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Historical weather extremes in the "Twentieth Century Reanalysis"

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Abstract

Meteorological or climatological extremes are rare and hence studying them requires long meteorological data sets. Moreover, for addressing the underlying atmospheric processes, detailed three-dimensional data are desired. Until recently the two requirements were incompatible as long meteorological series were only available for a few locations, whereas detailed 3-dimensional data sets such as reanalyses were limited to the past few decades. In 2011, the "Twentieth Century Reanalysis" (20CR) was released, a 6-hourly global atmospheric data set covering the past 140 years, thus combining the two properties. The collection of short papers in this volume contains case studies of individual extreme events in the 20CR data set. In this overview paper we introduce the first six cases and summarise some common findings. All of the events are represented in 20CR in a physically consistent way, allowing further meteorological interpretations and process studies. Also, for most of the events, the magnitudes are underestimated in the ensemble mean. Possible causes are addressed. For interpreting extrema it may be necessary to address individual ensemble members. Also, the density of observations underlying 20CR should be considered. Finally, we point to problems in wind speeds over the Arctic and the northern North Pacific in 20CR prior to the 1950s.

1. Introduction

A large part of the damage caused by ongoing and expected future climatic changes is not due to changes in the mean climate state, but rather due to changes in the frequency or intensity of extreme events. The recent focus on extreme events is mirrored in the Special Report on

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extremes commissioned by the Intergovernmental Panel on Climate Change (Seneviratne et al., 2012). However, our understanding of decadal-to-centennial variability in the frequency or intensity of extreme events is still rudimentary. One key limitation is the length of the observational record and suitable data products. Extreme events are rare by definition, and hence studying them statistically requires long records. At the same time, comprehensive three-dimensional weather data sets are important for addressing atmospheric processes. Long meteorological time series are available for several locations and allow studying extremes, but they are too few in number to address the processes from a spatial perspective. Global atmospheric data sets, conversely, have until recently only covered the last few decades, thus comprising only a limited number of extreme events. Examples include the widely used reanalysis data sets NCEP/NCAR (Kistler et al., 2001) and ERA-40 (Uppala et al., 2005), which reach back to 1948 and 1957, respectively. The new "Twentieth Century Reanalysis" (20CR, Compo et al., 2011), now combines length and comprehensiveness and extends the time scale for studying weather extremes back to 1871. In this volume we analyse historical extreme events in the 20CR data to learn about its applicability for this purpose.

The new data set supplements other sources of information. For many aspects, historical climatology provides the means to extend studies on meteorological extremes backwards in time (Bràzdil et al., 2005). Documentary data are indeed very suitable for the analysis of extreme events and their impacts, which were always relevant to society. They even allow conclusions on decadal-to-centennial variability of extreme events, such as in the case of Rhine floods (Wetter et al., 2011). For instance, floodings in the Alps were more frequent in the 1860s to 1880s than during the 20th century (triggering a political discussion, see Pfister and Brändli, 1999). In fact, for Switzerland, Pfister (2009) proposed the concept of a "disaster gap", a long period without major extreme events between the early 20th century and the 1980s (for an extensive on-line catalogue of historical weather information see EUROCLIMHIST, http://euroclimhist.unibe.ch/).

For more quantitative meteorological analyses, instrumental observations and products therefrom are required. Meteorological measurements have been performed on a large scale since the late 19th century (at some locations much earlier). However, for a long time they have only been available in the form of monthly mean values which do not allow studying extreme events. In recent years large efforts have been devoted to improving the historical instrumental record. Millions of historical observations have been digitised, so that long, sub-daily meteorological series start to become available (*e.g.,* Füllemann et al., 2011). On an international level, these efforts are coordinated within the "Atmospheric Circulation Reconstructions over the Earth" initiative (ACRE, www.metacre.org, Allan et al., 2011) and they feed into other international efforts such as the International Surface temperatures initiative (http://www.surfacetemperatures.org/) or the EarthTemp network (www.earthtemp.net/). The new sub-daily data allow a more detailed look at extreme events of the past.

The 20CR data set makes use of one specific part of these instrumental data, *i.e.,* air pressure measurements (Compo et al., 2011), and based on this information provides three-dimensional information on the global atmosphere every six hours. The data set potentially provides a powerful tool for studying extremes, but this yet remains to be established. At the same time 20CR supplements other data sources, including documentary and instrumental data, which provide rich information on local conditions and impacts.

The goal of this selection of short papers, which are the outcome of a Master's Seminar at the University of Bern in spring 2012, is to obtain information, albeit non-systematic and selective, on the value of 20CR for studying weather extremes. Selected events were studied in the 20CR data set and compared with other data sets and results from the literature. The goal of each individual paper was not only to better understand the event, but also to assess the suitability of 20CR in this regard. This note gives, on the one hand, a brief introduction to the six first papers of this electronic volume and presents common themes. On the other hand, a brief overall assessment of the case studies is given. Several further papers will follow in the near future and will complete this volume.

2. The data set

All papers in this volume use version 2 of 20CR. The "Twentieth Century Reanalysis" is a global three-dimensional atmospheric reanalysis data set reaching back to 1871 (Compo et al., 2011). It provides an ensemble of analyses based on the assimilation of only surface and sea level pressure observations, *i.e.,* the distribution of atmospheric mass. The data assimilation was performed using an Ensemble Kalman Filter technique, with first guess fields generated by a 2008 experimental version of the US National Center for Environmental Prediction Global Forecast System atmosphere/land model (NCEP/GFS, see Saha et al., 2010). The GFS model was integrated at a resolution of T62 in the horizontal (corresponding to a spatial resolution of 2° x 2°) and 28 hybrid sigma-pressure levels in the vertical. Boundary conditions were derived from monthly mean sea surface temperature and sea ice distributions from the HadISST data set (Rayner et al., 2003). The ensemble contains 56 members, each of which is equally likely (see Compo et al., 2011 for details).

The analysis is performed every six hours, but 3-hourly forecasts of some variables are also available, allowing an even more detailed view of the temporal development of some of the extreme events.

The literature using 20CR is growing rapidly. With respect to extremes, previous studies have used 20CR in statistical studies that addressed heat-waves and Eurasian blocking (Barriopedro et al., 2011; Dole et al., 2011), droughts (Wang et al., 2011; Hoerling et al., 2012; Varikoden et al., 2012), temperature extremes (Ouzeau et al., 2011), North Atlantic storminess (Donat et al., 2011; Brönnimann et al., 2012b; Wang et al., 2012; Krueger et al., 2013), hurricanes (Wang et al., 2012), North Atlantic blocking (Hakkinen et al., 2011; Rimbu and Lohmann, 2011), or extreme precipitation (Hao et al., 2011; Kunkel et al., 2012). Other studies have used 20CR to study individual extreme events (Cook et al., 2010; de Bruin and van den Dool, 2010; Giese et al., 2010; Moore et al., 2011; Webb, 2011; Smith et al., 2011; Stucki et al., 2012).

In the case of North Atlantic storminess, studies disagree concerning the agreement between 20CR and other observation-based analyses with respect to decadal and lower-frequency variability (Wang et al., 2012; Krueger et al., 2013). Also, some studies suggest that individual ensemble members need to be analysed rather than the ensemble mean when addressing extremes (Brönnimann et al., 2012b). For case studies, 20CR mostly turns out to be useful (*e.g.,* Giese et al., 2010; Webb, 2011; Stucki et al., 2012) and it might possibly be used for further impact-oriented applications such as downscaling. However, as for any new data set, the characteristics of 20CR are only slowly uncovered. Hence, this compilation of papers adds to the body of literature discussing advantages and shortcomings of 20CR for various applications.

3. Selection of events

For Part 1 of this compilation of papers, six events were chosen. Table 1 provides a list and references to the papers; Figure 1 gives a geographical overview of the locations. Further extreme events will be analysed in a second set of papers, which will follow in the near future and will complete this volume.

Most of the events considered occurred over North America or Central Europe, one in the European Arctic. Many events concerned storms, including a blizzard and a hurricane, and storm surges at the North Sea coast. Other events include a heavy precipitation event in Switzerland in 1993 and an analysis of Arctic winds. Although this compilation is not a systematic survey and is not nearly representative in space and time, the events cover typical ranges of meteorological and (in one case) climatological extremes with a focus on the northern mid-latitudes. With respect to time, the earliest of the events was in 1888, the latest in 1993. The last paper on winds in Spitsbergen, 1912-1913, does not cover an extreme weather event *per se*, but this period is relevant for Arctic climate as a pronounced temperature shift occurred in this region shortly afterwards (Overland et al. 2004) and little information is available on Arctic climate before this shift.

The second set of papers (not included in Table 1 and Fig. 1) will address further events in Europe as well as North America, mostly focusing on the early decades of 20CR, plus a tropical cyclone in Samoa in 1889.

In all cases, other data sets than 20CR were also consulted, including instrumental observations and derived products (*e.g.,* historical weather charts) or other reanalysis data sets. Moreover, literature was available in all cases to put the results found with 20CR into context.

Table 1. List of events in Part 1 of this compilation

Event	Location	Year	Paper
Storm surge	Holland	1953	Schneider et al., 2013
Storm surge	Hamburg	1962	Jochner et al., 2013
Flooding	Switzerland	1993	Stucki et al., 2013
Blizzard	New York	1888	Fischer et al., 2013
Hurricane	Galveston	1900	Neff et al., 2013
Wind	Spitsbergen	1912-1913	Brönnimann et al., 2013

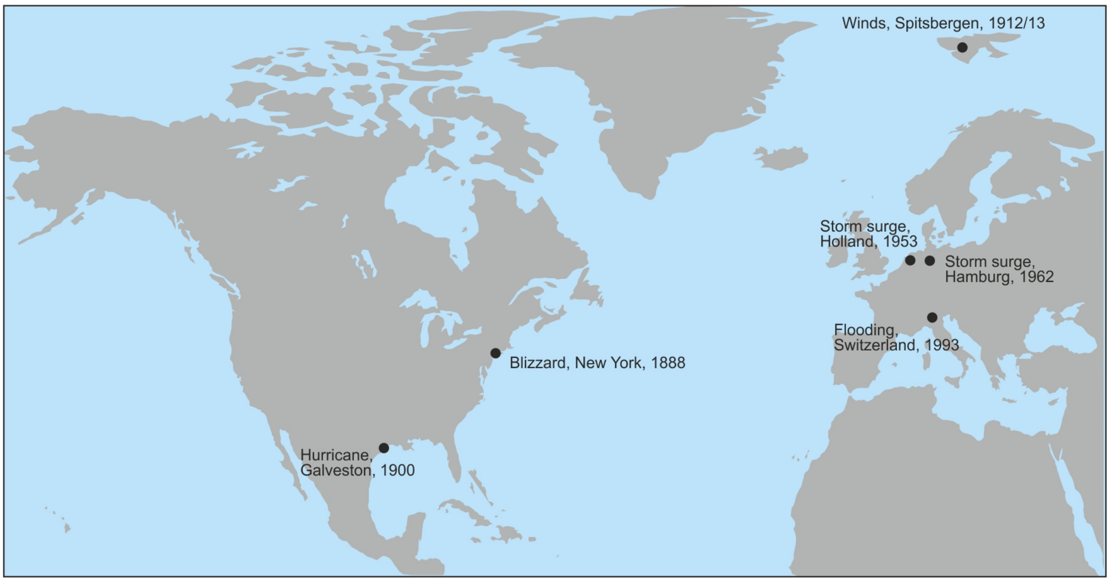

Figure 1. Map showing the locations of case studies compiled in Part 1 of this volume.

4. Analyses

The papers in Part 1 demonstrate that 20CR does capture all of the events in question. In fact, all papers show that important features are well reproduced at least qualitatively (note that Part 2 will include one event – the Samoa cyclone of 1889 - that is not captured in 20CR). Yet another example of a well reproduced extreme, in this case on a month-to-month scale, is presented in the following. Figure 2 shows monthly anomaly fields of total column ozone in 20CR (see Saha et al., 2010) for a specific month (March 1941) when extremely high values of total column ozone were observed over Oxford, UK, and New York, USA (see Brönnimann et al., 2004). The total column ozone anomaly in 20CR is in excellent agreement with the sparse observations (in fact, the two observation locations capture the maxima in the anomaly field). Moreover, anomalies in the flow near the tropopause (as depicted in 200 hPa geopotential height), to which total column ozone is closely related, show a consistent signature. The latter anomalies compare well with those in a statistical reconstruction based on historical upper-level data (Griesser et al., 2010), although magnitudes differ. This comparison suggests that based on 20CR, this event can be further studied and interpreted physically.

Although the events are reproduced in 20CR, the papers in this volume also show that the magnitudes of the events tend to be underestimated in the ensemble mean of 20CR compared to observations. This is expected due to various reasons, including

(1) a selection bias (events were selected because they were extreme in reality, not in 20CR),

(2) a smoothing effect due to averaging in the ensemble mean, aggravated in some cases by the sparsity of observations (*i.e.,* the analysis was not well constrained), and

(3) arguably unresolved effects and a limited spatial resolution compared to observations.

The range of individual ensemble members does not necessarily suffer from (2) but may still be unable to represent the magnitudes in all cases.

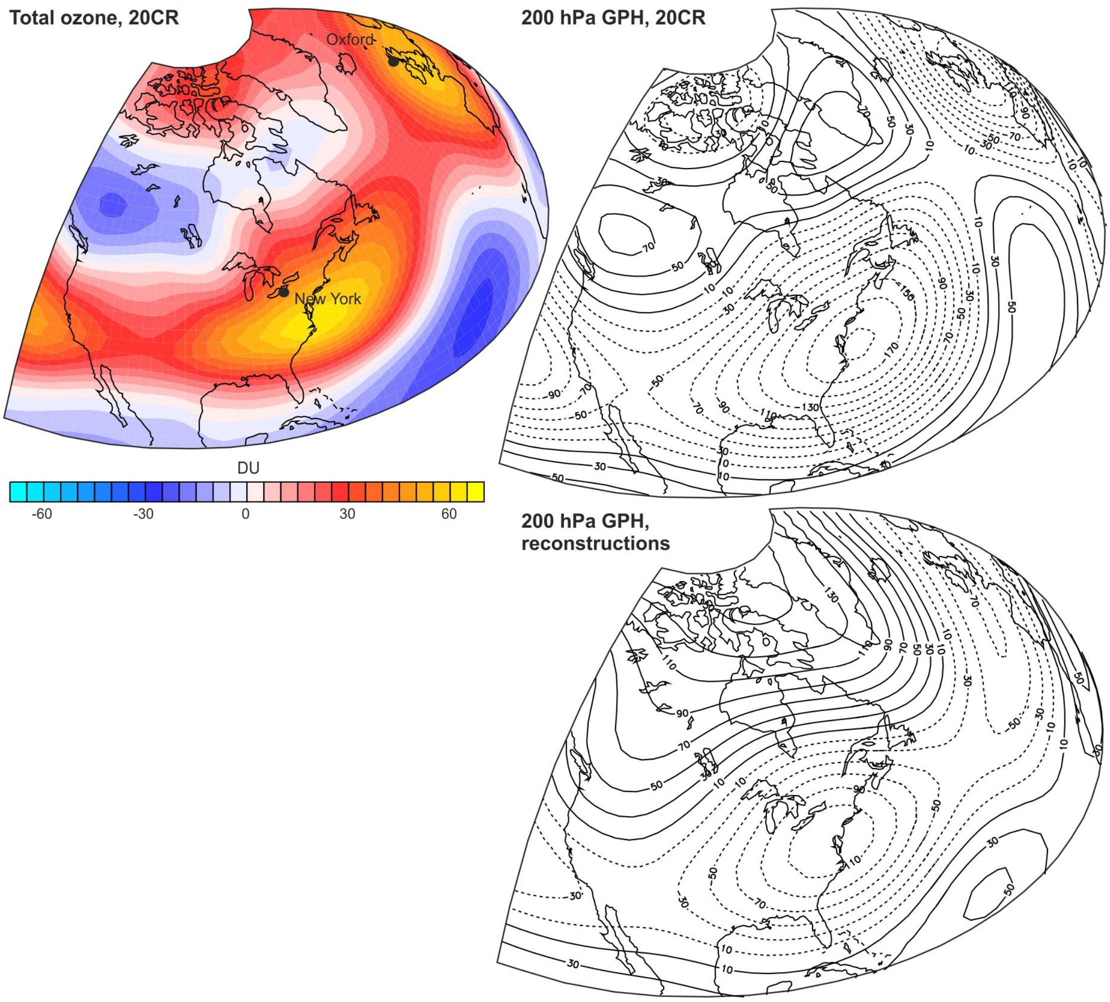

Figure 2. (left) Total column ozone anomalies in 20CR for March 1941, (right) anomalies of 200 hPa geopotential height (in gpm) in 20CR (top) and statistical reconstructions (bottom). Anomalies are with respect to March 1931-1950, without 1941.

Due to smoothing, the ensemble mean may not correctly depict characteristics of synoptic features. For instance, a small, intense feature may be reproduced in each individual ensemble member with correct strength and gradient, but at a slightly different position in space and time. In the ensemble mean the feature will therefore be too weak (with too weak gradients) and too large. As an example, Figure 3 shows sea-level pressure for 10 January 1919, 12 UTC. We show the 985 hPa contour for all ensemble members as well as for the ensemble mean (red). Two depressions can be seen, one over eastern Canada and one north of the British Isles. The depression over Canada is not well constrained by observations. In fact, within the displayed region of Canada no station pressure observations were available at all, whereas Western Europe and the North Atlantic are relatively well covered.

The depression over eastern Canada appears in most members, but not always at the same position. The ensemble mean does not cross the 985 hPa threshold so that no contour appears,

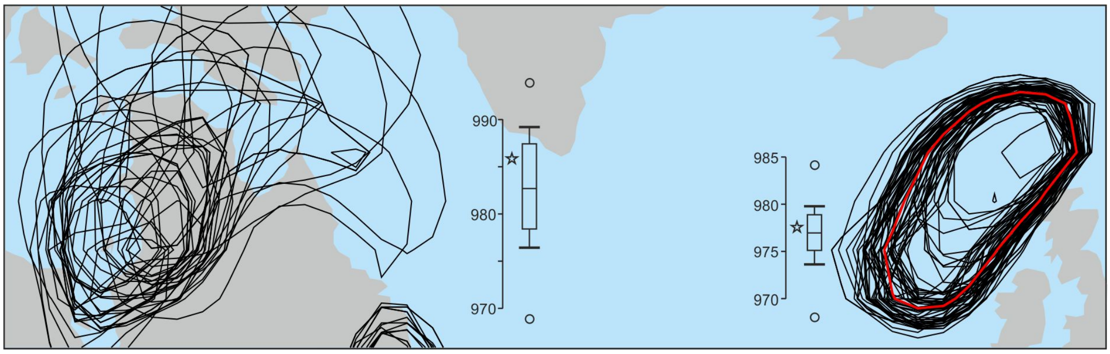

Figure 3. Mean sea-level pressure from 20CR for 10 January 1919, 12 UTC. Shown is the 985 hPa contour for each individual ensemble member (black) as well as for the ensemble mean (red). The bar plots give the statistics of the minimum mean-sea level pressure in hPa in the Canadian area (left) and the British Isles area (right). Circles denote minima and maxima, bars and whiskers denote the 10-, 25-, 50-, 75- and 90 percentile, respectively. The star denotes the minimum sea-level pressure found in the ensemble mean.

whereas 35 out of 56 individual members exhibit contours. The statistics of the spatial SLP minimum for all ensemble members are given in the bar plot, with the star denoting the minimum value in the ensemble mean. There is again a considerable spread in the minima. The ensemble mean clearly has a too high minimum that would correspond to the 67th percentile of the ensemble.

The cyclone north of the British Isles (Fig. 3) is much better depicted. All members show it at nearly the same position, and the minimum in the ensemble mean is only slightly above the median of the minima of the ensemble members. Even in this case, however, long tails of the distribution appear. Note again that each ensemble member is equally likely, physically consistent, and consistent with all ensemble members.

For analysing extreme events, the ensemble mean might be sufficient in the British Isles case but not in the Canadian case. Therefore, if possible and feasible, individual ensemble members should be analysed. However, in practice this poses considerable difficulties due to the large amount of data to be processed, hence information on the suitability of the ensemble mean is equally important as information on the members. The ensemble spread, which is readily accessible, will in many cases at least give a first indication of the associated uncertainties.

Finally, a shortcoming of 20CR is exposed in the case of wind speeds in the northern North Pacific and the Arctic in the paper by Brönnimann et al. (2013). Figure 4, taken from this paper, shows smoothed time series of ensemble mean wind speed and wind speed of the ensemble mean at the 0.995 sigma level for different areas. Wind speeds of the ensemble mean over the northern North Pacific, the Arctic, and north eastern Canada have more than doubled between the late 19th century and the 1920s (in the case of the North Pacific) or 1950s (Arctic); an artificial trend due to ensemble averaging. In contrast, ensemble mean wind speed increased, then decreased. Since the 1950s, changes were rather small.

The considered regions were very poorly observed in the early decades. As a contrast, wind speed time series for well covered regions are shown on the right side of the figure. A slight strengthening of wind speeds is also found there, but trends are much weaker.

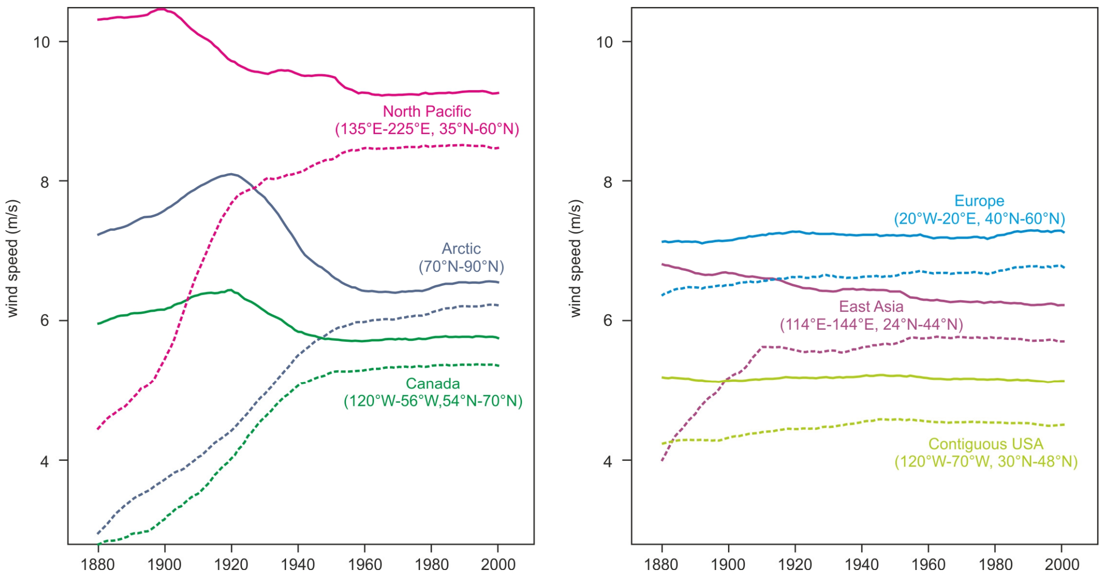

Figure 4. Twenty-year moving average of ensemble mean wind speed (solid) and wind speed of the ensemble mean (dashed) at the 0.995 sigma level for different regions (Brönnimann et al., 2013).

Biases have been documented for surface temperature as well as tropopause temperature over the Arctic (Brönnimann et al., 2012a). The surface temperature bias is understood to be the consequence of an error in the interpolation of the sea-ice data used as a boundary condition in the model. For the changes in wind, the cause is currently not known and hence this study points to further research needs. Also, the results confirm previous assessments (made with respect to storminess over the Atlantic) in that 20CR may be suitable for trend analyses after around 1950 (Wang et al., 2012; Brönnimann et al., 2012b).

5. Conclusions

The papers compiled in this collection analyse extreme events during the past 140 years using various sources of information. All papers use the "Twentieth Century Reanalysis" (20CR), and together they allow a very preliminary assessment of the suitability of the data set for this purpose. Despite differences in individual analyses and despite some shortcomings, all six events discussed in Part 1 of this compilation do appear in 20CR in a physically plausible manner (one event shown in Part 2 is not reproduced in 20CR). Important features are qualitatively, and sometimes also quantitatively, well represented. For these cases, 20CR allows further insights and further analyses of the mechanisms behind the events. Magnitudes are mostly underestimated in the ensemble mean.

The papers also show that the number of observations that was assimilated into 20CR might play a role. The examples given in this introductory paper – the two cyclones in 1919 and the wind speed trend in different regions – further support this point. The analyses also demonstrate that (particularly in these cases, but not exclusively) it may be helpful or even necessary to analyse individual ensemble members. Finally, our analyses show a likely problem in 20CR wind speeds over poorly observed and oceanic regions before the 1950s. We hope that the collection is helpful for other scientists trying to address extreme weather events in 20CR.

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