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Analysis of long-term European temperature records: 1751–1995

R. C. Balling Jr[1,*], R. S. Vose[1], Gerd-Rainer Weber[2]

[1]Office of Climatology and Department of Geography, Arizona State University, Tempe, Arizona 85287-1508, USA
[2]Gesamtverband des Deutschen Steinkohlenbergbaus, Gluckaufhaus, Friedrichstraße 1, D-45128 Essen, Germany

ABSTRACT: Monthly temperature records are assembled for 57 European stations, with some of the records extending nearly two and a half centuries. Our analyses reveal a statistically significant warming of approximately 0.5°C over the period 1751 to 1995. The period of most rapid warming in Europe occurred between 1890 and 1950, and there is quantitative evidence that some of the observed warming during this 60 yr period may be related to urbanization or other local effects; no warming was observed in the most recent half century. Urban effects or other local contaminations in the earliest records could not be quantified due to a dearth of reliable comparable data. The long-term warming in Europe has been confined to the low-sun months, and the coldest period since 1751 occurred near 1890.

KEY WORDS: Europe · Temperature records · Urban effects

1. INTRODUCTION

Interest in climate change has increased over the past decade due largely to the predictions associated with the greenhouse effect. According to many climatologists, the continued buildup of greenhouse gases in the atmosphere will lead to a substantial increase in planetary temperature, a rise in sea level, melting of ice caps and glaciers, and droughts in the continental interiors (Houghton et al. 1996). The temperature rise for mid-to-high latitude land areas such as Europe is predicted to be substantially greater than the increase expected for the planet as a whole (e.g. Cubasch et al. 1996, Jones et al. 1997, Déqué et al. 1998). These and other predictions for the future, and their implications for ecosystems and human societies, have led many scientists to examine the climatic records from throughout the world in hopes of finding signals that may or may not be consistent with the $2 \times CO_2$ simulation results.

For most of the planet, temperature records are sparse, particularly before the turn of the 20th century. Large ocean basins, desert regions, and mountainous areas are especially limited in their long-term historical temperature records. When interest is focused on temperature records that extend back in time by more than a century, few areas qualify for any meaningful analysis. Exploring these longer-term records is critical in understanding the reported 0.6°C temperature rise of the past century. For example, it is entirely possible that the warming in the record of the past century has been caused by an unusually cool period 100 yr ago as opposed to an unusually warm period in recent decades.

Fortunately, long-term monthly mean temperature records of over 2 centuries exist for dozens of stations throughout Europe. Although some of these data have been used effectively in analyses by other scientists (e.g. Jones et al. 1986, Arseni-Papadimitrou & Maheras 1991, Jones 1994, Weber 1994, Balling 1995, Charvátová & Strestik 1995), significant questions remain regarding the reliability and representativeness of these long-term records. In addition, many temperature observations are available for European stations that have not been identified or used in past published research. Given the potential importance of these records to many interrelated climate change questions and potential impact issues, we (1) assess the availabil-

*E-mail: robert.balling@asu.edu

ity of long-term European monthly mean temperature records and (2) identify any spatially coherent trends or discontinuities in the long-term historical temperature records.

2. MONTHLY TEMPERATURE DATA SETS

Three basic mean monthly temperature data sets are developed and/or used in this investigation; each is described in the following subsections.

2.1. The Jones temperature record. Although other regional temperature records are available from the thermometer network of the world (e.g. Hansen & Lebedeff 1987, Vinnikov et al. 1990), the most popular and widely used record has been developed and maintained by Jones (1994). Jones carefully assesses the homogeneity and representativeness of each time series, and every effort is made to identify and eliminate errant values. He converts the monthly observations (from both terrestrial and ocean areas) into 5° latitude by 5° longitude grid-box data, and all values are expressed as anomalies from a reference period defined as 1961 to 1990. The Jones record extends back to 1856 for most of the grid cells that cover Europe. In this investigation, the Jones monthly mean temperature records are assembled from 35° N to 70° N and 10° W to 55° E (Fig. 1).

2.2. Adjusted Global Historical Climatology Network temperature record. We extracted 50 quality-controlled, homogeneity-adjusted stations (Fig. 1) with data for 1851 to 1991 from the Global Historical Climatology Network (GHCN) database (Peterson & Vose 1997). The GHCN database actually contains a much larger number of stations for the study area. The present analysis, however, required all stations to have records before 1850, after 1960, and have no more than 1 'data gap' of 10 yr in length. These requirements dramatically reduced the number of available stations.

Each of these stations was subjected to the rigorous quality assurance procedure documented in Peterson et al. (1998) prior to their inclusion in GHCN. Specific quality problems addressed by this procedure include the presence of extreme values, mislocated stations,

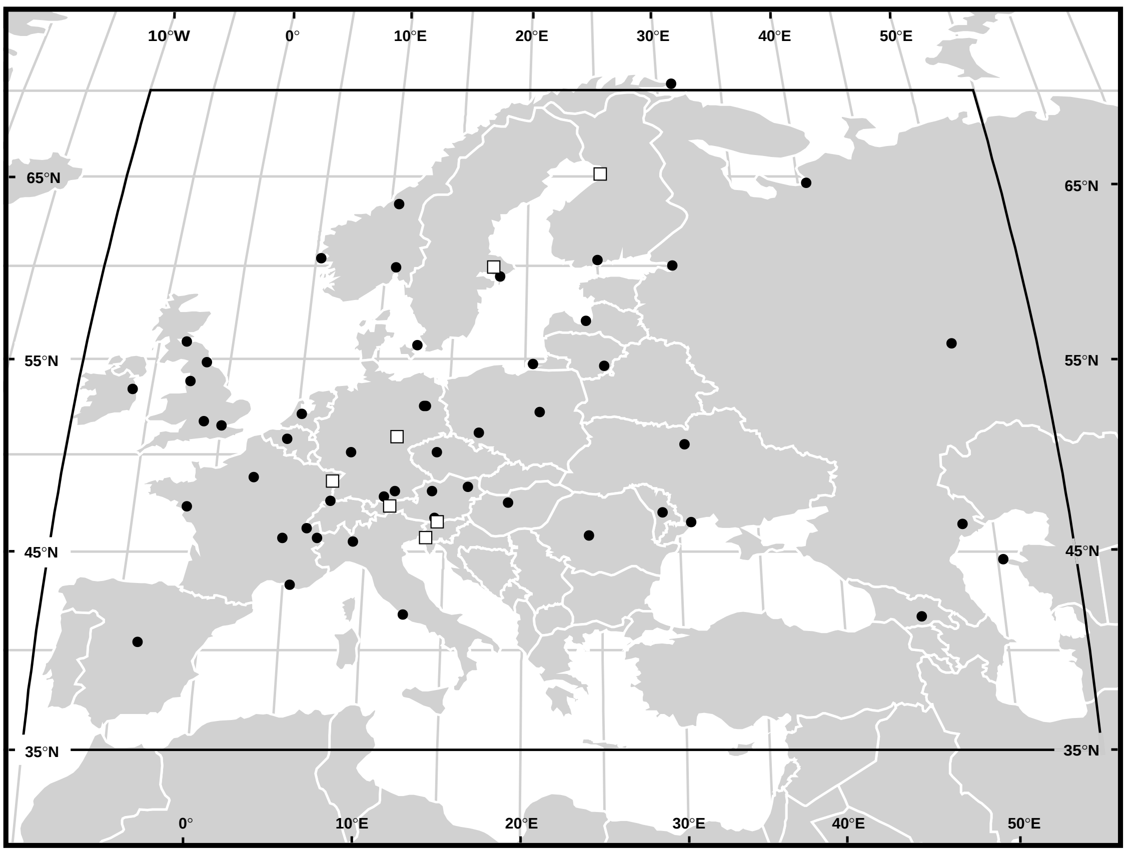

Fig. 1. Map of European study area with station locations. (●) GHCN stations; (□) additional long-term (i.e. pre-1851) stations. Table 1 provides a description of each station. The 35° N to 70° N and 10° W to 55° E box defines the boundary of the Jones temperature data

large changes in the mean and variance, runs of the same temperature value for 3 or more months, and consecutive years with exactly the same data. The GHCN homogeneity adjustments were developed using the method of Easterling & Peterson (1995). This method directly accounts for abrupt discontinuities (caused by e.g. station relocations, instrument and exposure changes, changes in calculation procedures for time-averaged values); however, the method is somewhat less effective in compensating for gradual inhomogeneities (e.g. changes in instrumentation calibration, yellowing of a white plastic instrument shelter, urbanization).

2.3. Unadjusted temperature time series. We developed an 'unadjusted' temperature database consisting of 57 stations dating from the mid-18th century to near present (Table 1, Fig. 1). While not completely homogeneous, these stations nonetheless represent an excellent opportunity to examine temperature patterns in Europe prior to 1851. The set was assembled by gathering climatic records from dozens of sources, subjecting these records to the same rigorous quality assurance reviews that were used in the development of the GHCN (except for a spatial outlier check, which could not be performed on all stations because of the lack of neighboring stations), and systematically selecting a set of stations that met the same period of record and completeness requirements applied in the selection of the adjusted network. Given the comprehensiveness of GHCN and the strict period of record requirements, this set only contains 7 more stations than the adjusted set.

3. RESULTS FROM 1851–1991

To be consistent with the Jones record, we converted each temperature value for each month and station to a monthly anomaly based on the 1961 to 1990 'normal' period. Some of the stations had limited data from the base period, and in those cases we adjusted the period by up to 10 yr. We then adjusted nearby stations similarly and determined the impact on their 'normals'; we used that adjustment in calculating the monthly anomalies for the stations with the limited data in the 1961 to 1990 period. The adjustments were small, and the procedure appeared to have no discernible impact on the final results. We then averaged the monthly anomalies for all available stations, and we also explored various gridding schemes to areally average the monthly data. Again, these decisions appeared to have only small impacts on the European-wide time series.

Over the period 1851 to 1991, the adjusted GHCN data reveal a statistically significant linear warming of 0.05°C decade^{-1} (Fig. 2) while the Jones record shows a warming of 0.04°C decade^{-1} from 1856 to 1991. The 2 data sets have a correlation of 0.88 and share the same basic variations and trends since the middle of the last century. Both data sets show a slight cooling from the middle of the last century to about 1890, a statistically significant warming from 1890 to 1950, cooling from 1950 to 1970 and a slight warming since the early 1970s. The record shows that the coolest period in Europe over the past century and a half occurred near 1890; similar findings can be found from many other analyses of European temperature times series (e.g. Manley 1974, Goossens & Berger 1986, Bárdossy & Caspary 1990, Arseni-Papadimitrou & Maheras 1991, Balling & Idso 1992a, b, Bradley & Jones 1992, Coops 1992, Parker et al. 1992, Kozuschowski et al. 1994, Schönwiese et al. 1994, Weber 1994, Balling 1995, Butler & Johnston 1995, Charvátová & Strestik 1995, Esteban-Parra et al. 1995, Brázdil et al. 1996, Oñate & Pou 1996). In addition, as shown in Fig. 3, the greatest warming occurs in the period November to May, and the least warming (and even cooling) occurs in the June to October months. The seasonality of the temperature trends is consistent with the numerical simulation of Jones et al. (1997), who found twice as much warming in December to February as June to August for an increase in atmospheric carbon dioxide levels.

The rapid and near-linear warming from 1890 to 1950 occurred at a rate of 0.15°C decade^{-1}; the Jones record for Europe shows a warming of 0.09°C decade^{-1} over the same period. The rate for the GHCN data is so great that one must wonder if urbanization or some other local effect during this period contributed to the observed warming in the GHCN data. The following analyses suggest that urbanization made a contribution to the observed pattern:

(1) The Jones temperature records were collected for 2 oceanic cells located close to the European continent with nearly continuous data through the period of interest. One cell is in the North Sea, centered on 57.5° N, 2.5° E, while the other oceanic cell is located west of France, centered on 47.5° N, 7.5° W. The average temperature anomalies for these oceanic cells show a statistically significant warming of 0.07°C decade^{-1} from 1890 to 1950, indicating that the European region warmed over this period of 6 decades, but the land-based stations warmed twice as fast as the oceanic observations.

(2) The GHCN time series from the 50 stations was treated as the dependent variable and the Jones oceanic data set (T_o) was treated as the independent variable in a simple linear regression analysis. The resulting equation developed over the period 1856 to 1991 takes the form GHCN = –0.01 + 0.98T_o, and the R-value is 0.58. In theory, the residuals from this equa-

Table 1. Description of European stations. Note: the first 50 stations are from the newly developed GHCN, and the last 7 stations are the extra stations not included in the GHCN. na: not available

Code	Latitude (N)	Longitude (E)	Elevation (m)	Start	End	% missing	Name
3664	70.40	31.10	15	1829	1994	5.8	Vardo
3669	63.40	10.50	115	1761	1981	0.4	Trondheim
3672	60.40	5.30	44	1816	1994	0.5	Bergen
3676	59.90	10.70	96	1816	1991	2.7	Oslo
3703	59.40	18.10	52	1756	1994	0.2	Stockholm
3727	60.30	25.00	58	1829	1994	0.4	Helsinki
3746	55.90	−3.20	134	1764	1960	0.2	Edinburgh
3768	51.50	0.00	7	1763	1969	2.2	Greenwich
3777	51.70	−1.20	63	1828	1980	0.1	Oxford
3782	53.80	−2.50	115	1848	1969	2.6	Stonyhurst
3785	54.80	−1.60	na	1847	1981	0.0	Durham
3800	53.40	−6.30	81	1831	1994	1.8	Dublin
3822	55.70	12.60	22	1768	1991	6.4	Copenhagen
3825	52.10	5.20	8	1706	1994	0.2	de Bilt
3829	50.80	4.40	104	1833	1994	0.4	Uccle
3833	47.60	7.60	318	1755	1980	1.3	Basel
3837	46.20	6.20	416	1753	1994	0.2	Geneva
3851	48.80	2.50	53	1757	1994	0.5	Paris
3858	47.30	−1.60	27	1851	1994	0.6	Nantes
3876	45.70	4.70	201	1851	1994	14.5	Lyon
3885	43.30	5.40	8	1838	1994	6.6	Marseille
3905	40.40	−3.70	657	1840	1991	9.6	Madrid
3962	52.50	13.30	51	1769	1993	1.1	Berlin-Dahlem
3963	52.50	13.40	50	1701	1993	8.4	Berlin
3977	50.10	8.70	109	1757	1961	19.9	Frankfurt
3988	48.10	11.70	529	1781	1991	0.0	Munich
3990	47.80	11.00	983	1781	1994	5.4	Hohenpeissenberg
3992	48.10	14.10	388	1767	1981	1.7	Kremsmuenster
3994	48.30	16.40	212	1775	1994	0.3	Vienna
4000	46.70	14.30	452	1813	1994	2.4	Klagenfurt
4005	50.10	14.30	381	1771	1994	5.0	Prague
4017	52.20	21.00	107	1779	1994	8.3	Warsaw
4018	51.10	17.00	119	1792	1994	0.9	Wrocław
4024	47.50	19.00	130	1780	1991	0.0	Budapest
4040	45.80	24.20	452	1851	1994	1.4	Sibiu
4047	45.50	9.20	103	1763	1987	4.4	Milan
4058	41.80	12.60	107	1811	1991	7.4	Rome
4079	64.60	40.60	13	1813	1994	1.4	Arkhangelsk
4092	60.00	30.30	4	1743	1994	5.3	St. Petersburg
4098	57.00	24.10	3	1795	1994	12.3	Riga
4101	54.70	20.50	27	1848	1993	2.2	Kaliningrad
4102	54.60	25.30	189	1777	1994	2.7	Vilnius
4106	55.80	49.10	64	1812	1994	8.6	Kazan
4132	50.50	30.50	179	1812	1994	5.3	Kiev
4137	47.00	28.90	90	1825	1990	7.7	Kisinev
4138	46.50	30.70	64	1821	1994	12.4	Odessa
4148	46.40	48.00	18	1837	1994	2.7	Astrahan
4156	41.70	44.80	490	1844	1993	4.4	Tbilisi
4159	44.60	50.30	3820	1848	1992	3.7	Fort Sevcenko
18246	45.70	6.90	2460	1818	1985	0.1	St. Bernard
3678	59.90	17.60	15	1774	1980	0.0	Uppsala
3854	48.60	7.60	154	1806	1980	0.0	Strasbourg
3949	50.90	11.60	155	1820	1980	0.0	Jena
3996	47.30	11.40	582	1777	1988	0.0	Innsbruck
4051	45.70	13.80	20	1803	1980	0.0	Trieste
9991	65.10	25.30	5	1846	1983	0.0	Oulu
9992	46.50	14.50	2044	1851	1980	0.0	Obirvill

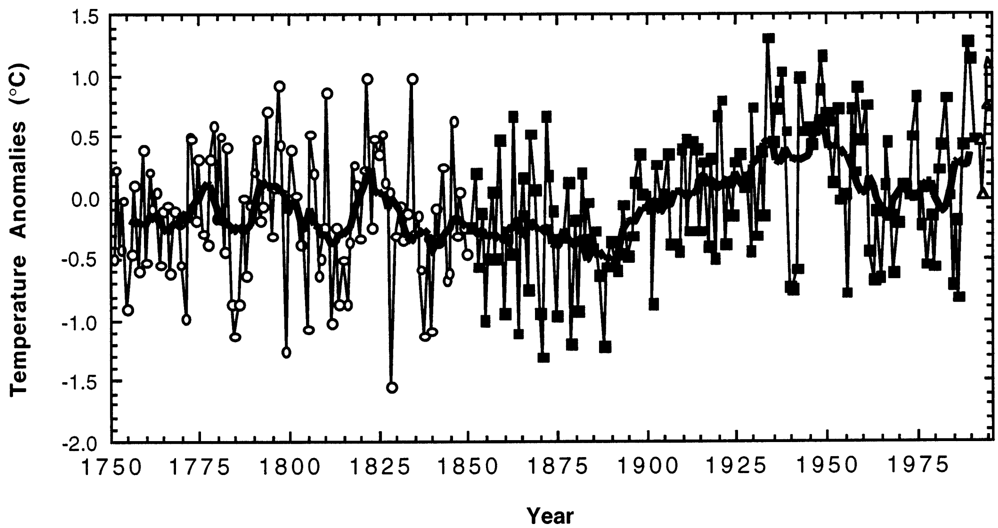

Fig. 2. Time series of adjusted GHCN anomalies (1961–1990 base period) from 1851 to 1991 (■), modified 'raw' temperature data from 1751 to 1850 (○), and adjusted Jones data from 1992 to 1995 (△). Thick line is an 11 yr running average

tion should be random through time with no significant trends through any subperiod. However, from 1890 to 1950, the residuals show a trend of 0.07°C decade^{-1} (Fig. 4). This result suggests that approximately half of the observed warming in European GHCN data over the period 1890 to 1950 may be related to urbanization effects (or some other process) and not to regional-scale warming.

(3) Similarly, the GHCN time series was again treated as the dependent variable and the Jones global (land and sea) temperature (T_g) dataset was treated as the independent variable in a regression analysis. This equation developed over the period 1856 to 1991 takes the form GHCN = 0.21 + 1.14T_g, the R-value is 0.41, and the residuals from this analysis show a significant trend of 0.07°C decade^{-1} over the 1890 to 1950 period. This result also suggests that as much as half of the observed warming European GHCN data over the period 1890 to 1950 may be related to urbanization or other local effects.

Even without some contaminating local effects, there is ample evidence that Europe was cool in the late 19th century, and warming occurred up to about 1950. But even with potential urban effects, the GHCN and the Jones records both show a cooling from 1950 to the mid-1970s and then a warming in the most recent period. Other investigators (e.g. Bárdossy & Caspary 1990, Beniston et al. 1994, Schönwiese et al. 1994) have linked these general temperature trends to variations in the (1) regional upper-level atmospheric circulation patterns, (2) European barometric pressures, and (3) the North Atlantic Oscillation.

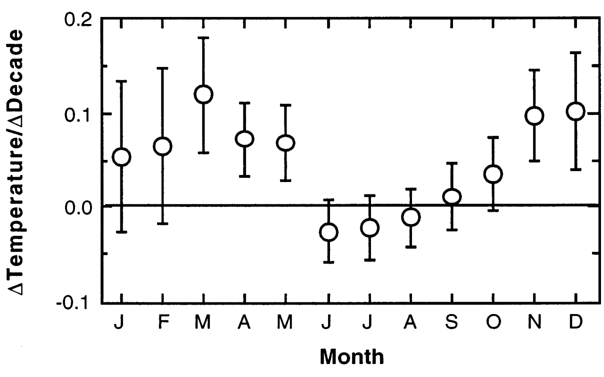

Fig. 3. Temperature trend (°C decade^{-1}) by month for the adjusted GHCN time series over the period 1851 to 1991. Error bars are for the 0.05 level of confidence

4. RESULTS FROM 1751–1995

A time series extending back to 1751 was extracted from raw data available through both the unadjusted GHCN collection (i.e. the pre-1851 data) and our own efforts to secure additional long-term station temperature data from European stations. As described earlier, each time series was converted to monthly anomalies based on a 1961 to 1990 base period, the monthly anomalies were averaged for all available stations, and the resulting monthly anomalies were averaged to generate a European mean annual anomaly. We again used various gridding schemes and found that gridding the data did not impact the final results. Obviously, as we extended the analyses further back in time, the number of stations declined and the distribution of the network changed substantially. This

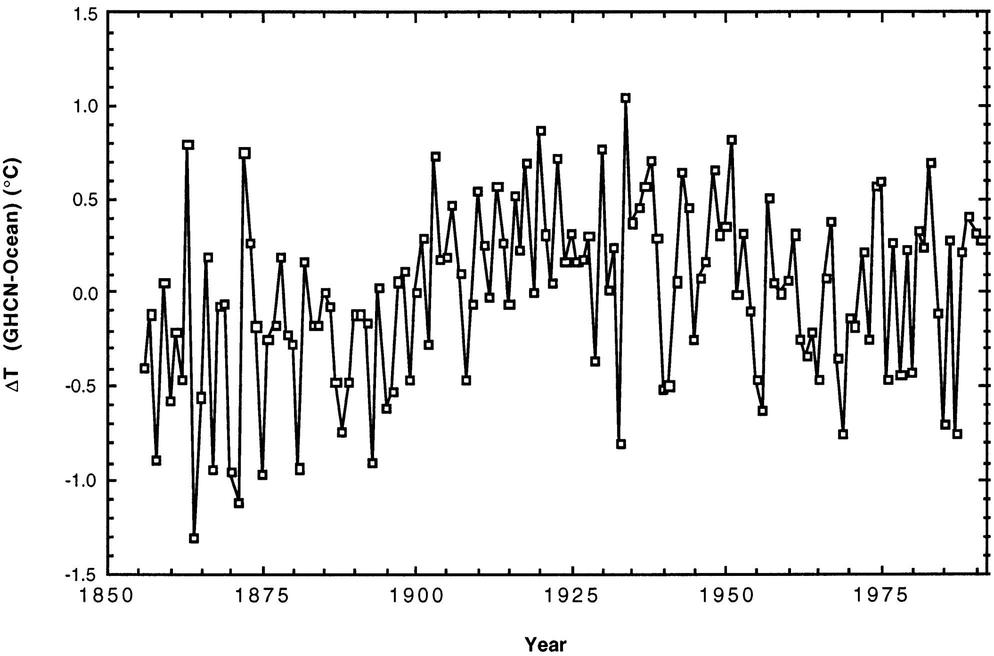

Fig. 4. Annual temperature differences (°C) between adjusted GHCN data and the Jones oceanic data over the period 1851 to 1991

inevitable problem introduces increasing uncertainty into our findings for the earlier years in the record.

Some of the stations undoubtedly experienced urban warming during the earliest part of the study period (Dronia 1967), but due to the lack of reliable and comparable data, no attempts were made in this investigation to determine the urban contamination during the period of the earliest temperature records. As a result, significant urban warming may be present in the earliest records, particularly given the growth that occurred in the early years in such centers as Greenwich, Paris, Oslo, Milan, Berlin, St. Petersburg, and Geneva.

Over the period 1851 to 1991, a simple regression analysis between the adjusted GHCN data and the unadjusted data, T_{unadj}, took the form GHCN = 0.108 + 1.028T_{unadj}, where the R-value was 0.98 and the standard error was 0.017°C. The resulting regression equation was applied to the data from 1751 to 1850 to generate a time series more compatible with the GHCN series. We eliminated stations from these analyses to determine the effect of a changing network through time, and we did not find that the change in network was substantially influenced the results. Finally, a regression equation in the form GHCN = 0.176 + 1.188 Jones (with R equal to 0.88 and standard error equal to 0.055°C) allowed for the GHCN series to be estimated for the 1992 to 1995 period.

The resulting 1751 to 1995 time series shows a significant trend of 0.02°C decade^{-1} for the entire 245 yr period (Fig. 2). A second degree polynomial curve was applied to the data, but the explained variance did not significantly improve. The extended long-term time series of temperatures shows a small, statistically insignificant cooling from 1751 to 1890, warming to 1950, cooling to the mid-1970s, and warming in the most recent period. The smoothed, 11 yr running average temperature anomalies also showed that the period near 1890 was the coldest time in the past two and a half centuries.

This long-term record is highly correlated with other local and regional temperature series within the European area. For example, the central England temperature time series of Manley (1974) has a correlation of 0.75 with the series developed in this investigation, though this high correlation is not entirely unexpected since some stations from central England were used in this study. A correlation of 0.80 exists between these GHCN-based data and the Austrian temperature record developed by Böhm (1992) over the period 1775 to 1989. Balling (1995) described an 8 station network in and around Germany with temperature data extending from 1775 to 1989, and a correlation of 0.91 exists between that record and the one developed in this study. In addition, Briffa et al. (1988) used tree rings to reconstruct European summer temperatures from 1750 to 1850, and they described cool conditions in 1812 to 1816, warm summers in the 1820s, and cool weather throughout the 1830s. Each of these subperiods of unusually warm or cool temperatures is in general agreement with the annual temperatures presented in Fig. 2.

The long-term temperature anomalies are judged to be normally distributed according to a Kolmogorov-Smirnov test. The first-order autocorrelation is small ($r = 0.21$), and a Box-Jenkins model fit to the time series confirms a small autocorrelation in the data and a significant, but small, deterministic trend term. The seasonal patterns for the long-term record are in agreement with the patterns shown in Fig. 3 for the time series beginning in 1851.

5. CONCLUSIONS

The following 3 major conclusions can be drawn from the development and analyses of the long-term European temperature record:

(1) The temperature time series for Europe shows a warming of approximately 0.5°C over the past 245 yr. The period of most rapid warming in Europe occurred between 1890 and 1950, and there is evidence that some of the observed warming during this 60 yr period may be related to urbanization or other local effects. Although difficult to quantify, there is reason to believe that the earlier records were also influenced by urban effects. Despite potential urban contamination to the temperature records, Europe has not experienced warming over the past 45 yr.

(2) Warming observed in Europe has been confined to the low-sun months. Some months during the summer season show a slight cooling in the long-term records.

(3) Our data suggest that the coldest period since 1751 occurred near 1890.

Europe represents less than 2% of the earth's surface, and trends and variations determined for Europe are certainly not global and may tell us little about the planetary response to the changes occurring in atmospheric composition. Nonetheless, some climate models predict substantial warming in Europe as the greenhouse gas concentrations increase, with the greatest warming to occur during the winter season (Jones et al. 1997). Our analyses certainly confirm the prediction of warming in winter, but the overall observed warming rate appears to be lower than what has been predicted by numerical climate models.

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