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# The January 2021 Cold Air Outbreak over Eastern China: Is There a Human Fingerprint?

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A cold air outbreak swept across eastern China in January 2021. It is characterized as a weakened cold event that would have been more severe with less anthropogenic warming.

On 6–8 January 2021, a cold air outbreak swept across eastern China, peaking over the North China Plain the night of 6 January, when 219 weather stations recorded the lowest nighttime temperature since 1961. In total, 498 stations recorded the lowest daytime or nighttime temperature since 1961 during the 3-day event. This event, together with two other cold outbreaks that affected the region on 13–15 December 2020 and 29 December 2020–1 January 2021, led to historic peak electricity demand and resumption of the operation of the only remaining coal-fired generating plant in Beijing.<sup>1</sup> This analysis puts the cold outbreak into historical perspective by considering changes in the likelihood of such events over 1961–2020 in the context of a climate that is being warmed by anthropogenic forcing.

## Event definition.

We define the event using a cold-degree days (CDD) metric calculated as the cumulative sum of negative daytime maximum and nighttime minimum temperature anomalies during a cold event (in degree days,

<sup>1</sup> <https://www.reuters.com/article/us-china-weather-energy-transportation-idUSKBN29D104>

using °C), where anomalies are defined relative to 1961–90, with the climatological values for calendar days being determined using 15-day moving windows. The CDD metric is similar to the heating degree days metric, except that temperature differences from climatology are accumulated rather than differences from a fixed temperature threshold, thus minimizing the influence of biases in model-simulated CDD. CDD is related to anomalous energy consumption during a cold event.

We focus on the January 2021 event because it was the most extensive of the three cold outbreaks in the 2020/21 winter as indicated by the number of stations observing record low temperatures since 1961. The associated atmospheric circulation features include a strengthened Ural high and a deepened East Asian trough, creating circulation conditions favoring the invasion of cold air into eastern China from the Arctic (see Fig. S1 in the online supplemental material; Zheng et al. 2021).

## Data and methods.

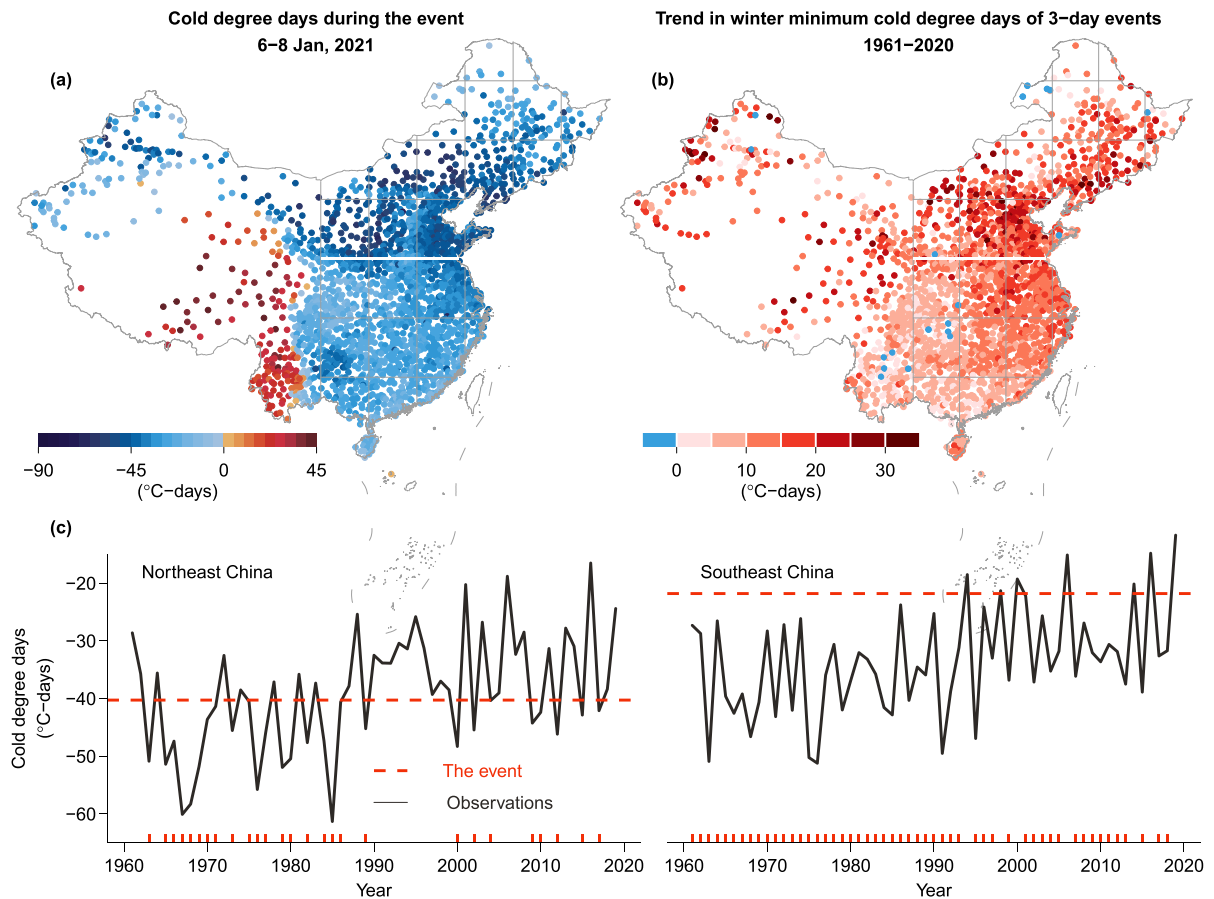
We acquired daily maximum and minimum temperatures from 2419 mainland China weather stations for 1961–2021. We also obtained simulations of these two variables from available climate models from phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al. 2016) that provided three or more merged historical and Shared Socioeconomic Pathway 5–8.5 simulations (SSP5–8.5; O’Neill et al. 2016) and natural-forcing only simulations for 1961–2020 as of July 2021 (see Table S1 in the online supplemental material). Although the CMIP6 natural-forcing only simulations for 2015–20 are driven by the SSP2–4.5 natural forcing agents (Gillett et al. 2016), using SSP2–4.5 simulations to extend the historical simulations (which end in 2014) reduces available climate model ensemble sizes (Table S1). Nevertheless, our conclusions are qualitatively robust to the choice of SSP simulations for data extension (Fig. S2).

We computed CDD for the event and annual CDD minima (CDDn) for 1961–2020 from consecutive 3-day CDD values for individual winters at individual stations. To investigate human influence on CDD, we first aggregated station temperatures to  $5^\circ \times 5^\circ$  grid cell values, and then computed CDD values from the gridded values. Stations with at least 90% of daily observations for all winters in 1961–2020 were used. Temperature simulations were linearly interpolated to the same  $5^\circ \times 5^\circ$  grid before computing model CDD values.

We use a GEV distribution-based fingerprinting method (Zwiers et al. 2011; Wang et al. 2017) to evaluate whether human influence is discernable in the 1961–2020 CDDn observations and, if so, to quantify the human influence on the likelihood of a 3-day outbreak as cold as or colder than the 2021 event. We focus on mainland China east of  $105^\circ\text{E}$ , which was the region most impacted by the event. We conduct separate fingerprinting analyses for northern and southern parts of the region to accommodate their different rates of CDDn change. These analyses were conducted on the  $5^\circ \times 5^\circ$  grid cells marked in Fig. 1, using only those with at least 10 sufficiently complete stations.

The method fits CDDn observations at valid grid cells to GEV distributions with grid-cell-specific location, scale, and shape parameters. At each grid cell  $s$ , the location parameter varies with time as a linear function  $\mu_{s,t} = c_s + X_{s,t}\beta$  of the climate model simulated response  $X_{s,t}$  of CDDn to external forcings at that grid cell. All grid cells share the same scaling factors  $\beta$  by assuming that the model responses have the same spatiotemporal patterns as those in the observations. The model response at a given grid cell to a given external forcing is estimated as the location parameter of a GEV distribution fitted to simulations of CDDn under that forcing. Location parameters, which are assumed to vary slowly as a consequence of forcing, are constrained to be constant within 5-yr periods. Scale and shape parameters are held constant throughout the period.

Uncertainty of the scaling factor estimates  $\hat{\beta}$  due to internal variability in model responses and observations is estimated with a two-stage spatiotemporal block bootstrap procedure

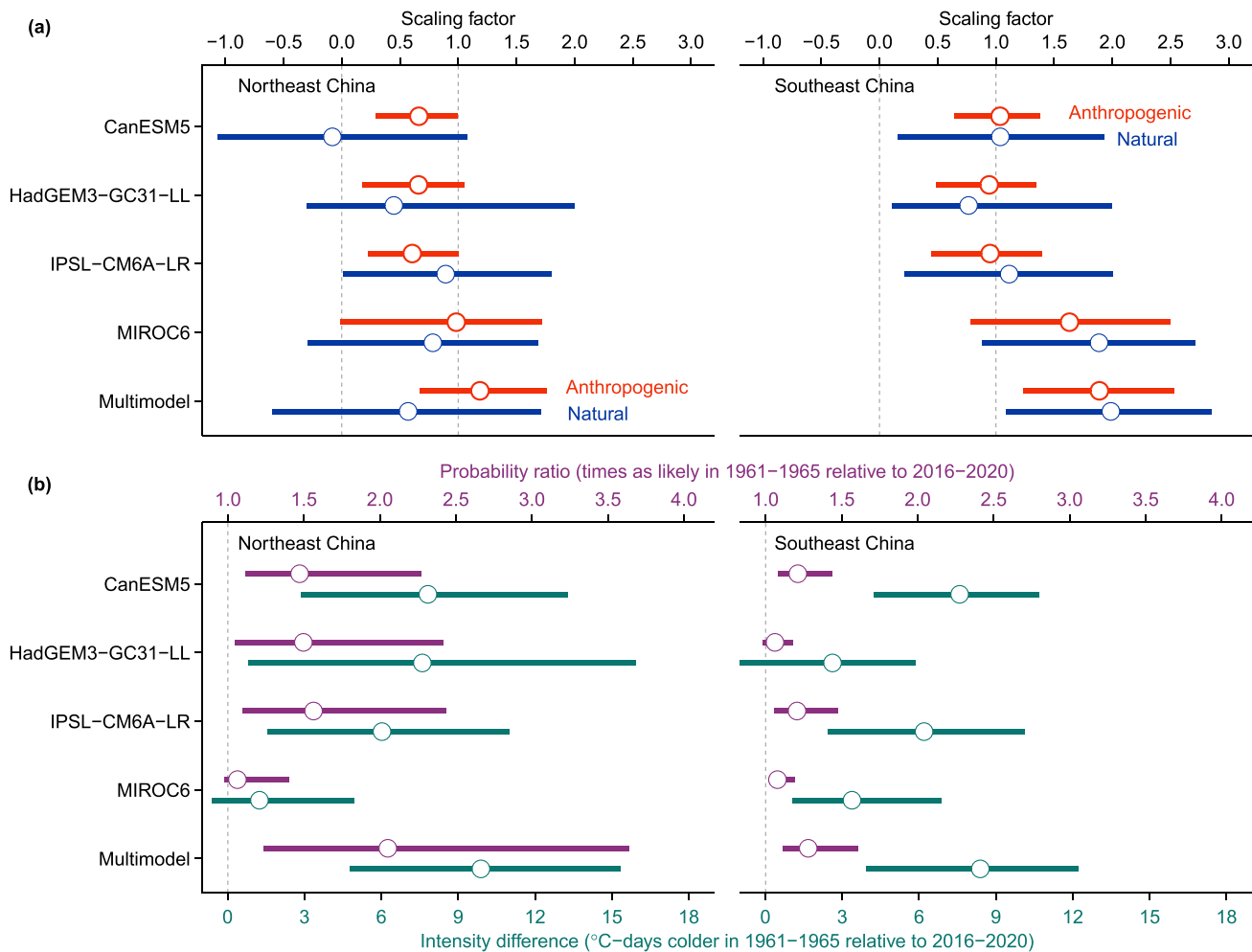


**Fig. 1. Characteristics of the January 2021 cold event and its climate background. (a) Cold degree days observed during the 3-day cold event of 6–8 Jan 2021. (b) The 1961–2020 trends in annual minimum cold degree days of 3-day cold events (CDDn). Grid cells north and south of the white lines mark the regions of detection and attribution analyses, which are referred to as Northeast and Southeast China, respectively. (c) Time series of CDDn from 1961 to 2020 derived from regional mean daytime and nighttime temperatures of the period over (left) Northeast and (right) Southeast China, respectively. Red dashed lines show CDD values for the event, and red ticks mark years with CDDn values colder than the event value.**

(Zwiers et al. 2011). We first examine the resulting confidence intervals to determine if human influence is detected in the CDDn observations. The human influence on the likelihood and intensity of the observed event is then evaluated by comparing the estimated frequency of 3-day events as severe as the observed event during 2016–20 with that during 1961–65 and by considering changes in CDD values of 3-day events in the two periods that have the same frequency as the observed event in 2016–20.

## Results.

*A mild 3-day cold event.* Although clusters of weather stations over regions such as the North China Plain reported record low temperatures during the event (Fig. S3), it was not a very extreme cold event on average when considering the entire northeastern and southeastern China domains. The event (Fig. 1a) occurred against a background of anthropogenic global warming. The corresponding warming of CCDn at nearly all stations (Fig. 1b) is consistent with the fact that regional CCDn values colder than observed during the 3-day event previously occurred in 27 and 52 of the 59 winters between 1961 and 2019 in northeastern and southeastern China, respectively (Fig. 1c). In northeastern China the observed event would have been considered mild during the first half of the period of record and not exceptionally cold during the second half of the period, whereas in southeastern China the event would have been considered mild throughout the period.



**Fig. 2. Detection of human influence on the strength and probability of the January 2021 cold event. (a) Scaling factors and their 5%–95% confidence intervals from two-signal fingerprinting analyses of CDDn over (left) Northeast and (right) Southeast China using single or multimodel anthropogenic and natural forcing response signals. (b) Regional median probability ratios and their 5%–95% confidence intervals comparing the estimated likelihood of colder than observed grid-cell CDD values during 1961–65 relative to 2016–20 (purple) in (left) Northeast and (right) Southeast China, and regional median differences in CDD values of 3-day events that have the same frequency as the observed event in 2016–20 and their 5%–95% confidence intervals (green).**

*Human influence on observed CDDn during 1961–2020.* Fingerprinting analyses (Fig. 2a) show that the climate model simulated weakening of the strength of cold events due to anthropogenic forcing is detected in the 1961–2020 CDDn observations in both northeastern and southeastern China. Detection occurs, with one minor exception, using signals estimated from either individual model ensemble simulations or multimodel ensemble simulations. The effect of natural external forcing is not detected in northeastern China except for IPSL-CM6A-LR, while it is detected in southeastern China using any of the ensembles. The natural forcing signal, which is small in all cases, cannot be detected if the anthropogenic forcing signal is not included in the fingerprinting analysis (Fig. S4). Overall, the results indicate that the observed warming of CDDn would have been unlikely in the absence of human-induced warming, thus establishing a physical basis for the attribution of the 2021 cold event.

Anthropogenic scaling factor confidence intervals for northeastern China are consistent with unity except when using signals from CanESM5 and IPSL-CM6A-LR, which are models with high climate sensitivity (e.g., Li et al. 2021). For southeastern China, anthropogenic scaling factors are consistent with unity except when using the multimodel mean signal, which appears to warm CDDn in this region significantly more slowly than observed.

*Human influence on the 2021 cold event.* The fingerprinting exercise provides observationally calibrated time-evolving GEV distributions conditional on model-simulated CDDn that can be used to estimate changes in the frequency and intensity of 3-day cold outbreaks caused by external forcing. Using the distributions conditional on the multimodel mean CDDn, we find that the likelihood of observing a cold event that is as cold or colder than the 2021 event was about 2.0 times as likely in 1961–65 than in 2016–20 in northeast China and perhaps 1.2 times as likely in southeast China (Fig. 2b; purple lines). Correspondingly, 3-day cold events with the estimated frequency of the 2021 event were roughly 9.0 degree-days colder during 1961–65 than during 2016–20 (green lines; Fig. 2b). Even though the event was regarded as being extreme and impactful, it evidently would have been substantially more intense in the absence of the warming that has occurred over the past 60 years. Uncertainties are large in part because our inferences are made on a grid box scale comparable to or smaller in size than that of the majority of Chinese provinces, which is the scale on which decision making on climate adaptation often occurs.

### Summary.

We analyzed the 3-day January 2021 cold event in China and its historical climate change background using a novel cold degree days metric in combination with a fingerprinting analysis technique designed specifically for extremes. Despite high impacts and the setting of a large number of cold temperature records, this was a relatively mild event regionally, with clear evidence that human influence on the climate has reduced the strength and probability of such events since 1961. Nevertheless, our inferences, which are made at the  $5^\circ \times 5^\circ$  scale using different model ensemble simulations, are relatively uncertain and should be used qualitatively. Studies have reported that the weakened winter Northern Hemisphere meridional temperature gradient (Ding et al. 2008) and Arctic sea ice loss (Mori et al. 2019) caused by anthropogenic warming may have induced more cold air outbreaks. Our results support the idea that anthropogenic warming has warmed cold outbreak events. Nevertheless, their impacts to, for example, people's perception of cold and heating energy demand, which are also affected by changes in exposure and vulnerability, may not have diminished accordingly.

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