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Importance of cold and dry surges in substantiating the NAM and ENSO relationship

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[1] We propose a possible mechanism for the influence of the Northern Hemisphere annular mode/Arctic Oscillation (NAM/AO) on westerly wind bursts (WWB). Using 26-year reanalysis data, we statistically demonstrate and evidentially confirm that the NAM intensifies WWB through Asian cold and dry surges. Twin cyclones with anomalous westerlies and updrafts were dominant in the western tropical Pacific in positive NAM years. This structure was caused by the inflow of cold and dry advections associated with cold and dry surges, which excited anomalous heat transport from the western tropical Pacific Ocean. This thermodynamic structure is similar to that of the Matsuno-Gill pattern. Observational evidence indicates that the surge associated with the NAM is a probable cause of El Niño outbreaks through the intensification of WWB, stemming from the WWB association with the Matsuno-Gill pattern. **Citation:** Nakamura, T., Y. Tachibana, and H. Shimoda (2007), Importance of cold and dry surges in substantiating the NAM and ENSO relationship, *Geophys. Res. Lett.*, *34*, L22703, doi:10.1029/2007GL031220.

1. Introduction

[2] The Northern Hemisphere annular mode/Arctic Oscillation (NAM/AO) and El Niño/Southern Oscillation (ENSO) play major roles in mid-latitude climates. Anomalous amplifications of the NAM result in unusual weather and climate in winter [*Xie et al.*, 1999; *Thompson and Wallace*, 2001] and summer [*Ogi et al.*, 2004]. For example, the disastrously hot 2003 European summer can be explained by the occurrence of an anomalous positive NAM phase [*Ogi et al.*, 2005]. Previously, both El Niño and anomalous NAM amplifications were thought to occur independently, with no significant correlation between them on an interannual timescale. Until recently, no studies had established a NAM influence on ENSO. *Nakamura et al.* [2006] demonstrated that NAM in early spring modulates the westerly wind burst (WWB) in the western equatorial Pacific, using both observational evidence and an atmospheric general circulation model. WWB is known to be a trigger for El Niño outbreaks. *Nakamura et al.* [2006] also showed that an anomalous positive NAM phase results in the emergence of El Niño in the following winter, thus suggesting that the NAM is a predictor of El Niño outbreaks. However it has not yet been demonstrated that the NAM causes El Niño.

[3] This study proposes a possible mechanism of NAM influence on WWB. Previous studies have suggested that the mid-latitudes exert an influence on the tropics. For example, *Chang et al.* [2005] demonstrated the influence of cold surges from East Asia on tropical circulations. A cold surge over the tropical Pacific may excite anomalous atmospheric heating from the warmer ocean below, leading to increased convective cloud activity. Meanwhile, the occurrence of the cold surge from East Asia could be related to NAM variation, as the NAM governs the Asian winter monsoon [*Gong et al.*, 2001; *Jeong and Ho*, 2005]. For that reason, we hypothesize that an anomalous NAM influences the Asian cold surge toward the tropics and that the surge strengthens atmospheric heating in the tropics through increased air-sea interaction. Furthermore, anomalous atmospheric heating over the western tropical Pacific induces the WWB by exciting an equatorial wave. Thus, the cold surge acts as a messenger from the NAM to ENSO.

[4] We used statistical analyses of a reanalysis data set to substantiate our hypothesis. In particular, we used a tropical atmospheric heat and moisture budget analysis to focus on the relationship between the NAM and the Asian cold surge and its thermodynamic influences on the WWB.

2. Data and Methods

[5] We used the NAM index defined by *Ogi et al.* [2004] as an indicator representing NAM fluctuation on an interannual timescale. The atmospheric data set was the National Center for Environmental Predictions (NCEP)/Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP)-II Reanalysis [*Kanamitsu et al.*, 2002], with a 26-year period (1979–2004).

[6] To examine the tropical atmospheric heat budget, we adopted the method described by *Yanai et al.* [1973] and obtained apparent heat sources (Q1) and moisture sinks (Q2) as residual terms of the thermodynamic equation calculated by using 6-hourly data. The vertical integration of Q1–Q2 is closely equivalent to sensible and latent heat fluxes from the surface (ocean or land) to the atmosphere. Monthly averaged values for each year and their deviation from the climatological mean were also calculated.

[7] The data, including Q1, Q2, and the NAM index, were filtered using the band-pass filter adopted by *Nakamura et al.* [2006], which passes the ENSO cycle timescale. The time series was advance-averaged for two successive months to exclude the influence of the timescale related to the Madden-Julian Oscillation (MJO), which may affect the NAM. For example, *Zhou and Miller* [2005] pointed the influence of the MJO on the NAM in the boreal winter. Because of the usage of 2-month averaged data, the MJO-related tropical influence upon the NAM is filtered out in this study. From

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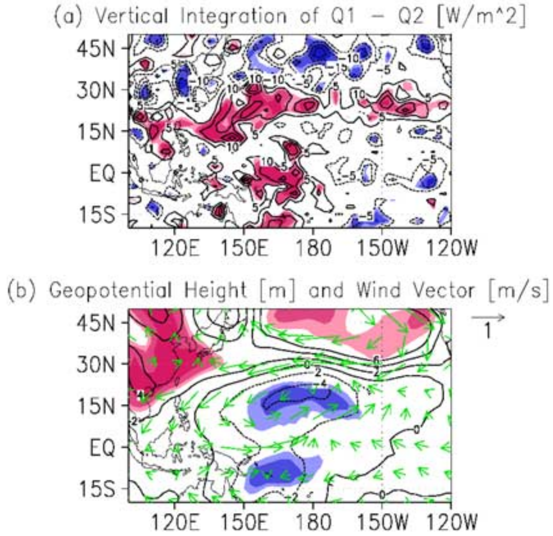

Figure 1. (a) Regression coefficients of vertically integrated Q1−Q2 upon the NAM index in spring. The vertical integration is executed by from 1000- to 200-hPa. Contours correspond to a local change in the Q1−Q2 when the NAM increases by its unit standard deviation. Contour lines are −20, −15, −10, −5, 5, 10, 15, and 20 [W/m^2]. Red (blue) shadings indicate positive (negative) correlations. Light, moderate, and heavy shadings indicate significant at 90, 95, and 99% confidence levels, respectively. (b) As in Figure 1a except for the geopotential heights at 925-hPa and contour lines are −4, −2, 2, 4, and 6 [m]. Green arrows indicate horizontal wind vectors regressed upon the spring NAM index. A length of the arrow corresponding with a unit wind speed [m/s] is shown at the upper right of the figure.

the 2-month averaged data, a 5-year moving average of each 2-month average was subtracted to exclude long-term variations. We used the filtered NAM index and field data to perform regression and correlation analyses. The filtered NAM index can be regarded as independent because the one-year lagged autocorrelation coefficient of the filtered NAM index was less than 0.3, indicating that the interactive contribution between the two time series was less than 10%. Therefore, the statistical significance of the correlations was evaluated using 22 degrees of freedom. All of the figures shown in this study are of spring (March–April mean), because the spring NAM is strongly related to WWB [*Nakamura et al.*, 2006].

[8] We calculated the monthly mean frequency fields of cold and dry surges and their interannual variations. Following *Jeong and Ho* [2005], we defined a cold surge as a period when the decrease in anomalous temperature and the magnitude of the anomalous northerly wind both exceed one standard deviation. We based standard deviation calculations on the deviations from the climatological mean of each time. Using the 6-hour resolution reanalysis data, we calculated the number of times the cold surge occurred in spring and the interannual variation in the spring mean frequency of cold-surge occurrence at each grid point. The same method used for calculation of the cold surge was applied to calculating the frequency of dry-surge occurrence, but using specific humidity. Composite analyses were then executed to examine the influence of the NAM on cold and dry surges.

[9] All of our figures illustrate patterns associated with the positive phase of the NAM as defined by *Thompson and Wallace* [1998], i.e., the presence of both a lower pressure in the Arctic area and a higher pressure in the mid-latitude area.

3. Results

[10] Figure 1a shows the regression coefficients of the vertical integrations of Q1−Q2 onto the spring NAM index, Figure 1b shows the regression coefficients of geopotential heights at 925-hPa with horizontal wind vectors onto the spring NAM index. The Figure 1a indicates that the equatorial atmosphere gains anomalous heat from the ocean in the tropical region between 150° and 180°E (hereafter referred to as the WWB region) when the spring NAM is in positive phase. Twin cyclones, i.e., two low-pressure anomalies, locate to the north and to the south of the WWB region as shown in Figure 1b. In the negative NAM condition, the heat and pressure anomalies are reversed, as shown in the linear regression analysis. These NAM signatures in the tropics are very similar to the well-known pattern of the tropical stationary Rossby atmospheric response to equatorial heat sources. Thus, the heat source induces westerlies in the lower equatorial atmosphere between the twin cyclones. The horizontal wind pattern with twin cyclones shown in Figure 1b indicates anomalous westerlies over the equator. This wind pattern corresponds well with the vertical cross-section of equatorial westerly anomalies shown by *Nakamura et al.* [2006, Figure 2]. There is no evidence for anomalous sea surface temperatures (SSTs) in regions of significant Q1-Q2 anomaly (figures not shown). Thus, local SST is not responsible for the formation of the anomalous atmospheric heating.

[11] The relationship between the NAM and heat and moisture advection was calculated. Figure 2a shows the regression coefficients of the meridional potential temperature advections at 925-hPa upon the spring NAM index. Figure 2b shows those of the meridional moisture advections. Cold and dry advections cover the western Pacific from 10° to 30°N. Figures 2c and 2d show vertical advections for the heat and moisture at 500-hPa. Significant cold and moist vertical advection anomalies are seen in the WWB region. The horizontal cold and dry advections are attributed to northerly wind over the region of climatologically large meridional temperature and moisture gradients. The cold and moist vertical advections in the WWB region are attributed to anomalous upward vertical motion. These results imply that, when the spring NAM is in positive phase, continental cold and dry air originating from East Asia could gain heat and moisture from the ocean.

[12] We also examined the relationship between the NAM and cold and dry surges from East Asia. Figure 3 exhibits the differences in cold and dry surge frequencies between anomalous positive NAM years and anomalous negative NAM years. In the western Pacific region from 10° to 30°N, cold and dry surges occurred more frequently in positive than in negative NAM phases. Therefore, the

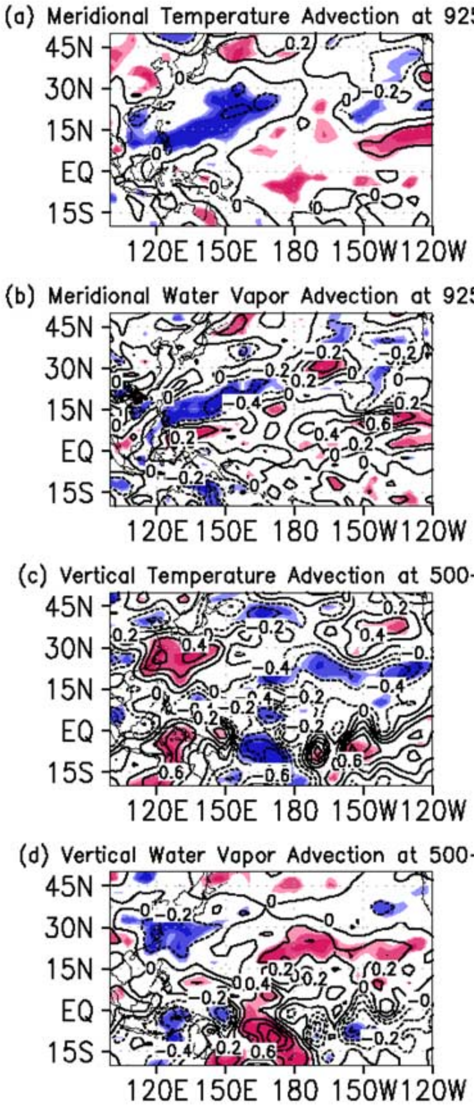

Figure 2. (a) As in Figure 1a except for the meridional advections of the potential temperature at 925-hPa and contour lines are from −1.0 to 1.0 with 0.2 [K/day] intervals. (b) As in Figure 2a except for the horizontal advection of the moisture. (c) As in Figure 2a except for the vertical advections of the potential temperature at 500-hPa. (d) As in Figure 2c except for vertical advection of the moisture. The unit of Figures 2b and 2d is changed to the heating rate of the condensation warming of the moisture.

anomalous NAM has an influence on the frequency of surge occurrence in the western tropical Pacific.

4. Discussion and Concluding Remarks

[13] We illustrated the influence of the spring NAM on WWB conditions. In the positive phase NAM, cold and dry surges tend to occur more frequently in low-latitude regions in the western Pacific. These regions correspond highly with those of significant cold and dry advection related to the NAM. Also the anomalies of vertical integrations of Q1−Q2 associated with the NAM are positive in these areas and in the WWB region. *Yanai et al.* [1973] showed that the vertically integrated Q1−Q2 can be an indicator of latent and sensible heat transport from the surface to the atmosphere. Thus, the tropical atmosphere gains anomalous heat from the ocean in positive NAM phase years. The surge associated with the NAM causes atmospheric heating, because the inflow of cold and dry air to the tropics causes large deviations in air-sea temperature and humidity differences. The geopotential height field indicates the presence of twin cyclones located north and south of the WWB region. In association with this geopotential pattern, significant westerly anomalies appear in the lower troposphere between the cyclones, where upward flows are also dominant. *Matsuno* [1966] and *Gill* [1980] showed that the generation of twin cyclones and westerlies with upward flows in the tropics is a stationary Rossby response of the tropical atmosphere to the equatorial heat source. This is referred to as the Matsuno-Gill pattern. The patterns demonstrated in this study are quite similar to those of the Matsuno-Gill pattern. *Lim and Chang* [1981] also proposed that Asian surges generated in mid-latitudes cause a tropical atmospheric response similar to the Matsuno-Gill pattern. The NAM-related surge is in accord with their suggestion. The NAM-related Matsuno-Gill-like pattern is not caused by tropical SST variations, but is dominated by atmospheric variations, as no significant correlations exist between the NAM and tropical SST. Consequently, the positive NAM

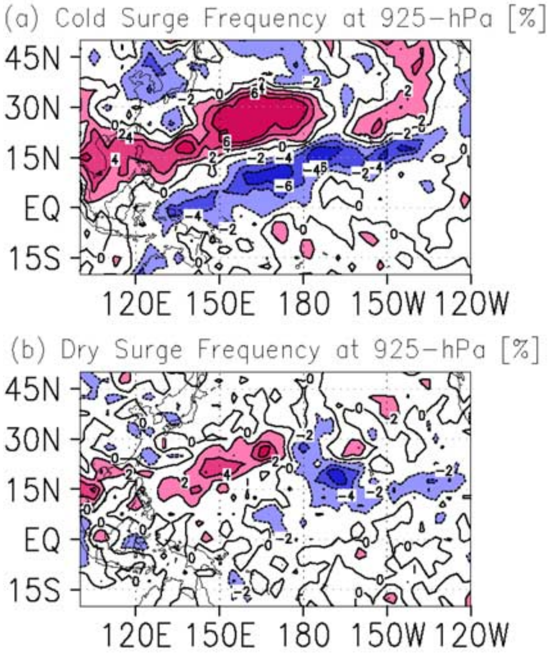

Figure 3. (a) Differences between the composite of frequencies of cold surge occurrence in the top 5 years of the positive NAM index (1982, 1986, 1990, 1994, and 1997) and those of the bottom 5 years of the negative NAM (1984, 1987, 1992, 1996, and 1999) in spring. Red (blue) shadings indicate that the surges occur more (less) frequently in the positive phase of the NAM than that of negative. Contour lines indicate −6, −4, −2, 0, 2, 4, and 6 [%] differences, respectively. (b) As in Figure 3a except for the dry surge occurrence.

intensifies the WWB by inducing a greater frequency of surge from Asia to the tropical Pacific than does the negative NAM.

[14] *Nakamura et al.* [2006] illustrated the presence of clear variations among the spring NAM, WWB, and an El Niño outbreak in the following winter. The WWB commonly serves as a trigger of ENSO [e.g., *Barnett*, 1983; *Luther et al.*, 1983; *Barnett et al.*, 1989]. *Bjerknes* [1969] pointed out the role of strong westerlies, such as the WWB, in inducing El Niño several months later through positive feedback of the air-sea interaction.

[15] We conclude that the NAM is a probable cause of El Niño outbreaks through the Asian cold and dry surges. The detailed process by which the NAM influences the surges, which may be related to the Asian monsoon, has yet to be described and will be pursued in forthcoming studies.

[16] A clearer understanding of NAM influence on ENSO may expand and deepen insight into the chaotic behavior of global climatic variability, such as regime shifts [*Minobe*, 1999; *Hare et al.*, 2000]. ENSO also influences mid- and high latitudes [e.g., *Kawamura*, 1998; *Kawamura et al.*, 2003]. The two-way interaction between the NAM and ENSO may be a cause of the chaos.

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