What caused the cool summer over northern Central Asia, East Asia and central North America during 2009?

2012 Environ. Res. Lett. 7 044015

(http://iopscience.iop.org/1748-9326/7/4/044015)

OPEN ACCESS
IOP Publishing   Environmental Research Letters
Environ. Res. Lett. 7 (2012) 044015 (7pp)   doi:10.1088/1748-9326/7/4/044015

What caused the cool summer over northern Central Asia, East Asia and central North America during 2009?

Kyung-Ja Ha[1], Jung-Eun Chu[1], June-Yi Lee[2,5], Bin Wang[2], Saji N Hameed[3] and Masahiro Watanabe[4]

[1] Division of Earth Environmental System, Pusan National University, Busan, Korea
[2] Department of Meteorology and International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, USA
[3] Center for Advanced Information Science and Technology, University of Aizu, Japan
[4] Atmosphere and Ocean Research Institute, University of Tokyo, Japan

E-mail: jylee@soest.hawaii.edu

Received 8 August 2012
Accepted for publication 3 October 2012
Published 26 October 2012
Online at stacks.iop.org/ERL/7/044015

Abstract
Cool and wet weather conditions hit northern Central Asia, East Asia and central North America during the 2009 summer in concert with a strong jet stream and a prominent meandering upper-level circulation in the Northern Hemisphere mid-latitudes despite the fact that the year 2009 is the fifth warmest year globally in the modern record. It is found that the conspicuous atmospheric variability in the entire Northern Hemisphere mid-latitudes during the summer of 2009 was caused by a combination of teleconnections associated with significant tropical thermal forcings, strong polar forcing, and interaction between high-frequency weather events and climate anomalies. The strong negative circumglobal teleconnection pattern associated with the deficient Indian summer monsoon rainfall and developing El Niño condition was the major contributor to the cool and wet summer in June. On the other hand, the July weather conditions were attributable to the high-latitude impact of the unprecedented negative Arctic Oscillation, together with the Rossby wave response to the subtropical heating generated by convective activities over the Western North Pacific summer monsoon region. It is also noted that enhanced storm track activity and frequent cold surges from high-latitudes may have played a role in the cool and wet summer over the regions of interest.

Keywords: cool summer, atmospheric variability, El Niño, circumglobal teleconnection, Arctic oscillation, Indian summer monsoon, Western North Pacific summer monsoon, cold surge

1. Introduction

The year 2009 has been ranked the fifth warmest year globally since the beginning of instrumental records in 1850, and the first decade of the 21st century (2000–9) was the warmest decade on record (WMO 2009, Willett *et al* 2010). In spite of the warming trend, many parts of the Northern Hemisphere (NH) mid-latitude including northern Central Asia, East Asia and central North America experienced a cool and chilly summer accompanied by above-normal precipitation in 2009 (figure 1(a)).

India suffered one of its worst droughts with a seasonal deficit of 23% (Ratnam *et al* 2010) and most of Europe was hit by a heat wave setting new maximum temperature records (WMO 2009). On the other hand, several regions in

[5] Address for correspondence: University of Hawaii/IPRC, POST Bldg, Room 409A, 1680 East-West Road, Honolulu, HI 96822, USA.

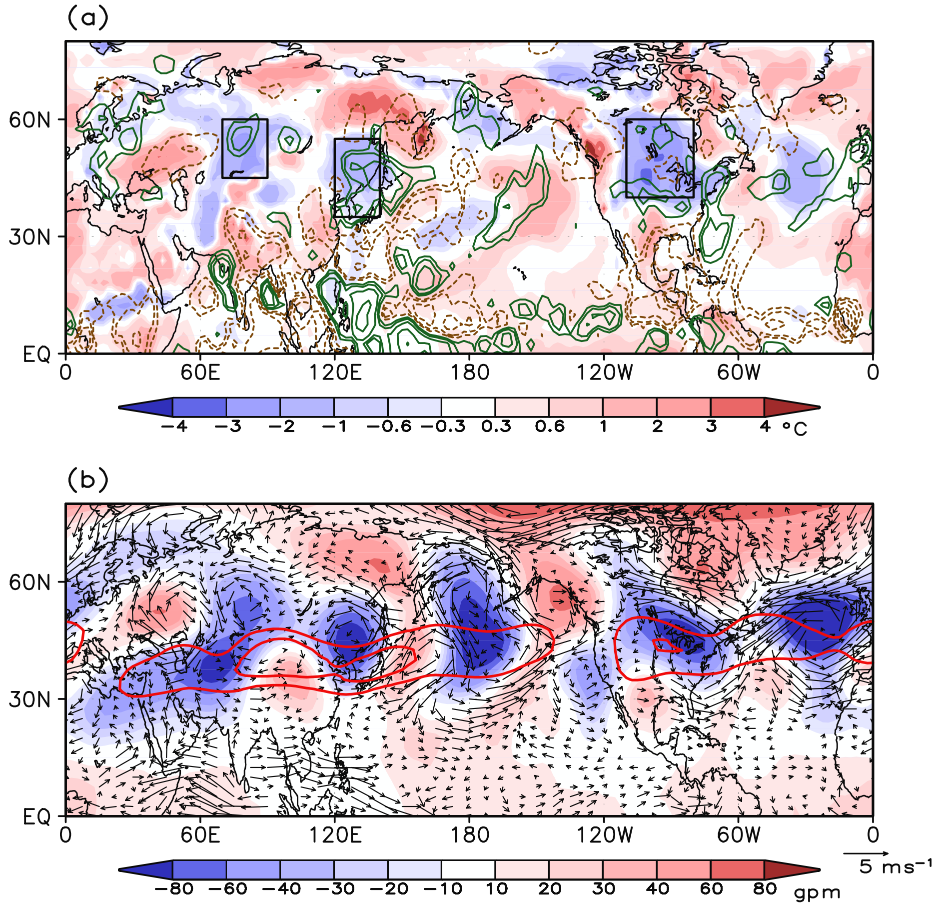

Figure 1. Spatial pattern of (a) the 2 m air temperature (TMP, shading) and precipitation (PRCP, brown and green contour) anomaly and (b) the 200 hPa geopotential height (Z200, shading) and 850 hPa wind (vector) anomaly during June–July 2009. In (a), the contour levels of PRCP are −6, −4, −2, −1, −0.5, 0.5, 1, 2, 4 and 6 mm day^{-1}. The three boxed regions indicate northern Central Asia (45°–60°N, 70°–90°E), northern East Asia (35°–55°N, 120°–140°E) and central North America (40°–60°N, 110°–80°W). In (b) 20 and 30 m s^{-1} of 200 hPa zonal wind are superimposed (red contour).

the central United States (US) experienced their coolest July in 115 years of records and many parts of Asia had heavy rains and floods along with below-normal temperatures (Arndt *et al* 2010). Unfortunately, most of the global climate models that participate in the real-time seasonal climate prediction at the Asia–Pacific Economic Cooperation Climate Center failed to predict the extreme climate anomalies over most of the NH mid-latitude even one month ahead. According to a report on the APEC Climate Center (APCC) Multi Model Ensemble (MME) prediction, the MME system failed to capture the El Niño developing during JJA 2009, but captured, to some extent, the dipole pattern of the observed precipitation anomaly characterized by enhanced precipitation over the Western North Pacific and Philippine Sea and reduced precipitation over the Indian monsoon region and the South China Sea (Wang *et al* 2010).

The extreme climate anomalies and weather events resulted in costly reparation for agriculture, transportation and other socio-economic activities. Investigation of the causes and underlying processes of the phenomena would improve our understanding of their origins and sources of predictability, and then eventually reduce future socio-economic losses by managing weather and climate risk. In particular, the cold summer of 2009 occurred against a global warming trend. Since most climate models tend to project continuous warming and increase of monsoon precipitation in the 21st century (Lee and Wang 2012), it is of particular importance to understand the sources of the cold summer of 2009.

Possible climate factors that can cause regional climate anomalies and extreme events in the NH mid-latitude include the El Niño-Southern Oscillation (ENSO) (e.g. Lau 1997, Wang *et al* 2009), the North Pacific SST variability (e.g. Lau *et al* 2004), the Arctic Oscillation (AO) (e.g. Thompson and Wallace 1998, 2000a, 2000b) , the Indian summer monsoon (ISM) and Western North Pacific summer monsoon (WNPSM) (e.g. Wang and Fan 1999, Lee *et al* 2012), circumglobal teleconnection (CGT) (e.g. Ding and Wang 2005 (hereafter DW05), Lee *et al* 2011), Tibetan plateau warming (e.g. Duan and Wu 2005) and WNP tropical cyclone activity (e.g. Sobel and Camargo 2005).

This study investigates the characteristics of the cool and wet summer over many parts of the NH extratropics in 2009 with particular attention to the following questions. (1) What

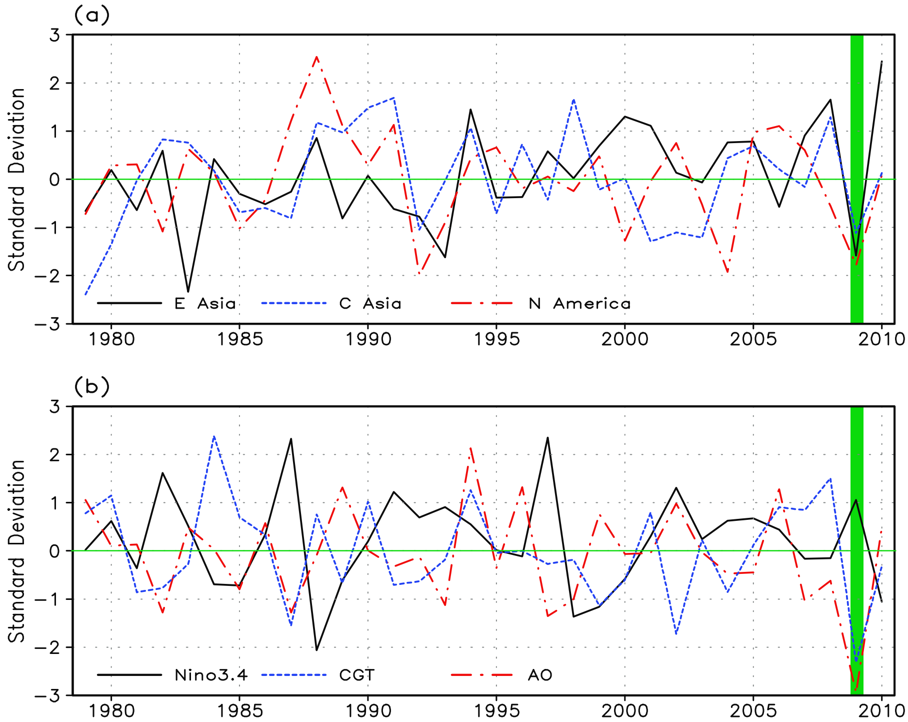

Figure 2. Time series of June–July mean (a) 2 m air temperature anomaly averaged over northern East Asia (35°–55°N, 120°–140°E), northern Central Asia (45°–60°N, 70°–90°E) and central North America (40°–60°N, 110°–90°W) and (b) anomaly of climate indices including the Nino 3.4, CGT and AO indices, normalized by their own standard deviations, for the 32 years of 1979–2010. The green vertical line refers to the summer of 2009.

are the dominant climate factors responsible for the cool and wet summer? (2) How does each factor contribute to the regional climate anomalies and extreme events over Asia and North America?

The observed data used are obtained from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data set (Xie and Arkin 1997) for precipitation (PRCP) and from the NCEP/Department of Energy (DOE) reanalysis II (NCEP R2) data (Kanamitsu *et al* 2002) for 2 m air temperature (2 m TMP), geopotential height at 200 hPa (Z200), zonal wind at 200 (U200) and 850 hPa (U850), meridional wind at 850 hPa and temperature at 850 hPa, from 1979 to 2010. The Nino 3.4 (5°S–5°N, 170°–120°W) SST index is obtained from the NCEP/Climate Prediction Center website. The AO index, defined as the first leading EOF mode of monthly mean height anomalies at 1000 hPa over the NH extratropics, comes from the NOAA web site: www.esrl.noaa.gov/psd/data/correlation/ao.data. The CGT index is defined as the interannual variability of Z200 averaged over the northwest of India (35°–40°N, 60°–70°E) using NCEP R2 (Ding and Wang 2005). The ISM index (ISMI) and WNPSM index (WNPSMI) are defined as follows (Wang and Fan 1999, Wang *et al* 2004):

$$\mathrm{ISMI} = U_{850}(5°\text{–}15°\mathrm{N}, 40°\text{–}80°\mathrm{E}) - U_{850}(20°\text{–}30°\mathrm{N}, 60°\text{–}90°\mathrm{E}),$$

$$\mathrm{WNPSMI} = U_{850}(5°\text{–}15°\mathrm{N}, 100°\text{–}130°\mathrm{E}) - U_{850}(20°\text{–}30°\mathrm{N}, 110°\text{–}140°\mathrm{E}),$$

where the areas in parentheses denote the regions over which U_{850} is averaged. The anomalies of all variables were calculated based on 1979–2010 climatology.

2. Characteristics of the 2009 summer

Figure 1(b) shows that a conspicuous wave train was dominant over the entire NH mid-latitude all through the troposphere during June–July (JJ) in 2009. Since the climate anomalies during August were significantly different from those during JJ, we focus on the JJ climate anomalies. The wave pattern had a zonal wavenumber-5 and barotropic structure associated with a waveguide induced by the enhanced westerly jet stream. In the mid-latitude continents, three prominent variability centers of barotropic cyclonic circulation are located over northern Central Asia (nCA, 45°–60°N, 70°–90°E), northern East Asia (nEA, 35°–55°N, 120°–140°E) and central North America (cNA, 40°–60°N, 110°–90°W) along with cold temperature and positive precipitation anomalies (figure 1(a)). In many parts of the regions, the temperature anomaly was lower than −2 standard deviation (SD) and the precipitation anomaly was higher than 2 SD of its interannual variation for the 32 years of 1979–2010.

The normalized time series of the temperature anomalies averaged over the three individual regions reveal that 2009 summer tied for the second coldest year over the nEA and the fourth coldest year over the nCA and ranked as the third coldest year over the cNA since 1979 (figure 2(a)). In particular, the cold temperature anomaly over nEA was

Table 1. Monthly anomalies of the Nino 3.4, CGT, AO, ISM and WNPSM indices normalized by their standard deviations from May to August 2009. Bold values indicate that the anomalies are larger than 1 standard deviation.

	Nino 3.4	CGT	AO	ISMI	WNPSMI
May	0.5	0.5	**1.6**	0.4	0.8
June	**1.0**	**−2.5**	**−2.3**	**−2.3**	0.5
July	**1.2**	**−1.0**	**−3.0**	−0.3	**1.1**
August	**1.0**	0.0	−0.1	**−2.2**	−0.2

clearly against the long-term warming trend of the region. On the other hand, nCA and cNA had three and two more cold summers, respectively, that were comparable with the summer of 2009 during recent decades. It is noted that all three regions had significant cold anomalies simultaneously in just 2009 and 1992. In fact, the interannual variations of JJ temperature over the regions are not significantly correlated with each other.

The aforementioned climate anomalies in the NH mid-latitudes were concurrent with equatorial Central Pacific warming (El Niño), and strong negative phases of AO and CGT (figure 2(b)), suggesting that tropical thermal forcing, high-latitude impact via AO and mid-latitude teleconnection were very strong during the time of interest. The El Niño developed from early summer of 2009 and the Nino 3.4 SST index anomaly was 1 SD in JJ. The AO and CGT anomalies reached −2.8 and −2.2 SD, respectively. The strong negative phase of AO represents above-normal temperature over the Arctic but below-normal temperature over the mid-latitudes. The CGT has been demonstrated as a dominant summertime teleconnection pattern having a zonal wavenumber-5 structure and geographically phase locked to preferred locations including the northeast Atlantic, western Europe, western Central Asia, East Asia, the Gulf of Alaska and northern North America. Ding and Wang (2005) considered the ISM as a primary forcing to CGT. An enhanced ISM initially generates an upper-level anomalous high to its northwest over west-central Asia, and then excites successive downstream cells along the waveguide through Rossby wave dispersion. The negative CGT can be excited by deficient ISM rainfall and deficient ISM is often induced by developing El Niños (DW05, Lee *et al* 2011).

Table 1 shows the monthly anomalies of Nino 3.4, CGT, AO and two monsoon circulation indices normalized by their own standard deviations from May to August 2009. While moderate to strong Pacific warming persisted during whole summer, the CGT and AO indices exhibited large month-to-month variation. The CGT was the lowest (−2.5 SD) in June but the AO was the lowest (−3.0 SD) in July. In August, the CGT and AO were near normal. The ISMI was −2.3 SD in June, indicating a severely deficient summer monsoon, but it was near normal in July. On the other hand, the WNPSM was very active in July with 1.1 SD of its circulation index.

3. Possible causes

The previous section indicates that the 2009 summer climate was symphonized by strong tropical thermal forcing, monsoonal heat sources, high-latitude impact via AO and mid-latitude wave activities along with an above-normal jet stream. This section is devoted to understanding how those climate factors were coordinated with each other to result in the cold summer over Asia and North America in 2009.

Composite analysis is adopted to better understand the relative role of the developing El Niño and the negative phases of the AO and CGT (figure 3). The developing El Niño composite is obtained from five summers in 1982, 1991, 1997, 2002 and 2006, the negative CGT composite from seven summers in 1981, 1982, 1987, 1989, 1999, 2002 and 2004, and the negative AO composite from six summers in 1982, 1987, 1993, 1997, 1998 and 2007 according to figure 2(b).

During the last few decades, El Niño developing summers were characterized by zonally elongated negative temperature anomalies over EA and the North Pacific and positive ones over mid-latitude NA (figure 3(a)). The Pacific East Asian teleconnection pattern through the bridge of the WNP anomaly (Wang and Zhang 2002) suggests that the developing El Niño contributes, in part, to nEA and some part of nCA but not to cNA.

The negative CGT composite pattern obtained in this study (figure 3(b)) is, to a certain extent, different from the one shown in DW05 that was obtained from the 56 yr data without the long-term trend and decadal variation. It is interesting to note that the 2009 summer pattern (figure 1(a)) more resembles DW05's pattern rather than figure 3(b) for the following two reasons. First, DW05's negative CGT pattern mainly emerged due to deficient ISM rainfall and a developing El Niño which is the case for summer 2009 while the negative CGT composite in this study mainly emerged due to deficient ISM without an El Niño. This is because during recent decades the negative correlation between ISM and ENSO has weakened (Kumar *et al* 1999). Second, the weaker trough over EA and NA and the stronger ridge over the North Pacific and the Gulf of Alaska in figure 3(b) (compared to DW05's result) reflect the global warming effect on the CGT pattern during recent decades that is not the case for the summer of 2009 (Lee *et al* 2011, Wang *et al* 2012). Taken together, it is suggested that the cool summer over nCA, nEA and cNA is, in part, attributable to the negative phase of CGT emerging due to deficient ISM and developing El Niño.

By definition, the negative AO composite is characterized by a zonally symmetric pattern of polar warming and mid-latitude cooling (figure 3(c)). It indicates that the negative AO mainly contributes to cooling of EA and western and central NA but not to nCA during the last few decades.

Further analysis on the monthly anomaly fields reveals that the negative CGT pattern associated with deficient ISM rainfall and El Niño developing was a major contributor to the cold summer in June but the western North Pacific–East Asia–North America teleconnection associated with the abundant WNPSM rainfall and negative AO contributed to the cold summer in July (see table 1). In August, the El Niño

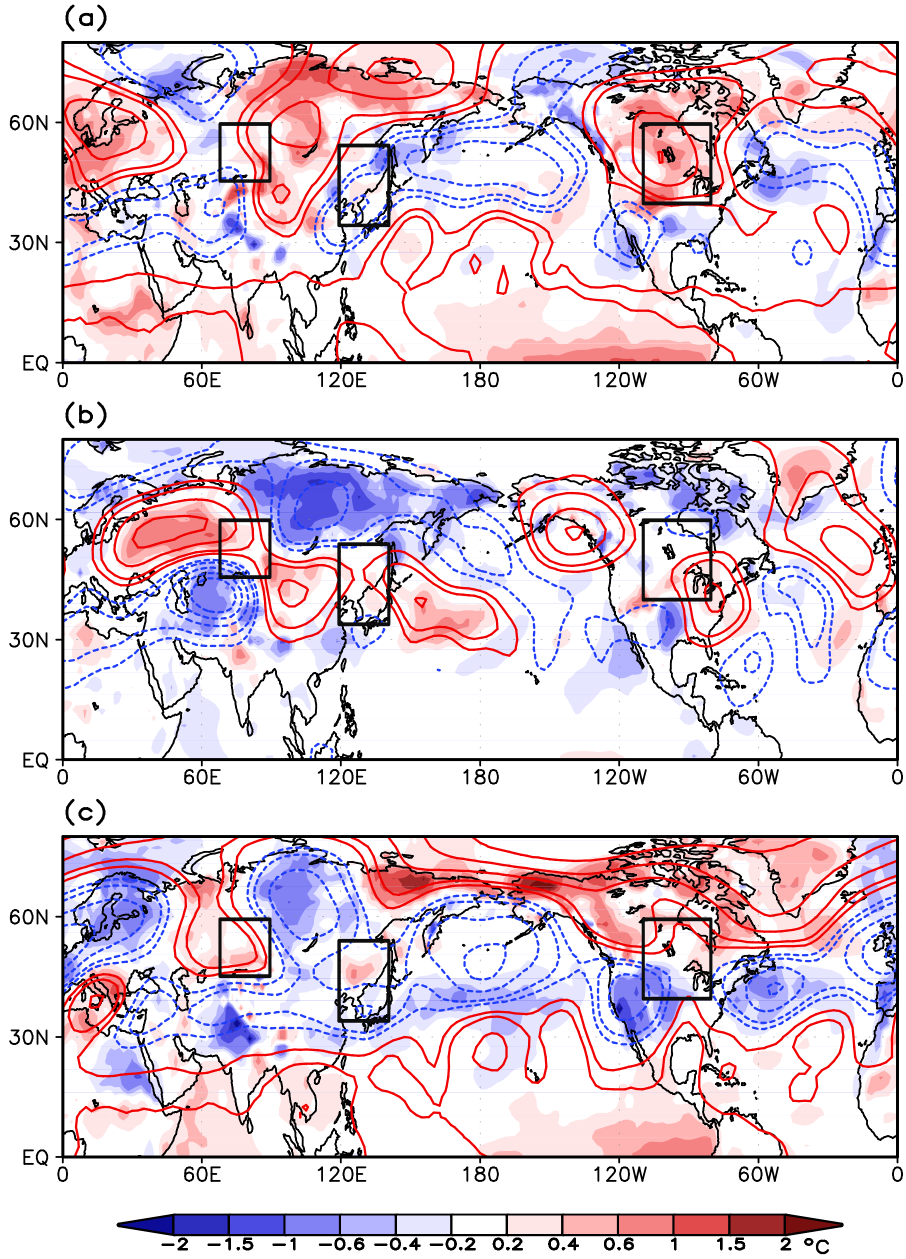

Figure 3. Composite maps of June–July mean 2 m air temperature (shading) and 200 hPa geopotential height (Z200, blue and red contour) anomalies during (a) the El Niño developing phase, (b) the CGT negative phase and (c) the AO negative phase. The contour levels of Z200 are −40, −30, −20, −10, −5, 5, 10, 20, 30 and 40 m. The three boxed regions indicate northern Central Asia, northern East Asia and central North America.

effect was dominant on the extratropical climate anomaly since the CGT, AO and WNPSM-related PJ teleconnection were all near normal.

4. Discussion

The 2009 summer climate anomaly was a unique case caused by a combination of a developing El Niño, the negative phases of CGT and AO, severely deficient ISM and enhanced WNPSM rainfall in recent decades. That is because the negative relationship between the ISM rainfall and ENSO has weakened during recent decades and the CGT and AO have no significant correlation (DW05, Wang *et al* 2012). Since 1979, just the summer of 1982 had similar climate conditions. However, during that summer, El Niño and AO effects were dominant, resulting in a cool summer in NA but a normal to hot summer over CA and NA (not shown).

We also note that the interaction between weather and climate played an important role in the cool and chilly summer of 2009 over nCA, nEA and cNA. The interactions of the mean flow with high-frequency transients make an environment that favors development of synoptic events, moisture convergence, more convective storms and summer rainfall (Hu and Feng 2010). Figure 4 shows the climatology and anomaly in JJ 2009 of 200 hPa storm track activity and 850 hPa meridional heat flux by synoptic eddies. The storm

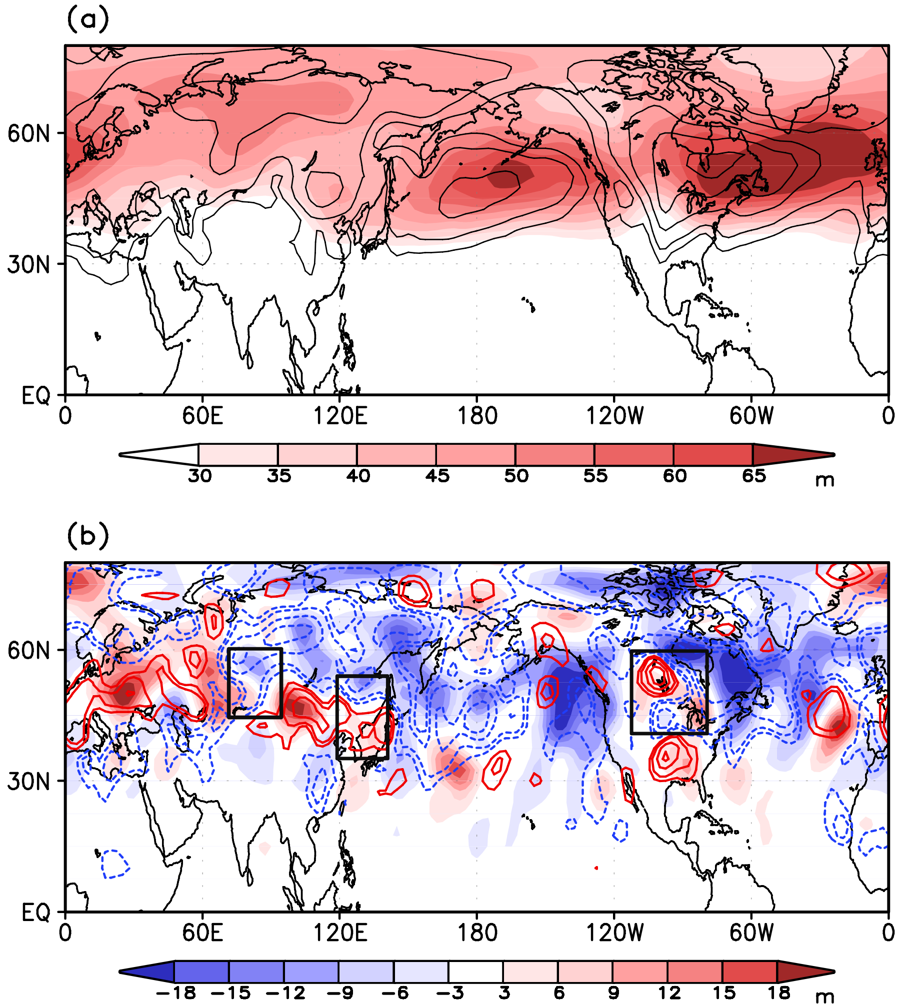

Figure 4. (a) Climatology and (b) 2009 anomaly of 200 hPa storm track (shading) and 850 hPa meridional heat flux by synoptic eddies (contours) during June and July. In (a), the contour intervals are 1, 2, 4, 6, 8 and 10 °C ms^{-1}. In (b), the contour intervals are −3, −2, −1, −0.5 (blue), 0.5, 1, 2 and 3 °C ms^{-1} (red). Refer to the text for a definition of storm track and meridional heat flux. In (b), the three boxed regions indicate northern Central Asia, northern East Asia and central North America.

track activity is defined as the root mean square of variance of 8-day filtered Z200. It is shown that an upper-level storm track was active along with frequent cold surges over nCA, nEA and cNA since a northerly was prevailing over the regions of interest. The impact of frequent cold surge and storm track activity seems to make the summer of 2009 unique because the impact was very weak in the summer of 1982 (not shown). The impact of interaction between weather and climate on extreme climate events deserves further study.

The monthly anomaly analysis indicates that the June–July mean state instead of the JJA mean is more robust to the described cool summer climate in 2009, which might be linked to the distinct changes of AO and CGT between June–July and August.

In 1992, the temperature patterns were similar to those in 2009 but the climate indices showed different anomaly patterns. It is found that the negative CGT pattern was most dominant during the 1992 summer among other climate factors. Associated with the negative CGT pattern, most of Asia and North America experienced cold temperatures. However, the impact of high latitude seemed to be very weak in 1992.

Most of the global climate models that participated in the real-time seasonal climate prediction at the Asia–Pacific Economic Cooperation Climate Center failed to predict the extreme climate anomalies over most of the NH mid-latitude even one month ahead (Wang *et al* 2010). Further study will address deficiencies and possibilities of the global climate models in predicting the conspicuous climate anomalies addressed in this study.

Acknowledgments

This work is supported by the National Research Foundation of Korea (NRF) through a Global Research Laboratory (GRL) grant (MEST 2011-0021927). J-Y Lee and B Wang acknowledge support from APEC Climate Center and IPRC, which is in part supported by JAMSTEC, NASA and NOAA. This is IPRC publication 913 and SOEST publication 8745.

References

Arndt D S, Baringer M O and Johnson M R (ed) 2010 State of the climate in 2009 *Bull. Am. Meteorol. Soc.* **91** S1–224

Ding Q and Wang B 2005 Circumglobal teleconnection in the Northern Hemisphere summer *J. Clim.* **18** 3483–505

Duan A M and Wu G X 2005 Role of the Tibetan plateau thermal forcing in the summer climate patterns over subtropical Asia *Clim. Dyn.* **24** 793–807

Hu Q and Feng S 2010 Influence of the Arctic oscillation on central United States summer rainfall *J. Geophys. Res.* **115** D01102

Kanamitsu M *et al* 2002 NCEP dynamical seasonal forecast system 2000 *Bull. Am. Meteorol. Soc.* **83** 1019–37

Kumar K K, Rajagopalan B and Cane M A 1999 On the weakening relationship between the Indian monsoon and ENSO *Science* **284** 2156–9

Lau K-M, Lee J-Y, Kim K-M and Kang I-S 2004 The North Pacific as a regulator of summertime climate over Eurasia and North America *J. Clim.* **17** 819–33

Lau N C 1997 Interactions between global SST anomalies and the midlatitude atmospheric circulation *Bull. Am. Meteorol. Soc.* **78** 21–33

Lee J-Y and Wang B 2012 Future change of global monsoon in the CMIP5 *Clim. Dyn.* at press (doi:10.1007/s00382-012-1564-0)

Lee J-Y *et al* 2011 How predictable is the Northern Hemisphere summer upper-tropospheric circulation? *Clim. Dyn.* **37** 1189–203

Lee J-Y *et al* 2012 Real-time multivariate indices for the boreal summer intraseasonal oscillation over the Asian summer monsoon region *Clim. Dyn.* at press (doi:10.1007/s00382-012-1544-4)

Ratnam J V *et al* 2010 Pacific Ocean origin for the 2009 Indian summer monsoon failure *Geophys. Res. Lett.* **37** L07807

Sobel A H and Camargo S J 2005 Influence of western North Pacific tropical cyclones on their large-scale environment *J. Atmos. Sci.* **62** 3396–407

Thompson D W J and Wallace J M 1998 The Arctic oscillation signature in the wintertime geopotential height and temperature fields *Geophys. Res. Lett.* **25** 1297–3000

Thompson D W J and Wallace J M 2000a Annular modes in the extratropical circulation, part I: month-to-month variability *J. Clim.* **13** 1000–16

Thompson D W J and Wallace J M 2000b Annular modes in the extratropical circulation, part II: trends *J. Clim.* **13** 1018–36

Wang B and Fan Z 1999 Choice of South Asian summer monsoon indices *Bull. Am. Meteorol. Soc.* **80** 629–38

Wang B, Kang I-S and Lee J-Y 2004 Ensemble simulations of Asian-Australian monsoon variability by 11 AGCMs *J. Clim.* **17** 803–18

Wang B and Zhang Q 2002 Pacific-East Asian teleconnection. Part II: how the Philippine Sea anomalous anticyclone is established during El Nino development *J. Clim.* **15** 3252–65

Wang B *et al* 2009 Advance and prospectus of seasonal prediction: assessment of APCC/CliPAS 14-model ensemble retrospective seasonal prediction (1980–2004) *Clim. Dyn.* **33** 93–117

Wang B *et al* 2010 Improvement of APCC seasonal prediction and assessment of characteristics and forecast of 2009/2010 climate anomalies *Report of APCC International Research Project 2010* (Busan: APEC Climate Center Korea)

Wang H, Wang B, Huang F, Ding Q and Lee J-Y 2012 Interdecadal change of the Northern summer circumglobal teleconnection (1958–2009) *Geophys. Res. Lett.* **39** L12704

Willett K M, Alexander L V and Thorne P W (ed) 2010 The global climate (in 'State of the climate in 2009') *Bull. Am. Meteorol. Soc.* **91** S19–51

WMO 2009 2000–2009, the warmest decade *Press Release No. 869* (Geneva: WMO)

Xie P and Arkin P A 1997 Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs *Bull. Am. Meteorol. Soc.* **78** 2539–58