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Influence of atmospheric circulation patterns on urban air quality during the winter

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ABSTRACT

Relationships between urban nitrogen dioxide (NO_2) and atmospheric circulation at two spatial scales were studied for Southern Sweden. Lamb Weather Types (LWT) describe the circulation (scale: thousands of kilometers) including non–directional (cyclonic and anticyclonic) and directional types depending on the wind direction. LWTs with low wind speeds (anticyclonic, NW and N) were associated with strongly elevated [NO_2], between 46–52% of the daily averages of NO_2 exceeded the 60 $\mu g\ m^{-3}$ air quality standard (AQS) when occurring during these LWTs. The lowest fractions of exceedances of NO_2 AQS were generally observed for LWTs E, S, SW and W. A larger scale circulation (several thousands of kilometers) was represented by the North Atlantic Oscillation (NAO) affecting meteorology over middle and high latitudes in the Northern Hemisphere. While a negative NAO index (NAOI) favors stagnant high pressure weather over Northern Europe, a positive NAOI is often associated with windy conditions. High [NO_2] was found to be frequent under negative NAOI. Additionally, larger fractions of exceedances of NO_2 AQS were observed for the majority of LWTs occurring at negative NAOI. It's concluded that both LWTs and NAOI had partly independent effects on the urban air quality in a North European city. These circulation indices can be useful tools for air pollution risk assessment and forecasting.

Keywords: *North Atlantic Oscillation, Lamb weather types, NO_2, urban air pollution, Gothenburg*

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1. Introduction

Many epidemiological studies show that nitrogen dioxide (NO_2) is an important air pollutant associated with human health effects such as cardiovascular and respiratory diseases (Samoli et al. 2006), either as a direct cause or as a proxy for other pollutants, e.g. ultrafine particles believed to cause severe health damage (Seaton and Dennekamp, 2003). In order to protect human health, air quality standards (AQS) for high priority air pollutants, such as NO_2, have been implemented by the European Union and many nations worldwide, obliging these nations to assure adequate air quality to their citizens.

In urban environments the dominant source for NO_2 is local traffic through the high temperature combustion in vehicle engines (Finlayson–Pitts and Pitts, 2000). Since the exhausts contain a mix of nitrogen oxides, traffic related emissions are normally given as NO_X=NO+NO_2, where the primary NO_2 proportion in Europe is currently rising due to the increased number of diesel fuelled vehicles and as an effect of certain particle filters (Pleijel et al., 2009; Beevers et al., 2012).

Meteorological conditions such as wind speed, temperature and humidity play important roles in affecting concentrations of NO_2 via removal, transformation, and transport processes (Arya, 1999). Wind drives the atmospheric transport and strongly affects vertical air mixing and thus the ventilation of the urban air. The understanding of how wind speed affects ground–level air pollution concentrations is relatively well established. Low wind speeds deteriorate air quality with respect to pollutants emitted near the ground due to restricted air ventilation (Jones et al., 2010). Stagnant atmospheric conditions with calm, clear weather often lead to stable atmospheric stratification which can transform into strong nocturnal temperature inversions due to rapid surface cooling. The resulting restriction in vertical air mixing near the surface consequently leads to poor air quality (Delaney and Dowding, 1998; Janhall et al., 2006; Olofson et al., 2009). Many of these factors vary on a range of spatial and temporal scales, which makes quantification of the meteorological influence on air pollution difficult. Fortunately, methods such as weather typing developed in synoptic climatology (e.g. Chen, 2000) provide an effective means to summarize typical sets of meteorological conditions and can thus be expected to be a useful tool for air pollution studies. Synoptic situations at regional scales (~1 000 km), such as the Lamb Weather Types (LWT), expresses the regional atmospheric vorticity (rotational movement of the air mass) and geostrophic wind flow conditions over a geographic site. 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. They have been shown to be skilful in characterizing local meteorological conditions relevant to air quality. Tang et al. (2009) showed that the occurrence of episodes of ozone in Southern Sweden is strongly correlated to the anticyclonic LWT. Similarly, Buchholz et al. (2010)

used an air pollution index together with "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; James, 2007), but have been developed into objective schemes that can be automated. More recently, Pope et al. (2014) and Russo et al. (2014) used weather classification schemes to identify situations with large/small potential for high air pollution concentrations, including NO_2.

On a larger scale, there is an important atmospheric mode of variability known as the North Atlantic Oscillation (NAO), which is active at middle and high latitudes in the Northern Hemisphere (Hurrell et al., 2003; Hurrell and Deser, 2010). The NAO index (NAOI) is widely used to characterize large scale atmospheric circulation (e.g. Chen and Hellstrom, 1999). NAO is constituted by two atmospheric action centers located over the North Atlantic, with more or less permanent geographical positions, called the Icelandic Low and the Azores High. The flow and distribution of air masses over Europe is strongly influenced by the atmospheric pressure dynamics between these nodes, especially during the boreal winter. When the atmospheric pressure difference is small between the nodes, NAO is in its negative mode (NAOI<0), resulting in cold and stable air masses over Northern Europe, normally originating from Arctic or Siberian regions. This frequently results in stable atmospheric conditions near the ground and as a result deteriorating air quality which has been shown for Gothenburg (Grundstrom et al., 2011). Low pressure systems with high wind speeds produced over the North Atlantic are common in northern Europe when NAOI is positive, e.g. when large atmospheric pressure differences between the two nodes prevail. These conditions typically provide better air quality due to improved ventilation. Any weather typing or atmospheric circulation index describes synoptic situations with an implicit spatial scale. While LWTs describe the weather on a local–regional scale, NAO determines weather patterns on a larger scale.

The aim of this investigation was to study how LWTs and NAOI can be used to assess urban air quality with respect to NO_2. For this purpose, the exceedances of AQS for the NO_2 concentration, $[NO_2]$, in Gothenburg were used. One hypothesis was that LWTs associated with calm weather conditions (low wind speeds) would cause more frequent exceedances of AQS than other LWTs. Further, the negative phase of the NAO was hypothesized to enhance the number of exceedances of AQS for a certain LWT. Finally, it was tested to what extent LWTs and NAOI, representing different scales, have independent effects on local air quality.

2. Materials and Method

2.1. Measurement sites and instrumentation

Monitoring of air quality and meteorology was performed on a rooftop 30 m above ground level in the commercial district of Gothenburg city center ("Femman"; 57°42.5384´N, 11°58.2252´E). The site is located adjacent to the central terminal for bus and trains and approximately 300 m away from a busy traffic route (E45). Hourly measurements of NO and NO_2 (Tecan CLD 700 AL chemiluminescence), atmospheric pressure (Vaisala PA11A), air temperature (Campbell Rotronic MP101 thermometer/hygrometer), wind speed and direction (Gill ultrasonic anemometer) were carried out. Additional hourly measurements of NO and NO_2 (Differential Optical Absorption Spectroscopy) were performed parallel to a road at ground level in the eastern central part of Gothenburg. That site is located at a busy traffic route (E6/E20) surrounded by low residential buildings, ~5 to 15 m tall ("Garda"; 57°42.0548´N, 11°59.7019´E). Data for the winter months (January, February, December) of the period 2001–2010 were used for NO and NO_2 (data coverage was 87% at the kerbside station) for all figures and tables except Table 2 where both winter and yearly data are presented. Sixty six percent of the data loss was the full months of January and February of 2002 and February of 2005, the rest was randomly distributed. The observations from the rooftop analysis during times with data loss at the kerbside have been omitted to allow for proper comparison between the two stations. Meteorological data series were essentially complete apart from relative humidity (47%). Due to the data loss, this variable was not included in the analysis.

2.2. LWT weather types

Daily mean sea level pressures (MSLP) for a 16 point–grid centered over the Gothenburg city center (57°7´N, 11°97´E) were obtained from the NCEP/NCAR Reanalysis database 2.5×2.5 degree pressure fields (Kalnay et al., 1996). Circulation indices, *u* (westerly or zonal wind), *v* (southerly or meridional wind), *V* (combined wind strength), ξ_u (meridional gradient of *u*), ξ_v (zonal gradient of *v*) and ξ (total shear vorticity) describing the geostrophic winds and Lamb weather types (Jenkinson and Collison, 1977) were calculated following Chen (2000). This classification scheme has 26 weather types: anticyclone (A), cyclone (C), eight directional types (NE, E, SE, etc.), 16 hybrid types (ANE, AE, ASE, CNE, CE, CSE, etc.). In this study, the 27 weather types were consolidated into 10 LWTs according to the directions of the geostrophic wind, directional: NE, E, SE, S, SW, W, NW, and N, rotational: A and C. Three of the six circulation indices used for determining LWTs were used to investigate the relationship between LWTs and the NAO index, NAOI: *u*, *v* and *V*, all with unit decapascals per latitude at 57°7´N.

2.3. NAOI

The NAOI data used in this study was obtained from the Climate Research Unit, University of East Anglia; (http://www.cru.uea.ac.uk/cru/data/nao/). The NAOI was calculated on a monthly basis from the difference in the normalized sea level pressure (normalization period 1951–1980) between Gibraltar and Southwest Iceland (Jones et al., 1997). Monthly NAOI varied between –4.85 and 5.26.

2.4. Calculations and evaluations of air quality standards

The majority of the analysis was restricted to the three winter months January, February and December with one exception, which included all months (see the end of the next paragraph). The monthly averages of the LWT indices were correlated to the monthly NAOI in the period 1948–2010. The remaining analyses were made for 2001–2010. Linear regression using the Pearson product moment correlation coefficient was used to assess statistical significance of the correlation of *u*, *v* and *V* with NAOI.

Around the world $[NO_2]$ is usually used as a quantity in AQS but with different limits applied in respective national legislations. In this paper we use the current legislation in Sweden consisting of limits based on hourly, daily or annual averages. Hourly and daily $[NO_2]$ were used to calculate the fraction of exceedances of AQS occurring during negative or positive NAOI for each LWT. The AQS were the daily average on 60 $\mu g\,m^{-3}$ and the hourly average on 90 $\mu g\,m^{-3}$. These AQSs signify 98–percentiles, allowing a maximum of 2% of the observations to exceed the limit values on an annual basis. Analysis was also conducted for the full calendar years to evaluate exceedances of AQS on an annual basis. In this analysis the AQS for NO_2 regulated by EU legislation were included. These standards are the yearly average on 40 $\mu g\,m^{-3}$ (no exceedance permitted) and the hourly standard 200 $\mu g\,m^{-3}$, allowed to be exceeded no more than 0.2% of the time.

The chi–square test was used to determine statistical significance of differences between frequencies of meteorological (wind speed and temperature) and NO_2 variables occurring during negative and positive NAOI for different LWTs.

3. Results

3.1. Relationship between LWT–indices and NAOI

Both the west–easterly wind component index (*u*) and the wind strength index (*V*) on which the LWTs are based had a similar significant positive correlations with the NAOI ($p<0.0001$) (Figure 1). The south–north wind component (*v*) correlated very weakly ($p=0.041$) with the NAOI (not shown), suggesting that NAOI is an indicator for the westerly wind flow over the area. However, more than 50% of the variation in both *u* and *V* were not explained by variation in NAOI.

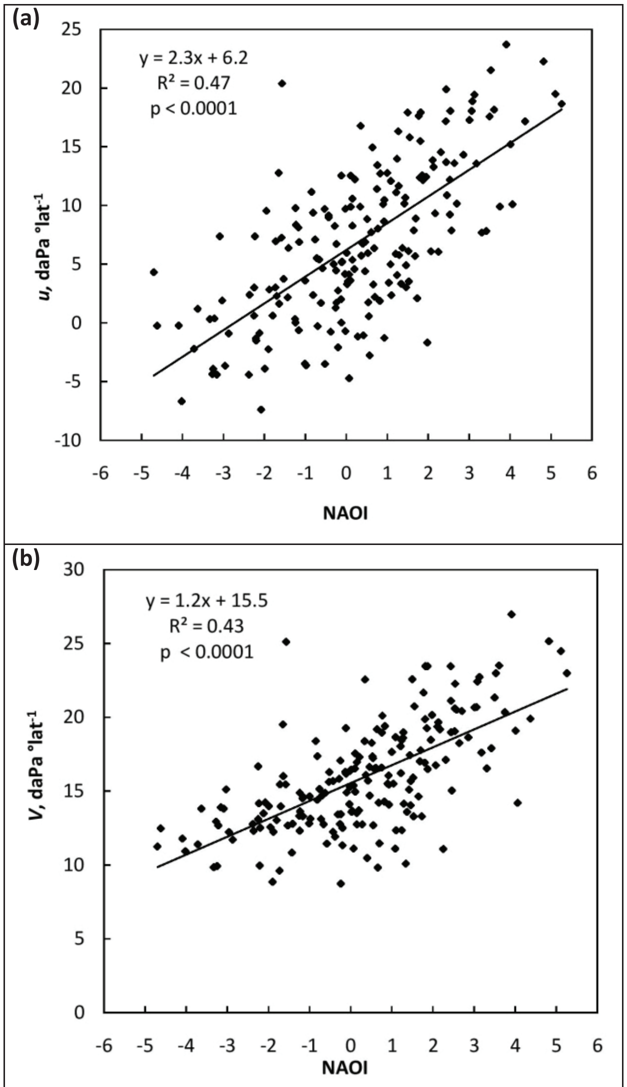

Figure 1. *Scatter plots with linear relationships between two monthly LWT indices of **(a)** west–easterly wind component (u) and **(b)** wind strength (V) and monthly normalized NAOI for January, February and December 1948–2010.*

3.2. Occurrence and meteorology of LWTs conditional on the NAOI

Figure 2 presents the abundance of different LWTs in positive and negative NAOI. LWTs with an easterly wind component (NE, E, and SE) were relatively uncommon, but significantly more frequent in negative NAOI conditions compared to positive NAOI. LWTs with a westerly wind component (SW, W, NW) were overall very common and much more frequent during positive NAOI (fraction ~50%), differing significantly from negative NAOI (fraction ~26%). LWTs A and C were both very common. While the fraction of LWT A did not differ significantly between negative and positive NAOI, LWT C was significantly more common during negative NAOI. The fraction of the LWTs, independently from NAOI conditions, can be found in Table 1.

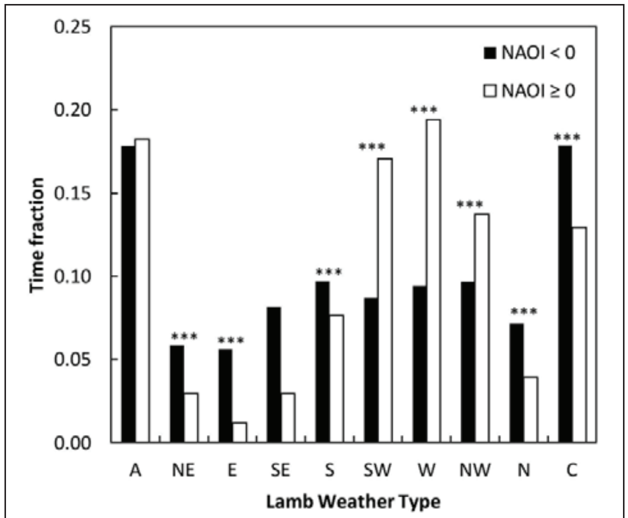

Figure 2. *The frequency in LWTs for Gothenburg, Sweden during negative and positive NAOI for January, February and December 2001–2010. The chi–square test shows statistical significance (*** p<0.001) of the difference in frequency of LWTs between negative and positive NAOI.*

As expected, the highest surface atmospheric pressure was obtained in LWT A and the lowest in C (Table 1). Furthermore, low pressure characteristic LWTs were also found to be S, SW and W and high pressure characteristic LWTs were NE, E, SE, NW and N. When NAOI was negative the LWTs generally showed higher atmospheric pressure and lower when NAOI was positive. From Table 1 it can also be inferred that average wind speeds were lowest in LWTs A, N, and NW. Average temperature varied considerably between LWTs, NE and E being the coldest and S, SW and W the warmest LWTs. On average the temperature was 1.1 °C lower and wind speed 0.7 m s^{-1} lower in negative compared to positive NAOI (Table 1).

3.3. The independent effects of NAOI and LWTs on exceedances of AQS

Table 2 shows the AQS valid in Sweden and the exceedances over the year but also during the winter months (J–F–D) and with the influence from NAOI. From a legal perspective only the annual evaluation is relevant, but the winter months typically represent the most polluted period with respect to NO_2. This can be explained by the stronger development of and longer periods with low wind speeds and stable temperature stratification during the long winter nights. In Table 3, the contributions of different LWTs to the exceedances of the four AQS are shown for the kerbside and the rooftop monitoring station. The probability of violating the AQSs was largest in LWTs A, NW and N, for the rooftop also LWT NE. For the kerbside the 40, 60 and 90 µg m^{-3} AQS were all exceeded, while at the rooftop only the 60 µg m^{-3} AQS was violated. The threshold 200 µg m^{-3} was rarely exceeded in both positive and negative NAOI (Table 2), but a clear majority of all situations with $[NO_2]>200$ µg m^{-3} were obtained in LWT NW (Table 3). The associated AQS was never violated. From Table 2 it is clear that during wintertime all $[NO_2]$ levels associated with the AQSs were higher in negative NAOI compared to positive one.

Table 1. *Number of daily observations (n) and mean values of meteorological variables (surface atmospheric pressure–P, temperature–T and wind speed–u) at the Gothenburg rooftop site, during different LWTs and during LWTs occurring during negative (NAOI<0) and positive (NAOI≥0) NAOI for January, February and December 2001–2010*

LWT	A	NE	E	SE	S	SW	W	NW	N	C	Average
n (days)	163	38	28	47	77	121	136	108	48	136	
Mean P (hPa)	1 027	1 017	1 017	1 014	1 005	1 004	1 005	1 012	1 016	993	1 011
Mean T (°C)	–1.6	–3.8	–4.5	–1.4	0.3	2.9	4.1	2.4	–1.2	0.3	–0.2
Mean u (m s^{-1})	2.7	4.1	5.1	3.9	3.9	5.1	5.4	3.4	2.7	3.9	4.0
LWT (NAOI<0)											
n (days)	70	23	22	32	38	34	37	38	28	70	
Mean P (hPa)	1 028	1 018	1 017	1 015	1 010	1 010	1 009	1 014	1 016	995	1 013
Mean T (°C)	–2.9	–4.9	–4.1	–0.6	0.0	0.8	2.2	0.9	–1.1	–0.8	–1.0
Mean u (m s^{-1})	2.7	4.0	5.2	3.5	3.5	3.9	4.3	2.8	2.6	3.7	3.6
LWT (NAOI>0)											
n (days)	93	15	6	15	39	87	99	70	20	66	
Mean P (hPa)	1 026	1 016	1 016	1 013	1 000	1 001	1 003	1 011	1 015	991	1 009
Mean T (°C)	–0.7	–2.0	–6.1	–3.1	0.6	3.8	4.9	3.2	–1.4	1.5	0.1
Mean u (m s^{-1})	2.7	4.2	4.9	4.9	4.4	5.6	5.9	3.7	2.8	4.1	4.3

Table 2. *Swedish air quality standards for NO_2 and the averages in number of exceedances per year at the kerbside and rooftop sites in Gothenburg for the years 2001–2010. The number of exceedances are presented on the basis of year, winter (J=January, F=February and D=December) and negative or positive NAOI. The data within the square brackets shows the range of the averages indicating the highest and the lowest observed values for a specific year*

			Kerbside			
NO_2 Threshold	Resolution	Limit not to be Exceeded	Year	JFD	NAOI<0 (JFD)	NAOI≥0 (JFD)
40 µg m^{-3}	Year	Average	47 [37, 59]	49 [36, 66]	54 [36, 66]	45 [9, 55]
60 µg m^{-3}	Days (24 h)	7 days yr^{-1}	80 [23, 152]	29 [5, 59]	16 [0, 59]	13 [0, 23]
90 µg m^{-3}	Hours	175 h yr^{-1}	687 [152, 1 668]	197 [32, 498]	127 [32, 498]	92 [0, 173]
200 µg m^{-3}	Hours	18 h yr^{-1}	12 [0, 80]	3 [0, 9]	1 [0, 8]	1 [0, 9]
			Rooftop			
40 µg m^{-3}	Year	Average	25 [23, 28]	30 [24, 38]	33 [27, 38]	28 [22, 37]
60 µg m^{-3}	Days (24 h)	7 days yr^{-1}	8 [0, 15]	4 [0, 9]	2 [0, 9]	2 [0, 8]
90 µg m^{-3}	Hours	175 h yr^{-1}	92 [20, 107]	39 [8, 74]	23 [5, 54]	20 [0, 48]
200 µg m^{-3}	Hours	18 h yr^{-1}	3 [0, 7]	2 [0, 7]	1 [0, 5]	1 [0, 6]

Table 3. *Number of observations of LWTs with an hourly and daily time resolution, and fraction of exceedances of Swedish air quality standards duringdifferent LWTs for January, February and December 2001–2010 at the Kerbside and Rooftop station*

Circulation Pattern	Resolution	A	NE	E	SE	S	SW	W	NW	N	C
LWT	Hours	3 909	912	672	1 129	1 849	2 905	3 264	2 591	1 152	3 264
LWT	Days	163	38	28	47	77	121	136	108	48	136
Kerbside											
40 µg m^{-3}	Hours	0.643	0.532	0.421	0.423	0.283	0.358	0.335	0.609	0.664	0.472
60 µg m^{-3}	Days (24 h)	0.497	0.368	0.250	0.276	0.221	0.190	0.184	0.463	0.521	0.243
90 µg m^{-3}	Hours	0.134	0.105	0.027	0.065	0.030	0.033	0.037	0.199	0.204	0.073
200 µg m^{-3}	Hours	0.0015	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000	0.0069	0.0000	0.0000
Rooftop											
40 µg m^{-3}	Hours	0.310	0.319	0.243	0.167	0.058	0.060	0.124	0.350	0.451	0.218
60 µg m^{-3}	Days (24 h)	0.092	0.053	0.036	0.021	0.013	0.008	0.037	0.093	0.042	0.022
90 µg m^{-3}	Hours	0.013	0.027	0.001	0.003	0.000	0.002	0.008	0.070	0.043	0.014
200 µg m^{-3}	Hours	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0073	0.0000	0.0003

3.4. Relationship between [NO_2] and wind speed in different LWTs

In Figure 3a–3d the fraction of the exceedance of the daily AQS 60 µg m^{-3} and the hourly AQS 90 µg m^{-3} is related to the fraction of hourly wind speeds lower than a threshold in the different LWTs for the kerbside and rooftop monitoring stations. The wind speed thresholds are those providing the strongest correlation, found to be 2.5 m s^{-1} for the daily AQS of 60 µg m^{-3} and 1.5 m s^{-1} for the hourly AQS 90 µg m^{-3}. The NO_2 levels were much higher, and the negative correlations with wind speed stronger, at the kerbside (Figure 3). However, statistically significant relationships were established in all cases, always with LWTs A, NW and N, having the highest fraction of exceedances of NO_2 AQS and the highest fraction of low wind speeds. The only exception was the AQS 90 µg m^{-3} at the rooftop station, where the exceedance was larger for NE than for A. For the hourly AQS 90 µg m^{-3} as much as 93% of the variation was explained by the fraction of wind speeds <1.5 m s^{-1} in the different LWTs at the kerbside. Thus, the different LWTs represent strongly contrasting conditions with respect to low wind speeds that promote high local air pollution, explaining a considerable part of the exceedances of AQS relevant NO_2 thresholds in different LWTs. Analysis was also conducted for the surface temperature but no significant relationship was found with the fraction of exceedances of NO_2 AQS.

3.5. The combined effect of LWT and NAOI on [NO_2]

In Figure 4a and 4b the difference in number of days with [NO_2]>60 µg m^{-3} and hours with [NO_2]>90 µg m^{-3} between negative and positive NAOI is presented for the kerbside monitoring station. With the exception of LWT A for the daily NO_2 threshold of 60 µg m^{-3}, exceedances of the AQS were larger in negative compared to positive NAOI and for LWTs A, NW and N compared to other LWTs. In many cases the difference between negative and positive NAOI was very large and statistically significant (LWTs S, SW, W, NW and C). For the hourly NO_2 threshold of 90 µg m^{-3} all LWTs showed higher fraction during negative NAOI and were highest for LWTs A, NW and N. Statistical significance of the NAOI impact was found for all LWTs apart NE and E. The general pattern of LWT dependence in [NO_2] exceeding the AQS was similar in positive and negative NAOI, but was higher in negative compared to positive NAOI. On average AQS exceedance was 1.7 times higher in negative NAOI for all LWTs combined. For LWT W the exceedance of hourly AQS 90 µg m^{-3} was more than 5 times larger in negative NAOI. Thus, both the large–scale NAO conditions and the more local LWT conditions contribute, partly independently, to the variation in the risk of exceeding AQS. This can also be seen in Table 2 where at both sites and for all but one AQS (the hourly threshold of 200 µg m^{-3}) the NO_2 levels were higher in negative NAOI compared to positive NAOI. The corresponding analysis was conducted for the roof top data but due to the small number of exceedances of NO_2 AQS within each LWT for this station, random effects become important and no significant differences were found between negative and positive NAOI for any LWT.

4. Discussion

Our study revealed a strong influence from the NAO on the occurrence and fraction of different LWTs, which is not surprising since both are in different ways related to surface atmospheric pressure. Both NAO and LWTs influenced the NO_2 levels in Gothenburg profoundly and partly independently. These weather pattern indices evidently illustrate great potential to serve as tools for air quality assessment and forecasting, potentially relevant to urban regions located in the Northern Hemisphere (NAO) but also to other regions located outside of the tropical zone around the globe (LWT). Air masses with low wind speeds represented by LWTs A, N and NW and the negative mode of NAO were associated with the highest NO_2 levels. Low wind speeds are known to promote poor air quality as shown by Jones et al. (2010) and Janhall et al. (2006). [NO_2] was higher in all LWTs when occurring during negative NAOI (with one exception for daily [NO_2]>60 µg m^{-3} for LWT A) compared to positive NAOI, and the fraction of exceedances doubled and sometimes tripled in for some LWTs in negative NAOI. Similar results on air quality, but without the NAO influence, were also found in other parts of Europe using different weather classification schemes in Germany, Spain, UK and Portugal (Buchholz et al., 2010; Monsalve et al., 2013; Pope et al., 2014; Russo et al., 2014), the anticyclonic weather type of which having relatively high levels of different air pollutants, including NO_2, in all the four studies, at least during the winter. Poor air quality due to restricted vertical air mixing (stable atmospheric stratification) could be potentially the result of lower temperatures which was associated with negative NAOI. However, no relationship was observed between temperature and the fraction of exceedances of NO_2 AQS. LWTs with a low average temperature did not show larger [NO_2] than warmer LWTs.

Due to the higher pollution levels and density of emission sources in continental and Southern Europe (Cyrys et al., 2012), air masses transported with southerly winds are expected to be more polluted. This was not apparent for [NO_2] in this study. The southerly LWTs (SE, S and SW) showed relatively low fraction in exceedance of AQS compared to other LWTs during both negative and positive NAOI, the higher wind speed at these LWTs also contributes to lower concentrations. Northerly winds are assumed to carry relatively clean air masses. LWTs N and NW were however associated with the largest number of exceedances of NO_2 AQS. For prevailing conditions in Gothenburg it seems to be a firm conclusion that the influence from LWTs on air quality depends predominantly on the degree to which they provide meteorological conditions which favor high local air pollution levels, i.e. low winds speeds (Figure 2), and not on variation among LWTs in the long–range transport direction of pollutants like NO_2. Even if a LWT indicates a wind direction, the air mass does not necessarily originate from this direction outside the domain in which the LWT was calculated. In fact, the trajectory of an air mass may undergo many changes in direction before crossing over a specific location. Tang et al. (2009) have for example shown that air masses moving in with southerly winds over Southern Sweden may sometimes originate from northern parts of the Baltic area. Transport of air pollutants may occur from other regions, but this contribution is minor for high NO_2 levels in Gothenburg, which are mainly a result of local emission sources in combination with the limited air mixing characteristic of certain LWTs. Another aspect supporting this is the striking difference in air quality between the kerbside and rooftop, showing larger contrasts in [NO_2] between LWTs at the kerbside. This emphasizes the large variation in pollutant exposure in the urban landscape but also that NO_2 pollution is a local scale issue due to its sensitivity to dilution effects which evidently increases with distance from emission sources.

Indices of the west–easterly (u) and the wind strength (V) component of the synoptic LWT system were related to NAOI. However, less than 50% of the variation in NAOI was explained by variation in V or u showing that the NAO– and the two LWT indices are not completely interdependent. The south–northerly wind component (v) did not show a significant correlation with NAOI. When positive NAOI prevails, weather systems containing mild and moist maritime air masses are normally transported by strong westerly winds over Northern Europe (Hurrell et al., 2003) and should therefore result in an increased number of LWTs with a westerly wind component. In line with this, the indices for V and u components were large and W, SW and NW were among the most common LWTs in positive NAOI situations. Also in Belgium, LWTs with a westerly component were more common during positive NAOI (Demuzere and van Lipzig, 2010). Chen (2000), without directly considering NAO, found similar results of the LWT distribution during the winter months for Southern Sweden. The average atmospheric pressure was low while temperatures and wind speeds were high during positive NAO conditions (and mainly the opposite for negative NAOI), further illustrating its influence on local meteorology. Also in South–west England local wind speeds were found to have a positive relationship with the NAOI (Phillips et al., 2013).

Some of the variation in LWT indices not explained by NAOI, can potentially be attributed to other weather patterns over Northern Europe. During negative NAOI the Arctic and Siberian high pressure affect air mass conditions to a larger extent (Hurrell et al., 2003), thus also the LWT indices and the resulting weather types. In Spain the number of storms had a stronger relationship with the Arctic Oscillation (AO) than with the NAO (Rangel–Buitrago and Anfuso, 2013). Additional analysis of the link between LWT indices and Arctic and/or Siberian air masses at negative NAOI situations would be necessary to verify their possible influence but is outside the scope of this study.

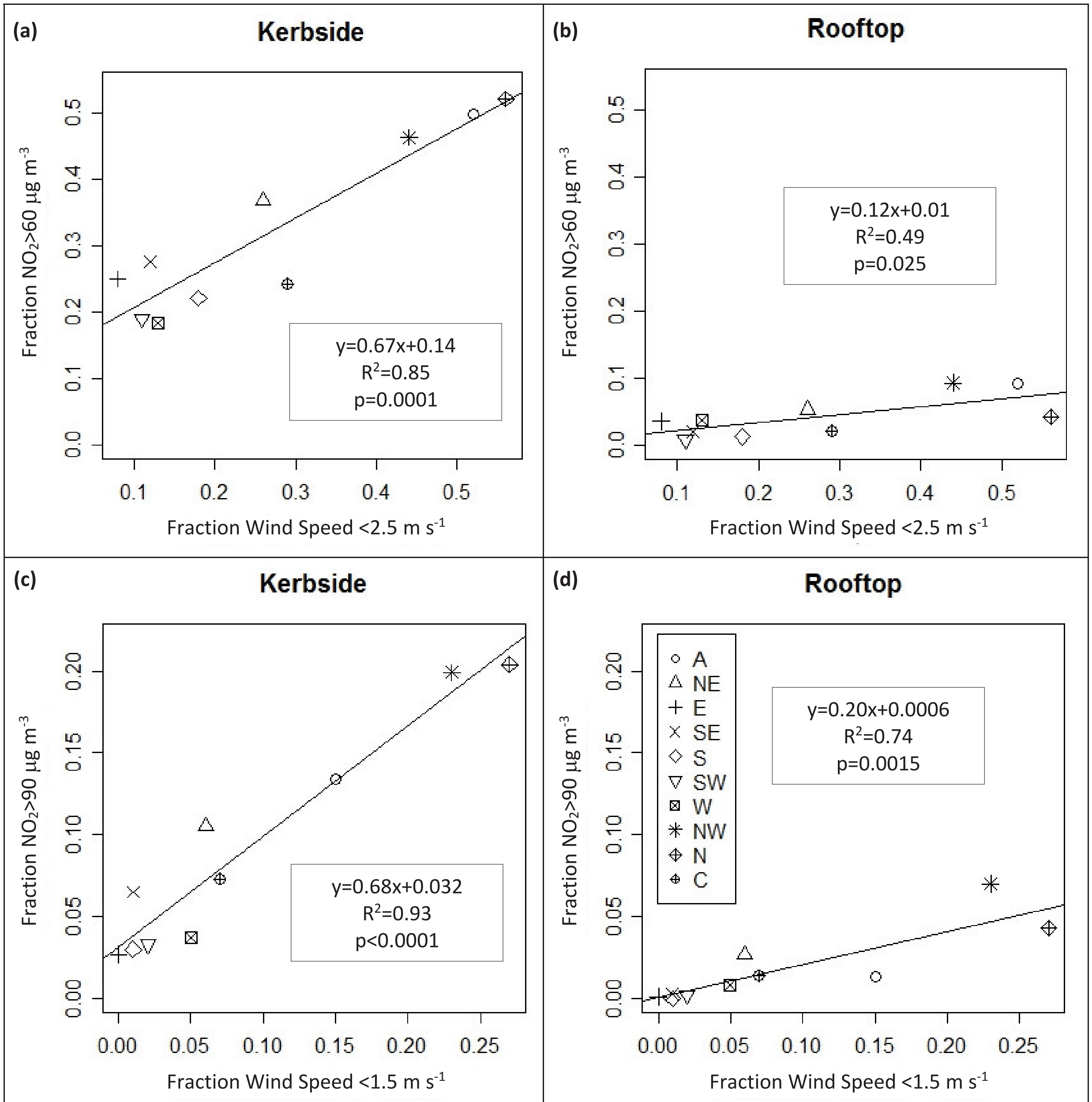

Figure 3. *Scatter plots with linear relationships between the fraction of wind speed lower than 2.5 m s^{-1} and daily [NO_2] larger than 60 μg m^{-3} at the kerbside **(a)**, rooftop **(b)** site and linear relationships between the fraction of wind speed lower than 1.5 m s^{-1} and hourly [NO_2] larger than 90 μg m^{-3}at the kerbside **(c)** and rooftop **(d)** site. All fractions are calculated for the specific LWTs.*

The most important conclusions from the present investigation were that LWTs, especially those associated with low wind speed conditions (A, NW and N), had a strong negative impact on air quality. When LWTs were combined with the NAOI the impact of weather on air quality was even more obvious. LWTs A, NW and N can therefore be classified as high risk LWTs, associated with an even higher risk when occurring during negative NAOI conditions. In health studies where different weather classifications (referred to as air mass type) were used to predict asthma and hospital admissions (Jamason et al., 1997; Morabito et al., 2006), the authors argue that the air mass type is a better predictor of the weather impact than a single meteorological variable. Rather than only considering temperature or relative humidity, the air mass type groups together similar days describing the simultaneous effect of several meteorological variables. Model predictions of synoptic weather/climate patterns such as LWTs and NAO can therefore be more informative about the full range of meteorological variables that potentially may influence the levels of different air pollutants (surface wind speed and direction, temperature, temperature stratification, relative humidity) represented by weather patterns and their impact on air pollution than projections of individual meteorological variables separately. Evidenced by this study was also that the fraction of very low wind speeds, rather than average wind speed, is of utmost importance for the link between high air pollution levels and weather types.

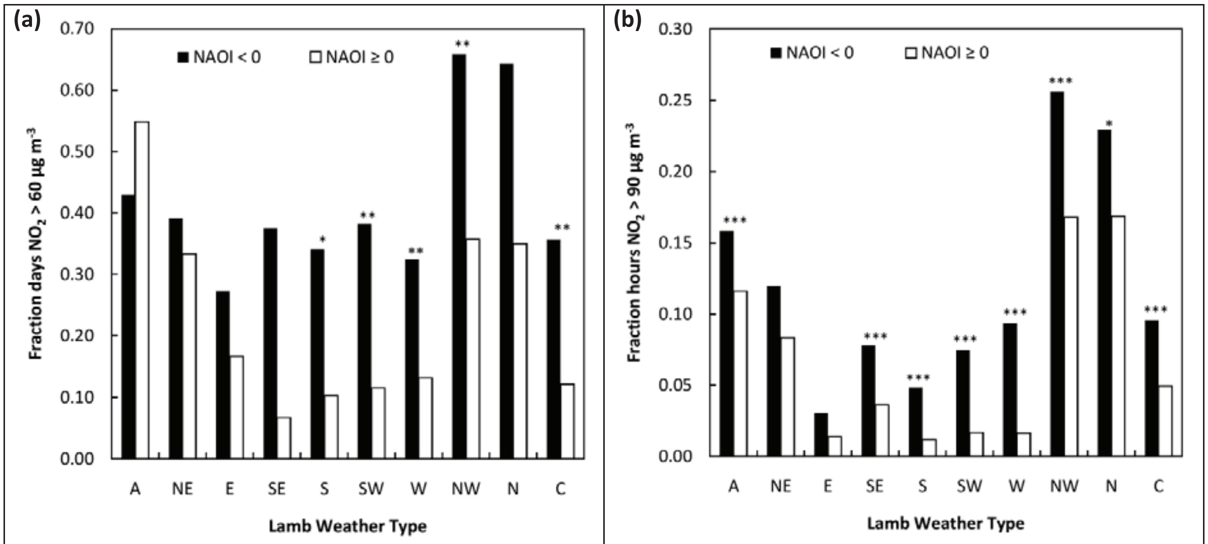

Figure 4. *Fraction of days when NO_2 exceeded 60 µg m^{-3}* ***(a)*** *and hours exceeded 90 µg m^{-3}* ***(b)*** *at the kerbside site, for different LWTs occurring in negative or positive NAOI. The chi–square test shows statistical significance (* $p<0.05$*; ** $p<0.01$*; *** $p<0.001$*) of the difference in frequency of exceedances of thresholds 60 µg m^{-3}* ***(a)*** *and 90 µg m^{-3}* ***(b)*** *for LWTs between negative and positive NAOI.*

Authorities responsible for air quality management sometimes experience problems in judging if high pollution levels are the result of altered emissions or weather conditions promoting restricted ventilation. LWT and NAO pattern could be used to develop an objective empirical based tool to define the influence from weather variability on air quality and separate it from the effects of altered emissions. Since the relationships of air pollution levels, here represented by [NO_2], with both LWTs and NAOI are very strong, these circulation indices, especially when used in combination, could become very useful in risk assessment and forecasting of high air pollution levels. The NAO phenomenon, predominantly active over the North Atlantic (Hurrell et al., 2003), permits applicability of our method in urban regions in the western parts of Europe and eastern parts of North America. The methodology regarding the use of the LWT classification for air quality risk assessment can essentially be applied to other urban regions on earth, with exception of the equatorial regions. This could provide a very useful tool for urban air quality management in e.g. emission reducing mitigation plans such as traffic congestion charges. In a recent study (Coria et al., 2013), the weather effect represented by wind speed was linked to urban air quality and traffic congestion charges in Stockholm. It was found that increased road charges at low wind speed situations would be more efficient in reducing the probability of exceeding AQS than in high wind speed situations. LWTs could be used with a similar approach where increased congestion charges would be motivated during days with calm and stagnant weather conditions, in this study mostly represented by LWTs A, N and NW. It should be noted, however, that different weather types may represent high risk for elevated air pollution concentrations in other geographical settings. In the study conducted in Portugal by Russo et al. (2014), the highest levels of NO_2 were observed in weather types NE, E and SE.

The demonstrated strong dependence of air pollution on weather patterns suggest that air pollution levels may change considerably as a result of climate change (Jacob and Winner, 2009) even if emissions remain constant. Global warming with increasing average global temperatures also has the potential to change the dynamics of other climate variables including the atmospheric circulation. LWTs can summarize the combination of important meteorological variables and the frequency of LWTs may change as a result of climate change. Output from General Circulation Models of the atmospheric stability index, Showalter Index, suggest that the westerly flow over the Atlantic will intensify and increase in frequency for North–western Europe, but also that strong atmospheric stability situations will become more frequent in the future (Hanafin et al., 2011). An increasing number of strong atmospheric stability events will likely lead to deteriorating air quality in cities. This calls for improved mitigation strategies to meet the potential climate change effect on air quality in the future.

5. Conclusions

- LWTs representing calm weather conditions (high fraction of low wind speeds) were A, N and NW.
- Considering only the LWT influence on the number of exceedances of NO_2 AQS, LWTs A, N and NW showed the highest fraction of exceedances for the 40, 60 and 90 µg m^{-3} AQS at the kerbside and for the 60 µg m^{-3} AQS at the rooftop.
- Considering only the NAOI influence on the number of exceedances of NO_2 AQS, the negative NAOI showed the highest fraction.
- LWTs and NAOI had partly independent effects on NO_2 but some of the variation in NO_2, unexplained by LWTs, was explained by the variation in NAOI.

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