Environmental Research Letters

LETTER

Long-term trends and impacts of polar cold airmass in boreal summer

Qian Liu1,2, Guixing Chen1,2 and Toshiki Iwasaki1,2

1 School of Atmospheric Sciences, and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Guangzhou, People’s Republic of China
2 Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, People’s Republic of China
3 Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan

E-mail: chenguixing@mail.sysu.edu.cn

Keywords: cold airmass, mid-high latitudes, isentropic analysis, heat wave, climate change

Abstract

The northern polar region possesses the most extensive cold airmass on Northern Hemisphere. The generation of this polar cold airmass and its outflow to lower latitudes play an important role in the climate system in terms of mass and heat exchanges. However, long-term changes in the polar cold airmass, especially in summer, and the climatic effects on mid-high latitudes are still unclear. Using an isentropic approach, we quantitatively show that the polar cold airmass amount has decreased rapidly since the 1980s, with a decade lagging behind the global warming. The equatorward flux of the cold airmass has also weakened, trapping the cold airmass in its source region. These profound changes in the cold airmass coincide with a period characterized by rapid surface warming and increasingly frequent heat waves in recent three decades over the mid-high latitude continents. Owing to regional differences in the cold airmass reduction, Europe and North America have experienced a surface warming faster than the Northern Hemisphere mean. Furthermore, such a long-term trend in the polar cold airmass can be attributed to Arctic sea ice loss and internal decadal variability of sea surface temperature in high-latitude oceans. Our results highlight that the isentropic analysis of cold airmass may serve a good detection of the climate change at polar region and mid-high latitudes.

1. Introduction

As an integral part of the Earth’s climate system, the polar cold airmass could reflect the local atmospheric energy budget and act as an indicator of polar change (Iwasaki et al 2014, Kanno et al 2019). The meridional flow of this cold airmass also plays an important role in global transport and the balance of heat, modulating the weather and climate at mid-high latitudes (Reed and Kunkel 1960, Cohen et al 2014, Chen et al 2015, Papritz and Spengler 2017, Coumou et al 2018, Pithan et al 2018, Papritz 2019). The climatic distribution and synoptic activity of the polar cold airmass can greatly influence the pattern of the mean surface air temperature and the occurrence of cold extremes during the winter season (Shoji et al 2014, Shepherd 2016). However, far fewer indications of such relationships during the summer season (Shimada et al 2018), when the polar cold airmass may act as an ‘air conditioner’ to restrain the occurrence of heat waves, have been reported. As the cold airmass flows equatorward, it may converge with the relatively warm-wet airmass, resulting in the formation of a frontal zone that may further influence precipitation (Zhao et al 2004, Ding and Chan 2005, Wang and Gu 2016). The resultant changes in temperature and rainfall pose threats to agricultural production, energy security and human health (Lesk et al 2016, Larcom et al 2019).

The global mean surface temperature has been observed to increase rapidly over the past few decades (Wuebbles et al 2017, Shukla et al 2019, NASA 2020). In particular, the surface temperature in the high latitudes of the Northern Hemisphere has warmed at a rate twice that of the global mean (Bekryaev et al 2010, Cohen et al 2014). Meanwhile, the occurrence frequency of hot extremes also shows an increasing trend (Seneviratne et al 2014). A series of extreme
warm summers, including the 2010 summer in Russia and the 2012 summer in the USA, have been observed in the northern mid-latitudes in recent years (Lau and Kim 2012, Barriopedro et al 2011, Schubert et al 2014, Hong et al 2017, Deng et al 2018). These facts strongly suggest that the polar cold airmass in boreal summer may have undergone an unprecedented change. Accordingly, an investigation of long-term variation in the polar cold airmass and its possible climatic effect in boreal summer is required; additionally, whether the polar cold airmass varies in synchronous phase with the global warming must be determined. Addressing these questions will help to comprehensively understand both the spatial heterogeneity of climate warming and the increased occurrence of heat waves.

2. Data and methods

In this study, the atmospheric variables, which are used to calculate the characteristics of the polar cold airmass, were obtained from the Japanese 55 year Reanalysis (JRA-55) during summers (June, July and August) from 1958 to 2017. The JRA-55 has a resolution of 6 h and 1.25°, with 37 vertical pressure levels. Previous study shows that the JRA-55 has good consistency with other reanalysis datasets in isentropic analysis (Kanno et al 2016). We also used the observed monthly sea surface temperature (SST) and sea ice extent from the Hadley Centre and the surface air temperature from the Climate Research Unit (CRU). The time series of the climate indices were obtained from the National Oceanic and Atmospheric Administration (NOAA).

The isentropic analysis method proposed by (Iwasaki et al 2014) was used to quantitatively describe the dynamic and thermal features of the threedimensional cold airmass in this study. The polar cold airmass is defined as the atmosphere below the potential temperature threshold ($\theta_T = 293$ K). The selection of $\theta_T$ is based on the analysis of mass stream function with mass-weighted isentropic zonal mean, so that most of the equatorward flow from polar regions are confined in the layer of cold airmass (Iwasaki et al 2014). The cold airmass amount or depth of pressure ($DP$) is given by the pressure difference between the ground surface ($p_s$) and the $\theta_T$ surface ($p(\theta_T)$),

$$DP = p_s - p(\theta_T).$$

(1)

In climatological analysis, the amount of cold airmass is highly proportional to the mean temperature or negative heat content in cold airmass, which can represent the coldness of cold airmass as well. The horizontal cold airmass flux ($F$) is defined as the vertical integral of the horizontal wind ($v$) and pressure ($p$),

$$F = \int_{p(\theta_T)}^{p_s} vdp.$$

(2)

Local changes in the cold airmass amount are attributed to the horizontal convergence of the cold airmass flux and diabatic cooling/heating at the $\theta_T$ surface,

$$\frac{\partial DP}{\partial t} = -\nabla \cdot \int_{p(\theta_T)}^{p_s} vdp + G(\theta_T).$$

(3)

Here, diabatic cooling and warming ($G(\theta_T)$) denote the generation and loss, respectively, of the cold airmass. Thus, the cold airmass amount is conserved in the Lagrangian sense under adiabatic conditions. This method has been well used to estimate the long-term trends of cold airmass activity in winter (e.g. Kanno et al 2019).

The numbers of heat wave days are identified by a relative threshold of the surface temperature (Deng et al 2018). For each single day in boreal summer (June, July and August), the threshold of a heat wave is calculated by the 95th percentile for a total of 60 years $\times$ 15 d (where the 15 d include the 7 d on either side of the target date). A heat wave day can be identified as a day when the daily mean surface temperature exceeds the threshold of the respective day. A heat wave event is identified as a period of three or more consecutive heat wave days. Thus, the number of heat wave days can be obtained by computing the total days of heat wave events during summer.

3. Results

3.1. Climatology of polar cold airmass in boreal summer

Here, we use an advanced quantitative method, referred to as isentropic analysis, to describe the amount, horizontal flux, and genesis/loss of the polar cold airmass. Figure 1(a) shows the climatological mean spatial distribution of the cold airmass amount in summer during 1958–2017. The summertime cold airmass distribution resembles a dome in the Northern Hemisphere and reaches a depth of more than 300 hPa near the North Pole. The cold airmass is concentrated mainly in the Arctic and the northern parts of the Atlantic and Pacific Oceans. Such a spatial pattern is attributed to the thermal features of the land and sea surface, causing the high-latitude ocean (continent) to act as the source (sink) of the cold airmass in the summer season (figure 1(b)). In other words, the cold airmass plays an important role in the exchange of heat between oceans and continents. That is, it warms up the ocean and cools down the continent in summer. The cold airmass is generated at a rate of 10–30 hPa day$^{-1}$ due to diabatic cooling over the mid- and high-latitude oceans. On the other hand, it tends to dissipate at a rate of 10–50 hPa day$^{-1}$ over the eastern Atlantic and Pacific Oceans and over the land at 50°–70°N.

The horizontal flux of the polar cold airmass is characterized by a circumpolar vortex and four main
equatorward streams in summer (figure 1(c)). Two of these streams originate from the Arctic Ocean and separately flow southeastward to northeastern North America and central Eurasia (‘A’ and ‘B’ in figure 1(c)). The third stream arises from the northern Atlantic Ocean, flows eastward and divides into two branches: one continues to flow eastward to Europe, while the other turns southward to the subtropical eastern Atlantic Ocean (‘C’). The fourth stream grows over the northern North Pacific Ocean and flows eastward, whereupon it is blocked by the Rocky Mountains and then turns southward to the subtropical eastern Pacific Ocean with most of its mass flux (‘D’). These equatorward streams weaken rapidly as they move to the relatively warm surface, forming zonal bands of cold airmass loss on land or at eastern parts of oceans. The streams over the Atlantic and Pacific Oceans are closely related to storm tracks (Hoskins and Hodges 2019), and all four streams are thought to influence the weather and climate along their paths.

3.2. Long-term change of polar cold airmass

Figure 2(a) illustrates the long-term variation in the Northern Hemisphere mean cold airmass during summer. The time series of the cold airmass amount is relatively flat during the 1950s–1970s, after which it begins to decrease since the 1980s and accelerates to a robust decreasing trend (−2.3 hPa decade$^{-1}$) around the late 1990s. This decreasing trend of polar cold airmass can be detected in most of mainstream reanalysis datasets, such as NCEP1, NCEP2, ERA20 C and ERA5 (supplementary figure 1 (available online at stacks.iop.org/ERL/15/084042/mmedia)), and it also shows a good agreement among the results with different $\theta_T$. The reduction in the cold airmass amount occurs approximately a decade later than the global warming trend that began in the 1970s (Wuebbles et al 2017, Shukla et al 2019). During the past three decades (from 1985 to 2017), the cold airmass amount displays a reduction of approximately 11%. Based on this decreasing trend, the cold airmass amount has continuously broken its record low in recent years. Regarding its spatial patterns, the cold airmass amount during 1958–1985 shows an increasing trend in most regions of the Northern Hemisphere and a decreasing trend in the northern Atlantic Ocean (figure 2(b)), resulting in an overall weak increasing tendency with relatively weak significance. This increasing tendency, however, reverses to a significant decreasing trend almost over the whole Northern Hemisphere during 1985–2017 (figure 2(c)). The decreasing trend has amplified at a rate of approximately −10 hPa decade$^{-1}$ along the boundaries of cold airmass, such as over the northern Pacific Ocean, northern Eurasia and North America. Such a long-term retreat of the polar cold airmass may correspond to the expansion of subtropical areas in recent decades (Scheff and Frierson 2012).

Compared with the cold airmass amount, the equatorward flux starts to decrease earlier (beginning in the 1970s) and decreases by approximately 21% until 2017 (figure 2(a)). This decrease occurs mainly over the continents and subtropical regions of the oceans near the main streams of the cold airmass (figure 2(d)). The weakening of equatorward cold airmass flux is jointly caused by the reduction in cold airmass and slowdown of lower tropospheric winds (figure not shown). As a result, the cold airmass becomes trapped in the Arctic and the high latitudes of the oceans, thereby weakening the meridional heat exchange in the troposphere and causing the boundaries of the cold airmass to retreat (figure 2(c)). Upon closer inspection, the four main streams of the cold airmass also experience an obvious decrease, especially over North America, the eastern Atlantic Ocean and the eastern Pacific Ocean, with reductions of approximately 32%, 35% and 19%, respectively,
since 1970 (supplementary figure 2). Moreover, the decrease in the zonal cold airmass flux also weakens the circumpolar vortex (figure 2(e)), causing the stagnation of the cold airmass and amplifying the spatial heterogeneity of lower tropospheric temperatures.

3.3. Impacts on surface air temperature
A reversed sequence (that is, an increasing surface air temperature with decreasing cold airmass) is observed over the continents at mid-high latitudes during summer (figure 3(a)). This increase in the surface air temperature also begins in the 1980s, coinciding with the reduction in the polar cold airmass. The surface temperatures over the mid- and high-latitude continents increase at a rate of 0.29 °C decade⁻¹, which is 25% higher than the average warming rate over the Northern Hemisphere. In particular, over Europe, East Asia, and northern and western North America, the surface temperature displays a warming tendency of more than 0.5 °C decade⁻¹ (supplementary figure 3(a)). Most of these warming areas appear in the transition region between cold and warm airmasses that may be sensitive to variations in the polar cold airmass and its streams. Regression analysis further shows that the land surface temperature north of 45°N can rise by 1.4 °C when the Northern Hemisphere mean polar cold airmass decreases by 10 hPa (supplementary figure 4(a)).
This cold airmass-related warming rate has a similar spatial pattern to the observed surface warming trend (figure 3(b) and supplementary figure 3(a)), suggesting that the recent summertime warming may be closely related to the reduction and stagnation of polar cold airmass. Areas that warm rapidly, such as Europe, northeastern Asia and North America, are also highly sensitive to changes in the cold airmass amount ($-0.15$ °C hPa$^{-1}$). Previous study reveals that the amplified warming in Europe-West Asia and northeastern Asia can be explained by the decadal change of silk road pattern (Hong et al 2017). Our analysis further shows that the weakening of the four main cold airmass streams is also strongly connected to the regional warming in their surrounding areas (supplementary figure 5), highlighting the importance of the polar cold airmass to the warming at mid-high latitudes and its heterogeneity.

As the mean surface air temperature increases in response to the summertime reduction in the polar cold airmass, the occurrence frequency of hot extremes is also expected to increase. The average number of heat wave days over the continents at mid-high latitudes exhibits a remarkable increase of 148% since the 1980s (figure 3(a)). Some regions in southern Europe, southern North America and East Asia are even characterized by a growth rate of 3.5 d per decade (supplementary figure 3(b)). As a result, over the last decade, the number of heat wave days exceeds 10 over these regions during summer. Such a rapid increase in the number of heat wave days in the Northern Hemisphere is strongly related to the decreases in the cold airmass amount and its equatorward flux (figure 3(c) and supplementary figure 4(b)). Cold airmass surge events also become less frequent with an extended interval period; as a result, it is much more difficult for their cooling effect to interrupt the maintenance of high surface temperatures. In particularly, the regions close to or on the pathway of circumpolar vortex and main streams of cold airmass flux experienced a much faster increase of hot extremes than other regions. Above results also highlight that the isentropic analysis of polar cold airmass is powerful for studying latitudinal heat exchanges not only in the winter but also in the summer.

3.4. Possible causes of the reduction in polar cold airmass

We further discuss the factors that contribute to the summertime reduction in the cold airmass amount,
most of which occurs over the mid-high latitudes of the Northern Hemisphere beginning in the 1980s (figure 2(c)). Since the hemispheric total cold airmass possesses an adiabatically conservative budget, it can be changed only by diabatic cooling/heating in the source/sink region. During 1985–2017, 69% of the reduction appears over the ocean and sea ice region (source region), while 31% occurs over the continents (sink region). Given this difference, the decreasing trend of the cold airmass generation in its source region is considered the dominant factor influencing the cold airmass reduction. Supplementary figure 6 shows the time series of some climate indices representing the principal changes in the ocean and sea ice regions throughout the Northern Hemisphere. The long-term variations in the sea ice extent and Atlantic Multidecadal Oscillation (supplementary figures 6(a) and (e)) are strongly related to the variation in the cold airmass with correlation coefficients of 0.71 and −0.77, respectively. These strong relations suggest the comparable importance of both Arctic and high-latitude oceans.

As shown in figure 4(a), the sea ice extent shows a markedly linear trend with a negative slope \((4.8 \times 10^5 \text{ km}^2 \text{ decade}^{-1})\) (Stroeve et al. 2012, Cohen et al. 2014). This melting of sea ice mainly occurs at the northernmost area of Atlantic Ocean during 1970–1985 (figure 4(b)) and the Arctic Ocean during...
4. Conclusions

Our study, for the first time, presents the quantitative cold air mass analysis of summertime climate change detection. The summertime polar cold air mass over the Northern Hemisphere has experienced a rapid decrease since the 1980s, causing an increase in the surface temperatures and numbers of heat wave days over the continents at mid-high latitudes. This reduction in the polar cold air mass is more than an expression of the global warming amplified in Arctic region; it is also regulated by the decadal variations in the SST of the oceans at mid-high latitudes. Thus, the recent accelerated warming and increased frequency of hot extremes at mid-high latitudes are connected to both internal variability and greenhouse gas forcing through the polar cold air mass. In addition, reduction in the cold air mass amount and slowdown of main streams also explain the spatial heterogeneity of surface warming in the Northern Hemisphere.

The detection of climate change in polar cold air mass may also provide further insights into the polar amplification and its various impacts in surrounding mid-high latitudes (Cohen et al 2014, Coumou et al 2018). Besides the direct impact on air temperature, the long-term change of polar cold air mass may have influence on other meteorological variables. The total cloud amount and frequency of overcast day are observed to decrease (Vautard et al 2009, Tang and Leng 2013, Xia et al 2013), which is probably caused by the weakening front activities with less cold air mass. The changes may further influence the radiation balance and relate to the solar ‘brightening’ in recent decades (Wild et al 2005, Wang and Wild 2016). The reduction of cold air mass and associated continental warming are also expected to affect vegetation growth and agriculture. The warming in mid-high latitudes is closely connected with a sharp increase of vapor pressure deficit, thereby reducing the vegetation greening trend (Yuan et al 2019). Our findings and previous studies highlight the need to further clarify the mechanism of how and to what extent the polar cold air mass affects extreme weather and climate at both global and regional scales.

Acknowledgments

The authors are grateful to four anonymous reviewers for the helpful comments. This work was supported by the National Key Research and Development Program of China (Grant 2016YFA0600704), the National Natural Science Foundation of China (NSFC) (Grant 41805122) and the Fundamental Research Funds for the Central Universities (Grant 74110-31610019) and the China Postdoctoral Science Foundation (Grant No. 2018M643292).

Data availability statement

The data that support the findings of this study are openly available. The SST and sea ice extent data are provided by Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadisst). The surface air temperature is provided by Climatic Research Unit (http://www.cru.uea.ac.uk/data). The JRA-55 is provided by the Japan Meteorological Agency (https://jra.kishou.go.jp/JRA-55). The climate indices are provided by the National Oceanic and Atmospheric Administration (https://www.esrl.noaa.gov/psd).

ORCID iDs

Qian Liu https://orcid.org/0000-0001-6595-2369
Guixing Chen https://orcid.org/0000-0002-3112-0668
Toshiki Iwasaki https://orcid.org/0000-0003-2110-0687

References

Barriopedro D, Fisher E M, Luterbacher J, Trigo R M and García-Herrera R 2011 The hot summer of 2010: re-drawing the temperature record map of Europe Science 332 220–4
Bekryaev R V, Polyakov I V and Alexeev V A 2010 Role of polar amplification in long-term surface air temperature variations and modern J. Clim. 23 3888–906
Chen T C, Tsay J D, Matsumoto J and Alpert J 2015 Development and formation mechanism of the Southeast Asian winter heavy rainfall events around the South China Sea. Part I: formation and propagation of cold surge vortex J. Clim. 28 1437–43
Cohen J et al 2014 Recent Arctic amplification and extreme mid-latitude weather Nat. Geosci. 7 627–37
Coumou D, Di Capua G, Vavrus S, Wang L and Wang S 2018 The influence of Arctic amplification on mid-latitude summer circulation Nat. Commun. 9 1–12
Deng K, Ting M, Yang S and Tan Y 2018 Increased frequency of summer extreme heat waves over Texas area tied to the amplification of pacific zonal SST gradient J. Clim. 31 5629–47
Ding Y and Chan J C 2005 The East Asian summer monsoon: an overview Meteor. Atmos. Phys. 89 117–42
Hong X, Lu R and Li S 2017 Amplified summer warming in Europe-West Asia and Northeast Asia after the mid-1990s Environ. Res. Lett. 12 094007
Hoskins B J and Hodges K I 2019 The annual cycle of Northern Hemisphere storm tracks. Part I: seasons J. Clim. 32 1743–60
Iwasaki T, Shoji T, Kanno Y, Sawada M, Ujiie M and Takaya K 2014 Isentropic analysis of polar cold airmass streams in the Northern Hemispheric winter J. Atmos. Sci. 71 2230–43
Kanno Y, Abdillah M and Iwasaki T 2016 Long-term trend of cold air mass amount below a designated potential temperature in Northern and Southern Hemispheric winters using reanalysis data sets J. Geophys. Res. Atmos. 121 10138–52
Kanno Y, Walsh J, Abdillah M, Yamaguchi J and Iwasaki T 2019 Indicators and trends of polar cold airmass Environ. Res. Lett. 14 023006
Larcom S, She P W and van Gevelt T 2019 The UK summer heatwave of 2018 and public concern over energy security Nat. Clim. Change 9 370–3
Lau W K and Kim K M 2012 The 2010 Pakistan flood and Russian heat wave: teleconnection of hydrometeorological extremes J. Hydrometeor. 13 392–403
Lesk C, Rowhani P and Ramankutty N 2016 Influence of extreme weather disasters on global crop production Nature 529 84–87
NASA Public Affairs 2020 NASA, NOAA analyses reveal 2019 second warmest year on record https://www.giss.nasa.gov/research/news/20200115/ (Accessed: 6 March 2020)
Papritz L 2019 Arctic lower tropospheric warm and cold extremes: horizontal and vertical transport, diabatic processes, and linkage to synoptic circulation features J. Clim. 33 993–1016
Papritz L and Spengler T 2017 A Lagrangian climatology of wintertime cold air outbreaks in the Irminger and Nordic Seas and their role in shaping air–sea heat fluxes J. Clim. 30 2717–37
Pithan F et al 2018 Role of air-mass transformations in exchange between the Arctic and mid-latitudes Nat. Geosci. 11 805–12
Reed R J and Kunkel B A 1960 The Arctic circulation in summer J. Meteor. 17 489–506
Schef f J and Frierson D M W 2012 Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones Geophys. Res. Lett. 39 L18704
Scheff J D, Wang H, Koster R D, Suarez M J and Groisman P Y 2014 Northern Eurasian heat waves and droughts J. Clim. 27 3169–207
Seneviratne S I, Donat M G, Mueller B and Alexander L V 2014 No pause in the increase of hot temperature extremes Nat. Clim. Change 4 161–3
Shepherd T G 2016 Effects of a warming Arctic Science 353 989–90
Shimada T, Kanno Y and Iwasaki T 2018 Low-level cool air over the midlatitude oceans in summer J. Clim. 31 2075–90
Shoji T, Kanno Y, Iwasaki T and Takaya K 2014 An isentropic analysis of the temporal evolution of East Asian cool air outbreaks J. Clim. 27 9337–48
Shukla P R, Skea J, Slade R, van Diemen R, Haughey E, Malley J, Pathak M and Portugal Pereira J eds 2019 Technical summary Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (https://www.ipcc.ch/site/assets/uploads/2019/08/FULLREPORT-1.pdf)
Stroeve J C, Serreze M C, Holland M M, Kay J E, Malanik J and Barrett A P 2012 The Arctic’s rapidly shrinking sea ice cover: a research synthesis Clim. Change 110 1005–27
Tang Q and Leng G 2013 Changes in cloud cover, precipitation, and summer temperature in North America from 1982 to 2009 J. Clim. 26 1733–44
Vautard R, Yiou P and Van Oldenborgh G J 2009 Decline of fog, mist and haze in Europe over the past 30 years Nat. Geosci. 2 115–9
Wang L and Gu W 2016 The Eastern China flood of June 2015 and its causes Sci. Bull. 61 178–84
Wang Y and Wild M 2016 A new look at solar dimming and brightening in China Geophys. Res. Lett. 43 11, 777–785
Wild M, Gilgen H, Roesch A, Olhuma A, Long C N, Dutton E G, Furgan B, Kallis A, Russak V and Tsevktov A 2005 From dimming to brightening: decadal changes in solar radiation at Earth’s surface Science 308 847–50
Wuebbles D J et al 2017 Our globally changing climate. In: Climate Science Special Report: Fourth National Climate Assessment vol 1, ed D J Wuebbles, D W Fahey, K A Hibbard, D J Dokken, B C Stewart and T K Maycock(Washington, DC: US Global Change Research Program) pp 35–72
Xia X 2013 Variability and trend of diurnal temperature range in China and their relationship to total cloud cover and sunshine duration Ann. Geophys. 31 795–804
Yuan W et al 2019 Increased atmospheric vapor pressure deficit reduces global vegetation growth Sci. Adv. 5 eaax1396
Zhao P, Zhang X, Zhou X, Ikeda M and Yin Y 2004 The sea ice extent anomaly in the North Pacific and its impact on the East Asian summer monsoon rainfall J. Clim. 17 3434–47