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# Detection of regional weekly weather cycles across Europe

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## Abstract

Daily rainfall and temperature data of 158 weather stations in eight European countries and Iceland are investigated to set up a weekly cycle. The time series are divided into five time slices that are analyzed separately. As they depend strongly on the data availability, the significance of weekly cycles is generally higher for the past three time slices of 1931–1960, 1961–1990, and 1991–2005 compared to the two earlier analyzed time slices of 1871–1900 and 1901–1930.

Precipitation does not follow any distinct significant weekly cycle. For temperature, however, significant weekly cycles exist in all analyzed countries. The weekly periodicities cannot be explained by random effects. A clear weekly signal is detected by means of a stationary block bootstrap approach. The cycles of temperature vary with the region and the time slice. However, they are found to be more stable for the last two time slices. For the dominant pattern of the weekly cycle in Germany, a coinciding significant weekly cycle of the large-scale circulation is detected for the time slice 1991–2005.

In Germany, persistence can be observed for the weekday holding the minimum value of the temperature variables. The minimum is observed to occur on Saturday for the past two time slices. When judging from significant results exclusively, most other countries also show persistence for the past two time slices, except for the weekday with the maximum value of the temperature variables. This weekday either is Tuesday for Iceland and the UK or Wednesday for Sweden and Norway.

**Keywords:** weekly weather cycle, weekly weather periodicities, persistence, block bootstrap

## 1. Introduction

Nowadays, human impact on climate change is not doubted by most scientists. In this context, an increase of global mean temperature by  $\sim 0.6 \pm 0.2$  K has been observed since the industrial era (Houghton *et al* 2002), and a warming of  $\sim 6$  K compared to the last ice age is in store. Hundreds of studies are dealing with climate change and its impacts in the past, present, and future. In order to understand the climate system, researchers fall back on global circulation models (GCMs). Although there is a general agreement on the usability of these models, their accuracy is rather imperfect. By identifying weekly cycles of meteorological variables based on measured

data, it is possible to understand the interaction of human activity with weather and also climate and, thus, ultimately to improve the GCMs.

Forster and Solomon (2003) found evidence of a weekly cycle in the diurnal temperature range (DTR) for many stations in the US, Mexico, Japan, and China. In their analysis, they compared the difference between the averaged Saturday to Monday DTR with the averaged Wednesday to Friday DTR. For Europe, however, they did not find any significant patterns of this weekday effect. Cerveny and Balling (1998) identified a weekly cycle of rainfall for the Northwest Atlantic region. For the time period from 1979–1992, Gordon (1994) found a significant, but very small, weekly periodicity of temperature for the northern hemisphere.

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Schultz *et al* (2007) investigated 219 observation stations in the US for a weekly cycle in rainfall. Neither occurrence nor rainfall amount were found to depend significantly upon the day of the week. In contrast, Bell *et al* (2008) detected weekly cycles in daily rainfall time series in the southeast of the US using Tropical Rainfall Measuring Mission (TRMM) satellite data as well as rain gauge data.

In accordance with weekly cycles of meteorological variables, weekly periodicities for air pollutants, such as O<sub>3</sub>, CO<sub>2</sub>, and NO<sub>2</sub> as well as solid particles (aerosols), were also found (e.g. Beany and Gough 2002, Jin *et al* 2005, Shutters and Balling 2006). Gong *et al* (2007) investigated weekly cycles of aerosol concentration and the covariations in meteorological conditions in major urban regions over east China. They detected a weekly cycle of PM10 (aerosol particulate matters of diameter <10 μm) concentration accompanied with weekly cycles of windspeed and air temperature in the lower troposphere. The authors hypothesize that the changes in the atmospheric circulation might be triggered by the accumulation of PM10 through diabatic heating of the lower troposphere: during the early part of the week the anthropogenic aerosols accumulate in the lower troposphere. Around midweek, they could induce radiative heating and destabilize the lower and middle troposphere. Anomalous vertical air motion and stronger winds could be the consequences and the resulting circulation could promote ventilation to reduce the aerosol concentration in the boundary layer during the latter part of the week.

In a paper which appeared recently, Sanchez-Lorenzo *et al* (2008) identified winter weekly cycles of different climate variables in Spain, which appears to be linked with winter SLP anomalies over western Europe.

An overview of studies dealing with weekly periodicities of meteorological variables as well as weekly emission cycles can be found in Bäumer and Vogel (2007), which hereinafter will be referred to as BV (2007). In their article, they found a weekly cycle of different meteorological variables in Germany from 1991–2005 based on the analysis of 12 weather stations with 15 years of data. They concluded that this periodicity effect is non-local. Therefore, local heat emissions cannot be the dominant process.

The question arises whether or not a weekly cycle already existed before 1991 and if so, whether it was the same cycle or whether it changed in accordance with the significant change of anthropogenic emissions that has occurred since German reunification in 1990. Hendricks Franssen (2008), hereinafter referred to as HF (2008), also identified individual weekdays with similarly strong deviations from the mean before 1991 when he analyzed the data from two Swiss meteorological stations. He also asked whether the weekly cycles observed by BV (2007) could be explained exclusively by random effects.

Similar to the study of Gong *et al* (2007), we hypothesize the existence of weekly weather cycles, which might be influenced indirectly by a weekly emission cycle through atmospheric dynamics on a regional scale.

The work described in the present paper extends that of BV (2007), as rainfall and temperature time series of nine countries and time slices dating back to 1871 are analyzed.

Additionally, it is aimed to find out whether or not weekly cycles existed before 1991, since the air composition especially after 1950 was strongly affected by human activities, possibly even with higher aerosol numbers (HF 2008). By including different nations in the analysis, it is possible to compare highly and less industrialized regions and to investigate whether or not this weekly cycle follows regional patterns. In addition, the magnitude of the difference between highest and lowest mean weekday temperature anomalies was investigated. To the authors' knowledge, a comprehensive long-term analysis of the weekly cycle of meteorological variables, including so many synoptic weather stations over the European continent, has not yet been performed.

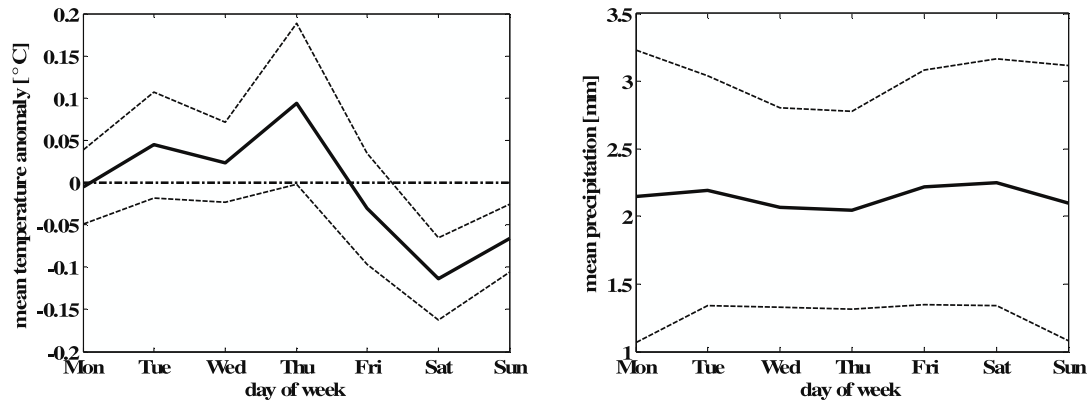
## 2. Data and methodology

158 European weather station time series were analyzed in terms of their weekly periodicities. The daily observation data were retrieved from the European Climate Assessment & Dataset (ECA&D) project (Klein Tank *et al* 2002) and the Global Historical Climatology Network (GHCN). The time series have different levels of urban influence. Analysis covered the variables of precipitation, mean temperature, minimum temperature, maximum temperature, and diurnal temperature range (DTR) in the following past and ongoing climatological normal periods: (i) 1871–1900, (ii) 1901–1930, (iii) 1931–1960, (iv) 1961–1990, and (v) 1991–2005. In order to obtain the daily mean temperature, the temperature values were taken at the so-called 'Mannheimer Stunden' at 7:30 CET, 14:30 CET, and 21:30 CET and eventually averaged by  $(T_{7:30} + T_{14:30} + 2T_{21:30})/4$ . Since April 2001, however, the mean daily temperature has been calculated by averaging the daily hour values. Systematic differences between the two different averaging schemes of more than 0.1 K could be observed for some coastal as well as mountainous regions. Passages of fronts might even cause deviations of several K. However, no inhomogeneities are expected to result from analyzing mean values of perennial time periods (DWD 2007).

The DTR, which is known to be a relatively constant variable over time, was calculated as  $T_{\max} - T_{\min}$ . For Germany, which was most interesting in this analysis, a total of 33 stations for precipitation, 41 stations for mean temperature, 43 stations for minimum temperature, 40 stations for maximum temperature, and 39 stations for DTR were used.

The applied calculations include the following six steps:

- (1) The data gaps of the time series are filled automatically with NaNs (not any number).
- (2) Each value of the time series day is assigned to the respective weekday (7 bins).
- (3) The anomalies are calculated for the temperature variables by removing the annual cycle. Therefore, the 31-day running mean is subtracted from the original time series following the approach of BV (2007). For the rainfall time series, the weekday means are analyzed instead of their anomalies due to rainfall discontinuity.
- (4) The mean values of each weekday (bin) are calculated. These mean values represent the weekly cycle.



**Figure 1.** Mean temperature anomaly (°C) of 43 (left) and mean precipitation (mm) of 33 (right) meteorological observation stations in Germany by day of the week (1991–2005). The thick solid line represents the mean values and the dashed lines the standard deviation.

- (5) The weekdays with the maximum and minimum mean values were determined, and the difference between the maximum and minimum mean value  $\Theta$  was calculated.
- (6) A *t*-test was performed to decide whether the mean values of the highest and lowest weekday populations differed significantly from each other. The test was carried out at the  $\alpha = 0.05$  and 0.01 significance levels. The prerequisite of normality of both populations was tested as well.

The stationary block bootstrap resampling method was applied to prove the existence of weekly cycles. It consists of drawing blocks of a measured time series of fixed lengths randomly in order to maintain the temporal dependence structure of the time series. These blocks are randomly rearranged. The block length was varied successively from 1 to 50, and 100 rearranged time series (realizations) were taken for each block length. For each realization, steps 2–5 were performed.

An objective circulation pattern (CP) classification algorithm based on the so-called Central Europe *Großwettertypen* was applied for the period 1991–2005 (Beck 2000). Sea level pressure (SLP) data from the NCEP/NCAR reanalysis project were used for the classification in the domain 40°N–75°N and 25°W–30°E. The occurrence frequencies of the resulting 18 CPs of each weekday were calculated and the resulting weekly cycles were checked for significance via the *t*-test and the stationary block bootstrap algorithm. Significant differing frequencies within the weekdays (weekly cycles) of certain CPs were compared to the observed weekly cycles of the temperature variables.

### 3. Results

#### 3.1. Temperature

Figure 1 (left) depicts the mean temperature anomaly of 43 meteorological observation stations in Germany by the day of the week. In contrast to the results of BV (2007), we found Thursday to be the day with the highest mean temperature anomaly within the period from 1991 to 2005 in Germany for the bulk of the stations. The results for the weekday holding the lowest mean temperature anomaly, Saturday, are in accordance

with their results. This slightly different finding can be explained by the more dense database underlying this work. The mean DTR and the maximum temperature anomalies show weekly periodicities similar to those of the mean temperature anomalies (table 1).

Contrary to the results of BV (2007), local, but also regional effects of the weekday periodicity were found. Again, the different results are probably due to the more dense database underlying this analysis. The cross-national distribution of the weekly cycle in terms of the weekday holding the maximum and minimum mean temperature is illustrated in figure 2. Clear regional patterns are observed. For the coastal region of the North Sea, the mean temperature anomaly is maximal for Tuesday and minimal for Saturday for many observation stations. Similar regional patterns are observed for the other temperature variables.

#### 3.2. Precipitation

Contrary to temperature, precipitation exhibits a more arbitrary spatial distribution (not shown). The mean rainfall values per weekday for the period 1991–2005 are illustrated in figure 1 (right). Saturday is slightly wetter than Thursday, which is found to be the driest day of the week. The difference between the averaged Saturday and Thursday values is 0.2 mm. However, Thursday and Saturday values are not significantly different at the  $\alpha = 0.05$  level.

The probability of a rainfall event with a rainfall threshold  $\geq 5$  mm is highest for Tuesday (15.7%) and Saturday (14.8%). As regards the probability of rainfall occurrence  $\geq 10$  mm, the order is reversed, with Saturday reaching the highest value of 6.9% and Tuesday 6.5% (not shown here). Again, both analyses do not match the 0.05 significance level for the difference between highest and lowest mean values.

#### 3.3. Evidence of the existence of weekly weather cycles

Figure 3 shows the dependence of the difference of the minimum and maximum mean values  $\Theta$  for the bootstrap samples on the block lengths for  $T_{\max}$  in Augsburg (1991–2005). Rearranging the artificial time series in blocks of 7 or a multiple of 7 days leads to the highest cycles in the

**Table 1.** Weekday with the maximum (minimum) mean value of precipitation amount, mean temperature, minimum temperature, maximum temperature, and diurnal temperature range. A *t*-test was performed to decide whether the mean values of the highest and lowest weekday populations differed significantly from each other. The test was carried out at the  $\alpha = 0.05$  and 0.01 significance levels. Results meeting the  $\alpha = 0.01$  significance level (dark gray) are considered as very significant, those meeting the  $\alpha = 0.05$  significance level (light gray) as significant; (n.d. = no data).

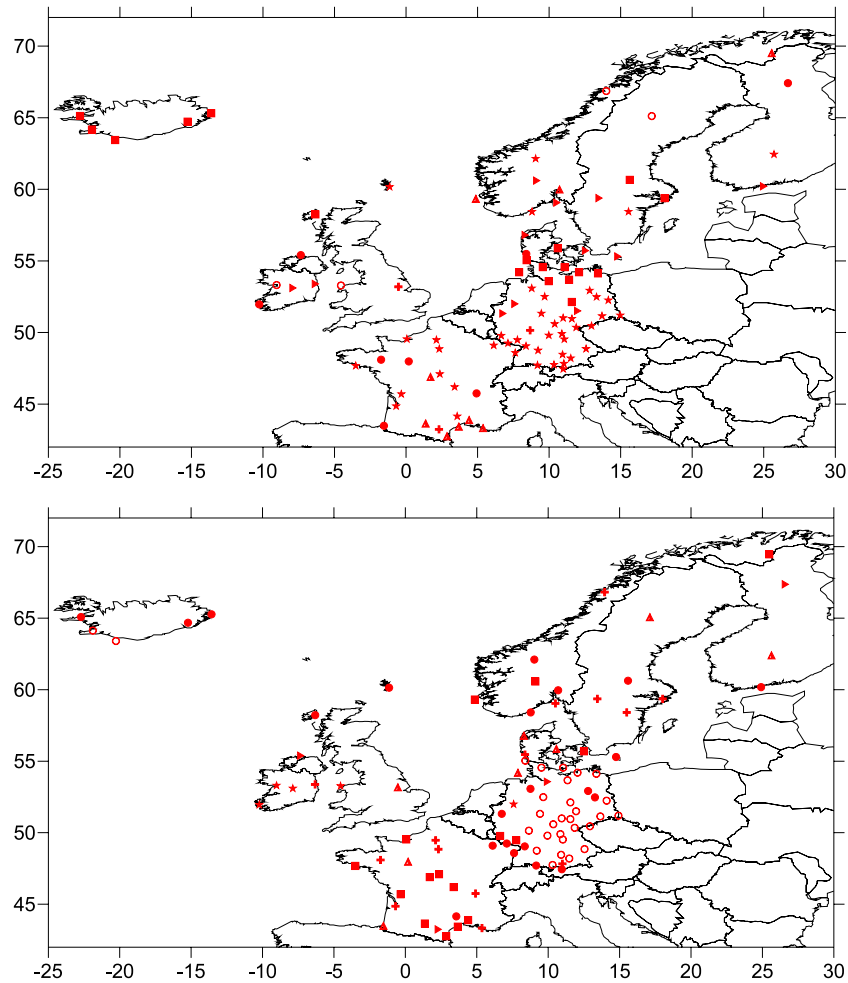
		1871–1900	1901–1930	1931–1960	1961–1990	1991–2005
Germany	Precipitation	Thu (Sun)	Sun (Thu)	Sun (Thu)	Wed (Fri)	Sat (Thu)
	$T_{\text{mean}}$	Thu (Mon)	Sun (Wed)	Mon (Fri)	Tue (Sat)	Thu (Sat)
	$T_{\text{min}}$	Thu (Mon)	Sun (Wed)	Mon (Sat)	Wed (Sun)	Fri (Sat)
	$T_{\text{max}}$	Wed (Mon)	Thu (Fri)	Mon (Fri)	Wed (Sat)	Thu (Sat)
	DTR	Tue (Thu)	Thu (Sun)	Mon (Fri)	Tue (Sat)	Thu (Sat)
Denmark	Precipitation	Wed (Sun)	Tue (Fri)	Wed (Sun)	Thu (Tue)	Sat (Thu)
	$T_{\text{mean}}$	Thu (Sat)	Fri (Wed)	Tue (Sat)	Wed (Sun)	Wed (Mon)
	$T_{\text{min}}$	Tue (Sat)	Sun (Wed)	Tue (Sat)	Wed (Sun)	Wed (Tue)
	$T_{\text{max}}$	Fri (Sun)	Fri (Wed)	Sun (Wed)	Wed (Sun)	Wed (Sat)
	DTR	Sat (Tue)	Fri (Sun)	Sun (Tue)	Thu (Fri)	Tue (Sat)
France	Precipitation	Fri (Wed)	Tue (Wed)	Sun (Fri)	Sat (Tue)	Fri (Tue)
	$T_{\text{mean}}$	Thu (Mon)	Wed (Sun)	Sat (Wed)	Tue (Mon)	Thu (Tue)
	$T_{\text{min}}$	Tue (Sun)	Fri (Sat)	Mon (Thu)	Wed (Thu)	Fri (Tue)
	$T_{\text{max}}$	Mon (Fri)	Wed (Sun)	Sat (Wed)	Tue (Sun)	Thu (Fri)
	DTR	Mon (Tue)	Mon (Sun)	Thu (Wed)	Tue (Wed)	Wed (Fri)
Finland	Precipitation	n.d.	Thu (Sun)	Thu (Sun)	Sun (Wed)	Thu (Wed)
	$T_{\text{mean}}$	n.d.	Sun (Thu)	Thu (Tue)	Fri (Mon)	Sat (Tue)
	$T_{\text{min}}$	n.d.	Mon (Thu)	Thu (Fri)	Sat (Tue)	Thu (Wed)
	$T_{\text{max}}$	n.d.	Sat (Thu)	Thu (Tue)	Fri (Sun)	Wed (Mon)
	DTR	n.d.	Wed (Sun)	Fri (Tue)	Tue (Sun)	Wed (Thu)
GB	Precipitation	n.d.	n.d.	Mon (Sat)	Fri (Mon)	Thu (Sun)
	$T_{\text{mean}}$	Sat (Tue)	Fri (Wed)	Sun (Fri)	Tue (Sat)	Tue (Sun)
	$T_{\text{min}}$	Sat (Mon)	Sat (Thu)	Sat (Wed)	Tue (Sat)	Tue (Sun)
	$T_{\text{max}}$	Sat (Thu)	Thu (Tue)	Sun (Fri)	Mon (Sat)	Tue (Wed)
	DTR	Mon (Thu)	Thu (Sat)	Sun (Tue)	Thu (Tue)	Sun (Wed)
Ireland	Precipitation	Thu (Sun)	Sat (Mon)	Mon (Sat)	Fri (Mon)	Thu (Sun)
	$T_{\text{mean}}$	Sat (Mon)	Mon (Thu)	Sat (Wed)	Mon (Sat)	Sat (Thu)
	$T_{\text{min}}$	Sat (Mon)	Sat (Thu)	Fri (Wed)	Mon (Wed)	Tue (Fri)
	$T_{\text{max}}$	Sun (Tue)	Mon (Thu)	Tue (Thu)	Mon (Fri)	Sat (Thu)
	DTR	Fri (Thu)	Mon (Sat)	Tue (Fri)	Wed (Fri)	Fri (Tue)
Iceland	Precipitation	n.d.	n.d.	Mon (Sat)	Tue (Sun)	Wed (Tue)
	$T_{\text{mean}}$	n.d.	n.d.	Tue (Sat)	Tue (Fri)	Tue (Sun)
	$T_{\text{min}}$	n.d.	n.d.	Tue (Sat)	Mon (Fri)	Wed (Sun)
	$T_{\text{max}}$	n.d.	n.d.	Wed (Sat)	Tue (Thu)	Tue (Sun)
	DTR	n.d.	n.d.	Wed (Fri)	Fri (Mon)	Tue (Sun)
Norway	Precipitation	Tue (Wed)	Mon (Sat)	Fri (Sun)	Fri (Mon)	Mon (Wed)
	$T_{\text{mean}}$	n.d.	n.d.	Wed (Mon)	Wed (Sun)	Wed (Mon)
	$T_{\text{min}}$	n.d.	n.d.	Sun (Mon)	Wed (Sun)	Wed (Tue)
	$T_{\text{max}}$	n.d.	n.d.	Mon (Fri)	Wed (Sun)	Fri (Thu)
	DTR	n.d.	n.d.	Mon (Fri)	Wed (Tue)	Tue (Wed)
Sweden	Precipitation	n.d.	Tue (Fri)	Wed (Sun)	Sat (Tue)	Fri (Sun)
	$T_{\text{mean}}$	n.d.	Sat (Thu)	Thu (Mon)	Wed (Sun)	Wed (Mon)
	$T_{\text{min}}$	n.d.	Sun (Thu)	Wed (Mon)	Wed (Sun)	Wed (Fri)
	$T_{\text{max}}$	n.d.	Sat (Wed)	Sat (Wed)	Wed (Sun)	Thu (Mon)
	DTR	n.d.	Thu (Tue)	Mon (Wed)	Tue (Sat)	Fri (Mon)

meteorological variables in terms of the difference of the maximum and the minimum mean weekday values. Choosing block lengths greater or less than 7 reduces  $\Theta$ , a measure for the magnitude of a cycle. The only conclusion one can draw is that there must exist a significant weekly weather cycle. The 7-day signal exists for all time slices and all variables. It is reduced for rainfall (not shown here). Figure 4 illustrates the weekly  $T_{\text{max}}$  anomaly distribution of 100 bootstraps in Augsburg (1991–2005) using a block length of 7 days. The quartiles and the median of Thursday

are clearly increased compared to those of Saturday and Sunday.

### 3.4. Persistence of weekly cycles

Apart from the spatial distribution of the weekly weather cycles in terms of temperature and precipitation, the persistence of these patterns has been analyzed for the five different time slices: (i) 1871–1900, (ii) 1901–1930, (iii) 1931–1960, (iv) 1961–1990, and (v) 1991–2005. The weekdays with



**Figure 2.** Weekday with maximum (top) and minimum (bottom) mean temperature from 1991–2005 (+ Monday; ■ Tuesday; ► Wednesday; ★ Thursday; ▲ Friday; ○ Saturday; ● Sunday).

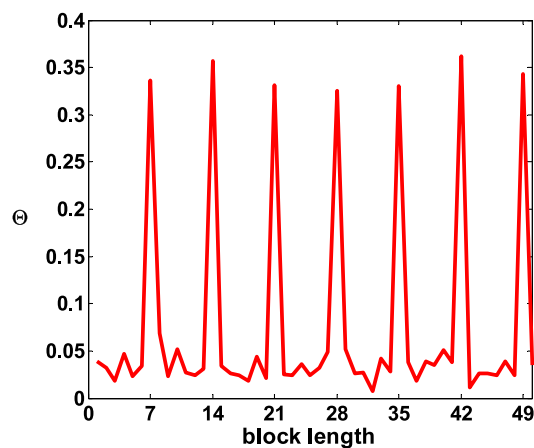
the maximum and minimum mean values of the precipitation amount, mean temperature, minimum temperature, maximum temperature, and DTR have been determined by separate averaging for each country and each time slice. The weekdays with the highest and lowest mean values were checked for their statistical significance using a *t*-test (table 1).

For Germany, no persistence can be observed for the weekday with a maximum value. For the weekdays holding the minimum values, however, a clear persistence on Saturday can be noticed for the temperature variables in the last two time slices, 1961–1990 and 1991–2005. This situation is reversed for the countries Denmark, Norway, Sweden, Finland, the UK, and Iceland, where the weekday with the maximum values of the temperature variables investigated shows persistent characteristics. For Finland, no clear results can be derived due to the reduced data availability. In France and Ireland, no persistent patterns are found. In the other countries, the maximum values occur either on Wednesday (Norway and Sweden) or on Tuesday (Iceland and the UK) for the past two time slices. The mean values of the highest and lowest weekday populations were checked for their differences from each other. Except for precipitation, the population mean values differ at the  $\alpha = 0.05$  significance level at least. No

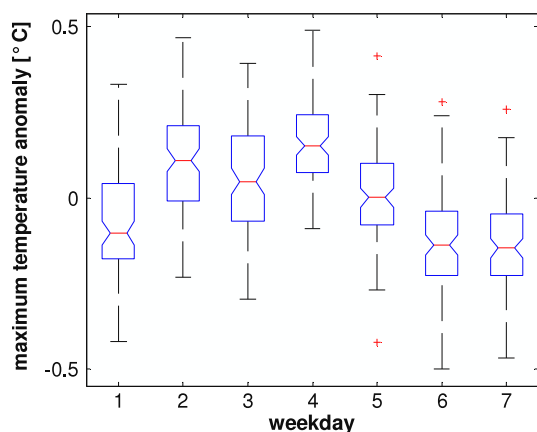
clear conclusions can be drawn with respect to the magnitude of the difference between the highest and lowest mean values. Germany and France, and, to a minor extent, the UK show comparatively high magnitudes of the minimum temperature and, hence, of the diurnal temperature range in the time slice 1871–1900 (not shown here).

### 3.5. Circulation patterns (CPs)

The *t*-test and the stationary block bootstrap prove evidence for weekly cycles of 10 out of 18 CPs (not shown). Figure 5 illustrates the weekly cycle of the circulation pattern CP1 and its sea level pressure composite field during the time slice 1991–2005. The pattern can be characterized as a *cyclonic west situation*. Its occurrence frequency amounts to 12% within the period 1991–2005. CP1 is found to have a significant weekly cycle. Its occurrence frequency shows a maximum at Thursday and a minimum at Saturday. The weekly cycle of the occurrence frequency of CP1 is in agreement with the weekly cycle of the mean temperature anomaly for the analyzed observation stations in Germany (figure 1).



**Figure 3.** The dependence of the difference of the minimum and maximum mean values  $\Theta$  for 100 bootstrap samples on the block lengths for  $T_{\max}$  at the observation station in Augsburg (1991–2005).

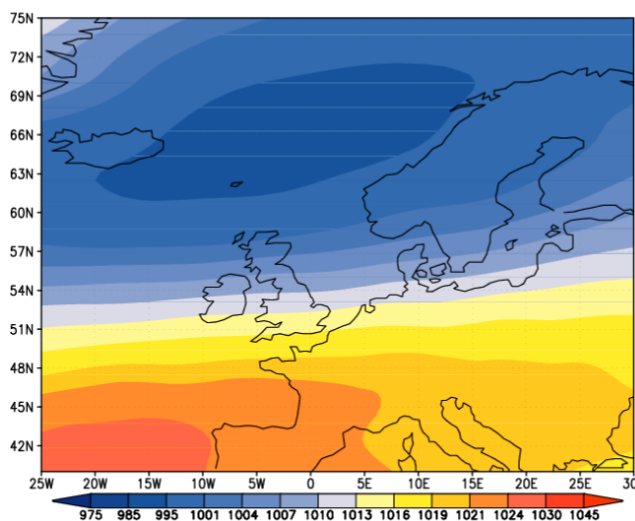
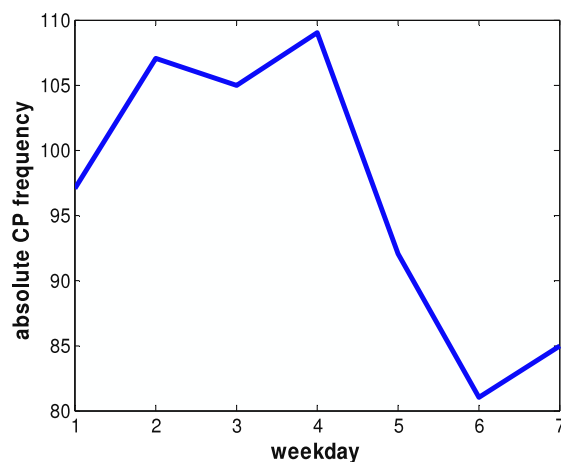


**Figure 4.** Box-whisker plots showing the weekly  $T_{\max}$  anomaly distribution of 100 bootstraps of block length 7 in Augsburg (1991–2005). The boxes have lines at the lower  $Q_1$  and upper quartile  $Q_3$  (blue horizontal lines) and the median values  $Q_2$  (red horizontal lines). The whiskers (black lines) are lines extending from each end of the boxes to show the extent of the rest of the data. The maximum length of the whiskers is determined by  $1.5 \times (Q_3 - Q_1)$ . Outliers (red crosses) are data with values beyond the ends of the whiskers.

#### 4. Conclusions

Analysis provides evidence for the existence of significant weekly cycles of the temperature variables (mean temperature, minimum temperature, maximum temperature, and diurnal temperature range) for Europe. Hence, this analysis is in agreement with the earlier studies conducted by Gordon (1994) and BF (2007), but could not confirm findings of Forster and Solomon (2003), who could not find any weekend effect of the DTR in Europe. Performed block bootstrap experiments disprove speculations (as for example expressed by HF 2008; Coakley 2000) of the observed weekly cycle being an artifact resulting from the applied methodology. Weekly cycles were identified from 1871.

As the analyzed stations have different levels of urbanization and heat emission, the spatial patterns of weekly



**Figure 5.** Absolute occurrence frequency of circulation pattern CP1 for each weekday for the time slice 1991–2005 (top). SLP composite of the objectively derived circulation pattern CP1. The pattern characterizes the *cyclonic west situation* (bottom).

temperature cycles cannot be related to local effects alone. The spatial distribution of the weekly cycle clearly shows regional patterns. The observed regional weekly cycles of mean temperature for the central and southern part of Germany (maximum at Thursday, local maximum at Tuesday, and minimum at Saturday) are found to be in accordance with the synoptic situation over central Europe. The most frequent circulation pattern, CP1, which can be described as a *cyclonic west situation*, shows a significant weekly cycle with the same structure. Therefore, we conclude that the weekly temperature cycles might be influenced by atmospheric circulation, which is possibly triggered by regional accumulation of air pollutants in the lower atmosphere. However, further analysis will be necessary to verify the covariation of the identified weather cycles with the large-scale circulation on weekly timescale. In addition to that, air quality parameters should also be considered.

For rainfall, the differences of the weekday with the highest and lowest values are not significant (tested at the  $\alpha = 0.05$  and  $0.01$  significance levels). Hence, no clear weekly periodicities are concluded for rainfall.

## Acknowledgments

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