Boreal Winter MJO Teleconnection in the Community Atmosphere Model Version 5 with the Unified Convection Parameterization

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ABSTRACT

The Madden–Julian oscillation (MJO), the dominant mode of tropical intraseasonal variability, influences weather and climate in the extratropics through atmospheric teleconnection. In this study, two simulations using the Community Atmosphere Model version 5 (CAM5)—one with the default shallow and deep convection schemes and the other with the unified convection scheme (UNICON)—are employed to examine the impacts of cumulus parameterizations on the simulation of the boreal wintertime MJO teleconnection in the Northern Hemisphere. It is demonstrated that the UNICON substantially improves the MJO teleconnection. When the UNICON is employed, the simulated circulation anomalies associated with the MJO better resemble the observed counterpart, compared to the simulation with the default convection schemes. Quantitatively, the pattern correlation for the 300-hPa geopotential height anomalies between the simulations and observation increases from 0.07 for the default schemes to 0.54 for the UNICON. These circulation anomalies associated with the MJO further help to enhance the surface air temperature and precipitation anomalies over North America, although room for improvement is still evident. Initial value calculations suggest that the realistic MJO teleconnection with the UNICON is not due to the changes in the background wind, but rather primarily to the improved tropical convective heating associated with the MJO.

1. Introduction

The Madden–Julian oscillation (MJO), the dominant mode of intraseasonal atmospheric variability in the tropics (Madden and Julian 1971, 1972), characterized by a horizontally large-scale (10^3–10^4 km) pattern of atmospheric convection and circulation that propagates eastward along the equator with a time scale of 30–90 days (Zhang 2005). Numerous efforts have been made to understand and to better predict this phenomenon. One of the reasons is because the MJO has a global impact on weather and climate through its teleconnections (Kim et al. 2006; Zhang 2013). For example, the MJO modulates the Northern Hemisphere climate modes, such as the Arctic Oscillation (AO; L’Heureux and Higgins 2008), the North Atlantic
Oscillation (NAO; Cassou 2008; Lin et al. 2009; Riddle et al. 2013), and the Pacific–North American teleconnection pattern (PNA; Mori and Watanabe 2008; Johnson and Feldstein 2010; Riddle et al. 2013). Through changes in large-scale circulations, the influence of the MJO can reach to the mid- and high-latitude climate, including precipitation (Jones 2000; Bond and Vecchi 2003; Guan et al. 2012; Zhou et al. 2012) and surface temperature (Lin and Brunet 2009; Zhou et al. 2012; Yoo et al. 2014). In addition to these, numerous extreme weather and climate phenomena have been found to be linked with the MJO [see review in Zhang (2013)]. A recent study of Matsueda and Takaya (2015), for example, presents how the extratropical extreme warm and cold events during boreal winter are associated with wave responses to tropical MJO forcing. Understanding the MJO and its teleconnection is therefore crucial for an accurate forecast of extratropical weather and climate including for North America, especially for the 2–4-week range.

Despite the importance of MJO teleconnection, realistic representation of the MJO has been a longstanding challenge for global climate models (Slingo et al. 1996; Lin et al. 2006; Kim et al. 2009; Hung et al. 2013). Lin et al. (2006) showed that in the Coupled Model Intercomparison Project phase 3 (CMIP3), only 2 of the 14 models showed the spectral characteristics of the MJO that were comparable to observations. Most of the CMIP3 models lacked of pronounced peaks at the MJO time scales in their outgoing longwave radiation (OLR) or 850-hPa zonal wind power spectra, and could not produce a realistic eastward propagation of the MJO. Although the spectral characteristics of the MJO were generally improved by the CMIP5 models, the improvement was incremental at best, and many other aspects of the MJO still needed further improvements in order to be realistic (Hung et al. 2013).

Various attempts to improve MJO simulations by modifying a few particular aspects of the cumulus parameterization often degrade the basic wind state despite success in capturing the MJO itself (Kim et al. 2011), which is known as the MJO paradox. Simulating extratropical circulation response to the MJO is therefore extremely challenging because it requires both realistic MJOs in the tropics, which function as a wave source, and a realistic mean wind state as a waveguide. This MJO–mean state tradeoff could have hindered the use of comprehensive models for an MJO teleconnection study. In terms of wave dynamics, the role of the MJO and the mean state can be understood as follows: a realistic MJO simulation is important as an ultimate wave source (although the wave source is also a function of wind), and the background wind plays a critical role in wave excitation and propagation (Sardeshmukh and Hoskins 1988; Jin and Hoskins 1995).

Park (2014a) presents a unified convection scheme (UNICON) that can replace both deep and shallow convection schemes. With the UNICON, the MJO simulation in the Community Atmosphere Model version 5 (CAM5; Park et al. 2014) is significantly improved (Park 2014b). Specifically, CAM5 with the UNICON can capture the MJO variability centered between 30 and 60 days at zonal wavenumbers 1–3 in the wavenumber–frequency power spectra for both OLR and 850-hPa zonal wind. Also, the eastward propagation of the MJO can be clearly seen in the lead–lag correlation of precipitation anomalies. Note that most of the CMIP3 and CMIP5 models, as well as the CAM5 with its default convection schemes, are not capable of simulating these features. Furthermore, the improvement in MJO simulation is conducted without serious degradation of the basic mean state. This is an important result as many climate models still suffer from the MJO paradox.

Motivated by the fact that CAM5 with the UNICON is capable of simulating both the MJO and the mean state reasonably well, we aim to investigate whether the improved MJO only refines the representation of tropical convection or also enhances the extratropical intraseasonal variability associated with the MJO. To achieve this aim, we compare two CAM5 simulations, one with the UNICON and the other with the default CAM5 convection schemes. To the best of our knowledge, this is the first study where a comprehensive climate model is used to study the MJO teleconnection. Section 2 describes the models, data, and methodology. Section 3 compares the MJO teleconnection between the observation and model simulations. Mechanisms of how the MJO teleconnection is improved in the UNICON are also investigated in this section. Conclusions and discussion are given in section 4.

2. Models, datasets, and methods
   a. UNICON

While a complete description of the UNICON is given in Park (2014a), we summarize here some of the unique characteristics of the UNICON to help readers understand the results presented in this paper. The UNICON is a process-based parameterization that represents subgrid convective plumes and mesoscale organized flow without relying on any equilibrium assumptions such as convective available potential energy or convective inhibition closures. The scheme is designed to simulate all dry–moist, forced–free, and shallow–deep convection within a single framework in a seamless,
consistent, and unified way, replacing both the shallow and deep convection schemes. In principle, the UNICON can be used for any horizontal resolution as a scale-adaptive scheme. The UNICON successfully simulates atmospheric variability of various spatial and temporal scales (e.g., the diurnal cycle of precipitation and El Niño–Southern Oscillation), since it is able to simulate complex interactions between convective updraft, convective downdraft, and mesoscale organized flow (Park 2014b).

b. CAM5 simulations

We use two Atmospheric Model Intercomparison Project (AMIP)-type global simulations made with CAM5 at a horizontal resolution of 1.9° lat × 2.5° lon with 30 vertical layers, which are later interpolated to 2.5° lat × 2.5° lon resolution for the comparison with observations. The AMIP-type simulations are forced by the observed interannual and seasonal varying sea surface temperature (SST) and sea ice concentration. For our simulations, such boundary conditions are prescribed for 27 yr from January 1979 to December 2005. In this study we focus on December–February (DJF), the boreal winter season in which the MJO and its teleconnection to the extratropics are the most pronounced. Identical settings are used except for the choice of convective parameterization schemes. One simulation uses the default shallow (Park and Bretherton 2009) and deep (Zhang and McFarlane 1995) convection schemes in the CAM5, while in the other simulation the UNICON treats both the deep and shallow convection in a unified manner. Throughout this paper, CAM5 with the UNICON scheme will be referred to as the UNICON, while CAM5 with the default shallow and deep convection schemes will be referred to as CAM5.

c. Observational data

To compare with the model simulations, we make use of datasets from the National Oceanic and Atmospheric Administration (NOAA) for the following two variables: the CPC Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin 1997) for precipitation and the interpolated OLR (Liebmann and Smith 1996). All other variables used in this study, including geopotential height and zonal wind, are obtained from the daily-mean European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim, hereafter ERA-I) dataset (Dee et al. 2011). The period of the data is selected to be consistent with our AMIP simulations described above.

d. The MJO

To investigate the MJO, we derive two daily principal components (i.e., PC1 and PC2) from leading combined empirical orthogonal functions (EOFs) of three 20–100-day bandpass filtered variables averaged over 15°S–15°N: OLR and zonal winds at 850 and 200 hPa, following the diagnostics suggested by the U.S. CLIVAR MJO working group (Waliser et al. 2009). As in Wheeler and Hendon (2004), a typical life cycle of the MJO is divided into eight phases, with each phase related to the location of the MJO convection center. For example, in phases 2 and 3 (6 and 7), anomalous convection associated with the MJO is located over the Indian (western Pacific) Ocean. Our analysis is centered on MJO phases 3 and 7 as these two have received much attention due to their pivotal roles in the tropics–extratropics connection. For example, cluster analyses have shown that about 10 days after MJO phase 3 (phase 7), circulation anomalies in the extratropics tend to resemble a negative (positive) PNA-like pattern (Johnson and Feldstein 2010; Riddle et al. 2013). Likewise, the probability of negative AO/NAO occurrence decreases (increases) about 10 days after the MJO passes phase 3 (phase 7).

To examine the MJO and its teleconnection to the extratropics, we compute pentad (5-day average) PC time series and identify periods of active MJO by using the following conditions: 1) the MJO phase must increase in numerical order, with the exception of phase 8 to phase 1, with the MJO amplitude $[=(PC1^2 + PC2^2)^{1/2}]$ being greater than 1 for the entire period; and 2) such periods must last longer than six consecutive pentads, while the MJO does not remain in one particular phase for more than four pentads (L’Heureux and Higgins 2008).

Two composite techniques are employed to examine the MJO and its teleconnection to the extratropics: the MJO life cycle composite and the lagged composite. First, before we apply the composite techniques, the seasonal cycle of each variable is removed by subtracting the first three harmonics of the daily climatology. A 201-point, 20–100-day Lanczos bandpass filter is then applied to retain only the intraseasonal variability. To construct the MJO life cycle composite, a variable of interest (e.g., OLR anomalies) is averaged for each phase of the active MJOs. This allows us to investigate the entire evolution of the MJO cycle. The lagged composite is useful to focus on a particular phase of the MJO (e.g., phase 3). For this composite, days from the active MJO periods for the selected phase form the lag zero, and the successive lag days of the periods are used irrespective of the MJO activeness.

e. The PNA and NAO

To obtain patterns and daily time series of the PNA and the NAO, we perform the rotated principal
component analysis\(^1\) with daily standardized 500-hPa geopotential height anomalies in the region between 20° and 90°N (Barnston and Livezey 1987; Feldstein 2000). In observations, the PNA and NAO patterns emerge as the second and first leading modes, respectively (Figs. 1a,d). However, the first leading mode in both the UNICON and CAM5 simulations corresponds to the PNA pattern, while the second mode corresponds to the NAO (Figs. 1b,c,e,f). Nonetheless, simulated patterns are fairly similar to their observed counterparts. The PNA and NAO indices are obtained by projecting the pattern onto the daily anomalies over the North Pacific and North America (0°–90°N, 150°E–30°W) and over the North Atlantic (0°–90°N, 150°W–30°E), respectively.

\( f. \) Initial value calculation

To understand the mechanisms behind the improvement of the MJO teleconnection in simulations, we take the initial value calculation approach using the spectral dry dynamical core developed at the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory. The model is run for 20 days at the T42 horizontal resolution with 20 vertical levels (Yoo et al. 2012b). Because of the imbalance between the initial state and the model, an additional time-independent forcing is included in each experiment in order to eliminate the initial tendency. Such a forcing can be obtained by integrating the model one step forward in time with the initial state. For the detailed description of these techniques, we refer the readers to Franzke et al. (2004) and Yoo et al. (2012b).

\(^1\)Rotated principal component analysis is commonly used to define the PNA and NAO patterns. This technique has advantages over principal component analysis when finding regional-scale teleconnection patterns in a hemispheric dataset [see discussion in Horel (1981)].

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**Fig. 1.** Loading patterns of (top) PNA and (bottom) NAO using the datasets from (a),(d) ERA-I, (b),(e) UNICON, and (c),(f) CAM5. The patterns are obtained as the first two leading modes of the rotated principal component analysis of daily standardized 500-hPa geopotential height anomalies in the region between 20° and 90°N.
Eight initial value calculations are performed in this study (Table 1); four calculations are initialized with the time mean DJF climatological basic state of the UNICON, while the other four calculations are initialized with the corresponding state from CAM5. Then, the UNICON climatological state simulations are then perturbed by four MJO-like tropical forcings; two are based on the UNICON, while the other two are from CAM5. These four forcings are similarly applied to simulations initialized by the CAM5 climatological state. Here, the horizontal structures of the tropical forcings are based on the composites of convective precipitation rate anomalies associated with MJO phases 1 and 5. These two phases, instead of MJO phases 3 and 7, are chosen because 1) it takes about 10 days for the MJO to change its phase from phase 1 (phase 5) to phase 3 (phase 7) (Zhang 2005) and 2) this time scale is consistent with the time scale of tropically excited, poleward propagating Rossby waves to reach high latitudes (Hoskins and Karoly 1981). Therefore, the model’s responses on approximately days 10–15 to MJO phase 1 (phase 5) heating anomalies match the lag 0–10 days of MJO phase 3 (phase 7). Pronounced power is observed at these scales for the UNICON, despite being too strong, indicating that the tropical convective variability associated with the MJO is reasonable in the simulation (Fig. 2b). Meanwhile, the power for the CAM5 shows a variance that is too weak at the MJO spatial and temporal scales, and is biased toward temporally longer and spatially shorter scales (Fig. 2c). The power ratio of the eastward versus westward propagating component over the 30–60 days and zonal wavenumbers 1–3 measures the strength of the eastward propagation associated with the MJO (e.g., Kim et al. 2009). In the UNICON, the power ratio is 2.26, which is about half of the value for the NOAA (4.05), while it is 1.05 in CAM5, indicating that the MJO in the UNICON is improved over CAM5 with a stronger eastward propagation at reasonable temporal and spatial scales.

The MJO life cycle composites of OLR further reveal that the timing and pattern of tropical convection associated with the MJO are better simulated in the UNICON than in CAM5 (Figs. 2d–f). For the UNICON, the OLR anomalies are well organized and centered in the tropics, similar to the observations. For example, for MJO phase 3 (phase 7), enhanced (reduced) convection anomalies can be seen over the Indian Ocean in the UNICON (Fig. 2e), similar to the observation (Fig. 2d). Dipole patterns of OLR are also shown for these phases over the Indian Ocean and Maritime Continent. These features cannot be seen for CAM5 (Fig. 2f).

In the following subsections, we will first explore the simulated extratropical circulation changes associated with the MJO. Then using an idealized model, we will investigate the physical mechanisms

### Table 1. A table of eight initial value calculations performed using the combination of two basic states and four tropical heatings.

<table>
<thead>
<tr>
<th>Basic state</th>
<th>UNICON heating</th>
<th>CAM5 heating</th>
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<tr>
<td>UNICON state</td>
<td>UNICON state/ Phase 3</td>
<td>UNICON state/ Phase 3</td>
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<tr>
<td>CAM5 state</td>
<td>CAM5 state/ Phase 3</td>
<td>CAM5 state/ Phase 3</td>
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3. Results

We start by revisiting the improvements in the MJO made by the UNICON (Fig. 2). First, we examine the DJF frequency–wavenumber spectra, which are calculated using tropical OLR (10°S–10°N) with the following steps: 1) the daily climatology is removed, 2) the time mean of each DJF is removed, 3) a frequency–wavenumber spectrum is computed for each DJF period of data, and 4) the spectra for all years are averaged. As can be seen in the spectrum using the NOAA OLR (Fig. 2a), the MJO variability is centered temporally at 30–60 days (or approximately 0.033–0.016 cycles per day) and spatially at zonal wavenumbers 1–3. Pronounced power is observed at these scales for the UNICON, despite being too strong, indicating that the tropical convective variability associated with the MJO is reasonable in the simulation (Fig. 2b). Meanwhile, the power for the CAM5 shows a variance that is too weak at the MJO spatial and temporal scales, and is biased toward temporally longer and spatially shorter scales (Fig. 2c). The power ratio of the eastward versus westward propagating component over the 30–60 days and zonal wavenumbers 1–3 measures the strength of the eastward propagation associated with the MJO (e.g., Kim et al. 2009). In the UNICON, the power ratio is 2.26, which is about half of the value for the NOAA (4.05), while it is 1.05 in CAM5, indicating that the MJO in the UNICON is improved over CAM5 with a stronger eastward propagation at reasonable temporal and spatial scales.
for better simulation of MJO teleconnection in the UNICON.

a. Improved MJO teleconnection with the UNICON

Figures 3 and 4 show the lagged composites of 300-hPa geopotential height anomalies associated with the MJO. For lag day 0 of MJO phase 3, a dipole pattern of negative and positive anomalies is well established over the central Pacific Ocean, both in ERA-I (Fig. 3a) and the UNICON (Fig. 3b). Section 3b will show that these anomalies are formed by a suppressed convection over the Maritime Continent and western Pacific Ocean about 10 days before when MJO passes phase 1. This result is consistent with previous studies in which it was shown that such negative convection anomaly suppresses poleward wave activity (Fig. 3 in Yoo et al. 2012a). Lin et al. (2009) also found a consistent pattern of reduced poleward wave train on lag day 0 of MJO phase 3. On lag +5, the wave train develops downstream toward North America. On lag +10 and +15 days, the wave train resembles a negative PNA-like pattern with a positive anomaly over the East Coast of North America. This PNA-like response is well captured in the UNICON, although the positive anomaly over the East Coast is too elongated in the southwest–northeast direction. It will be shown later in this section that the development of surface air temperature and precipitation anomalies associated with the MJO over North America is consistent with these circulation anomalies.

In contrast, although the suppressed wave train from the central Pacific is captured, the circulation anomalies in CAM5 for MJO phase 3 appear to be substantially different from the observations (Fig. 3c). First, the amplitude of the anomalies is much smaller than the
observation, probably due to the unrealistically weak MJO variance. Second, poleward wave train anomalies are dislocated; the positive anomaly over the North Pacific Ocean is shifted eastward, and the negative anomaly over Alaska is located too poleward. Last, the positive anomaly over the East Coast is too weak and insignificant. As a result, the overall pattern of circulation anomalies does not project strongly onto a negative PNA-like pattern on lag +10 and +15 days of MJO phase 3.

For MJO phase 7, similar patterns of circulation anomalies, but with reversed signs, can be seen for the observations and the UNICON (Figs. 4a,b). About 10 days before MJO phase 7, MJO passes phase 5, which is associated with an enhanced convection over the Maritime Continent and western Pacific Ocean that leads to an increased poleward wave activity (Fig. 3 in Yoo et al. 2012a). On lag day 0 of phase 7, the UNICON captures the enhanced wave trains emanating from the date line of the tropics, propagating across North Pacific and into North America (Fig. 4b). On lag +10 and +15 days, these wave trains strongly project onto a positive PNA-like pattern. In contrast, in the CAM5, such poleward propagating Rossby waves are almost completely absent. Instead, on lag day 0, synoptic-scale waves from East Asia develop to form PNA-like and then NAO-like patterns on lag +5 and +10 days.
respectively (Fig. 4c). Because the observed connection between the MJO and circulation anomalies over North Pacific and North America can be explained by linear wave dynamics (e.g., Yoo et al. 2012b), we can speculate that for the CAM5 there is no systematic impact of the MJO on the extratropical circulation anomalies.

For a quantitative evaluation, the pattern correlations of the simulated 300-hPa geopotential height composites against their observed counterparts are calculated for all MJO phases (Table 2). Overall, the correlations for UNICON are higher than those for CAM5, which is consistent with interpretation of Figs. 3 and 4. The mean pattern correlation averaged across all MJO phases (rightmost column in Table 2) demonstrates that UNICON (0.54) exhibits a superior skill to simulate the MJO teleconnection pattern than CAM5 (0.07). Note that the skill score (pattern correlation) varies from one MJO phase to another. For example, both models show relatively high (low) skill in phase 4 (phase 2). While explaining the differences of the two models in each phase is beyond the scope of this study, we suspect that this phase dependency might originate from detailed structure of MJO-associated tropical heating, since the basic states of the two models are similar to each other (Fig. 9).

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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNICON</td>
<td>0.53</td>
<td>0.23</td>
<td>0.49</td>
<td>0.59</td>
<td>0.58</td>
<td>0.53</td>
<td>0.66</td>
<td>0.70</td>
<td>0.54</td>
</tr>
<tr>
<td>CAM5</td>
<td>-0.06</td>
<td>-0.16</td>
<td>0.31</td>
<td>0.40</td>
<td>-0.05</td>
<td>0.00</td>
<td>0.10</td>
<td>0.04</td>
<td>0.07</td>
</tr>
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</table>

Having established that realistic extratropical circulation anomalies associated with the MJO are represented in the UNICON than in CAM5, we now examine the relationship between the MJO and the two leading extratropical climate modes, the PNA and the NAO. These two modes are the primary atmospheric teleconnection patterns that reflect large-scale changes in atmospheric conditions, such as wind, temperature, precipitation, and so on. Despite the reddened power spectrum, the PNA can be understood, at least partly, as a forced response to a tropical convection (Feldstein 2002) and it has a robust relationship with the MJO (Johnson and Feldstein 2010; Riddle et al. 2013). On the other hand, although the NAO life cycle is dominated by nonlinear processes (Feldstein 2003), its relationship with MJO phases has been reported (Cassou 2008; Lin et al. 2009; Riddle et al. 2013).

The MJO–PNA relationship is well captured in the UNICON (Fig. 5). In ERA-I, the lagged composite of the PNA index for all MJO phases illustrates the cyclic behavior of the MJO–PNA relationship (Fig. 5a). For example, on lag day 0 of MJO phases 3–6, negative PNA index composites indicate that daily circulation anomalies over the North Pacific and North America tend to project a negative PNA-like pattern. In contrast, on lag day 0 for MJO phases 7–2, the PNA index composites

**Table 2.** Latitude weighted, centered (i.e., with the domain mean removed) pattern correlations with the ERA-I using the Northern Hemisphere DJF 300-hPa geopotential composites for all MJO phases on lag day 0.

**Fig. 5.** Lagged composites of PNA index associated with all MJO phases for (a) ERA-I, (b) UNICON, and (c) CAM5. Solid (dashed) contours are positive (negative) and the zero contours are omitted. Positive (negative) values that exceed the 95% confidence level of a Student’s t test are shaded by warm (cold) color.
reverse the sign of PNA, which suggests that a positive PNA-like pattern is likely to form. A similar pattern is reproduced by the UNICON with about 50% greater amplitude (Fig. 5b). The overestimated amplitude is probably because the MJO variance in the UNICON is greater than that of the observation (Fig. 2b). Unlike the UNICON, this MJO–PNA relationship in CAM5 is only marginally shown (Fig. 5c).

On the other hand, the match between the observation and the UNICON for the MJO–NAO relationship is less clear (Fig. 6). The composite using the ERA-I-based NAO index shows that the positive sign of the NAO is likely to take place approximately 5 days after the MJO passes phases 3–4 (Fig. 6a). Also, the composite shows negative values for the positive lags until day +25 of MJO phases 7–8. This is generally consistent with the findings by Cassou (2008) on the occurrence frequency of NAO events associated with MJO phases. However, the UNICON instead shows almost the opposite sign of the NAO index composite (Fig. 6b). CAM5 does not capture the MJO–NAO relationship as well (Fig. 6c). As will be mentioned later, the mismatch is likely due to large wind biases in both simulations over the North Atlantic, which can substantially alter the direction of the Rossby wave propagation. It is noted here that the statistical significance of the MJO–NAO relationship is not as robust as the MJO–PNA relationship even in observations. For example, the connection between MJO phases 2–4 and positive NAO is not found in cluster analysis (Riddle et al. 2013).

We now perform a similar analysis for the surface air temperature over the North Pacific and North America (Fig. 7). In this region, the upper-tropospheric circulation anomalies associated with the MJO are particularly improved in the UNICON simulation (Figs. 3 and 4). In observations, after the MJO passes phase 3, significant cold and warm anomalies develop over Alaska and eastern Canada, respectively (Fig. 7a). This is consistent with the results reported in previous studies (Vecchi and Bond 2004; Lin and Brunet 2009; Zhou et al. 2012), although the amplitude of the anomalies is slightly weaker than that of Zhou et al. (2012), who used a different dataset at a higher resolution.

In the UNICON, while these anomalies are shifted eastward and their amplitudes are overestimated (Fig. 7b), the timing of the development is closely emulated. The cold anomaly over Alaska, for example, starts to appear on lag day 0, and spreads toward the Northwest Territories of Canada on lag +5 and +10 days. The formation of this cold anomaly coincides with the development of anticyclonic (cyclonic) circulation in the east (west). This result indicates that in the UNICON, as for the observations (Yoo et al. 2012a), the circulation-induced temperature tendency (i.e., the thermal advection) plays an important role in the extratropical surface air temperature anomalies associated with the MJO. The cold anomaly along the East Coast is also captured in the UNICON despite that the pattern is somewhat too elongated in the southwest–northeast direction. For MJO phase 7, a similar pattern of anomalies with the opposite sign can be seen in both the observation and the UNICON (Figs. 7d,e).

The surface air temperature anomalies of CAM5 (Figs. 7c,f) only slightly resemble the observed patterns (Figs. 7a,d). For example, while the warm anomaly over the eastern Canada during phase 3 is well captured, the anomaly does not evolve with time as observed. In addition, the patterns of phase 7 (Fig. 7f) do not bear much

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**Fig. 6.** As in Fig. 5, but for the NAO index.
resemblance to the observation (Fig. 7d). This is consistent with the fact that the circulation anomalies are unsuccessfully represented in CAM5 (green contours).

Last, the precipitation anomalies associated with the MJO are explored (Fig. 8). The MJO is known to affect the precipitation rate over the North Pacific and America through its modulation on water vapor transport from the tropics (e.g., Guan et al. 2012). At around 40°N, 150°W, reduced (enhanced) precipitation anomalies for MJO phase 3 (phase 7) can be seen in the observations (Figs. 8a,d). Similar to the surface air temperature, we pay attention to large-scale features of the CMAP data, while readers are referred to Zhou et al. (2012) for finescale features. At a continental scale, the precipitation anomalies in both simulations arguably resemble the observed pattern (Figs. 8b,c,e,f). However, the simulated anomalies are not collocated with those in the observation. For example, the anomalies over the southern part of Alaska and the West Coast of Canada are slightly mismatched by the UNICON in both phases,
and these anomalies in CAM5 fail to show the correct sign over Alaska and the West Coast of Canada. Nevertheless, pattern correlations between the simulated and observed patterns for the domain are improved from 0.05 for CAM5 to 0.36 for the UNICON. For the East Coast, both models perform poorly, presumably because the influence of the MJO on the precipitation is not significant, and the circulation anomalies of the MJO are distorted in the region.

b. Initial value calculations

To investigate the mechanisms by which the UNICON improves the MJO teleconnection, we first examine the changes in the background wind for DJF between the UNICON and the CAM5 (Fig. 9). It can be seen that the 200-hPa zonal wind difference is small over Asia and the western Pacific. Sardeshmukh and Hoskins (1988) showed that for a barotropic atmosphere, the Rossby wave source \( S \) is a function of irrotational wind \( (v_x) \) and absolute vorticity gradient \( (\zeta) \), that is, \( S = -\nabla \cdot (v_x \zeta) \). Because of the local maximum of absolute vorticity gradient, as well as the divergence anomalies associated with the MJO, the exit of the Asian jet is the key region for exciting poleward propagating Rossby waves associated with the MJO (Adames and Wallace 2014). Thus, the minimal difference in the
upper tropospheric zonal wind over Asia and the Pacific suggests that wave excitation in both simulations would not considerably differ, if the tropical forcing associated with the MJO were the same. This will be demonstrated later by perturbing the UNICON (CAM5) background state using the CAM5 (UNICON) MJO forcing.

We note that in the western Northern Hemisphere, the 200-hPa zonal wind difference between the UNICON and CAM5 (right panel in Fig. 9) is not negligible; the North American jet in the UNICON is contracted westward, while the African jet is extended westward. Also, compared to the ERA-I, both simulations show strengthened zonal wind over the Gulf of Mexico and over western Europe, and a weakened zonal wind over the east of Greenland (left and middle panels in Fig. 9). This indicates that over the North Atlantic, large differences occur in the waveguide between the observation and the simulations. Thus it is not surprising that the simulated circulation anomalies over the North Atlantic are not well matched with the observation (Figs. 3 and 4).

Having identified that the basic states of the simulations are comparable in the Pacific sector, we now examine the circulation response to distinct MJO forcings from the UNICON and CAM5. Figure 10 illustrates the development of the 300-hPa geopotential height

![Figure 9](image) Contours of the difference of December–February mean 200-hPa zonal wind between (left) UNICON minus ERA-I, (middle) CAM5 minus ERA-I, and (right) UNICON minus CAM5 is shown in contours with solid (dashed) contours being positive (negative) and the zero contours are omitted. The contour interval is 2.5 m s$^{-1}$. Pink shading indicates that the mean wind of ERA-I $>30$ m s$^{-1}$.

![Figure 10](image) (top)–(bottom) Temporal evolution (days 3, 6, 9, and 12) of the anomalous 300-hPa geopotential height of MJO phases 1 for (left) UNICON and (right) CAM5. All panels show the deviation from the initial state. The contour interval is 5 m in the left and 2 m in the right panels. Solid (dashed) contours are positive (negative) and the zero contours are omitted. For the top panels, the tropical convective forcing added during the first 5 days of integration is shaded.
anomalies over the first 12 days after introducing the MJO phase 1 heating, where the anomalies are defined as the deviation from the initial state of each simulation. For the initial value calculation using the heating and the basic (initial) state from the UNICON (left panels in Fig. 10), the overall circulation response resembles that in Fig. 4. By day 6, reduced Rossby waves rise from the tropics to East Asia and the Pacific Ocean. These anomalies form a negative PNA pattern on days 9 and 12 of the simulation, with negative centers near 20°N, 160°W and 60°N, 120°W and positive centers near 45°N, 155°W and 30°N, 80°W. An almost identical pattern can be seen from the lagged composite of the UNICON (Fig. 3b) on lag day 0 and lag +5 days. This result also holds for the MJO phase 5 heating (left panels in Fig. 11) with the opposite sign of the response, and is congruous with the fact that the PNA can be simulated using a linearized barotropic model with tropical divergence forcing (e.g., Higgins and Mo 1997).

The match for the CAM5 between the initial value calculation (right panels in Figs. 10 and 11) and the AMIP-type simulation (Figs. 3c and 4c) is poor. For example, forced by the enhanced convection over the warm pool area (shaded top right panel of Fig. 11), the initial value calculation shows poleward and eastward propagating waves indicating a positive PNA phase. However, in the CAM5, waves emanate rather from the mid to low latitudes (Fig. 4c). Such a development of waves can take place when an initial perturbation that mimics high-frequency midlatitude eddies is given directly to the circulation fields (Figs. 1 and 2 in Franzke et al. 2004). Thus, our results suggest that the impact of the MJO on the extratropics is too weak for CAM5, presumably due to the unrealistically weak MJO variance. This results in a negligible influence of the tropical excitation on poleward propagating waves, and allows the midlatitude eddies to dominate.

To ensure that the effect of changes in the basic state is negligible, the initial calculations are repeated by intermixing the UNICON basic state with the CAM5 tropical heating and vice versa. As expected from the minimal difference of zonal wind between the UNICON and CAM5, the circulation response is sensitive only to the tropical forcing, and almost identical patterns of wave trains in the Pacific sector are reproduced (not shown). Also, over the Atlantic sector, some discrepancies can be seen in the circulation response due to the basic state, but are not large.

4. Conclusions and discussion

In this study, we analyze two long-term AMIP-style simulations made with the Community Atmosphere Model version 5 (CAM5) with a focus on their representations of the boreal winter Madden–Julian oscillation (MJO) teleconnection. In one of the simulations, a recently developed cumulus parameterization scheme [the unified convection scheme (UNICON) of Park (2014a)] replaces the default shallow and deep convection schemes of CAM5. It is demonstrated that when
employing the UNICON, CAM5 is capable of reproducing the observed tropics–extratropics connection associated with the MJO. Specifically, the simulated extratropical upper tropospheric circulation anomalies coherently evolve with the convective anomalies of the MJO in the tropics, and bear a strong resemblance to those in the observations. The simulation with the UNICON also represents a realistic relationship between the MJO and one of the most frequently recurring circulation patterns in the midlatitudes, the Pacific–North American pattern (PNA). In North America, the enhanced representation of the MJO teleconnection leads to realistic surface air temperature and precipitation anomalies associated with the MJO. The CAM5 simulation with the default convection schemes lacks these salient features related to the MJO teleconnection, suggesting that the convection scheme plays a crucial role in the simulation of the MJO teleconnection.

Successful simulation of the MJO teleconnection has been a longstanding challenge for climate models, probably due to their inability to represent a reasonable MJO without sacrificing the mean state. The progress made with the UNICON may be because the UNICON enables the host GCM, CAM5, to simulate a reasonable MJO and a realistic mean state at the same time. It was shown that the two CAM5 simulations exhibit a very similar mean upper-level zonal wind field in the North Pacific basin despite substantial differences in their representation of the tropical convective anomaly associated with the MJO. This suggests that the tropical heating anomalies play critical roles in the MJO teleconnection. The results of initial value calculations, performed with a dry primitive equation model by switching the basic state and the MJO-associated tropical forcing from the two CAM5 simulations, further support this view.

While reaffirming the MJO–PNA relationship, the observed MJO–North Atlantic Oscillation (NAO) relationship is not well reproduced in the simulation with the UNICON. Although it requires further analysis to explain the less successful simulation of the MJO–NAO relationship, the results in this study indicate that mechanisms other than the tropospheric Rossby wave propagation (e.g., Horel and Wallace 1981; Hoskins and Karoly 1981) may play an important role in the MJO–NAO relationship. Recent studies suggest that the Rossby waves excited from the tropics may propagate poleward not only through the troposphere, but also through the stratosphere (e.g., Butler et al. 2014). The Rossby waves propagating through the stratosphere can play a key role in modulating the NAO via the troposphere–stratosphere coupling (e.g., Baldwin and Dunkerton 1999, 2001). In our next step, we will examine whether such a pathway through the stratosphere can explain the MJO–NAO relationship.

The results of our study also suggest that further improvements in the MJO performance itself are required to better simulate the MJO teleconnection. For example, the powers of tropical outgoing longwave radiation (OLR) still shift to low frequencies in the simulation with the UNICON (Fig. 2b). Also, the MJO-related tropical OLR anomalies from the UNICON are about 50% stronger than in the observation. Last, although greatly improved, the OLR patterns associated with the MJO in the UNICON do not perfectly match those of the observations. This is especially true for some phases (e.g., phases 3, 7, and 8) and is probably linked to the phase-dependent MJO teleconnection performance in Table 2. The MJO is an important source of predictability of the extratropical weather in the subseasonal time scale (e.g., Vitart and Molteni 2010; Vitart et al. 2012). Therefore, it is of great interest to explore whether the changes in the convection scheme that lead to an improved simulation of the MJO teleconnection would also lead to an enhanced forecast for extratropical weather phenomena, especially for the 2–4-week target, which represents a significant gap in current prediction capabilities between medium-range weather forecast (up to 2 weeks) and seasonal prediction (≥1 month). To explore this issue, we plan to conduct reforecast experiments using the two versions of CAM5 used in this study.

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