



## Long-distance pollen transport from North America to Greenland in spring

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[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 precise timing of the deposition of exotic grains. The ongoing “Epilobe” project monitors the deposition of exotic grains on the 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.

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### 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 windblown 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 to 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 [Rousseau *et al.*, 2003, 2004, 2006] 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

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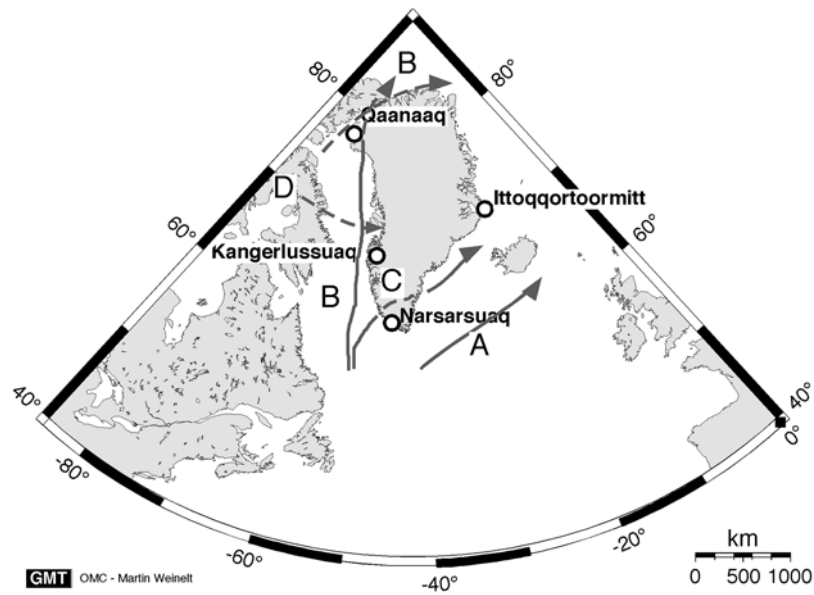
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**Figure 1.** Location of the four pollen traps, Qaanaaq, Kangerlussuaq, Narsarsuaq, and Ittoqqortoormiit in Greenland. Cyclone tracks over Greenland are from *Chen et al.* [1997]. A–D, main pathways; E and F, secondary pathways.

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, 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, owing to annual sampling, which made the identification uncertain of the source of exotic pollen grains [*Bourgeois et al.*, 1985, 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.

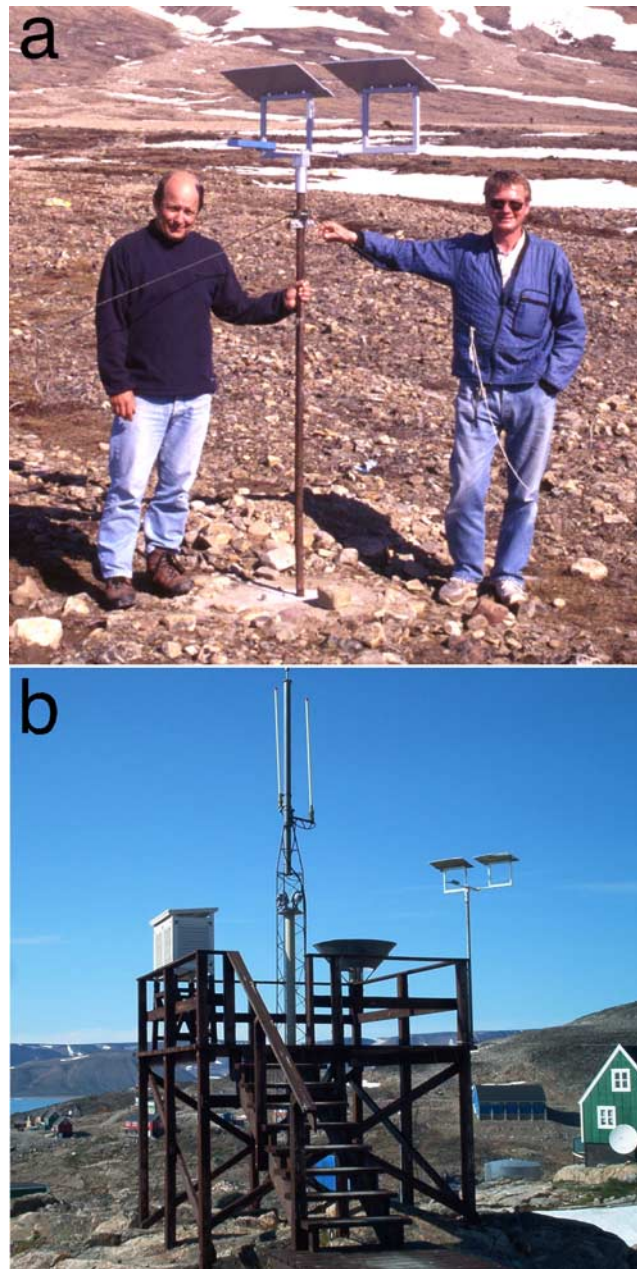
## 2. Material and Methods

[5] Within the “EPILOBE” 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 (Ittoqqortoormiit, 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 × 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 [*Rousseau et al.*, 2003, 2004, 2006]. Previous studies in the Arctic mainly reported yearly observations of pollen flux [*Ritchie and Lichti-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-distance transport to these remote stations. However, since 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.

[7] 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], 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, 1999b]. Numerous computations were performed for a



**Figure 2.** Pollen stations in Qaanaaq and Ittoqqortoormiit installed close to meteorological stations.

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. Although the long-distance transport was initially determined for Narsarsuaq [Rousseau *et al.*, 2003, 2006], 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

[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*; 1 hornbeam, *Carpinus*; walnut, *Juglans*) out of a total of 107 grains. This

**Table 1.** Exotic Pollen Grains Identified in the Four Stations in Greenland in 2004 and 2005

Pollen	Source	QO4, 12–25 Apr	QO5, ?	KO4, 3–16 May	KO5, ?	N04, 3–16 May	N05, 16–29 May	I04, 14–26 Jun	I05, 25 Apr to 8 May
<i>Abies</i>	fir					1			
<i>Carpinus</i>	hornbeam	1				1	2		
<i>Carya</i>	hickory								1
<i>Castanea</i>	chestnut						1	1	
<i>Corylus</i>	hazel			3		1			
<i>Fagus</i>	beechnut							1	
<i>Humulus</i>	hops			3					
<i>Juglans</i>	walnut	1				1	2		
<i>Pinus</i>	pine	28	x	2	x	4	1	2	5
<i>Platanus</i>	plane	5		1					1
<i>Quercus</i>	oak	38		12		2		2	6
<i>Ulmus</i>	elm						1		
Total exotic		73		21		10	7	6	13
Percent exotic		68.22		9.13		2.83	0.53	0.69	20.97
Total counted		107	-	230	-	353	1316	871	62

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*; hops, *Humulus*; 2 pine, *Pinus*; 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 of shrub tundra, composed of birch (*Betula*), juniper (*Juniperus*), and willow (*Salix*).

[10] At Narsarsuaq, where evidence of long-distance transport has been reported [Rousseau *et al.*, 2003, 2004, 2006], only 10 exotic grains (4 pine, *Pinus*; 2 oak, *Quercus*; 1 fir, *Abies*; hazel, *Corylus*; walnut, *Juglans*; hornbeam, *Carpinus*) 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 Ittoqqortoormiit in 2004, the filter exposed during weeks 25–26 (14–26 June) recorded 6 exotic grains (2 pine, *Pinus*; oak, *Quercus*; 1 chestnut, *Castanea*; 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 (16–29 May) 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 to 8 May) in Ittoqqortoormiit 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

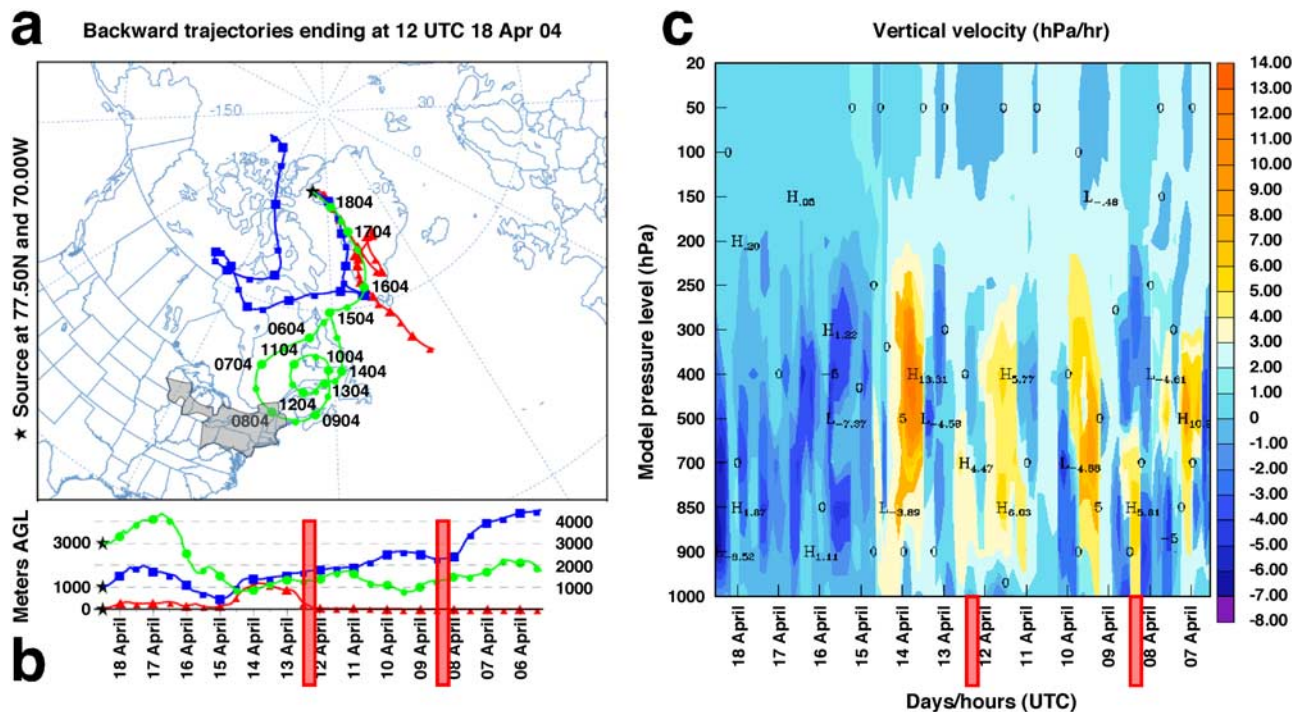
considerably higher percentage of exotic grains compared to the 2004 record. Most notable is the occurrence of hickory, which is solely a North American tree [Thompson *et al.*, 1999a, 1999b].

[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 (Table 1). 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 [Rousseau *et al.*, 2003, 2004, 2006].

[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 12-hour intervals, for 314 hours of the 14 days of the fortnight records of exotic pollen grains. As in previous studies [Rousseau *et al.*, 2003, 2004, 2006], three altitudes were investigated; ground level, 1000 and 3000 m. 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. Given these air mass trajectories the most probable dates for the exotic



**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), 1000 m (blue), and 3000 m (green) on 18 April 2004. The 3000-m air parcel passed over the grey area in northeastern America, which represents the area from where all the identified 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 18 April 2004 was at a lower elevation (between 1000 and 2000 m) on 8 and 12 April 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 18 April 2004 versus time. Yellow to brown values indicate upward movements, and light blue to purple indicate downward movements. The light 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.

pollen to arrive at the different sampling stations can be summarized as follows:

[17] In 2004, exotic pollen deposited in Qaanaaq on 18 April (Figure 3), corresponded to the transport of pollen grains captured in the source area on 8 and 12 April. In Kangerlussuaq, the exotic pollen deposited on 13 May (Figure 4), were captured on 4 May in the growing area. The transport of exotic pollen grains to Narsarsuaq ended on 10 May (Figure 5); they were deposited over the source area on 3 and 4 May. Finally, exotic pollen arrived at Ittoqqortoormiit on 19 June, which corresponded to grains captured between 8–13 June 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.

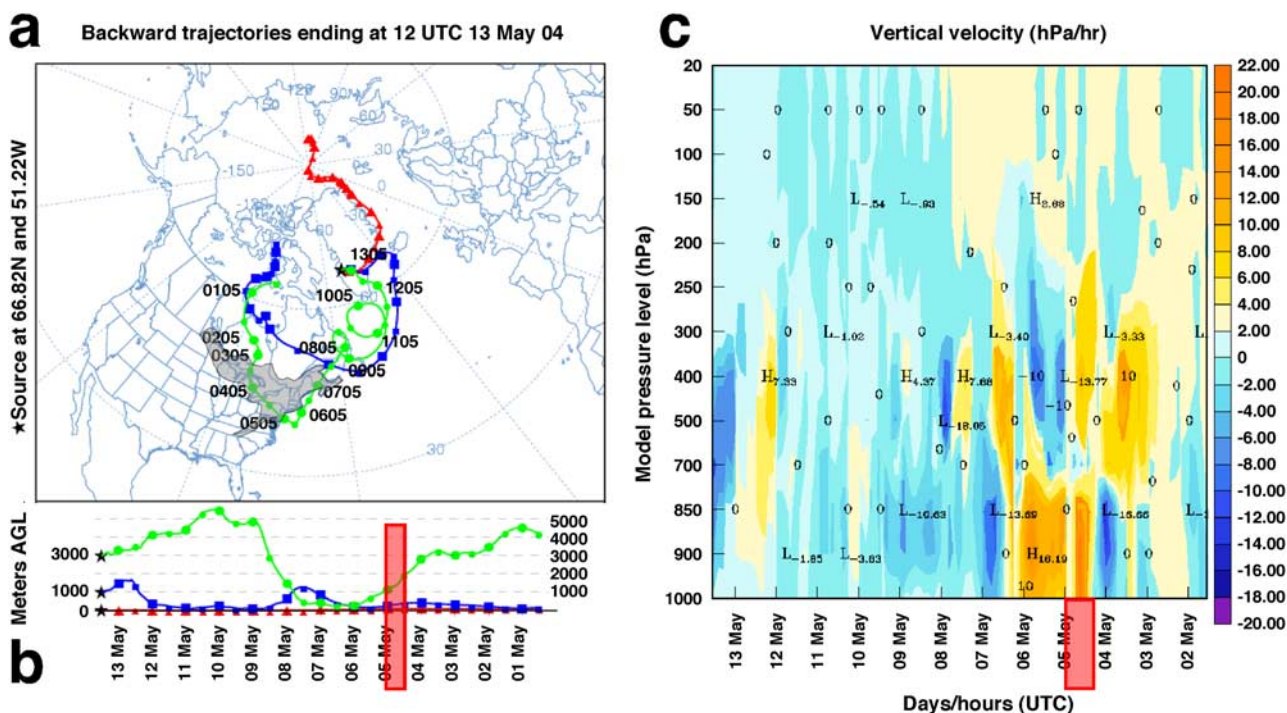
[18] In 2005, exotic pollen deposited at Narsarsuaq on 17 May, were captured on 5 May in the emission area of the northeastern United States (Figure 7). The transport of the exotic grains, among them hickory which is strictly a North American tree, to Ittoqqortoormiit occurred on 25 April

(Figure 8). The pollen grains were advected into the atmosphere from the source region on 14 April.

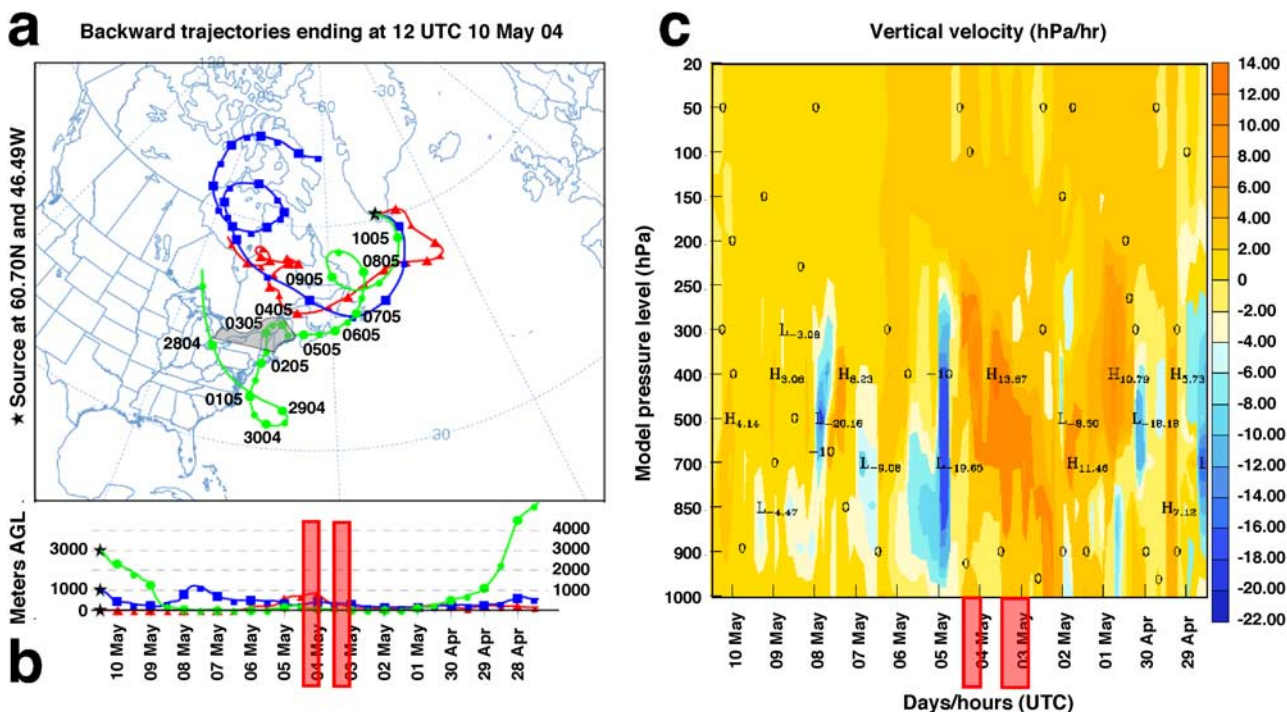
[19] The air masses responsible for the transport of the exotic grains over the sampling stations are consistently at a 3000-m elevation. However, when the air mass is passing over the source areas of the trees, the elevation is much lower permitting the capture of enough grains to be subsequently transported 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 [Rousseau *et al.*, 2003, 2004, 2006].

#### 4. Discussion

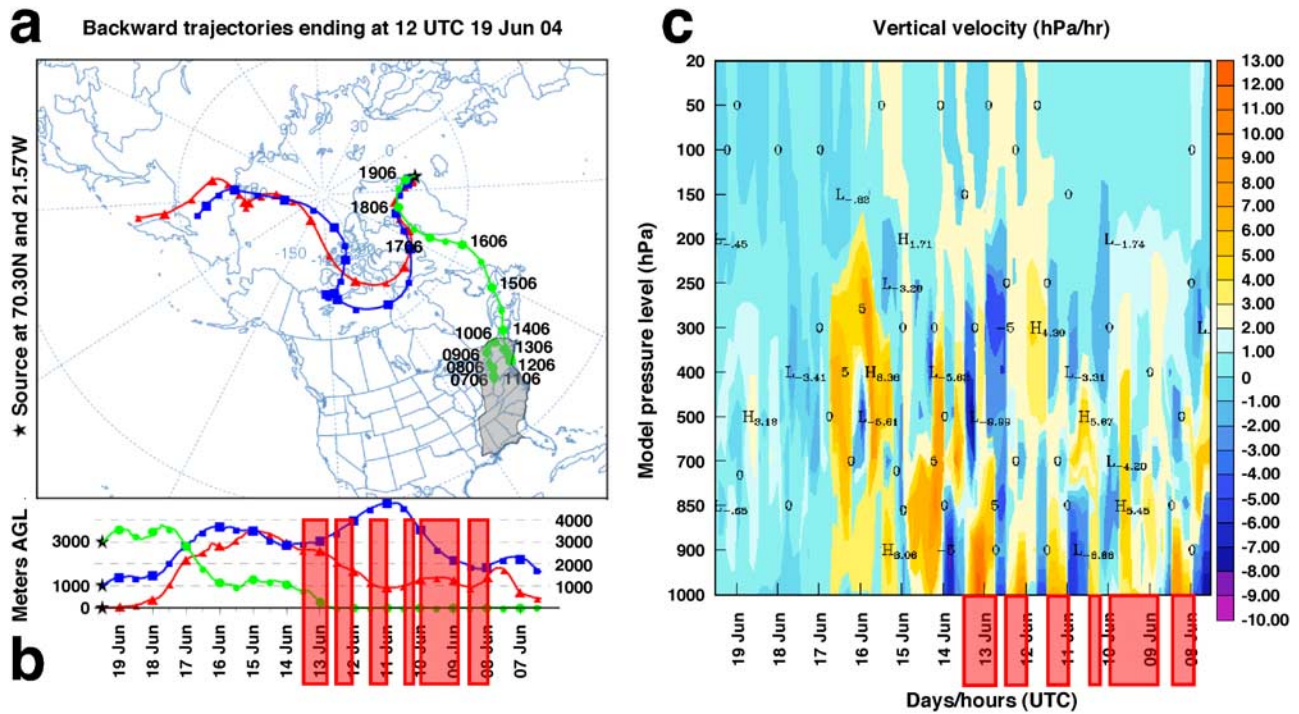
[20] Two groups according to the altitude of the capture of the exotic grains can be distinguished. The first group refers to air parcels between 1000 and 3000 m over the source region as is the case for Qaanaaq and Kangerlussuaq in 2004, and Narsarsuaq and Ittoqqortoormiit in 2005. The second group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



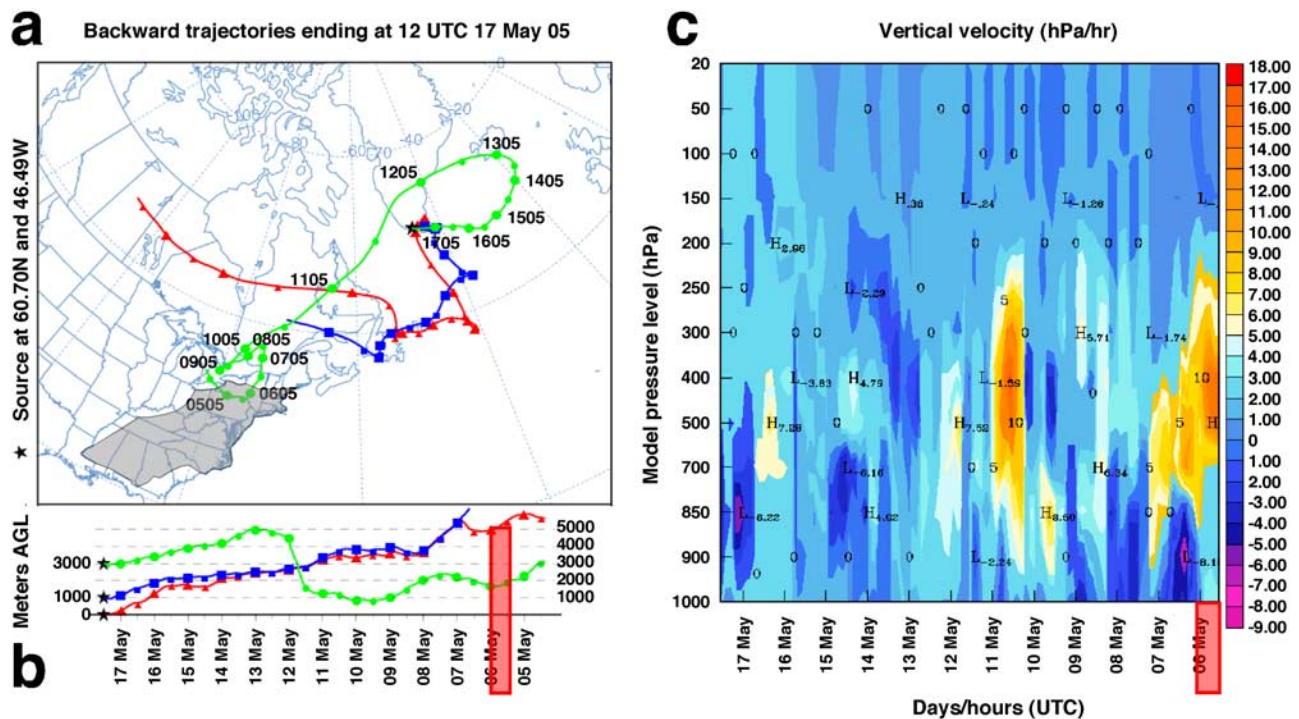
**Figure 4.** Transport to Kangerlussuaq on 13 May 2004. (a) Backward trajectories as in Figure 3. (b) Altitudinal variation of the three air parcels used in the backward trajectory analysis. The 3000-m air volume over Kangerlussuaq on 13 May 2004 was at lower elevation (between 1000 and 2000 m) on 4 May 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) Same as in Figure 3.



**Figure 5.** Transport to Narsarsuaq on 10 May 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 10 May 2004 was at a lower elevation (between ground level and 1000 m) on 3 and 4 May 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) Same as in Figure 3.



**Figure 6.** Transport to Ittoqqortoormiit on 19 June 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 Ittoqqortoormiit on 19 June 2004 was at a lower elevation (between ground level and 1000 m) on 8–13 June when it passed over the area where pine (*Pinus*), oak (*Quercus*), chestnut (*Castanea*), and beech (*Fagus*) are all growing (as in Figure 3). (c) Same as in Figure 3.



**Figure 7.** Transport to Narsarsuaq on 17 May 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 17 May 2005 was at lower elevation (between ground 1000 and 2000 m) on 5 May 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) Same as in Figure 3.





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 owing 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.

[24] 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.

[25] 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. On the basis of 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 Ittoqqortoormiit, 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

[26] Our results show that various air mass trajectories transported exotic pollen grains to Greenland from North-eastern 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.

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