NOAA Technical Memorandum ERL ARL-158

THE ANALYSIS OF METEOROLOGICAL CONDITIONS AND HAZE DISTRIBUTION FOR THE SECOND ARCTIC GAS AND AEROSOL SAMPLING PROGRAM (AGASP II), MARCH-APRIL 1986

G. A. Herbert
H. A. Bridgman
R. C. Schnell
B. A. Bodhaine
S. J. Oltmans

Air Resources Laboratory
Silver Spring, Maryland
November 1987

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

NOAA Technical Memorandum ERL ARL-158

THE ANALYSIS OF METEOROLOGICAL CONDITIONS AND HAZE DISTRIBUTION FOR THE SECOND ARCTIC GAS AND AEROSOL SAMPLING PROGRAM (AGASP II), MARCH-APRIL 1986

G. A. Herbert

Geophysical Monitoring for Climatic Change

H. A. Bridgman

Cooperative Institute for Research in Environmental Sciences
Campus Box 449
University of Colorado
Boulder, Colorado

R. C. Schnell
B. A. Bodhaine
S. J. Oltmans

Geophysical Monitoring for Climatic Change

Air Resources Laboratory
Silver Spring, Maryland
November 1987

UNITED STATES
DEPARTMENT OF COMMERCE

C.William Verity
Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

Environmental Research
Laboratories

Vernon E. Derr,
Director

NOTICE

For sale by the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

CONTENTS

The Analysis of Meteorological Conditions and Haze Distribution for the Second Arctic Gas and Aerosol Sampling Program (AGASP II), March-April 1986

G. A. Herbert, H. A. Bridgman,* R. C. Schnell, B. A. Bodhaine and S. J. Oltmans

ABSTRACT. The second Arctic Gas and Aerosol Sampling Program (AGASP II) was conducted across the non-Soviet Arctic in March and April 1986, to study the aerosol, chemical, and optical properties of Arctic haze. One component of the program was conducted with a specially instrumented NOAA WP-3D aircraft. Measurements of wind, pressure, temperature, ozone, water vapor, condensation nuclei (CN) concentration, and aerosol scattering extinction (b_{sp}) were used to determine the locations of significant haze layers. The first three NOAA WP-3D research flights were conducted north of Pt. Barrow, Alaska, and over the Beaufort Sea northeast of Barter Island, Alaska. The following three sampled conditions in the high Arctic near Alert, Northwest Territories, Canada. In the Alaskan Arctic, the WP-3D documented a strong and persistent haze zone from 960 to 750 mb between two thermally stable levels of the atmosphere. When the haze was most dense, it contained CN concentrations >60,000 cm^{-3}, aerosol black carbon concentrations of up to 900 ng m^{-3}, aerosol b_{sp} of 90×10^{-6} m^{-1}, and SO_2 concentrations of 15 ppb. Optical depths in the haze exceeded 0.75 on occasion. Away from the main haze core, CN concentrations were in the 500-3000 cm^{-3} range, aerosol b_{sp} values were in the $(30\text{-}50) \times 10^{-6}$ m^{-1} range, and SO_2 was <1 ppb. The WP-3D aircraft flew downwind and around the Prudhoe Bay oil field complex and found no evidence that the operations were contributing to Arctic haze. In the Canadian Arctic near Alert the haze was much lighter, appeared to be of background level, and was well mixed throughout the troposphere. Typical CN concentrations were 50-200 cm^{-3}, aerosol b_{sp} was $(20\text{-}30) \times 10^{-6}$ m^{-1}; and SO_2 was >1 ppb. On all but one flight ozone was depleted to near 0 ppb beneath the surface temperature inversion, compared with a 35-45 ppb range in the free troposphere. Near the tropopause, a region essentially devoid of aeorsols was observed in all sectors of the Arctic. Above the tropopause, stratospheric aerosols were measured in concentrations lower than observed in 1983 (following the El Chichon eruption).

*Permanent address: Department of Geography, University of Newcastle, NSW, 2308 Australia.

INTRODUCTION

The Arctic Gas and Aerosol Sampling Program (AGASP) is a multifaceted cooperative research program designed to determine the distribution, transport, chemistry, aerosol physics, and radiative effects of the polar-wide air pollution phenomenon know as Arctic haze. The research was conceived, organized, and directed by the National Oceanic and Atmospheric Administration (NOAA), and the Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder. AGASP has involved participants from the United States, Canada, Norway, Sweden, Federal Republic of Germany, and Denmark and has covered two intensive field study periods in March-April 1983 and March-April 1986. The core field research program consists of airborne measurements tied to similar baseline station measurements at Pt. Barrow, Alaska; Alert, Northwest Territories; and Ny Alesund, Spitzbergen. The results of the 1983 program were published in special issues of Geophysical Research Letters (Vol. 11, no. 5, May 1984) and Atmospheric Environment (Vol. 19, no.12, December 1985). Equipment descriptions may be found in those issues (Schnell, 1984).

The second phase of the AGASP (AGASP II) began in March 1986 with intensive ground-based operations at various locations in the Arctic, followed in April by research flights covering the Arctic from Alaska to Greenland. One component of the airborne operations was flights by an extensively instrumented NOAA WP-3D Orion research aircraft. This aircraft flew three missions to the Alaskan north slope in support of baseline monitoring at Barrow, and three missions in the Canadian Arctic, based at Thule, Greenland. The latter flights were related to the Canadian Baseline Station at Alert, operated by the Atmospheric Environment Service, Canada (Hoff and Trivett, 1984). They were flown in conjunction with the Twin Otter research aircraft of the National Aeronautical Establishment of Canada and the C-131 research aircraft of the University of Washington. The results from the companion aircraft measurements are published in separate reports and, therefore, are not included in this technical memorandum (Radke et al., 1986; Leaitch and MacPherson, 1986).

The NOAA WP-3D aircraft used in AGASP II carried sensors to measure the physical and chemical composition of Arctic haze. These instruments included a General Electric condensation nucleus (CN) counter (Bodhaine and Murphy, 1980), an MRI 1511 integrating nephelometer (Ruby and Waggoner, 1981), and a Dasibi ozone monitor (Oltmans, 1985). Omega dropwindsondes were used to obtain the vertical distribution of wind, temperature and water vapor below the aircraft over remote areas (Franklin, 1983; Julian, 1982). The meteorological measurements available from the NOAA aircraft also included wind speed and direction, atmospheric and cabin pressure, and air temperature corrected for air speed and water vapor (Derr and Gunter, 1982; Emmanuel, 1983).

The purpose of this report is to present the distribution of meteorological, aerosol, and ozone variables with height and distance along the WP-3D flight track and to present some highlights of the aircraft flights. Other cooperative programs conducted on the WP-3D, such as continuous measurements of graphitic carbon, PAN, SO_2, trace gases, H_2O_2, solar radiation, aerosol chemistry, and optical depth, will be able to use these data to interpret their measurements.

As part of each flight, detailed profiles and cross sections from 30 m above the surface to the stratosphere were flown to establish the vertical and horizontal pattern of Arctic haze. Cross sections of the atmosphere were used to display potential temperature and wind values vs. pressure along the flight track for AGASP-I (Raatz et al., 1985). Similar cross sections are presented in this report, but they deviate from custom by the use of a linear pressure scale as a vertical coordinate, which expands the lower atmospheric levels where most variations of the haze constituents of interest occur. Synoptic maps at 850 and 500 mb provided background meteorological information. Measurements during flights were supported by a nose camera, used to record cloud and haze conditions.

The cross sections were drawn in terms of both latitude and longitude and follow the general outbound path of the aircraft. When large time differences between the outbound and the return flight occurred (usually in the southern half of the Alaskan flights), we averaged some values. In other situations, when portions of the flights had significant components perpendicular to the cross section, only the data reasonably near the principal longitude were considered in the analyses. The mountains shown on the cross sections at 63°N (in Alaska) are the Alaskan range and at 68°N the Brooks range.

About half of the sounding data is derived from dropwindsondes. Dropwindsonde pressure, wind, and potential temperature were checked against similar measurements from the aircraft and the nearest rawinsonde. Rawinsonde data, for Barrow in particular, were found to agree with the meteorological data from the aircraft.

Cross sections depicting ozone and some haze parameters (CN concentrations, b_{sp}) are presented for specific parts of the flight track to highlight spatial variations in haze and differences in haze concentrations between days. A flight log for each flight, representing a compilation of the observations of a number of scientists on the aircraft, is also included.

The 1986 eruption of the Augustine volcano (59.37°N, 153.42°W), 260 km southwest of Anchorage, provided a potential source for gases and aerosol during the AGASP-II flights. According to Yount et al. (1987), the initial eruptions late on March 27 produced an almost continuous ash plume injected to 4 km above the summit vent (1.2 km MSL), punctuated by intermittent explosive events to 12 km and above. Approximately 14 major explosive-type events were reported between March 27 and April 3. For the first 24 h of the eruption, winds in the mid-troposphere were southwesterly, transporting the ash up the Cook Inlet and to the west of Anchorage. Ash injected above 3-km altitude, during March 27 and early March 28, may have been transported over central Alaska, possibly as far north as the Brooks Range. Later in the period, when the large low-pressure region was established in the western Arctic basin, the winds aloft over Alaska became westerly and any residual ash would have been transported into northwestern Canada. Ash from eruptions occurring after March 29 was most likely transported across northern Canada to Greenland, assuming it remained aloft for periods of 5 days and longer. Aerosol samples collected on the flights show that the NOAA WP-3D encountered probable Augustine aerosols on one occasion between Fairbanks and Anchorage well south of the haze study area.

1. FLIGHT 201, APRIL 2-3, 1986

1.1 Flight Track

Figure 1.1 (left) shows the NOAA WP-3D flight track, which originated in Anchorage (ANC). The track over the lower half of Alaska to Barrow (BRW) jogged east to avoid Mt. Denali, then passed to the west of Fairbanks. The WP-3D flew to a point north of BRW and conducted a sounding over the Arctic Ocean ice to the northwest, upwind of the BRW Geophysical Monitoring for Climatic Change (GMCC) station. A series of level flight "legs" was included in the sounding to accommodate radiation and turbidity measurements, as shown in the detail to fig. 1.1 (right). Once the sounding was completed, a "porpoising" (up and down) flight mode was adopted to search for and define some boundaries of an exceptionally dense haze layer encountered early in the flight. Low-level sampling in the haze terminated north of Wainwright, Alaska, before the aircraft climbed out and return to ANC by the most direct route. Total flight time was 9 h, and 34 min.

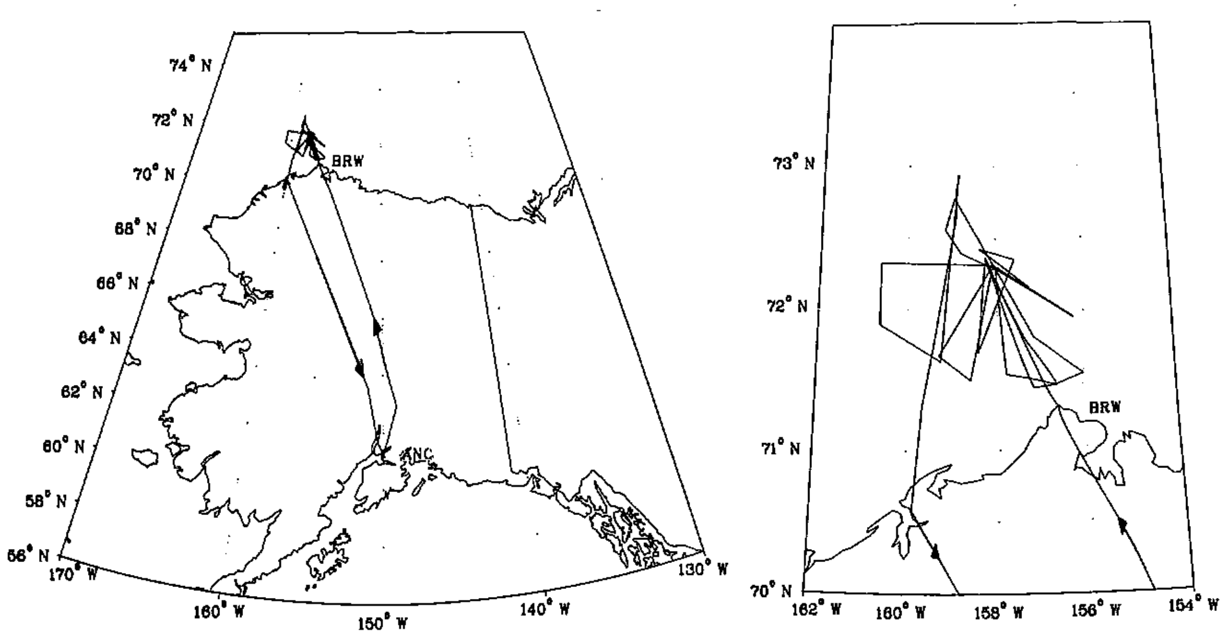


Figure 1.1--(Left) Horizontal projection of the aircraft flight track on a latitude-longitude grid, April 2-3, 1986. (Right) Detailed projection of the flight track north of Barrow (BRW).

1.2 Flight Log

APRIL 2, 1986 (GMT)

1927	Takeoff from Anchorage.
1928	Begin data record.

1928-2005	Climb to 395 mb, 7200 m.
2003	Passed through a weak haze layer that could have been of volcanic origin, 63.4°N, 149.3°W, 421 mb, 6809 m.
2038-2042	Climb to 368 mb, 7800 m, 66.5°N, 151.0°W.
2045-2053	Intersected the stratosphere at 66.72°N, 151.28°W, 367 mb, 7774 m.
2057	Ozone increased from 36 to 60 ppb. Went through a small tongue of stratospheric ozone.
2118	We are flying north of the Brooks range above a very heavy haze aerosol layer. We are in an aerosol-free zone with CN concentrations in the low teens.
2122	We just passed from clean air into dirty air.
2130	CN are starting to drop off slightly as we climb toward the stratosphere into the aerosol-free zone again.
2132	We are still heading north toward BRW. Successful dropwindsonde release at 70°N, 154.82°W. We can see haze over the north slope. The haze has a whitish look with the sun behind it.
2151	Begin descent over ice north of BRW, 71.28°N, 156.73°W.
2159	We are maneuvering for our up-sun and down-sun runs in the haze. There are no clouds over the ice, just a diffuse white haze.
2211	At this point, about 160 km north off the coast from BRW, there appears to be a banded cloud formation right at the ice surface. These are slight, little, zippy clouds that have a very long fetch to them. They are about 1-2 km from crest to crest, like a sinusoidal gravity wave; 72.08°N, 157.96°W, 426.8 mb, 6723 m.
2217	Southbound on the solar radiation run. There are no clouds visible beneath us now, though it is hazy. The ice has a lot of little cracks in it, but no large open leads.
2221	On a 90° sun-run. There are absolutely no clouds visible above or below; 72.15°N, 158.04°W.
2228-2254	Descend from 426 to 670 mb through a background-type haze.
2253-2313	Level run in light haze.
2313-2323	Descend from 670 to 795 mb through a light haze with some CN peaks to 275 cm^{-3} and b_{sp} to 50 v 10^{-6} m^{-1}.

2323 Level at 794 mb, 2009 m.

2332 Encountered the edge of a haze band with a very large increase in CN concentration (130 cm^{-3} to 20,000 cm^{-3} in 40 s), 72.22°N, 158.30°W, 794 mb, 2009 m. Aerosol b_{sp} increased from 30 v 10^{-6} m^{-1} to 50 v 10^{-6} m^{-1}. RH jumped from 47% to 75%.

2333 We are in a cloud-free area within a strong haze band.

2345 For the last 10 min we have been recording very strong peaks in CN and carbon. Ozone is holding steady at 40 ppb. We have very heavy haze around us that we can see visually, and this visual haze is very thick in all directions. There was a period 5 min previous to this in which we could not see the ice from 2000 m altitude. We are now reversing direction to fly out the side of the haze. We can see better, and the CN counts are starting to drop.

2353 Clear of haze layer, 792 mb, 2022 m, near where we entered it. The edge is well defined with CN dropping from 10,000 to 200 cm^{-3} in a few seconds.

April 3, 1986 (GMT)

0000 Descending, 72.35°N, 158.11°W, 803 mb, 913 m.

0007-0021 Level at 898 mb, 1002 m.

0022 Light haze, 72.OO°N, 156.14°W, 897 mb, 1000 m. CN increased from 200 to 600-700 cm^{-3}.

0028 Clear of haze, 936 mb, 659 m.
0056 Ascending from 1000 mb, 74 m beneath a haze layer.

0100 Haze base CN counts climbed from 191 to >6000 cm^{-3}; 71.65°N, 158.37°W, 932 mb, 702 m.

0108 CN > 10,000 cm^{-3}, b_{sp} = 85 v 10^{-6} m^{-1}.

0120 CN counts fall to background, 72.34°N, 159.52°W, 677 mb, 3268 m. Diffuse top to haze layer.

0127 We are descending and turning to go into the haze zone as we head back toward BRW.

0144 Haze encountered again, 71.78°N, 159.13°W, 842 mb, 1534 m. CN climbed from 200 to 15,000 cm^{-3}.

0209 Begin "porpoising," southbound at 72.85°N, 159.02°W, 837 mb, 1586 m through the haze zone. High CN counts with significant variability.

0249 We are on the coast at Wainwright, 70.69°N, 159.82°W. We are getting ready to climb out and return to ANC. The haze is still here and fairly thick.

0251 End "porpoising" flight mode, 70.59°N, 159.85°W, 836 mb, 1590 m. Begin climb, to return to Anchorage.

0304 Entered stratosphere, 69.78°N, 158.50°W, 345 mb, 8033 m. Ozone increases from 30 to 40 ppb.

0314 In aerosol-free zone, 328 mb, 8558 m.

0326 Level at 294 mb, 9293 m.

0436 Begin descent into Anchorage.

0439 Entering troposphere at 62.40°N, 150.71°W, 363 mb, 7137 m.

0501 Landed at Anchorage.

1.3 Synoptic Situation

The 500- and 850-mb level maps shown in figs. 1.2 and 1.3 respectively represent general synoptic-scale conditions at the time of the AGASP flight 201. The 500-mb level (nominally at 5.5 km altitude) is representative of the upper troposphere in the Arctic, and generally contains lesser amounts of haze than at lower levels. The 850-mb level is at a standard altitude of 1.5 km and is considered to be the most representative of the mandatory pressure levels in terms of the transport of Arctic haze.

A large, low-pressure cell, which formed in the northern portion of the Beaufort Sea on March 31, 1986, determined both the winds aloft over northern Alaska and the transport of pollutants to this region for the period prior to the flight. This center of low pressure remained relatively stationary at about 78°N, 150°W during the flight period. The day before the flight, a low-pressure region formed along the Aleutians and moved into the Gulf of Alaska. At the 500-mb level and above, the westerly winds over Alaska were determined by the Arctic basin low. At 850 mb, easterly winds were prevalent in south and central Alaska (determined by the lows in the Gulf of Alaska) and were westerly north of the Brooks Range (determined by flow around the Beaufort Sea low). A substantial temperature gradient of 12°C was observed between ANC and BRW at 850 mb.

Table 1 contains the surface weather observations from the BRW GMCC station for the 8-h period the WP-3D was north of the Brooks Range. [A description of the GMCC station, its surrounding geography and climatology can be found in Bodhaine and Harris (1982)]. The wind direction changed gradually from westerly to northwesterly and the speed decreased by 2 m s^{-1} during this period. The temperature also decreased 4.5°C, with most of the decrease occurred after 0100 GMT, April 3. It is noteworthy that the cloud cover observation from the National Weather Service office in BRW, 8 km to the southwest, changed from overcast to broken at the

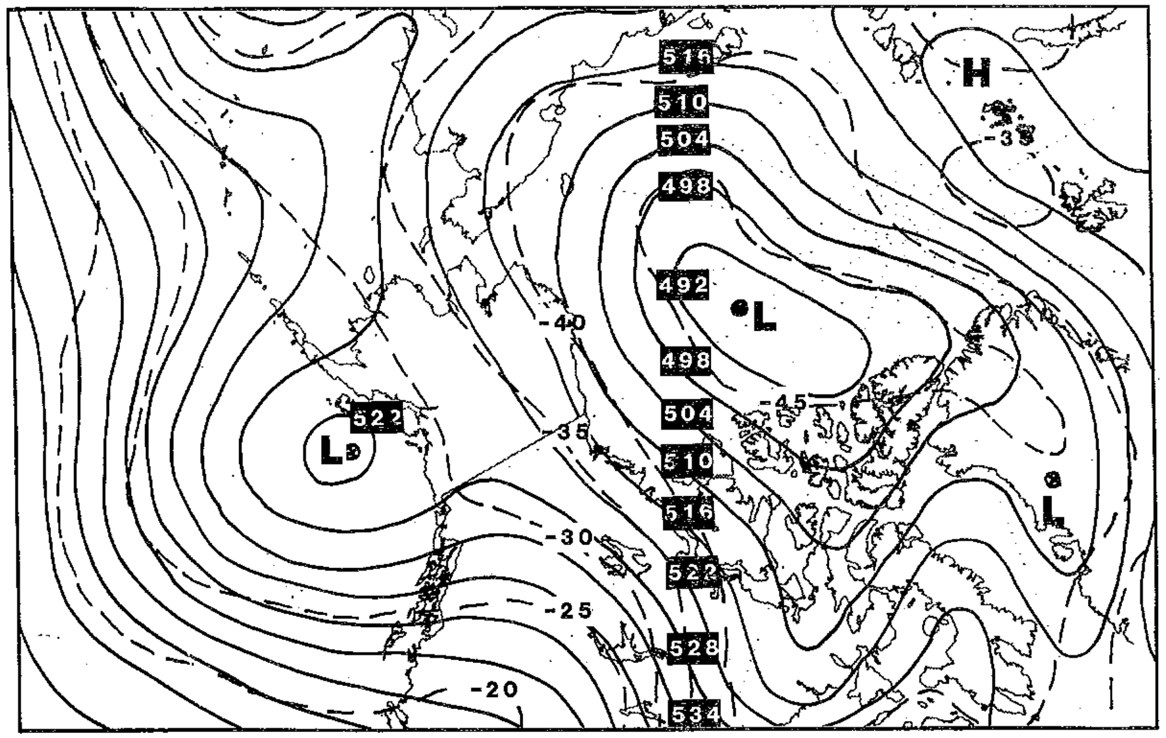


Figure 1.2--500-mb synoptic map for the western Arctic at 0000 GMT, April 3, 1986. Included are pressure altitude (geopotential decameters, solid isolines), and temperature (5°C, dashed isolines).

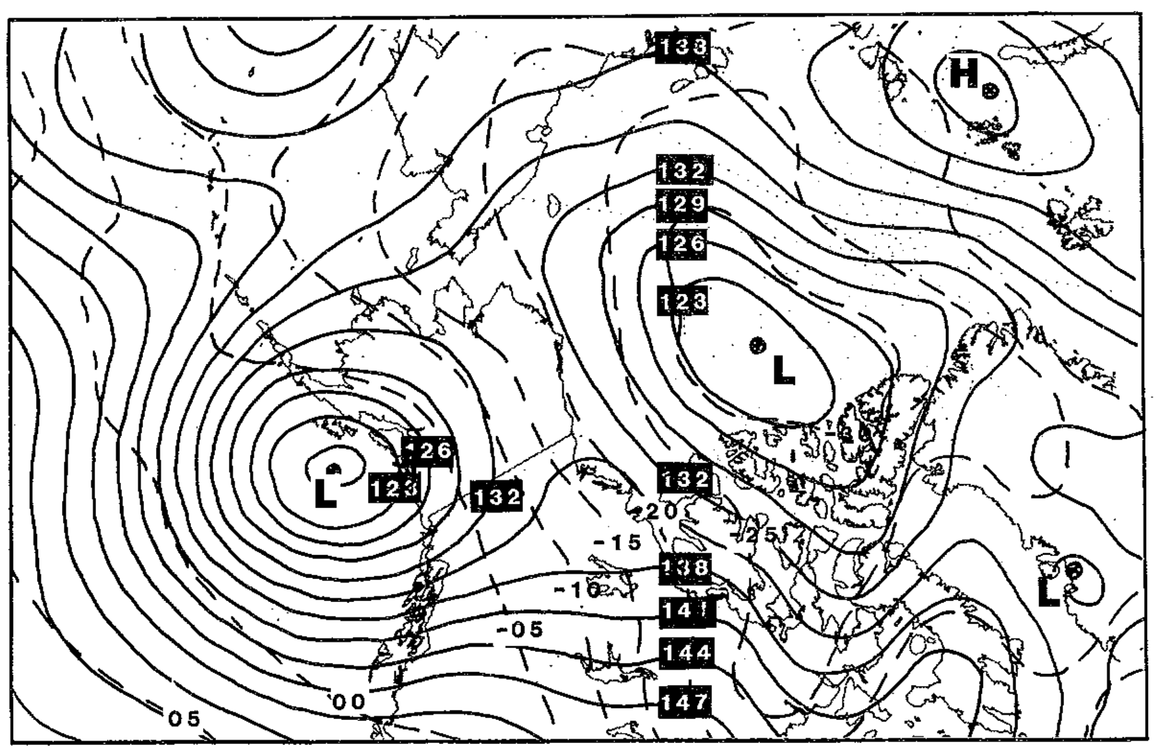


Figure 1.3--850-mb synoptic map for the western Arctic at 0000 GMT, April 3, 1986. Included are pressure altitude (geopotential decameters, solid isolines), and temperature (5°C, dashed isolines).

same time. The clouds were reported to be at an altitude of 6 km. Higher resolution data showed that the minimum pressure occurred at 0120 GMT. It is apparent that a minor trough that was making its way around the Arctic low passed BRW at that time. This was one of a series of minor low-pressure troughs that flowed around the Arctic low with 12-24 h interval spacing.

Table 1--Surface weather observations, April 2-3, 1986; Barrow GMCC station hourly average values

Time (GMT)	Wind Direction (Deg)	Wind Speed (m s^{-1})	Pressure (mb)	Temp. (°C)	Clouds*
April 2					
2100	265	6.0	1010.6	-22.1	-OVC
2200	270	5.9	1010.7	-22.0	-OVC
2300	275	5.9	1010.6	-22.1	-OVC
April 3					
0000	285	5.3	1010.4	-22.4	-OVC
0100	300	5.2	1010.3	-22.9	-OVC
0200	305	4.8	1010.5	-23.9	-BKN
0300	315	3.8	1010.5	-25.1	-BKN
0400	321	3.8	1010.6	-26.5	-BKN

*OVC = overcast; BKN = broken; minus indicates a thin cloud layer.

1.4 Atmospheric Cross Sections

The WP-3D aircraft climbed out of ANC to a cruising altitude near 400 mb. At the halfway point it climbed to 350 mb where the aircraft encountered stratospheric air for a short time (fig. 1.4). In this air, there is an abrupt increase in the ozone (fig. 1.5), but no significant change in either CN or b_{sp}. The aircraft conducted a sounding 75 km northwest of BRW, including five level runs for turbidity and radiation measurements at 427, 672, 795, 900, and 1000 mb. It was on the 795-mb leg that high concentrations of aerosols were first encountered in a major haze layer. The aircraft later climbed to 600 mb and descended to 940 mb to determine the vertical extent of the haze layer. The remainder of the available research flight time was used flying from north to south, alternating climbs and descents, in a "porpoising" fashion between 807 and 868 mb, to measure the horizontal and vertical extent of the haze plume cross section. The first sounding (with level runs) lasted 3 h, the second (with climb and descent) lasted 55 min, and the porpoising lasted 1 h. This phase of the sampling ended to the north of Wainwright, Alaska (AIN), at which time the WP-3D climbed to a cruising level of 295 mb (9.2 km) for the return flight.

On the return flight, the aircraft re-entered the stratosphere at 340 mb, 69.6°N, where ozone concentrations increased abruptly from 40 to 50 ppb, then rose to a peak of 170 ppb at 67°N (fig. 1.5). Ozone values remained above 100 ppb until the aircraft began a descent into ANC, crossing the tropopause at about 310 mb, 62.5°N. Between 68.5° and 68.3°N, elevated CN concentrations were observed in association with elevated ozone.

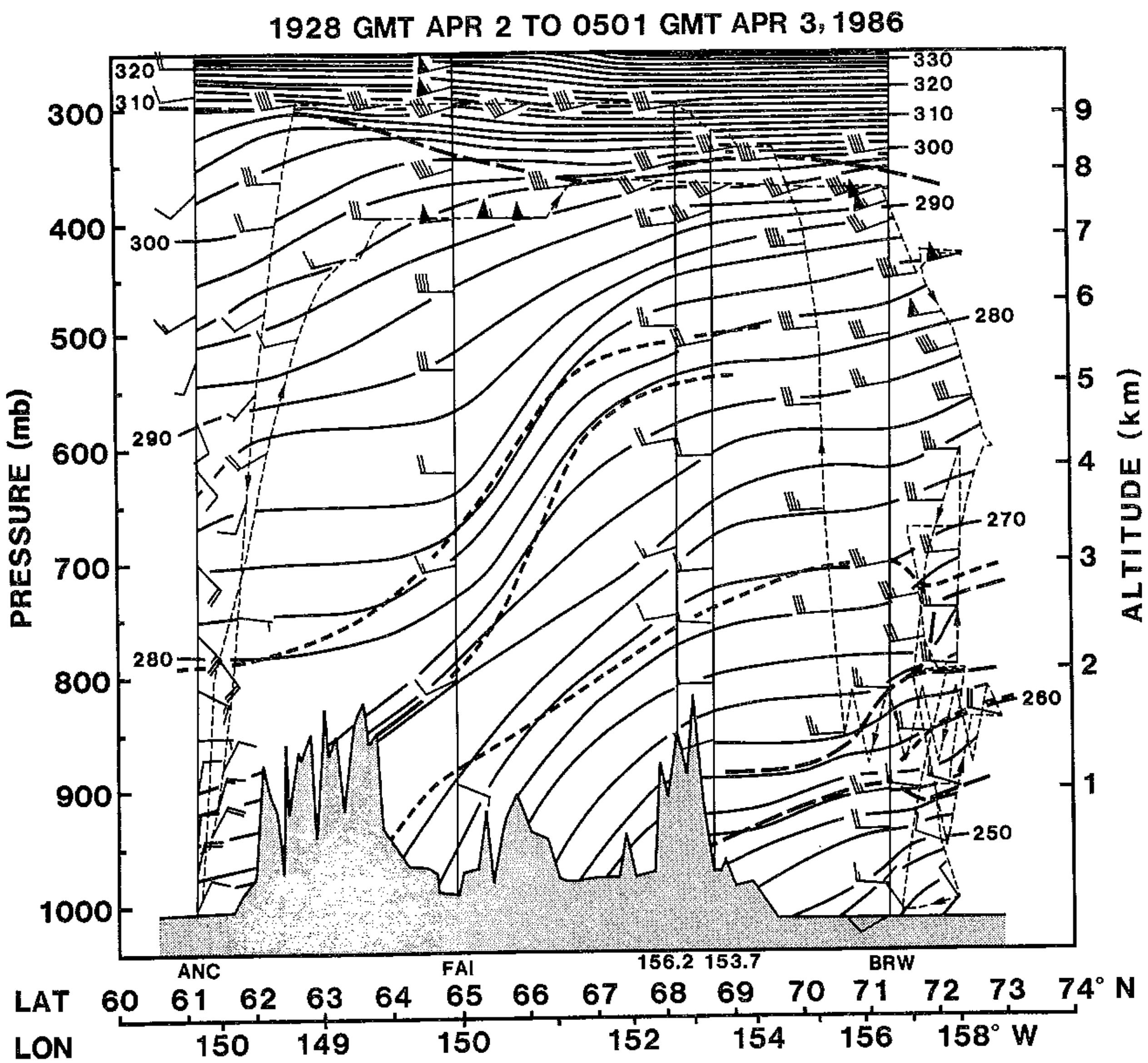


Figure 1.4--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Anchorage and Pt. Barrow, April 2-3, 1986. The tropopause and surface inversion are indicated by thick long-dashed lines, stable layers by thick, short-dashed lines, and the aircraft flight track by thin dashed lines. Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. ANC is Anchorage; FAI is Fairbanks; and BRW is Barrow.

Following procedures by Raatz et al. (1985), we can use the atmospheric cross section in fig. 1.4 to illustrate four principal air masses encountered during flight 201. In this and all subsequent cross sections on all flights, aircraft data were used in preference to sounding data if data conflicts occurred. When data contradictions occurred because of the time difference on the outward and inbound flights, mainly south of FAI, preference was given to the inbound data because they usually included higher aircraft altitudes, thus better representing the location of the tropopause.

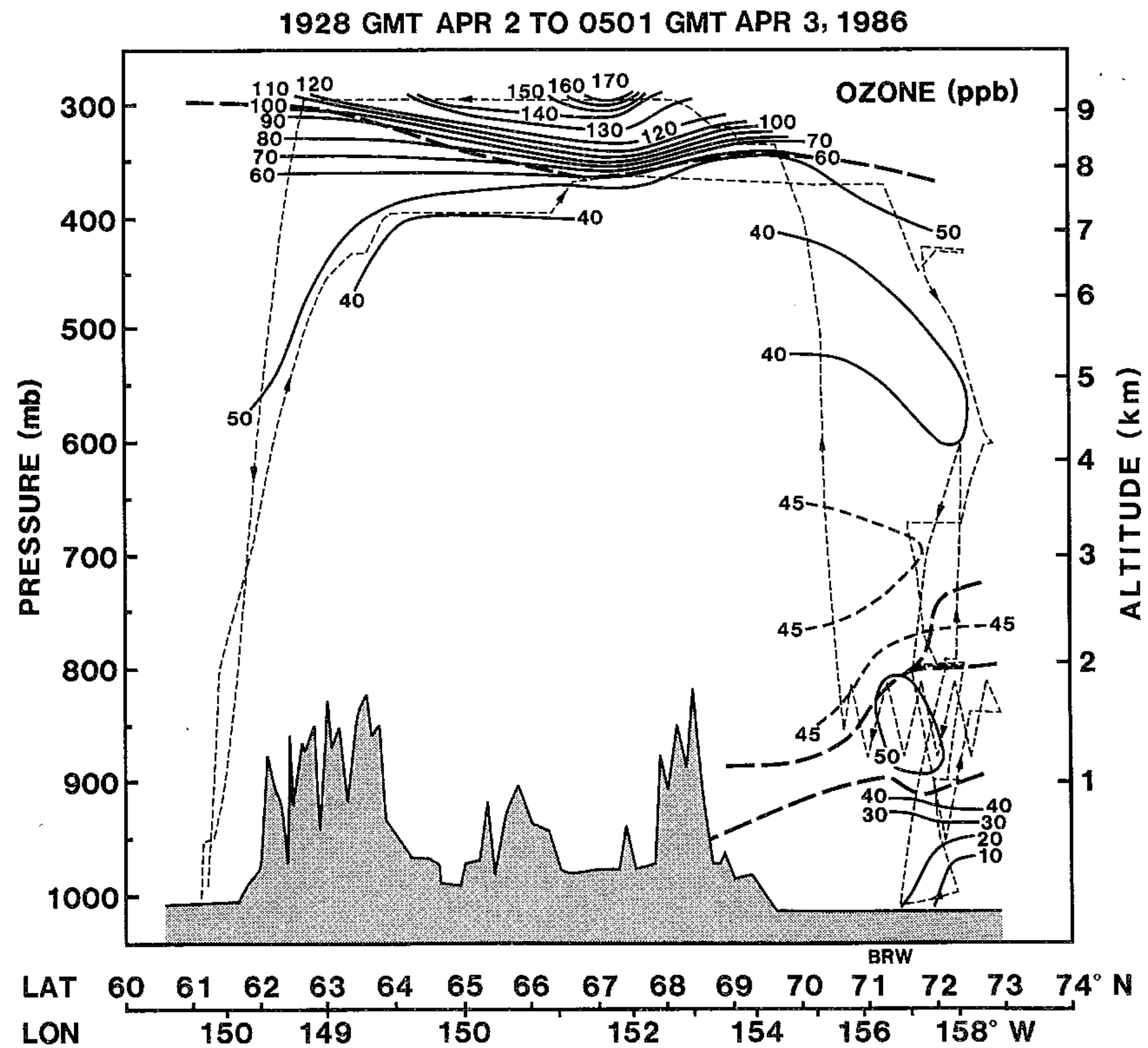


Figure 1.5--Latitude-altitude cross section of ozone, April 2-3, 1986. The tropopause and surface inversion are indicated by the thick dashed lines, and the aircraft flight track by the thin dashed line. BRW is Barrow. Dashed lines are for intermediate values.

The boundaries between the four air masses are shown in fig. 1.4 by thick dashed lines associated with the tropospheric isentropic analysis. The first air mass is maritime air of Pacific origin, which was advected over the southern portion of Alaska by a weak low pressure system in the Gulf of Alaska (fig. 1.2). In this air mass, between 500 and 800 mb, winds were westerly at 5 m s^{-1} and the air contained elevated moisture levels. At higher elevations, winds increased to greater than 15 m s^{-1} near the tropopause.

The Pacific air mass was separated from the colder drier Arctic air to the north, by a zone of steeply sloped isentropic surfaces over central Alaska, extending from below 800 mb at 61°N to 500 mb at 69°N. This Arctic air mass, originating from a large stationary low pressure system located about 1000 km northeast of BRW, extended from 900 mb to the tropopause over most of the cross section north of 69°N. In this second air mass, winds continued to be westerly throughout the troposphere. The air mass includes a zone of discontinuity, shown by the short-dashed line in fig. 1.4 that extends from 700 mb at the north edge of the analysis to the surface south of FAI, separating more stable air below from less stable air aloft. Ozone concentrations (fig. 1.5) remained relatively constant throughout this air mass until the tropopause, where a major increase in ozone gradient occured as the aircraft entered the stratosphere.

The third air mass was the atmospheric layer north of the Alaskan coast, the lower boundary of which was the surface inversion between 950 and 900 mb. The upper boundary extended from 900 mb at 69N to close to 700 mb at 72.5°N (fig. 1.4). Figure 1.6 shows that this layer contained increased moisture compared with the Arctic air mass above. This air mass contained the major haze layer first encountered by the aircraft at 795 mb.

Below the surface inversion was a fourth air mass, consisting essenetially of modified air from the third air mass. Here in the boundary layer, ozone concentrations (fig. 1.5) decreased to near zero levels and mixing ratios (fig. 1.6) were 10-15 g kg^{-1} lower than in the air mass above. The loss of ozone in the boundary layer is a fairly common feature in the Arctic over the ice, and has been reported in earlier studies (Raatz et al., 1985).

Water vapor concentrations shown in fig. 1.6 were highly variable in both the horizontal and vertical in the troposphere over the ice north of BRW. In general, the moist layer at 900 ± 50 mb separated a dry surface layer from another dry layer above 820 mb that was associated with the trough aloft. There is an indication, based mainly on the BRW sounding, that the southern edge of the region at 71°N had the higher moisture values. This is consistent with the shift on the north side of the region to a more northerly wind component.

It is difficult to understand the observations of clouds at 6 km altitude at BRW (table 1) and the low moisture amounts measured above 500 mb. Neither the aircraft observers nor the aircraft continuous camera data confirmed the presence of clouds of the extent reported by ground observers. For instance, at 2211 GMT the flight logs report clouds in long thin bands near the ice surface, but these clouds are almost certainly not the clouds reported at 6 km from BRW. A possibility exists that the observers were reporting a cloud layer on the basis of an elevated moisture layer at 5 km observed in a previous sounding combined with the visual observation of haze aloft. Considering that the haze north of Barrow was strong enough to obscure the surface from an altitude of 2 km, surface observers may be reporting haze as cloud.

Further, at the time the WP-3D flew over the GMCC station, surface reports of broken conditions were also not confirmed by airborne visual or aircraft nose camera observations.

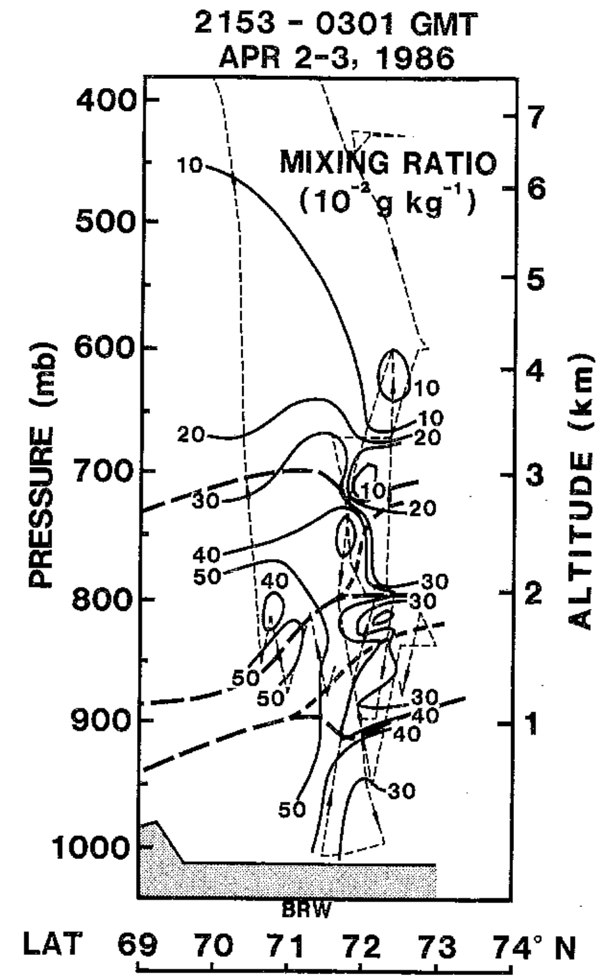


Figure 1.6--Latitude-altitude cross section of water vapor mixing ratio near Barrow (BRW), April 2-3, 1986. Stable layers are indicated by thick dashed lines and the flight track by a thin dashed line.

1.5 Haze Distribution

A vertical profile through the edge of a thick layer ("major haze layer") is shown in fig. 1.7 for an ascending profile between 0056 and 0126 GMT, April 3, at 72.35°N latitude, 159°W longitude. The haze, as determined by CN concentrations and b_{sp} (Radke, et al., 1984) had a sharp lower boundary at 950 mb at the top of the surface temperature inversion. The lower portion of the haze layer was associated with relatively moist air and slightly elevated ozone concentrations. The peak in b_{sp} (90×10^{-6} m^{-1}) occurred just below the top of the moist layer at 870 mb. CN concentrations held fairly steady, in the 9000-10000 cm^{-3} range, from 880 to 790 mb both within and above the moist layer. The haze and the higher moisture correlate well with

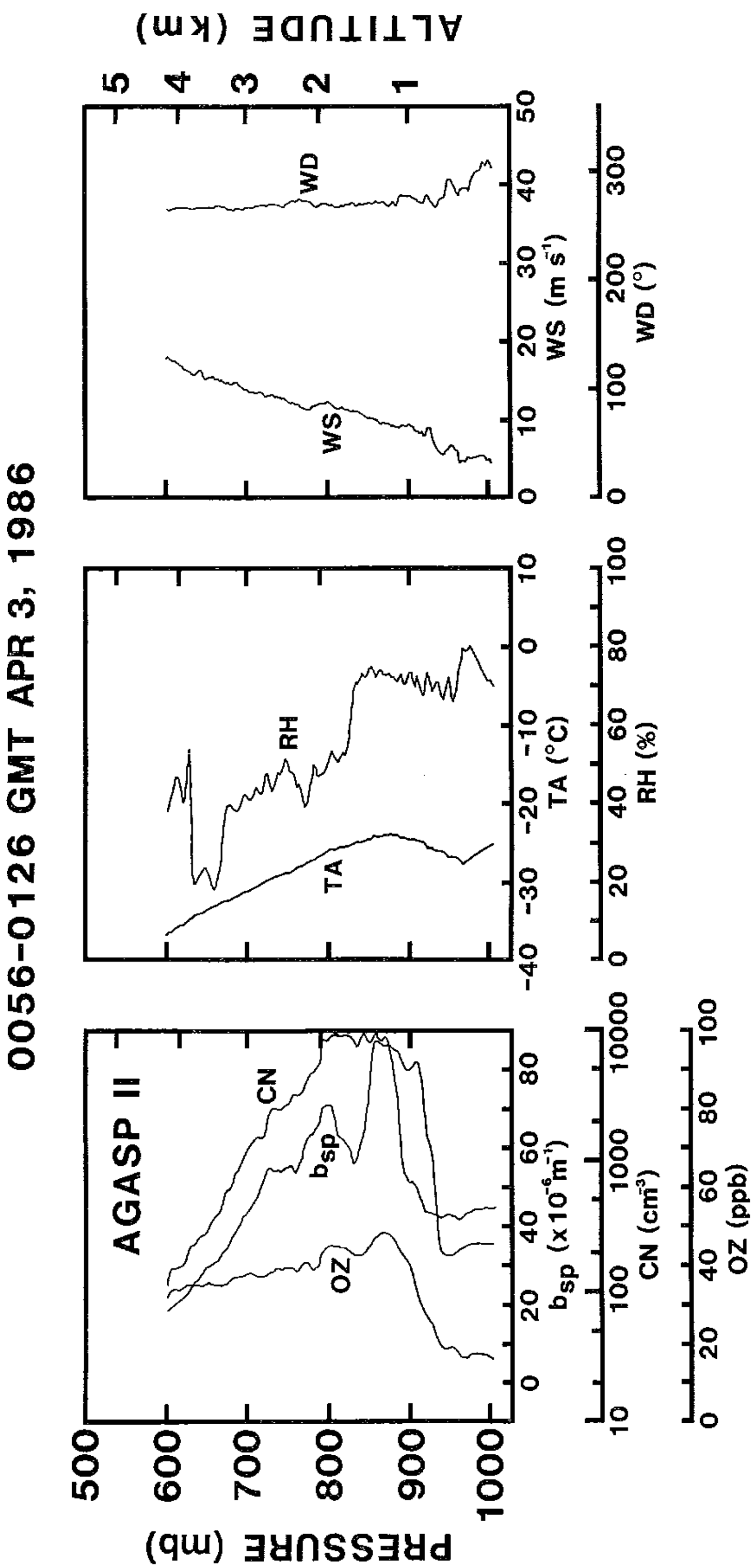


Figure 1.7--Vertical profiles of ozone (OZ), b_{sp}, CN concentration, ambient temperature (TA), relative humidity (RH), wind speed (WS), and wind direction (WD) through the major haze layer, April 2-3, 1986.

the layer of warmer air between 940 and 830 mb. Wind direction throughout the profile was steady from 270°-280°, increasing in speed from 4 m s^{-1} near the surface to 15 m s^{-1} at 600 mb.

This haze zone had been penetrated earlier at 72.28°N, 158.27°W, 2332 GMT, 794 mb, as shown in fig. 1.8. After flying level for 10 min in the haze, the aircraft reversed track from 188° to 22° and flew out of the side of the haze zone at a point 30 km from the entry point. In fig. 1.8, an abrupt increase in CN concentration to 70,000 cm^{-3} occurred at the haze boundary coincident with a sharp increase in RH from 50% to 75%. Aerosol b_{sp} increased from 35 × 10^{-6} m^{-1} at the edge to 60 × 10^{-6} m^{-1} near where the aircraft reversed direction. The penetrations shown in figs. 1.7 and 1.8 were separated by 2.5 h; the data shown in fig. 1.7 were collected 90 km upwind of the data exhibited in fig. 1.8. At a haze flow rate of 10 m s^{-1}, these two penetrations occurred about 190 km apart with reference to the flowing haze stream. By comparing figs. 1.7 and 1.8, we can observe that b_{sp} at the same level (794 mb) and 36 km in from the edge of the haze at the turning point (thought to be about equivalent to the point where the profile shown in fig. 1.7 was undertaken) were both in the (55-60) × 10^{-6} m^{-1} range. CN concentrations were higher in the side penetration (*16,000 cm^{-3}) compared with the profile (*10,000 cm^{-3}), but were in agreement 4 min later (14 km ground distance). Ozone was 39 ppb at both locations. These data suggest that the haze maintained fairly persistent qualities over large distances (times) along its axis on this day.

Aerosol b_{sp} and CN data from a series of north-south flight legs perpendicular to the haze transport zone are shown in fig. 1.9. From this figure it may be observed that the peak b_{sp} value of 60 × 10^{-6} m^{-1} at 800 mb, 72°N, corresponds to the region of the first observation of the major haze layer as reported in Flight Log 201, April 2, 1986, 2057 GMT (Sec. 1.2). Thirty millibars below that point, a minimum b_{sp} value of 30 × 10^{-6} m^{-1} was recorded. Thirty kilometers to the south, b_{sp} values >60 × 10^{-6} m^{-1} were again observed. Aerosol b_{sp} values were lower above 700 mb and below the Arctic inversion at 900 mb. Background b_{sp} levels of <5 × 10^{-6} m^{-1} were measured in the high troposphere.

The full extent of the spatial variations in the aerosols may be seen in the comparison diagram of CN concentrations, shown in fig. 1.9 (right). Because of the nature of the CN variations, a logarithmic spacing was applied for the contour values for CN >200 cm^{-3}. At 794 mb, 72°N, CN concentrations exceeded 60,000 cm^{-3}, but because of the tight spacing of the contour, this is not shown. In the layer bounded by 800 and 900 mb, there is an undulation between maximum and minimum CN values. Between 750 and 600 mb there is a pronounced north to south gradient. Below the Arctic inversion, a decrease in the concentration of CN with height is apparent.

A comparison of figs 1.9 (left) and 1.9 (right) illustrates the general agreement between the b_{sp} and CN measurements in the regions of maximum aerosol concentrations. An example of this is the maximum at 790 mb and 72°N extending well along the temperature discontinuity to below 850 mb. Although the elevated CN counts at 72°N between 800 to 920 mb are not mirrored in the aerosol scattering measurements, the minimum in b_{sp} aligns with a relative minimum in CN concentrations between 850 and 930 mb at 71.4°N. Below the Arctic surface inversion,

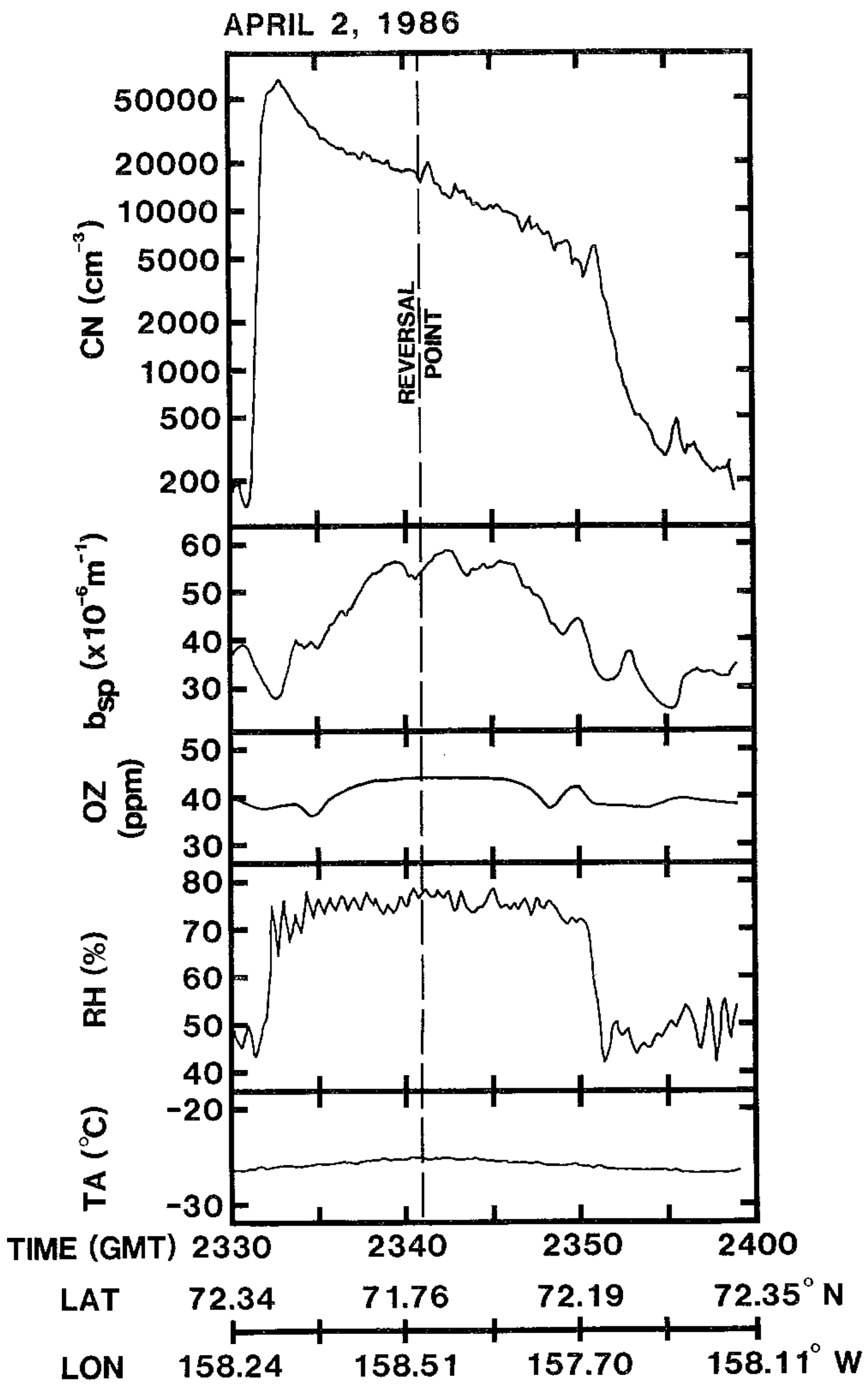


Figure 1.8--Time series (top to bottom) of CN concentration, b_{sp} , ozone (OZ), relative humidity, and temperature from 2330 to 2400 GMT when the aircraft encountered the major haze layer (794 mb, 1825 m altitude), April 2-3, 1986. At the reversal point, the aircraft changed direction from 188° to 22° and flew out of the side of the haze layer at 2351 GMT.

the b_{sp} values were relatively constant at (45-50) × 10^{-6} m^{-1}. The CN values show pronounced variability, especially in the 50 mb below the inversion, but near the surface a relatively steady CN value of about 200 cm^{-3} was measured.

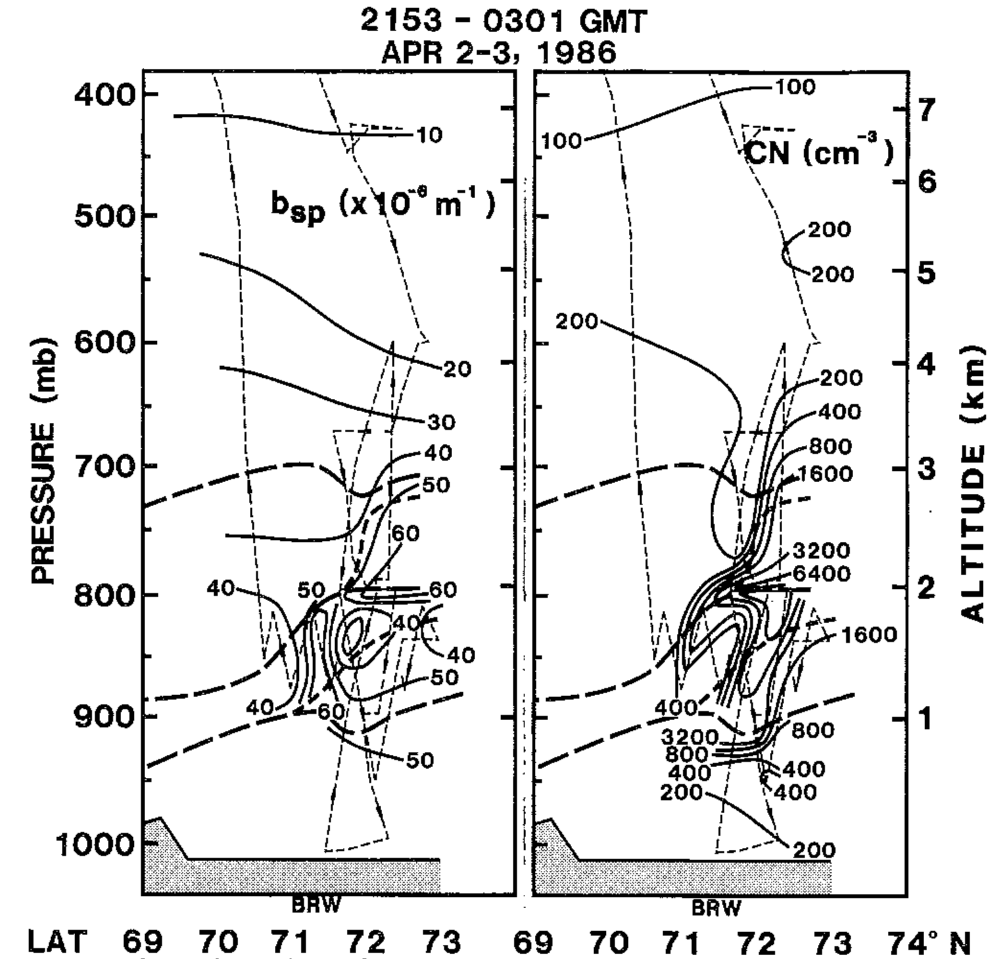


Figure 1.9--Cross sections of b_{sp} and CN concentration for the aircraft profiles north of Barrow (BRW), April 2-3, 1986. Stable layers are indicated by thick dashed lines and the flight track by a thin dashed line. CN concentrations are scaled logarithmically.

2. FLIGHT 202, APRIL 8, 1986

2.1 Flight Track

The original plan was to fly a great-circle route from Anchorage (ANC) to Alert, to conduct a haze study above the Atmospheric Environment Canada, Baseline Station at Alert, and then to land at Thule, Greenland. This flight plan was changed en route when weather conditions at Thule went below landing minimums. The alternate plan to conduct a sampling mission in the Beaufort Sea region was implemented. The aircraft flew a great circle route from ANC, passing west of Fairbanks (FAI), then over Mt. Michelson (2699 m) in the Brooks Range, to an area 300 km northeast of Barter Island (BTI), where the study was centered. The aircraft returned to ANC via FAI. The flight track is shown in fig. 2.1. A pre-dawn departure placed the aircraft in a position to view of Arctic basin at sunrise, providing an excellent view of the layered nature of the haze. Total flight time was 10 h, 41 min.

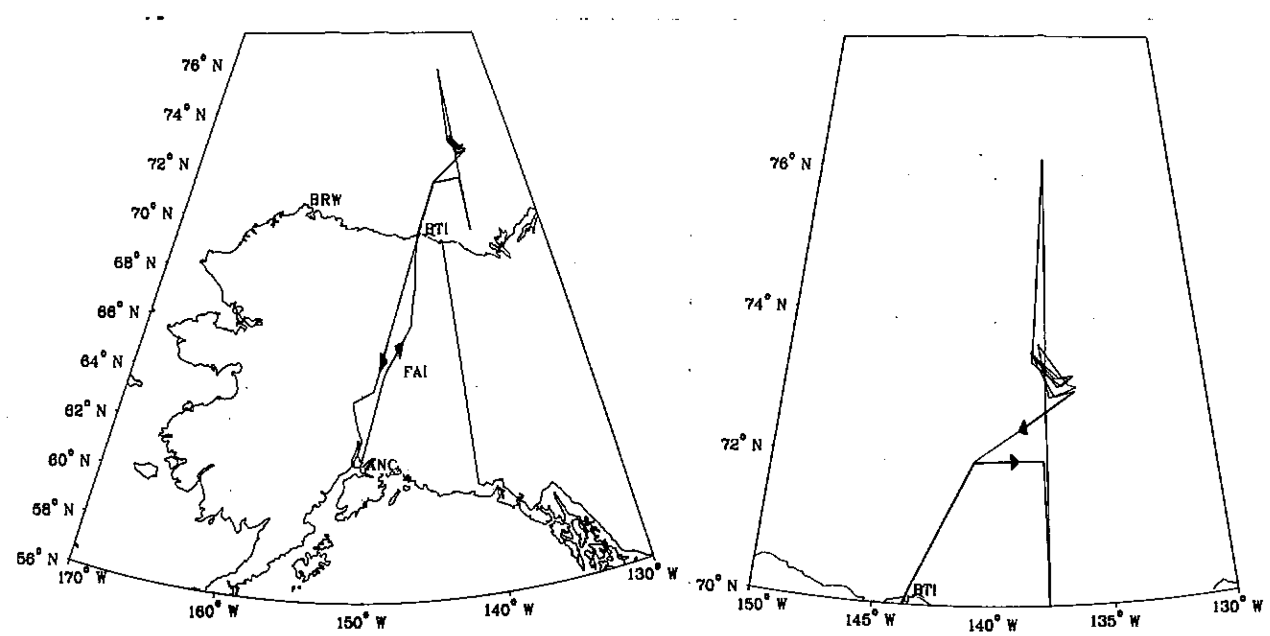


Figure 2.1--(Left) Horizontal projection of the aircraft flight track on a latitude-longitude grid, April 8, 1986. (Right) Detailed projection of the flight track north of the Alaskan coast. BRW is Barrow; BTI is Barter Island; FAI is Fairbanks; and ANC is Anchorage.

2.2 Flight Log

April 8, 1987 (GMT)

1220	Takeoff from Anchorage.
1250	Sighted haze bands on the horizon.
1309	Level at flight altitude 407 mb, 7048 m.

1340	Entered stratosphere, 66.6°N, 144.5°W, 411 mb, 6980 m; ozone increased from 35 to 70 ppb.
1352	Flying at tropopause, 67.5°N, 144.9°W, 397 mb, 7236 m; CN at 20-30 cm^{-3}.
1355	Sunrise.
1428	Pronounced haze layers in all directions around Barter Island. Haze against the Brooks Range. Haze top at 7.5 km. Returning to the troposphere, 70.1°N, 143.6°W, 382 mb.
1430	Because of high winds and blowing snow in Thule, it was decided to conduct measurements over the Beaufort sea and return to Anchorage.
1439	Flying along the tropopause, 70.8°N, 142.7°W, 356 mb, 7995 m. CN at 2-10 cm^{-3}; ozone, high 60's ppb.
1501	Begin descent from 353 mb, 8071 m.
1530	The sky at flight level is clear. There is a dense haze layer below us.
1538	Start first level radiation run, 70.0°N, 137.8°W, 707 mb, 2933 m. Ozone, 37 ppb; CN at 100 cm^{-3}.
1559	Start second level radiation run 823 mb, 1722 m. Light haze.
1617	Start third level radiation run at 917 mb, 829 m. CN > 7200 cm^{-3}.
1636	Start fourth level radiation run at 1027 mb.
1651	Open leads in the ice are visible.
1653	Haze is dense, 74.0°N, 137.4°W, 912 mb, 876 m, as we climb into the bottom of a layer. CN jumped from 200 to >1000 cm^{-3} in 15 m.
1656	Begin fifth level radiation run at 848 mb, 1484 m in middle of thick haze. CN counts are >2000 cm^{-3} with b_{sp} at 34×10^{-6} m^{-1}.
1729	Flying in and out of a thin haze layer, 812 mb, 1845 m.
1730	Begin sixth level radiation run at 811 mb, 836 m.
1745	Southbound trying to stay in this thin haze layer that is very well defined, but not very deep; 810 mb, 1844 m. CN at 150-220 cm^{-3}, $b_{sp} = 33 \times 10^{-6}$ m^{-1}.
1824	Begin seventh level radiation run at 1022 mb.

1845	Flew into the base of a well-defined haze layer while climbing. CN jumped from 200 to 3000 then up to 5000 cm^{-3}. Aerosol b_{sp} >75 × 10^{-6} m^{-1}.
1846	Begin eighth level radiation run at 912 mb, 879 m in thick haze.
1900	Haze visible, 912 mb, 879 m.
1923	Begin ninth level radiation run at 699 mb, 2986 m at top of haze layer.
1928	Counting from the bottom up, we can see one very distinct thin haze layer, a very large clear space, another dark haze layer, a very thin space, another dark haze layer, a thin space, and then another dark haze layer.
1958	Begin tenth level run at 429 mb, 6681 m before climbing.
2037	Entered stratosphere, 72.0°N, 140.8°W, 362 mb, 7885 m. Ozone climbed from 35 to 70 ppb.
2056	Increase in CN from <50 cm^{-3} up to 500 cm^{-3}.
2057	CN increases from 300 to >60,000 cm^{-3}. Ozone up to 98 ppb; b_{sp} at 4 × 10^{-6} m^{-1}.
2058	Level flight at 295 mb, 9184 m. CN >50,000 cm^{-3}; ozone >110 ppb.
2140	CN count returns to ambient levels; 295 mb, 9267 m. Ozone 165 ppb.
2232	In stratosphere at 450 mb, 6346 m, 62.68°N, 150.29°.
2239	Elevated ozone values at 79 ppb to 663 mb, 3442 m.
2301	Landed at Anchorage.

2.3 Synoptic Situation

This mission was flown between two synoptic map times. Unlike during flight 201, when there was relatively little change in pressure surfaces, there was considerable change during this flight period. The 500-mb map (fig. 2.2), which depicts the situation in the upper troposphere, indicates that the winds flowing over the Beaufort Sea were northerly in response to a low-pressure trough to the east. The trough connected a low-pressure center over the Canadian archipelago with a low in the gulf of Alaska east of ANC. To the west, a ridge of high pressure over the Bering Straits was building over the Alaskan north slope. The height of the 500-mb surface at BTI increased from 5190 to 5260 m during the time of the flight.

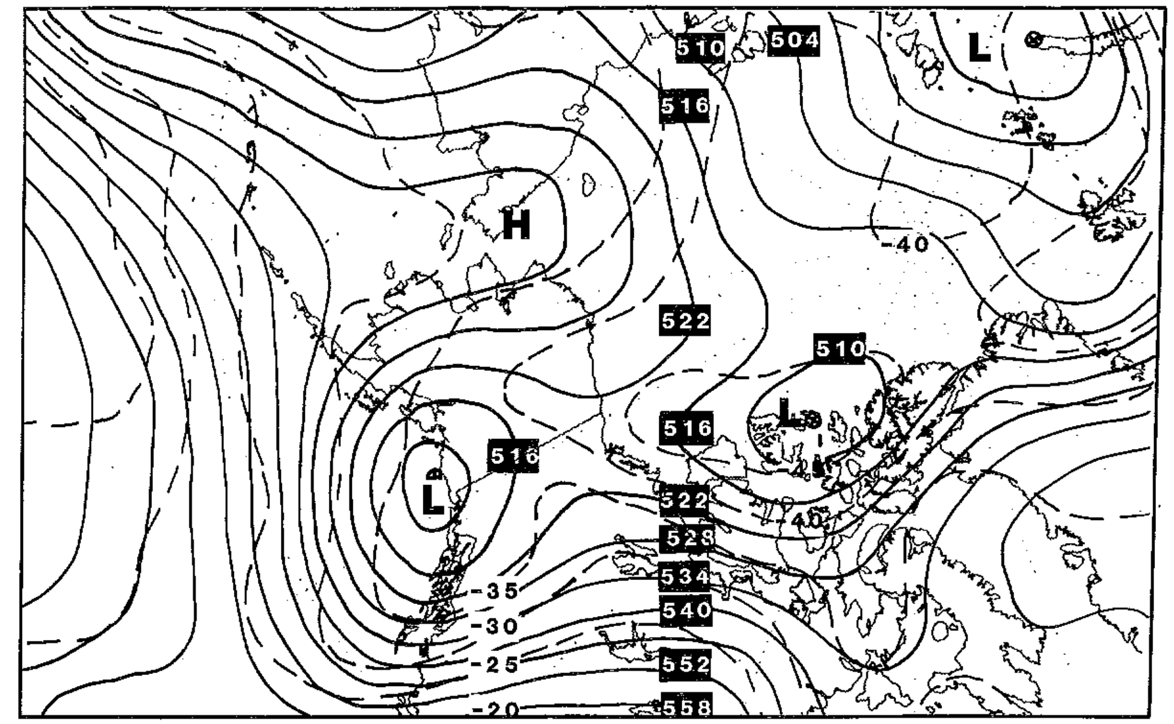


Figure 2.2--500-mb synoptic map for the western Arctic at 1200 GMT, April 8, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

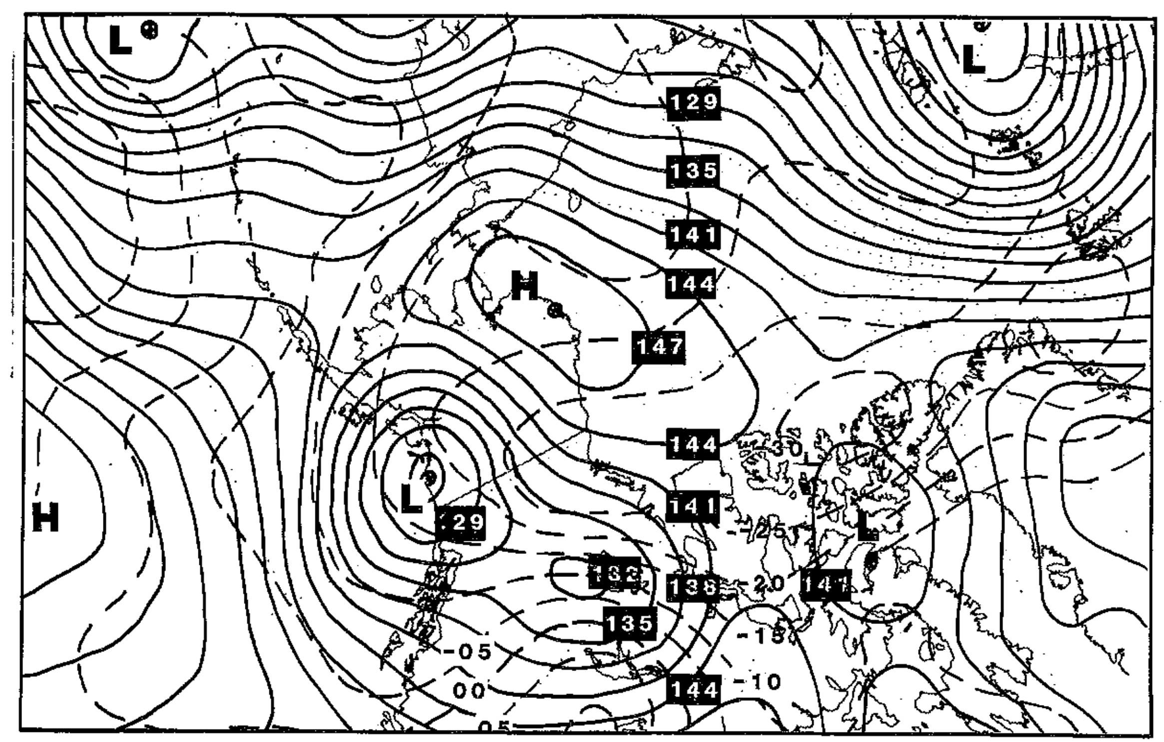


Figure 2.3--850-mb synoptic map for the western Arctic at 1200 GMT, April 8, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

At 850 mb (fig. 2.3), the Beaufort Sea was dominated by high pressure centered slightly to the west of Barrow (BRW), with a ridge extending to the east. By 0000 GMT, August 9, the ridge had moved into a position south of BRW. At the surface, the high-pressure cell was centered over BTI. The large tilt to the axis of this system was consistent with its relatively rapid eastward movement. To the south, the low-pressure system centered to the southeast of ANC was coupled with a secondary low over British Columbia.

2.4 Atmospheric Cross Sections

Because of rapid changes in meteorological conditions during the flight period, the meteorological data from the aircraft during the outbound portion of the flight lack agreement with data obtained on the return, 10 h later. This discrepancy is most apparent where the time span is greatest, south of 68°N. To maintain consistency with data from the dropwindsondes, most of which were released during the latter half of the mission, only the data from the return flight are used in the cross-section analysis over Alaska.

Unlike for the first mission, the winds for flight 202 were variable across the region (fig. 2.4). Above 500 mb, the flow was northerly in response to the trough to the east of BTI. Between 500 and 800 mb over the Arctic basin, the winds were northeasterly to the south of the high-pressure ridge and northwesterly to the north. Below 800 mb the flow was light and variable, but with a general southerly component. At lower altitudes, over the southern half of the flight track, the flow was northeasterly because of the gulf low. The shift in the winds from northeasterly to northwesterly between soundings 141.9 and 140.6 in the layer between 500 and 800 mb indicates the center of the ridge at this location (71.8°N, 141.2°W).

Over the Arctic Ocean there were two temperature discontinuities of significance, as shown in fig. 2.4: (1) the top of the Arctic inversion at 900 mb; and (2) the demarcations between the moist and dry layers in the 750-800 mb level. Thus, the top of the Arctic boundary layer was not a single well-defined level but rather an isentropic layer generally bounded by the 900- and 950-mb pressure levels. This zone also separated a moist surface layer to the south from drier air in the 950-900 mb region. Between 800 and 850 mb, north of 73°N, higher levels of water vapor mixing ratio were observed, as shown in fig. 2.5. Above 700 mb, the mixing ratio decreased to mid-Arctic tropospheric levels, consistent with descending air in a high-pressure region.

The flight north grazed the stratosphere (indicated by the thick dashed line in the 400-mb region in fig. 2.4) at 66.5°N and again at 70.5°N. Note that on the outbound flight from ANC, ozone values, (fig. 2.6) were typically between 40 and 50 ppb until the aircraft reached 66.5°N, whereupon they increased to 80 ppb. The return flight was in the stratosphere from 72°N to well into the descent over ANC at 61°N. Peak ozone concentrations of 180 ppb were observed at 63°N. In the period between the outbound and return flights, it appears that stratospheric air was descending into the northwest quadrant of the low-pressure system east of ANC, with the result that ozone concentration at 500 mb increased 45 ppb in the intervening 10-h period.

Over the ice in the Arctic Basin, ozone concentrations decreased by a factor of 4 (40 to 10 ppb) between 900 and 1000 mb, and ozone concentrations measured during the level flight legs at 1027 and 1022 mb (72°-74°N) were close to zero.

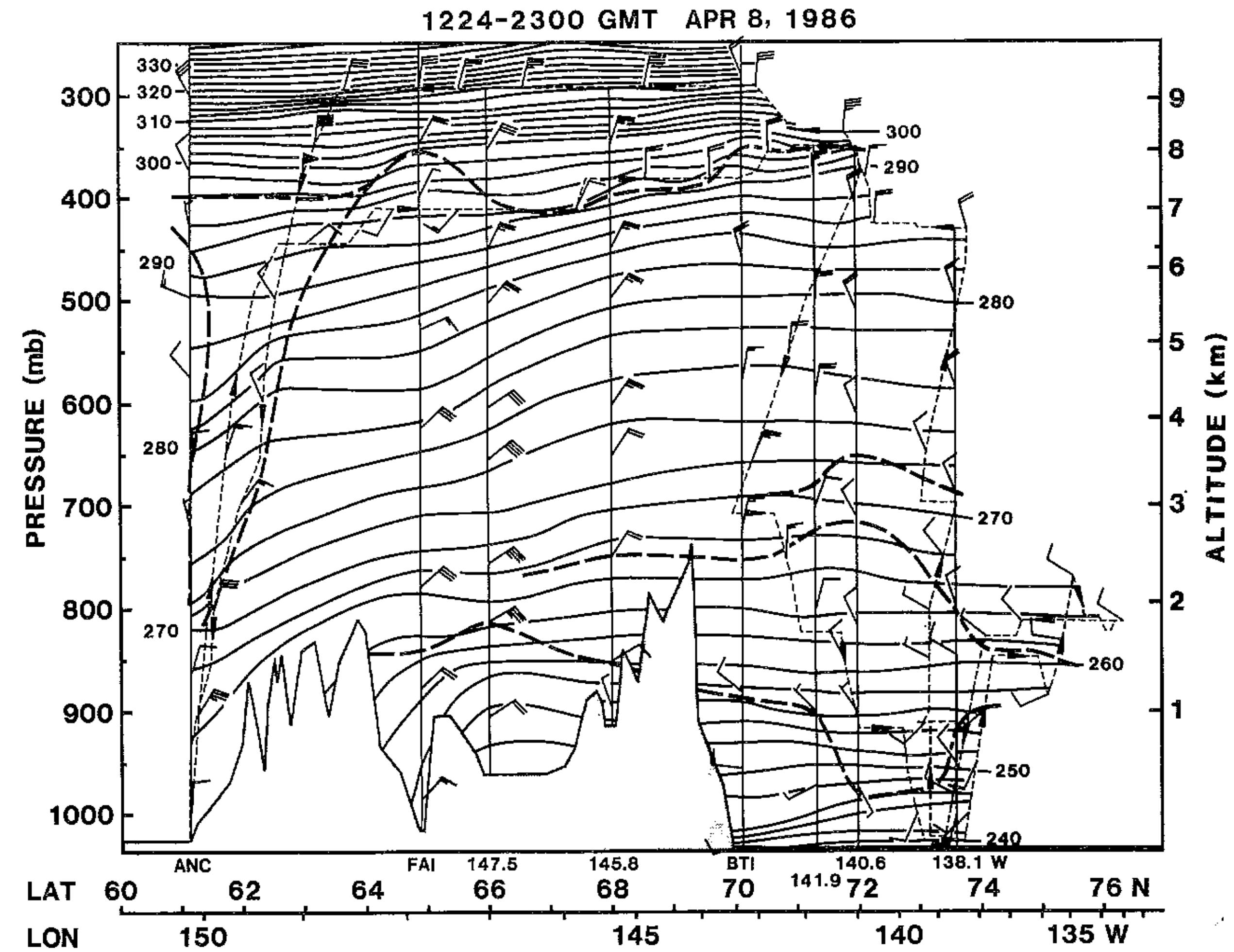


Figure 2.4--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Anchorage and the ice pack north of Barter Island, April 8, 1986. The tropopause, stable layers, and surface inversion are indicated by thick dashed lines, and the aircraft flight track by thin dashed lines. Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. ANC is Anchorage; FAI is Fairbanks; and BTI is Barter Island.

2.5 Haze Distribution

While flying north, the aircraft encountered two regions of elevated CN concentrations. The first was in the high troposphere at 64.8°N, 411 mb, and the second was in the low stratosphere at 69.0°N, 397 mb. There were no significant variations in b_{sp} in conjunction with these high CN regions. On the return flight, the aircraft encountered an extensive and very heavy CN layer in the stratosphere; concentrations reached 60,000 cm^{-3} at 70.4°N, at 300 mb. The extent and structure of this layer and its association with ozone concentrations >100 ppb suggest that the aerosol was possibly from Mt. Augustine in southwest Alaska, which erupted between March 27 and April 3, 1986. The high CN concentrations were not matched by higher-than-normal b_{sp}, which remained around 5×10^{-6} m^{-1}. This indicates that the aerosol layer was either old enough to exhibit the removal of accumulation-mode and larger aerosols or possibly was the result of

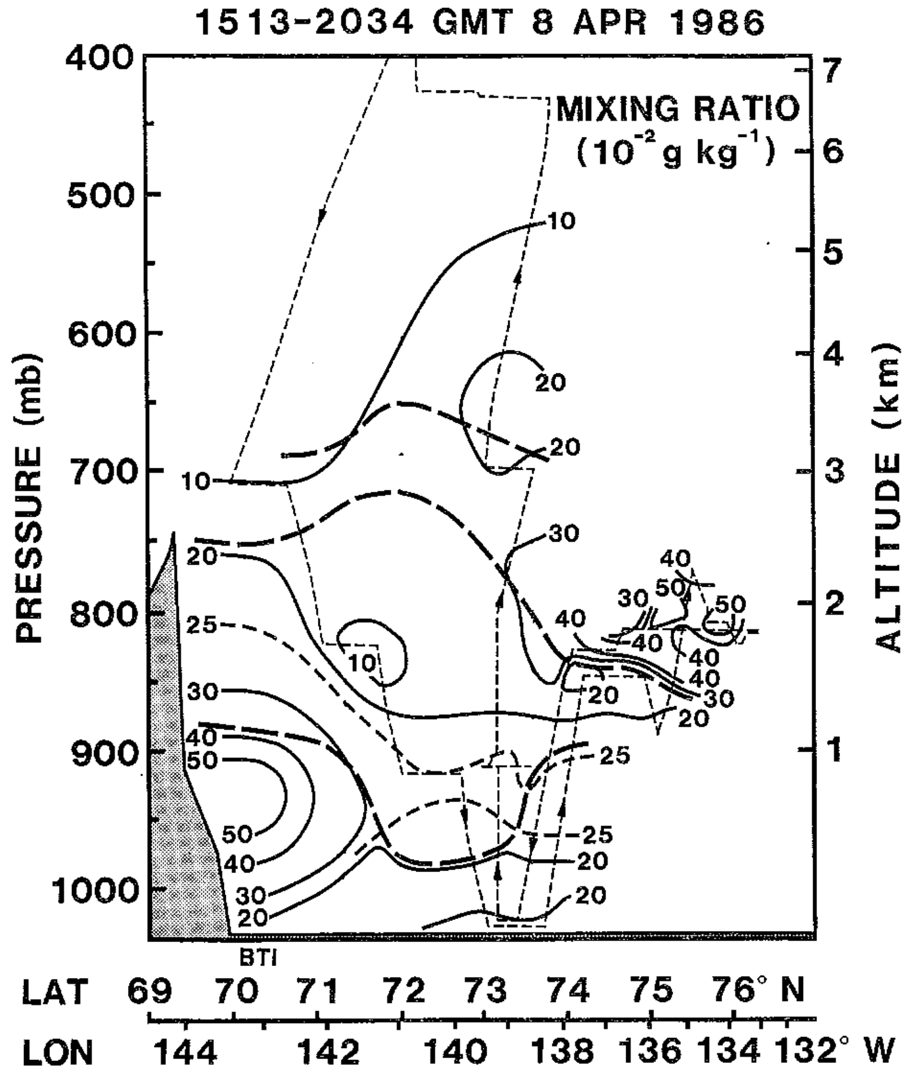


Figure 2.5--Latitude-altitude cross section of water vapor mixing ratio over the ice pack north of Barter Island, April 8, 1986. Stable layers are shown by thick long-dashed lines, and the aircraft flight track by a thin dashed line. Intermediate values are shown by thicker dashed lines.

recent gas-to-particle conversion of volcanic SO_2 to H_2SO_4 droplets, which would be detected as CN but not produce a large b_{sp} signal. H_2SO_4 droplet aerosols were observed in the Arctic stratosphere during AGASP-I (Shapiro et al., 1984).

Over the Arctic ice, a haze transport zone was encountered between 850 and 950 mb. This zone had characteristics similar to those observed on the previous flight. A number of passes and profiles were made through this transport zone (fig. 2.7). The cross section of b_{sp} in fig. 2.7 (left) shows a plume-like region of elevated values centered at 73.5°N extending from the surface to 850 mb. The b_{sp} peak of 60×10^{-6} m^{-1} at 912 mb is comparable with that observed in the large haze event of flight 201, although the area encompassed by the 60×10^{-6} m^{-1} isoline is much smaller than that observed on April 2. The maximum b_{sp} values were observed during the

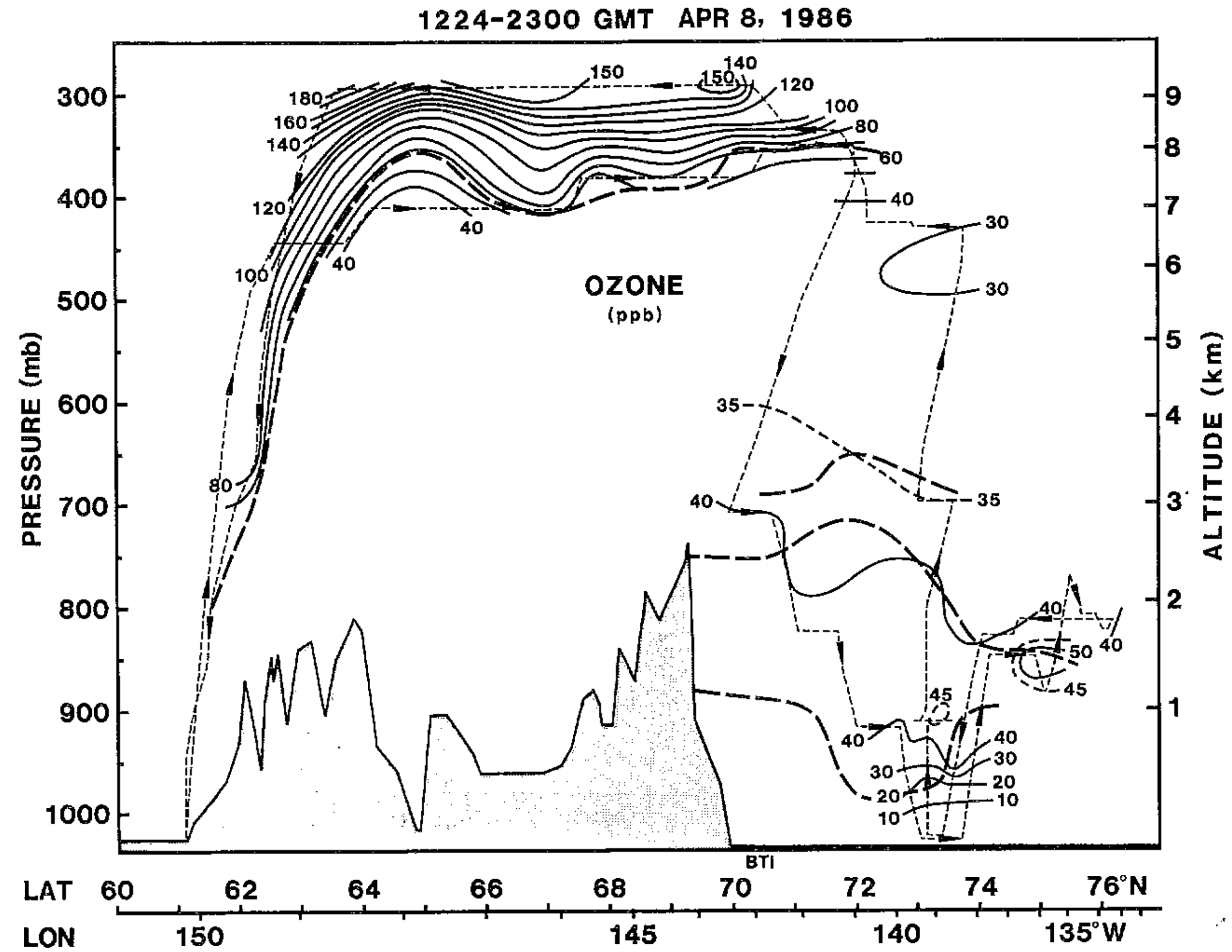


Figure 2.6--Latitude-altitude cross section of ozone, April 8, 1986. The tropopause, surface inversion, and stable layers are shown by thick dashed lines, and the aircraft flight track by a thin dashed line. BTI is Barter Island. Intermediate values are shown by thicker dashed lines.

last descent below the Arctic inversion and on the climb to begin the return flight. It would thus appear that the aerosol-laden pollution plume moved into the region from the northwest during the 2-h period separating the two aircraft soundings. Aerosol b_{sp} values above 850 mb decreased in a uniform fashion typical of the relatively clean midtroposphere in the Arctic. The relatively low altitude of the strong haze layer is consistent with subsiding air. High CN concentrations, >2000 cm^{-3}, were coincident with the region of maximum b_{sp}, as shown in fig. 2.7 (right). Although the b_{sp} and CN peaks at 912 mb, 73.1°N correspond well, there is a secondary peak in CN at 870 mb, 74°N that does not have correspondingly larger b_{sp} readings. Below the Arctic surface inversion the CN concentrations decreased rapidly to background levels of about 200 cm^{-3}. A third region of elevated CN values of 400 cm^{-3} was observed on the level flight leg at 430 mb between 73.0° and 72.4°N.

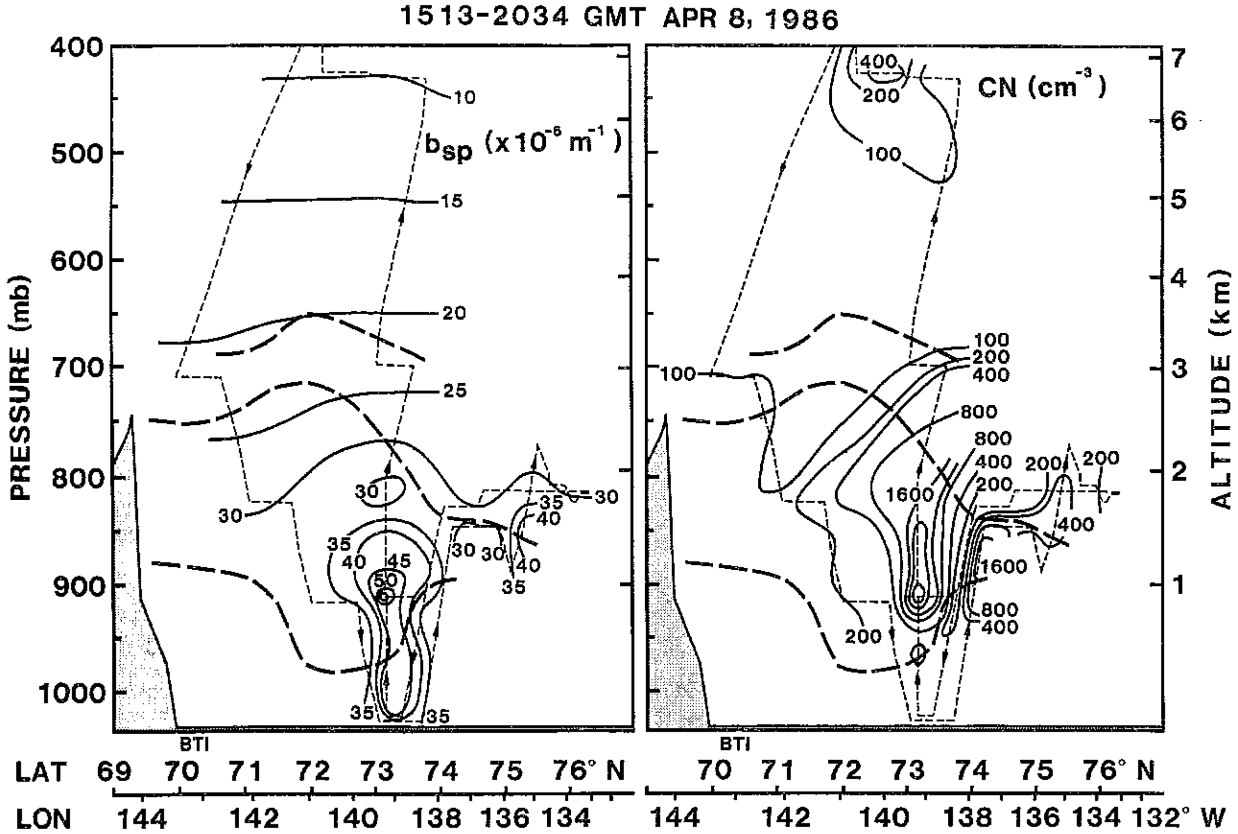


Figure 2.7--Cross sections of b_{sp} and CN concentration for the aircraft profiles over the ice pack north of Barter Island (BTI), April 8, 1986. Stable layers are indicated by thick dashed lines and the flight track by a thin dashed line. CN concentrations are scaled logarithmically. A maximum in aerosol concentration occurs just above the surface temperature inversion.

3. FLIGHT 203, APRIL 9-10, 1986

3.1 Flight Track

The flight track from Anchorage (ANC) to Barrow (BRW) shown in fig. 3.1 was similar to that flown in mission 201 (fig. 1.1). Because of a large number of open leads in the ice pack north of BRW, the "radiation" profile was conducted to the southeast of BRW over the tundra. There, snow cover provided a more uniform background for the radiation measurements, and by flying upwind (southeasterly winds below 800 mb) of BRW we avoided measuring pollution from the town itself. Following a low descent over the Dewline (DEW) station runway, about 1 km west of the GMCC station, the return flight went by way of Prudhoe Bay (PUO) to monitor the pollution from the oil-producing complex, and by Fairbanks (FAI) to tie aircraft measurements to the University of Alaska Poker Flat Observatory. A measurement profile and low pass were conducted at each of the latter locations. Total flight time was 9 h, and 44 min.

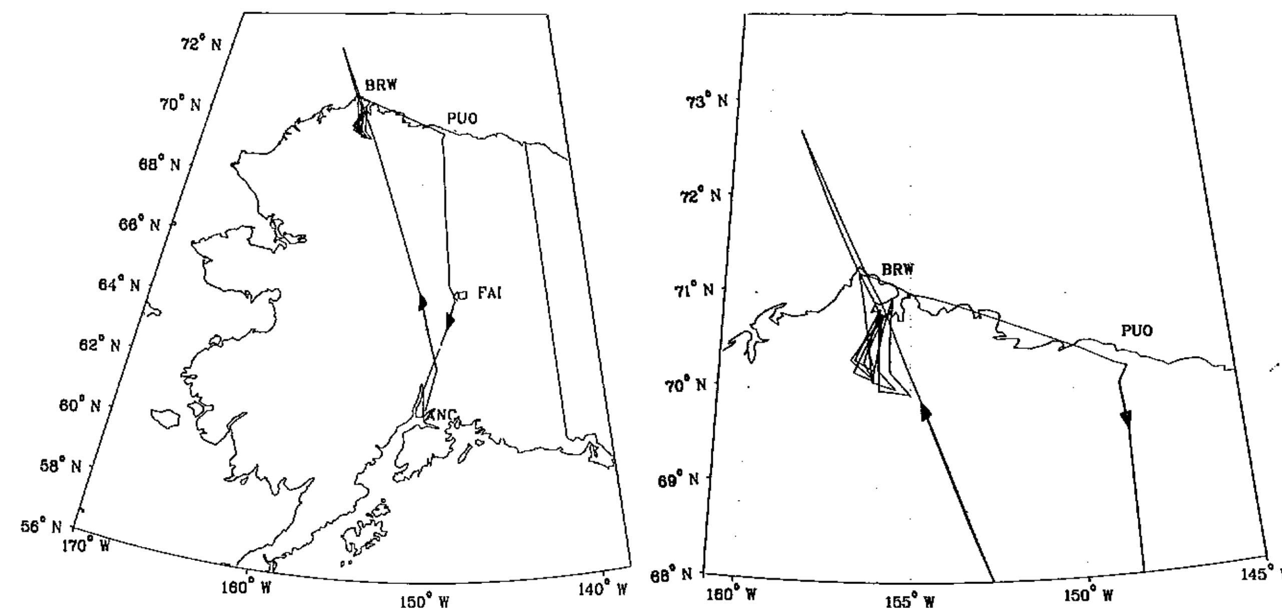


Figure 3.1--(Left) Horizontal projection of the aircraft flight track on a latitude-longitude grid, April 9-10, 1986. (Right) Detailed projection of the flight track near Barrow (BRW); PUO is Prudoe Bay; FAI is Fairbanks.

3.2 Flight Log

April 9, 1987 (GMT)

1910	Take off from Anchorage.
1936	A jump in ozone concentration at 1933 GMT indicates passage into the stratosphere, 62.8°N, 149.2°W, 437 mb, 6552 m.
1948	According to the ozone now at 74 ppb, we just went higher into the stratosphere. The stratosphere is devoid of CN at this point, 63.7°N, 149.7°W, 393 mb, 7311 m.

2007 As we climbed, we saw a very sharp, well-defined haze band below us along the tropopause.

2008 The haze band has a narrow layer of clear air below it and a more diffuse layer above, which is possibly the low-level aerosol layer being measured at this time.

2033 Level at 66.6°N, 151.4°W, 347 mb, 7253 m.

2050 As we cross the Brooks Range we can see a visible haze layer below us. The CN counts are rising. The impression is that there is a haze layer high in the troposphere or haze throughout the troposphere.

2109 Between us and the surface the haze appears to be visually stronger. This suggests that the haze over Anchorage was a separate event from the haze being observed north of the Brooks Range. From the top down, we can see one distinct layer, a diffuse layer, a much thicker layer, and a clean area, and then a very diffuse layer nearer the surface.

2124 As we go farther north the upper level haze layers have almost completely disappeared and we seem to be entering an area of general light and diffused haze beneath us.

2148 We are in cirrus clouds. The ocean is very broken up off Barrow so we are doing a 180 to conduct our solar radiation profiles over the north slope tundra.

2157 Turned toward the east, now heading south-southeast 72.8°N, 158.7°W, 400 mb, 7195 m.

2202 The ice is broken up quite badly here. We can see our contrail just above us and its shadow is also visible on the ice.

2205 We are encountering ice crystals in this area, and the CN counts have dropped off dramatically from some 100's to <10 cm^{-3}.

2227 Large increase in CN counts, which could possibly be the remnants of our contrail from the north-bound leg.

2234 The peak in the CN reported earlier contains a large concentration of black carbon.

2241 Encountering a small CN peak, which may again be part of the aircraft plume.

2242 Begin descent over Barrow, 70.0°N, 154.9°W, 417 mb, 6890 m.

2259 Begin 20-min level run, 71.0°N, 155.7°W, 719 mb, 2782 m.

2312 Our contrails are observed to be drifting to the east.

2326 The overall impression is that there is very little visible haze and very light background conditions at this time from 812 to 417 mb.

2328 Begin 24-min level run, 70.5°N, 156.1°W, 836 mb, 1587 m.

2355 Sharp, well-defined haze layer with a top in the region of 880 mb, 1155 m.

2359 Haze thinning out at 930 mb, 716 m.

2360 Begin 25-min level run, 70.5°N, 156.4°W, 931 mb.

April 10, 1986 (GMT)

0040 Begin 17-min level run, 70.7°N, 156.0°W, 1023 mb.

0119 Low pass over the Dewline Station runway, north of the Barrow GMCC station. Good intercalibration with GMCC station in southeasterly flow.

0125 Climbing to 930 mb, 713 m for flight to Prudhoe Bay just at base of haze layer.

0142 Still at 930 mb; we can see haze out the window, suggesting we are in the lower level of the layer. CN climbed from 175 to 7300 cm^{-3} and b_{sp} from 50×10^{-6} to $>100 \times 10^{-6}$ m^{-1} in bottom of the layer.

0149 More haze; our CN counts went up an order of magnitude as we went up in altitude from 930 to 919 mb, a height change of 100 m.

0154 Flying along the coast in a south-southeasterly direction. We are climbing up along the bottom of a sloping haze layer, slipping up occasionally to determine its base altitude.

0205 Flying in a southeasterly direction now over the ARCO fields at Prudhoe Bay. Eight to ten producing wells are in view; some are flaring. There does not seem to be any signature from the field at 1 km altitude.

0217 Descending into the boundary layer at Dead Horse airport to measure the pollution at this level.

0218 Low pass by the Dead Horse airport.

0219 Begin a complete circle around Prudhoe Bay, counterclockwise, at a height of about 150 m.

0225 We found no evidence of any pollution coming from the Prudhoe Bay Complex. The haze layer measured over Barrow extended upwind of Prudhoe Bay.

0227 Depart the Prudhoe Bay area for Fairbanks for a descent near the Poker Flat Observatory. Elevated b_{sp} values were observed at 650 mb on this southerly climbing profile.

0311 Begin descent to Fairbanks, 66.1°N, 148.3°W, 347 mb, 8167 m.

0401 Low pass by Fairbanks airport, 64.8°N, 147.8°W below level of Poker Flat Observatory.

0402 Climb out to ferry altitude.

0409 A pronounced increase in the ozone concentration indicates the presence of stratospheric air, 64.5°N, 148.1°W, 510 mb, 5451 m.

0415 Ozone >100 ppb.

0431 Return to tropospheric air, 62.9°N, 149.73°W, 365 mb, 7825 m.

0438 Begin descent to Anchorage.

0454 Landed at Anchorage.

3.3 Synoptic Situation

Unlike for flight 202, 30 h earlier, the height changes of the isobaric surfaces over the Arctic Ocean were small during the period of flight 203. Throughout this discussion the period of focus begins at about 1900 GMT, April 9 and ends at 0500 GMT, April 10. The high-pressure ridge moving into the region during the previous flight was in place at this time, as observed in fig. 3.2. At 500 mb and above, the ridge had a major axis in a northeast-southwest direction passing directly over BRW. The height rise at 500 mb at BRW in the 12 h preceding the sampling time was only 30 m. The winds at 500 mb were west-southwesterly.

At lower levels, the high pressure was located over the Beaufort Sea to the east of BRW, as seen in fig. 3.3. Winds below 800 mb were southeasterly in response to this system. The BRW sounding at 0000 GMT, April 10, showed a very shallow, moist boundary layer, capped by a dry layer up to 800 mb, probably produced by subsiding air on the south side of the high pressure system. The shift to southwesterly winds above 700 mb is associated with an increase in moisture. At 500 mb, the air was almost saturated, as evidenced by persistent contrails from the WP-3D.

The National Weather Service observer reported scattered clouds from 1900 to 2200 GMT, and changed the observation to overcast clouds at 2300 GMT, April 9. The estimated height was 6 km. The observer at PUO reported clear skies for the same period. With the eastward movement and filling of the small low located to the south of ANC, the winds back from east to northeasterly during the flight period.

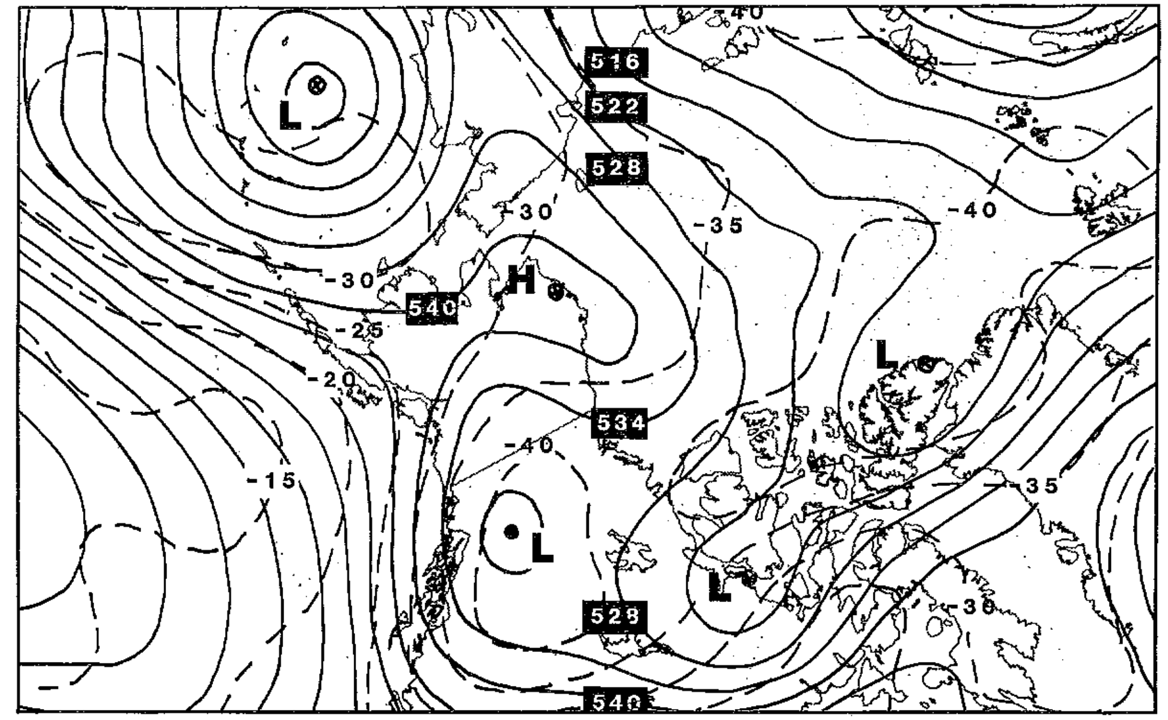


Figure 3.2--500-mb synoptic map for the western Arctic at 0000 GMT, April 10, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

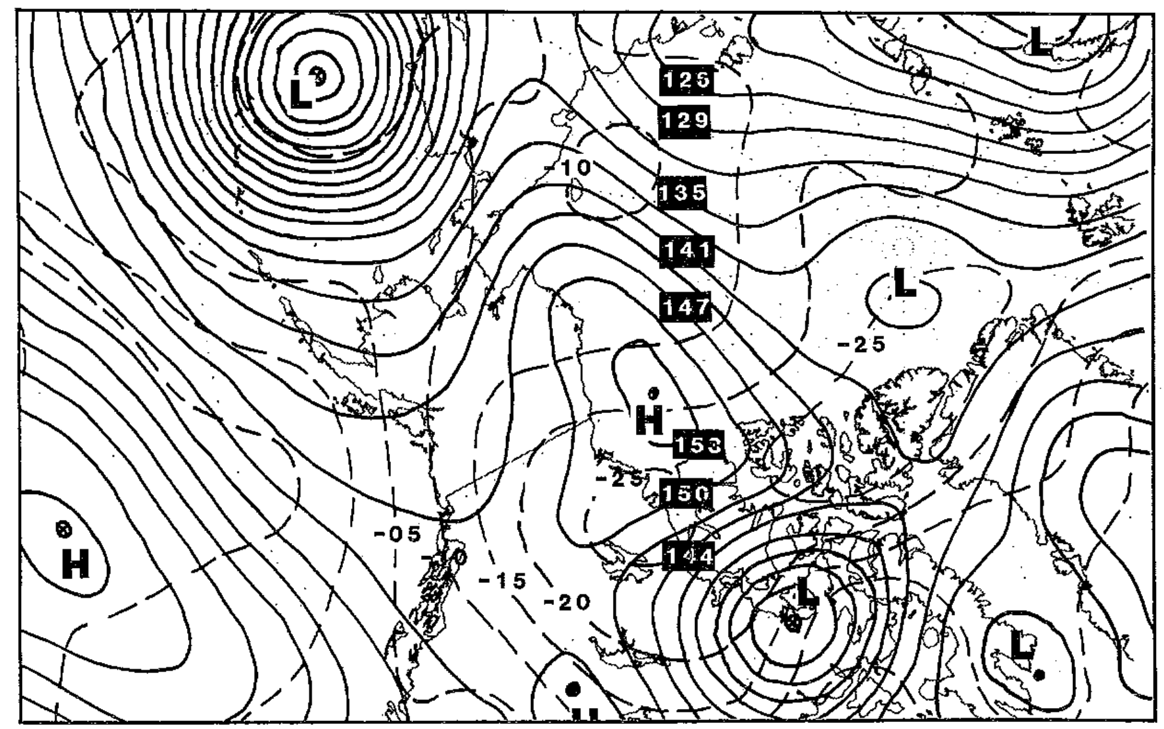


Figure 3.3--850-mb synoptic map for the western Arctic at 0000 GMT, April 10, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

3.4 Atmospheric Cross Sections

The cross-section analysis is somewhat complicated, because two separate routes were flown north of FAI and because the meteorology changed rapidly in the 9 h that separated the ascents and descents over ANC. For the southern half of the cross section shown in fig. 3.4, emphasis was given to the return

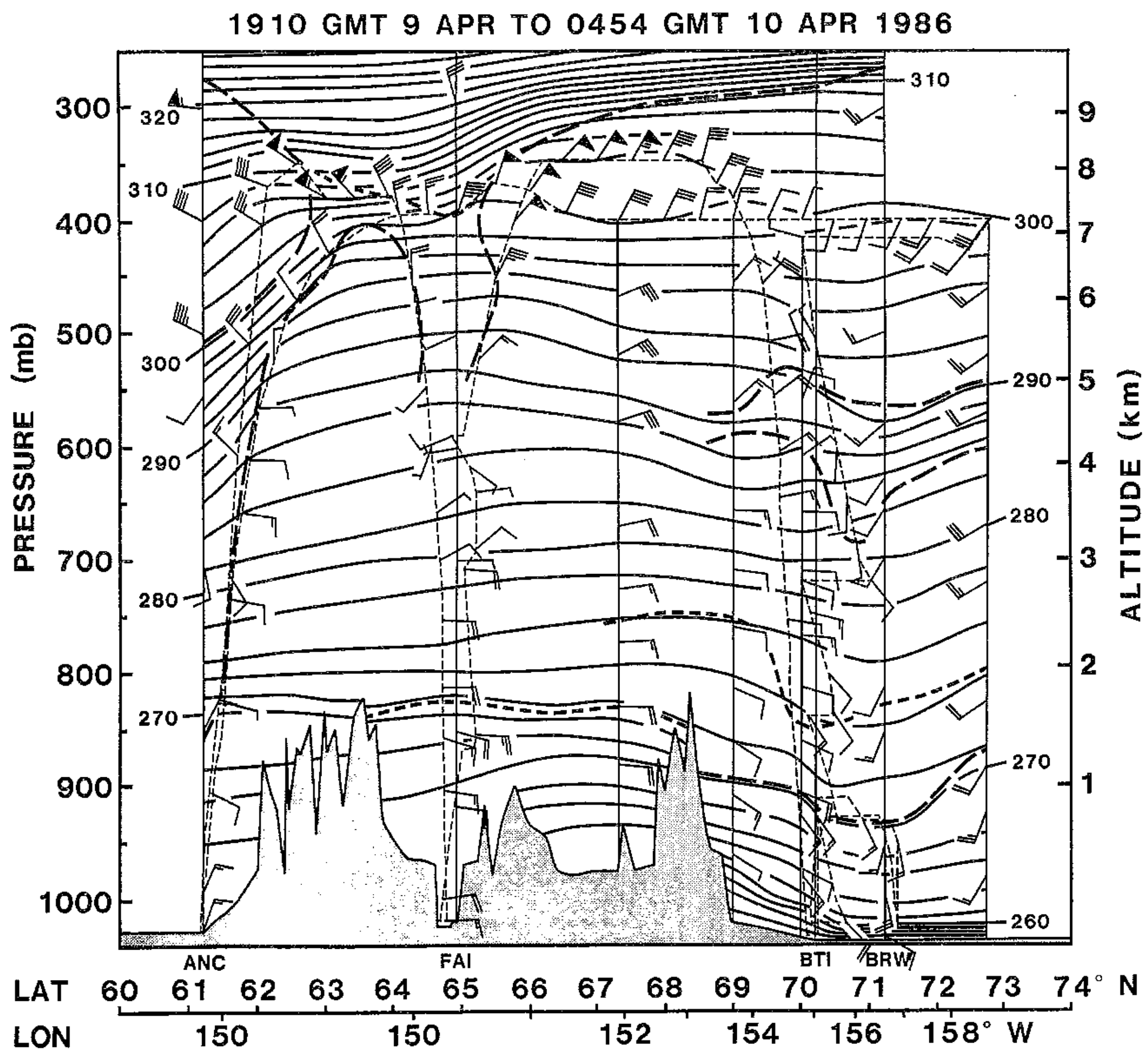


Figure 3.4--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Anchorage and Barrow, April 9-10, 1986. The tropopause and surface inversion are indicated by thick long-dashed lines, stable layers by thick short-dashed lines, and the aircraft flight track by thin dashed lines. Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. ANC is Anchorage; FAI is Fairbanks; and BRW is Barrow.

flight where the sounding at FAI and the descent into ANC best depict the troposphere-stratosphere interface. On the northern half, emphasis was given to the flight to and around BRW because most research time was spent in that section. The topography follows the ANC-FAI-BRW track.

The flight north followed the 400-mb surface except for a short excursion to 370 mb at 65°N to stay in the stratosphere. A sounding was made south of BRW with a number of intermediate level legs. During the sounding near BRW, the wind direction changed from northeasterly at 3 kilometers altitude to southeasterly near the surface. Winds were easterly at all levels over FAI.

Above 500 mb over Alaska, the winds gradually turned from west-northwesterly, over ANC to northwesterly over the Brooks Range. At this level a trough with an east-west orientation was progressing around the back side of the low centered over northern British Columbia (fig. 3.2). In conjunction with this trough the stratosphere extended down to the 400-mb level with high ozone levels to below 500 mb (fig. 3.5). On the basis of these elevated ozone concentrations, there appear to be extensive perturbations to the tropopause in this region. The remnants of an earlier frontal zone may have produced the structure observed aloft over ANC. The surface analysis for 0000 GMT, 10 April shows a frontal zone extending from the Gulf of Alaska into British Columbia and across central Canada.

North of the Brooks Range the tropopause was above 300 mb, as shown on the cross sectional analysis in fig. 3.4. The dropwindsondes released at 67.3° and 70.0°N both show the winds to be easterly in the troposphere below 500 mb in this region, whereas the dropwindsonde at 72.8°N shows that southwesterly flow persisted over the ice at all levels. The aircraft soundings and level flights made in the BRW area were within the center of the 850-mb ridge that lay over the Beaufort Sea. The general absence of a significant temperature gradient across Alaska north of 63°N may be observed in the uniform barotropic nature of the atmosphere (fig. 3.4). In the lowest levels over BRW, it appears that the surface layer had been compressed by subsidence aloft north of the Brooks Range. The top of the Arctic inversion was at about 940 mb. The top of the Arctic boundary layer at 1015 mb was marked by a sharp temperature gradient. This was also the top of the moist surface layer.

The analysis of moisture north of the Brooks Range (fig. 3.6) shows three distinct moist layers: one centered at 650 mb, one centered at 800 mb, and the surface layer. A dry zone was centered at 900 mb just above the surface inversion. The 650-mb moisture is consistent with ice crystal observations that were noted in the flight log (2205 GMT) and surface observation of scattered clouds, at 6 km. There is considerable variation in the mixing ratio concentration along any segment of the flight track. The values aloft were generally higher than in the preceding two flights. The surface layer was drier and shallower than that observed in the previous two flights.

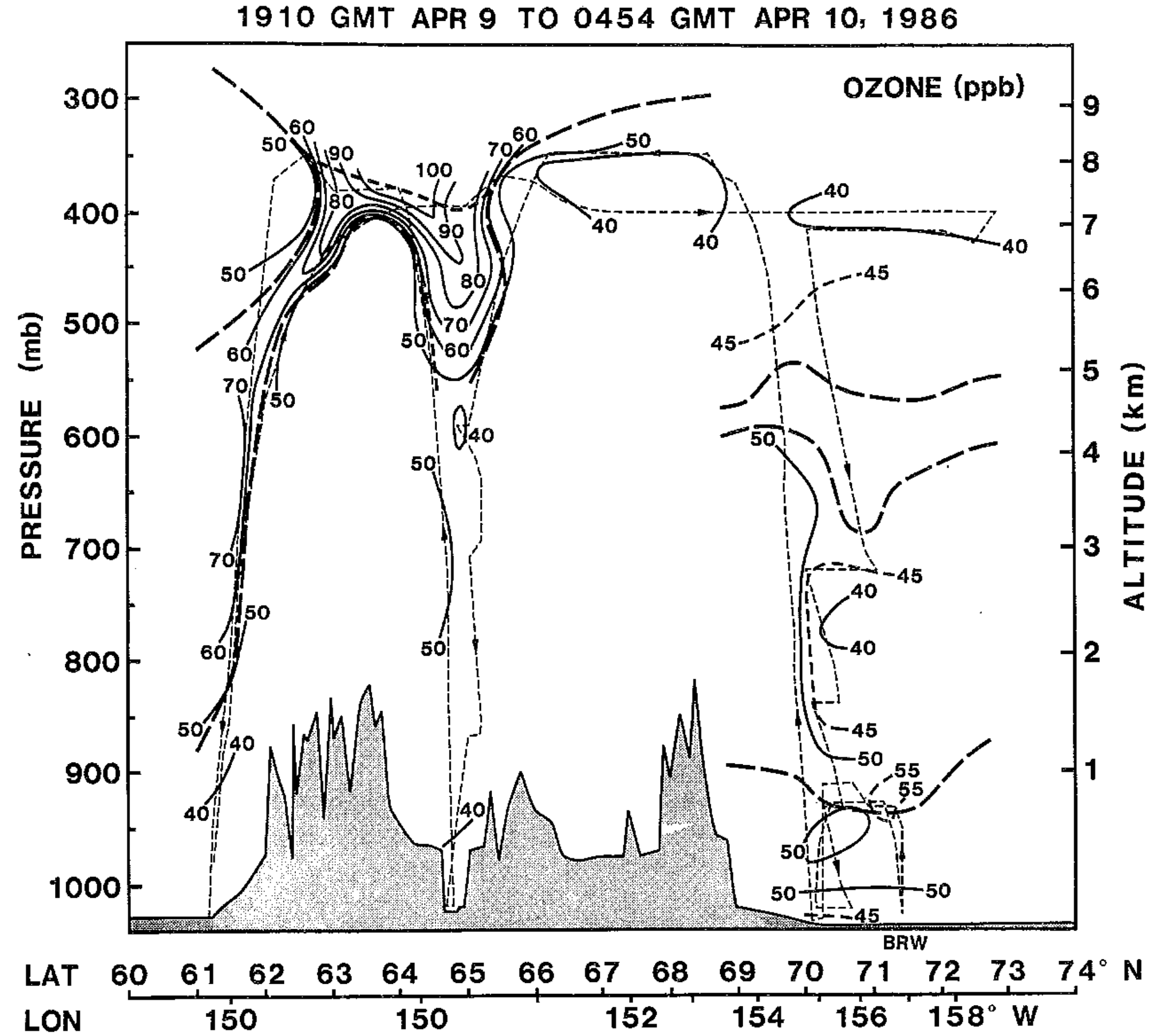


Figure 3.5--Latitude-altitude cross section of ozone along the flight track, April 9-10, 1986. The tropopause and stable layers are shown by the thick long-dashed lines. The aircraft flight track is shown by a thin dashed lines. Immediate values are shown by thick dashed lines.

3.5 Haze Distribution

The b_{sp} values shown in fig. 3.7 (left) exhibit a maximum of 70×10^{-6} m^{-1} at 920 mb, 71°N, corresponding to a peak in CN concentrations of >2000 cm^{-3} shown in fig. 3.7 (right). The tropospheric ozone maximum also occurred in this same region, as observed earlier in fig. 3.5. These maximum values in b_{sp}, CN, and ozone occurred just above the Arctic temperature inversion. The elevated aerosol concentrations correspond to the lowest water vapor mixing ratio values observed over BRW. Outside this single, well-defined southern edge of the haze zone at 950-900 mb, background values were observed in both b_{sp} and CN concentrations.

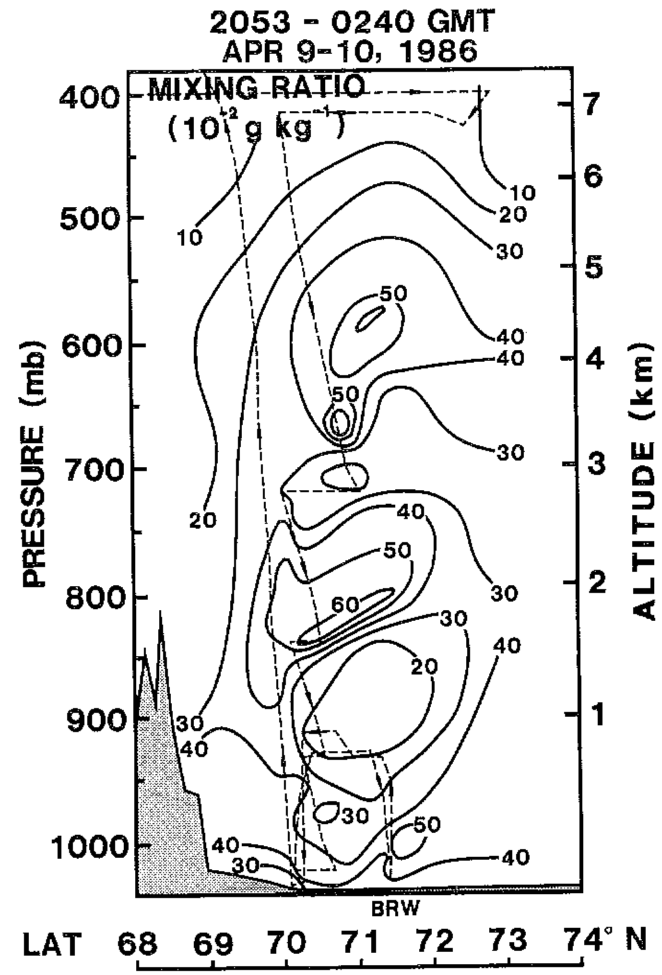


Figure 3.6--Latitude-altitude cross section of water vapor mixing ratio near Barrow (BRW), April 9-10, 1986. The flight track is shown by a thin dashed lines.

The region of high CN concentration at 420 mb is most likely WP-3D aircraft exhaust generated 47 min earlier on a 400-mb flight leg. An average settling velocity of 11 cm s^{-1} would have allowed the plume to reach this new level in time to be sampled on the lower return leg. On this day ozone was not depleted near the surface, probably because better vertical mixing occurred. Surface ozone measurements obtained at the BRW GMCC station for this period were consistent with the aircraft measurements.

3.6 Haze Profiles Over BRW and Prudhoe Bay

Haze profiles from 835 mb to the surface through the main haze layer off BRW are shown in fig. 3.8. The absence of a haze layer below 975 mb and the well-mixed ozone profile provided a unique opportunity to study the possible contribution of the Prudhoe Bay oil field complex to Arctic haze.

To do so, a flight was made from BRW to PUO within the cleaner air below the haze. Occasionally the aircraft ascended into the haze layer centered at 910-930 mb to give the measurements a reference level traceable back to the haze over BRW.

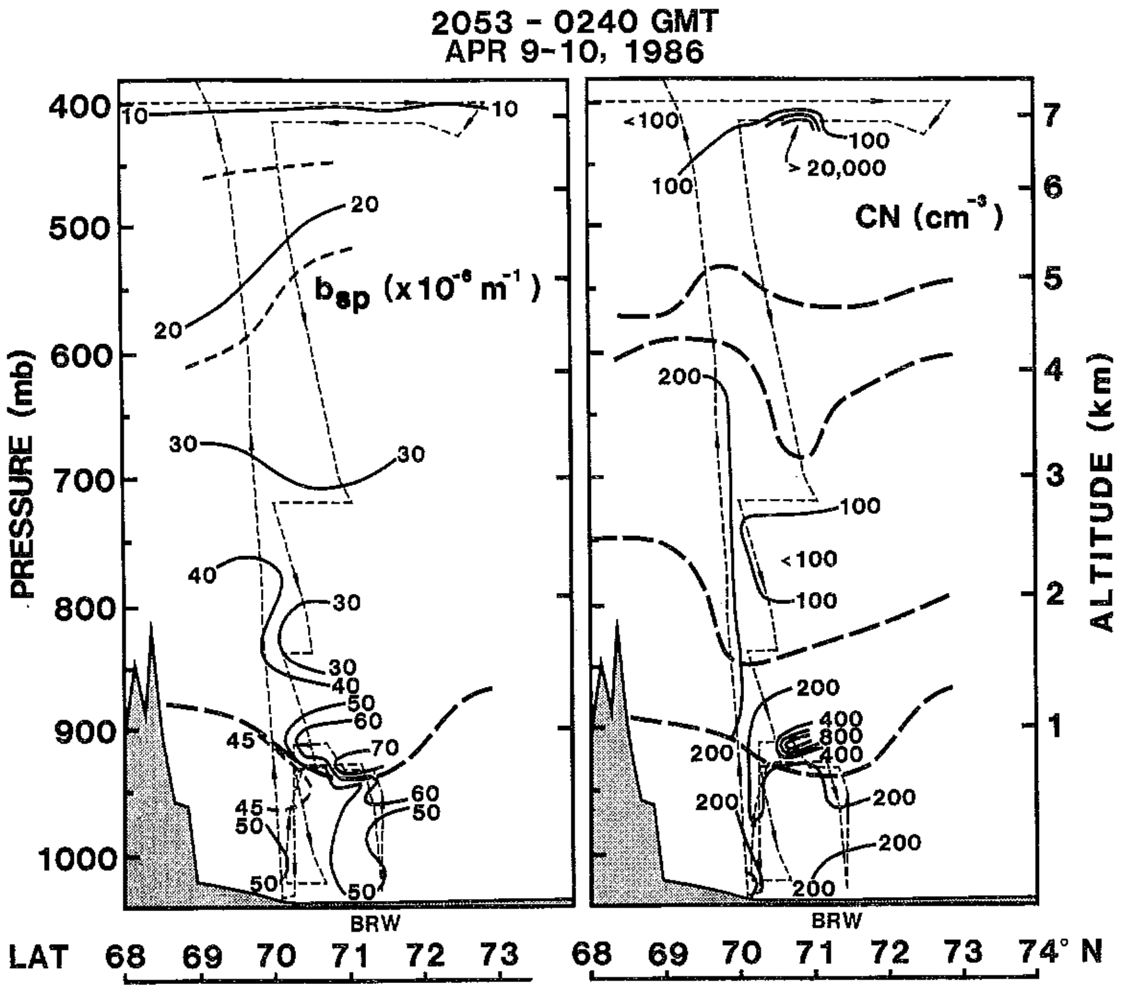


Figure 3.7--Cross sections of b_{sp} and CN concentration for aircraft profiles near Barrow (BRW), April 9-10, 1986. Stable layers are shown by thick long-dashed lines, and the flight track by a thin dashed line. A maximum in aerosol concentrations occurs just above the surface temperature inversion.

The aircraft descended over PUO, and conducted a touch-and-go maneuver at the Dead Horse Airport. The aircraft began the descent from just within the base of the haze layer, as shown in fig. 3.8. The dashed portion of the profile is the upper portion of the earlier profile over BRW.

After the pass at the airport, the aircraft flew a large circular pattern around the Prudhoe Bay and Kuparuk fields at 150-m altitude. The only strong aerosol or anthropogenic gas signature observed was measured at runway level from a 727 jet which landed in front of the NOAA WP-3D.

At this point, there is no evidence that the Prudhoe Bay-Kuparuk oil field activities were contributing in any way to the Arctic haze observed in the region on April 10, 1986. Subsequent checks confirm that the field was in regular production on April 10-11, 1986.

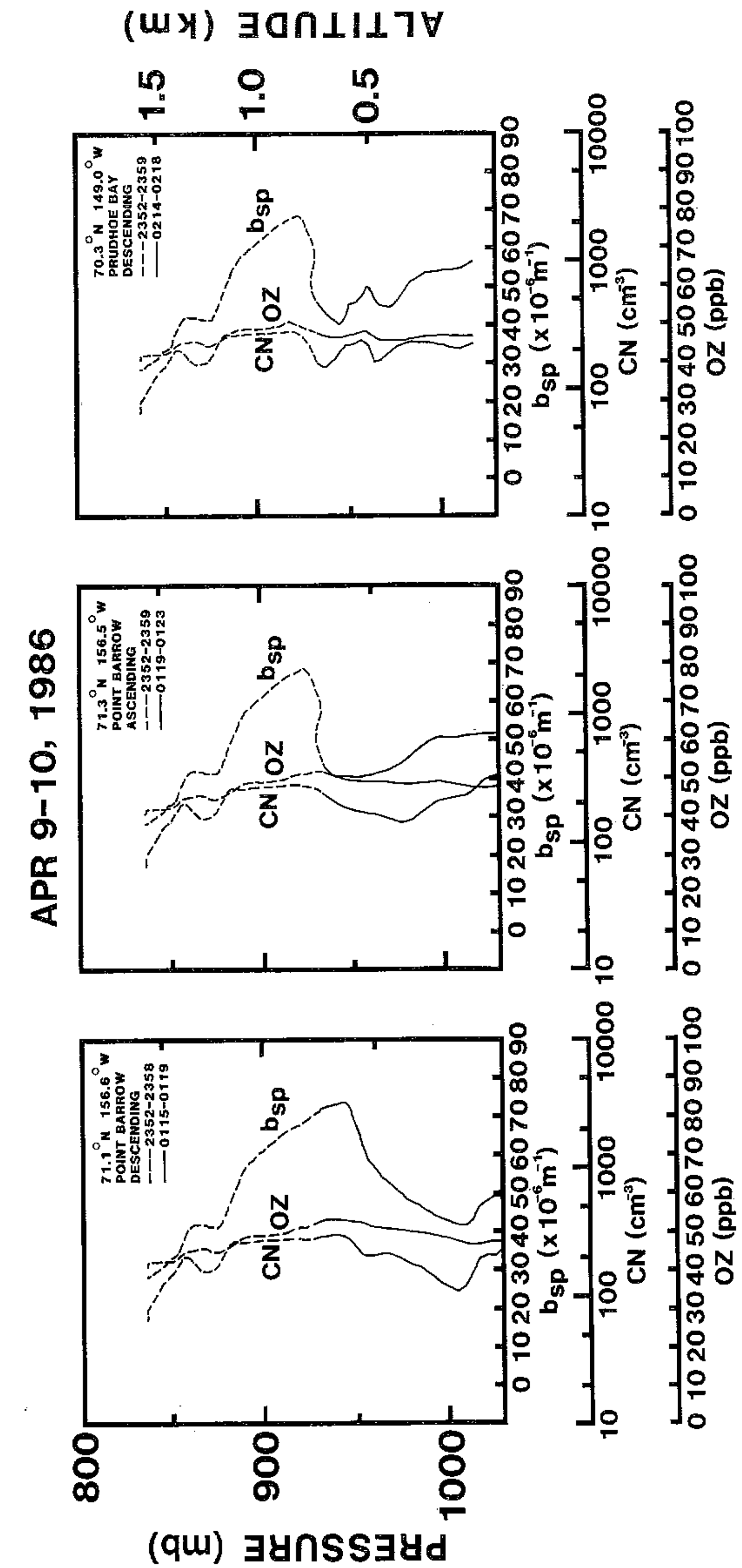


Figure 3.8--Vertical profiles in the lower troposphere of CN, ozone (OZ), and B_{sp} at Barrow and Prudhoe Bay, April 9-10, 1986. The portion of the profile above 925 mb was taken from a descending flight over Barrow, and represents the general haze situation above the surface inversion. The increase in b_{sp} between 900 and 950 mb indicates a layer of accumulation-mode aerosols just above the inversion. Prudhoe Bay parameters near the surface area are virtually the same as at Barrow, indicating Prudhoe Bay was not a source of Arctic haze.

4. FLIGHT 204, APRIL 13, 1986

4.1 Flight Track

The aircraft flew from Anchorage (ANC) to Alert (YLT), via Mould Bay (YMD), and then on to Thule (BGTL). The primary purpose of the flight was to measure haze and meteorology across the Arctic basin and to conduct a profile upwind of Alert in conjunction with the National Aeronautical Establishment Twin Otter and the University of Washington C-131. During the flight, the aircraft flew in and out of clean air just below the stratosphere and into the stratosphere between 68°-69°N and 81°-83°N on the track to YLT, and from 77°-79°N between YLT and BGTL. The horizontal projection of the flight track is shown in fig. 4.1. The total flight time was 9 h, 38 min.

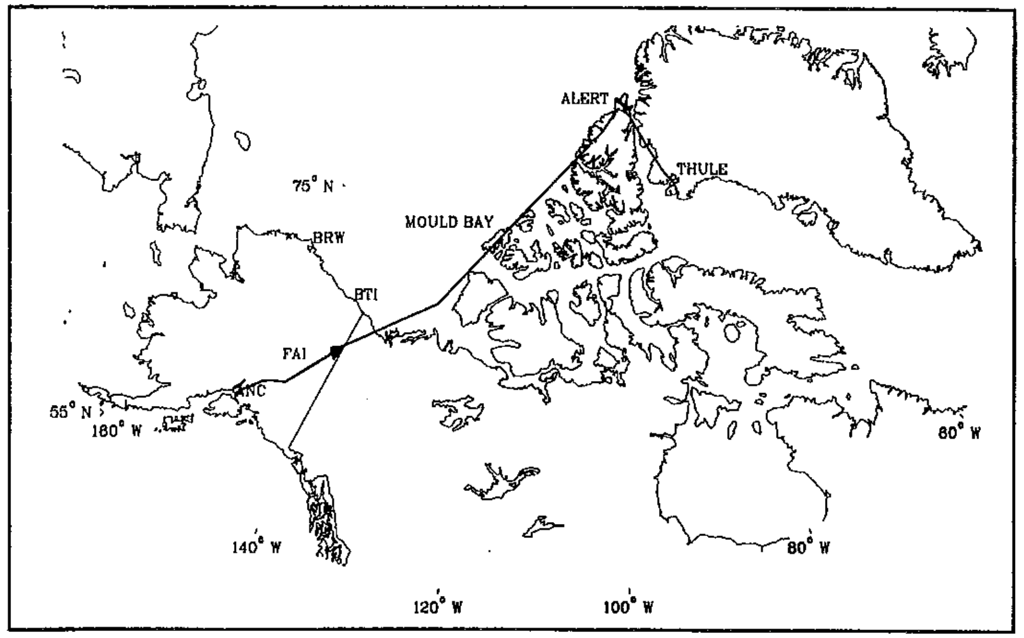


Figure 4.1--Horizontal projection of the aircraft flight track on a latitude-longitude grid between Anchorage, Alert, and Thule, April 13, 1986. BRW is Barrow; BTI is Barter Island; FAI is Fairbanks; ANC is Anchorage.

4.2 Flight Log

April 13, 1986 (GMT)

0916	Take off from Anchorage.
0916-0948	Climb to 407 mb, 7052 m; begin flight to Alert; nice tail wind.
1008	Patchy CN concentrations just under stratosphere.
1028	Spectacular aurora borealis display.

1042	Sunrise; wind shifting 180° through north, 66.4°N, 142.4°W.
1043-1050	Entering stratosphere; ozone increases to 100 ppb from 50 ppb. CN increases to >600 cm^{-3} from low 20's.
1051-1101	Rapid CN decrease; ozone increase to >100 ppb; altitude 380 mb, 6960 m.
1102-1115	CN peak to 1226 cm^{-3}, then gradual decrease to <100 cm^{-3}; ozone remains high, >100 ppb.
1115	Ozone begins to drop; CN decreases rapidly to 40 cm^{-3}; 379 mb, 7552 m, 68°N, 139°W.
1129	Out of stratosphere, ozone falling below 65 ppb; head wind 33 m s^{-1}, entering high-pressure area, 69.1°N, 137.4°W.
1152	Several layers of haze visible ahead of aircraft.
1209	North of Canadian coast; murky white haze visible from our altitude, passing through small haze layer; 382 mb, 7245 m, 71°N, 132°W.
1219	Strong head winds affecting ground speed.
1253	Very low CN; big haze layers below; flying in aerosol-free zone between top of troposphere and bottom of stratosphere, 73.7°N, 126.1°W.
1318	Middle of high-pressure system; headwinds sharply diminished, 75.4°N, 122.5°W.
1335	Thin cirrus or ice crystal clouds around us.
1348	Low-level cloud deck ahead and below.
1359-1408	Climb to 351 mb, 78.2°N, 113.7°W. CN <100 cm^{-3}; ozone at 45 ppb.
1422	Ozone increasing, entering bottom of stratosphere.
1447	Patchy CN; ozone 131 ppb; CN <5 cm^{-3}, 80.8°N, 98.5°W.
1518	Crossing Ellesmere Island; ozone still high; 3-4 bands of haze visible below us.
1547	Haze seems to follow edge of Ellesmere Island. South of the island, there is little haze. Area has same appearance as haze against Brooks Range in Alaska.
1611	Begin descent over Alert from 352 mb, 8066 m.
1630	Level at 725 mb, 2658 m for 17 min, 83.1°N, 60.8°W.

1639	Thin haze; limited structure; CN mainly <100 cm^{-3}.
1707	Rapid fall in ozone as surface is approached (below 900 mb). During the descent the haze was uniformly thin, more like background haze off Alaska.
1733	Begin climb to 480 mb and flight to Thule; haze visibly light and white and may be enhanced by scattering from low sun angle.
1816	Ozone increases to 75 ppb as we enter the bottom of the stratosphere, 79.2°N, 66.8°W, 397 mb, 7233 m.
1831-1854	Descend and land at Thule.

4.3 Synoptic Situation

The synoptic situation during the flight on April 13, 1986, is best shown by 500- and 850-mb maps at 1200 GMT (figs. 4.2, 4.3). The initial situation was established 36 h earlier. At 500 mb at that time, the western Arctic was dominated by an omega-shaped ridge over Alaska and a trough over Baffin Bay which extended its influence over the north Canadian continent. There was a fairly strong pressure gradient between the ridge and the Baffin Bay low. A weak area of higher pressure extended over the pole, and there was a low over the north Siberian coast on the opposite side of the Arctic. At 850 mb, the ridge was more extensive, covering most of Alaska and northern Canada, and the low over Baffin Bay was less apparent. This situation remained the same through 1200 GMT on April 12, with the Baffin Bay low weakening slightly.

By 0000 GMT on April 13, a weak trough existed over Alaska at 500 mb, covering the shallow ridge at 850 mb. At 850 mb, winds across northern Canada were southeasterly at 10-15 m s^{-1}, but continued light and variable over Alaska. At 500 mb, the trough over Baffin Bay was separated from that over Alaska by an area of higher pressure (across the Canadian Arctic Islands). Winds at this level were easterly across the northern border area of Canada, southeasterly across northern Alaska, and northwesterly to westerly across central and southern Alaska. By 1200 GMT on April 13, during the flight, the situation at 500 mb was virtually identical to that 12 h before. A weak trough had replaced the ridge over central Alaska at 850 mb.

4.4 Atmospheric Cross Sections

Two latitude-altitude cross sections of potential temperature were drawn, to represent the flight tracks from Anchorage to Alert, and from Alert to Thule. Data were available for this analysis from the aircraft; from radiosonde information at 1200 GMT on April 13, at Anchorage (ANC), Fairbanks (FAI), Barter Island (BTI), Sachs Harbour (YSY), Mould Bay (YMD), Alert (YLT) and Thule (BGTL); and from five dropwindsondes released from the aircraft, four between ANC and YLT and one between YLT and BGTL.

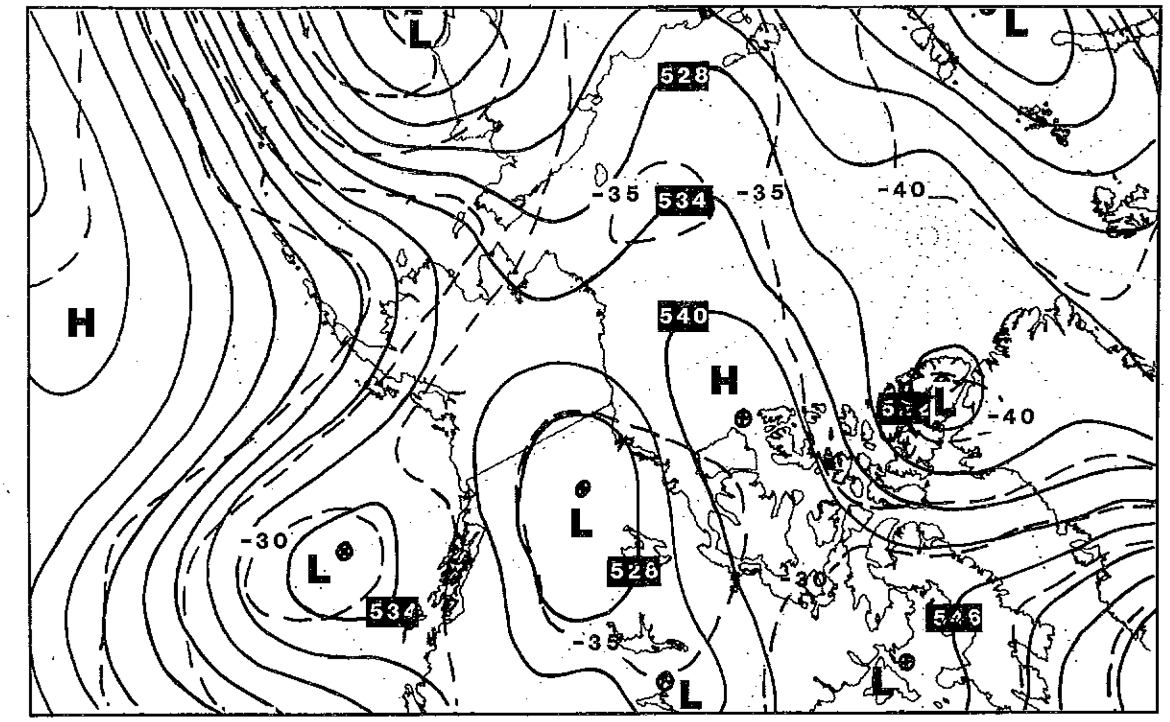


Figure 4.2--500-mb synoptic map for the western Arctic at 1200 GMT, April 13, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

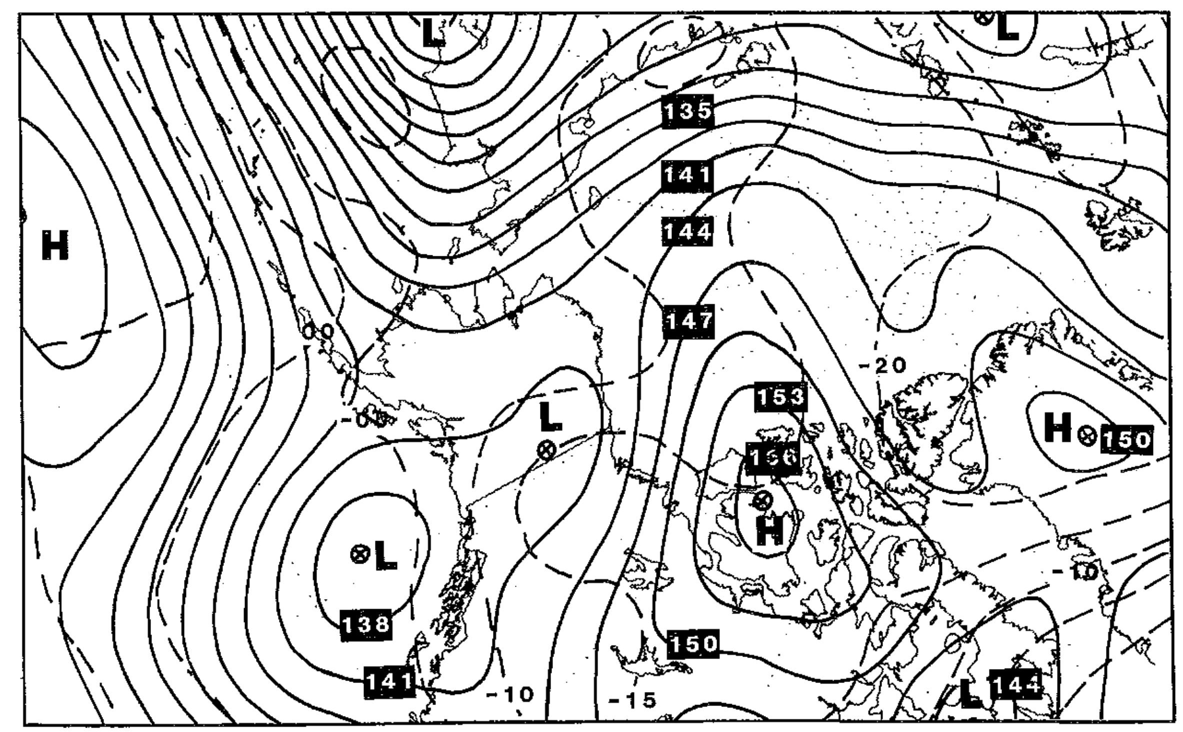


Figure 4.3--850-mb synoptic map for the western Arctic at 1200 GMT, April 13, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

Between ANC and YLT, the aircraft flew across the ridge of high pressure (fig. 4.4). From initial winds that were westerly at ANC the aircraft encountered easterlies at 67°-68°N, associated with its flight into a small tropopause lowering. After emergence from the stratosphere, strong easterlies (38 m s^{-1}) over the BTI area occurred; they diminished rapidly in speed below 550 mb. North of YSY, the strength of the easterlies dropped considerably in the center of the ridge. A wind shift to northwesterly occurred over YMD, as the Baffin Bay low began to exert its dominance. A westerly jet stream (70 knots) was encountered at 78°N, just before the aircraft entered the stratosphere a second time. After passing through the center of the low, the aircraft flew in northeasterly winds over Alert.

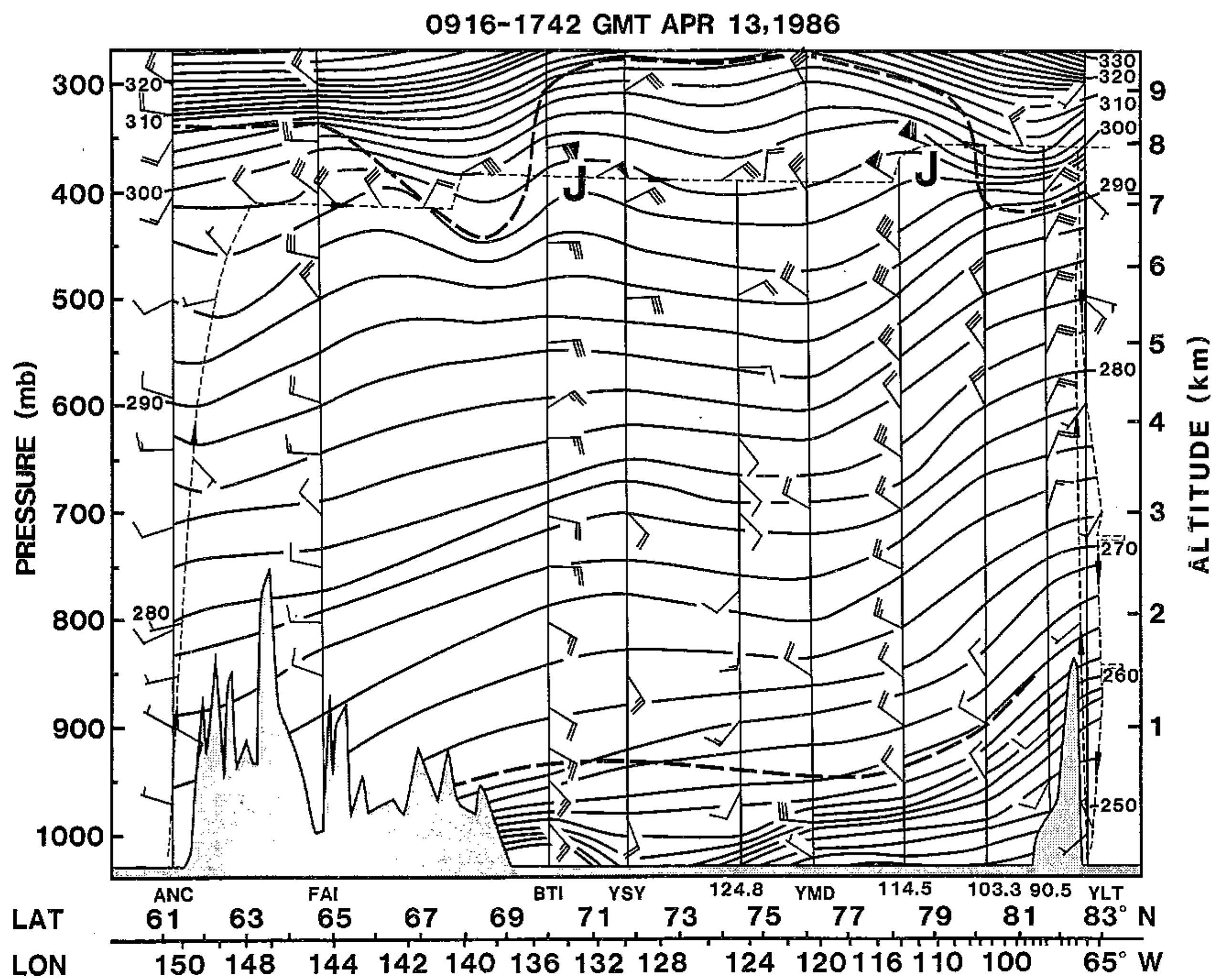


Figure 4.4--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Anchorage and Alert, NWT, April 13, 1986. The tropopause and surface inversion are indicated by thick dashed lines. The flight track is shown by a thin dashed line. The jet stream cores are indicated by a "J". Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. ANC is Anchorage; FAI is Fairbanks; BTI is Barter Island; YSY is Sachs Harbor; YMD is Mould Bay; and YLT is Alert.

There were no fronts or areas of strong mid-level stability in the atmosphere between ANC and YLT. The isentropes gradually tilted upward with height toward the Baffin Bay low. The surface inversion occurred between 920 and 950 mb, except against the mountain ridge west of YLT, where it rose to 860 mb. The wind shifts that occurred along the aircraft flight track also occurred at all levels in the atmosphere.

Atmospheric moisture remained fairly constant with altitude north of the Brooks Range except for a patch of moister air near the center of the ridge at 500-600 mb, and a pool of moisture trapped below the surface inversion at 80°N, as shown in fig. 4.5. Clouds with ice crystals were observed near the surface at 80°N.

As the aircraft flew south from YLT to BGTL (fig. 4.6), it encountered a weak westerly flow south of the center of the low. Isentropes were constant with height. The aircraft entered the stratosphere between 77° and 78°N as it encountered a broad shallow lowering in the tropopause.

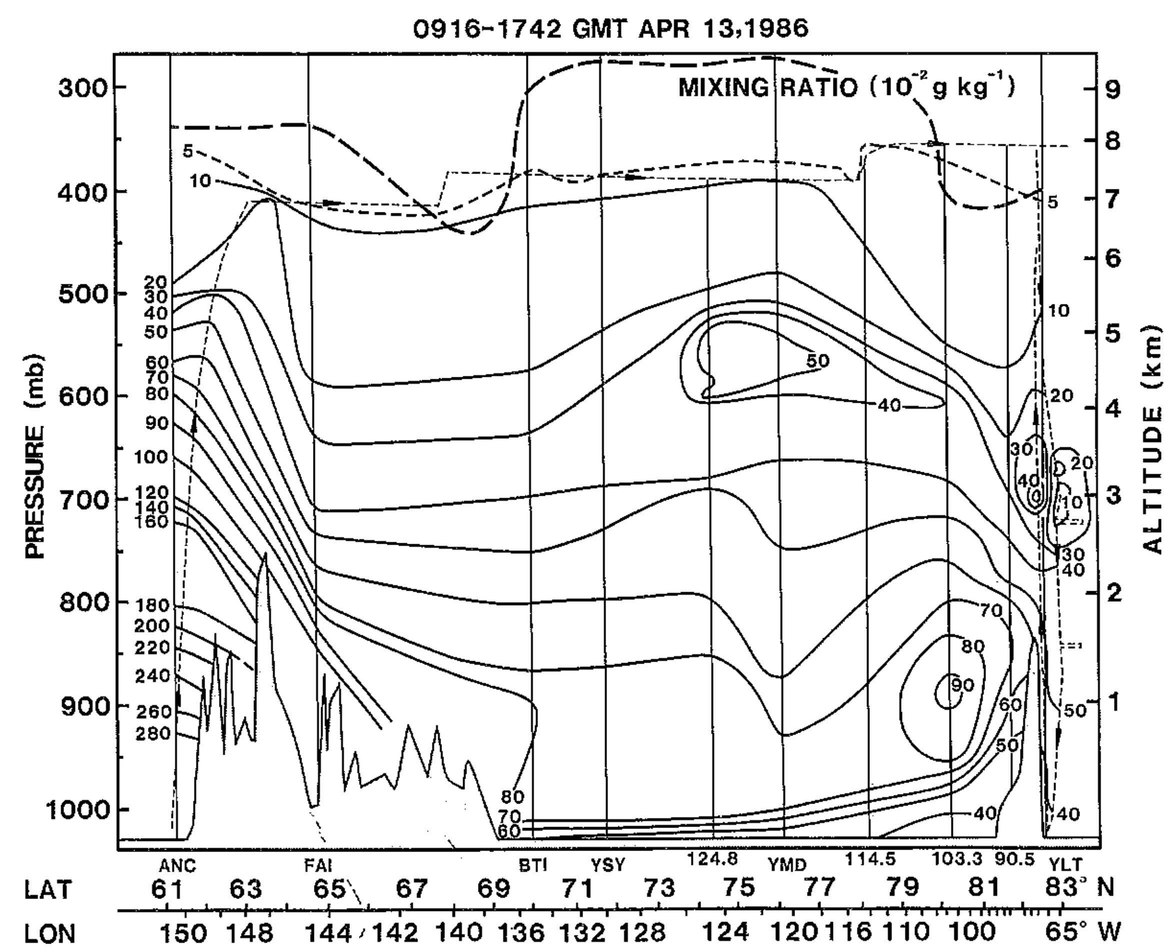


Figure 4.5--Latitude-altitude cross sections of water vapor mixing ratio between Anchorage and Alert, April 13, 1986. The aircraft flight track is shown by a thin dashed line. ANC is Anchorage; FAI is Fairbanks; BTI is Barter Island; YSY is Sachs Harbor; YMD is Mould Bay; and YLT is Alert.

4.5 Distributions of Ozone, CN, and b_{sp} at the Tropopause

During the flight between ANC and YLT, at 380 mb, the aircraft passed in and out of the stratosphere twice and into the stratosphere a third time between YLT and BGTL. Figure 4.7 presents ozone, CN, and b_{sp} data between 66° and 70°N, where the aircraft first flew into the stratosphere. Ozone concentrations exceeded 100 ppb between 67° and 69°N below 380 mb as the stratosphere intruded into lower altitudes over a relatively shallow zone. In the center of the ozone maximum, CN concentration also showed a maximum (>1000 cm^{-3}), indicating an incursion of stratospheric aerosols to lower altitudes. Aerosol b_{sp}, however, showed little variation across the tropopause, indicating the presence of relatively few particles in the accumulation mode (0.1-1.0 μm).

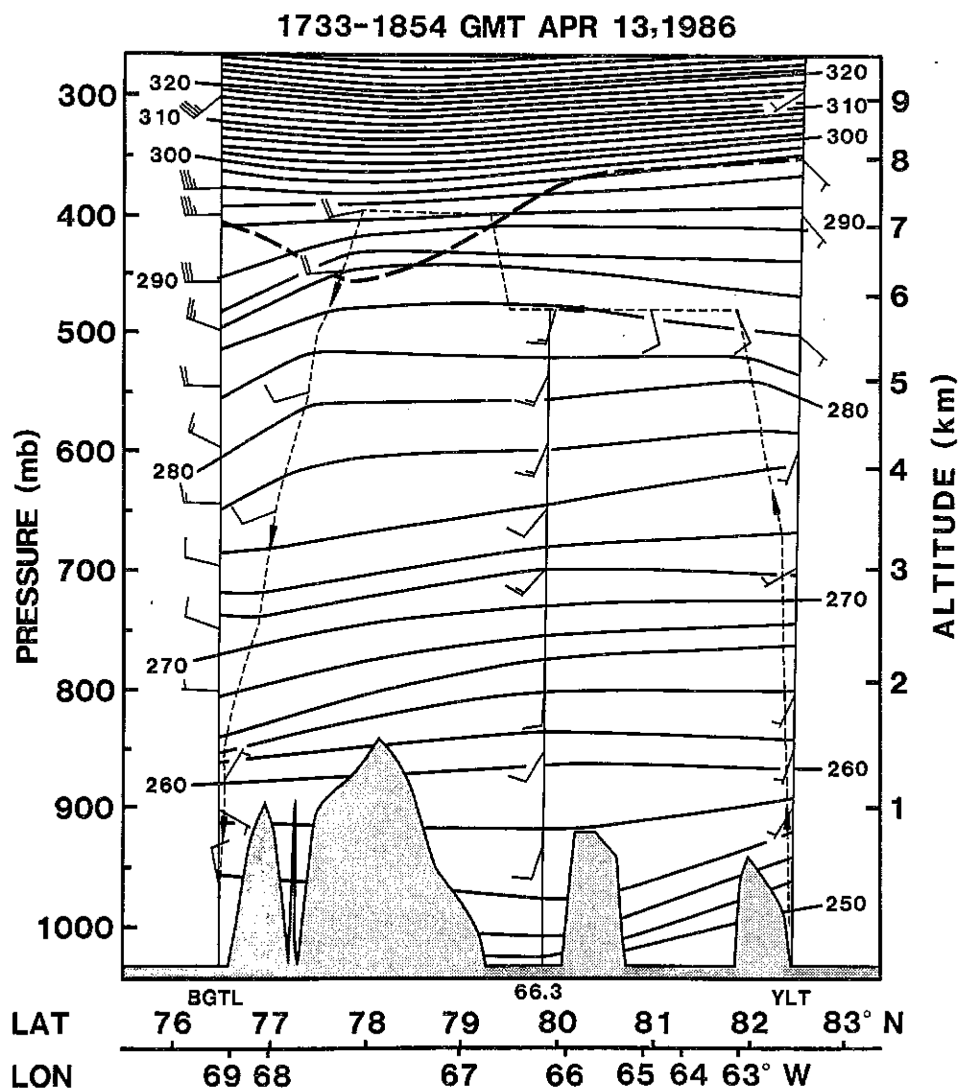


Figure 4.6--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Alert, NWT, and Thule, Greenland, April 13, 1986. The tropopause is shown by the thick dashed line, and the flight track by the thin dashed line. YLT is Alert and BGTL is Thule.

The aircraft also entered the stratosphere between 78 and 83°N (fig. 4.8). In this case ozone reached concentrations >150 ppb between 81° and 82°N, indicating stronger penetration of the stratosphere than earlier. The tropopause in this region was low in altitude over a broad zone. While b_{sp} decreased steadily with height (from 12×10^{-6} to 5×10^{-6} m^{-1}), CN exhibited areas of elevated concentrations (>100 cm^{-3}) at the entrance to and exit from the stratosphere. The aircraft also encountered stratospheric aerosols at 81°-82.5°N, but concentrations were much lower than earlier in the flight.

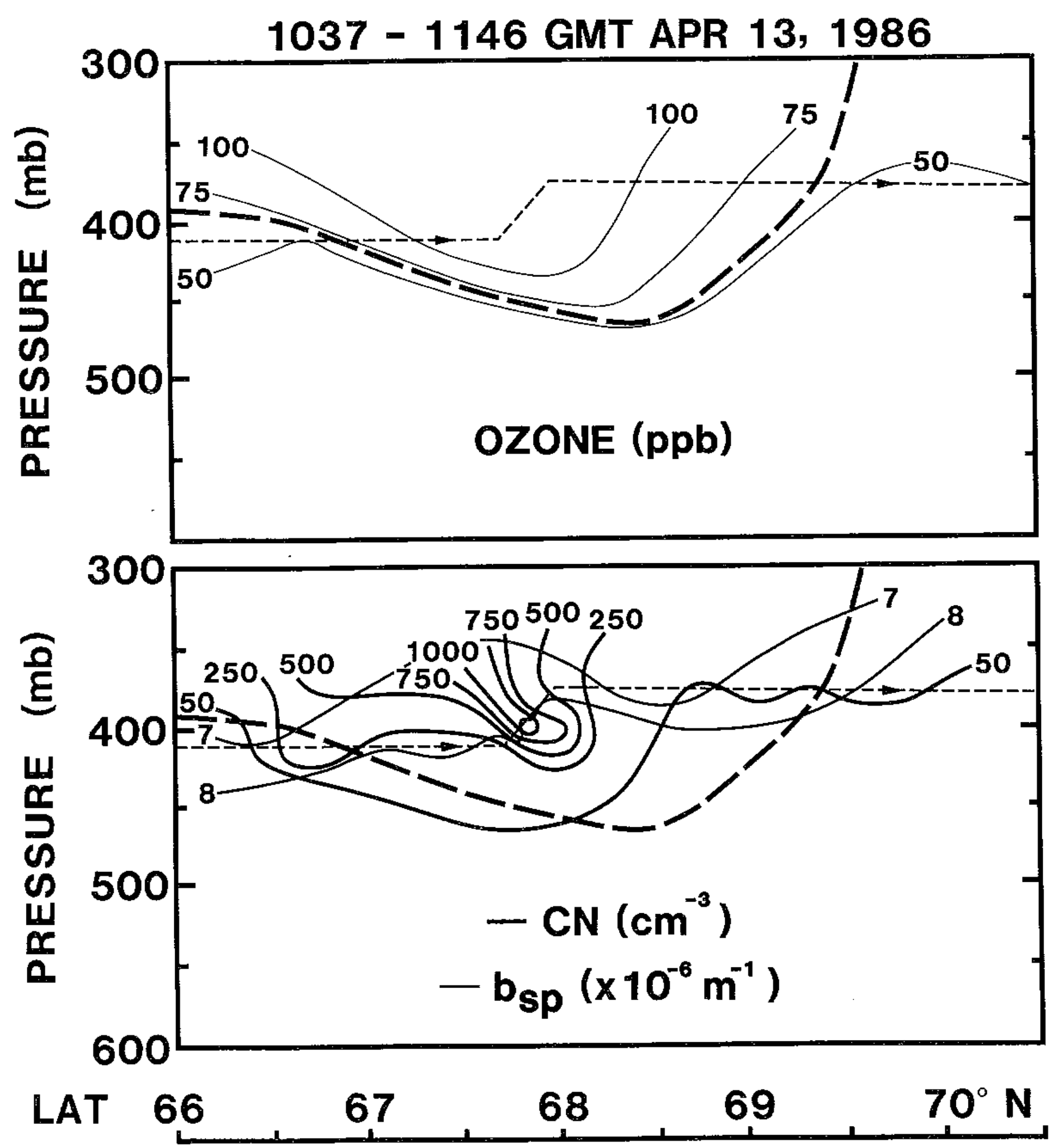


Figure 4.7--Cross sections of ozone, CN concentration, and b_{sp} across a small tropospheric dip (thick dashed line) between 66° and 70°N, April 13, 1986. The flight track is shown by a thin dashed line.

The penetration of the stratosphere between YLT and BGTL (77.5°-79.5°N), as shown in fig. 4.9, provided the most dramatic evidence of aerosol layering of the three encounters. In this stratospheric penetration, ozone concentrations rose to >90 ppb while b_{sp} again decreased fairly regularly with height (from 16×10^{-6} to 8×10^{-6} m^{-1}). Below the tropopause, tilting upward from 540-500 mb at 77°N to 500-460 mb at 81°N, a wide band of CN concentrations >50 cm^{-3} existed. This band was parallel to the tropopause. Between this area and the tropopause itself, a much cleaner region (CN <25 cm^{-3}) existed. Above the tropopause, a region of CN concentrations >50 cm^{-3} was again encountered. [A similar situation occurred on flight 205 (fig. 5.6) and Flight 206 (fig. 6.7)].

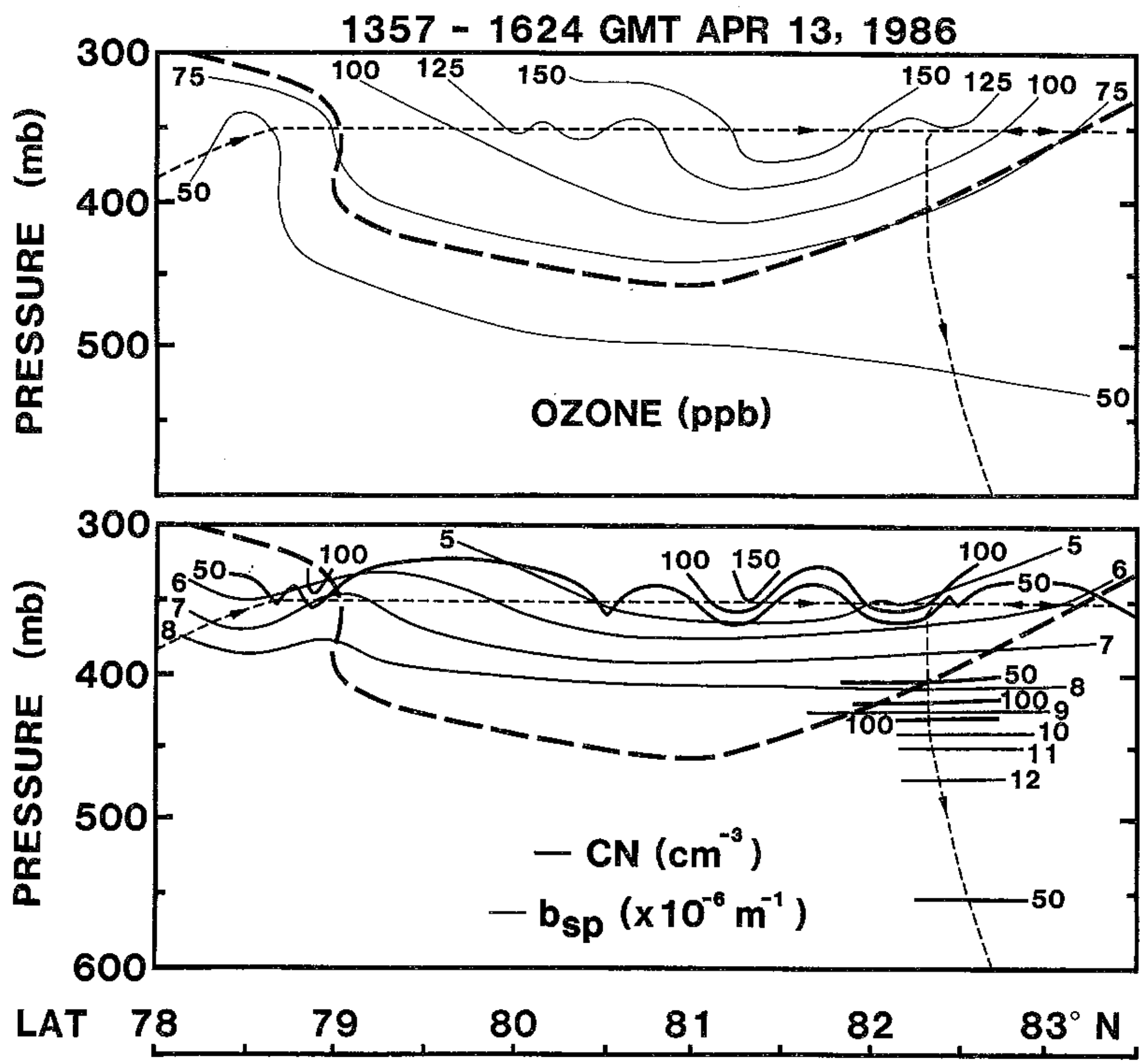


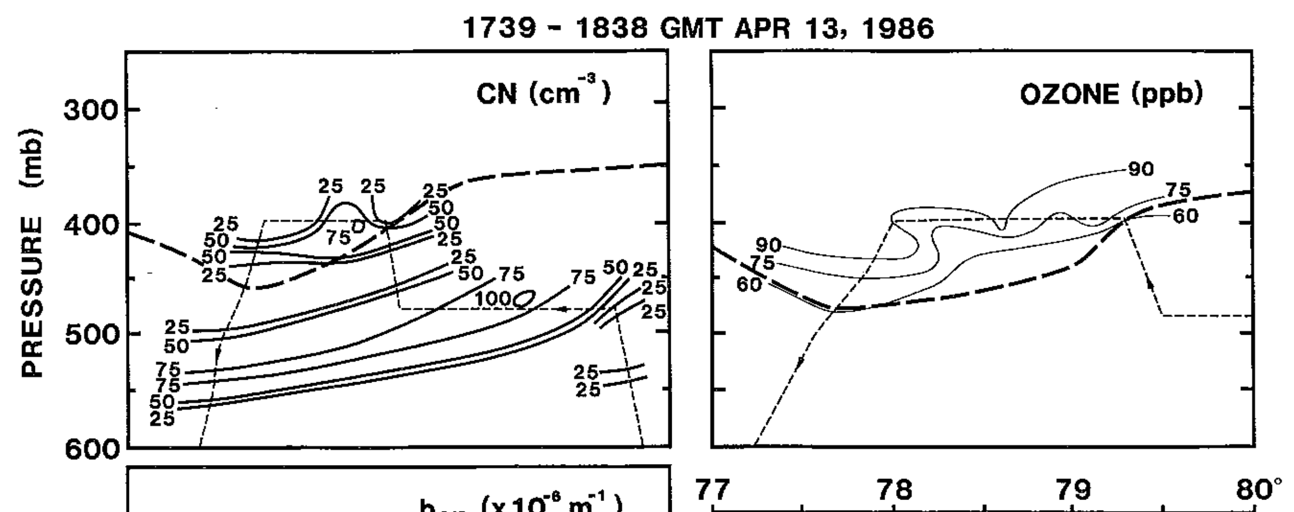
Figure 4.8--Cross sections of ozone, CN concentration, and b_{sp} along the flight track (thin dashed line) between 78° and 83°N, April 13, 1986. The tropopause is shown by the thick dashed line.

4.6 Cross Sections of CN, b_{sp}, and Ozone Over Alert

A major purpose of the WP-3D flights in the Canadian Arctic was to measure haze and ozone parameters in a detailed cross section over the ice upwind of the Alert baseline station. Figure 4.10 presents vertical-horizontal cross sections of CN concentration, b_{sp}, and ozone for a 2.5-h period over YLT during flight 204.

The aircraft began a descent over YLT while it was in the stratosphere; ozone values were 115 ppb at 350 mb. CN concentrations in this area exceeded 100 cm^{-3}, indicating an incursion of small stratospheric aerosols to levels below 400-mb pressure altitude. Below the tropopause, the atmosphere was cleaner; CN concentrations fell to <25 cm^{-3} at about 600 mb. Beginning at 700 mb, CN rose slowly toward the surface, eventually reaching 200 cm^{-3} along the lowest portion of the flight track. Aerosol b_{sp} was uniform in lateral distribution, increasing from 10×10^{-6} m^{-1} at the top of the profile to 45×10^{-6} m^{-1} in the lower tropopause.

Ozone was steady at 40 ppb for the portion of the troposphere above 700 mb, then steadily decreased toward the surface, eventually diminishing to <5 ppb over the ice near YLT. [Loss of ozone at lower levels, particularly below the surface inversion was also observed on flight 205 (fig. 5.7) and flight 206 (fig. 6.7)].



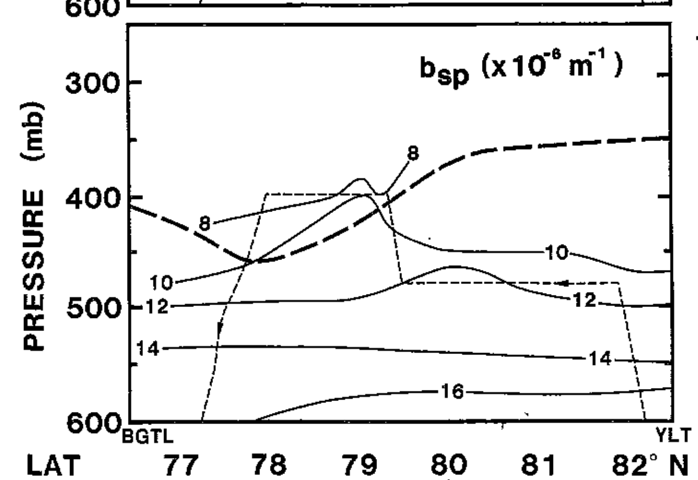


Figure 4.9--Cross sections of CN, concentration, ozone, and b_{sp} along the flight track (thin dashed line) between Alert and Thule, 77°-82°N, April 13, 1986. The tropopause is shown by the thick dashed line.

It is the overall impression of the scientists on this flight that the haze in the YLT region was of a general background nature and had none of the structure and intensity of the haze over the BRW region or the Beaufort Sea region that was observed on earlier flights.

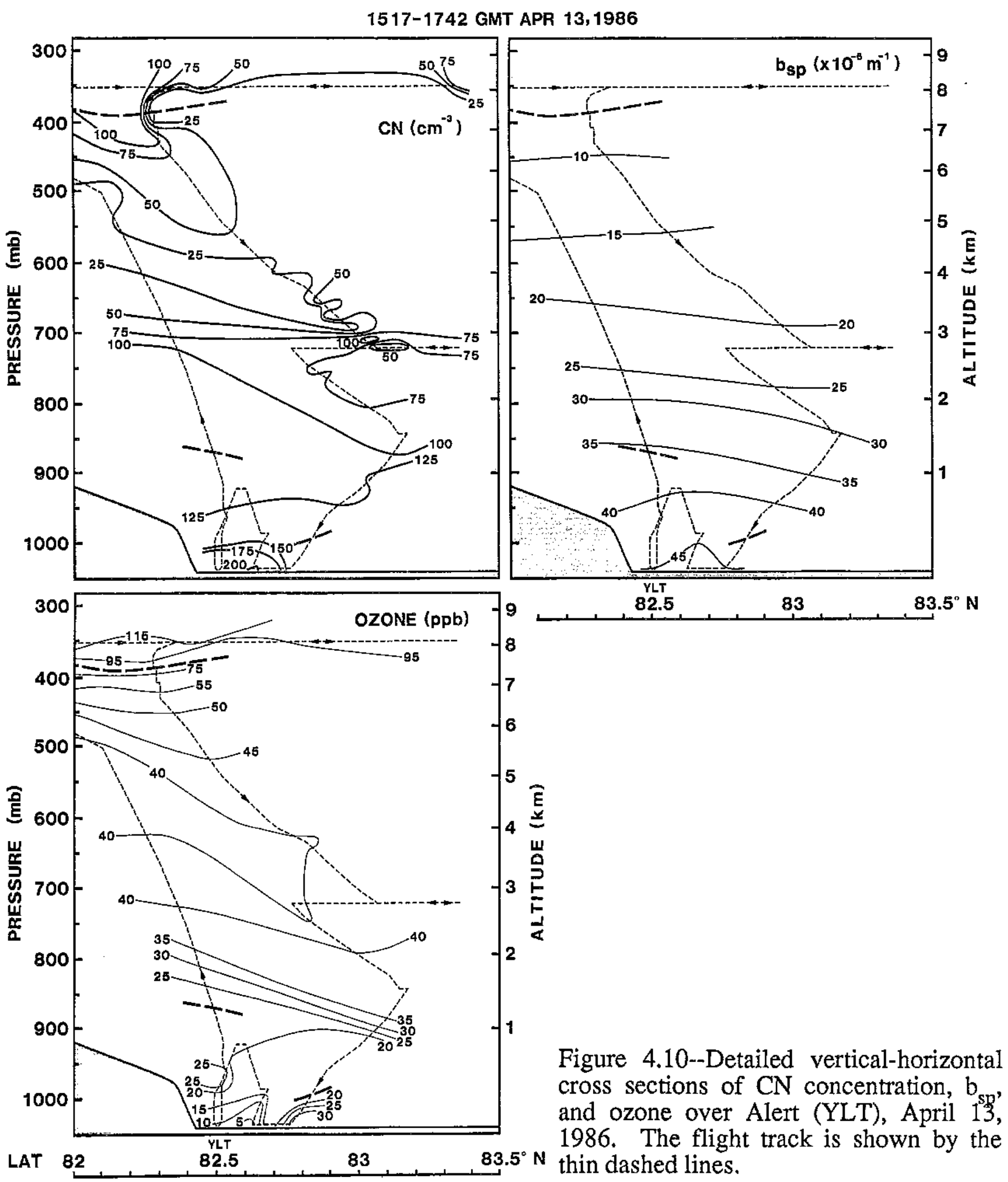


Figure 4.10--Detailed vertical-horizontal cross sections of CN concentration, b_{sp}, and ozone over Alert (YLT), April 13, 1986. The flight track is shown by the thin dashed lines.

5. FLIGHT 205, APRIL 14-15, 1986

5.1 Flight Track

The aircraft flew from Thule to Alert, conducted vertical profiles over the Alert baseline station, then returned to Thule. The WP-3D profiles were preceded by a similar University of Washington C-131 flight. The NOAA WP-3D flew into the stratosphere on the outbound leg. The horizontal projection of the flight track is given in fig. 5.1. Total flight time was 7 h, 21 min.

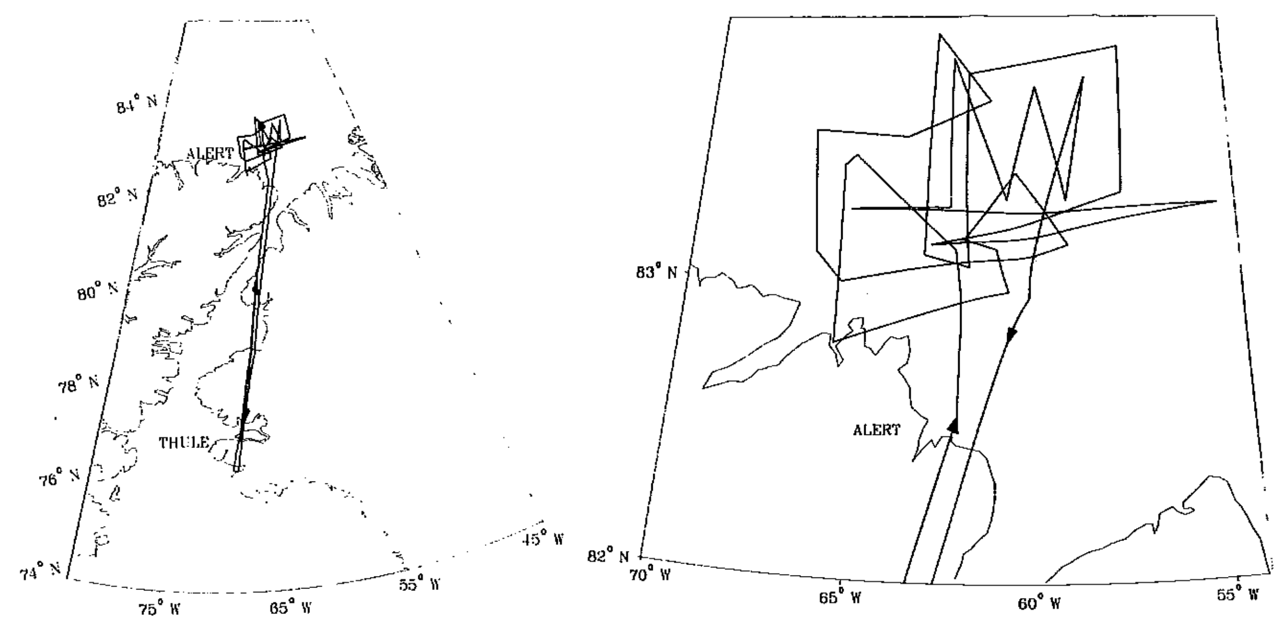


Figure 5.1--(Left) Horizontal projection of the aircraft flight track on a latitude-longitude grid between Thule, Greenland, and Alert, NWT, April 14-15, 1986. (Right) Detailed projection of the flight track near Alert.

5.2 Flight Log

April 14, 1986 (GMT)	
1737	Take off from Thule.
1737-1754	Climb to 477 mb, 5913 m; several well-defined haze layers visible.
1811	Visible haze layer, 5910 m; CN over 100 cm^{-3} at times but variable; three other haze layers in front and below; higher humidity associated with haze (40-50%), 78.8°N, 67.3°W.
1830	Haze is very patchy.
1839-1844	Climb to 461 mb, 6129 m; brushed bottom of haze layer, 81.3°N, 64.5°W. 1848 GMT, approaching Alert; 5 or 6 haze streaks clearly visible below and in front of us.

1900	Topographical effect creating clouds at the edge of Alert; Alert is overcast, ice is cloud free, hills behind Alert are cloud free.
1903	Northeast of Alert; climb to 407 mb, 7048 m sun run measurements to 1929 GMT, 82.7°N, 62.4°W.
1921	Six distinct haze layers visible below us and to the north; clarity between layers varies; a little roll cloud is visible just above the ice.
1931	Begin descent to Alert from 416 mb, 6902 m.
1952-2013	Sun measurement run; level at 706 mb, 2940 m; very clean air at northern end of run, 83.2°N, 62.5°W.
2013	Begin descent to 1027 mb.
2031-2034	Below 970 mb; sharp decrease in ozone from about 40 to near 0 ppb; very clean boundary layer with CN <10 cm^{-3}.
2035	Moisture haze in the Alert area, CN very low, ozone depleted at 1018 mb; alternating cloud, dry, cloud periods in wave-like pattern near the ice; visibility poor due to roll clouds along ice.
2046	Higher CN between area of clouds; within clouds, no CN, 1007 mb, 150 m.
2050-2106	Climb to 760 mb into a haze layer, 83.7°N, 63.2°W.
2113	Haze layer very dry, CN Z100 cm^{-3}; carbon in the top portion of the layer only, 765 mb, 2301 m.
2238	In center of very thin haze layer at 670 mb, 3343 m. Maximum CN just over 100 cm^{-3}.
2329-2342	Climb to 379 mb, 7500 m, 83.5°N, 58.7°W.
0016	Returning to Thule; 382 mb, enter stratosphere; ozone >70 ppb; CN patchy; 79.8°N, 65.9°W.
0040	Stratospheric ozone and potential temperature directly correlated with each other.
0037-0058	Descend to Thule.

5.3 Synoptic Situation

The synoptic situation during the flight at 0000 GMT, April 15, had slowly evolved from that described on April 13 (sec. 4.3). By 0000 GMT on April 14, the trough over Baffin Bay had begun to reestablish its strength. Easterlies became dominant at all levels in this area. Farther to

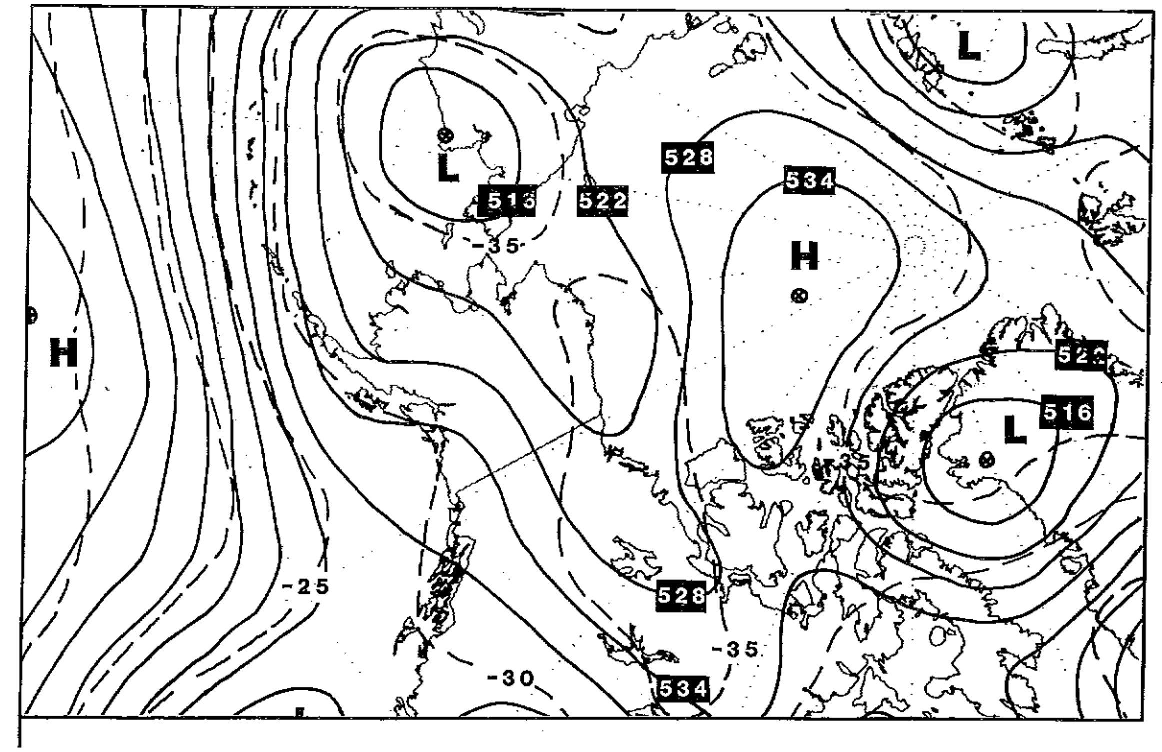


Figure 5.2--500-mb synoptic map for the western Arctic at 0000 GMT, April 15, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

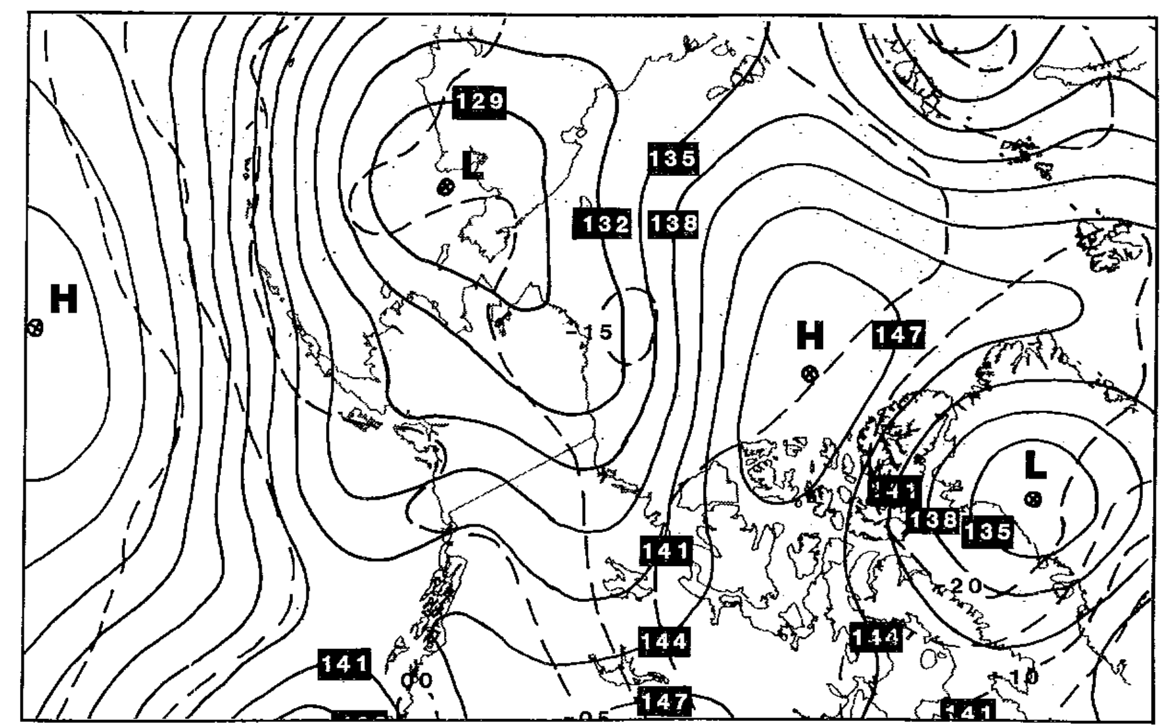


Figure 5.3--850-mb synoptic map for the western Arctic at 0000 GMT, April 15, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

the west there was little change in either the ridge over the Canadian Arctic or the trough over Central Alaska. A weak high existed over the pole.

Over the next 12 h, the strengthening of the low over the Alert-Thule area, and the combining of the Alaskan trough with the encroaching stronger low off Alaska's west coast began to influence the ridge over the Canadian Arctic. The ridge became more elongated meridionally and extended over the Arctic ice cap. Easterlies continued to dominate the Alert-Thule area.

By 0000 GMT on April 15 (figs. 5.2, 5.3) the ridge over the Canadian Arctic became an omega block situation. The main zonal flow was across central Alaska and central northern Canada, at 500 mb and above. Air flow at 850 mb in these areas was southwesterly and less than 5 knots. The 850-mb geopotential heights over Thule were about 1330 m, while in the ridge to the west-northwest, they were 1500 m. The aircraft flew across the center of the low between Thule and Alert, encountering increasing easterly wind strength (up to 8 m s^{-1}) as the pressure gradient between the ridge and the low increased.

5.4 Atmospheric Cross Sections

The cross section of potential temperature and wind during the flight on April 14-15 is presented in fig. 5.4, and moisture in fig. 5.5. Air flow throughout the troposphere along the flight track was light to moderate northeasterly as the aircraft flew just east of the center of the low. Information from radiosondes released at Alert (YLT) and Thule (BGTL) at 0000 GMT on April 15, and from three dropwindsondes released from the aircraft during the flight, supplemented the meteorological information measured on the aircraft.

Between 78° and 82°N, over the bays and ice floes of west Greenland, a strong stable air layer existed at 730 to 850 mb. Moisture decreased fairly regularly with height between BGTL and YTL, but layers with higher moisture alternated with drier regions over BGTL and over the ocean near YLT.

5.5 Distributions of Ozone, CN, and b_{sp} at 300-600 mb Between Alert and Thule

The aircraft flew across the tropopause between 77° and 80°N on the inward leg, where stratospheric air was sampled at 480 mb. The aircraft measured ozone concentrations >175 ppb at 350 mb and 78° N (fig. 5.6). The lowering of the stratosphere occurred across a broad area and did not constitute a folding event. The CN concentrations and b_{sp} measurements both established the pressure of a distinct clean layer (CN < 25 cm^{-3}; $b_{sp} < 6 \times 10^{-6}$ m^{-1}) just below the main portion of the tropopause and within the lower portion of the stratosphere below 400 mb (78°-80°N). On either side of this clean zone, b_{sp} increased. The clean air, just below the tropopause, seems to be a regular Arctic feature, as it was also observed during flights 204 (fig. 4.9) and 206.

5.6 Cross Sections of CN, b_{sp}, and Ozone Over Alert

Figure 5.7 presents the vertical-horizontal cross section over YLT for flight 205. Several interesting features are apparent. For instance, although CN concentrations were relatively low, higher concentrations were observed in layers, and in a few CN patches. Above 650 mb, with the exception of two small areas, CN concentrations remained below 25 cm^{-3}. The haze layer,

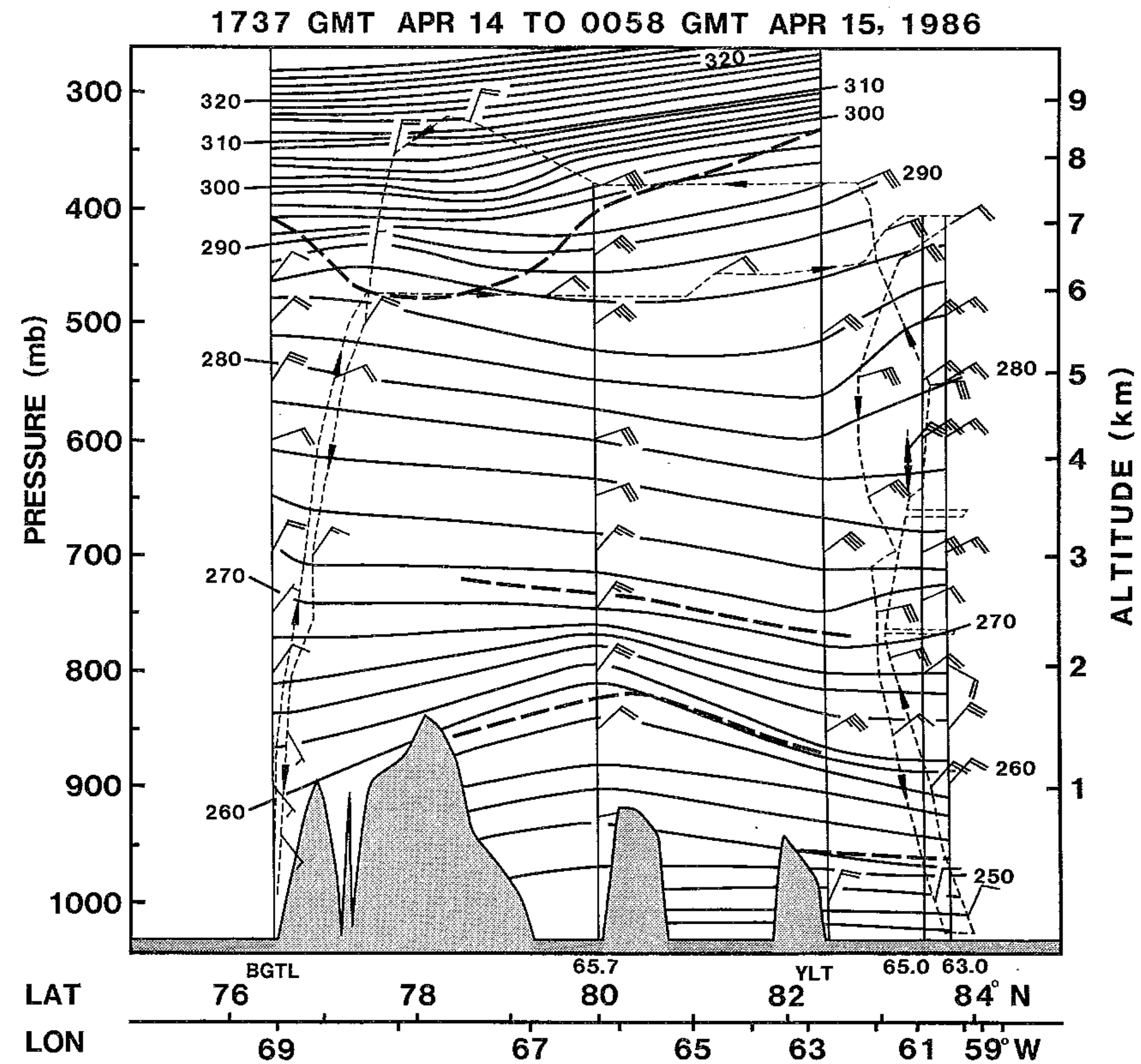


Figure 5.4--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Thule, Greenland, and Alert, NWT, April 14-15, 1986. The tropopause, surface inversion, and main stable layers are indicated by thick dashed lines. The flight track is shown by a thin dashed line. Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. BGTL is Thule and YLT is Alert.

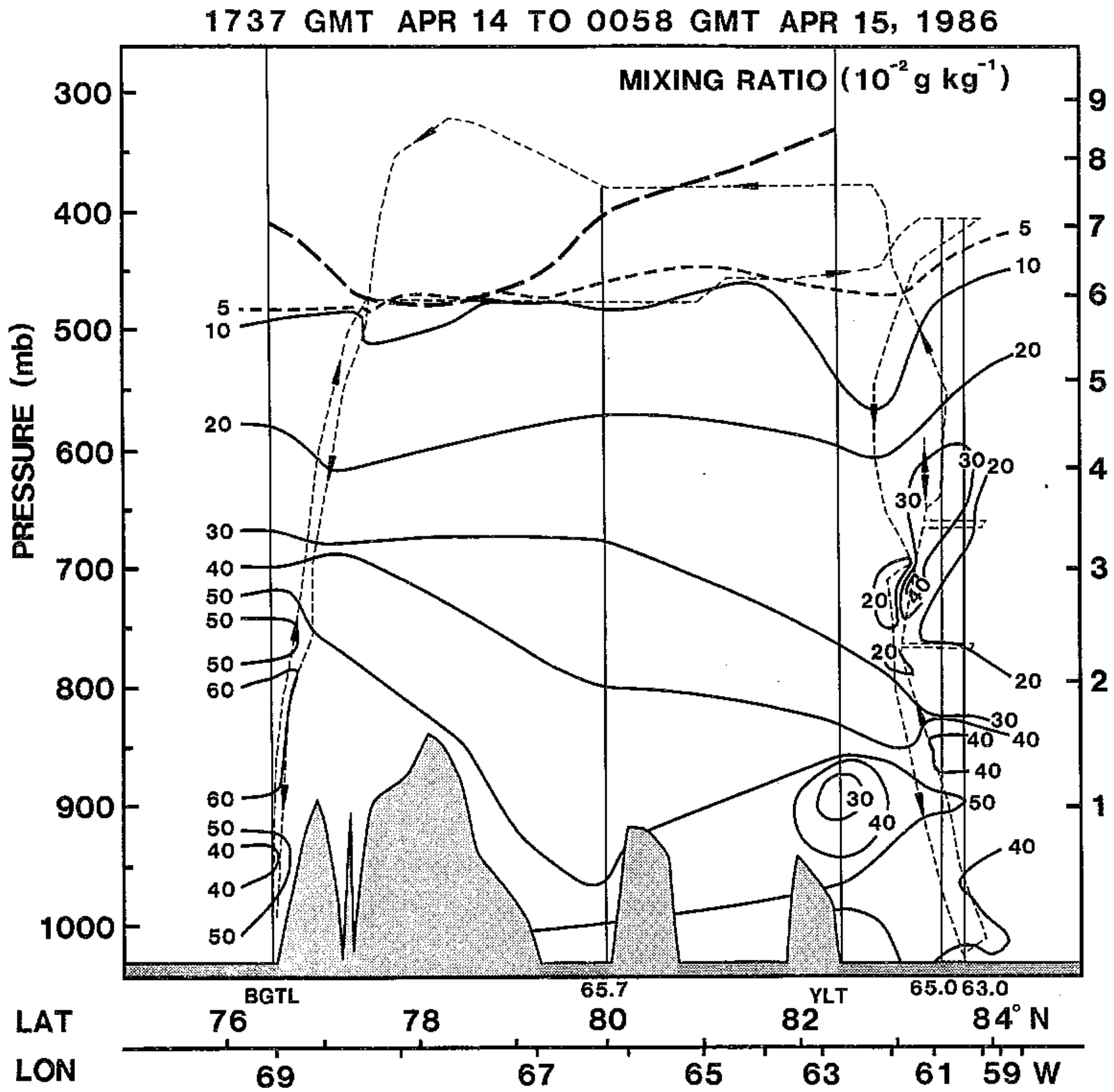


Figure 5.5--Latitude-altitude cross section of water vapor mixing ratio between Thule (BGTL) and Alert (YTL), April 14-15, 1986. The flight track is shown by a thin dashed line. Intermediate values are shown by thick dashed lines.

where CN concentrations were >100 cm^{-3}, existed between 750 and 800 mb. From this altitude, CN generally diminished toward the surface, with the exception of two patches of >100 cm^{-3}. The surface inversion layer (below 950 mb) had little effect on the CN distributions. Ozone in the troposphere decreased in both directions from a broad maximum of 45 ppb between 700 and 800 mb, coincident with the elevated CN concentrations. Toward the surface, ozone diminished very rapidly beneath the surface inversion, decreasing from 40 ppb to <10 ppb between 950 and 980 mb pressure altitude. This loss of ozone below the surface inversion was observed on all three flights over the ice off Alert.

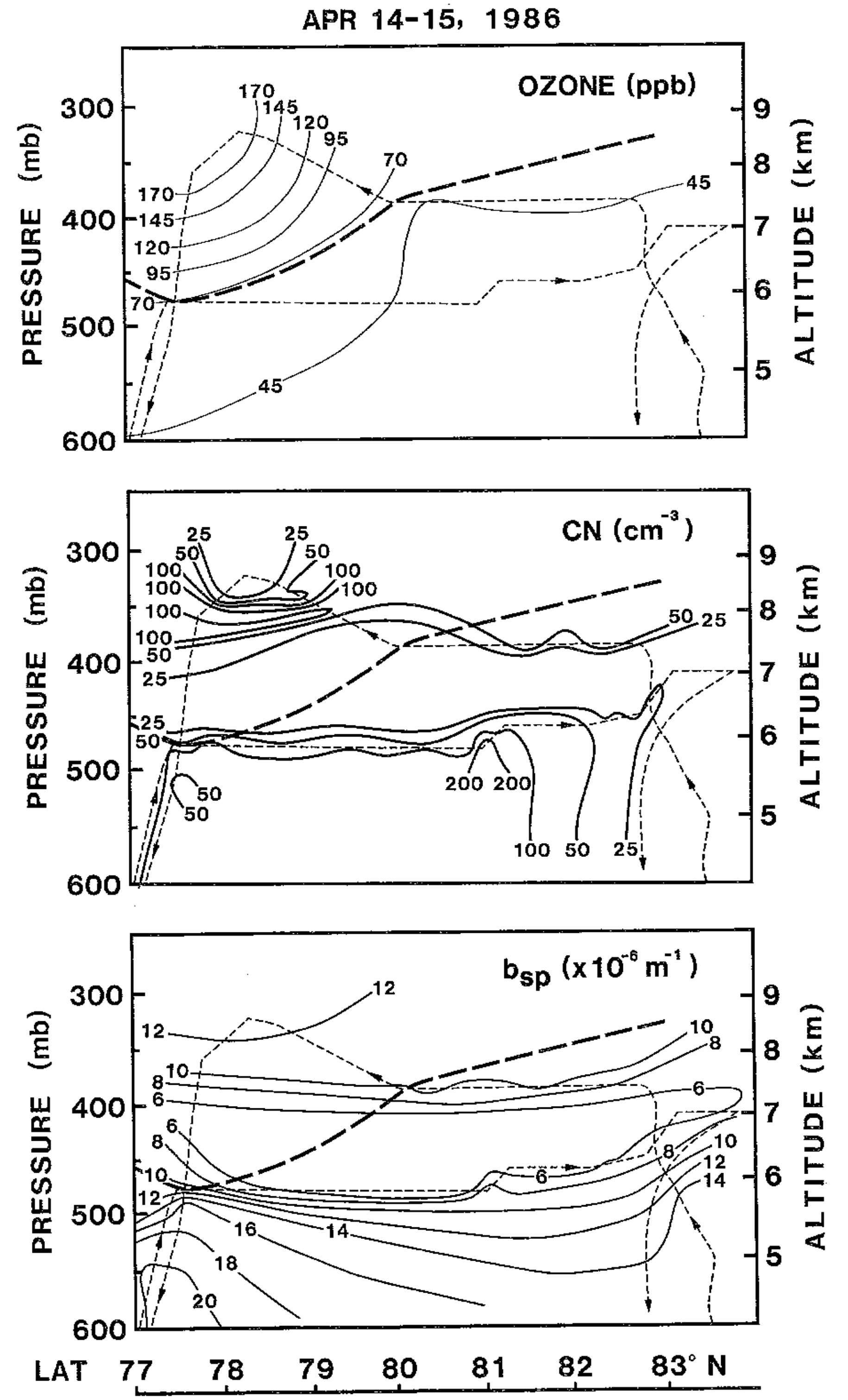


Figure 5.6--Cross section of ozone, CN concentration, and b_{sp} along the flight track above 600 mb between Thule and Alert, April 14-15, 1986. The tropopause is shown by the thick dashed line and the flight track by the thin dashed line.

Aerosol b_{sp} exhibited none of the structural features of either ozone or CN. Instead, b_{sp} increased from $15 \times 10^{-6}\ m^{-1}$ at 550 mb to $45 \times 10^{-6}\ m^{-1}$ near the surface, somewhat akin to the water vapor distribution (fig. 5.5).

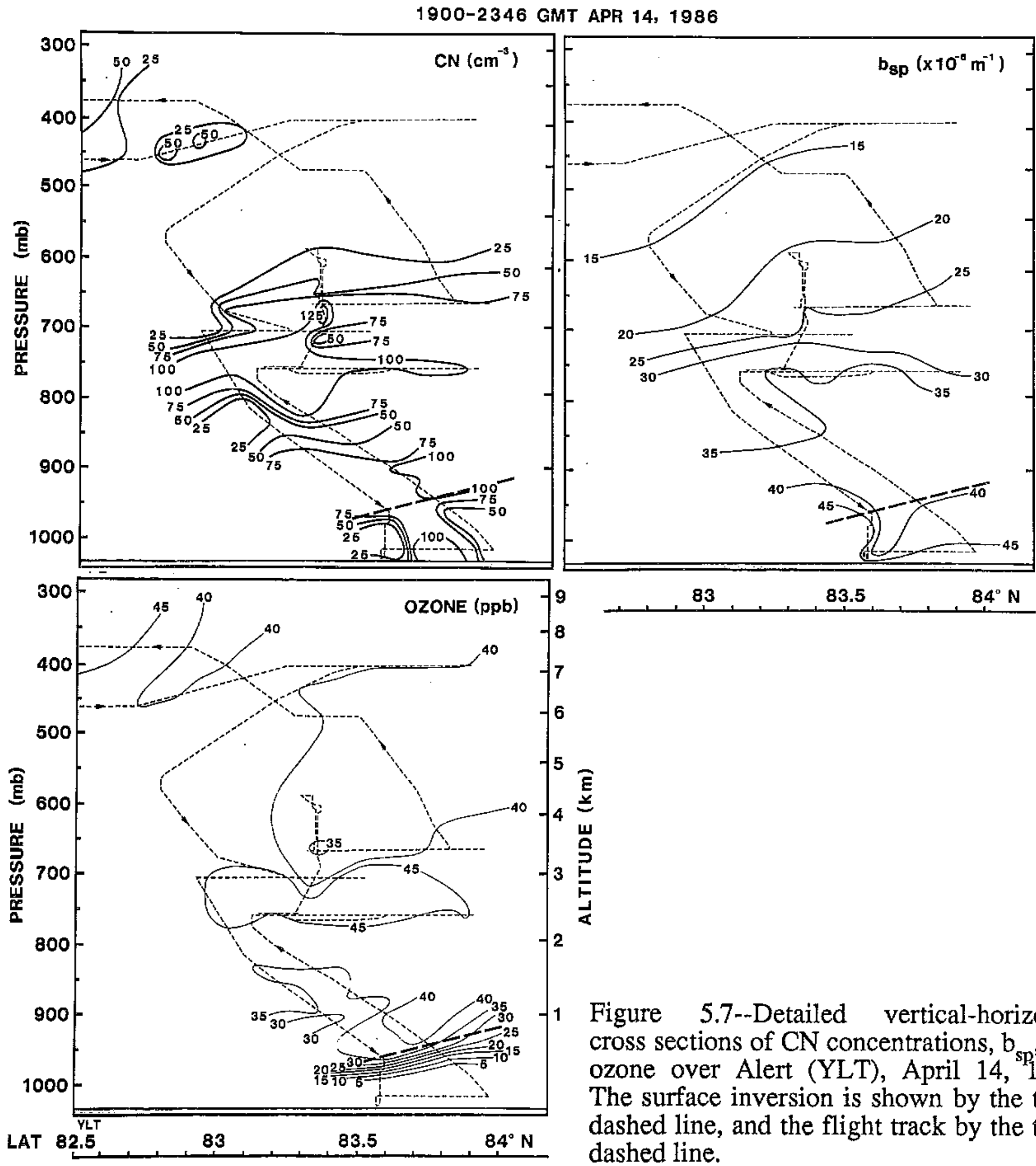


Figure 5.7--Detailed vertical-horizontal cross sections of CN concentrations, b_{sp}, and ozone over Alert (YLT), April 14, 1986. The surface inversion is shown by the thick dashed line, and the flight track by the thick dashed line.

6. FLIGHT 206, APRIL 15-16, 1986

6.1 Flight Track

The aircraft flew from Thule to Alert, conducted a sounding in conjunction with the National Aeronautical Establishment Twin Otter, and then flew on to Anchorage. A relatively strong haze layer was encountered just north of Thule at 480 mb. Little haze was evident over Alert. During the flight to Anchorage, the aircraft brushed the stratosphere several times and flew in the clean air in the tropopause region. The horizontal projection of the flight track is given in fig. 6.1. Total flight time was 10 h, 1 min.

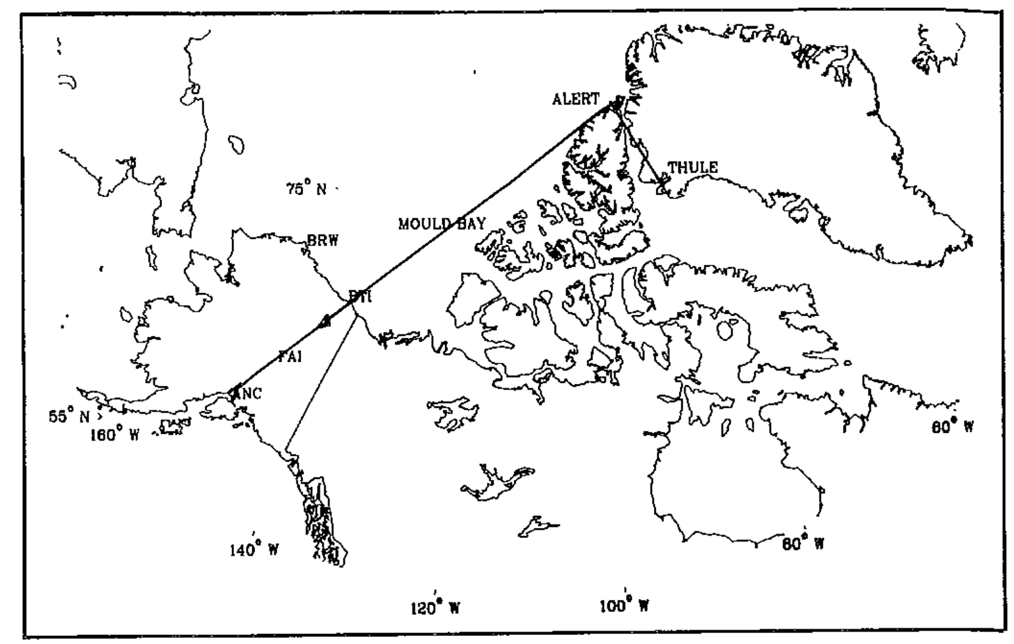


Figure 6.1--Horizontal projection of the aircraft flight track on a latitude-longitude grid between Thule, Alert, and Anchorage, April 15-16, 1986. BRW is Barrow, BTI is Barter Island; FAI is Fairbanks; ANC is Anchorage.

6.2 Flight Log

April 15, 1986 (GMT)

1733	Takeoff from Thule.
1733-1755	Climb to 475 mb, 5948 m, into a haze layer with a base at 505 mb, 5489 m and top at 475 mb, 5945m (CN reached 6000 cm^{-3}).
1826	Flying toward Alert and intersecting small haze layer.
1913	Sun run measurement, 482 mb, 5841 m, 83.0°N, 60.8°W.
1922	Begin descent east of Alert; Twin Otter following. General light haze; no clouds.

1946	In light background haze (CN = 80-90 cm^{-3}), descending through 623 mb, 3912 m.
2016	Passing through 955 mb, 500 m; CN near zero; humidities above 50%; 82.9°N, 56.9°W.
2021	1014 mb at surface near Alert; remain below 971 mb until 2049, then climb.
2113	660 mb, 3444 m, level flight in and out of top of light tropospheric haze flying toward Anchorage, 83.1°N, 71.3°W.
2143	379 mb, 7550 m, north of Canadian Islands in high Arctic; lots of haze visible below, 82.7°N, 90.5°W, but none at our altitude. Very clean air.
2226	Have been flying through top of troposphere and lower stratosphere, 335 mb, 8406 m, 80.3°N, 116.1°W.
2324	Small haze patch, 337 mb, 8370 m, at very top of troposphere, 75.9°N, 133.5°W.
0027	Barter Island area; general whitish haze all over area below us.
0040	Approaching Brooks Range; four distinct haze layers visible in front, separated by clear layers, 69.8°N, 143.6°W. No haze south of range. Range acts like a haze dam.
0103	Ozone, b_{sp}, and CN equipment no longer operable for rest of flight due to power failure in the electronics rack.
0159-0234	Descend and land at Anchorage.

6.3 Synoptic Situation

Over the 24 h from 0000 GMT, April 15, to 0000 GMT, April 16, the synoptic situation changed only slightly. At 1200 GMT on April 15, the high-pressure system over the Arctic Ocean and polar region was semi-isolated from the rest of Canada by a connection between the lows over Alaska and Baffin Bay. However, a weak ridge still existed over the Alaska-Canada border area. At 500 mb, westerly flow across eastern Alaska and northern Canada was replaced by easterly winds over Baffin Bay. Air flow was weak and variable over northern Canada at 850 mb, except for easterly winds in the Alert-Thule area where the pressure gradient was stronger.

During the flight on April 15-16, the synoptic situation remained basically the same as on the previous day (figs. 6.2 and 6.3). The aircraft flew close to the center of the low from Thule to Alert and then across the ridge and into the Alaskan low on its return to Anchorage. Transition from low pressure to high pressure in the ridge to low pressure was gradual, with no frontal discontinuities.

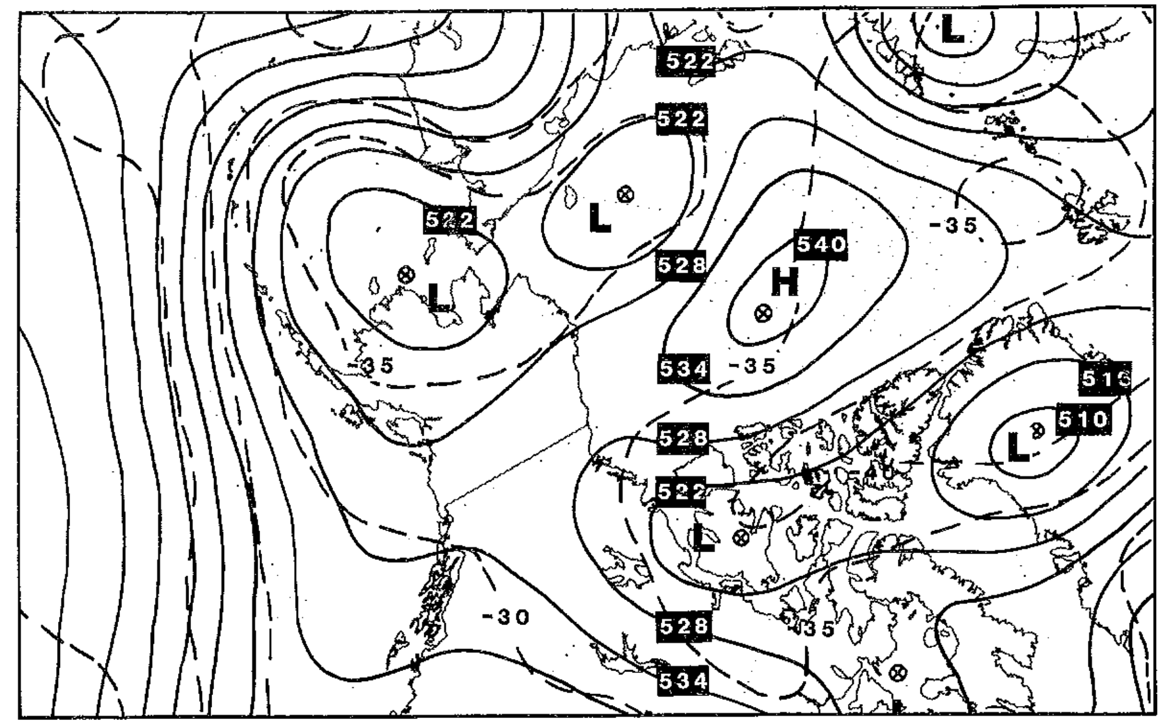


Figure 6.2--500-mb synoptic map for the western Arctic at 0000 GMT, April 16, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

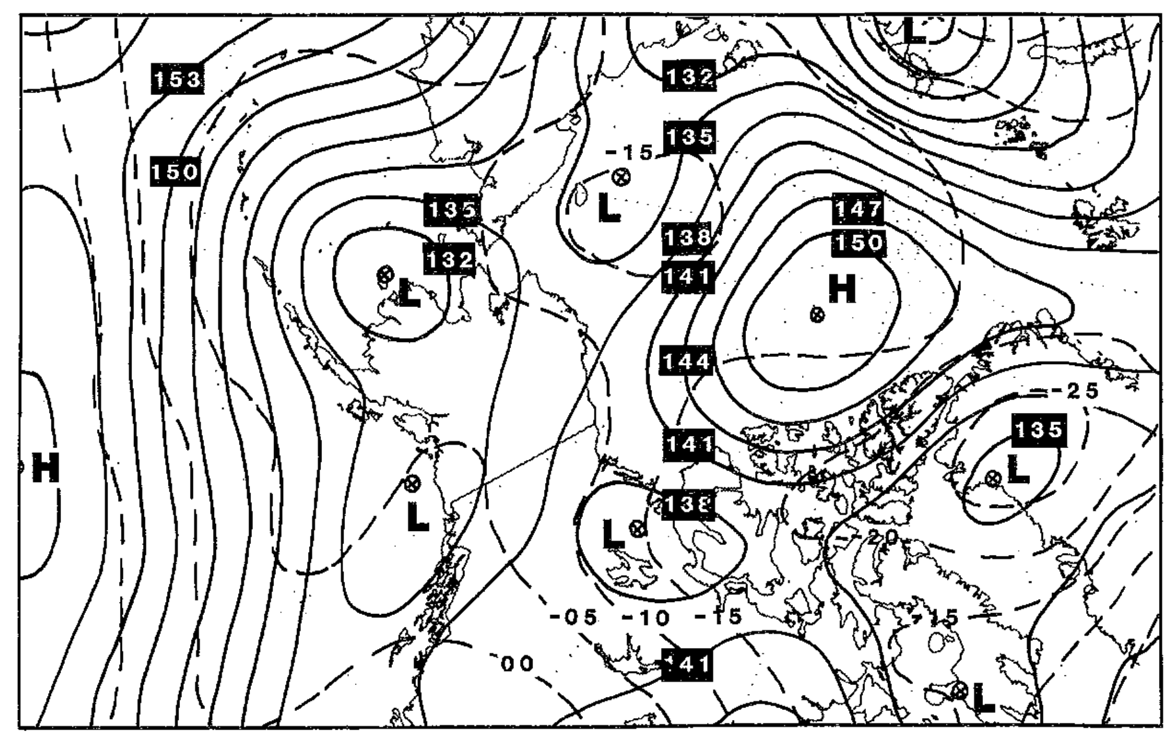


Figure 6.3--850-mb synoptic map for the western Arctic at 0000 GMT, April 16, 1986. Included are pressure altitude (geopotential decameters, solid isolines) and temperature (5°C, dashed isolines).

6.4 Atmospheric Cross Sections

Latitude-altitude cross sections of potential temperature and winds were constructed along the flight track from Thule (BGTL) to Alert (YLT) (fig. 6.4) and from YLT to Anchorage (ANC) (fig. 6.5). Data measured by the aircraft are supported by radiosonde information (0000 GMT) from BGTL, YLT, Mould Bay (YMD), Barter Island (BTI), Fairbanks (FAI), and ANC as well as by data from two dropwindsondes on the Thule-Alert leg.

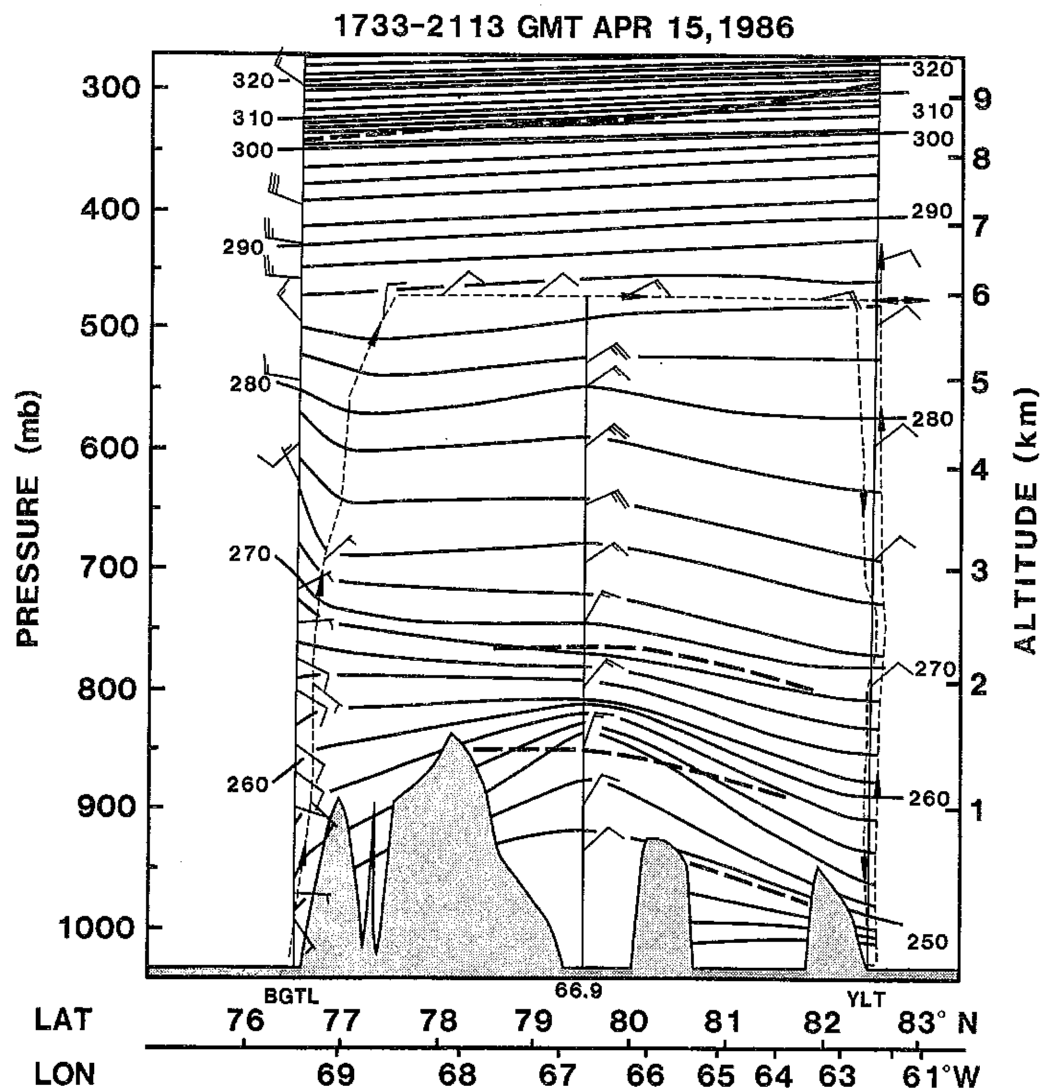


Figure 6.4--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Thule, Greenland, and Alert, NWT, April 15, 1986. The tropopause, main stable layers, and surface inversion are indicated by thick dashed lines. The flight track is shown by a thin dashed line. Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. BGTL is Thule and YLT is Alert.

The atmosphere between BGTL and YLT (fig. 6.4) was much the same as during the previous flight, with light easterly winds, and the tropopause remained above 400 mb. The stable layer at 770-870 mb between 79° and 82°N remained in place, and a surface inversion existed below 900 mb between 81° and 82°N. Moisture distribution (not shown) was also similar to that from the previous flights with mixing ratios slightly higher over the ocean near YLT than over BGTL. The aircraft intersected a haze layer at 77.4° N and 480 mb, as it flew out of BGTL.

Weak easterly winds continued throughout the atmosphere as the aircraft flew from YLT to ANC (fig. 6.5). The main exception to this description was an easterly jet (40 m s^{-1}) just below the tropopause at 81°-82°N. The aircraft entered the bottom of the stratosphere several

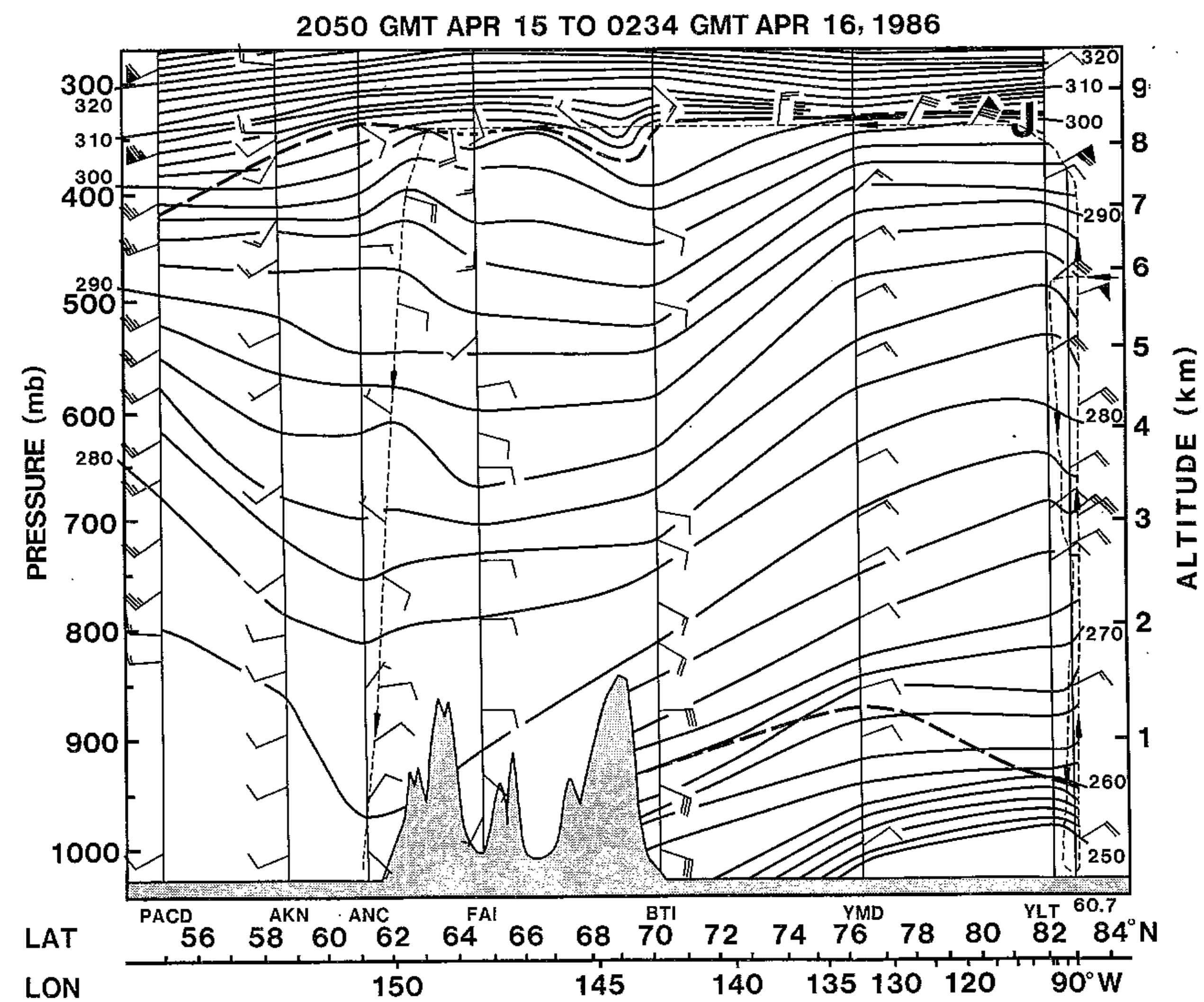


Figure 6.5--Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 5 m s^{-1}) between Alert, NWT, and Anchorage, AK, April 15-16, 1986. The tropopause and surface inversion are shown by thick dashed lines; the flight track is shown by the thin dashed line. Aircraft dropwindsonde locations are shown by longitude under a vertical solid line. The easterly jet is marked with a "J." YLT is Alert; YMD is Mould Bay; BTI is Barter Island; FAI is Fairbanks; ANC is Anchorage; AKN is King Salmon; and PACD is King Cove.

times at 377 mb, and flew in and out of a small tropopause dip at 68°-70°N. Aside from a surface inversion below 900 mb northeast of the Alaskan coast, the atmosphere exhibited no discontinuities. The aircraft flew through the ridge and into an area of even weaker and more variable winds over Alaska. The isentropes sloped upward across the ridge toward the Baffin Bay low.

The moisture cross section, shown in fig. 6.6, exhibits layering below 800 mb over the ocean near YLT, and an abrupt decrease in moisture in the ower atmosphere in the center of the ridge YMD. Moisture increased toward the Alaskan coast particularly up against the north coast mountain range. Over the interior of Alaska, moisture levels were considerably higher than farther north, but generally decreased fairly regularly with altitude.

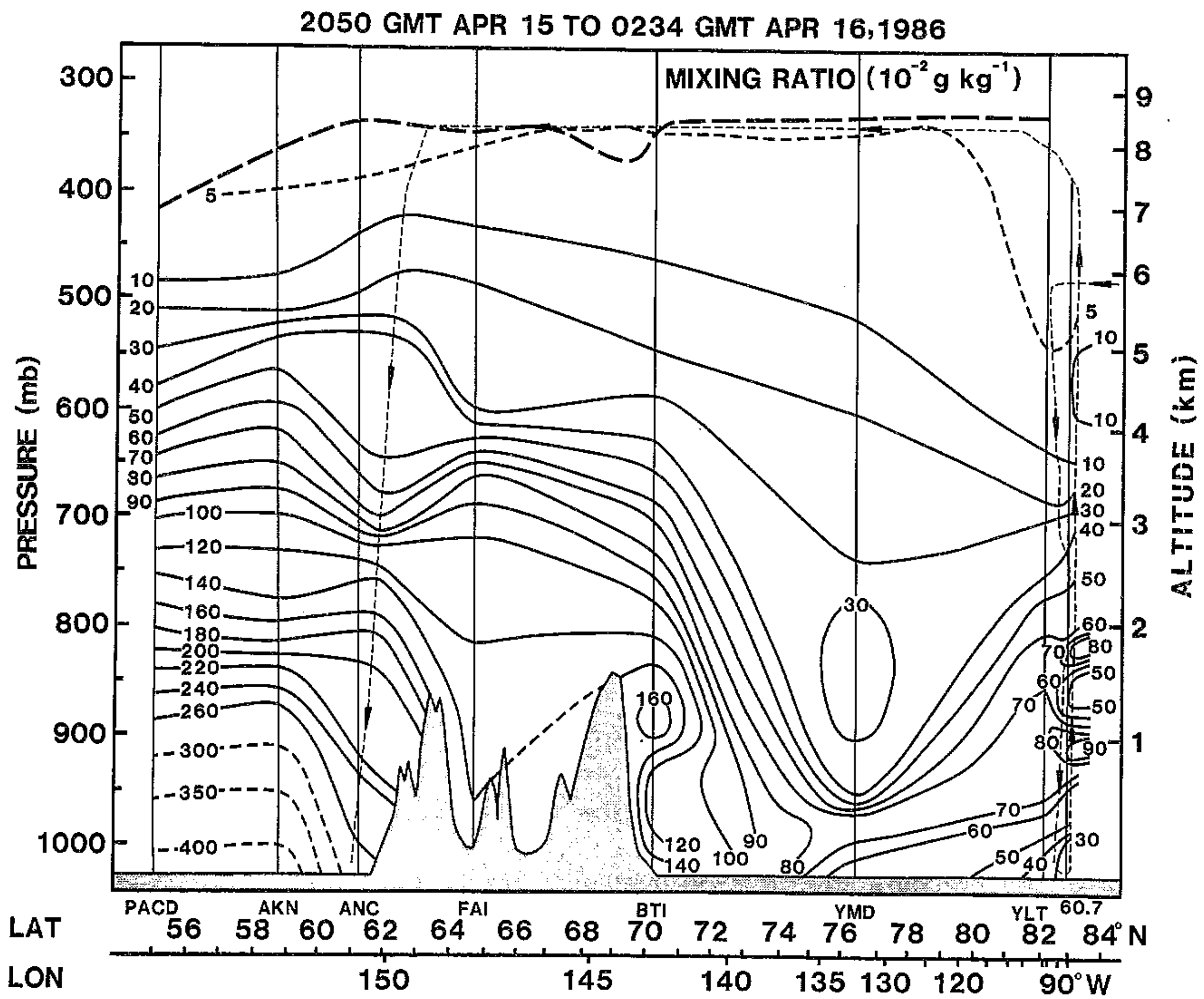


Figure 6.6--Latitude-altitude cross section of water vapor mixing ratio between Alert and Anchorage, April 15-16, 1986. The flight track is shown by the thin dashed line. YLT is Alert; YMD is Mould Bay; BTI is Barter Island; FAI is Fairbanks; ANC is Anchorage; AKN is King Salmon; and PACD is King Cove. Intermediate values are shown with thick dashed lines.

6.5 Cross Sections of CN, b_{sp}, and Ozone Over Alert

Details of CN concentrations in the atmosphere over the ice near YLT exhibit similar complexities to occurrences on previous flights. Figure 6.7 exhibits an aerosol-free zone at 400 mb, just below the tropopause, where CN is <25 cm^{-3}. Between 500 and 600 mb, CN increases to >75 cm^{-3}, with patches of CN >100 cm^{-3}. At 800 mb, the aircraft again encountered a cleaner atmospheric layer, and CN concentrations fell below 25 cm^{-3}. CN concentrations increased

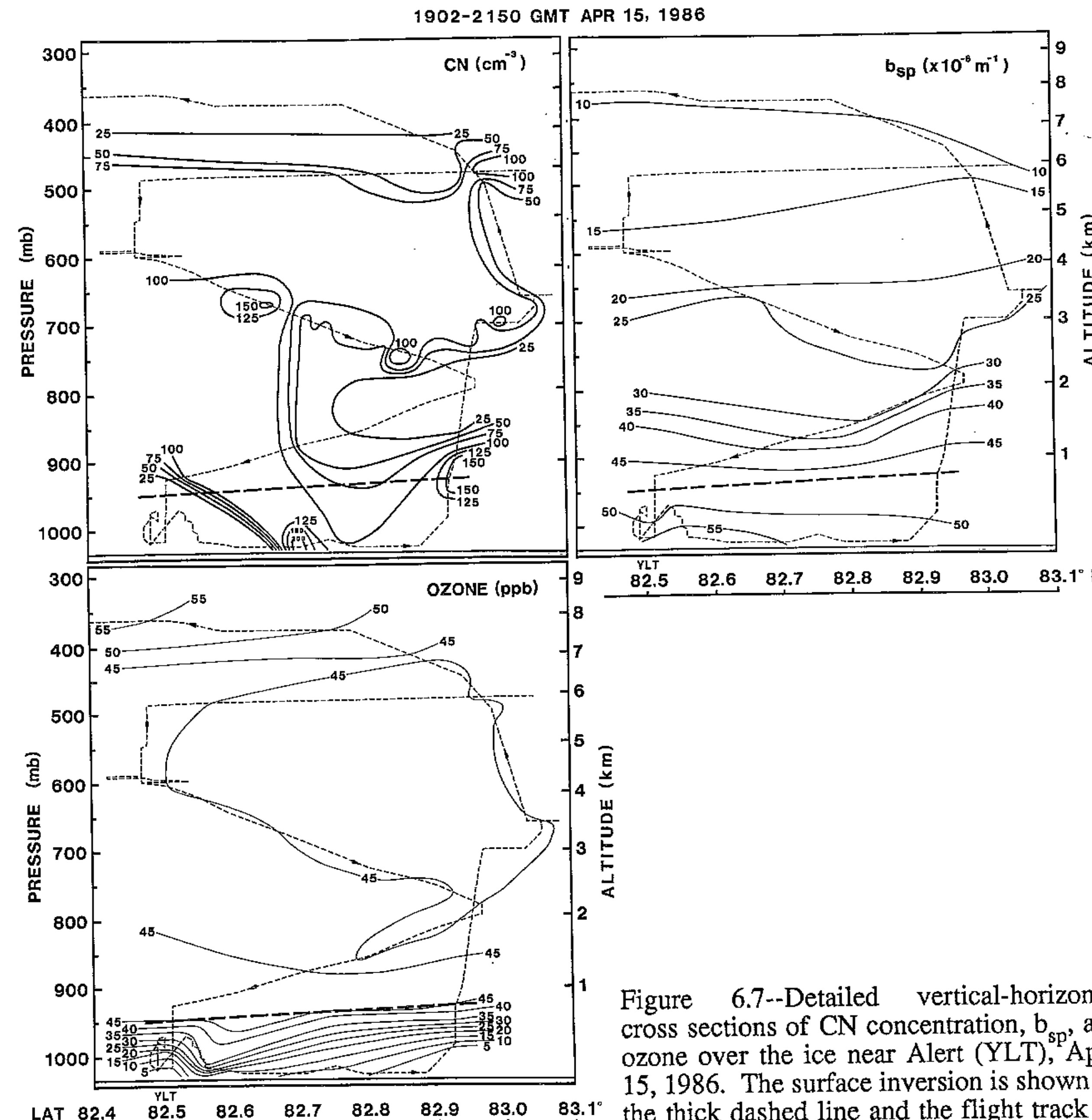


Figure 6.7--Detailed vertical-horizontal cross sections of CN concentration, b_{sp}, and ozone over the ice near Alert (YLT), April 15, 1986. The surface inversion is shown by the thick dashed line and the flight track by the thin dashed line.

again toward the surface, but fell to <25 cm^{-3} again over YLT, while remaining higher over the ice to the north. The structure of aerosol b_{sp} was similar to that on previous flights, exhibiting a regular increase from 10×10^{-6} m^{-1} at 400 mb to 55×10^{-6} m^{-1} at the surface. Aerosol b_{sp} does not respond to changes in atmospheric structure as rapidly as CN concentrations do, and thus b_{sp} showed less patchiness or layering.

Ozone decreased dramatically below the surface inversion, changing from 45 ppb to less than 5 ppb over a 500-m elevation change. In the middle and upper troposphere, ozone values remained consistently around 45 ppb.

6.6 Distributions of Ozone, CN, and b_{sp} at the Tropopause

Aside from a patch of haze with CN concentrations >6,000 cm^{-3} (fig. 6.8), the flight from Thule to Alert showed few other features of interest. During the flight from Alert to Anchorage, however, the aircraft, flying at 337 mb, intersected the stratosphere between 68.5° and 69.5°N; there ozone increased to 170 ppb where it entered the stratosphere. During most of the rest of the flight, ozone remained between 45 and 65 ppb. CN were not detectable in the clean-air region below the stratosphere, except in occasional patches of concentrations >15 cm^{-3}. These patches always occurred in areas where ozone was 50-60 ppb, and were observed just beneath the tropopause.

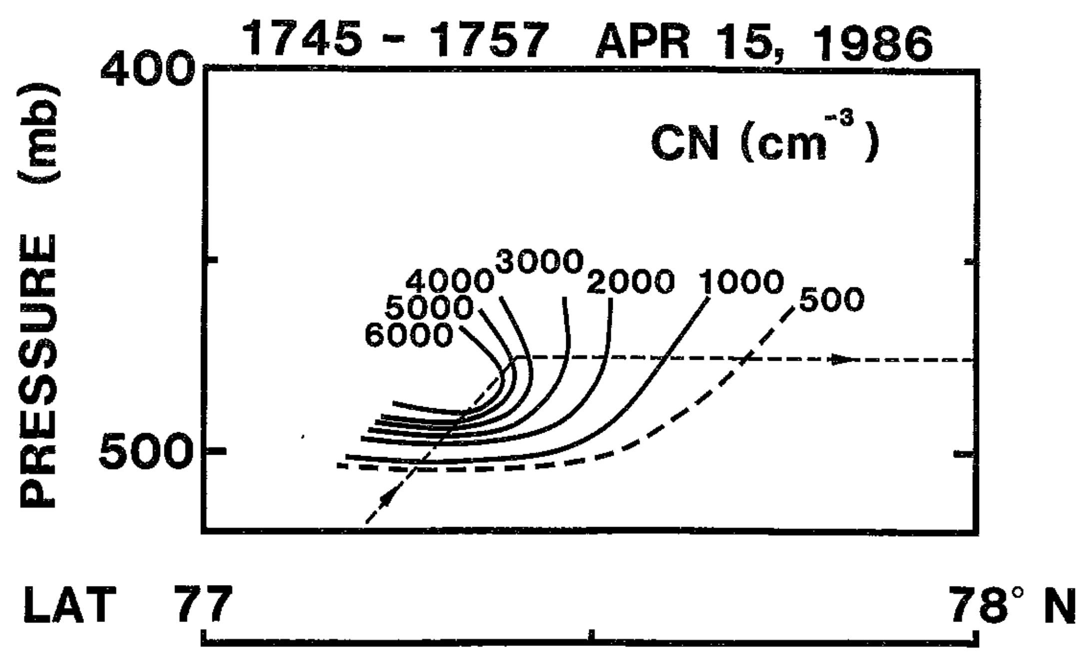


Figure 6.8--High CN concentrations in the haze patch above Thule, April 15, 1986. Aerosol b_{sp} and ozone values were not affected.

ACKNOWLEDGMENTS

This research report is made possible by the support efforts of more than 100 people at government facilities, universities, private companies, and non-profit institutions. In particular, we thank the staff at the Office of Aircraft Operations, Miami, Florida, for persevering during the equipment installation phase of the project and for conducting field operations under less-than-ideal conditions.

Data processing was undertaken by Bill Otto, NOAA, and word processing by Rita Rosson, Marilyn Van Asche, and Lee Prendergast, NOAA.

Financial support for the project was provided by NOAA/GMCC; the Office of Naval Research (Leonard Johnson, contract No. N0014-85-F-0013); the National Aeronautics and Space Administration (Robert Watson, contract No. 16,031; Dixon Butler contract No. W16,231; the Defense Nuclear Agency (David Auton, contract No. BR03301000); and individual National Science Foundation grants to university participants.

REFERENCES

Bodhaine, B. A., and M. E. Murphy, 1980. Calibration of an automatic condensation nuclei counter at the South Pole. J. Aerosol Sci. 11:305-312.

Bodhaine, B. A., and J. M. Harris (eds.), 1982. Geophysical Monitoring for Climatic Change, No. 10:Summary Report 1981. NOAA/ERL Air Resources Laboratory, Boulder, CO, 158 pp.

Derr, V. E., and R. L. Gunter, 1982. EPOCS 1980: Summary Data Report. NOAA Tech. Memo. ERL WPL-101, NOAA Environmental Research Laboratories, Boulder, CO, 173 pp.

Emmanuel, C. B., 1983. The NOAA WP-3D meteorological research aircraft. Preprints, 5th Symp. on Meteorogical Observations and Instrumemtation, Toronto, Ont., American Meteorological Society, Boston, MA, 216-221.

Franklin, J., 1983. Omega dropwindsonde processing. NOAA Tech. Memo. ERL AOML-54, NOAA Environmental Research Laboratories, Boulder, CO, 34 pp.

Hoff, R. M., and N. B. A. Trivett, 1984. Ground-based measurements of Arctic haze mode at Alert, N.W.T. during the Arctic Gas and Aerosol Sampling Project (AGASP). Geophys. Res. Lett. 11:389-392.

Julian, P. R., 1982. The aircraft dropwindsondes system in the Global Weather Experiment. Bull. Amer. Meteorol. Soc. 73:619-627.

Leaitch, W. R., and J. I. MacPherson, 1986. Preliminary data report on measurements made with the National Aeronautical Establishment Twin Otter at Alert, NWT during 1986. Atmospheric Environment Service, Ontario, Canada, 70 pp.

Oltmans, S. J., 1985. Tropospheric ozone at four remote observatories. In Atmospheric Ozone, C. S. Zerefor and A. Ghazi (eds.), D. Reidel, Boston, MA, 796-802.

Raatz, W. E., R. C. Schnell, and B. A. Bodhaine, 1985. Atmospheric cross sections for the Arctic Gas and Aerosol Sampling Program, March-April 1983. NOAA Tech. Memo. ERL ARL-134, Environmental Research Laboratories, Boulder, CO, 50 pp.

Radke, L. F., J. H. Lyons, D. A. Hegg, P. V. Hobbs, and I. H. Bailey, 1984. Airborne observations of Arctic aerosols: I, Characteristics of Arctic haze. Geophys. Res. Lett. 11:393-396.

Radke, L. F., C. A. Brock, J. H. Lyons, and P. V. Hobbs, 1986. Preliminary analysis and integration of the flight-level and lidar data taken by the University of Washington during AGASP II. Cloud and Aerosol Research Group, University of Washington, Seattle, 103 pp.

Ruby, M. G., and A. P. Waggoner, 1981. Intercomparison of integrating nephelometer measurements. Environ. Sci. Technol. 15:109-113.

Schnell, R. C., 1984. Arctic haze and the Arctic Gas and Aerosol Sampling Program (AGASP). Geophys. Res. Lett. 11:361-364.

Schnell, R. C., T. B. Watson, and B. A. Bodhaine, 1988. NOAA WP-3D instrumentation and flight operations on AGASP-II. Submitted to J. Atmos. Chemistry.

Shapiro, M. A., R. C. Schnell, F. P. Parungo, S. J. Oltmans, and B. A. Bodhaine, 1984. El Chichon volcanic debris in an Arctic Tropospause fold. Geophys. Res. Lett. 11:421-424.

Yount, M. E., T. P. Miller, and B. M. Gamble, 1987. The 1986 eruption of Augustine Volcano, Alaska: Hazards and effects. In Geologic Studies of Alaska, U.S. Geological Survey Circular 998, T. D. Hamilton, and J. P. Galloway (eds.), U.S.G.S., Federal Center, Denver, CO, 195 pp.