2 Data & Methods

The methods used in this study follow those used by Moberg et al. (2006) and Chen et al. (2006). A brief description is given below, while detailed information can be found in these references, except for the regional division used here. For the regional analysis, we followed the regional divisions used by the recent IPCC special report (IPCC 2012), rather than the approach used by Moberg et al. (2006) and Chen et al. (2006).

EMULATE collected a dataset containing daily temperature and precipitation observations over European locations having data starting before 1901. This dataset is the basis for the analyses in this atlas. Up to four daily climate variables are available: minimum and maximum temperature (Tmin/Tmax), mean temperature (Tmean), and precipitation (Prec). We focus on three periods: 1801–2000, 1851–2000, and 1901–2000. Since a trend analysis is extremely sensitive to the starting and ending of the time series, particular attention is paid to the missing data in these beginning and ending periods. A data completeness criterion has been applied to filter out stations with insufficient data for the proposed analyses. We divided each analysis period in question into three sub periods: one 20-year period at the beginning, one 20-year period at the end of the series and the entire period in between (160, 110, or 60 years according to the period analyzed). A station passed the filter if it did not have more than 4% of missing values in the two 20 year blocks at the beginning and end and at most 6% missing values in the longer block in between. All the stations that passed the criterion and are used in this work are listed in Table 2.1 and shown in Figs. 2.1, 2.2 and 2.3.

For the 200-year period (1801–2000) we can use only three stations with Tmin/Tmax, and seven stations with Tmean measurements. No precipitation observations are available for this period. Looking at the 150-year period (1851–2000) the number of observations is increased to nine for Tmin/Tmax, thirteen for Tmean, and nine for precipitation. For these two periods the analyses were carried out for each station with sufficient data. The number of stations for these two periods is too few to undertake any averaging or regionalization approaches. For the 100-year period (1901–2000) significantly more stations are available: we have 57 observation sites for Tmin/Tmax, 54 for Tmean, and 100 for Precipitation. The stations are fairly unevenly distributed over the study area, although we find the highest station density in Central Europe. The relatively high number of observation sites for this period provides the possibility to group the stations into regions, which enables a regional analysis and inter comparison between regions.

Using regional divisions for the regional analysis facilitates direct comparison of the regional trends with other estimates and model simulations. As indicated in Figs. 2.1, 2.2 and 2.3, the following three regions were created: NEU (Northern Europe), CEU (Central Europe), and SEU (Southern Europe).

The climate indices described in the next section were computed for all stations belonging to a particular region. Afterwards the time series have been averaged arithmetically. The resulting averaged time series was taken as the regional mean and was subject to a linear trend analysis over the whole 100-year period.

The quality of the station series selected for this study varies. All series have been corrected for obvious errors whereas efforts towards homogenizing the database could not be undertaken. Relatively few series have undergone intensive testing and correction for inhomogeneities, among them the very long records for some Swedish stations (Moberg and Bergström 1997). Some of the series have been used more frequently than others in the literature and are in this context also more quality controlled. We have to keep in mind that inhomogeneous data can cause errors in estimated trend values as demonstrated by Venema et al. (2012). In particular with respect to the method of linear regression, which is more sensitive to values at the beginning and end of the respective time series analyzed for linear trend. During the recent past substantial efforts have been undertaken to improve the availability and quality of long-term climate observations. For example, 557 monthly long-term observation series for the Greater Alpine Region where collected,

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Table 2.1 Data availability for the three groups of observation at the meteorological stations used

ID	Lat	Lon	Station	Country	Tmin/Tmax	Tmean	Prec
1	48.08	15.45	Graz university	Austria	x	x	x
2	47.27	11.40	Innsbruck university	Austria	x	x	x
3	48.05	14.13	Kremsmünster	Austria	x	x	x
4	47.80	13.00	Salzburg	Austria	x	x	x
5	47.05	12.95	Sonnblick	Austria	x	x	x
6	48.23	16.35	Wien	Austria	x	x	x
7	50.90	4.53	Brussels-Uccle	Belgium	x	x	x
8	43.85	18.38	Sarajevo	Bosnia	x	x	x
9	45.17	14.70	Crikvenica	Croatia		x	
10	45.82	15.98	Zagreb	Croatia	x	x	x
11	50.08	14.42	Prag	Czech	x	x	x
12	55.28	14.78	Hammer odde fyr	Denmark	x	x	x
13	55.45	8.40	Nordby	Denmark	x	x	x
14	55.85	10.60	Tranebjerg	Denmark	x	x	x
15	56.77	8.32	Vestervig	Denmark	x	x	x
16	60.32	24.97	Helsinki	Finland	x	x	x
17	43.31	5.40	Marseille	France	x	x	x
18	48.82	2.34	Paris parc montsouris	France	x	x	x
19	49.88	10.88	Bamberg	Germany	x	x	x
20	52.45	13.30	Berlin	Germany	x	x	x
21	53.03	8.78	Bremen	Germany	x	x	x
22	48.73	9.72	Göppingen	Germany			x
23	49.28	9.17	Gundelsheim	Germany			x
24	53.48	10.25	Hamburg-Bergedorf	Germany	x	x	x
25	53.55	9.97	Hamburg-Fuhlsbüttel	Germany	x	x	x
26	53.15	11.03	Hitzacker	Germany			x
27	47.80	11.00	Hohenpeissenberg	Germany	x	x	x
28	48.42	8.67	Horb-Betra	Germany			x
29	47.68	10.05	Isny	Germany			x
30	50.93	11.58	Jena	Germany	x	x	x
31	49.03	8.35	Karlsruhe	Germany	x	x	x
32	49.20	8.10	Landau/Pfalz	Germany			x
33	48.85	12.92	Metten	Germany			x
34	48.17	11.50	Muenchen	Germany	x	x	x
35	49.22	9.52	Oehringen	Germany			x
36	52.38	13.07	Potsdam	Germany	x	x	x
37	48.72	9.22	Stuttgart	Germany	x	x	x
38	48.02	8.82	Tuttlingen	Germany			x
39	47.87	11.78	Valley-Mühltal	Germany			x
40	53.78	7.90	Wangerooge	Germany			x
41	52.90	8.43	Wildeshausen	Germany			x
42	47.42	10.98	Zugspitze	Germany	x	x	x
43	37.97	23.72	Athens	Greece	x	x	x
44	65.08	−22.73	Stykkisholmur	Iceland		x	x
45	53.37	−6.35	Dublin	Ireland			x
46	44.48	11.50	Bologna	Italy	x	x	x
47	44.82	11.50	Ferrara	Italy			x
48	45.15	10.75	Mantova	Italy			x
49	45.50	9.20	Milano	Italy	x	x	x
50	38.11	13.36	Palermo	Italy			x
51	45.38	10.87	Verona-Villafranca	Italy			x

Table 2.1 (continued)

ID	Lat	Lon	Station	Country	Tmin/Tmax	Tmean	Prec
52	52.10	5.18	De Bilt	Netherlands	x	x	
53	52.97	4.76	De Kooy	Netherlands			x
54	53.13	6.58	Eelde	Netherlands			x
55	53.18	6.60	Groningen	Netherlands			x
56	52.40	6.05	Heerde	Netherlands			x
57	52.31	4.70	Hoofddorp	Netherlands			x
58	52.64	5.07	Hoorn	Netherlands			x
59	51.68	3.86	Kerkwerve	Netherlands			x
60	51.57	4.53	Oudenbosch	Netherlands			x
61	51.18	5.97	Roermond	Netherlands			x
62	52.88	7.06	Terapel	Netherlands			x
63	53.37	5.22	West-Terschelling	Netherlands			x
64	51.98	6.70	Winterswijk	Netherlands			x
65	60.65	6.22	Bulken	Norway			x
66	59.12	11.38	Halden	Norway			x
67	63.22	11.12	Lien I Selbu	Norway			x
68	38.72	−9.15	Lisboa Geofisica	Portugal	x	x	
69	44.42	26.10	Bucuresti	Romania			x
73	51.65	36.18	Kursk	Russia		x	x
77	59.97	30.30	St Petersburg	Russia	x	x	x
79	38.37	−0.50	Alicante	Spain	x	x	x
80	38.88	−6.83	Badajoz	Spain	x	x	x
81	42.36	−3.72	Burgos	Spain			x
82	36.50	−6.23	Cadiz	Spain	x	x	
83	37.14	−3.63	Granada	Spain	x	x	x
84	40.41	−3.68	Madrid	Spain	x	x	
85	37.98	−1.12	Murcia	Spain	x	x	x
86	37.42	−5.90	Sevilla	Spain			x
87	41.44	−2.48	Soria	Spain	x	x	x
88	41.64	−4.77	Valladolid	Spain	x	x	x
89	60.62	15.67	Falun	Sweden	x	x	x
90	65.07	17.15	Stensele	Sweden	x		x
91	59.35	18.05	Stockholm	Sweden	x	x	
92	59.87	17.63	Uppsala	Sweden	x	x	x
93	56.87	14.80	Växjö	Sweden	x		x
94	47.55	7.58	Basel	Switzerland	x	x	x
95	46.93	7.42	Bern	Switzerland	x	x	x
96	47.05	6.99	Chaumont	Switzerland			x
97	46.25	6.13	Geneva	Switzerland	x	x	x
98	46.00	8.97	Lugano	Switzerland	x	x	x
99	47.25	9.35	Säntis	Switzerland	x	x	x
100	46.23	7.37	Sion	Switzerland		x	x
101	47.38	8.57	Zurich	Switzerland	x	x	x
102	54.35	−6.65	Armagh	UK	x		x
103	52.20	0.13	Cambridge	UK			x
104	52.42	−1.83	CET	UK	x	x	
105	51.77	−1.27	Oxford	UK	x		x
106	58.33	−6.32	Stornoway	UK	x		
107	45.03	35.38	Feodosija	Ukraine	x		x
108	50.40	30.45	Kiev	Ukraine	x	x	x
109	49.60	34.55	Poltava	Ukraine	x	x	

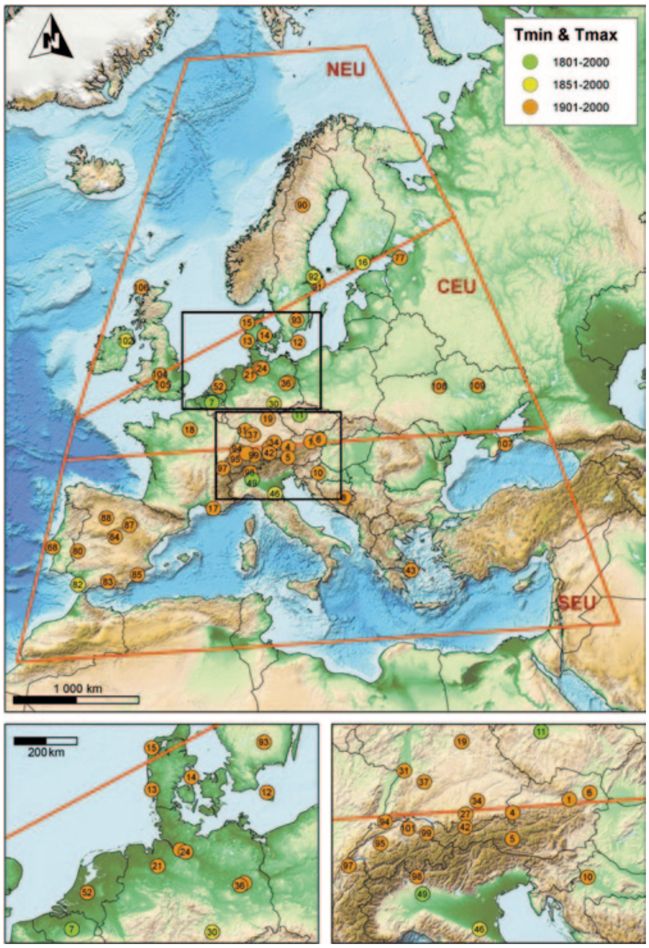

Fig. 2.1 Overview map showing the meteorological Tmin and Tmax observations used for each period and the regional division used for the period 1901–2000

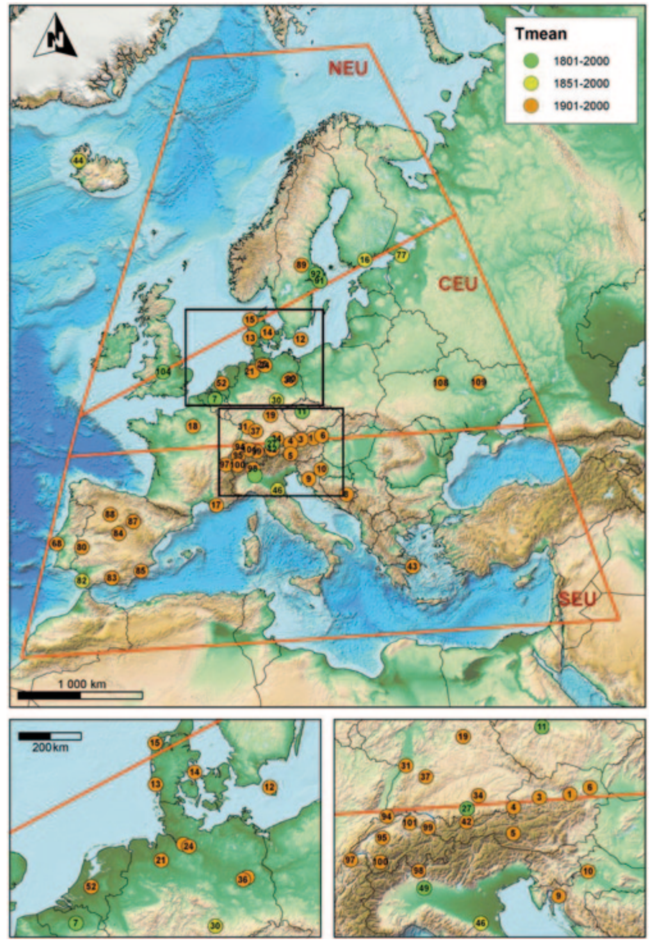

Fig. 2.2 Overview map showing the meteorological Tmean observations used for each period and the regional division used for the period 1901–2000

quality controlled and homogenized within the HISTALP project (Auer et al. 2007). There is an obvious need for increased resources and efforts going into further developing homogenization methods in order to improve data quality especially for observations with temporal resolution higher than monthly, last but not least with respect to climatology beyond mean conditions. Brunet and Jones (2011) estimate that about 80 % of past climate data is still unavailable to the research community hampering a more robust assessment of climate parameters.

2.1 Climate Indices Calculated

All the selected indices have been computed for each of the three periods described above. Typically there was one value per season per index comprising the index timeseries (100, 150 or 200 years) which was then used for the trend estimation. The indices are listed and explained in Table 2.2. Most indices are either percentiles or percentile-based. With percentiles the most extreme values in both tails of

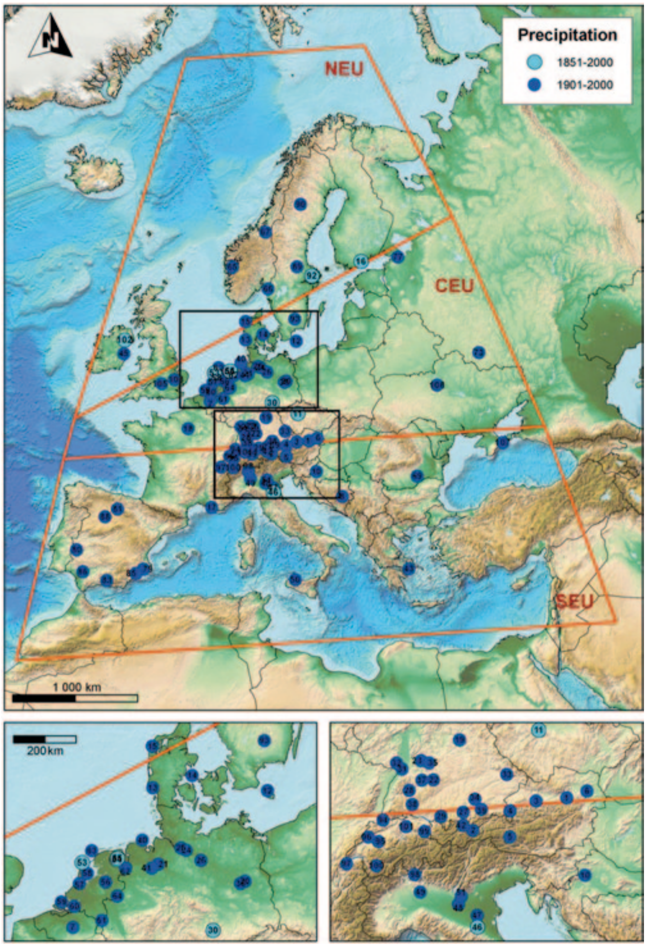

Fig. 2.3 Overview map showing the meteorological precipitation observations used for each period and the regional division used for the period 1901–2000

the frequency distribution of a variable can be captured. For example, the 2 % highest values exceed the 98th percentile. Some indices use thresholds calculated for a reference period to be exceeded or fallen below. For those 1961–1990 was used as reference. For the temperature variables both the 2nd and 98th percentile were chosen in order to capture extremely cold and warm conditions, whereas for precipitation only the 98th percentile was utilized. In the literature the usage of 1st/99th percentile (instead of 2nd and 98th) is more common. However, using somewhat lower thresholds can yield more robust results. The index time series to deal with are relatively short, e.g. one index value per season yields 150 values for the 150-year period. In this way three values exceed the threshold (98th) instead of one (99th). Considering the characteristics of extremes connected to issues related to data quality this can be a useful measure.

Not all the indices are real extremes indices. Some of them represent mean conditions to make it possible to illustrate similarities and differences between changes in extremes and in mean conditions. In addition to the mean indices, the following indices are not based on percentiles. The Heat Wave Duration Index (HWDI), daily precipitation intensity indices (SDII98 and SDII), highest 5-day total rainfall (R5d), highest daily rainfall (R1d) and the highest number of consecutive dry days (CDD).

All indices were computed separately for each of the 3-month seasons (MAM = March–May, JJA = June–August, SON = September–November, and DJF = December–February). Further details on the indices used can be found in Moberg et al. (2006) and Beniston et al. (2007).

2.1.1 Trend Analysis

The ordinary least squares method was used to estimate linear trends of the temperature and precipitation indices. The trend was computed for each particular period in question: 200 years, 150 years, and 100 years. For easy comparison among different periods, all trends were given in *unit/100years*. The significance of a particular trend estimated was determined by a t-test on the estimated slope of the regression as done in Moberg et al. (2006). The lag-1 autocorrelation in each series has been taken into account to adjust the degrees of freedom accordingly. Trends that are determined to be significant at the 5 and 1 % level were flagged in diagrams and tables that present the results.

Table 2.2 Extremes indices calculated

#	Variable	Identifier	Parameter	Unit
1	*Tmin/Tmax*	MEANTN	Mean Tmin	°C
2		MEANTX	Mean Tmax	°C
3		TN2P	Tmin 2nd percentile	°C
4		TN98P	Tmin 98th percentile	°C
5		TN2N	[a]# of days below the reference 2nd Tmin percentile	[days]
6		TN98N	[a]# of days exceeding the reference 98th Tmin percentile	[days]
7		CSDI10	[b]Cold spell duration index	[days]
8		TX2P	Tmax 2nd percentile	°C
9		TX98P	Tmax 98th percentile	°C
10		TX2N	[a]# of days below the reference 2nd Tmax percentile	[days]
11		TX98N	[a]# of days exceeding reference 98th Tmax percentile	[days]
12		WSDI90	[c]Warm spell duration index	[days]
13		HWDI	[d]Heat wave duration index	[days]
14	*Tmean*	MEANTG	Mean Tmean	°C
15		TG2P	Tmean 2nd percentile	°C
16		TG98P	Tmean 98th percentile	°C
17		TG2N	[a]# of days below reference 2nd Tmean percentile	[days]
18		TG98N	[a]# of days exceeding reference 98th Tmean percentile	[days]
19	*Precipitation*	PRECTOT	Precipitation total	[mm]
20		PREC98P	Precipitation 98th percentile	[mm]
21		R98N	[a]# of days exceeding reference 98th precipitation percentile	[days]
22		R98T	Fraction of precipitation above the reference 98th precipitation percentile	[%]
23		SDII98P	Daily rainfall intensity of rainfall events above 98th reference precipitation percentile	[mm]
24		SDII	Simple daily rainfall intensity index	[mm]
25		R5d	Greatest 5-day total rainfall	[mm]
26		R1d	Greatest daily total rainfall	[mm]
27		CDD	max # of consecutive dry days (<1 mm)	[days]

[a] Reference percentile based on 1961–1990
[b] CSDI10: Cold Spell Duration Index. Counted are the total number of at least 6 consecutive days with Tmin below long-term 10th percentile (1961–1990)
[c] WSDI90: Warm Spell Duration Index. Counted are the total number of at least 6 consecutive days with Tmax exceeding long-term 90th percentile (1961–1990)
[d] HWDI: Heat Wave Duration Index ($Tx_{ij} > Tx_{inorm} + 5$). Let Txij be the daily maximum temperature at day *i* of period *j*. Let Tx_{inorm} be the calendar day mean calculated for a 5 day window centered on each calendar day during the base period (1961-1990).Then counted are the total number of spells of at least 6 consecutive days exceeding Tx_{inorm}+5 °C

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