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Crop harvest in Denmark and Central Europe contributes to the local load of airborne *Alternaria* spore concentrations in Copenhagen

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Abstract. This study examines the hypothesis that Danish agricultural areas are the main source of airborne *Alternaria* spores in Copenhagen, Denmark. We suggest that the contribution to the overall load is mainly local or regional, but with intermittent long distance transport (LDT) from more remote agricultural areas. This hypothesis is supported by investigating a 10 yr bi-hourly record of *Alternaria* spores in the air from Copenhagen. This record shows 232 clinically relevant episodes (daily average spore concentration above 100 m^{-3}) with a distinct daily profile. The data analysis also revealed potential LDT episodes almost every year. A source map and analysis of atmospheric transport suggest that LDT always originates from the main agricultural areas in Central Europe. A dedicated emission study in cereal crops under harvest during 2010 also supports our hypothesis. The emission study showed that although the fields had been treated against fungal infections, harvesting still produced large amounts of airborne fungal spores. It is likely that such harvesting periods can cause clinically relevant levels of fungal spores in the atmosphere. Our findings suggest that crop harvest in Central Europe causes episodes of high airborne *Alternaria* spore concentrations in Copenhagen as well as other urban areas in this region. It is likely that such episodes could be simulated using atmospheric transport models.

1 Introduction

The importance of understanding the spatial and temporal distribution of fungal spores has recently been highlighted by Lang-Yona et al. (2012) by presenting seasonal variations of airborne fungal spore concentrations in 2009 at a site in Israel, based on quantitative real time polymerase chain reaction (qPCR) analysis (Lang-Yona et al., 2012). Similarly, studies from the same group in Israel suggest that fungal spore concentrations peak during spring and autumn (Burshtein et al., 2011). The authors discuss whether these peaks could be related to spring blooms and autumn decomposition of the vegetation.

Fungal spore concentrations can also be obtained using volumetric spore traps of the Hirst design (Hirst, 1952). The advantage of the Hirst trap is that it provides a daily or bi-hourly record of fungal spore concentrations that may be used to construct actual calendars of bioaerosols (e.g. Ceter et al., 2012; Melgar et al., 2012; Skjøth and Sommer, 2010). The disadvantage of the Hirst trap is that the associated method for counting of the spores in microscopes only provides observations of fungal spores at the genus level (e.g. Ceter et al., 2012; Skjøth and Sommer, 2010), whereas qPCR can quantify fungal spores at the species level. This disadvantage is outweighed by the long time series with high temporal resolution, often covering several years with bi-hourly records (Oliveira et al., 2009; Stepalska et al., 1999; Stepalska and Wolek, 2009) or even up to 10 yr or more (Aira et al., 2008; Hjelmroos, 1993; Skjøth and Sommer, 2010). Despite these advantages with data from the Hirst trap, data of fungal spores are rare in comparison to pollen data. This is even more pronounced when the numbers of studies on data from Hirst traps are compared to studies on atmospheric trace gasses such as ozone. This lack of scientific attention has been recognized for a number of years, e.g. by an editorial in The Lancet (2008) and by the recommendation in Allergy by Cecchi et al. (2010); as such they both suggested further studies in aerobiology. Studies on bio-aerosols such as airborne fungal spores are therefore highly needed.

The first long term study on fungal spores in the air of Copenhagen by Skjøth and Sommer (2010) showed that the genera *Cladosporium* and *Alternaria* both have their maximum concentrations during summer, but that *Cladosporium* has a much longer season. This suggests that the source of these two important genera of fungal spores can be different.

Observations from Hirst traps for the last 5–10 yr have been used to improve knowledge of aeroallergens, especially concerning possible source locations of these aeroallergens. These studies include source-receptor studies on pollen from *Fagus* (Belmonte et al., 2008), *Betula* (Mahura et al., 2007; Skjøth et al., 2007; Veriankaite et al., 2010), Poaceae (Smith et al., 2005), Olea (Hernandez-Ceballos et al., 2011b), *Ambrosia artemisiifolia* (Cecchi et al., 2007; Fernández-Llamazares et al., 2012; Sikoparija et al., 2009) and *Quercus* (Hernandez-Ceballos et al., 2011a). This suggests that similar analysis on fungal spore observations (e.g. *Alternaria*) from the Hirst trap also can identify sources of the most important genera of fungal spores.

Fungal spores that are among the most often observed genera are *Aspergillus, Pennicillium*, *Cladosporium* and *Alternaria* (Lang-Yona et al., 2012; Larsen, 1981). The genus *Alternaria* includes numerous plant pathogens (Gravesen et al., 1994) and *Alternaria* spores are considered an important part of the total fungal spectrum in, e.g. potato crops (e.g. Escuredo et al., 2011; Iglesias et al., 2007). *Alternaria* spores of the species *Alternaria alternata* can also threaten human health (Damato and Spieksma, 1995) and cause allergic symptoms in sensitized individuals when the atmospheric concentrations are high (Gravesen, 1979). The observational methods in the Danish and the European monitoring programme rely on visual identification of pollen and fungal spores. This means that this method cannot identify *Alternaria alternata* from the genus *Alternaria*. The threshold of 100 spores m^{-3} is based on the methods that include both a slit sampler (for growing colonies and subsequent identification) and a Hirst trap for providing atmospheric concentrations (Gravesen, 1979). As such, the threshold of 100 spores m^{-3} includes both allergenic and non-allergenic fungal spores from the genus *Alternaria*. The sources of airborne *Alternaria* spores are considered to be mainly vegetation such as forest and agricultural land (e.g. Stepalska et al., 1999) during the drying and decomposition of aboveground plant tissues (Escuredo et al., 2011; Iglesias et al., 2007). The studies by Skjøth and Sommer (2010) showed that in Denmark the *Alternaia* season ends in the middle of September, which is about a month before leaf fall in the forests. Similar studies from Poland showed that the peak of the *Alternaria* spore season is found in July–August, while October–November has a relatively small load of *Alternaria* spores (Stepalska et al., 1999). This suggests that decomposition of tree leaves does not contribute to the overall *Alternaria* load in Northern and Central Europe. In the UK, agricultural areas near Cardiff and Derby have been suggested as potential sources of high *Alternaria* concentrations (Corden et al., 2003), and studies from northern Portugal and Poland have shown that rural areas have a higher load of *Alternaria* than nearby urban areas (Oliveira et al., 2009). Wheat harvesting has previously been shown to release large numbers of spores into the air (Friesen et al., 2001), exposing harvesters to large amounts of viable fungi (Hill et al., 1984). Vegetation in agricultural areas is therefore a likely main source of *Alternaria* spores in many parts of Europe. Studies from the USA have shown that spores from agricultural areas that are infected with soybean rust (*P. meibomiae* and *P. pachyrhizi*) have the potential to be transported more than 1000 km under favourable weather conditions (Isard et al., 2005, 2007). European studies on other aeroallergens have shown that the overall load in a region is typically due to local sources with intermittent long distance transport from remote regions (Skjøth et al., 2009; Smith et al., 2008). *Alternaria* spores vary in size (10–40 µm × 10–220 µm), have cylindric forms and fall speeds between 0.4 and 4 cm s^{-1} (McCartney et al., 1993). *Alternaria alternata* is among the smallest among this group of fungal spores, with an aerodynamic diameter of 19 µm. It is therefore likely that *Alternaria* spores, including *Alternaria alternata*, have a similar potential for atmospheric transport as other aeroallergens. This suggests that the temporal and spatial variation of *Alternaria* spores is mainly dependent on the proximity of local sources and only secondarily dependent on long distance transport (LDT) from areas with a high load of *Alternaria*.

In this study we hypothesize that Danish agricultural areas are the main source of airborne *Alternaria* spores in Denmark, and that the contribution to the overall load is mainly local but with intermittent LDT from non-Danish areas with both a high density of agricultural areas and a potentially high load of *Alternaria* due to harvest. We have adapted a protocol that has been used in several similar European studies on allergenic pollen since 2007 (Hernandez-Ceballos et al., 2011b; Sikoparija et al., 2009; Stach et al., 2007) and use the definitions of local regional and long distance transport as given by Orlanski (1975). Here we investigate our hypothesis by analysing a 10 yr record of bi-hourly *Alternaria* spore observations from Copenhagen with respect to seasonality, overall daily pattern and potential source areas to LDT, combined with a dedicated field study on potential emission sources in agricultural areas.

Table 1. Seasonal spore index, day of season start, day of season end, and day of maximum spore concentration and its value. Sum of spores during season, sum on low days and sum on high days and number of days above the critical threshold of 100 spores as a daily mean value. The sum of low days and high days correspond to the total accumulated catch during the season (the days that cover 95 % of the entire catch) and not the entire year.

Year	Seasonal Spore Index	Day of season start	Day of season end	Day of maximum concentration	maximum value spores m^{-3}	Sum of spores in season	Sum, low days in season	Sum, high days in season	Days above 100 (high) spores m^{-3}
2001	9431	6 Jul	20 Sep	17 Aug	1016	8966	1875	7091	23
2002	7046	5 Jul	12 Sep	29 Jul	567	6686	1877	4809	21
2003	4488	18 Jul	18 Sep	19 Jul	279	4257	1291	2966	17
2004	5651	2 Jul	8 Sep	6 Aug	607	5321	1266	4055	18
2005	8141	21 Jun	20 Sep	10 Aug	468	7565	1600	5965	20
2006	10 781	1 Jul	21 Sep	11 Aug	682	10 251	2164	8087	27
2007	7813	20 Jun	28 Aug	17 Jul	588	7386	1735	5651	22
2008	5276	26 Jun	11 Sep	31 Aug	313	5006	2208	2798	17
2009	10 511	1 Jul	15 Sep	9 Aug	595	9989	1780	8209	31
2010	7519	8 Jul	8 Sep	3 Aug	689	7178	1651	5527	27
Mean	7946	1 Jul	12 Sep	6 Aug	580	7261	1745	5516	23
SD	2239	7 days	7 days	13 days	208	2044	315	1917	5

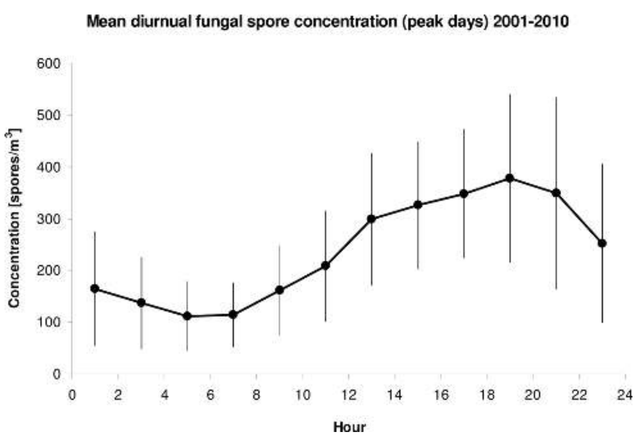

Fig. 1. Mean diurnal *Alternaria* spore concentration for days above 100 spores m^{-3}, $n = 232$. The error bar for each mean value corresponds to 1 standard deviation.

2 Methodology

2.1 Spore trap data and analysis of episodes

Measurements from Copenhagen obtained within the Danish pollen and spore program (Skjøth and Sommer, 2010; Sommer and Rasmussen, 2009) have been analysed for 2001–2010 with respect to *Alternaria* spores. In the monitoring programme, *Alternaria* spores are identified at genus level and counted at 640× magnification on 12 transverse strips for every two hours. The total area of investigation corresponds to 9.75 % of the total sample. This area and the flow rate of the fungal spore trap can be used to convert the spore count into bi-hourly concentrations or daily mean concentrations. The trap was located on the roof of the Danish Meteorological Institute (55°43′ N, 12°34′ E) in the centre of Copenhagen at a height of 15 m above sea level. The near surroundings to the trap in Copenhagen are urban, while nearby areas within a distance of ≥ 30 km are mainly agricultural in both southern Sweden and Denmark, as described by Skjøth et al. (2008). Summaries of the data for the 10 years are organised in two tables in a similar way as Kasperzyk et al. (2011) with respect to the annual spore index (the summation of daily mean values), day with maximum concentration and start of season (Table 1). The annual spore index is dimensionless by convention in aerobiology (Mandrioli et al., 1998), although Buters et al. (2012) recently have argued that the unit of the associated equation must be $\sum$ grains m^{-3}. The *Alternaria* seasons were defined using the 95 % method (Goldberg et al., 1988), as this is the standard analytical method in the Danish pollen and spore program (Skjøth and Sommer, 2010; Sommer and Rasmussen, 2009). Each of the 10 yr are therefore investigated during that period, when the accumulated number of fungal spores are between 2.5 % and 97.5 % of the total annual catch. The daily average concentration of 100 *Alternaria* spores m^{-3} has been reported as a clinical threshold for allergic symptoms (Gravesen, 1979; Ricci et al., 1995). Therefore, days with daily average concentration above 100 spores m^{-3} were investigated for the mean diurnal variation (Fig. 1). *Alternaria* episodes ($>$ 100 spores m^{-3}) that showed diurnal patterns that were markedly different from the mean daily cycle (Table 2) were investigated further using back trajectory analysis, in a similar way as in related studies on *Betula* (Skjøth et al., 2009), *Quercus* (Hernandez-Ceballos et al., 2011a), *Olea* (Fernández-Rodríguez et al., 2012; Hernandez-Ceballos et al., 2011b)

Table 2. Days with episodes (above 100 spores m^{-3}) of fungal spores with a markedly different daily pattern compared to the overall daily pattern of the 232 episodes recorded in Copenhagen during 2001–2010.

Date/hour	1	3	5	7	9	11	13	15	17	19	21	23
22 Jul 2001	264	276	384	216	300	216	36	132	84	156	192	180
21 Jul 2003	84	156	204	252	336	384	192	24	48	24	84	12
26 Jul 2003	168	564	432	156	24	0	0	36	0	12	0	60
5 Sep 2004	408	384	204	228	132	228	180	120	144	84	36	0
25 Aug 2005	348	324	300	492	216	84	0	48	0	24	0	36
10 Aug 2006	1452	876	840	600	504	36	96	420	228	420	384	192
25 Aug 2006	384	456	168	288	312	180	168	216	120	180	108	120
26 Aug 2006	168	144	192	84	132	180	108	180	60	12	0	12
05 Aug 2007	708	540	540	732	444	492	480	288	420	444	96	36
11 Aug 2007	216	324	264	252	252	252	444	60	0	48	48	12
31 Aug 2008	660	420	540	480	228	600	336	180	84	144	72	12
22 Jul 2009	312	264	444	264	168	216	360	192	24	36	12	48
27 Jul 2009	48	48	156	348	276	36	96	12	12	132	48	84
6 Aug 2010	468	420	420	276	324	168	396	228	312	204	72	108
11 Aug 2010	216	360	336	336	228	24	12	0	0	24	12	12
16 Aug 2010	1344	1428	300	312	204	420	204	504	312	12	0	48

and *Ambrosia artemisiifolia* (Fernández-Llamazares et al., 2012; Kasprzyk et al., 2011; Sikoparija et al., 2009).

2.2 Field observations and emission estimates

Emission estimates of *Alternaria* spores during harvest were obtained at four locations around Tune, Roskilde, Denmark. Samples were obtained from wheat and barley fields between 18 August and 16 September 2011. The measurements were taken as grab samples (i.e. a small but representative sample) from the exhaust airstream of the harvesting machine. The grab samples were allowed to immediately sediment onto glass slides for later microscopic counting of spores. Visual inspection of the fields revealed that none of the crops displayed signs of fungal infection. The barley fields had been treated against fungal infections by spraying with pyraclostrobin and tebuconazole on 15 June 2011. The wheat fields had been treated against fungal infections by spraying with propiconazole on 18 April 2011, with pyraclostrobin, epoxiconazole and boscalide on 25 May 2011, and again with epoxiconazole and boscalide on 16 June 2011. All applications were according to manufacturers' and agricultural advisors' recommendations, targeting the fungicide resistance spectra of local fungal pathogens. The fungicides used were neither targeted at, nor are claimed active against *Alternaria* spp., although it cannot be excluded that the fungicides used in the study fields initially had an inhibitory effect on *Alternaria* spp. Even though *Alternaria triticina* has been reported to cause fungal infections in wheat in India (Singh et al., 1998) and Argentina (Perelló and Sisterna, 2005), in Europe the economic effect of *Alternaria* spp. is considered insignificant in barley (Gannibal, 2008) and rare in wheat (Gultyaeva, 2008), making their chemical control unnecessary. During maturing and senescence of crop plants, prior to harvest the earlier applied systemic fungicides will cease to have an effect, which indeed is a regulatory condition for their use. Therefore, as *Alternaria* spp. are common to the environment, having a role in the decay of organic matter (Kirk et al., 2008), any *Alternaria* spores found in this study most likely will reflect the normal course of fungal invasion of grain crops during early summer, occurring in most or all fields of Central and Northern Europe where moist conditions occur intermittently during the weeks prior to harvest.

The harvester was a CASE-IH Agriculture model 7120 Axialflow combine with a type 3050 cutter table (width 915 cm). During sampling of emission estimates, the harvester advanced at ca. 4 km h^{-1}, with its air throughput being set to ca. 950 (unitless machine value, corresponding to ca. 570 m^3 min^{-1}). The straw shredder was running on two sampling dates, on the two others it was turned off.

Samples of emissions were obtained by manually directing the harvester's exhaust air stream through a 155 cm long piece of ventilation pipe (polished steel; inner diameter, 20 cm) and abruptly closing the input end with a padded nylon-covered lid. Immediately after closure, the pipe was positioned upright, with the lid on the upper end. The bottom end was maintained open for 10 s to allow coarse particles to escape. Then the bottom was sealed using a standard ventilation pipe stopper (polished steel, with a rubber seal around the edge). The stopper had a glass slide centred on the flat inner side. The effective sedimentation distance, from the surface of the padded lid to the surface of the glass slide, was 155.5 cm. Samples of emissions were produced by allowing particles to sediment onto the glass slide from the air column inside the pipe for 9 min. After sedimentation, the slide was removed and archived for later microscopic analysis. In several cases, residual control samples were taken by continuing the sedimentation for another 9 min on a fresh glass slide and maintaining the pipe firmly in an upright position. Negative control samples included environmental air from the middle and from the upwind end of each field. Prior to each sampling, the inside of the pipe was cleaned with a stream of clean air.

The glass slides for emission estimates were identical to those slides that are used in the Danish pollen and spore program (Skjøth and Sommer, 2010; Sommer and Rasmussen, 2009). The surfaces of the slides were inspected for *Altenaria* spores by using the spore counting method for *Alternaria* in the Danish pollen and spore program (Skjøth and Sommer, 2010). The microscopic counts were then converted to spores per volume of air in the exhaust air of the harvesting machine by using the area that has been investigated on the slide with the microscope (0.00006552 m^2), and the sedimentation distance inside the pipe (1.55 m) for the third dimension. The spore concentrations were converted to estimates of *Alternaria* spores per ha of harvested field by using the width of the cutting table (9 m) and the driving speed (4 km h^{-1}) of the harvesting machine, and by assuming that the grab sample was representative for the exhaust air stream (570 m^3 min^{-1}) of the harvesting machine. Microscopic counts and calculated fungal spore densities for each sample, along with estimated emission factors for the fields, are presented in Table A1.

2.3 Model calculations and potential source map

Agricultural areas under rotation and with mechanical harvesting methods have been identified in the CLC2000 dataset (European Commission, 2005) to consist of the following three land cover types: non-irrigated arable land (code 211), permanently irrigated land (code 212), and pastures (code 231). The land cover data have been extracted for Central and Northern Europe (Fig. 2) and gridded to a tenth of the EMEP50 grid (http://www.emep.int/grid/griddescr.html) using a similar methodology as Skjøth et al. (2010) and Fernández-Rodríguez (2012). The EMEP grid is commonly used for inventories in European air quality studies including the use of the chemistry transport models EMEP (Fagerli and Aas, 2008; Simpson et al., 2012), the EMEP4UK (Vieno et al., 2010) and DEHM (Brandt et al., 2012; Skjøth et al., 2011). This procedure allows easy comparison of density of relevant emission areas throughout the region and analysis in relation to atmospheric transport (e.g. Fernández-Rodríguez et al., 2012).

Back trajectories were computed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler et al., 2007). Trajectories were calculated using the GDAS (Global Data Analysis System) meteorological files maintained by ARL, with a temporal resolution of 3 h and a spatial resolution of 1 degree × 1 degree. Air mass trajectories were calculated at Copenhagen during the identified

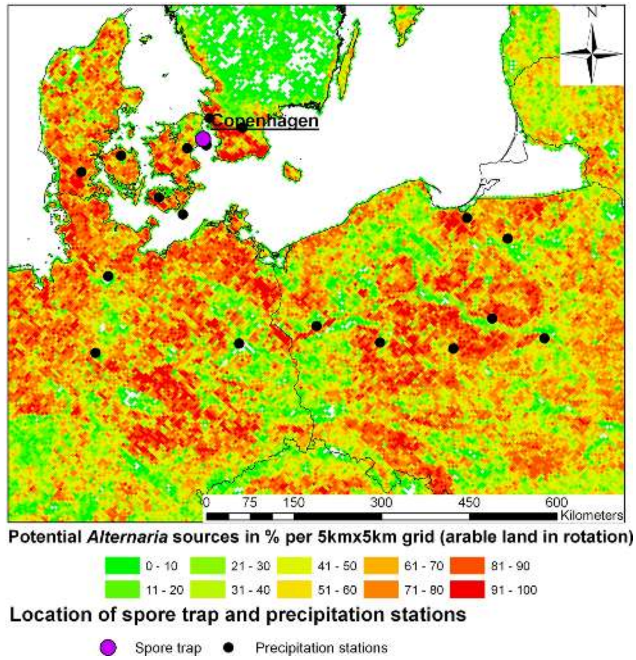

Fig. 2. Site map including the location of the spore trap in Copenhagen, the used precipitation stations (Table A2) and the density of agricultural areas under rotation – the potential source of *Alternaria* spores during harvest.

episodes with a receiving height of 500 m, which in general is representative for this kind of aerobiological studies (e.g. Hernandez-Ceballos et al., 2011a). Air mass trajectories were plotted 48 h back in time with 2 h steps between each trajectory, corresponding to the time step of the fungal spore observations – following the method described by Stach et al. (2007) and later used by Skjøth et al. (2008, 2009), Smith et al. (2008), Sikoparija et al. (2009), and Hernandez-Ceballos et al. (2011a, b) – by using either the ACDEP (Skjøth et al., 2002) in the matrix style (Skjøth et al., 2007) or the HYSPLIT (Draxler et al., 2007) models. Measured precipitation from weather and climate stations have been used as an estimate for potential *Alternaria* spore release due to harvest in the potential source regions (Fig. 2 and Table A2) by assuming that dry weather and dry fields are required for intense harvesting. Local meteorological observations of wind speeds during the episodes (Table A3) have been obtained from one meteorological mast located approx. 1500 m south of the pollen trap (Skjøth et al., 2008), which is operated by Aarhus University for use in the so-called integrated monitoring of air quality in Denmark (Hertel et al., 2007).

3 Results

3.1 Seasonal and daily variations of *Alternaria* in Copenhagen

The annual spore index of *Alternaria* in Copenhagen varied by more than a factor of two in the spore index from 4488 in 2003 to 10 781 in 2006 (Table 1). The mean of the season start was day number 182, while the mean maximum day during the season was number 218, with a standard deviation of 7 and 13 days, respectively. The highest daily concentration was 1016 spores m^{-3} on 17 August 2001 (the second largest was 853 spores m^{-3} on the following day, not shown). The highest observed bi-hourly concentration was 2727 spores m^{-3} (not shown). A total 232 days during the 10 yr period had high concentrations above the clinical threshold of 100 spores m^{-3}. The contribution from individual years ranged from 17 high days in 2003 (of 70 days in total within the spore season) and 2008 (of 60 days in total) to 31 days in 2009 (of 76 days in total). The contribution of the high days to the total seasonal load varied from about 55 % in 2008 to more than 82 % in 2009. The analysis of bihourly *Alternaria* spore concentrations at high days shows a typical daily pattern (Fig. 1), with high concentrations in the late afternoon reaching 378 spores m^{-3} and a minimum at 112 spores m^{-3} early in the morning. Sixteen (16) of the 232 high days had a very different pattern compared to the typical daily pattern (Table 2). These non-typical daily patterns were identified by both visual inspection of each individual day and correlation analysis of the individual days with the mean pattern. Additionally, an inspection of the day before and the day after the period was also carried out in a similar methodology as given in other studies (Sikoparija et al., 2009; Skjøth et al., 2009). Except for the year 2002, each year had one or more of these 16 non-typical high days. Trajectory calculations show that all of the 16 non-typical high days had air masses arriving from main agricultural areas in southern Scania (Sweden), Denmark, Poland or Germany. The three most outstanding episodes with respect to both load and pattern are discussed in detail in Sect. 3.3 using trajectories and the source map (Figs. 3–5).

3.2 *Alternaria* emission sources in local agricultural fields

Analysis of the field data revealed between 10^6 and 10^7 *Alternaria* spores m^{-3} in the exhaust air of the harvesting combine (Table A1). These have been converted into emission between 1.2×10^{10} and 6.7×10^{10} *Alternaria* spores ha^{-1} during harvest. Residual control slides from a second sedimentation period gave 10–15 % of the initial slide. This suggests that the sedimentation efficiency in the pipe was 85–90 % for *Alternaria* spores when using 9 min sedimentation time. Negative controls always counted as zero (data not shown). In addition, when the farmer let the machine run idle (the machine not advancing, i.e. no grain being harvested, but the motors running at normal speed), we were unable to find spores in the exhaust of the machine.

3.3 Trajectory calculations, potential source map and long distance transport

The inventory of potential sources to *Alternaria* spores in Central and Northern Europe (Fig. 2) reflects the density of managed agricultural areas that are under rotation. The inventory shows that the potential sources to *Alternaria* spores are found in many parts of the studied area. The highest densities (70–100 %) are found in western Denmark, central and northern Germany, southern Scania (Sweden) and central Poland. Much lower densities (0–20 %) are found in most of southern Sweden, southern Germany, along the border between Germany and Poland, the southern parts of Poland and the Baltic countries.

In Sects. 3.3.1–3.3.3, the three most outstanding episodes with respect to both load and pattern are discussed in detail, using trajectories and the source maps and the overall weather pattern, including measured accumulated precipitation in the potential source region.

3.3.1 Episode 1: 30–31 August 2008

Daily average *Alternaria* spore concentrations observed on 30 and 31 August 2008 in Copenhagen were 161 and 313 spores m^{-3}, respectively. Hourly *Alternaria* spore concentrations were low in the beginning of the period and increased quickly to above 700 spores m^{-3} late in the evening of the 30th and remained at a level of around 600 spores m^{-3} until midday the 31st (Fig. 3a). From midday the 31st and until late in the evening, the concentrations gradually decreased below 100 spores m^{-3}. The weather in the study region had a high pressure ridge extending from Iceland (1029 hPa) over Scandinavia ($\sim$ 1020 hPa) to northern Germany and central Poland (1022–1023 hPa). This caused air masses to be pushed from the north towards Copenhagen. Around midday of the 30th, wind speeds decreased (by investigating the distance between the trajectory points) and the air masses remained for a number of hours over Denmark and Scania, the southernmost province of Sweden, before arriving in Copenhagen. Similar situations with low wind speeds were also present the 31st (Fig. 3b and c). This was also reflected by measured wind speeds down to about 1 m s^{-1} at nighttime during the episode (Table A3). A few mm of precipitation were recorded on the 29th in the entire region, and the most eastern parts of Denmark and Sweden also recorded precipitation on the 28th and 27th (Table A2). This suggests harvesting possibilities in Denmark and Sweden starting the 30th and good harvesting possibilities on 31 August.

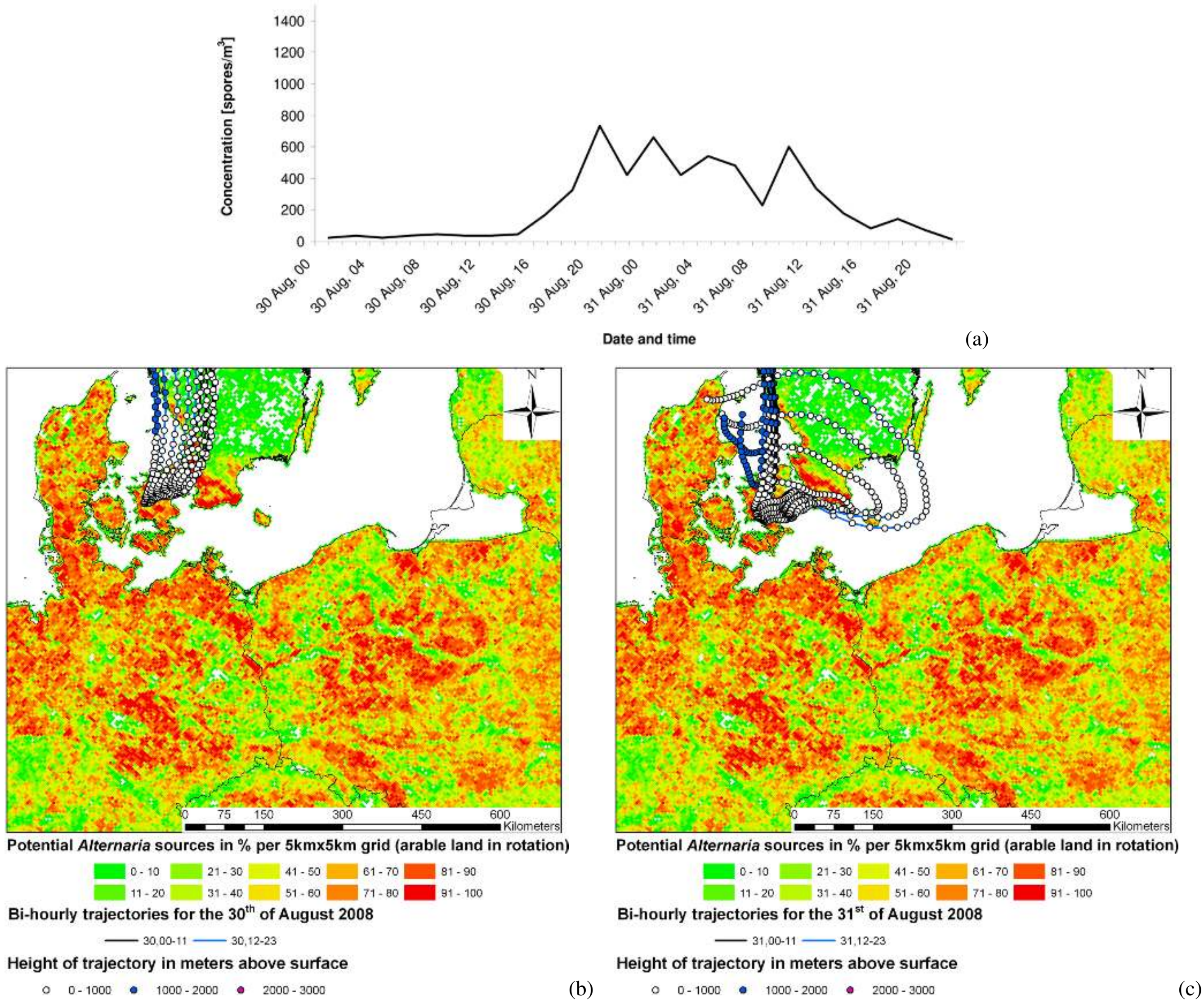

Fig. 3. **(a)** Bi-hourly variation in *Alternaria* spore concentrations (spores m^{-3}) obtained in Copenhagen 30 and 31 August 2008. Back-trajectories arriving at the spore trap in Copenhagen: **(b)** 30 August; **(c)** 31 August. The distance between two dots on a trajectory corresponds to one hour of atmospheric transport.

3.3.2 Episode 2: 10–11 August 2010

Daily average *Alternaria* spore concentrations observed on 10 and 11 August 2010 in Copenhagen were 153 and 130 spores m^{-3}, respectively. Hourly *Alternaria* spore concentrations had a number of peaks (200–400 spores m^{-3}) from the beginning of the period until midday 11 August (Fig. 4a). After that the concentrations remained low. The weather in the study region was dominated by a high pressure system (1018–1019 hPa) over central Germany and Poland, which during most of the period pushed air masses from the south and southwest towards Copenhagen, passing either Danish or German land areas including water areas (Fig. 4b and c). Measured wind speeds ranged from about 2 m s^{-1} to more than 6 m s^{-1}, where the highest wind speeds were observed in the afternoon of the 11th (Table A3). Heavy precipitation was recorded over eastern parts of Denmark and Scania on 9 August (Table A2). The eastern, western and southern parts of Denmark recorded almost no precipitation from 5 to 11 August 2010, suggesting generally good harvesting possibilities in most of Denmark and northern Germany until at least 10 and partly 11 August.

3.3.3 Episode 3: 15–16 August 2010

Daily average *Alternaria* spore concentrations observed on 15 and 16 August 2010 in Copenhagen were 262 and 424 spores m^{-3}, respectively. Hourly *Alternaria* spore concentrations were low until around midday of the 15th

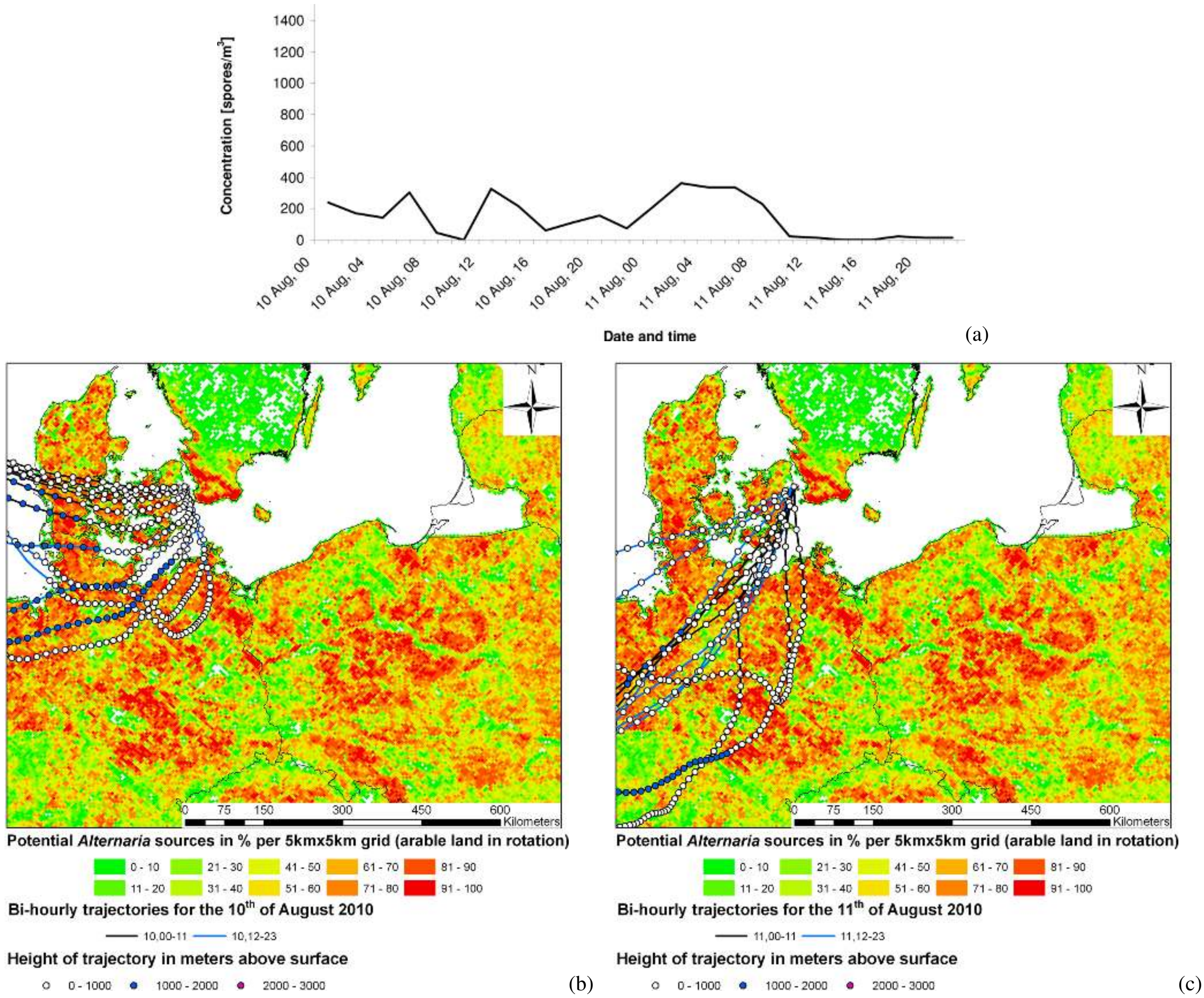

Fig. 4. (a) Bi-hourly variation in *Alternaria* spore concentrations (spores m^{-3}) obtained in Copenhagen 10 and 11 August 2010. Back-trajectories arriving at the spore trap in Copenhagen: **(b)** 10 August; **(c)** 11 August. The distance between two dots on a trajectory corresponds to one hour of atmospheric transport.

and then had two distinct peaks exceeding 1000 and 1400 spores m^{-3} late in the evening the 15th and during early morning the 16th (Fig. 5a). Hereafter concentrations remained high at between 200 and 400 spores m^{-3} until late in the evening of the 16th, when concentrations dropped to near zero. The weather in the study region had a high pressure area (∼ 1010–1021 hPa) covering most of Poland, the Baltic countries, Russia and reaching down to the Balkan region. At the same time, minor low pressure centres (1006–1013 hPa) were located over southern Sweden and Germany. This caused air masses from the Eastern and the Baltic states to be pushed towards Denmark in the beginning of the period. These air masses arrived in Copenhagen from the northwest, passing over northern parts of Scania. Around midday of the 15th, winds veered to the south so that the air masses originated from either Germany or Poland. These air masses crossed the Baltic Sea and arrived in Copenhagen either directly from the sea or by crossing the southern parts of Scania in Sweden. Measured wind speeds ranged from about 1 m s^{-1} to more than 6 m s^{-1}, where the highest wind speeds occurred on the first half of the 16th (Table A3). Heavy precipitation was recorded over Denmark and Scania the 13th and 15th (Table A2). Medium precipitation was recorded at Wielkopolski 13, 14 and 15 August, while the remaining 6 Polish stations recorded limited or no precipitation. This suggests that during the episode there were limited harvesting possibilities in Denmark/Sweden and good harvesting possibilities in Poland.

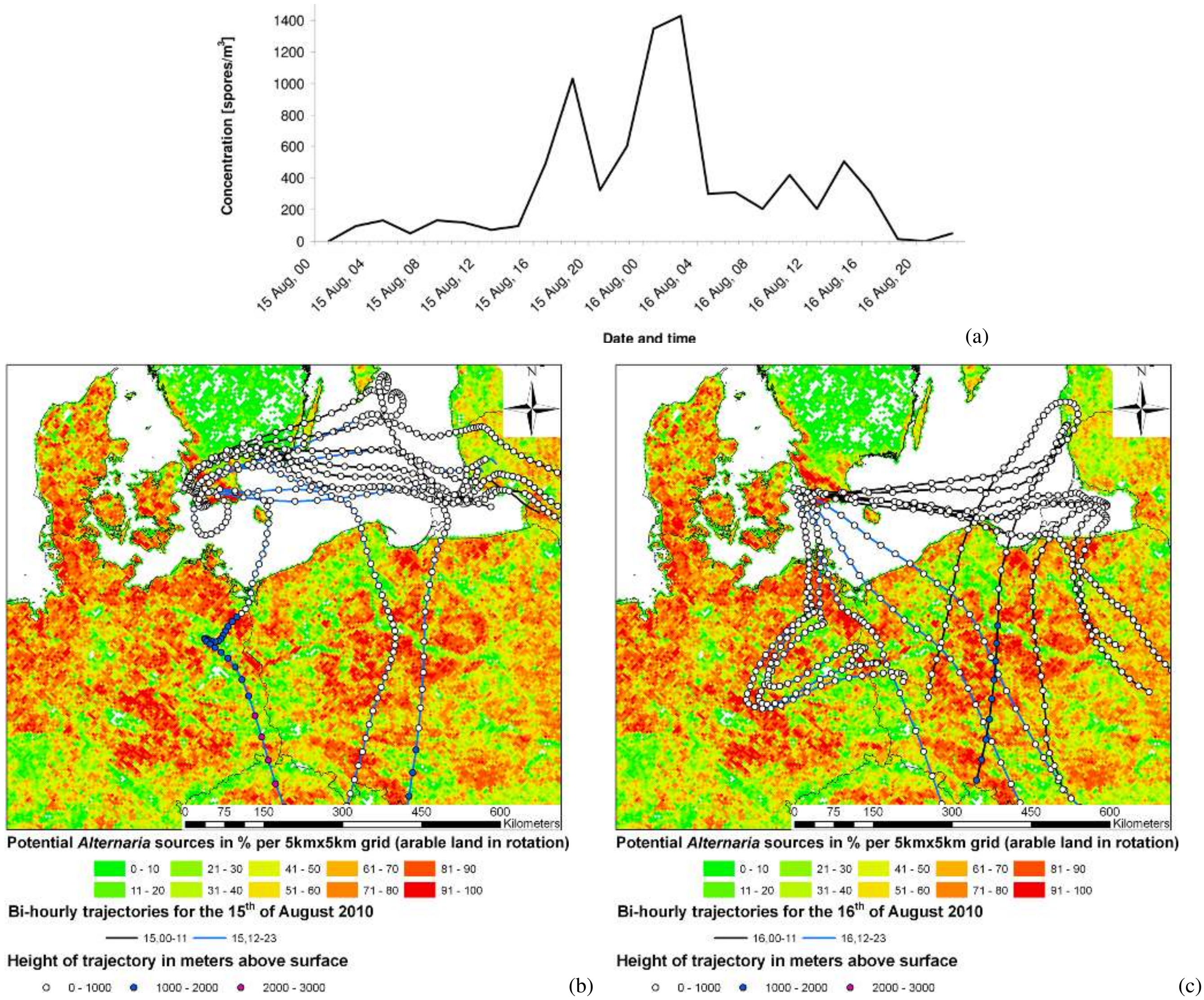

Fig. 5. (a) Bi-hourly variation in *Alternaria* spore concentrations (spores m^{-3}) obtained in Copenhagen 15 and 16 August 2010. Back-trajectories arriving at the spore trap in Copenhagen: **(b)** 15 August; **(c)** 16 August. The distance between two dots on a trajectory corresponds to one hour of atmospheric transport.

4 Discussion

The measured airborne concentrations of *Alternaria* spores in Copenhagen show that the majority of the 232 high days have a strong diurnal pattern with a maximum in the late afternoon and a minimum during night or early morning (Fig. 1). If the main source of *Alternaria* spores were remote sources, then this daily pattern could have been either non-existent or peaked at any time of the day, as the big plumes of LDT of aeroallergens can arrive in Copenhagen at any time of the day or night (Mahura et al., 2007; Skjøth et al., 2007, 2008). The number of high days are outnumbered by low days (Table 1), but every year the total load during the season has been dominated by the high days, which contributed up to 82 % of the entire *Alternaria* load during the season (Table 1). Here we have investigated all 232 high days individually. Only 16 (Table 2) of the 232 high days have a diurnal pattern that deviates from the overall pattern (Fig. 2). The potential source map (Fig. 2) shows that Denmark is dominated by land cover types that can be a strong source of *Alternaria* spores. Additionally, the emission study from a typical land cover with agricultural production in rotation shows that emission during harvest releases a large amount of *Alternaria* spores, even when the fields have been treated with fungicides. Finally, the small fraction of high days, which show a diurnal pattern that differs from the overall pattern, have been analysed with respect to air mass transport (using HYSPLIT and the reanalysis meteorological dataset). In all cases, the air masses came from more remote areas that are also dominated by land cover types containing potential sources to *Alternaria* spores. Such episodes were identified almost every year during the study period (Table 2). Additionally, it was shown that even if a region such as eastern Denmark and southern Sweden had obtained very large amounts of rain, making harvest very difficult, more remote regions, e.g. Poland, could have contributed with large amounts of *Alternaria* spores (Fig. 5). Overall, these studies suggest that the daily load of *Alternaria* spores is dominated by local or regional sources with intermittent LDT from more remote sources, in e.g. Germany and Poland, and that these LDT episodes can happen almost every year.

Recently, a number of source receptor studies on aeroallergens have been carried out by combining measured concentrations from the Hirst traps with trajectory calculations. These studies have identified both local sources and intermittent long distance transport from regions with high source densities. Common to all of these source-receptor studies is that they focus on pollen such as *Betula* (Mahura et al., 2007; Skjøth et al., 2007, 2008; Veriankaite et al., 2010), *Quercus* (Hernandez-Ceballos et al., 2011a) *Olea* (Fernández-Rodríguez et al., 2012; Hernandez-Ceballos et al., 2011b) and *Ambrosia artemisiifolia* (Fernández-Llamazares et al., 2012; Kasprzyk et al., 2011; Sikoparija et al., 2009). Our study suggests that the methodology used for allergenic pollen can be extended to fungal spores and that agricultural fields are a potential source of elevated *Alternaria* spore concentrations.

The *Alternaria* spore emissions we have measured during harvest may be considered average for state-of-the-art agricultural practice. Fungal disease was not observed in either wheat or barley fields that were harvested. Despite this, fungal spore concentrations were recorded during harvest using grab samples from the exhaust to estimate emissions from the harvesting machine. The grab samples were taken on four different days from different fields containing barley and wheat. These emission estimates from measurements in the Danish fields gave surprisingly uniform results, about 5×10^{10} spores ha^{-1} during harvest. With this emission factor, a simple Eulerian box model calculation suggests that if 2 % of the entire surface area in a region is harvested, the threshold of 100 spores m^{-3} would be exceeded in the harvested region. Here it is assumed that spores are kept airborne the entire day, that spores are well mixed in the atmosphere up to 1000 m, that all fungal spores are kept in the local region and that all harvested areas have an emission factor similar to the Danish areas that were treated with fungicides. Thus, our emission factor could be related to the geographical location or could be a function of agricultural management, such as the use of machinery or application of fungicides. How the real distribution in the atmosphere will be in case the emission factor varies between fields, and when atmospheric transport and deposition is taken into account, are not known. However, it is known that the concentrations in rural areas typically are larger than in nearby urban areas (Kasprzyk and Worek, 2006). This suggests the importance of atmospheric transport from nearby agricultural sources. Furthermore, the low variation in the samples suggests that the experimental method is robust for estimating emission estimates, despite the crude sampling technique, and that it only requires a small number of samples. Surprisingly, fungal spore emissions were not increased after the rain period between 21 August and 10 September 2011, which one could have expected, as wet periods are known as periods of fungal growth. Instead, harvesting over moist soil after the rain period appeared to result in lower spore emissions. Observations similar to ours have been made for other agricultural fungal spores (Friesen et al., 2001) and for pollutants, such as ammonia. Here the local emission depends strongly on both climate as well as agricultural production methods (Gyldenkærne et al., 2005; Sommer et al., 2003, 2006). Our estimated emission of spores during harvest was of the same order of magnitude as in the study by Friesen et al. (2001), but using a much simpler approach. The simplicity of our method may therefore make it applicable to different areas.

The map produced in this study (Fig. 2) suggests that most of Denmark, southern Scania (Sweden), the northern and central parts of Poland and Germany, in contrast to southern Poland, have a high density of potential *Alternaria* source areas. Previously, the southern parts of Poland have been identified as having a lower *Alternaria* load compared to central Poland, especially Poznan (Stepalska et al., 1999). This lower load stood in contrast to the longer vegetation period in southern Poland compared to central Poland (Stepalska et al., 1999). The study by Stepalska et al. (1999) therefore indicates that there must be a higher density of sources in central Poland, thus supporting our map. If agricultural areas are the main source of *Alternaria* spores in Denmark, then it is likely that the fungal spore concentration is higher in western Denmark than eastern Denmark (Copenhagen). In our map of potential source areas, western Denmark has a considerably higher proportion of potential source areas than eastern Denmark. Similar relationships have previously been suggested by Corden et al. (2003), as Corden et al. (2003) found a high *Alternaria* spore load in Derby with high agricultural production and a low annual spore load at the coastal site in Cardiff, which had very limited cereal production. Also in southern Poland, results from the operational trap in Rzeszow were compared with results from a rural trap 10 km away (Kasprzyk and Worek, 2006). In the year 2001, the load was about the same at the two Polish sites, while the *Alternaria* load in the rural area was more than double the urban load in 2002 and with a markedly different seasonal pattern. For Denmark, such relationships remain to be investigated using more than one spore trap. Such studies would provide valuable information about western Denmark and can also be used to test the hypothesis in this paper as well as investigating the robustness of the proposed source map.

In a Spanish potato crop treated with fungicides, *Alternaria* spores were recorded during the entire growth season, but with a peak in *Alternaria* concentration during leaf senescence (Escuredo et al., 2011; Iglesias et al., 2007). This suggests that although fields are treated against fungal disease (and visual inspection does not reveal *Alternaria* attack), spores are still present in the field and released in varying quantities throughout the entire season. The Spanish studies also showed that the fungal spore load in the region of Ourense is higher in the field area (Escuredo et al., 2011) compared to the load that is observed in the nearby city area (Aira et al., 2008). This again stresses the importance of atmospheric transport on the local scale. More importantly, other studies by Hill et al. (1984) and Friesen et al. (2001) have observed very high amounts of spore release during harvesting. Similarly, Mitakakis et al. (2001) found periods of *Alternaria* burst during mowing and harvesting of grass in Australia. *Alternaria* spp. have been named among the agents of fungal diseases in wheat (*alternaria* leaf blight *A. triticina*; black head molds, *Alternaria* spp.) and barley (kernel blight, *Alternaria* spp.). Our study focused on a specific harvest situation, and samples were taken from a few wheat and barley fields that had been treated with fungicides. Sampling in infested crops, or crops that have not been treated with fungicides, or harvesting using different methods might therefore yield significantly different emission factors. If emission factors can be obtained from both growing crops and crop harvest (e.g. by using the simple methodology that we employed), then this will provide the much needed emission factors that can be used by atmospheric modellers in order to increase understanding of how *Alternaria* spores are released and distributed in the atmosphere.

The main characteristics of the spore season show that the annual variations in the spore index from Copenhagen varies by more than a factor of two from less than 5000 to more than 10 000. The annual index of *Alternaria* spores and the number of days with clinically relevant levels are correlated ($r^2 = 0.67$, column 2 and 10 in Table 1), which is not surprising as these numbers are highly dependent: the main load of *Alternaria* spores in Copenhagen is due to episodes of peak days (Table 1). The total uncertainty due to the counting method (Carinanos et al., 2000; Sikoparija et al., 2011; Sterling et al., 1999), i.e. the person that counts, means basic measurement errors and meteorology can easily reach 50 % in total on individual days (Pedersen and Moseholm, 1993). This error requires large differences in the counts in order to be statistically significant. However, much larger samples, such as the samples that produced Fig. 1 (with $n = 232$), only require a 10 % difference in order to be statistically significant when the formula by Pedersen and Moseholm (1993) is used. This small difference must however also be compared to the rather large variation in the actual dataset as given by the error bars on Fig. 1. The error bars in Fig. 1 and the 10 % difference as requirement for statistical significance therefore suggest that the observed daily variation is both statistically significant and physically relevant. The annual level in Copenhagen is generally higher than the levels that are observed on the Spanish part of the Iberian Peninsula (Aira et al., 2008; Rodriguez-Rajo et al., 2005) or in Sweden (Hjelmroos, 1993), where the annual spore index of *Alternaria* has been reported to be in the range of 1000–4000. Similar levels as in this study were also reported for Warszawa in a Polish study by Stepalska et al. (1999). The same Polish study also showed that the annual loads in Poznan can have an index that exceeds 30 000. Such large loads were also observed by Angulo-Romero et al. (1999) and Maya-Manzano et al. (2012) in Merida in 1997, where the spore index for *Alternaria* was about 20 000, 25 000 and 50 000, respectively. The studies from Spain also pointed out that large geographic variations exist in the spore count, as another site, Caceres, only had a spore index of about 2000. Here it is worth to note that Caceres is a region in Spain with limited crop production, while Merida is a Spanish region with large amounts of irrigated crops such as maize, tomato and fruit trees (Maya-Manzano et al., 2012). The study by Mayo-Manzano et al. (2012) as well as Stepalska et al. (1999) show that the variation in the load in the same biogeographical region can differ by more than a factor of ten between years and between sites. Such large variations can be difficult to explain and map using volumetric spore traps alone. The seasonal variation found in this study with only one single peak has been found in most European studies such as Poland, Sweden, England and Spain. Bimodal peaks are only found in the Mediterranean region (Angulo-Romero et al., 1999; Cosentino et al., 1995; De Linares et al., 2010; Giner et al., 2001; Lang-Yona et al., 2012; Maya-Manzano et al., 2012). All these studies on annual loads, on seasonal variations as well as our study highlight the interrelated connection between overall weather in the geographical regions as well as the abundance of local sources. Studies that focus on various aspects of source mapping (e.g. observations of load and comparisons between sites, source-receptor studies such as using trajectories or actual mapping of potential sources) are therefore all highly needed for fungal spores. Such studies provide much needed insight into an area that, according to an editorial in The Lancet (2008), has to some degree been forgotten and therefore needs much more scientific attention.

A number of studies have shown similar daily patterns as our study of *Alternaria* spore concentrations. Stepalska and Wolek (2009) showed that in Krakow the distribution of peak concentrations had a similar pattern as the peak concentrations in this study. In Krakow, peak concentrations are most often observed in the late afternoon, about a factor of three more often than during night and early morning (Stepalska and Wolek, 2009). Similar observations, with a peak in the late afternoon and a minimum in the night or early morning, were found in the north of Portugal (Oliveira et al., 2009; Rodriguez-Rajo et al., 2005), north of Spain (Aira et al., 2008), south of Spain (Angulo-Romero et al., 1999; Giner et al., 2001) and Italy (Ricci et al., 1995). This suggests that at all these sites, including Denmark, the overall load of *Alternaria* is due to local or regional sources and

Table A1. Observed *Alternaria* spores in grab samples from the harvesting machine, the calculated concentration of spores m^{-3} in the exhaust air and the corresponding emission factor from harvested fields.

Date	Crop	Remarks	Spores on slide ($0.6552\,cm^2$)	Concentration (spores m^{-3})	Emission factor per ha
18 Aug 2011	Wheat		721	4.0E+07	6.7E+10
18 Aug 2011	...	Residual control of previous sample	106	–	–
21 Aug 2011	Barley		630	3.5E+07	5.9E+10
21 Aug 2011	Barley		592	3.3E+07	5.5E+10
21 Aug 2011	Barley		662	3.7E+07	6.2E+10
21 Aug 2011	...	Residual control of previous sample	76	–	–
10 Sep 2011	Wheat		376	2.1E+07	3.5E+10
10 Sep 2011	Wheat		172	9.6E+06	1.6E+10
16 Sep 2011	Barley	Soil very wet.	131	7.3E+06	1.2E+10
16 Sep 2011	Barley	Soil very wet.	186	1.0E+07	1.7E+10

local dispersion. It is not known if LDT is a contributing factor at locations other than Copenhagen. This again calls for dedicated source-receptor studies on fungal spores from sites other than Copenhagen. Such studies can also be considered an answer to both the editorial in The Lancet (2008) as well as the overall recommendations given by Cecchi et al. (2010).

In Denmark, *Cladosporium* and *Alternaria* dominate the atmospheric fungal spore flora by 68.9 % and 9.4 % of the total fungal spore catch, respectively (Larsen, 1981). High season for fungal spores is June until October, but external meteorological factors affect the fluctuation from day to day and year to year (Larsen, 1981). Our studies suggest that the *Alternaria* concentrations can be explained by combining source maps with atmospheric transport. Such information can be relevant for both agriculture as well as patients that are sensitized to fungal spores. The number of patients that are sensitive to fungal spores is usually much lower than to pollen (Damato and Spieksma, 1995). A recent study estimates that 2.4 % of the entire population is sensitized to fungal spores (Elholm et al., 2010). However, the same data (Elholm et al., 2010) showed that asthmatics had a significantly higher prevalence of fungal spore sensitisation compared to non-asthmatics: 6.6 % vs. 2.0 % in the two genera, respectively. For sensitisation to *Alternaria*, the corresponding figures were 6.1 % vs. 1.7 %, and it has also been observed that the clinical reaction to fungal spores is often stronger than the reaction towards pollen (Sigsgaard personal communication). This calls for additional efforts in research, diagnosis and treatment of allergy, which would be a direct response to the editorial in The Lancet (2008), as well as the overall recommendations on aerobiological research as given by Cecchi et al. (2010), such as collection and analysis of aerobiological data on large spatial scales.

5 Conclusions

The present study supports the hypothesis that Danish agricultural areas are the main source of airborne *Alternaria* spores in Denmark, meaning that the source of the overall load is mainly local or regional, but with intermittent LDT from more remote agricultural areas. These LDT episodes contributed to a large degree to the total annual load of *Alternaria* spores. In fact, the high days dominate the overall *Alternaria* load, although high days are always outnumbered by low days. The hypothesis is supported by the analysed data of the 10 yr bi-hourly record of *Alternaria* in Copenhagen that shows a distinct daily profile of 232 clinically relevant episodes (Fig. 1) and the identification of potential long distance transport episodes (Table 2) from areas that could be potential source regions (Figs. 3, 4 and 5, respectively). The emission studies in cereal crops under harvest also support our hypothesis. The results showed that although the fields had been treated against fungal infections, harvesting still produced large amounts of airborne fungal spores. The findings agree well with related studies that show high *Alternaria* spore load in agricultural areas in Central Europe. This supports the hypothesis that crop harvest in Central Europe causes episodes of high airborne *Alternaria* spore concentrations in Copenhagen as well as other urban areas in this region.

Our findings have several implications. Firstly, forecasting of fungal spore quantities relevant to allergy patients in Denmark must take into account long distance transport, and cannot be based on measured concentrations in Denmark alone. Secondly, allergy patients need a warning several days ahead to plan their medical intake. This information is not available for fungal spores, as the Danish information system on fungal spores is very simplistic and is based on information

Table A2a. Daily measured precipitation in mm day^{-1} in the potential source region to the episodes of *Alternaria* spore concentrations (spores m^{-3}) that were measured 30–31 August 2008. The last 7 days of recorded precipitation until the potential episode is used as an indicator of good harvesting possibilities. "–" usually means no precipitation was recorded, but could potentially also mean technical problems.

Station/Date	31	30	29	28	27	26	25
061800 – Kastrup	0.0	0.0	3.3	3.8	6.6	0.0	0.0
061490 – Gedser	0.0	0.0	2.0	0.0	0.8	0.0	0.3
061200 – Beldringe	0.0	0.0	–	0.0	0.0	0.0	0.3
061410 – Abed	–	0.0	3.0	0.0	2.3	0.0	0.0
061700 – Roskilde/Tune	0.0	0.0	1.8	2.8	7.1	0.0	0.5
026230 – Hörby	0.0	0.0	2.8	8.1	3.8	0.0	0.8
026110 – Helsingborg	0.0	0.0	1.5	4.8	5.8	0.0	2.8
Berlin_Tegel	0.0	0.0	0.1	0.8	0.0	0.0	0.0
Hamburg	0.0	0.0	0.0	0.0	0.0	0.7	0.0
Hannover	0.0	0.0	0.0	0.5	0.0	0.0	0.0

Table A2b. Daily measured precipitation in mm day^{-1} in the potential source region to the episodes of *Alternaria* spore concentrations (spores m^{-3}) that were measured 10–11 August 2010. The last 7 days of recorded precipitation until the potential episode is used as an indicator of good harvesting possibilities. "–" usually means no precipitation was recorded, but could potentially also mean technical problems.

Station/Date	11	10	9	8	7	6	5
Kastrup	0.3	0.0	28.4	0.3	0.0	1.8	2.8
Skrydstrup	3.0	0.0	2.0	0.3	0.0	0.0	2.0
Gedser	0.5	0.0	0.3	0.0	0.0	1.0	2.0
Beldringe	0.0	0.0	0.0	0.0	0.0	0.0	–
Abed	0.3	0.0	0.0	0.3	0.0	–	0.0
Roskilde/Tune	0.0	0.0	0.0	0.0	0.0	0.0	1.8
Hörby	0.0	0.3	21.3	1.8	1.0	0.0	0.0
Helsingborg	0.0	0.0	24.6	0.0	0.0	0.0	1.8
Berlin_Tegel	0.0	0.0	0.3	0.3	0.0	11.6	0.0
Hamburg	2.1	0.7	0.7	0.1	0.0	0.0	4.5
Hannover	0.8	3.4	0.0	0.2	0.1	0.0	0.1

from Copenhagen alone (Skjøth and Sommer, 2010). An extension of the spore monitoring programme by using several spore traps would most likely be very useful, as our study suggests that the fungal spore load might be higher in other parts of the country. An alternative is to supplement the current information system with the mathematical model systems from chemical weather forecasting (e.g. Kukkonen et al., 2012) and extend these to include the spore production and emission from countries such as Germany and Poland, as well as the agricultural production in Denmark. This approach might however be very difficult as all relevant *Alternaria* sources remain to be identified. Furthermore, this as well as other studies suggest that the emission pattern is related to both biology and agricultural production methods.

Table A2c. Daily measured precipitation in mm day^{-1} in the potential source region to the episodes of *Alternaria* spore concentrations (spores m^{-3}) that were measured 15–16 August 2010. The last 7 days of recorded precipitation until the potential episode is used as an indicator of good harvesting possibilities. "–" usually means no precipitation was recorded, but could potentially also mean technical problems.

Station/Date	16	15	14	13	12	11	10
Kastrup	0.5	49.3	0.0	25.4	1.8	0.3	0.0
Roskilde/Tune	0.3	36.8	0.0	29.7	3.0	0.0	0.0
Hörby	5.3	8.1	0.0	22.9	0.0	0.0	0.3
Helsingborg	0.0	19.8	0.0	22.9	0.8	0.0	0.0
Poznan	0.0	0.0	3.0	0.0	0.3	0.0	0.0
Plock	0.0	0.0	0.0	0.0	0.0	36.6	0.0
Warszawa	1.5	0.0	0.0	2.0	0.0	0.0	15.0
Kolo	6.1	0.0	4.1	0.0	0.0	0.0	4.1
Wielkopolski	0.0	12.7	7.9	8.4	0.0	0.0	1.8
Olsztyn	1.0	0.0	5.1	0.0	0.0	0.0	20.3
Elblag	1.5	0.0	0.0	0.0	0.0	4.1	0.0

Table A2d. Geographical coordinates of precipitation stations obtained from National Centre for Environmental Prediction (NCEP) and Deutscher Wetterdienst (only German stations).

ID	Name	Lat (°)	Lon (°)
061800	Kastrup	55.617	12.650
061700	Roskilde/Tune	55.583	12.133
026230	Hörby	55.867	13.667
026110	Helsingborg	56.033	12.767
123300	Poznan	52.417	16.850
123600	Plock	52.583	19.733
123750	Warszawa	52.167	20.967
123450	Kolo	52.200	18.667
123000	Wielkopolski	52.750	15.283
122720	Olsztyn	53.767	20.417
121600	Elblag	54.167	19.433
061100	Skrydstrup	55.233	9.267
061490	Gedser	54.567	11.967
061200	Beldringe	55.483	10.333
061410	Abed	54.833	11.333
03313	Berlin_Tegel	52.550	13.300
01459	Hamburg	53.633	9.983
01538	Hannover	52.450	9.667

In our study we have identified possible LDT episodes, suggested a gridded inventory of potential source areas, verified potential sources to local emission peaks from harvesting and found the typical daily pattern in the observed load of *Alternaria* spores. Each of these pieces of information will be very useful in the daily information to the public as well as in forecasting. The episodes that we analysed in detail showed that it is possible to have high days that follow each other and that the change from low to high load of *Alternaria* is related to both a change in weather and potential source area. Such

Table A3. Observed wind speed (m s^{-1}) on the days with episodes (above 100 spores m^{-3}) of fungal spores that were selected and presented in Table 2.

Date/hour	1	3	5	7	9	11	13	15	17	19	21	23
22 Jul 2001	2.2	3.5	3.1	3.3	3.8	3.8	5.5	5.2	3.9	4.0	3.3	2.2
21 Jul 2003	3.0	2.8	4.2	3.9	3.9	4.3	1.3	1.5	1.8	1.6	1.1	1.5
26 Jul 2003	2.8	2.8	3.7	5.4	3.2	4.1	4.7	5.2	2.5	2.9	2.6	2.6
5 Sep 2004	1.7	2.0	2.3	2.5	2.7	3.3	3.2	2.9	3.2	2.6	2.7	3.3
25 Aug 2005	3.2	3.7	4.0	4.3	4.9	5.1	5.2	7.8	5.7	4.3	3.0	3.5
10 Aug 2006	1.8	1.2	1.2	2.4	4.2	5.1	4.4	5.2	4.1	2.0	1.3	0.9
25 Aug 2006	1.3	1.2	0.7	1.7	2.2	2.6	2.7	2.0	1.4	1.6	1.3	1.5
26 Aug 2006	1.5	1.7	0.7	1.6	1.4	2.8	2.6	3.1	2.4	1.6	1.4	1.4
5 Aug 2007	2.7	2.2	1.9	1.0	2.3	3.4	3.8	4.0	3.6	3.4	3.1	1.8
11 Aug 2007	3.2	2.0	2.3	1.9	2.6	3.4	2.1	5.2	3.1	2.1	1.0	3.2
31 Aug 2008	2.1	1.1	0.6	0.9	2.5	3.5	3.3	4.1	4.3	4.0	4.6	5.1
22 Jul 2009	1.3	1.7	2.0	2.3	4.4	4.4	2.9	4.0	4.1	4.0	3.3	2.7
27 Jul 2009	2.7	4.0	3.0	3.5	4.4	3.8	4.0	4.4	3.8	2.9	2.3	3.9
6 Aug 2010	1.4	0.8	1.9	3.9	3.6	4.1	2.8	3.7	3.5	3.4	1.8	2.1
11 Aug 2010	4.2	2.6	2.5	3.3	4.2	5.3	6.0	6.4	5.0	3.8	3.0	1.9
16 Aug 2010	5.5	5.7	5.4	5.7	6.0	5.5	5.5	3.4	3.1	2.4	0.9	1.2

patterns can be simulated with atmospheric transport models. Furthermore, development of emission models and inventories makes it possible to use source-based models such as DEHM (Brandt et al., 2012), SILAM (Sofiev et al., 2006) and COSMO-ART (Zink et al., 2012) for improved understanding of aeroallergens and ultimately better information to the public.

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References

Aira, M. J., Rodriguez-Rajo, F. J., and Jato, V.: 47 annual records of allergenic fungi spore: Predictive models from the NW Iberian Peninsula, Ann. Agr. Env. Med., 15, 91–98, 2008.

Angulo-Romero, J., Mediavilla-Molina, A., and Domínguez-Vilches, E.: Conidia of *Alternaria* in the atmosphere of the city of Cordoba, Spain in relation to meteorological parameters, Int. J. Biometeorol., 43, 45–49, 1999.

Belmonte, J., Alarcon, M., Avila, A., Scialabba, E., and Pino, D.: Long-range transport of beech (*Fagus sylvatica* L.) pollen to Catalonia (north-eastern Spain), Int. J. Biometeorol., 52, 675–687, 2008.

Brandt, J., Silver, J. D., Frohn, L. M., Geels, C., Gross, A., Hansen, A. B., Hansen, K. M., Hedegaard, G. B., Skjøth, C. A., Villadsen, H., Zare, A., and Christensen, J. H.: An integrated model study for Europe and North America using the Danish Eulerian Hemispheric Model with focus on intercontinental transport of air pollution, 2012, Atmos. Environ., 53, 156–176, 2012.

Burshtein, N., Lang-Yona, N., and Rudich, Y.: Ergosterol, arabitol and mannitol as tracers for biogenic aerosols in the eastern Mediterranean, Atmos. Chem. Phys., 11, 829–839, doi:10.5194/acp-11-829-2011, 2011.

Buters, J. T. M., Thibaudon, M., Smith, M., Kennedy, R., Rantio-Lehtimäki, A., Albertini, R., Reese, G., Weber, B., Galan, C., Brandao, R., Antunes, C. M., Jäger, S., Berger, U., Celenk, S., Grewling, L., Jackowiak, B., Sauliene, I., Weichenmeier, I., Pusch, G., Sarioglu, H., Ueffing, M., Behrendt, H., Prank, M., Sofiev, M., and Cecchi, L.: Release of Bet v 1 from birch pollen from 5 European countries. Results from the HIALINE study, Atmos. Environ., 55, 496–505, 2012.

Carinanos, P., Emberlin, J., Galan, C., and Dominguez-Vilches, E.: Comparison of two pollen counting methods of slides from a hirst type volumetric trap, Aerobiologia, 16, 339–346, 2000.

Cecchi, L., Malaspina, T., Albertini, R., Zanca, M., Ridolo, E., Usberti, I., Morabito, M., Dall'Aglio, P., and Orlandini, S.: The contribution of long-distance transport to the presence of Ambrosia pollen in central northern Italy, Aerobiologia, 23, 145–151, 2007.

Cecchi, L., D'amato, G., Ayres, J. G., Galan, C., Forastiere, F., Forsberg, B., Gerritsen, J., Nunes, C., Behrendt, H., Akdis, C., Dahl, R., and Annesi-Maesano, I.: Projections of the effects of climate change on allergic asthma: the contribution of aerobiology, Allergy, 65, 1073–1081, 2010.

Ceter, T., Pinar, N., Güney, K., Yildiz, A., Asci, B., and Smith, M.: A 2-year aeropalynological survey of allergenic pollen in the atmosphere of Kastamonu, Turkey, Aerobiologia, 28, 355–366, 2012.

Corden, J. M., Millington, W. M., and Mullins, J.: Long-term trends and regional variation in the aeroallergen *Alternaria* in Cardiff and Derby UK – are differences in climate and cereal production having an effect?, Aerobiologia, 19, 191–199, 2003.

Cosentino, S., Fadda, M. E., and Palmas, F.: Pollen and mould allergy in Southern Sardinia (Italy): Comparison of skin-test frequencies and air sampling data, Grana, 34, 338–344, 1995.

Damato, G. and Spieksma, F. T. M.: Aerobiologic and Clinical Aspects of Mold Allergy in Europe, Allergy, 50, 870–877, 1995.

De Linares, C., Belmonte, J., Canela, M., de la Guardia, C. D., Alba-Sanchez, F., Sabariego, S., and Alonso-Pérez, S.: Dispersal patterns of Alternaria conidia in Spain, Agr. Forest Meteorol., 150, 1491–1500, 2010.

Draxler, R., Stunder, B., Rolph, G., and Taylor, A.: Hysplit4 users guide – Version 4.8, 198 pp., 2007.

Elholm, G., Omland, Ø., Schlünssen, V., Hjort, C., Basinas, I., and Sigsgaard, T.: The cohort of young Danish farmers – A longitudinal study of the health effects of farming exposure, Clinical Epidemiology, 2010, 45–50, 2010.

Escuredo, O., Seijo, M., Fernández-González, M., and Iglesias, I.: Effects of meteorological factors on the levels of *Alternaria* spores on a potato crop, Int. J. Biometeorol., 55, 243–252, 2011.

European Commission: Image2000 and CLC2000 Products and Methods European Commission, Joint Research Center (DG JRC), Institute for Environment and Sustainability, Land Management Unit, I-21020 Ispra (VA), Italy, 2005.

Fagerli, H. and Aas, W.: Trends of nitrogen in air and precipitation: Model results and observations at EMEP sites in Europe, 1980–2003, Environ. Pollut., 154, 448–461, 2008.

Fernández-Llamazares, Á., Belmonte, J., Alarcón, M., and López-Pacheco, M.: *Ambrosia L.* in Catalonia (NE Spain): expansion and aerobiology of a new bioinvader, Aerobiologia, 28, 435–451, 2012.

Fernández-Rodríguez, S., Skjøth, C. A., Tormo-Molina, R., Brandao, R., Caeiro, E., Silva-Palacios, I., Gonzalo-Garijo, A., and Smith, M.: Identification of potential sources of airborne Olea pollen in the Southwest Iberian Peninsula, Int. J. Biometeorol., accepted, 2012.

Friesen, T. L., De Wolf, E. D., and Francl, L. J.: Source strength of wheat pathogens during combine harvest, Aerobiologia, 17, 293–299, 2001.

Gannibal, Ph. B. (A.A. Jaczewski Laboratory of Mycology and Phytopathology, All-Russian Institute of Plant Protection, St. Petersburg, Russia): *Alternaria alternata* (Fr.) Keissl., Cladosporium herbarum (Pers.) Link., Epicoccum purpurascens Ehrenb., Botrytis cinerea Pers. – Black Ear of wheat, edited by: Afonin, A. N., Greene, S. L., Dzyubenko, N. I., and Frolov, A. N., Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries, in: Economic Plants and their Diseases, Pests and Weeds [Online], available at: http://www.agroatlas.ru/en/content/diseases/Hordei/Hordei_Alternaria_alternata/, 2008.

Giner, M. M., García, J. C., and Camacho, C. N.: Airborne *Alternaria* spores in SE Spain (1993–98), Grana, 40, 111–118, 2001.

Goldberg, C., Buch, H., Moseholm, L., and Weeke, E. R.: Airborne Pollen Records in Denmark, 1977–1986, Grana, 27, 209–217, 1988.

Gravesen, S.: Fungi as a Cause of Allergic Disease, Allergy, 34, 135–154, 1979.

Gravesen, S., Frisvad, J. C., and Samson, R. A.: Microfungi, Munksgaard, ISBN: 9788716114365, 168 pp., 1994.

Gultyaeva, E. I. (A.A. Jaczewski Laboratory of Mycology and Phytopathology, All-Russian Institute of Plant Protection, St. Petersburg, Russia): *Alternaria alternata* (Fr.) Keissl., Cladosporium herbarum (Pers.) Link., Epicoccum purpurascens Ehrenb., Botrytis cinerea Pers. – Black Ear of wheat, edited by: Afonin, A. N., Greene, S. L., Dzyubenko, N. I., and Frolov, A. N., in: Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries. Economic Plants and their Diseases, Pests and Weeds [Online], available at: http://www.agroatlas.ru/en/content/diseases/Tritici/Tritici_Alternaria_alternata/, 2008.

Gyldenkærne, S., Ambelas Skjøth, C., Hertel, O., and Ellermann, T.: A dynamical ammonia emission parameterization for use in air pollution models, J. Geophys. Res.-Atmos., 110, D07108, doi:10.1029/2004JD005459, 2005.

Hernandez-Ceballos, M. A., Garcia-Mozo, H., Adame, J. A., Dominguez-Vilches, E., Bolivar, J. P., De la Morena, B. A., Perez-Badia, R., and Galan, C.: Determination of potential sources of Quercus airborne pollen in Crdoba city (southern Spain) using back-trajectory analysis, Aerobiologia, 27, 261–276, 2011a.

Hernandez-Ceballos, M. A., Garcia-Mozo, H., Adame, J. A., Dominguez-Vilches, E., De la Morena, B. A., Bolivar, J. P., and Galan, C.: Synoptic and meteorological characterisation of olive pollen transport in Cordoba province (south-western Spain), Int. J. Biometeorol., 55, 17–34, 2011b.

Hertel, O., Ellermann, T., Palmgren, F., Berkowicz, R., Løfstrom, P., Frohn, L. M., Geels, C., Skjøth, C. A., Brandt, J., Christensen, J., Kemp, K., and Ketzel, M.: Integrated air-quality monitoring – combined use of measurements and models in monitoring programmes, Environ. Chem., 4, 65–74, 2007.

Hill, R. A., Wilson, D. M., Burg, W. R., and Shotwell, O. L., Viable Fungi in Corn Dust, Appl. Environ. Microbiol., 47, 84–87, 1984.

Hirst, J. M.: An automatic volumetric spore trap, Ann. Appl. Biol., 39, 257–265, 1952.

Hjelmroos, M.: Relationship between airborne fungal spore presence and weather variables: Cladosporium and Alternaria, Grana, 32, 40–47, 1993.

Iglesias, I., Rodríguez-Rajo, F., and Méndez, J., Evaluation of the different *Alternaria* prediction models on a potato crop in A Limia (NW of Spain), Aerobiologia, 23, 27–34, 2007.

Isard, S., Russo, J., and Ariatti, A.: The Integrated Aerobiology Modeling System applied to the spread of soybean rust into the Ohio River valley during September 2006, Aerobiologia, 23, 271–282, 2007.

Isard, S. A., Gage, S. H., Comtois, P., and Russo, J. M.: Principles of the atmospheric pathway for invasive species applied to soybean rust, Bioscience, 55, 851–861, 2005.

Kasprzyk, I. and Worek, M.: Airborne fungal spores in urban and rural environments in Poland, Aerobiologia, 22, 169–176, 2006.

Kasprzyk, I., Myszkowska, D., Grewling, L., Stach, A., Sikoparija, B., Skjøth, C. A., and Smith, M.: The occurrence of Ambrosia pollen in Rzeszow, Krakow and Poznan, Poland: investigation of trends and possible transport of *Ambrosia* pollen from Ukraine, Int. J. Biometeorol., 55, 633–644, 2011.

Kirk, P. M., Cannon, P. F., Minter, D. W., and Stalpers, J. A.: Dictionary of the Fungi, 10th Edn., Wallingford, CABI, p. 22, 2008.

Kukkonen, J., Olsson, T., Schultz, D. M., Baklanov, A., Klein, T., Miranda, A. I., Monteiro, A., Hirtl, M., Tarvainen, V., Boy, M., Peuch, V.-H., Poupkou, A., Kioutsioukis, I., Finardi, S., Sofiev, M., Sokhi, R., Lehtinen, K. E. J., Karatzas, K., San José, R., Astitha, M., Kallos, G., Schaap, M., Reimer, E., Jakobs, H., and Eben, K.: A review of operational, regional-scale, chemical weather forecasting models in Europe, Atmos. Chem. Phys., 12, 1–87, doi:10.5194/acp-12-1-2012, 2012.

Lang-Yona, N., Dannemiller, K., Yamamoto, N., Burshtein, N., Peccia, J., Yarden, O., and Rudich, Y.: Annual distribution of allergenic fungal spores in atmospheric particulate matter in the Eastern Mediterranean; a comparative study between ergosterol and quantitative PCR analysis, Atmos. Chem. Phys., 12, 2681–2690, doi:10.5194/acp-12-2681-2012, 2012.

Larsen, L. S.: A 3-Year-Survey of Micro-Fungi in the Air of Copenhagen 1977–79, Allergy, 36, 15–22, 1981.

Mahura, A., Korsholm, U., Baklanov, A., and Rasmussen, A.: Elevated birch pollen episodes in Denmark: contributions from remote sources, Aerobiologia, 23, 171–179, 2007.

Mandrioli, P., Comtois, P., and Levizzani, V.: Methods in Aerobiology: Pitagora Editrice, Bologna, ISBN 88-371-1043-X, 262 pp., 1998.

Maya-Manzano, J., Fernández-Rodriguez, S., Hernández-Trejo, F., Díaz-Peres, G., Gonzalo-Garijo, Á., Silva-Palacios, I., Munoz-Rodriguez, A., and Tormo-Molina, R.: Seasonal Mediterranean pattern for airborne spores of *Alternaria*, Aerobiologia, 28, 515–525, 2012.

McCartney, H. A., Schmechel, D., and Lacey, M. E.: Aerodynamic Diameter of Conidia of Alternaria Species, Plant Pathol., 42, 280–286, 1993.

Melgar, M., Trigo, M., Recio, M., Docampo, S., García-Sánchez, J., and Cabezudo, B.: Atmospheric pollen dynamics in Münster, north-western Germany: a three-year study (2004–2006), Aerobiologia, 28, 423–434, 2012.

Mitakakis, T. Z., Clift, A., and McGee, P. A.: The effect of local cropping activities and weather on the airborne concentration of allergenic *Alternaria* spores in rural Australia, Grana, 40, 230–239, 2001.

Oliveira, M., Ribeiro, H., Delgado, J., and Abreu, I.: Seasonal and intradiurnal variation of allergenic fungal spores in urban and rural areas of the North of Portugal, Aerobiologia, 25, 85–98, 2009.

Orlanski, I.: A rational subdivision of scales for atmospheric processes, B. Am. Meteorol. Soc., 56, 527–530, 1975.

Pedersen, B. V. and Moseholm, L.: Precision of the daily pollen count. Identifying sources of variation using variance component models, Aerobiologia, 9, 15–26, 1993.

Perelló, A. E. and Sisterna, M. N.: Leaf blight of wheat caused by Alternaria triticina in Argentina, New Disease Reports, 11, 24–28, 2005.

Ricci, S., Bruni, M., Meriggi, A., and Corsico, R.: Aerobiological monitoring *Alternaria* fungal spores: a comparison between surveys in 1992 and 1993 and local meteorological conditions, Aerobiologia, 11, 195–199, 1995.

Rodriguez-Rajo, F. J., Iglesias, I., and Jato, V.: Variation assessment of airborne Alternaria and Cladosporium spores at different bioclimatical conditions, Mycol. Res., 109, 497–507, 2005.

Sikoparija, B., Smith, M., Skjøth, C. A., Radisic, P., Milkovska, S., Simic, S., and Brandt, J.: The Pannonian plain as a source of *Ambrosia* pollen in the Balkans, Int. J. Biometeorol., 53, 263–272, 2009.

Sikoparija, B., Pejak-Sikoparija, T., Radisic, P., Smith, M., and Soldevilla, C. G.: The effect of changes to the method of estimating the pollen count from aerobiological samples, J. Environ. Monit., 13, 384–390, 2011.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model – technical description, Atmos. Chem. Phys., 12, 7825–7865, doi:10.5194/acp-12-7825-2012, 2012.

Singh, R. V., Singh, A. K., and Singh, S. P.: Distribution of pathogens causing foliar blight of wheat in India and neighboring countries, in: Helminthosporium Blights of Wheat: Spot Blotch and Tan Spot, edited by: Duveiller, E., Dubin, H. J., Reeves, J., and McNab, A., Mexico, D.F., CIMMYT, 59–62, 1998.

Skjøth, C. A. and Sommer, J.: Two extended pollen and fungal spore calendars for Denmark, their representativeness and cross-reactivity between pollen and food products, Presented at the 9th international Congress on Aerobiology, Buenos Aires, Argentina, 23–27 August, Abstract and Poster, 2010.

Skjøth, C. A., Hertel, O., and Ellermann, T.: Use of the ACDEP trajectory model in the Danish nation-wide Background Monitoring Programme, Phys. Chem. Earth, 27, 1469–1477, 2002.

Skjøth, C. A., Sommer, J., Stach, A., Smith, M., and Brandt, J.: The long range transport of birch (*Betula*) pollen from Poland and Germany causes significant pre-season concentrations in Denmark, Clin. Exp. Allergy, 37, 1204–1212, 2007.

Skjøth, C. A., Sommer, J., Brandt, J., Hvidberg, M., Geels, C., Hansen, K., Hertel, O., Frohn, L., and Christensen, J.: Copenhagen – a significant source of birch (*Betula*) pollen?, Int. J. Biometeorol., 52, 453–462, 2008.

Skjøth, C. A., Smith, M., Brandt, J., and Emberlin, J.: Are the birch trees in Southern England a source of Betula pollen for North London?, Int. J. Biometeorol., 53, 75–86, 2009.

Skjøth, C. A., Smith, M., Sikoparija, B., Stach, A., Myszkowska, D., Kasprzyk, I., Radisic, P., Stjepanovic, B., Hrga, I., Apatini, D., Magyar, D., Paldy, A., and Ianovici, N.: A method for producing airborne pollen source inventories: An example of *Ambrosia* (ragweed) on the Pannonian Plain, Agr. Forest Meteorol., 150, 1203–1210, 2010.

Skjøth, C. A., Geels, C., Berge, H., Gyldenkærne, S., Fagerli, H., Ellermann, T., Frohn, L. M., Christensen, J., Hansen, K. M., Hansen, K., and Hertel, O.: Spatial and temporal variations in ammonia emissions – a freely accessible model code for Europe, Atmos. Chem. Phys., 11, 5221–5236, doi:10.5194/acp-11-5221-2011, 2011.

Smith, M., Emberlin, J., and Kress, A.: Examining high magnitude grass pollen episodes at Worcester, United Kingdom, using back-trajectory analysis, Aerobiologia, 21, 85–94, 2005.

Smith, M., Skjøth, C. A., Myszkowska, D., Uruska, A., Malgorzata, P., Stach, A., Balwierzg, Z., Chlopek, K., Piotrowska, K., Kasprzyk, I., and Brandt, J.: Long-range transport of *Ambrosia* pollen to Poland, Agr. Forest Meteorol., 148, 1402–1411, 2008.

Sofiev, M., Siljamo, P., Ranta, H., and Rantio-Lehtimaki, A.: Towards numerical forecasting of long-range air transport of birch pollen: theoretical considerations and a feasibility study, Int. J. Biometeorol., 50, 392–402, 2006.

Sommer, J. and Rasmussen, A.: Measurements of pollen and spores in Denmark 2009 (in Danish: Pollen- og sporemålinger i Danmark sæsonen 2009): The Astma-Allergy Association, Universitetsparken 4, 4000 Roskilde, Denmark, 45 pp., 2009.

Sommer, S. G., Genermont, S., Cellier, P., Hutchings, N. J., Olesen, J. E., and Morvan, T.: Processes controlling ammonia emission from livestock slurry in the field, Eur. J. Agron., 19, 465–486, 2003.

Sommer, S. G., Zhang, G. Q., Bannink, A., Chadwick, D., Misselbrook, T., Harrison, R., Hutchings, N. J., Menzi, H., Monteny, G. J., Ni, J. Q., Oenema, O., and Webb, J.: Algorithms determining ammonia emission from buildings housing cattle and pigs and from manure stores, Elsevier Academic Press Inc, San Diego, 335 pp., 2006.

Stach, A., Smith, M., Skjøth, C. A., and Brandt, J.: Examining *Ambrosia* pollen episodes at Poznañ (Poland) using back-trajectory analysis, Int. J. Biometeorol., 51, 275–286, 2007.

Stepalska, D. and Wolek, J.: Intradiurnal periodicity of fungal spore concentrations (Alternaria, Botrytis, Cladosporium, Didymella, Ganoderma) in Cracow, Poland, Aerobiologia, 25, 333–340, 2009.

Stepalska, D., Harmata, K., Kasprzyk, I., Myszkowska, D., and Stach, A.: Occurrence of airborne *Cladosporium* and *Alternaria* spores in Southern and Central Poland in 1995–1996, Aerobiologia, 15, 39–47, 1999.

Sterling, M., Rogers, C., and Levetin, E.: An evaluation of two methods used for microscopic analysis of airborne fungal spore concentrations from the Burkard Spore Trap, Aerobiologia, 15, 9–18, 1999.

The Lancet: Allergic rhinitis: common, costly, and neglected, The Lancet, 371, p. 2057, 2008.

Veriankaite, L., Siljamo, P., Sofiev, M., Sauliene, I., and Kukkonen, J.: Modelling analysis of source regions of long-range transported birch pollen that influences allergenic seasons in Lithuania, Aerobiologia, 26, 47–62, 2010.

Vieno, M., Dore, A. J., Bealey, W. J., Stevenson, D. S., and Sutton, M. A.: The importance of source configuration in quantifying footprints of regional atmospheric sulphur deposition, Sci. Total Environ., 408, 985–995, 2010.

Zink, K., Vogel, H., Vogel, B., Magyar, D., and Kottmeier, C.: Modeling the dispersion of *Ambrosia artemisiifolia* L. pollen with the model system COSMO-ART, Int. J. Biometeorol, 56, 669–680, doi:10.1007/s00484-011-0468-8, 2012.