Annals of Glaciology 35 2002

A three-dimensional residence-time analysis of potential summertime atmospheric transport to Summit, Greenland

Jessica E. MILLER,[1] Jonathan D. W. KAHL,[1] Fred HELLER,[1] Joyce M. HARRIS[2]

[1] *Atmospheric Sciences Group, Department of Mathematical Sciences, University of Wisconsin–Milwaukee, Milwaukee, WI 53201, U.S.A.*
E-mail: kahl@uwm.edu

[2] *Climate Monitoring and Diagnostics Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80303, U.S.A.*

ABSTRACT. The interannual variations in atmospheric transport patterns to Summit, Greenland, are studied using twice-daily, three-dimensional, 10 day backward trajectory data corresponding to the summers (1 June–31 August) of 1989–98. While previous trajectory climatology studies have been prepared for Summit, the present work considers both the horizontal and vertical components of transport. A three-dimensional residence-time methodology is employed to account for both horizontal and vertical components of transport. The vertical transport component is quantified by passing all trajectories through a three-dimensional grid and tracking the time spent (i.e. the residence time) in each gridcell. This method also allows inspection of trajectory altitude distributions corresponding to transport from upwind regions of interest. The three-dimensional residence-time methodology is shown to be a valuable tool for diagnosing the details of long-range atmospheric transport to remote locations. For Summit, we find that the frequent transport from North America tends to occur at low altitudes, whereas transport from Europe is highly variable. Mean summertime flow patterns are described, as are anomalous patterns during 1990, 1996 and 1998.

INTRODUCTION

Summit, Greenland (72°34′N, 37°38′W; 3420 m a.s.l.), is a widely studied location for ice-core data (e.g. Meeker and others, 1997) and air/snow transfer processes (Dibb and Jaffrezo, 1997). The sources of airborne material reaching the Greenland ice sheet have also been studied (Davidson and others, 1993; Kahl and others, 1997, 1999; Slater and others, 2001). The general conclusion of studies like these is that long-range transport is an important determinant of the content of the air and surface snow at the receptor, and thus is a significant air/snow transfer process.

In this work we also study long-range air movement to Summit, but here we emphasize the vertical component of transport. As air parcels travel long distances, they vary in height as they respond to atmospheric motions on a variety of scales. By using a three-dimensional analysis of air-parcel trajectories, we can determine the altitude at which the trajectories pass over particular upwind areas on the way to Summit. If the trajectories arriving at Summit follow a path that passes near the surface at certain upwind locations, these locations will have a higher probability of contributing to the composition of the air at Summit. By tracking the number of hours traveling air parcels spend over a location at a particular altitude, we determine which areas are frequent passageways for the air trajectories before arriving at the receptor at Summit.

We recognize that the determination of source regions contributing material deposited to the snow surface at Summit requires the consideration of several atmospheric processes. These include background concentrations of chemical species of interest (i.e. atmospheric loading beyond the reach of the back trajectories), atmospheric injection, transformation and removal processes, as well as transport and diffusion over continental and hemispheric-scale distances. As discussed by Kahl and others (1997), the uncertainties introduced by considering atmospheric transport alone (as revealed by modeled trajectories) are often constrained during long-range airflow to the Greenland ice sheet. We therefore consider our analysis to represent the potential for upwind source contributions to the air and snow chemistry at Summit.

In a few previous studies addressing atmospheric transport to Summit, a two-dimensional approach has been used. Kahl and others (1997) found that for the two pressure altitudes examined (700 and 500 hPa, or approximately 2.8 and 5.5 km m.s.l., respectively) the summertime transport is shorter than the transport in other seasons due to the weaker atmospheric circulation. The 700 hPa analysis revealed that the North American continent is the most important potential source region for continental impurities, while at 500 hPa, transport occurs from North America, as well as regions further west, including the North Pacific Ocean and Asia. In a later study, Kahl and others (1999) applied a two-dimensional residence-time approach, a precursor to the methodology used here, to diagnose the interannual variability of large-scale transport features.

Three-dimensional trajectories have also been utilized for studying the transport to Greenland. Using three-dimensional trajectory analysis to depict transport to Dye 3, along the southeast coast of Greenland, Davidson and others (1993) found that there is less long-range transport in the summer, due to weaker wind speeds. These authors emphasized the need for longer trajectories in order to identify potential contributions from more distant source regions. Dibb and others (1996) used three-dimensional trajectories to investigate chemical signatures associated with

https://doi.org/10.3189/172756402781816663 Published online by Cambridge University Press

the transport of biomass-burning emissions from North America. More recently, Slater and others' (2001) analysis of three-dimensional back trajectories again revealed the importance of transport from North America. Although Slater and others' work considered three-dimensional transport to Summit, the vertical component of transport was not considered in a comprehensive or systematic manner.

The present work expands upon previous studies by emphasizing the vertical component of transport through three-dimensional residence-time analysis of the paths of 10 day air trajectories to Summit.

DATA AND METHODOLOGY

Trajectory calculations

Trajectories were calculated twice daily during 10 summer seasons (1 June–31 August, 1898–1998). The summer season was selected to complement air- and snow-chemistry measurements taking place at Summit during these summers (Dibb and Jaffrezo, 1997). Trajectories spanning 10 days of upwind travel were used, because shorter trajectories may not be indicative of important upwind source regions (Davidson and others, 1993; Kahl and others, 1997).

The atmospheric trajectory model used here is a hybrid isentropic/mixed-layer model developed by Harris and Kahl (1994), with meteorological input (of 2.5° latitude by 2.5° longitude) consisting of initialization fields from the European Centre for Medium-Range Weather Forecasts (Simmons and others, 1995). In a model of this type, air parcels are advected along surfaces of constant potential temperature, which may vary substantially with altitude. However, once the trajectories reach a height that is within 100 m of the Earth's surface, the transport is modeled by an average wind of the 100–600 m above-ground layer. This accounts for the inconsistencies that might arise should the isentropic surface intersect the surface of the Earth. Once the isentropic surface regains an altitude above 100 m, the trajectories are again calculated along the original isentropic surface.

The model features a dynamic "theta-chooser" algorithm, in which the potential temperature surface corresponding to the desired arrival altitude (3500 m m.s.l.) is independently determined for each trajectory, using model sounding data at Summit. This algorithm ensures that all trajectories arrive at the desired altitude; an improvement over previous isentropic models (e.g. Harris and Bodhaine, 1983).

The interpolation of meteorological data does create some uncertainties in the modeled trajectories (Kahl and Samson, 1986; Stohl, 1998). However, the resulting uncertainties are minimized via the use of a large trajectory database, and are acceptable for determining regional origins of parcels (Kahl, 1993).

Three-dimensional residence time

Using the trajectory datasets described above, the three-dimensional residence time (e.g. Ashbaugh, 1983) is calculated for each summer, as well as the average for the 10 year period. An annular grid with horizontal resolution of 120 km by 120 km is used, centered over the North Pole, and extending southward to 20° N (Kahl and others, 1999).

To calculate the residence time, the trajectories are first interpolated from 3 hour intervals to 1 hour intervals. Each individual trajectory is then processed through an algorithm

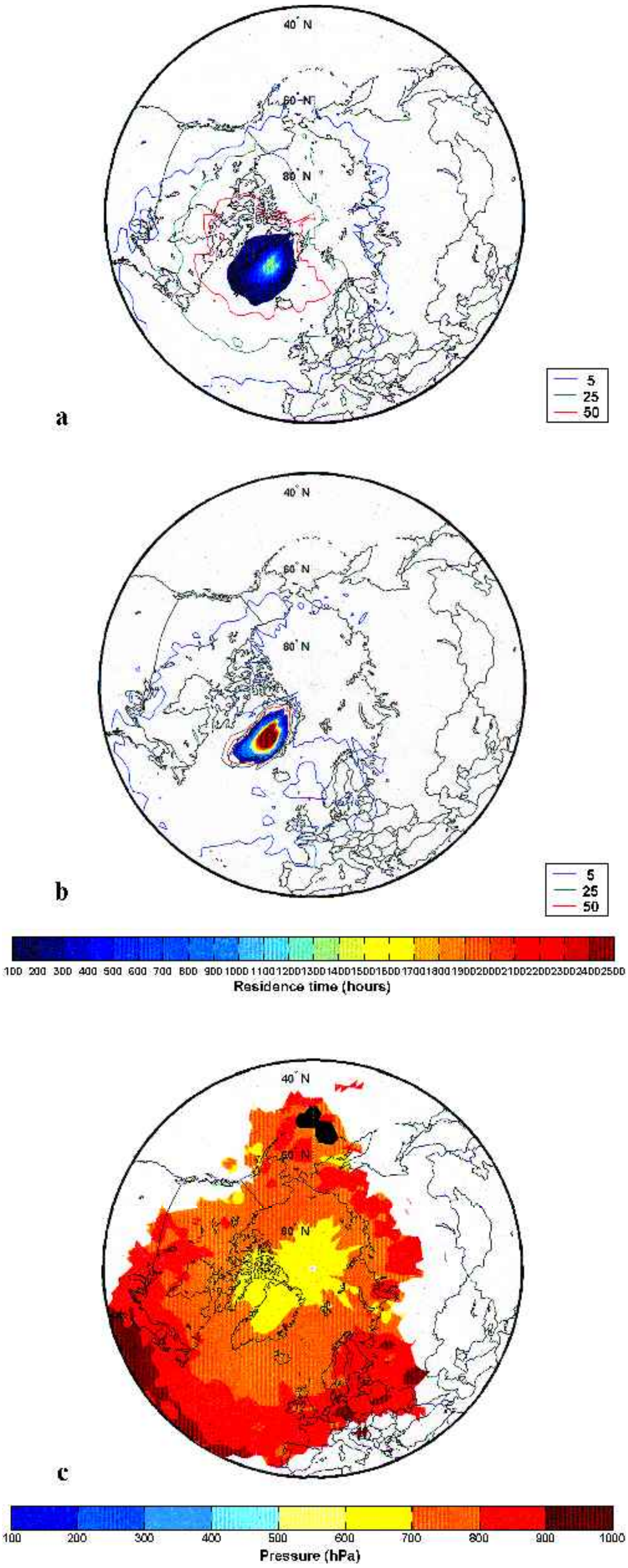

Fig. 1. Ten-year averaged, summertime residence-time values for 10 day back trajectories arriving at Summit, Greenland: (a) total-column residence time (hours), (b) lowest-bin residence time (hours), and (c) mean pressure (hPa). The residence time shows the amount of time trajectories spend over an area before their arrival at Summit; total column includes trajectories at all heights, while lowest bin includes the lowest 1500 m. Pressure values of the trajectories en route to Summit are analogous to altitude, where high-pressure values indicate low altitudes (black indicates areas devoid of trajectory passage).

https://doi.org/10.3189/172756402781816663 Published online by Cambridge University Press

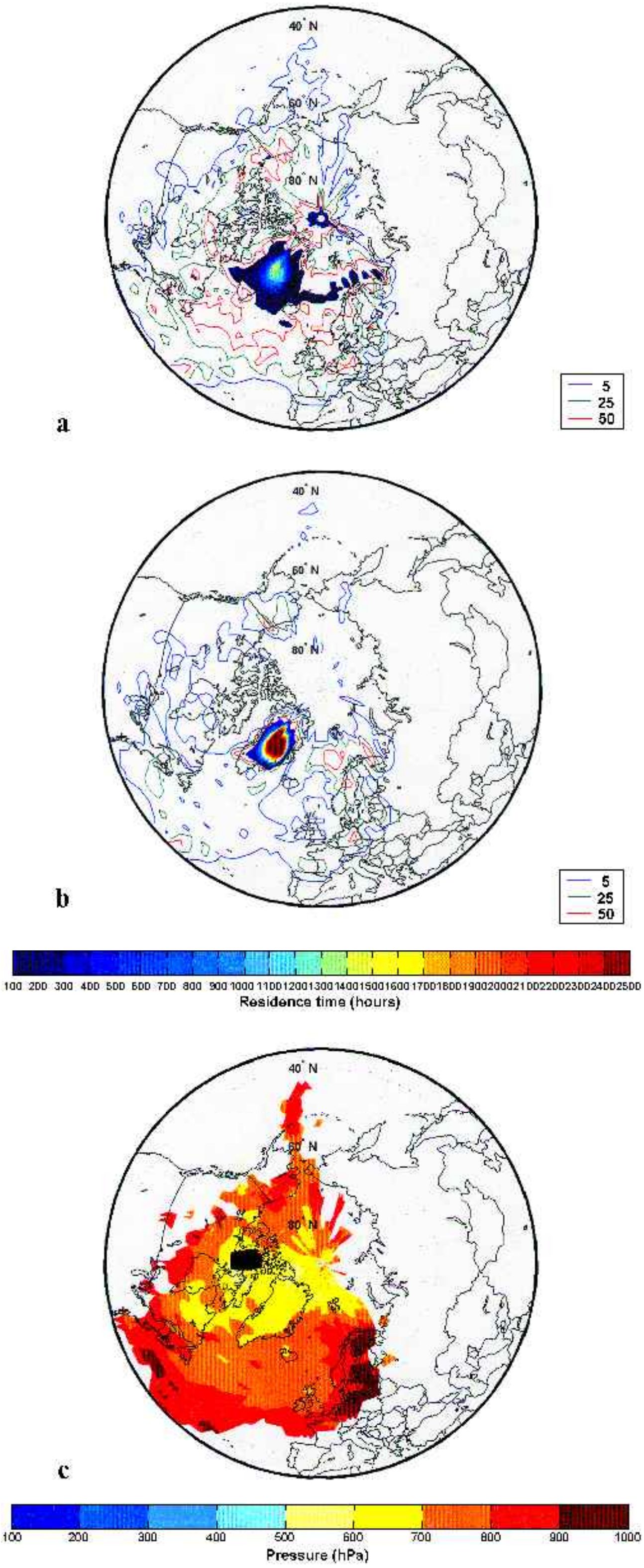

Fig. 2. Residence time and pressure for trajectories of summer 1990, as in Figure 1: (a) total-column residence time (hours), (b) lowest-bin residence time (hours), and (c) mean pressure (hPa).

which tracks the number of hours spent (i.e. the residence time) in each gridcell. This analysis gives the "total-column" residence time, indicating the horizontal projection of trajectory passage en route to the receptor, independent of altitude.

Next, the vertical domain is divided into seven partitions of 1500 m each. When a trajectory passes over a horizontal gridcell, the height and pressure of the air parcel are stored for later use. The vertical position information is used in two ways; the first being to increment the proper vertical partition, thereby extending the total-column residence-time analysis to three dimensions. We refer to this method of accounting for the vertical transport component as the "binning approach".

The second way involves consideration of the distribution of trajectory altitude corresponding to passage above individual gridcells. After all of the trajectories for a particular period are processed by the total-column residence-time algorithm, the stored pressure and height values are used to compute descriptive statistics, including moments, extreme values and cumulative frequency distributions. In this analysis we focus on the spatial distribution of three variables: the total-column residence time, the "lowest-bin" residence time (i.e. transport occurring in the lowest 1500 m of the atmosphere) and the mean pressure (indicating the average trajectory altitude).

RESULTS AND DISCUSSION

Examination of the 10 year average total-column residence time, which does not involve any type of vertical dependency, reveals that the residence time is nearly equally distributed in the area surrounding the receptor (Fig. 1a and b). This is due in part to a natural geometric tendency (Poirot and Wishinski, 1986) requiring all trajectories to pass over nearby gridcells en route to Summit. However, there is a slight extension toward the west that would suggest that the main summer pathway to the receptor at Summit is to the west of Greenland, in northeastern North America. Because of this distribution, any non-marine material contributions that would affect the air composition at Summit are likely to be from North America. This finding is consistent with previous studies (Kahl and other, 1997; Slater and others, 2001).

The mean summer residence times are > 5 hours in most of Canada, and > 50 hours in extreme northeastern Canada. The extreme western portion of North America is not frequented by summertime trajectories en route to Greenland. The east coast of the United States is also noted as a potential pathway, since residence times in this region exceed 5 hours.

There is very little influence from Europe, although in northern Europe, spanning from the western edge of Russia to the United Kingdom, there is an area where the 10 year average residence times are 5–25 hours. In a northern section of Scandinavia, there is a small area with average residence-time values of 25–50 hours. There is little influence from the interior of Asia, or from locations south of 40° N latitude.

We now turn to the vertical component of transport by presenting the mean pressure of the trajectories passing over each gridcell, as well as the residence time of the lowest 1500 m ("lowest bin").

The mean pressure (Fig. 1c) shows the average vertical position of the trajectories when they pass over a given location; large values imply trajectory passage at lower altitudes. The highest values are in the lower latitudes, south of Greenland, with mean pressures of 1000–800 hPa (approximately 99 and 1930 m m.s.l., respectively). In the areas closer to Summit, the trajectories pass through the area between 800 and 600 hPa (1930 and 4229 m m.s.l.), which is consistent with the high altitude of the receptor. The relatively few trajectories that pass through Europe (see Fig. 1a) tend to do so at low altitudes (1000–800 hPa).

The residence time of the lowest vertical bin (0–1500 m)

https://doi.org/10.3189/172756402781816663 Published online by Cambridge University Press

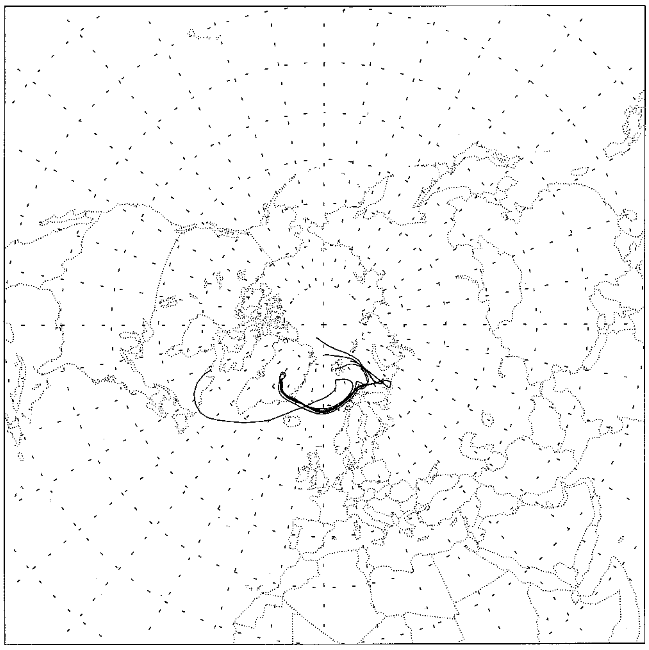

Fig. 3. Trajectory plot for 20–22 June 1990. This plot shows a 3 day span of 10 day isentropic trajectories to Summit that originate primarily from northern Europe.

is crucial in determining the areas where surface-level sources could contribute material to the air that arrives at Summit (Fig. 1b). The lowest-bin results show that the predominant areas where trajectories pass near the surface during travel to Summit are to the west of Greenland. There is a maximum of 25 hours in northeastern Canada, areas known to contribute organic material related to forest fires (Dibb and others, 1996). There are also areas of > 5 hours in northern Europe. Because the total residence time for the areas in North America is in the range 5–50 hours (Fig. 1a), it can be concluded that most trajectories that pass over the eastern region of North America do so at a low level.

In order to examine deviations from the 10 year average, we now examine the individual anomalous summers from 1989 through 1998. The summer of 1990 was a particularly anomalous period with respect to transport. Note that the total-column residence time for this period (Fig. 2a), as for the other individual summers, is rather noisy as compared to the 10 year mean (Fig. 1a). The 1990 total-column residence time shows transport extending further in all directions, reflecting a particularly vigorous atmospheric circulation. There appears to be a path extending westward from northwestern Russia, with total-column residence times exceeding 100 hours. Examination of individual trajectories for a 2 day period in June 1990 (Fig. 3) reveals a pattern of continuous transport from this area. Synoptic meteorological charts for this period (not shown) indicate an anticyclone in the Barents Sea as the cause of this easterly flow to Summit.

There are also values as high as 50 hours in central Europe, which is appreciably south and east of where similar values are located in the average plot. Significant lowest-bin residence-time values are also found in this area (Fig. 2b). The mean pressure further elucidates the significant low-level transport from central Europe for the summer of 1990 (Fig. 2c). The pressures at which trajectories passed through this area are 1000–800 hPa (99 and 1930 m m.s.l.), with a significantly large area of 1000–900 hPa (99–980 m m.s.l.) pressure spanning much of Europe.

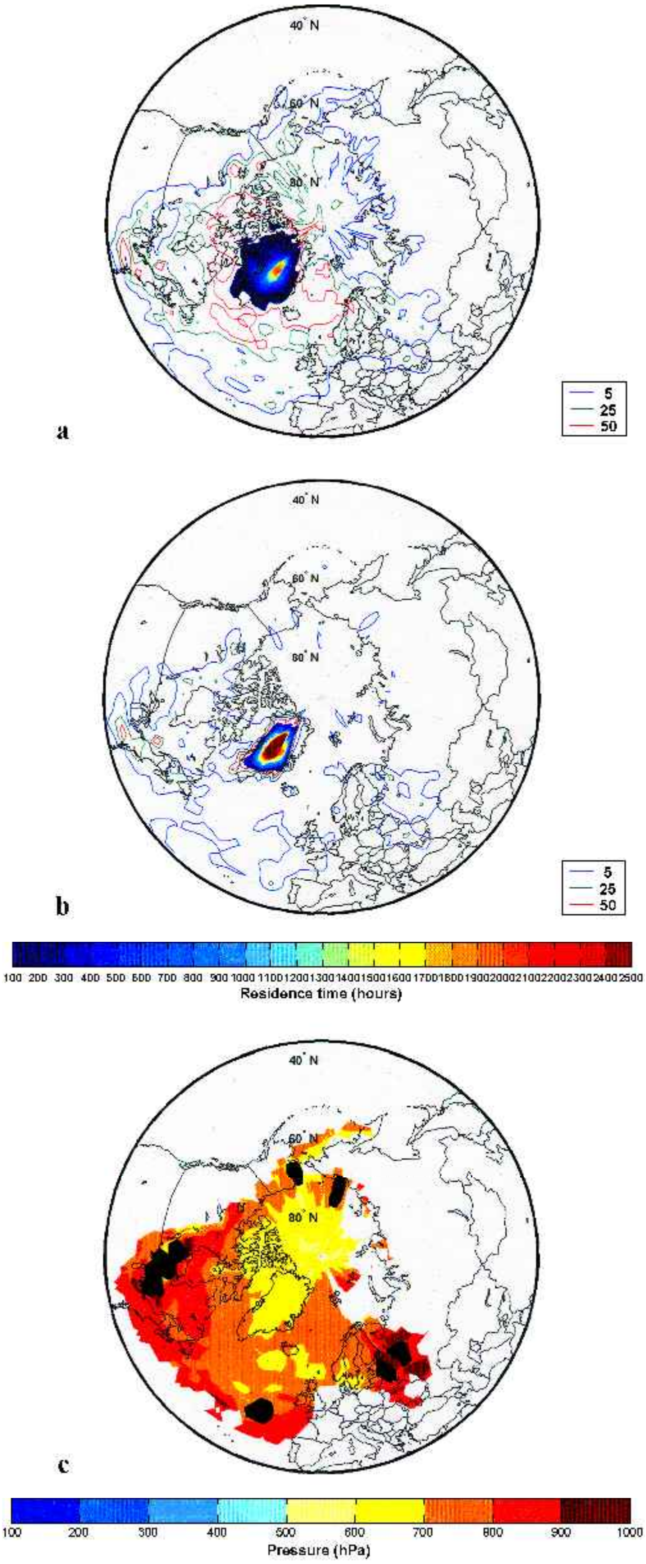

Fig. 4. Residence time and pressure for trajectories of summer, 1998, as in Figure 1: (a) total-column residence time (hours), (b) lowest-bin residence time (hours), and (c) mean pressure (hPa).

There is also a small maximum in lowest-bin residence time over the Great Lakes region of the United States. Inspection of the plots of lowest-bin residence time, as well as the mean pressure, reveals that these trajectories followed a pathway to Summit at low altitudes.

The relatively high number of residence-time hours in northeastern Canada (Fig. 2a) appear to be mostly mid-level trajectories (approximately 700–600 hPa, or 2954 and

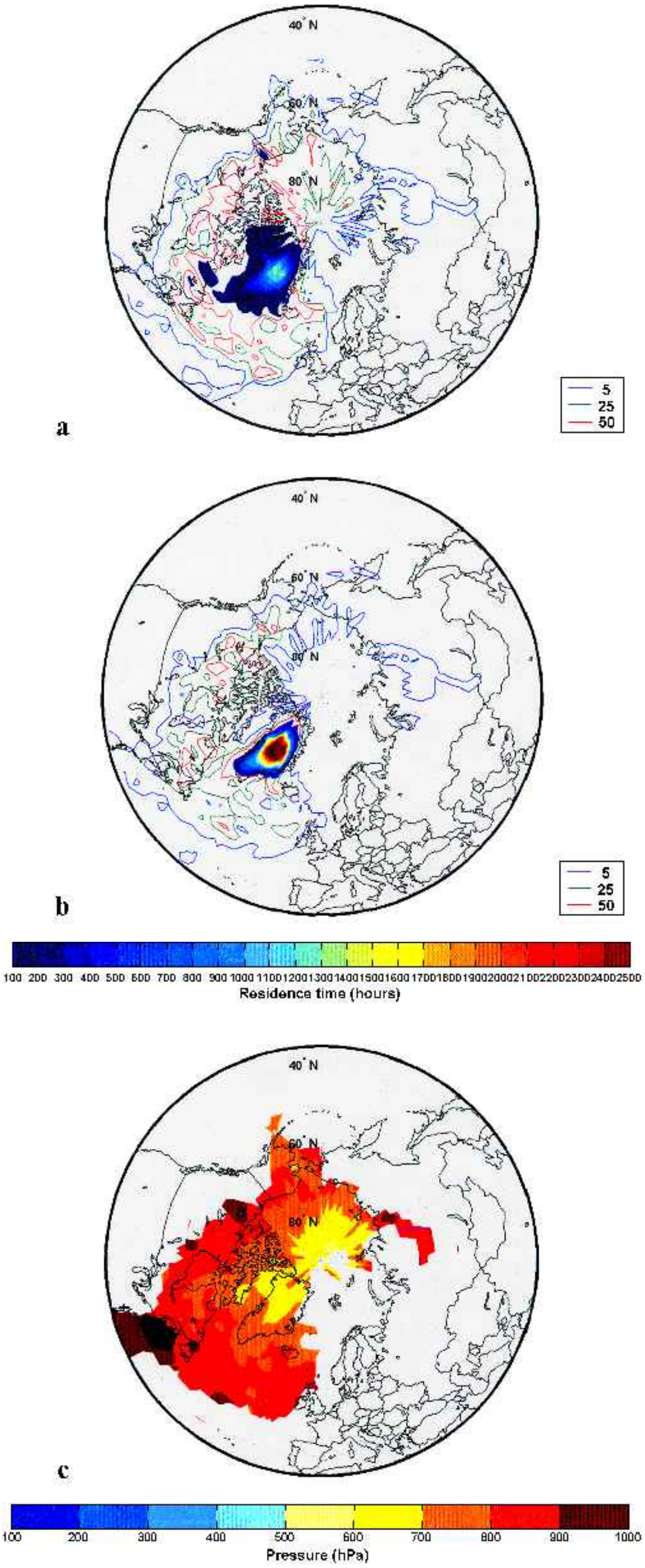

Fig. 5. Residence time and pressure for trajectories of summer 1996, as in Figure 1: (a) total-column residence time (hours), (b) lowest-bin residence time (hours), and (c) mean pressure (hPa).

4229 m m.s.l., respectively; Fig. 2c). Residence time of the lowest bin of >50 hours is also shown near the Alaska/Canada border. Thus, the summer of 1990 exhibited an extremely varied flow, with longer than usual trajectories following several different pathways.

The summer of 1998 was another unusual year, in terms of atmospheric transport to Summit. There is a maximum of total-column residence-time hours centered over the eastern United States, with values exceeding 50 hours in a larger area (Fig. 4a). There is also an area exceeding 50 hours in southeastern Canada. The lowest-bin results (Fig. 4b) demonstrate that these areas are dominated by low-altitude trajectories. The mean pressure plot from this season verifies this claim (Fig. 4c), with pressures of 1000–900 hPa (99–980 m m.s.l.), and 900–800 hPa (980–1930 m m.s.l.) for areas in Canada and the eastern United States, respectively. These plots also reveal anomalous, low-altitude transport from central and southern Europe.

The summer of 1996 was anomalous in a different way, with <5 hours total-column residence time for all of Europe (Fig. 5a). Nearly all of the transport came from the west, with a reduced southern component. Nearly all of the residence-time hours are concentrated in Canada, with many of them being low-altitude trajectories (Fig. 5b). There are areas dispersed throughout Canada where the lowest-bin residence times exceed 50 hours, with mean pressures of 1000–800 hPa (99–1930 m m.s.l.; Fig. 5c). For 1996, Slater and others (2001) found that $>20\%$ of 10 day trajectory origins were located in the Yukon and Siberia.

Of the 10 summers, the origins of the 10 day transport to Summit were furthest afield in 1996. The trajectories extended as far westward as eastern Russia. Furthermore, the residence-time analysis areas show that these were low-altitude trajectories. This pattern is indicative of a summer with a much more vigorous circulation. There is also a highly anomalous feature of five residence-time hours, in the lowest bin, over a large area within central Siberia. This is likely a result of rapid transport over the North Pole.

The remainder of the individual summer seasons, excluding 1990, 1996 and 1998, exhibited transport patterns quite similar to the 10 year average (Fig. 1).

CONCLUSIONS

The three-dimensional residence-time approach is a particularly valuable tool for diagnosing details of both the horizontal and vertical components of long-range atmospheric transport. Knowledge of the vertical component of transport, rather than just the horizontal projection of long-range air trajectories, allows an assessment of the potential for particular upwind source regions to contribute material, whether natural or anthropogenic, to a remote location. In addition to revealing features of the vertical component of transport, our analysis has confirmed many previous conclusions drawn by studies utilizing two-dimensional trajectories.

Application of the three-dimensional residence time technique to summertime, 10 day atmospheric transport to Summit, Greenland, has revealed the following:

North America has the greatest potential to contribute non-marine material to be transported to Summit.

Most transport from North America tends to occur in the lowest 1500 m of the atmosphere, thus enhancing the potential for both natural and anthropogenic source contributions.

Considerable interannual variability is found for transport from Europe, with some years exhibiting transport at low altitudes.

The summertime Northern Hemispheric circulation was particularly vigorous in 1990, with potential source contributions further afield in all directions. Significant low-altitude transport from central and northern Europe, as well as from the Great Lakes region of North America, was observed during this season.

Unusually persistent, low-altitude transport from eastern North America was observed during summer 1998.

No transport from Europe was observed during summer 1996. Very strong low-altitude winds during this season created trajectories extending as far upwind as eastern Siberia, as well as over-the-pole transport from central Siberia.

Future work will include comparing these transport results to corresponding chemical measurements in order to further assess the role of meteorology in the air/snow transfer process. The methodology described here is also being applied to atmospheric transport issues at other locations.

ACKNOWLEDGEMENTS

This work was supported by the U.S. National Science Foundation's Office of Polar Programs.

REFERENCES

Ashbaugh, L. L. 1983. A statistical trajectory technique for determining air pollution source regions. *APCA J.*, **33**(11), 1096–1098.

Davidson, C. I., J. Jaffrezo, M. J. Small, P. W. Summers, M. P. Olson and R. D. Borys. 1993. Trajectory analysis of source regions influencing the South Greenland ice sheet during the Dye 3 gas and aerosol sampling program. *Atmos. Environ.*, **27A**(17–18), 2739–2749.

Dibb, J. E. and J.-L. Jaffrezo. 1997. Air–snow exchange investigations at Summit, Greenland: an overview. *J. Geophys. Res.*, **102**(C12), 26,795–26,807.

Dibb, J. E., R. W. Talbot, S. I. Whitlow, M. C. Shipham and R. C. Bales. 1996. Biomass burning signatures in the atmosphere and snow at Summit, Greenland: an event on 5 August 1994. *Atmos. Environ.*, **30**(4), 553–561.

Harris, J. M. and B. A. Bodhaine, *eds.*. 1983. *Geophysical monitoring for climatic changes. Summary report, 1982.* Boulder, CO, National Oceanic and Atmospheric Administration. Environmental Research Laboratories. (GMCC Report 11.)

Harris, J. M. and J. D. W. Kahl. 1994. Analysis of 10-day isentropic flow patterns for Barrow, Alaska: 1985–1992. *J. Geophys. Res.*, **99**(D12), 25,845–25,855.

Kahl, J. D. W. 1993. A cautionary note on the use of air trajectories in interpreting atmospheric chemistry measurements. *Atmos. Environ.*, **27A**(17/18), 3037–3038.

Kahl, J. D. W. and P. J. Samson. 1986. Uncertainty in trajectory calculations due to low resolution meteorological data. *J. Climate Appl. Meteorol.*, **25**(12), 1816–1831.

Kahl, J. D. W., D. A. Martinez, H. Kuhns, C. I. Davidson, J.-L. Jaffrezo and J. M. Harris. 1997. Air mass trajectories to Summit, Greenland: a 44-year climatology and some episodic events. *J. Geophys. Res.*, **102**(C12), 26,861–26,875.

Kahl, J. D. W., J. A. Galbraith and D. A. Martinez. 1999. Decadal-scale variability in long-range atmospheric transport to the Summit of the Greenland ice sheet. *Geophys. Res. Lett.*, **26**(4), 481–484.

Meeker, L. D., P. A. Mayewski, M. S. Twickler, S. I. Whitlow and D. Meese. 1997. A 100,000-year history of change in continental biogenic emissions and related atmospheric circulation inferred from the Greenland Ice Sheet Project ice core. *J. Geophys. Res.*, **102**(C12), 26,489–26,504.

Poirot, R. L. and P. R. Wishinski. 1986. Visibility, sulfate and air mass history associated with the summertime aerosol in northern Vermont. *Atmos. Environ.*, **20**(7), 1456–1469.

Simmons, A. J. R., R. Mureau and T. Petroliagis. 1995. Error growth and estimates of predictability from the ECMWF forecasting system. *Q. J. R. Meteorol. Soc.*, **121**(527), 1739–1771.

Slater, J. F., J. E. Dibb, B. D. Keim and J. D. W. Kahl. 2001. Relationships between synoptic-scale transport and interannual variability of inorganic cations in surface snow at Summit, Greenland: 1992–1996. *J. Geophys. Res.*, **106**(D18), 20,897–20,912.

Stohl, A. 1998. Computation, accuracy and applications of trajectories: a review and bibliography. *Atmos. Environ.*, **32**(6), 947–966.