Skewness of Temperature Data Implies an Abrupt Change in the Climate System between 1985 and 1991

A. Skelton[1], N. Kirchner[1], and I. Kockum[2]

[1]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden.

[2]Department of Clinical Neurosciences, Karolinska Institutet, Stockholm, Sweden.

Corresponding author: Alasdair Skelton (alasdair.skelton@geo.su.se)

Key Points:

- Skewness is used to search for abrupt changes in temperature time series from Europe
- An abrupt change is identified at 17 sites probably between 1985 and 1991
- Arctic sea ice loss potentially coupled with sulfate aerosol emission reductions is a possible cause
- Slowdown of Atlantic Meridional Overturning Circulation is less likely as a cause

Abstract

Instrumental records of mean annual temperature extend back to the seventeenth and eighteenth centuries at multiple sites in Europe. For such long time series, we expect and find that histograms of mean annual temperature data become skewed towards higher temperatures with time because of global warming. However, we also find that skewness changed abruptly and started increasing between 1985 and 1991 (95% confidence) at 17 sites. We argue that this finding may imply an abrupt change in the climate system affecting Europe which probably occurred at this time. One possible cause is a climate tipping point having been passed. Of known tipping elements, we find Arctic sea ice loss, potentially linked to reduced sulfate aerosol emissions and coupled to temperature by an albedo feedback mechanism, a likely candidate. This is based on good correlations of sea ice extent and sulfate aerosol emissions with skewness of mean annual temperature data.

Plain Language Summary

In this study we find evidence of a sudden change in the climate that affected Europe and probably occurred between 1985 and 1991. This finding is based on a statistical analysis of temperature data collected since the seventeenth or eighteenth century at 17 sites in Europe. Our analysis shows that the chance of a given year being warmer than average started to rise at all sites at that time. We compared the results of our analysis with possible causes of a change to the climate. The causes we considered were changes of ocean circulation, loss of sea ice from the Arctic Ocean and a reduction in particle emissions in Europe. Based on this comparison, we were able to show that loss of sea ice, possibly linked to particle emission reductions, was a possible cause of the change we detected. We note that sea ice loss becoming irreversible is a possible tipping point in the climate system. This is because sea ice loss makes the Earth darker which allows it to absorb more heat from the Sun, making the Earth even warmer. Based on our findings, we suggest that this climate tipping point may have been passed.

1 Introduction

The one instrumental record of temperature extending back to the seventeenth century (1659) is held at the Hadley Centre in England. Instrumental records of temperature extending back to the eighteenth century are held in Uppsala, Stockholm, Torino, Milan, Kremsmünster, Regensburg, Padua, Prague, Vienna, Innsbruck, Karlsruhe, Budapest, Hohenpeissenberg, Münster, Verona and Stuttgart. Data collected from these stations show 2000-2009 average temperatures ranging from 1.2°C (Hadley Centre) to 2.7°C (Münster) higher than corresponding 1850-1899 averages (Manley, 1953; 1974; Parker et al., 1992; Auer et al., 2007). These values can be compared with corresponding average temperature increases, calculated here from the HadCRUT4 temperature time series (Morice et al., 2012), of 1.4°C for Europe and 0.7°C globally. The rates of warming from 1990 to 2018, calculated here from the same temperature time series, are 0.37°C/decade (R^2 = 0.58) in Europe and about 0.17°C/decade (R^2 = 0.71) globally. For comparison and of relevance for this study, Arctic air temperatures increased at a rate of 0.76°C/decade from 1998 to 2012 (Huang et al., 2017). Here, we use the change in asymmetry in the distribution of mean annual temperature data, quantified by change in skewness, to test the hypothesis that the observed increase in the rate of warming occurred abruptly. We focus on the time period from the first half of the twentieth century to the early twenty-first century and restrict our analysis to Europe because of the availability of instrumental records of mean annual temperature that extend back to the seventeenth and eighteenth centuries, which is required for our statistical approach to give meaningful results.

2 Time series of mean annual temperature measurements

With the exception of the record held at the Hadley Centre, all instrumental records used in our study (Table 1; Fig. 1) are from recognized World Meteorological Office (WMO) Centennial Observing Stations or catalogued as part of the Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP: Auer et al., 2007). Mean annual temperature data are homogenized at all sites with the exception of Prague-Klementinum. The purpose of homogenization is to filter effects, such as changes in location, changes in site surroundings (urban heat island), change of instruments and changes of observation times from the data. The procedures used for homogenization of data from the HISTALP sites are described by Auer et al. (2007). The procedures used for homogenization of data from Stockholm and Uppsala are described by Moberg et al. (2002) and Bergström & Moberg (2002). The instrumental record held at the Hadley Centre is compiled from overlapping records from multiple sites in central England. The record until 1991 was compiled by Manley (1953, 1974) and Parker et al. (1992) and is kept up to date by the Hadley Centre at the UK Meteorological Office. The procedures used for homogenization of data are described by Parker et al. (1992) and presently a -0.2°C adjustment for urban warming is applied.

3 Skewness as a test for abrupt changes of mean annual temperature

Skewness has been used previously to test for regime shifts in ecological systems (Guttal and Jayaprakash, 2008) and abrupt changes in precipitation (He et al., 2013). Skewness has also been used with variance and autocorrelation as an early warning signal for a critical transition to eutrophication (Wang et al., 2012) and in conjunction with a tipping point analysis of Antarctic ice mass loss (Golledge et al., 2017). Here we use change of skewness to test for abrupt changes of mean annual temperature. For a time series from year y to year Y consisting of measurements of mean annual temperature (T_i: $i = y, \ldots, Y$), the sample Pearson skewness coefficient (γ_Y) is given by (Sokal and Rohlf, 1995):

$$\gamma_Y = \frac{\sum_{i=y}^{Y}(T_i - \bar{T})^3/(Y-y)}{s^3} \qquad (1)$$

where $\bar{T}$ is the sample mean and s is the standard deviation. For each instrumental record of mean annual temperature (Fig. 1), we calculate skewness (γ_Y), with $Y - y$ (which defines a "sliding window") set to a fixed length of 175 years. We then plotted time series of skewness for each instrumental record (Fig. 2). Each time series of Y starts 175 years after the first year of measurement and ends on the last year for which measurements are published. The chosen length of the sliding window represents a trade off between having sufficient data for our analysis and being able to capture changes during the latter half of the twentieth century. However, by using sliding windows of different lengths for the longer time series from the Hadley Centre and Uppsala, we show that our results are fairly insensitive to window length (Fig. S1).

The skewness of mean annual temperature data from all sites show an abrupt change at some point between 1975 and 1999 (Fig. 2). The mean of this range is between 1985 and 1991 (95% confidence). The median year is 1990. Before this change occurred, skewness was close to zero or negative at all sites and gradually decreasing at most sites. After this change occurred, skewness started increasing gradually at a few sites and sharply at most sites. Reinforcing this finding, an overall change from negative skew, i.e. towards cooler temperatures (before 1901) to positive skew i.e. towards warmer temperatures (after 1990) can be visualized qualitatively on histograms of mean annual temperature data (Fig. 3).

4 An abrupt change in the climate system

Here we argue that the sharp increase of positive skewness of mean annual temperature data between 1985 and 1991 points to an abrupt change in the climate system or some other anthropogenic change causing warming in Europe. Possible candidates which are known to have changed during the twentieth century include slowdown of Atlantic meridional overturning circulation (Rahmstorf et al., 2015), reduced sulfate aerosol emissions (Acosta Navarro et al., 2016) and Arctic sea ice loss (Schweiger et al., 2019).

The Atlantic Meridional Overturning Circulation (AMOC) is a system of ocean currents which are driven by water density differences related to temperature and salinity. The AMOC redistributes heat making it an integral part of the climate system. Observed cooling in the subpolar Atlantic as well as direct measurements indicate that the AMOC has been slowing down (Sroskosv and Bryden 2015, Rahmstorf et al., 2015, Caeser et al., 2018), a change which has been identified as a tipping element in the climate system (Lenton et al., 2008; 2019). It has been argued that AMOC slowdown couples with warming in Europe and might, for example, have been a contributory cause of the 2015 heat wave (Duchez et al., 2016). The AMOC started slowing down in the 1950s, recovered partly between 2000 and 2010, but has slowed down again since then (Fig. 4a). Here, we test for correlation between the AMOC index of Caeser et al. (2018) and skewness of mean annual temperature data from 17 sites to test the hypothesis that abrupt changes of skewness at these sites relate to AMOC slowdown. The AMOC index used by Caeser et al. (2018) was calculated from sea-surface temperature (SST) data from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) using a calibration factor to convert from SST to flow in Sverdrups, Sv (1 Sv = $1 \times 10^9\ m^3\ s^{-1}$) of 3.8 Sv/K which was derived from the CMIP5 models. In our analysis: 1) we used Spearman's rank correlation coefficients (r_s) because our tests concern abrupt nonlinear changes; 2) we (arbitrarily) used Evans (1996) classification for describing correlation strength; and 3) we considered a value of r_s significant if a *p-value* below 0.05 was calculated after correcting for multiple testing. Following this procedure, we calculated significant values of r_s at 9 of 17 sites. These values range from 0.390 to 0.618 at 8 sites (Table 2) implying a "moderate" positive correlation. The value obtained at the ninth site is -0.405 (Table 2) implying a "moderate" negative correlation. Given that we obtained both positive and negative values of r_s and, at the other 8 of 17 sites, values of r_s were less than 0.4 and *p-values* were greater than 0.05, we rule out AMOC slowdown as a probable cause of the abrupt change of skewness.

Sulfate aerosols emissions have decreased since the 1980s in Europe (Fig. 4b). Because sulfate aerosols reflect solar radiation, reduced emissions of sulfate aerosols are thought to increase radiative forcing (Myhre et al., 2013). Also, reduced sulfate aerosol emissions have been put forward as one cause of amplified warming in the Arctic region (Acosta Navarro et al., 2016). Here, we test for correlation between sulfate aerosol emissions in Europe from Smith et al. (2011) and skewness of mean annual temperature data from 17 sites to test the hypothesis that abrupt changes of skewness at these sites relates to sulfate aerosol emissions reductions. We calculated significant values of r_s at 14 of 17 sites. These values range from -0.471 to -0.860

implying a "strong" negative correlation (Table 2). Therefore, we cannot rule out reduced sulfate aerosol emissions as a contributory cause of the abrupt change of skewness.

Arctic sea ice loss has also been identified as a tipping element in the climate system (Lenton et al., 2008; 2019). Gridded extent from historical observations (Walsh et al., 2019) and model reconstructions (Schweiger et al., 2011; 2019) indicate a reduction in sea ice extent and volume. This loss of sea ice has been highlighted as a cause of amplified warming in the Arctic (Dai et al., 2019). The Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS and PIOMAS-20C) reconstructions of Arctic sea ice volume show a weak decline from 1900 to 1940, an overall increase from 1940 to 1990, and thereafter a rapid decline (Fig. 4c). Here we test for correlation between sea ice volume from the PIOMAS and PIOMAS-20C model reconstructions (Schweiger et al., 2011; 2019) and sea ice extent from SIBT1850 historical observations (Walsh et al., 2019) and skewness of mean annual temperature data from 17 sites to test the hypothesis that abrupt changes of skewness at these sites relates to Arctic sea ice loss. For PIOMAS, we calculated significant values of r_s at 16 of 17 sites. These values range from -0.725 to -0.914 (Table 2), implying a "strong" to "very strong" negative correlation. For PIOMAS-20C, we calculated significant values of r_s at 13 of 17 sites. These values range from -0.439 to -0.896 (Table 2), implying a "strong" negative correlation. For SIBT1850, we calculated significant values of r_s at 13 of 17 sites. These values range from -0.416 to -0.701 (Table 2), implying a "moderate" to "strong" negative correlation. Overall, we cannot rule out Arctic sea ice loss as a contributory cause of the abrupt change of skewness.

5 Conclusions

Based on skewness of mean annual temperature data from 17 sites in Europe, we identify an abrupt change in the climate system affecting Europe which probably occurred between 1985 and 1991. By testing for correlations of skewness of main annual temperature data with the AMOC index, sulfate aerosol emissions and measures of Arctic sea ice loss, we identify Arctic sea ice loss and sulfate aerosol emission reductions in Europe as possible contributory causes of this abrupt change. We note that sulfate aerosol emission reductions in Europe, as one potential cause of Arctic warming (Acosta Navarro et al., 2016), and Artic sea ice loss are coupled, and may both have contributed to the abrupt change discussed in the present study. We further note that Pistone et al. (2013) estimated that measured albedo forcing due to Arctic sea ice loss (0.21 $\pm$ 0.03 W/m^2) equates to 10% of radiative forcing from increased carbon dioxide concentrations (estimated to 2.1 W/m^2 for 412 ppmv CO_2 using the equation of Myhre et al., 1998). We thus infer that coupling between mean annual temperature in Europe and Arctic sea loss could relate to an albedo feedback mechanism. If so, we argue that a climate tipping point, beyond which complete loss of summer Arctic sea ice is inevitable, might have been passed between 1985 and 1991. We conclude by emphasizing the urgent need for a rapid reduction of greenhouse gas emissions so as to limit further irreversible damage to the climate system due to anthropogenic global warming.

Acknowledgments, Samples, and Data

Two anonymous reviewers are thanked for thorough and constructive reviews. The data used in this study are provided as supplementary information (Table S1). These data can also be accessed as follows. Hadley: Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadcet/); Uppsala: Swedish Meteorological and Hydrological Institute (https://www.smhi.se/data/meteorologi/temperatur/uppsalas-temperaturserie-1.2855, click on "Uppsalas temperaturserie 1722-2019"); Stockholm: Bolin Centre Database (https://bolin.su.se/data/stockholm); Prague: Czech Hydrometeorological Institute (http://portal.chmi.cz/historicka-data/pocasi/praha-klementinum?l=en); All other site: Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (http://www.zamg.ac.at/histalp/). This research was conducted using funds provided by the Bolin Centre for Climate Research at Stockholm University.

References

Acosta Navarro, J. C., Varma, V., Riipinen, I., Seland, Ø., Kirkevåg, A., Struthers, H., Iversen, T., Hansson, H.-C. & Ekman, A. M. L. (2016). Amplification of Arctic warming by past air pollution reductions in Europe. *Nature Geoscience*, 9, 277-282

Auer I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovicp, Z. & Nieplovaq, E. (2007). HISTALP – Historical instrumental climatological surface time series of the greater Alpine region 1760-2003. *International Journal of Climatology*, 27, 17-46

Bergström, H. & Moberg, A. (2002). Daily air temperature and pressure series for Uppsala (1722–1998). *Climatic Change*, 53, 213-252

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, 556, 191-196

Dai, A., Luo, D., Song, M. & Liu, J. (2019). Arctic amplification is caused by sea-ice loss under increasing CO2. *Nature Communications*, 10, 121

Duchez, A., Frajka-Williams, E., Josey, S. A., Evans, D. G., Grist, J. P., Marsh, R., McCarthy, G. D., Sinha, B., Berry, D. I. & Hirschi, J. J-M. (2016). Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environmental Research Letters*, 11, 074004

Evans, J.D. (1996). Straightforward Statistics for the Behavioral Sciences. Brooks/Cole Publishing, Pacific Grove. 600 pp.

Golledge, N. R., Thomas, Z. A., Levy, R. H., Gasson, E. G. W., Naish, T. R., McKay, R. M., Kowalewski, D. E. & Fogwill, C. J. (2017). Antarctic climate and ice-sheet configuration during the early Pliocene interglacial at 4.23 Ma. *Climate of the Past*, 13, 959-975

Guttal, V. & Jayaprakash, C. (2008). Changing skewness: an early warning signal of regime shifts in ecosystems. *Ecology Letters*, 11, 450-460

He, W., Wan, S., Jiang, Y., Jin, H., Zhang, W., Wu, Q. & He, T. (2013). Detecting abrupt change on the basis of skewness: numerical tests and applications. *International Journal of Climatology*, 33, 2713-2727

Huang, J., Tengd, F.-Z., Shena, B., Xiaoe, S., Langa, X., Maa, H.-R., Fuf, Y. & Peng, Y. (2017). Recently amplified arctic warming has contributed to a continual global warming trend. *Nature Climate Change*, 7, 875–879

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Science*, 105, 1786-1793

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. & Schellnhuber, H. J. (2019). Climate tipping points — too risky to bet against. *Nature*, 575, 592-595

Manley, G. (1953).The mean temperature of Central England, 1698 to 1952. *Quarterly Journal of the Royal Meteorological Society*, 79, 242-261

Manley, G. (1974). Central England Temperatures: monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society*, 100, 389-405

Moberg, A., Bergström, H., Ruiz Krigsman J. & Svanered, O. (2002). Daily air temperature and pressure series for Stockholm (1756-1998). *Climatic Change*, 53, 171-212

Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P.D. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset. *Journal of Geophysical Research*, 117, D08101

Myhre, G., Highwood, E.J., Shine, K.P. & Stordal, F. (1998). New estimate of radiative forcing due to well mixed greenhouse gases. *Geophysical Research Letters*, 25, 2715-2718

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura T. & Zhang, H. (2013) Anthropogenic and Natural Radiative Forcing. In T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley, (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp 658–740), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Parker, D.E., Legg, T.P. & Folland. C.K. (1992). A new daily Central England Temperature Series, 1772-1991. *International Journal of Climatology*, 12, 317-342

Pistone, K., Eisenman, I. & Ramanathan, V. (2013). Observational determination of albedo decrease caused by vanishing Arctic sea ice. *Proceedings of the National Academy of Science*, 111, 3322-3326

Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S. & Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, 475-480

Schweiger, A., Lindsay, R., Zhang, J., Steele, M. & Stern, H. (2011). Uncertainty in modeled arctic sea ice volume, *Journal of Geophysical Research*, 116, C00D06

Schweiger, A.J., Wood, K.R. & Zhang, J. (2019). Arctic Sea Ice Volume Variability over 1901–2010: A Model-Based Reconstruction. *Journal of Climate*, 32, 4731-4752

Smith, S.J., van Aardenne, J., Klimont, Z., Andres, R.J., Volke, A. & Delgado Arias, S. (2011). Anthropogenic Sulfur Dioxide Emissions: 1850–2005, *Atmospheric Chemistry and Physics*, 11, 1101-1116

Sokal, R. R. & Rohlf, F. J. (1995). Biometry. The Principles and Practice of Statistics in Biological Research. Third edition. Freeman, New York, 880 pp.

Srokosz, M.A. & Bryden, H. L. (2015). Observing the Atlantic Meridional Overturning Circulation yields a decade of inevitable surprises. *Science*, 348, 1255575

Walsh, J. E., Chapman, W. L., Fetterer, F. & Stewart, J. S. (2019). Gridded Monthly Sea Ice Extent and Concentration, 1850 Onward, Version 2. [Sea Ice Area]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center [Accessed: Jan 9, 2020]

Wang, R., Dearing, J., Langdon, P., Zhang, E., Yang, X., Dakos V. & Scheffer, M. (2012). Flickering gives early warning signals of a critical transition to a eutrophic lake state. *Nature*, 492, 419-422

Figure captions

Figure 1. Time series of mean annual temperature data. Temperature data (grey lines) with 11-year moving averages (black lines) are shown for stations and time intervals listed in Table 1. Note that the length of the y-axis (mean annual temperature) is the same (6 degrees) for all plots but values differ between plots. Also, note that the x-axis is from 1650 to 2020 for the Hadley Centre, 1700 to 2020 for Uppsala, and 1750 to 2020 for all other stations.

Figure 2. Time series of skewness (γ_Y) of mean annual temperature data. Skewness (γ_Y) is shown from year *y* to year *Y* (plotted on the x-axis) for sites listed in Table 1. The year in which an abrupt change is indicated by change of skewness (i) was estimated as the intersection of linear regressions of data before (red circles)and after (blue circles) time i for which a maximum sum of R^2 values was obtained. The mean value of i for 17 sites falls between 1985 to 1991 (95% confidence). The median year is 1990.

Figure 3. Histograms of mean annual temperature data. Histograms show mean annual temperature data for stations and time intervals listed in Table 1. The y-axes are the same for all sites except the Hadley Centre and that the length of the x-axis (mean annual temperature) is the same (6 degrees) for all plots except for Vienna and Münster but values differ between plots.

Figure 4. Time series of (a) the AMOC index of Caeser et al., 2016 (blue circles), (b) sulfate emissions reported by Smith et al., 2011 (yellow circles) and (c) PIOMAS (orange circles, primary axis) and PIOMAS-20C (red circles, primary axis) model reconstructions of Arctic sea ice volume (Schweiger et al., 2011; 2019) and SIBT1850 data (purple circles, secondary axis) historical observations of Artic sea ice extent (Walsh et al., 2019).

Table 1. Instrumental records of mean annual temperature, sorted according to starting year of time series.

Site	Country	Time series	Homogenized	WMO	HISTALP	Reference
Hadley Centre	England	1659-2018	x			Parker et al. 1992
Uppsala	Sweden	1722-2018	x	x		Bergström & Moberg 2002
Stockholm	Sweden	1756-2018	x	x		Moberg et al. 2002
Torino	Italy	1760-2010	x		x	Auer et al. 2007
Milan	Italy	1763-2011	x		x	Auer et al. 2007
Kremsmünster	Germany	1768-2018	x	x	x	Auer et al. 2007
Regensburg	Germany	1773-2014	x		x	Auer et al. 2007
Padua	Italy	1774-2010	x		x	Auer et al. 2007
Prague	Czech Republic	1775-2018		x		CHMI
Vienna	Austria	1775-2018	x		x	Auer et al. 2007
Innsbruck	Austria	1777-2018	x		x	Auer et al. 2007
Karlsruhe	Germany	1779-2014	x		x	Auer et al. 2007
Budapest	Hungary	1780-2014	x		x	Auer et al. 2007
Hohenpeissenberg	Germany	1781-2018	x	x	x	Auer et al. 2007
Münster	Germany	1781-2014	x		x	Auer et al. 2007
Verona	Italy	1788-2011	x		x	Auer et al. 2007
Stuttgart	Germany	1792-2014	x		x	Auer et al. 2007

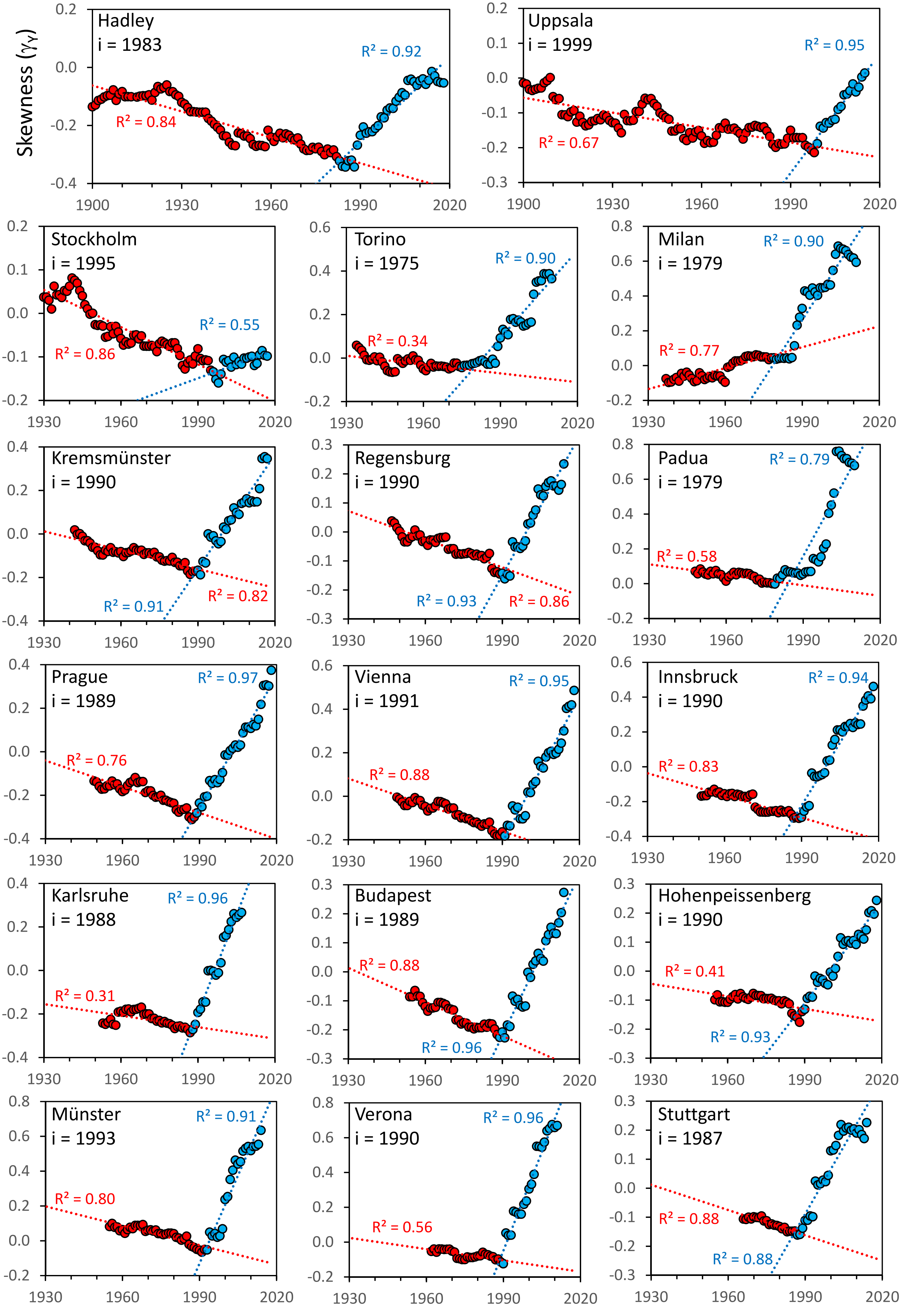
Note. Abbreviations WMO = World Meteorological Office Centennial Observing Stations; HISTALP = Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region; and CHMI = Czech Hydrometeorological Institute.

Table 2. Correlation matrix for skewness of mean annual temperature data with AMOC index, with SO_2 aerosol emissions in Europe, and with PIOMAS and PIOMAS-20C model reconstructions of Arctic sea ice volume and SIBT1850 measurements of Arctic sea ice extent.

Site		AMOC index	SO_2 (Europe)	PIOMAS	PIOMAS-20C	SIBT1850
Hadley	r_s	0.300 (*0.121, 0.461*)	**-0.860** (*-0.909, -0.788*)	**-0.902** (*-0.953, -0.802*)	**-0.605** (*-0.720, -0.457*)	-0.255 (*-0.420, -0.073*)
	p	0.06	< 0.01	< 0.01	< 0.01	0.30
Uppsala	r_s	**0.390** (*0.217, 0.539*)	**-0.645** (*-0.753, -0.504*)	**-0.725** (*-0.860, -0.493*)	-0.212 (*-0.386, -0.024*)	-0.170 (*-0.343, 0.014*)
	p	< 0.01	< 0.01	< 0.01	1.35	3.44
Stockholm	r_s	**0.574** (*0.399, 0.709*)	-0.229 (*-0.435, -0.001*)	0.024 (*-0.294, 0.337*)	0.208 (*-0.013, 0.410*)	0.336 (*0.130, 0.515*)
	p	< 0.01	2.38	45.12	3.19	0.08
Torino	r_s	0.067 (*-0.160, 0.287*)	**-0.552** (*-0.704, -0.352*)	**-0.862** (*-0.939, -0.704*)	**-0.675** (*-0.790, -0.513*)	**-0.591** (*-0.729, -0.407*)
	p	28.73	< 0.01	< 0.01	< 0.01	< 0.01
Milan	r_s	**-0.405** (*-0.585, -0.188*)	0.026 (*-0.212, 0.261*)	**-0.852** (*-0.933, -0.688*)	**-0.472** (*-0.640, -0.262*)	**-0.416** (*-0.594, -0.200*)
	p	0.02	42.56	< 0.01	< 0.01	0.01
Kremsmünster	r_s	0.336 (*0.112, 0.528*)	**-0.720** (*-0.830, -0.555*)	**-0.882** (*-0.943, -0.763*)	**-0.510** (*-0.675, -0.298*)	**-0.551** (*-0.700, -0.355*)
	p	0.17	< 0.01	< 0.01	< 0.01	< 0.01
Regensburg	r_s	**0.593** (*0.396, 0.738*)	**-0.599** (*-0.751, -0.386*)	**-0.843** (*-0.926, -0.683*)	-0.403 (*-0.597, -0.165*)	**-0.441** (*-0.622, -0.215*)
	p	< 0.01	< 0.01	< 0.01	0.05	0.01
Padua	r_s	0.216 (*-0.037, 0.442*)	**-0.800** (*-0.886, -0.662*)	**-0.837** (*-0.926, -0.656*)	**-0.518** (*-0.688, -0.295*)	**-0.518** (*-0.687, -0.295*)
	p	4.55	< 0.01	< 0.01	< 0.01	< 0.01
Prague	r_s	0.375 (*0.142, 0.569*)	**-0.655** (*-0.792, -0.454*)	**-0.911** (*-0.958, -0.818*)	**-0.565** (*-0.723, -0.350*)	**-0.541** (*-0.699, -0.332*)
	p	0.09	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
Vienna	r_s	**0.446** (*0.221, 0.626*)	**-0.499** (*-0.681, -0.259*)	**-0.872** (*-0.938, -0.746*)	**-0.439** (*-0.628, -0.201*)	**-0.476** (*-0.649, -0.255*)
	p	0.01	< 0.01	< 0.01	0.02	< 0.01
Innsbruck	r_s	0.344 (*0.105, 0.546*)	**-0.731** (*-0.844, -0.554*)	**-0.914** (*-0.959, -0.824*)	**-0.713** (*-0.828, -0.538*)	**-0.581** (*-0.731, -0.378*)
	p	0.25	< 0.01	< 0.01	< 0.01	< 0.01
Karlsruhe	r_s	0.267 (*-0.003, 0.501*)	**-0.608** (*-0.765, -0.384*)	**-0.829** (*-0.926, -0.629*)	**-0.722** (*-0.838, -0.541*)	**-0.452** (*-0.649, -0.200*)
	p	2.50	< 0.01	< 0.01	< 0.01	0.03
Budapest	r_s	**0.553** (*0.333, 0.716*)	**-0.615** (*-0.771, -0.389*)	**-0.853** (*-0.931, -0.700*)	**-0.616** (*-0.765, -0.403*)	**-0.466** (*-0.651, -0.230*)
	p	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Hohenpeissenberg	r_s	0.180 (*-0.076, 0.413*)	**-0.471** (*-0.670, -0.211*)	**-0.899** (*-0.951, -0.795*)	**-0.713** (*-0.832, -0.530*)	**-0.570** (*-0.727, -0.356*)
	p	8.28	0.03	< 0.01	< 0.01	< 0.01
Münster	r_s	**0.618** (*0.413, 0.764*)	-0.273 (*-0.514, 0.008*)	**-0.812** (*-0.910, -0.628*)	**-0.461** (*-0.654, -0.213*)	-0.374 (*-0.580, -0.124*)
	p	< 0.01	2.70	< 0.01	0.02	0.17
Verona	r_s	**0.545** (*0.295, 0.725*)	**-0.748** (*-0.866, -0.553*)	**-0.905** (*-0.958, -0.791*)	**-0.689** (*-0.824, -0.482*)	**-0.594** (*-0.759, -0.358*)
	p	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Stuttgart	r_s	**0.486** (*0.222, 0.684*)	**-0.617** (*-0.790, -0.352*)	**-0.872** (*-0.940, -0.735*)	**-0.896** (*-0.948, -0.798*)	**-0.701** (*-0.831, -0.498*)
	p	0.02	< 0.01	< 0.01	< 0.01	< 0.01

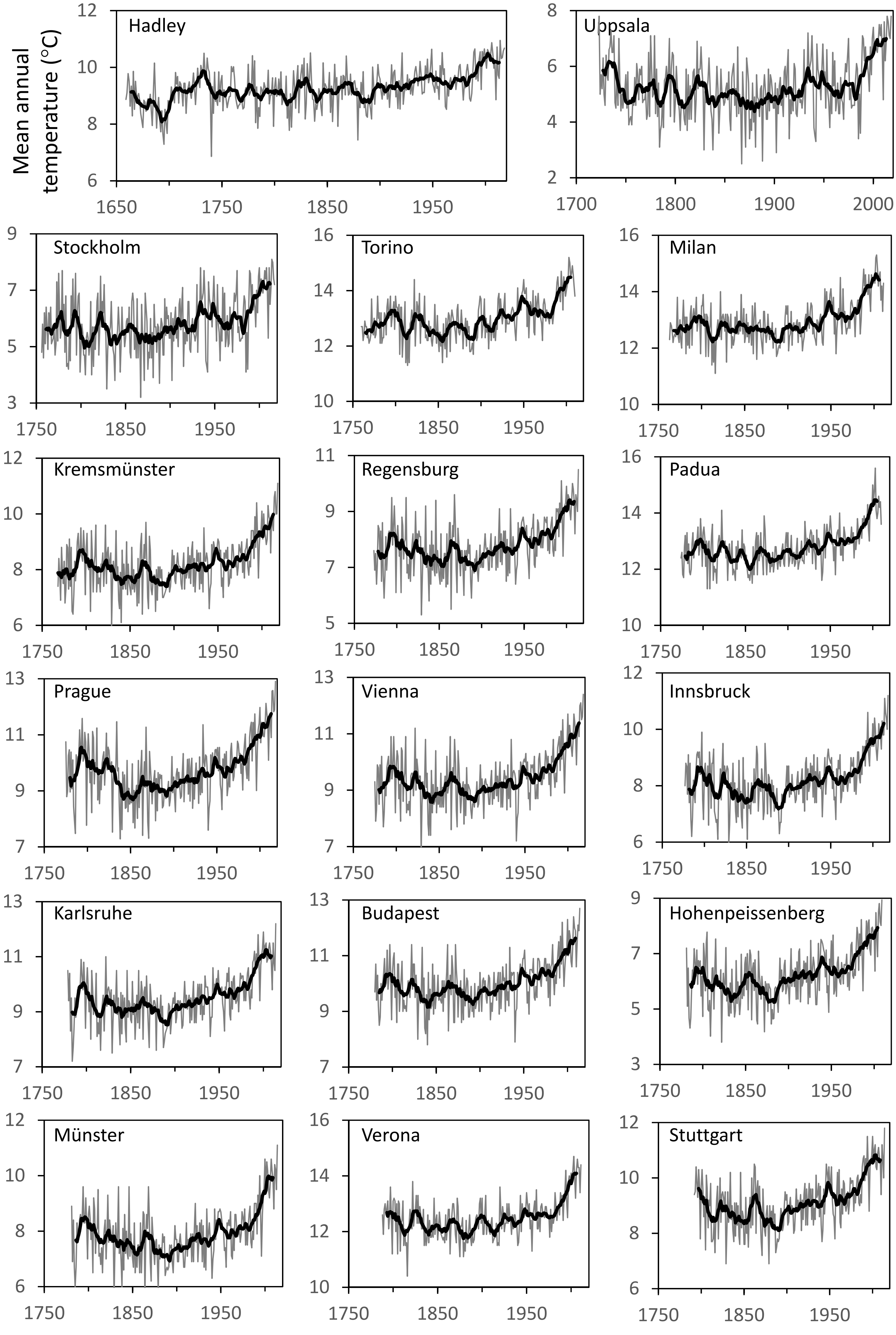
Notes: Spearman's rank correlations (r_s) are reported with 95% confidence intervals (bracketed and in italics) and 2-sided p-values (p) corrected for multiple testing. Entries in bold differ from zero with 95% confidence after correction for multiple testing. These entries are shaded with greyscale intensity following Evins (1966) classification for describing correlation strength: i.e. weak (r_s = 0.20-0.39: light shading), moderate (r_s = 0.40-0.59; moderate shading), strong (r_s = 0.60-0.79; heaving shading) and very strong (r_s = 0.80-1.00; very heavy shading) correlations.

Figure 1.



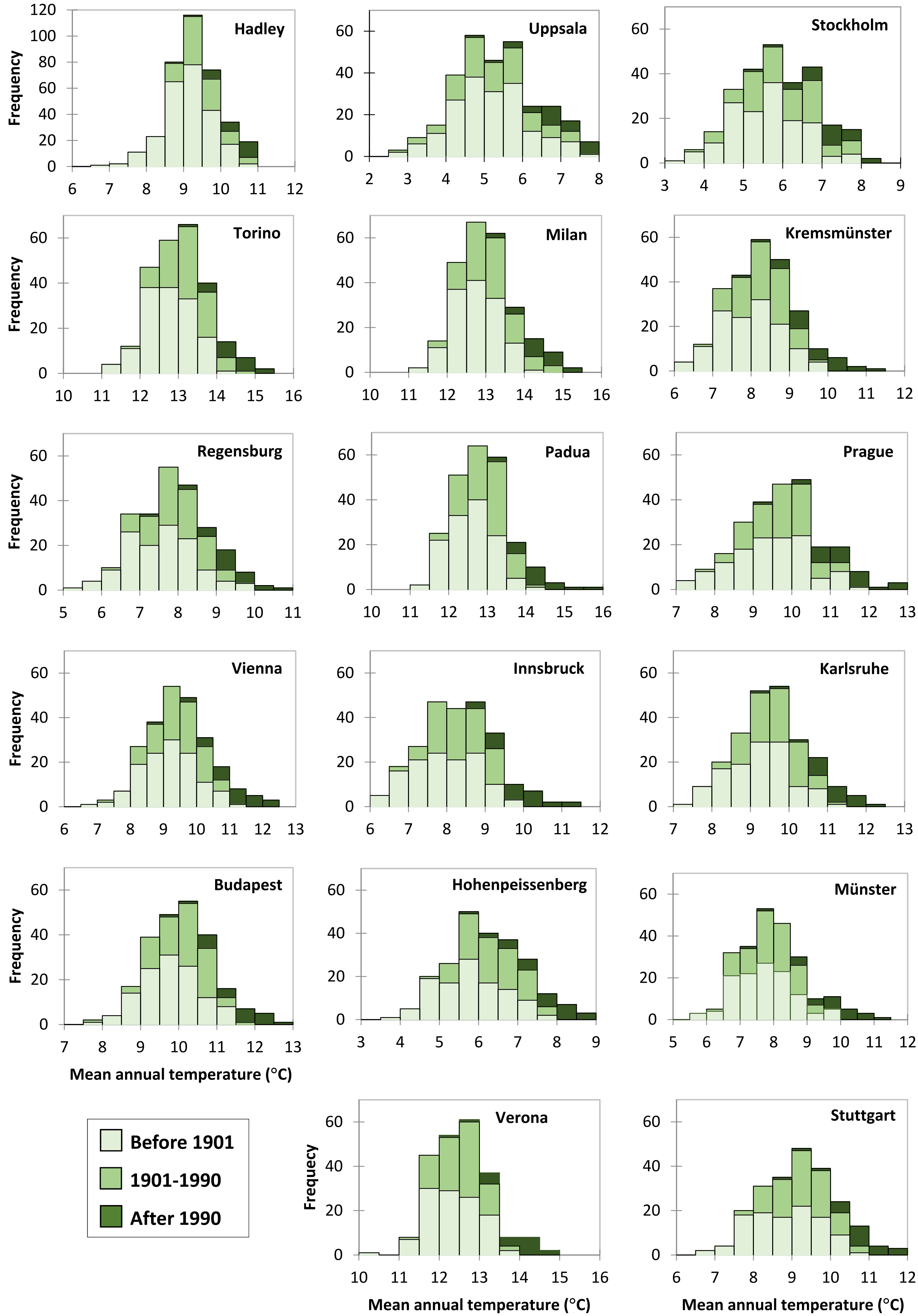
Skewness (γY)
Hadley
i = 1983
R² = 0.92
R² = 0.84
Uppsala
i = 1999
R² = 0.95
R² = 0.67
Stockholm
i = 1995
R² = 0.55
R² = 0.86
Torino
i = 1975
R² = 0.90
R² = 0.34
Milan
i = 1979
R² = 0.90
R² = 0.77
Kremsmünster
i = 1990
R² = 0.91
R² = 0.82
Regensburg
i = 1990
R² = 0.93
R² = 0.86
Padua
i = 1979
R² = 0.79
R² = 0.58
Prague
i = 1989
R² = 0.97
R² = 0.76
Vienna
i = 1991
R² = 0.95
R² = 0.88
Innsbruck
i = 1990
R² = 0.94
R² = 0.83
Karlsruhe
i = 1988
R² = 0.96
R² = 0.31
Budapest
i = 1989
R² = 0.88
R² = 0.96
Hohenpeissenberg
i = 1990
R² = 0.41
R² = 0.93
Münster
i = 1993
R² = 0.91
R² = 0.80
Verona
i = 1990
R² = 0.96
R² = 0.56
Stuttgart
i = 1987
R² = 0.88
R² = 0.88

Figure 2.



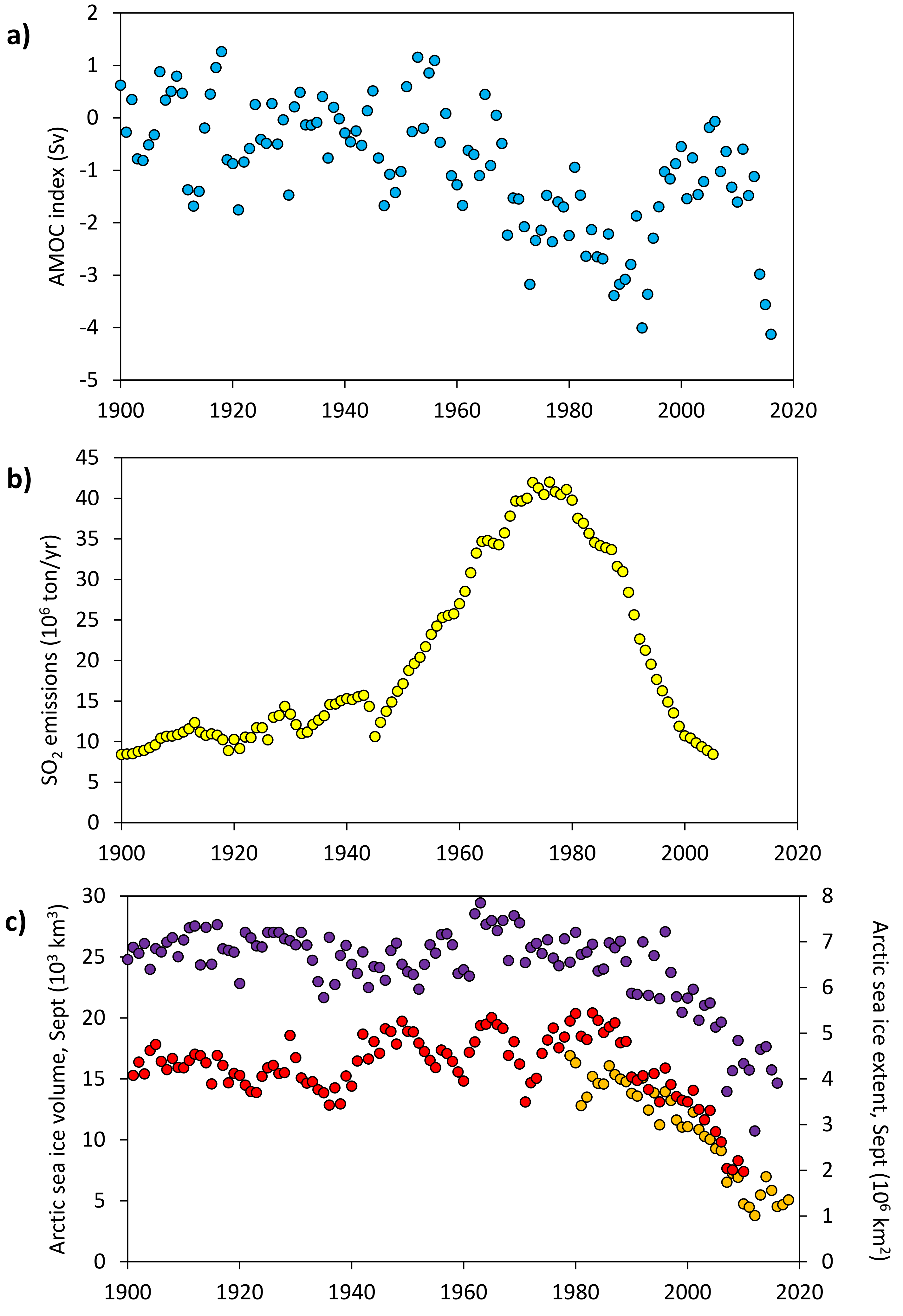
Mean annual temperature (°C)
Hadley
Uppsala
Stockholm
Torino
Milan
Kremsmünster
Regensburg
Padua
Prague
Vienna
Innsbruck
Karlsruhe
Budapest
Hohenpeissenberg
Münster
Verona
Stuttgart

Figure 3.



Hadley
Uppsala
Stockholm
Torino
Milan
Kremsmünster
Regensburg
Padua
Prague
Vienna
Innsbruck
Karlsruhe
Budapest
Hohenpeissenberg
Münster
Verona
Stuttgart
Frequency
Mean annual temperature (°C)
Before 1901
1901-1990
After 1990

Figure 4.



a)
AMOC index (Sv)
2
1
0
-1
-2
-3
-4
-5
1900
1920
1940
1960
1980
2000
2020
b)
SO_2 emissions (10^6 ton/yr)
45
40
35
30
25
20
15
10
5
0
1900
1920
1940
1960
1980
2000
2020
c)
Arctic sea ice volume, Sept (10^3 km^3)
30
25
20
15
10
5
0
Arctic sea ice extent, Sept (10^6 km^2)
8
7
6
5
4
3
2
1
0
1900
1920
1940
1960
1980
2000
2020