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Speeding extreme cold events under global warming

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E-mail: hjp@lzu.edu.cn**Keywords:** extreme cold event, anthropogenic effect, meridional circulation**Abstract**

Regional anthropogenic warming caused stronger and shorter cold events in the winter (December–February) of 2020–21, with the strongest cooling of -10°C covering an area of $1.63 \times 10^7 \text{ km}^2$ over East Asia. In contrast to previous cold events, the extreme cold events in 2020–21 were a result of meridional circulation change due to stronger regional anthropogenic warming. Our results show a multi-aspect anthropogenic effect in the process of cold events, and illustrate that anthropogenic effect played a role not only in the thermodynamic process but also in the dynamic process. The exchange of equilibrium from low to high index does not take fewer cold events anymore; new principles on equilibrium have appeared and will soon play an effect in more fields of climate change.

1. Introduction

Previous studies have shown that global warming increases the background mean temperature and seems to decrease the frequency of cold events (e.g. Christiansen *et al* 2018). However, the winter of 2020–21 was a year with high-frequency cold events, which raises the question of the effect of anthropogenic warming on changes in cold events. The circulation configuration of 2020–21 was closely related to the persistent and extensive anticyclone centered around the Ural Mountains, which was induced by the negative phase of the Arctic Oscillation, and by La Niña condition over the Pacific Ocean (WMO 2020). During late December of 2020, heavy snow occurred in North China, with the maximum decrease in temperature exceeding 8°C . Nine counties in Jilin and Liaoning experienced their maximum decrease in temperature on record (Li *et al* 2021). During early January of 2021, cold-wave processes affected East Asia. The maximum decrease in temperature was more than 12°C in Eastern China. Low-temperature freezing and snow disasters influenced agriculture and animal husbandry, caused road icing and was harmful for transportation and power supply (Li *et al* 2022).

Previous studies have shown that the occurrence of cold events is closely associated with the

equilibrium of a low-index flow, and fewer cold events in the equilibrium of a high-index flow (Charney and DeVore 1979, Huang *et al* 2017). The change in equilibrium is closely associated with regional warming, such as the obvious zonal temperature difference between ocean and land, and the meridional thermal difference between mid and high latitudes of the Northern Hemisphere (Li *et al* 2020b). The new multiple equilibrium theory (Li *et al* 2020a) proposed that the equilibrium of a low index with stronger meridional circulation leads to a probability of cold events. Cold events in 2020–21 are examples of a low index of equilibrium with a stronger meridional thermal index. Therefore, it is worth conducting further investigation of these cold events. In this study, we analyzed the characteristics of cold events in the winter of 2020–21 and qualified the roles of anthropogenic effects in these cold events.

2. Data and methods

The study area covers (100° – 140° E, 20° – 60° N). The daily mean surface air temperature (SAT) and geopotential height fields at 1000 and 500 hPa were obtained from the NCEP I Reanalysis (Kalnay *et al* 1996). Multi-model ensemble simulations for the period 1951–2100 were obtained from the Coupled Model Intercomparison Project 6 (CMIP6) archive.

Table 1. Summary of CMIP6 models used in this study.

Model	Institute and country	Resolution
NESM3	Nanjing University of Information Science and Technology, China	192 × 96
MRI-ESM2-0	Meteorological Research Institute, Japan	320 × 160
MIROC6	Atmosphere and Ocean Research Institute Japan	256 × 128
FGOALS-g3	Chinese Academy of Sciences, China	180 × 80
CanESM5	Canadian Centre for Climate Modelling and Analysis, Canada	128 × 64
KACE-1-0G	Korea Meteorological Administration, Republic of Korea	192 × 144
CESM2-WACCM	National Center for Atmospheric Research, USA	288 × 192
KIOST-ESM	Korea Institute of Ocean Science and Technology, Republic of Korea	192 × 96
MPI-ESM1-2HR	Deutsches Klimarechenzentrum, Germany	384 × 192
INM-CM4-8	Institute for Numerical Mathematics, Russia	180 × 120
INM-CM5-0	Institute for Numerical Mathematics, Russia	180 × 120
MPI-ESM1-2-LR	Max Planck Institute for Meteorology, Germany	192 × 96
AWI-CM-1-1-MR	Alfred Wegener Institute, Germany	384 × 192
IITM-ESM	Centre for Climate Change Research, India	192 × 94
TaiESM1	Research Center for Environmental Changes, Taiwan	288 × 192
CMCC-ESM2	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	288 × 192
CMCC-CM2-SR5	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy	288 × 192
IPSL-CM6A-LR	Institut Pierre Simon Laplace, France	144 × 143
EC-Earth3-Veg	Swedish Meteorological and Hydrological Institute, Sweden	512 × 256
EC-Earth3-Veg-LR	Swedish Meteorological and Hydrological Institute, Sweden	320 × 160
EC-Earth3	Swedish Meteorological and Hydrological Institute, Sweden	512 × 256
NorESM2-LM	Norwegian Meteorological Institute, Norway	144 × 96
NorESM2-MM	Norwegian Meteorological Institute, Norway	288 × 192
ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organisation, Aspendale, Australia	192 × 145
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organisation, Aspendale, Australia	192 × 144
GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, USA	360 × 180

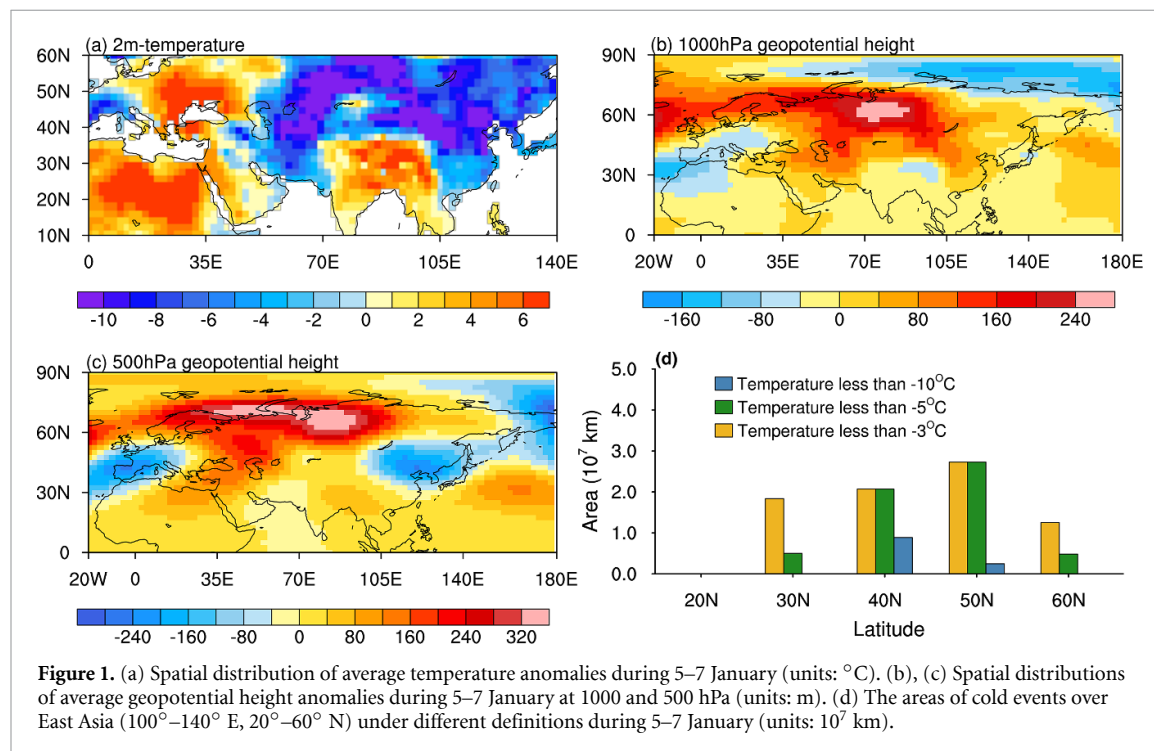


Figure 1. (a) Spatial distribution of average temperature anomalies during 5–7 January (units: °C). (b), (c) Spatial distributions of average geopotential height anomalies during 5–7 January at 1000 and 500 hPa (units: m). (d) The areas of cold events over East Asia (100°–140° E, 20°–60° N) under different definitions during 5–7 January (units: 10⁷ km²).

Table 2. The area influenced by cooling of -3°C , -5°C and -10°C over East Asia. Units: 10^7 km^2 .

Latitude	SAT less than -3	SAT less than -5	SAT less than -10
20° N	0	0	0
30° N	1.84	0.50	0
40° N	2.07	2.077	0.89
50° N	2.73	2.73	0.25
60° N	1.25	0.48	0

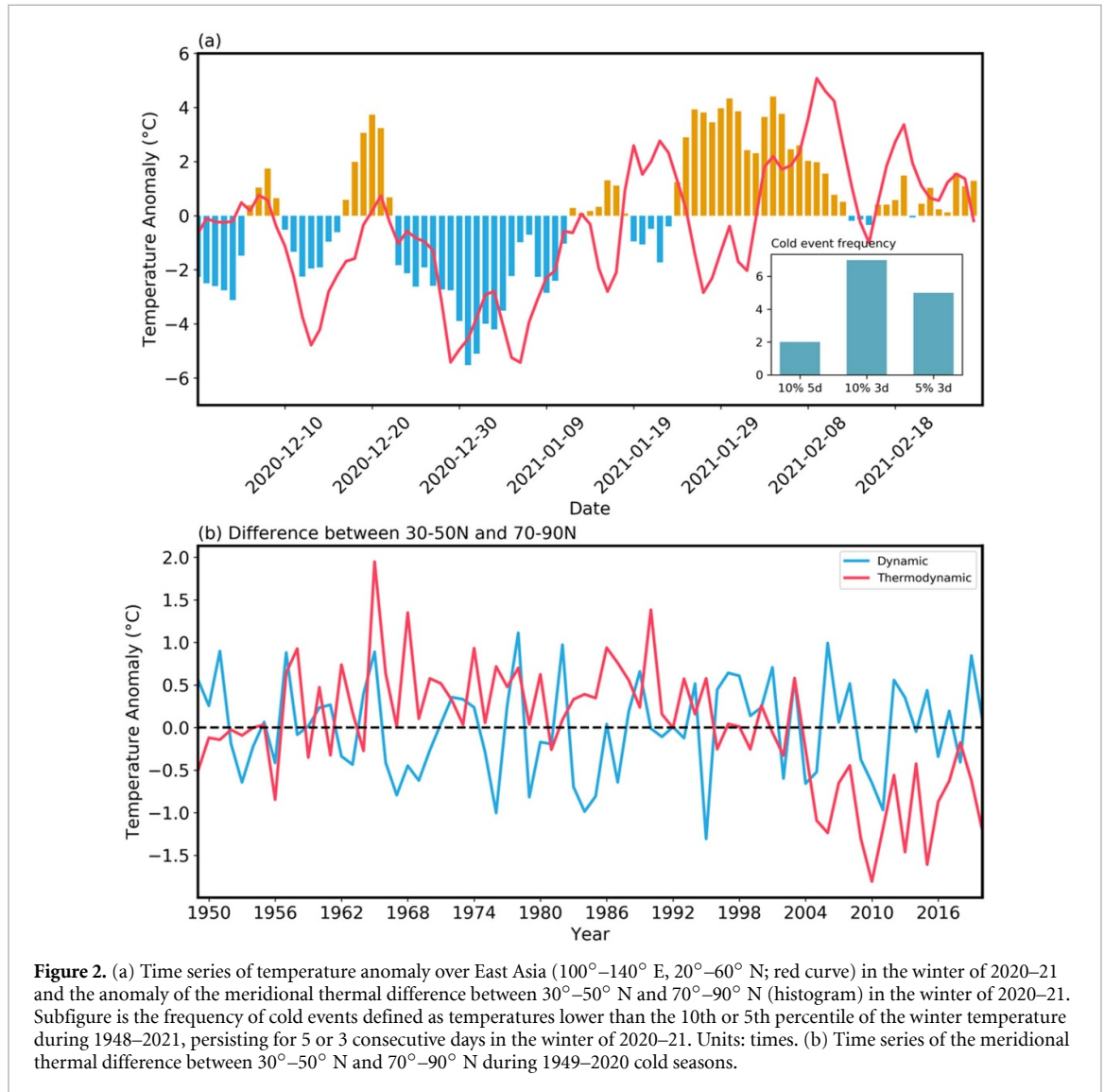


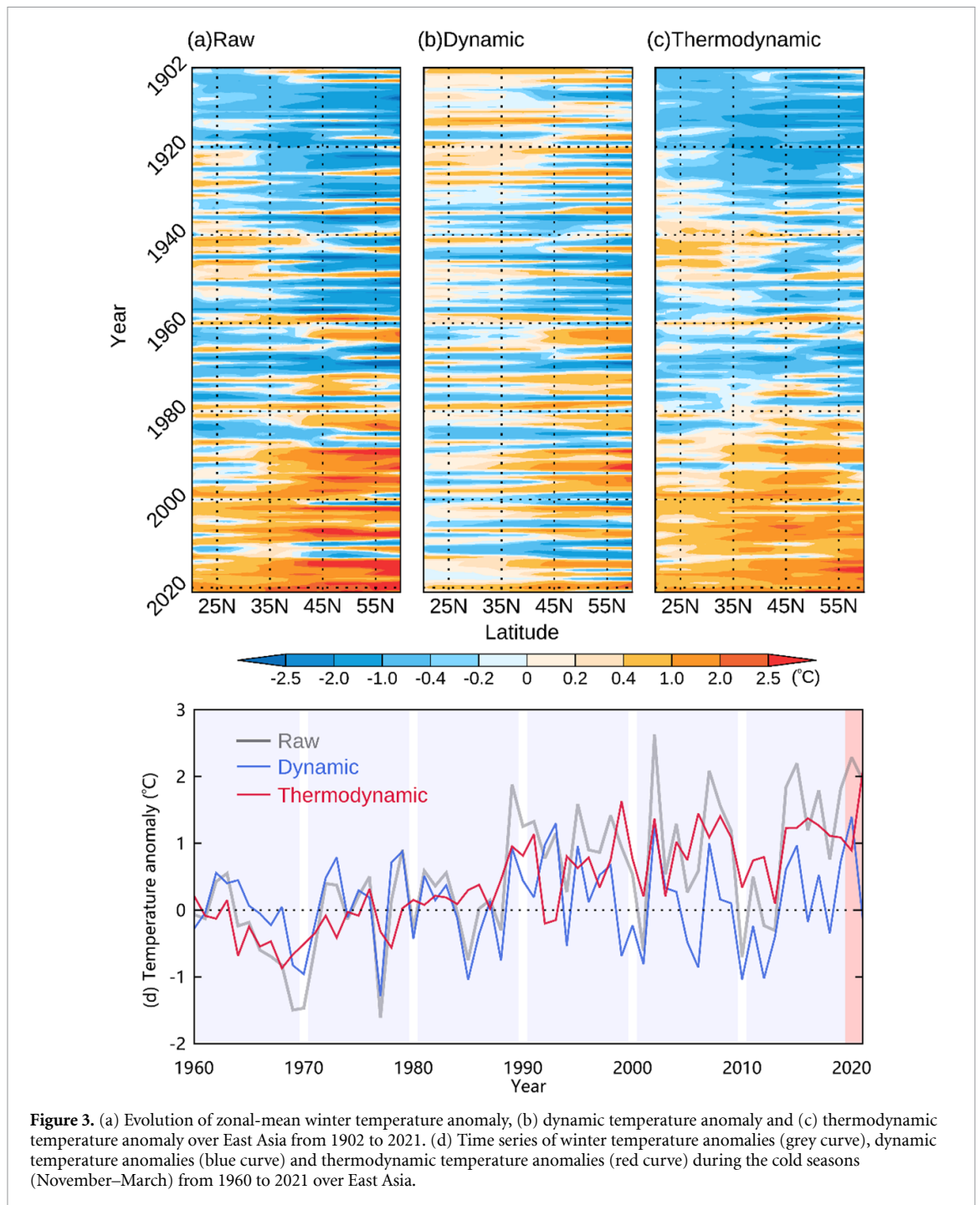
Figure 2. (a) Time series of temperature anomaly over East Asia (100° – 140° E , 20° – 60° N ; red curve) in the winter of 2020–21 and the anomaly of the meridional thermal difference between 30° – 50° N and 70° – 90° N (histogram) in the winter of 2020–21. Subfigure is the frequency of cold events defined as temperatures lower than the 10th or 5th percentile of the winter temperature during 1948–2021, persisting for 5 or 3 consecutive days in the winter of 2020–21. Units: times. (b) Time series of the meridional thermal difference between 30° – 50° N and 70° – 90° N during 1949–2020 cold seasons.

To explore the future change of cold events, 26 CMIP6 climate models were considered in our study (table 1), including both historical simulations (1950–2014) and future projections based on the SSP 1–2.6 and SSP 5–8.5 scenarios (2015–2100) (O’Neill *et al* 2017).

Sea-level pressure data with a resolution of $1^{\circ} \times 1^{\circ}$ for 1901–2021 were collected from the National Oceanic and Atmospheric Administration (NOAA)/Cooperative Institute for Research in Environmental Sciences 20th Century Reanalysis (20CR) version 3 (Compo *et al* 2011) and the ERA5 monthly mean reanalysis (Hersbach *et al* 2019). Monthly global land SAT data from 1901 to 2021 at a resolution

of $0.5^{\circ} \times 0.5^{\circ}$ were obtained from the Climate Research Unit (version TS4.05) of the University of East Anglia (Mitchell and Jones 2005) and the ERA5 monthly mean reanalysis (Hersbach *et al* 2019).

The dynamic adjustment method was proposed by Wallace *et al* (2012) to separate dynamic and adjusted SATs. Dynamic SAT is associated with atmospheric circulations, and is called dynamically induced SAT. After removing the dynamically induced SAT variability, the residual is associated with radiative forcing factors, such as the buildup of greenhouse gases (GHGs), stratospheric ozone depletion, volcanic eruptions, and aerosol emissions,



with a dominant role played by anthropogenic GHGs (Zhang *et al* 2017). This component is called adjusted SAT or radiatively forced SAT variability.

3. Results

The cold events in 2020–21 caused high-frequency and stronger cooling (figure 1(a)). Cold events were reported on 12–14, 27, and 29–30 December in 2020, and on 1–5 and 14–16 January in 2021 (China Meteorological Administration 2020, 2021), and reached the historic lowest record during the last 67 years in some areas (Xu and Singh 2021). As seen from

the associated circulation pattern, the geopotential height at 1000 hPa exhibits a larger change around the Ural Mountains (figure 1(b)), and East Asia was dominated by a sustained anticyclone centered over the Ural Mountains at 500 hPa during this period (figure 1(c)). Meanwhile, there were unusual low-pressure centers in both upstream regions (North Africa and western Europe) and downstream regions (East Asia).

Influenced by this circulation pattern, North-east China was behind the deepened East Asian trough and ahead of the enhanced Siberian cold high; therefore, a descending movement and upper-level

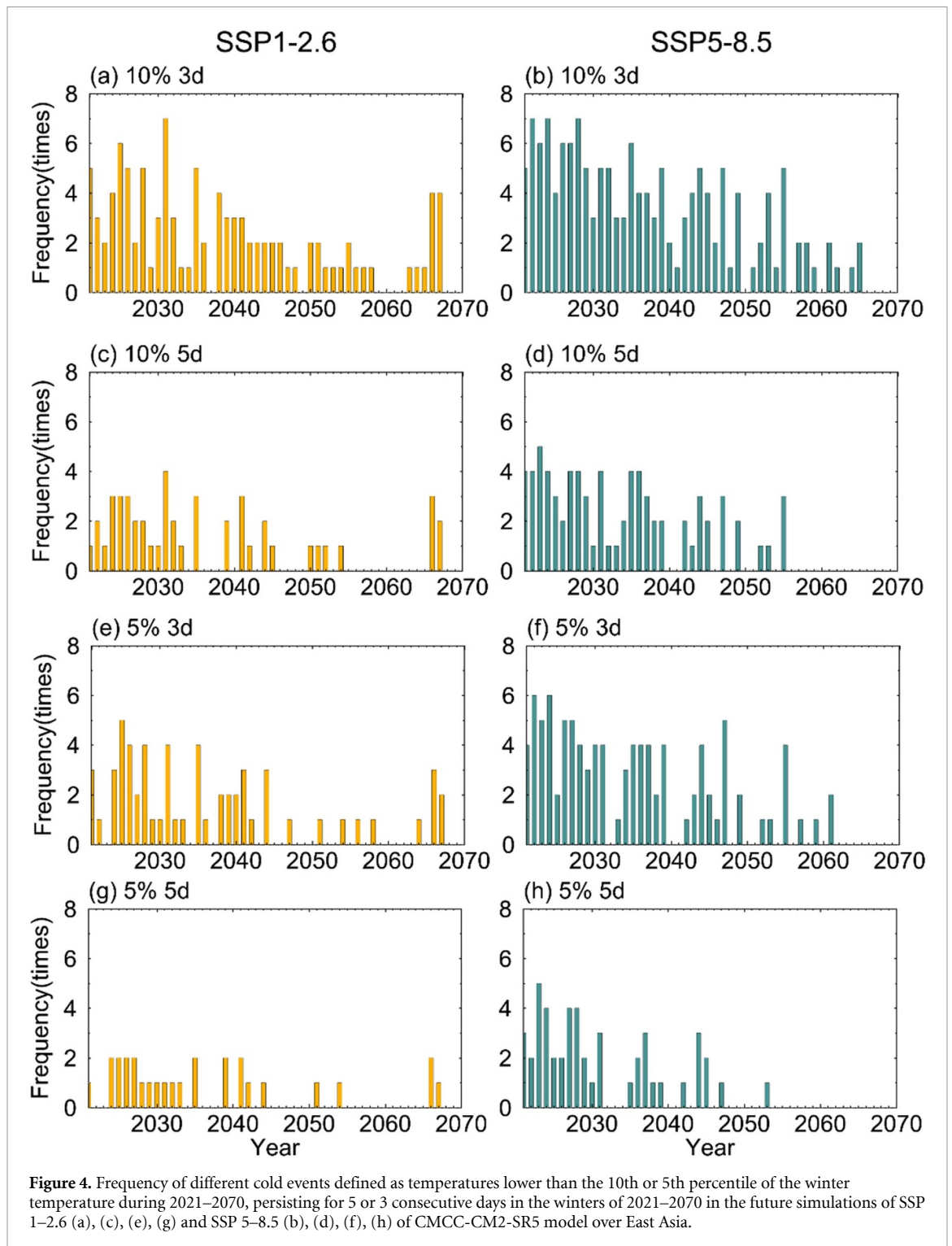
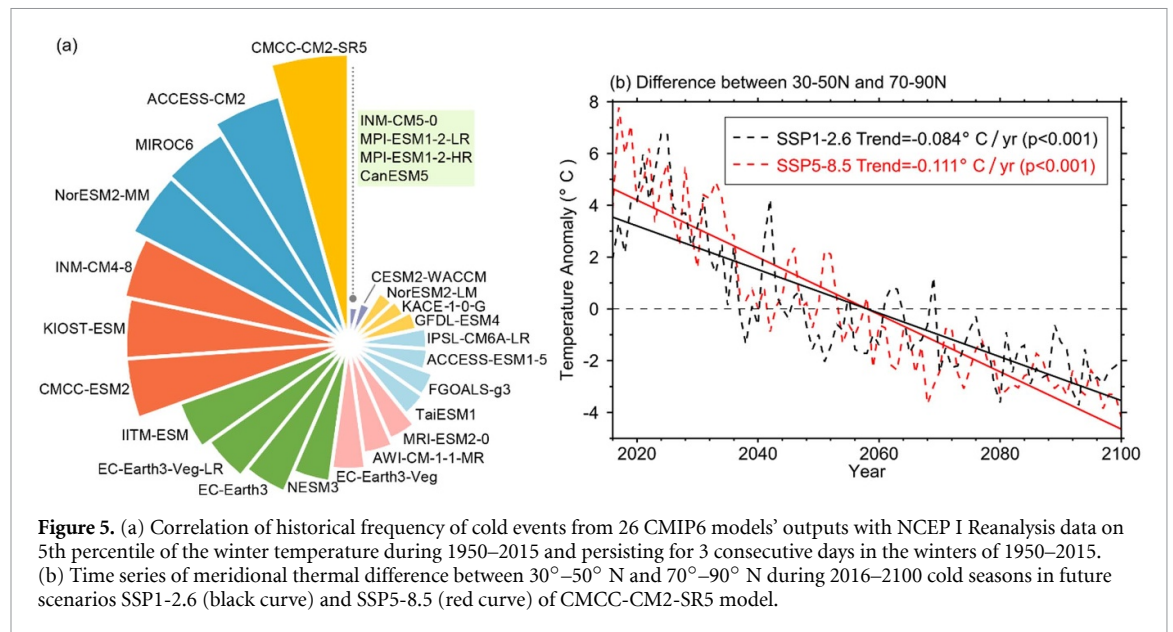


Figure 4. Frequency of different cold events defined as temperatures lower than the 10th or 5th percentile of the winter temperature during 2021–2070, persisting for 5 or 3 consecutive days in the winters of 2021–2070 in the future simulations of SSP 1–2.6 (a), (c), (e), (g) and SSP 5–8.5 (b), (d), (f), (h) of CMCC-CM2-SR5 model over East Asia.

northwesterly prevailed, which were favorable for cold events (Zheng *et al* 2021). The resulting northerly cold air provided favorable condition for severe cold winters in East Asia. When the polar vortex weakened or even split, it allowed frigid air to escape and push southward toward East Asia and cooled East Asia, the cold events that occurred in the winter of 2020–21. The areas affected by the cold events showed clear zonal differences (figure 1(d)). The most widespread area was located near 50° N with the largest area of $5.71 \times 10^7 \text{ km}^2$, where the decrease was even

over 10 °C, followed by the area near 40° N; however, the largest cooling area was concentrated at -3 °C (figure 1(d), table 2).

According to reports on the cold events in 2020–21, the cold event frequency in the winter of 2020–21 was five times (China Meteorological Administration 2020, 2021). Traditionally, cold events in China are defined as temperatures lower than the 10th percentile of the average temperature, persisting for 5 consecutive days (Zhang and Qian 2011). According to this definition, the frequency of the latest cold events was



two times, which is not consistent with the reports of the CMA (figure 2(a)). However, cold events with the definition of 5% and 3 d occurred five times, which is consistent with the reports of the CMA.

As is shown in figures 3(a)–(c), both raw and thermodynamic temperature anomalies were mainly in the negative phase at 20°–60° N before 1980, and in the positive phase after 1980. The raw and thermodynamic temperatures increased sharply after 1980, especially north of 40° N. From the time series of temperature in figure 3(d), the temperatures were maintained at a low level before 1980. The obvious increasing of raw temperature since the 1990s was mainly induced by the enhanced warming of thermodynamic temperature. The thermodynamic temperature was much higher than the dynamic temperature in 2020–21 (The light red background area in figure 3(d)). When the thermodynamic temperature was in an upward (warming) phase in 2020–21, it balanced or reduced the dynamic cooling and resulted in a relatively high value of raw temperature. Therefore, the 2020–21 was a good period for studying the effect of regional warming on cold events.

The occurrence of cold events in the winter of 2020–21 decreased temperatures over the mid-to-high latitudes of the Northern Hemisphere, reduced the temperature difference between the high and mid latitudes, and led to a weak meridional circulation (figure 2(a)). Yao *et al* (2022) suggested that the weak meridional circulation favors the decrease of westerly wind and results in more cold air from the Arctic. Meanwhile, the temperature adjusted by anthropogenic factors (figure 3) was at a high level in 2020–21, which quickly offset the cooling from the Arctic (Guan *et al* 2015), the meridional circulation turn positive (histogram in figure 2(a)), terminating the cold events, and shortening the duration of each cold event. Such a mechanism in the equilibrium of a low

index resulted in stronger and shorter cold events in the past winter.

4. Conclusions

During the winter of 2020–21, cold events swept over Northeast Asia, which were characterized by the lowest historical temperatures. The enhanced Arctic warming contributed to the stronger explosion of cold air, and the equilibrium state of the low index by thermodynamic temperature decreased the duration of each cold event and led to stronger and shorter cold events. From 2000 to 2010, the natural oscillation was stronger than the anthropogenic meridional thermal temperature, and showed a high index of equilibrium, resulting in typical high-frequency cold events (Huang *et al* 2017). In the winter of 2020–21, although the natural oscillation was abnormally strong, the thermodynamic meridional thermal index was also powerful and dominated equilibrium in the low index. Therefore, the cold events in 2020–21 were typical of stronger and shorter characteristics due to anthropogenic warming.

The anthropogenic effect is also illustrated by the CMIP6 models' outputs. The positive contribution by GHGs is illustrated in frequency of different cold events in SSP 1–2.6 (figures 4(a), (c), (e) and (g)) and SSP 5–8.5 (figures 4(b), (d), (f) and (h)) from 2021 to 2070 by CMCC-CM2-SR5 model (it has the largest correlation coefficient of 0.32, passing the 95% confidence level with the reanalysis dataset on the extreme cold events of 5th percentile of the average temperature and persisting 3 consecutive days; figure 5(a)). Figure 4 illustrates that the high emission scenario has a higher-level frequency of extreme cold events, even the temperatures lower than the 5th percentile of the average temperature and persisting 5 consecutive days (figure 4(h)); it is also a result

of enhanced decreasing of meridional temperature (figure 5(b)) difference in SSP 5–8.5 and contributes to more extreme cold events.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors have declared that no competing interests exist.

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