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Will boreal winter precipitation over China increase in the future? An AGCM simulation under summer "ice-free Arctic" conditions

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Frequent winter snowstorms have recently caused large economic losses and attracted wide attention. These snowstorms have raised an important scientific question. Under scenarios of future global warming, will winter precipitation in China increase significantly and produce more snow in the north? Using Coupled Model Intercomparison Project phase 3 (CMIP 3) model projections under the Special Report on Emissions Scenario A1B scenario, we generated a possible future Arctic condition, the summer (September) "ice-free Arctic" condition. We then used corresponding monthly sea surface temperature (SST) values and a set of CO_2 concentrations to drive an atmospheric general circulation model (AGCM), for simulating East Asian climate change. The experimental results show that during the boreal winter (December-January-February; DJF), global surface air temperature would increase significantly under this scenario, producing substantial warming in Arctic regions and at high latitudes in Asia and North America. The Siberian High, Aleutian Low and East Asian winter monsoon would all weaken. However, because of increased transport of water vapor to China from the north, winter precipitation would increase from south to north. In addition, the significant increase in winter temperature might cause fewer cold surges.

ice-free Arctic, sea ice, climate change, East Asian winter monsoon, winter precipitation

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The East Asian winter monsoon is not only the most powerful winter monsoon worldwide, but also the most active winter circulation pattern in the Northern Hemisphere. This monsoon causes cold waves, temperature drops, snowstorms and other disastrous weather. With the monsoon outbreak, a rapid southward incursion of cold air brings severe weather, such as gales, cooling, frost, rainstorms, freezing rain and serious sandstorms, to most areas of East and Southeast Asia [1]. In recent years, the impacts of frequent snowstorms on northern China have included substantial economic losses, causing widespread concern. These impacts have raised an important scientific question. Under future global warming conditions, will winter precipitation increase significantly and lead to more snowstorms in northern China?

In the context of global climate change, changes in the cryosphere have become an active research area. Qin et al. [2] studied the spatial distribution and temporal variation of snow cover in northwest China and its response to climate change. Moreover, many studies of the polar cryosphere show that Arctic sea ice has significantly declined over the past few decades [3,4], and may continue to decrease in the future. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models anticipate that summer sea ice in the Arctic will melt completely within 60–70 years. Given that the melt rate of sea ice simulated by the IPCC models is significantly slower than observed [5], several scientists argue that there will probably be a complete melt of Arctic summer sea ice within 30 years [6]. This outcome is called the "ice-free Arctic" summer.

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The Arctic cryosphere plays an important role in the climate system, and recent studies [7] have shown that reduced thickness and extent of Arctic sea ice caused a significant increase in ocean-atmosphere heat flux, and played a role in surface air temperature increase in the Arctic region. Research also shows that the decrease of Arctic sea ice is associated with significant changes in large-scale atmospheric circulation in the Northern Hemisphere [8]. Chinese scientists have also conducted many studies in this area [9–11]. Many studies have shown that Arctic sea ice is closely linked to the climate of East Asia [12,13] or other regions [14,15]. The purpose of this study is to use an atmospheric general circulation model (AGCM) estimate of climate change over East Asia under summer ice-free Arctic conditions.

1 Model and experimental design

The model used is the Institute of Atmospheric Physics (IAP) grid-point, nine-layer atmospheric general circulation model (IAP9L-AGCM) developed by Zeng et al. [16–18], based on the IAP grid-point two-layer atmospheric general circulation model (IAP2L-AGCM). IAP9L-AGCM is a C-grid point model with 4°×5° horizontal resolution. σ-p vertical coordinates divide the atmosphere into nine model levels. The top level is 10 hPa. The AGCM has been widely used in short-term climate prediction, interannual and interdecadal climate variability research, studies of the interaction mechanism between components in climate systems and paleoclimate simulation studies [19–21].

We designed and performed two experiments. The first is a control experiment, and is driven by 1971–2000 multi-year monthly mean sea surface temperature and CO_2 content from historical records. The second is a sensitivity experiment that incorporates summer ice-free Arctic conditions. The data used to drive the AGCM in the second experiment include monthly average sea ice concentration and sea surface temperature (SST), from the Coupled Model Intercomparison Project phase 3 (CMIP 3) models under the A1B scenario (including 55 runs of 22 atmosphere-ocean coupled models). First, the extent of sea ice is calculated according to its concentration. If the extent during September in a given year is less than 1.0×10^6 km^2, summer ice-free Arctic conditions are assumed to have occurred [6]. That year is then recorded as the initial year of summer ice-free Arctic conditions. The experiment includes 7 runs of 5 models, including Meteo-France Centre National de Recherches Meteorologiques CM3 Model (CNRM_CM3), United States National Oceanic Atmospheric Administration Geophysical Fluid Dynamics Laboratory CM2.1 Model (GFDL_CM2.1), Japan Centre for Climate System Research/National Institute for Environmental Studies/Frontier Research Centre for Global Change(CCSR/NIES/FRCGC) high and medium resolution Model for Interdisciplinary Research On Climate Version 3.2 (MIROC3.2_hires and MIROC3.2_medres (3 runs)) and the United Kingdom Met Office Hadley Centre for Climate Prediction and Research UKMO-HadCM3, with outputs reaching this standard. We then calculate a ten-year average monthly mean SST from the initial year in the multi-model ensemble (MME), as boundary conditions for the sensitivity experiment. Finally, based on the initial year and corresponding CO_2 concentration from the Bern-CC model (reference case[1)]) under the A1B scenario defined in the IPCC Third Assessment Report, we obtain an ensemble CO_2 concentration as a possible case under summer ice-free Arctic conditions (for more specific information about the experiments, please consult reference [22]).

The other settings of the sensitivity experiment are the same as those in the control experiment. Both experiments are integrated for 35 years, and model output for the last 30 years is analyzed. The changes shown in Figures 2–7 are the differences between outputs of the sensitivity experiment and control experiment. A two-tailed Student's *t*-test was used to test these results for statistical significance.

Figure 1 shows the distribution of Arctic sea ice and sea surface temperature (SST) in the Northern Hemisphere under summer ice-free Arctic conditions, from the control and sensitivity experiments. Comparison of Figure 1(a) and (b) shows that no Arctic sea ice occurs in September in the sensitivity run, and that the winter (DJF) mean area of this ice is substantially reduced (Figure 1(c) and (d)), especially along its borders with the North Atlantic and North Pacific. Moreover, a substantial increase occurs in sea ice temperature.

2 Simulations and projections of winter climate

Under summer ice-free Arctic conditions, surface air temperature (SAT) increases over the entire Northern Hemisphere, and includes a degree of regional variation (Figure 2). The greatest warming is over the Arctic, with an increase in surface air temperature as much as 18°C. This increase is accompanied by increases over Asia and at high latitudes in North America, by as much as 6–12°C. Changes in surface temperature over low-latitude oceans are relatively small, with an increase of approximately 3°C. Because of the difference in thermal capacity of continents and oceans, the magnitude of warming is not identical. High-latitude regions are more sensitive to warming. Moreover, the reduction in Arctic sea ice thickness and area caused by warming could further strengthen the warming over the Arctic region through "snow/ice albedo feedback".

1) A "reference" case was defined with an average ocean uptake for the 1980s, of 2.0 PgC/a.

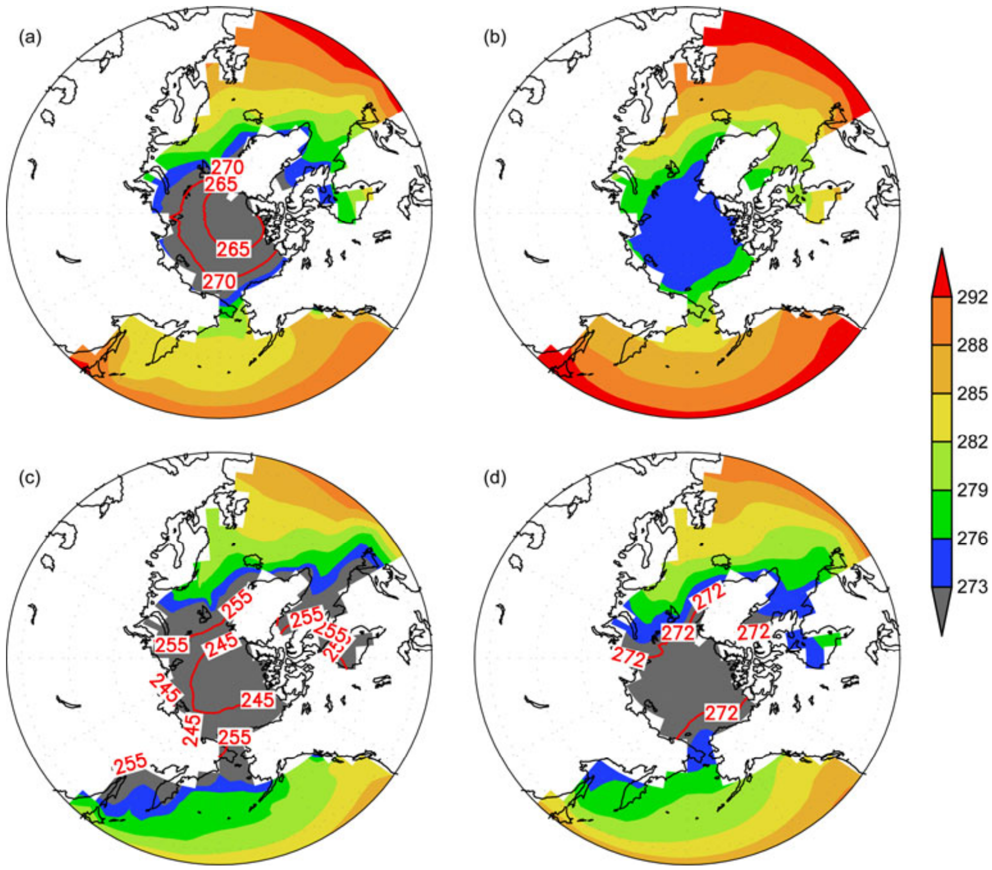

Figure 1 Arctic sea ice and SST settings of control experiment (September (a), winter (DJF) mean (c)), sensitivity experiment (September (b), and winter (DJF) mean (d)) shaded color represents the SST (K); grey-shaded area represents sea ice area; red line represents ice temperature (K).

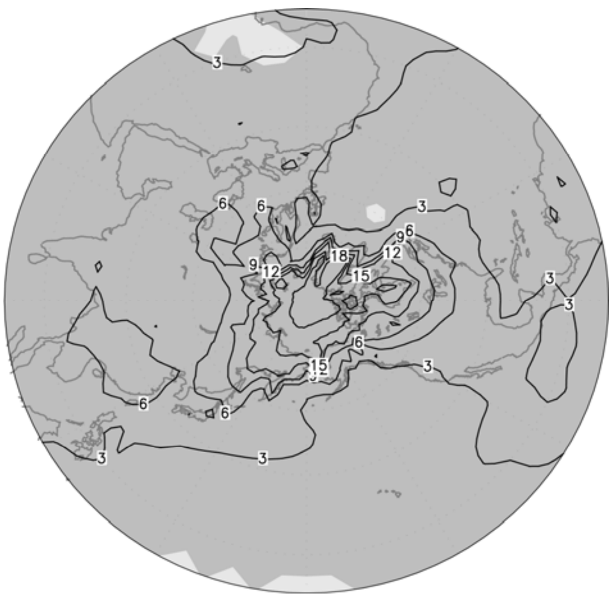

Figure 2 Changes in winter mean surface air temperature (SAT) under summer ice-free Arctic conditions (°C). Light (dark) gray shading illustrates the significance at 5(1)% level, determined from two-tailed Student's *t*-test.

Because the underlying surface is the direct heat source for the atmosphere, the increase in global surface temperatures warms the atmosphere. The increase in CO_2 concentration changes the energy balance of the earth-atmosphere system. These changes would redistribute the air mass, and be reflected in sea-level pressure (SLP) changes. Figure 3 shows changes in the winter mean SLP under the summer ice-free Arctic condition. The SLP increases over the North Pacific. The center of this pattern is near the Aleutian Islands. The area south of 60°N over the Eurasian mainland is dominated by a decrease in SLP, whereas the area north of 60°N shows a relatively strong increase. These SLP changes would result in a weakening of both the winter Aleutian Low and Siberian High. The primary reason for these results may be that the magnitude of the increase in winter surface air temperature over the Eurasian mainland is greater than that over the North Pacific, decreasing thermal contrast between the continent and ocean. The resulting air mass redistribution decreases the intensity of the Siberian High and Aleutian Low. These changes could reduce the pressure gradient between the continent and ocean, significantly weakening the East Asia winter monsoon.

The change in the monsoon may be reflected in the wind field. The multi-year average East Asian winter monsoon is characterized by a consistent northwest airflow over Siberia and Northern China at low levels (here, 850 hPa), a northerly airstream over the southeast China and South China

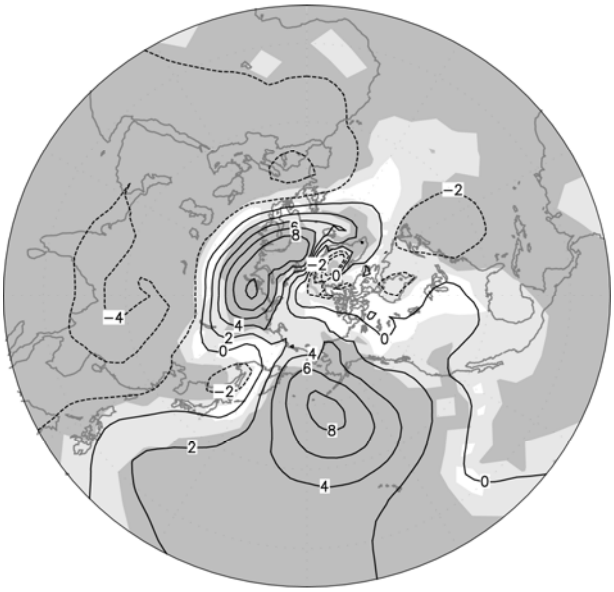

Figure 3 Changes in winter mean sea-level pressure under summer ice-free Arctic conditions (hPa). Light (dark) gray shading illustrates the significance at 5(1)% level, determined from two-tailed Student's *t*-test.

Sea regions, and a weak southwest flow over southwest China resulting from a trough over the Bay of Bengal region [23,24]. Under summer ice-free Arctic conditions, anticyclonic circulation anomalies occur at 850 hPa over the northern Pacific in winter (Figure 4). These anomalies correspond to the weakening Aleutian Low. A significant southerly wind anomaly dominates the area from the South China Sea through central and eastern China to Lake Baikal.

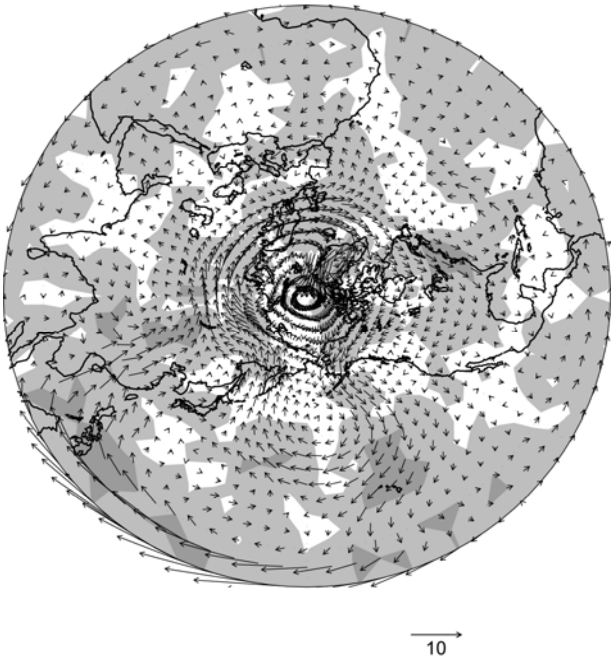

Figure 4 Changes in winter mean wind field at 850 hPa, under summer ice-free Arctic conditions (m/s). Light (dark) gray shading illustrates the significance at 5(1)% level, determined from two-tailed Student's *t*-test.

This indicates that the prevailing northwesterly East Asian winter flow at 850 hPa is weakened. In addition, easterly wind anomalies occur at high latitudes of the Northern Hemisphere near the polar regions, whereas westerly wind anomalies occur in the polar regions themselves. These findings are similar to the results of Overland and Wang [8], obtained through data reanalysis.

Snowstorms, freezing rain and other severe weather caused by winter monsoon variation are closely associated with precipitation changes. At high latitudes of the Northern Hemisphere, winter precipitation (including snow) generally increases under summer ice-free Arctic conditions, especially over southern China and Greenland, and decreases over the North Pacific (Figure 5). Although air temperature and precipitation both increase, the winter mean SAT remains below 0°C over most of northern China, as the red isotherm indicates. Therefore, the condition for snowfall is still satisfied.

Increasing south-to-north precipitation in China may be associated with the weakening of the East Asian winter monsoon. Atmospheric moisture and vapor transport are closely related to precipitation, as discussed in the following section.

Under summer ice-free Arctic conditions, significant positive water vapor transport anomalies occur over Indochina and the South China Sea. A significant water vapor transport convergence occurs over central and eastern China. There is a weak water vapor transport anomaly from the northwest, over most of northern China. Since the average winter water vapor transport originates from the north, the abnormal moisture transport pattern indicates more water vapor from the north. This change is an important reason for

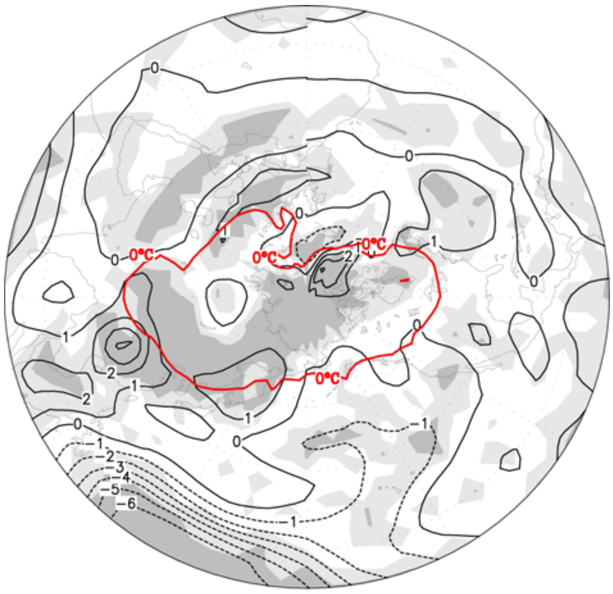

Figure 5 Changes in winter mean precipitation under summer ice-free Arctic conditions (mm/d). Red isotherm corresponds to winter mean SAT of 0°C. Light (dark) gray shading illustrates the significance at 5(1)% level, determined from two-tailed Student's *t*-test.

the increased winter precipitation in China. This increased water vapor transport results from enhanced atmospheric water vapor content at high latitudes from warming and sea ice melt, rather than from strengthening of the circulation. This is clearly shown in Figure 7.

Another obvious change is a water vapor transport anomaly stretching from the sea near the Bahamas to the Atlantic and Mediterranean region. This anomaly may be an important reason for the increase in precipitation over parts of the North Atlantic (north of 20°N, 45°–75°W) and the Mediterranean.

Figure 7 shows the simulated change (%) of winter, column-integrated water vapor in the sensitivity run, compared with that of the control run. This calculation uses the formula

$$\frac{\left(\int_{p_9}^{p_1} q_s dp - \int_{p_9}^{p_1} q_c dp\right)}{\int_{p_9}^{p_1} q_c dp} \times 100\%, \qquad (1)$$

where q_s and q_c are specific humidities of the sensitivity and control runs, respectively. Pressures at the lowest and highest levels of IAP9L-AGCM are p_9 and p_1, respectively.

These results show that atmospheric, column-integrated water vapor increases to a substantial extent over the Northern Hemisphere during winter (Figure 7), because of the reduction of sea ice content and substantial warming under summer ice-free Arctic conditions. The relative increase at high latitudes is greater than at lower latitudes, and is especially great over polar regions. The greatest relative increase reaches 200%.

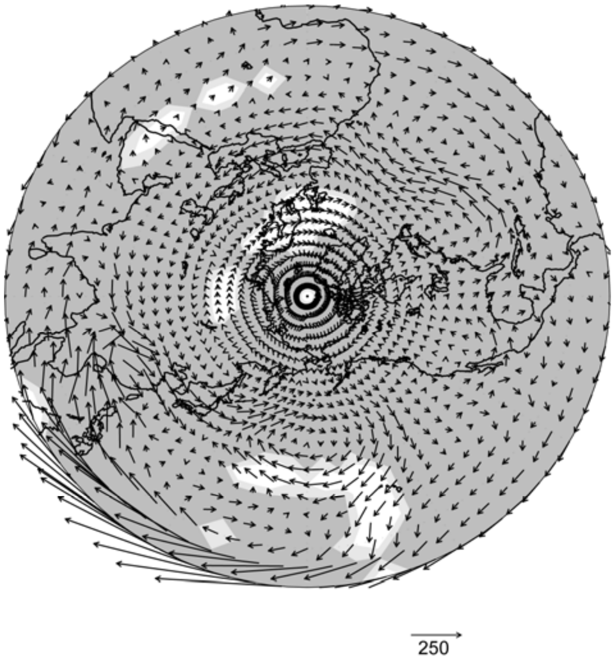

Figure 6 Changes in winter mean water vapor transport under summer ice-free Arctic conditions (kg/(m s)). Light (dark) gray shading illustrates the significance at 5(1)% level, determined from two-tailed Student's *t*-test.

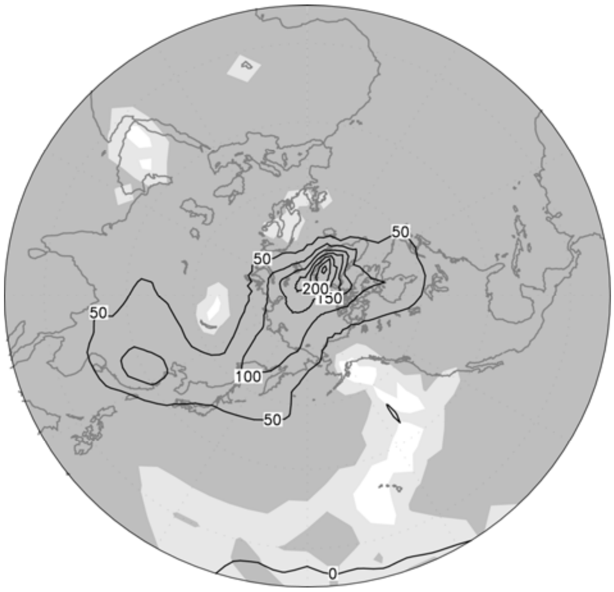

Figure 7 Changes in winter mean integrated water vapor under summer ice-free Arctic conditions (%). Light (dark) gray shading illustrates the significance at 5(1)% level, determined from two-tailed Student's *t*-test.

The effect of increased water vapor is greater than that of the weakened winter monsoon circulation. The net effect is an increase in water vapor transport to China. The preceding analysis shows that despite a significant temperature increase, winter mean SAT is still less than 0°C in many parts of northern China (Figure 5). In view of these thermal conditions, the combined effect would be to increase the probability of heavy snowstorms with cold waves.

3 Summary and discussion

Experiments were conducted to study potential climate change if the Arctic becomes ice-free in summer, under a future global warming scenario. The "ice-free" Arctic summer simulation is characterized by a weakened East Asian winter monsoon circulation, and increased precipitation (including snow).

The winter mean surface air temperature (SAT) increases over the entire Northern Hemisphere, especially over the polar region and high-latitude mainland. The general warming trends, particularly those over the source of cold waves, may in theory reduce or weaken cold waves.

The greater warming over land areas may decrease the thermal contrast between land and ocean in winter, consequently decreasing the intensities of the winter Aleutian Low and the Siberian High. These changes could ultimately weaken the monsoon circulation. Changes in the winds at 850 hPa confirm these conclusions.

Accompany with the weakened East Asian winter monsoon, winter precipitation in China will increase. A strengthened water vapor transport furnishes water vapor for increased precipitation. Although the warming is significant, average winter surface air temperature remains less than 0°C in most areas of northern China, as Figure 5 shows. As a result, parts of northern China may receive more snow. Moreover, these regions would receive more heavy snow in the event of a cold wave. This result should be of particular concern.

This study presents several possible features of East Asian climate under summer ice-free Arctic conditions. Because of considerable uncertainty in prediction and projection using climate models, more research is urgently needed. We also performed analyses using CMIP3 coupled model outputs. These analyses are consistent with IAP9L-AGCM simulations of water vapor transport and atmosphere-ocean flux. The mechanism underlying the changes and differences between models should be further explored, by comparing simulations based on different coupled models and on AGCMs.

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