The Madden–Julian Oscillation and Boreal Winter Forecast Skill: An Analysis of NCEP CFSv2 Reforecasts

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ABSTRACT
The Madden–Julian oscillation (MJO) is the main mode of tropical intraseasonal variations and bridges weather and climate. Because the MJO has a slow eastward propagation and longer time scale relative to synoptic variability, significant interest exists in exploring the predictability of the MJO and its influence on extended-range weather forecasts (i.e., 2–4-week lead times). This study investigates the impact of the MJO on the forecast skill in Northern Hemisphere extratropics during boreal winter. Several 45-day forecasts of geopotential height (500 hPa) from NCEP Climate Forecast System version 2 (CFSv2) reforecasts are used (1 November–31 March 1999–2010). The variability of the MJO expressed as different amplitudes, durations, and recurrence (i.e., primary and successive events) and their influence on forecast skill is analyzed and compared against inactive periods (i.e., null cases). In general, forecast skill during enhanced MJO convection over the western Pacific is systematically higher than in inactive days. When the enhanced MJO convection is over the Maritime Continent, forecasts are lower than in null cases, suggesting potential model deficiencies in accurately forecasting the eastward propagation of the MJO over that region and the associated extratropical response. In contrast, forecasts are more skillful than null cases when the enhanced convection is over the western Pacific and during long, intense, and successive MJO events. These results underscore the importance of the MJO as a potential source of predictability on 2–4-week lead times.

1. Introduction
Since the discovery of the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972, 1994), several studies have demonstrated its influential nature in weather and climate variability (Becker et al. 2011; Goswami and Mohan 2001; Hendon and Liebmann 1990; Higgins and Shi 2001; Jin et al. 2013; Jones 2000; Jones and Carvalho 2002, 2012, 2014; Jones et al. 2004b; Lau and Waliser 2012; Maloney and Hartmann 2000; Matthews and Meredith 2004; McPhaden 2004; Riddle et al. 2013; Vecchi and Bond 2004; Zhang 2005, 2013). The MJO has a slow eastward propagation and longer time scale relative to synoptic variability and significant interest exists in exploring the predictability of the MJO and its influence on extended-range weather forecasts (2–4-week lead times). The prediction skill and potential predictability of the MJO have been studied with statistical and dynamical models and useful skill extends to about 2–4 weeks (Jiang et al. 2008; Jones et al. 2004a; Seo 2009; Vitart 2014; Vitart and Jung 2010; Vitart and Molteni 2010; Waliser et al. 2003; Wang et al. 2014).

Early studies showed that the MJO influences the forecast skill in the extratropics (Ferranti et al. 1990;
Hendon et al. 2000; Jones et al. 2000; Lau and Chang 1992). Jones and Schemm (2000) showed that strong convective activity associated with the MJO increases the forecast skill over South America. Using the NASA Goddard Laboratory for the Atmosphere (GLA) climate model, Jones et al. (2004c) found the predictability in the Northern Hemisphere midlatitudes to be about 2–3 days higher during active MJO days than in inactive periods. Jones et al. (2004b) showed the frequency of extreme precipitation events and their predictability to be higher during active MJO days. Rodney et al. (2013) developed an empirical multilinear regression model to forecast surface air temperatures over North America during winter and found the skill to be higher when the MJO is active and in phases 3, 4, 7, and 8 of Wheeler and Hendon (2004).

An interesting characteristic of the MJO is its high degree of variability expressed as different durations, phase evolutions, and amplitudes (or intensity) as it propagates eastward. In addition, the MJO occurs irregularly in time. The MJO may occur isolated or in a sequence of events (Jones 2009; Jones and Carvalho 2011; Matthews 2000, 2008). A new event may originate just after the termination of a previous event and is called a successive event. When the MJO reappears, the first occurrence is known as the primary event. While previous studies indicate that the forecast skill in the extratropics tends to be higher when the MJO is active (Jones and Schemm 2000; Jones et al. 2004b,c, 2011a,b; Vitart 2014; Vitart and Jung 2010), the extent to which the variability of the MJO impacts the predictive skill has yet to be addressed. The large sample of NCEP CFS (version 2) reforecasts (Saha et al. 2014) provides a unique opportunity to further examine how the variability of the MJO impacts the forecast skill. Wang et al. (2014) determined the useful forecast skill of the MJO in the CFSv2 model to be about 20 days. Here, the focus is on the boreal winter extratropics and the following questions are investigated: 1) Does the forecast skill in the boreal winter extratropics vary with MJO phases? 2) Does the duration of the MJO have an important modulation on forecast skill in the boreal winter extratropics? 3) Do intense MJO events have more impact in the extratropics forecast skill than weak events? 4) Is the extratropical forecast skill different during primary and successive MJO events? Section 2 discusses the data and methodology and section 3 discusses the results. Section 4 summarizes the main conclusions.

2. Data and methodology

To identify MJO events, daily averages of zonal winds at 850-hPa (U850) and 200-hPa (U200) from the NCEP Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) are used (1 January–31 December 1979–2010). Daily averages of outgoing longwave radiation (OLR) (Liebmann and Smith 1996) are used to characterize convective anomalies associated with the MJO. To isolate the MJO signal, the seasonal cycle is first removed and the time series are detrended and filtered in the frequency domain to retain intraseasonal variations (20–200 days). This procedure follows Matthews (2000, 2008), who determined that the wide 20–200-day band more accurately represents isolated MJO events. Note that the wide bandpass filter is applied after removing the seasonal cycle (Jones 2009; Jones and Carvalho 2011).

MJO events are identified with combined empirical orthogonal function (EOF) analysis of equatorially averaged (15°S–15°N), OLR, U200, and U850 bandpass-filtered anomalies. The first two EOFs (see Fig. 1 in Jones 2009) are in good agreement with Wheeler and Hendon (2004), and the phase diagram of the first two normalized principal components (PC1, PC2) approximately follows the eight-phase convention of the real time multivariate MJO (RMM) index. The main difference between the approach used here and Wheeler and Hendon (2004) is the use of bandpass filtered anomalies. The RMM index is significantly noisier than the bandpass filtered index and is meant to be used for real-time applications and/or when the length of the time series is not long enough that application of bandpass filtering is not possible. Additional discussion about identification of MJO events is provided in Jones and Carvalho (2012).

MJO events are defined according to these conditions: 1) the phase angle between PC1 and PC2 systematically rotates counterclockwise, indicating eastward propagation at least to the Maritime Continent; 2) the normalized amplitude is always larger than 0.35; 3) the mean amplitude during the event is larger than 0.9; and 4) the entire duration of the event lasts 30–90 days (Jones 2009; Jones and Carvalho 2011; Jones and Carvalho 2012). A total of 22 MJO events were identified during 1 November–31 March, 1999–2010. Days in which the conditions above are not satisfied are considered null (or inactive) MJO days. A total of 13 periods of sequentially inactive MJO days are identified lasting between 6 and 126 days. The interannual variability of the null cases includes 3 warm (155 days), 6 cold (350 days), and 3 neutral (155 days) ENSO phases. The results are analyzed by comparing the statistics for each MJO phase against the null case. To improve the clarity of the figures, however, the results are presented by averaging the forecast skill into four phases: phases 1 and 2 (PI), phases 3 and 4 (PII), phases 5 and 6 (PIII), and phases 7
and 8 (PIV). Although the grouping in phases could have been done differently (e.g., grouping phases 1 and 8, 2 and 3, etc.), the choice stated above was deemed optimal. For instance, the skill score statistic (defined below) has the same sign between phases 7 and 8 (not shown) and is statistically significant in many of the analyses discussed next.

The influence of the MJO on boreal winter forecast skill is examined using 500-hPa geopotential height (Z500); Z500 anomalies from CFS reanalysis are calculated by subtracting the daily climatology and are used to validate the forecasts. Forecasts of Z500 anomalies are calculated by subtracting the daily climatology; systematic error correction (Saha et al. 2010) is also subtracted from the daily Z500 anomalies to remove the mean model bias during 1999–2010. In the remainder of this study, we contrast forecast skill during periods of MJO activity (22 events: four phases) with null cases (13 events).

The mean anomaly correlation coefficient (MACC) is used to analyze forecast skill:

\[
\text{MACC} = \frac{\langle (O')(F') \rangle}{\sqrt{\langle (O')^2 \rangle \langle (F')^2 \rangle}},
\]

where \( O' \) is the observed daily anomaly and \( F' \) is the daily anomaly forecast. Each grid point is weighted by the square root of the cosine of the latitude in the domain (20°–60°N). Brackets indicate computation over the spatial domain. Although there are different ways of computing MACC (Déqué and Royer 1992), the arithmetic mean over the sample size is used in this work (denoted by overbars). The CFS reforecasts (version 2) were initialized four times daily during 1 November–31 March 1999–2010. Forecast skill is analyzed for lead times from 1 to 45 days.

To determine the statistical significance of differences in MACC between MJO and null cases, a Fisher transformation is first applied to the MACC at each lead time to ensure Gaussian distribution (Jones et al. 2004c; Miller and Roads 1990; Wilks 2006):

\[
\Gamma(r) = 0.5 \ln \left( \frac{1 + \rho}{1 - \rho} \right),
\]

where \( \rho \) is the MACC at the lead time \( \tau \). Next, the test statistic \( Z \) is computed for differences between \( \Gamma \) in MJO phases and null cases at each lead time:

\[
Z = \frac{(\Gamma_{\text{MJO}} - \Gamma_{\text{null}})}{\sqrt{\frac{\sigma^2_{\text{MJO}}}{N_{\text{MJO}}} + \frac{\sigma^2_{\text{null}}}{N_{\text{null}}}}},
\]

where \( \sigma \) is the variance of \( \Gamma \) and \( N \) is the number of cases. Values of \( Z \) greater than 1.64 (1.96) indicate that differences in \( \Gamma \) are statistically significant at 90% (95%) level.

3. Results

Before considering the influence of the MJO on the forecast skill in the Northern Hemisphere extratropics, it is appropriate to consider the average MJO life cycle in the period of analysis. Composites of OLR bandpass filtered anomalies (Fig. 1a) show the typical evolution of the MJO (Hendon and Salby 1994), where a dipole of enhanced/suppressed convective activity propagates eastward from equatorial Africa to the western Pacific. Alternating OLR signals in South America are also evident. In contrast, OLR anomalies composite during null cases (Fig. 1b) do not show any significant and spatially organized structure in tropical convection.

Composites of Z500 anomalies (Fig. 1c) show wave train patterns originating in the subtropics and extending to the midlatitudes of both hemispheres, consistent with wave activity during the MJO cycle (Matthews et al. 2004; Seo and Son 2012). The wave train patterns are more evident in PI, PII, and PIV and less so in PIII. The extratropical response is clearly more intense in PIV than in any other phase. Composites of Z500 anomalies during null cases (Fig. 1d) also show evidence of a wave train pattern in both hemispheres that is likely related to ENSO interannual variability contained in the sample of null cases (see section 2).

Figure 2a shows MACC during active MJO and null days. MACC during active MJO in PI, PII, PIII, and PIV phases is compared against MACC during null days and statistical significance in the differences is estimated with the Z test (Fig. 2b). The skill of CFSv2 forecasts of Z500 extend to 8 days lead time (MACC = 0.6; Fig. 2a) for both active MJO in the PI, PII, and PIII phases and in null days. The forecast skill during MJO in the PIV phase (enhanced convection over the western Pacific and Western Hemisphere) is higher than in any other situation especially for 7–15-day lead times (week 2). The differences in skill between MJO in PIV phase and null cases grow rapidly from 4 to 7 days lead time (Fig. 2b) and are statistically significant (95% level) from 7 to 15 days lead. These results differ from those of Jones et al. (2004c), who found higher predictability in the Northern Hemisphere when the active MJO convection is in the Indian Ocean. It is difficult to perform a direct comparison between the two studies, given the differences in methodology. Nevertheless, some important points are...
relevant to note. Jones et al. (2004c) used twin-predictability experiments with the NASA GLA climate model with prescribed climatological sea surface temperatures; the GLA model was based on finite differences and had low horizontal resolution ($4^\circ \times 5^\circ$ longitude). Moreover, the small sample size included only 15 MJO events with two members per forecasts. Although the GLA model had the best MJO representation at the time, some misrepresentations of the MJO life cycle also existed. For instance, the GLA model had significantly less intraseasonal variability in the eastern Indian Ocean than in observations [cf. Figs. 1 and 4 from Waliser et al. (2003)]. This study is based on a fully coupled climate model (CFSv2), real forecasts, and a much larger sample size. The extratropical response associated with the MJO during the forecast period is likely model dependent, as each model has different skill in representing the initiation of the MJO, maintaining the amplitude and propagation of the oscillation as well as the associated teleconnection.

The variability of the MJO and its influence in the Northern Hemisphere forecast skill is now examined in detail. The frequency distributions of durations and amplitudes of MJOs are shown in Fig. 3. The duration is almost uniformly distributed in the period of analysis (Fig. 3a), whereas the amplitude is skewed to the right (Fig. 3b). Potential changes in forecast skill are contrasted between short and long as well as weak and intense MJO events. The median duration is used to separate short (31–48 days) and long (61–78 days) MJO events. Similarly, the median amplitude separates low (0.1–1.5) and high (2.6–4.0) amplitude MJO events. The recurrence of the MJO and forecast skill is analyzed separately for 13 primary and 9 successive events.

Figure 4 compares the MACC skill scores between long and short MJO durations along with statistical
significance in the differences. Useful skill (MACC $\geq 0.6$) extends to about 8 days during long and short MJO durations in PI, PII, and PIII phases and null cases. The skill in MJO PIV is clearly separated from other cases for both long and short durations, but the difference is statistically significant (above 90%) only for long durations and 7–10 days lead time (Figs. 4a,b). Interestingly, the skill during long MJO in PIII, when enhanced convection is over the Maritime Continent, is actually lower than the null case for 4–7 days lead time (Figs. 4a,b), but they are not statistically significant. These differences could be related to the difficulty that global models have in maintaining the eastward propagation of the MJO across the Maritime Continent (Inness and Slingo 2003, 2006), which can certainly impact the forecasts in the extratropics. A possible “predictability barrier” of the MJO in that region is still an open issue (Neena et al. 2014; Vintzileos and Pan 2007).

Variations in forecast skill separated by MJO amplitudes show that low amplitudes in PIV have higher skill than in null cases during 4–12 days lead time (Figs. 5c,d). A somewhat different behavior is found in the forecast skill during high MJO amplitudes in PIV such that the skill is higher than null for 10–15 days lead times (Figs. 5a,b). Moreover, the skill score for low MJO amplitudes in PI is lower (90% level) than null cases for short lead times (1–4 days). The results above highlight the difficulty in forecasting the extratropical impacts of
Fig. 3. Frequency distributions of MJO (a) duration and (b) amplitude.
the MJO during short and low amplitude events moving across the Maritime Continent.

The irregularity of the MJO has received substantial attention since its discovery and special efforts are dedicated to identify the initiation mechanisms of the oscillation (Gottschalck et al. 2013; Yoneyama et al. 2013). In the context of forecasting the MJO impacts, the extratropical forecast skill of Z500 separated into primary and successive events shows a different behavior when the MJO is active (Fig. 6). The forecast skill during primary MJOs in PIV is higher than in null cases (Figs. 6a,b) and grows slowly from 5-day lead to a near constant value at 9–15-day lead times; it also remains below the 90% significance level. In contrast, the forecast skill during successive MJOs in PIV is higher than in null cases (Fig. 6c) and the differences grow faster at 5–15-day lead times and, in fact, are statistically significant at 95% level after 7-day lead. Differences in forecast skill during MJOs in PI, PII, and PIII are not statistically different than in null cases. One still notes, however, the low skill for MJO in PIII, suggesting a potential difficulty of the CFSv2 model in representing the extratropical response when the active convective phase is in the Maritime Continent (Figs. 6b,d).

4. Summary and conclusions

This study examines the influence of the MJO on the forecast skill of the NCEP CFSv2 model. The analysis focuses on the boreal winter extratropics and different characteristics of the MJO (phase, duration, amplitude, and recurrence) are analyzed separately. Forecast skill during active MJO in PIV phase (enhanced MJO convection over the western Pacific) is systematically higher than in inactive days. This contrasts with the climate model experiments discussed in Jones et al. (2004c), who found higher predictability in the Northern Hemisphere when the enhanced MJO convection is over the Indian Ocean. In Jones et al. (2004c), predictability...
in the Northern Hemisphere extratropics is also higher than in null conditions for enhanced convection over the western Pacific, but the results are not statistically significant. Here, when the enhanced MJO convection is over the Maritime Continent (PIII), forecasts of Z500 in the CFSv2 model are actually lower than in null cases but in general not statistically significant. In Jones et al. (2004c), predictability in the extratropics is higher than in null conditions when the enhanced convection is over the Maritime Continent, although not statistically significant. Both studies are based on two very distinct models and forecast experiments. The differences above highlight potential model deficiencies in accurately forecasting the eastward propagation of the MJO and the associated extratropical response. Similar results are found in Matsueda and Endo (2011), who concluded that models participating in TIGGE experiment have different skills during the MJO phases.

Differences in forecast skill during primary and successive MJO events are also investigated. Forecast skills during both types of MJOs are higher than in null cases when enhanced MJO convection is over the western Pacific. Interestingly, the analysis suggests that forecast skill during successive MJOs is higher than in primary events and the differences extend to week-2 lead time. This further motivates the investigation of potential predictability associated with the MJO and its impacts in the extratropics, particularly in lead times beyond the limit of deterministic predictability (~10 days). The mechanisms associated with extratropical responses during primary and successive MJOs are currently being investigated and will be reported in a future paper.

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REFERENCES


Fig. 6. As in Fig. 4, but for MACC and Z statistics during primary and successive MJO events and null cases.


