GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L04104, doi:10.1029/2003GL018645, 2004

The Madden-Julian Oscillation (MJO) and northern high latitude wintertime surface air temperatures

Gabriel A. Vecchi and Nicholas A. Bond

Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA

Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, USA

Received 16 September 2003; revised 15 December 2003; accepted 9 January 2004; published 19 February 2004.

[1] The Madden-Julian Oscillation (MJO) is the primary mode of large-scale intraseasonal variability in the tropics. Recent work has connected the MJO to atmospheric variability in mid-latitudes. We focus on relationships between the MJO and wintertime surface air temperatures in the Northern Hemisphere high latitudes. The MJO is diagnosed using principal EOF of 850 hPa zonal winds from the NCEP/NCAR Reanalysis for 1979–2002. Station data are used for surface air temperature in Alaska, Canada, the former U.S.S.R., Greenland, and Iceland. The phase of the MJO has a substantial systematic and spatially coherent effect on intraseasonal variability in wintertime surface air temperature through the global Arctic. Composites of geopotential height and specific humidity suggest that radiative and advective effects are important in the observed connections. These statistical connections may be useful for wintertime temperature forecasts. The mechanisms connecting intraseasonal tropical variability with polar and sub-polar variability bear examination. *INDEX TERMS:* 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 1610 Global Change: Atmosphere (0315, 0325); 9315 Information Related to Geographic Region: Arctic region. **Citation:** Vecchi, G. A., and N. A. Bond (2004), The Madden-Julian Oscillation (MJO) and northern high latitude wintertime surface air temperatures, *Geophys. Res. Lett.*, *31*, L04104, doi:10.1029/2003GL018645.

1. Introduction

[2] The MJO is the dominant mode of large-scale sub-seasonal tropospheric variability over the tropical Indian and Pacific Oceans. The MJO is a coherent, eastward propagating perturbation in tropical sea level pressure and upper level zonal wind and atmospheric convection, with a relatively broad spectral peak of 30–90 days [e.g., *Madden and Julian*, 1994]. The dynamical processes responsible for the MJO remain incompletely understood, with much work ongoing on the subject. The prediction of the MJO over multiple cycles remains a promising yet elusive goal [e.g., *Waliser et al.*, 2003].

[3] The impact of the MJO on the atmospheric circulation outside of the tropics has been of considerable interest. There is evidence that deep tropical convection forces the mid-latitude flow both directly [e.g., *Hoskins and Karoly*, 1981; *Horel and Wallace*, 1981], and indirectly [e.g., *Schubert and Park*, 1991]. Connections have been found between midlatitude weather variations and the MJO [e.g., *Higgins and Mo*, 1997; *Mo and Higgins*, 1998; *Jones*, 2000; *Bond and Vecchi*, 2003].

[4] *Bond and Vecchi* [2003; henceforth BV03] focus on MJO-related precipitation in the Pacific Northwest of the U.S.A., but show composites of the 500 hPa height anomaly field associated with the MJO over much of the Northern Hemisphere (their Figures 7 and 8); these figures show atmospheric variability associated with the MJO extending into the high latitudes of the Northern Hemisphere. The present study explores the extent to which the MJO is significantly associated with weather variability in the northern high latitudes. We find that there are significant and coherent air temperature variations in the global Arctic, whose amplitude and robustness suggest the relationship may be usefully exploited for weather forecasts out to as much as the 30–60 day range. Our results compel examination of the dynamics linking the MJO to weather variations in high latitudes.

2. Data and Methods

[5] For specification of the MJO, and for determining its relationship to the atmospheric circulation over high northern latitudes, we use the NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996]. The MJO is diagnosed as in BV03, using an index based on time series of the principal components of the two leading EOF modes of the intraseasonal 850 mb zonal wind (U850) in the band from 5°S to 5°N, and a technique based on that of *Shinoda et al.* [1998]. The MJO index used here differs from that of BV03 in that an MJO amplitude threshold of 1σ, rather than 0.7σ, is used in the current work for consistency with other published work [e.g., *Maloney and Hartmann*, 1998] (the principal results described in this note are evident using the threshold of 0.7σ). The MJO is considered active when there is a coherent eastward propagating intraseasonal signal in near-equatorial U850. The MJO index is available online at http://ferret.pmel.noaa.gov/mjo.

[6] The MJO is divided into eight Phases; each Phase has an average duration of roughly 6 days, and is related to the longitude of the U850 signal. See BV03 for a description of the tropical U850 and atmospheric convection structures. We use 500 hPa geopotential height (Z500) and 700 hPa specific humidity (SH700) fields from the Reanalysis to diagnose flow over high latitudes.

[7] To diagnose the surface air temperature (SAT) variations over land, daily station data from various sources are

0094-8276/04/2003GL018645$05.00

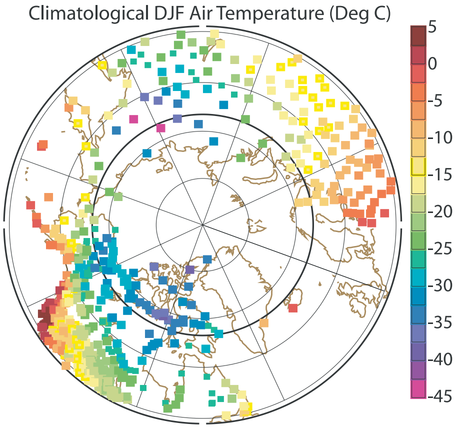

Figure 1. Climatological DJF SAT at the weather stations used in the analysis. Units are °C.

used, which cover over 300 degrees of longitude in the Arctic. For weather stations in the former U.S.S.R. and Greenland, daily mean SAT data is used, while for the weather stations in Alaska, Canada, and Iceland, daily minimum SAT is used. For those Alaska and Canada stations where average daily SAT is available, the results described here are insensitive to the use of daily-mean or minimum SAT; we perform our analysis on minimum SAT because it is more consistently available.

[8] For Alaska and the U.S. Air Force base in Keflavik, Iceland, we use daily minimum SAT data at a representative sample of locations from the National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC); the data records for the stations are of varying length over the period 1979–2002. For Canada we use daily minimum SAT data available from Environment Canada; the data records for the stations are of varying length over the period 1979–2000. The daily mean SAT data record from Sermilik, Greenland is available from 1979–2000 [*Hasholt and Christiansen*, 2003]. In the former U.S.S.R. we use 6-hourly mean SAT data, which is then averaged to form daily-mean SAT data; data are available for 223 stations over the period 1979–1990 [*Razuvaev et al.*, 1993]. We limit our analysis to those stations whose records span at least eight winters; changes in this limit do not significantly affect the result.

[9] The season considered is the winter defined as December through February (DJF). For reference, we show the DJF climatological SAT at each station in Figure 1. For each of the data sets described above, monthly climatologies were constructed and then interpolated to daily values, which were then subtracted to form SAT anomalies. Monthly, rather than daily, climatologies are used in order to lessen the possible aliasing from missing data of high- and low-freqency energy. Composites with respect to the MJO are constructed by averaging daily values for each of the eight Phases. Statistical significance of the SAT composites was estimated using a two-tailed Normal- *z* test.

3. Results

[10] We first focus our analysis on northern North America, Greenland, and Iceland, as those stations have records that extend through the 1990s. The spatial structure of the 1979–2002 composite Western Hemisphere DJF SAT and circulation anomalies for three selected MJO Phases (2, 5, and 7) is shown in Figure 2. The upper panels of Figure 2 show composite SAT anomalies for all Western Hemisphere stations with at least eight winters of data in our record north of 50°N (masked at the 90% level), overlayed by the composite SH700. The lower panels of Figure 2 show composite anomalies of SH700 overlayed by Z500. Though the fields of Figure 2 are for three MJO Phases, other MJO Phases exhibit SAT anomaly patterns of similar magnitude and spatial coherence; we make equivalent maps of all the MJO Phases available online at http://ferret.pmel.noaa.gov/MJO_NH.

[11] Tropical convective anomalies associated with each phase are as follows: Phase 2 is associated with enhanced (reduced) convection of the central Indian Ocean (western Pacific warm pool), Phase 5 is associated with enhanced convection over the Maritime Continent, and Phase 7 is associated with enhanced (reduced) convection over the west Pacific warm pool (the eastern Indian Ocean). *Bond and Vecchi* [2003] give descriptions of the evolution of the tropical variability associated with each phase of the MJO.

[12] The SAT signals associated with the MJO are regionally spatially coherent; for example, there is a general warming (cooling) of central and northern Alaska during Phases 2 and 7 (5). Significant SAT anomalies are seen both

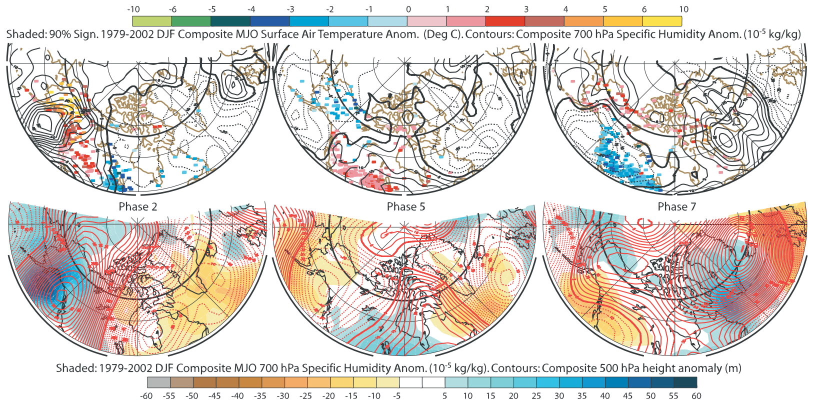

Figure 2. Western Hemisphere 1979–2002 DJF composites of atmospheric variability for three MJO Phases. Upper panels show the 90% significant SAT anomaly (shaded, °C), and SH700 anomalies (contoured, 5×10^{-5} kg/kg interval). Lower panels show the SH700 (shaded, 10^{-5} kg/kg) and Z500 anomalies (contoured, 5 m interval).

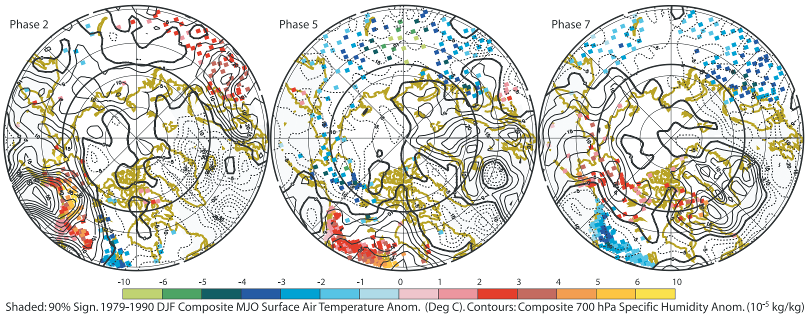

Figure 3. Global northern high-latitude 1979–1990 DJF composites of atmospheric variability for three MJO Phases, as in upper panels of Figure 2.

in Sermilik, Greenland and Keflavik, Iceland: cooling in Sermilik in Phase 2 and warming at both stations in Phase 7.

[13] The composite SH700 and Z500 anomaly fields suggest SAT signals due to the MJO result from both advective and radiative processes. With regard to the latter, cool (warm) surface temperatures occur under dry (moist) air at 700 mb, due to the positive relationship between mid-troposphere specific humidity and downward longwave radiation [*Overland et al.*, 1997; *Adams et al.*, 2000]. Further, the 500 hPa height anomaly maps suggest that advection of moisture by the anomalous circulation results in some of the SH700 patterns: e.g., the moistening over central Alaska during Phase 2 is associated with a strong ridge over the Pacific Northwest, which would tend to drive flow of moist North Pacific air onto land.

[14] Horizontal advection appears to also contribute to the SAT changes. For example, during the cooling in central Canada in Phase 2 there is strong flow of cold air from the Arctic associated with a strong ridge over the North Pacific and a strong trough centered over eastern Canada. The warming in central Alaska during Phase 2 also appears to be partly driven by advection of warm air from the North Pacific onto the continent. The effect of the combined warm and moist air of the North Pacific may be why the Phase 2 SAT anomalies over central Alaska are so strong (>5°C!).

[15] The circulation anomalies associated with the MJO over the period 1979–2002 are evident across the western Arctic; thus we now explore the composite SAT signal over the global northern high latitudes. Figure 3 shows the 90% significant global SAT DJF composites over the period 1979–1990 for the same MJO Phases shown in Figure 2, the composite SH700 anomalies over the period 1979–1990 is overlayed in contours. (We make similar plots for all eight phases available at http://ferret.pmel.noaa.gov/MJO_NH). Notice that there are significant anomalies over most of the northern high latitudes at some point during the MJO cycle. The relationship of these anomalies to the SH700 anomalies is similar to that found over the Western Hemisphere in the longer record. For example, in Phases 5 and 7 most of northern Russia is colder than average (Phase 5 anomalies >5°C in central Siberia!), these SAT anomalies are generally associated with mid-troposphere drying; the converse is true in western Russia and the Baltic Republics in Phase 2.

[16] The composites shown in Figure 3 also allow us to explore some aspects of the robustness of the composite over the Western Hemisphere. The basic character of the composites over the Western Hemisphere presented in Figures 2 and 3 is the same: e.g., Phase 2 is associated with warm Alaska and western Canada, cooling in central Canada, warming over the Canadian Arctic islands. We note that the Western Hemisphere composites over 1979–2002 and 1979–1990 are of the same general character as those over the period 1990–2002 (not shown). We also note that similar results arise when the data from the former U.S.S.R. is divided into two halves—though the reduction in degrees of freedom makes computing statistical significance in the sub-record composites problematic. The statistical significance and robustness of the MJO composite SAT signal suggest that the signal is not a statistical artifact; the composite represents a systematic relationship between intraseasonal variability in the tropics and high-latitudes.

4. Summary and Discussion

[17] A statistically significant, spatially coherent signal was found between wintertime atmospheric variability in the northern high latitudes and intraseasonal convective variability in the tropics. The Madden-Julian Oscillation [see *Madden and Julian*, 1994] is connected to variations in high-latitude surface air temperature (SAT) through its effects on mid-tropospheric humidity and height anomalies. The relationship between atmospheric circulation and SAT anomalies suggests that both radiative and advective effects are important in controlling the SAT variations. While the MJO is a phenomenon most prominent in the tropical Indo-Pacific, it is clear from this and other work [e.g., *Higgins and Mo*, 1997; *Mo and Higgins*, 1998; *Jones*, 2000; BV03] that it has global impacts.

[18] Previous work has documented impacts of the tropical Pacific on interannual timescales, namely in association with the El Niño/Southern Oscillation (ENSO) on the Arctic [e.g., *Papineau*, 2001; *Quadrelli and Wallace*, 2002]. We find here that the connection appears to occur on intraseasonal timescales as well. It bears noting that the SAT signal found by *Papineau* [2001] (∼1°C) is weaker than that found here for the MJO (generally >2°C and can exceed 5°C). The circulation variability within the Arctic itself is dominated by a mode referred to as the Northern Annular Mode [NAM; e.g., *Thompson and Wallace*, 1998]; variations to the mean flow associated with this mode may modulate the response of the Arctic to the MJO. To put the MJO-related signal in context, we note that the amplitude of the SAT and Z500 anomalies associated with the

MJO are on the same order as that associated with the NAM [e.g., *Thompson and Wallace*, 1998; *Quadrelli and Wallace*, 2002].

[19] Other significant relationships of high-latitude weather to the MJO are likely to be significant. Though not shown here, we have found connections similar to those in SAT with precipitation and snowfall. Also, in Figures 2 and 3 there are moisture and circulation anomalies of considerable amplitude over Europe, for which we have not explored air temperature connections; an MJO-related air temperature signal in these regions may also be of potential forecast significance. We have found MJO-related SAT signals in three stations for which we have data in Antarctica (Sipple, McMurdo, and Byrd). However, these results are more speculative because much less data is available to us at Southern Hemisphere high latitudes. Since there is indication that tropical variability associated with ENSO impacts atmospheric circulation over Antarctica [e.g., *Cullather et al.*, 1996; *Bromwich et al.*, 2000], we suggest that exploring connections on intraseasonal timescales should yield interesting results.

[20] While the results presented here seem to be robust, it is important to note three potentially significant caveats. First, the analysis record is of limited length; though the results are significant and robust, they should be revisited as the record lengthens. Second, the period of analysis (1979 to 2002) included a tendency for more warm than cold ENSO conditions [*Trenberth and Hoar*, 1996; *Harrison and Larkin*, 1997], and for the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997] to be in a positive state. It is unknown whether these interannual to decadal-scale background conditions influence the response of the atmospheric circulation over the high northern latitudes to the MJO, and hence represent an important context for the results found here. Third, our analysis has had the benefit of hindsight in specification of the MJO. In order to make predictions based on the MJO, the MJO itself needs to be forecast. The MJO is monitored in real time (e.g., http://www.cpc.ncep.noaa.gov/products/intraseasonal/index.html), and extrapolations from its current state over at least a fraction of a cycle are currently being made [e.g., http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/]. Hence it may be feasible to exploit the tendency of the MJO to follow a "life-cycle" to make predictions on the 30-day timescale. To extend the predictions further, it is important to improve the ability of dynamical models to reproduce the evolution of the MJO. This will require better understanding of the underlying mechanisms of the MJO.

[21] Finally, we note that this analysis is statistical in nature and does not establish the processes connecting MJO variability in the tropics and atmospheric variability in the Arctic. Dynamical analyses of the connections between the MJO and high-latitude atmospheric variability are necessary to understand the nature of the connection, and may help in development of intraseasonal weather predictions.

[22] **Acknowledgments.** We thank D. E. Harrison for encouragement and suggestions. NAB appreciates the support from the Pan-American Climate Studies (PACS) program of NOAA's Office of Global Programs (OGP). GAV acknowledges support by NOAA (OAR HQ and OGP). This publication was supported by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement #NA17RJ1232, Contribution No. 1020. It is NOAA's Pacific Marine Environmental Laboratory Contribution No. 2619.

References

Adams, J. M., N. A. Bond, and J. E. Overland (2000), Regional variability of the Arctic heat budget in fall and winter, *J. Climate*, *13*(9), 3500–3510.

Bond, N. A., and G. A. Vecchi (2003), The influence of the Madden-Julian Oscillation (MJO) on Precipitation in Oregon and Washington, *Wea. Forecasting*, *18*(4), 600–613.

Bromwich, D. H., A. N. Rogers, P. Kllberg, R. I. Cullather, J. W. C. White, and K. J. Kreutz (2000), ECMWF Analyses and Reanalyses Depiction of ENSO Signal in Antarctic Precipitation, *J. Climate*, *13*(8), 1406–1420.

Cullather, R. I., D. H. Bromwich, and M. L. Van Woert (1996), Interannual variations in Antarctic precipitation related to El Niño-Southern Oscillation, *J. Geophys. Res.*, *101*(D4), 19,109–19,118.

Gloerson, P. (1995), Modulation of hemispheric sea-ice cover by ENSO events, *Nature*, *373*, 503–506.

Hasholt, B., and H. H. Christiansen (2003), Rock temperatures, Sermilik, Southeast Greenland, Boulder, CO, National Snow and Ice Data Center, digital media.

Harrison, D. E., and N. K. Larkin (1997), Darwin sea level pressure, 1876–1996: Evidence for climate change?, *Geophys. Res. Lett.*, *24*(14), 1779–1782.

Higgins, R. W., and K. C. Mo (1997), Persistent North Pacific circulation anomalies and the tropical intraseasonal oscillation, *J. Climate*, *10*, 223–244.

Horel, J. H., and J. M. Wallace (1981), Planetary scale atmospheric phenomenon associated with the Southern Oscillation, *Mon. Weather Rev.*, *109*, 813–829.

Hoskins, B. J., and D. J. Karoly (1981), The steady linear response of a spherical atmosphere to thermal and orographic forcing, *J. Atmos. Sci.*, *38*, 1179–1196.

Jones, C. (2000), Occurrence of extreme precipitation events in California and relationships with the Madden-Julian Oscillation, *J. Climate*, *13*, 3576–3587.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Madden, R. A., and P. R. Julian (1994), Observations of the 40–50 day tropical oscillation—A review, *Mon. Wea. Rev.*, *122*, 814–837.

Maloney, E. D., and D. L. Hartmann (1998), Frictional moisture convergence in a composite life cycle of the Madden-Julian oscillation, *J. Climate*, *11*, 2387–2407.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Mo, K. C., and R. W. Higgins (1998), Tropical convection and precipitation regimes in the western United States, *J. Climate*, *11*, 2404–2423.

Overland, J. E., J. M. Adams, and N. A. Bond (1997), Regional variation of winter temperatures in the Arctic, *J. Climate*, *10*(5), 821–837.

Papineau, J. M. (2001), Wintertime temperature anomalies in Alaska correlated with ENSO and PDO, *Int. J. Climatol.*, *21*, 1577–1592.

Quadrelli, R., and J. M. Wallace (2002), Dependence of the structure of the Northern Hemisphere annular mode on the polarity of ENSO, *Geophys. Res. Lett.*, *29*(23), doi:10.1029/2002GL015807.

Razuvaev, V. N., E. G. Apasova, and R. A. Martuganov (1993), Temperature and precipitation data for 223 USSR stations, ORNL/DCIAC-56, NDP-040, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Schubert, S. D., and C.-K. Park (1991), Low-frequency intraseasonal tropical extratropical interactions, *J. Atmos. Sci.*, *48*, 629–650.

Shinoda, T., H. H. Hendon, and J. Glick (1998), Intraseasonal variability of surface fluxes and sea surface temperature in the tropical western Pacific and Indian Oceans, *J. Climate*, *11*, 1685–1702.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300.

Trenberth, K. E., and T. J. Hoar (1996), The 1990–1995 El Niño-Southern Oscillation event: Longest on record, *Geophys. Res. Lett.*, *23*(1), 57–60.

Waliser, D. E., K. M. Lau, W. Stern, and C. Jones (2003), Potential predictability of the Madden-Julian Oscillation, *Bull. Am. Meteorol. Soc.*, *84*(1), 33–50.

N. A. Bond and G. A. Vecchi, Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, WA 98115, USA. (nicholas.a.bond@noaa.gov; gabriel.a.vecchi@noaa.gov)