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Scientific Paper

THE IMPACT OF ARCTIC CIRCULATION ON TRACE GAS MEASUREMENTS AT ALERT, CANADA

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Abstract: The Canadian Baseline Observatory at Alert (82°28′N, 62°30′W) is situated at the northern tip of Ellesmere Island in the high arctic. It is the most northerly station in the WMO GAW network. Apart from the local camp, which is sectored out, the nearest major source region for anthropogenic material is over 2500 km away, over the pole to northern Russia. Correlations of positive deviations from the modelled time series curves of measured values with 5 day back trajectories confirm that the short term variations in the concentrations of carbon dioxide and methane are due to long range transport of material from the temperate regions of Eurasia.

To obtain a quantitative understanding of the relationship between the physical processes of long range tracer transport from the industrial emissions in Eurasia and the magnitude and duration of tracer gas measurement anomalies over the Canadian Arctic, a series of simulations using a regional atmospheric dynamical model is carried out to reproduce specific events of positive CO_2 anomalies observed at Alert. These simulations identify various distinctive tracer transport pathways from Eurasia to the Canadian Arctic. These pathways can be categorized into 3 distinctive groups: (1) direct transport pathway, (2) transport via northern Siberia, across the pole, and (3) recirculation of Arctic air mass.

1. Introduction

As part of a global network under the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) Program, in 1986, Canada established a baseline air chemistry observatory at Alert, located at 82°28′N, 62°30′W on the northern tip of Ellesmere Island in the Canadian Arctic. Data from these types of stations are required to allow further studies on the possible effects of mankind's activities on climate, transport and deposition of potentially toxic substances, and the source/sink distribution of the biogeochemical cycles. The focus of the Alert program is on the measurements of major "greenhouse" gases, such as carbon dioxide, methane, nitrous oxide and the chlorinated fluorocarbons and their substitutes, and to monitor their concentration levels, their variability and possible long-term trends. The measurement program also makes observation of aerosols, such as black carbon, which are thought to have an impact on climate. It is the most northerly monitoring station in the WMO network, and, as such, it is isolated from human influence, and far removed from the major industrial regions of the northern hemisphere. Nevertheless, the temporal changes in the concentration of atmospheric carbon dioxide and methane in the Arctic atmosphere have been shown to reflect the source and sink strengths in the lower latitudes (Worthy *et al.*, 1994), particularly during the dark season.

The high Arctic is a polar desert with minimal vegetation compared to the temperate regions. The Arctic Ocean is ice covered throughout the year, except for a short summer period when the ice recedes from the continental and island coastal margins. The land around Alert is covered with snow from September to June, and has a sparse covering of polar desert vegetation during the snow free months of July and August. During the snow free season, the vegetation has no observed effect on the diurnal cycle of either carbon dioxide or methane. The only "local" source of pollutants at Alert is the weather station and military camp, which is located 6 km to the NNE of the Observatory; however, only a small fraction of the baseline data comes from this sector and there is no obvious influence on the data (WORTHY *et al.*, 1994).

While there is very little development in the Canadian high arctic area, there is considerable development in the Russian arctic between latitudes 60°N to 70°N (Fig. 1). The closest major urban or industrial region to Alert north of 60°N on the Canadian side of the Arctic is Prudhoe Bay (1800 km from Alert) on the Alaskan north slope. It is a region with a small population but extensive gas and oil extraction activity. On the Russian side of the Arctic there is also considerable industrial activity north of 60°N in the areas of Murmansk (2044 km), Vorkuta (2634 km), Noril'sk (2474 km) and Yakutsk (3653 km), but these are quite far away. Between these areas in Siberia and northern Europe, and the Alert Observatory, there is nothing to significantly modify the atmospheric concentration of carbon dioxide or methane in the high Arctic atmosphere.

Yet there is considerable variability in the carbon dioxide time series, as Fig. 2 clearly shows. The variability in the carbon dioxide is also reflected in the methane and black carbon time series, as is clearly evident in Fig. 3, reproduced here from WORTHY *et al.* (1994). While there is a possibility of influence from the local source for carbon dioxide and black carbon at the Alert Observatory, there is no know local source for methane in the winter. This variability is therefore most likely due to material transported to Alert from source regions further south. Thus, even though the Alert Observatory is located in an isolated location in the remote high Arctic, the CO_2 time series cannot be considered to be homogenous (free and clear of industrial influences). Just how this material reaches so far into the Arctic is the topic of this paper.

2. Trajectory Analyses of Observation

Given the lack of significant industrial sources for CO_2 and CH_4 in the high Arctic wintertime, it is clear that long range atmospheric transport plays an important role in the short term variability, as well as in the long term trends and seasonal cycles of carbon dioxide and other trace gases. The transport processes are reflection of synoptic and large-scale weather patterns, the general features of which are shown in Fig. 4, along with potential anthropogenic source regions. The mean winter time low-level flow in the polar region shown in the schematic diagram in Fig. 4 is controlled by an elongated upper air low pressure system, stretching from northeaster Siberia, across the pole and towards Hudson Bay in Canada (not shown). While the climatological mean distribution of synoptic systems in the Arctic is well known (MAXWELL, 1980), the day to day patterns may be considerably different (HOPPER and HART, 1994).

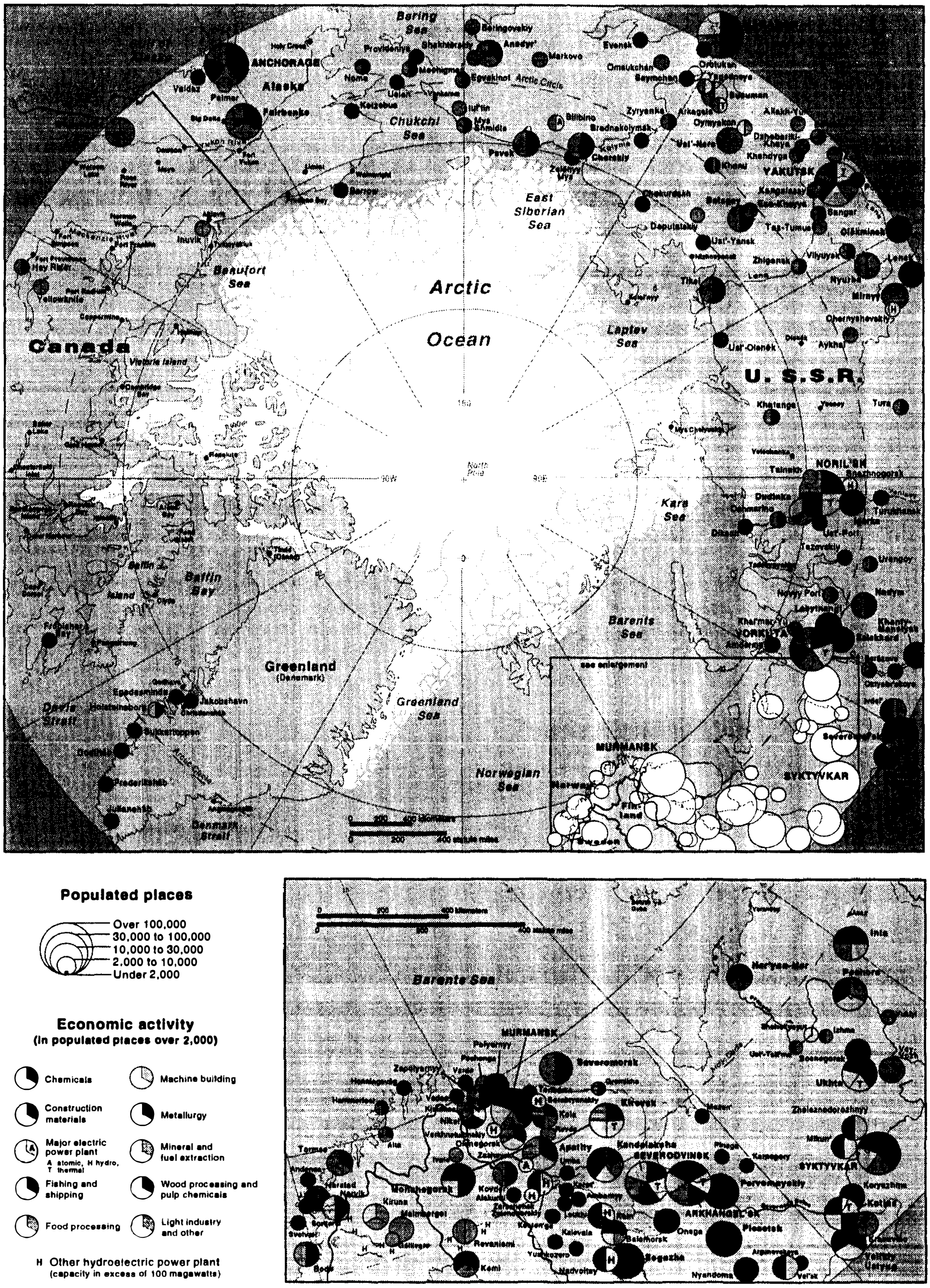

Fig. 1. Geographical distribution of economic activities north of 60°N (Source: CENTRAL INTELLIGENCE AGENCY ATLAS, 1971).

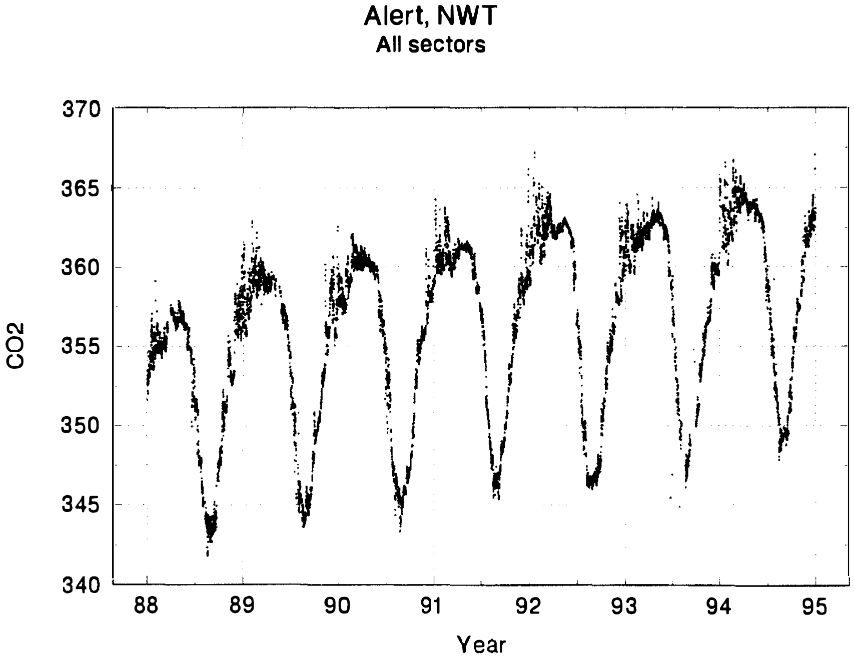

Fig. 2. *Six hourly averaged CO_2 data are shown without any data selection, except to remove data obviously contaminated due to local sources or instrumental malfunction.*

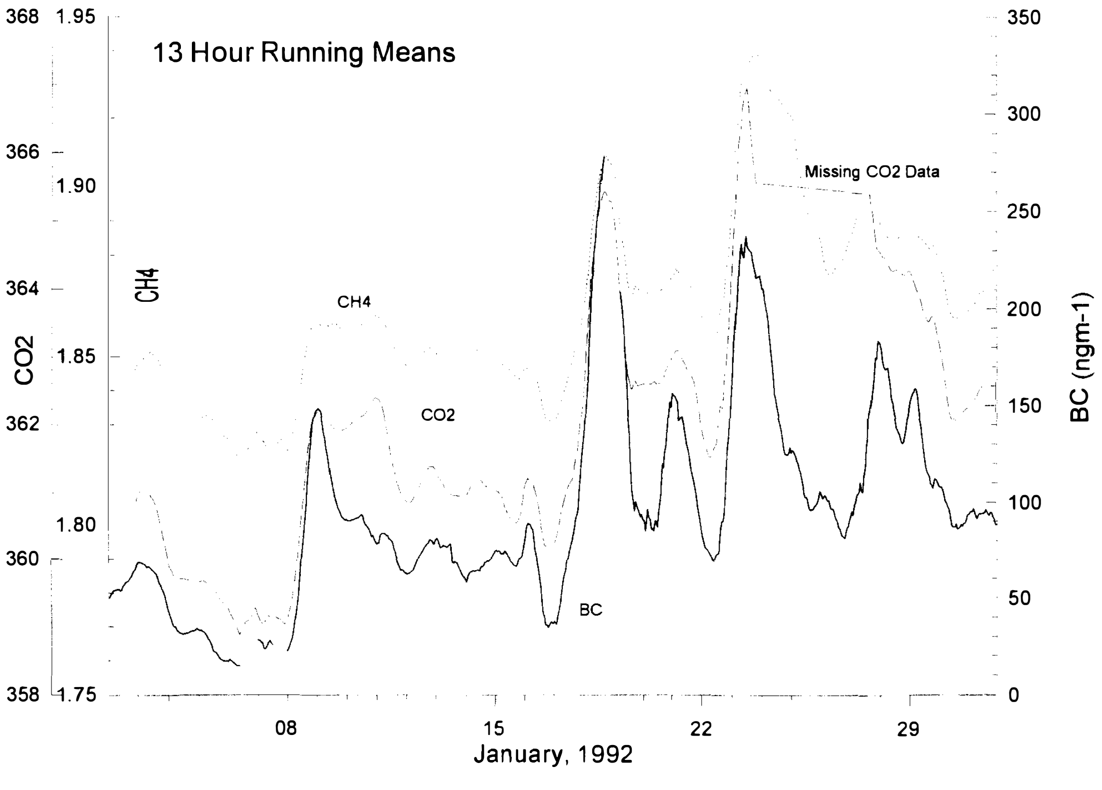

Fig. 3. *Thirteen hour running mean values of carbon dioxide (CO_2), methane (CH_4) and black carbon (BC) are plotted for January 2 to 31, 1992.*

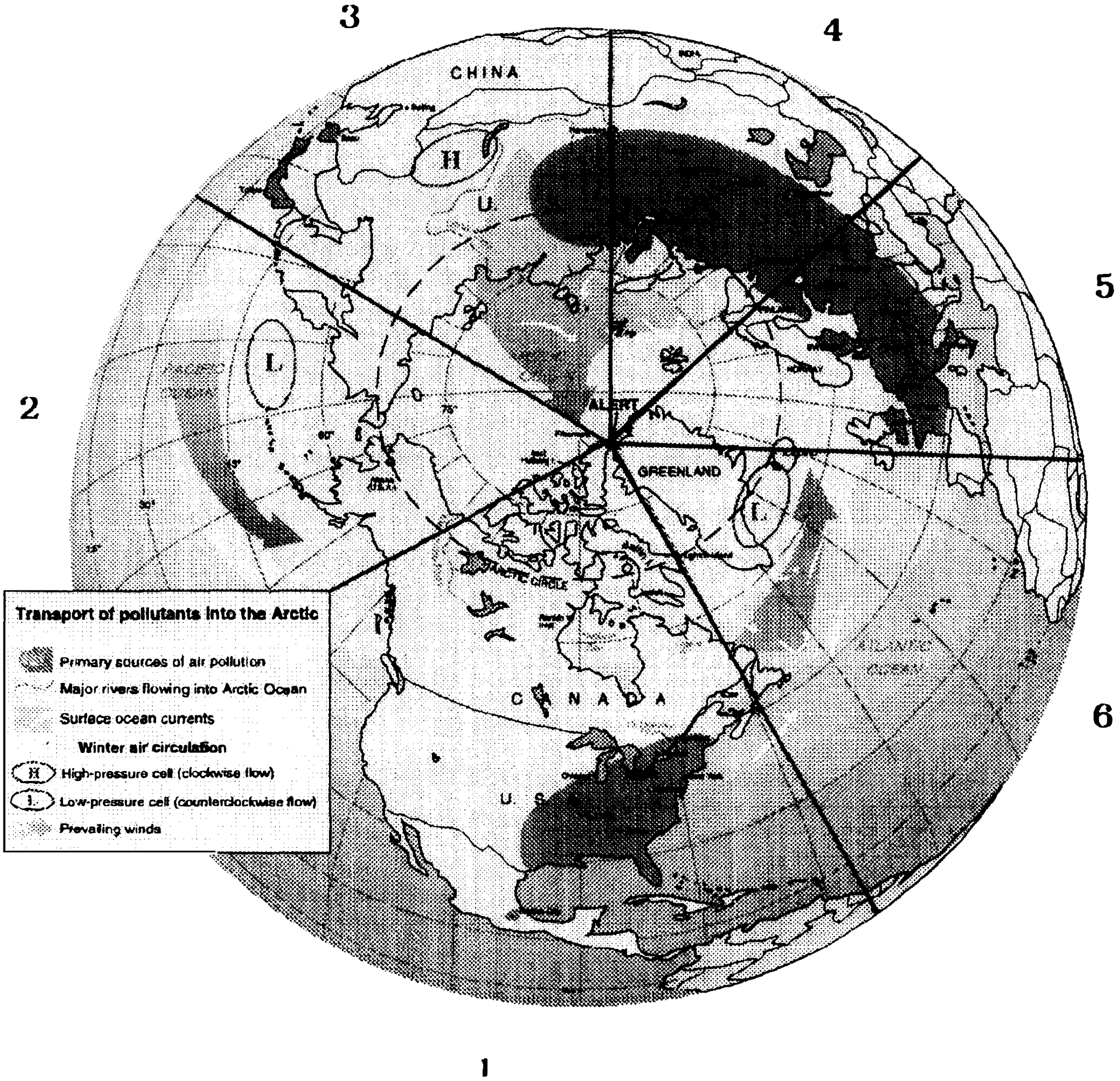

Fig. 4. Generalized air and ocean circulation patterns in the high northern latitudes are shown with the sectors used for assigning source regions to the 5 day back trajectories. (Used with permission of the Canadian Geographical Magazine.)

Worthy *et al.* (1994) have shown that the short term variability (2–5 days) in the continuous time series of carbon dioxide (CO_2), methane (CH_4) and black carbon (BC) during the months of January and February (see Fig. 3) is the result of rapid transport of air from anthropogenic source regions in Eurasia some 2500 to 3000 km from Alert. Most of these episodes result from rapid long range transport across the pole from central Siberia to Alert. During the polar night, the Arctic atmosphere is very stable. Under these conditions, pollutants injected into the Arctic can travel large distances as a cohesive plume because of the minimal vertical or horizontal mixing. It should also be noted that by the end of March, the variability diminishes significantly related, probably, to increased mixing in the Arctic atmosphere. These elevated episodes occur every year in the long term time series of both carbon dioxide and methane.

Table 1. *Defined sector boundaries accounting for the different anthropogenic inputs.*

Sector	Region	Sector boundary
1	Northern Canada	0° – 90°
2	Northern Pacific + Alaska	90° – 150°
3	Eastern Russia	150° – 210°
4	Western Russia	210° – 255°
5	Europe	255° – 300°
6	North Atlantic+Greenland	300° – 360°

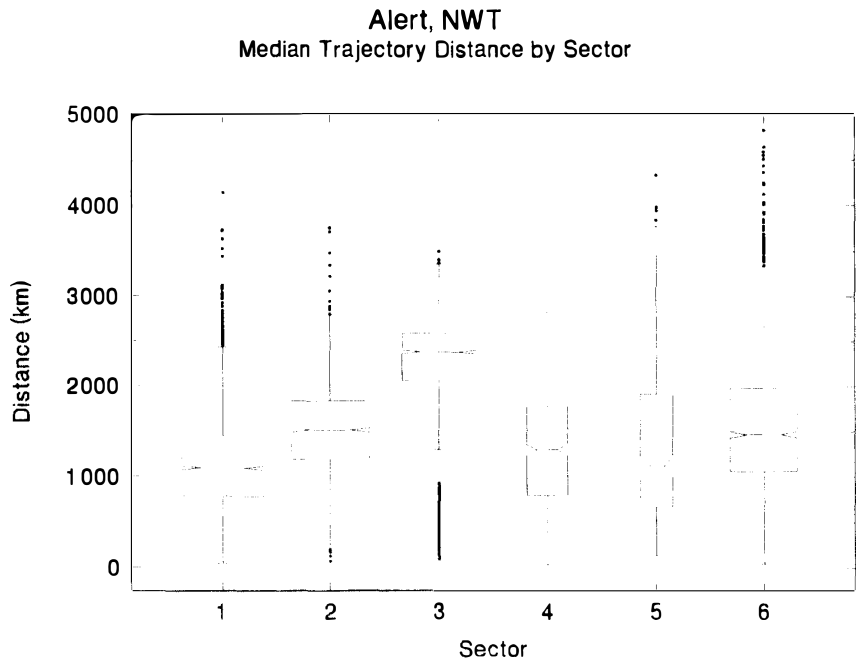

Fig. 5. *Notched box plot of the radial distances to the 5 day end points of the trajectories in each of the sectors (defined in Fig. 4) for the 1988 to 1994 study period, as given in Fig. 4.*

Five-day air mass trajectories (OLSEN *et al.*, 1978) are calculated 4 times per day, with a time step for the trajectory end points of 6 hours. These trajectories are used to characterize the 5 years (1988–1992) of continuous carbon dioxide data, and to identify the "clean" air sectors. In order to assign these events to potential anthropogenic source regions, six geographical sectors have been defined (WORTHY *et al.*, 1994). The sectors are shown in Fig. 4, and were defined by latitude and longitude co-ordinates and from 0 to 360 degrees westward. Table 1 defines the sector boundaries which account for the different anthropogenic inputs.

The 5 day back trajectory positions are classified into these 6 sectors. A trajectory is assigned to the sector only if at least 3 of the 4 trajectory points for that 5th day lie within the same sector. Radial distances from Alert to the air parcel end point position 5 days earlier are also calculated. Figure 5 summarizes the radial distance travelled by the 5-day back trajectories in each sector over the 5 year period. In the figure, the width of the box plot is proportional to the square root of the number of trajectories in each sector. The box containes 50% of the data and the horizontal line represents the median value. The notches represent approximately the 95% confidence limit for the median. It is obvious that the Sector 3 trajectories travel the furthest, and that the median radial distances for the other sectors are much shorter and are similar in magnitude to each other. The frequency of trajectories in Sectors 4 and 5 are much less than 15 percent of the total, while the remaining are approximately equally distributed in the other 4 sectors.

In an earlier trajectory analysis study, HIGUCHI *et al.* (1987) using data from the flask sampling program, have shown that the short-term positive CO_2 concentration anomalies at Alert are usually associated with air masses arriving from northern Europe and Siberia, while negative concentration anomalies are usually related to air coming from northern open oceanic areas.

Figure 6 shows the box plot of the CO_2 concentration by sector for the 5 year period. The large variability results from the fact that the data are not detrended nor deseasoned. Nevertheless it is quite clear that the concentrations in Sectors 3, 4, and 5 are significantly higher that the other sectors (*i.e.*, the notches in the boxes do not overlap). This indicates that, even though Sector 3 is the predominant long range transport sector, the shorter trajectories of the "European Sectors" also carry higher concentrations of CO_2 into the Arctic, confirming the interpretation of the flask data by HIGUCHI *et al.* (1987).

Typically, the integrations to obtain back trajectories can be made only for periods up to 5 to 10 days before some of the assumptions are violated (HIGUCHI *et al.*, 1987), such as the effects of emission sources and mixing along transport paths. These factors

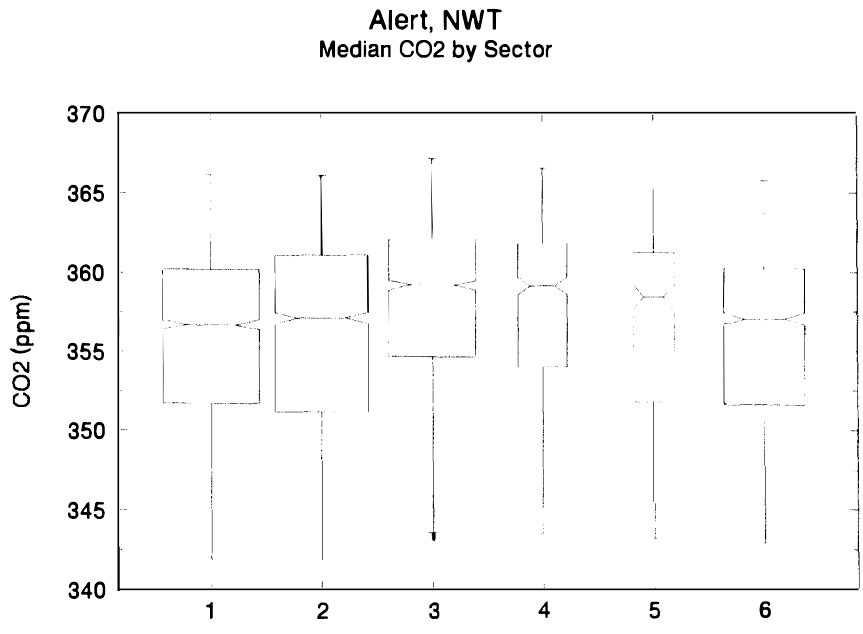

Fig. 6. Notched box plot of the CO_2 concentration by sector for the 5 year study period (1988 to 1994).

need to be included in order to obtain a quantitative assessment of the impact of CO_2 transport from the industrial sources in Eurasia on the short-term fluctuations in the Canadian Arctic.

3. Simulations of CO_2 Transport Pathways to Alert

In order to obtain a quantitative understanding of the relationship between the physical processes of long range tracer transport from the industrial emissions in Eurasia and the magnitude and duration of tracer gas measurement anomalies over the Canadian Arctic, a series of simulations using a regional atmospheric dynamical model is conducted to reproduce specific events of positive CO_2 anomalies observed at Alert. A detailed description and validation of the Arctic regional dynamical model is given in

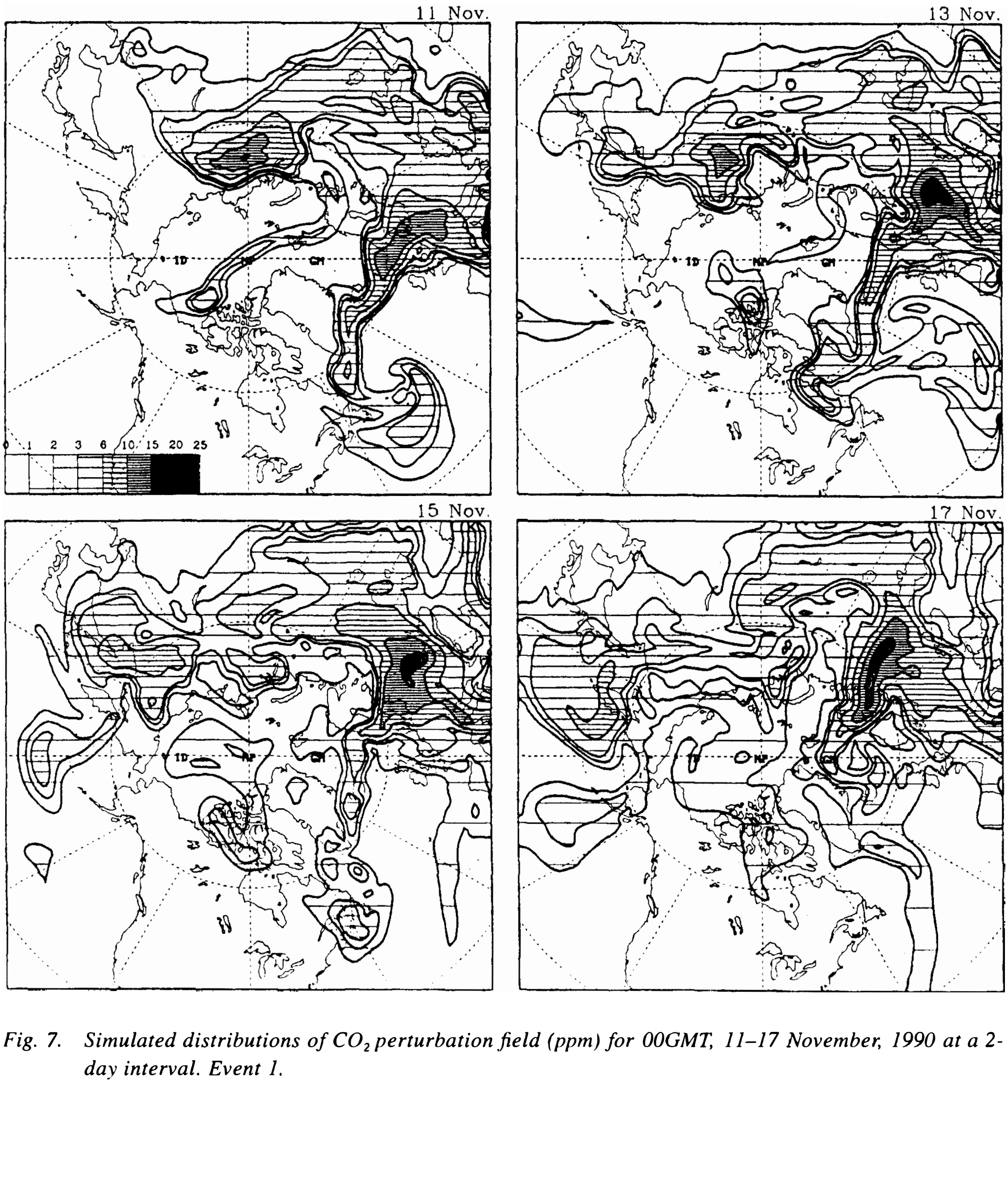

Fig. 7. Simulated distributions of CO_2 perturbation field (ppm) for 00GMT, 11–17 November, 1990 at a 2-day interval. Event 1.

YUEN *et al.* (1996).

We choose 3 sequential positive anomaly episodes in CO_2 measurements at Alert during November and December of 1990, to quantitatively examine the evolution of the spatial distribution of CO_2 as it is being transported from the emission region in northern Europe to the Canadian Arctic along certain transport pathways. These 3 episodic events are classified as Event 1, Event 2 and Event 3.

To prescribe a realistic temporal and spatial distributions of the Eurasian CO_2 emission sources as a perturbation forcing function at the bottom of the model, we estimate the 1990 emission field by scaling the 1980 CO_2 emission data on a 5° × 5° latitude-longitude grid (MARLAND *et al.*, 1985) by the ratio between the 1990 and 1980 global emissions. As the total global carbon emission increased from about 5.09 GtC in 1980 to about 5.97 GtC in 1989 (MARLAND and BODEN, 1991), we approximate the 1990 global emission to be around 6.04 GtC, assuming similar growth rate in 1989 and 1990. Seasonality in the emission rate over Europe is about 8.7% and 9.2% of the annual value for November and December, respectively (ROTTY, 1987). In our simulation exercise, we use a constant emission rate fixed at 8.7% of the 1990 annual European emission value. These emission sources show highest values in the industrial and population centres of western Europe (see Fig. 4).

Figure 7 shows the CO_2 perturbation field at four different time frames associated

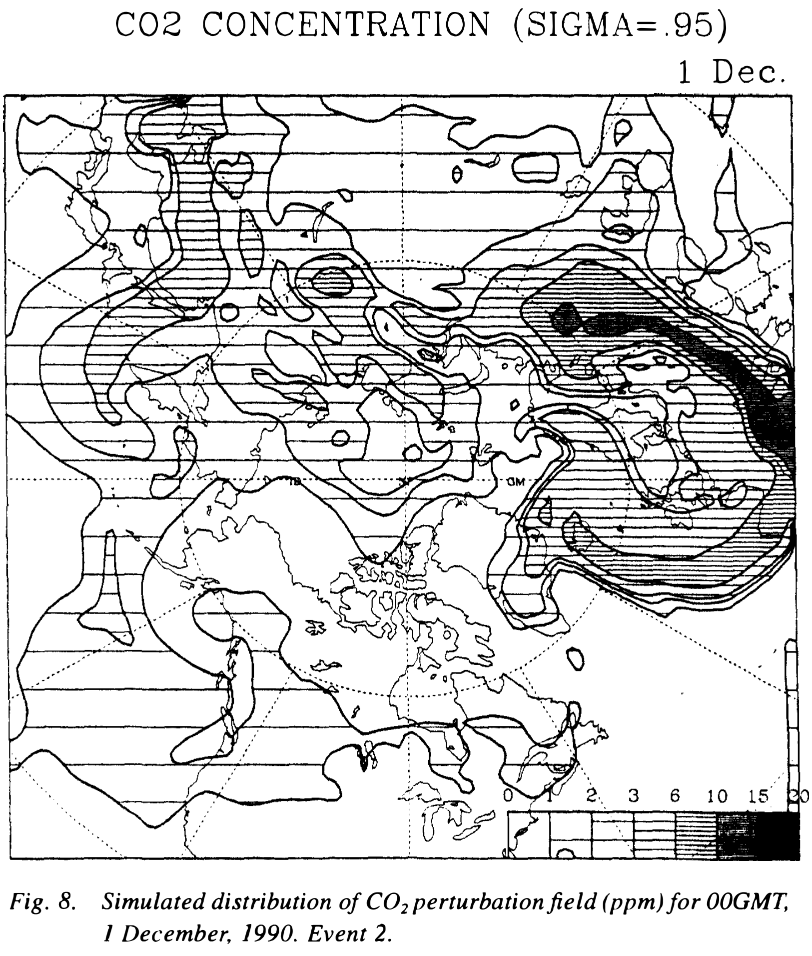

Fig. 8. Simulated distribution of CO_2 perturbation field (ppm) for 00GMT, 1 December, 1990. Event 2.

with the occurrence of Event 1 around mid November. The direct cross-Arctic transport of CO_2 from Eurasia to the Canadian Arctic Islands associated with this positive CO_2 anomaly event at Alert appears to be typical of one of the transport pathways of pollutants into the Canadian Arctic (Raatz, 1991; Worthy *et al.*, 1994). The pathway is strongly controlled by the high pressure systems extending from Siberia to Alaska/Yukon. The amount of time taken by the anthropogenic CO_2 to travel from the northern Eurasia sources to the Canadian Arctic for Event 1 is about 2 weeks. The model gives an anomaly CO_2 concentration of about 1 ppm (parts per million) over northern Ellesmere Island, in a general agreement with the positive deviation measurement associated with Event 1 of 1.5 ppm at Alert.

Figure 8 shows a simulated CO_2 anomaly intrusion of about 1–2 ppm over the northern part of the Canadian Arctic Archipelago associated with Event 2 in early December, after a rapid transport across the pole from eastern Siberia. The model simulation allows tongue of only a weak concentration to reach the Canadian Arctic, somewhat inconsistent with a large positive deviation of about 5 ppm observed at Alert for Event 2. The discrepancy between the simulation and the observation is due primarily to the neglect in the model of large midlatitude sources of biospheric CO_2, which enters the Arctic on an episodic basis in the fall and winter seasons (Yuen *et al.*, 1996). Thus, less than 50% of the positive CO_2 anomaly observed at Alert associated with Event 2 comes

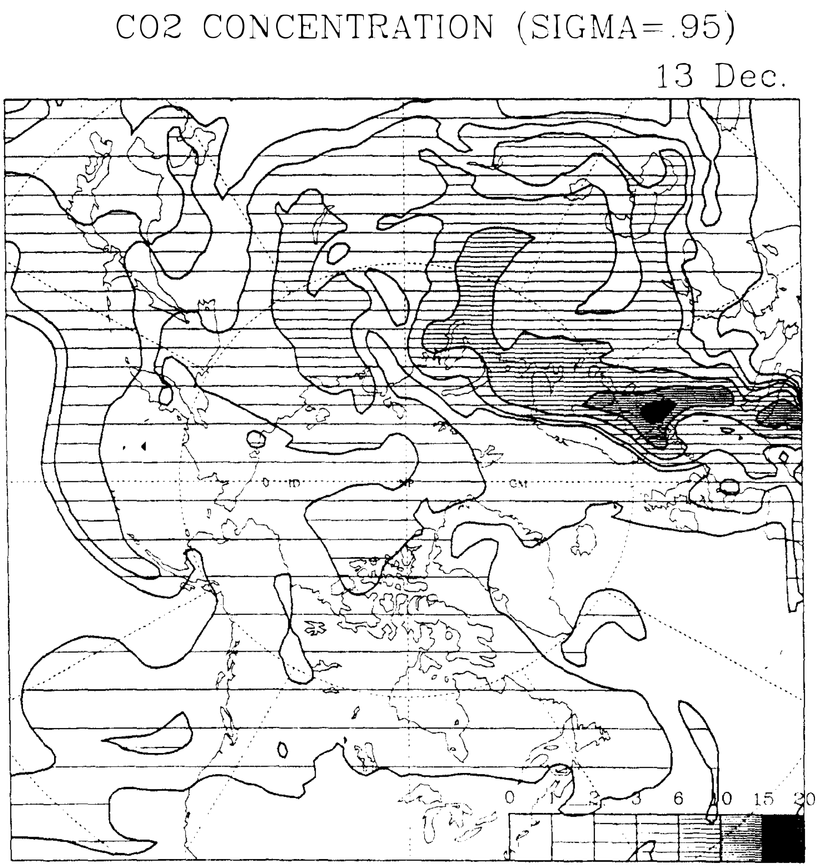

Fig. 9. Simulated distribution of CO_2 perturbation field (ppm) for 00GMT, 13 December, 1990. Event 3.

from anthropogenic sources in northern Eurasia.

Simulation of Event 2 shows that the anthropogenic CO_2 from the Eurasian sources travels eastward to eastern Siberia before it is "picked up" by a strong cross-Arctic flow and advected, over the pole, towards the Canadian Arctic. The transport time for this pathway is on the order of several weeks to a month.

The CO_2 perturbation field associated with Event 3 in mid December is shown in Fig. 9. Simulation of this particular episode seems to suggest that the positive CO_2 anomaly observed at Alert is related to a recirculation of Arctic air mass already laden with anthropogenic CO_2, not by cross-Arctic transports associated with Events 1 and 2. The model simulates an intrusion of about 2 ppm over Ellesmere Island; this value is relatively close to about 3 ppm observed at Alert.

4. Conclusions

Measurements of greenhouse trace gases, such as CO_2 and CH_4, at Alert in the Canadian Arctic show very distinctive features of various time scales. For example, time series of CO_2 shows very obvious seasonal cycle and a long term trend related to the photosynthetic-decay process of the midlatitude land biosphere and the anthropogenic CO_2 emissions, respectively. But also present in the time series is a very clear short term variability on a synoptic time scale of several days to a week.

Through trajectory analyses, it has been demonstrated that long range atmospheric transport of material into the Arctic from the midlatitude plays an important role in the short term variability, as well as in the long term trends and the seasonal cycles of CO_2 and other trace gases. These transport processes are reflection of synoptic and large-scale weather patterns. The short term variability is associated with rapid transport of air from anthropogenic source regions in Eurasia, some 2500 to 3000 km from Alert. Much of these positive anomaly episodes result from rapid long range transport across the pole from central Siberia to Alert. A trajectory analysis gives only a qualitative indication of a possible relationship between the source distribution and the measurement site, within the source-receptor conceptual framework.

In order to obtain a quantitative understanding of the relationship between the long range transport processes of trace gases from the emission sources in Eurasia and the measurements of anomalies over the Canadian Arctic, we have used a regional atmospheric dynamical model to simulate specific events of positive CO_2 anomalies observed at Alert. Three distinctive tracer transport pathways from Eurasia to the Canadian Arctic have been identified. These are: (1) direct cross-Arctic pathway, (2) transport via northern Siberia, across the pole, and (3) recirculation of Arctic air mass. Transport time for various pathways ranges from about 1–2 weeks (direct pathway) to over a month (transport via Siberia). Furthermore, the magnitude of the short term variability at Alert cannot be entirely accounted for by the anthropogenic CO_2 emissions from Eurasia.

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