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ARCTIC TROPOSPHERE CARBON DIOXIDE;
LOW-ALTITUDE AIRCRAFT SAMPLING

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ABSTRACT

This paper presents data from low altitude (<4500 m) aircraft sampling for CO₂ in the arctic atmosphere. The data cover the period from late spring to late summer when environmental changes at the tundra and sea ice are most pronounced. Results of the data analysis show the effect of regional sources and sinks for CO₂ on the lower troposphere. The annual ice and open water zones of the Arctic Ocean covered by the flights transects appear to act as a potential sink for carbon dioxide.

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INTRODUCTION

Continuous infrared analysis of carbon dioxide began at a clean air coastal site near Barrow, Alaska (71.3°N, 156.7°W) in 1961 (Kelley, 1964, 1969 and 1973). Prior to this, seasonal and meridional variations were determined (Bolin and Keeling, 1963) from flask samples collected from aircraft operating at high altitude (>5500 m). As a result of a combination of data from surface station, ship, and aircraft samples (Bolin and Keeling, 1963) a distributional pattern emerged which showed that the annual variation was greatest in the atmosphere over arctic latitudes (~12 ppm) and that minimal annual fluctuations in CO₂ existed at the South Pole (~1 ppm). Both polar areas, however, reflected similar long-term trends in the gradual annual increase of CO₂ in the atmosphere (Keeling *et al.*, 1976) which persists to the present time.

Early attempts to assess the reasonability of the Barrow site as a background station for the long-term measurement of CO₂ were made (Kelley, 1964) by joining in a cooperative flask sampling program with the Scripps Institution of Oceanography (C. D. Keeling) which extended the collection of near surface sampled air from land based stations to far out over the Arctic Ocean at various occupied scientific stations on the ice. Associated with the same program, a limited number of samples were collected along transects at various inland sites and from low level aircraft flights. The results of the inland station data, collected mostly during late summer and early fall, showed high variability in CO₂ concentration which was presumed to be due to the effects of vegetation. Based on analyses of data for near-surface CO₂ collected over a long period of time from the Barrow sites, ice stations and ships, and spread over a wide latitudinal area in the arctic and subarctic regions, we directed some of our research effort to a systematic analysis of

CO₂ levels in the lower troposphere (<4500 M) with emphasis on the seasonal ice zone of the Arctic Ocean and the tundra areas of the North Slope of Alaska. In addition, we hoped that the results of the low altitude aircraft data would compliment some of the implications to be found in the earlier high altitude data of Bolin and Keeling (1963).

The atmospheric CO₂ concentration level begins to rise at Barrow, Alaska in late August, months before it does at mid-latitudes (late October) and reaches a worldwide high (for clean backgrounds) of about 340 ppm in late May, months after northern hemispheric anthropogenic space heating has ceased and lower latitude photosynthesis has begun. Furthermore, the late spring high is a resurgence rather than a continuous climb to that level, and the high levels persist for 1-2 weeks a few hundred km offshore as compared to Barrow (Kelley, 1973 and this work). Our estimates of the arctic source-sink strengths for CO₂, and for the role that annual sea ice plays in the winter-summer mixing ratio of atmospheric CO₂, have been published elsewhere (Gosink and Kelley, 1982b). This article deals with the results of our low altitude aircraft atmospheric CO₂ program, and shows the intensity of regional sources and sinks for CO₂ on the lower troposphere.

EXPERIMENTAL METHODS

Transition from the exclusive use of infrared analysis to gas chromatography occurred over several years. By 1975, gas chromatographic techniques were our primary analytical method and all measurements continued to be referred to CO₂ standards provided by the Scripps Institution of Oceanography (C. D. Keeling). The gas chromatographic procedure, standards and accuracy have been published elsewhere (Gosink and Kelley, 1982). The sample collection procedures are described below.

A Naval Arctic Research Laboratory (Barrow, Alaska) Twin Otter aircraft was usually used to collect air samples. Air was conducted to a 250 ml sampling flask *via* a small viton diaphragm air pump in the non-pressurized cabin at a rate of about 4-5 l/min. The air intake tubing (Teflon) was located on a strut well ahead of the engines. A twin-engine C117 aircraft was also occasionally used. The tubing was placed in one of the clean air scoops mounted above the fuselage forward of the engines. Sampling flight plans were established to fly 150 to 1000 km north of Barrow, Alaska. Samples were periodically collected at approximately 100 m altitude outbound. At the farthest point, a vertical profile was made from 40 m to 4500 m altitude. Samples taken inbound were made at 3200 m to a point usually about 80 km inland. Another set of samples was taken to establish a vertical profile over land.

Care was taken to flush the short section of glass tubing leading to the stopcock before the stopcock to the highly evacuated sample bulb was opened. After 1.5-2 minutes of flushing, the bulb was slightly pressurized before the stopcock was closed.

Some air samples were collected and held briefly under slight positive pressure in teflon coated steel and glass (10 ml) gas tight syringes. It was necessary to employ oversize O-rings under the teflon coated plunger in order to achieve a gas tight fit at low temperatures. Analyses were completed within 24 hours; usually within 1 to 6 hours. Samples held in these syringes were stable for 24-72 hours, depending on the particular syringe in question. The samples in the slightly pressurized gas sample bottle were stable for several weeks. All of our ambient air analyses over several years, using hand methods of readout of the stripchart recordings agreed with the NOAA/GMCC site daily observations by 1-2 ppm. We were both using the Index Scale of Reference.

AIRCRAFT OVERFLIGHTS OF THE ARCTIC ICE AND TUNDRA

Figures 1a-d and Figures 1e,f show horizontal and vertical profiles, respectively, of atmospheric carbon dioxide over land and over seasonal ice from late spring to late summer when the surface environmental changes are most pronounced. Other seasonal data show smaller or no horizontal and vertical change. The area sampled was always within a few hundred km from Point Barrow, Alaska.

There was a strong enrichment of CO_2 over the predominantly annual sea ice, and a noticeable depletion only 80 km inland on 26 June 1977 (Fig. 1a). The sea ice was nearly continuous and had only recently begun to melt about 150 km north of Point Barrow at that time. Thus, offshore CO_2 evolution would have been high due to optimal opening of brine channels (Gosink and Kelley, 1982a, b). The tundra at that time was free of snow and ice, and was biologically active (i.e., soil respiration and photosynthesis were active). A few weeks later, 7 July 1977, there was only a suggested trend in enrichment over the ocean portion of the north-south transect. The sea ice around Point Barrow was breaking up and melting out to 300 km by that time, thus low PCO_2 surface waters may have influenced the local lower atmosphere at that time. There was, however, evidence for significant (10 ppm) enrichment at low altitudes offshore on 18 July 1977 for a flight 300 km east of Point Barrow. That flight maintained nearshore altitudes over melting sea ice of about 150 m dropping to 15 m 100 km offshore over continuous annual ice which was only beginning to melt. The data for 20 July 1977 shows essentially constant oceanic atmospheric concentrations of CO_2 out to nearly 1000 km north of Point Barrow. It is important to note that the 20 July 1977 flight was at 2 km altitude, whereas the previous two were conducted at 30 m over the ice.

The data shown in Figure 1b is for the same time period as Figure 1a, but a year later. In 1978 the ice had already broken up several weeks earlier than the previous year. The data from these flights show an essentially constant low level atmospheric concentration of CO_2 from inland 90 km south of Point Barrow to 300 km offshore to the north. The only exception was the early far inland data of 20 June 1978. There was a sharp depression in atmospheric CO_2 130 km inland, presumably due to the uptake of CO_2 by the vegetation. The higher values 90 km inland may represent seasonal changes with respect to latitude when the surface was still thawing, and soil respiration was dominant. Similar data of slightly depressed CO_2 values near the mountains and of higher levels of CO_2 further north over the tundra, have been observed in the past at surface monitoring sites (Kelley, 1964).

In early June of 1979, the sea ice and tundra were only beginning to thaw within 100 km of Point Barrow. The CO_2 partial pressure was essentially constant at 340-341 ppm to 850 km north of Point Barrow, and only dropped 2-3 ppm, 200 km inland. Carbon monoxide at that time showed a more dramatic change and has been reported elsewhere (Gosink and Kelley, 1979).

Figure 1c shows the data from a flight transect during late summer (8-9 September 1978). Freezing had set in so that the intense biological activity in the tundra active layer had greatly diminished, yet the ground had not frozen and could still outgas without biological fixation of the CO_2 (Coyne and Kelley, 1971). The oceans were nearly clear of all ice out to about 200 km, and skim ice was visible in the many leads in the pack ice. Low PCO_2 water was still at the surface. This is in contrast to the 27 June 1978 data (Fig. 1b) when biological activity was uniformly high. The far inland atmospheric concentrations of CO_2 in this case were high and variable, and decreased northward to the coast where the 150-200 km of open low PCO_2 water appeared to influence lower troposphere. Our aircraft sample data near Point Barrow are in

general agreement with the NOAA/GMCC recorded values at Barrow for the 2 days prior to and during the flight as shown by the small bar in Figure 1c. The surface winds were from a clean air northern (oceanic) sector. Winds aloft near Point Barrow usually have a westerly origin when the surface winds are from the north, and thus would have been influenced by the low PCO_2 open waters of the Chukchi and northern Bering Seas. The air from the pack ice region is clearly enriched in CO_2 near the surface as shown in Figures 1c and 1f. Figure 1f is a vertical profile 320 km offshore for the 8 September 1978 flight (Fig. 1c).

Figure 1d presents data for a flight transect three weeks later after the tundra had frozen (30 September 1978). There had been almost continuous high winds and wave activity from the northeast and northwest. The surface sea water equilibrium PCO_2 level remained surprisingly low at about 270 ppm 20 km offshore. There was however, a definite but small (2-3 ppm) trend for enrichment 300 km offshore for the air at 3200 m which suggests possible enrichment by either new sea ice or high PCO_2 surface waters farther out in the pack ice. Annual sea ice was forming in the leads in the pack ice, which was still 150 km offshore of the vicinity of Point Barrow. The offshore vertical gradient for the same flight is shown in Figure 1e.

The strong vertical and horizontal changes in the atmospheric concentration of carbon dioxide as shown in Figure 1d was not common. It does, however, show how local natural effects can influence the data at the clean air CO_2 monitoring site. This incident prompted the studies by Peterson *et al.* (1980), and Halter and Peterson (1981) in which they re-investigated the Barrow, Alaska CO_2 monitor data with respect to wind trajectory. Those studies substantiated the concepts of significant surface effects in the arctic as presented in this article.

By 8 November 1978, the annual sea ice had reformed. There was high PCO_2 water (341 ppm) under the ice and a noticeable enrichment of CO_2 in the air above the sea ice 180 km north of Barrow at that time. The air near (30 m) the surface 180 km north of Barrow had a concentration of approximately 340 ppm CO_2 , 80 km north it was 332 ppm and at Barrow it was 327 ppm (~ 328 ppm according to the NOAA/GMCC data).

On five occasions, both north and south of Point Barrow, vertical profiles showed the layered presence of higher (6-10 ppm) CO_2 near 1 km altitude. Occasionally, enrichment at 3 km was evident too. These data are not due to analytical error or contamination from the aircraft. A complementary study on aerosols (G. Shaw, University of Alaska, personal communication), on one flight showed that there were increases in aerosols at those same levels. These data suggest boundary layer entrapment. Ozone, which was also observed concurrently with CO_2 on some flights, displayed a minimum in the CO_2 maximum layers. On 16 January 1978, a low CO_2 concentration rather than a CO_2 maximum was evident at 600 meters. The ozone concentration in the CO_2 minimum layer was also reversed in that it displayed a maximum.

The winter profiles were variable for the month of January 1978. There was generally a small trend for enrichment for CO_2 near the surface. The air at altitude over the sea ice usually was more highly enriched compared to the over-land profile. Seventeen out of 20 flights over a two-year period did show clearly positive to slight enrichments in CO_2 near the surface as compared to higher altitudes.

SUMMARY AND CONCLUSIONS

Low altitude aircraft sampling (<4500 m) for atmospheric CO_2 shows how intense ground level sources and sinks can, on occasion, modify the observations

made on a fixed ground level station (e.g., Fig. 1c). Layering effects are also seen on occasion as opposed to continuous gradients. The most important fact is that the annual ice and open water zones of the Arctic Ocean appear to be a significant source of CO_2 in the winter and sink in the summer, which is further substantiated by high altitude flights (Bolin and Keeling, 1963), the low altitude data presented here and the trajectory analysis of Halter and Peterson (1981). Therefore, future atmospheric models should account for the natural sources and sink of CO_2 in the arctic (Gosink and Kelley, 1982) and not consider them as essentially ice-sealed inert regions.

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FIGURE CAPTIONS

- Figure 1a. Horizontal profiles of atmospheric CO₂ at low and high altitudes north and south of Point Barrow, Alaska, June-July 1977.
- Figure 1b. Horizontal profile of atmospheric CO₂ at low altitude north and south of Point Barrow, Alaska, June-July 1978.
- Figure 1c. High and low altitude horizontal profiles of atmospheric CO₂ north and south of Point Barrow, Alaska, 8-9 September 1978.
- Figure 1d. High and low altitude horizontal profiles of atmospheric CO₂ north of Point Barrow, Alaska 30 September 1978.
- Figure 1e. Vertical profile of CO₂ and temperature 320 km north of Point Barrow, Alaska, 8 September 1978.
- Figure 1f. Vertical profile of CO₂ and temperature 260 km north of Point Barrow, Alaska, 30 September 1978.