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Observed warming of cold extremes is not captured with a fixed threshold definition

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As the climate warms, it is expected that cold extremes will become milder[1]. However, a recent study by Cohen et al.[2] found that the observed trends in the temperature of cold extremes are weak and not statistically significant over selected midlatitude regions. They speculate that the lack of trends could be linked to the strong Arctic warming that has simultaneously occurred. Here we show that the lack of detectable trends found by Cohen et al.[2] is an artifact of their choice to use a fixed threshold to define cold extremes and does not represent how the temperature of extreme cold days is changing.

To determine the temperature of cold extremes, Cohen et al.[2] first define cold events to be winter days where the regional average temperature falls below the 5th percentile of all winter days over 1960–2023. They then calculate the change in temperature of these events over time (in units of °C/30 events). Importantly, the 5th percentile threshold they use to define the events is fixed over the entire period. This is problematic as illustrated by an idealized temperature distribution that shifts from a colder to a warmer climate (Fig. 1a). Even with a uniform shift in the temperature distribution (including the coldest days), the average temperature of the days below a fixed threshold barely changes (Fig. 1a). This is the result of the artificial upper limit, which restricts how much the temperature of cold extremes can warm.

We note that this issue is not sensitive to the details of how the fixed threshold is calculated (such as the percentile or time period used) – if the threshold is fixed, it will not capture the warming of the cold extremes. The fixed threshold definition also leads to the interpretation that the temperature of cold extremes stops increasing when cold events have warmed so much that there are not any cold events. This occurs in the regions analyzed by Cohen et al.[2], with many of the most recent years featuring no cold events (see e.g. their Fig. 6a).

To quantify the implications of using a fixed threshold to define the temperature of cold events, we use a very simple statistical model where the daily winter temperature is represented by a Gaussian distribution that is shifting at a constant rate over time. As an example, we calculate from ERA5 reanalysis[3] the standard deviation of daily variations in winter temperature (4.04 °C) and the winter mean warming trend (0.39 °C/decade) of the Central and Eastern United States (CEUS) region used by Cohen et al.[2]. We use these parameters to randomly generate temperatures for 90 days per year, over 64 years (representing the 1960–2023 period), and repeat this for 10,000 samples. We then calculate the trends in the temperature of cold extremes with the fixed threshold definition using this synthetic model data where, by construction, the coldest days are warming at the same rate as the mean warming.

According to the simple statistical model, the expected trend using a fixed threshold is on average 0.03 °C/30 events (Fig. 1c), and only 17% of the samples show a statistically significant increase in temperature. The trend in ERA5 reanalysis over the CEUS of 0.02 °C/30 events found by Cohen et al.[2] using the fixed threshold is in good agreement and well within the expected range from the statistical model that represents a uniform warming of the temperature distribution (Fig. 1c). Calculating the trends from the synthetic model data with respect to time instead of event results in an average trend of 0.05 °C/decade with the fixed threshold. This is almost eight times weaker than the known trend of 0.39 °C/decade that the entire distribution (including the cold days) shifts.

These results indicate that the weak and statistically insignificant changes in temperature using a fixed threshold are not representative of the true changes in the temperature of cold extremes. While multiple metrics can often be valid and complimentary, we show here that the fixed threshold metric used by Cohen et al.[2] is not suitable for detecting trends in observations since it is not able to detect known, specified changes in extreme temperature from synthetic data.

To better represent the changes in temperature of cold extremes, we use a slightly modified version of the definition used by Cohen et al.[2] Instead of a fixed threshold, we use a moving threshold (Fig. 1b) where the 5th percentile is calculated each winter to define cold events over which we calculate trends. This is equivalent to calculating the trends in temperature of the coldest four days each winter, which is similar to more standard metrics of cold extreme intensity that examine the coldest day or night of the year[1,4,5]. The statistical model shows much stronger warming that is nearly always statistically significant and the magnitude (0.29 °C/30 events, 0.39 °C/decade) is consistent with how the entire distribution is changing. The ERA5 trend over 1960-2023 in the CEUS region using this modified metric shows a strong increase in temperature (0.34 °C/30 events, 0.46 °C/decade), is highly statistically significant, and well within the range of trends from the statistical model with the moving threshold. In contrast to the fixed threshold definition, all regions investigated by Cohen et al.[2] show statistically significant increases in temperature over 1960–2023 (first row of Table 1).

Cohen et al.[2] also analyze trends starting in 1990 and 2000 and find weak trends over those periods. We note that over shorter periods and in small regions it is expected that internal variability will dominate over

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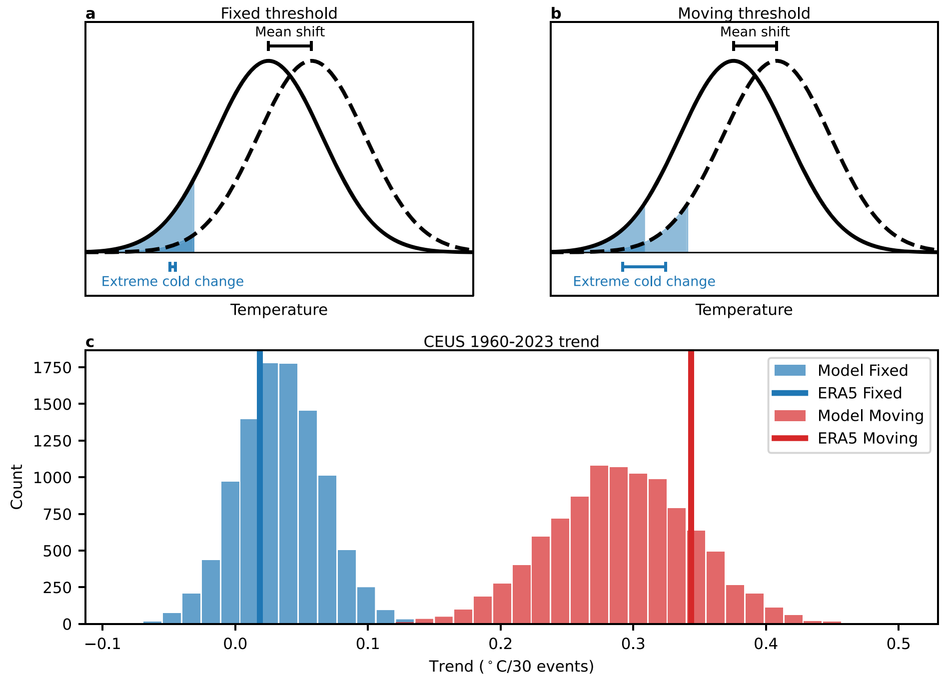

Fig. 1 | The impacts of using fixed and moving thresholds to define cold events. a Illustration of a hypothetical, idealized temperature distribution that shifts uniformly from a cooler climate (solid black distribution) to a warmer climate (dashed black distribution). The blue shading under the curves represents the cold events below a threshold that stays fixed under the uniform warming and the blue bracketed line indicates the change in temperature below the threshold. **b** As in (**a**) but using a moving threshold to define cold events. **c** Histogram of the 64-year trends in using a fixed threshold (blue) and a moving threshold (red) from the statistical model with a uniform shift in the temperature distribution. We use the standard deviation of 4.04 °C and mean trend of 0.39 °C/decade, which corresponds to the values for the Central and Eastern United States (CEUS) region. The standard deviation was calculated after removing the winter mean temperature trends and aggregating all daily average data. The vertical lines indicate the corresponding ERA5 trends in the temperature of cold extremes over 1960–2023 in the CEUS region from using the fixed (blue) and moving threshold (red).

Table 1 | Summary of the regional trends in cold extremes using a fixed and moving threshold

	CEUS		SSNC		NEUR		SEUR	
	Fixed	Moving	Fixed	Moving	Fixed	Moving	Fixed	Moving
1960–2023	0.02	**0.34**	**0.11**	**0.15**	−0.01	**0.38**	−0.01	**0.17**
1990–2023	0.04	**0.39**	−0.02	−0.19	−0.08	0.28	−0.09	**0.39**
2000–2023	−**0.89**	−0.21	−0.02	0.25	0.25	**0.97**	−0.24	**0.51**

Trends in the temperature of cold events (°C/30 events) from ERA5 reanalysis using fixed and moving threshold and across different time periods. The regions used are the same as in Cohen et al.[2]: Central and Eastern United States (CEUS; 30° to 50°N, 75° to 110°W), Southern Siberia and Northern China (SSNC; 40° to 60°N, 80° to 120° E), Northern Europe (NEUR; 50° to 65°N, 0° to 45° E) and Southern Europe (SEUR;35° to 50°N, 0° to 45°E). Bold values indicate statistical significance at the $p = 0.05$ level. Following Cohen et al.[2] we use a python scipy stats to calculate statistical significance.

the forced response[6,7], and thus few statistically significant trends are expected. The simple statistical model also suggests this, with for example, a statically significant increase occurring in only 35% of the samples with a moving threshold (and only 4% of the samples using the fixed threshold) over a 24-year trend using the standard deviation and mean shift for the CEUS region.

Despite the large impact of internal variability, the moving threshold metric shows clearer warming trends over the shorter periods, including statistically significant increases in temperature in half of the regions (second and third row Table 1). The lack of short-term trends found in some regions (e.g. CEUS trends starting in 2000) amidst stronger warming in other regions and in long-term trends is consistent with what is expected from internal variability[7].

Cohen et al.[2] highlight the weak, insignificant trends in the temperature of midlatitude cold extremes to argue for further investigation to explain the causes and suggest a role for Arctic amplification. While there are still uncertainties in how and to what extent the Arctic may influence the midlatitudes, our results indicate no physical explanation is needed to explain the lack of trends in cold extremes they find. The weak, insignificant trends found by Cohen et al.[2] are an inevitable consequence of defining cold extremes with a fixed threshold, which does not capture how the temperature of the coldest days is changing. A similar metric using a moving threshold reveals a clear increase in temperature of cold extremes over the midlatitudes, in agreement with previous analysis that use more standard metrics of cold extreme intensity[1,4,5,7].

Data availability

The ERA5 data used in this study is available at https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download.

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R.B. conceived of study, performed the analysis, and wrote the original draft. M.S. discussed the results and edited the manuscript.

Competing interests
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Additional information
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