3. HOW UNUSUAL WAS THE COLD WINTER OF 2013/14 IN THE UPPER MIDWEST?

Klaus Wolter, Martin Hoerling, Jon K. Eischeid, Geert Jan van Oldenborgh, Xiao-Wei Quan, John E. Walsh, Thomas N. Chase, and Randall M. Dole

The frigid 2013/14 Midwestern winter was 20–100 times less likely than in the 1880s due to long-term warming, while winter temperature variability has shown little long-term change.

*Introduction***.** Below-normal temperatures covered the Upper Midwest and Great Lakes region from November 2013 through April 2014, the longest such consecutive monthly stretch since 1995–96, culminating in the coldest winter since 1978/79.[1] The U.S. economy suffered a severe setback,[2] in part due to the harsh winter (Boldin and Wright 2015; Bloesch and Gourio 2015). Direct economic losses due to wintry weather totaled at least $4 billion (U.S. dollars).[3] The largest Great Lakes ice extent since 1979[4] hindered shipping exceptionally long into spring.[5] The frigid weather after two decades of mostly mild winters surprised many, who were not warned by seasonal forecasts either (see Supplemental Figs. S3.1, S3.2).

The severity of individual daily and weekly cold spells was not exceptional compared to previous cold waves, especially during the 1980s (Peterson et al. 2013; van Oldenborgh et al. 2015), despite the media commotion about the so-called "polar vortex".[6] However, the full winter temperature anomaly exceeded two standard deviations, the only land region to do so globally (Supplemental Fig. S3.3).

Our paper poses three questions: How extreme was the cold winter of 2013/14 in its core region? Have winter temperatures been getting more variable? What are the odds of a cold winter this extreme, in the past, present, and future? We analyze observations and models to address these questions.

*Data and Methods***.** Gridded monthly mean temperature data (Lawrimore et al. 2011) were analyzed for 1880–2014. The region from 40°–50°N and 75°–100°W (box in Fig. 3.1a) represents the core of the cold anomaly, and has temperature records since the late 19th century. We refer to this domain as the "greater Upper Midwest" (GUM).

Gridded satellite-based snow cover data from 1966/67 onwards (Robinson and Dewey 1990) was used to establish a snow cover history for the GUM, given potential snow contributions to cold conditions through snow-albedo feedbacks (e.g., Wagner 1973; Namias 1985; Leathers and Robinson 1993).

To isolate the role of radiative forcing, coupled climate model simulations were investigated with NCAR's Community Earth System Model version 1 (CESM1), for transient runs from 1920 onwards (Kay et al. 2014). The simulations consist of 30 ensemble members driven by anthropogenic greenhouse gases, aerosols, and natural external radiative forcing during the historical record, and with the RCP8.5 emissions scenario after 2005. In addition, single runs from 30 different CMIP5 models (Taylor et al. 2012) were examined that have been forced in a similar manner as CESM1, but over a longer period (from 1880/81 onwards).

Results. a. The observed 2013/14 event and its historical context. The winter 2013/14 temperature anomaly was −4.1°C for the full GUM area compared to

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[1] www.ncdc.noaa.gov/sotc/national/2014/2

[2] http://blogs.wsj.com/economics/2014/11/26/the-weather-really-can-hold-back-the-economy-its-not-just-an-excuse/

[3] www.munichre.com/en/reinsurance/magazine/topics-online/2015/03/harsh-winter

[4] www.glerl.noaa.gov/data/ice/imgs/IceCoverAvg1973_2014.jpg

[5] www.nrcc.cornell.edu/newsletter/GL2014-06.pdf

[6] http://en.wikipedia.org/wiki/2013–14_North_American_cold_wave

AFFILIATIONS: Wolter, Eischeid, Quan, and Chase—Cooperative Institute for Research in the Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; Hoerling and Dole—NOAA/Earth System Research Laboratory/Physical Sciences Division, Boulder, Colorado; van Oldenborgh—Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands; Walsh—University of Alaska Fairbanks, Fairbanks, Alaska

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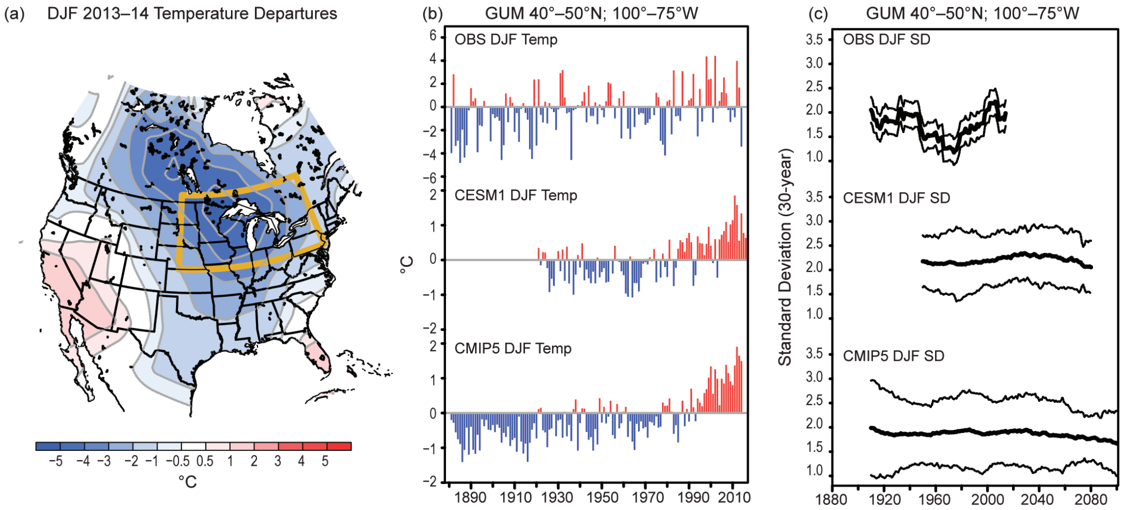

Fig. 3.1. (a) DJF 2013/14 temperature anomalies (°C) for NCDC gridded data (1981–2010 base period). Spherical rectangle delineates the GUM (40°–50°N, 100°–75°W). (b) Time series for GUM DJF temperature anomalies (°C) for (top) NCDC 1881–2013 base period, (middle) transient 1921–2013 CESM1 30-member ensemble average, and (bottom) 1881–2013 CMIP5 30-model ensemble member averages. (c) Standard deviations (sliding 30-year periods) in °C for GUM in (top) observations, (middle) CESM1, and (bottom) CMIP5. 95% confidence intervals (dashed lines) were estimated based on resampling for the observational record (top), and the actual sliding distribution of 30-ensemble member standard deviations for the model results (middle, bottom).

1981–2010 means (Fig. 3.1a). It was the coldest winter since 1978/79 in this region, and ranked 10th coldest since 1880/81 (Fig. 3.1b, top). Aside from 1978/79 and 1935/36, all other colder winters occurred before 1919. A wider seasonal average from December 2013 through March 2014 was even the coldest since 1903/04. Snow cover was ample (seventh highest since 1966/67), but not at record-levels. The enhanced snow cover is consistent with a strong negative correlation (r = −0.75) of GUM winter temperatures and snow cover anomalies observed over 1966/67 to 2013/14 (Supplemental Fig. S3.4). This association is reproduced in CESM1 (Supplemental Fig. S3.5).

b. Externally forced variability of GUM winter temperatures. Two independent estimates of the externally forced variability in winter temperatures for the period of record are shown in Fig. 3.1b (middle for CESM1, bottom for CMIP5). The dominant feature of this forced variability is a warming trend, especially post-1980. The preponderance of observed warm winters in the last few decades is thus consistent with an emergent radiatively forced warm signal, making the 2013/14 cold event even more unusual.

The risk assessment of a cold winter must also account for changes in variability. The long-term observed standard deviation for GUM winter temperatures is 1.9°C. Over the last century, the range of observed standard deviations (30-year values) has been between 1.2°C for the mid-20th century and 2.2°C for the late 20th century (Fig. 3.1c), showing a significant increase prior to 2005, but only to levels slightly higher than in the early 20th century. During the same period, 30-year standard deviations for individual model runs have varied from about 1.0°C to about 3.0°C (Fig. 3.1c), a larger range than for the observations. However, *average* CESM1 and CMIP5 standard deviations show very little long-term trend over the last century, and even into the future. Observations and models agree that the risk of seasonal extremes is largely dictated by changes in long-term mean temperatures.

Observed winter temperatures have increased +1.0°C (+2.3°C) during 1921–2013 (1881–2013) over the GUM based on linear trend analysis. These warming rates fit into the range of modeled trends for these two periods in CESM1 (Fig. 3.2a) and CMIP5 (Fig. 3.2b), respectively. Admittedly, the observed temperature increase since the late 19th century is on the high end of the modeled temperature increases, while the observed warming since 1921 is right in the middle of the CESM1 trend distribution. However, the range of modeled temperature increases is more than 2°C for both periods, illustrating the considerable unforced component of long-term trends in this region. In the case of the CESM1 distribution, the range in trends

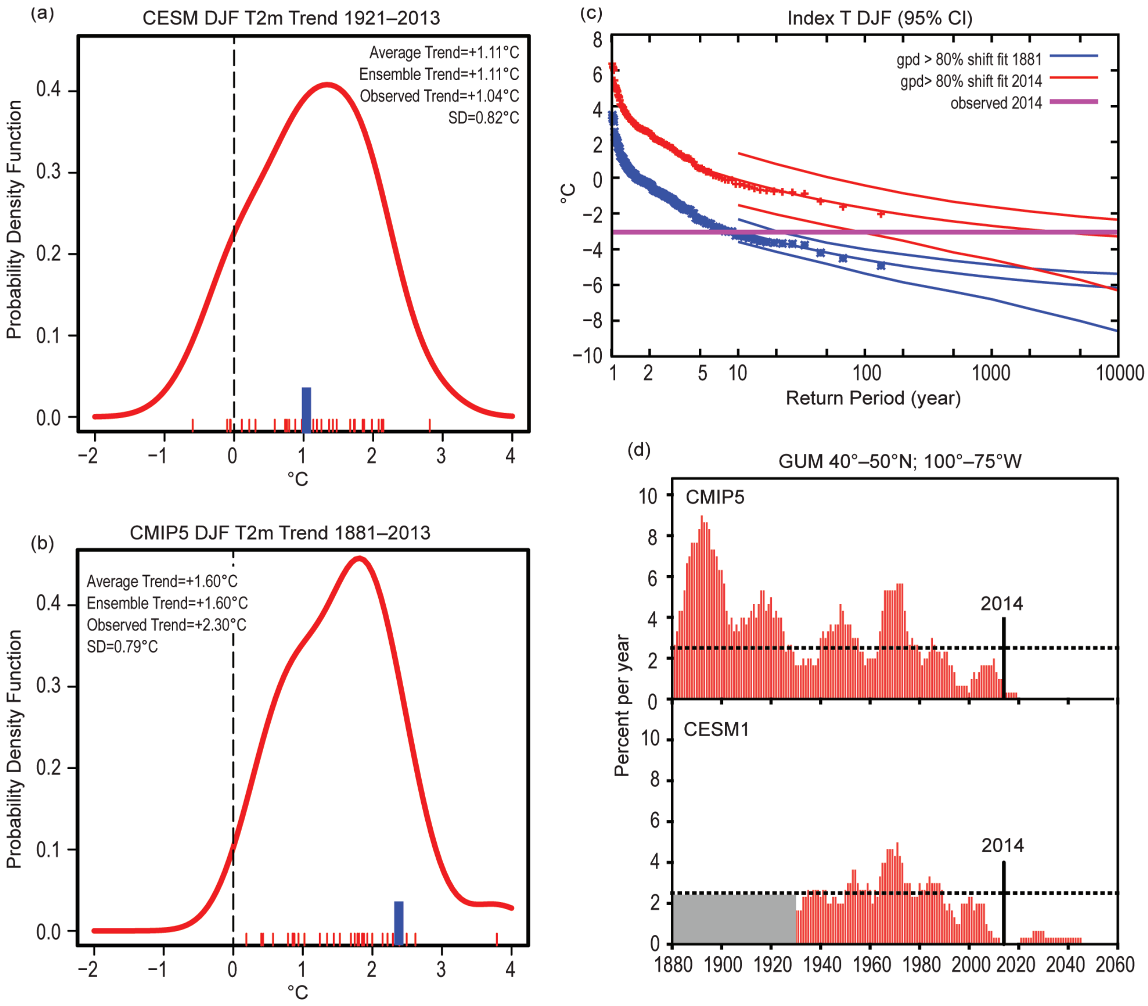

Fig. 3.2. (a) Temperature trends (°C) for CESM1 30 ensemble members since 1921 versus observations in GUM (blue tick). (b) Temperature trends (°C) for CMIP5 30-model ensemble member since 1881 versus observations in GUM (blue tick). (c) GPD fit to observed GUM temperature anomalies (°C, 95% confidence interval) with the effects of NCDC global temperature linearly subtracted from the position parameter, referenced at 1881 (blue) and 2014 (red), similar to van Oldenborgh et al. (2015). (d) Frequency distribution of −2 std dev winter temperatures in GUM from 10-year samples among 30 ensemble members since 1881 (CMIP5; top), and since 1921 (CESM1; bottom).

is entirely due to internal coupled ocean–atmosphere variability. In the case of the CMIP5 distribution, different model sensitivities to similar external forcing also contribute to the range, as discussed in Hawkins and Sutton (2009).

c. Late 19th century versus current odds. The observational GUM winter temperature time series was analyzed with a generalized Pareto distribution (GPD) fit (Fig. 3.2c) in order to assess extreme event probabilities through time. In this statistical modeling of tail events, we assumed no change in the scale and shape parameter of extreme cold events over time, supported in part by Fig. 3.1c. Our empirically derived change in cold event probability (expressed as a change in return periods) is thus driven by the mean warming of +2.3°C since 1881. The blue symbols in Fig. 3.2c represent conditions at the beginning of the record (1881), while the red symbols refer to present conditions. While a winter comparable to 2013/14 would have been roughly a once-a-decade event in 1881 (return periods from 5–20 years), it has become roughly a once-in-a-thousand years event in 2014 (return periods from 90 to over 10 000 years). This implies that extremely cold winters are two orders of magnitude less frequent in today's climate than in that of around 1881. Using a

Gaussian fit rather than GPD, the change in probability for such a cold winter would go from once-in-14 years in 1881 to once-in-200 years in 2014 (Supplemental Fig. S3.6). Due to the area-averaging, these changes in odds are more extreme than those found by van Oldenborgh et al. (2015) for individual stations since 1951, but match the drastic reduction in odds that Christidis et al. (2014) computed for cold springs in the United Kingdom.

An alternative approach to estimating the change in odds for an extreme cold winter is through diagnosis of the historical climate simulations. By pooling all ensemble members for moving 10-year windows, we computed the frequencies of two-sigma cold events since 1881 (1921) for CMIP5 (CESM1), shown in Fig. 3.2d. The CMIP5 results (Fig. 3.2d, top) confirm close to once-per-decade odds for the late 19th century, while 2014 is close to the "point of no return" by not showing this kind of severity again for the next half-century. The CESM1 results (Fig. 3.2d, bottom) are a little less extreme with a few "outlier" winters reaching the same severity as 2013/14 until about 2040, suggesting return periods around once-in-300 years. In sum, the model results are consistent with empirically derived results since both analyses rely on similar long-term warming trends, while the model data affirm little change in the scale parameter over time.

Conclusions. Our analysis of a 134-year record of winter season temperatures indicates that a cold winter of the severity observed over the GUM region in 2013/14 would have been a once-a-decade phenomenon at the end of the 19th century, but has become extraordinarily unlikely in the early 21st century. The reason for this reduced risk lies in overall warming since 1881, the principal cause for which appears to be the long-term change in external radiative forcing. Our results for this cold event are consistent with numerous other assessments of changing odds for cold winters and the role of climate change (e.g., Perlwitz et al. 2009; IPCC 2013; Christidis et al. 2014; van Oldenborgh et al. 2015). A new aspect of our analysis is the demonstration that the 2013/14 cold was not a symptom of a more variable climate, supported by a large ensemble of historical simulations that show little detectable change in winter season temperature variability over the GUM.

Both observed and modeled GUM winter temperatures are strongly related to snow cover. Observed snow cover has exhibited no long-term decline over this region (Hughes and Robinson 1996; Frei et al. 1999), with the last 20 years even showing an increase. If the modeled future reduction in snow cover does not materialize, cold winters may remain possible a little longer.

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