Bridging the gap in NOAA's extended and long range prediction systems through the development of new forecast products for weeks 3 and 4

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1. Main Goals of the Project

- To transition a statistical MJO/ENSO phase model into an operational CPC week 3-4 temperature and precipitation outlook for all seasons
- To develop additional hybrid dynamical/statistical forecast tools for weeks 3-4

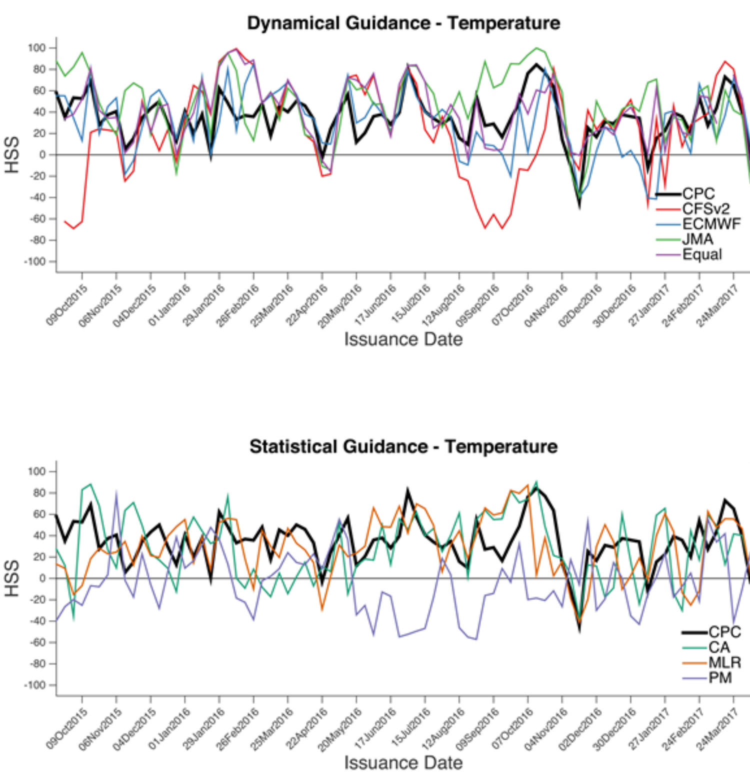
2. Results and Accomplishments

Our work over the past three years has aided the development of NOAA's first forecast products for weeks 3-4 while also advancing our fundamental understanding of teleconnection pattern predictability for lead times of three to four weeks. We successfully transitioned statistical forecast guidance into the NOAA/CPC experimental and operational week 3-4 products. We have monitored the performance of these products, which have demonstrated positive skill during the experimental implementation period. We completed projects that provided insight into the dynamical processes associated with subseasonal predictability, and we tested a new forecast approach for subseasonal teleconnection pattern forecasts. We describe our primary accomplishments below.

2.1 Transitioning forecast guidance for weeks 3 and 4 into operations

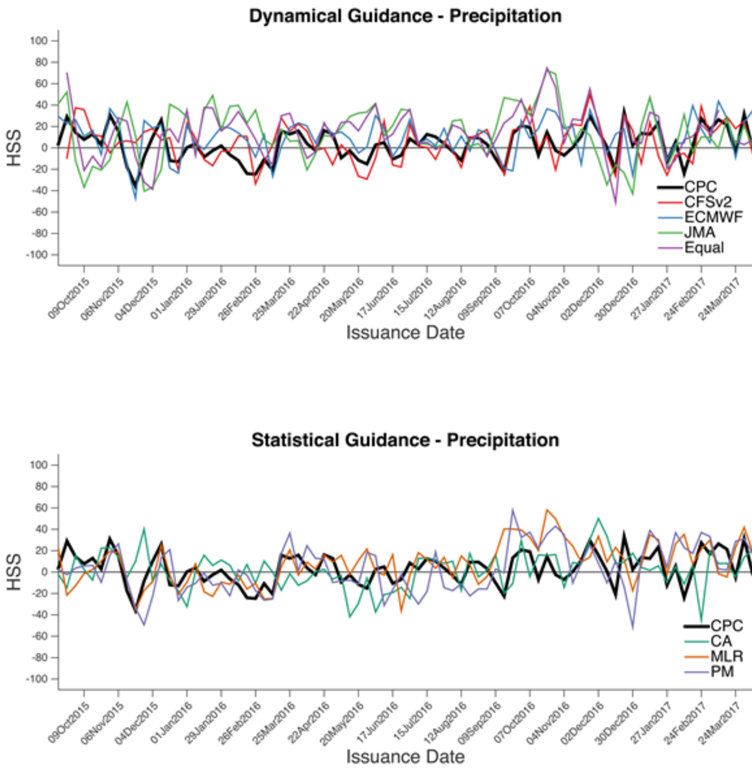
One of the primary objectives of the project was to transition the statistical model of Johnson et al. (2014) into operational CPC forecast guidance for weeks three and four. This model generates probabilistic forecasts for lead times of up to four weeks based on the initial states of the Madden-Julian Oscillation (MJO), El Niño-Southern Oscillation (ENSO), and the linear trend. Dr. Daniel Harnos, in close support with Co-PIs L'Heureux, Baxter, and Johnson, led the subsequent refinement and operational transition efforts of the MJO/ENSO statistical guidance. Key refinements included the extension from December – March to all three-month seasons, the addition of precipitation predictions, and the development of a complementary product based on multiple linear regression (MLR).

The MJO/ENSO statistical models were successfully transitioned into the implementation of CPC's Experimental Week 3-4 Outlooks in September 2015. This guidance was updated weekly and supplied to the forecast team. We then monitored the performance of this statistical forecast tools since the start of the experimental implementation period. Overall, we have found that the statistical guidance provides skillful temperature and precipitation outlooks in week 3-4, although the skill for temperature understandably is higher. For the two forms of statistical guidance that we have transitioned, the MJO/ENSO phase model (PM) of Johnson et al. (2014) and the MJO/ENSO MLR developed during the project, the MLR model generally has performed better during the experimental implementation period (Figs. 1 and 2). For temperature, the MLR model generally has been competitive with the dynamical guidance in terms of Heidke Skill Scores (HSSs). The statistical precipitation guidance also has been competitive with the dynamical guidance, and the MLR model actually has outperformed all the dynamical guidance in year 2 (Fig. 2). Therefore, we consider the transition of the statistical guidance to be successful. The MJO/ENSO statistical guidance was officially transitioned into operations for CPC Week 3-4 temperature outlooks on May 19, 2017, and the Week 3-4 precipitation outlook remains experimental.



	9/2015 To 8/2016	9/2016 To 4/2017	All Dates
CPC	36.3	32.7	34.9
CFSv2	29.5	15.1	23.8
ECMWF	39.1	17.3	30.6
JMA	48.3	45.9	47.4
Eq. Wtd	46.7	30.8	40.5
CA	27.3	29.9	28.3
MLR	29.9	28.3	29.3
PM	-4.8	-1.9	-3.6

Figure 1: Heidke skill scores (HSSs) of CPC's Experimental Week 3-4 Temperature Outlook for the implementation period beginning in September 2015. Top left panel indicates the HSS time series for the dynamical guidance, and the bottom left panel indicates the corresponding time series from the statistical guidance. The table on the right indicates the mean HSSs for the first year, second year, and the full period. "CPC" indicates the official CPC outlook, "CFSv2," "ECMWF," and "JMA" are the dynamical models used, and "Eq. Wtd" indicates the equal-weighted dynamical model ensemble. "CA" indicates the constructed analog statistical guidance, "MLR" is the multiple linear regression model, and "PM" is the MJO/ENSO phase model.



	9/2015 To 8/2016	9/2016 To 4/2017	All Dates
CPC	0.6	7.3	3.2
CFSv2	2.2	8.8	4.8
ECMWF	8.8	13.6	10.7
JMA	13.5	14.3	13.8
Eq. Wtd	12.6	17.5	14.5
CA	-2.2	7.4	1.5
MLR	-0.8	21.9	8.1
PM	-5.5	16.6	3.2

Figure 2: As in Fig. 1 but for precipitation.

2.2 Weeks 3-4 forecasts of North American teleconnection pattern indices

Given the promising results from the MJO/ENSO statistical guidance for CPC's Experimental Week 3-4 Outlooks, we have sought ways to enhance week 3-4 forecast guidance by (1) determining other sources of forecast skill aside from the MJO, ENSO, and linear trend, and (2) attempting to incorporate that knowledge into forecast guidance. Over the past two years of the project, Dr. Jiaxin Black under the guidance of Co-I Johnson completed a study that analyzed statistical forecasts of the dominant Northern Hemisphere teleconnection pattern indices, given that these teleconnection patterns are strong modulators of North American temperature and precipitation. Specifically, this work incorporates a partial least-squares regression (PLSR) method to generate 2-week statistical forecasts of the Pacific/North American (PNA) pattern, North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices. The candidate predictor fields include tropical outgoing longwave radiation (OLR) and Northern Hemisphere 300 hPa and 50 hPa geopotential height. Overall, we find that the wintertime PLSR forecasts for the 1980-2013 period are skillful at all lead times to five weeks and perform similarly well as the CFSv2 dynamical model forecasts in weeks 3-4 for the 1999-2010 period (Fig. 3).

A potential benefit of the PLSR approach is the ability to isolate a small number of predictor patterns to shed light on the physical sources of skill for the teleconnection patterns. Indeed, we identify several OLR and 300 hPa geopotential height patterns that are responsible for most of the teleconnection pattern skill (not shown). These results have the promise of providing guidance to forecasters on important precursor tropical convection and atmospheric circulation patterns that lead to skillful teleconnection pattern forecasts in weeks 3-4.

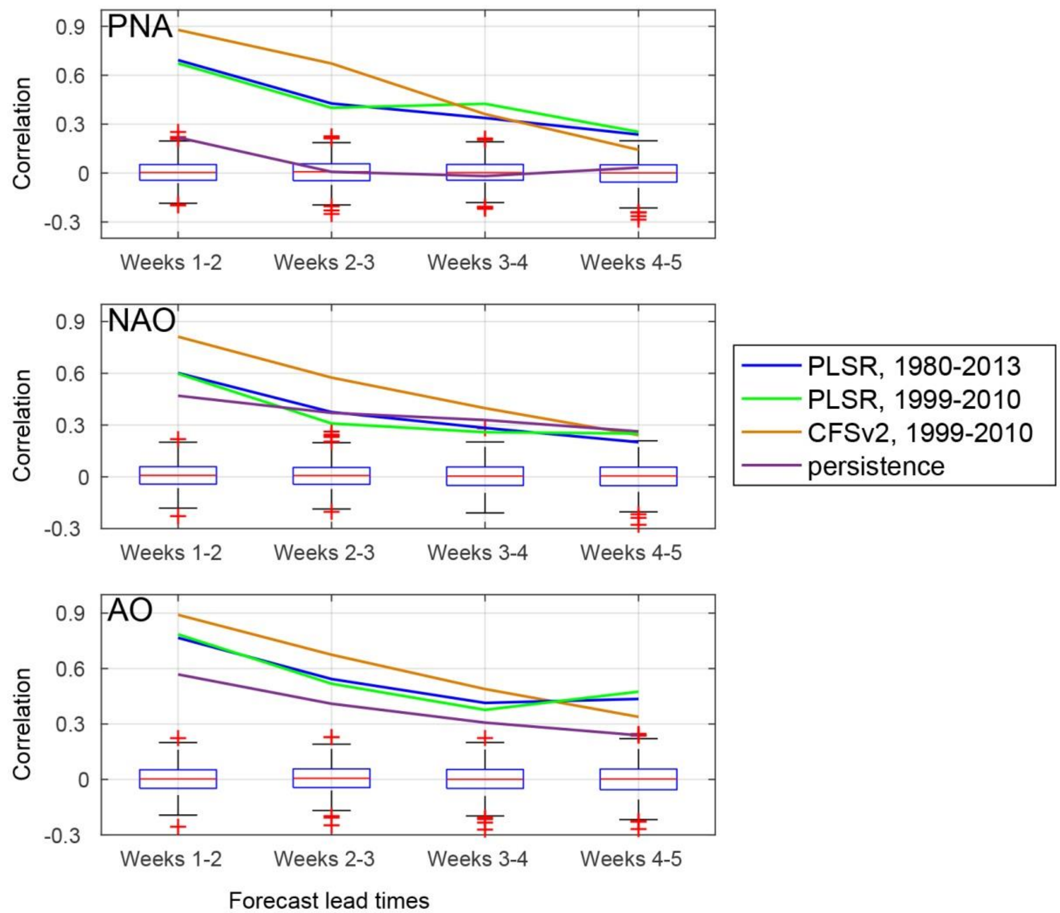


Figure 3: Box plots of the correlation between PLSR-derived forecasts and observed wintertime (DJF) 2-week-averaged PNA (top), NAO (middle), and AO (bottom) index time series at different forecast lead times. The box plots are generated based on reshuffled data using a Monte Carlo approach. The blue (green) lines denote the correlation of PLSR forecasts evaluated from 1980-2013 (1999-2010). The yellow lines denote the correlation of CFSv2 dynamical forecasts evaluated from 1999-2010. The purple solid and black dashed lines denote the correlation from persistence and climatological forecasts, respectively. Adapted from Black et al. (2017).

2.3 Enhancing our understanding of predictability in weeks 3-4

Several projects undertaken by Co-PI Feldstein and Co-I Johnson focused on the large-scale dynamics of patterns associated with North American predictability in weeks 3-4, providing promise for the development of indices that may aid predictions at these lead times. Co-PI Feldstein has guided several studies focusing on the dynamics and impacts of the MJO. In one study, Goss and Feldstein (2015) found that the extratropical response to tropical MJO heating is sensitive to the details of the initial flow pattern in both a simple dynamical model and observations. These results suggest that further improvement of 3-4 week probabilistic forecasts for North America may occur by taking into account the initial state of the extratropics. Goss and

Feldstein (2017) examined the impact of individual centers of MJO convection on the midlatitude circulation with both an idealized model and with ERA-Interim data. They determined that individual centers of MJO convection excite teleconnections of opposite sign in midlatitudes. The midlatitude response is dominated by the influence of the MJO convection center with the largest amplitude. These results indicate that possible improvement in operational week 3 and 4 forecast may occur if the relative amplitudes of the MJO centers of convection are taken into account. Lukens et al. (2017) further investigated the dynamics of the midlatitude MJO response by examining the relationship between MJO tropical convection, the Rossby wave source, and the extratropical response with an idealized model. They found that the initial anomalies are excited by advection of the climatological absolute vorticity by the anomalous divergent wind in the subtropics and by the anomalous horizontal divergence with the tropics. The resulting anomaly is then advected eastward by the climatological zonal wind toward the central Pacific, after which amplification and dispersion into the extratropics takes place.

Another study focused on the interaction between tropical Indo-Pacific warm pool convection, constructive interference with the climatological stationary wave, and the Northern Hemisphere extratropical circulation over the course of a few weeks. Constructive interference during winter, as measured by a Stationary Wave Index (SWI), tends to occur about one week after enhanced warm pool convection, and is followed by an increase in Arctic surface air temperature, along with a reduction of sea ice in the Barents and Kara Seas. This is followed two weeks later by a weakening of the stratospheric polar vortex, and a decline of the Arctic Oscillation index. All of these associations are reversed in the case of destructive interference. These results (Goss et al. 2016) suggest that inclusion of a SWI and the state of the stratosphere together with the Wheeler and Hendon (2004) MJO index may also improve probabilistic forecasts for lead times of up to four weeks. In a related study, Flournoy et al. (2016) show that MJO tropical convection impacts the surface temperature over Alaska through several processes tied to the excitation of poleward propagating Rossby waves.

Co-PI Feldstein also has investigated the dynamics of teleconnection patterns over the North Pacific that are known to have significant climate impacts over North America. Tan et al. (2015) specifically focuses on the Eastern Pacific (EP) pattern, reaffirming the importance of tropical convection for the variability of North Pacific teleconnection patterns on timescales of a few weeks. Yuan et al. (2015) used self-organizing map analysis to characterize the continuum of wintertime North Pacific teleconnection patterns. These results reveal an intraseasonal shift in the frequency of occurrence of some patterns within the continuum, suggesting that it might be better to perform separate probabilistic forecasts for each month, rather than performing the probabilistic forecasts with several months, e.g., December-March, lumped together. Finally, Dai et al. (2017) compared the formation mechanism for the PNA when MJO-like tropical convection is active and when it is inactive. This study reveals that the PNA tends to develop from distinct initial extratropical flow patterns, especially over Eurasia, depending on whether the convection is active or inactive.

Co-I Johnson also examined subseasonal climate variability associated with El Niño episodes and completed a study examining the role of the nonlinearity between deep convection and eastern equatorial Pacific sea surface temperatures (SSTs) on the diversity of El Niño teleconnection patterns (Johnson and Kosaka 2016). This work reveals that the wintertime climate impacts of El Niño over North America vary based on whether the eastern Pacific is convective (EPC) or non-convective (EPN). These results suggest that forecast guidance for weeks 3-4 that incorporates the phase of ENSO may benefit by differentiating the particular type of El Niño.

2.4 Development of hybrid dynamical/statistical forecast tools

We have begun to explore subseasonal sources of forecast skill in dynamical models and have explored frameworks for developing hybrid dynamical/statistical forecast tools. We have analyzed hindcasts covering the period of 1980-2016 from the Geophysical Fluid Dynamics Laboratory (GFDL) high-resolution Forecast-oriented Low Ocean Resolution (FLOR) model, which has demonstrated success in the seasonal prediction of surface weather and tropical cyclone/extratropical storm activity (e.g., Vecchi et al. 2014; Jia et al. 2015; Yang et al. 2015; Murakami et al. 2016; Jia et al. 2017). However, few studies have examined the subseasonal forecast skill of FLOR. As an initial effort, we have examined the role of atmospheric initialization in subseasonal forecast skill by comparing two versions of initialization: FLOR-p1, which uses atmospheric initial conditions (AICs) from prior ensemble simulations of the atmospheric component of FLOR that is forced by observed SST alone, and FLOR-p2, which uses observed AICs by relaxing surface pressure, horizontal winds and temperature throughout the entire atmosphere to Modern Era Retrospective-Analysis for Research and Applications reanalysis on a 6-hour time scale. Therefore, FLOR-p1 primarily captures the forcing from the ocean surface, whereas FLOR-p2 includes the additional contribution from realistic AICs. Figures 4 and 5 show the HSSs of weekly ensemble mean T2m and precipitation forecasts, respectively, of 50th percentile exceedance evaluated for both FLOR-p1 and FLOR-p2 models at lead times of 1 through 5 weeks. Figures 4 and 5 reveal that the forecast skill of T2m and precipitation increases dramatically for the first two weeks over the majority of North America from FLOR-p1 to FLOR-p2. FLOR-p2 also performs noticeably better at week 3, particularly for temperature, indicating that accurate AICs are important for week 3-4 forecasts over North America. Perhaps not surprisingly, the skill in weeks 3-4 is much higher for temperature than for precipitation.

Although this CTB project has officially ended, Co-I Johnson is currently working with Dr. Ángel Muñoz to leverage such promising skill and refining forecasts through statistical post-processing techniques. The intention is that such methods also could be adapted for operational models like the CFSv2. We also are in the process of investigating the sources of predictability.

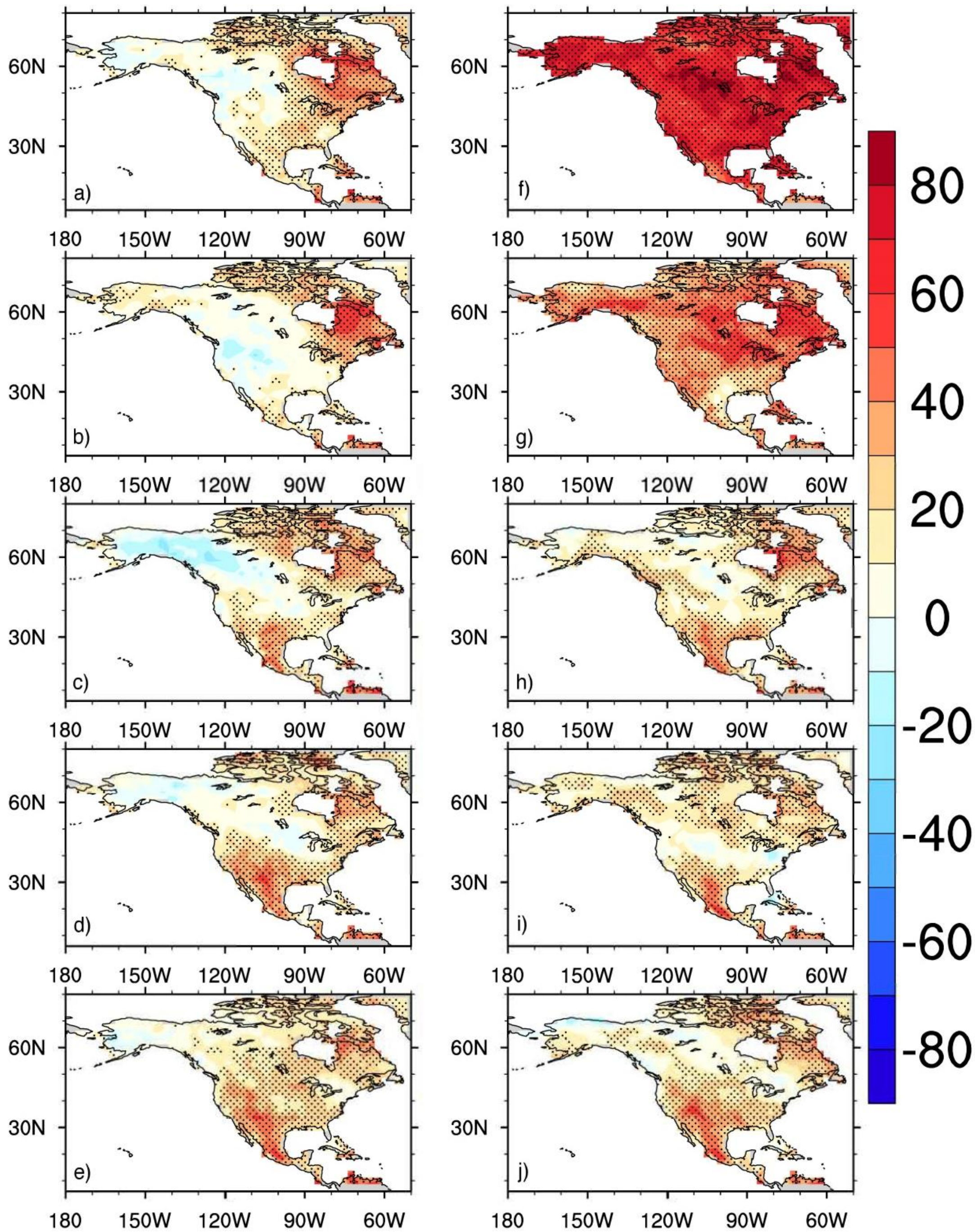


Figure 4: Heidke skill scores (HSSs) of wintertime (DJF) weekly ensemble mean T2m hindcasts for 50th percentile exceedance from FLOR-p1 (a-e) and FLOR-p2 (f-j) at lead times of 1 through 5 weeks. A bias correction is applied prior to the calculation of the HSS. Stippling denotes 5% significance level using a Monte-Carlo approach with randomly reshuffled samples.

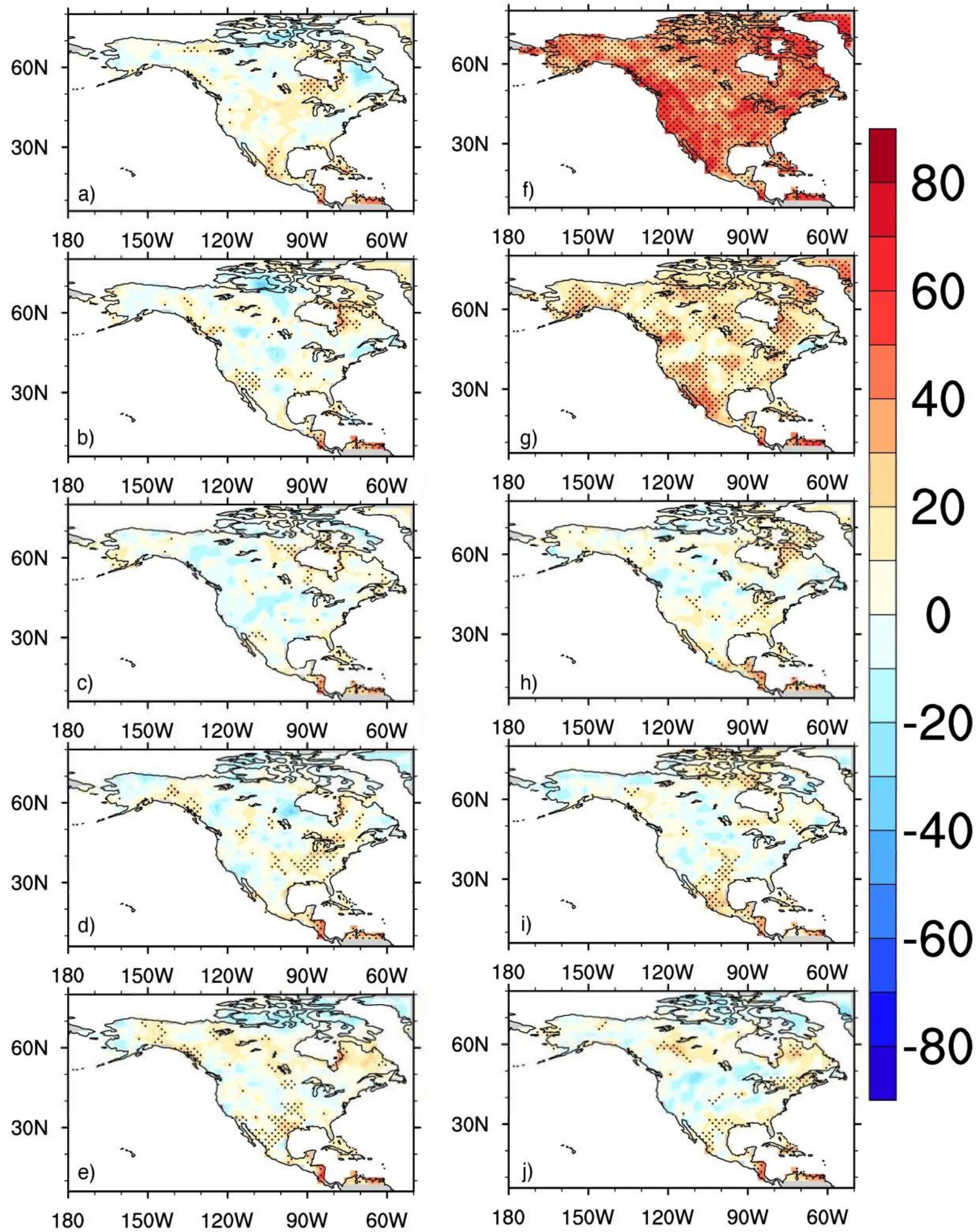


Figure 5: Same as Fig. 2, but for weekly aggregate precipitation.

3. Highlights of Accomplishments

- Successful transition of the MJO/ENSO statistical models in CPC's Experimental Week 3-4 temperature and precipitation outlooks and into the operational Week 3-4 temperature outlook. The MLR statistical model has demonstrated substantial temperature prediction skill throughout the experimental implementation period.
- Twelve published papers supported by the grant
- Seven presentations delivered by contributors to the project, including two NOAA MAPP webinars and two invited presentations
- Substantial advances in understanding dynamics of midlatitude dynamics contributing to North American weeks 3-4 predictability and the development of new international collaborations as a result of these efforts

4. Transition to Applications

As discussed in Section 2.1, the MJO/ENSO statistical models were transitioned into the implementation of CPC's Experimental Week 3-4 Outlooks in September 2015. The week 3-4 temperature guidance was officially transitioned to operations in May 2017. The statistical guidance has demonstrated forecast skill, particularly for temperature, and has become an integral part of CPC's weeks 3-4 forecast process.

5. Publications from the Project

Black, J., **N. C. Johnson**, **S. Baxter, S. B**. **Feldstein, D. S. Harnos**, and **M. L'Heureux**, 2017: The predictors and forecast skill of Northern Hemisphere teleconnection patterns for lead times of 3-4 weeks. *Monthly Weather Review*, **145**, 2855-2877.

Dai, Y., **S. B. Feldstein**, B. Tan, and S. Lee, 2017: Formation Mechanisms of the Pacific–North American Teleconnection with and without Its Canonical Tropical Convection Pattern. *J. Climate*, in press.

Flournoy*, M. D., **S. B. Feldstein**, S. Lee, and E. E., Clothiaux, 2016: Exploring the Tropically Excited Arctic Warming Mechanism with station data: Links between tropical convection and Arctic downward infrared radiation. *J. Atmos. Sci.*, 73, 1143-1158.

Goss*, M., and **S. B. Feldstein**, 2015: The impact of the initial flow on the extratropical response to Madden Julian Oscillation convective heating. *Mon. Wea. Rev.*, **143**, 1104-1211.

Goss*, M., and **S. B. Feldstein**, 2017: Why do similar patterns of tropical convection yield extratropical circulation anomalies of opposite sign? *J. Atmos. Sci.*, in press.

Goss*, M., **S. B. Feldstein**, and S. Lee, 2016: Stationary wave interference, and its relation to tropical convection and Arctic warming. *J. Climate*, **29,** 1369-1389.

Horton, D. E., **N. C. Johnson**, D. Singh, D. L. Swain, and N. S. Diffenbaugh, 2015: Contribution of changes in atmospheric circulation patterns to extreme temperature occurrence. *Nature*, **522**, 465-469.

Jiang, Z., **S. B. Feldstein**, and S. Lee, 2017: The relationship between the Madden Julian Oscillation and the North Atlantic Oscillation Quart. *Quart. J. Roy. Met. Soc.*,**143**, 240-250.

Johnson, N. C., and Y. Kosaka, 2016: The impact of eastern equatorial Pacific convection on the diversity of boreal winter El Niño teleconnection patterns. *Climate Dynamics*, **47**, 3737-3764.

Lukens*, K. **S. B. Feldstein**, C. Yoo, and S. Lee, 2017: The dynamics of the extratropical response to Madden–Julian Oscillation convection. *Quart. J. Roy. Met. Soc.*,**143**, 1095-1106.

Tan, B., J. Yuan, Y. Dai, **S. B. Feldstein**, and S. Lee, 2015: The linkage between the Eastern Pacific teleconnection pattern and convective heating over the tropical western Pacific. *J. Climate*, **28**, 5783-5794.

Yuan J., B. Tan, **S. B. Feldstein**, and S Lee, 2015: Wintertime North Pacific teleconnection patterns: seasonal and interannual variability. *J. Climate*, **28**, 8247–8263.

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