The winter of 2013–14 had unusual weather in many parts of the world. Here we analyze the cold extremes that were widely reported in North America and the lack of cold extremes in Western Europe. We study the winter weather and cold extremes in these two regions statistically and investigate how this winter fits in with the climate model representation of global warming.

Figure 1a shows the winter [December–February (DJF)] 2-m temperature (T2m) in the Northern Hemisphere. Temperatures were up to 5°C lower than normal (1981–2010) in central North America and somewhat less anomalous in Turkmenistan and Iran. This was balanced by above-average temperatures over the Arctic, Europe, and the North Pacific. The deviations were more pronounced and farther south in other aspects that represent the severity of winter weather: the coldest day of the year (Fig. 1b) and the lowest minimum temperature of the year (Fig. 1c). The anomalous temperature pattern was caused by large deviations from normal in the circulation. In January, the jet stream that normally circles the cold air over the Arctic was displaced to North America (a wavenumber-1 anomaly). In January and February, it was split in two, with a second pole over Siberia (wavenumber-2). The winter mean (DJF) circulation can be seen in the height of the 500-mb surface (Z500) in Fig. 1d.

Fig. 1. (a) Mean winter 2m temperature (T2m) as anomalies relative to 1951–2010 (K). (b) Mean winter minimum temperature (Tn) in the winter relative to 1951–2010 (K). (c) Lowest daily mean 2m temperature in the winter relative to 1951–2010 (K). (d) Mean height of 500-mb surface indicating the mean atmospheric flow (m). (e),(f) Same for two cold outbreaks in North America: 7 and 30 Jan 2014. [Source: ECMWF ERA-interim (T2m,Tn), NCEP/NCAR R1 (Z500)]
Two features of the winter of 2013–14 that stood out were cold outbreaks in North America that caused extensive problems and the very low winter-averaged temperatures in the Great Lakes area. A widely reported extreme occurred on January 6, 2014 in Chicago, Illinois. The minimum temperature at Midway Airport reached −26.1°C that morning, the coldest observation of the year at that station. The outbreak was due to Arctic air flowing south into the Midwest (Fig. 1e), with Chicago among the coldest stations compared to normal (Fig. 1c). A second cold outbreak at the end of January brought unusually cold weather to the southeastern United States (Fig. 1f). In parts of the northern United States and Canada, below-normal temperatures persisted for much of the winter. This led to an almost complete freezing over the Great Lakes, which had not occurred in 35 years. In Chicago, the December–February winter mean minimum temperature was the sixth coldest on record. (The extended winter December–March temperature was the coldest on record within observational errors.) The severe winter was associated with large economic losses.

In contrast, the winter in most of Europe was notable for its lack of cold outbreaks. In the Netherlands, it was the first recorded winter with no days with a daily mean temperature below zero. The winter-mean temperature was also among the highest recorded there. We do not discuss the extreme precipitation that also occurred in North America and Europe that winter, such as the record winter precipitation in northern Italy and in England (due to a very persistent low-pressure area just west of Scotland) and the drought in the western United States.

To look at the statistics of the cold outbreaks, we consider the lowest minimum temperature of the year (from July to June). For the winter temperature we take the conventional December–February season of the daily minimum temperature. These are first analyzed in some detail at two meteorological stations with relatively long time series in the areas with the reportedly most extreme weather. The Chicago Midway Airport station data for 1928–present were retrieved from the GHCN-D v2 database; the De Bilt data for 1901–present were retrieved from the KNMI database (accessible via www.knmi.nl). The very nonstandard thermometer hut at De Bilt prior to 1950 does not appear to affect the monthly means of the minimum temperatures in winter, and we assume this also holds for the daily temperatures. In a second step, we check that the results are representative of the Midwest and continental Europe, respectively.

Figures 2a,b show the winter mean minimum T2m and the lowest minimum temperature in Chicago. This station has a continental climate, with low temperatures in winter, large day-to-day variability and a large negative skewness (−0.44±0.02) typical for the northern U.S. winter: cold extremes are larger in amplitude than warm extremes. The winter mean minimum temperature has a significant positive trend of 1.9±0.9K/K (p<0.025) times global mean temperature. We compute trends as the regression on the GISTEMP global mean temperature smoothed with a 4-yr running mean to remove ENSO-related fluctuations to first order. Uncertainties are 1σ errors; significances on temperature changes are one-sided. The maximum temperature has a smaller, nonsignificant trend (0.9±0.8K/K (p<0.1, not shown). The trend in the lowest minimum temperature of the year is even more pronounced, but of course has larger uncertainties as well (3.5±1.6K/K (p<0.025).

To determine the return time of the coldest outbreak in the winter of 2013–14, the annual minima Tg are fitted to a Generalized Extreme Value (GEV) distribution, excluding the winter to be studied. This distribution describes the tail of extremes within a larger dataset with three parameters. The location parameter μ describes the mean, the scale parameter σ describes the width, and shape parameter ξ describes how “fat” the tail is. A negative shape parameter indicates a threshold above which the probability is zero. The effects of global warming are included to first order by allowing the location parameter μ to vary, assuming a linear dependence on the (low-pass filtered) global mean temperature Tg: μ = μ0 + αTg. We assume that the other two parameters, the scale parameter σ and the shape parameter ξ, have not changed appreciably. This method is a refinement of the one used in van Oldenborgh (2007) and Otto et al. (2012). Note that there is strong evidence that the scale parameter also decreases for winter extremes,
Fig. 2. (a) December–February averaged Chicago (Midway Airport) minimum temperatures (GHCN-D v2). (b) Lowest minimum temperature in the winter. (c) Statistical trend analysis of the winter mean minimum temperature. (d) Same for the lowest minimum temperature of the winter. (e)–(h) Same for De Bilt, the Netherlands except that the high extremes of the winter mean and coldest winter temperature are analyzed.
but the amount of information in the observations is too small to fit both. As can be seen from the figures, varying only the position parameter is a reasonable approximation.

The return time of the observed lowest temperature in the winter of 2013–14 is the inverse GEV for \( T_n \) equal to the observed value and \( T_n \) the global mean temperature in 2014. Graphically, it can be read off as the point in Fig. 2d where the GEV fit for 2014, the central red line is equal to the observation, denoted by the purple horizontal line. The 95% uncertainty interval is determined by the upper and lower red lines. Knowing the dependence on \( T_n \), we can also compute the return time of this event in another climate, say that of 1951. This climate is defined as the GEV function with \( T_n = T_n (1951) \) — that is, shifted down by \( [T_n (2014) - T_n (1951)] \alpha \) from the climate of 2014 (blue lines). The observations are also plotted twice: once shifted with the fitted trend to where they would have been in the climate of 2014 (red points) and once shifted to the climate of 1951 (blue points). Again, the difference between the two sets of observations is the trend times the difference in (low-pass filtered) global mean temperature, \([T_n (2014) - T_n (1951)] \alpha \), because we assume that the distribution of cold extremes just shifts and does not change shape.

For the cold extremes in minimum temperature in Chicago we obtain a good fit with a similar dependence on the global mean temperature as the simple trend analysis, \( \alpha = 3.6 \pm 1.6 \text{ K/K} \), \( p < 0.025 \). The return time of the January 6 event, \(-26.1 \text{ °C} \), is 12 years in the current climate with a broad 95% uncertainty range from 6 to 44 years due to the limited number of years. In the colder climate of the 1950s, the return time would have been 4 years with an uncertainty range from 3 to 7 years. The difference is statistically significant (\( p < 0.02 \)). This agrees well with the impression that one gets by eye from Fig. 2b: colder extremes than the one observed in January 2014 were common up to the early 1980s, but have become rarer since then. We repeated the analysis for N-day periods up to two weeks and found very similar results (not shown). The coldest day of the year was a reasonable measure of cold waves during this winter.

The return time of the whole winter is harder to describe statistically. We use a Generalized Pareto Distribution (GPD) fitted to the 20% coldest winters, with a threshold \( \mu \) that varies with the global mean temperature but the scale and shape parameters \( \sigma, \xi \) fixed, again shifting only the distribution. Because of the smaller number of data points, the uncertainties are larger than in the case of the cold waves. The results are shown in Fig. 2c. Again, a positive trend is fitted, \( 2.8 \pm 1.6 \text{ K/K} \) times global mean temperature. The return time of the observed winter mean temperature in 2013–14 in the current climate is quite large, about 100 years. However, the uncertainties are so large that the 95% confidence interval starts at 25 years. Around 1951, a winter like this would not have been so unusual, with a return time of roughly 20 years. The difference is significant at \( p < 0.01 \): a cold winter like 2013–14 is now significantly less likely than it was around 1951 based on the trend up to last year.

We contrast this with the temperatures in De Bilt, the Netherlands. This station has a maritime climate with relatively mild winters, smaller variability, and, again, negative skewness (\(-0.66 \pm 0.03\)): cold outbreaks of Siberian air can be much colder below the mean than mild air from the Atlantic Ocean can be above the mean (this holds for most of Europe). The lower variability makes the trends clearer than in Chicago. The winter mean minimum temperature has risen \( 1.0 \pm 0.6 \text{ K/K} \), \( p < 0.05 \) times faster than the global mean temperature (Fig. 2e). The maximum temperatures also went up with a factor \( 1.0 \pm 0.5 \text{ K/K} \), \( p < 0.05 \) (not shown) and the cold extremes have a trend of \( 1.7 \pm 1.3 \text{ K/K} \), \( p < 0.1 \) (Fig. 2f), excluding the record winter of 2013–14, again with lower significance than the winter mean due to higher variability.

Fitting a GEV to the winter minima of minimum temperatures in De Bilt, but now for the high extremes, we find a completely different picture (Fig. 2h). The fit has a more strongly negative shape parameter \( \xi = 0.6 \), which means that the PDF has a finite cutoff above which the probability is zero. In the climate of 2014, this threshold is still lower than the observed value of \(-3.1 \text{ °C} \), leading to an infinite fitted return time. More relevantly, the 95% uncertainty range starts at about 250 years. In the climate of 1951, a winter with a lowest minimum temperature of \(-3.1 \text{ °C} \) would have been extremely unlikely, as this value would have been well above even the upper bound of the 95% uncertainty interval around the threshold.

The whole winter temperature was the second-highest observed. This is not so unusual in the current climate (return time 20 years), but would have been very unlikely 65 years ago (return time 650 years). Both numbers have large uncertainties due to the small number of data points fitted, but the ratio of the return times is significantly different from one at \( p < 0.05 \).

The question naturally arises to what extent these two stations are representative of the climate and
Fig. 3. Return time (yr) of (a) the mean of December–February minimum winter temperature of 2013–14 in the climate of 1951 and (b) 2014 at 473 GDCN-D stations in the Great Lakes area with at least 100 years of data. (c) The lowest minimum temperature in this winter in the climate of 1951 and (d) 2014 at 72 ECA&D stations in continental Europe with at least 65 years of data.

weather of the regions. It could be that urban heat island effects play a role or that other inhomogeneities have not been accounted for. To investigate this, we have repeated the calculations for the winter mean minimum temperature at 473 GDCN-D stations in North America with at least 100 years of data, and the lowest winter temperature at 72 ECA&D stations in Europe with at least 65 years of publicly available data. The results are shown in Fig. 3.

There is quite a bit of scatter in the return times of adjacent stations. Due to the limited length of the observed record, the exact value of return times well over 100 years should not be taken too seriously. The coldest days of the year are not very exceptional (not shown), even in the current warmer climate, with return times similar to the 6 to 44 years we found for Chicago. Weekly averaged minimum temperatures give virtually indistinguishable results for this part of the world. However, just like at the single station, the winter mean temperatures have become exceptional. In the climate of 1951, this winter would not have been exceptional, with return times below 100 years at most stations (Fig. 3a). However, due to the warming trend, the winter means of minimum temperatures were very unusual in the current climate. Return times larger than 100 years occur in Illinois, Wisconsin, and Michigan (Fig. 3b), roughly coinciding with the coldest area in Fig. 1a. The return times could not be evaluated in Canada due to a lack of publicly available data. If the area there is similar in size to the U.S. region, the area covered with >100 year return times covers on the order of 1% of Earth’s land surface. This indicates that we should expect on average roughly one such anomaly per year somewhere over land. In fact, one such event also occurred in the United States recently, albeit of the opposite sign: the return times in the current climate are very similar to those of the March–May 2012 maximum temperatures (not shown).

In Europe, the opposite holds. The winter mean temperature was not very unusual for the current climate (not shown), but the absence of cold waves in a region stretching from the United Kingdom in the northwest to Austria in the southeast was very remarkable, with many more high return times above 200 years (yellow, orange, and red dots) in southern Germany, Austria, and Switzerland. In the Netherlands and Belgium, these values were above the threshold in the climate of 1951, but also in southern Germany, Switzerland, and Austria the return times would have been much longer then.

Looking at the whole Northern Hemisphere, it is clear that the increases in winter mean and minimum temperatures are not localized coincidences. Figure 4a shows that the winter temperature has increased over most of the northern midlatitudes and Arctic, most strongly over land areas and high latitudes. The increase in coldest days of the year mirrors this pattern, albeit with more noise and somewhat higher amplitudes (Fig. 4b), with decreases in southeastern Europe. In northern Europe, a large part of these increases are due to trends in the circulation (Fig. 4c), with more westerly winds in
winter, although the uncertainties are large due to the large natural variability in winter. Haarsma et al. (2013) shows that this increase is the thermal wind reaction to the increased temperature contrast between stronger upper tropospheric warming over the subtropics and reduced warming over the North Atlantic. A connection with global warming is possible but cannot be formally established, as the models are not very consistent, and in general show smaller trends.

To summarize, we have shown that the cold waves in the Midwest in winter 2014 were individually not very unusual in the current climate, with a return time of between 5 to 44 years of the coldest day of the year estimated from past observations, estimated with a statistical model that assumes all cold extremes warm at the same rate. The same holds for longer-duration averages up to a month. They would have been even less unusual around 1950 due to the positive trend in cold extremes. The unusual aspect of this winter in North America was the persistence of cold conditions, causing mean winter temperatures with return times of more than 100 years in the current climate over 3 states. In the climate of half a century ago, the statistical analysis indicates that they would have been less unusual, with return times below 100 years.

The situation is very different for the absence of cold waves in Western Europe last winter. In the central Netherlands and Belgium, the lack of cold nights was very unusual in the current climate and would have been extremely improbable in the climate of the 1950s. The difference is due to the skewness of the temperature distribution in these areas that makes large cold extremes more likely than equally large warm extremes. The generally higher trend in the cold extremes mirrors the higher trends in the coldest areas from which the cold air originates—the Canadian and Siberian high latitudes. The trends in these areas have been attributed to anthropogenic emissions. Invoking the two-step attribution procedure, we can also attribute the decrease in frequency of cold extremes to these factors.

The argument above assumes that the temperature of the source region of the cold air is the dominant

Fig. 4. (a) Mean winter temperature trend (K/K) (GISTEMP). (b) Trend in lowest daily mean temperature in the winter (K/K) (NCEP/NCAR R1). (c) Trend in winter sea level pressure (hPa/K) (NCEP/NCAR R1). (d)–(f) The same for the CMIP5 multimodel ensemble—note the factor-4 difference in scale between the SLP trend plots [on top of the trivial factor 100 due to the units of (Pa/K)]. All trends are defined as the regression on the GISTEMP global mean temperature, low-pass filtered with a 4-yr running mean, and exclude the winter of 2013–14. In (a)–(c), grid points in which the trend is not significant at $p < 0.1$ are shaded in a lighter color. For surface air temperature and sea level pressure, the same 42 CMIP5 models were used as in van Oldenborgh et al. (2013) except that for each model all ensemble members were averaged rather than selecting one. The annual minimum of minimum temperature used the 25 models of Sillmann et al. (2013b).
factor determining cold outbreaks. Another possibility would be that the circulation has changed, either in the mean or in the variability. In Western Europe, there has on average been a shift toward more westerly circulation types, which contributed to the rise in winter temperatures and therefore the decline of cold extremes. No such change can be detected over North America. We also verified that there have been no significant changes in the autocorrelation of sea level pressure (SLP) or Z500 excursions, nor in their amplitude, up to 10 days (not shown). Screen and Simmonds (2013) find a negative trend in wave-number-1 and 2 power globally, and no signal over the North American/Atlantic sector. This points to the direct temperature effects as the dominant factor in determining the statistics of cold waves in North America. Since we submitted this paper, this argument has also been published by Screen (2014).

The question remains on the causes of the persistence of the low temperatures in North America last winter. One factor is undoubtedly the ice cover on the Great Lakes: once these were largely frozen in January, the ice enabled much lower minimum temperatures in the region due to the albedo and the large amounts of heat required to melt the ice. This cooled the February and spring temperatures. The same probably holds for the snow cover anomalies, but only during the melting season, which in this area is mainly March. However, these effects only explain a small part of the persistence in the winter, December–February.

The main factor seems to be the persistent anomalous flow pattern bringing Arctic air to North America (Fig. 1d). This winter, this pattern consistently extended to the Atlantic Ocean and Western Europe, bringing record seasonal precipitation to Britain and mild temperatures to the continent. It was not coherent beyond Europe: over Asia the sign of the anomalies changed from December to January and back again in February. The coexistence of a cold winter in the U.S. Midwest and a mild one in continental Europe is the opposite of what is usually found in the historical record. The correlation of winter mean temperatures in Chicago and De Bilt is $r=-0.29$ ($p<0.01$). This is also true of extremes: of the five previous very cold winters in Chicago, three were associated with (very) harsh winters in Europe (1979, 1963, 1982) and two with average winters there (1977, 1936). The observed connections between North America and Europe in the winter of 2013–14 were therefore the exception, not the rule.

A quick look at the CMIP5 set of coordinated climate model experiments shows the same features that we found in the observations. The trends in winter mean temperatures (Fig. 4d) agree well with the observed trends within natural variability in these areas (Box 11.2, Fig. 1, Kirtman et al. 2013). The trend in observed coldest minimum temperatures of the year has the same pattern but is stronger (Fig. 4e; cf. Sillmann et al. 2013a). The SLP trends agree in pattern over Europe (Fig. 4f) but disagree in strength (note the difference in scale, cf. van Oldenborgh et al. 2009). The agreement between the observed and modeled temperature trends strengthens the evidence that cold extremes—both short cold outbreaks and whole-winter temperatures—are becoming less frequent due to the drivers of climate change in these models, mainly greenhouse gas emissions. The winter of 2013–14 strongly confirmed this trend in Europe and showed the still-large variability to the negative side in North America.

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**FOR FURTHER READING**


