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A method to assess the inter-annual weather-dependent variability in air pollution concentration and deposition based on weather typing

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HIGHLIGHTS

- Yearly anomalies in air pollution were explained by variation in Lamb Weather Types.
- A novel method to assess annual anomalies in air pollution is suggested.
- Adjusting for anomalies improved significance of temporal trends in air pollution.
- Most pollutants showed no trend or a negative trend but urban ozone had a positive trend.

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ABSTRACT

Annual anomalies in air pollutant concentrations, and deposition (bulk and throughfall) of sulphate, nitrate and ammonium, in the Gothenburg region, south-west Sweden, were correlated with optimized linear combinations of the yearly frequency of Lamb Weather Types (LWTs) to determine the extent to which the year-to-year variation in pollution exposure can be partly explained by weather related variability. Air concentrations of urban NO_2, CO, PM_{10}, as well as O_3 at both an urban and a rural monitoring site, and the deposition of sulphate, nitrate and ammonium for the period 1997–2010 were included in the analysis. Linear detrending of the time series was performed to estimate trend-independent anomalies. These estimated anomalies were subtracted from observed annual values. Then the statistical significance of temporal trends with and without LWT adjustment was tested. For the pollutants studied, the annual anomaly was well correlated with the annual LWT combination (R^2 in the range 0.52–0.90). Some negative (annual average [NO_2], ammonia bulk deposition) or positive (average urban [O_3]) temporal trends became statistically significant ($p < 0.05$) when the LWT adjustment was applied. In all the cases but one (NH_4 throughfall, for which no temporal trend existed) the significance of temporal trends became stronger with LWT adjustment. For nitrate and ammonium, the LWT based adjustment explained a larger fraction of the inter-annual variation for bulk deposition than for throughfall. This is probably linked to the longer time scale of canopy related dry deposition processes influencing throughfall being explained to a lesser extent by LWTs than the meteorological factors controlling bulk deposition. The proposed novel methodology can be used by authorities responsible for air pollution management, and by researchers studying temporal trends in pollution, to evaluate e.g. the relative importance of changes in emissions and weather variability in annual air pollution exposure.

1. Introduction

Air pollution exposure is in many cases highly temporally variable. Emission rates, (photo)chemical activity and dispersion depend on meteorological conditions (Arain et al., 2007; Jones et al., 2010; Pleijel et al., 2004). Hence, the meteorological conditions strongly affect the short-term variability in the concentration of key air pollutants such as nitrogen oxides ($NO_x = NO_2 + NO$), particulate matter (PM), carbon monoxide (CO) and ozone (O_3) as

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well as the deposition of sulphate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+) and base cations.

Even on an annual time scale, there is a considerable variation in air pollution levels. This may pose a problem for managers and policy makers responsible for air pollution monitoring and control regarding e.g. assessments of the results of emission reductions. When the air quality standards (AQS) are met in one year, it may be concluded that the situation is fine and further action to abate emissions are not required. The following year, there is once again exceedance of AQS, which may lead to the conclusion that this is caused by increasing emissions. However, in addition to possibly existing upward or downward time series trends related to emissions, a large part of the inter-annual variability in air pollution concentrations may be the result of the variation in the pattern of weather conditions characterizing a particular year. Thus the yearly anomaly in air pollution concentration would to a certain extent be a function of a considerable year-to-year variation in those conditions (e.g. dispersion, photochemistry and precipitation) promoting high or low air pollution concentrations or deposition. The annual time unit, which is most commonly used when evaluating AQSs, is therefore too short to evaluate effects of abatement measures and trends in pollutants, since large year-to-year variation occur depending on the weather profiles. However, adjustments for the influence of inter-annual variation in weather, if this influence can be quantified, may enhance the detection of temporal trends in air pollution concentration and deposition caused by long term changes in emissions.

Similar to air pollution concentrations, deposition of compounds such as SO_4^{2-}, NO_3^- and NH_4^+, presents substantial inter-annual variation, possibly superimposed on temporal trends caused by emission changes. The deposition of these compounds is mostly monitored on a monthly basis. Acidification of forest soils and surface waters remain a serious problem in south-west Sweden (Akselsson et al., 2013; Sverdrup et al., 2005). Furthermore, there is a substantial risk of N leaching from forest soils (Akselsson et al., 2010). Hence, it is important to assess the changes of both sulphur and nitrogen deposition over time. The deposition of sulphur and nitrogen to Norway spruce forests at northern latitudes is dominated by wet deposition. In southwest Sweden, the share of dry deposition constitute approximately 30% of the total deposition of inorganic nitrogen (Karlsson et al., 2011), while in northern Sweden this share is close to zero. Approximately the same applies to sulphur deposition.

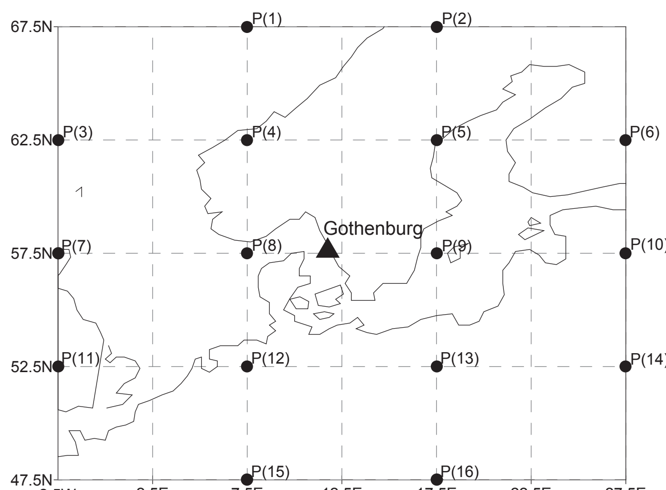

Fig. 1. Map showing the atmospheric pressure grid points used to calculate the Lamb Weather Types.

Grundström et al. (2015) showed that the urban concentrations of NO_2 are strongly influenced by the prevailing weather types for Gothenburg, south-west Sweden, during the winter. Similarly, Tang et al. (2009) showed that ozone concentrations in south Sweden are linked to weather types. Both these studies used Lamb Weather Types (LWTs), which represent an efficient tool for characterising local meteorological conditions based on synoptic scale sea level pressure (Chen, 2000). The distribution of the sea level pressure provides information about the synoptic air mass movement and vorticity, which has been proven to be a useful summary of the local meteorological conditions (Chen, 2000; Demuzere and van Lipzig, 2010; Grundström et al., 2015), based on a set of objective rules (Jenkinson and Collison, 1977). LWTs provide an effective way to classify the prevailing local weather from the regional directional flow of air masses. Similarly, Buchholz et al. (2010) used an air pollution index together with so called Grosswetterlagen (GWL), weather types for Central Europe, to identify situations with high air pollution levels. LWT and GWL schemes both started as subjective schemes for weather typing (Lamb, 1950), but have been developed into objective schemes that can be automated (James, 2007). The GWL scheme represents the weather pattern on a continental scale prevailing for several consecutive days i.e. differing from the LWTs which are normally defined with a higher resolution (regional and daily to sub-daily). More recently, Pope et al. (2014) and Russo et al. (2014) used similar weather classification schemes to successfully identify situations with large/small potential for high air pollution concentrations. Finally, Zhang et al. (2016) successfully used synoptic weather patterns to assess the effect of the East Asian Monsoon on the air quality over the North China Plains.

In this study, we suggest a novel method to quantitatively estimate the influence of the weather conditions represented, by Lamb Weather Types, on the annual anomalies of urban air concentrations of NO_2, PM_{10}, CO, urban and rural air concentrations of O_3, as well as the deposition of SO_4^{2-}, NO_3^- and NH_4^+ as throughfall (precipitation that passed through the forest canopy, TF) and bulk (deposition with the precipitation over open field, BD) deposition at a rural site in the Gothenburg region. The aim of our study was to provide an objective tool to assess the weather influence on annual anomalies in air pollution levels and to improve the possibility to detect temporal trends due to emission changes. Our hypotheses were that: 1. A large fraction of the inter-annual variability in air pollution concentrations can be explained by the frequency distribution of LWTs, 2. The trends for the air pollutants caused by emission changes is easier to be detected, when the LWT related annual anomalies are removed.

2. Methods

2.1. Data

Data were obtained from three monitoring sites. From the rooftop monitoring station Femman in central Gothenburg (30 m above street level, 57°42′N, 11°58′E) data regarding air concentrations of NO_2 (Tecan CLD 700 AL chemiluminescence), CO (Unor 610), O_3 (Monitor Labs 9810) and PM_{10} (Tapered Element Oscillating Microbalance, Series 1400b) were obtained. The Femman house is one of the tallest buildings in the City of Gothenburg and surrounding buildings are not likely to influence the flow of air pollutants. To compare the urban O_3 data with a nearby rural site, data from the Råö monitoring station (Thermo Environmental Model 49 UV monitor) of the EMEP (European Monitoring and Evaluation Programme) network (www.emep.int) 40 km S of Gothenburg (57°23′N, 11°54′E) was used. From the Hensbacka rural site 90 km N of Gothenburg (58°26′N, 11°44′E) data on BD and TF