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LETTER

Cold waves are getting milder in the northern midlatitudes

Geert Jan van Oldenborgh[1], Eli Mitchell-Larson[2], Gabriel A Vecchi[3], Hylke de Vries[1], Robert Vautard[4] and Friederike Otto[2]

[1] Royal Netherlands Meteorological Institute (KNMI), R&D Weather and Climate Models, De Bilt, The Netherlands
[2] School of Geography & the Environment and Department of Physics, University of Oxford, Oxford, United Kingdom
[3] Geosciences Department and Princeton Environmental Institute, Princeton University, Princeton, NJ, United States of America
[4] IPSL/LSCE, Gif-sur-Yvette, France

E-mail: oldenborgh@knmi.nl

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Abstract

The strong two-day cold wave in the midwestern United States in January 2019 again ignited the discussion as to whether cold waves are getting more severe or not as a result of Arctic amplification due to climate change. Assessing the evolution of cold waves in the northern hemisphere midlatitudes in the observations has been difficult because the variability of cold waves is large compared to anthropogenic warming. In order to detect changes in cold spells, two complementary ways to optimise the signal-to-noise ratio are employed: multi-decadal series at individual stations, and for shorter time periods by using spatially aggregated measures. Global warming is now strong enough to make trends clear at individual stations when considering long enough (>50 yr) records of daily minimum and maximum temperature. Calculating the land area that has temperatures below the 1-in-10 year return value (defined over 1951–1980) enables us to investigate trends over a shorter time horizon. The long-term station data have strong decreases everywhere in the lowest minimum temperature. Warming trends in the lowest maximum temperature are smaller over most of the Northern Hemisphere, with dataset-dependent indications of possible negative trends in parts of the United States and Mexico. Considering the area experiencing cold waves over the last decades, the most notable feature is a sharp decline of this area since the 1980s. The natural variability is still so large that it is possible to arbitrarily select starting dates after the decline for which the trend is slightly positive in smaller regions like North America or Europe. However, these values are within uncertainties compatible with a steady decline and have differing starting dates in North America and Europe. An analysis of the entire northern midlatitudes confirms the steady decrease in severity and frequency of cold waves over the last decades in the observations.

1. Introduction

A very strong two-day cold wave enveloped the midwestern United States on 30–31 January 2019 (NWS 2019), leading to over 20 reported deaths (BBC 2019). The anomalously cold temperatures were the result of a perturbed jet stream which ordinarily bounds the tropospheric polar vortex, causing a southward incursion of cold Arctic air over the continent (WMO 2019). Cold waves are a common occurrence in North America, just the last five years saw further widely reported North American cold waves in January 2014, November 2014, February 2015, and the winter of 2017/18. Over these years the long-used meteorological term 'polar vortex' entered the public lexicon (Waugh *et al* 2017). Heavy media coverage of the recent January 2019 cold wave reignited the public and scientific debates over whether such events are increasing or decreasing in their severity and frequency in response to anthropogenic climate change as a result of the fast warming of the high latitudes, referred to as Arctic amplification (Newson 1973, Francis and Vavrus 2012, Barnes 2013).

Europe has also experienced a series of recent cold waves, albeit these have not been exceptional relative to recent historical norms Examples are the winter of 2009/10, January 2012, and January 2017. These European cold waves were primarily attributed to negative anomalies in the Arctic and North Atlantic Oscillations and were severe, but within expected variability (Cattiaux *et al* 2010, Anagnostopoulou *et al* 2017, Christiansen *et al* 2018). February and March 2018 had very cold days for the time of year in the Alps and eastern Europe respectively (and brought some skating possibilities to the Netherlands). However, compared to the whole winter these cold waves were milder or not much colder than normal in Europe.

The recent perceived prevalence of cold waves, exacerbated by heightened media attention to each event, is at odds with a rather obvious first-order hypothesis: a warming climate should lead to warm extremes getting warmer, and cold extremes getting less cold. This first-order trend has indeed been validated, both with regard to specific cold waves becoming less severe and frequent than they would have been without anthropogenic warming (Cattiaux *et al* 2010, Screen *et al* 2015, van Oldenborgh *et al* 2015), and as a regional, long-term trend toward milder and less frequent cold waves across the United States over many decades (Peterson *et al* 2013, EPA 2016, Vose *et al* 2017) and similarly over Europe (see e.g. Charlton-Perez *et al* 2019). Cold waves have not been increasing in frequency and severity, rather they have been getting milder, as expected. For example, the cold winter of 2013/14 in the Upper Midwest region of the US was shown to have been 20–100 times less likely to occur in todays climate relative to the 1880s due to long-term warming (Wolter *et al* 2015).

However, it has been proposed that Arctic amplification and associated accelerated Arctic sea ice loss can lead to a slow-down and/or higher amplitude (more equatorward extent) of the jet stream, which in turn leads to increased extreme winter weather in the Northern midlatitudes (Francis and Vavrus 2012). This, and variations invoking the influence of snowcover on the position and strength of the jet stream (Henderson *et al* 2018), has sometimes been referred to as the 'warm Arctic/cold continents' hypothesis starting around 2000 (Overland *et al* 2011, Cohen *et al* 2013). Studies exploring this link in observations and model simulations have yielded mixed results, with some finding a link between Arctic amplification or sea ice loss from 1990 onwards and midlatitude winter weather (Cohen *et al* 2014, Kretschmer *et al* 2018), and others finding no such link (Screen and Simmonds 2013, McCusker *et al* 2016), or further concluding that any cooling was the result of large interannual variability, and only very weakly forced by sea ice loss and unlikely to continue in a warming climate (Sun *et al* 2016, Blackport *et al* 2019). Others have disputed whether the jet stream wave extent or sinuosity has even increased beyond what can be explained by internal atmospheric variability (Barnes 2013, Barnes and Screen 2015, Cattiaux *et al* 2016). Several recent studies in this field have made the even stronger claim that the observed frequency of extreme winter weather events is increasing (Kim *et al* 2017, Cohen *et al* 2018).

Here, we investigate claims that the trends in circulation are strong enough to overcome long-term warming and have reversed the tendency toward less frequent and less severe cold waves over the last decades. We consider observations only, using measures with a good enough signal-to-noise ratio to be able to draw conclusions in the presence of large natural variability. We optimise the signal-to-noise ratio in two complementary analyses. The first takes local temperature data and long time series, the second spatially aggregated data with lower variability to study trends on shorter time scales.

2. Data and methods

In order to assess the local trends we use station data. Our primary measure of a cold wave at each station for each year is the annual minimum of the daily minimum temperature, denoted by TNn. To study winter extremes in the Northern Hemisphere we define the year as starting in July and ending in June, so the minimum is taken over the whole winter. In the Southern Hemisphere there is a small chance that the extreme falls around 1 July and is counted twice. We choose a one-day time scale, because one-day daily temperature minima are often-quoted when describing the severity of a cold wave (e.g. Alexander *et al* 2006, van Oldenborgh *et al* 2015) and have been recommended by the expert team on climate change detection and indices (Karl *et al* 1999). We compare this with the lowest maximum temperature of the year, TXn. Cold wave magnitude measures based on longer time scales, 3, 7 and 14 days, are shown in the supplementary material is available online at stacks.iop.org/ERL/14/114004/mmedia.

As the trend in global mean surface temperature (GMST) has not been linear we use a nonlinear trend measure: the regression on the GISTEMP (Hansen *et al* 2010) global mean temperature smoothed with a four-year running mean. This measure posits that, to leading order, local temperature extremes scale with the global long-term mean, which in turn scales with the global mean radiative forcings (Tebaldi and Arblaster 2014). This scaling has been used in extreme event attribution studies (e.g. van Oldenborgh *et al* 2015, Uhe *et al* 2016, Kew *et al* 2019). We note that we do not presently apply this method in order to perform 'detection and attribution', rather we use it to describe components of temperature change linearly connected to global temperature changes. Local and global temperature changes are also induced by influences other than greenhouse gas forcing to varying degrees, such as local aerosol forcings, urban heat

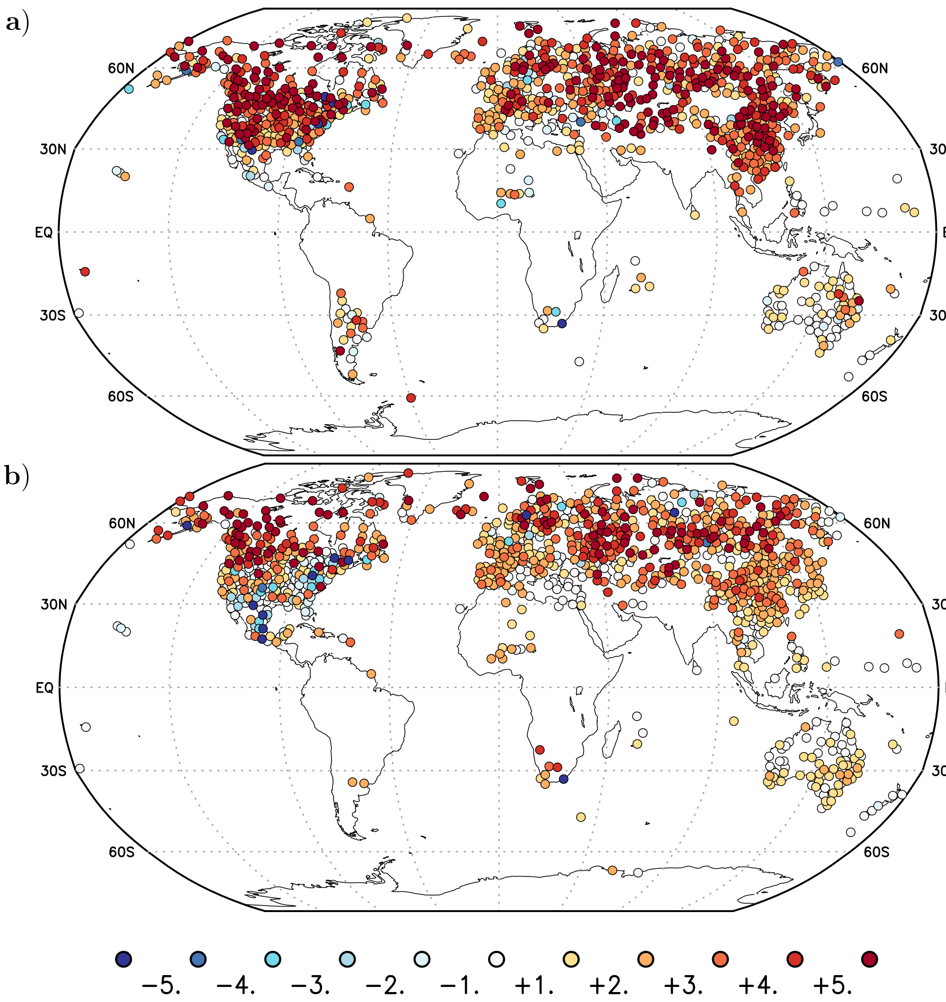

Figure 1. (a) Trend 1901–2018 in lowest daily minimum temperature of the year TNn (July–June) as a regression on the smoothed global mean temperature [K/K]. Data: 1026 GHCN-D stations with at least 50 years with 80% valid data, GISTEMP global mean surface temperature smoothed with a 4 yr running mean. (b) The same for the lowest maximum temperature of the year TXn at 1094 stations.

island and irrigation cooling effects, in addition to natural variability; and we do not attempt to formally separate these influences. We do note that the effects of the local forcings can often be discerned on maps by their locations: in areas of strong air pollution, near cities or irrigated areas.

We use station data from the GHCN-D database (Menne *et al* 2012), available from www.ncdc.noaa.gov/ghcnd-data-access. The version downloaded on 4 August 2019 contains minimum temperatures for 35 182 stations worldwide, of which 9116 have at least 50 years with data. Requiring a minimum inter-station distance of 2° reduces this to 1631 stations. We consider data from the twentieth century to be more reliable than earlier data as in many countries standard Stevenson screens were introduced around 1900. Requiring at least 50 years in 1900–2018 with no more than 20% missing data each year leaves us with 1026 stations, which make up the dataset used for figure 1. The series in the GHCN-D dataset have in general not been homogenised, so there are stations that show non-physical trends due to changes in observation practices or station relocations, or trends linked to changing local environments such as growing cities or increased irrigation. The largest non-physical trends stand out as isolated outliers against the more homogeneous background of climate change signals. An example is Bridgeville, DE, USA, which shows as a blue dot on figure 1 with a trend of −4 K/K. However, inspection of the time series shows that this is due to a roughly three degree Celsius downward discontinuity around 1955. The Historical Observing Metadata Repository indeed shows that the station was moved on 10 October 1954.

The second analysis uses a spatially aggregated measure to reduce the variability and enable the characterisation of trends over shorter time periods. For this we consider the land area that has a coldest day of the year that is colder than the 10 year return value. Similar measures were used for cold waves by Karl *et al* (1996), EPA (2016), Christiansen *et al* (2018) and Coumou and Robinson (2013) for heat waves. We use the

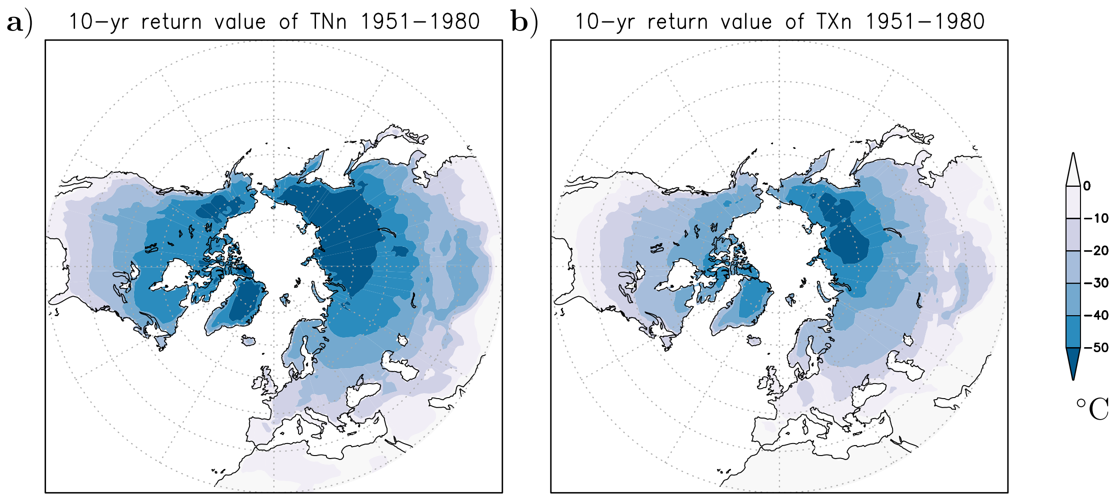

Figure 2. (a) The 10 yr return value of the lowest minimum temperature of the year (July–June) from a GEV fit over 1951–1980 in the Berkeley Earth daily minimum temperature analysis. (b) The same for the lowest maximum temperature of the year (TXn). Latitude circles are at 25°, 35°,…

Berkeley Earth analysis of daily temperatures over land (Rohde *et al* 2013) starting in 1880. As mentioned above, data from the 1800s are less reliable. We found an implausible cooling trend over northern Europe over 1900–1950 that appears based on very fragmentary station data. We therefore only show European data starting in 1950. Trends before 1950 were also in contradiction to station data in northern Siberia in earlier versions of the Berkeley Earth analysis.

All calculations use 1951–1980 as the reference period to estimate the 10 year return values. These are estimated for each grid point by fitting the lowest daily minimum temperature of the year (July–June) to a generalised extreme value (GEV) function using a log-likelihood method (Coles 2001). These temperatures are shown in figure 2. We define North America to include the land area in 25–50 °N, 50–130 °W, Europe as 35–72 °N, 15 °W–40 °E and the whole midlatitudes as 30–60 °N. The latter region does not have complete coverage in Central Asia (figure 2). The period up to 1950 is less reliable for Europe and the whole northern midlatitude regions.

We have compared the area measures in Europe against the E-OBS daily data (van der Schrier *et al* 2013) 1950–2019 and in the United States against the gridMET dataset (Abatzoglou 2013) 1979–2019.

3. Trends in cold waves

Figure 1(a) shows the long-term trends in the lowest minimum temperature of the year (TNn) in GHCN-D station with at least 50 years with 80% valid data. The trend values go to five times the global mean temperature trend. Except for isolated stations the trend is strongly positive almost everywhere: over 50–100 year time scales, cold extremes are getting warmer in all areas of the globe where we have sufficient data, including virtually all of the northern midlatitudes. There are no obvious associations with urban areas or other local factors. In these midlatitudes the trend is a factor three to more than five times the global mean trend, except near coasts. This is even faster than the winter mean temperature trend, which is only a factor two to three higher than the global mean temperature rise (van Oldenborgh *et al* 2015). The spatial homogeneity of the trends over almost continental-sized regions motivates us to posit that global warming is the dominant forcing of the trend in cold waves on these long time scales. We conclude that almost everywhere the local trend over 50 years or longer is towards milder cold waves as defined by the lowest minimum temperature of the year. This also holds for 7 d averaged minimum temperatures (suppl. mat. figure S1).

The trend in the lowest maximum temperatures of the year (figure 1(b)) is in general smaller than the trend in minimum temperatures, around three times the trend in global mean temperature for large parts of the globe. There are broad regions with slight negative trends, such as the central-eastern United States and large swaths of Mexico. A further investigation of this region shows that these negative trends do not appear in the Berkeley Earth analysis (see suppl. mat. figure S2).

As the signal-to-noise ratio is lower over shorter time periods than 50–100 year, it is not possible at this point to detect trends over the last few decades at a single location. To study these we turn to our spatially aggregated measure of cold waves. Figure 3(a) shows the fractional area affected by cold waves in North America as a function of time, where a cold wave is defined by a lowest minimum temperature of the year TNn below the 10 year return value in 1951–1980. By definition this fraction is 0.1 on average over 1951–1980. It can be seen to decrease strongly: what used to be a 1 in 10 year cold wave is now much rarer.

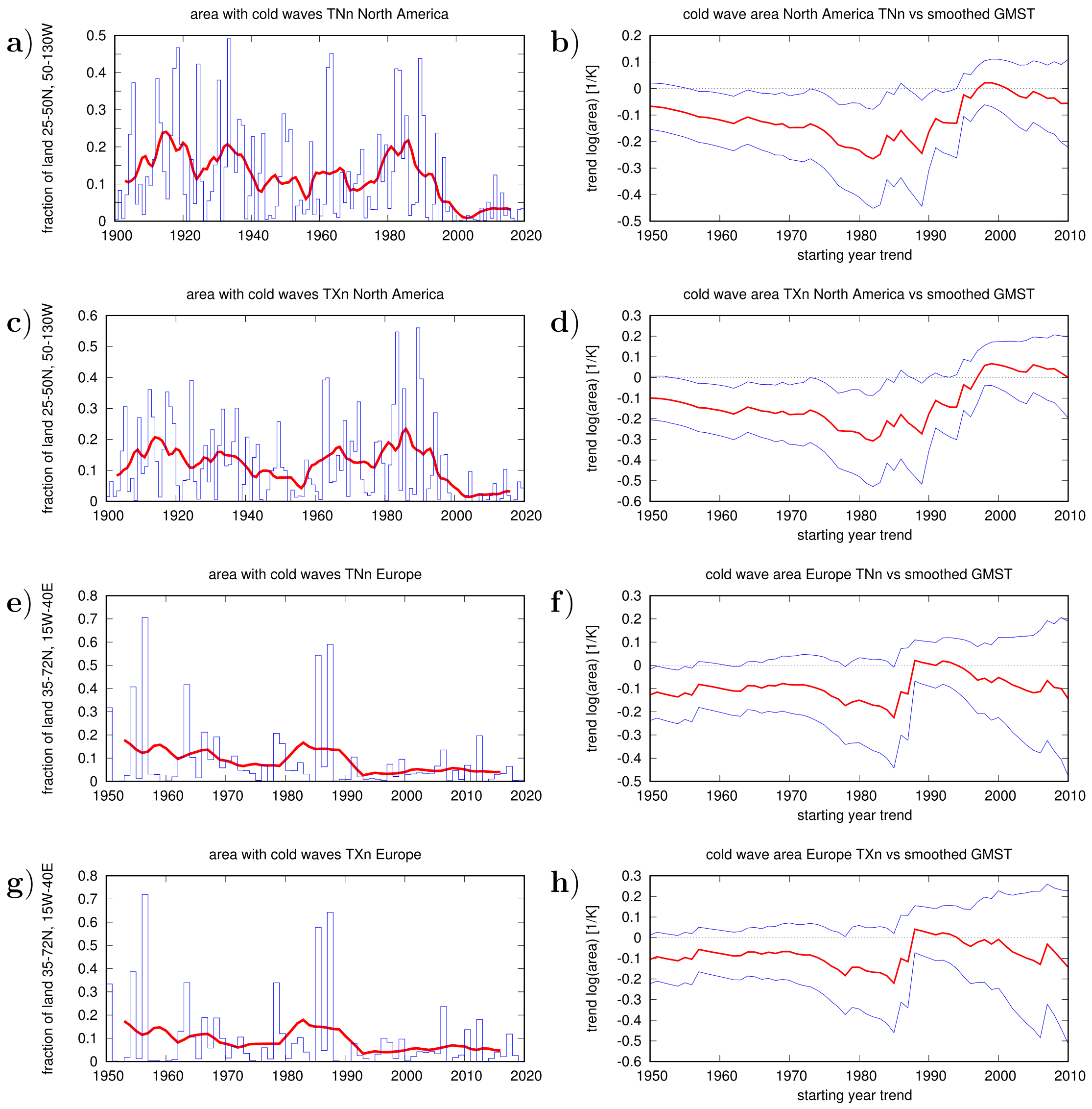

Figure 3. (a) Fraction of land area in North America (land points in 25–50 °N, 50–130 °W) 1900–2019 with lowest minimum temperature of winter below the 10 year return value defined over 1951–1980, the red line indicates a 10 yr running mean. (b) Trends (regression of the logarithm of the fraction on smoothed GMST) as a function of starting date, the end date is always the winter of 2018/19. The 95% confidence intervals are indicated by blue lines. (c), (d) The same for the lowest maximum temperature of the year, TXn. (e)–(h) The same for Europe (land points in 35–72 °N, 15 °W–40 °E) 1950–2019.

During the last winter of 2018/19 only 3% of the North America area studied experienced a lowest minimum temperature below the 1 in 10 year return value, in spite of the strong cold wave of 30–31 January 2019.

However, the decrease is not monotonic: there continue to be harsher winters and milder winters. Due to what we hypothesize is natural variability, it is possible to find intervals ending in winter 2018/19 over which the trend is nominally positive, albeit with a large uncertainty that encompasses the long-term trend. Figure 3(b) shows the trend as a function of the starting date for North America. One can obtain a slightly positive trend by choosing a start year in the range 1997–2000, just after the strong decline in cold waves after the 1980s. All other start years give a decrease in the area with cold waves. These nominally positive trends are compatible with the long-term negative trend within uncertainties and hence compatible with natural variability. The starting years for a positive trend do coincide with the time that winter (December–February) Arctic amplification starts in the ERA5 reanalysis, around 2000 in the 60–90 °N averaged 2 m temperature.

Using the much shorter gridMET analysis 1979–2019, with a reference period 1979–2008, gives similar results: cold wave areas in the two datasets are correlated at $r = 0.96$. However, due to the different reference period and smaller decorrelation scales the trends in the cold wave area are positive for a somewhat broader range of start years, 1997–2004 (not shown).

Measured by the lowest maximum temperature of the year, the largest cold waves in North America occurred in the 1980s. The area covered by 1 in 10 year cold in North America decreased very steeply after that

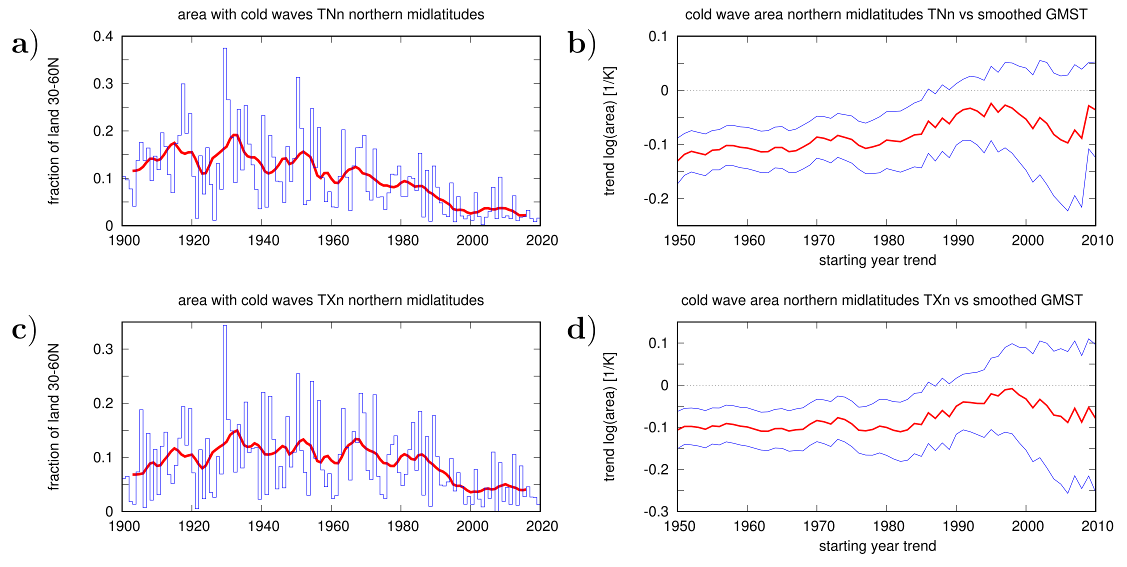

Figure 4. As figure 3 but for the whole northern midlatitudes. The data before 1950 is less reliable.

until 2000 and stayed constant at this very low level after that (figures 3(c), (d)).

In Europe the variability is even larger, due to the smaller area and influence of large modes of winter weather variability such as the North Atlantic Oscillation (figure 3(e)). In a very harsh winter such as occurred in 1956, more than 70% of Europe experienced a cold wave in TNn with a probability that was 1 in 10 yr (10% per year) or rarer over 1951–1980. Trends from 1950 onwards show a clear decline (figure 3(f)), but again it is possible to choose starting years for a short-term trend that give a small positive number, for Europe that is 1988–1994 except 1991. However, as was the case for North America, this trend and all others are compatible with the long-term trend from 1950 onwards. In Europe the years from which a (non-significant) positive trend is found is ten years earlier than in North America and our measure of the onset of Arctic amplification.

Comparing these results to those obtained from the E-OBS analysis 1950–2019 shows a high correlation in cold wave areas ($r = 0.95$). However, using this data set as basis for the analysis the trend is always negative: there are no start years that give a positive cold wave area trend (not shown).

As in North America, the largest area with cold waves defined by the lowest maximum temperature of the year occurred in the 1980s. This ceased by 1990 and stayed roughly constant at a much lower level since then (figures 3(g), (h)).

To improve the signal-to-noise ratio further we also analyse the northern hemisphere midlatitudes as a whole. Figure 4 confirms that previously noted short-term positive trends in the area covered by cold waves were just local fluctuations, as this aggregate measure of cold waves shows negative trends for all starting years in TNn. Using TXn this holds for all starting dates except 1995, 1997 and 1998, as there have been large declines in cold wave area from around 1980 to 2000 and again a decline from 2010 to 2018/19. This resulted in negative trends in the cold wave area starting before and after the late 1990s. All these fluctuations are compatible with natural variability.

Longer cold waves, defined by the lowest 3, 7 and 14 d averaged minimum and maximum temperatures give the same results (Suppl. Mat. figures S3 and S4).

4. Conclusions

We have investigated whether there is observational evidence to support the notion that cold waves in the northern midlatitudes are becoming more severe or more frequent. Variability of wintertime temperature extremes in this region is large, often hiding a trend signal. So in order to obtain reasonable signal-to-noise ratios needed to assess trends potentially linked to climate change, we need to consider either long (multi-decadal) time series at a series of locations, or a spatial aggregate across continents or the whole hemisphere for shorter time scales. We chose a standard indicator of wintertime temperature extremes: TNn, the lowest minimum temperature of the year, where we define the year (non-standard) from July to June in order to keep the whole winter in one year. In addition we consider TXn, the lowest maximum temperature of the year. One-day, three-day, seven-day and 14 d cold waves all give similar results.

Station observations with at least 50 years of data show a strong warming in cold waves everywhere in the northern midlatitudes, of three to five times the rate of global mean temperature rise over 1900–2018. As an aggregate index we chose the fraction of land area in North America (25–50 °N), Europe (15 °W–40 °E) and all northern midlatitudes (30–60 °N) with TNn below the 10 yr return value estimated over 1951–1980. All regions show a strong decrease in the area affected by cold waves since 1950. In the subset regions of North America and Europe, it is possible to obtain a small positive trend by choosing the starting date of the trend judiciously, but the values are within the uncertainties around the long-term trends. For the midlatitudes as a whole, there are no positive trends whatsoever in the lowest minimum temperatures and only a lack of trend at a very low level in the maximum temperature. We conclude that, as expected from the observed planetary warming driven in large part by increasing greenhouse gases, cold waves in the northern midlatitudes are getting less severe, and find no robust evidence to the contrary.

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Data availability

The data that support the findings of this study are openly available at the data providers, NCEI and Berkeley Earth. The latest version of the data of figures 1 and S1 is also available at climexp.knmi.nl under 'Daily station data'. The figures can be reproduced by following the link 'Correlate with a time series'. The data of figures 2–4 and S2–S4 can be recomputed after selecting the relevant Berkeley Earth daily temperature field by following the links 'Compute mean, s.d. or extremes' (figure 2), 'Correlate with a time series' (figure S2) and filling out the form 'Area with extremes' (figures 3, 4, S3, S4).

ORCID iDs

Geert Jan van Oldenborgh https://orcid.org/0000-0002-6898-9535
Eli Mitchell-Larson https://orcid.org/0000-0002-3775-3482
Gabriel A Vecchi https://orcid.org/0000-0002-5085-224X
Hylke de Vries https://orcid.org/0000-0002-6124-1102
Robert Vautard https://orcid.org/0000-0001-5544-9903
Friederike Otto https://orcid.org/0000-0001-8166-5917

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