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1 Abstract

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3 [1] In the Arctic domain there is evidence for very long distance transport of pollen grains from 4 boreal forests to tundra environments. However, the sampling protocol used in earlier studies did 5 not allow the determination of the precise timing of the deposition of exotic grains. The ongoing 6 "Epilobe" project monitors the deposition of exotic grains on both western and eastern coasts of 7 Greenland utilizing wind filters, which are changed weekly throughout the entire year. A 8 combination of the identification of tree pollen grains, the dates of deposition of the pollen on the 9 filters, and the distribution map of the trees identified, allows the selection of modeled backward 10 trajectories of air parcels responsible for the capture of the grains in the growing area of 11 northeastern North America, and their long distance transport to Greenland. A survey of data 12 obtained from four stations, analyzed during 2004 and 2005, indicates the occurrence of a general 13 pattern, every spring, which follows the main cyclone tracks reaching this Arctic region. 14

1

2 **1. Introduction**

3

4 [2] Pollen transport is a crucial topic as it has a strong societal impact, especially when 5 considering allergies [Guérin, et al., 1993; Michel, et al., 1976]. For decades, aerobiologists 6 investigated this particular aspect of plant phenology, which eventually led to modeling [Chuine 7 and Belmonte, 2004; Ranzi, et al., 2003] the particular relationship between pollen emission and 8 temperature variations [Cambon, 1980; Cour, 1974; Palacios, et al., 2007]. To accomplish this, 9 therefore the biologists had to consider not only the local pollen dissemination but also a more 10 complex process, involving some transport, especially wind blown material. Besides societal 11 concern [Michel, et al., 1976], the same preoccupations are faced by ecologists in terms of 12 understanding the large scale transportation and deposition of exotic grains [Porsbjerg, et al., 13 2003], i.e. pollen grains released by plants which are not growing in the studied region [Peternel, 14 et al., 2006; Smith, et al., 2005]. Such investigations in temperate regions are much more difficult 15 to carry out [Hicks, 1985], because usually pollen is identified mostly at the generic level, except 16 if particular pollen is easily distinguished, i.e. from tropical or subtropical trees [Cambon, et al., 17 1992]. However, such tasks are much easier in the higher latitudes where the vegetation is greatly 18 reduced and less diverse. Therefore, in high latitudes, the patterns of long-distance transport can 19 be easily observed [Andrews, et al., 1980; Bourgeois, et al., 1985; Campbell, et al., 1999; 20 Franzen, et al., 1994; Gajewski, 1995; Hicks, et al., 2001; Hjelmroos and Franzen, 1994; Jacobs, 21 et al., 1985; Janssen, 1973; Nichols, 1967; Ritchie, 1974; Ritchie and Lichti-Federovich, 1967; 22 Ritchie, et al., 1987; Short and Holdsworth, 1985]. In understanding the very long-range 23 transport of pollen grains, most of which range from 15-30 microns, except for the larger 24 bisaccate grains of conifer, bigger than a few microns, they can be considered as aerosol 25 components [*Hicks and Isaksson*, 2006; *Prospero, et al.*, 2005]} and a proxy indicator for more 26 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 29 of the Great Lakes was the source region. The timing of the deposition regularly occurred during 30 the second half of May but the air mass trajectories differed. On the other hand, long distance 31 transport to the North Pole in 2002 was found to have originated from Western Europe and

1 Eastern Siberia [Rousseau, et al., 2004]. These were the first analyses to develop a complete 2 description of the transport from the source area to the deposition site, characterizing the air 3 masses responsible, and detailing the timing of the capture and deposition of the grains. Previous 4 sampling in the Arctic region had demonstrated the occurrence of long distance pollen transport, 5 but samples taken from snow or ice layers were limited to seasonal resolution, i.e. late 6 winter/spring snow and in the summer melt layers [Bourgeois, et al., 1985; Bourgeois, et al., 7 2001; Hicks, et al., 2001; Ritchie, 1974; Ritchie and Lichti-Federovich, 1967]. Other published 8 data from fossil pollen records has led to assumptions about averaged trajectories. These studies 9 did not allow for the precise description of long distance transport to the Arctic, due to annual 10 sampling, which made the identification uncertain of the source of exotic pollen grains 11 [Bourgeois, et al., 1985; Bourgeois, et al., 2001; Hicks, et al., 2001; Ritchie, 1974; Ritchie and 12 Lichti-Federovich, 1967].

13 [4] Because we are currently limited to four sampling sites, the general transport pattern for 14 the entire island of Greenland cannot be identified. In order to improve our understanding, a 15 network of pollen stations is required all along the western and eastern coasts. At present it is not 16 possible to locate sampling stations on the ice sheet. With an increased sampling network and 17 continued monitoring, a much more reliable scenario for further modeling experiments will be 18 possible. Nevertheless, the long distance pollen transport reported here from four stations with 19 weekly resolution for the spring of 2004 and 2005 adds significantly to our understanding of 20 circulation patterns from northeastern North America to Greenland.

21

22 2. Material and methods

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24 [5] Within the "EPILOBE" (French name of willowweed, *Epilobium*, the national flower of 25 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, 26 27 69.35°W) and eastern (Ittoggortoormitt, 70.48°N, 21.95°W) coasts of Greenland. They are 28 situated within a maximum of 10 m from a meteorological station (Figure 1) and except in 29 Kangerlussuaq, the pollen stations are located next to the sea. The interest in having a rotating 30 frame on which the filters are placed is that it also collects the pollen from the local vegetation, if 31 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 1 2 filters are composed of several crossed bands of gauze bathed in a siliconed glue and set in a 3 plastic framework. Half of each filter is processed for pollen extraction and the other half retained 4 for future analysis. The yearly survey of the pollen occurrence is recorded for all four localities 5 yielding a very precise record of the local vegetation, timing of pollen deposition, and also 6 evidence for seasonal transport of exotic grains [2004; 2006; Rousseau, et al., 2003]. Previous studies in the Arctic mainly reported yearly observations of pollen flux [Ritchie and Litchi-7 8 Federovich, 1967, Ritchie, 1974, Bourgeois et al., 1985, 2001; Hicks et al., 2001].

9 [6] Before the pollen stations were installed (Figure 2), ground samples in their vicinity 10 were collected and analyzed. A few exotic pollen grains were identified, mainly pine (*Pinus*) at 11 Kangerlussuaq, and oak (*Quercus*) at Narsarsuaq, indicating long-distant transport to these 12 remote stations. However, since the the surface samples were taken more inland than that of the 13 pollen stations, mostly close to the sea, we are confident that the grains identified in the filters are 14 not reworked ones..

15 Only the results from fortnightly filters showing exotic grains are reported here. Using the 16 dates of the filter exposures, backward air mass trajectories are then computed for every day in 17 the two week period using the HYSPLIT on-line application [Draxler and Hess, 1998; 18 HYSPLIT4Model, 1997], model details can be found at 19 (http://www.arl.noaa.gov/ready/hysplit4.html). The potential trajectories are selected to explain 20 the observed long distance transport considering the probable dates of pollen emission and the 21 dates of the air mass passing over the region of growing trees specific to the identified pollen 22 captured at the Greenland sites [Thompson, et al., 1999a; b]. Numerous computations were 23 performed for a single day, with noon chosen as the most representative of the different times. 24 We introduced the coordinates of the filters as our targets and thus when exotic grains were 25 identified in the filters, trajectories were computed for the total time interval during which the 26 filters were exposed, i.e. 14 days. In the first step, days were selected which corresponded to 27 backward trajectories passing over the growing area, including all the trees producing the 28 observed pollen. In a second step, we considered the elevation at which air parcels were passing 29 over the determined area, rejecting those passing too high. Finally we considered the vertical 30 motion, a very important factor, associated with the potential air mass: if upward motion existed 31 for favoring the convection of the grains, and similarly if downward motion was present at the 32 target location, then we selected the considered computation. By using this protocol it allowed us 33 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.

5 **3.** Results

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- 7 3.1 Pollen counts (Tab. 1)
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10 [8] At Qaanaaq in 2004, the filter exposed during weeks 16-17 (12-25 April) recorded 73 11 exotic grains (38 oak – *Quercus*, 28 pine -*Pinus*, 5 plane -*Platanus*, and 1 hornbeam – *Carpinus*-12 and walnut –*Juglans*, respectively) out of a total of 107 grains. This indicates that the majority of 13 transported pollen grains corresponding to 68.22% of the total counted , was exotic.

14 [9] At Kangerlussuaq in 2004, the filter exposed during weeks 19 and 20 (3-16 May) 15 recorded 21 exotic grains (12 oak - *Quercus*, 3 hazel – *Corylus*- and hops –*Humulus*, 2 pine -16 *Pinus*, and 1 plane - *Platanus*) among a total of 230 identified grains. This is a considerably less 17 (6.57%) than in Qaanaaq. Indeed, the local vegetation in Kangerlussuaq is more abundant, 18 consisting of shrub tundra, composed of birch (*Betula*), juniper (*Juniperus*), and willow (*Salix*).

19 [10] At Narsarsuag, where evidence of long distance transport has been reported [2004; 20 2006; Rousseau, et al., 2003]., only 10 exotic grains (4 pine - Pinus, 2 oak - Quercus, 1 fir -21 Abies, hazel - Corylus, walnut - Juglans - and hornbeam - Carpinus, respectively) in over 353 22 grains were identified for weeks 19-20 (3-16 May, 2004). This corresponds to an even smaller 23 percentage, 2.83%, compared to the two other west coast stations which are located further north. 24 The local tundra vegetation surrounding the meteorological station is represented by birch 25 (Betula), horsetail, willow (Salix), alder (Alnus), heath (Erica) and genera in the sedge family 26 (Cyperaceae).

[11] On the eastern coast, at Ittoqqortoormitt in 2004, the filter exposed during weeks 2526 (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.

31 [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.

4 [13] Conversely in Narsarsuaq, exotic pollen was identified during weeks 20-21 (May 16-5 29) with 2 grains each of hornbeam - Carpinus - and walnut - Juglans, 1 each of chestnut -6 Castanea, pine - Pinus - and elm - Ulmus, representing 0.53% of the total 1316 grains . The filter 7 exposed during weeks 17-18 (25 April -8 May) in Ittoqqortoormitt yielded 13 exotic pollen 8 grains out of 62 counted, (20.97%) corresponding to 6 grains of oak - Quercus, 5 pine - Pinus, 1 9 plane - Platanus - and 1 hickory - Carya. This is a considerably higher percentage of exotic 10 grains compared to the 2004 record. Most notable is the occurrence of hickory, which is solely a 11 North American tree [Thompson, et al., 1999a; b].

12 [14] Out of six cases in 2004 and 2005, the deposition of exotic pollen grains in the filters 13 occurred half the time between weeks 19 and 21. With the exception of the east coast station in 14 2004 where exotic grains were registered during weeks 25-26, deposition occurred in nearly all 15 cases between weeks 16 and 21. These findings are in agreement with the time of pollination 16 (weeks 15 to 31) determined for the various trees species at four different stations in Southern 17 Ontario, Canada, [Cambon, 1994; Cambon, et al., 1992]. One interesting feature of the data is 18 that the southernmost station, Narsarsuaq, recorded long distance pollen transport in variable 19 proportions during these two additional years of our experiment, yet reproduced similar 20 observations to the earlier studies. Indeed, in 2002, among 5514 grains counted, only 19 (0.34%) 21 were from exotic plants while one year later, among 6888 grains counted, 336 (4.89%) originated 22 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.

28

29 3.2 Backward trajectories

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31 [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:

9 [18] In 2004, exotic pollen deposited in Qaanaaq on April 18 (Figure 3), corresponded to 10 the transport of pollen grains captured in the source area on April 8 and 12. In Kangerlussuaq, the 11 exotic pollen deposited on May 13 (Figure 4), were captured on May 4 in the growing area. The 12 transport of exotic pollen grains to Narsarsuaq ended on May 10 (Figure 5); they were deposited 13 over the source area on May 3 and 4. Finally, exotic pollen arrived at Ittoqqortoormitt on June 19, 14 which corresponded to grains captured between June 8-13 by an air mass passing over the eastern 15 coast of Greenland. The latter date appears to be the most probable as the earlier ones are related 16 to very low air mass elevations (Figure 6). In each case deposition occurred from an air mass 17 flowing at 3000 m over the Greenland stations.

18 [19] In 2005, exotic pollen deposited at Narsarsuaq on May 17, were captured on May 5 in 19 the emission area of the northeastern United States (Figure 7). The transport of the exotic grains, 20 among them hickory which is strictly a North American tree, to Ittoqqortoormitt occurred on 21 April 25 (Figure 8). The pollen grains were advected into the atmosphere from the source region 22 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],...

30

31 4. Discussion

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[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.

7 [22] The timing of the capture of the pollen grains at these stations occurred between mid-8 April and mid-June. This finding is in agreement with the emission interval that Cambon 9 [Cambon, 1994; Cambon, et al., 1992] determined in her yearly surveys of the pollen emission 10 around Toronto, Ontario. The quantity of exotic grains is relatively low except in Qaanaaq. The 11 duration of the transport is unlikely to be responsible for the low number of grains collected at 12 the other stations as the time taken is similar in the majority of cases. Several factors have been 13 invoked to explain variations in pollen grains on the filters ([Rousseau, et al., 2006]. First, 14 according to previous investigations on the northern growth limit of these trees, the maximum 15 pollen emission varies between trees (Cambon, 1992, 1994; Cambon et al., 1992), leading to the 16 differential release of diverse pollen types into the atmosphere. For example, while oak (*Quercus*) 17 mostly flowers between the second half of April until mid-June, with a maximum earlier, 18 hornbeam (Carpinus) flowers between the end of May until mid June Thus, in Qaanaaq, such 19 difference in the timing of pollen emission could explain partly the observed variations between 20 the two taxa. Second, the meteorological conditions for pollen capture may have been less 21 favorable during this particular time leading to a reduction in pollen transport (weak upward air 22 motion). The comparison of the upward intensity during the capture interval as indicated by the 23 red boxes shows such diverse conditions (Fig. 3c-8c) the strongest upward motion occurs during 24 the transport to Kangerlussuaq in 2004 (Fig. 4c). Third, even given favorable conditions for 25 pollen capture, downward air motion at the filter location could be highly variable. Moreover, the 26 reconstructed air velocity diagrams plotted in figures 3c to 8c show that the strength of the 27 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 28 29 effects, could result in a large reduction in the number of pollen grains remaining in the air parcel 30 reaching Greenland. This is also shown in the velocity diagrams, which provide evidence for 31 severe downdrafts of the atmosphere, for example, during the transport to Narsarsuaq in 2004 and 32 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.

5 [24] When comparing the results obtained from one year to another at Ittogqortootmitt, the 6 capture and deposition dates differ by two months, while the total grains deposited are an order of 7 magnitude larger in 2004. Indeed, although exotic pollen reaches the different stations on the 8 coasts of Greenland, the identified trees vary from place to place, from one year to another, and 9 the pattern of the air masses responsible for the transport varies as does the timing and the 10 quantity of transported grains. In the later case, the amount of pollen grains deposited on the 11 filters is linked mostly to the local production in the source area. Yearly pollen monitoring along 12 a north south transect in Western Europe indicated that pollen production depends largely on 13 temperatures affecting the trees during the year prior to pollination [Cour, et al., 1993]. The 14 deposited quantity also depends on the different conditions that prevailed during transport in the 15 air mass affecting the preservation of the grains. Marked reduction in the abundance can occur 16 during transport due to losses via washout by precipitation [Barry, et al., 1981]. The observed 17 counts in Narsarsuaq in both 2004 (10) and 2005 (7) are similar compared to those reported in 18 2002 (19), despite a much lower percentage of exotic grains out of the total identified. This is 19 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 1 2 reported that the majority of precipitation over Greenland occurs in the southern region, peaking 3 in winter and spring [Chen, et al., 1997]. Thus, the dominance of the Labrador Sea and Icelandic 4 cyclones determines the amount of precipitation over Greenland. Based on the location of the 5 cyclone centers, they then determined five classes of cyclone tracks around Greenland (Figure 1). 6 Track A is related to sea-level circulation, dominated by the Icelandic low. Track B is a major 7 storm track into Baffin Bay from the south and from Hudson Bay. Track C corresponds to 8 cyclones moving across the southern part of the Greenland ice-sheet and moving through the 9 Denmark Strait. These three groups represent the three main tracks of the cyclone activity over 10 Greenland. Tracks B and C are related to high precipitation over the southern region. Track D 11 represents the cyclones approaching Greenland from the west which form during summer when 12 polar and arctic front jets move northward. Track E characterizes cyclones formed in Baffin Bay 13 moving northward and causing precipitation over the north coastal region. These latter two tracks 14 are considered secondary. This characterization of cyclonic activity over Greenland fits with our 15 pollen observations at the four stations installed on the both western and eastern coasts of 16 Greenland. The observations of exotic pollen in Narsarsuaq, Kangerlussuaq and even Qaanaaq 17 seem to be related to Track B cyclones, with a probable Track E effect in Qaanaaq. The results 18 obtained in Ittoqqortoormitt, especially in 2005, indicate the influence of Track C. This pattern of 19 the cyclone activity responsible for the precipitation regime, lends support as to why long 20 distance pollen transport from North America to Greenland is observed in association with wet 21 deposition.

22

23 5. Conclusion

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[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.

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11 **References**

- Andrews, J. T., W. N. Mode, and P. T. Davis (1980), Holocene climate based on pollen transfer functions, Eastern Canadian Arctic, *Arctic and Alpine Research*, 12, 41-64.
- Barry, R. G., D. L. Elliott, and R. G. Crane (1981), The palaeoclimatic interpretation of exotic
 pollen peaks in Holocene records from the eastern Canadian Arctic: a discussion, *Rev. Palaeobot. Palynol.*, 33, 153-167.
- Bourgeois, J. C., R. M. Koerner, and J. C. Alt (1985), Airborne pollen: A unique air mass tracer,
 its influx to the Canadian high Arctic., *Ann. Glaciol.*, 7, 109-116.
- Bourgeois, J. C., K. Gajewski, and R. M. Koerner (2001), Spatial patterns of pollen deposition in
 arctic snow, *J. Geophys. Res.*, 106(D6), 5255-5265.
- Cambon, G. (1980), Dispersion aéroplanctonique et climats: variations latitudinales des spectres
 polliniques de l'atmosphère en Méditerranée occidentale., *Mem. Mus. Nat. Hist. Nat. Paris*,
 serie B, 27, 57-65.
- Cambon, G. (1994), Modern pollen spectra and vegetation in southern Ontario, Canada., *Rev. Palaeobot. Palynol.*, 82, 147-155.
- Cambon, G., J. C. Ritchie, and P. Guinet (1992), Pollen marqueur de transports à longue distance
 dans l'atmosphère du sud de l'Ontario (Canada), *Canadian J. Botany*, 70, 2284-2293.
- Campbell, I. D., K. McDonald, M. Flannigan, and J. Kringayark (1999), Long-distance transport
 of pollen into the Arctic, *Nature*, 399, 29-30.
- 30 Chen, Q. S., D. H. Bromwich, and L. S. Bai (1997), Precipitation over Greenland retrieved by a
- 31 dynamic method and its relation to cyclonic activity, *J. Climate*, 10, 839-870.
- 32 Chuine, I., and J. Belmonte (2004), Improving prophylaxis for pollen allergies: Predicting the time

- course of the pollen load of the atmosphere of major allergenic plants in France and Spain,
 Grana, 43, 65-80.
- Cour, P. (1974), Nouvelles techniques de détection des flux et des retombées polliniques: Etude de
 la sédimentation des pollens et des spores à la surface du sol, *Pollen et Spores*, 16, 103-141.
- 5 Cour, P., G. Cambon, J. Ferrier, D. Duzer, L. Janzon, L. Quet, Y. Loublier, J. Olivier, and R. Gros
- 6 (1993), Calendriers polliniques de l'Europe occidentale, région méditerranéenne comprise, in
- 7 <u>Pollen et allergies</u>, edited by Guérin, B., J. Bousquet, P. Cour, Evrard, F. Guérin, N. Nolard, G.
- 8 Peltre and Y. Sell, pp. 255-270, Allerbio, Varennes-en-Argonne.
- 9 Draxler, R. R., and G. D. Hess (1998), An overview of the Hysplit_4 modelling system for
 10 trajectories, dispersion and deposition, *Australian Met. Mag.*, 47, 295-308.
- Fraile, R., A. I. Calvo, A. Castro, D. Fernandez-Gonzalez, and E. Garcia-Ortega (2006), The
 behavior of the atmosphere in long-range transport, *Aerobiologia*, 22, 35-45.
- 13 Franzen, L. G., M. Hjelmroos, P. Kallberg, E. Brorstromlunden, S. Juntto, and A. L. Savolainen
- 14 (1994), The yellow-snow episode of Northern Fennoscandia, March-1991. A case-study of
- long-distance transport of soil, pollen and stable organic-compounds, *Atmosph. Env.*, 28, 35873604.
- Gajewski, K. (1995), Modern and Holocene pollen assemblages from some small Arctic lakes on
 Somerset Island, NWT, Canada, *Quat. Res.*, 44, 228-236.
- Guérin, B., J. Bousquet, P. Cour, Evrard, F. Guérin, N. Nolard, G. Peltre, and Y. Sell (Eds.)
 (1993), *Pollen et allergies*, 279 pp., Allerbio, Varennes-en-Argonne.
- Helbig, N., B. Vogel, H. Vogel, and F. Fiedler (2004), Numerical modelling of pollen dispersion
 on the regional scale, *Aerobiologia*, 3, 3–19.
- Hicks, S. (1985), Modern pollen deposition records from Kuusamo, Finland, <u>Grana</u>, 24, 167-184.
- 24 Hicks, S., and E. Isaksson (2006), Assessing source areas of pollutants from studies of fly ash,
- charcoal, and pollen from Svalbard snow and ice, J. Geophys. Res., 111, D02113,
 doi:10.1029/2005JD006167.
- Hicks, S., H. Tinsley, A. Huusko, C. Jensen, M. Hättestrand, A. Gerasimides, and E. Kvavadze
 (2001), Some comments on spatial variation in arboreal pollen deposition: first records from
- the Pollen Monitoring Programme (PMP), *Rev. Palaeobot. Palynol.*, 117, 183-194.
- 30 Hjelmroos, M., and L. G. Franzen (1994), Implications or recent long-distance pollen transport
- 31 events for the interpretation of fossil pollen records in Fennoscandia, *Rev. Palaeobot. Palynol*.,

1 82, 175-189.

- HYSPLIT4Model (1997), (HYbrid Single-Particle Lagrangian Integrated Trajectory)
 <u>http://www.arl.noaa.gov/ready/hysplit4.html, NOAA Air Resources Laboratory, Silver Spring,</u>
 MD.
- 5 Jacobs, J. D., W. N. Mode, and E. K. Dowdeswell (1985), Contemporary pollen deposition and
- 6 the distribution of *Betula glandulosa* at the limit of low arctic tundra in Southern Baffin Island,
 7 Nwt, Canada, *Arctic and Alpine Res.*, 17, 279-287.
- Janssen, C. R. (1973), Local and regional pollen deposition, in *Quaternary plant Ecology*, edited
 by Birks, J. H. B. and R. G. West, pp. 30-43, Blackwell Scientific, Oxford.

Michel, F. B., P. Cour, L. Quet, and J. P. Marty (1976), Qualitative and quantitative comparison of
 pollen calendras for plain and mountain areas, *Clin. Allergy*, 6, 383-393.

- 12 Nichols, H. (1967), Pollen diagrams from Sub-Arctic Central Canada, Science, 155, 1665-1668.
- Palacios, I. S., R. T. Molina, and A. F. M. Rodriguez (2007), The importance of interactions
 between meteorological conditions when interpreting their effect on the dispersal of pollen
 from homogeneously distributed sources, *Aerobiologia*, 23, 17-26.
- 16 Peternel, R., J. Culig, I. Hrga, and P. Hercog (2006), Airborne ragweed (Ambrosia artemisiifolia
- 17 L.) pollen concentrations in Croatia, 2002-2004, Aerobiologia, 22, 161-168.
- Porsbjerg, C., A. Rasmussen, and A. Backer (2003), Airbone pollen in Nuuk, Greenland, and the
 importance of meteorological parameters, *Aerobiologia*, 19, 29-37.
- 20 Prospero, J. M., E. Blades, G. Mathison, and R. Naidu (2005), Interhemispheric transport of viable
- fungi and bacteria from Africa to the Caribbean with soil dust, *Aerobiologia*, 21, 1-19.
- Ranzi, A., P. Lauriola, V. Marletto, and F. Zinoni (2003), Forecasting airbone pollen
 concentrations: Development of local models, *Aerobiologia*, 19, 39-45.
- 24 Ritchie, J. C. (1974), Modern pollen assemblages near arctic tree Line, Mackenzie Delta Region,
- 25 Northwest-Territories, *Canadian J. Bot.*, 52, 381-396.
- Ritchie, J. C., and S. Lichti-Federovich (1967), Pollen dispersal phenomena in Arctic-Subarctic
 Canada, *Rev. Palaeobot. Palynol.*, 3, 255-266.
- Ritchie, J. C., K. A. Hadden, and K. Gajewski (1987), Modern pollen spectra from lakes in Arctic
 Western Canada, *Canadian J. Bot.*, 65, 1605-1613.
- 30 Rousseau, D. D., D. Duzer, J. L. Etienne, G. Cambon, D. Jolly, J. Ferrier, and P. Schevin (2004),
- 31 Pollen record of rapidly changing air trajectories to the North Pole, J. Geophys. Res., 109.

- 1 D06116, doi:10.1029/2003JD003985.
- 2 Rousseau, D. D., P. Schevin, D. Duzer, G. Cambon, J. Ferrier, D. Jolly, and U. Poulsen (2006),

New evidence of long distance pollen transport to southern Greenland in late Spring, *Rev. Palaeobot. Palynol.*, 141, 277-286.

- 5 Rousseau, D. D., D. Duzer, G. Cambon, D. Jolly, U. Poulzen, J. Ferrier, P. Schevin, and R. Gros
- 6 (2003), Long distance transport of pollen to Greenland, *Geophys. Res. Lett.*, 30, 1766, doi:
 7 1710.1029/2003GL017539.
- Short, S. K., and G. Holdsworth (1985), Pollen, oxygen isotope content and seasonality in an ice
 core from the Penny ice cap, Baffin Island, *Arctic*, 38, 214-218.
- Smith, M., J. Emberlin, and A. Kress (2005), Examining high magnitude grass pollen episodes at
 Worcester, United Kingdom, using back-trajectory analysis, *Aerobiologia*, 21, 85-94.
- 12 Thompson, R. S., K. H. Anderson, and P. J. Bartlein (1999a), Atlas of relations between climatic
- parameters and distributions of important trees and shrubs in North America; introduction and
 conifers, 269 pp., U. S. Geological Survey, Denver.
- Thompson, R. S., K. H. Anderson, and P. J. Bartlein (1999b), <u>Atlas of relations between climatic</u>
 parameters and distributions of important trees and shrubs in North America; harwoods, 423
- 17 pp., U. S. Geological Survey, Denver.
- Tunved, P., E. D. Nilsson, H. C. Hansson, J. Strom, M. Kulmala, P. Aalto, and Y. Viisanen
 (2005), Aerosol characteristics of air masses in northern Europe: Influences of location,
 transport, sinks, and sources, J. Geophys. Res., 110. D07201, doi:10.1029/2004JD005085

21

1 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.

5 6 Figure 2. Pollen stations in Qaanaaq and Ittoqqortoormitt respectively, installed close to meteorological stations.

- 7 Figure 3. Long distance transport of pollen to Qaanaaq, Greenland in April 2004. (a) Backward 8 trajectories provided by the HYSPLIT model of air parcels reaching Qaanaaq at different 9 altitudes: ground level (red), 1000m (blue) and 3000m (green) on April 18, 2004. The 10 "3000m" air parcel passed over the grey area in Northeastern America which represents 11 the area from where all the identied pollen types caught in the filters originated - oak 12 (Quercus), pine (Pinus), plane (Platanus), hornbeam (Carpinus) and walnut (Juglans)-13 (from [*Thompson*, et al., 1999a; 1999b]). (b) Altitudinal variation of the three air parcels 14 used in the backward trajectory analysis. The "3000 m" air parcel over Qaanaaq on April 15 18, 2004, was at a lower elevation (between 1000 and 2000 m) on April 8 and 12 when it 16 passed over the area where "exotic" trees grow. The red bar indicates the time span when 17 potential uplift of the pollen was possible. (c) Updrafts and downdrafts in the atmosphere. 18 Velocity of the air parcel passing over the growing area in northeastern North America, 19 which reached Qaanaaq at 3000 m on April 18, 2004 versus time. Yellow to brown 20 values indicate upward movements; light blue to purple indicate downward movements. 21 The light colored red box characterizes the timing of the uplift of the pollen 22 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 (*Platanus*) 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

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Pollen i	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	х	2	Х	4	1	2	5
Platanus	plane	5		1					1
Quercus	oak	38		12		2		2	6
Ulmus	elm						1		
Total	Total exotic			21		10	7	6	13
% e	% exotic			9,13%		2,83%	0,53%	0,69%	20,97%
Total c	Total counted		-	230	-	353	1316	871	62