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Ensemble meteorological reconstruction using circulation analogues of 1781–1785

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Abstract

This paper uses a method of atmospheric flow analogues to reconstruct an ensemble of atmospheric variables (namely sea-level pressure, surface temperature and wind speed) between 1781 and 1785. The properties of this ensemble are investigated and tested against observations of temperature. The goal of the paper is to assess whether the atmospheric circulation during the Laki volcanic eruption (in 1783) and the subsequent winter were similar to the conditions that prevailed in the winter 2009/2010 and during spring 2010. We find that the three months following the Laki eruption in June 1783 barely have analogues in 2010. The cold winter of 1783/1784 yields circulation analogues in 2009/2010. Our analysis suggests that it is unlikely that the Laki eruption was responsible for the cold winter of 1783/1784, of the relatively short memory of the atmospheric circulation.

1 Introduction and motivation

The goal of this paper is to propose an ensemble of meteorological reconstructions around the North Atlantic from a gridded dataset of sea-level pressure that was obtained from early instrumental observations. This reconstruction is built on a technique of flow analogues that has been used in various contexts to analyse the atmospheric circulation (Lorenz, 1969; Zorita and von Storch, 1999; Vautard and Yiou, 2009).

The synoptic variability of the atmospheric circulation during the past centuries has been extensively studied from early instrumental records and proxy reconstructions (Cook et al., 1998; Jones et al., 1999; Luterbacher et al., 2002; Jacobeit et al., 2003). Such studies have attempted to reconstruct one trajectory of the climate system, given sometimes loose boundary and initial conditions. It is striking that very few reconstructions of the atmospheric circulation over the North Atlantic agree on periods preceding 1850 AD (Souriau and Yiou, 2001), mainly because of the lack of geographical constraints. Indeed, such reconstructions rely on one or two proxy records (Appenzeller et al., 1998; Cook et al., 1998; Luterbacher et al., 1999), while the North Atlantic circulation spatial structure exhibits a complexity that can hardly be captured by just two locations (Hurrell et al., 2003; Kimoto and Ghil, 1993; Michelangeli et al., 1995; Jacobeit et al., 2003, e.g.). Hence it can be argued that it is necessary to obtain ensembles of reconstructed trajectories so that the uncertainty of reconstructions can be assessed.

Ensembles of reanalyses for the past two centuries have been proposed by Compo et al. (2011). Such exercises allow to sample this meteorological uncertainty (Palmer, 2002), which is connected to the chaos of atmospheric variability (Lorenz, 1963; Ghil et al., 2008). Here, we propose an alternative approach to produce an ensemble of meteorological conditions for 1781–1785 AD.

The motivation of our study stems from the eruption of the Icelandic volcano Laki in 1783, one of the largest volcanic eruption of the last millennium. The Laki started to erupt in June 1783 and ten eruption episodes followed until February 1784 (Thordarson and Self, 2003), releasing lar amounts of SO_2, HCl, HF, CO_2 into the atmosphere. Those events killed one third of the population in Iceland. The volcanic sulfate aerosols and gases (sulfur and acids) were reported to travel to continental Europe in the days and weeks that followed the eruptions (Thordarson and Self, 2003). Such sulfate aerosols are believed to have increased mortality rates in Europe to respiratory affections (Desaive et al., 1972; Garnier, 2009a; Schmidt et al., 2011). It is probable that volcanic gases also affected public health (Durand and Grattan, 1999; Grattan et al., 2003; Witham and Oppenheimer, 2004). Modelling studies of the tropospheric chemistry transport have suggested that the environmental and health impact of the Laki was connected to dry deposition of sulfate dioxide rather than sulfuric acid (Stevenson et al., 2003).

Historians have reported that the summer of 1783 had been unusually warm in Western Europe (Garnier, 2009b) and the Eastern USA, although this warmth was not felt in Eastern Europe or Central Asia (Thordarson and Self, 2003). The goal of this paper is to estimate the meteorological conditions that prevailed after the Laki volcanic eruption in 1783, although we do not model the transport of volcanic gases and aerosols.

CPD
9, 5157–5182, 2013

In March 2010, the Icelandic volcano Eyjafjallajökull erupted, with an explosive phase in April 2010. This caused havoc in air transport, due to the presence of volcanic ash that traveled into continental Europe. Although the type of volcano was different from the Laki, it is interesting to investigate whether the atmospheric circulation conditions in Spring 2010 were similar to those in Spring 1783, in order to first guess how volcanic aerosols and gases in 1783 could have been transported into Europe. Hence, we first investigate whether the atmospheric circulation of North Atlantic region during the spring of 2010 was similar to the one in spring 1783.

The winter of 1783/1784 has been reported to be particularly cold in Western Europe and Eastern USA (Le Roy Ladurie, 2006; Franklin, 1784; Brazdil et al., 2010). This cold winter has sometimes been associated to the Laki eruption in spring (Wood, 1992; Brazdil et al., 2010). D'Arrigo et al. (2011) have compared the winter in 2009/2010, which was a record of cold in North America and extremely cold in Europe, to the 1783/1784 winter, from proxy reconstructions of the North Atlantic Oscillation (NAO) and the Niño 3 indexes. They conclude that although the atmospheric circulation and temperature patterns were probably similar, it is difficult to attribute a volcanic cause to the cold winter in 1783/1784. Our second issue is to re-examine the similarity between the winters of 1783/1784 and 2009/2010, and investigate the path taken by the climate trajectory between the first Laki eruption to the following winter.

Our analysis relies on a dataset of daily sea-level pressure obtained by Kington (1988). This dataset covers the period between 1781 and 1785 and has a regular grid. We use a methodology of windowed pressure analogues (Yiou et al., 2012) to infer sea-level pressure, temperature and wind fields over the North Atlantic. Such fields are reconstructed from the Kington (1988) SLP data and the NCEP reanalysis (Kalnay et al., 1996). The data and methodology are described in Sect. 2. Discussion and conclusion appear in Sect. 4. The results of the SLP, temperature and wind speed reconstructions from analogues are given in Sect. 3. In this section, we also compare the temperature reconstructions with observed temperatures in Western Europe.

CPD
9, 5157–5182, 2013

2 Data and methods

2.1 Historical period

We used the gridded sea-level pressure (SLP) dataset of Kington (1988), as our *target* reconstruction set. This dataset is based on ≈ 70 early instrumental records from several stations across Europe, from the French Société Royale de Médecine and the Societas Meteorologica Palatina of Mannheim (Kington, 1988, p. 23). The original surface pressure data were converted to SLP by heuristic corrections accounting for estimates of temperature (Kington, 1988). The data was cast on a regular grid (5 by 5°) covering the eastern North Atlantic (Kington, 1988). The data covers the period between 1 January 1781 to 30 November 1785, on a daily timescale. The region covered by this dataset is (30° W–30° E; 35–70° N). This dataset was used by studies of the climate impact of the Laki eruption in 1783 (Thordarson and Self, 2003; Schmidt et al., 2011; Oman et al., 2006).

The datafile was provided by Prof. P. D. Jones (CRU, UEA, UK). We performed a quality check of the data in order to remove outliers and errors in dating codes. We hence verified visually that the datafile we used in this paper conforms to the maps published by Kington (1988). Many homogeneity issues can affect the original data on which this set is built (Peterson et al., 1998; Caussinus and Mestre, 2004). Those issues include potential changes in instruments, location and surroundings. Assessing the homogeneity of this dataset is out of the scope of this paper, but this issue is a caveat of the study. The methodology to produce the gridded dataset from station data can also induce biases that are difficult to constrain.

For verification purposes, we used observed temperature time series in 10 locations in Europe, covering the Laki period. Although quality checks of the time series were performed, their homogeneity is less constrained than for periods after 1850, when meteorological networks started to thrive in Europe. The French station data (Dijon, La Rochelle, Montmorency and Saint Malo) come from the Société Royale de Médecine (in Paris). The other European station data (Bologna, Copenhagen,

CPD
9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.

Mannheim, Munich, Prague and Rome)were extracted from the ephemerides of the Societas Meteorologica Palatina of Mannheim. The time series were digitized from the databases at: meteo.academie-medecine.fr and bibliotheque.meteo.fr.

2.2 Reanalysis data

The *base* dataset for our study is the NCEP reanalysis (Kalnay et al., 1996) between 1948 and 2012 on a daily timescale. We used the SLP, surface temperature and wind speed at 1000 hPa for the climate reconstructions. The reanalysis data was extracted over the North Atlantic region (80° W–30° E; 30–70° N), with a spatial resolution of 2.5 by 2.5°. For comparison purposes with the Kington dataset, the NCEP SLP was regridded by averaging onto the Kington grid (smaller domain and lower spatial resolution). The effect of the spatial resolution is illustrated in the Supplementary Information movie.

We also computed reconstructed fields for surface temperature and surface wind speed from the NCEP data. A land-sea mask was used to estimate continental surface temperature, especially over France.

2.3 Flow analogues

In this paper, we use the methodology and terminology of Yiou et al. (2012) to obtain atmospheric reconstructions based on analogues. This type of approach was also proposed by Schenk and Zorita (2012) in a different context. The *target* period to be reconstructed is 1781 to 1785, with a constraint on the SLP field of Kington (1988). The analogues of SLP are computed from the SLP of NCEP reanalysis, which we call the *base* dataset. Contrary to the simple example of Yiou et al. (2012), the base and target datasets cover very different periods of time and yield (at the origin) different spatial resolutions.

In order to reconstruct time continuous sequences, the analogues were computed on moving windows of 5 days. This means that for each sequence of 5 consecutive days between 1781 and 1785, we determine the $N = 20$ sequences of 5-days in NCEP that are closer in terms of root mean square (RMS) (Yiou et al., 2012). The quality of the N analogues in the NCEP reanalysis "reference set" is estimated a posteriori by their Spearman spatial correlations (von Storch and Zwiers, 2001) with the "target" SLP field of Kington (1988). Hence, the RMS is optimized on 5 day sequences, and the correlation score is computed on daily reconstructions.

The choice of the window length is a tradeoff between the regularity of the the reconstruction (hence avoiding too many strong discontinuities in the dates of analogues) and quality of the analogues (in terms of correlation). This choice can be guided by the temporal persistence of atmospheric structures. Synoptic structures generally have an average persistence of a few days. We assessed this persistence by estimating the autocorrelation observed in the Kington SLP dataset. For each gridpoint, we computed the autocorrelation function of SLP, with lags between 1 and 20 days (Fig. 1). The median autocorrelations drop rapidly to an asymptotic value near $C = 0.18$. We bootstrapped the dates in the SLP dataset in order to obtain confidence intervals for the "background" auto-correlation of the dataset. We find that a lag of 5 days is the longest window for which more than 75 % of the gridpoints yield positive auto-correlations and more than 10 % of the gridpoints are below the background autocorrelation. This provides a heuristic way of justifying a window length of $W = 5$.

The dates of the 20 analogues allow us to make three dimensional reconstructions of the atmospheric flow and temperature for that period. The reconstruction is performed on weighted moving windows of $W = 5$ days shifted by increments of $\delta = 2$ days, in order to obtain a temporal continuity of the fields, as argued by Yiou et al. (2012). Each analogue reconstruction can be viewed as a possible trajectory of the climate system that is coherent with SLP conditions. Note that each day in an analogue reconstruction is a weighted average of 2 moving windowed analogues.

The reconstructions we propose have a resolution of 2.5 by 2.5° and cover the whole North Atlantic. In this paper, we chose to reconstruct *anomalies* of SLP, surface temperature and surface wind speed. The anomalies are determined with respect to the 1971–2000 reference period. The reason for not reconstructing *absolute* fields, rather

CPD
9, 5157–5182, 2013

than anomalies, is that we do not have 30 yr climatologies during the 18th century for all fields (apart from SLP and surface temperature).

3 Results

3.1 SLP analogues

The SLP reconstruction is compared to the target dataset of Kington (1988) with a resolution of 5 by 5°. We show the scores of the $N = 20$ analogue reconstructions. RMS and correlation values for daily SLP anomalies are shown in Fig. 2 for each day between 1 January 1781 and 30 September 1785, and for each analogue. The RMS values exhibit a seasonal cycle, with higher values in winter and better scores in summer. The reason for this seasonal cycle is the seasonality of SLP variance in the extra-tropics, as suggested by Yiou et al. (2012).

The correlation values are on average above $r = 0.7$. We computed the empirical probability distribution of the correlation r of the N analogues and the target SLP (shadings in Fig. 2). We show that SLP analogues that are optimized for RMS can yield very low spatial correlation values (sometimes below 0.4), although the distribution is centered above 0.7 (red line). This is further illustrated in the Supplementary Information (movie) comparing the target dataset and the reconstructions from the daily first and tenth analogues, between 1783 and 1784. The illustration shows that the analogues are optimized over a relatively small proportion of the eastern North Atlantic and European region. The summers of 1783 and 1784 are the ones with the highest average RMS values (Fig. 2). During those two summers, we find that the analogue reconstructions can yield rather different behaviors and hence low correlation values with the target SLP dataset.

In order to investigate the distribution of the trajectories on which we base the analogue reconstruction, we count the occurence of years from the NCEP reanalysis (covering 1948 to 2012) from the dates of the $N = 20$ windowed analogues. For a given

CPD
9, 5157–5182, 2013

day in 1781 to 1785, the years of the analogues are counted only once. This avoids a potential bias when several analogues fall within the same year: for example, if the 20 analogues of a given target day fall on nearby days from the same base year, but this base year never appears in the analogues of the other days of the target month, this would put an unwanted weight to that year. Then, for each target month (between January 1781 and October 1785), we count the number of occurrences of daily analogue years. A given year in the NCEP reanalysis is picked 5 times on average in the SLP analogues, for the whole period. Unusual frequency of a year in the SLP analogues (higher than 90th percentile) reaches 12 days in a month. We focus on the period encompassing the Laki eruption (1 May 1783 to 30 April1784) (Fig. 3).

We find that the year 2010 is frequently picked in the analogues of May 1783 (Fig. 3), but this is before the Laki eruption. From June to the end of 1783, the frequency of the year 2010 in the analogues never reaches a 90th quantile, and is below the median quantile of frequencies, apart from July, August and December 1783. This implies that the atmospheric circulation of spring 2010 is unlikely to be similar to spring 1783 that witnessed the Laki eruption.

The SLP analogues start to be picked in 2010 in a significant way in October 1783. As suggested in Fig. 3, we verified that from December 1783 to February 1784, the analogue dates are picked between November 2009 and January 2010 in a high proportion (i.e., above the 90th percentile). This can be interpreted by a high correlation between the atmospheric circulation during the winters 1783/1784 and 2009/2010. The latter winter yielded an anomalous negative phase of the North Atlantic Oscillation (Cattiaux et al., 2010; Cohen et al., 2010; D'Arrigo et al., 2011) and underwent extremely cold and snowy conditions.

3.2 Temperature estimates

In this section, we first focus on the 12 month period that includes the Laki eruption, between May 1783 to April 1784 (Fig. 4). The 20 analogues are spatially averaged in order to provide a composite monthly reconstruction of temperature anomalies.

CPD
9, 5157–5182, 2013

We find warm temperature conditions in May 1783 (right before the first Laki eruption, on 8 June 1783) over Western Europe and Southern Greenland. This warm temperature anomaly intensifies over Western Europe until August 1783. It remains positive until october 1783. This warm anomaly is consistent with the historical records for France and some parts of Western Europe (Le Roy Ladurie, 2006). It is also consistent with climate model simulations after the Laki eruption (Chenet et al., 2005), although this experiment did not take the radiative response of the Laki gas and aerosol emissions.

The temperature anomaly over Europe becomes negative and increasingly cold between November 1783 and February 1784. This cooling is also found in the North Eastern US, although not as intense as in Europe. We note that the Western Arctic remains anomalously warm. The cold European and North American cold anomaly is also evidenced by historical records in Europe (Le Roy Ladurie, 2006) and the USA (Franklin, 1784).

The time series of the analogue temperature reconstruction for France between 1781 and 1785 is shown in Fig. 5. The monthly mean of the 20 analogue reconstructions shows the warm anomaly in the summer of 1783 followed by the cold winter anomaly. In this very short time series (less than 5 yr), only 1783 and 1784 yield such a large temperature swing between a warm summer and cold winter in France. This shows that the temperature anomalies are controled by the circulation anomalies.

We compared the analogue temperature anomaly reconstruction with early meteorological observations in France and Europe, between 1781 and 1785. The temperature observations were obtained from the Societé Royale de Médécine de Paris and Societa Mateorologicas Palatina of Mannheim. The data are monthly averaged for 10 stations (Fig. 6). The correlations between the median of 20 analogue reconstructions and the observed series exceeds $r = 0.42$ (with p values lower than 5×10^{-3}) for all cities except Bologna, Rome and Dijon. The temperature observations yield a larger variance than the average reconstruction over France. This is due to the spatial averaging in Fig. 5. The warm anomaly in France in the summer 1783 is well reproduced by the analogue reconstruction. The amplitude of the following winter anomaly is weaker and

CPD
9, 5157–5182, 2013

lags by two months. The other periods of the reconstructions yield much weaker amplitudes than the observations, although the correlations are significantly positive. One caveat of this comparison is that the homogeneity of the observed temperature times series is barely verified. For example, it has been documented that the thermometer used for La Rochelle record was changed in 1782, from a Sigaud de Lafond thermometer to a Mannheim thermometer (meteo.academie-medecine.fr), whose features could have been different.

The reconstructed temperature anomaly fluctuations over France are coherent with historical chronicles between 1781 and 1785 (Le Roy Ladurie, 1971, 2006; Garnier, 2009b). These historical qualitative compilations (partly based on diaries and crop/harvest yields) suggest this sequence of warm summers and cold winters during those five years.

This result suggests that the atmospheric circulation played a major role in the summer temperature variation in 1783. This role seems less clear in the years that precede and follow the Laki eruption. But this conclusion should be moderated by the low number of observations before 1783.

3.3 Wind estimates

We computed 1000 and 500 hPa wind anomaly reconstructions from SLP analogues for the 12 months following the first Laki eruption (Figs. 7 and 8). Such anomalies are superimposed over a generally northeastward flow. The wind anomaly reconstructions in May and July 1783 does not seem favourable to an optimal transport of air masses from Iceland to continental Europe. The conditions in June, August and September seem more favourable to transport from Iceland to western continental Europe. This is coherent with the early observations of Mourgue de Montredon (1783), as pointed out by Chenet et al. (2005).

The northward flow over the north eastern US explains the warm temperatures that were reconstructed there. The reconstructed wind field over the Labrador region does not explain how volcanic gases from the Laki could be transported directly to the

Eastern US. As found in the experiments of Chenet et al. (2005), our reconstructed field suggests a route around Greenland and the Arctic region.

The winter wind anomaly reconstruction at 1000 hPa indicates anticyclonic circulations conveying cold air from the Arctic to western continental Europe, between November 1783 and February 1784. This explains the cold temperature anomalies reconstructed in Fig. 4.

4 Discussion and conclusions

We have applied a method of analogues of circulation to propose a reconstruction of the daily atmospheric flow conditions and surface temperature between 1781 and 1785. We find that the atmospheric variability explains a significant part of the observed temperature in Europe ($r > 0.4$ over France, Germany and Denmark). In particular, we find that the very warm summer and cold winter in Europe and East US, after the Laki eruption can be explained by the atmospheric circulation variability. This result is robust to the 20 analogue trajectories, which all correspond to this warm to cold temperature oscillation.

We emphasise that only *anomalies* of meteorological variables are reconstructed by this method. The absolute fields can be obtained once a background climatology is determined. This can be done from monthly reconstructions (Luterbacher et al., 2002; Jacobeit et al., 2003) during the 18th century or a contemporary climatology (from a reanalysis), so that the differences can be very large. This means that the wind transport inference is qualitative (or else strong hypotheses need to be formulated).

The results on temperature reconstructions are coherent with historical and proxy records in Europe, especially during the Laki eruption period. D'Arrigo et al. (2011) suggested that the winter conditions in 1783/1784 resembled those of the 2009/2010 winter. Our analysis confirms this inference, although the 1783/1784 winter was not as cold as 2009/2010, at least in France.

This paper shows that the atmospheric circulation trajectory that lead to the cold winter in 1783/1784 does not stem from spring-summer-early fall conditions in 2009, because the dates of analogues are mostly picked in other years than 2009. The distribution of the dates of analogues shows that even though some years can be dominating the analogue distributions, the seasonal variability does not follow a consistent path throughout a year, and there is no link between the spring and following winter atmospheric conditions that could be identified from the dates of analogues. Therefore, if we admit that the winter of 2009/2010 is analogous to the winter of 1783/1784 in terms of atmospheric circulation and temperature, the paths that lead to such conditions were rather different in both cases because the Fall seasons preceding the cold winters of 1783 and 2009 have no striking analogues. Hence we find unlikely that the the cold winter in 1783/1784 was caused by the Laki volcanic eruption, because the "memory" of the atmospheric circulation ranges between 5 days to a couple of weeks (Fig. 1).

We have produced an ensemble of analogue reconstructions for SLP, temperature and wind speed over the North Atlantic, with a daily time scale and the spatial resolution of the NCEP reanalysis. Other variables have been produced for instance at various pressure levels (as was tested by Yiou et al., 2012). Those variables include temperatures, geopotential height, wind speed and relative humidity. Such a production can be used to constrain a chemistry transport model in order to investigate the trajectories of volcanic aerosols from Iceland to Europe.

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CPD

9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.

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CPD
9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437–471, 1996. 5160, 5162

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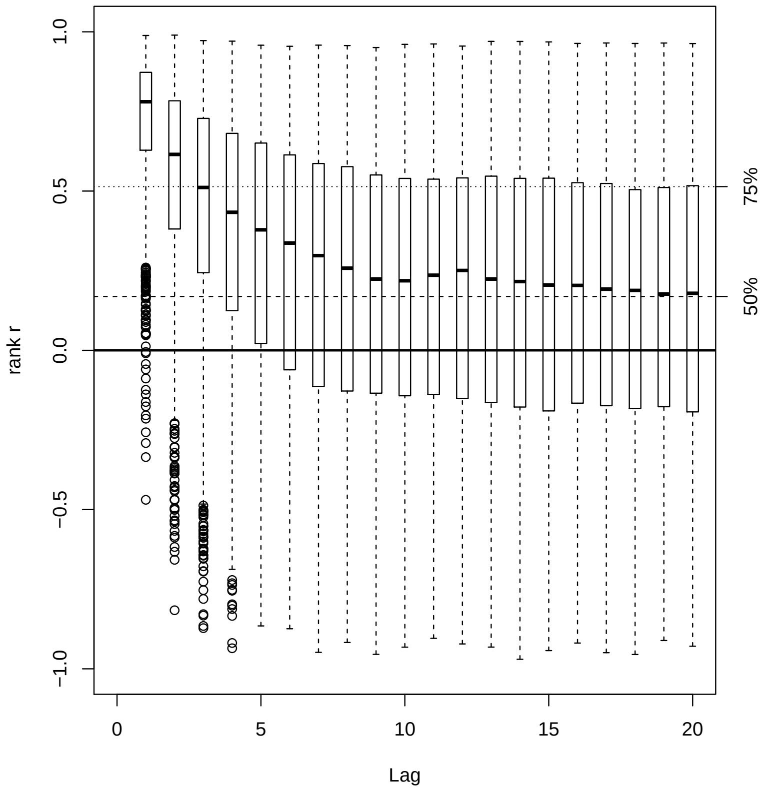


Fig. 1. Distribution of autocorrelation functions for each grid point in the Kington (1988) SLP dataset, for lags between 0 and 20 days. Each box and whisker plot is drawn for a lag and all grid points with data. The horizontal dashed line represents the 50th quantile of autocorrelation values when days are picked at random. The horizontal dotted line is the 75th quantile of autocorrelation values for days picked at random.

CPD
9, 5157–5182, 2013

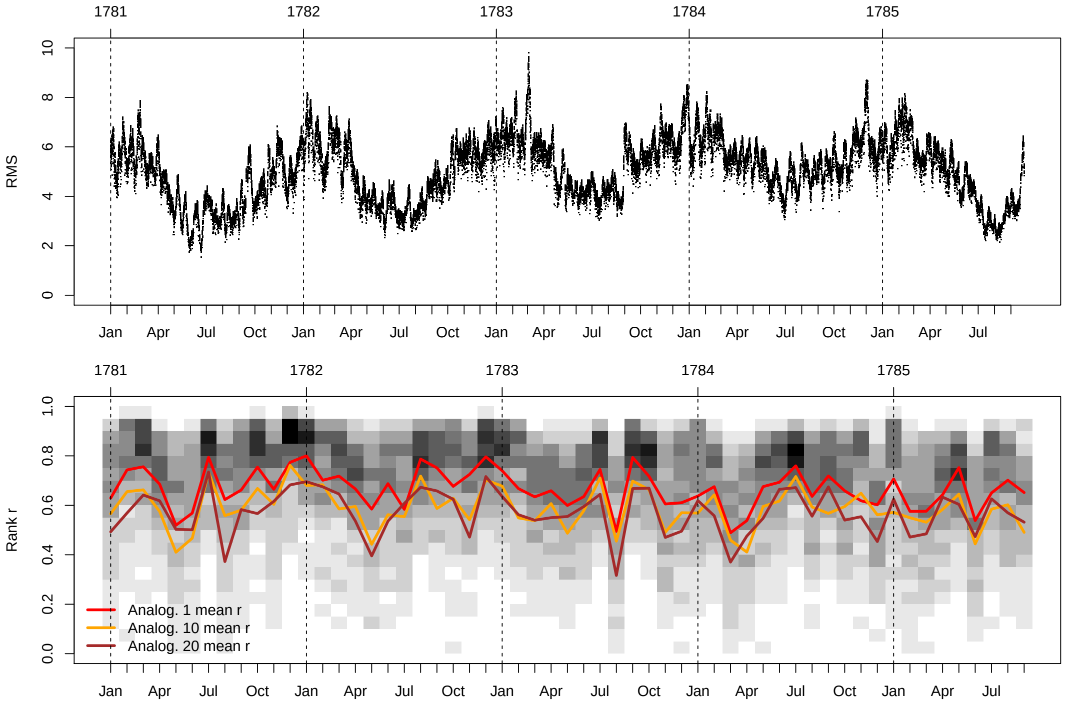
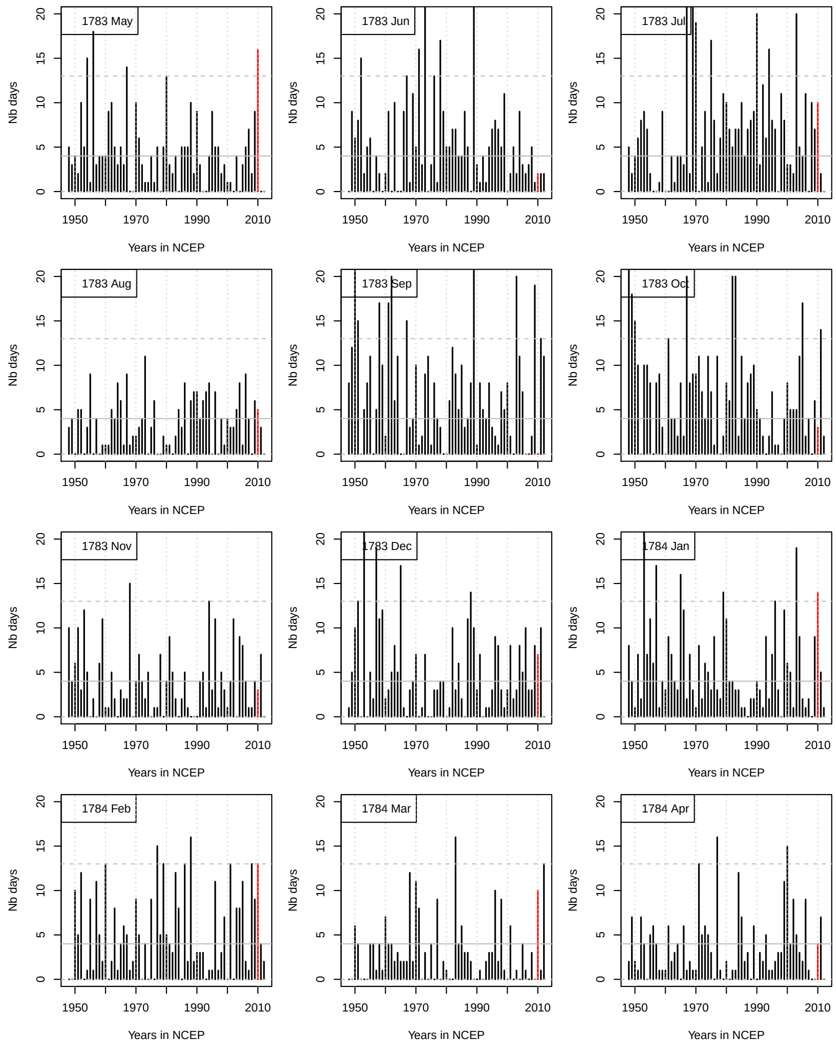


Fig. 2. Scores (correlation and RMS) of analogues. Upper panel: RMS values between Kington (1988) SLP anomalies and analogues in NCEP, between 1781 and 1785 for each day and all 20 analogues. Each dot represents one day and one analogue. Lower panel: spatial rank correlation between the Kington (1988) SLP anomalies and 20 best analogues from RMS, on monthly averages. The shaded squares represent the probability dstribution of the correlation values (dark greys indicate higher probability) for each month, for 20 analogues and daily reconstructions. The red line represents the monthly mean of Spearman correlations between the first analogue and the Kington SLP anomalies.

CPD
9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.



CPD
9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Fig. 3. Histograms of years of the 20 first analogues (between 1948 and 2012), for the months between May 1783 and April 1784. The 2010 year is outlined in red. The horizontal red lines represent the median frequency of the years of analogues. The horizontal dashed lines are the 10th and 90th quantiles of the frequency of the years of analogues.

CPD

9, 5157–5182, 2013

Temperature anomalies (post 178305)

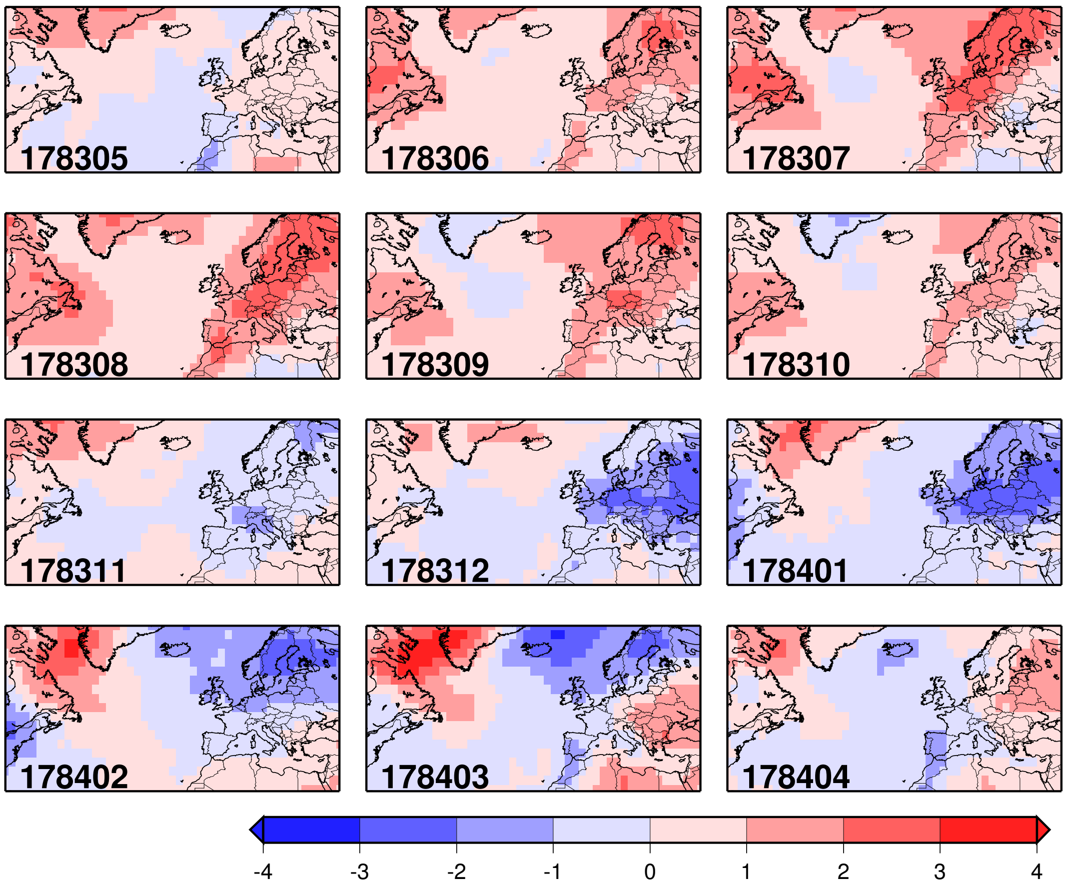


Fig. 4. Median of 20 surface air temperature anomaly reconstructions (in °C) between May 1783 and April 1784. The months are indicated in the lower left corners of the panels as $10^2\,y + m$, where y and m are respectively the year and the month.

CPD
9, 5157–5182, 2013

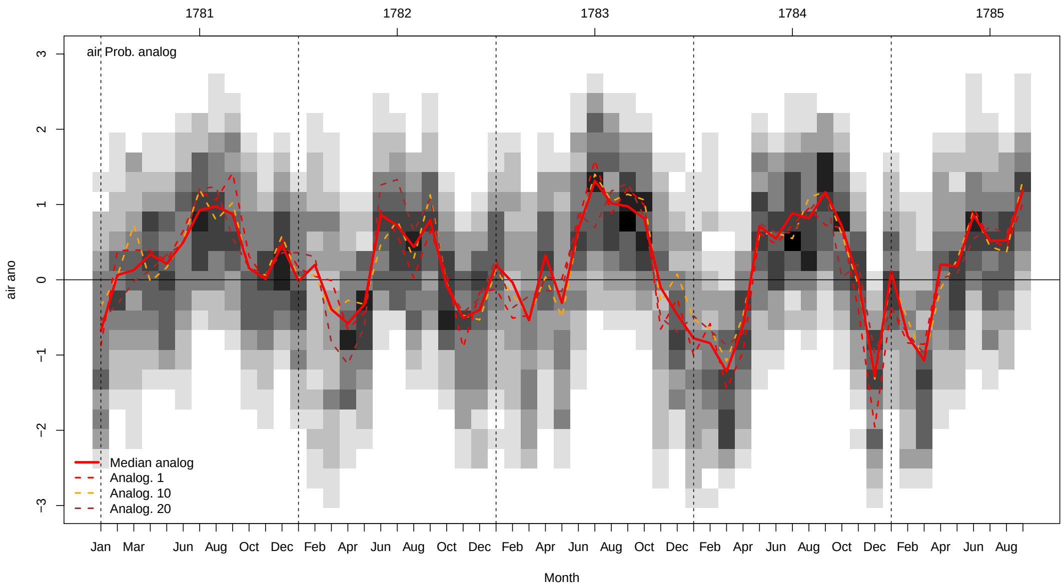


Fig. 5. Median of 20 surface air temperature anomaly reconstructions for France in 1783–1784 (red line, in °C). The grey squares represent the monthly probability distribution of the 20 analogue reconstructions.

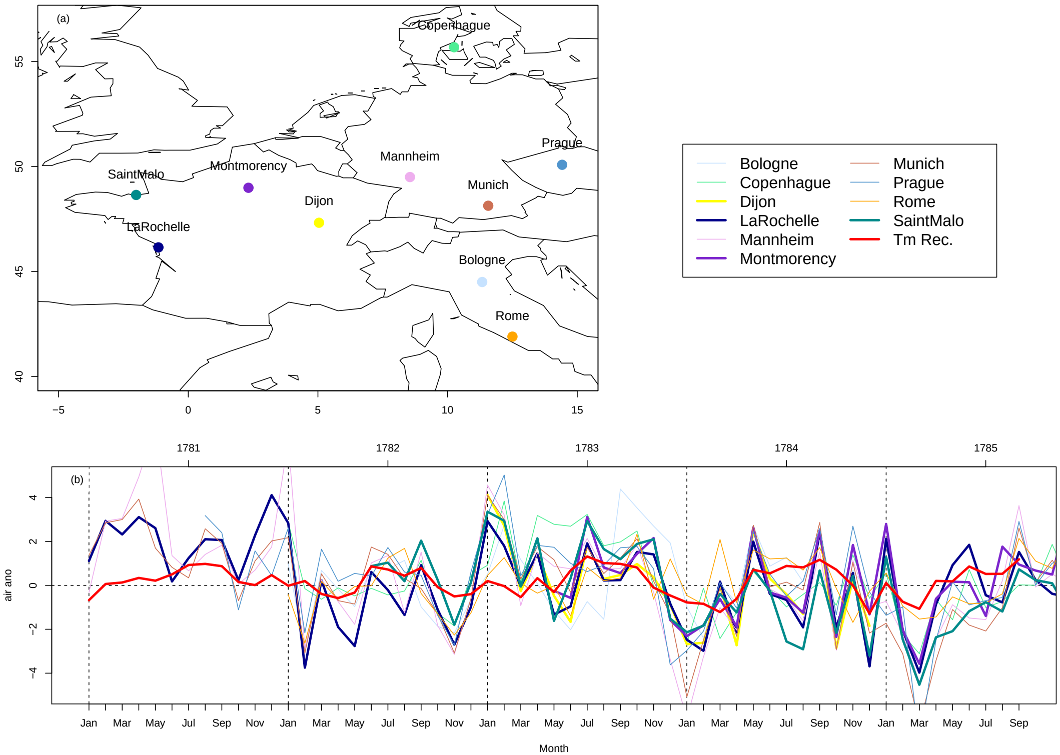


Fig. 6. Upper panel: observations of temperature anomalies in Europe. Lower panel: monthly averages of temperature anomalies for each observed time series (in °C), and median analogue reconstruction for France (thick red line).

CPD
9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄| |►
◄ ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

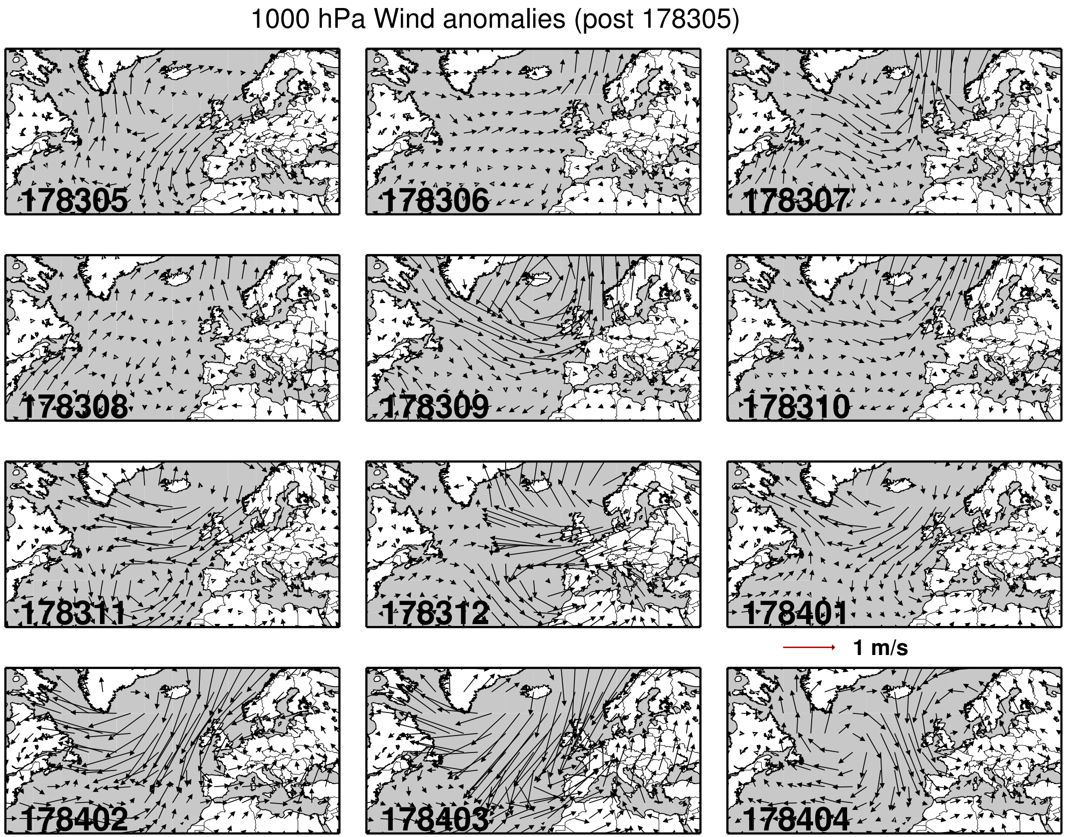


Fig. 7. Anomalies of wind speed at 1000 hPa between May 1783 and April 1784. The red horizontal arrow indicates the wind speed scale (in $m\,s^{-1}$).

500 hPa Wind anomalies (post 178305)

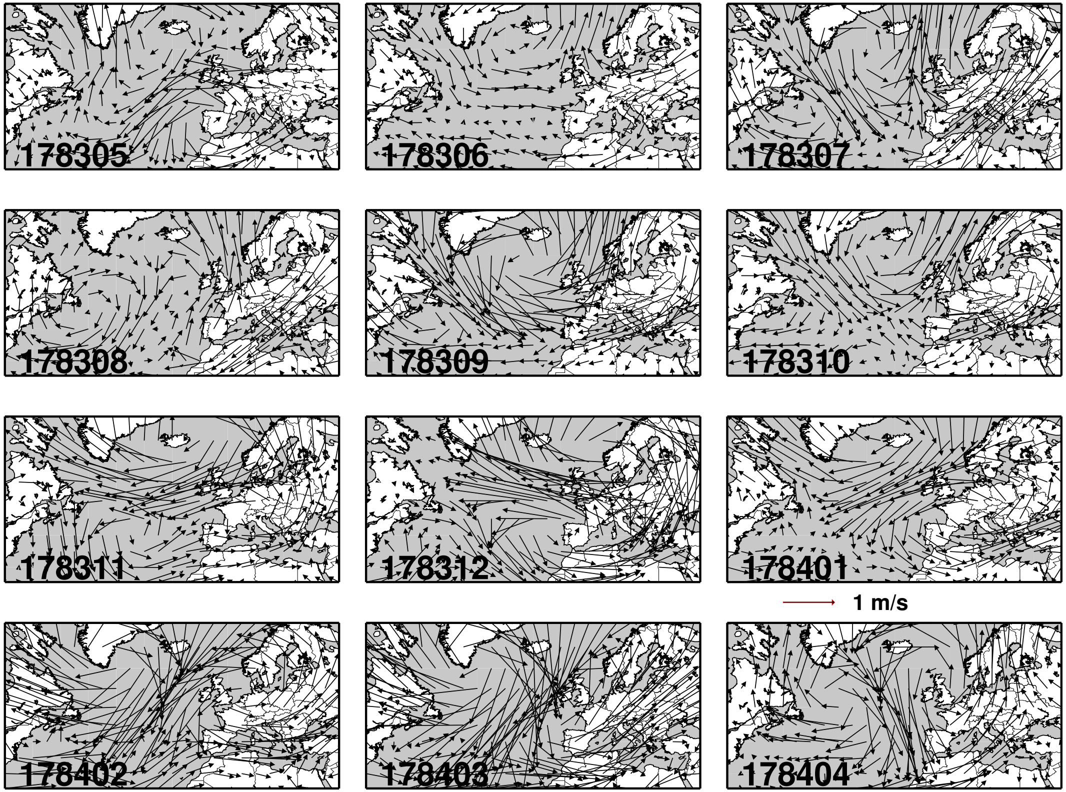


Fig. 8. Anomalies of wind speed at 500 hPa between May 1783 and April 1784. The red horizontal arrow indicates the wind speed scale (in $m\,s^{-1}$).

CPD
9, 5157–5182, 2013

Circulation analogues for climate reconstructions (1781–1785 AD)

P. Yiou et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion