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Denis-Didier Rousseau[1,2†], Patrick Schevin[3], Jackie Ferrier[3], Dominique Jolly[3], Tore Andreasen[4], Svend Erik Ascanius[5], Svend-Erik Hendriksen[6], and Ulrik Poulsen[7]

[1]Ecole Normale Supérieure, Laboratoire de Modélisation Dynamique, UMR CNRS 8539, 24 rue Lhomond, 75231 Paris cedex 5, France

[2]Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

[3]Université Montpellier II-CNRS, Institut des Sciences de l'Evolution, place Eugène Bataillon, 34095 Montpellier cedex 05, France

[4]Danish Radio-Sonde Station, DK - 3980 Ittoqqortroormitt, Greenland

[5]Danish Meteorological Institute (DMI), DK - 3971 Qaanaaq, Greenland

[6]Danish Meteorological Institute (DMI), DK - 3910 Kangerlussuaq, Greenland

[7]Danish Radio-Sonde Station, DK - 3923 Narsarsuaq, Greenland

† to whom correspondence should be addressed; Email: denis.rousseau@lmd.ens.fr

Abstract

[1] In the Arctic domain there is evidence for very long distance transport of pollen grains from boreal forests to tundra environments. However, the sampling protocol used in earlier studies did not allow the determination of the precise timing of the deposition of exotic grains. The ongoing "Epilobe" project monitors the deposition of exotic grains on both western and eastern coasts of Greenland utilizing wind filters, which are changed weekly throughout the entire year. A combination of the identification of tree pollen grains, the dates of deposition of the pollen on the filters, and the distribution map of the trees identified, allows the selection of modeled backward trajectories of air parcels responsible for the capture of the grains in the growing area of northeastern North America, and their long distance transport to Greenland. A survey of data obtained from four stations, analyzed during 2004 and 2005, indicates the occurrence of a general pattern, every spring, which follows the main cyclone tracks reaching this Arctic region.

1. Introduction

[2] Pollen transport is a crucial topic as it has a strong societal impact, especially when considering allergies[*Guérin, et al.*, 1993; *Michel, et al.*, 1976]. For decades, aerobiologists investigated this particular aspect of plant phenology, which eventually led to modeling [*Chuine and Belmonte*, 2004; *Ranzi, et al.*, 2003] the particular relationship between pollen emission and temperature variations [*Cambon*, 1980; *Cour*, 1974; *Palacios, et al.*, 2007]. To accomplish this, therefore the biologists had to consider not only the local pollen dissemination but also a more complex process, involving some transport, especially wind blown material. Besides societal concern [*Michel, et al.*, 1976], the same preoccupations are faced by ecologists in terms of understanding the large scale transportation and deposition of exotic grains [*Porsbjerg, et al.*, 2003], i.e. pollen grains released by plants which are not growing in the studied region [*Peternel, et al.*, 2006; *Smith, et al.*, 2005]. Such investigations in temperate regions are much more difficult to carry out [*Hicks*, 1985], because usually pollen is identified mostly at the generic level, except if particular pollen is easily distinguished, i.e. from tropical or subtropical trees [*Cambon, et al.*, 1992]. However, such tasks are much easier in the higher latitudes where the vegetation is greatly reduced and less diverse. Therefore, in high latitudes, the patterns of long-distance transport can be easily observed [*Andrews, et al.*, 1980; *Bourgeois, et al.*, 1985; *Campbell, et al.*, 1999; *Franzen, et al.*, 1994; *Gajewski*, 1995; *Hicks, et al.*, 2001; *Hjelmroos and Franzen*, 1994; *Jacobs, et al.*, 1985; *Janssen*, 1973; *Nichols*, 1967; *Ritchie*, 1974; *Ritchie and Lichti-Federovich*, 1967; *Ritchie, et al.*, 1987; *Short and Holdsworth*, 1985]. In understanding the very long-range transport of pollen grains, most of which range from 15-30 microns, except for the larger bisaccate grains of conifer, bigger than a few microns, they can be considered as aerosol components [*Hicks and Isaksson*, 2006; *Prospero, et al.*, 2005]} and a proxy indicator for more general atmospheric circulation [*Fraile, et al.*, 2006; *Tunved, et al.*, 2005].

[3] Analysis of long distance transport of tree pollen to Narsarsuaq, Southern Greenland, in 2002 and 2003 [2004; 2006; *Rousseau, et al.*, 2003] indicated that eastern North America, south of the Great Lakes was the source region. The timing of the deposition regularly occurred during the second half of May but the air mass trajectories differed. On the other hand, long distance transport to the North Pole in 2002 was found to have originated from Western Europe and

Eastern Siberia [*Rousseau, et al.*, 2004]. These were the first analyses to develop a complete description of the transport from the source area to the deposition site, characterizing the air masses responsible, and detailing the timing of the capture and deposition of the grains. Previous sampling in the Arctic region had demonstrated the occurrence of long distance pollen transport, but samples taken from snow or ice layers were limited to seasonal resolution, i.e. late winter/spring snow and in the summer melt layers [*Bourgeois, et al.*, 1985; *Bourgeois, et al.*, 2001; *Hicks, et al.*, 2001; *Ritchie*, 1974; *Ritchie and Lichti-Federovich*, 1967]. Other published data from fossil pollen records has led to assumptions about averaged trajectories. These studies did not allow for the precise description of long distance transport to the Arctic, due to annual sampling, which made the identification uncertain of the source of exotic pollen grains [*Bourgeois, et al.*, 1985; *Bourgeois, et al.*, 2001; *Hicks, et al.*, 2001; *Ritchie*, 1974; *Ritchie and Lichti-Federovich*, 1967].

[4] Because we are currently limited to four sampling sites, the general transport pattern for the entire island of Greenland cannot be identified. In order to improve our understanding, a network of pollen stations is required all along the western and eastern coasts. At present it is not possible to locate sampling stations on the ice sheet. With an increased sampling network and continued monitoring, a much more reliable scenario for further modeling experiments will be possible. Nevertheless, the long distance pollen transport reported here from four stations with weekly resolution for the spring of 2004 and 2005 adds significantly to our understanding of circulation patterns from northeastern North America to Greenland.

2. Material and methods

[5] Within the "EPILOBE" (French name of willowweed, *Epilobium*, the national flower of Greenland) project, four pollen sites, each with two filters exposed to the wind, were installed on the western (Narsarsuaq 61.15°N, 45.43°W; Kangerlussuaq, 67°N, 50.7°W; Qaanaaq, 77.5°N, 69.35°W) and eastern (Ittoqqortoormitt, 70.48°N, 21.95°W) coasts of Greenland. They are situated within a maximum of 10 m from a meteorological station (Figure 1) and except in Kangerlussuaq, the pollen stations are located next to the sea. The interest in having a rotating frame on which the filters are placed is that it also collects the pollen from the local vegetation, if present.. The same collection protocols are used at each station and the pollen is acquired

throughout the year. One filter is changed weekly and the second fortnightly. The 26 x 26 cm filters are composed of several crossed bands of gauze bathed in a siliconed glue and set in a plastic framework. Half of each filter is processed for pollen extraction and the other half retained for future analysis. The yearly survey of the pollen occurrence is recorded for all four localities yielding a very precise record of the local vegetation, timing of pollen deposition, and also evidence for seasonal transport of exotic grains [2004; 2006; *Rousseau, et al.*, 2003]. Previous studiesin the Arctic mainly reported yearly observations of pollen flux [*Ritchie and Litchi-Federovich*, 1967, *Ritchie*, 1974, *Bourgeois et al.*, 1985, 2001; *Hicks et al.,* 2001].

[6] Before the pollen stations were installed (Figure 2), ground samples in their vicinity were collected and analyzed. A few exotic pollen grains were identified, mainly pine (*Pinus*) at Kangerlussuaq, and oak (*Quercus*) at Narsarsuaq, indicating long-distant transport to these remote stations. However, since the the surface samples were taken more inland than that of the pollen stations, mostly close to the sea, we are confident that the grains identified in the filters are not reworked ones..

Only the results from fortnightly filters showing exotic grains are reported here. Using the dates of the filter exposures, backward air mass trajectories are then computed for every day in the two week period using the HYSPLIT on-line application [*Draxler and Hess*, 1998; *HYSPLIT4 Model*, 1997], model details can be found at (http://www.arl.noaa.gov/ready/hysplit4.html). The potential trajectories are selected to explain the observed long distance transport considering the probable dates of pollen emission and the dates of the air mass passing over the region of growing trees specific to the identified pollen captured at the Greenland sites [*Thompson, et al.*, 1999a; b]. Numerous computations were performed for a single day, with noon chosen as the most representative of the different times. We introduced the coordinates of the filters as our targets and thus when exotic grains were identified in the filters, trajectories were computed for the total time interval during which the filters were exposed, i.e. 14 days. In the first step, days were selected which corresponded to backward trajectories passing over the growing area, including all the trees producing the observed pollen. In a second step, we considered the elevation at which air parcels were passing over the determined area, rejecting those passing too high. Finally we considered the vertical motion, a very important factor, associated with the potential air mass: if upward motion existed for favoring the convection of the grains, and similarly if downward motion was present at the target location, then we selected the considered computation. By using this protocol it allowed us to considerably constrain the selection of the potential "candidates among all the computations performed.[7] Although the long distance transport was initially determined for Narsarsuaq [2006; *Rousseau, et al*., 2003], here we report on the stations operating in 2004 and 2005 which also show evidence of long distance transport whose source region can be identified.

3. Results

3.1 Pollen counts (Tab. 1)

[8] At Qaanaaq in 2004, the filter exposed during weeks 16-17 (12-25 April) recorded 73 exotic grains (38 oak – *Quercus*, 28 pine -*Pinus*, 5 plane -*Platanus*, and 1 hornbeam – *Carpinus*- and walnut –*Juglans*, respectively) out of a total of 107 grains. This indicates that the majority of transported pollen grains corresponding to 68.22% of the total counted , was exotic.

[9] At Kangerlussuaq in 2004, the filter exposed during weeks 19 and 20 (3-16 May) recorded 21 exotic grains (12 oak - *Quercus*, 3 hazel – *Corylus*- and hops –*Humulus*, 2 pine - *Pinus*, and 1 plane - *Platanus*) among a total of 230 identified grains. This is a considerably less (6.57%) than in Qaanaaq. Indeed, the local vegetation in Kangerlussuaq is more abundant, consisting ofshrub tundra, composed of birch (*Betula*), juniper (*Juniperus*), and willow (*Salix*).

[10] At Narsarsuaq, where evidence of long distance transport has been reported [2004; 2006; *Rousseau, et al*., 2003]., only 10 exotic grains (4 pine - *Pinus*, 2 oak - *Quercus*, 1 fir - Abies, hazel - *Corylus*, walnut – *Juglans* - and hornbeam - *Carpinus*, respectively) in over 353 grains were identified for weeks 19-20 (3-16 May, 2004). This corresponds to an even smaller percentage, 2.83%, compared to the two other west coast stations which are located further north. The local tundra vegetation surrounding the meteorological station is represented by birch (*Betula)*, horsetail, willow (*Salix*), alder (*Alnus*), heath (*Erica*) and genera in the sedge family (Cyperaceae).

[11] On the eastern coast, at Ittoqqortoormitt in 2004, the filter exposed during weeks 25-26 (14-26 June) recorded 6 exotic grains (2 pine - *Pinus* - and oak - *Quercus* , 1 chestnut – (*Castanea*) and beech - *Fagus*) in 871 grains. This is the lowest percentage, 0.69% out of the four stations. As in Qaanaaq, the local vegetation is very sparse and reduced to dwarf plants.

[12] The record is different for the exotic pollen grains transported in 2005. Two stations,

Kangerlussuaq and Qaanaaq, indicated only the transport of pine grains, which substantially differs from the results of the previous year. As pine is highly transportable and found nearly everywhere, trajectories were not calculated for these stations in 2005.

[13] Conversely in Narsarsuaq, exotic pollen was identified during weeks 20-21 (May 16-29) with 2 grains each of hornbeam - *Carpinus* - and walnut - *Juglans*, 1 each of chestnut - *Castanea*, pine – *Pinus* - and elm - *Ulmus*, representing 0.53% of the total 1316 grains . The filter exposed during weeks 17-18 (25 April -8 May) in Ittoqqortoormitt yielded 13 exotic pollen grains out of 62 counted, (20.97%) corresponding to 6 grains of oak - *Quercus*, 5 pine - *Pinus*, 1 plane - *Platanus* - and 1 hickory - *Carya*. This is a considerably higher percentage of exotic grains compared to the 2004 record. Most notable is the occurrence of hickory, which is solely a North American tree [*Thompson, et al.*, 1999a; b].

[14] Out of six cases in 2004 and 2005, the deposition of exotic pollen grains in the filters occurred half the time between weeks 19 and 21. With the exception of the east coast station in 2004 where exotic grains were registered during weeks 25-26, deposition occurred in nearly all cases between weeks 16 and 21. These findings are in agreement with the time of pollination (weeks 15 to 31) determined for the various trees species at four different stations in Southern Ontario, Canada, [*Cambon*, 1994; *Cambon, et al.*, 1992]. One interesting feature of the data is that the southernmost station, Narsarsuaq, recorded long distance pollen transport in variable proportions during these two additional years of our experiment, yet reproduced similar observations to the earlier studies. Indeed, in 2002, among 5514 grains counted, only 19 (0.34%) were from exotic plants while one year later, among 6888 grains counted, 336 (4.89%) originated from 12 different exotic trees [2004; 2006; *Rousseau, et al.*, 2003],.

[15] A large degree of variability in both the diversity and abundance is demonstrated between stations within a given year as well as from year-to-year for any single station. Pollen diversity was greater in 2004 than in 2005. While not directly addressed by this study, further investigations in temperature conditions prevailing the source area may have to be conducted as well as meteorological conditions during the transport itself.

3.2 Backward trajectories

[16] Backward air mass trajectories have been calculated at 12h intervals, for 314 hours of

the 14 days of the fortnight records of exotic pollen grains. As in previous studies [2004; 2006; *Rousseau, et al*., 2003], three altitudes were investigated; ground level, 1000 and 3000 meters. As air parcels change altitude with time, these altitudes designate their respective level at the time of pollen deposition in Greenland. For each station, the computed trajectories were then compared with the compiled distribution of trees to check whether the source area consisted of tree types consistent with the exotic pollen grains.

[17] Given these air mass trajectories the most probable dates for the exotic pollen to arrive at the different sampling stations can be summarized as follows:

[18] In 2004, exotic pollen deposited in Qaanaaq on April 18 (Figure 3), corresponded to the transport of pollen grains captured in the source area on April 8 and 12. In Kangerlussuaq, the exotic pollen deposited on May 13 (Figure 4), were captured on May 4 in the growing area. The transport of exotic pollen grains to Narsarsuaq ended on May 10 (Figure 5); they were deposited over the source area on May 3 and 4. Finally, exotic pollen arrived at Ittoqqortoormitt on June 19, which corresponded to grains captured between June 8-13 by an air mass passing over the eastern coast of Greenland. The latter date appears to be the most probable as the earlier ones are related to very low air mass elevations (Figure 6). In each case deposition occurred from an air mass flowing at 3000 m over the Greenland stations.

[19] In 2005, exotic pollen deposited at Narsarsuaq on May 17, were captured on May 5 in the emission area of the northeastern United States (Figure 7). The transport of the exotic grains, among them hickory which is strictly a North American tree, to Ittoqqortoormitt occurred on April 25 (Figure 8). The pollen grains were advected into the atmosphere from the source region on April 14.

[20] The air masses responsible for the transport of the exotic grains over the sampling stations are consistently at a 3000 m elevation. However, when the air mass is passing over the source areas of the trees, the elevation is much lower permitting the capture of enough grains to be subsequently transported by this higher altitude air mass, and recorded at our stations over Greenland. Such a pattern has already been reported for similar long-distance transport to Narsarsuaq in 2002 and 2003 for grains characteristics of US trees, as well as to the North Pole in 2002 for pollen released by European trees [2004; 2006; *Rousseau, et al*., 2003],..

4. Discussion

[21] Two groups according to the altitude of the capture of the exotic grains can be distinguished. The first group refers to air parcels between 1000 and 3000 m over the source region as is the case for Qaanaaq and Kangerlussuaq in 2004, and Narsarsuaq and Ittoqqortoormitt in 2005. The second group consists of air parcels below 1000 m passing over the source area, which occurred in the transport to Narsarsuaq and Ittoqqortoormitt in 2004.

[22] The timing of the capture of the pollen grains at these stations occurred between mid-April and mid-June. This finding is in agreement with the emission interval that Cambon [*Cambon*, 1994; *Cambon, et al.*, 1992] determined in her yearly surveys of the pollen emission around Toronto, Ontario. The quantity of exotic grains is relatively low except in Qaanaaq. The duration of the transport is unlikely to be responsible for the low number of grains collected at the other stations as the time taken is similar in the majority of cases. Several factors have been invoked to explain variations in pollen grains on the filters ([*Rousseau, et al.*, 2006] . First, according to previous investigations on the northern growth limit of these trees, the maximum pollen emission varies between trees (Cambon, 1992, 1994; Cambon et al., 1992), leading to the differential release of diverse pollen types into the atmosphere. For example, while oak (*Quercus*) mostly flowers between the second half of April until mid-June, with a maximum earlier, hornbeam (*Carpinus*) flowers between the end of May until mid June Thus, in Qaanaaq, such difference in the timing of pollen emission could explain partly the observed variations between the two taxa. Second, the meteorological conditions for pollen capture may have been less favorable during this particular time leading to a reduction in pollen transport (weak upward air motion). The comparison of the upward intensity during the capture interval as indicated by the red boxes shows such diverse conditions (Fig. 3c-8c) the strongest upward motion occurs during the transport to Kangerlussuaq in 2004 (Fig. 4c). Third, even given favorable conditions for pollen capture, downward air motion at the filter location could be highly variable. Moreover, the reconstructed air velocity diagrams plotted in figures 3c to 8c show that the strength of the downdrafts of the atmosphere varied not only from place to place but also from one year to another. Fourth, washout by rain during the transport to Greenland associated with turbulence effects, could result in a large reduction in the number of pollen grains remaining in the air parcel reaching Greenland. This is also shown in the velocity diagrams, which provide evidence for severe downdrafts of the atmosphere, for example, during the transport to Narsarsuaq in 2004 and 2005 (Fig. 5c and 7c), Ittoqqortoormitt in 2004 and 2005 (Fig. 6c and 8c).

[23] A comparison of the results obtained for the western coast of Greenland in 2004 shows differences in the number and type of exotic grains. The total of grains transported varies

between 107 and 353. The duration of transport is 6-11 days, dates of deposition occur in mid April or May while the exotic grains are captured from the source region around the beginning of the month. In contrast, the east coast station has a total of 871 pollen grains with dates of capture and deposition delayed until June.

[24] When comparing the results obtained from one year to another at Ittoqqortootmitt, the capture and deposition dates differ by two months, while the total grains deposited are an order of magnitude larger in 2004. Indeed, although exotic pollen reaches the different stations on the coasts of Greenland, the identified trees vary from place to place, from one year to another, and the pattern of the air masses responsible for the transport varies as does the timing and the quantity of transported grains. In the later case, the amount of pollen grains deposited on the filters is linked mostly to the local production in the source area. Yearly pollen monitoring along a north south transect in Western Europe indicated that pollen production depends largely on temperatures affecting the trees during the year prior to pollination [*Cour, et al.*, 1993]. The deposited quantity also depends on the different conditions that prevailed during transport in the air mass affecting the preservation of the grains. Marked reduction in the abundance can occur during transport due to losses via washout by precipitation [*Barry, et al.*, 1981]. The observed counts in Narsarsuaq in both 2004 (10) and 2005 (7) are similar compared to those reported in 2002 (19), despite a much lower percentage of exotic grains out of the total identified. This is totally different to the values published for 2003, which indicated 239 exotic grains out of 6820,

[25] Considering the airmass loops, their paths indeed reflect the influence of depression passing over a certain place, thus complicating the computation of the trajectories. Chen et al. [*Chen, et al.*, 1997] concluded that frontal cyclones were the main meteorological system responsible for the precipitation regime over Greenland. They identified three main regions according to precipitation amounts and also distinguished the possible effects of the relief on moving cyclones. Interestingly, a comparison of these regions with our trajectories shows some similarities.

[26] The first area they identified is from South Greenland north to 68°N. Cyclones passing close to the southwest coast of Greenland or Cape Farewell are responsible for heavy precipitation over this area, and can induce lee cyclogenesis on the eastern coast. The second region is located northward of the southern region and referred to as the Central region. This area has an important blocking effect on cyclones moving from west to east. The third region is

located to the north of 80°N, where few cyclones influence this region during summer. They reported that the majority of precipitation over Greenland occurs in the southern region, peaking in winter and spring [*Chen, et al.*, 1997]. Thus, the dominance of the Labrador Sea and Icelandic cyclones determines the amount of precipitation over Greenland. Based on the location of the cyclone centers, they then determined five classes of cyclone tracks around Greenland (Figure 1). Track A is related to sea-level circulation, dominated by the Icelandic low. Track B is a major storm track into Baffin Bay from the south and from Hudson Bay. Track C corresponds to cyclones moving across the southern part of the Greenland ice-sheet and moving through the Denmark Strait. These three groups represent the three main tracks of the cyclone activity over Greenland. Tracks B and C are related to high precipitation over the southern region. Track D represents the cyclones approaching Greenland from the west which form during summer when polar and arctic front jets move northward. Track E characterizes cyclones formed in Baffin Bay moving northward and causing precipitation over the north coastal region. These latter two tracks are considered secondary. This characterization of cyclonic activity over Greenland fits with our pollen observations at the four stations installed on the both western and eastern coasts of Greenland. The observations of exotic pollen in Narsarsuaq, Kangerlussuaq and even Qaanaaq seem to be related to Track B cyclones, with a probable Track E effect in Qaanaaq. The results obtained in Ittoqqortoormitt, especially in 2005, indicate the influence of Track C. This pattern of the cyclone activity responsible for the precipitation regime, lends support as to why long distance pollen transport from North America to Greenland is observed in association with wet deposition.

5. Conclusion

[27] Our results show that various air mass trajectories transported exotic pollen grains to Greenland from Northeastern America following the major cyclone tracks, which are responsible for the precipitation regime over Greenland. These air parcels are at different altitudes leading to more complex modeling than originally expected or previously recorded. The patterns of the trajectories are different from one week to another, from one year to another and also from one locality to another. Further experiments and continued monitoring are needed to assess the variability and to validate the potential usefulness of such results for paleoclimatic studies.

~~Indeed as models of pollen dispersion and transport become more available and reliable on local or regional scales [*Helbig, et al.*, 2004], modeling transport over longer distances of several thousands kilometers will require more sophisticated parameterizations as our results clearly show, in order to fully understand the general atmospheric curculation involved.~~

[28] Acknowledgements. We would like to thank anonymous reviewers for comments, Joyce Gavin and Alex-Chepstow-Lusty for discussions and extensive editing of this paper. This research is supported by a grant from the French Polar Institute Paul-Emile Victor (IPEV) and the help of the local operator, even among the co-authors, is greatly appreciated. This is LDEO yyy.

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Figure captions

Figure 1. Location of the four pollen traps, Qaanaaq, Kangerlussuaq, Narsarsuaq and Ittoqqortoormitt in Greenland. Cyclone tracks over Greenland from Chen et al. [*Chen, et al.*, 1997] A-D main pathways, E,F secondary pathways.

Figure 2. Pollen stations in Qaanaaq and Ittoqqortoormitt respectively, installed close to meteorological stations.

Figure 3. Long distance transport of pollen to Qaanaaq, Greenland in April 2004. (a) Backward trajectories provided by the HYSPLIT model of air parcels reaching Qaanaaq at different altitudes: ground level (red), 1000m (blue) and 3000m (green) on April 18, 2004. The "3000m" air parcel passed over the grey area in Northeastern America which represents the area from where all the identied pollen types caught in the filters originated - oak (*Quercus)*, pine (*Pinus)*, plane (*Platanus)*, hornbeam (*Carpinus*) and walnut (*Juglans)*- (from [*Thompson, et al*., 1999a; 1999b]). (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The "3000 m" air parcel over Qaanaaq on April 18, 2004, was at a lower elevation (between 1000 and 2000 m) on April 8 and 12 when it passed over the area where "exotic" trees grow. The red bar indicates the time span when potential uplift of the pollen was possible. (c) Updrafts and downdrafts in the atmosphere. Velocity of the air parcel passing over the growing area in northeastern North America, which reached Qaanaaq at 3000 m on April 18, 2004 versus time. Yellow to brown values indicate upward movements; light blue to purple indicate downward movements. The light colored red box characterizes the timing of the uplift of the pollen corresponding to the interval when the selected air parcel passed over the source region.

Figure 4. Transport to Kangerlussuaq on May 13, 2004. (a) Backward trajectories (as in Figure 3). (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The “3000 m” air volume over Kangerlussuaq on May 13, 2004, was at lower elevation (between 1000 and 2000 m) on May 4 when it passed over the area where oak (*Quercus)*, hazel (*Corylus)*, hops (*Humulus)*, pine (*Pinus)*, and plane (*Platanu*s) are all growing (as in Figure 3). (c) as in Figure 3.

Figure 5. Transport to Narsarsuaq on May 10, 2004. (a) Backward trajectories (as in Figure 3). (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The "3000 m” air volume over Narsarsuaq on May 10, 2004, was at a lower elevation

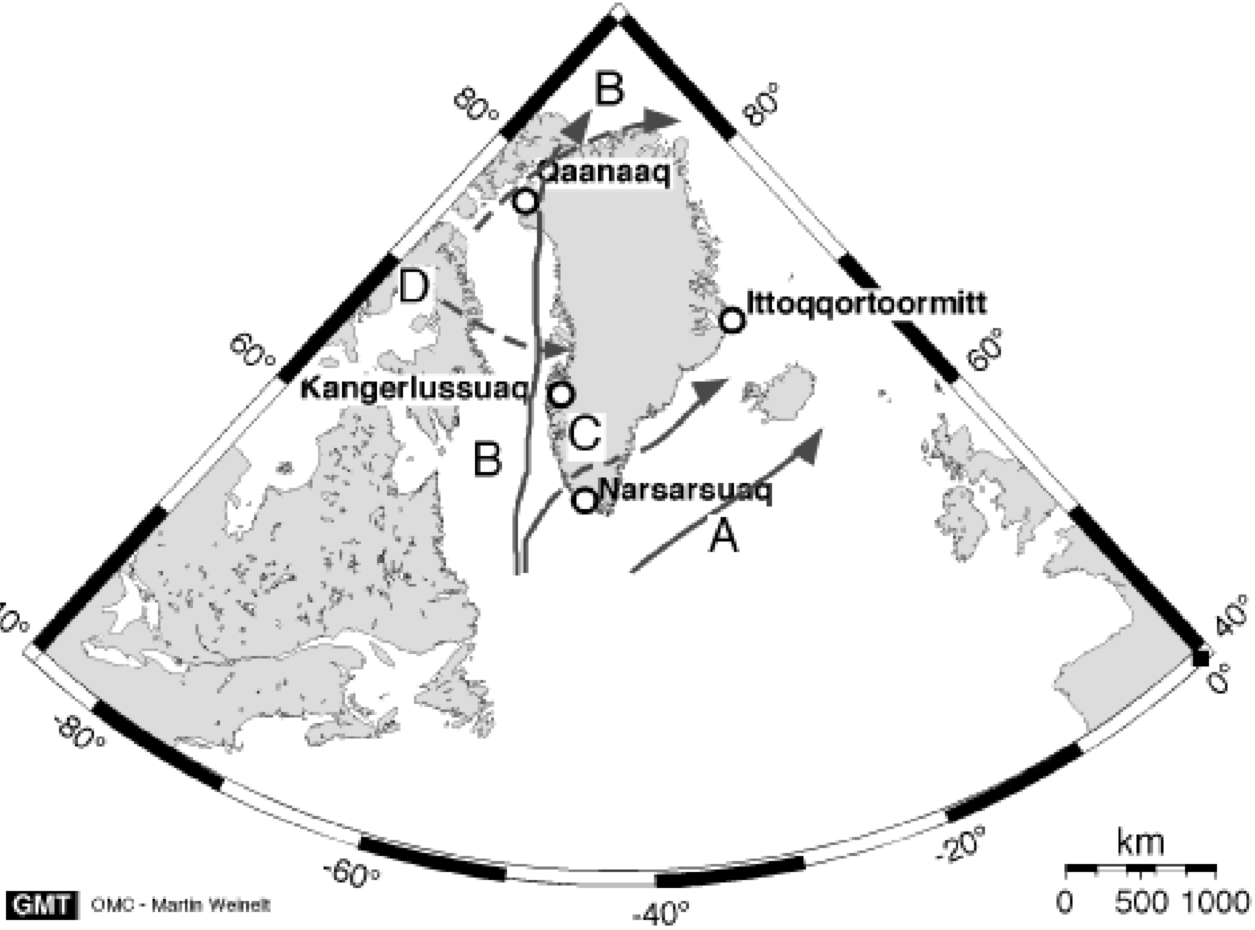
(between ground level and 1000m) on May 3 and 4 when it passed over the area where pine (*Pinus)*, oak (*Quercus)*, fir (Abies), hazel (*Corylus)*, walnut (*Juglans)* and hornbeam (*Carpinus*) all grow (as in Figure 3). (c) as in Figure 3.

Figure 6. Transport to Ittoqqortoormitt on June 19, 2004. (a) Backward trajectories (as in Figure 3). (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The "3000 m" air volume over Ittoqqortoormitt on June 19, 2004, was at a lower elevation (between ground level and 1000 m) on June 8 to 13 when it passed over the area where pine (*Pinus)*, oak (*Quercus*), chestnut (*Castanea*) and beech (*Fagus)* are all growing (as in Figure 3). (c) as in Figure 3.

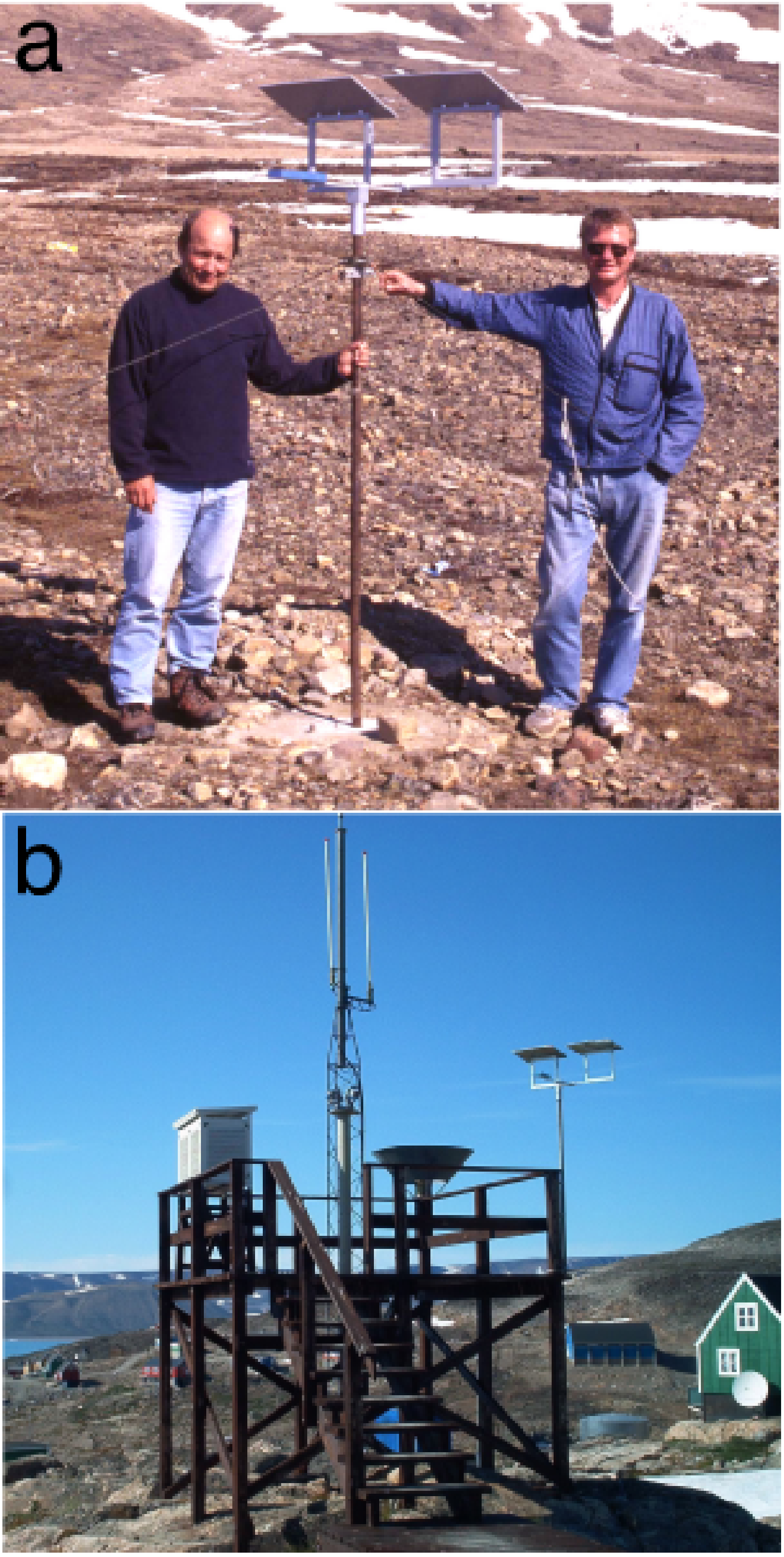
Figure 7. Transport to Narsarsuaq on May 17, 2005. (a) Backward trajectories (as in Figure 3). (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The "3000 m" air volume over Narsarsuaq on May 17, 2005, was at lower elevation (between ground 1000 and 2000m) on May 5 when it passed over the area where hornbeam (*Carpinus*), walnut (*Juglans)*, chestnut (*Castanea)*, pine (*Pinus)* -and elm (*Ulmus)*, are all growing (as in Figure 3). (c) as in Figure 3.

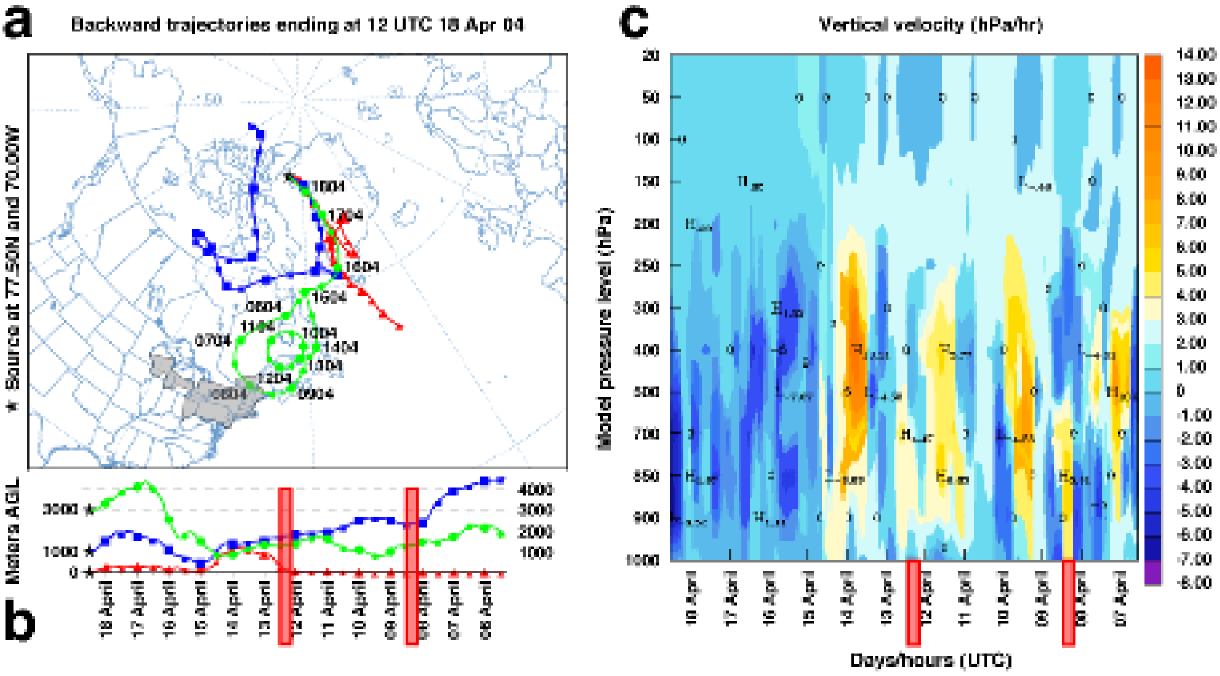
Figure 8. Transport to Ittoqqortoormitt on April 25, 2005. (a) Backward trajectories (as in Figure 3). (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The "3000 m" air volume over Ittoqqortoormitt on April 25, 2005, was at lower elevation (between ground 1500 and 2000m) on April 14 when it passed over the area where oak (*Quercus)*, pine (*Pinus)*, plane (*Platanus)* and hickory (*Carya)* are all growing (as in Figure 3). (c) as in Figure 3.

Table 1. Exotic pollen grains identified in the four stations in Greenland in 2004 and 2005

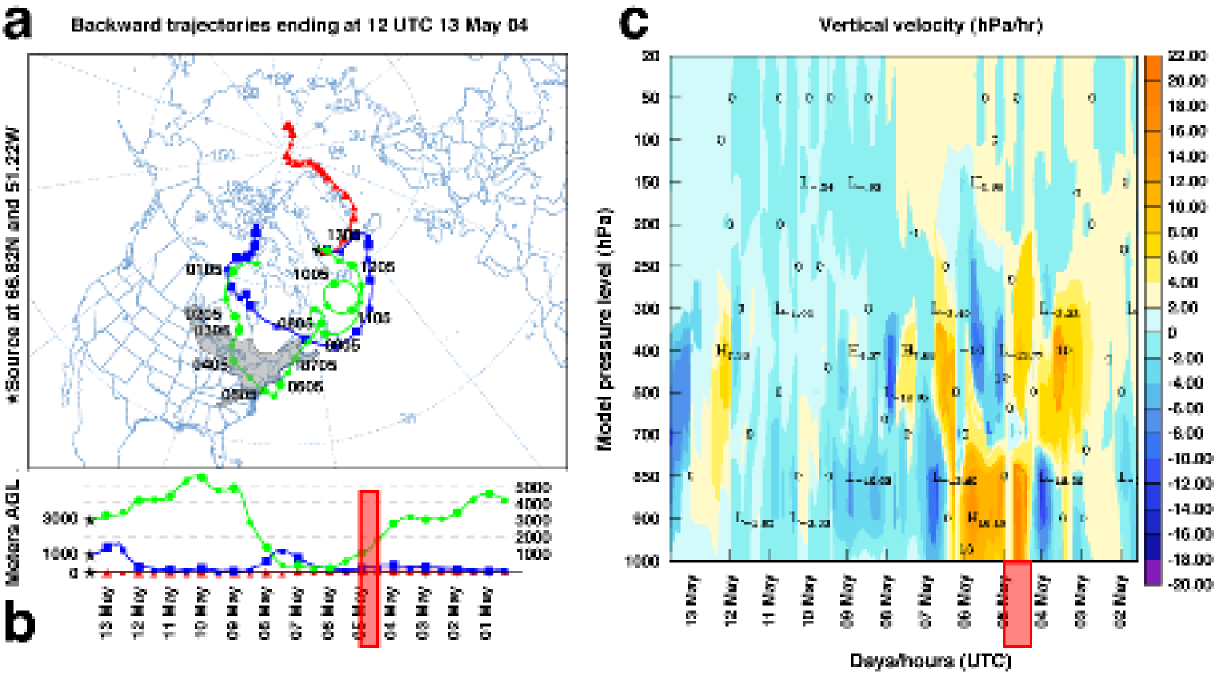


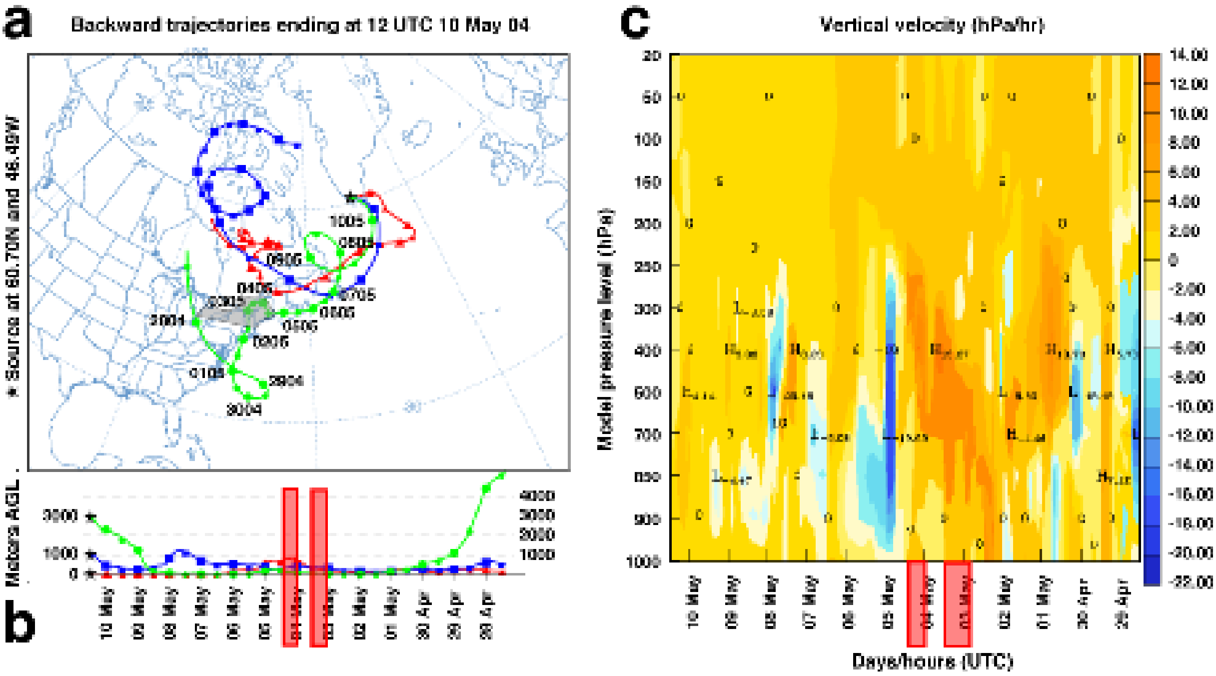
B
80°
80°
Qaanaaq
D
Ittoqqortoormitt
60°
60°
Kangerlussuaq
C
B
Narsarsuaq
A
40°
40°
0°
-80°
-60°
-40°
-20°
km
0
500
1000
GMT
OMC - Martin Weinelt

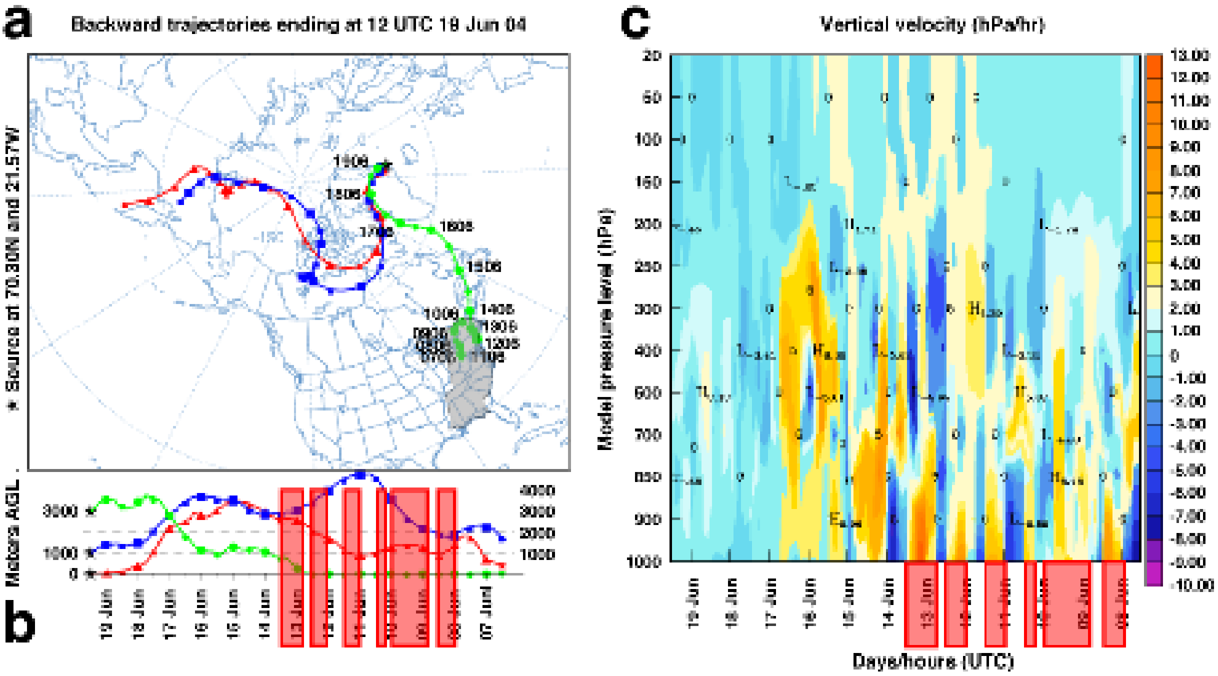

a
b

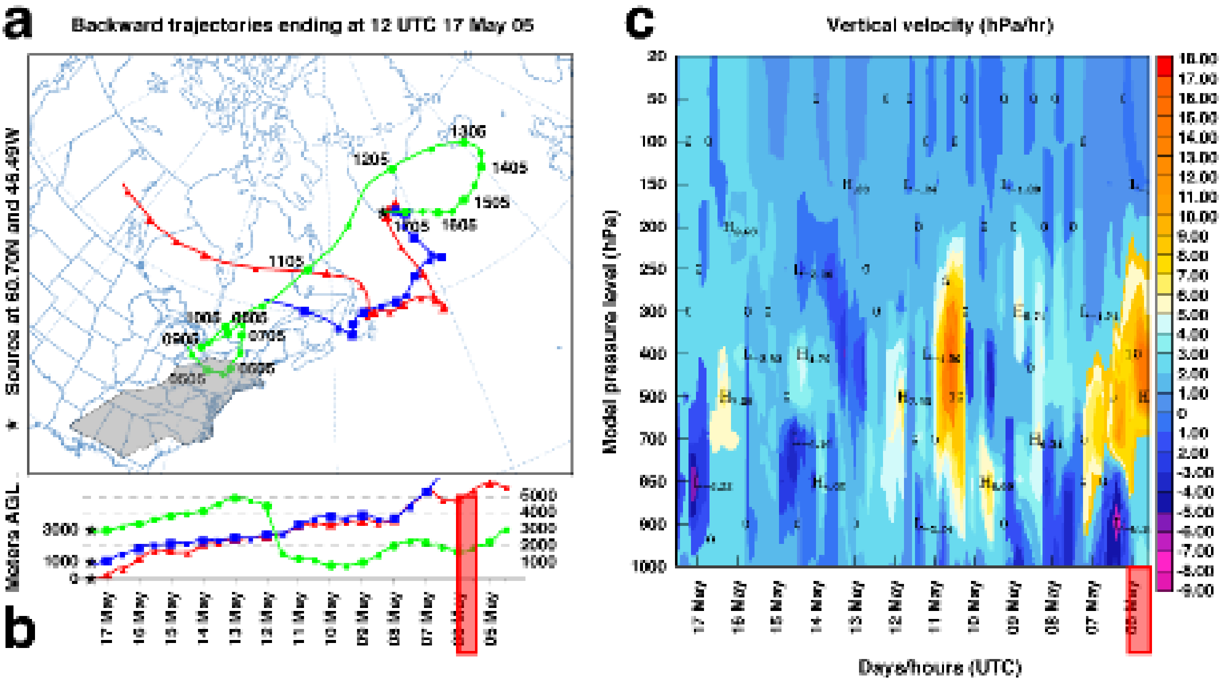


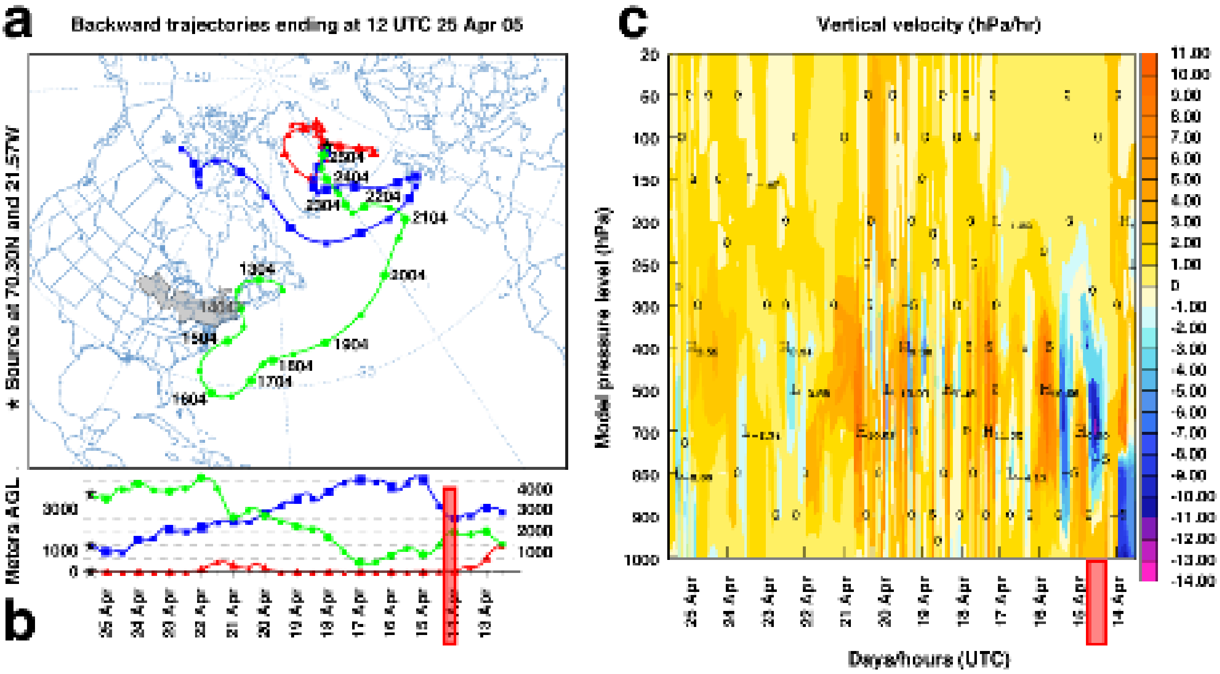
a
Backward trajectories ending at 12 UTC 18 Apr 04
★ Source at 77.50N and 70.00W
1604
1704
1504
0604
1104
0704
1004
1404
1304
1204
0804
0904
Meters AGL
3000
1000
0
4000
3000
2000
1000
18 April
17 April
16 April
15 April
14 April
13 April
12 April
11 April
10 April
09 April
08 April
07 April
06 April
b
c
Vertical velocity (hPa/hr)
Model pressure level (hPa)
20
50
100
150
200
250
300
400
500
700
850
900
1000
18 April
17 April
16 April
15 April
14 April
13 April
12 April
11 April
10 April
09 April
08 April
07 April
Days/hours (UTC)
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00


a
Backward trajectories ending at 12 UTC 13 May 04
★Source at 66.82N and 51.22W
b
Meters AGL
13 May
12 May
11 May
10 May
09 May
08 May
07 May
06 May
05 May
04 May
03 May
02 May
01 May
c
Vertical velocity (hPa/hr)
Model pressure level (hPa)
Days/hours (UTC)


a
Backward trajectories ending at 12 UTC 10 May 04
★ Source at 60.70N and 46.49W
1005
0805
0605
0705
0406
0505
0305
0506
3004
0205
0105
2904
3004
Meters AGL
3000
1000
0
4000
3000
2000
1000
b
10 May
09 May
08 May
07 May
06 May
05 May
04 May
03 May
02 May
01 May
30 Apr
29 Apr
28 Apr
c
Vertical velocity (hPa/hr)
Model pressure level (hPa)
20
50
100
150
200
250
300
400
500
700
850
900
1000
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
-18.00
-20.00
-22.00
10 May
09 May
08 May
07 May
06 May
05 May
04 May
03 May
02 May
01 May
30 Apr
29 Apr
Days/hours (UTC)


a
Backward trajectories ending at 12 UTC 19 Jun 04
Source at 70.30N and 21.57W
Meters AGL
b
c
Vertical velocity (hPa/hr)
Model pressure level (hPa)
Days/hours (UTC)


a
Backward trajectories ending at 12 UTC 17 May 05
Source at 60.70N and 46.49W
1305
1205
1405
1505
1605
1005
1105
0805
0905
0705
0605
0505
Meters AGL
5000
4000
3000
2000
1000
b
17 May
16 May
15 May
14 May
13 May
12 May
11 May
10 May
09 May
08 May
07 May
06 May
05 May
c
Vertical velocity (hPa/hr)
Model pressure level (hPa)
Days/hours (UTC)
18.00
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00



a
Backward trajectories ending at 12 UTC 25 Apr 05
★ Source at 70.30N and 21.57W
b
Meters AGL
c
Vertical velocity (hPa/hr)
Model pressure level (hPa)
Days/hours (UTC)

Pollen identified		QO4	Q05	K04	K05	N04	N05	I04	I05
		12-25/4	?	3-16/5	?	3-16/5	16-29/5	14-26/6	25/4-8/5
Abies	fir					1			
Carpinus	hornbeam	1				1	2		
Carya	hickory								1
Castanea	chesnut						1	1	
Corylus	hazel			3		1			
Fagus	beeche							1	
Humulus	hops			3					
Juglans	walnut	1				1	2		
Pinus	pine	28	x	2	x	4	1	2	5
Platanus	plane	5		1					1
Quercus	oak	38		12		2		2	6
Ulmus	elm						1		
Total exotic		73		21		10	7	6	13
% exotic		68,22%		9,13%		2,83%	0,53%	0,69%	20,97%
Total counted		107	-	230	-	353	1316	871	62