Possible mechanism of abrupt jump in winter surface air temperature in the late 1980s over the Northern Hemisphere

Yeong-Hee Kim1, Maeng-Ki Kim2, William K. M. Lau3, Kyu-Myong Kim4, and Chun-Ho Cho5

1School of Environmental Science and Engineering, Pohang University of Science and Technology, Pohang, South Korea, 2Department of Atmospheric Science, Kongju National University, Gongju, South Korea, 3Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA, 4Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, 5National Institute of Meteorological Sciences, Seogwipo, South Korea

Abstract Possible cause of an abrupt warming in winter mean surface air temperature in the midlatitudes of the Northern Hemisphere in the late 1980s is investigated using observation and reanalysis data. To determine the timing of abrupt warming, we use a regime shift index based on detection of the largest significant differences between the mean values of two contiguous periods. Results show that the abrupt warming occurred in association with a regime shift after the 1980s in which the zonal mean sea level pressure (SLP) is significantly increased (decreased) at the latitude 25–35°N (60–70°N), in the form of north-south dipole-like SLP anomaly spanning the subtropics and high latitude. The dipole SLP anomaly can be attributed to a northward expansion of Hadley cell, a poleward broadening and intensification of the Ferrel cell, coupled with a collapse of polar cell. During the abrupt warming, strong anomalous southerly warm advection at the surface was induced by an enhanced and expanded Ferrel circulation, in association with a northward and downward shift of maximum center of northward eddy heat flux over the midlatitudes. An intensification of polar jet subsequent to regime shift may be instrumental in sustaining the warming up to more than 5 years.

1. Introduction

The Earth’s climate system is characterized by interannual variation as well as long-term variations with decadal or interdecadal time scales. Long-term variations that have a step function-like abrupt change are often referred to as “climate regime shifts” or “climate transitions,” defined as rapid reorganizations of climate systems from one relatively stable state to another.

Many previous studies have argued that an abrupt winter climate change occurred in the Northern Hemisphere in the late 1980s based on several lines of evidence: a significant decrease in the Arctic sea level pressure (Walsh et al., 1996), a reduction of the extent of sea ice in the southern Okhotsk Sea (Tachibana et al., 1996), an intensification of upper air polar vortex (Tanaka et al., 1996), a decrease of Aleutian Low central pressure (Overland et al., 1999), a decadal-scale shift in atmospheric circulation (Watanabe and Nitta, 1999), a weakening in the East Asia winter monsoon (Jhun and Lee, 2004), changes of warmer winter sea surface temperature in the northern North Pacific (Xiao and Li, 2007), a decrease of snow days in Swiss (Marty, 2008), a change of the propagation of quasi-stationary planetary waves (Wang et al., 2009), and climate transition of the sea surface temperature (SST) in the North Pacific (Yeh et al., 2011).

Although several hypotheses have been proposed to explain the regime shift in the late 1980s, including the connection of Arctic Oscillation (Comiso, 2003; Jhun and Lee, 2004; Lo and Hsu, 2010) and even the transition from a solar dimming to a solar brightening climate (Norris and Wild, 2007), and independency from tropical variations (Yasunaka and Hanawa, 2003), and wave pattern connected to equatorial Atlantic warming (Ye et al., 2015), the mechanism responsible for this regime shift is not fully understood. Yasunaka and Hanawa (2003) suggested that most of the regime shifts before the late 1970s were closely linked to tropical variation such as changes in the Niño 3.4 SST, while the late 1980s regime shift was independent of tropical variations.

Recently, Lo and Hsu (2010) suggested that the abrupt warming over the midlatitude was linked to the Pacific Decadal Oscillation-like pattern and Artic Oscillation-like pattern. Xiao et al. (2012) suggested that the decadal abrupt changes (DACs) in the 1980s of the Northern Hemisphere midlatitude SST were the possible origin of
the DACs of the northern extratropical ocean-atmosphere system in annual mean, stressing the decadal anomalies of the Ferrel cells and the meridional mass exchanges between the northern midlatitude and Arctic. Lee et al. [2013] suggested that the robust warming over the East Asia region is caused by changes in circulations over the North Pacific and Eurasian continent and anomalous warm advection over the East Asia region due to an enhanced North Pacific Oscillation-like sea level pressure pattern. Ye et al. [2015] showed that the surface warming over Eurasia in the 1980s is largely related to the change in the atmospheric circulation which linked to the wave train originated from equatorial Atlantic warming and associated enhanced convection.

On the other hand, Li and Wang [2003] suggested that the Ferrel cell may play an important role in the basic physical processes of the Northern Hemisphere annular oscillations, because it contributes to the strong dynamic property of the general circulation in the middle-high latitudes, indicating that the Ferrel circulation is potentially important in modulating midlatitude and high-latitude climate [Chen et al., 2011]. However, the role of Ferrel cell is not fully explored in modulating the behavior of regime shifts over middle-higher latitudes, which is related to eddy activities over the midlatitude. In this study, we explored the intensification and expansion of the meridional circulation associated with the winter mean surface air temperature regime shift in the late 1980s. In addition, possible causes are discussed from several points of view based on the comparison between this result and previous results.

2. Data and Method

In this study we used monthly surface air data at observational stations obtained from the Goddard Institute for Space Studies Surface Temperature Analysis (GIlimP) (http://data.giss.nasa.gov/gistemp/station_data/). Data were recorded from observation stations in the cities of Seoul (127°E, 37.6°N), Tokyo (139.8°E, 35.7°N), and Beijing (116.3°E, 39.9°N). These cities are the capitals of South Korea, Japan, and China, respectively, which are located over East Asia. In this study, we used the global land surface monthly temperature data from the Climate Research Unit (CRU) analysis, which has a resolution of 0.5° × 0.5°, for 1901–2009 [Kistler et al., 2001]. In addition, we employed the monthly mean temperature, meridional wind, and sea level pressure (SLP) data from the National Centers for Environmental Prediction-National Center for Atmospheric Research Reanalysis 1 (NCEP R1), covering the years from 1948 to present [Kalnay et al., 1996]. The data set has a horizontal resolution of 2.5° × 2.5° and extends from 1000 to 10 hPa with 17 vertical pressure levels. We adopt NCEP R1 data from 1958 to 2011 because of the lack of upper air data observations during the earlier decade (1948–1957) [Kistler et al., 2001]. In this study winter means were constructed from the monthly means by averaging data for December, January, and February (DJF). Here the winter of 1986 refers to the 1986/1987 winter.

A variety of methodologies have been used to detect abrupt jump in climate variables [Rodionov, 2004; Kim et al., 2009]. In this study we adopt the regime detection algorithm designed by Rodionov [2004], which evaluates the difference between the mean values of two consecutive time periods of a given length. The method is based on the sequential application of the Student’s t test, as a function of two parameters: the probability level, p, and the cutoff length of the regime, l. This study sets the cutoff regime length (l) to 15 years and the probability level (p) to 0.1. Detection of a regime shift is based on the magnitude of the regime shift index (RSI), which is the cumulative sum of normalized anomalies of the time series values from the hypothetical mean level for the new regime. If the RSI remains positive or negative for all l years, a regime shift is declared. For more details on calculating the RSI, refer to Rodionov [2004, 2006].

The mean meridional circulation, which is composed of zonal mean meridional velocities (v), can be described by a mass stream function (MSF, $\Psi_M$), which is defined by integrating the northward mass flux above a particular pressure level, pl, as follows:

$$\Psi_M = \frac{2\pi a \cos \phi}{g} \int_0^{pl} [v] \, dp$$

(1)

Here $\phi$ is latitude and $g$ is acceleration of gravity. In this study in order to understand the regression relationship between meridional circulation and other variables, Hadley circulation index (HCI) is defined by the maximum value of $\Psi_M$ for Hadley cell. Similarly, Ferrell circulation index (FCI) is defined by negative maximum
value of $\Psi_M$ for the Ferrel cell. Note that a higher HCl signifies a stronger Hadley circulation while the larger negative FCI value, a stronger Ferrel circulation.

3. Results

3.1. Abrupt Jump of Winter Mean Surface Air Temperature

Application of the RSI algorithm to the observed winter mean surface air temperature data obtained from GISTEMP revealed that all three stations experienced an abrupt warming in the late 1980s, indicating a climate regime shift (Figure 1). In Seoul and Tokyo (Figures 1a and 1b), the abrupt temperature change appeared in 1986 with RSI values of 0.60 and 1.09, respectively. In Seoul, the mean temperature during the period before the regime shift was $\pm 2.0^\circ\text{C}$, while the mean temperature after the regime shift was $\pm 0.1^\circ\text{C}$. The temperature after the regime shift has never reached values lower than the long-term mean value before the regime shift ($\pm 2.0^\circ\text{C}$). This is also true for Tokyo, except that the temperature difference before and after the regime shift was of $1.3^\circ\text{C}$. In Beijing, the regime shift occurred in 1987, 1 year later than in Seoul and Tokyo. These results for the three observation stations indicate that the location of the abrupt warming may shift northward over time. To confirm the timing and the spatial range of the abrupt warming, we expanded the RSI algorithm analysis to the Northern Hemisphere.

Figure 2 shows the spatial distribution of the regime shift years in the 1980s over the Northern Hemisphere based on CRU land surface temperature data. The abrupt warming was evident in East Asia, Europe, and the...
southeastern U.S. in the late 1980s. The abrupt warming occurred mainly in 1986 over East Asia, including the Korean Peninsula, Japan, and parts of China. In 1987, the abrupt warming was detected in northwestern regions of the European continent. The abrupt warming mainly appeared in eastern part of the European continent, northern China, and the southeastern part of U.S. in 1988. Over Eastern Asia, and eastern Eurasia, the abrupt warming appeared to start at midlatitudes in mid-1980’s over East Asia and moved to high latitudes in the late 1980’s. However, over Europe and western Eurasia, the abrupt change took place mostly around 1987–1988. Thus, the abrupt warming occurs over much larger scale. On the other hand, the region where the abrupt warming was observed in the late 1980s is consistent with that reported by Lo and Hsu [2010], although they did not focus on the location of specific regime shift years, gradual shift with time, and associated meridional circulation.

We found that the abrupt warming occurred over the middle and high latitude of the Eurasia mainly from 1986 to 1989 (Figure 2). As shown in Figure 1, after the abrupt jump, winter temperature did not come back to previous mean state for almost 20 years, implying that during the transition period (1986 to 1989) some important events occurred on much larger scale in the Northern Hemisphere. Thus, in this study we concentrated on the characteristics of the transition period. To compare this period with the before/after the transition period, we chose 1976–1985 as the reference period. We only considered the period of 10 years after 1976 as the reference period, because a significant climate regime shift occurred around 1976, as shown in Overland et al. [1999] and Wang et al. [2009]. In addition, we also investigated the long-term period (~2009) after the transition period in order to ascertain that the posttransition period is sustained over a longer period.

3.2. SLP and Meridional Circulation Change

Figure 3 shows the mean SLP difference between the transition period and the reference period. The difference patterns are generally characterized by a dipole structure with action centers over the midlatitude and high latitude. During the transition period, the SLP increased over midlatitude, especially in North Pacific.
Ocean and Mediterranean Sea and western Atlantic Ocean, while the SLP decreased over high latitude around North Pole, especially in Beaufort Sea and Greenland. In East Asia region, the high-pressure anomaly over subtropical Pacific and the low-pressure anomaly over Siberian region provide a favorable condition to increase anomalous southeasterlies which enhances warm advection to East Asia. As a result, the pressure gradient between Siberian High and Aleutian Low is weakened, leading to a reduction in frequency and intensity of cold wave in the East Asia. Note that the southwestern branch of Aleutian Low is significantly weakened and the center of Aleutian Low is shifted to the north during the transition period. These provide strong evidence that SLP dipole is closely related to the abrupt jump in winter surface temperature over East Asia, as shown in Figures 1 and 2.

Over the Atlantic, the Azores High is intensified and extended to the northwestern part of Atlantic Ocean during the transition period, while the Iceland low is strengthened and expended to the northwestern Atlantic. This configuration favors stronger southeasterly compared to the reference period, thereby providing an increased warm advection to North America region. Over the Europe, a regime shift is manifested in anomalous high pressure over the Mediterranean Sea and anomalous low pressure over the broadening area of high latitude to North Pole spanning the Greenland, Iceland, and the Scandinavian Peninsula. As shown in East Asia and eastern United States, spatial pattern of the location of temperature regime matches SLP anomaly pattern very well.

To clarify the relationship between SLP anomaly and pattern of abrupt warming, we have investigated the relationship for each year of transition period (not shown). Although the locations and intensities of SLP anomaly are somewhat different with each other, overall patterns with major action centers over the Pacific, Atlantic, and high latitude including North Pole are very similar, indicating that abrupt warming is consistent with associated significant SLP change during the transition period.

As shown in Figure 3, while the intensity of SLP anomaly is different, the sign of SLP anomaly is almost the same along with longitude, indicating that the SLP anomaly may be induced by global forcing. In order to verify this, we calculated mass stream function (MSF) using equation (1) based on the zonal mean meridional velocity. Figure 4a shows anomalous mass stream function (shading) for the transition period and climatological
MSF (contour) for the reference period. As classified by two contour lines of zero value which are located in 30°N and 60°N, three distinct cells, Hadley, Ferrel, and polar cells with the centers at 10°N, 47°N, and 70°N, respectively, are clearly depicted during the reference period (Figure 4a). During the transition period three pronounced MSF anomaly features stand out. The first, having two maximum positive anomalies over 20–25°N and 30–35°N, can be interpreted as the northward extension and strengthening of the descending branch of the Hadley cell over the subtropics. The second signals an enhancement and poleward expansion of the Ferrel cell with maximum negative anomalies over 45–50°N. The last represents a weakening and poleward shrinking of the polar cell.

During the transition period, the center of the Ferrel cell is strongly intensified, stretching over the entire troposphere over the latitude belts of 45–50°N. This feature of the of Ferrel cell is matched with the northward transport of eddy heat flux through the troposphere to the Arctic region (see discussion in section 3.3) and anomalous warm advection from the subtropics to higher latitude at the surface of the middle latitude. Thus, the abrupt warming is strongly associated with the intensification and northward expansion of Ferrel circulation. Northward expansion of thermally directly induced Hadley circulation also positively contributes to that of thermally indirectly induced Ferrel circulation, as shown in Figure 4a.

Figure 4b shows zonal mean SLP difference between the transition period and the reference period. The significant changes in SLP appear over the latitude between 20–40°N and 55–75°N. These regions correspond to the latitudes with enhanced descending motion and ascending motion during the transition period. Therefore, the intensification and northward expansion of the Ferrel cell induce the dipole SLP difference.
pattern between midlatitude and high latitude with a node at 50°N. The switching point at 50°N for the positive and negative SLP anomaly coincides roughly with the center location of the Ferrel cell. This suggests that the intensification of the Ferrel cell is responsible for the intensification of subtropical high and subpolar low, and thereby, this seesaw SLP anomaly pattern transports relatively more heat from the subtropics to higher latitude and subpolar region via the midlatitude, compared to the reference period. These two cell intensity changes reinforce descending motion over the latitude 30–40°N and ascending motion over the latitude 60–70°N (Figures 4a and 4b).

Figure 5. Latitude-height distribution of the difference in northward heat transport between transition period and the reference period. Green dots with different size indicate three levels of the significance.

### 3.3. Northward Movement of Polar Jet and Associated Eddy Activities

Figure 5 shows spatial pattern of zonal mean temperature and zonal mean zonal wind change in the Northern Hemisphere. The most significant change in zonal mean temperature occurred in the large vertical
range from the middle to the upper layer in the troposphere and the latitude range from 30°N to 45°N with the maximum value at 40°N, which is corresponding to anomalous boundary between Hadley cell and Ferrell cell indicating that adiabatic warming induced by anomalous downward motion may be responsible for the atmospheric warming. In subtropical region, adiabatic warming can be the strongest because air is relatively dry and anomalous downward motion is strong. On the other hand, surface warming occurred over 50°N, at a higher latitude than the center of atmospheric warming. The zonal mean surface warming is related to anomalous warm advection originated from the intensification of Ferrell cell and its northward expansion (see Figure 4). This is consistent with Tandon et al. [2013], Ceppi et al. [2014], and Garfinkel and Wauch [2014], which showed that atmospheric warming over the midlatitude can play an important role in driving the poleward jet movement in response to climate change. Figure 5b shows that during the transition period, the zonal mean polar jet becomes stronger over around 50°N while subtropical jet becomes weaker over around 25°N compared to the reference period. This is consistent with the thermal wind relationship, as shown in Figures 5a and 5b. The northward movement of polar jet after the regime shift can block the invasion of cold air from the polar region and confine cold air to the polar region. This means that winter mean temperature over midlatitude, especially 40–60°N latitude band, is increased and the frequency of cold wave may possibly be reduced.

To further explore the relationship between HC, FC, and zonal mean temperature, we calculated the correlation map between the two variables for the various time periods (1958–1985, 1975–1985, and 1986–2009). Figure 6 shows correlation pattern of HCl and −FCI with zonal mean temperature and zonal wind during the period (1986–2009) after abrupt jump in order to see the consistent persistence of the relationship. Correlation pattern of −FCI with zonal mean temperature (Figure 6b) and zonal wind (Figure 6d) resembles spatial pattern of zonal mean temperature and zonal wind anomaly between the transition period and the reference period (Figures 5a and 5b), indicating that the intensity of FC is directly responsible for atmospheric warming over the latitude belts of 30–50°N. However, contrary to our expectations, correlation pattern with
HCI with zonal mean temperature shows that atmospheric warming along with strong HC appears over the tropics and the latitude band of 50°–70°N while atmospheric warming does not appear over the latitude band of 30°–50°N. This suggests that the zonal temperature anomaly over the midlatitude is not directly associated with variability of Hadley circulation. However, this does not necessarily mean that abrupt jump is not related.

Figure 7. Latitude-height distribution of the difference in (a) total, (b) stationary, and (c) transient eddy heat flux between transition period and the reference period. Green dots with different size indicate three levels of the significance.
to changes in the intensity of Hadley circulation. As shown in Figure 5, the center position of FC is not changed after abrupt jump in spite of the intensification and the northward expansion of FC, while the center position of HC is shifted to northward and the intensity is strengthened. Thus, the FCI represents the intensity of FC very well, but the HCI is influenced not only by the intensity but also by the north expansion of HC. In fact, regression pattern of the latitude of boundary at 500 hPa between HC and FC with the zonal mean temperature shows strong atmospheric warming signals (over at least 5% of significant level) especially 700–200 hPa around 40°N of the center along with an increase of boundary latitude between HC and FC (not shown). This is corresponding to the northward movement of the northern boundary of HC (see Figure 4a). Thus, the relation between HC and zonal mean temperature anomaly is influenced due to the northward expansion of HC, but not the intensity changes of the HC, suggesting that the HC is indirectly related to FC and thereby influence on the zonal mean temperature anomaly.

Figure 7a shows that total eddy heat flux is clearly changed with a decrease over the north of subtropical region, an increase at the surface in the higher latitude of 45–65°N, and an increase around 80°N of the polar region. The structure of total eddy heat flux change is strongly related to the atmospheric stability which can be deduced from vertical structure of temperature. The vertical temperature change over the subtropical region of 30–40°N (Figure 5a) shows that the middle and lower troposphere is stabilized after the regime shift while upper troposphere became unstable, and thereby an increase of eddy heat flux in the upper troposphere and a decrease of eddy heat flux in the lower troposphere. Over the high latitude (45–65°N) north of 40°N, eddy heat flux is significantly increased at the surface. The increase of eddy heat flux is likely due to a decrease of static stability over the region which is mainly due to surface warming, as shown in Figure 5a. The anomaly pattern of eddy heat flux shows that the center of eddy activities has migrated to the northward and downward compared to climatological action center over 50°N (Figure 7a), suggesting that the eddy activities became more active at the surface of the higher latitude than the reference period. The increase of eddy heat flux over the middle to high latitude means that excess heat transported to the polar region by eddy activities and thereby can have impact on the surface condition over the polar region. The persistence of northward transport of eddy heat flux should have an influence on the sea ice melting over the polar region for a long time since the regime shift. Spatial pattern of total eddy heat flux is mostly similar to that of stationary eddy heat flux, as shown in Figures 7a and 7b. However, the role of transient eddy heat flux over the polar region around 80°N is comparable with or more important than that of stationary eddy heat flux (Figure 7c). It should be noted that total eddy heat flux over the polar region is significantly changed both at the surface and in the atmosphere, while both stationary and transient eddy heat fluxes are significantly changed only at the surface, not in the atmosphere. These indicate that both transient and stationary components are important for transporting heat to the polar region through midlatitude eddy activities.

In wave-zonal flow interaction view, the FC is forced by poleward transport of eddy flux and coupled to zonal mean zonal wind and temperature [Holton and Hakim, 2012]. Since in quasi-geostrophic frame stream function $\Psi$ in the midlatitude is propositional to second derivative of heat flux $\left(\partial^2 v^* T^*/\partial y^2\right)$, the sign of $\Psi$ is negative in the midlatitude where eddy heat flux is largest at low levels as shown in Figure 7 (contour), indicating indirect Ferrel circulation. Thus, large decrease (increase) in the southward (northward) of the center with maximum heat flux is corresponding to the northward shrinking (expansion) of southern (northern) boundary of Ferrel circulation, which is consistent with the northward expansion of Hadley (Ferrel) circulation as shown in Figure 4. After all, the intensification of the FC and the associated northward heat transport to the high latitude at the lower troposphere during the transition period clearly contribute to surface warming over the high latitude and the Arctic region.

4. Conclusion and Discussions

In this study, we analyze the characteristics of the abrupt jump in winter mean surface air temperature over the Northern Hemisphere in the late 1980s using observation data and reanalysis data and investigate the possible mechanism of the abrupt warming with a focus on mean meridional circulation, particularly Ferrel cell. To detect the timing of abrupt warming, we adopt a regime shift index which is based on determining the significance of differences between the mean values of two consecutive time periods of a given length. Results show that the abrupt warming mainly occurred over three regions, East Asia, Europe, and the southeastern part of North America during the transition period (1986–1989) compared to the reference period.
(1976–1985). The abrupt warming jump is strongly associated with enhanced warm advection induced by SLP dipole anomaly pattern with enhanced north-south pressure gradient between the subtropics and higher latitude. The SLP dipole anomaly is significantly related to the intensification and northward expansion of the Ferrel cell and partly to the northward broadening of Hadley cell and the weakening of polar cell. Furthermore, the analysis shows that the intensification of Ferrel cell induces a stronger polar jet by increasing middle-upper troposphere warming over the subpolar and thereby inducing positive north-south temperature gradient. The intensification of polar jet during the transition period and during the long-term posttransition period is responsible for sustaining the prevailing climatic state. During the transition period, the center of eddy activities migrated northward and downward compared to climatological center over 50°N, indicating that the eddy activities became more active at the surface of the higher latitude than the reference period. The increase of eddy heat flux over the middle to high latitude means that additional heat transported to the high latitude and polar region by eddy activities and may have an impact on the surface condition over the regions, i.e., snow melting. The persistence of northward transport of eddy heat flux is likely to have an influence on the sea ice melting over the polar region for a long time and play an important role in sustaining the regime shift.

As a possible interpretation on the cause of abrupt jump, we suggest that both the weakening of the polar cell due to warming of the northern high latitude [Liu et al., 2007] and poleward expansion of the Hadley cell under global warming [Hu and Fu, 2007; Lu et al., 2007] may provide the Ferrel cell with favorable condition for the intensification and poleward extension during winter season. Another strong possibility is that the abrupt jump may be strongly linked to abrupt reduction in snow water equivalent which is induced by land-atmosphere interaction spanning from middle latitude and high latitude, especially over snow/ice surface during winter season.

In this work, we did not address the issue regarding whether or not the change in regional dynamics can be associated with global warming. For that purpose, we need to carry out global warming experiments with climate models and/or analyze outputs CMIP5 models under different warming scenarios.

Acknowledgments
The authors thank the Physical Science Division (PSD) for providing the NCEP Reanalysis I data from their website https://www.esrl.noaa.gov/psd/. Sergei N. Rodionov for providing RSI tool from the website http://www.climatologic.com/home, and the Climate Research Unit (CRU) for providing global land surface monthly temperature data from the website www.cru.uea.ac.uk/data. This research is supported by a project “NIMR-2012-B-2 (Development and application of methodology for climate change prediction)”. This work was partially supported by the Strategic Science Investment fund at NASA Goddard Space Flight Center and the Modeling Analysis and Prediction program of NASA Headquarters. Partial support was also provided by the DOE/PNNL grant 4331620 to ESSIC, University of Maryland.

References
Ceppi, P., M. D. Zelinka, and D. L. Hartmann (2014), The response of the Southern Hemispheric eddy-driven jet to future changes in shortwave radiation in CMIP5, Geophys. Res. Lett., 41, 3244–3250, doi:10.1002/2014GL060043.

Chen, L., M. Song, and J. Liu (2011), Ferrel Circulation variability and in the Southern Hemisphere and its linkages with tropical and subtropical sea surface temperature, J. Geophys. Res., 116, D12106, doi:10.1029/2010JD015409.

Comiso, J. C. (2003), Warming trends in the Arctic form clear sky satellite observations, J. Clim., 16, 3498–3510.

Garfinkel, C. I., and D. W. Wauch (2014), Tropospheric Rossby wave breaking and variability of the latitude of the eddy-driven jet, J. Clim., 27, 7069–7085, doi:10.1175/JCLI-D-14-00081.1.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister (2014), Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 dataset, Int. J. Climatol., 34(3), 623–642, doi:10.1002/joc.3711.

Holton, J. R., and G. J. Hakim (2012), An Introduction to Dynamic Meteorology, 5th ed., 552 pp., Academic Press, San Diego, Calif.

Hu, Y., and Q. Fu (2007), Observed poleward expansion of the Hadley circulation since 1979, Atmos. Chem. Phys., 7, 5229–5236, doi:10.5194/acp-7-5229-2007.

Jhun, J. G., and E. J. Lee (2004), A new East Asian winter monsoon index and associated characteristics of the winter monsoon, J. Clim., 17(4), 711–726.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, Bull. Am. Meteorol. Soc., 77, 437–471.

Kim, C., M.-S. Suh, and K.-O. Hong (2009), Bayesian changepoint analysis of the annual maximum of daily and subdaily precipitation over South Korea, J. Clim., 22, 6741–6757, doi:10.1175/2009JCLI2800.1.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, Bull. Am. Meteorol. Soc., 82, 247–267.

Lee, S.-S., S.-H. Kim, J.-G. Kim, K.-J. Ha, and Y.-W. Seo (2013), Robust warming over East Asia during the boreal winter monsoon and its possible causes, Environ. Res. Lett., 8, 1–6, doi:10.1088/1748-9326/8/3/034001.

Li, J., and J. X. L. Wang (2003), A modified eddy zonal index and its physical sense, J. Geophys. Res., 108(D23), 4150, doi:10.1029/2002JD003164.

Liu, J., J. A. Curry, Y. Dai, and R. Horton (2007), Causes of the northern high-latitude land surface winter climate, Geophys. Res. Lett., 34, L14702, doi:10.1029/2007GL030196.

Lo, T. T., and H. H. Hsu (2010), Change in the dominant decadal patterns and the late 1980s abrupt warming in the extratropical Northern Hemisphere, Atmos. Sci. Lett., 11(3), 210–215, doi:10.1002/asl.275.

Lu, J., G. Vecchi, and T. Rechich (2007), Expansion of the Hadley cell under global warming, Geophys. Res. Lett., 34, L06805, doi:10.1029/2006GL028443.

Marcy, C. (2008), Regime shift of snow days in Switzerland, Geophys. Res. Lett., 35, L12501, doi:10.1029/2008GL033998.

Norris, J. R., and M. Wild (2007), Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar “dimming” and solar “brightening”, J. Geophys. Res., 112, D08214, doi:10.1029/2006JD007794.

Overland, J. E., J. M. Adams, and N. A. Bond (1999), Decadal variability of the Aleutian Low and its relation to high-latitude circulation, J. Clim., 12(5), 1542–1548.

Rodionov, S. N. (2004), A sequential algorithm for testing climate regime shifts, Geophys. Res. Lett., 31, L09204, doi:10.1029/2004GL019448.

Rodionov, S. N. (2006), The use of prewhitening in climate regime shift detection, Geophys. Res. Lett., 33, L12707, doi:10.1029/2006GL025904.
Tachibana, Y., M. Honda, and K. Takeuchi (1996), The abrupt decrease of the sea ice over the southern part of the Sea of Okhotsk in 1989 and its relation to the recent weakening of the Aleutian Low, *J. Meteorol. Soc. Jpn.*, 74(4), 579–584.

Tanaka, H. L., R. Kanohgi, and T. Yasunari (1996), Recent abrupt intensification of the northern polar vertex since 1988, *J. Meteorol. Soc. Jpn.*, 74(5), 947–954.

Tandon, N. F., E. P. Gerber, A. H. Sobel, and L. M. Polvani (2013), Understanding Hadley cell expansion versus contraction: Insights from simplified models and implications for recent observations, *J. Clim.*, 26, 4304–4321, doi:10.1175/JCLI-D-12-00598.1.

Walsh, J. E., W. L. Chapman, and T. L. Shy (1996), Recent decrease of sea level pressure in the central Arctic, *J. Clim.*, 9(2), 480–486.

Wang, L., R. Huang, L. Gu, W. Chen, and L. Kang (2009), Interdecadal variations of the East Asian winter monsoon and their association with quasi-stationary planetary wave activity, *J. Clim.*, 22, 4860–4872, doi:10.1175/2009JCLI2973.1.

Watanabe, M., and T. Nitta (1999), Decadal changes in the atmospheric circulation and associated surface climate variations in the Northern Hemisphere winter, *J. Clim.*, 12(2), 494–510.

Xiao, D. and J. P. Li (2007) Main decadal abrupt changes and decadal modes in global sea surface temperature field [in Chinese], *Chin. J. Atmos. Sci.*, 31(5), 839–854.

Xiao, D., J. Li, and P. Zhao (2012), Four-dimensional structures and physical process of the decadal abrupt changes of the northern extratropical ocean-atmosphere system in the 1980s, *Int. J. Climatol.*, 32(7), 983–994, doi:10.1002/joc.2326.

Yasunaka, S., and K. Hanawa (2003), Regime shifts in the Northern Hemisphere SST field: Revisited in relation to tropical variations, *J. Meteorol. Soc. Jpn.*, 81(2), 415–424.

Ye, K., R. Wu, and Y. Liu (2015), Interdecadal change of Eurasian snow, surface temperature, and atmospheric circulation in the late 1980s, *J. Geophys. Res. Atmos.*, 120, 2738–2753, doi:10.1002/2015JD023148.

Yeh, S. W., Y. J. Kang, Y. Noh, and A. J. Miller (2011), The North Pacific climate transitions of the winters of 1976/77 and 1988/89, *J. Clim.*, 24(4), 1170–1183, doi:10.1175/2010JCLI3325.1.