**Predictability of the North Atlantic Oscillation on Intraseasonal Time Scales**

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**LONG-TERM GOALS**

Evidence clearly shows that the intra-seasonal variability of the atmospheric circulation in the North Atlantic, and in particular the North Atlantic Oscillation (NAO), is impacted by tropical convection related to the phase of the Madden-Julian Oscillation, or MJO (Cassou 2008; Lin et al. 2009). The long-term goals of this project are:

1. To understand the dynamics of the extratropical response to the components of the MJO heating and cooling.
2. To understand what components of the heating in various MJO phases are critical. Does the propagation speed of the MJO play any role? Is propagation from the Indian Ocean to the western Pacific critical for the mid-latitude response, or is the Indian Ocean heating the only key forcing?
3. To assess the potential added predictability of the NAO based on the potential predictability of the MJO.

**OBJECTIVES**

1. To understand how the extratropical responses to the components of the MJO heating and cooling interact to affect the NAO. In particular to the roles of the Rossby wave source, synoptic eddy momentum flux convergence, Rossby wave breaking and storm track shifts in altering the North Atlantic circulation.
(2) To assess the probability distribution function (pdf) of MJO propagation phase speeds in observations, and the probability of MJO convection transitioning from the Indian to Pacific Oceans.

(3) To assess the dependence of mid-latitude response to MJO on the propagation speed and propagation range discovered in Objective (2).

(4) To utilize the MJO as a source of tropical predictability to improve (a posteriori) dynamical reforecasts of the North Atlantic intra-seasonal variations within an operational prediction system.

**APPRAOCH**

**Objective (1):**
In order to gauge the impact of the MJO on the North Atlantic variability, MJO-related tropical diababtic heating derived from TRMM satellite data was added to the CESM as it runs: at each time step the four-dimensional (time varying) MJO-heating is added to the temperature tendencies produced by the model’s dynamics and physical parameterization subroutines before these tendencies are used to update the temperature field. Large ensembles of seasonal simulations (1 Oct – 31 Mar) made with (HTG simulations) and without (CTL simulations) the added heating are used to assess the effect on the NAO. The HTG experiment has the MJO-heating identical for each winter simulation, following several MJO episodes whose properties (e.g. dependence on the annual cycle evolution) are derived from the TRMM observations.

**Objective (2):**
The pdf of observed MJO propagation in the ERA-Interim reanalysis and NOAA OLR data sets for the 32-year period 1980/81-2011/12 winters (October 1 – March 31) are assessed using the MJO diagnostic, based on the diagnostics developed by CLIVAR Madden – Julian Oscillation working group (Kim et al. 2009) and the Wheeler- Hendon index (Wheeler and Hendon, 2004).

Unfiltered daily anomalies of OLR, u200 and u850 are first calculated by subtracting the annual mean and first 4 annual harmonics over all years of data. A 201-point Lanczos filter is used to construct intraseasonal (20 – 100 day) bandpass-filtered daily anomalies. Multivariate EOFs are calculated using the filtered all three fields averaged between 15°S - 15°N. Each field was normalized by the square root of the zonal mean of the temporal variance at each longitudinal point. The normalized time series of principal components PC1 and PC2 are calculated by projecting the data onto the observed EOFs to obtain the two PCs that are divided by their respective standard deviations. The normalized PCs are termed as real-time multivariate MJO indices. The daily amplitude and phase of the MJO are obtained from the two leading PCs. Using the phase propagation and examining the 20-100 day filtered OLR, individual episodes and the phase speed have been identified.

**Objective (3):**
We construct MJO heating evolutions based on satellite data, as in Objective (1), but with a range of phase speeds to match the observed range of phase speeds, including evolutions in which the MJO does not propagate out of the Indian Ocean. Reforecasts of CFSv2 (the NOAA seasonal coupled forecast model) are then run with and without these idealized added heatings in large ensembles from a variety of observed initial conditions. The goal is to assess mid-latitude responses that are significant and sensitive to the characteristics of MJO propagation.
Objective (4):
We construct “observed” diabatic heating from the thermodynamic equation as a residual, estimating all other terms from the high resolution ERA-Interim reanalysis. Principal Component analysis of the tropical component of this heating is used to summarize the observed evolution of diabatic heating as a relatively small number of three-dimensional patterns over all winter days in the ERA-Interim analysis. Reforecast for a large number of winter initial conditions will be made with CFSv2 and the observed heating for that particular period added. Large ensemble sizes will be used. The improvement in North Atlantic and North Pacific mid-latitude forecast skill will be assessed in terms of circulation regimes.

Key GMU individuals and the roles they play are given here:
David Straus (GMU): Supervises design and execution of project; carries out diagnoses of all results. Leads in constructing observed MJO heating.
J. Shukla (GMU): Aids in overall project planning.
Priyanka Yadav (GMU): Runs observational and model diagnostics and runs CFSv2 experiments
Sara Amini (GMU): Assists in diagnosis of model experiments
Erik Swenson (GMU): Runs CESM, Designs idealized MJO heating, runs CFSv2 experiments

WORK COMPLETED

Objective (1)
This work for this objective has been completed, and published in the Journal of the Atmospheric Sciences (Straus et al., 2015).

Objective (2)
The diagnosis of the probability distribution function (pdf) of observed MJO phase speeds and propagation characteristics has been completed (see Results section below) and is being prepared for publication.

Objective (3)
A range of MJO heating profiles based on TRMM data, but idealized to correspond to different phase speeds, has been constructed, and reforecasts using this heating have been started.

RESULTS

Objective (1):
Straus et al. (2015), in the simulations described above, achieved a synthesis of relationships between the MJO-related cycle of tropical heating and cooling, the upper level tropical and subtropical Rossby wave source, and the far-field responses. The leading two predictable component modes of total tropical diabatic heating, Rossby wave source, geopotential height, synoptic scale vorticity flux, and storm track kinetic energy show a coherent response to the MJO heating which is sensitive to the details of the heating evolution. Remarkably, the evolution of these modes is related to the daily evolution of the state of the North Atlantic circulation, which is assessed independently with a cluster analysis based on unfiltered daily data. In terms of the impact on overall variability, the NAO in its positive (negative) phase is under- (over-) represented in the CESM control runs in comparison to the ERA-Interim. This error in the circulation regime statistics is corrected in the simulations with added MJO heating.
Objective (2):

For each winter (32 winters), the MJO episodes are identified subjectively based on the location of convection using 20-100 day band pass filtered raw OLR anomalies and their corresponding MJO phase. An example of the identification of various MJO propagation phase speeds from observations is shown in Figure 1a, which shows the time-longitude section of 20-100 day band pass filtered OLR, showing eastward propagation of MJO episodes for the 1991-1992 winter for the period of 1 Oct – 31 Mar, with the corresponding MJO phases shown in Figure 1b. The red arrow indicates a SLOW category MJO episode (22 days to propagate from MJO phase 3 to MJO phase 6). The purple arrow indicates a FAST MJO episode (9 days to propagate from MJO phase 3 to MJO phase 6). (MJO phase 3 has convection centered over the Indian Ocean, phase 6 over the Western Pacific.)

The three types of categories identified are:

1. **IONP**: When heating is in the Indian Ocean (phase 3) but does not propagate into West Pacific (phase 6). (14 cases)
2. **SLOW**: episodes in which the heating takes greater than 15 days to propagate into the West Pacific (10 cases)
3. **FAST**: episodes in which the heating takes less than 10 days to propagate into the West Pacific (27 cases)

The equatorial OLR evolution, lag composites of OLR for day -10 to 30 are calculated for each category. Figure 2 shows the time-longitude plot of OLR composites. The MJO episodes that do not propagate into Pacific have a weaker OLR signal.

To see the mid-latitude response, the intraseasonal geopotential height composites at 500 hPa are calculated with various lags with respect to the time of Indian Ocean heating. The geopotential height anomalies are calculated from the full low-pass field minus a fit of the low pass series to the first four Legendre polynomials in time for the same season. This is equivalent to retaining only periods of 20-90 days with the seasonal mean being removed from each season. Figure 3 and 4 show intraseasonal geopotential height composites at 500 hPa for the Slow and Fast categories. The response to the SLOW episodes has an Arctic Oscillation character by day 10, with a strong North Pacific response. The North Atlantic (the strong negative height values over Greenland in particular emphasize NAO+) response takes longer to set up; here it can be seen at 15 days. The response to the FAST episodes, seen in Figure 4, is quite different, with very little propagation over the pole and much more of a PNA development. A clear development of the PNA and downstream propagation along the great circle route into the Atlantic can be seen from day 0 to day +10.

Objective (3):

Idealized MJO heating has been constructed for a range of phase speeds, and applied to the CFSv2 in a small number of test reforecasts (2 winter initial conditions for each of 32 winters). Figure 5 shows the added heating (contours, with an interval of 0.3° K/day) and the response of the full coupled model omega (vertical velocity) field, for 3 levels (300 hPa, top; 500 hPa middle; 700 hPa, bottom) for FAST episodes (left-hand panels) and SLOW episodes (right-hand panels). For testing purposes, more than one episode per season was added in these reforecasts. In the full set of experiments, only one episode per winter will be included.
Figure 1. (a) (upper panel) Time-longitude section of 20-100 day band-pass filtered observed OLR showing eastward propagation of MJO episodes for 1991-92 winter for the period of 1 Oct – 31 Mar. The corresponding MJO phases are shown in (b) (lower panel). Red arrow indicate SLOW category MJO episode (22 days to propagate from phase 3 to phase 6). Purple arrow indicate FAST MJO episode (9 days to propagate from phase 3 to phase 6). See text for details.
Figure 2. Time-longitude plot of 20 – 100 days band–pass filtered OLR lagged composites from -10 to +20 days for the 3 categories. The red line indicates day 0 (convection in Indian Ocean). 0 on the Y-axis indicates day -10.
Figure 3. 500hPa Intraseasonal Geopotential height anomaly lagged composites for SLOW MJO episodes (>15 days to propagate from Indian Ocean to West Pacific). Green shading denotes negative anomalies and yellow indicates positive anomalies. Contour interval is 10m.
Figure 4. 500hPa Intraseasonal Geopotential height anomaly lagged composites for FAST MJO episodes (< 10 days to propagate from Indian Ocean to West Pacific). Green shading denotes negative anomalies and yellow indicates positive anomalies. Contour interval is 10m.
Figure 5. Longitude time plots of pressure vertical velocity (*100) in hPa/s (averaged 15S - 15N) from reforecasts of CFSv2 in which idealized MJO FAST (left) and SLOW (right) episode heating was added. The pressure velocity is shaded, and the corresponding added heating is shown in contours. Contours are at an interval of 0.3 degree/day. Dashed contours show negative values (cooling) and lines show positive added heating values. Minimum contour interval is 0.3 and maximum is 1.5. Top panels show 300 hPa, middle panels 500 hPa, bottom panels 700 hPa.
IMPACT/APPLICATIONS

Adding Heating Technique:
Our results clearly indicate that the technique of adding intra-seasonally varying diabatic heating to a state-of-the-art coupled weather/climate models is feasible, and can lead to validation of hypotheses made from observations, in this case the effects of intra-seasonal tropical heating variability on NAO variability. Since models are known to have a number of difficulties in simulating the MJO and other intra-seasonal oscillations, this technique will see a productive use in other scientific studies.

MJO Propagation Speed Variability
The observed work on the differing mid-latitude responses to fast and slow MJO episodes should clarify what aspects of the MJO are essential to predict in order to improve prediction of the mid-latitude response.

Application of observed MJO heating in re-forecasts
Knowledge of maximum increase in mid-latitude forecast skill, given perfect knowledge of MJO heating in the future, will help to determine what level of resources should be put into improved MJO forecasts, either dynamical or statistical.

REFERENCES


PUBLICATIONS