and its role as an ENSO precursor and predictor in the North American Multi-Model Ensemble. *J. Climate* (in press).

Paolino, D. A., J. L. Kinter III, B. P. Kirtman, D. Min, D. M. Straus, 2012: The impact of land surface initialization on seasonal forecasts with CCSM. *J. Climate,* **25**, 1007-1021.