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The influence of cruise ship emissions on air pollution in Svalbard – a harbinger of a more polluted Arctic?

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Abstract

In this study we have analyzed whether tourist cruise ships have an influence on measured sulfur dioxide (SO_2), ozone (O_3), Aitken mode particle and equivalent black carbon (EBC) concentrations at Ny Ålesund and Zeppelin Mountain on Svalbard in the Norwegian Arctic, during summer. We separated the measurement data set into periods when ships were present and periods when no ships were present in the Kongsfjord area, according to a long-term record of the number of passengers visiting Ny Ålesund. We show that when ships with more than 50 passengers cruise in the Kongsfjord, measured daytime-mean concentrations of 60-nm particles and EBC in summer show enhancements of 72 and 45 % relative to values when no ships are present. Even larger enhancements of 81 and 72 % were found for stagnant conditions. In contrast, O_3 concentrations were 5 % lower on average and 7 % lower under stagnant conditions, due to titration of O_3 with the emitted nitric oxide (NO). The differences between the two data subsets are largest for the highest measured percentiles while relatively small differences were found for the median concentrations, indicating that ship plumes are sampled relatively infrequently even when ships are generally present but carry high concentrations. We estimate that the ships increased the total summer mean concentrations of SO_2, 60-nm particles and EBC by 15, 18 and 11 %, respectively. Our findings have two important implications: firstly, even at such a remote Arctic observatory as Zeppelin, the measurements can be influenced by tourist ship emissions. Careful data screening is recommended before summer-time Zeppelin data is used for data analysis or for comparison with global chemistry transport models. However, Zeppelin remains one of the most valuable Arctic observatories, as most other Arctic observatories face even larger local pollution problems. Secondly, given landing statistics of tourist ships on Svalbard, it is suspected that large parts of the Svalbard archipelago are affected by cruise ship emissions. Thus, our results may be taken as a warning signal of future pan-Arctic conditions, if Arctic shipping becomes more frequent and emission regulations are not strict enough.

ACPD
13, 3071–3093, 2013

1 Introduction

Ship traffic is a substantial source of pollution globally, and it is of particular concern in regions with heavy ship traffic (e.g. near ports or major shipping lanes) or where few other pollution sources exist, such as the high-latitude regions. Norwegian coastal ship traffic, for instance, is responsible for more than 1/3 and 1/6 of the Norwegian emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2), respectively, and contributes substantially to coastal pollution (Dalsøren et al., 2007). While shipping in the high Arctic is currently limited by sea ice, observations in the Arctic boundary layer suggest that shipping around the periphery of the Arctic Ocean is an important source of black carbon (BC – we use BC as qualitative term for material that (1) has a high fraction of sp^2-bonded carbon; (2) consists of aggregates of carbon spherules; (3) is themally refractory up to 4000 K; (4) is hydrophobic; (5) is strongly broadband absorbing for visible light) and polycyclic aromatic hydrocarbons (Xie et al., 2007). Arctic ship emissions also contribute to the radiative forcing of the climate system and may be important for regional climate change (Ødemark et al., 2012).

Oil and gas extraction in the Arctic is expected to increase in the future and this will require corresponding increases of shipping activity (Peters et al., 2011). Furthermore, diminishing summer sea ice due to climate warming will likely prompt a substantial number of cargo ships to take the shorter passages through the Arctic instead of using their current routes. This could lead to large increases of ship emissions in the Arctic (Corbett et al., 2010). For extreme scenarios, it has been estimated that ship emissions of ozone precursors could lead to more than a doubling of summer-time Arctic surface ozone concentrations (Granier et al., 2006). More realistic scenarios for the year 2030 lead to smaller changes in ozone but maintain larger than 50 % increases of BC concentrations, unless BC emission reduction measures are implemented (Dalsøren et al., 2012).

One particular type of Arctic ship activity has already increased substantially during the last two decades, namely sight-seeing ship cruises. Major touristic goals in

ACPD
13, 3071–3093, 2013

the polar regions are the Antarctic Peninsula, Greenland and Svalbard (Spitsbergen), and concern is rising that cruise ship emissions affect the pristine polar atmospheres and fragile ecosystems. For instance, Graf et al. (2010) found that tourist ships are the largest local source of SO_2 and BC in the Antarctic and entirely dominate SO_2 and BC emissions near the Antarctic Peninsula. They also reported a 43 % increase in the number of tourist ships visiting Antarctica over the short period from 2004/2005 to 2007/2008. Similar increases have been reported for the Arctic. The annual number of tourists landing on Svalbard increased from 40 000 at the end of the 1990s to 100 000 during the period 2006–2010 (Hagen et al., 2012). According to the emission inventory of Vestreng et al. (2009), 93 % of the BC and 90 % of the NO_x emissions in the Svalbard archipelago (10–35° E; 74–81° N) in the year 2007 were due to marine transport (primarily cruise ships and coal transportation), while land-based emissions accounted for less than 10 %. Furthermore, most of the emission increase from 2000 to 2007 (BC: 56 %, NO_x: 54 %) was due to cruise ships. The emission inventory (Vestreng et al., 2009) is likely conservative as the BC emission factors used are probably too low for Arctic conditions (Lack and Corbett et al., 2012).

In this study, we investigate the influence of ship plumes on the measurements of SO_2, O_3, Aitken mode particle and equivalent BC (EBC) concentrations in the Svalbard village of Ny Ålesund and at the nearby Arctic background monitoring station at Zeppelin Mountain. This area is influenced by tourist ships cruising in the Kongsfjord and anchoring at Ny Ålesund. Weinbruch et al. (2012) analyzed aerosol samples taken at Zeppelin during a measurement campaign with electron microscopy and suggested that soot (characterised by its composition of spherules) was only observed when cruise ships were present in the Kongsfjord. According to Eleftheriadis et al. (2009), 0.2 % of the measured EBC values at Zeppelin appear to be influenced by local pollution, probably from ships. However, to date no systematic long-term study on the influence of ship emissions on measurements at Zeppelin has been published. The purpose of this study is to quantify this influence.

ACPD
13, 3071–3093, 2013

2 Methods

2.1 Study area and some meteorological considerations

The region of our study is shown in Fig. 1. Sight-seeing ships with typically a few hundred but up to 3000 tourists often cruise in the Kongsfjord and anchor in the village of Ny Ålesund (11.93° E, 78.92° N). Research and supply vessels visit Ny Ålesund as well. The village is a permanent settlement (population in winter some 35, more in summer) with a number of international research stations. There is a small power station for electric power generation but energy demands in summer are modest and power plant emissions are low compared to ship emissions (Vestreng et al., 2009). In this paper, we present measurement data collected at a temporary station in the "center" of the village (red dot in Fig. 1) and at the permanent research station Zeppelin, which is located some 2 km away from Ny Ålesund at an altitude of 472 m (blue dot in Fig. 1). The station is situated in an unperturbed Arctic environment on a ridge of Zeppelin Mountain and is accessible to researchers by a cable car.

The meteorological conditions in the study area are complex, due to the mountain ranges on both sides of the fjord (Fig. 1) and the temperature contrasts between sea and land. Winds are channeled inside the fjord, and surface wind measurements at Ny Ålesund and Zeppelin are not representative for general wind conditions in the area. Likewise, boundary-layer heights and thus vertical mixing are highly variable (Vihma et al., 2011). The Zeppelin station is often above a temperature inversion layer but can also be located within the boundary layer (Tunved et al., 2012; Di Liberto et al., 2012). Pollution plumes are rare at Zeppelin (Eleftheriadis et al., 2009) because of the low emissions in the village, the distance to the station and the limited vertical mixing. However, smoke stacks of large ships are elevated emission sources and their buoyant exhaust can rise substantially.

To identify the influence of ship emissions on aerosol and air chemistry measurement data, we use a very simple approach: we bin the data according to the ship presence in the fjord (see Sect. 2.2). A more specific approach of quantifying ship plume influence

ACPD
13, 3071–3093, 2013

was not possible since the combination of moving sources and the complex local meteorology make predictions of exhaust transport to the stations difficult. The lack of specificity of our criteria implies that clean conditions can be expected at the stations most of the time even when ships are in the fjord, but pollution events are expected to be much more frequent under these conditions than when no ships are present.

2.2 Ship presence in the Kongsfjord

The harbor master of Kingsbay AS company keeps detailed hourly records about when ships arrive and leave the dock or anchor position, as well as on the number of people visiting the island (H. Gisnås, personal communication, 2012). This record is generally of high quality but it is known that occasionally ships have not been registered. Figure 2 shows the total number of passengers visiting Ny Ålesund between the years 2000 and 2011. Between the years 2000 and 2007, tourist numbers have more than doubled, while since then there is no clear trend in the number of passengers. A similar trend has been reported by Hagen et al. (2012) for the entire Svalbard archipelago, where a total of about 200 ship landing sites have been used in recent years. According to data in Fig. 1 and in Hagen et al. (2012), Ny Ålesund accounts for some 15 % of all Svalbard ship landings.

Ship names are not recorded in a systematic enough way to clearly identify each vessel, which would allow estimating its pollutant emissions. Therefore, we use the number of passengers as a proxy for the size of a ship and the corresponding pollutant emissions. The correlation between the number of passengers and a ship's emissions is probably relatively weak and, therefore, we separate all data in only two classes: (1) when no ship was present in the fjord (case "no ships"); (2) when ship(s) with a total of more than 50 passengers were present (case "ships"). However, 500 passengers were used as a threshold for 24-h samples of SO_2 (see Sect. 1.4).

Tourist ships typically cruise in the Kongsfjord for a few hours before or after visiting Ny Ålesund, and it also takes some time to reach or leave Ny Ålesund from outside the Kongsfjord. Pollutant emissions are likely also higher when the ships cruise in the

ACPD
13, 3071–3093, 2013

fjord than when they are anchored. However, no information is available to us about the duration of the Kongsfjord cruises and the exact routes the ships take. We therefore consider ships to be in the Kongsfjord from the registered arrival time until 4 h after the registered departure time from Ny Ålesund. This also leaves some margin for the presence of pollution and transport to the Zeppelin station after a ship has left the fjord. When considering measurements in Ny Ålesund, only a 2 h extension was used because the strongest influence there is expected when ships are at anchor. Although these time margins are somewhat arbitrary, they do not matter for quantifying the total ship influence as long as they cover the periods with potential ship presence.

Tourists visit Ny Ålesund mainly during the months from June to August, so only this period is considered in our study. Ships normally arrive during daytime and leave before the evening, so we restrict most of our analysis to daytime hours from 08:00 a.m. to 08:00 p.m. local time (06:00 a.m. to 06:00 p.m. UTC).

2.3 Measurements in Ny Ålesund

From July 2008 to August 2010, a measurement campaign was carried out to investigate the impact of local pollution sources on air concentrations in Ny Ålesund. For this purpose a monitoring station was set up in the "center" of Ny Ålesund where carbon monoxide, SO_2, NO_x and EBC measurements were carried out with a sampling time of 1–5 min. However, BC data were not available to us, so for this study only hourly SO_2 averages were used, since of the remaining compounds SO_2 is the most specific indicator of ship emissions. SO_2 was measured using a model Teledyne API 100E UV fluorescence SO_2 analyzer. High instrumental stability was achieved with the use of an optical shutter to compensate for photomultiplier drift and a reference detector to correct for changes in UV lamp intensity. A hydrocarbon "kicker" and advanced optical design were combined to prevent inaccuracies due to interferents. The instrument is usually used for monitoring higher concentrations than the background conditions in Ny Ålesund, so the concentrations measured during the campaign were below the detection limit most of the time. However, there were weekly tests on blank values which

ACPD
13, 3071–3093, 2013

were used to remove a drift in the data. Therefore, while mean concentrations may be highly uncertain, the enhanced SO_2 concentrations in ship plumes can be quantified.

2.4 Equivalent BC, particle size distribution, SO_2 and O_3 measurements at Zeppelin

Monitoring of light absorbing particles at Zeppelin was performed since the year 2002 with a custom-built particle soot absorption photometer (PSAP). In this instrument, light at 530 nm wavelength illuminates two 3 mm diameter spots on a single filter substrate, on one of which particles are collected from ambient air flushed through the filter, and the other kept clean as a reference (Bond et al., 1999). The change in light transmittance across the filter is measured to derive the particle light absorption coefficient σ_{ap}, corrected for the influence of scattering particles. Conversion of σ_{ap} to BC concentrations requires the assumptions that all the light absorption measured is from BC, and that all BC has the same light absorption efficiency. We convert σ_{ap} values to EBC mass concentrations using a value of $10\,m^2\,g^{-1}$, typical of aged BC aerosol (Bond et al., 2005).

The particle size distributions were measured using a Differential Mobility Particle Sizer (DMPS) consisting of a Differential Mobility Analyser (Knutson and Whitby, 1975) and a TSI 3010 particle counter. The sheath flow is a closed-loop system (Jokinen and Makela, 1997). DMPS data from Zeppelin have been presented previously (Stroem et al., 2003) and cover the size range from 13.5 to 700 nm diameter (bin limits). For this study we only use the size bin which includes the 60 nm diameter (referred to as PN60), which represents a typical size of relatively fresh ship exhaust. Over the years (2003–2010) different size bins were used. From 2003–2007 the mean value of the size bin used is 63.5 nm; from 2008–2009 63.1 nm and in 2010 59.7 nm.

SO_2 is sampled with the three stage filter pack method, which is the reference method in the European Monitoring and Evaluation Program (EMEP/CCC, 2001; Aas et al., 2007). SO_2 is absorbed on a potassium hydroxide impregnated Whatman 40

ACPD
13, 3071–3093, 2013

filter, extracted in the laboratory with a hydrogen peroxide solution and analyzed with an ion chromatograph. The sampling duration is 24 h, so only full days with/without ship presence were distinguished for SO_2.

O_3 is measured with an UV-absorption instrument API400A with a lower detection limit of 0.6 ppbV. Zero-span checks are done every second week to compensate for zero drift and a manual calibration is done once a year using a TEI 49 CPS #60955-329 as a reference. The air intake is through a 4.5 m FEP tube with an outer diameter of 6.35 mm and an inner diameter of 4.75 mm.

3 Case study

On 1 July 2009, the cruise ship *Vistamar* with 281 passengers on board arrived in the harbor at 07:30 a.m. and departed at 10:30. At 10:30, another ship, *Athena*, with 377 passengers arrived and stayed until 15:30. In addition, smaller ships also arrived during the afternoon (*Albarquel*, 9; *Quest*, 53; and in the evening an expedition with 73 persons). Total passenger numbers as a function of time of day are shown in Fig. 3b (black line). During this day, the wind speeds measured at Zeppelin were only around $1\,m\,s^{-1}$ with first north-westerly and then southerly directions. The low wind speeds lead to accumulation of pollution in the fjord. The SO_2 measurements in Ny Ålesund show a first peak in SO_2 of $0.6\,\mu g\,m^{-3}$ when *Vistamar* arrived and a more pronounced maximum of $1.1\,\mu g\,m^{-3}$ when *Athena* was in the harbor (and *Vistamar* probably still cruising in the fjord). Two peaks can also be identified in the NO_x measurements at Ny Ålesund (not shown), both associated with the 2nd SO_2 peak. The hourly peak (day-time mean) concentrations of SO_2 of $1.1\,\mu g\,m^{-3}$ ($0.46\,\mu g\,m^{-3}$), respectively, can be compared to the average summer-time daily maximum (day-time mean) SO_2 concentrations of $1.0\,\mu g\,m^{-3}$ ($0.3\,\mu g\,m^{-3}$), respectively. The hourly peak value is around the 90th percentile for summer, daytime concentrations.

ACPD
13, 3071–3093, 2013

At Zeppelin, the maximum hourly EBC concentration was 64.1 ng m^{-3}, which is above the 95th percentile of all summer daytime values. The PN60 concentration was 1461 cm^{-3}, also above the 95th percentile. Even the 24-h-mean SO_2 value from the filter measurements of 0.19 µg m^{-3} was above the 95th percentile of all summer values. For the time period of the peak EBC concentrations at Zeppelin, we also analyzed the particle number size distribution of the aerosol and found that it has a similar shape to size distributions typical of ship emissions as determined in the laboratory (Petzold, 2008). This provides strong evidence that the enhanced EBC concentrations in this case were indeed due to ship emissions. At the same time as EBC and Aitken mode particles peak, O_3 shows a concentration dip, which can be explained by titration of O_3 with nitric oxide (NO) emitted by the ships.

4 Statistical analysis

For the statistical analysis, we group all measurement data according to ship presence into two classes: "no ships" and "ships". For these groups, the SO_2 concentrations in Ny Ålesund, and the O_3, EBC and PN60 concentrations at Zeppelin are shown in box and whiskers plots (Fig. 4). There is a strong decreasing trend of the summer-mean EBC concentrations at Zeppelin between 2003 and 2005, with the 2006–2011 summer-mean concentrations only about 1/3 of the values measured during the previous years. The reasons for this decrease are not entirely clear, although emission reductions in Eurasian source areas may play a role (Hirdman et al., 2010b). To reduce the impact of this trend on our analysis, we consider two separate periods, 2003–2005 and 2006–2011 for EBC.

For SO_2 in Ny Ålesund, the mean concentrations for the group "no ships" are 0.28 µg m^{-3} and for "ships" 0.40 µg m^{-3}. According to a *t*-test, the means are statistically significantly different. As expected, the medians for both groups are similar, as ship plumes do not reach the station all the time even when ships are present.

ACPD
13, 3071–3093, 2013

Similarly, at Zeppelin the mean EBC concentrations when no ships are present (for the first/second period) are 16.9/7.0 ng m^{-3} and when ships are present they are 24.7/10.0 ng m^{-3}. Also the 75 % and 95 % percentile concentrations are consistently enhanced when ships are present, for both periods considered. A corresponding result is obtained for PN60, for which the mean concentration are also significantly higher for periods with ship presence (297.6 cm^{-3}) than without (173.3 cm^{-3}). In contrast, for O_3, the mean concentrations are 2.8 µg m^{-3} lower when ships are present than when no ships are present. As for the case study, we attribute this to titration of O_3 by NO in the ship plumes.

We repeated the above analysis but considering only low wind speed conditions. In this case, the differences between the two classes are even larger. For instance, the mean PN60 at Zeppelin during the period 2003–2010 are 81 % higher when ships are present than when no ships are present. This shows that ship influence is enhanced under low wind speed conditions, as expected.

To exclude that differences between our two classes "ships" and "no ships" are due to a varying frequency of ships as a function of time of day associated with an independent daily cycle of pollutants, we repeated the analysis shown in Fig. 4, but for every hour of the day separately. Figure 5 shows that the EBC and PN60 concentrations are higher in the afternoon than in the morning, regardless of ship presence. They are consistently higher throughout the day when ships are present, with very few exceptions, notably in the early morning hours, when ships only start arriving and the number of "ships" cases is very low. The O_3, concentrations are consistently lower throughout the day when ships are present.

To determine the overall effect of ship emissions on the mean measured pollutant concentrations in Ny Ålesund and at Zeppelin taking into account the different frequency of periods with or without ships, we compare the mean concentration, averaged over all "no ships" periods ("background"), with the total mean concentration, averaged over the entire time. This was done for summer (June, July, August) during daytime only, for summer including night-time periods, and for summer during daytime and with

ACPD
13, 3071–3093, 2013

low-wind conditions only (Table 1). As can be expected, the relative increases of the total mean concentrations over the background mean concentrations are largest during daytime and for low-wind conditions. For this period, the relative ship-related increases over the background for EBC are 24/30 %, and for PN60 31 %. There is still a substantial increase of the mean concentrations due to ships for all wind conditions (12/23 % and 32 %), and even when including the night-time periods as well (8/11 % and 18 %). Mean SO_2 concentrations are also enhanced by the ship emissions, while O_3 concentrations are decreased by 2–4 %. However, the influence of the ships on annual mean concentrations is minimal (not shown), since SO_2 and EBC concentrations during the Arctic haze season (winter and early spring) are much higher than in summer, and ship influence is small during that period.

5 Discussion and conclusions

In this study we have shown that tourist ships have a substantial influence on measured SO_2, EBC, PN60 and O_3 concentrations at Ny Ålesund and Zeppelin during summer. When ships with a total of more than 50 passengers cruise in the Kongsfjord, measured daytime-mean concentrations of SO_2 in Ny Ålesund and EBC and PN60 at Zeppelin show enhancements of 45 %, 44 % and 72 % over values averaged over periods when no ships are present. Even larger enhancements for EBC and PN60 of 72 % and 81 % were found under low-wind conditions, while differences when the entire summer (including night-time) was considered, were slightly lower, 37 % and 58 %, respectively. The differences between the two data subsets are largest for the highest measured percentiles while relatively small differences were found for the median concentrations, indicating that ship plumes carry high concentrations but are sampled relatively infrequently. In contrast, O_3 concentrations were decreased during periods when ships were present, a consequence of titration with NO emissions. Thus, no indication of net O_3 formation in the ship plumes was found but this could still occur further away.

ACPD
13, 3071–3093, 2013

Taking into account the different frequencies of periods with ship or no ship influence, we evaluated the total effect of ship plumes on SO_2, EBC and PN60 concentrations by calculating the increases of the summer-mean concentrations over background conditions without ship influence. These increases were 15 %, 11 % and 18 %, respectively, for SO_2, EBC and PN60 for summer. Larger increases were found for daytime only periods, and even larger increases for daytime low-wind periods only. For the entire year, the influence of ships is negligible since the pollutant concentrations in winter and spring are much higher than in summer and few ships are present during that period. However, with respect to the shortwave radiative effects of aerosols (including the albedo effect of the deposition of BC on the snow), the spring to summer period is particularly important (Quinn et al., 2008). It can also be expected that summer-time BC deposition is enhanced by a similar factor as BC concentrations, whereas annual total deposition is probably enhanced only marginally by the ship emissions.

The values reported in this paper are only lower estimates for the ship influence on pollutant concentrations. Our relatively simple method of separating the data into periods when ships were present in the fjord and periods when there were no ships does not account for the fact that ship emissions may reside inside the fjord for a longer time and reach the stations outside the periods flagged as influenced by ships in our data sets. Furthermore, some ships may cruise in the fjord for a longer time than assumed in this study, and we know that occasionally ships are not registered at all. This means that even the periods classified as without ships may to some extent be influenced by local ship emissions and may thus not fully represent true background conditions. Furthermore, ships cruising outside the Kongsfjord are not considered in this study, but they may still have some effect on the measured concentrations.

All in all, this leads us to the conclusion that tourist cruise ships have a substantial influence on the measured SO_2, PN60, EBC and O_3 concentrations (and likely the concentrations of many other compounds) at Ny Ålesund and Zeppelin during summer. This makes it more difficult to compare the measured concentrations with the concentrations simulated by chemistry transport models (e.g. Shindell et al., 2008), which do

ACPD
13, 3071–3093, 2013

not correctly include these local emissions. Data analyses can also be affected by the ship influence. For instance, the source region analyses of Hirdman et al. (2010a,b) used the highest and lowest 10 % of the measured concentrations but the former may have been contaminated substantially by ship plumes, probably explaining the lack of a clear source region signal in summer. Nevertheless, Zeppelin remains one of the most valuable Arctic observatories, since most other stations face even more severe local contamination problems. Furthermore, a careful screening of the Zeppelin data allows excluding periods influenced by ship emissions. We estimate that during the years 2002 to 2011, data were contaminated by local ship emissions only during around 60 h per year. However, it is difficult to screen monitoring data with coarse temporal resolution (e.g. filter samples), since most of the samples will contain some influence from ship plumes.

This study has shown that ships cruising in the Arctic can already now have a substantial influence on the pollutant concentrations in pristine areas of the Arctic, at least on a local scale. If Arctic shipping in summer will increase as predicted over the next few decades (e.g. Corbett et al., 2010) the entire Arctic may be affected by ship emissions. Thus, the influence currently seen at Ny Ålesund and Zeppelin may be a harbinger of a much more pronounced Pan-Arctic ship pollution influence in the future. More stringent regulations on ship emissions could help to reduce this impact.

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ACPD
13, 3071–3093, 2013

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ACPD
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ACPD
13, 3071–3093, 2013

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ACPD
13, 3071–3093, 2013

Table 1. Mean EBC [ng m^{-3}], PN60 [cm^{-3}], ozone [µg m^{-3}] at Zeppelin, and SO_2 concentrations at Zeppelin and in Ny Ålesund (NA-SO_2) [µg m^{-3}] when periods with ship influence were filtered out ("background", bkgr) and for the entire data set (all), for various averaging time periods. Relative increases (incr) over the background periods are given in %.

Substance, years used	Summer, daytime only, low wind			Summer daytime only			Summer		
	bkgr	all	incr	bkgr	all	incr	bkgr	all	incr
EBC 2003–2005	19.9	24.7	24 %	16.9	19.0	12 %	16.2	17.6	8 %
EBC 2006–2011	8.0	10.3	30 %	7.0	8.6	23 %	7.3	8.2	11 %
PN 2003–2010	199	261	31 %	173	228	32 %	182	215	18 %
O_3 2003–2011	59.4	57.7	−4 %	58.9	57.4	−2 %	58.7	57.6	−2 %
SO_2 2003–2011	–	–	–	–	–	–	55.5	64.0	15 %
NA-SO_2 2008–2010	–	–	–	0.28	0.33	18 %	0.20	0.24	21 %

ACPD
13, 3071–3093, 2013

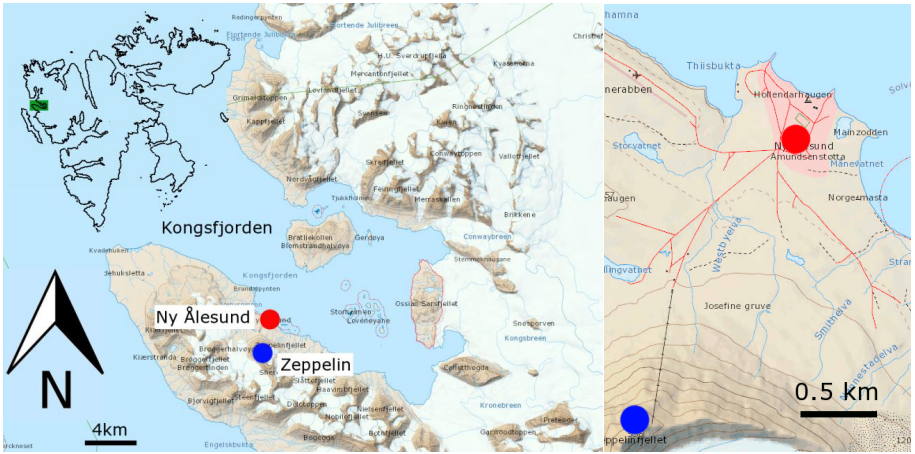

Fig. 1. Left panel: map of the Kongsfjord area of Svalbard, showing the locations of the village of Ny Ålesund (red dot) and the Zeppelin Mountain station (blue dot). The inset in the upper left corner shows the coastlines of Svalbard, the green rectangle indicating the approximate extent of the map. Right panel: detailed map of the Ny Ålesund area, with the red dot showing the position of the Ny Ålesund monitoring station, and the blue dot showing the position of the Zeppelin mountain station (Courtesy of Norwegian Polar Institute, http://toposvalbard.npolar.no/).

ACPD
13, 3071–3093, 2013

The influence of cruise ship emissions on air pollution in Svalbard

S. Eckhardt et al.

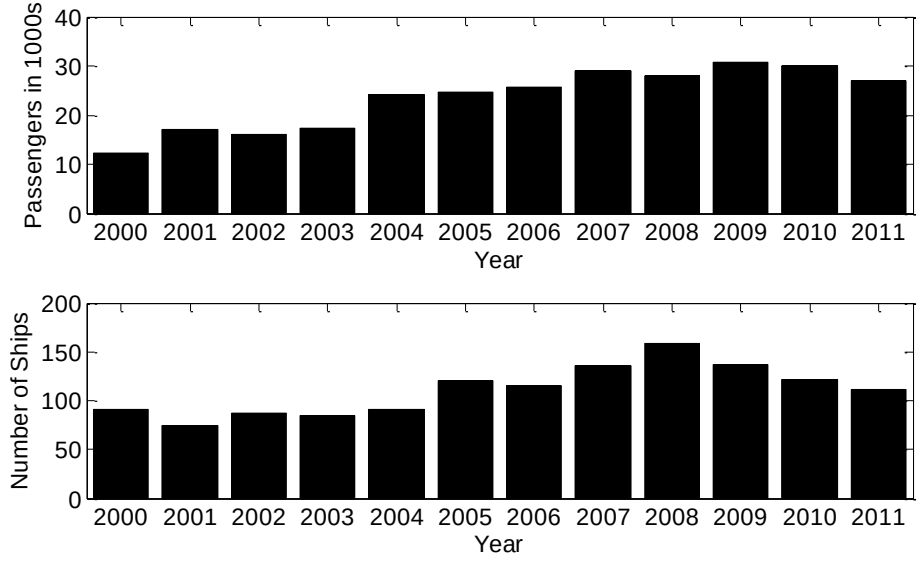

Fig. 2. Total number of ship passengers visiting Ny Ålesund per year (upper panel) and number of ships registered in the Ny Ålesund harbor log (lower panel).

ACPD
13, 3071–3093, 2013

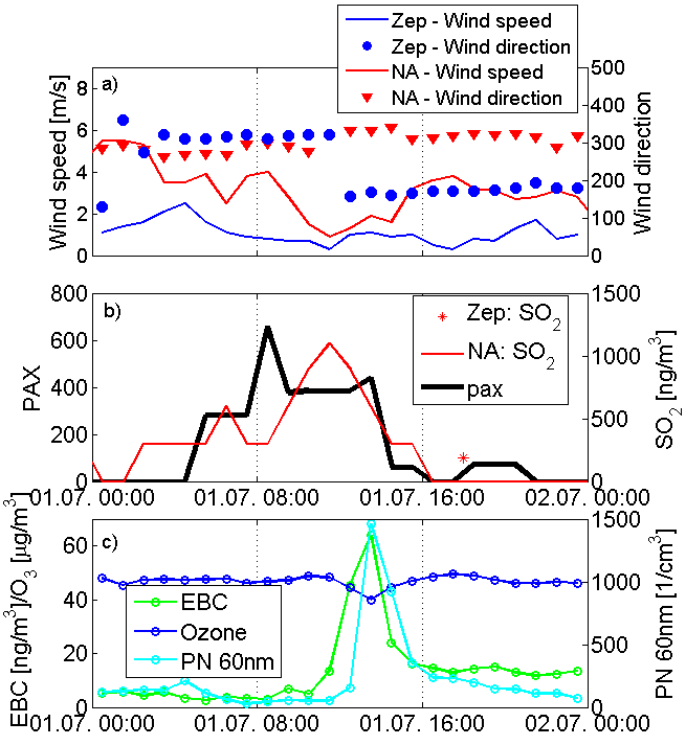

Fig. 3. Wind and air chemistry measurements at Zeppelin and in Ny Ålesund during 1st July 2009. The top panel **(a)** shows hourly measurements of wind speed [m/s] and wind direction at Zeppelin (blue) and in Ny Ålesund (red). In the middle panel **(b)**, the black line indicates the number of passengers in the harbor (PAX), the red line shows the continuous SO_2 measurements in Ny Ålesund, and the red asterisk shows the daily average SO_2 concentration at Zeppelin from filter sample measurements. In the lower panel **(c)**, the green line is the EBC concentration, the light blue line the PN60 concentration, and the dark blue line shows the ozone concentration, all measured at Zeppelin.

ACPD
13, 3071–3093, 2013

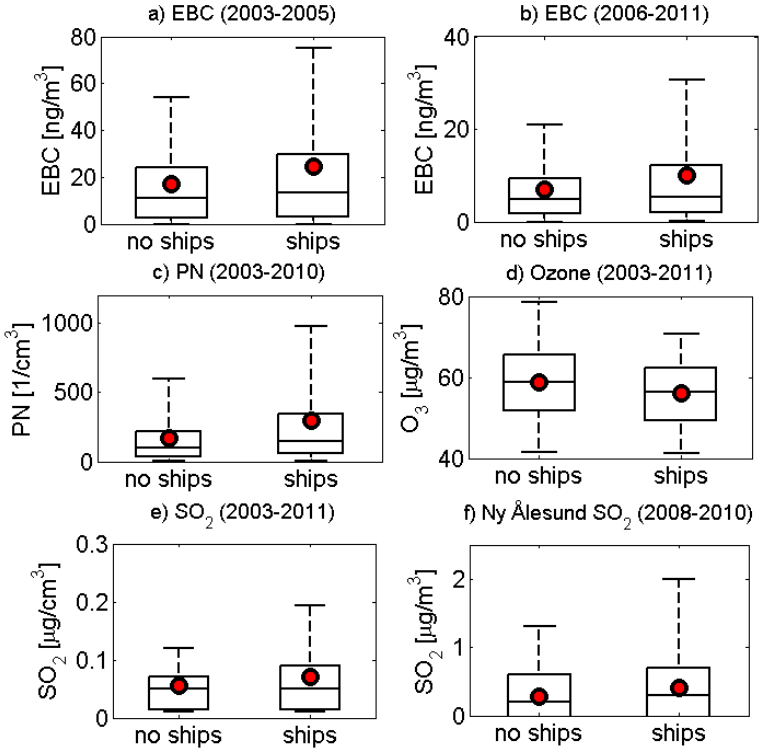

Fig. 4. Box and whisker plots of EBC (**a** and **b**), particle number concentration for particles in the 60 nm size bin **(c)**, ozone **(d)**, and SO_2 **(e)** at Zeppelin, and SO_2 at Ny Ålesund **(f)**, for the two periods when ships are present in the harbor, or not. In the title of each panel the years used for the analysis are reported. The boxes extend from the 25th to the 75th percentile, the whiskers show the 5th and 95th percentile, and the thick red dots are the mean values. Data shown are for summer (June, July, August) and for daytime (06:00 a.m.–06:00 p.m. UTC).

ACPD
13, 3071–3093, 2013

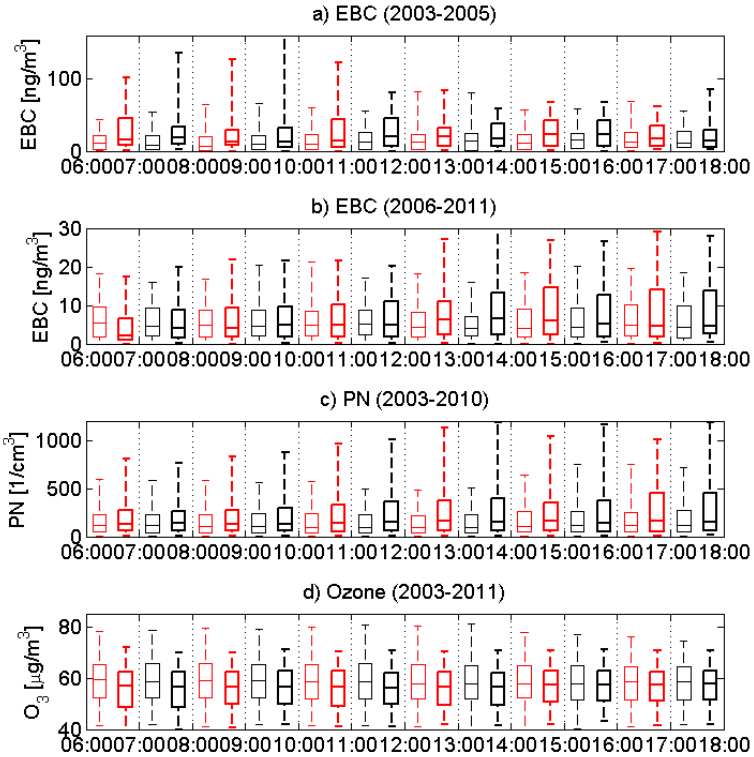

Fig. 5. Box and whisker plots of EBC, particle number concentration for the 60 nm size bin, and ozone measured at Zeppelin for each hourly interval between 06:00 a.m. and 06:00 p.m. UTC for the two categories describing whether ships are present in the harbor, or not. The boxes with the thin lines show the data when there are no ships, the boxes with the thick lines the data when there are ships. For clarity of presentation, the colors alternate every hour. Data shown are for summer (June, July, August) during the years given in each panel title.

ACPD
13, 3071–3093, 2013