The summer northern annular mode and abnormal summer weather in 2003

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[1] The summer Northern Hemisphere annular mode (summer NAM), a new mode determined through empirical orthogonal function (EOF) analysis for each individual calendar month, can describe aspects of anomalous summers such as the summer of 2003, which featured warm temperatures in Europe, Canada and Russia and cold temperature in Japan. Atmospheric circulation anomalies of the summer NAM closely resemble the anomalies in the summer of 2003 and the summer NAM index was quite large during the period from mid-July to early August when abnormal weather took place in Europe, Canada and Russia. The index includes representations of hemispheric double-jet streams and blockings that support extended periods of abnormal weather. The double-jet is formed and maintained by wave forcing during the period. In contrast to the Arctic and North Atlantic oscillations, the summer NAM pattern accounts for many of the anomalous weather features observed during summer of 2003. **Citation:** Ogi, M., K. Yamazaki, and Y. Tachibana (2005), The summer northern annular mode and abnormal summer weather in 2003, *Geophys. Res. Lett.*, *32*, L04706, doi:10.1029/2004GL021528.

1. Introduction

[2] The northern mid-latitudes experienced abnormal weather in summer 2003. Summer temperatures in Europe were the highest of the past 500 years [*Luterbacher et al.*, 2004]. In Canada, the summer of 2003 was the fourth warmest of the 56-year record of countrywide measurements [*Levinson and Waple*, 2004]. Across most of Russia, above-normal temperatures were recorded in July 2003 and August 2003 was one of the warmest over Russia in the last 100 years [*Levinson and Waple*, 2004]. In contrast, summer temperatures in Japan were the coolest of the past ten years. It is important to understand and be able to forecast both summer and winter climates on a global scale. However, knowledge of summer extratropical planetary-scale atmospheric circulations is still scant.

[3] The Northern Hemisphere annular mode (NAM) is the leading mode in empirical orthogonal function (EOF) analysis of zonal-mean geopotential height field from the surface to 50 hPa in all the calendar months, and is characterized by a seesaw pattern in atmospheric mass between the mid- and high latitudes [*Limpasuvan and Hartmann*, 1999; *Thompson and Wallace*, 2000, 2001]. The NAM dominates atmospheric phenomena during the Northern Hemisphere winter and has a deep barotropic annular pattern [e.g., *Thompson and Wallace*, 2000]. The NAM is identical with the Arctic Oscillation (AO), which is the leading mode in EOF analysis of sea level pressure field during winter [*Thompson and Wallace*, 1998]. The time score of the NAM is referred to as the AO index [*Thompson and Wallace*, 1998].

[4] As atmospheric variability is largest in winter, the spatial pattern of the conventional NAM mostly reflects the one in the winter atmosphere, even if an EOF analysis is made in all calendar months. *Ogi et al.* [2004a] recently performed an EOF analysis for each individual calendar month and showed a large variation in the spatial pattern of the leading mode. The leading mode of the EOF in summer months, hereafter the summer northern annular mode (summer NAM), has a smaller meridional scale than the conventional NAM presented by *Thompson and Wallace* [2000]. In the troposphere, the summer NAM pattern shows negative heights over the Arctic Ocean and positive heights over the mid-latitudes, especially Europe, the Sea of Okhotsk–Bering Sea, and North America. Associated summertime low-level temperature anomalies show warm anomalies over mid-latitudes, especially Europe, the Sea of Okhotsk, and northern America, and cool anomalies over the Arctic Ocean.

[5] This paper examines anomalous summer weather in 2003 using the summer NAM and shows that the summer NAM explains the anomalous summer. In addition, this paper shows that neither the conventional NAM nor the North Atlantic oscillation (NAO) [*Hurrell*, 1995] explain the abnormal summer in 2003. Furthermore, neither ENSO nor the Indian dipole mode [e.g., *Saji et al.*, 1999] was abnormal in summer 2003. Thus, tropical phenomena alone did not cause the abnormal weather during this period.

2. Data

[6] *Ogi et al.* [2004a] determined the NAM using EOF analysis of the temporal covariance matrix separately for each calendar month. A zonally averaged monthly geopotential height field from 1000 hPa to 200 hPa and poleward of 40°N was used. The analysis was based on 45 years (1958–2002) of monthly-mean data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis [*Kalnay et al.*, 1996]. The time series of the new NAM was named the seasonally varying NAM (SV NAM) index [*Ogi et al.*, 2004a]. Spatial patterns and time series (1948–2002) of the SV NAM index are available on the web at http://wwwoa.ees.hokudai.ac.jp/svnam.

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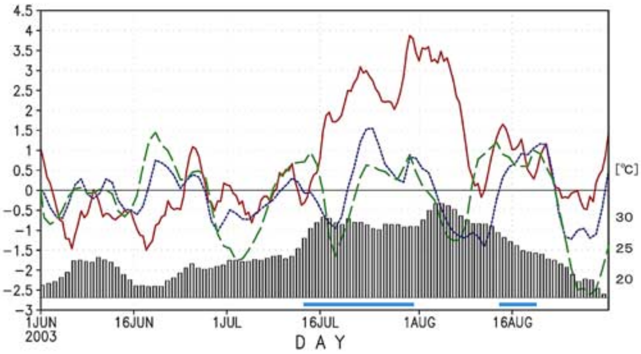

Figure 1. Daily time series of the summer NAM index from June through August 2003 (red line). Blue and green lines indicate daily time series of the AO and NAO indices, respectively. The bar graphs below the curves indicate the mean maximum temperatures in five cities in Europe: Paris, Moscow, Helsinki, Warsaw, and Vienna. The light blue lines below the bar graph indicate the period when the maximum temperature anomalies are below −3°C in Tokyo. Temperatures are smoothed with a 5-day running average.

[7] The summer NAM in this study is defined as the average of the leading EOF modes for summer months (June, July and August) for simplicity, since the individual EOF leading mode in a summer month is similar to each other. To calculate the daily time series of the summer NAM index in 2003, we use the daily grid point value (GPV) data issued by the Japan Meteorological Agency for atmospheric data in 2003. The daily time series of the summer NAM index in summer 2003 is calculated from the projection of daily zonal mean geopotential height anomalies onto the summer NAM by using the GPV data. Daily anomaly fields are departures from daily climatology, which is calculated from a linear interpolation of monthly climatologies. Daily anomaly fields in 2003 were derived from daily GPV data subtracted from daily NCEP climatology. The surface meteorological station data used in this study are available from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html). The AO/NAO index shown by blue/green lines in Figure 2 is available from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html).

3. Summer Atmospheric Pattern in 2003

[8] The summer atmospheric pattern of 2003 was clearly dominated by the summer NAM. Time series in Figure 1 include the summer NAM index in 2003 (the red line). The index shows small negative values through late June, and then becomes positive and fluctuates with small amplitudes until mid-July. In mid-July, the index abruptly increases and large positive indices exceeding 2 persist until early August. The index peaks in late July with a value near 4. The extremely high values persist for at least two weeks concomitant with disastrously hot weather in Europe and cool weather in Japan.

[9] In contrast, neither the AO index (the blue line in Figure 1) nor the NAO index (the green line) indicate the anomalous weather of summer 2003. The AO/NAO index fluctuated around zero from June through August 2003. No significant change occurs in these indices between mid-July and the beginning of August, when the summer NAM index abruptly increases.

[10] The horizontal anomaly structure of the 500-hPa geopotential height field when the summer NAM index is large, between mid-July and mid-August 2003, shows a north–south seesaw pattern (Figure 2a). An area of negative anomalies is centered over the Arctic Ocean; positive anomalies were present in the subarctic, especially over northwestern Eurasia, the northern Sea of Okhotsk, and Canada. The blocking signatures are apparent in northeastern Europe and the northern Sea of Okhotsk (circles in Figure 2a). Warm temperature anomalies (Figure 2b) are consistent with the positive geopotential height anomalies (Figure 2a). Temperature anomalies over northwestern Eurasia, northeastern Siberia, and Canada during the period exceeded 3 K. The summer atmospheric pattern in 2003 is quite similar to the summer NAM pattern [see *Ogi et al.*, 2004a, Figures 2 and 10]. On the other hand, the traditional NAM pattern exhibits a larger meridional scale than the summer NAM pattern. Because of this spatial difference, the original AO index cannot exhibit an anomalous summer annular pattern as occurred in 2003.

[11] In a large positive phase of the summer NAM, a double-jet structure appears in the upper troposphere [*Ogi et al.*, 2004a]. The double jet, two separate polar and subtropical jet streams, tends to cause atmospheric blocking that stops the eastward propagation of cyclones and anticyclones and therefore supports long-lasting weather anomalies [*Maeda et al.*, 2000]. In normal summers, the high-latitude polar jet is much weaker than the lower-latitude subtropical jet. In early and mid-June when the summer NAM index is small and negative, the high-latitude jet is absent, and the zonal-mean zonal wind shows a single jet structure (Figure 3a). However, when the summer NAM index is positive, the geopotential height gradient along the coast of the Arctic Ocean is large, implying an enhancement of westerly winds at high latitudes. In fact, a high-latitude westerly jet is present in the zonal-mean zonal wind map (Figure 3b) when the summer NAM index is large. The subtropical jet in summer shifts its position poleward from its winter position, and the positive summer NAM is characterized by a prominent double-jet structure. The prominent double-jet structure in 2003 resembles an objectively presented zonal-mean zonal wind pattern when the summer NAM index is +3 [see *Ogi et al.*, 2004a, Figure 7].

[12] The zonal-mean zonal wind associated with the winter NAM is maintained by interactions between zonal wind and waves, such as planetary-scale Rossby waves and baroclinic waves. [*Limpasuvan and Hartmann*, 1999, 2000; *Yamazaki and Shinya*, 1999; *Kimoto et al.*, 2001]. The zonal-mean zonal wind associated with the summer NAM is also maintained by the waves. The Eliassen-Palm (EP) flux with the transformed Eulerian mean formulation is widely used in dynamic meteorology to diagnose such a wave and zonal-mean flow interaction. Arrows in Figure 3 represent the EP flux and show propagation of wave activity [*Andrews and McIntyre*, 1976]. EP flux divergence indicates acceleration of the zonal-mean zonal wind due to waves, i.e., wave forcing. When the summer NAM is negative (Figure 3a), waves are generated from a broad latitude zone (50–70°N) in the lower troposphere and

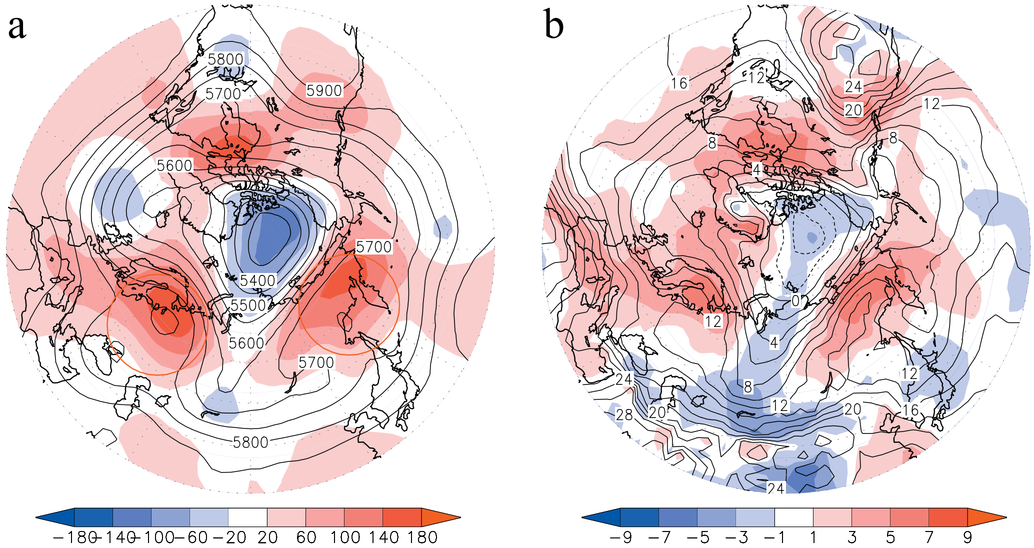

Figure 2. (a) 500-hPa geopotential height and (b) 850-hPa temperature anomalies for 17 July–6 August 2003. Shading denotes anomalies and contours are values. The positions of the blocking are marked with red circles.

propagate both equatorward and poleward in the upper troposphere. EP flux converges in the high-latitude upper troposphere where the jet is decelerated there and the wave activity maintains a single-jet structure centered at 45°N. In contrast, when the summer NAM is positive (Figure 3b), waves are mostly generated from high latitudes (60–70°N) and propagate only equatorward in the upper troposphere. The EP flux divergence between 65–80°N in the upper troposphere changed from large negative values (Figure 3a) to near-zero values (Figure 3b). This change is consistent with less deceleration in the westerly wind in that area. Large EP flux convergence is present at 50–60°N in the upper troposphere. This meridional difference in the EP flux divergence enables the double-jet structure to persist. The EP flux consists of vertical (eddy heat flux) and meridional (eddy momentum flux) components. Decomposition of the EP flux divergence (wave forcing) into the two components reveals that the meridional component mainly produces the difference in the wave forcing in the middle and upper troposphere between the two periods (figures not shown).

[13] We also examined the onset of the double-jet in mid-July. The EP flux changed its direction equatorward in high-latitudes during the onset period. The double-jet structure was generated by the wave forcing, mainly its meridional component, while the Coriolis force due to the residual meridional flow tended to compensate the generation of the double-jet (Figure 4). The extreme positive phase of the summer NAM of the summer 2003 was formed and maintained by the wave forcing, particularly by the convergence of the eddy momentum flux. This result is consistent with *Ogi et al.* [2004a].

[14] The horizontal structure of the double jet can be inferred from the 500-hPa geopotential heights (contours in Figure 2a). The meandering polar jet surrounding the Arctic Ocean is separated from the subtropical jet at around 45°N. Blocking associated with warm weather is obvious in

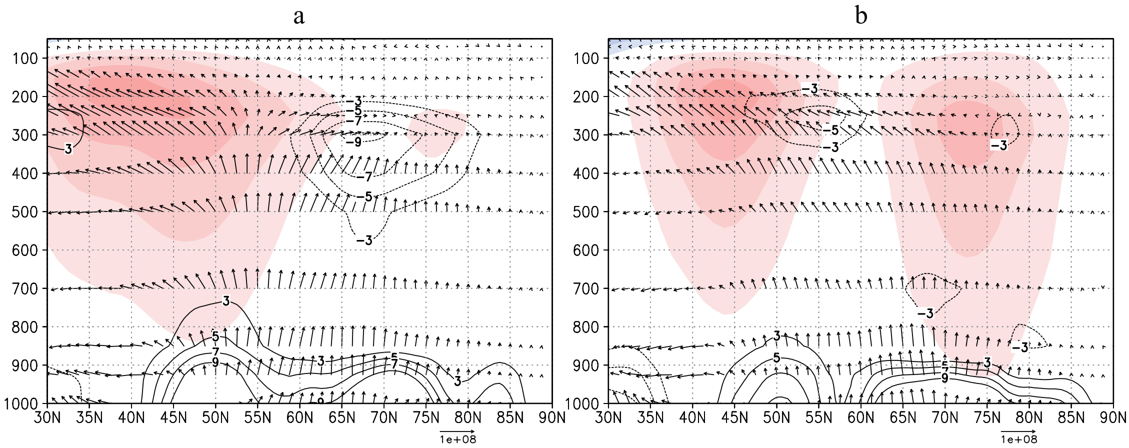

Figure 3. Zonal-mean zonal wind for (a) 3–23 June (a negative summer NAM index period from in Figure 2), and (b) 17 July–6 August (an extreme positive summer NAM index period from in Figure 2.) 2003. Shading indicates wind speeds (5, 10, 15, 20 m/s). Contours denote wave forcing, i.e., EP flux divergence. Contour intervals are 2 m/s/day (±9, ±7, ±5, ±3). Vectors are the Eliassen-Palm flux. The reference arrow for the EP flux vector of 1×10^8 (Kg/s^2) is shown at the bottom. The vertical length of the arrow is 100 times larger than its horizontal length.

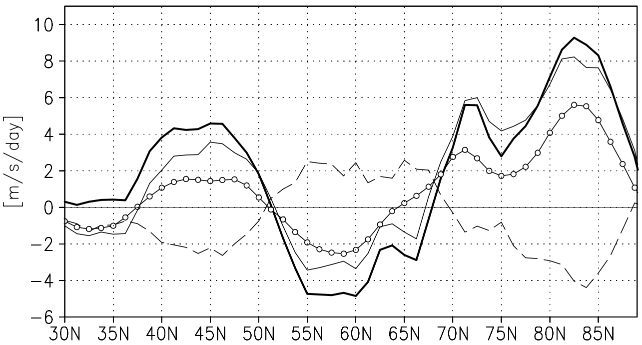

Figure 4. EP flux divergence (thick solid line), its meridional component (thin solid line), Coriolis acceleration due to residual meridional wind (dashed line) and observed zonal-mean zonal wind change (solid line with circles) for 200–500 hPa layer during the period from 00 UTC 15 July to 00 UTC 17 July 2003.

northeast Europe. In addition, a strong subtropical high extends northeastward from Africa toward northeast Europe. The strong subtropical high and blocking caused the extremely hot summer in Europe. Rossby waves propagated eastward from this blocking region and forced another blocking in far eastern Siberia (Figure 2a) [*Ogi et al.*, 2004b; *Tachibana et al.*, 2004; *Nakamura and Fukamachi*, 2004]. A surface anticyclone, the Okhotsk high [*Ninomiya and Mizuno*, 1985; *Kodama*, 1997], developed below the upper-level blocking in eastern Siberia. The high supported cold air advection toward Japan from the Okhotsk and Bering seas and brought about cool summer in Japan.

4. Conclusions and Discussion

[15] Abnormal weather in the summer of 2003 was not restricted to Europe, but rather occurred hemispherically and was diagnosed by an abnormally high value of the summer NAM index. The resemblance between the summer 2003 and summer NAM patterns suggests that the 2003 pattern was not abnormal. However, its amplitude was abnormally large; values were four standard deviations from the mean. Recently *Levinson and Waple* [2004] suggested that the East Atlantic (EA) pattern is an explanatory pattern of anomalous weather in Europe. Although the EA pattern can capture the regional anomalous weather in Europe, none of anomalous weathers in Canada, Russia and Japan can be represented by the EA pattern. The summer NAM, however, can account for much of the anomalous weather for the hemispheric.

[16] The summer NAM index shows a significant increasing trend of 0.36/decade from 1958 to 2002, which might relate to the winter NAM trend [*Thompson et al.*, 2000] and global warming. European summer temperatures have also shown a significant increasing trend in the past three decades and heat waves tend to occur frequently [*Schar et al.*, 2004; *Beniston*, 2004]. If this trend continues, hot summer weathers in Europe, Canada and Russia as in 2003, may occur more frequently and occasional cool summers in Japan despite global warming. The summer NAM may hold a key to understanding anomalous extra-tropical summer variations such as occurred in 2003.

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