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The impact of the Madden-Julian Oscillation trend on the Arctic amplification of surface air temperature during the 1979–2008 boreal winter

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[1] One of the most prominent and important features of climate change is that surface air temperature (SAT) change is greatest at high latitudes. The cause for this Arctic amplification of SAT is uncertain. Using ERA-Interim reanalysis data, we show that Arctic amplification during the past 30 years (1979 to 2008) is linked to the Madden-Julian Oscillation (MJO), the primary mode of intraseasonal variability in the tropics. Specifically, it is shown that interdecadal changes in the frequency of occurrence of individual MJO phases have had considerable influence on the Arctic warming during the boreal winter. During that time period, MJO phases 4–6 exhibited a large increase and phases 1–2 a moderate decrease in their frequency of occurrence. Time lagged composites of the SAT show that MJO phases 4–6, which correspond to enhanced localized tropical heating, are followed 1–2 weeks later by Arctic warming. Similarly, MJO phases 1–2, which are associated with more zonally uniform tropical heating, are followed by Arctic cooling. These relationships between the Arctic SAT and the spatial structure of the tropical heating are consistent with the poleward propagation mechanism of Lee et al. (2011a, 2011b). By incorporating both the trend in MJO phase and the intraseasonal SAT anomaly associated with the MJO, it was found that the MJO-induced SAT trend accounts for 10–20% of the observed Arctic amplification over the Arctic Ocean.

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1. Introduction

[2] Arctic amplification, i.e., the interdecadal trend in surface air temperature (SAT) being larger at high latitudes than at other latitudes, is one of the most prominent and robust features of climate change over the last century [e.g., *Johannessen et al.*, 2004; *Serreze and Francis*, 2006]. Despite its urgent implications, including an increased melting rate of the Greenland ice sheet and reduction in Arctic biodiversity, as well as alterations of the atmospheric circulation [*Arctic Climate Impact Assessment*, 2005], its cause is not well understood. Positive surface albedo feedback (SAF) [*Budyko*, 1969; *Sellers*, 1969], which is associated with sea-ice and snow-cover retreat, has been supported by some climate model simulations [*Holland and Bitz*, 2003; *Hall*, 2004]. However, there are model simulations which can successfully produce Arctic amplification without SAF, leading to the interpretation that the atmospheric circulation is in part responsible for the Arctic amplification [e.g., *Alexeev et al.*, 2005; *Cai and Lu*, 2007].

[3] Observational datasets also show contradictory evidence as to whether Arctic amplification is caused by SAF or by changes in the atmospheric circulation. In their analysis of ERA-40 reanalysis data, *Graversen et al.* [2008] found that Arctic warming occurs well above the surface, hence they concluded that SAF cannot account for the warming and instead attributed the trend to an accelerated atmospheric moist energy transport from lower latitudes [*Graversen*, 2006]. However, this claim was questioned by *Screen and Simmonds* [2010], who concluded that reduction in sea ice cover played the major role in the trend, because the warming is strongest at the surface (in ERA-Interim reanalysis data) where fluxes have their greatest impact, and because of the large linear congruence between the declining sea ice and air temperature. On the other hand, the results from recent observational and modeling studies suggest that poleward heat transport associated with Rossby waves excited by tropical convection also plays an important role for the enhanced high latitude warming [*Ding et al.*, 2011; *Lee et al.*, 2011a, 2011b; *Schneider et al.*, 2011]. In this paper, we present further evidence of this linkage between tropical convection and Arctic amplification by showing that interdecadal variability of the Madden-Julian Oscillation (MJO), the most prominent mode of intraseasonal variability in the tropics [*Madden and Julian*, 1994], makes an important contribution to Arctic amplification.

[4] The recent study of *Lee et al.* [2011a] found evidence that Arctic amplification arises from changes in the frequency of occurrence of a few intraseasonal time-scale teleconnection patterns associated with increased convective precipitation over the Indian and western Pacific Oceans. Using a coupled self-organizing map analysis of 250-hPa streamfunction and tropical convective precipitation, they showed that the interdecadal trend in the Northern Hemisphere (NH) winter streamfunction field during 1959 to 2001 is associated with an increase in the frequency of patterns that resemble the positive Pacific/North American (PNA) and circumglobal streamfunction patterns [*Branstator*, 2002], and a corresponding decrease in the frequency of PNA and circumglobal streamfunction patterns of opposite sign. The high-latitude warming takes place through an increased adiabatic warming, poleward stationary eddy heat flux, and downward infrared radiative flux. This mechanism of tropical heating-driven Arctic amplification was first proposed by *Lee et al.* [2011b]. In that study, the mechanism was tested

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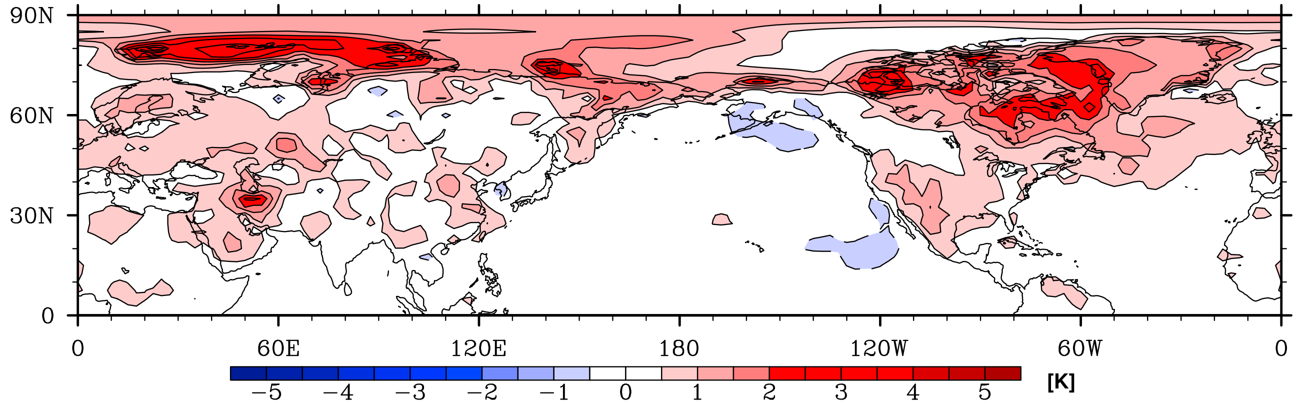

Figure 1. The P2-P1 SAT, where P1 and P2 correspond to the boreal winter (November through March) for 1979–1993 and 1994–2008, respectively. The contour interval is 0.5 °C. Zero contours are omitted.

by imposing zonally localized convective heating in an atmosphere-mixed layer ocean model of the Cretaceous-early Cenozoic equable climate.

[5] Because the MJO is associated with zonally localized convective heating, the findings of *Lee et al.* [2011a] allude to the possibility that Arctic amplification may be related to interdecadal variability of the MJO. Indeed, the MJO has considerable influence on the extratropical atmospheric circulation, possibly through Rossby wave propagation [e.g., *Matthews et al.*, 2004]. Recent studies have shown that the positive (negative) phase of the North Atlantic Oscillation (NAO) occurs with increased likelihood 1–2 weeks after MJO phases 3–4 (7–8), which corresponds to enhanced convection over the Indian (western Pacific) Ocean [*Cassou*, 2008; *Lin et al.*, 2009] (these studies use the index of *Wheeler and Hendon* [2004] to define the MJO). In addition, the positive (negative) PNA has been observed to occur more frequently 1–2 weeks after MJO phases 5–8 (1–4) [*Johnson and Feldstein*, 2010]. Moreover, two independent studies of daily SAT station data over North America for the winter season revealed systematic variation of the SAT spatial pattern contingent upon the MJO phase [*Vecchi and Bond*, 2004; *Lin and Brunet*, 2009].

[6] Motivated by these previous studies, we investigate whether changes in the frequency of different MJO phases also contribute toward Arctic amplification. To address this problem, in this study, we will compare the interdecadal SAT trend associated with these changes in the MJO to the full interdecadal SAT trend.

2. Data and Methods

[7] To study the MJO and its relationship with the SAT, we use 30 boreal winters (November through March during 1979 to 2008) of the daily multivariate MJO index [*Wheeler and Hendon*, 2004] (http://www.bom.gov.au/climate/mjo/). The MJO index is defined by the principal components of the two leading combined EOFs of the intraseasonal 200- and 850-hPa zonal winds and outgoing longwave radiation (OLR), averaged over the band from 15°S to 15°N. The MJO has eight phases, following *Wheeler and Hendon* [2004, see Figure 8], with phases 2–4 corresponding to enhanced convection over the Indian Ocean and the western Maritime Continent, and phases 5–7 to strengthened convection over the eastern Maritime Continent and the western Pacific Ocean.

[8] For daily SAT, we use the European Center for Medium-Range Weather Forecasts ERA-Interim (1979 to 2008) reanalysis [*Dee and Uppala*, 2009]. It will be shown that our results are insensitive to the choice of reanalysis dataset (see the auxiliary material).[1] The interdecadal trend in SAT is defined as the difference between the time mean for two different 15-year winter periods: 1979 to 1993 (P1) and 1994 to 2008 (P2) (see Figure 1). To examine the intraseasonal time scale SAT changes associated with the MJO, the seasonal cycle is removed at each grid point by subtracting the first three harmonics of the calendar mean for each day. This is followed by the application of a 101-point, 5-100-day, band-pass digital filter.

3. Results

[9] We start by probing the P2-P1 SAT change, which shows widespread warming over the Barents and Kara seas and much of the North American and Eurasian landmasses (about 1–4 °C) (Figure 1). A comparison of the frequency of occurrence of those days that the MJO amplitude exceeds a value of 1.5 (our definition of an active MJO, which corresponds to 30% of the days within the dataset) for P2 (blue bars in Figure 2) and P1 (red bars in Figure 2) shows a notable increase for phases 4–6, a moderate decrease for phases 1–2, and minimal change for the other phases. The changes in the frequency of occurrence for phases 1 and 4–6 in Figure 2 exceed the 95% confidence level for a Monte Carlo test based on 1000 random samples. This trend in MJO frequency of occurrence is insensitive to the threshold value. Because the average MJO amplitude over the entire period is 1.25, we have also examined the frequency of occurrence with threshold values of 1.0 and 1.25, which include about 70% and 45% of the total number of days, respectively. For both cases, it is found that the changes in the frequency of occurrence are similar to those shown in Figure 2.

[10] It is important to note that the change in the frequency of occurrence of the MJO phase corresponds to an interdecadal

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049881.

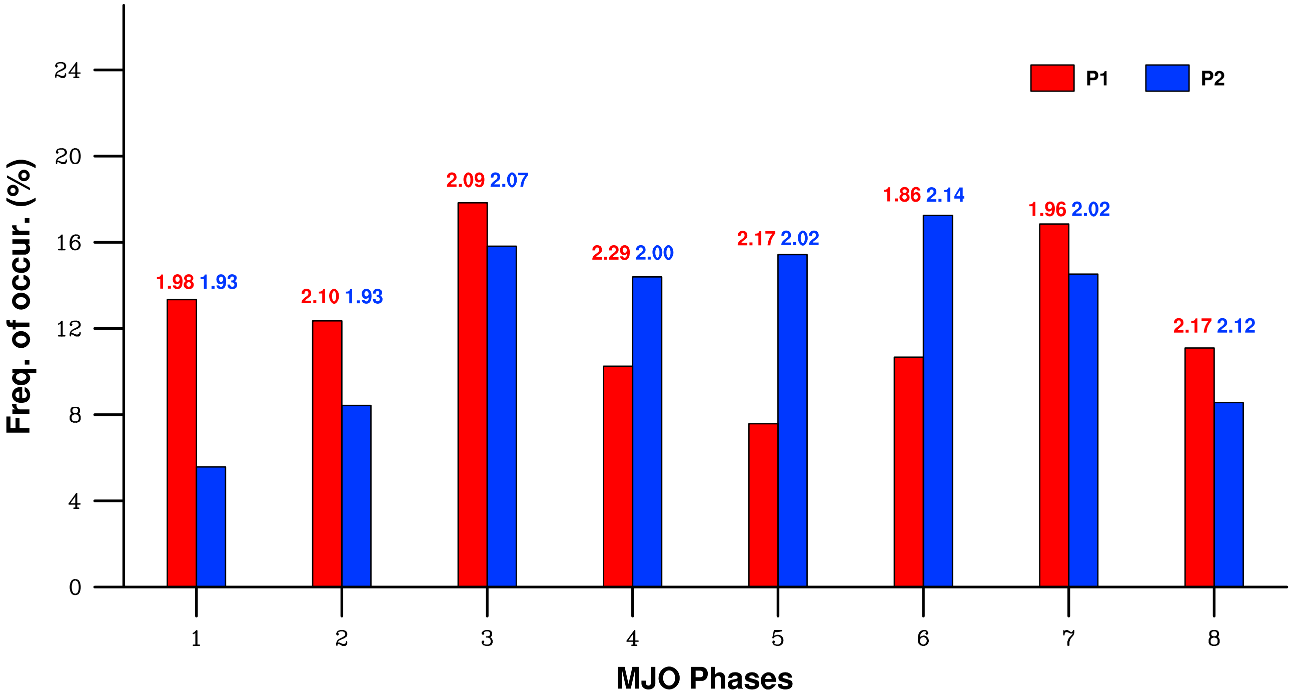

Figure 2. Frequency of occurrence (%) for each MJO phase. The days are included when the MJO index exceeds a value of 1.5. The red bars are for P1, and the blue bars for P2. The total numbers of days are 712 (P1) and 771 (P2). The numbers on top of the bars indicate the average amplitude for each phase of P1 (red) and P2 (blue).

trend in tropical convection. Both the increased frequency of phases 4–6 and decreased frequency of phases 1–2 indicate that tropical convection, hence precipitation, at interdecadal time scales is reduced over the Indian Ocean and increased over the Maritime Continent and western Pacific Ocean. Interestingly, these interdecadal time scale changes in the intraseasonal MJO resemble the interdecadal trend obtained from other independent precipitation datasets, such as the Global Precipitation Climatology Project, and Climate-Prediction-Center Merged Analysis of Precipitation [see *Lee et al.*, 2011a, Figures 1b and 1c].

[11] Lagged composites of the SAT associated with each of the MJO phases show systematic variation. We focus on MJO phases 1 and 5 (Figure 3), because (i) those phases show large changes in their frequency of occurrence, and (ii) in general, phases 1–4 (5–8) indicate a similar Arctic cooling (warming) 1–2 weeks after the MJO passes through that phase (not shown). As can be seen from Figure 3, for phase 1, Arctic cooling is evident on lag +5 through lag +15 days (Figure 3, left), while phase 5 shows Arctic warming on lag +10 and lag +15 days (Figure 3, right). These changes in Arctic SAT are consistent with the findings of *Lee et al.* [2011a, 2011b], who showed that enhanced, zonally localized convection is associated with an elevated high latitude SAT. Similar changes are observed in tropical convection associated with the MJO. For example, in the first panels of Figure 3, which show the total OLR composites on lag day 0, where total is defined as the sum of the anomalous OLR associated with the MJO plus the climatological OLR, it can be seen that phase 5 is associated with more intense and zonally localized tropical convection than phase 1. Furthermore, the time scale of the high latitude SAT response to tropical convection is in agreement with that obtained from observational and idealized model studies of tropically-forced, poleward propagating Rossby wave trains [*Hoskins and Karoly*, 1981; *Kiladis and Weickmann*, 1992].

[12] To examine the effect of the MJO changes on the interdecadal SAT trend, we incorporate the changes in the MJO frequency of occurrence (Figure 2) with the intraseasonal SAT anomaly associated with the MJO (Figure 3), and retrieve an interdecadal MJO-induced SAT trend (hereafter, for brevity, the MJO-induced SAT trend). In mathematical form,

$$(\bar{T}_2(\lambda,\theta) - \bar{T}_1(\lambda,\theta))_{MJO}(\tau) = \frac{\sum_{i=1}^{8} \Delta T_{2,i}(\lambda,\theta,\tau) N_{2,i}}{N_2} - \frac{\sum_{i=1}^{8} \Delta T_{1,i}(\lambda,\theta,\tau) N_{1,i}}{N_1}, \qquad (1)$$

where subscripts 1 and 2 denote P1 and P2, respectively, λ and θ are latitude and longitude, respectively, an overbar indicates the time mean, and τ is the lag day. On the right-hand-side, $\Delta T_{1,i}$ and $\Delta T_{2,i}$ are the MJO SAT anomalies for P1 and P2 (as in Figure 3), respectively, and $N_{1,i}$ and $N_{2,i}$ are the number of days in P1 and P2, respectively, for MJO phase i, that the threshold value is exceeded (as in Figure 2). Note that because of the application of the band-pass filter (section 2), ΔT_i does not contain information of any long-term trend. The numbers in the denominator, N_1 and N_2, correspond to the numbers of days for the entire P1 and P2, respectively.

[13] It is striking that the MJO-induced SAT trend patterns over the Arctic for lag +5 days (Figure 4b) and lag +10 days (Figure 4c), along with the time average (Figure 4d), are similar to the observed P2-P1 high latitude SAT trend