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Weekly cycles in precipitation in a polluted region of Europe

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Abstract

Weekly cycles in aerosol concentration and corresponding cycles in precipitation have been reported over Europe, but results are conflicting. To obtain a large potential effect of aerosols on precipitation we here focus on a highly polluted region on the borders between Germany, Poland and the Czech Republic. Meteorological parameters from 30 surface stations in a mix of urban, rural and remote locations were analyzed for the time period 1983–2008, using three different tests: the Kruskal-Wallis test, a spectral analysis and a comparison of the regular 7-day week to constructed 6- and 8-day weeks. We expect a clear and statistically significant weekly cycle to pass all three tests. Precipitation amount and meteorological variables associated with convective conditions, such as the frequency of heavy precipitation events and observations of rain showers, showed two-peak weekly cycles with maxima on Tuesdays and during weekends. The amplitude of the precipitation cycle increased with longitude towards the more polluted eastern part of the region, but the statistical significance of the cycles did not change correspondingly. The amplitudes of the weekly cycles were in many cases larger for the heavily polluted 1983–1987 period than for the cleaner 2004–2008 as well as the total period, but were equally often largest in the clean period. Moreover, of all the variables, periods and seasons investigated, the weekly cycles were statistically significant only for summertime values of light precipitation frequency and cloud amount, and only by one of the three tests applied. Conclusively, clear weekly cycles in meteorological variables were not found in this polluted region of Europe.

1 Introduction

Over the past decades, Europe has experienced substantial reductions in pollution levels. For instance, European emissions of sulphur dioxide – precursor to the cloud-active sulphate aerosols – were cut by 73% between 1980 and 2004 (Vestreng et al., 2007). High aerosol concentrations influence cloud properties by increasing cloud droplet numbers and decreasing cloud droplet radii (Twomey, 1977), which again has been suggested to lower the efficiency of collision-coalescence, slowing down warm rain formation (Albrecht, 1989). However, the magnitude and even sign of the effect that decreased droplet sizes has on precipitation is less clear (Stephens and Feingold, 2009; Levin and Cotton, 2008). Some conclude that the aerosol influence on precipitation is small or even negligible (e.g., Alpert et al., 2008; Halfon et al., 2009; Schultz et al., 2007). Others find an effect (e.g. Gunn and Phillips, 1957; Rosenfeld, 2000; Jirak and Cotton, 2006; Teller and Levin, 2006; Koren et al., 2008), but the collected model and observation studies indicate that the aerosol-precipitation link is non-linear and depends on conditions such as background aerosol concentrations (Andreae et al., 2004), cloud lifetime (Givati and Rosenfeld, 2004) and cloud base temperature (Rosenfeld et al., 2008).

Weekly cycles have been observed in measurements of atmospheric air pollution in many regions of the world (e.g. Gong et al., 2007; Jin et al., 2005; Marr and Harley, 2002) and provide an interesting approach to search for anthropogenic effects on climate, as no natural process with a constant cycle of 7 days over long time periods is know to exist (Sanchez-Lorenzo et al., 2008). Yet studies of weekly cycles in meteorological parameters yield highly contrasting results (see e.g. Schultz et al., 2007). A weekly cycle in pollution levels has also been observed over Europe (e.g. Bäumer et al., 2008), with maximum concentrations during central weekdays and minimum concentrations in the weekends. But while Bäumer and Vogel (2007) found corresponding significant weekly cycles in meteorological variables such as temperature, cloud amount and precipitation for 12 stations in Germany, Barmet et al. (2009) performed a similar study of 17 stations in Switzerland and did not find statistically significant weekly cycles for any meteorological quantities. Instead, they attributed their different conclusion to more rigorous statistical tests, and suggested that significant weekly cycles might be detectable if applying the same methods to data from more heavily polluted regions.

In the present paper, we therefore utilize the methods of Barmet et al. (2009), focusing on a particularly polluted region of central Europe located on the borders between

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Germany, Poland and the Czech Republic. This region, formerly know as the Black Triangle, was the most polluted part of Europe in the 1980s and early 1990s (Vestreng et al., 2007), but (largely due to the combined impacts of political and economic changes in the 1990s) experienced a substantial decline in pollution levels thereafter (Hůnová et al., 2003). Weekly cycles in various meteorological parameters are analyzed, looking for midweek- to weekend differences in the means. We compare the meteorological cycles to weekly cycles in pollution measured at a station within the region, and suggest explanations to the observed similarities and differences between pollution and meteorology. Proving any cause-effect relationships, however, is beyond the scope of this paper. Instead, we focus on determining whether meteorological variables, and particularly precipitation, display well-pronounced and statistically significant weekly cycles in this polluted region, as suggested by Barmet et al. (2009).

2 Data

We used data from synoptic weather stations, provided by the European Centre for Medium-Range Weather Forecasts' (ECMWF) Meteorological Archive and Retrieval System. Data were available for 00:00, 06:00, 12:00 and 18:00 UTC for the period 1983 to 2008. All stations in the area 49.50°–52.00° N and 12.00°–18.00° E were extracted, and only the ones with more than 75% of valid data over the time series were kept. This selection gave a total of 30 stations – see dots in Fig. 1 – among which 22 had more than 95% data coverage over the time series.

The following meteorological variables were analyzed: precipitation amount, precipitation frequency, cloud amount, frequency of rain showers (a weather type noted by the meteorological observer at the weather station), frequency of light precipitation events (defined as less than 0.5 mm over 12 h), frequency of heavy precipitation events (defined as more than 10 mm over 12 h), atmospheric surface pressure, wind speed, horizontal visibility and temperature.

We also looked at weekly cycles in pollution measured at a single station from the European Monitoring and Evaluation Programme (EMEP) network. The station has a particularly long and consistent time series and high data credibility (W. Aas, personal communication, 2008), and is located in a rural area of Svratouch in the Czech Republic (see triangle in Fig. 1), at 49°44′ N, 16°2′ E, and 737 m a.s.l.

3 Methods

First, as proposed by Bäumer and Vogel (2007) analyzing a similar data set, seasonality was removed by subtracting a 31-day running mean – both from the time series of each station and from a regional mean time series. The regional mean was calculated by averaging daily values for all the 30 stations. The resultant "anomaly time series" were then divided into weekdays, and the mean weekly anomalies could thus be calculated.

The peak-to-peak amplitude of a weekly cycle was defined simply as the difference between the highest and the lowest weekly value. To test whether the weekly cycles were significant or not, we followed the methods of Barmet et al. (2009):

1. The Kruskal-Wallis test is a non-parametric (i.e. no assumptions of population distributions such as normality) method for testing equality of population medians among groups. Our data were divided into 7 groups (giving six degrees of freedom); one for each day of the week. Barmet et al. (2009) demonstrated the superiority of the Kruskal-Wallis test to regular t-tests or Wilcoxon rank-sum tests for the purpose of analyzing weekly cycles.
2. A signal of strong weekly periodicity would be visible as a peak at $1/7\,\mathrm{d}^{-1}$ (and the multiples of it) in a spectral density plot. Periodograms were made for this purpose by use of the spec.pgram function of R (R development Core Team, 2007).
3. Grouping the meteorological data into artificial 6- and 8-day weeks and comparing the amplitude of these to the 7-day week should indicate whether the 7-day week

in fact stands out from the others. If it does not, the 7-day weekly cycle is likely to be an artifact.

The tests were performed on anomaly time series as well as raw time series, and on regional means as well as on individual station time series. Given the tendency of clouds and precipitation to react differently to aerosols under different temperature regimes (Rosenfeld et al., 2008), we also studied summer (June through August) and winter (December through February) data separately.

Gong et al. (2006) found a strengthening of the weekly cycles in China for periods of higher pollution loads, and similar findings were reported by Bell et al. (2008) for the US. Our analyses were therefore applied to the total period 1983–2008 as well as to the more heavily polluted five-year period 1983–1987 and the cleaner five-year period 2004–2008, to see if the weekly cycles in the most polluted period were stronger also in the Black Triangle.

4 Results and discussion

To indicate whether pollution in the Black Triangle displays a weekly cycle similar to what is reported in other regions of Europe, we first present measurements of sulphur dioxide at a selected station in the region. We also show measurements of horizontal visibility, which may be seen as a proxy for aerosol concentrations. Weekly cycles in precipitation and other meteorological parameters are then presented and compared.

4.1 Sulphur dioxide and horizontal visibility

While weekly cycles in ground based measurements of pollutants not necessarily imply the presence of similar cycles in cloud condensation nuclei (CCN) at heights of cloud droplet formation as noted by Bell et al. (2008), a strong 7-day cyclic behavior is at least an indication of anthropogenic influence on the atmosphere in the area. It is not given that all anthropogenic sources of pollution display weekly cycles in their emission levels. E.g., large coal-fired power plants, which dominate the Black Triangle region (Hůnová et al., 2003), may not be tuned down during the weekends in the same way as for instance traffic in major cities. We therefore need to look at measurements within the region for evidence of weekly pollution cycles.

An important precursor to CCN is sulphur dioxide, which by gas-to-particle conversion is the most important source of sulphate aerosols. At Svratouch, a rural area in the central Czech Republic, we find a cyclic variation in the SO_2 concentration over the course of a typical week – see Fig. 2. Although a 7-day periodicity does not show up on a periodogram (not shown), the Kruskal-Wallis test reveals a significant (p-value of 0.001) difference in the median of the 7 days. The figure shows that the concentration is highest on Tuesdays and lowest on Sundays, the difference between these two days being 15 % of the daily mean of 5.16 $\mu g\,m^{-3}$. Using only urban stations, similar periodicities in PM_{10} was found by Barmet et al. (2009) for Switzerland, with peak concentrations on Wednesdays and a difference in concentrations of 24% between the most and the least polluted day.

Primary and secondary aerosols from industrial activity will affect the local atmospheric turbidity, so weekly variations in the concentration of aerosols may be found indirectly by studying records of horizontal visibility. Indeed, a weekly variation is visible in the mean horizontal visibility of the 30 stations in the Black Triangle (Fig. 3). The phase-to-phase amplitude is larger in the more polluted 1983–1987 period (red dashed line) than in the cleaner 2004–2008 period (blue dotted line) as well as the total 1983–2008 period (black solid line). For the total period, the visibility differs by 1.3 km or 8% between Sundays and Fridays. For the more polluted period the difference is 13%, while the cleaner period has a difference of 8%. The cycles for all periods are highly significant by the Kruskal-Wallis test ($p \ll 0.001$). The visibility decreases steadily throughout the week consistent with an aerosol concentration build-up, culminating in a minimum on Fridays, and increases during the weekend until Sunday. The Tuesday peak noted in SO_2 concentrations at Svratouch is not recognized in the visibility plot.

More extensive studies are necessary to identify the phase and significance of the weekly cycles of pollution in the Black Triangle region. Even so, the fact that a weekly cycle is at all visible in this industrialized but rural area is a strong indication that weekly cycles in anthropogenic pollutants are not just an urban phenomenon. Thus, a potential climatic effect may not necessarily be expected only near urban centers but also in regional means as investigated here. Bäumer and Vogel (2007) found for 12 German stations that weekly cycles in meteorological parameters were not limited to the urban stations, but were also present at the more remote sites, and similar findings were reported by Sanchez-Lorenzo et al. (2008).

4.2 Precipitation amount

For precipitation in the Black Triangle, the shape of the weekly cycle is much less smooth than what was found for instance for stations in Switzerland (Barmet et al., 2009), Germany (Bäumer and Vogel, 2007) or Spain (Sanchez-Lorenzo et al., 2008): the solid black line in Fig. 4a shows that precipitation does vary over the course of the week, but while a weekend maximum is present, there is an additional maximum on Tuesdays. Recall that this was the weekday with highest SO_2 concentrations in Svratouch. The phase-to-phase amplitude of the cycle is 16% (corresponding to 0.23 mm) of the daily mean precipitation, but the Kruskal-Wallis test shows that there is no significant difference in the median precipitation anomaly between the seven days. Also, spectral analysis shows no peak at $1/7\,d^{-1}$ (see Fig. 5). The same is found when analyzing each station individually, but when basing the analysis on raw data and not anomalies, 3 out of 30 stations have significant variations in precipitation amounts over a typical week by the Kruskal-Wallis test. Neither of the individual stations, for neither anomaly nor raw values, however, show peaks in periodograms at $1/7\,d^{-1}$. Furthermore, the "6- or 8-day test" shows no clear differences in the amplitudes between a 6-, 7- or 8-day week for any of the above cases – see for instance the plot for regional mean precipitation anomaly in Fig. 6.

If precipitation has in fact been under strong influence of aerosol concentrations we would expect more pronounced weekly cycles in precipitation for the polluted period 1983–1987 than for the total period and the relatively clean 2004–2008 period. We find that the mid-week precipitation maximum is higher for the polluted period (see red dashed line in Fig. 4a) than for the total period, but the clean period (blue dotted line) displays an equally strong maximum here. None of the three periods showed statistically significant cycles by any of the tests.

The Tuesday and weekend maxima are also visible in the summer data (Fig. 4b). Gong et al. (2007) found similar patterns in summertime weekly cycles in China, and hypothesized that diabatic heating of the emitted particular matter could result in mid-week convective motions, which would provide ventilation and thereby diminish the aerosol concentrations and hence its effect on the local meteorology later in the week. While the reoccurring Tuesday peaks in SO_2 and precipitation amount may be signs of such a process, this hypothesis cannot explain the increased weekend precipitation. For the total period, winter precipitation has a more smooth (although weaker in amplitude) cycle with enhanced precipitation only in the weekends (Fig. 4c). Again, however, none of the seasonal cycles are significant by any of the statistical tests.

In general, these results are consistent with previous analyses of weekly precipitation cycles in Europe, where highest precipitation amounts were found during central weekdays. Yet, in line with the findings of Barmet et al. (2009) and contrary to their prospect, the weekly cycles were not found to be statistically significant even in this heavily polluted region. This may indicate that aerosols are not exerting a large enough impact on the local meteorology for such a significant relationship to occur. Alternatively, the high background aerosol concentrations in the Black Triangle area may have lowered the clouds' susceptibility to the day-to-day aerosol variations according to e.g. Andreae et al. (2004), in which case a strong weekly cycle in precipitation would not be expected in this region at all.

The results for precipitation frequency are very similar to the precipitation amounts and are therefore not shown.

4.3 Frequency of light precipitation events

Studies of precipitation trends in regions with large changes in pollution levels have often shown aerosol signals only in the lightest precipitation types (e.g. Qian et al., 2008; Liu et al., 2011). In fact, a recent study compared trends in pollution to trends in precipitation in the Black Triangle area, and found a possible signal only in the frequency of light precipitation events (Stjern et al., 2010).

Here, we see a mid-week suppression in the light precipitation frequency (Fig. 7a), consistent with aerosol suppression of precipitation during the most polluted weekdays. As it is reasonable to assume that these very light precipitation events originate from rather shallow clouds, and not from deep convective clouds which would tend to produce more intense precipitation events, this mid-week suppression is in line with the theories of Albrecht (1989). The weekday-weekend difference is significant by the Kruskal-Wallis test for summers, with a p-value of 0.03 and a phase-to-phase amplitude corresponding to 20% of the mean (Fig. 7b). As the figure shows, the phase-to-phase amplitude of the summer cycle is larger (39%) for the polluted 1983–1987 period (red dashed line) than for the total period (solid black line), and smaller and more variable for the clean period (blue dotted line). But while we would expect the largest precipitation suppression to coincide with the high mid-week aerosol concentrations also during summertime, the frequency of light precipitation events for the polluted period increases throughout the week and reaches a maximum on Sundays. The shape of the summertime light precipitation cycle bears similarities to the cycle of horizontal visibility, which is diminished over the course of the week (Fig. 3). Gradual increases in the concentration of ice nuclei (to which soot may be a source) could conceivably produce this increase in summertime light precipitation due to glaciation and the Bergeron-Findeisen effect (e.g. Wallace and Hobbs, 1977), provided that the clouds consist of regions with supercooled droplets. However, this would have to be confirmed by concrete measurements of ice nuclei as well as cloud base temperatures. Moreover, the summer cycle in light precipitation is only significant by one of three tests, and could therefore just as likely be coincidental.

The winter cycle in light precipitation is not significant for any of the three periods considered (see Fig. 7c). None of the above light precipitation cycles produced significant peaks in the periodograms, and the amplitudes for 6-, 7- and 8-day weeks were similar.

4.4 Other meteorological parameters

The weekly cycle in cloud amount (Fig. 8) is statistically significant for summers by the Kruskal-Wallis test, with an amplitude of 8%. Like for light precipitation events, there is an increase in summertime cloud amounts (with a secondary maximum on Tuesdays) over the course of the weak. A similar but non-significant cycle in wind speed is also observed for summers (not shown).

The increase in cloud amount and wind speed over the week is consistent with the hypothesis of Gong et al. (2007) mentioned in the previous section. To look deeper into the potential presence of a mid-week enhancement of convective activity, we study also the frequency of heavy precipitation events and the occurrence of rain showers. Phase-to-phase amplitudes for these parameters are 45% and 16%, respectively, and both display similar Tuesday peaks. None are however found to be significant by any of the test.

For the polluted period the winter cycle in cloud amount is significant in the Kruskal-Wallis test on the 95% level, and is like wintertime light precipitation events for the same period marked by a mid-week depression and weekend enhancement. Other meteorological parameters, such as atmospheric surface pressure and temperature were also investigated, but showed no weekly cycles, neither statistically nor visibly in plots.

4.5 Spatial variation in the amplitude of the weekly precipitation cycle

Barmet et al. (2009) did not find any difference regarding the significance of the weekly precipitation cycle between different areas within Switzerland, whereas Bäumer and

Vogel (2007) found more intense weekly cycles in temperature in the South-East of Germany, which corresponds to the German part of the Black Triangle area. As eastern European countries had a later and more slow reduction in pollution emission levels (Vestreng et al., 2007), it is interesting to see whether the phase-to-phase amplitude of the weekly cycle in precipitation amount at each location varies with the given location's longitude. Figure 9 shows a tendency for the variation in precipitation over the week to be larger the further east within the BT a station is located; the (Spearman's) correlation coefficient between longitude and phase-to-phase amplitude is 0.51 and significant at the 99% level. However, none of 30 stations had significant weekly cycles in precipitation amount, and like in Barmet et al. (2009) the p-value of the Kruskal-Wallis test did not show any corresponding systematic geographic variation.

5 Summary and conclusion

A station in the Czech Republic shows highest levels of SO_2 on Tuesdays and lowest during weekends, while horizontal visibility in the region as a whole shows a gradual deterioration through the week and improvements during the weekends.

Precipitation amount and other meteorological variables typically associated with convective situations (such as the frequency of heavy precipitation events and higher wind speeds) also display a two-peak weekly cycle with maxima on Tuesdays and during weekends. These cycles are more pronounced when studying only summer data compared to when studying only winter data or all days in the year. An effect can be imagined where midweek increases in aerosol loads near the surface trigger diabatic heating and thus convective motions as suggested by Gong et al. (2007). However, such a mechanism can not explain occurrence of weekend maxima in the same meteorological variables. Furthermore, none of the above parameters are found to display significant cycles by any of the three tests applied.

The weekly cycles of cloud amount and the frequency of light precipitation events are dominated by mid-week decreases and weekend maxima. For summers, both these parameters show significant differences in the median of the 7 days by the Kruskal-Wallis test. A mid-week suppression of summertime light precipitation events is consistent with the findings of Gong et al. (2007) for China. Barmet et al. (2009), on the other hand, did not find a significant weekly cycle in light precipitation for 17 stations in the less polluted Switzerland.

Ultimately, however, none of the meteorological variables investigated (based on neither raw nor anomaly data and neither for regional mean nor for single stations) passed all three tests for significance of the weekly cycles. In fact, we found no station or variable that showed a significant peak at 1/7 days by use of spectral analysis, and for all parameters the amplitude of the 7-day cycle was of similar magnitude as constructed 6- and 8-day weeks. Finally, there was no systematic tendency for the weekly cycles to be stronger or more significant for the polluted 1983–1987 period than for the cleaner 2004–2008 period.

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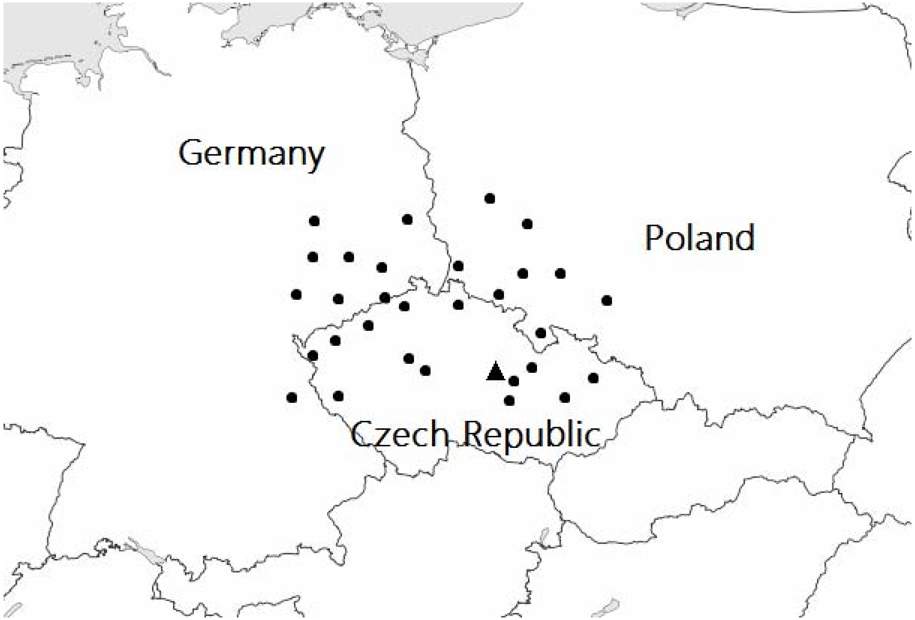

Fig. 1. The Black Triangle area. Surface stations with meteorological observations are marked as dots, and the EMEP station in Svratouch is marked as a triangle.

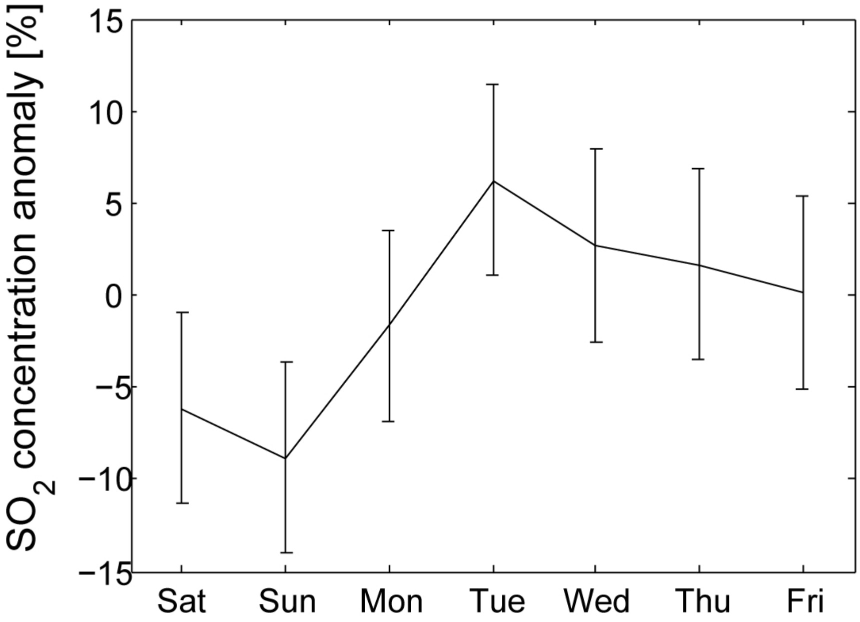

Fig. 2. Weekly cycle of SO$_2$ anomaly in Svratouch, Czech Republic, 1990–2008. Vertical bars show ±1 standard deviation.

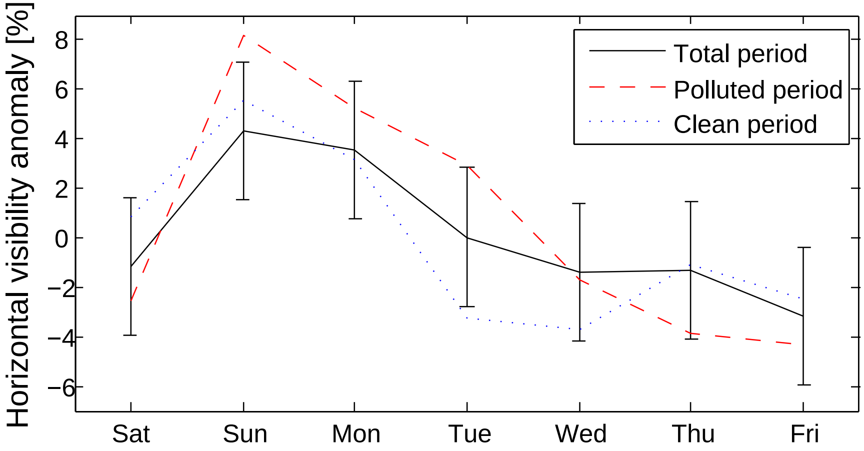

Fig. 3. Weekly cycle of horizontal visibility anomaly for the mean of the 30 stations in the Black Triangle, for the entire 1983–2008 (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line). All days with fog are removed from the data. Vertical bars show ±1 standard deviation for the total period.

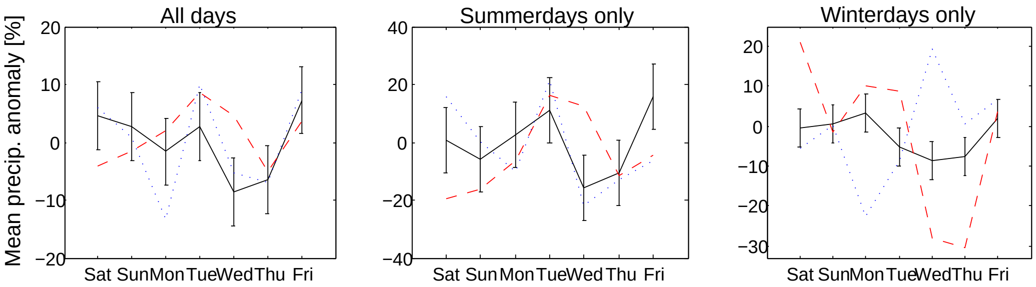

Fig. 4. Regional mean weekly cycles in precipitation amount anomaly, for the entire 1983–2008 (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line) for **(a)** all days, **(b)** summer days and **(c)** winter days. Vertical bars show ±1 standard deviation for the total period.

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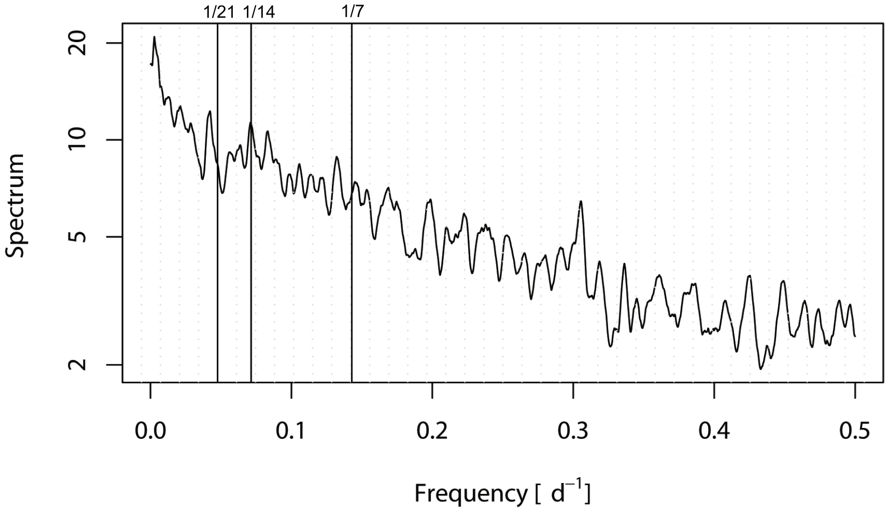

Fig. 5. Smoothed periodogram of regional mean daily precipitation anomaly from 1983–2008. Solid vertical lines show the frequency of a week (1/7 and multiples of it).

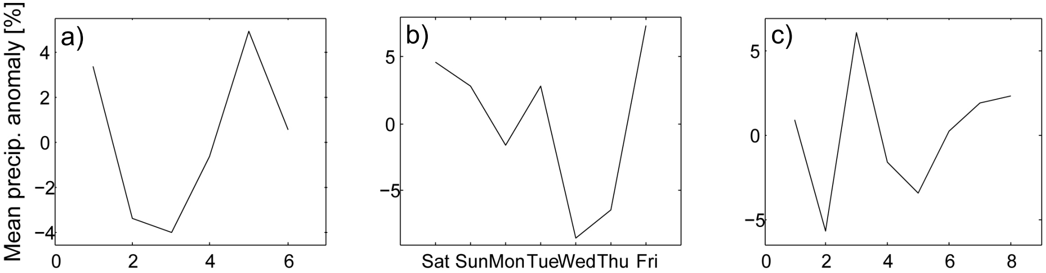

Fig. 6. Average weekly cycles of the precipitation anomaly for constructed 6-day weeks, the actual 7-day weeks, and constructed 8-day weeks.

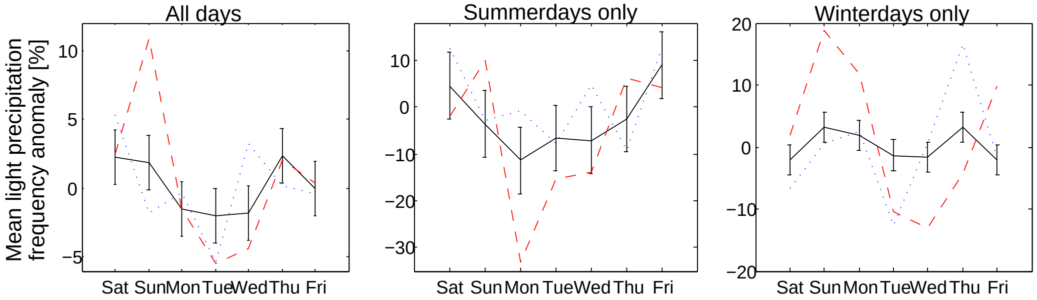

Fig. 7. Regional mean weekly cycles in the light precipitation frequency anomaly, for the entire 1983–2008 (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line) for **(a)** all days, **(b)** summer days and **(c)** winter days. Vertical bars show ±1 standard deviation for the total period.

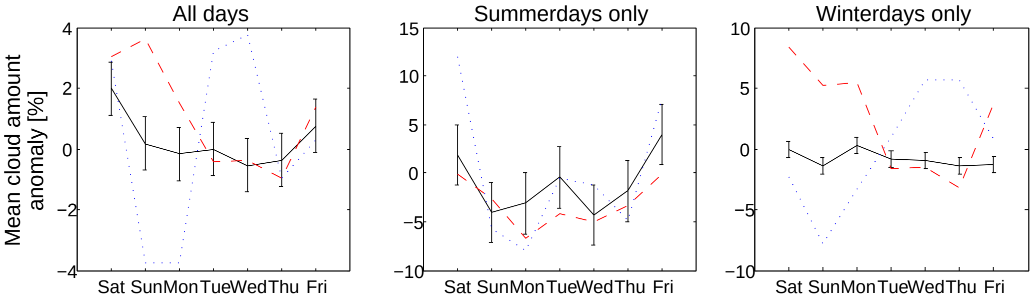

Fig. 8. Regional mean weekly cycles in cloud amount anomaly, for the entire 1983–2008 (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line) for **(a)** all days, **(b)** summer days and **(c)** winter days. Vertical bars show ±1 standard deviation for the total period.

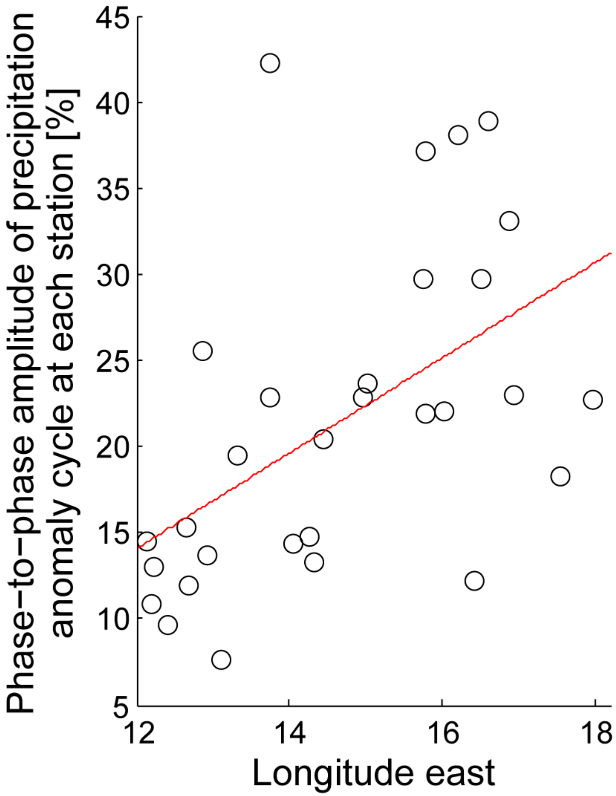

Fig. 9. Phase-to-phase amplitudes of the weekly cycles in precipitation amount at individual stations, plotted against the stations' longitude coordinate, based on precipitation amount anomalies from 1983–2008.