Summer Arctic Cold Anomaly Dynamically Linked to East Asian Heat Waves

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(Manuscript received 12 June 2018, in final form 3 December 2018)

ABSTRACT

During recent years, the rapidly warming Arctic and its impact on winter weather and climate variability in the mid- and low latitudes have been the focus of many research efforts. In contrast, anomalous cool Arctic summers and their impacts on the large-scale circulation have received little attention. In this study, we use atmospheric reanalysis data to reveal a dominant pattern of summer 1000–500-hPa thickness variability north of 30°N and its association with East Asian heat waves. It is found that the second thickness pattern exhibits strong interannual variability but does not exhibit any trend. Spatially, the positive phase of the second thickness pattern corresponds with significant Arctic cold anomalies in the mid- and low troposphere, which are surrounded by warm anomalies outside the Arctic. This pattern is the thermodynamic expression of the leading pattern of upper-tropospheric westerly variability and significantly correlated with the frequency of East Asian heat waves. The Arctic has experienced frequent summer cold anomalies since 2005, accompanied by strengthened tropospheric westerly winds over most of the Arctic and weakened westerlies over the mid- and low latitudes of Asia. The former significantly enhances baroclinicity over the Arctic, which dynamically contributes to increased frequency of anomalous low surface pressure during summer along with decreased frequency over high latitudes of Eurasia and North America. The latter is exhibited by sustained high pressure anomalies in the mid- and low troposphere that dynamically facilitate the occurrence of East Asian heat waves. A systematic northward shift of Asian zonal winds dynamically links Arctic cold anomalies with East Asian heat waves and produces a seesaw structure in zonal wind anomalies over the Arctic and the Tibetan Plateau (the third pole). Evidence suggests that enhanced Arctic westerlies may provide a precursor to improve predictions of the East Asian winter monsoon, though the mechanism for this lag association is unclear.

1. Introduction

Over the past two decades, Arctic warming and Arctic sea ice loss are among the most remarkable signals of change in the climate system and have received a great deal of attention, particularly in summer. The Arctic dipole anomaly, Arctic anticyclonic surface wind anomalies, enhanced downwelling longwave radiation, and increased Atlantic and Pacific water inflow are believed to contribute to Arctic sea ice loss (Shimada et al. 2006; Wang et al. 2009; Ogi et al. 2010; Polyakov et al. 2010; Overland et al. 2012; Wu et al. 2012; Ding et al. 2017). Observations and model simulations demonstrate that anomalies in Arctic sea ice and atmospheric circulation affect summer atmospheric circulation variability over Eurasia (Wu et al. 2009, 2013; Screen 2013). Arctic sea ice loss would reduce (enhance) summer precipitation over the mid- and high latitudes of East Asia (northern Europe) (Wu et al. 2013; Screen 2013). However, what dominant features of summer Arctic temperature variability in the mid- and low troposphere that closely relate to atmospheric variability in the mid- and low latitudes of East Asia remain unclear.

Summer high temperature and heat waves have frequently occurred worldwide since the beginning of the 2000s, and they directly caused a high fatality and produced widespread economic impacts (Meehl and Tebaldi 2004; Barriopedro et al. 2011; Bador et al. 2017). Compared with 1991–2000, casualties related with high temperature and heat waves increased by more than...
2000% in 2001–10 (WMO 2013). East Asia has experienced frequent heat waves since the 1990s (Ding et al. 2010). The well-documented example is the East Asian heat waves of 2013 (Min et al. 2014; Imada et al. 2014; Zhou et al. 2014). South Korea had its hottest summer nights and second hottest summer days since 1954 (Min et al. 2014), and China suffered the strongest heat wave since 1951 (Zhou et al. 2014). Anthropogenic global warming generally has been shown to increase the likelihood of summer heat waves over East Asia (Sun et al. 2014; Min et al. 2014; Coumou et al. 2014, 2015; Mann et al. 2017). Additionally, sea surface temperature (SST) anomalies, Arctic sea ice loss/snow cover melting, and precipitation anomalies in India and the South China Sea also contribute to East Asian summer high temperature and heat waves (Hu et al. 2011; Sun 2014; Min et al. 2014; Imada et al. 2014; Tang et al. 2014; Liu et al. 2015). Sun (2014) proposed that SST over the mid–North Atlantic in July 2013 was the warmest in the past 160 years, which connects to weakening of the East

**FIG. 1.** The first two patterns of summer (JJA) 1000–500-hPa thickness variability north of 30°N. (a) Normalized PC time series (red: PC1; blue: PC2), the red dashed line represents a linear trend in PC1, and the blue dashed line indicates the mean of PC2 averaged over 2007–12. (b) Summer 1000–500-hPa thickness anomalies, derived from a linear regression on the normalized detrended PC1, the white and black contours represent thickness anomalies at 95% and 99% confidence levels, respectively. (c) As in (b), but for the regression on the normalized PC2. (d)–(f) Summer 1000–500-hPa thickness anomalies (relative to the mean averaged over 1979–2016) in (d) 2006, (e) 2013, and (f) 2016. The first two patterns, respectively, account for 29% and 10% of the variance.
Asian upper-level westerly and strengthening of the northwest Pacific subtropical high (NWPSH) through a teleconnection wave train. This contributes to surface air temperature variability and heat waves over the Jianghuai–Jiangnan region of China. More direct causes can be attributed to sustained high pressure systems, particularly the NWPSH (Wang et al. 2013; Sun 2014; Imada et al. 2014; Wang et al. 2017; Freychet et al. 2017; Gao et al. 2018). It is not clear whether simultaneous Arctic atmospheric circulation anomalies during summer are linked to summer heat waves in East Asia, and this is the question explored in this study. We use National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data to identify dominant patterns of summer (JJA) atmospheric thickness (1000–500 hPa) variability north of 30°N and demonstrate the association between summer Arctic cold anomalies and East Asian heat waves.

2. Data and methods

Atmospheric data used in this study include monthly mean sea level pressure (SLP), winds, and geopotential heights from January 1979 to December 2016, and daily surface air temperatures (SATs), SLP, air temperatures, and winds at 17 pressure levels from 1 January 1979 to 31 December 2016. Data were obtained from the NCEP–NCAR Reanalysis-I (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1), with a
horizontal resolution of $2.5^\circ \times 2.5^\circ$ and 17 pressure levels (1000–10 hPa) in the vertical direction. Daily SATs are used to calculate the frequency of summer (June–August) extreme heat wave events, identified when daily SATs are above 1 standard deviation for a given date and location (note similar results were obtained using a 1.5-standard-deviation threshold). Similarly, daily SLP data are used to assess the frequency of summer anomalous low pressure when daily SLP is below $-1.5$ standard deviations for a given date and location.

This study uses NWPSH indices, which include intensity, ridge location, and western ridge point, obtained from National Climate Center (China; http://cmdp.ncc-cma.net/Monitoring/cn_index_130.php). The NWPSH intensity index is defined as the sum of the grid area with a geopotential height $5880$ gpm multiplied by the difference between the geopotential height ($5880$ gpm) minus $5870$ gpm within $10^\circ$–$60^\circ$N and $110^\circ$–$180^\circ$E. The NWPSH ridge location is defined as the average of the latitudes at each longitude where zonal wind $u = 0.0$ and $\partial u / \partial y > 0.0$ at $500$ hPa within $10^\circ$–$60^\circ$N and $110^\circ$–$150^\circ$E. The NWPSH western ridge point is defined as the westernmost location of the isoline with $5880$ gpm within $10^\circ$–$60^\circ$N and $90^\circ$E–$180^\circ$. This study also uses the monthly mean Arctic Oscillation (AO) index for the period from 1979 to 2016 (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao_index.b50.current.ascii).

We use summer mean 1000–500-hPa atmospheric thickness to approximately represent a vertically averaged air temperature in the mid- and lower troposphere. The empirical orthogonal function (EOF) analysis method is applied to extract the first two dominant patterns of summer mean 1000–500-hPa atmospheric thickness variability north of $30^\circ$N for the period 1979–2016. The first two patterns account for 29% and 10% of the variance. Similarly, EOF analysis is also used to analyze the leading pattern of summer 300 hPa zonal wind variability north of $20^\circ$N, which accounts for 14% of the variance.

The maximum Eady growth rate (EGR) relates baroclinic instability to the vertical wind shear (Vallis 2006; Simmonds and Lim 2009), characterizing the conduciveness of the environment to synoptic development (Crawford and Serreze 2016). EGR $\sigma_E$ is given by

$$\sigma_E = 0.3098 \left| \frac{f}{N} \frac{\partial U}{\partial z} \right|,$$

where $f$ is the Coriolis parameter, $U$ is the vertical profile of the daily zonal wind, $z$ is the vertical coordinate, and
$N$ is the Brunt–Väisälä frequency $[N^2 = (g/\theta)(\partial\theta/\partial z)]$, where $g$ is acceleration due to gravity, and $\theta$ is potential temperature. For EGR at 600 hPa, the vertical profiles of $\theta$ are calculated as differences between their daily values at 500 and 700 hPa. The vertical shear of $U$ is calculated in terms of the daily meridional temperature gradient using the thermal wind equation.

3. Results

a. Atmospheric thickness variability and Arctic cold anomaly

SATs are generally used to characterize Arctic warming and Arctic amplification. Because SATs are strongly influenced by sea ice concentrations and SST, however, differences in SATs between the Arctic and mid-latitudes may exaggerate the thermal contrast of the column in the mid- and lower troposphere (Sellevold et al. 2016; Wu 2017). This study uses the summer 1000–500-hPa thickness to represent the mean temperature in the mid- and lower troposphere (Overland and Wang 2010; Francis and Vavrus 2015), and its first two dominant patterns are shown in Figs. 1a–1c. The leading pattern displays strong interannual variability superposed on...
an interdecadal shift, that is, from frequent negative phases prior to 1998 to more frequent highly positive phases afterward (Fig. 1a). According to the Student’s t test, the significance of the shift exceeds the 99% confidence level. Spatially, positive thickness anomalies cover much of the domain north of 30°N, particularly over the Arctic, Eurasia, and North America where significant positive anomalies are observed (Fig. 1b). This interdecadal shift is generally consistent with changes in surface wind variability over the Arctic Ocean in both spring [April–June (AMJ)] and summer [July–September (JAS)]: An anomalous cyclone prevailed prior to the late 1990s, which was replaced by an anomalous anticyclone over the Arctic Ocean in later years (Wu et al. 2012). This interdecadal shift is consistent with the
rapid declining trend in September sea ice extent. Thus, this leading pattern is closely associated with both summer Arctic warming and sea ice loss.

Here we focus primarily on the second thickness pattern because it is associated with summer high temperatures and heat waves in Asia and North America. This pattern displays strong interannual variability but does not exhibit any trend or shift (Fig. 1a). Spatially (Fig. 1c), negative thickness anomalies are observed in the Arctic north of 70°N, indicating Arctic cold anomalies in the mid- and low troposphere. Positive thickness anomalies appear mainly over northern Europe, northeastern Atlantic, western North America, the Bering Sea, north-central Canada, and mid- and low latitudes of East Asia. Over the eastern Pacific–North America and northern Pacific–East Asia, positive anomalies form a “comma” structure, which is associated with the upper-tropospheric steering flow anomalies (see the following section). All extreme positive anomalies occurred after 2005, that is, 2006, 2013, and 2016, with values exceeding 1.5σ, corresponding with Arctic cold anomalies (Figs. 1d–f). The negative phases of the second principal component (PC2) dominated during 2007–12, implying summer Arctic warm anomalies (Fig. 1c), consistent with the well-documented rapid Arctic sea ice loss period. Years exhibiting summer Arctic cold anomalies seem to be become more frequent in the context of Arctic warming. It should be pointed out that two thickness patterns are independent from each other and the leading thickness pattern cannot obscure the expression of the second thickness pattern. Additionally, although summer 500-hPa height anomalies exhibit a great similarity to 1000–500-hPa thickness anomalies (Figs. 1c, 2), differences are also visible, including extents and amplitudes of positive and negative anomalies.

b. Dynamic linkages between Arctic cold anomalies and East Asian heat waves

Significant correlations between the leading thickness pattern and frequency of summer heat waves are mainly confined to near the Ural Mountains (40°–60°N, 40°–80°E), North America, and the Arctic, rather than over East Asia (not shown). Cold anomalies are also observed over near Alaska, but they are not significant (Fig. 1b). This study, therefore, focuses on the second thickness pattern. The positive phase of PC2 correlates significantly with heat waves over the mid- and low latitudes of Asia, particularly over the Tibetan Plateau (the third pole) and the coast of East Asia (Fig. 3a). Significant correlations also exist over most of Europe, northern Canada, southwestern United States, and northern North Pacific Ocean. Decreased heat waves are observed over the Arctic Ocean, consistent with
Arctic cold anomalies (Fig. 1c). Thus, a dipole structure is apparent between the Arctic and several midlatitude continental areas, particularly with the third pole. Over East Asia, the regionally (25.71°–39.05°N, 80.625°–135°E) averaged frequency of summer heat waves exhibits an increasing trend at the 99% confidence level (Fig. 3b). The frequency of East Asian heat waves exceeded 1.0σ in 1994, 2001, 2006, 2010, 2013, and 2016 (Fig. 3b). Consequently, East Asian heat waves frequently occurred after 2005. It should be pointed out that if the criterion for heat waves is instead defined as ≥1.5 standard deviations, very similar results are obtained (not shown).

Why do Arctic cold anomalies correspond with more intense and frequent summer heat waves in the mid- and low latitudes of East Asia? We find that this association
is closely related to the large-scale upper-tropospheric zonal wind variability. The positive phase of the second thickness pattern significantly strengthens upper-tropospheric westerlies over most of the Arctic (Fig. 4a), while over Eurasia, wind anomalies display a belt structure with significantly weaker westerlies in the mid- and low latitudes of Asia and Europe. This wind pattern closely resembles the leading pattern of summer 300 hPa zonal wind variability north of 20°N (not shown; $r = 0.81$; Fig. 4b). The area-weighted, regionally averaged 300 hPa westerly north of 70°N (Arctic westerly index) is also significantly correlated with the second thickness pattern ($r = 0.88$; Fig. 4c). In the upper troposphere, Arctic westerly strength is out of phase with that in the mid- and low latitudes of Asia. The normalized Arctic westerly indices exceeded 1.5σ in 2006, 2013, and 2016, corresponding with strong East Asian heat waves (Fig. 3b). Over the mid- and low latitudes of Asia, weakened upper-tropospheric steering flow (Fig. 4d) favors the stagnation of air masses and dynamically contributes to sustained high pressure anomalies in the mid- and low latitudes of Asia. The normalized Arctic westerly indices exceeded 1.5σ in 2006, 2013, and 2016, corresponding with strong East Asian heat waves (Fig. 3b). Over the mid- and low latitudes of Asia, weakened upper-tropospheric steering flow (Fig. 4d) favors the stagnation of air masses and dynamically contributes to sustained high pressure anomalies in the mid- and low latitudes of Asia. The normalized Arctic westerly indices exceeded 1.5σ in 2006, 2013, and 2016, corresponding with strong East Asian heat waves (Fig. 3b). Over the mid- and low latitudes of Asia, weakened upper-tropospheric steering flow (Fig. 4d) favors the stagnation of air masses and dynamically contributes to sustained high pressure anomalies in the mid- and low latitudes of Asia. The normalized Arctic westerly indices exceeded 1.5σ in 2006, 2013, and 2016, corresponding with strong East Asian heat waves (Fig. 3b). Over the mid- and low latitudes of Asia, weakened upper-tropospheric steering flow (Fig. 4d) favors the stagnation of air masses and dynamically contributes to sustained high pressure anomalies in the mid- and low latitudes of Asia. The normalized Arctic westerly indices exceeded 1.5σ in 2006, 2013, and 2016, corresponding with strong East Asian heat waves (Fig. 3b). Over the mid- and low latitudes of Asia, weakened upper-tropospheric steering flow (Fig. 4d) favors the stagnation of air masses and dynamically contributes to sustained high pressure anomalies in the mid- and low latitudes of Asia. The normalized Arctic westerly indices exceeded 1.5σ in 2006, 2013, and 2016, corresponding with strong East Asian heat waves (Fig. 3b). Over the mid- and low latitudes of Asia, weakened upper-tropospheric steering flow (Fig. 4d) favors the stagnation of air masses and dynamically contributes to sustained high pressure anomalies in the mid- and low latitudes of Asia.

Positive Arctic westerly anomalies are not confined to the upper troposphere; they are evident throughout the troposphere and stratosphere (Fig. 5). Negative westerly anomalies in the mid- and low latitudes also penetrate through the troposphere and stratosphere. Such a change is attributed to a systematic northward shift of zonal winds, dominantly characterized by a shift of the East Asian westerly jet. In fact, the Eurasian westerly jet systematically migrates northward (Fig. 4a). Additionally, a dipole structure in zonal wind anomalies is also observed over the Arctic and the third pole (Figs. 4a,d, 5), similar to the pattern in temperature anomalies discussed previously. Over the Arctic, negative temperature anomalies are completely confined to below 300 hPa and the top level of the stratosphere, with positive temperature anomalies between them (Fig. 6). Tropospheric temperature anomalies in the mid- and low latitudes are in phase with Arctic temperature anomalies in the upper troposphere and much of stratosphere. Strengthening of tropospheric westerly winds may enhance baroclinicity in the mid- and low troposphere, which dynamically favors the occurrence of anomalous low pressure during summer. Figure 7 supports this deduction. We find that significant increases in baroclinicity are observed over the Arctic Ocean, surrounded by negative anomalies outside the Arctic (Fig. 7a). Decreases in baroclinicity emerge over high latitudes of Eurasia and North America, northern North Pacific, and East Asia, generally consistent with warm areas shown in Figs. 1c and 3a. Significant increases in the frequency of anomalous low pressure are confined to the Arctic Ocean and northern North Atlantic, while negative anomalies cover most of Eurasia and North America (Fig. 7b). Over high latitudes of the continents, decreases in the frequency of anomalous low pressure may imply that thermal exchanges between the Arctic Ocean and lower latitudes weaken. It should be noted that if the threshold used to define anomalous low pressure is set to below $-1.0$ or $-2.0$ standard deviations in
daily SLP anomalies, very similar results are obtained (not shown).

4. Discussion

a. Roles of NWPSH in East Asian heat waves

Although the NWPSH is believed to contribute to East Asian heat waves (Luo and Lau 2017; Gao et al. 2018), some major characteristics of this subtropical high, including intensity and location, are not significantly correlated with the second thickness pattern or with the Arctic westerly index. We find that correlation coefficients of the second thickness pattern with the NWPSH intensity, ridge location, and western ridge point indices are 0.07, −0.09, and −0.24, respectively. While East Asia experienced abnormal high temperature and heat waves in 2013, the NWPSH was in a neutral phase (Fig. 8). The statistical association between the NWPSH and heat waves also differs from that in Fig. 3a (not shown). Thus, increasingly frequent East Asian heat waves cannot be simply attributed to the NWPSH.

b. Possible dynamic processes linking Arctic cold anomalies

We assess the statistical relationship between summer Arctic cold anomalies in the mid- and low troposphere
and East Asian heat waves. As previously noted, we find strengthened westerly winds in the Arctic along with weakened zonal winds in the mid- and low latitudes of East Asia, which we attribute to a systematic northward shift of the zonal wind belts. The present study, however, cannot identify the mechanism responsible for this shift nor for the temporal/spatial behavior of the second thickness pattern. It is possible that natural variability may be a major reason for recent changes in this pattern.

Here we carry out the case analysis of summer 2013 (Fig. 1) to explore possible reasons for summer Arctic cold anomalies in terms of wave-flow interactions at 500 hPa:

\[
\frac{\partial \theta}{\partial t} = - \nabla \cdot \mathbf{v} \theta - \frac{\partial \theta}{\partial p} \nabla - \nabla \cdot \mathbf{v} \nabla - \frac{\partial \theta}{\partial p} + \mathbf{F},
\]

where \( \theta \) is potential temperature, \( \mathbf{v} \) is horizontal wind vector, and \( \mathbf{F} \) is the forcing term (Hoskins and Pearce...
The overbar and prime denote time mean and transient eddy terms, respectively. For this case, the time mean is defined as the mean over 2013 JJA (92 days), and the transient eddy is obtained by subtracting the time mean for a given date and location. Summer 500 hPa temperature anomalies are shown in Fig. 9; the spatial pattern closely resembles the thickness anomaly pattern shown in Fig. 1e. Negative anomalies are confined to the Arctic, surrounded by positive anomalies to the south. Summer 500 hPa potential temperature anomalies closely resemble that in Fig. 9 (not shown). We then calculated the contributions of each term \[-\mathbf{\nabla} \cdot \mathbf{\nabla} \theta, -\overline{\mathbf{\omega}} (\partial \theta / \partial p), -\nabla \cdot \mathbf{\nabla} \theta, -\partial \theta / \partial p\] to the mean potential temperature tendencies (Fig. 10). We find that both positive and negative contributions from each term occur simultaneously in the Arctic, and negative contributions mean that both mean potential temperature advection by the mean flow as well as transient eddy flux divergence contribute to summer Arctic cold anomalies. Compared to the transient eddy flux divergence, the vertical advection of mean potential temperature plays a more important role in driving Arctic cold anomalies. Over the mid- and low latitudes of Asia and northwestern Pacific, negative vertical advections are predominant except for central and eastern China where the vertical advection is positive, contributing to increases in mean potential temperature (Figs. 6, 9). The summer mean vertical velocities at 500 hPa during 2013 (Fig. 11) suggest that vertical motions dominate the contribution of vertical advection of mean temperature (Fig. 10b). We repeat the same analysis process for 2006 and 2016 summers, producing similar results (not shown). This implies that Arctic upward motion in the mid- and low troposphere is a major reason for summer Arctic cold anomalies. Ogi et al. (2004) investigated summer annual mode and its association with anomalies in zonal mean temperature and meridional circulation and found that summer Arctic cold anomalies in the mid- and low troposphere correspond to upward motion anomalies (see their Fig. 3d), consistent with results here. Although anomalous atmospheric circulation patterns discussed by Ogi et al. (2004) exhibit some similarities to the second thickness pattern, their differences are robust (Fig. 12). We also note that downward and upward motions coexist simultaneously over the Arctic (Fig. 11) and their roles are opposite.

c. Precursor to predict East Asian winter monsoon

Finally, we find that the strengthened summer Arctic westerly is significantly correlated with the ensuing Asian winter climate variability (Fig. 13). The correlation between the Arctic westerly index and the winter Siberian high index is \(-0.59\), significant at 99% confidence level (Fig. 13a). At 500 hPa, geopotential height anomalies exhibit a tripole structure, and the positive height anomalies cover East Asia, indicating a weakened east trough (Fig. 13b). This configuration resembles the so-called Eurasian pattern (Wallace and Gutzler 1981; Wang and Zhang 2015). Negative SLP anomalies occupy the mid- and high latitudes of Eurasia (Fig. 13c). Thus, winter atmospheric circulation anomalies associated with strengthened Arctic westerly winds result in anomalous winter warming and a weakened winter monsoon over East Asia (Fig. 13d). Thus, the summer Arctic westerly index is an important precursor for winter surface air temperature anomalies over East Asia and it may prove to be useful predictor. It is not clear, however, which mechanisms are responsible for this lagged relationship. It is possible that summer high temperatures and strong heat waves in central and eastern Asia produce anomalies in soil temperature and moisture that lead to a weakened East Asian winter monsoon. This question requires further investigation.

5. Conclusions

This study reveals the first two dominant patterns of summer 1000–500-hPa thickness variability north of 30°N, and they, respectively, account for 29% and 10% of the variance. The leading thickness pattern displays strong interannual variability superposed on an inter-decadal shift that occurred in the late 1990s, consistent with summer Arctic warming and rapid Arctic sea ice loss. Spatially, positive thickness anomalies cover much domain north of 30°N, particularly over the Arctic, Eurasia, and North America where significant positive anomalies are observed. The second thickness pattern exhibits strong interannual variability but does not exhibit any trend or shift. The positive phase of the second thickness pattern corresponds with significant Arctic cold anomalies in the mid- and low troposphere, which are surrounded by warm anomalies outside the Arctic. Arctic cold anomalies have occurred more frequently in the context of Arctic warming (2005–16).

The second thickness pattern is the thermodynamic expression of the leading pattern of upper-tropospheric westerly variability and shows significant positive correlations with frequencies of East Asian heat waves. In the upper troposphere, enhanced Arctic westerly winds are out of phase with winds in the mid- and low latitudes of Asia. The stronger Arctic westerly winds significantly enhance baroclinicity, which dynamically contributes to increased frequency of anomalous low pressure over the Arctic. The weaker westerly winds favor stagnation of warm air and dynamically contributes to sustained high pressure anomalies in the mid- and low troposphere, increasing the likelihood of East Asian heat waves.
These wind anomalies can be attributed to a systematic northward shift of zonal winds, dominantly characterized by a shift of the East Asian westerly jet. This shift dynamically produces a dipole structure in zonal wind anomalies over the Arctic and the third pole. Dynamic analysis indicates that Arctic upward motion in the mid- and low troposphere is a major reason for summer Arctic cold anomalies. The enhanced Arctic westerly and Arctic cold anomalies during summer may provide a precursor to predict East Asian winter monsoon.

Acknowledgments. We thank Professor Jianqi Sun and two anonymous reviewers for their insightful comments, which significantly improved this manuscript. The authors are grateful to NCEP–NCEP for providing atmospheric reanalysis data. BW was supported by the National Natural Science Foundation of China (41730959, 41790472, and 41475080) and the National Key Basic Research Project of China (2015CB453200), and JF was supported by NASA Grant NNX14AH896 and funding from the Woods Hole Research Center.

REFERENCES


