The impact of the Madden-Julian Oscillation trend on the Antarctic warming during the 1979-2008 austral winter

Short Title: The impact of the MJO on the recent Antarctic warming trend during winter

CHANGHYUN YOO
Graduate Student

Department of Meteorology, The Pennsylvania State University, University Park, PA

SUKYOUNG LEE
Professor

Department of Meteorology, The Pennsylvania State University, University Park, PA

AND STEVEN FELDSTEIN
Professor and Senior Scientist

Department of Meteorology, The Pennsylvania State University, University Park, PA

1 Corresponding author address: Changhyun Yoo, Center for Atmosphere and Ocean Science, Courant Institute, New York University, 251 Mercer Street, New York, NY 10012.

E-mail: cyoo@cims.nyu.edu, Tel: 1-814-441-8246, Fax: 1-212-995-4121

2 Current affiliation: Postdoctoral fellow, Center for Atmosphere Ocean Science, Courant Institute, New York University, New York
Abstract

Antarctica is one of the regions where the Earth’s surface is warming most rapidly. The interdecadal warming trend over much of Antarctica during the austral winter is about 1°C decade$^{-1}$, which is almost twice that of the global mean. There is increasing observational and modeling evidence that high-latitude warming is linked to localized heating in the tropics. Here we show that interdecadal changes in the spatial patterns of the extratropical response to various phases of the MJO explain 10-20% of the interdecadal warming over Antarctica, possibly through the poleward propagation of tropically forced Rossby wave trains.

Keywords: MJO; Rossby wave trains; Antarctic warming
1. Introduction

Climate change over Antarctica (Turner et al. 2005) and the Southern Ocean contributes to the melting of snow and ice, and a rising of sea level, which influences the global ocean circulation through its impact on the density of surface water (Goosse and Fichefet 1999). A thorough examination of the Antarctic temperature changes since the late fifties using various reconstruction datasets (Chapman and Walsh 2007; Monaghan et al. 2008; Steig et al. 2009) revealed that there were warming trends over much of Antarctica during the austral winter and spring. Given that this trend is widespread across Antarctica, with some locations indicating a trend value that exceeds the 95% confidence level (Schneider et al. 2011), an effort to discern plausible mechanisms for this warming trend is essential for formulating an effective monitoring strategy, for improving climate models, and therefore for narrowing uncertainties in climate prediction.

The results from a recent modeling study suggest that the austral winter warming over West Antarctica since the late 1970s is associated with increased warm advection, caused by the atmospheric Rossby wave response to sea surface temperature (SST) changes in the central tropical Pacific (Ding et al. 2011). This contrasts the warming over the Antarctic Peninsula during the austral spring and summer, which may be driven by the response to stratospheric ozone depletion and increased atmospheric loading of greenhouse gases (Thompson and Solomon 2002; Marshall et al. 2004; Arblaster and Meehl 2006). However, because previous studies used seasonal mean SST and circulation patterns (Ding et al. 2011; Schneider et al. 2011), it remains unclear as to how the Rossby waves, which fluctuate on intraseasonal time scales, contribute to the interdecadal time-scale winter Antarctic warming.
For the observed boreal winter Arctic warming from the late 1950s to the early 2000s, it was indeed shown that increases in the frequency of occurrence of poleward propagating Rossby waves excited by convection over the western tropical Pacific and Indian Oceans have had considerable influence (Lee et al. 2011). This linkage between intraseasonal tropical convection and the winter Arctic temperature trend was underscored by the finding that interdecadal trends in the frequency of particular phases of the Madden-Julian Oscillation (MJO) the principal mode of intraseasonal variability in the tropics (Madden and Julian 1971), have contributed to the boreal winter Arctic warming during the past 30 years (Yoo et al. 2011). Therefore, we ask if interdecadal trends in the MJO during the austral winter also make a substantial contribution to the Antarctic warming.

2. Data and Methods

We used 30 years of the daily multivariate (May-September, 1979-2008) MJO index, which can be obtained from the Australian Bureau of Meteorology website (http://www.bom.gov.au/climate/mjo/; Wheeler and Hendon 2004). 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, averaged latitudinally over the band from 15°S to 15°N. As in Yoo et al. (2011), we define the MJO to be active if an MJO index amplitude threshold of 1.5 is exceeded.

For the SAT, we use the daily European Center for Medium-Range Weather Forecasts ERA-Interim (1979-2008) reanalysis (Dee et al. 2011), as well as the NCEP/DOE reanalysis dataset (NCEP2; Kanamitsu et al. 2002). To retain the intraseasonal variability of the MJO,
while excluding interannual variability, the seasonal cycle is removed at each grid point by subtracting the first three harmonics of the calendar mean for each day, followed by the application of a 101-point, 5-100-day, band-pass digital filter.

3. Results

Figure 1 illustrates the interdecadal surface air temperature (SAT) trend for the extended austral winter (May-September), where the trend is defined as the difference between the ECMWF ERA-Interim reanalysis data for two 15-year periods: 1979-1993 (P1) and 1994-2008 (P2). These particular time periods are chosen to include only post-1979 observations, which contain modern satellite data and thus reduces uncertainties and bias especially at high latitudes (Bromwich et al. 2007). Both positive and negative trends over Antarctica can be seen, with the former comprising a much larger area. Extrema can be found in the positive trend (1°C to 4°C) near 150°W, 80°S and 0°, 75°S, and in the negative trend (-1°C to -3°C) near 60°E, 75°S and 180°, 70°S (Fig. 1). A similar pattern and amplitude has been found by Ding et al. (2011), who compared a combination of ERA-40 and ERA-Interim, NCEP2, station data (Turner et al. 2004), and AVHRR satellite data (Steig et al. 2009), and found good agreement amongst all datasets, with NCEP2 being the outlier (Fig. S1a).

To assess the extent to which the interdecadal SAT trend (Fig. 1) is influenced by changes in the MJO (for brevity, the MJO-induced SAT trend), we start with the method developed by Yoo et al. (2011), which combines the P1 and P2 intraseasonal SAT associated with the MJO and interdecadal changes in the frequency of occurrence of the MJO phases using the following equation:
\[
\left( \overline{T_2(\lambda, \theta)} - \overline{T_1(\lambda, \theta)} \right)_{\text{MJO}}(\tau) = \frac{\sum_{i=1}^{8} \Delta T_{2,i}(\lambda, \theta, \tau) N_{2,i}}{N} - \frac{\sum_{i=1}^{8} \Delta T_{1,i}(\lambda, \theta, \tau) N_{1,i}}{N}.
\] (1)

On the left-hand side of equation (1), the MJO-induced SAT trend is a function of longitude (\(\lambda\)), latitude (\(\theta\)), and lag day (\(\tau\)). Overbars indicate time average, and the subscripts 1 and 2 on both sides of (1), respectively, denote P1 and P2. The summation is performed for the lagged composite of intraseasonally-filtered SAT (May-September, 1979-2008) associated with each MJO phase, \(\Delta T_{m,i}\), and the number of active MJO days, \(N_{m,i}\), over MJO phase \(i\), where \(m = 1, 2\).

The summed values for each period are, respectively, divided by \(N\), which corresponds to the number of days in P1 or P2. After decomposing \(\Delta T_{m,i} = \Delta[T]_i + \Delta T^*_{m,i}\) and \(N_{m,i} = [N]_i + N^*_{m,i}\), where square brackets denote an average over P1 and P2, and asterisks indicate a deviation from this average, we can write (1) as

\[
\left( \overline{T_2(\lambda, \theta)} - \overline{T_1(\lambda, \theta)} \right)_{\text{MJO}}(\tau) = \left[ \sum_{i=1}^{8} \frac{\left\{ \Delta[T]_i(\lambda, \theta, \tau) N^*_{2,i} - \Delta[T]_i(\lambda, \theta, \tau) N^*_{1,i} \right\}}{N} \right] (a)
\]

\[
+ \sum_{i=1}^{8} \frac{\left\{ \Delta T^*_{2,i}(\lambda, \theta, \tau) [N]_i - \Delta T^*_{1,i}(\lambda, \theta, \tau) [N]_i \right\}}{N} (b)
\]

\[
+ \sum_{i=1}^{8} \frac{\left\{ \Delta T^*_{2,i}(\lambda, \theta, \tau) N^*_{2,i} - \Delta T^*_{1,i}(\lambda, \theta, \tau) N^*_{1,i} \right\}}{N} (c)
\] (2)

Equation (2) indicates that the MJO-induced SAT trend includes contributions from (a) interdecadal changes in the frequency of occurrence of each MJO phase and (b) interdecadal changes in the intraseasonal SAT spatial pattern associated with each MJO phase. Term (c), which is a nonlinear combination of \(\Delta T^*\) and \(N^*\), is found to be negligible.

Examination of the MJO-induced SAT trend averaged over lag +3 through lag +11 days (Fig. 2c) indicates a resemblance with the observed P2-P1 SAT trend pattern (Fig. 1). For this...
calculation, lag +3 through lag +11 days are chosen as this is the time period over which a
convectively-driven Rossby wave packet propagates from the tropics to high latitudes (Hoskins
and Karoly 1981). The high latitude warming near 60°E, 150°W and 0°, as well as the cooling in
the vicinity of 180°, all show particularly good agreement, although near the South Pole, the
MJO-induced SAT trend shows warming while the P2-P1 SAT trend cooling. For individual grid
points, we performed a Monte Carlo test that is comprised of 1000 repetitions of the same
calculation using randomly selected days. It can be seen that the majority of grid points are
statistically significant above the 90% confidence level. The ratio (Fig. 2d) between the MJO-
induced SAT trend (Fig. 2c) and the observed P2-P1 SAT trend (Fig. 1) shows that interdecadal
changes in the MJO can explain about 10-20% of the observed Antarctic warming for the austral
winter. This percentage is similar to that obtained for the MJO-induced interdecadal Arctic
warming for the boreal winter (Yoo et al. 2011).

Through the use of equation (2), it can be further shown that most of the MJO-induced
SAT trend is driven by interdecadal changes in the intraseasonal SAT spatial patterns associated
with each MJO phase (Fig. 2b), with interdecadal changes in MJO phase frequency of
occurrence contributing to a widespread Antarctic cooling (Fig. 2a). The MJO-induced SAT
warming associated with each phase is displayed in Table 1, which shows the ratio of the area-
averaged (70°S-90°S) SAT trend for each phase divided by the total area-averaged MJO-induced
SAT trend. The ratios for the MJO frequency change contributions are very small for most MJO
phases, with most of the cooling coming from phases 7 and 8. In contrast, the contributions
arising from the intraseasonal SAT pattern changes are large, especially for phases 1, 5, 7, and 8.
The linkage between the spatial structure of the MJO tropical convection and polar SAT change is illustrated in Fig. 3 which shows the total OLR wavenumber power spectra averaged over 15°S-15°N along with the composite lag +3 through lag +11 time-averaged intraseasonal SAT anomalies. In Fig. 3a, the total OLR is defined as the sum of the climatological OLR plus the anomalous OLR associated with each MJO phase. We focus on zonal wavenumbers 1 and 2 since Hoskins and Karoly (1981) showed that most of the wave propagation from the tropics to high latitudes is associated with these wavenumbers. As can be seen in Fig. 3a, MJO phase 4 (thick dashed dot curve) exhibits the largest zonal wavenumber 1 and 2 spectral power, while MJO phase 8 (solid curve) shows the weakest power for these wavenumbers. As was shown by Lee et al. (2011) and Yoo et al. (2011), enhanced localized tropical heating is followed by Arctic SAT warming and a more zonally uniform tropical heating by Arctic SAT cooling. Figures 3a and 3b show that a consistent relationship is present during the austral winter, since MJO phase 4, with its large amplitude planetary-scale tropical convection, is associated with intraseasonal Antarctic SAT warming (Figs. 3b and 3c), and vice versa for MJO phase 8 (Figs. 3e and 3f). Table 1 shows that phase 8 is the dominant contributor to the Antarctic interdecadal SAT warming, with the contribution from phase 4 being much smaller. A comparison of the composite intraseasonal SAT for P1 and P2 in Fig. 3 shows that the increased warming for phase 4 (Fig. 3d) and the decreased cooling associated with phase 8 (Fig. 3g) both contribute toward an interdecadal warming at Antarctica. Similar properties are found for MJO phases 1, 5, and 7, which also contribute toward the Antarctic warming.

The statistical significance of the P2 minus P1 SAT difference was calculated for all 8 MJO phases (not shown). The approach adopted was to use the Student’s t-test for the difference
of means for a null hypothesis of a zero difference between the P1 and P2 SAT composites for all eight MJO phases. The results of this calculation (not shown) found that between 20% and 60% of the area poleward of 60ºS is statistically significant at the 90% confidence level. Such fractional areas are well in excess of that necessary to satisfy field significance (Livezey and Chen 1983). These findings suggest that the difference between the P1 and P2 spatial patterns, for all eight MJO phases, is likely not attributable to random variability. Instead, plausible explanations may involve differences in the background flow or in the MJO convective heating between P1 and P2, both of which will influence wave propagation from the tropics to high latitudes.

The above methodology that uses (2) to distinguish between the frequency and spatial pattern changes associated with the MJO-induced SAT trend was applied to the findings of Yoo et al. (2011). This calculation was performed for the interdecadal Arctic warming trend for the 1979-2008 extended boreal winter (November through March) using the ERA-Interim SAT data and the Wheeler and Hendon MJO index. The MJO-induced SAT trend and its ratio to the corresponding observed P2-P1 SAT trend are shown in Figs. 4c and 4d, along with the frequency (Fig. 4a) and spatial pattern (Fig. 4b) contributions to the trend. As can be seen in Figs. 4a and 4b, for the Arctic winter (also see Table 1), interdecadal changes in both the frequency of occurrence of various MJO phases and changes in the extratropical SAT spatial patterns make an important contribution to the interdecadal warming trend, with the former contribution being a little less than 10% greater than the latter.
4. Discussion

The interdecadal SAT changes associated with the MJO are not found to be sensitive to the choice of dataset; the MJO-induced SAT trends from two different datasets (ECMWF, Fig. 2c; NCEP2, Fig. S1b) show high spatial correlations with each other (0.77 and 0.75 for the 30ºS - 90ºS and 60ºS - 90ºS domains, respectively), even though the NCEP2 P2-P1 SAT trend (Fig. S1a) is somewhat different from its ECMWF counterpart. These two MJO-induced SAT trends resemble not only the P2-P1 SAT trend observed with ECMWF data, but also that of AVHRR satellite data (see Fig. 1 in Ding et al. (2011)). Therefore, we find that each of the MJO-induced SAT trend patterns and the ECMWF and AVHRR P2-P1 SAT trend patterns are more similar to each other than to the NCEP2 P2-P1 SAT trend pattern. Because the NCEP2 P2-P1 SAT trend pattern is the lone exception amongst all other P2-P1 and MJO-induced SAT trend patterns, it is likely that the shortcoming lies in the NCEP2 P2-P1 SAT trend pattern, and that this limitation comes from the representation of processes that do not involve tropically excited Rossby waves (Ding et al. 2011) such as the MJO. In addition, the MJO-induced circulation trend shows a clear signal of poleward propagating Rossby wave trains (Fig. S2). This result not only suggests that the tropically forced, poleward propagating Rossby wave trains play a substantial role in polar amplification over Antarctica, but also alludes to the possibility that other processes that involve localized tropical convection, such as the El-Niño/Southern Oscillation, may also contribute to Antarctic polar amplification.

A similar examination with global data for the boreal and austral winter seasons indicates that the summer hemisphere polar amplification is weak with much less similarity between the P2-P1 and MJO-induced SAT trend patterns (Fig. S3), presumably due to the weaker generation
of poleward propagating Rossby waves into that hemisphere. Also, during the summer,
stratospheric ozone depletion (Thompson and Solomon 2002; Gillett and Thompson 2003) and
surface albedo feedback (Budyko 1969; Sellers 1969) can be important in the Southern and
Northern Hemispheres, respectively.
References


Acknowledgments

We thank anonymous reviewer for constructive comments and suggestions, which have helped to improve the manuscript. This study is supported by National Science Foundation Grants ATM-0852379, AGS-1036858, and by National Oceanic and Atmospheric Administration Grant NA100AR4310251.
Table 1: The area-averaged (70°S-90°S) MJO-induced SAT trend (°C) due to changes in the MJO phase frequency of occurrence (for brevity, MJO freq.; top row) and changes in the intraseasonal SAT spatial patterns between P1 and P2 (for brevity, SAT pttn.; second row). The same calculation for the Arctic (70°N-90°N) during the boreal winter (November through March) is shown in the bottom two rows.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJO freq.</td>
<td>3e-4</td>
<td>0.028</td>
<td>-0.042</td>
<td>-0.004</td>
<td>0.052</td>
<td>0.002</td>
<td>-0.272</td>
<td>-0.575</td>
<td>-0.811</td>
</tr>
<tr>
<td>SAT pttn.</td>
<td>0.565</td>
<td>-0.352</td>
<td>-0.180</td>
<td>0.128</td>
<td>0.418</td>
<td>-0.256</td>
<td>0.431</td>
<td>1.057</td>
<td>1.811</td>
</tr>
<tr>
<td>MJO freq.</td>
<td>0.064</td>
<td>0.139</td>
<td>0.047</td>
<td>-0.384</td>
<td>0.242</td>
<td>0.481</td>
<td>-0.024</td>
<td>-0.031</td>
<td>0.544</td>
</tr>
<tr>
<td>SAT pttn.</td>
<td>0.686</td>
<td>0.718</td>
<td>0.158</td>
<td>-1.203</td>
<td>-0.541</td>
<td>0.429</td>
<td>0.057</td>
<td>0.162</td>
<td>0.466</td>
</tr>
</tbody>
</table>
Figure 1: The P2-P1 SAT, where P1 and P2 correspond to austral winter (May through September) during 1979-1993 and 1994-2008, respectively. The contour interval is 0.25°C. Zero contours are omitted.
Figure 2: The MJO-induced SAT trend (°C) associated with a) changes in the MJO frequency of occurrence and b) changes in the intraseasonal SAT spatial patterns between P1 and P2, summed over all 8 MJO phases. Panel c) shows the total MJO-induced SAT trend, and panel d) is the ratio between panel c) and the observed P2-P1 SAT trend (Fig. 1). In panel d), values are not displayed when negative, and the ratio is multiplied by the sign of the MJO-induced SAT trend.
Figure 3: Wavenumber power spectra of total OLR composites for all 8 MJO phases (panel a), where total is defined as the climatological OLR plus the anomalous OLR associated with the MJO. Lagged composites of intraseasonal SAT (°C) associated with MJO phase 4 (panels b-d) and phase 8 (panels e-g) averaged over lag +3 through lag +11 days are shown for P1, P2, and P2 minus P1. Positive (negative) values that exceed the 90% confidence level for a Student’s $t$-test are shaded in red (blue).
Figure 4: As for Fig. 2, except that the extended boreal winter (November through March) for the Northern Hemisphere is shown. Panels c) and d) are, respectively, unsmoothed versions of Figs. 4d and 4e of Yoo et al. (2011).