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Weekly cycles in precipitation and other meteorological variables 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 the focus will here be 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. A clear and statistically significant weekly cycle will be expected to pass all three tests. Precipitation amount as well as 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 amplitudes of the weekly cycles were in many cases larger for the heavily polluted 1983–1987 period than for the cleaner 2004–2008 period, but were equally often largest in the cleaner 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 (the Kruskal-Wallis test). 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 aerosol-precipitation interactions depend 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). Specifically, the findings of Rosenfeld et al. (2008) indicate that in very warm and moist air masses aerosols are expected to enhance precipitation in deep convective clouds, while Teller and Levin (2006) find the opposite effect in convective clouds with cold cloud bases. Similarly, in warm shallow clouds, increased concentration of condensation nuclei suppress precipitation (e.g. Rosenfeld, 2000), while clouds containing supercooled droplets could be expected to produce more precipitation under increased concentrations of ice nuclei due to the Bergeron-Findeisen effect (Wallace and Hobbs, 1977). Moreover, aerosols do not only affect precipitation through cloud microphysics, but could also influence clouds and precipitation through radiative effects (Rosenfeld et al., 2008). Ultimately, the aerosol-precipitation link is non-linear and contains potentially cancelling mechanisms, challenging the discovery of an aerosol signal in meteorological data.

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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 (Schultz et al., 2007), most likely due to a combination of varying statistical methods and the above mentioned non-linearity of the aerosol-precipitation effects. 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 Sanchez-Lorenzo (2008) found corresponding weekly cycles in climate variables for 13 stations in Spain, their findings was later disputed by Hendricks Franssen et al. (2009), who found no significant weekly cycles performing more rigorous statistical analyses of the same data. Similarly, Bäumer and Vogel (2007) found significant weekly cycles in temperature, cloud amount and precipitation for 12 stations in Germany, while 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 too 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, the methods of Barmet et al. (2009) will therefore be utilized, focusing on a particularly polluted region of central Europe located in the area where the borders between Germany, Poland and the Czech Republic meet in a triangle. Formerly know as the Black Triangle, this region 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. The meteorological cycles are compared to weekly cycles in pollution measured at four stations within the region, and explanations to the observed similarities and differences between pollution and meteorology are suggested. Proving any cause-effect relationships, however, is beyond the scope of this paper. Instead, the main point is 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 (MARS). 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, which gave a total of 60 stations. Due to limited data availability in the MARS archive for many stations, particularly in the first years of the time series, a choice was made to only use stations with more than 75 % of valid data over the time series. 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. Further analyses of the data were based on daily values, which were created in the following manner: precipitation is measured in 12-h intervals, so daily precipitation sums were created by summing the precipitation amounts available within a day. For the other meteorological variables, daily means were calculated by averaging the four available hourly observations for each day.

Weekly cycles in sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) measured at a selection of four stations from the European Monitoring and Evaluation Programme (EMEP) network were also analyzed for the period 1983–2008, where exact time series length varied between the four stations. The station names are Svratouch in the Czech Republic (49°44′ N, 16°2′ E, 737 m a.s.l., data for 1989–2008), Košetice in the Czech Republic (49°35′ N, 15°05′ E, 534 m a.s.l., data for 1989–2008), Sniezka in Poland (50°44′ N, 15°44′ E, 1604 m a.s.l., data for 1991–2008) and Brotjacklriegel in Germany (48°49′ N, 13°13′ E, 1016 m a.s.l., data for 1983–July 2004), and are marked as triangles in Fig. 1.

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 according to a moving window. This was done both for the time series of each single station and from the regional mean time series. The regional mean was calculated by averaging daily values for all the 30 available stations in the Black Triangle region, and later references to regional mean time series/weekly cycles in this study

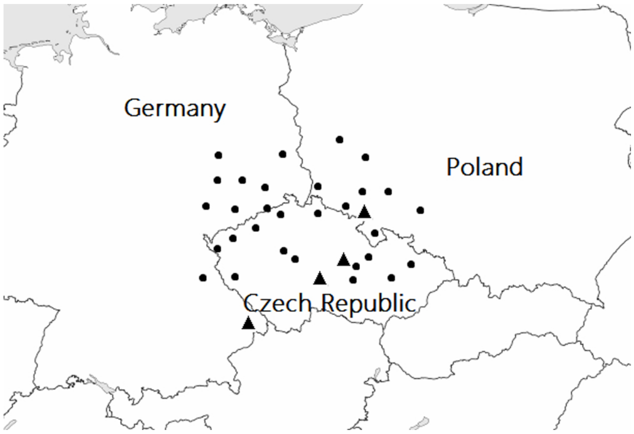

Fig. 1. The Black Triangle area. The 30 surface stations with meteorological observations are marked as dots, and the 4 EMEP stations marked as triangles.

will henceforth refer to such an averaging. The resultant "anomaly time series" were finally 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, the methods of Barmet et al. (2009) were followed:

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. If nothing else is stated, a statistically significant result will refer to a significance level of 5 % (a p-value lower than 0.05).

2. A signal of strong weekly periodicity would be visible as a peak at 1/7 days (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 weekly cycles of the 6- and 8-day weeks were additionally tested statistically using the Kruskal-Wallis test, as done for the 7-day week in point 1.

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), summer (June through August) and winter (December through February) data were also studied 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. The analyses were therefore applied to the total period 1983–2008 as well as to the more heavily polluted five-year period 1983–1987 (referred to hereafter as the polluted period) and the cleaner five-year period 2004–2008 (referred to hereafter as the cleaner period), to see if the weekly cycles in the most polluted period were stronger also in the Black Triangle.

In cases where indications of a weekly cycle in a parameter was present, an additional test of the robustness of this cycle was applied. Following Hendricks Franssen (2008), a Monte Carlo experiment was performed where the 1983–2008 time series of the variable in question was randomly rearranged and then sorted by weekday. The experiment was repeated 100 times, and the number of experiments with weekly cycle amplitudes equal to or above the amplitude of the original time series was counted. If a large percentage of the random experiments yield amplitudes equal to or above the amplitude of the original time series, this would indicate that the significance of the weekly cycle in question may be a product of chance.

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, measurements of sulphur dioxide and nitrogen dioxide at four stations in the region will first be presented. Observations of horizontal visibility, which may be seen as a proxy for aerosol concentrations, will also be shown. Weekly cycles in precipitation and other meteorological parameters are then presented and compared.

4.1 Sulphur dioxide, nitrogen 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) or ice nuclei (IN) 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. For instance, large coal-fired power plants, which dominate the Black Triangle region (Hůnová et al., 2003), may not be tuned down during

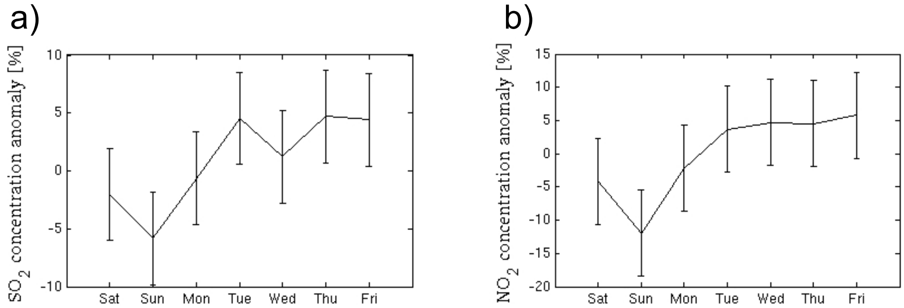

Fig. 2. Weekly cycles of **(a)** SO_2 anomaly and **(b)** NO_2 anomaly at the mean of four rural stations in the Black Triangle, 1983–2008 (exact time series varies between the stations, see Sect. 2). Vertical bars show ±1 standard deviation.

the weekends in the same way as for instance traffic in major cities. In addition to measurements of sulphur dioxide (SO_2), which by gas-to-particle conversion to sulphate aerosols is an important precursor to CCN, weekly cycles of nitrogen dioxide (NO_2) will therefore also be presented. While the major source of SO_2 are coal fired power plants, NO_2 is to a larger extent emitted trough traffic and other sources that show clearer weekly cycles. Presented results are based on daily averages of four rural EMEP stations in the Black Triangle region, accounted for in Sect. 2.

A cyclic variation in the SO_2 concentration is present over the course of a typical week – see Fig. 2a. A 7-day periodicity does not show up on a periodogram (not shown). The phase-to-phase amplitudes of the cycles of constructed 6, 7 and 8 days weeks are similar, but the Kruskal-Wallis test reveals a significant (p-value of 0.02) difference in the median of the 7 days, while the Kruskal-Wallis test performed on the 6- and 8-day weeks gives non-significant results (p-values of 0.99 and 0.96, respectively). The figure shows that the concentration is highest on Tuesdays and lowest on Sundays, the difference between these two days being 10 % of the daily mean of $3.5\,\mu g\,m^{-3}$. NO_2 shows a more smooth weekly cycle, with lowest values on Sundays, a continuous build-up through the week, and highest values on Fridays – see Fig. 2b. The amplitude is 19 % of the mean of $2.1\,\mu g\,m^{-3}$, and the Kruskal-Wallis test shows that the difference in the median of the weekdays is highly significant for the 7-day week (p-value $\ll 0.01$), and non-significant for the 6- and 8-day weeks (p-values of 0.98 and 0.97, respectively). The amplitude of the 7-day week is about nine times higher than the amplitudes of the 6- and 8-day weeks (Fig. 3), and a clear peak at 1/7 days is present in the periodogram (Fig. 4). Furthermore, none of the random Monte Carlo experiments showed amplitudes equal to or above that of the original time series.

Based on four urban stations in Switzerland for the period 1998–2006, Barmet et al. (2009) found weekly periodicities in PM_{10} which passed all three tests for robustness, with peak concentrations on Wednesdays and a difference in concentrations of 24 % between the most and the least polluted day. The inability to obtain similar results with SO_2 measurements for the 1983–2008 period in the Black Triangle is most likely due to the fact that the major source of SO_2 is power plants, which may have less distinct weekly emission cycles. Recall also that the presented SO_2 and NO_2 cycles are based on measurements at rural sites.

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. 5). 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 is not present in the visibility plot. 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). For the total period (black solid line), 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 three periods are highly significant by the Kruskal-Wallis test (p-value $\ll 0.001$).

More extensive studies including more stations and more chemical species 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.

4.2 Precipitation amount

For precipitation in the Black Triangle for the 1983–2008 period, the shape of the weekly cycle is much less smooth than what was found for instance for 17 stations in Switzerland for the period 1992–2006 (Barmet et al., 2009): the solid

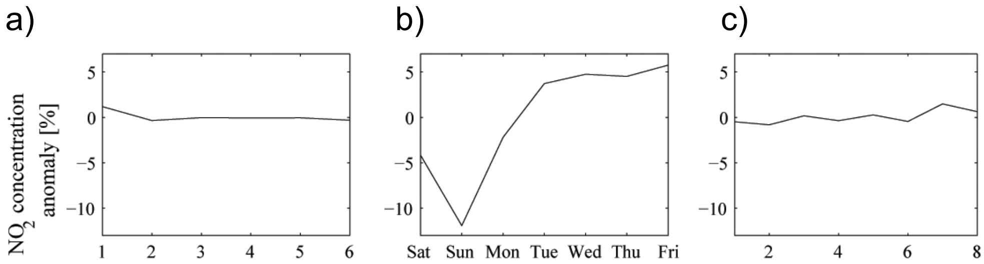

Fig. 3. Weekly cycles of NO_2 concentration (average of 4 EMEP stations in the Black Triangle) anomaly for 1983–2008, for **(a)** constructed 6-day weeks, **(b)** the actual 7-day weeks, and **(c)** constructed 8-day weeks.

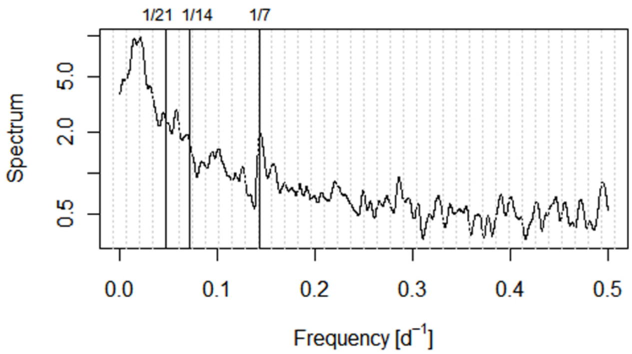

Fig. 4. Smoothed periodogram of NO_2 concentration (average of 4 EMEP stations in the Black Triangle) anomaly from 1983–2008. Solid vertical lines show the frequency of a week (1/7 days and multiples of it).

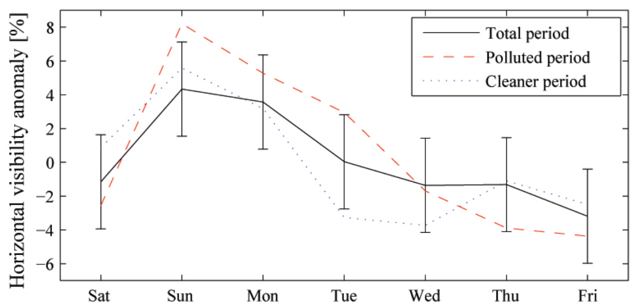

Fig. 5. Weekly cycles of regional mean (average of the 30 stations in the Black Triangle) horizontal visibility anomaly, for the entire 1983–2008 period (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line). All days with fog are removed from the data. Vertical bars show ±1 standard deviation.

black line in Fig. 6a 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. 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 (that is, the p-value was higher than 0.05). Also, spectral analysis shows no visible peak at 1/7 days (see Fig. 7). The same is found when analyzing each station individually. 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, which may be coincidental as it is only slightly higher than the 1.5 stations expected to show falsely significant cycles by chance when using a 5 % significance level. None of the individual stations, for neither anomaly nor raw values, show visible peaks in periodograms at 1/7 days. 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. 8).

As previous studies have reported stronger weekly cycles in periods of higher pollution loads (e.g. Gong et al., 2006; Bell et al., 2008), the weekly cycles in precipitation for the polluted period 1983–1987 have been compared to the weekly cycles of the cleaner 2004–2008 period. Figure 6a (red dashed line) shows that the mid-week precipitation maximum is higher for the polluted period than for the total period (solid black line), but the cleaner period (blue dotted line) displays an equally strong maximum here. Again, the weekly cycles for neither the polluted nor the cleaner period displayed visible peaks at 1/7 days in periodograms, showed clear differences in the amplitudes between a 6-, 7- or 8-day weeks, or provided statistically significant differences in the median precipitation anomaly between the weekdays by the Kruskal-Wallis test.

The Tuesday and weekend maxima are also visible in the summer data for all three periods (Fig. 6b). If driven by aerosol influence on convective clouds, enhance mid-week precipitation would imply convective precipitation enhancement as found for instance by Bell et al. (2008). However, such an effect would require very warm and moist air masses (Rosenfeld et al., 2008), which is not the most common conditions in the Black Triangle, even in the summertime. For

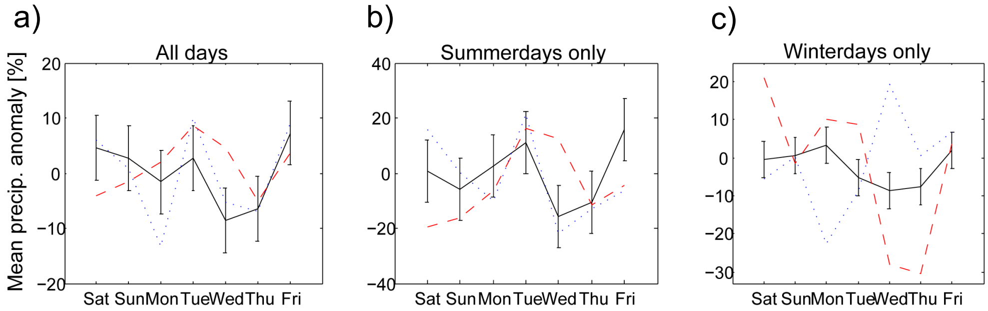

Fig. 6. Weekly cycles of regional mean (average of the 30 stations in the Black Triangle) precipitation amount anomaly, for the entire 1983–2008 period (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line) for **(a)** all days, **(b)** summer days and **(c)** winter days. Vertical bars show ±1 standard deviation for the total period.

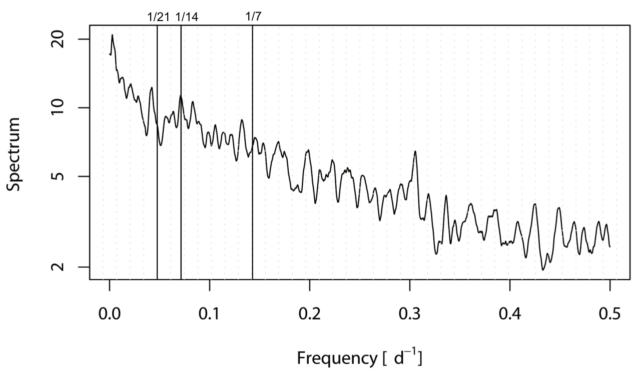

Fig. 7. Smoothed periodogram of regional mean (average of the 30 stations in the Black Triangle) daily precipitation anomaly from 1983–2008. Solid vertical lines show the frequency of a week (1/7 and multiples of it).

instance, dew point temperatures exceeding 20 °C rarely occur at any of the 30 stations. Alternatively, Gong et al. (2007) found similar patterns in summertime weekly cycles in precipitation in China, and hypothesized that diabatic heating of the emitted particular matter could result in mid-week convective motions and thus mid-week increases in convective precipitation. These convective motions would in turn 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 (and weaker in amplitude) cycle with enhanced precipitation only in the weekends (Fig. 6c, black solid line). Precipitation from cold shallow clouds would most likely produce an opposite signal (enhanced mid-week precipitation in the potential presence of more IN), but an explanation could be sought in convective-type precipitation, which might be suppressed by increased aerosol concentrations from convective clouds with cold cloud bases. Again, however, neither summertime nor wintertime data showed clear weekly cycles by any of the three tests for neither the total, the polluted nor the cleaner period.

In general, there seems to be some agreement between weekly variations in pollution and precipitation for the investigated region. However, in spite of the high pollution loads in the Black Triangle, the weekly precipitation cycles were not found to be statistically significant, similar to the findings of Barmet et al. (2009) for a selection of stations in the less polluted Switzerland. Whether this is because the aerosols are not exerting a large enough impact on the local meteorology for such a significant cycle to occur, or because the signal is hidden in the counteractive effects of the aerosol-precipitation relationship, is difficult to say.

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., 2009; 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., 2011). It is reasonable to assume that these light precipitation events originate from rather shallow clouds, and not from deep convective clouds which would tend to produce more intense precipitation. For warm clouds, one would therefore expect a decrease in light precipitation on weekdays with more pollution, in line with the theories of Albrecht (1989). For clouds containing supercooled droplets, one might expect an increase in light precipitation on weekdays with more pollution (Wallace and Hobbs, 1977).

Here, we see a mid-week suppression in the light precipitation frequency for all three periods (Fig. 9a), consistent with aerosol suppression of precipitation during the most polluted weekdays. This effect is most pronounced for the

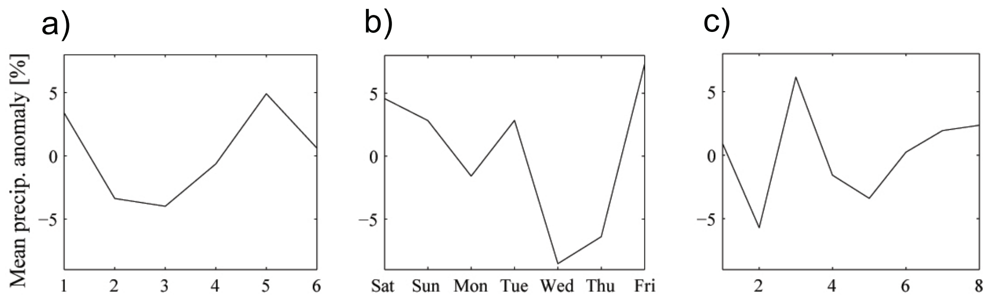

Fig. 8. Weekly cycles of regional mean (average of the 30 stations in the Black Triangle) precipitation anomaly for 1983–2008, for **(a)** constructed 6-day weeks, **(c)** the actual 7-day weeks, and **(c)** constructed 8-day weeks.

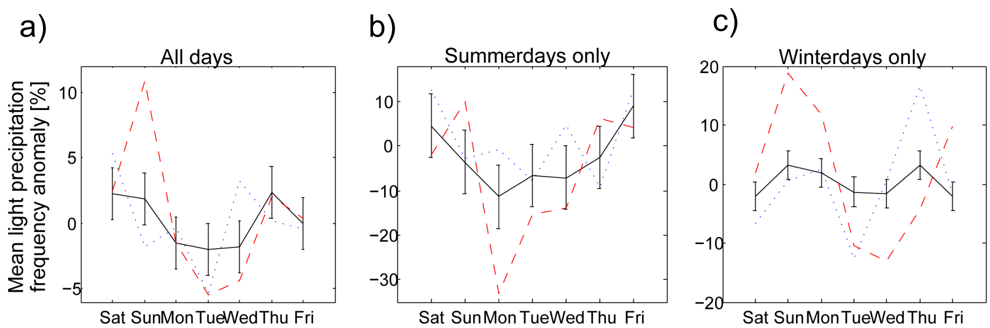

Fig. 9. Weekly cycle of regional mean (average of the 30 stations in the Black Triangle) light precipitation frequency anomaly, for the entire 1983–2008 period (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line) for **(a)** all days, **(b)** summer days and **(c)** winter days. Vertical bars show ±1 standard deviation for the total period.

polluted period (red dashed line), but the weekly cycles do not pass any of the three tests applied for neither the total, the polluted nor the cleaner period.

For summers, the weekday-weekend difference for the total period is significant by the Kruskal-Wallis test, with a p-value of 0.03 and a phase-to-phase amplitude corresponding to 20 % of the mean (Fig. 9b, black solid line). The phase-to-phase amplitude of the summer cycle is larger (39 %) for the polluted period (red dashed line) than for the total period, and smaller and more variable for the cleaner period (blue dotted line). The summertime light precipitation cycles (all periods) have no mid-week depression but increase throughout the week and reach a maximum on Sundays. The shape of the weekly cycle thus bears similarities to the cycles of NO_2/horizontal visibility, which increase/decrease over the course of the week (Fig. 2b/Fig. 5). Gradual increases in the concentration of ice nuclei (to which soot may be a source) over the week could conceivably produce this increase in summertime light precipitation, provided that the clouds consist of regions with supercooled droplets even at this time of year. This would have to be confirmed by concrete measurements of ice nuclei as well as cloud base temperatures. In any case, the summer cycle in light precipitation is only significant by the Kruskal-Wallis test and shows no distinct cycles by the two other tests: the Kruskal-Wallis test does not give significant results for the 6- and 8-day weeks, but the amplitudes of the 6- and 8-day weeks are similar to the 7-day week, and no peak is visible in a periodogram. Furthermore, 10 out of 100 random Monte Carlo simulations show amplitudes similar to or above the observed 20 %, signifying the possibility of the 7-day weekly cycle being significant by chance.

The winter cycle in light precipitation (see Fig. 9c) is not significant by the Kruskal-Wallis test for any of the three periods considered. None of these weekly cycles produce visible peaks in the periodograms, and the amplitudes for 6-, 7- and 8-day weeks are similar.

4.4 Other meteorological parameters

The weekly cycle in cloud amount (Fig. 10) is statistically significant for summers by the Kruskal-Wallis test, with an amplitude of 8 %. However, the amplitudes of the 6- and 8-day weeks are similar to the 7-day week (7 % and 9 %, respectively), there is no visible peak at 1/7 days in the periodogram, and 22 of the 100 Monte Carlo runs have amplitudes equal to or above the observed amplitude. Like for light precipitation events, there is an increase in summertime cloud amounts (with a secondary maximum on Tuesdays) over the course of the week. A similar but non-significant cycle in wind speed is also observed for summers (not shown).

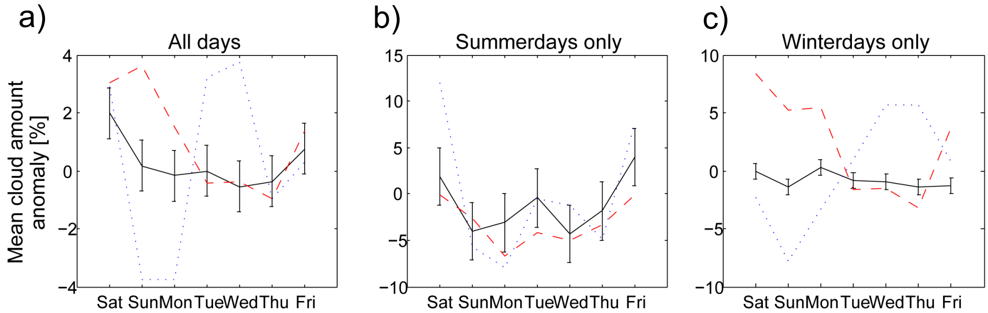

Fig. 10. Weekly cycles of regional mean (average of the 30 stations in the Black Triangle) cloud amount anomaly, for the entire 1983–2008 period (solid black line), the more polluted 1983–1987 period (red dashed line) and the cleaner 2004–2008 period (blue dotted line) for **(a)** all days, **(b)** summer days and **(c)** winter days. Vertical bars show ±1 standard deviation for the total period.

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, the frequency of heavy precipitation events and the occurrence of rain showers were also analyzed. Phase-to-phase amplitudes for these parameters are 45 % and 16 %, respectively, and both display similar Tuesday peaks. None are however found to have distinct weekly cycles by any of the three test.

For the polluted period the winter cycle in cloud amount has an amplitude of 7 % and is like wintertime light precipitation events for the same period marked by a mid-week depression and a weekend enhancement. The cycle of the 7-day week is significant by the Kruskal-Wallis test, but the amplitudes of the 6- and 8-day weeks are in fact larger than that of the 7-day week and more than 70 of the 100 random Monte Carlo runs had amplitudes above 7 %.

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

As eastern European countries experienced a later and more slow reduction in pollution emission levels (Vestreng et al., 2007), it is interesting to check whether this is reflected in the weekly cycles. There is a tendency for the phase-to-phase amplitude in precipitation amount to be larger the further east within the Black Triangle 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, the p-values of the Kruskal-Wallis test are statistically insignificant for all the stations and the magnitude of the p-value do not show a corresponding systematic geographic variation.. Instead, the correlation between amplitude and longitude may be a result of spatial autocorrelation among the stations as well as an increasingly continental climate towards the east.

5 Summary and conclusion

An average of four stations in the Black Triangle region shows highest levels of SO_2 on Tuesdays and lowest during weekends. NO_2 from the same stations and horizontal visibility in the region as a whole show a gradual increase/deterioration through the week and lower values/improvements during the weekends, respectively.

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 robust weekly 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 for the total 1983–2008 period, 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.

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 robustness of the weekly cycles. In fact, no station or meteorological variable showed a clear 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. 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.

The lack of clear weekly cycles 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. Also, as accounted for in the introduction, convective precipitation would be enhanced or suppressed in cases of warm moist air or cold cloud bases, respectively, and a mix of those counteracting effects could hide a potential signal. Similarly, precipitation from shallow clouds might be enhanced by aerosols in case of cold clouds but suppressed in case of warm clouds. A study including measurements of cloud temperatures and, preferably, CCN and IN concentrations, would help diagnose the absence of weekly cycles in precipitation in this polluted region.

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