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DEPARTMENT OF COMMERCE
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METEOROLOGY AND AEROSOL DISTRIBUTION DURING AGASP-III: THE "HAZE" FLIGHTS (MARCH 16-30, 1989)

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Abstract. The third Arctic Gas and Aerosol Sampling Program (AGASP-III) was conducted over the Norwegian Sea and near Svalbard, in the Scandinavian Arctic, in March 1989. The NOAA WP-3D aircraft, with special aerosol and gas sampling instrumentation added, made six flights (out a total of eleven) in which extensive time was spent over the pack ice. These six flights are analyzed in this study. Measurements of wind, pressure, temperature, relative humidity, ozone, and condensation nucleus (CN) concentration were used to identify the air mass type, recent origin, and existence of pollution-derived aerosols, i.e., haze. Significant regions of elevated CN concentrations that could be traced to known northern European source regions were encountered during three of the flights in the lowest 3 km. On the other three flights the CN concentrations were representative of "clean background" conditions at this latitude. Significant concentrations of CN (CN>10,000 cm^{-3}) found immediately below the tropopause on three flights indicated vigorous gas-to-particle conversion. In two instances significant ozone destruction was detected in the surface layer.

1. INTRODUCTION

The Arctic sampling expeditions known as the Arctic Gas and Aerosol Sampling Program (AGASP) were organized and directed by the National Oceanic and Atmospheric Administration (NOAA) and by the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, to determine the distribution, chemistry, radiative effects, and transport of Arctic air pollution. The first field research program, AGASP-I, March-April 1983, consisted of airborne measurements in conjunction with baseline measurements at Barrow, Alaska; Alert, Northwest Territories (NWT) and Ny Ålesund, Svalbard (*Schnell*, 1984). The second sampling program, AGASP-II, April 1986, was conducted over Alaska and Northwest Greenland in the vicinity of the Canadian baseline station at Alert, NWT (*Schnell et al.*, 1989).

On the basis of aerosol chemistry measurements from the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) station at Point Barrow, Alaska (BRW), for the period 1978-1979, *Rahn and McCaffrey* (1980) described Arctic haze as the abundance of tropospheric aerosol of midlatitude origin that has been transported to the Arctic. Over northern Alaska the haze exhibits a pronounced seasonality with late winter-spring values an order of magnitude larger than the typical summer values (*Bodhaine*, 1986). The vertical distribution of haze in the vicinity of Barrow was measured for the first time during the AGASP-I flights (*Schnell and Raatz*, 1984). For the period when the highest concentrations of aerosol were observed aloft, air mass trajectory analysis indicated a likely source region to be northeastern Europe (*Harris*, 1984). During AGASP-II, Aitken nucleus concentrations in excess of 10,000 cm^{-3} were observed in conjunction with strong evidence of gas-to-particle conversion in polluted air of northwestern European origin (*Herbert et al.*, 1989*a, b*).

AGASP-III was conducted as part of a larger atmospheric-oceanographic study titled the Coordinated Eastern Arctic Experiment (CEAREX). The main objective of CEAREX was to understand the ocean, atmosphere, and air-ice-ocean exchange processes in the Fram Strait region. Of considerable importance were the direct measurements of heat, moisture, and momentum flux in the planetary boundary layer (PBL) to understand the mesoscale and submesoscale processes influencing the behavior of ice and the transport of heat northward (CEAREX Drift Group, 1990). In addition to the flights to obtain the momentum, heat, and moisture flux measurements in the PBL (*Walter and Overland*, 1991), flights were dedicated to the study of polar lows and the aerosol-chemistry distribution. The purpose of these latter flights was to measure the properties of Arctic aerosols and gases with particular attention to Arctic haze and its composition, source, and transport, and to determine the Arctic springtime radiation budget with particular attention to surface reflectance, air chemistry, and aerosol physics under cloud and cloud-free conditions. To the maximum degree possible, aerosol and chemistry measurements were made on every flight.

For the first time in the planning of a research flight program in the Arctic, forward trajectories calculated from forecast winds were used in scheduling the flights. The Program for Operational Trajectories (POT) (*Heffter and Stunder*, 1987) was used to estimate the transport of pollution from eight major northern European source regions to determine the most favorable times and locations for sampling. The wind fields were derived from the National Meteorological Center's medium-range forecast run, which is made twice daily. Forecast trajectories were calculated at the 950 hPa (~0.5 km), 850 hPa (1.4 km), and 700 hPa (3.0 km) levels daily by the NOAA Air Resources Laboratory staff in Silver Spring, Maryland, and sent by Fax, in graphical form, to the AGASP operations center in Bodø, Norway. In most instances the forecasts included a 60-h forecast from the 0000 UTC analysis and a 48-h forecast based on a 24-h forecast. The forecasts arrived in Bodø at about 1500 UTC, in ample time to plan the flight for the next day.

The eight locations from which trajectories originated were selected to represent the northern edge of major European source regions. Specifically, London, England; Essen, Germany; Warsaw, Poland; and Kiev, Ukraine represent major industrial regions in northern Europe. The remainder, Leningrad (St. Petersburg), Murmansk on the Kola Peninsula, Vorkuta in the Pechora Basin, and Norilsk represent potential source regions in the Soviet Arctic, as identified by *Ottar* (1989) and *NILU* (1986). Forward trajectories calculated twice daily from each of these locations were used to determine the most favorable days to intercept pollution in the Svalbard region. Once the working regions northwest and southeast of Spitsbergen had been identified, forward trajectories to these regions would have been more useful but were unavailable.

In this report we present observations of condensation nucleus (CN) and ozone concentrations, and associated meteorological variables, as functions of height and distance along the aircraft flight track, for the six "haze" flights using the NOAA WP-3D aircraft. The relevance of the varied meteorological situations for the distribution of aerosols and ozone is discussed. A detailed discussion of the aircraft instrumentation and flight plans can be found in *Schnell et al.* (1993). This is the third in a series of four reports that discuss the meteorological conditions and aerosol distributions during AGASP (*Raatz et al.*, 1985*a* and *Herbert et al.*, 1987, 1993).

2. FLIGHT 303, MARCH 16, 1989

2.1 Overview

Long-range atmospheric transport in the northern European region was dominated by a strong zonal flow for the first week after the aircraft arrived. Although a series of mature cyclones traversed the Greenland Sea during this period, for the most part they were too far to the west to cause significant meridional transport over the continent. Thus the trajectories from all the selected source regions were toward the east and confined to the continent. Between March 10 and 13 smaller cyclones migrated into the Barents Sea and stalled, advecting surface air from the Kola Peninsula to the north. Still the transport forecast for March 15 was not encouraging. The weather maps for the March 13 indicated that the cyclone track had moved to the Scandanavian coast, causing significant meridional transport in the 950-850 hPa layer. As a result of this change in the flow, the trajectories forecast for 1200 UTC March 16 (Fig. 2.1) showed that the transport of air was from the Leningrad region to the north of Svalbard and from the Kola region into the Barents Sea to the south of Svalbard.

The flight conducted on March 16, designated AGASP-III 303, combined two objectives. The first was to study a weak polar low situated at 75°N, 9°E, and the second was to sample the region immediately north and east of Spitzbergen for haze, in response to the transport forecasts. A plot of the flight track and the flight log are found in Appendix A.

2.2 Synoptic Situation

The midtropospheric circulation a week prior to this flight consisted of a well-developed trough extending south from Greenland and a ridge extending from the western Soviet Union across the Barents Sea over Svalbard. This led to strong southerly winds over the sampling region and southwesterly winds over the northern European source regions. Thus a series of cyclones that formed near Iceland migrated across the Greenland and Norwegian Seas toward Svalbard. As the ridge diminished in intensity during the period, winds aloft diminished in speed over Svalbard, and one of the larger cyclones stalled in this region on the March 13. The stationary front extended from north of Svalbard across Novaya Zemlya into the northern Soviet Arctic. To the north of this stationary front, transport at lower levels was from the east, originating in source regions northeast of the Ural Mountains 3 days earlier.

The 500 hPa height analysis shown in Fig. 2.2 is based on the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis for this time. A plan view of the flight track is included on the 500 hPa analysis. The mission was conducted along the eastern edge of a slow-moving trough that extended from a low to the southwest of Svalbard to a secondary low off the Norwegian coast. The trough had dominated the weather in this region for the previous 3 days. Midtropospheric winds were south-southwesterly from Bodø to a point over Spitzbergen where they backed to the southeast, indicating that an easterly component to the north of the trough axis extended across Spitsbergen to Franz Josef Land.

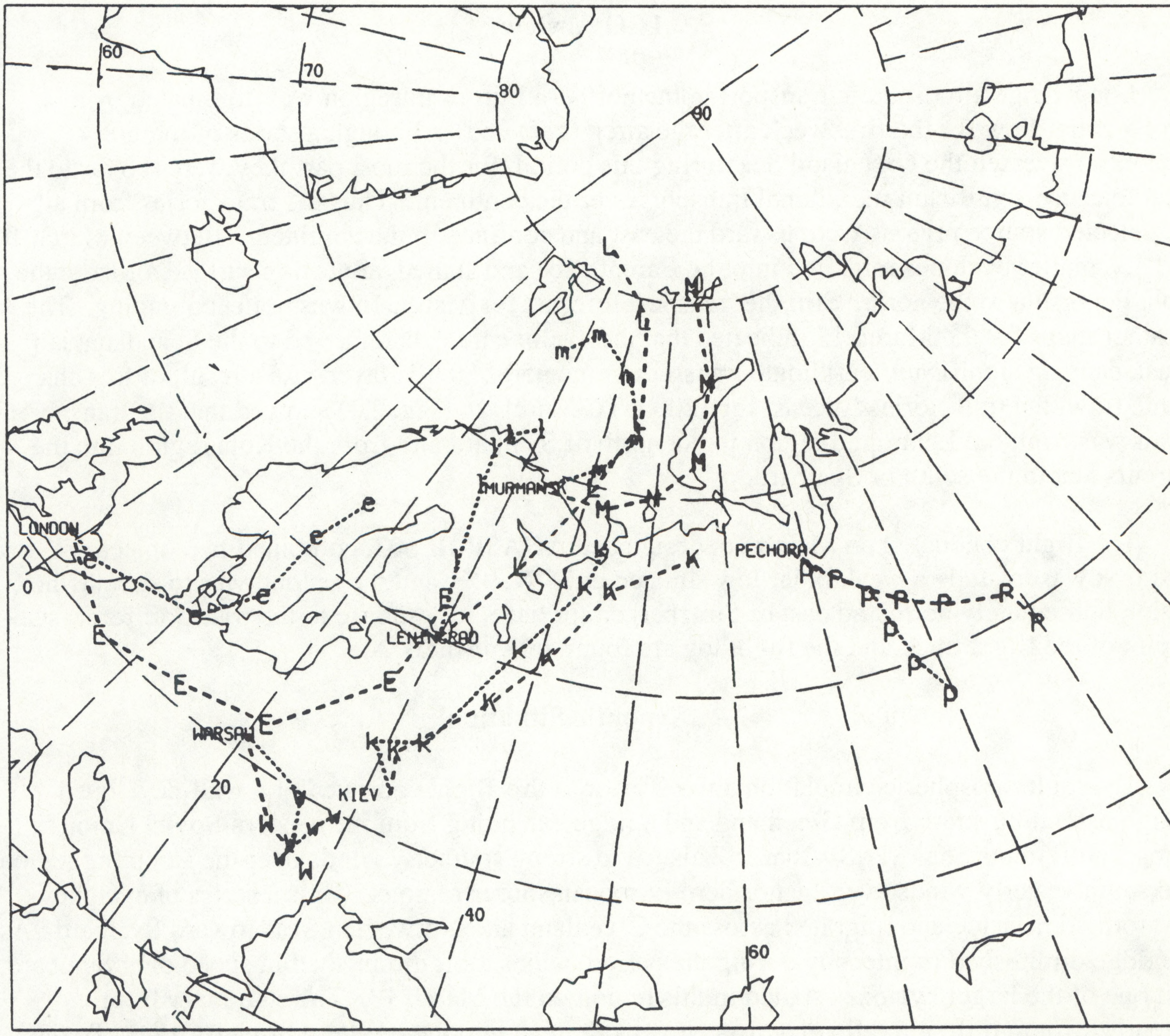

Figure 2.1. Horizontal projection of the Program for Operational Trajectory (POT) 60-h transport forecasts verifying 1200 UTC, March 16, 1989, originating from London (E), Warsaw (W), Kiev (K), Leningrad (L), Muransk (M), and Pechora (P). Lower case letters depict 950-hPa transport, upper case 850-hPa transport.

Both low-pressure centers indicated at 500 hPa were also present at 850 hPa (Fig. 2.3), with very little vertical displacement, consistent with the slow-moving nature of the storm systems. The low-pressure center at the northwest corner of Spitsbergen was the remnant of a former system and was tied to the stationary front at the surface extending to the east. The 850 hPa analysis did not show the depression at 75°N, 9°E, which was studied during this flight. The ridge at 60°E is significant because it had been part of a high-pressure region over the Ural Mountains since the beginning of the month.

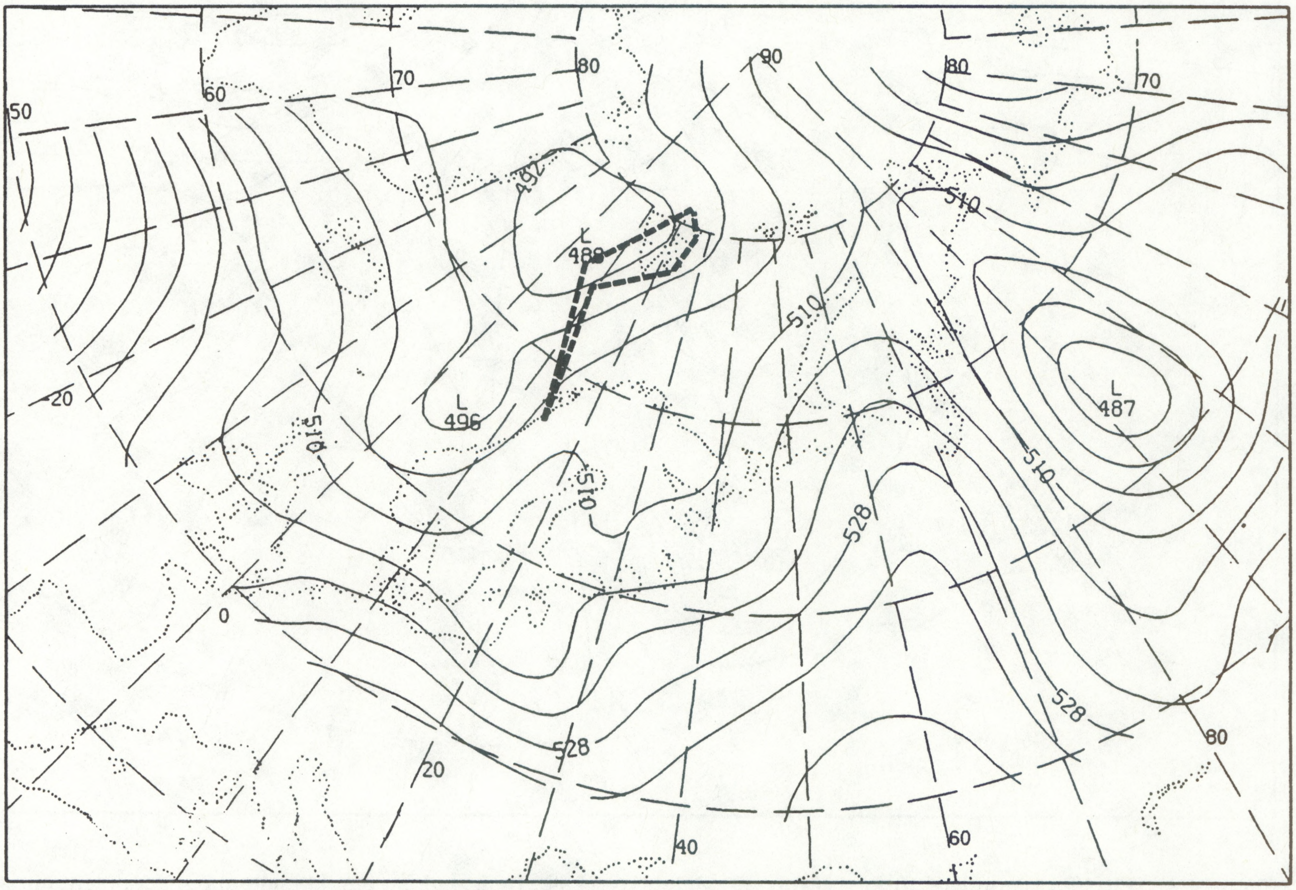

Figure 2.2. 500 hPa synoptic map for 1200 UTC, March 16, 1989. Height contours are indicated are in geopotential decameters. The WP-3D flight track is shown by the heavy dashed line.

2.3 Transects and Profile

At the time of takeoff, the Bodø sky was overcast, consisting of a broken layer of alto-cumulus and scattered cumulus, and the wind was easterly at 8 m s^{-1}. Figure 2.4 shows the humidity was clearly high during the northbound transect. The elevated CN concentrations from 69° to 70°N are difficult to explain in light of the high humidity and the presence of clouds at this altitude. Andøya, Norway, reported altocumulus clouds (5/10) in this region. At 71°N, CN concentrations decreased to levels typical of the upper troposphere, but farther north there were large variations. Because of an equipment malfunction, there were no ozone observations during this flight. The gradual increase in wind speed in Fig. 2.4 from the time the aircraft reached cruising altitude to 74°N indicates that the flight track was crossing the lower extent of the jet stream at an oblique angle. The moist baroclinic zone to the south of 72.5°N was clearly of maritime origin. Through the jet and to the north, the flow was under the influence of the low-pressure system centered at 76°N 0°E at 1200 UTC (Fig. 2.2). The decrease in the relative

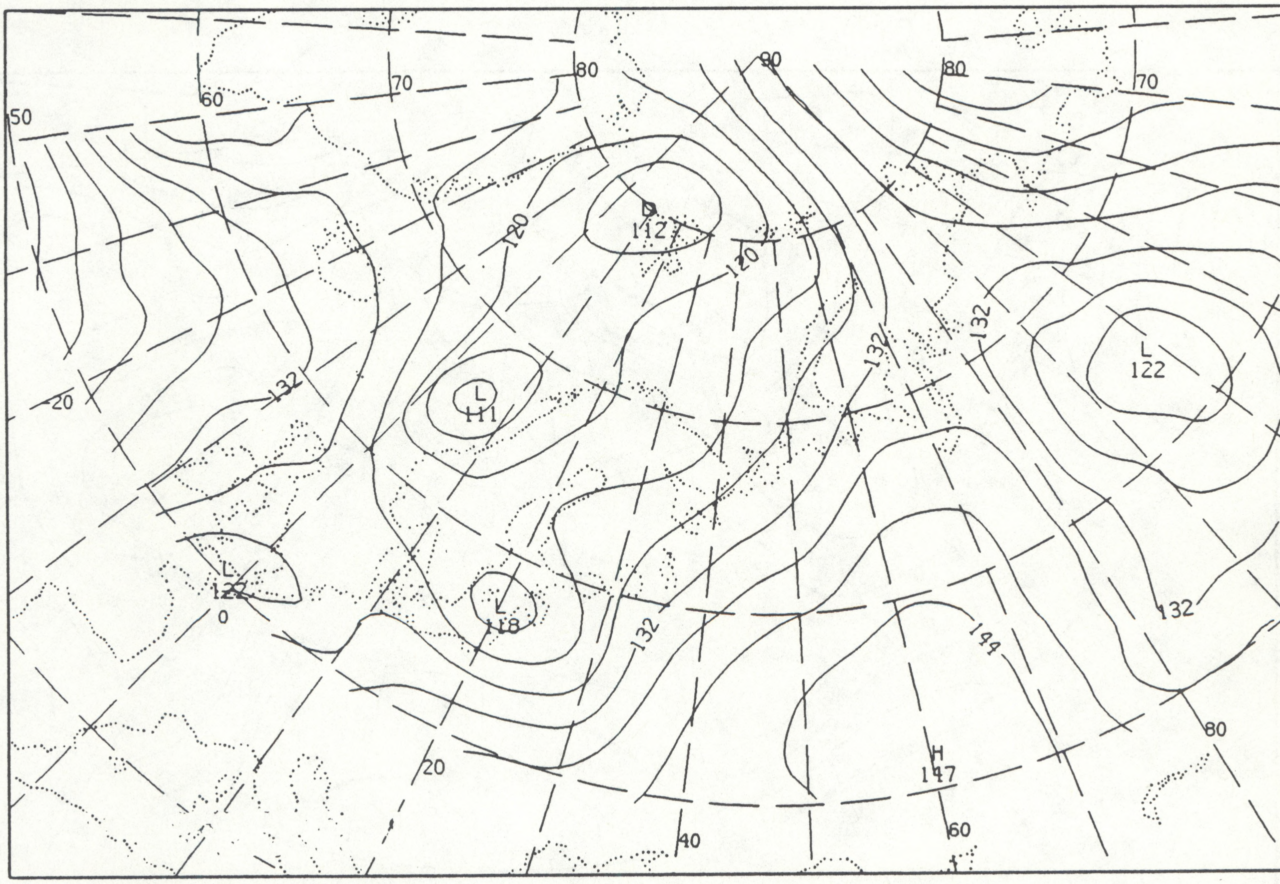

Figure 2.3. 850 hPa synoptic map for 1200 UTC, March 16, 1989. Indicated are height contours in geopotential decameters.

humidity and the large fluctuations in CN concentrations along with small changes in the potential temperature indicate that this air was of stratospheric origin. At 78°N when the winds began to back from the prevailing southerly to a southeasterly direction, the aircraft was passing over the coast of Spitsbergen just south of Longyearbyen. At that time Longyearbyen reported snow showers in the previous hour, and broken stratocumulus and cumulus clouds having a base of 0.8 km. On basis of visual observations of haze layers to the north and east of Nordaustlandet (Appendix A), the descent was initiated at 80.3°N, 28.8°E.

Figure 2.5 shows that three regimes of significance were encountered during this descent off the northeast tip of Svalbard. Tropospheric air was encountered once again at about 480 hPa. A relatively unstable layer, with low relative humidity and elevated CN concentrations (600-1000 cm^{-3}) existed to the 760 hPa level where the aircraft entered the more stable Arctic PBL. The variations of CN concentrations in the 530-820 hPa layer are not typical of Arctic haze layers observed on the Western Arctic basin, where layers are shallower in vertical extent and the variations are greater (*Herbert et al.*, 1989*b*). It should be noted that this layer was free of clouds.

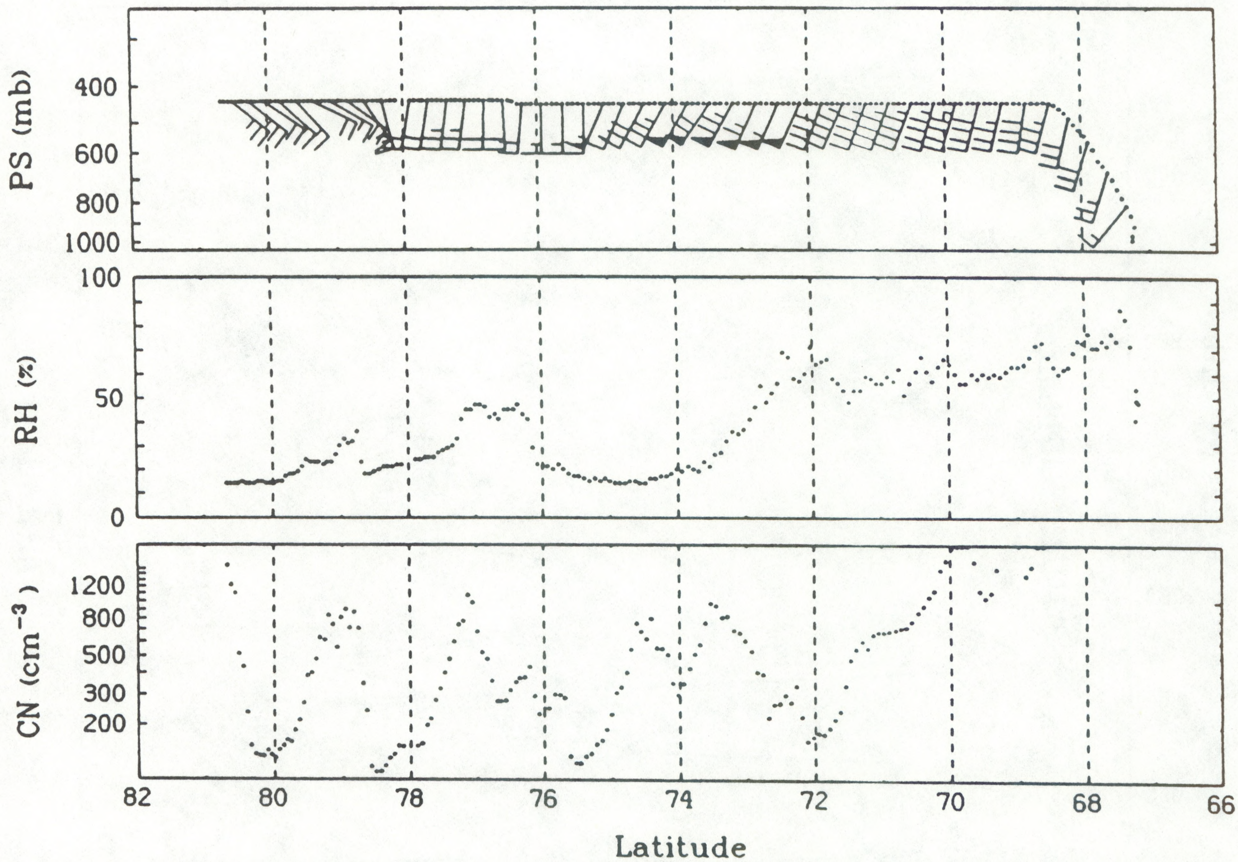

Figure 2.4. Aircraft transect, northbound leg, 0835-1140 UTC, March 16, 1989. Aircraft flight level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), and condensation nucleus concentration (CN) are shown in respective panels.

Below 760 hPa the relative humidity increased and the CN concentration decreased to values that are typical of the marine boundary layer.

The southbound traverse shown in Fig. 2.6 was flown at three different layers, and a sounding was made to the east of the storm at 74°N. The first leg at 849 hPa was along the east coast of Svalbard. Hopen Island reported snow showers with broken low and middle clouds. The relative humidity (RH) varied considerably during the level segments north of the low and gradually increased to near saturation south of the low, 74°-70°N. Except for a brief pulse at 76°N, the CN concentrations observed during the southbound traverse were typical of background values in maritime air.

2.4 Discussion

Forecast trajectories for the 850 hPa level for this time indicated that the Leningrad region could have been a source region (Fig. 2.1). At 700 hPa the Kola region could have contributed to the aerosol loading north of Spitsbergen at this time. Dynamic forcing of the air around the low

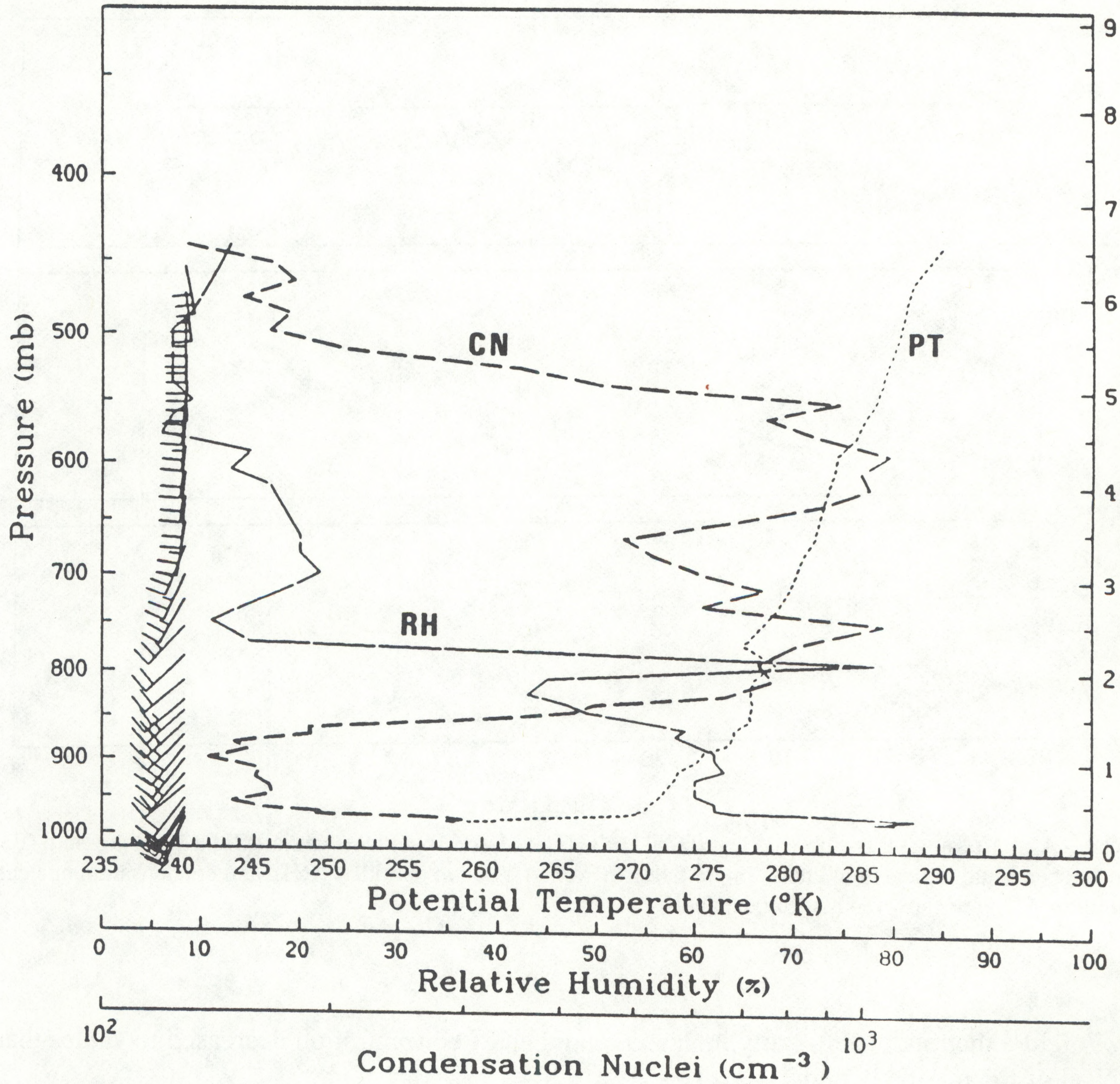

Figure 2.5. Aircraft sounding, 1209-1242 UTC, March 16, 1989. Profiles of potential temperature (PT), RH (RH), and condensation nucleus concentration (CN) are shown.

colocated with the topographic forcing caused by the low's proximity to the east coast of Greenland caused the descending motion upstream. (See *Shapiro* (1985) for a detailed study of a similar storm.)

During the descent to the north of Spitsbergen a 3-km-deep layer of elevated CN concentrations was encountered. The low relative humidity values in this layer suggest a continental source region. An examination of the flow in conjunction with a quasistationary front in the region for the previous 3 days and the indications of an easterly component at 700 hPa to the north of the front suggest a potential source to the east. Both considerations seem to confirm the source regions suggested by the forecast trajectories. Below 760 hPa the aircraft entered the

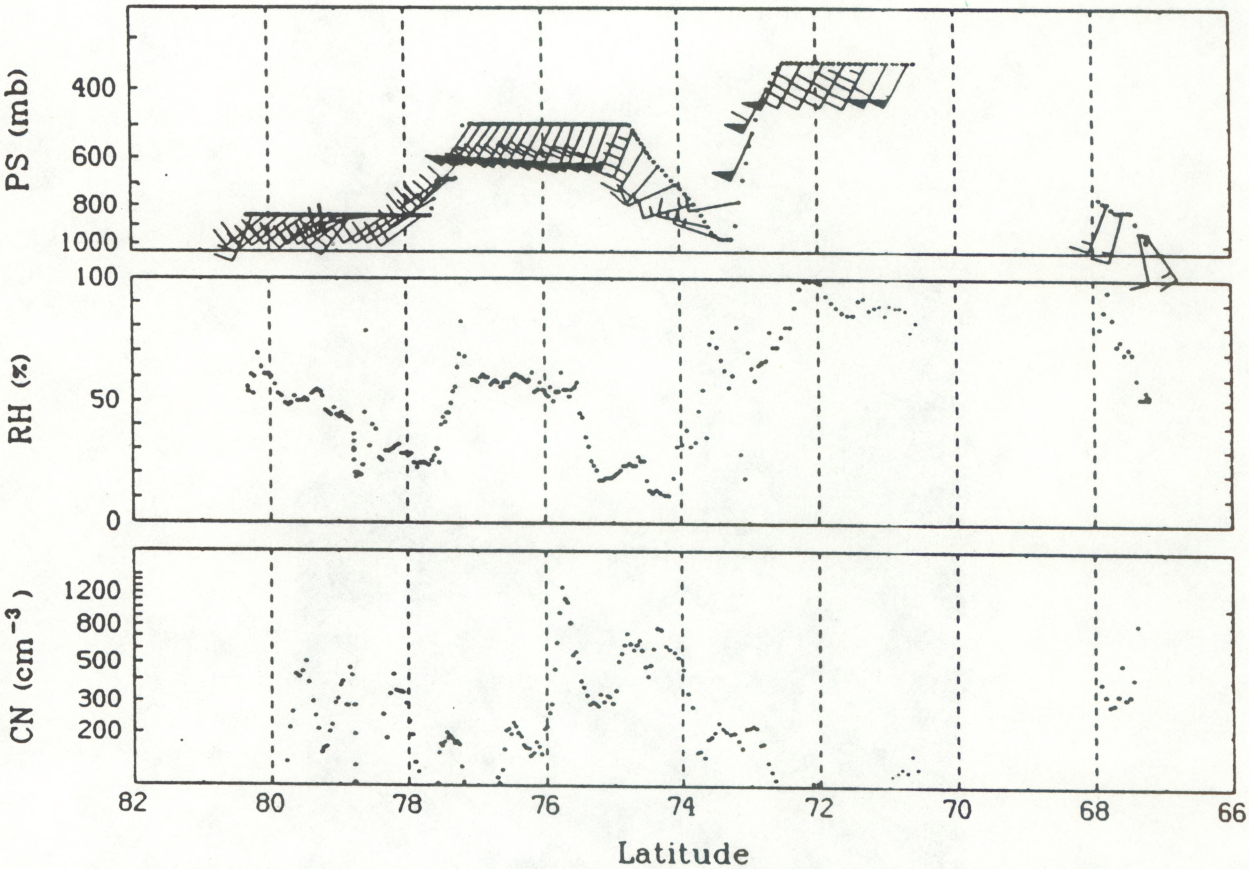

Figure 2.6. Aircraft transect, southbound leg, 1254-1725 UTC, March 16, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), RH (RH), and condensation nucleus concentration (CN) are shown in respective panels.

marine boundary layer. The southwesterly winds in this layer would have passed over Spitsbergen before being sampled in this location.

For the inbound flight there is no meteorological explanation for the brief period of elevated CN concentrations at 75.8°N. There is no other apparent indication of pollution during this flight. Once the sounding into the storm was begun the aerosol concentration decreased significantly and the humidity increased. This indicated a return of maritime Atlantic air.

Rawinsonde measurements along the flight track for this period indicated a significant amount of moisture at all levels. All surface observations for the midday period indicated broken or overcast conditions, with low and middle clouds predominating. Furthermore, clouds seemed to increase over the northern half of the track as the day progressed. Specifically, the satellite photograph indicated clear conditions to the southeast of Spitsbergen at 0802 UTC while Hopen Island reported blowing snow, see Fig. 2.7. Later Hopen Island reported snow showers and broken cloud conditions consisting of low and middle clouds.

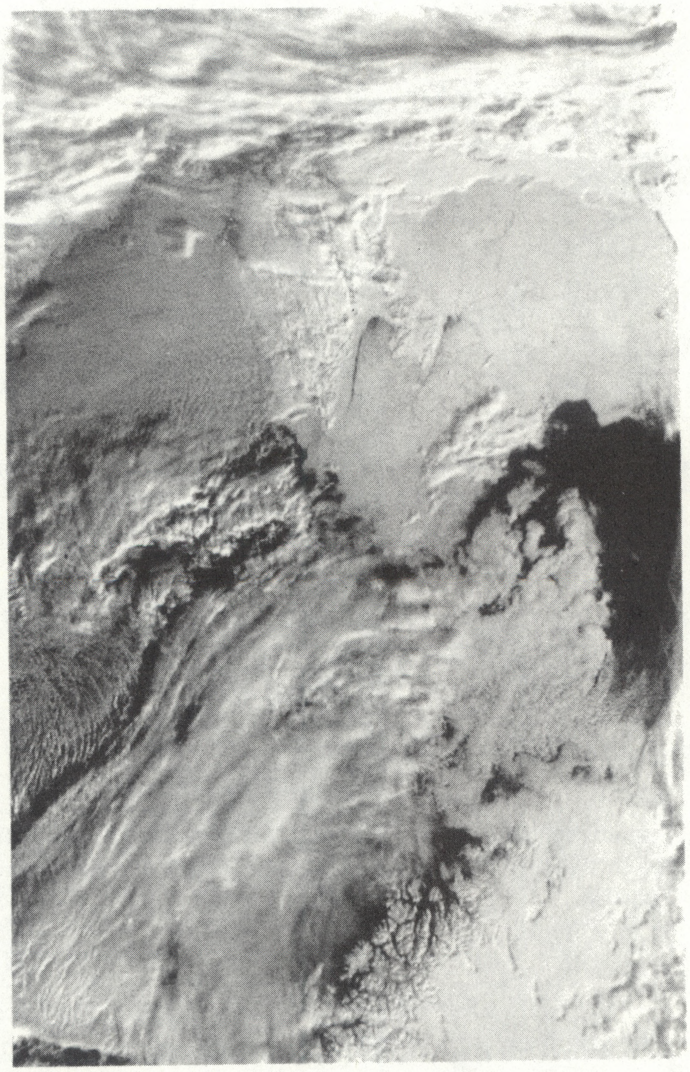

Figure 2.7. Visual satellite image of northern Norway, the Barents Sea, and Svalbard, taken 0802 UTC, March 16, 1989. The Norwegian coast in the vicinity of Andoya and Tromso, is visible in the lower central part of the image, and the southern coast of Svalbard is visible in the upper centeral part of the image.

3. FLIGHT 306, MARCH 21, 1989

3.1 Overview

Responding to southerly winds ahead of a low-pressure system moving north in the Norwegian Sea, air mass trajectory forecasts at both the 950 and 850 hPa levels on March 20, valid for March 21, indicated northward transport of air from the European Arctic into the Barents Sea, from Fennoscandia to the Pechora Basin. Furthermore, the air mass originating in the vicinity of the Kola Peninsula the previous day was forecast to have passed southern Spitsbergen 12 hours earlier (Fig. 3.1). Under the influence of an approaching trough, from lower latitudes, the suggested transport aloft from the British Isles was over Scandinavia and into the Norwegian Sea. Clearly this was the strongest push of northern European air into the Svalbard region since the beginning of the study.

This particular flight, designated AGASP-III 306, was dedicated exclusively to aerosol and gas sampling. The study region was to be to the southeast of Spitsbergen over the pack ice. Because easterly winds were reported in the lower layers, it was desirable to work upwind of the Svalbard land mass to minimize topographical disturbances of the flow. The southern boundary of the working area was set by the location of the ice edge at roughly 76°N. The eastern boundary was 30°E, the edge of the Soviet air space. A plot of the flight track and the associated flight log are found in Appendix A.

3.2 Synoptic Situation

Two days earlier a weak low-pressure system had moved across northern Scandinavia accompanied by a trough aloft. Figure 3.2 shows the ridge over eastern Europe at 500 hPa that built in behind the trough that was present on March 19. The low-pressure regions over the Norwegian Sea and Taymyr Peninsula were slowly moving features that 24 hours earlier were situated slightly to the south of their position on this day. The ridge extended across the Arctic Basin into Siberia. As inferred from this map, upper tropospheric winds were in the 5-15 m s^{-1} range from the southwesterly direction. At the 850 hPa level there was considerably more support for a surface low-pressure system on the Norwegian coast (Fig. 3.3). The circulation supported a well-developed easterly flow in the lower troposphere for the northern extent of the flight track.

In Fig. 3.4, data at different times and locations are combined to present a composite cross section of the thermal structure of the atmosphere. The observations of wind and temperature from rawinsondes were shown to extend from the surface to the top of the chart, 250 mb. The three rawinsondes were from Bodø (BOD), Bear Island (BAR), and Barentsburg (BRG). They were launched at 1200Z, March 21. Rawinsonde data used in this report are plotted on adiabatic diagrams in Appendix B. The set of data plotted on the cross section from the aircraft itself spans the time from takeoff to landing, 0920-1900Z March 21. Since there were as much as 6-h time discrepancies between platform intersection points, it is not surprising that there are differences in the winds and temperatures. The analysis is in terms of potential temperature, which tends to be conserved in stable layers associated with frontal zones.

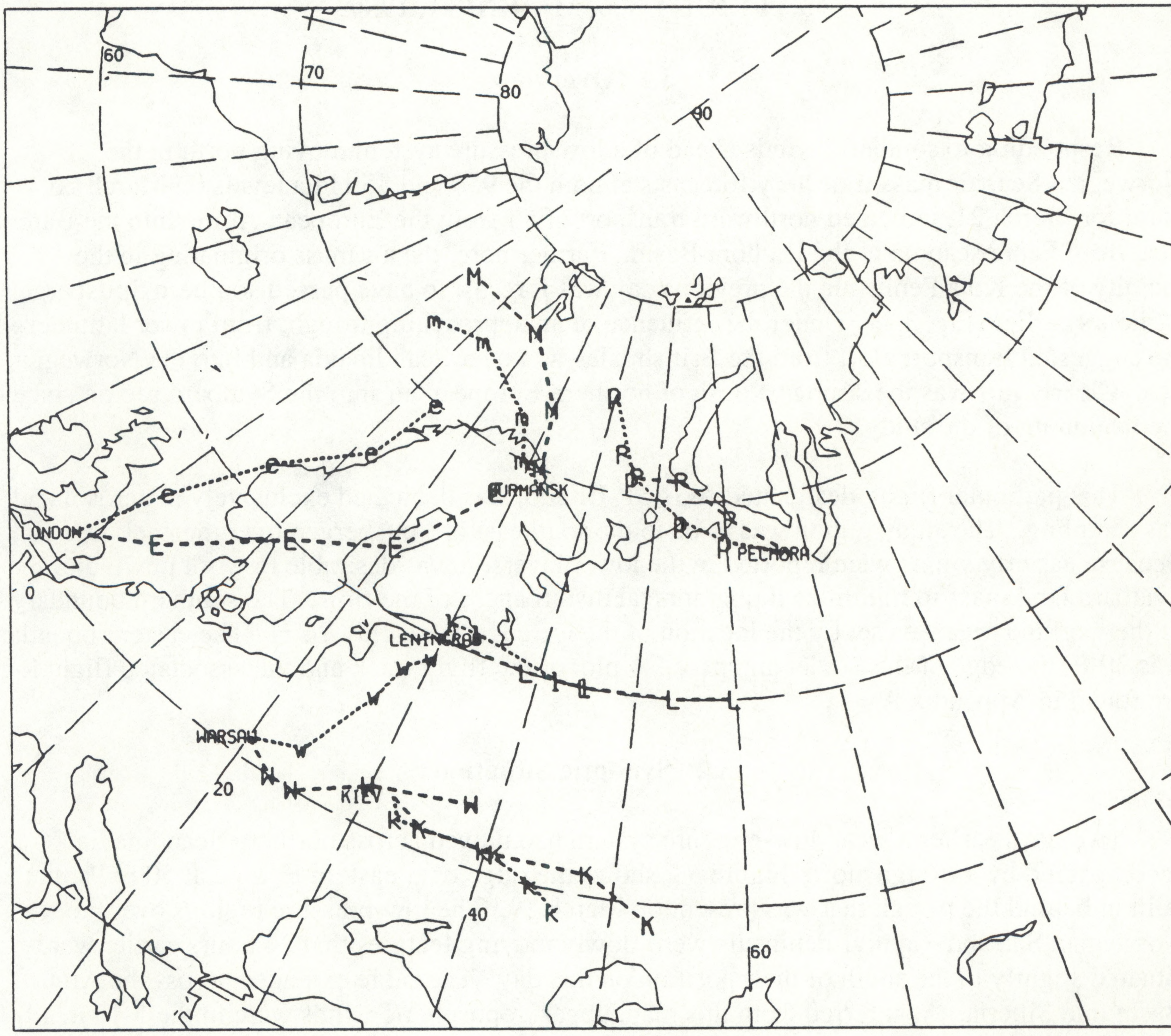

Figure 3.1. Horizontal projection of the Program for Operational Trajectory (POT) 48-h transport forecasts verifying 1200 UTC, March 21, 1989, originating from London (E), Warsaw (W), Kiev (K), Leningrad (L), Muransk (M), and Pechora (P). Lower case letters depict 950-hPa transport, upper case 850-hPa transport.

As illustrated in Fig. 3.4, the WP-3D aircraft proceeded from Bodø, Norway, to the sampling region, 78.3°N, 27.5°E, where a profile was begun. At three levels, 409, 770, and 993 hPa, traverses were made to obtain stable radiation observations. Typically, profiles were flown at a descent rate of about 9 hPa min^{-1} (150 m min^{-1}). Interspersed were three "radiation runs" consisting of level legs flown parallel and perpendicular to the direction of the sun for a total of about 7 min each. The legs were usually flown at the ferry flight altitude, immediately before the descent, at a mid-sounding point, usually about 700 hPa, and near the surface. When haze layers

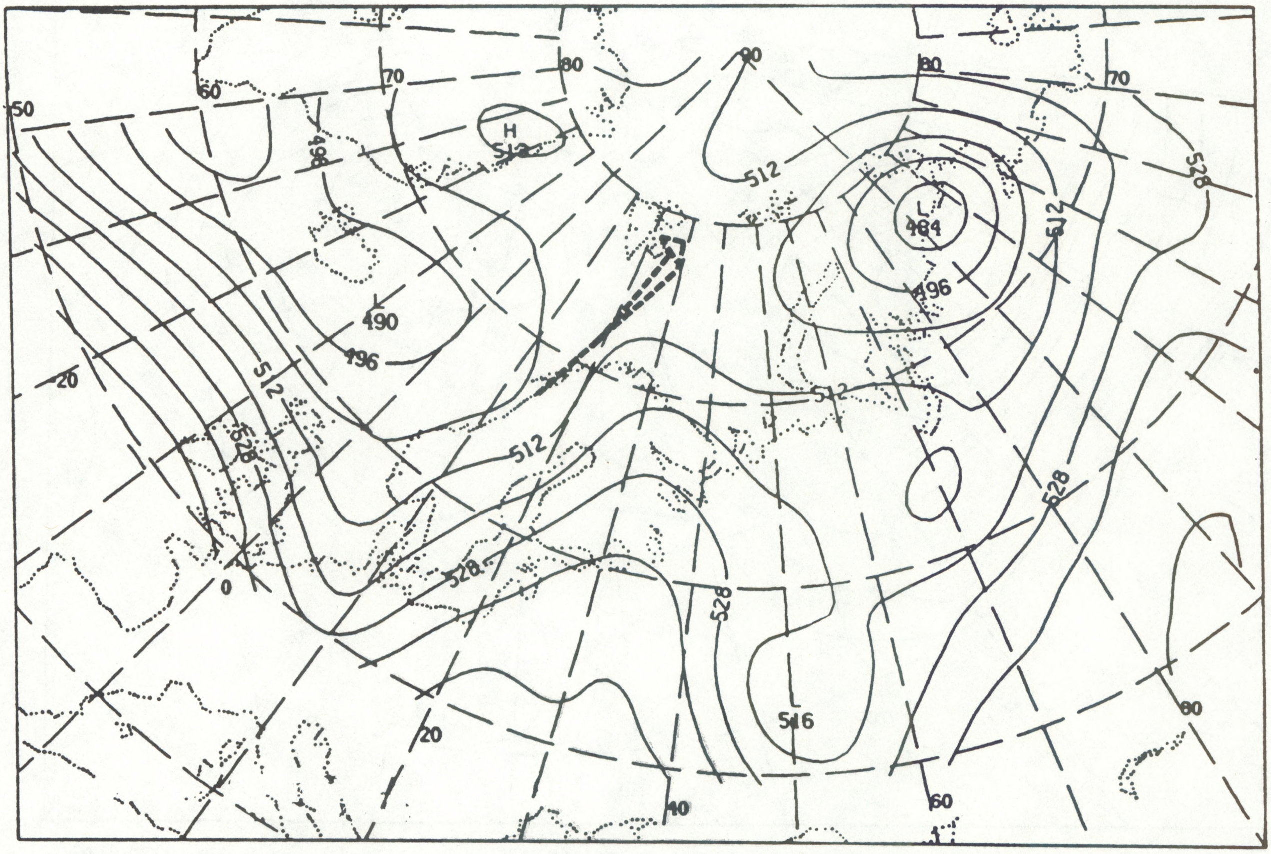

Figure 3.2. 500 hPa synoptic map for 1200 UTC, March 21, 1989. Indicated are height contours in geopotential decameters. The WP-3D flight track is shown by the heavy dashed line.

were encountered, longer traverses were flown to allow for extensive filter sampling of the layer. See *Schnell et al.* (1993) for more details. After sampling in the region southeast of Svalbard for about 4 hours, the WP-3D returned to Bodø.

3.3 Transects and Profile

In Fig. 3.5, the RH values indicate that the aircraft passed through the polar front shortly after its departure from Bodø. Below the front the RH was greater than 90%; it was snowing at the time in Bodø. There was considerable moisture along the flight track, RH > 80% to 72°N, which gradually declined to 50% at 78°N. The winds at flight level gradually turned and decreased in strength, but there was no indication of a significant shift until 75.2°N when the wind backed to an easterly direction. The RH shows a significant decrease at this location as well. The CN concentrations are unusually low, in the 100-400 cm^{-3} range to 71.6°N, indicating the possibility of savaging by condensation processes in air that arrived in this region from along the polar front. As the RH decreased at 72°N, the CN concentrations increased abruptly. At 75°N, at

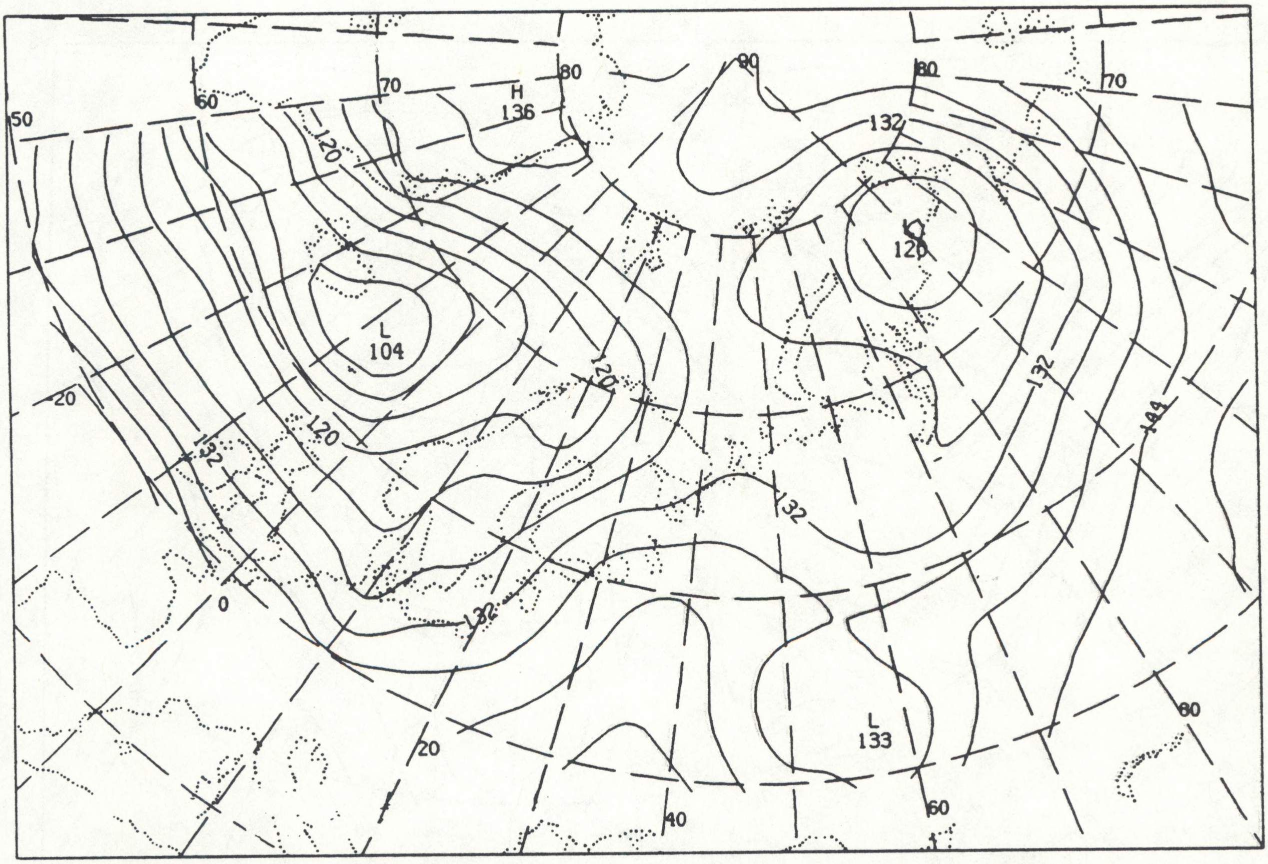

Figure 3.3. 850 hPa synoptic map for 1200 UTC, March 21, 1989. Indicated are height contours in geopotential decameters.

the southern edge of the warm segment of the polar front (see Fig. 3.4), the CN concentration decreased again in conjunction with a rise in RH. The change in CN concentration at this latitude was supported by a change in the wind direction and speed, a veering of the wind indicating a more westerly component. While ozone concentrations were also slightly higher between 73° and 74°N and show more variability in the maritime air, the mean was relatively steady at about 35 ppb during this northbound flight.

In Fig. 3.6, the profile at 78°N indicates that there were two distinct transitions. The first was at 470 hPa where the aircraft descended from the upper extent of the warm frontal zone into a relatively unstable region below. The abrupt decrease in RH and the wind shift from a light westerly to a steady easterly direction mark this transition. The second was at 880 hPa when the aircraft entered the Arctic boundary layer (see Fig. 3.4). At this point the RH increased to near saturation and remained above 70% to the surface. Immediately above the Arctic inversion there are two layers, each 100 hPa thick, in which the RH varied considerably more than it did above. The layers were also more stable than above and were denoted by shifts in the wind direction.

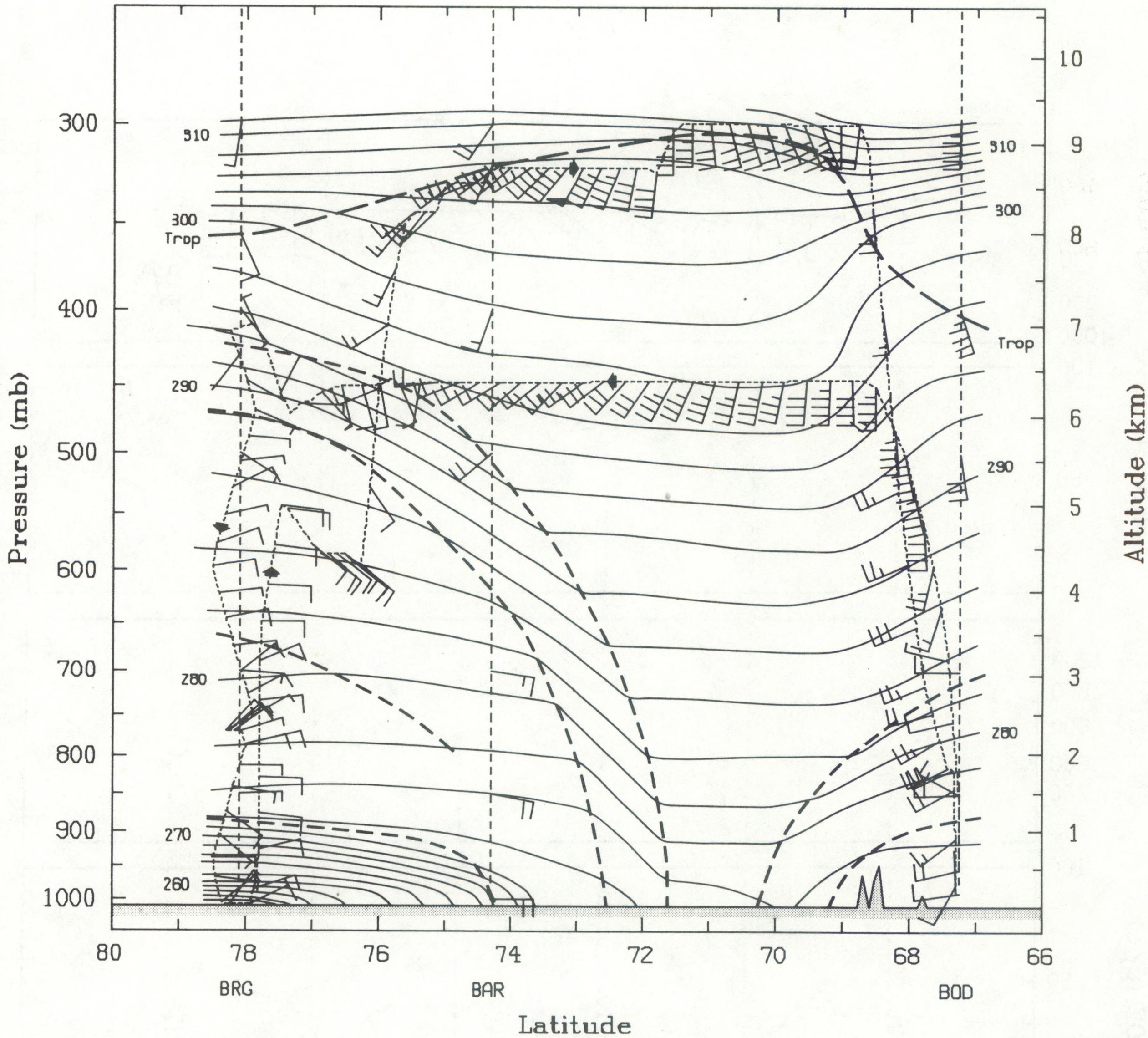

Figure 3.4. Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 10 knots) between Bodø and 79°N, 0920-1900 UTC, March 21, 1989. The tropopause is indicated by a thick long-dashed line; stable layers, frontal zones, and the top of the Arctic boundary layer by thick short-dashed lines; and the aircraft flight track by thin-dashed lines. Arrows are placed at the beginning of each hour to indicate the direction of the aircraft. Vertical dashed lines show the rawinsonde location (BOD, BAR, and BRG).

The magnitude of the CN concentrations and the variability with height were similar to those seen in the western Arctic (*Herbert et al.*, 1989*b*). In the relatively unstable, dry layer between 470 and 680 hPa there were two distinct layers of elevated CN concentrations. In both cases the peak concentrations were in excess of background for this region. Visual observations from the aircraft were of dense haze throughout this layer. Below 680 hPa the CN concentration was uniformly above 800 cm^{-3}; the layering was not as apparent as it was above. The ozone showed a slight increase to 550 hPa, and was relatively constant at 45-55 ppb to the top of the Arctic inversion. Below that level the values decreased to about 25 ppb. The lowest ozone value measured on this profile was 20 ppb at 1009 hPa.

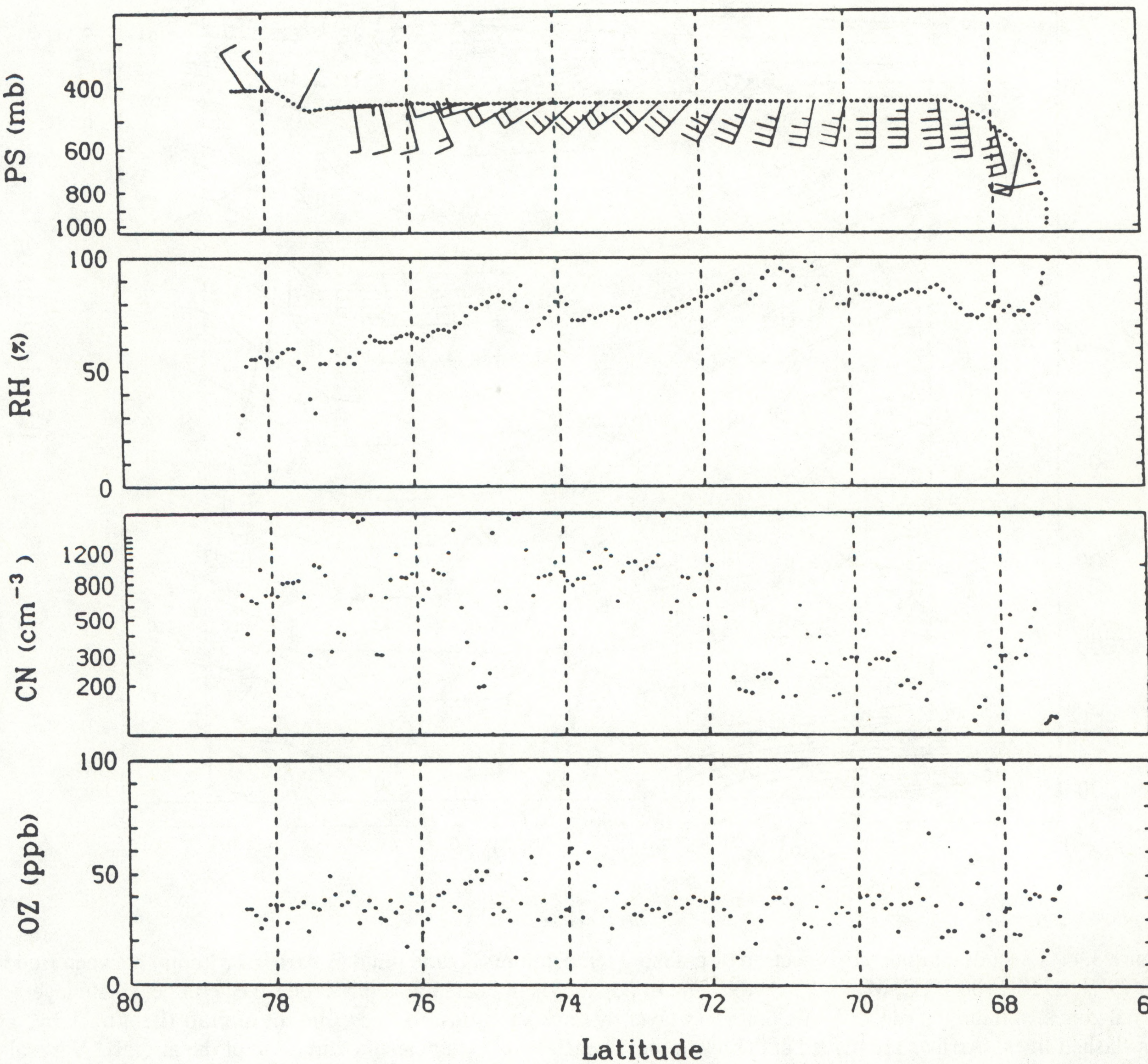

Figure 3.5. Aircraft transect, northbound leg, 0920-1148 UTC, March 21, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

The southbound transect began at 77.4°N at 560 hPa (Fig. 3.7) in the dry region, as seen on the RH profile. RH gradually increased and CN concentrations correspondingly decreased to 71.8°N, where the aircraft entered the stratosphere. Once again the ozone values seem to be a little higher at about 74°N, but the significant rise was at the tropopause. The elevated CN values observed in Fig. 3.5 between 71.8° and 75.2°N in the maritime air were not evident at 321 hPa on the return flight. The ozone concentrations clearly indicate the point where the aircraft crossed from the stratosphere to the troposphere on the descent into Bodø (Fig. 3.4).

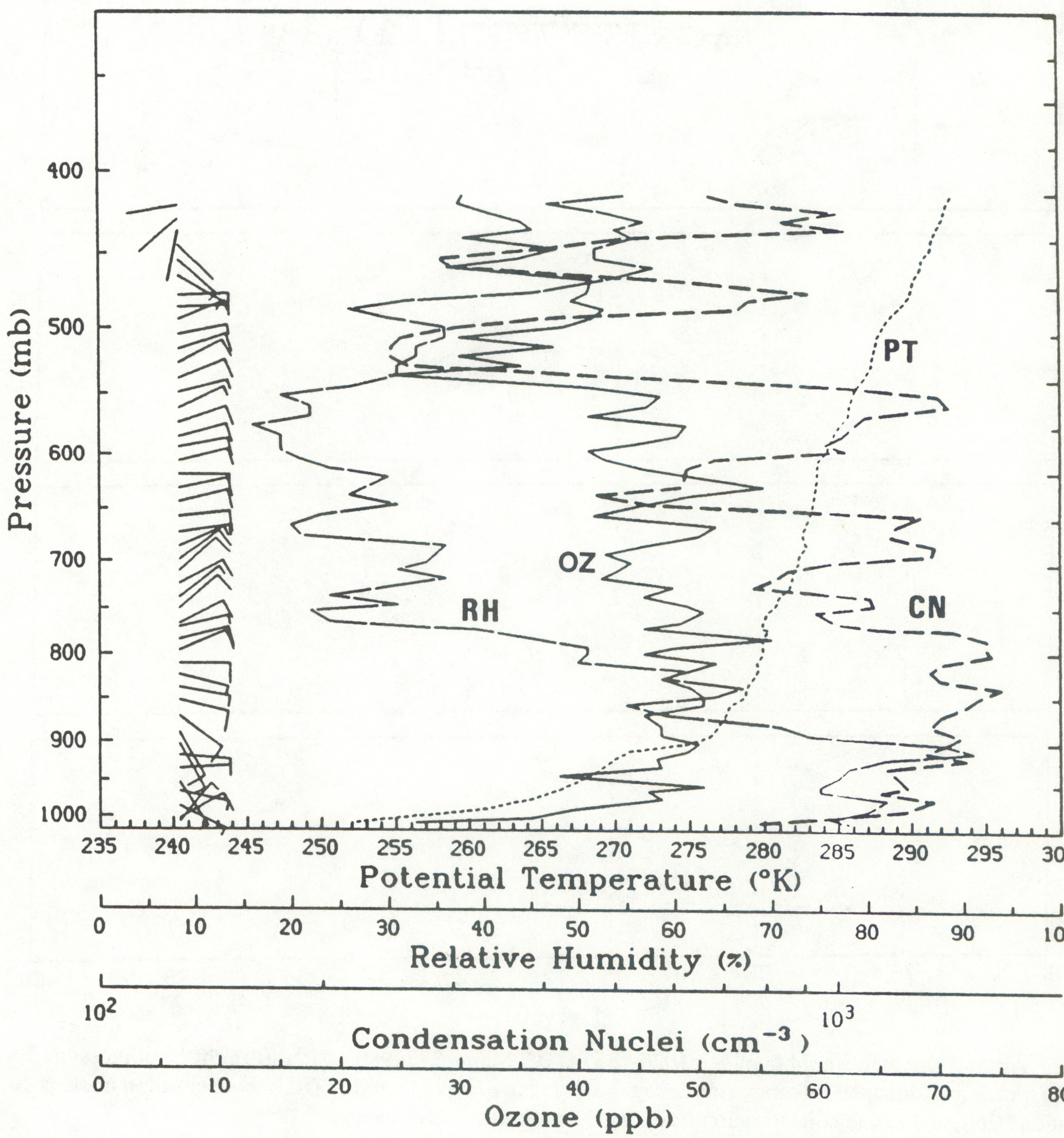

Figure 3.6. Aircraft sounding, 1200-1304 UTC, March 21, 1989. Profiles of potential temperature (PT), RH (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown.

3.4 Discussion

Starting at 700 hPa on the ascent from Bodø to the interception of the frontal zone at 75.2°N, the aircraft was in the warm sector of an occluded frontal system, Fig. 3.4. The aircraft did not clear the clouds until reaching 460 hPa. The recent history of this air showed that it was from over Scandinavia and the North Atlantic. The relative humidity in this air mass decreased as the

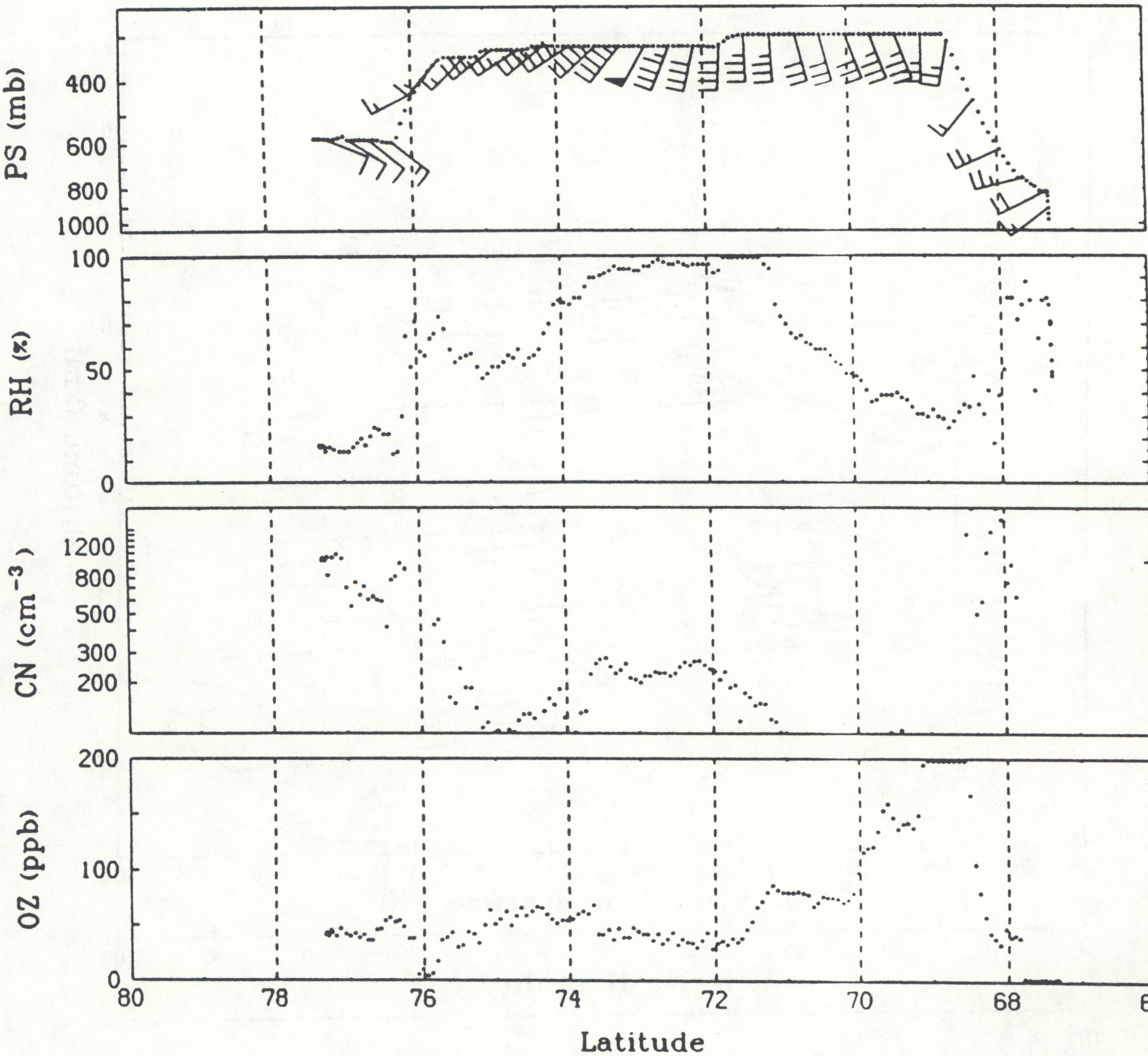

Figure 3.7. Aircraft transect, southbound leg 1620-1857 UTC, March 21, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

aircraft moved north, reflecting a more continental history. Precipitation and cloud savaging probably account for the low CN concentrations south of 72°N. There was a slight increase in the RH, and a corresponding decrease in CN concentration as the aircraft approached the warm front. Patches of haze, reported by the aircraft crew from 72° to 75.6°N, became more dense and persistent to 78°N. CN concentrations varied considerably in the frontal zone, indicating sloping layers of clear and aerosol-laden air. These aerosol layers are clearly evident at 430 and 480 hPa in the profile. In the unstable continental polar air below the warm front and above the Arctic boundary layer, the CN concentrations were more uniform, not showing the layer structure often seen in polluted air masses at high latitudes. Again, as in the midtroposphere, when the RH increased in the boundary layer, the CN concentration decreased. Clearly the character of the CN profile suggests local production of aerosols at 500 hPa and above; long-range transport explains the values below 500 hPa. The potential temperature in the center of the lowest aerosol layer (930 hPa) was 269 K (Fig. 3.4), which corresponds well to the -5°C observed over the Kola Peninsula 48 hours earlier. The layer at 700 hPa with a potential temperature of 828 K would have originated about 10° farther south.

During the return flight, at 500 hPa from 76.1°N, the aircraft was in the continental air mass. The wind shift from an easterly direction to a southwesterly direction, along with an abrupt increase in the relative humidity, signaled the return to the maritime air mass (Fig. 3.4). On the basis of ozone concentrations in the 70-85 ppb range from 71.4° to 70°N, the aircraft was immediately below the tropopause. The aircraft was in this air mass until entering the stratosphere at 70°N. The aircraft returned to the troposphere at the 440 hPa level during the descent into Bodø (Fig. 3.4).

4. FLIGHT 307, MARCH 23, 1989

4.1 Overview

With the discovery of substantial aerosol concentrations in the vicinity of Svalbard on the March 21 flight, it was our intent to return to this region as soon as possible to resample the aerosol. The transport forecast from the Kola Peninsula for March 23 indicated that the plume that was over the Svalbard region for the previous 2 days had moved to the southwest into the Norwegian Sea (Fig. 4.1). The transport forecast at 950 and 850 hPa for the 48-h period preceding this time showed considerable transport from the eastern European source regions into the western Barents and Kara Seas. With the passage of a low-pressure system at 850 hPa over Fennoscandia, easterly winds to the north of this low could have advected eastern European air in the western Barents Sea to the vicinity of Svalbard in the preceding 24 hours. On the basis of this prospect and the possibility of resampling the aerosols encountered on flight 306, a mission was scheduled.

4.2 Synoptic Situation

Figure 4.2 shows a low-pressure region extending across the North Atlantic from the tip of Greenland into the Norwegian Sea, and a weak high-pressure region over the northern half of Greenland, as was the situation at 500 hPa during the previous flight (Fig. 3.2). A second, stationary low was north of the Taymyr Peninsula. By this date the ridge that had been over Scandinavia had moved to the east, being replaced by the very weak trough shown centered over the Barents Sea at the time of the map. Winds at 500 hPa in the region of the flight were generally less than 10 m s^{-1}. At 850 hPa (Fig. 4.3) the Barents Sea low and the Greenland high were significantly stronger. This leads to a much stronger easterly geostrophic component to the wind at that level than at the 500 hPa level.

The outbound flight followed the same path as on March 21. Detailed plan views of the flight tracks can be found in Appendix A. Designated AGASP-III 307, the flight proceeded from Bodø to a point southeast of Spitsbergen, 77°N, 29°E, where the aircraft turned to the north. Shortly thereafter the descent profile began, and included three level segments at 375, 793, and 1003 hPa to measure the radiation balance. The aircraft then made a haze survey to 700 hPa and back to 920 hPa before proceeding south at 885 hPa in a layer of elevated CN concentrations. At 74°N 22°E, 3 hours and 51 minutes after the descent began, the WP-3D left the sampling area, climbing to 375 hPa. An additional sounding was made at 71°N 11°E to examine a haze layer observed at this latitude on the northbound flight. The aircraft returned to Bodø at 710 hPa.

4.3 Transects and Profile

The analysis of potential temperatures along the flight track was based on the 1200 UTC, March 23 rawinsondes from BOD and BAR, in addition to aircraft data (Fig. 4.4). Southerly winds prevailed during the ascent from Bodø to about 70°N due to the influence of the low-pressure system in the Norwegian Sea. Overall there is a gradual decrease in the RH during this northbound transect (Fig. 4.5). In this region over the northern Norwegian coast, the CN

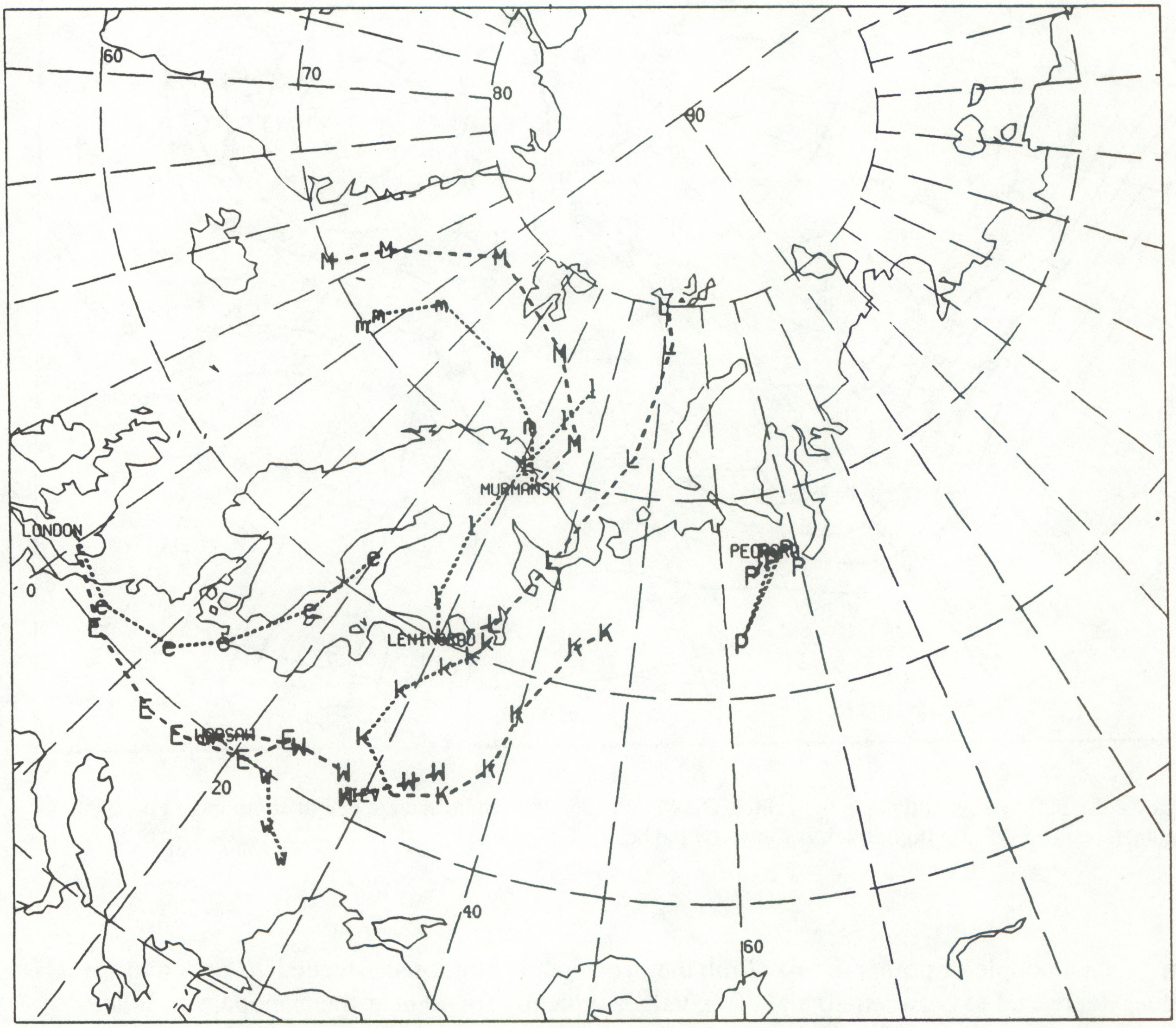

Figure 4.1. Horizontal projection of the Program for Operational Trajectory (POT) 60-h transport forecasts verifying 1200 UTC, March 23, 1989, originating from London (E), Warsaw (W), Kiev (K), Leningrad (L), Muransk (M), and Pechora (P). Lower case letters depict 950-hPa transport, upper case 850-hPa transport.

concentrations were in the 100-300 range with a brief period in excess of 300 cm^{-3} between 69.2° and 69.9°N. At 70°N, in conjunction with a shift in the wind to northwest, the CN concentrations dropped to <200 cm^{-3}, well below typical background level. The CN concentrations remained at this low level to 72°N. At 72°N the winds veered to the east-southeast with an average speed of 11 m s^{-1}. The CN concentrations at this transition increased to values in excess of 3000 cm^{-3}. There was also a slight increase in the ozone concentration at 72°N. From 74° to 78°N the concentrations of CN were exceedingly variable, and these decreased as the aircraft proceeded north. During the climb to 375 hPa the values decreased further to "background" levels of 300

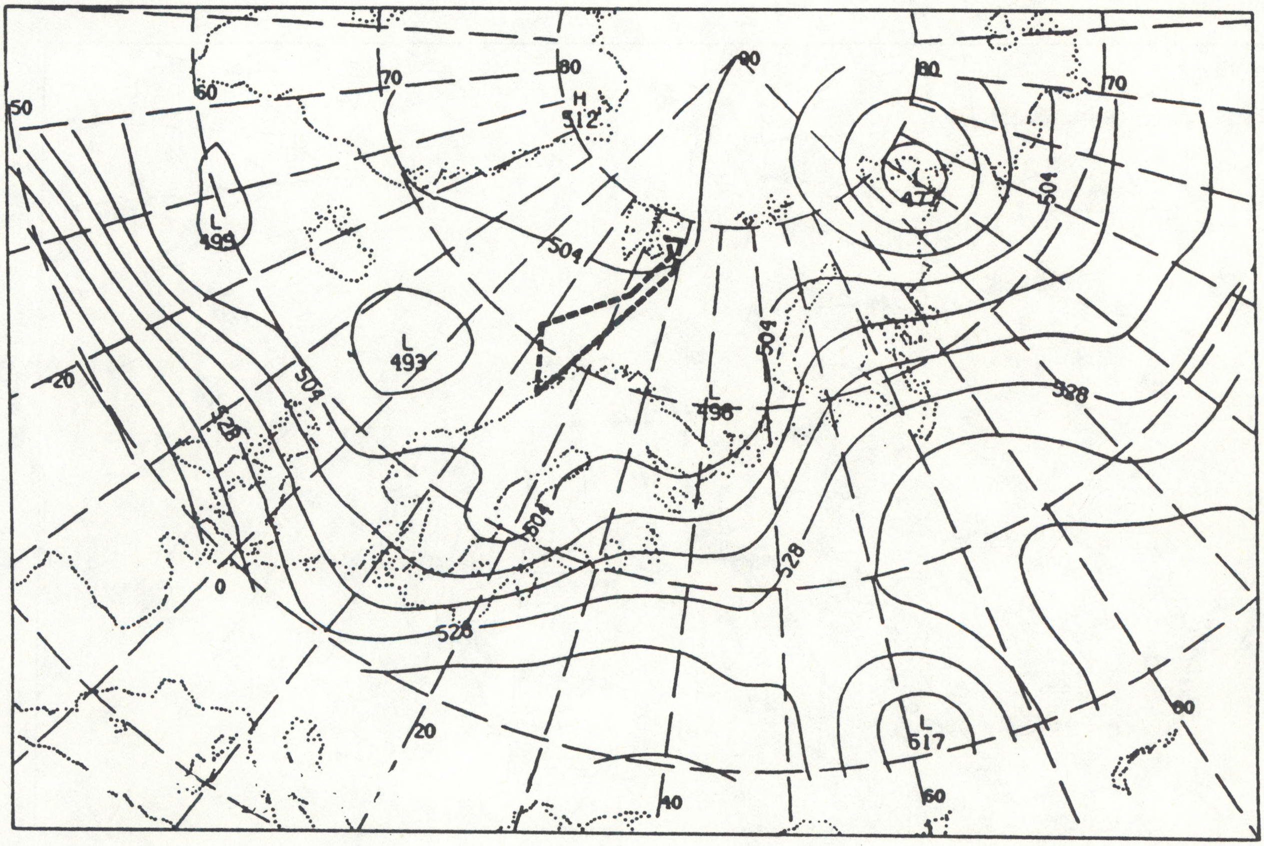

Figure 4.2. 500 hPa synoptic map for 1200 UTC, March 23, 1989. Indicated are height contours in geopotential decameters. The WP-3D flight track is shown by the heavy dashed line.

cm^{-3}. At a couple of points in this climb the ozone concentrations exceeded 70 ppb, and the RH values decreased to between 20 and 30%, values typically found near the tropopause. In the absence of a sounding at Barentsburg it is not possible to determine the exact height of the tropopause at this latitude in this region (Fig. 4.4). The shift in the wind to a northerly direction at 78°N may indicate subsiding air in this region.

Figure 4.6 shows that during the descent at 78°N only two significant discontinuities were encountered. The first was at 700 hPa, the top of the primary stable layer, where the winds began to veer from being northerly to more easterly. Above that level the sounding was reasonably unstable, with RH values in the 40-60% range above 600 hPa. The 600-700 hPa layer was relatively dry. During the descent the CN concentrations gradually increased from very low values of less than 200 cm^{-3} at 450 hPa to 300 cm^{-3} at the top of the inversion. Below 700 hPa the RH was increasing and the CN concentrations were in the 500-1000 cm^{-3} range. The second discontinuity was at 915 hPa, marking the top of the Arctic PBL (see also Fig. 4.4). It is at this point that the CN concentrations were a maximum; they began to decrease as the aircraft approached the surface. The wind speed also increased to the surface as the direction backed to a

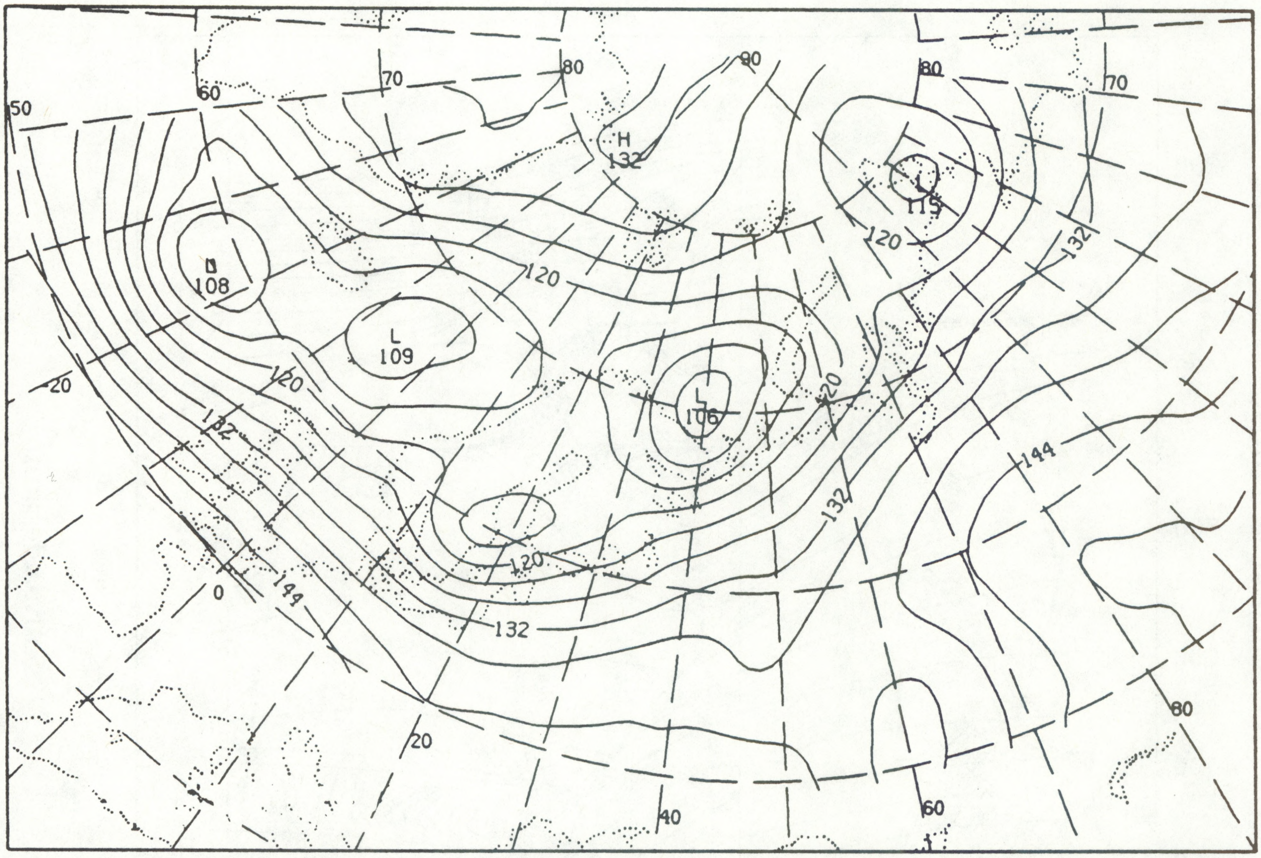

Figure 4.3. 850 hPa synoptic map for 1200 UTC, March 23, 1989. Indicated are height contours in geopotential decameters.

more northerly direction. Ozone concentrations were relatively steady in the range of 30-50 ppb, with only a slight indication of destruction below 990 hPa. The lowest 10-s value during this flight was 15 ppb, observed at 1002 hPa.

The southbound flight transect (Fig. 4.4) began with a sounding to 998 hPa followed by an extended run across the pack ice between 920 and 860 hPa. From 78° to 74°N the aircraft was in the dry, stable layer immediately above the Arctic PBL. Figure 4.7 shows the CN concentrations north of 75°N while somewhat elevated, were relatively uniform. Larger variations were encountered between 75° and 73°N (500-1200 cm^{-3}), indicating the presence of light haze at the intersection of the stable layer and the polar front. At 74.5°N values increased to in excess of 1000, indicating moderate haze. Winds in this layer are commonly in excess of 20 m s^{-1} from the east-northeast. At 74°N the aircraft began a climb to 306 hPa, penetrating the stratosphere at 72.4°N, as indicated by the ozone values. Throughout this region the CN concentrations were elevated and showed considerable variability, as they did on the northbound flight. CN concentrations were in the 1000-2000 cm^{-3} range during the descent at 71°N and along the return at 710 hPa.

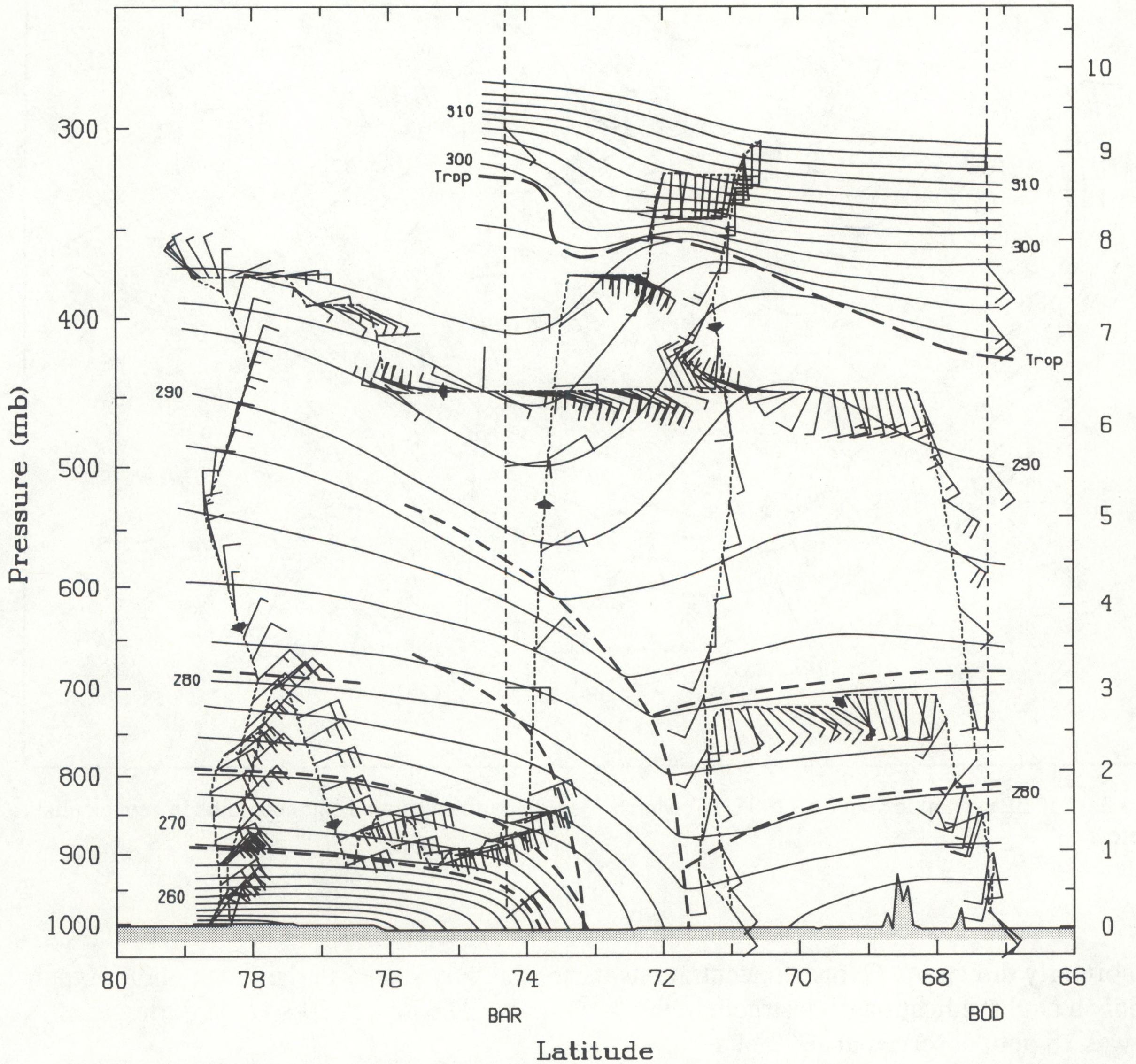

Figure 4.4. Latitude-altitude cross section of potential temperature (k) and wind (1 barb = 10 knots) between Bodø and 79°N, 0804-1748 UTC, March 23, 1989. The tropopause is indicated by a thick long-dashed line; stable layers, frontal zones, and the top of the Arctic boundary layer by thick short-dashed lines; and the aircraft flight track by thin-dashed lines. Arrows are placed at the beginning of each hour to indicate the direction of the aircraft . Vertical dashed lines show the rawinsonde location (BOD and BAR).

4.4 Discussion

Shortly after take-off the aircraft encountered a polluted air mass with CN concentrations in excess of 3000 cm^{-1}. Winds were southeasterly throughout this region, suggesting a local, northern Scandinavian source region. The forecast trajectories suggested the source of this pollution to be the Kola Peninsula or industrial regions to the south in the vicinity of Leningrad.

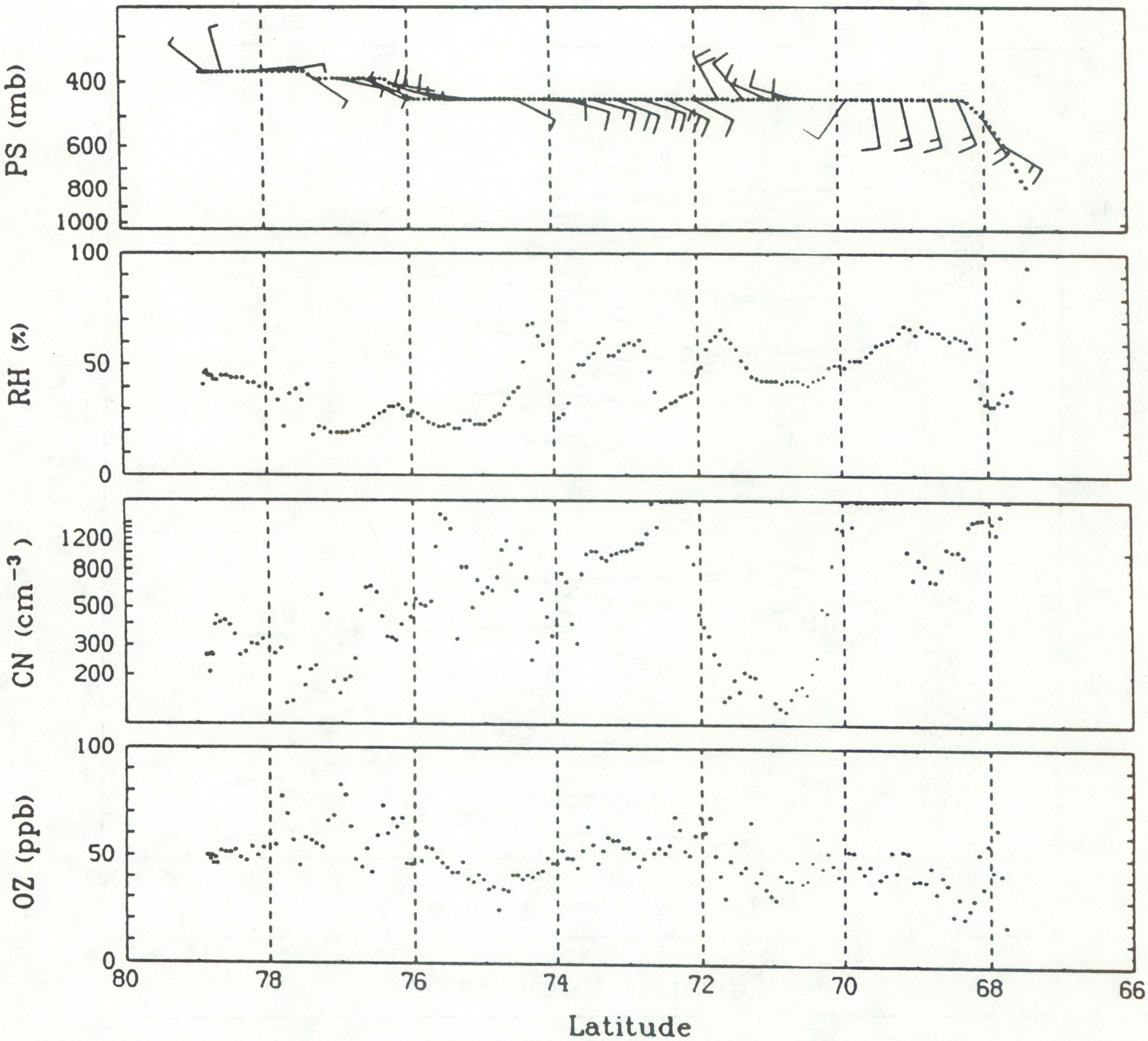

Figure 4.5. Aircraft transect, northbound leg 0805-1050 UTC, March 23, 1989. Aircraft flight level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

Although there were relatively clear regions between 70.4° and 72°N and above 400 hPa north of 76.4°N, these were the only ones encountered during the northbound flight. Variations in the CN concentrations at 72°-75°N are possibly associated with convection in the relatively unstable air above the frontal zone, the southern edge of which was at 72°N. Precipitation scavenging probably accounts for the very low CN concentrations between 70.2° and 72°N. Observations made aboard the aircraft reported clouds at 71.5°N. Andoya and Bear Island were both reporting cumulonimbus clouds at this time.

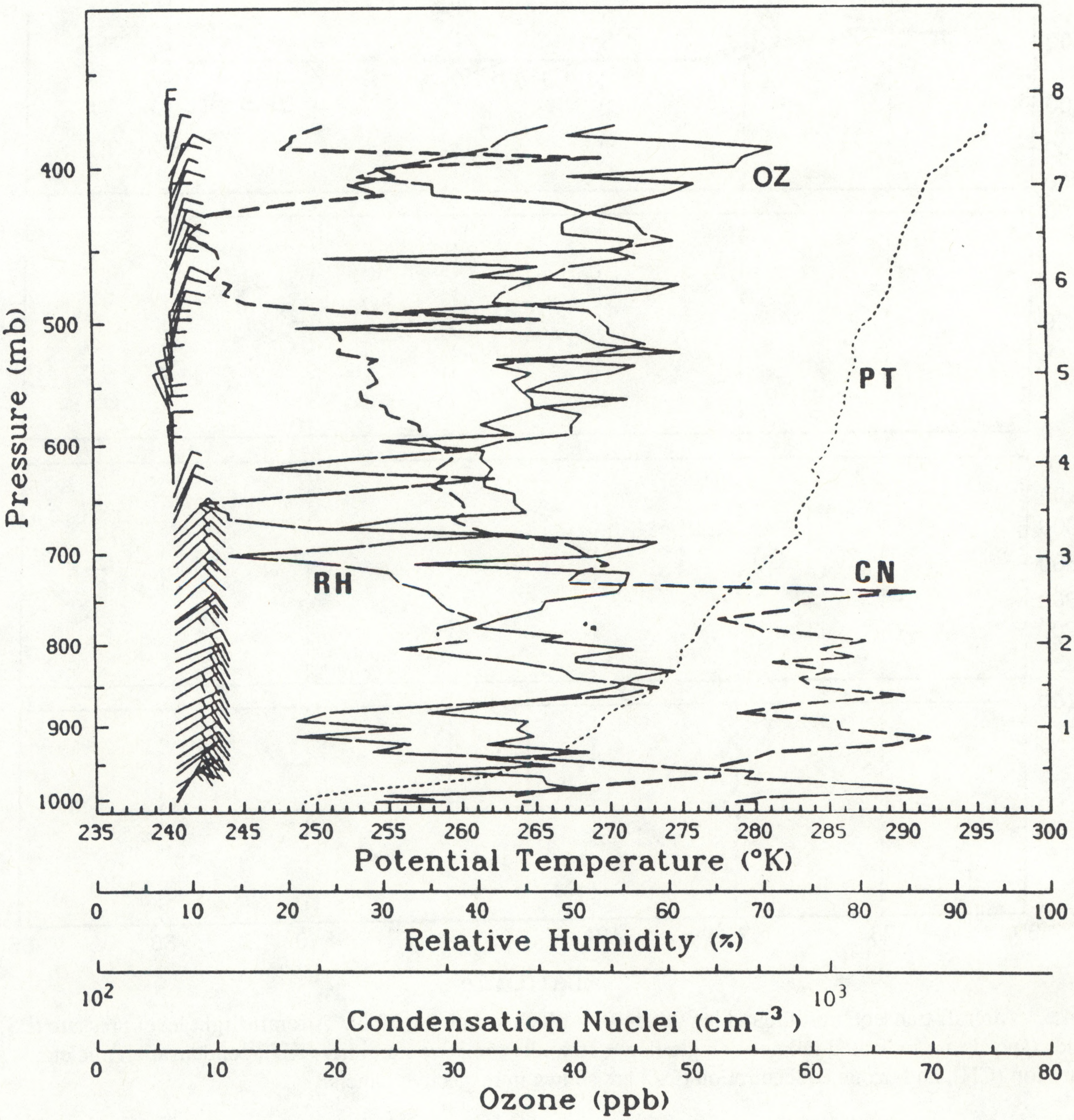

Figure 4.6. Aircraft sounding, 1056-1136 UTC, March 23, 1989. Profiles of potential temperature (PT), relative humidity (RH), condensation nuclei concentration (CN), and ozone concentration (OZ) are shown.

A satellite photograph taken at 0726 UTC (Fig. 4.8) showed significant cloudiness in the Barents Sea and over the pack ice east of Svalbard. In particular there were low clouds associated with the surface low to the northeast of the Kola Peninsula. The northern edge of this cloud system was within 100-200 km of the ice edge. While the ice edge and some larger leads were visible, the photograph appears to be show cirrus overcast or haze. Hopen reported cirrus clouds throughout the day. The only low clouds visible in this region were orographic along the eastern slopes of the islands making up Svalbard.

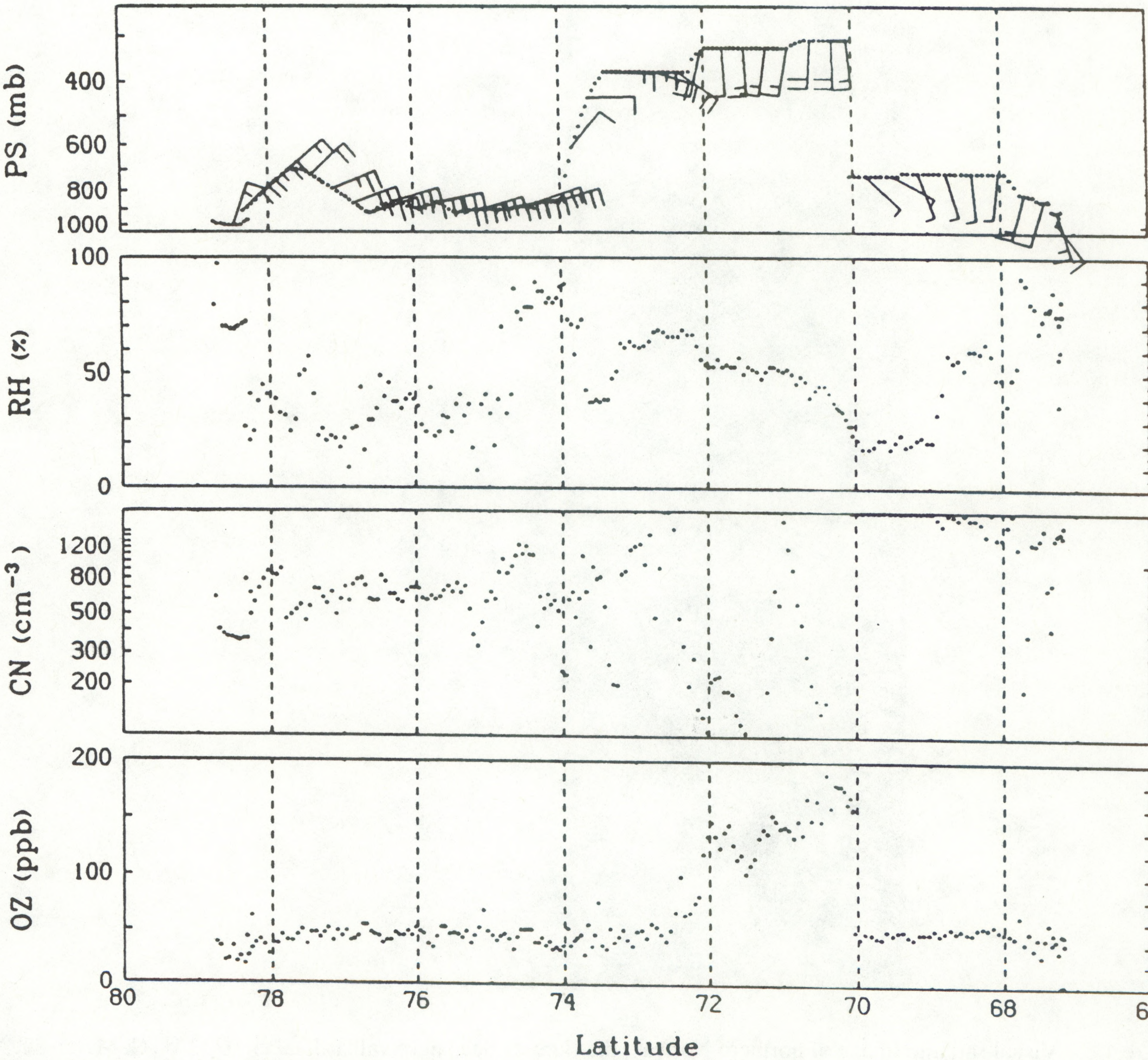

Figure 4.7. Aircraft transect, southbound leg 1223-1749 UTC, March 23, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH) and condensation nucleus concentration (CN), and ozone concentrations (OZ) are shown in respective panels.

Haze was prevalent below 690 hPa on the descent at 78°N, though for most of layer above 960 hPa it was light. For only two brief periods, lasting about a minute each, did the ozone drop below 20 ppb, indicating ozone destruction (at 78.6° and 78.35°N). South of 74°N there seems to have been widespread pollution, as indicated by the aerosol concentrations.

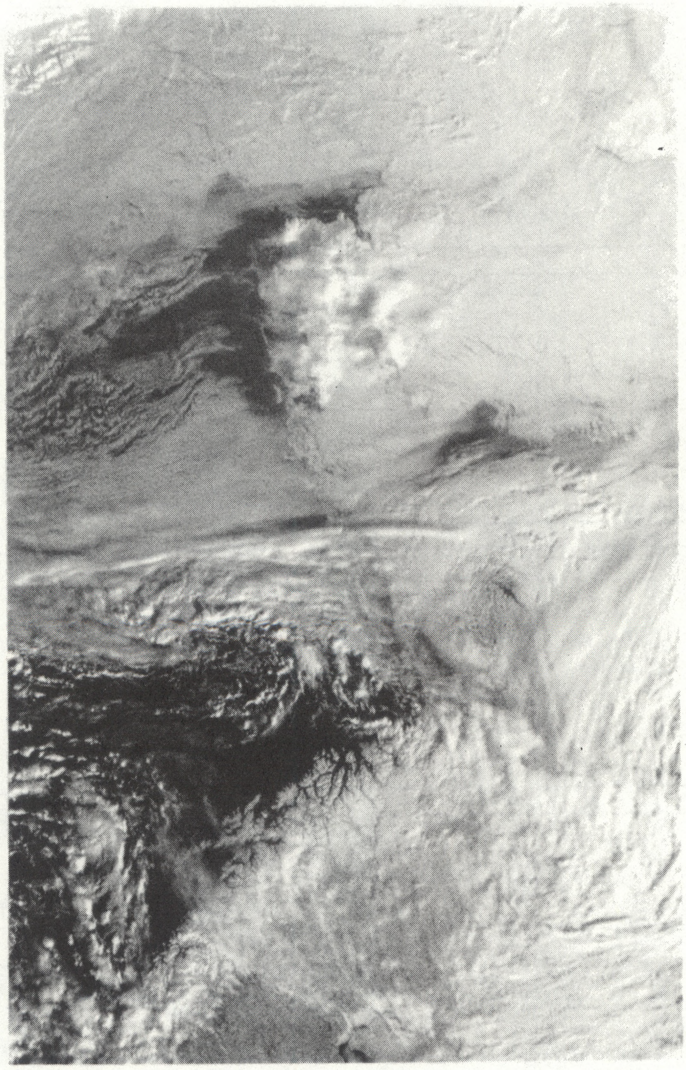

Figure 4.8. Visual satellite image of northern Norway, the Barents Sea, and Svalbard, taken 0723 UTC, March 23, 1989. The Norwegian coast in the vicinity of Andoya and Tromso is visible in the lower central part of the image, and the west coast of Svalbard is visible in the upper centeral part of the image.

FLIGHT 309, MARCH 27, 1989

5.1 Overview

The flight on March 27, designated AGASP-III 309, was scheduled primarily to study the importance of the different processes that maintain the Arctic PBL that decouples the ice surface from the free troposphere (*Walter and Overland*, 1991). The study was conducted in the vicinity of the CEAREX "O" (Oceanographic) ice camp (83°N, 10°E) where surface meteorological observations were being made at the same time (*Guest and Davidson*, 1989). Slight modifications in the flight plan of the transit legs of the mission allowed the accurate measurement of the solar radiation flux and the properties of aerosols and gases in the high Arctic.

Surface wind conditions in the vicinity of O camp dictated the timing for this flight. The forecast trajectories being used to depict the flow from major European source regions indicated no significant meridional transport (Fig. 5.1). On the basis of this prognosis, a haze flight would not normally have been scheduled for this particular day.

5.2 Synoptic Situation

At 500 hPa, Fig. 5.2 shows the region along the flight track, including Svalbard, under the influence of a weak high-pressure system, the northern extension of a strong ridge over western Scandinavia. The ridge arrived in this region from the west earlier in the day. For the preceding 3 days the flow aloft over Svalbard had been from the north in response to the low currently to the north of the Taymyr Peninsula. Except for the very southern end, where stronger winds (>50 knots) were associated with the advancing ridge, light winds prevailed along most of the flight track. A weak trough off the northeast coast of Greenland is significant to the weather in the vicinity of the O camp. A small but vigorous low-pressure system at the surface (80°N, 5°W), coupled to this trough, advected moist, maritime air into the study region (*Walter and Overland*, 1991).

The potential for the northward transport of polluted air was thought to be improved by the passage of a weak low-pressure system across southern Scandinavia 2 days earlier. But a stationary front to the north, and associated high pressure over the Barents Sea limited the northward transport at low levels to the continent. For the 24-h period preceding the flight the low-level winds over the source regions were northerly, thus forecast trajectories from the major pollution sites showed a meandering character for this period (Fig. 5.1).

Departing Bodø, the NOAA WP-3D climbed to a ferry altitude of 447 hPa on a heading that took the flight along the west coast of Spitsbergen, as shown in Fig. 5.2. The aircraft passed 92 km to the west of the Norwegian baseline station at Ny Ålesund (78.93°N, 11.88°E). At 83.3°N, 10°E the aircraft began the descent to the surface. Seven-minute long "radiation" runs were conducted at 447, 759, and 912 hPa. The NOAA WP-3D spent the next 2 hours and 15 minutes sampling the Arctic PBL in the vicinity of the CEAREX O camp. During this time the aircraft was below 990 hPa (180 m). The aircraft returned to Bodø along approximately the same track used on the northbound leg, at the 293 hPa level.

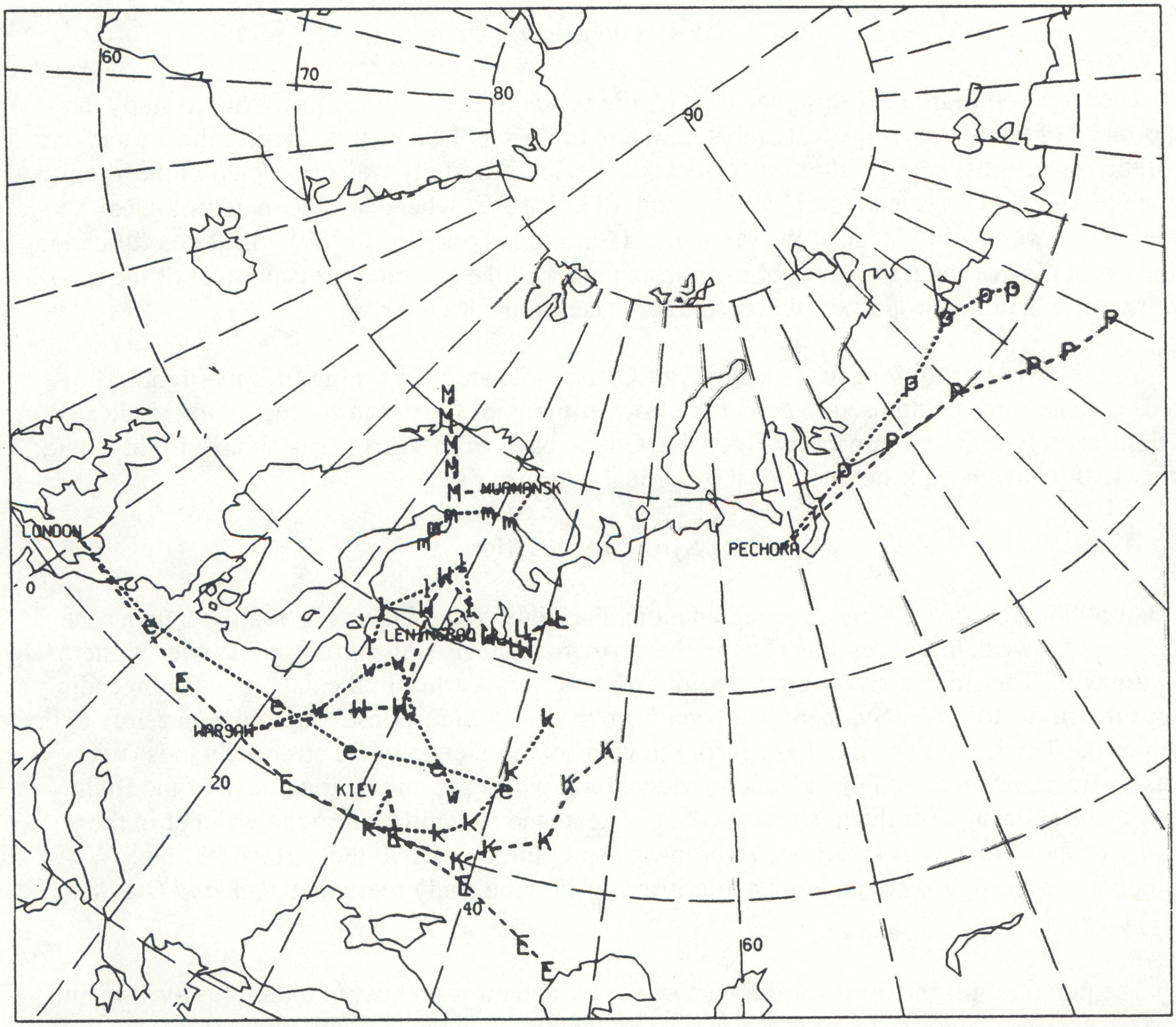

Figure 5.1 Horizontal projection of the Program for Operational Trajectory (POT) 60-h transport forecasts verifying 0000 UTC, March 27, 1989, originating from London (E), Warsaw (W), Kiev (K), Leningrad (L), Muransk (M), and Pechora (P). Lower case letters depict 950-hPa transport, upper case 850-hPa transport.

5.3 Transects and Profiles

The analysis of the distribution of potential temperature along the flight track (Fig. 5.3) was based on the 1200 UTC, March 27, BOD, BAR, and BRG rawinsondes and the meteorological observations from the WP-3D.

For the first 5 minutes of the flight, from the surface to 700 hPa, the wind was from the east. The transition from the surface layer to midtropospheric air occurred in the stable layer between

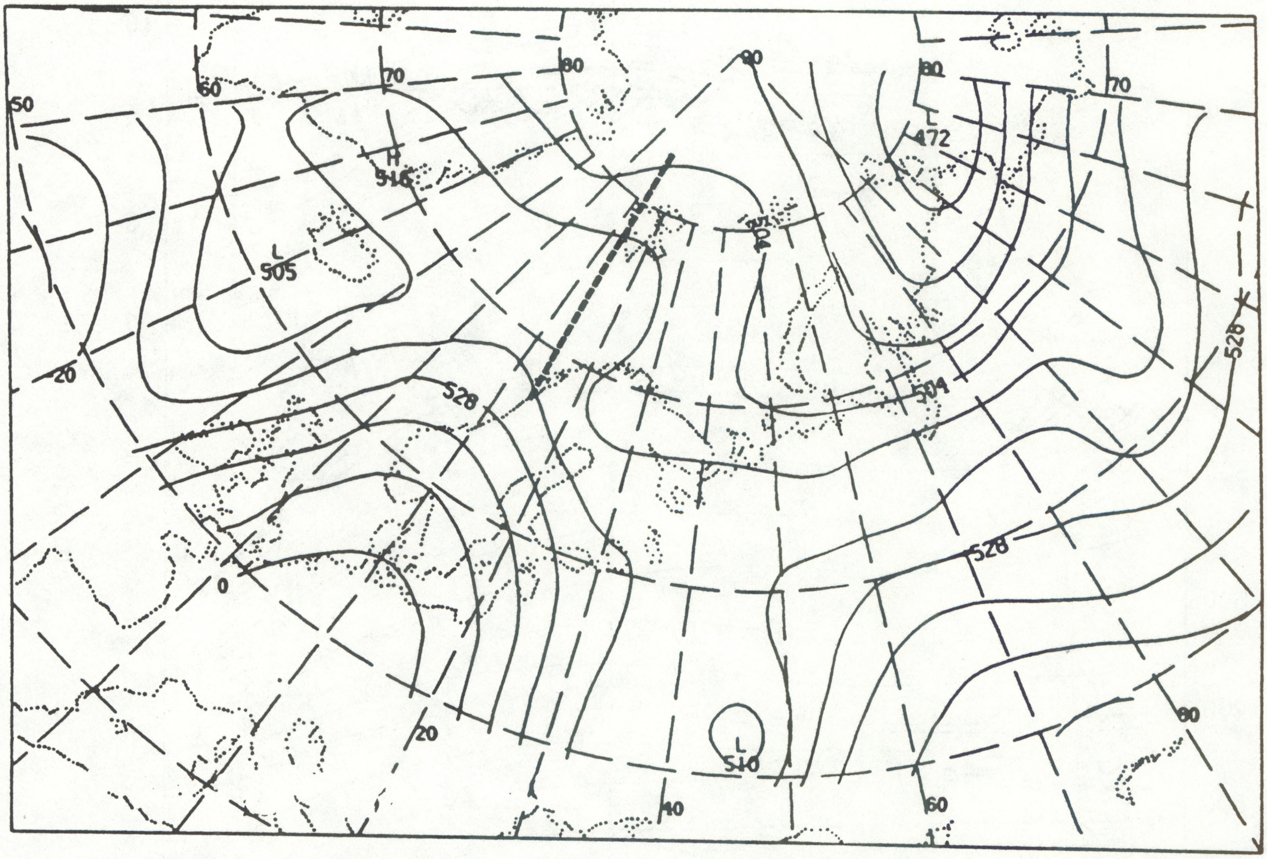

Figure 5.2. 500 hPa synoptic map for 1200 UTC, March 27, 1989. Indicated are height contours in geopotential decameters. The WP-3D flight track is shown by the heavy dashed line.

700-500 hPa. At this level the winds veered to a westerly direction, and the RH and CN concentrations decreased abruptly (Fig. 5.4). From the northwest coast of Norway to 75°N the low RH indicates a uniform air mass. At 76°N the aircraft was in a transition zone, coming under the influence of the small trough off the Greenland coast. When the winds shifted to the south at 79°N, the RH was 50%, indicating that the transition was complete. Dryer air was encountered north of 82°N. Elevated CN concentrations were associated with a southerly wind component. Ozone concentrations were steady in the range of 30-50 ppb. The only 60 ppb values after ascent were between 78° and 79°N, a dry region with westerly winds.

In addition to the PBL at 926 hPa, two stable layers of significance were encountered during the descent from cruise pressure, 446 hPa (Fig. 5.5). The first was a thin layer from 620 to 640 hPa and the second at 720-770 hPa; both are marked by an abrupt increase in the RH. Although there was a slight turning of the wind to a more southerly direction below the 720-770 hPa layer, the only significant change in wind direction occurred below 950 hPa where the wind turned from a southwesterly direction aloft to southeasterly at the surface.

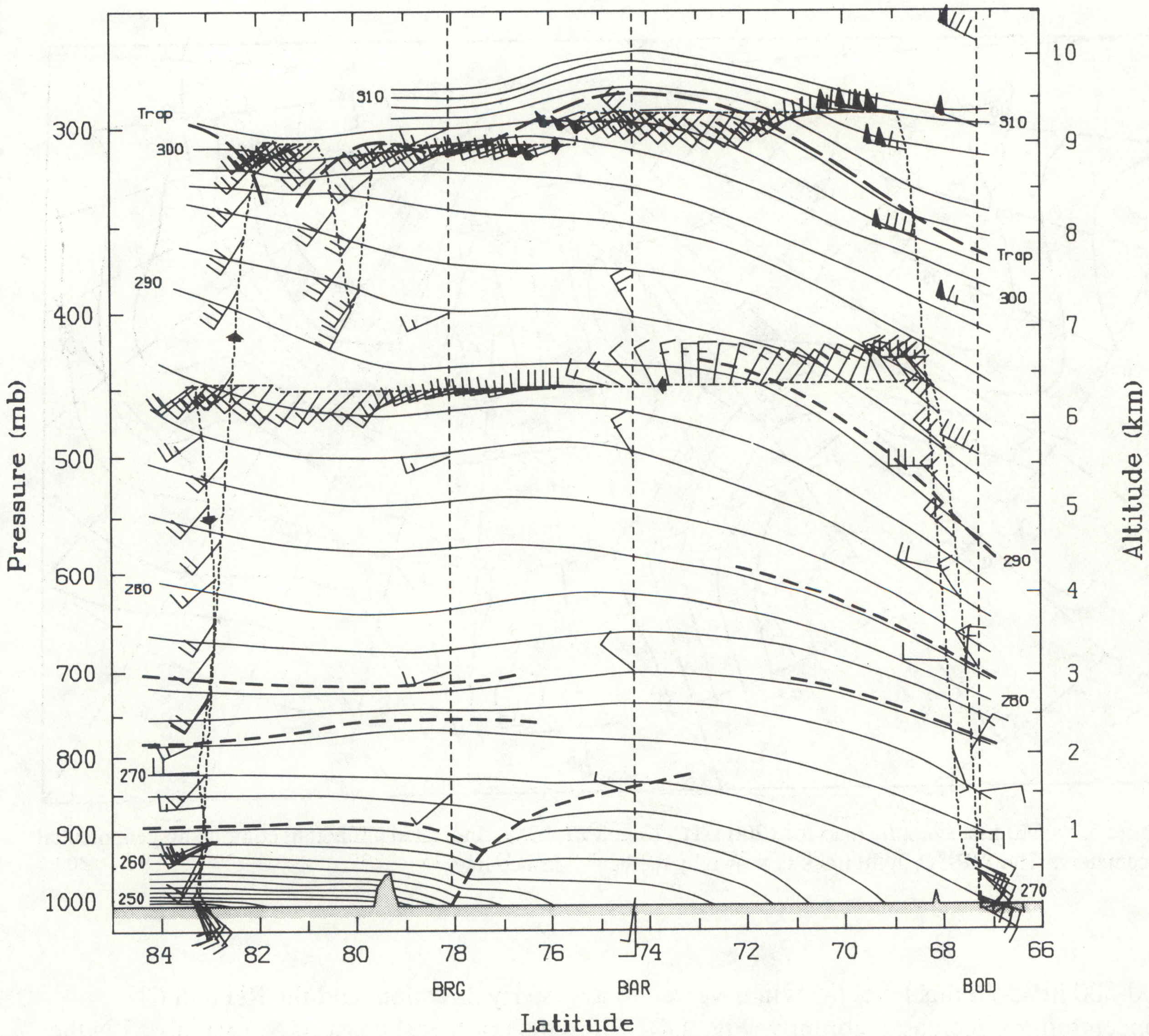

Figure 5.3. Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 10 knots) between Bodø and 84°N, 0712-1736 UTC, March 27, 1989. The tropopause is indicated by a thick long-dashed line; stable layers, frontal zones, and the top of the Arctic boundary layer by thick short-dashed lines; and the aircraft flight track by thin-dashed lines. Arrows are placed at the beginning of each hour to indicate the direction of the aircraft. Vertical dashed lines show the rawinsonde location (BOD, BAR, and BRG).

Figure 5.5 shows the vertical distribution of CN and ozone concentration. With the exception of a very narrow layer at 980 hPa where CN concentrations ranged from 600 to 1100 cm^{-3}, all other values are typical of midtropospheric, midlatitude concentrations, 300-500 cm^{-3}. From the base to the top of each stable layer there was a consistent decrease in the CN concentrations. For most of the descent, and the subsequent ascent as well, the ozone concentrations were within a range that is typical of the lower troposphere, specifically from 30 to 50 ppb. A minor peak of 60 ppb was encountered immediately above the 720-760 hPa layer. There is also evidence of ozone destruction in the surface layer, where the concentrations fell to below 20 ppb.

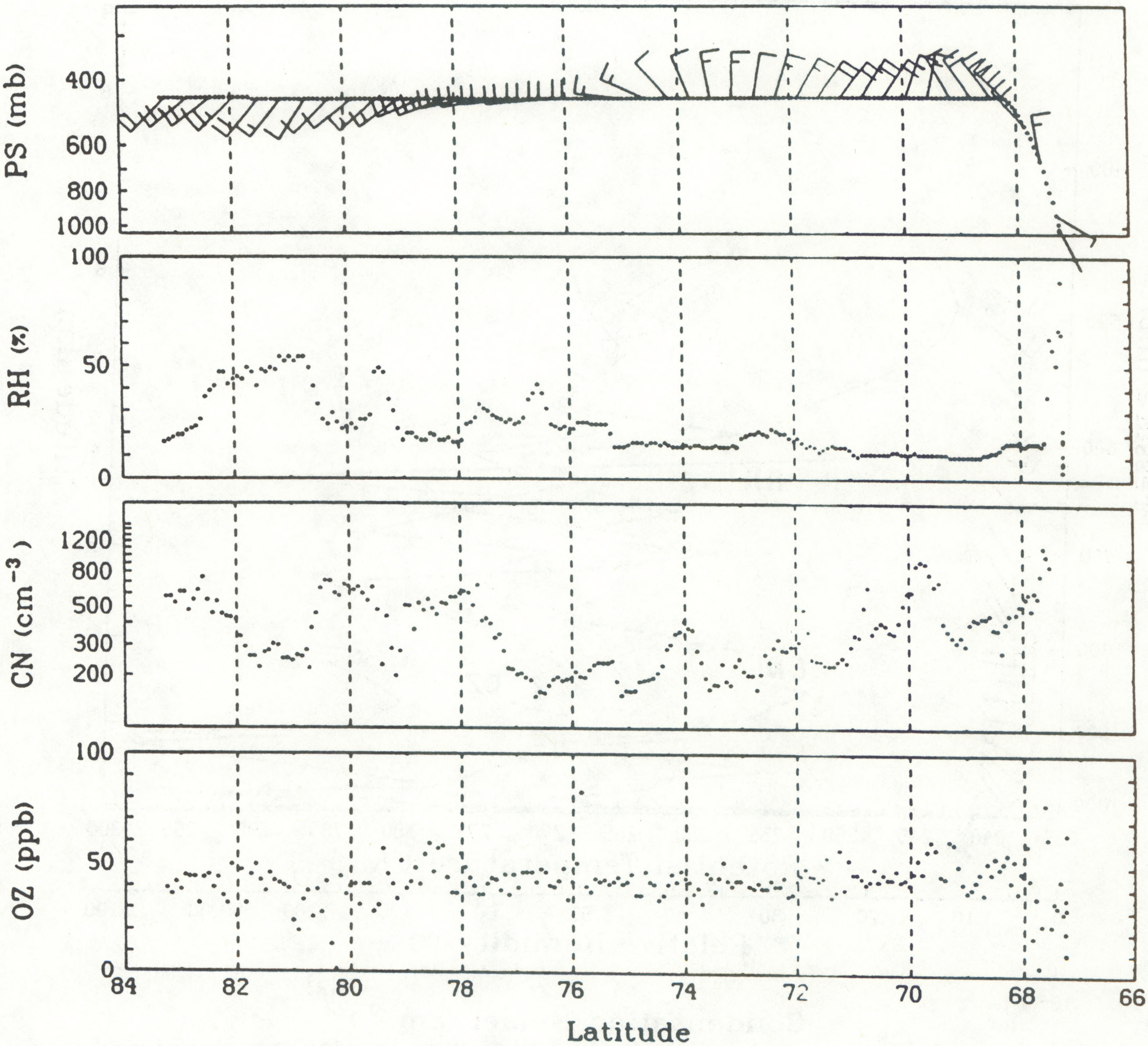

Figure 5.4. Aircraft transect, northbound leg, 0703-1040 UTC, March 27, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentrations (CN), and ozone concentrations (OZ) are shown in respective panels.

Temperatures at the time of the ascent from the CEAREX sampling area were slightly cooler than during the descent. During the return flight (Fig. 5.6), on the basis of changes in the wind direction, potential temperature, and the ozone concentration gradient, the aircraft entered the stratosphere at three locations. The first was from 307 hPa and 81.6°N to 330 hPa and 80.4°N. The second at 307 hPa was from 79.5° to 76.3°N. And the third was from 293 hPa and 71.6°N to 371 hPa and 68.5°N. The wind speeds south of 70°N were significantly higher than on the outbound flight (Fig. 5.4). As the aircraft approached Bodø, the RH and CN concentration increased when the wind shifted to the southeast.

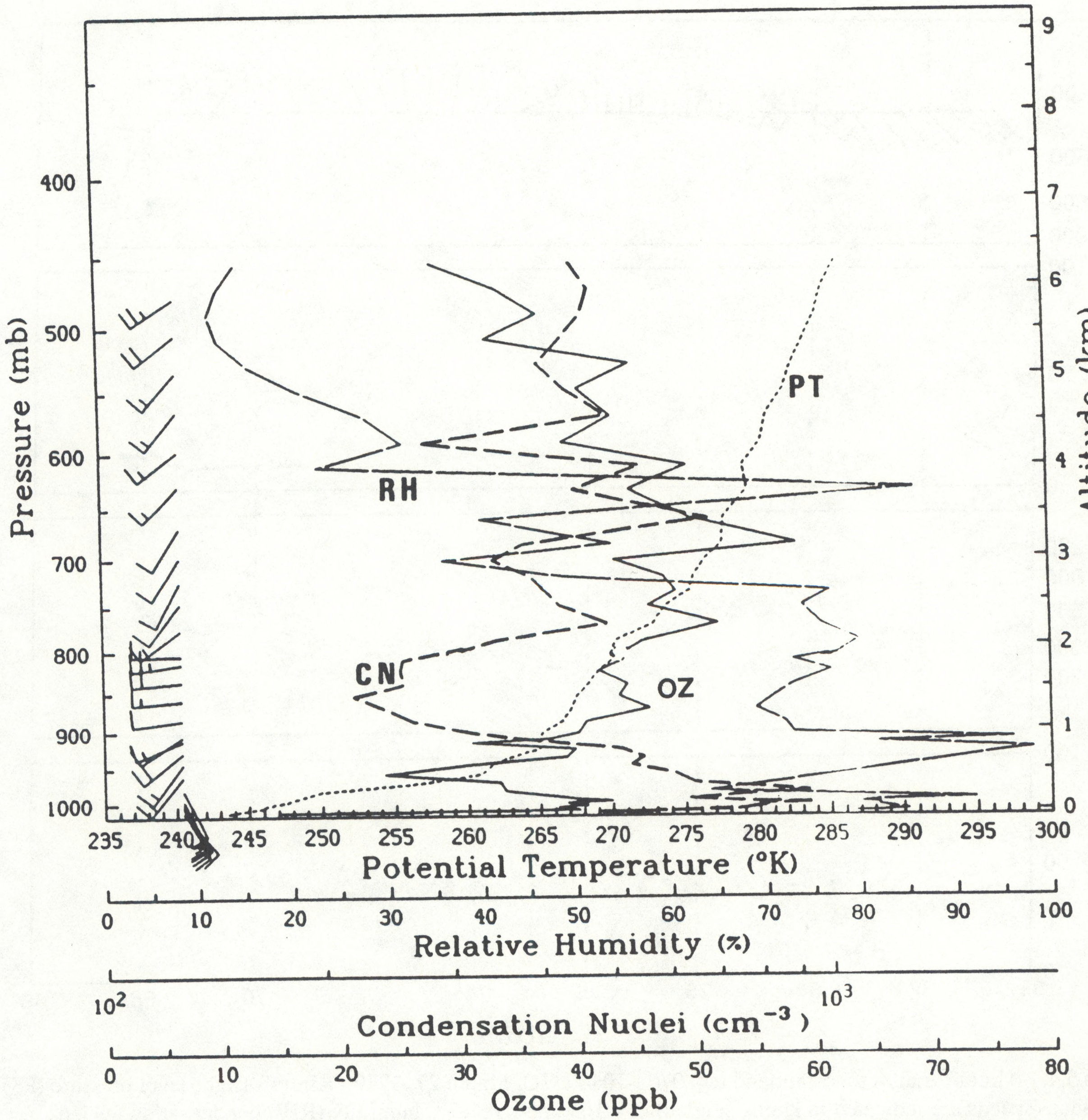

Figure 5.5. Aircraft sounding, 1050-1152 UTC, March 27, 1989. Profiles of potential temperature (PT), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown.

5.4 Discussion

The elevated RH and CN values south of 68°N (Fig. 5.4) reflect the polluted nature of the surface air mass over Fennoscandia below 700 hPa. The very low RH between 68°N and 71°N indicated that subsidence was occurring on the eastern side of the ridge (Fig. 5.2), as confirmed by the slope of the isentropic surfaces on this portion of the flight (Fig. 5.3) and the stronger winds aloft. At 69°N, where the wind shifted to the northeast, a transition back into air of lower-tropospheric origin began. Cirrus clouds were reported in this region.

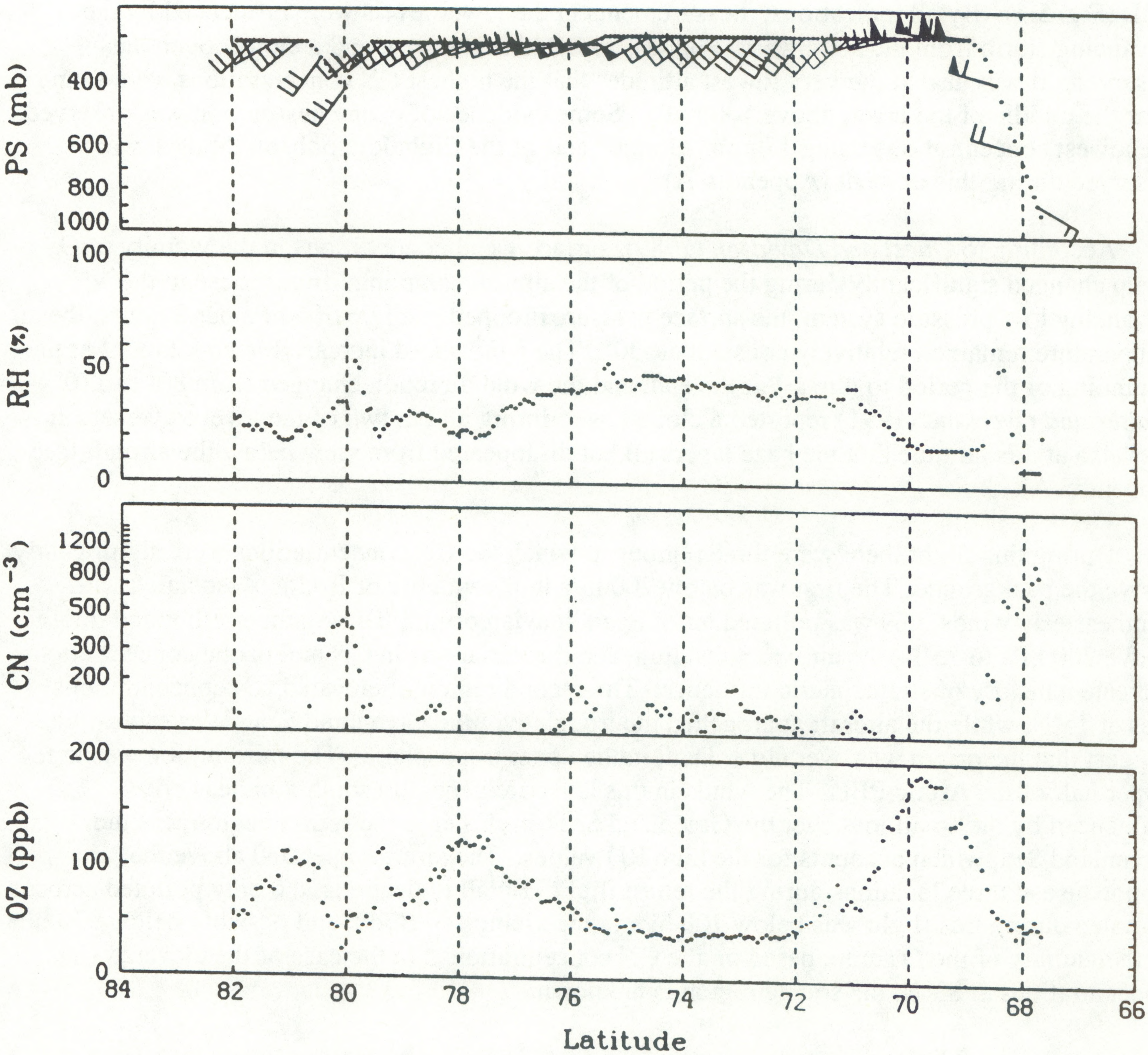

Figure 5.6. Aircraft transect, southbound leg 1423-1724 UTC, March 27, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nuclei concentration (CN), and ozone concentration (OZ) are shown in respective panels.

The elevated CN and ozone concentrations at 69.5°-70°N also suggest that in part this air may have been of stratospheric origin. By 72°N RH had increased and the wind was beginning to shift, showing a change in air mass. The change from very low RH values south of 76°N to higher more variable values to the north corresponds to a shift in the wind direction from northerly to southwesterly (Fig. 5.4) at about the same location. As the aircraft approached the low-pressure system to the northwest of Svalbard, RH values continued to increase.

The RH remained relatively constant during the descent, reaching saturation in the Arctic PBL (Fig. 5.5). By all indications, measurements in the lower levels were influenced by the advancing storm from the southwest. Fog was reported in the area, and a cloud cover was observed. It was also at the very lowest altitudes that the highest CN concentrations were found near the middle of the layer, above 1000 hPa. Some evidence of ozone destruction was observed, the lowest concentrations being 17 ppb. On the basis of the flight log, only slight haze was observed during this descent (Appendix A).

According to *Guest and Davidson* (1989), surface weather conditions in the vicinity of O camp changed significantly during the period of the aircraft sampling. In response to the advancing low-pressure system, the surface pressure dropped at a rate of 5 hPa per 3 hours; the air temperature remained relatively constant at -30°. The wind speed increased from <2 m s^{-1} at the beginning of the period to 4 m s^{-1} at the end, and the wind direction changed from 80° to 110°. *Walter and Overland* (1991) reported a cloud cover during all but two of the level traverses. It was also at this latitude that the haze layers all but disappeared from view below the aircraft (see Appendix A).

During this flight there were three regions in which the CN concentrations were significantly above the background. The first was below 700 hPa in the vicinity of Bodø. Associated with southeasterly winds, this was polluted air of Scandinavian origin. During the northbound transect above 700 hPa to 75°N, the air was subsiding, and the variations in CN and ozone concentrations indicate a history of stratospheric influence. The second region of elevated CN concentrations was at 75°N, while the aircraft approached the trough over the Greenland Sea. Westerly winds suggest that the origin was over Greenland, in the upper troposphere. The third region was in the upper half of the Arctic PBL. The winds in this layer are generally south-southeasterly, influenced by the small low over the Greenland Sea. In this case the source region was the Greenland Sea, which accounts for the high RH values. The aircraft operated above the tropopause at three locations during the return flight. By all indications, the only polluted aerosol sampled during this flight was below 700 hPa in the vicinity of Bodø, and possibly below 970 hPa in the vicinity of the O camp, based on the CN concentrations. In the case of the elevated CN concentrations at 83°N, the source region is unknown.

6. FLIGHT 310, MARCH 29, 1989

6.1 Overview

For the previous 5 days north and westerly winds were reported at 500 hPa at both Barentsburg and Bear Island. This unfavorable flow was the result of the semistationary low-pressure system to the east in the vicinity of the Taymyr Peninsula. The March 27 flight had confirmed the absence of any significant amount of haze above the Arctic PBL north of Svalbard. This finding agreed with pollution transport from northern European source regions suggested by the forecast trajectories (Fig. 6.1). The important change in conditions on March 29 was that the high pressure along the northern Norwegian coast 2 days earlier had been replaced by a rapidly moving low-pressure system. Associated with this low, the trajectories indicated a potential for low-level transport from the region of the western Soviet Arctic into the Barents and Norwegian Sea. Although the forecast trajectories indicated that only the lowest levels, 950 hPa, and the region southeast of Svalbard were potential sampling regions, a haze flight was nonetheless scheduled. Two other factors were important in making this determination. First, the transport forecast for the next few days looked even less encouraging. Second, the project staff had been in Norway for more than 3 weeks and logistics costs were such that there was increasing pressure to use the assigned flight hours before the end of March.

The flight, designated AGASP-III 310, was originally scheduled to sample aerosols over the ice sheet to the southeast of Spitsbergen. At the time, the cloud cover beginning at about 76°N was extensive, so the flight track was extended to the north until clear air could be found (Fig. 6.2). This occurred at about 82°N.

6.2 Synoptic Situation

The 500 hPa ridge that was slightly to the east of the flight track during flight 309, had taken a position over the Barents Sea, to the east (Fig. 6.2). A fast-moving low-pressure system was centered at 74°N, 10°E at the time of the flight. The lowest pressures were slightly to the west of the flight track. The position of the low at 850 hPa was slightly to the east of that at 500 hPa, indicating a positive tilt to the system (Fig. 6.3). This particular storm system had been located 600 km south of Iceland 2 days earlier. The system subsequently moved through the Norwegian Sea to the present position between the north coast of Norway and Svalbard. This movement and deepening led to rapidly changing conditions over the sampling region. The geostrophic wind gradient decreased rapidly at 80°N, near the northern edge of the cloud cover.

Tropospheric sampling was begun at 82°N, with clear air below, so that a uniform underlying ice surface could be obtained for representative radiation flux measurements. The radiation measurements were conducted at this location, and the descent profile was begun. Radiation runs were conducted at 367 and 1005 hPa. For the next 2 hours and 45 minutes, Arctic PBL samples were taken along a southerly track to the east of Svalbard. The aircraft returned to cruising altitude at 76°N and returned to Bodø along the same track as was used on the northbound flight.

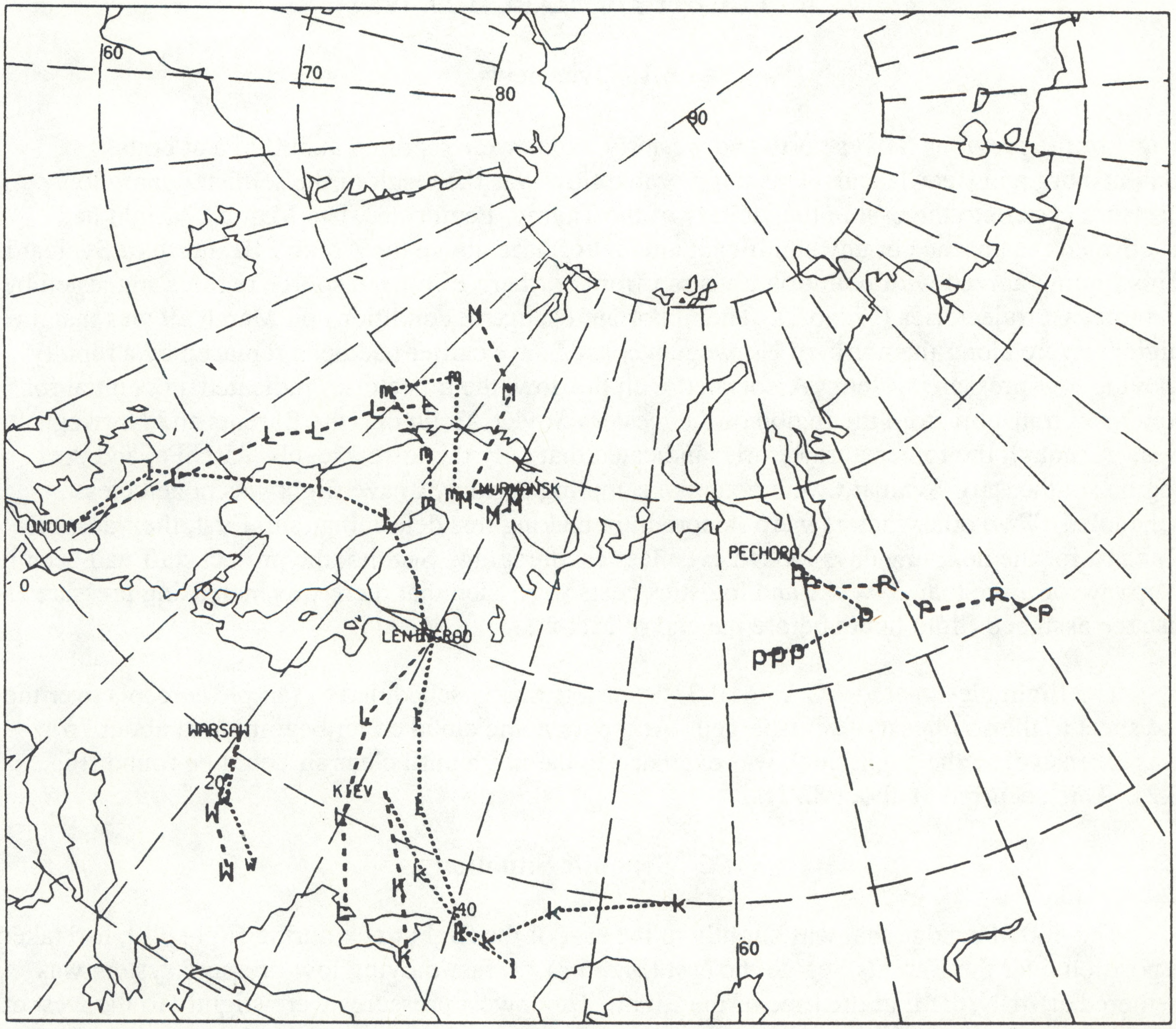

Figure 6.1 Horizontal projection of the Program for Operational Trajectory (POT) 60-h transport forecasts verifying 1200 UTC, March 29, 1989, originating from London (E), Warsaw (W), Kiev (K), Leningrad (L), Muransk (M), and Pechora (P). Lower case letters depict 950-hPa transport, upper case 850-hPa transport.

6.3 Transects and Profiles

The analysis of potential temperature along the flight track consisted of rawinsonde observations from BOD, BAR, and BRG at 1200 UTC, March 29, in addition to the aircraft observations for the duration of the flight (Fig. 6.4).

During the climb to cruising altitude north of Bodø, the aircraft passed through the transition zone separating the boundary layer from 550 to 520 hPa, marked primarily by a decreasing relative humidity at 67.8°N (Fig. 6.5). The winds shifted from the west to the south at 71°N,

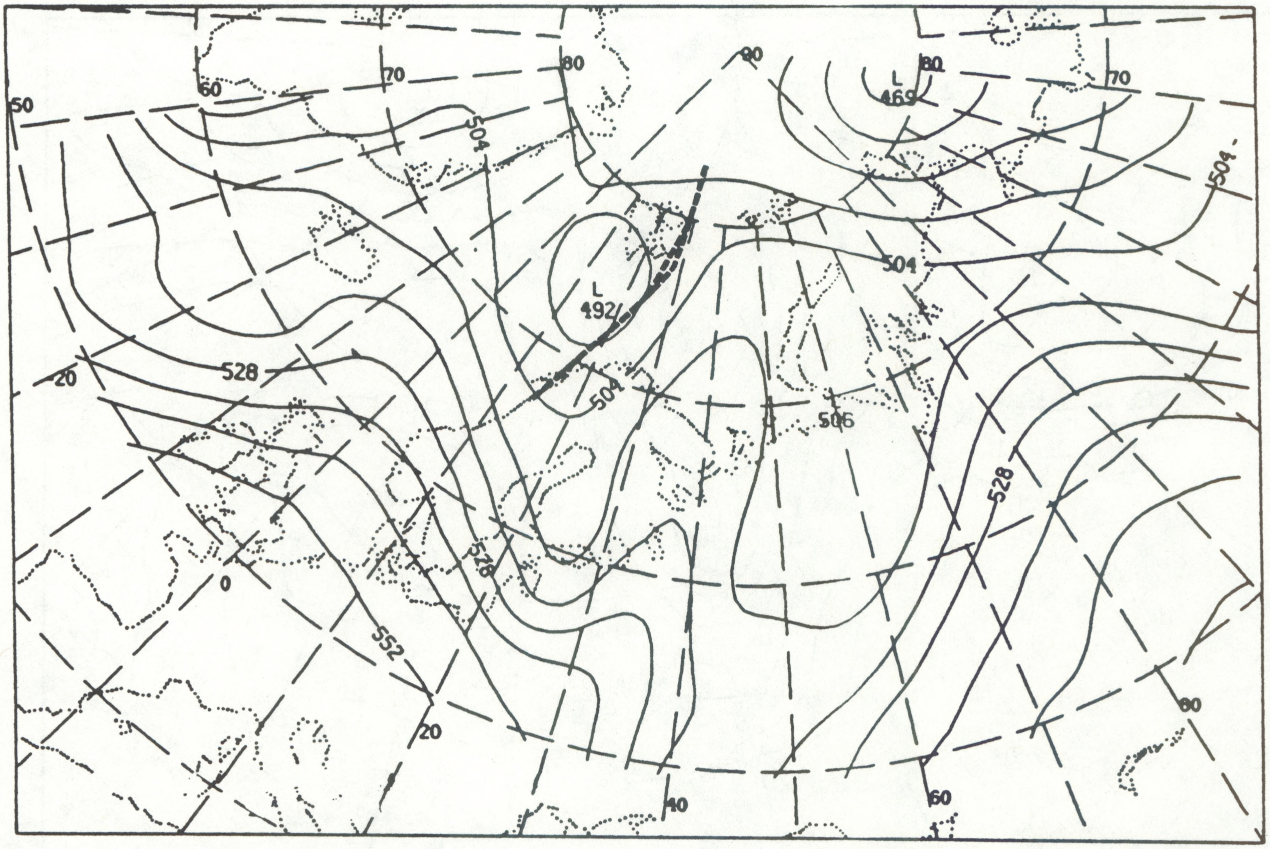

Figure 6.2. 500 hPa synoptic map for 1200 UTC, March 29, 1989. Indicated are height contours in geopotential decameters. The WP-3D flight track is shown by the heavy dashed line.

indicating a second change in air mass. A simultaneous increase in ozone concentrations to values in excess of 100 ppb and decrease in CN concentrations indicates the presence of air of recent stratospheric origin. A second region of recent stratospheric influence was between 74° and 75°N, where ozone values exceed 80 ppb and the RH was at a local minimum. The two peaks in the ozone trace indicate that the aircraft was not in the stratosphere during the entire period from 72° to 74.5°N. Abrupt increases in RH and CN concentrations at 75°N, coupled with an increase in wind speed to the north, indicate a change in air mass. CN concentrations exceeded 10,000 cm^{-3} momentarily (then decayed to more typical values in the subsequent 10 minutes) in the region bounded by 74.7° and 77.3°N. While the CN concentrations returned to more typical values by 78°N, the RH stayed at an elevated level. Hopen Island at 76.5°N reported overcast conditions composed of low and middle clouds, with snow and blowing snow at this time.

The profile at 82°N began at 368 hPa (Fig. 6.6). Although minor stable layers were encountered, the two of significance were at 390-420, and at 840-860 hPa where the winds shifted from westerly to easterly. Stable layers separated regions of higher RH from a 5-km-deep layer in which the RH did not exceed 30%. The saturated surface layer was capped by a secondary

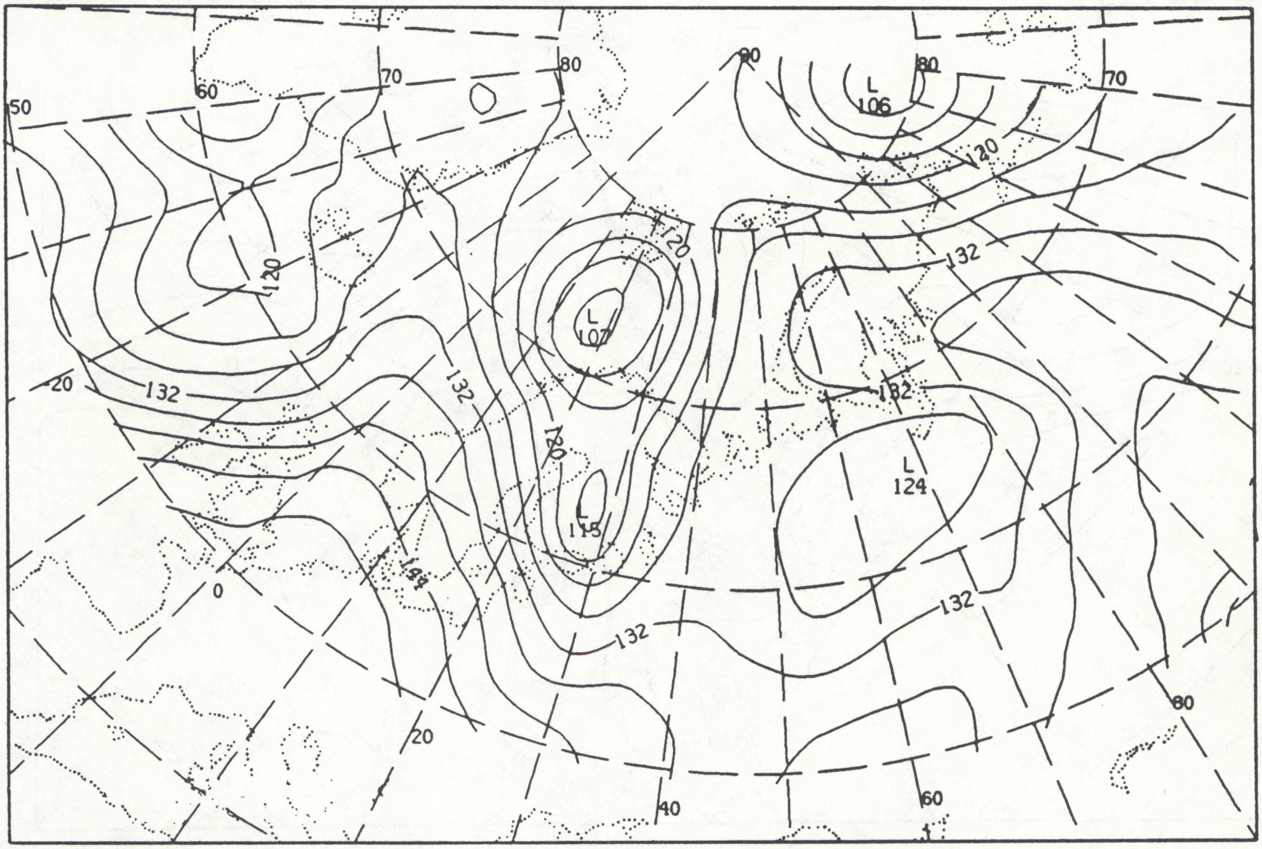

Figure 6.3. 850 hPa synoptic map for 1200 UTC, March 29, 1989. Indicated are height contours in geopotential decameters.

inversion with a base at 950 hPa. The CN concentrations throughout the sounding were consistently less than 300 cm^{-3} above 500 hPa; below that level they varied around the 400 cm^{-3} level. Above the Arctic PBL at 840 hPa, the ozone concentrations varied between 45 and 70 ppb. At the top of the surface layer, at 950 hPa, the values dropped rapidly in response to the destruction that was occurring at the surface.

The southbound transect (Fig. 6.7) shows that the aircraft was below 700 hPa to about 76°N, at which time it climbed to 300 hPa for the return to Bodø. North of 82°N, in the lowest layers, there was clear evidence of ozone destruction. From 82° to 75°N the ozone values were typical of the midtroposphere. During this portion of the flight the RH was near saturation and the aircraft was in and out of clouds and snow showers (see Appendix A). To the south, ozone concentrations were in the 100-300 ppb range, as commonly found in stratospheric air. The RH was near 100% as long as the aircraft was in the Arctic PBL. Variations in the RH at about 81°N occurred during a climb above the Arctic PBL. RH values were near zero in the stratosphere. After the aircraft completed the sounding at 81°N, CN concentrations increased as the plane flew south, stabilizing at about 500 cm^{-3}. Between 73° and 72°N, CN concentrations exceeded 1500 cm^{-3}, which is

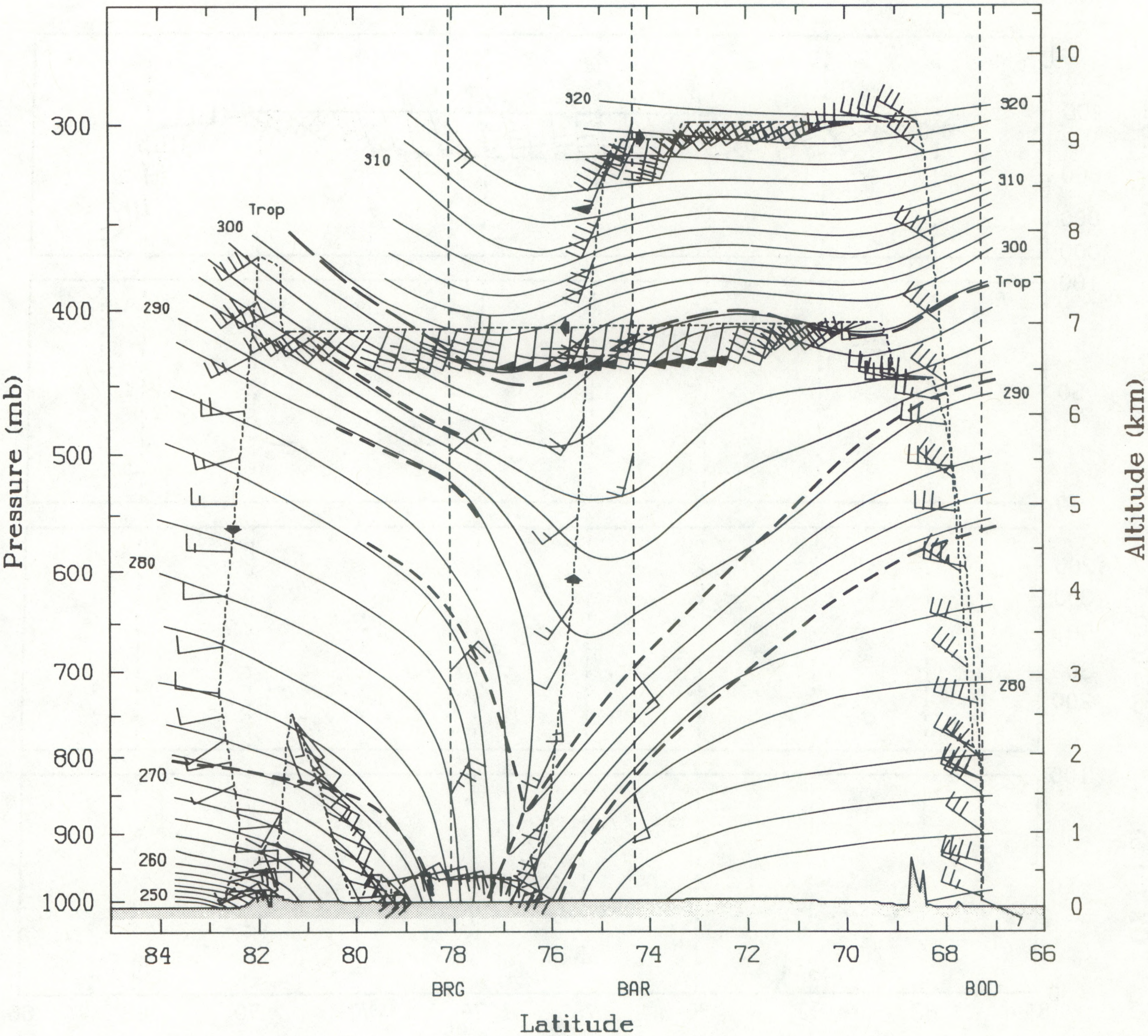

Figure 6.4. Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 10 knots) between Bodø and 84°N, 0815-1747 UTC, March 29, 1989. The tropopause is indicated by a thick long-dashed line; stable layers, frontal zones, and the top of the Arctic boundary layer by thick short-dashed lines; and the aircraft flight track by thin-dashed lines. Arrows are placed at the beginning of each hour to indicate the direction of the aircraft . Vertical dashed lines show the rawinsonde location (BOD, BAR, and BRG).

unusually high for this region of the troposphere. Local pollution is indicated by high CN concentrations in the vicinity of Bodø.

6.4 Discussion

Shortly after reaching cruise altitude, 409 hPa, the aircraft entered the stratosphere at 71.2°N (Fig. 6.4). On the basis of the ozone concentrations and winds, the aircraft flight level of 409 hPa was at or above the tropopause to 75°N. For a brief period at 74°N it appears that the tropopause

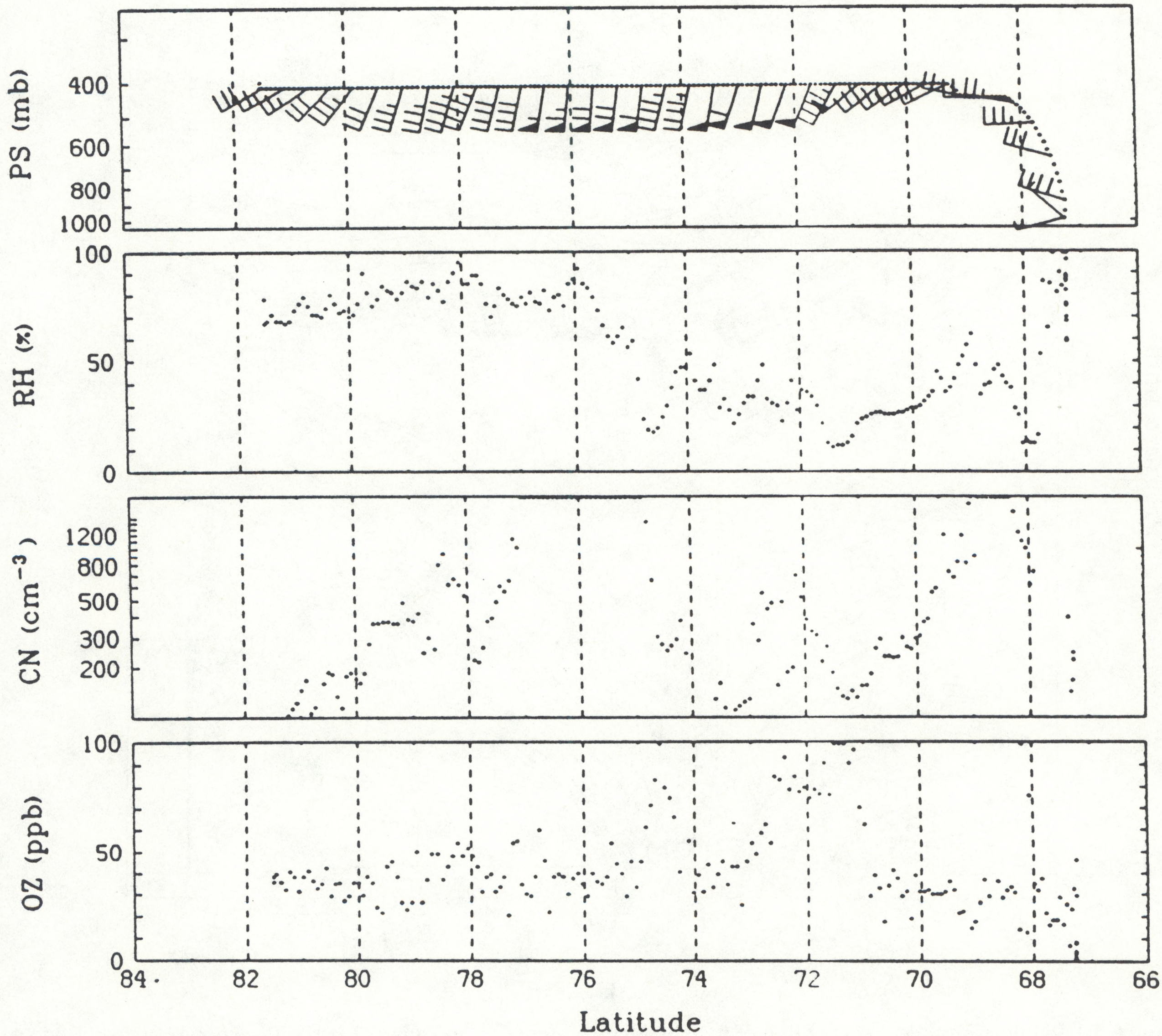

Figure 6.5. Aircraft transect, northbound leg 0801-1114 UTC, March 29, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

was above the aircraft. The low tropopause in this region was in association with the low-pressure region centered at 74°N, 15°E and 500 hPa (Fig. 6.2). In the stratospheric air, the CN concentrations were typically in the 100-300 cm^{-3} range immediately below the tropopause at 69°N, and they exceeded 2000 cm^{-3} north of 75°N. For a brief segment after leaving the stratosphere at 75°N, CN concentrations in excess of 10,000 cm^{-3} were encountered. At 76.1°N the aircraft entered a dense cirrus cloud, and the CN concentrations decreased gradually, returning to typical values of less than 500 cm^{-3} at 78°N. Cirrus clouds were reported again at 81.5°N (see Appendix A).

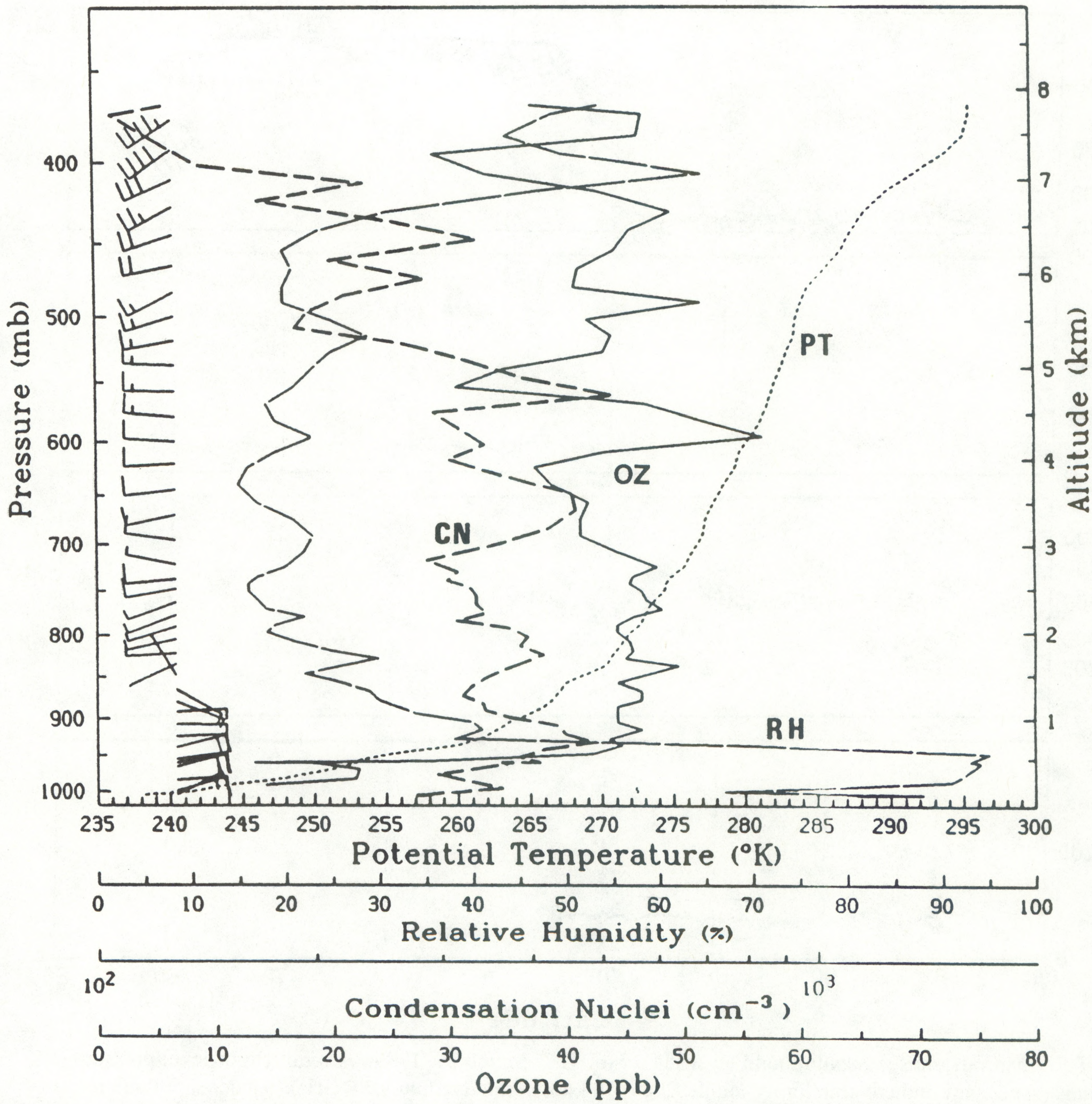

Figure 6.6. Aircraft sounding, 1140-1219 UTC, March 29, 1989. Profiles of potential temperature (PT), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown.

There is little to suggest any significant haze in this region. During the descent at 82°N the only visual report of haze was at the 520 hPa level, where light haze was reported ahead of the aircraft (Appendix A). Between 420 and 840 hPa, the low RH and uniform westerly winds coupled with slightly elevated ozone concentrations suggest an upper tropospheric, or lower stratospheric signature. Greenland, 1-2 days transit time upwind, could have caused significant vertical displacement, thus producing such a signature. In the Arctic PBL the winds shifted abruptly to the east (Fig. 6.4), and the characteristics of the air mass changed. Specifically, the

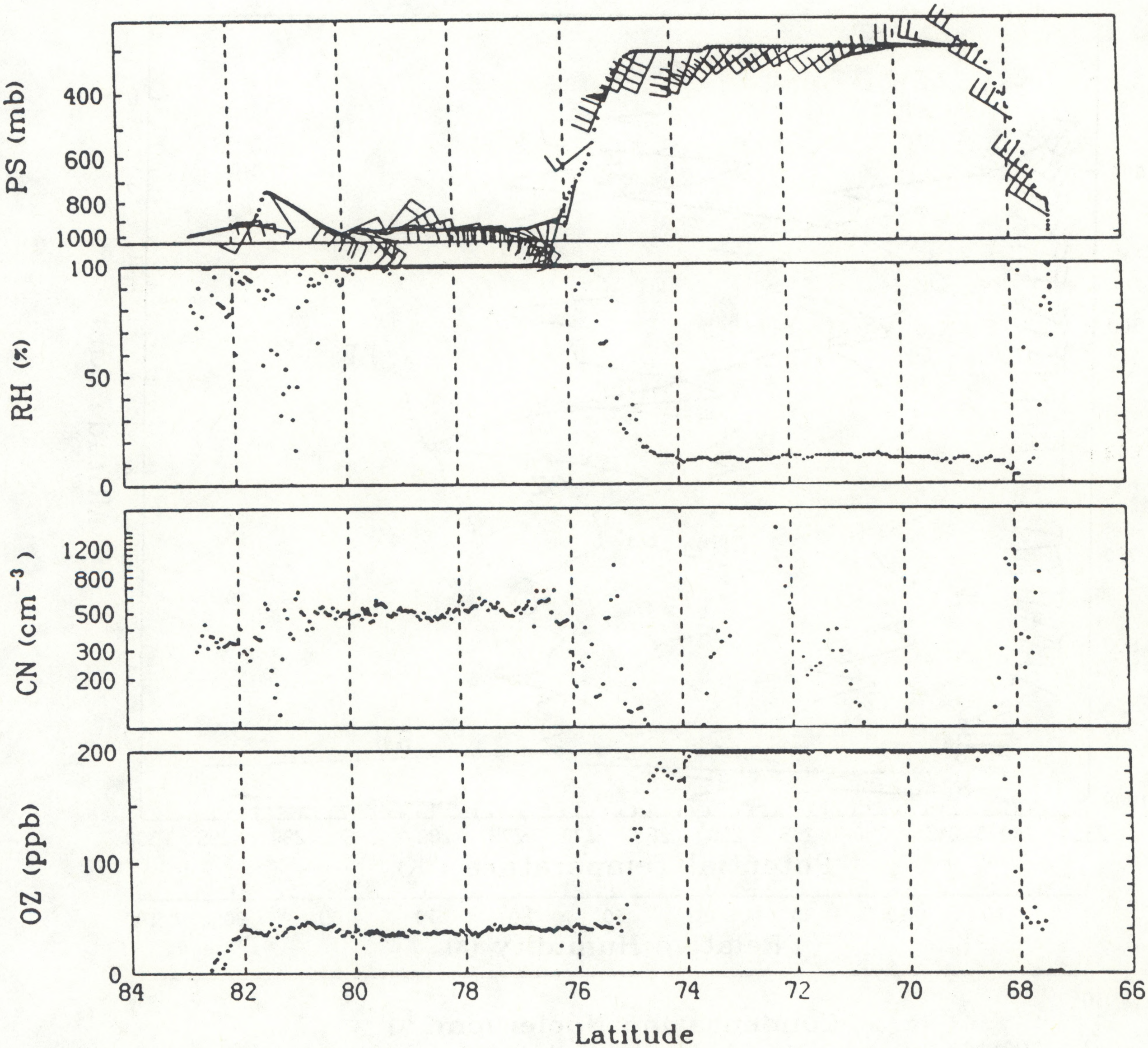

Figure 6.7. Aircraft transect, southbound leg 1258-1746 UTC, March 29, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

RH increased to near saturation in the sublayer below 950 hPa, and the CN concentrations decreased to values in the 300 cm^{-3} range. In the surface layer the ozone concentrations decreased to values that are below detection by the instrumentation. For periods of minutes while the aircraft flew within 20 m of the surface, the ozone concentrations were below the detection level of the instrumentation.

Except for a short period at 81°N when the aircraft climbed above the Arctic PBL, the southbound transect (Fig. 6.7) was in the same air mass until the ascent at 76°N. During the climb to cruise pressure the aircraft passed through the occluded front, below 850 hPa, and through the tropopause at 360 hPa and 75°N (Fig. 6.4). A large excursion was observed in the CN concentration between 73° and 72°N, which the crew aboard the aircraft attributed to sulfuric acid particles. Clearly the aircraft was in the stratosphere at this point, and the event was not supported by changes in any other variable. There is also no apparent transport explanation. The aircraft remained in the stratosphere until 410 hPa (68.1°N, 15.3°E) on the descent into Bodø.

A model that suggests elevated CN concentrations immediately below the tropopause was clearly validated during this flight. The stratosphere intersection at 410 hPa on the northbound flight showed excessive CN concentrations on both sides. CN concentrations in the 300-500 cm^{-3} range seem to typify the "clean" lower troposphere encountered during the descent at 82°N. In contrast to the previous flight, the Arctic PBL contained the same concentrations of CN as measured above the PBL. Clearly the ozone depletion in the lowest 20 m over the ice was more extensive than during any other flight. The return flight offered an extended period of sampling in the Arctic PBL, with a slight increase in the RH and in CN concentrations to the south, and an extended sampling of the stratosphere south of 75°N.

7. FLIGHT 311, MARCH 30, 1989

7.1 Overview

The flight scheduled for March 30, designated AGASP-III 311, was an Arctic PBL turbulence study over the CEAREX O camp (83°N, 10°E), similar to the flight on March 27. The 48-h transport forecast for 1200 UTC March 30 showed transport from the central European industrial regions to be easterly in response to low pressure to the north (Fig. 7.1). A high-pressure ridge over northern Europe for the previous 3 days limited the extent of meridional

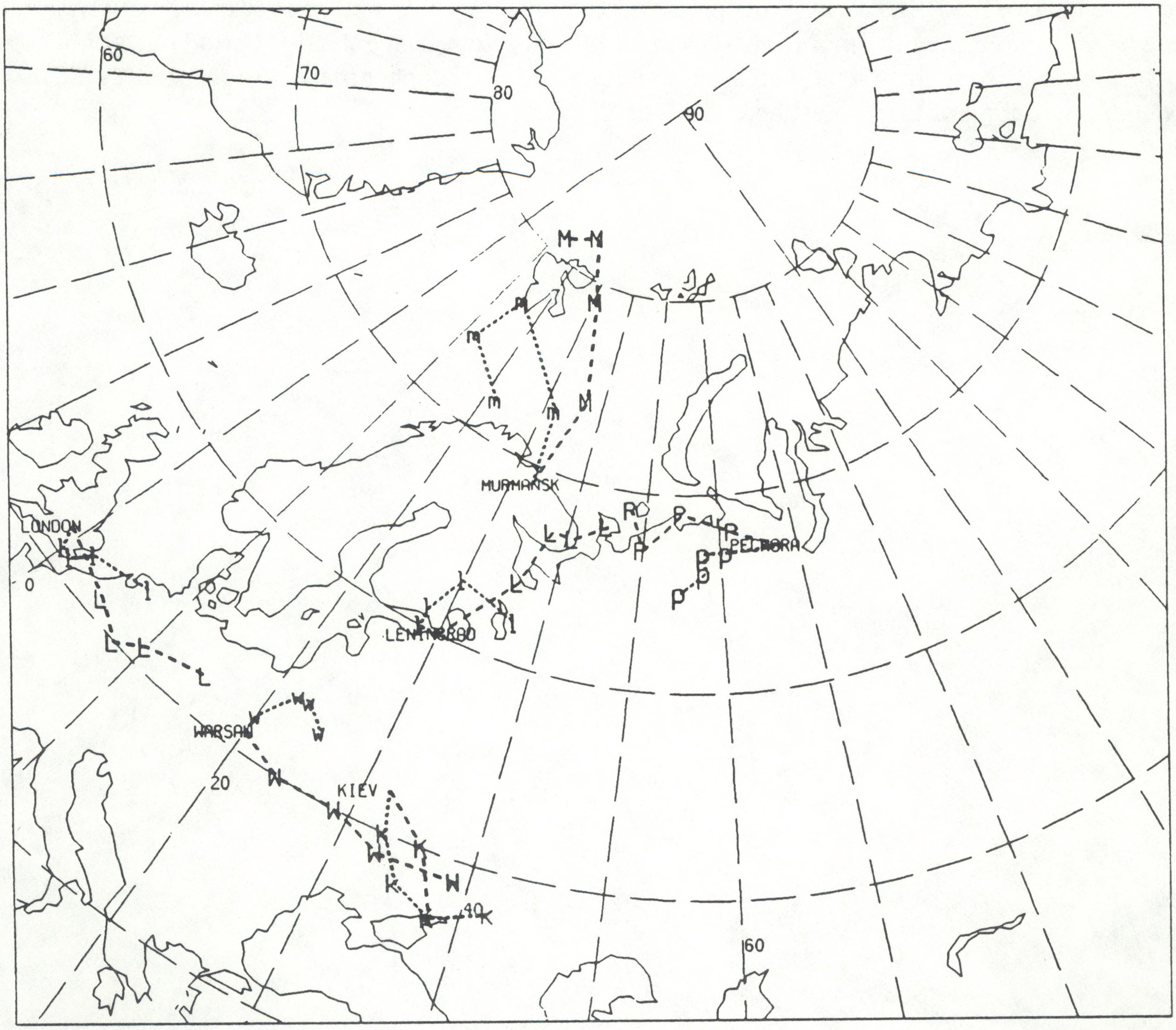

Figure 7.1 Horizontal projection of the Program for Operational Trajectory (POT) 48-h transport forecasts verifying 1200 UTC, March 30, 1989, originating from London (E), Warsaw (W), Kiev (K), Leningrad (L), Muransk (M), and Pechora (P). Lower case letters depict 950-hPa transport, upper case 850-hPa transport.

transport during this period (Fig. 5.2). The trajectories from the north Soviet coastal region, the Kola Peninsula in particular, indicated transport to the north of Svalbard at 850 hPa into the Norwegian Sea at 950 hPa. This low-level transport was in large part determined by the low-pressure system that was at that time located over the Barents Sea southeast of Svalbard. Although this was the most favorable pollution transport prediction in the last three flights, considering the extensive low-level cloudiness observed during the previous days flight, it is likely that air parcels following these trajectories would have experienced considerable condensation. The detailed flight track is shown in Appendix A.

7.2 Synoptic Situation

At 500 hPa , the closed low situated south of Svalbard 24 hours earlier had filled and became an open trough to the east of the flight track (Fig. 7.2). Because of the position of the trough, and the extent of the ridge over Greenland, the winds were northwesterly along the entire length of the transit flights. North of Svalbard the gradient decreased; the winds decreased in speed and became more variable in direction. The closed low at 850 hPa had moved in a northeasterly direction in the past 24 hours to a position in the Barents Sea (Fig. 7.3). At the surface, a high-pressure system was positioned in the Greenland Sea in conjunction with conditions aloft.

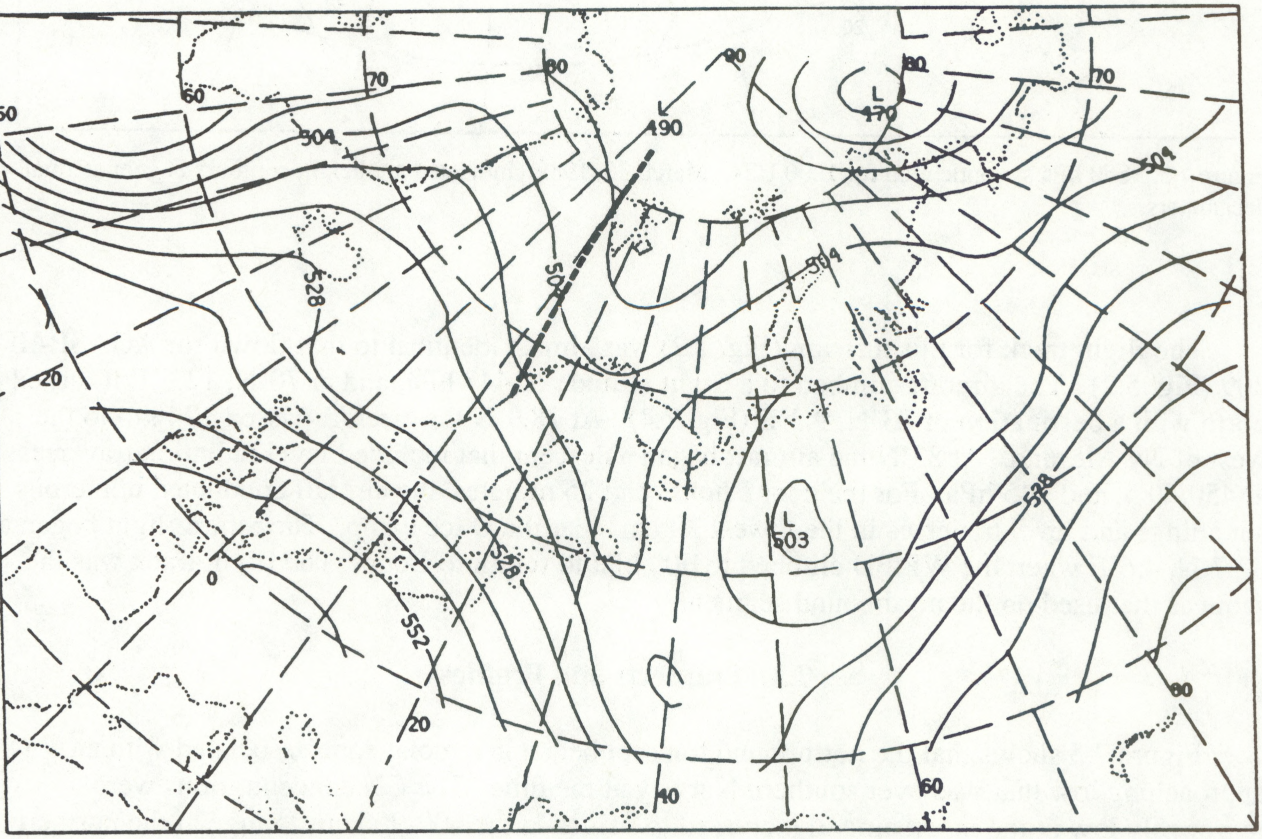

Figure 7.2. 500 hPa synoptic map for 1200 UTC, March 30, 1989. Indicated are height contours in geopotential decameters. The WP-3D flight track is shown by the heavy dashed line.

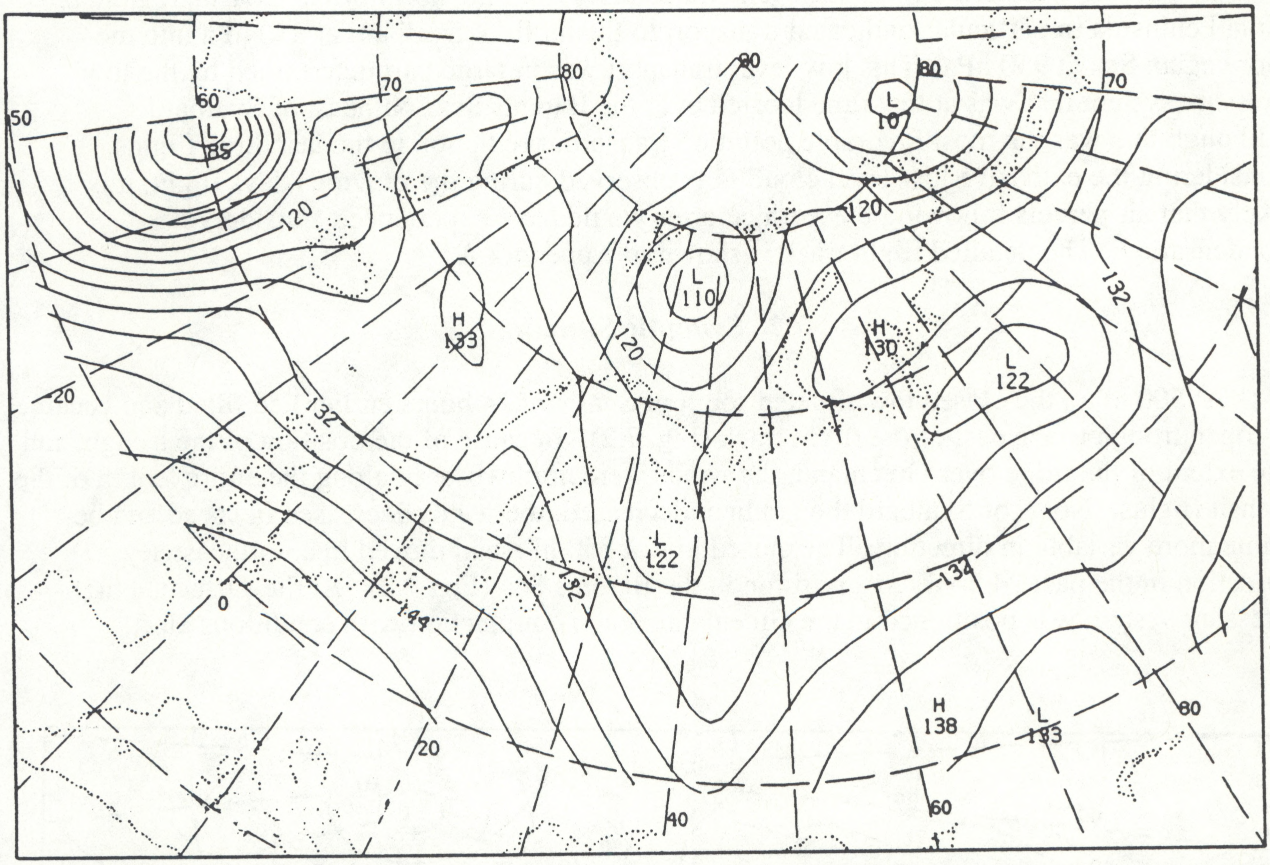

Figure 7.3. 850 hPa synoptic map for 1200 UTC, March 30, 1989. Indicated are height contours in geopotential decameters.

The flight track for this mission (Fig. 7.2) was almost identical to that flown for AGASP-III 309 (Fig. 5.2). The aircraft climbed to a flight altitude of 447 hPa, and at 70°N, 12.6°E it turned north with a destination of 83°N, 9.3°E (Fig. 7.4). At 78.9°N the aircraft passed 124 km to the west of Ny Ålesund. At 83°N the aircraft began a descent that included level radiation traverses at 450, 785, and 945 hPa. For the next 2 hours and 25 minutes, the aircraft conducted numerous soundings and level traverses in the lowest 300 m, near the O ice camp. The return flight began at 82.7°N, 4.6°E when the WP-3D climbed to 300 hPa to return to Bodø. The flight track was the same as that used on the northbound segment.

7.3 Transects and Profiles

Figure 7.5 shows that the northbound transect began in a moist zone associated with an approaching low that was over southern Norway at the time. The CN concentrations were reasonably low in the moist air and increased to values in the 600-900 cm^{-3} range at the northern edge of the moist air. The flight-level winds, CN, and ozone concentrations were unusually steady from this point to 80°N, which was consistent with the uniform 500 hPa height contours along the flight track (Fig. 7.2). At 80°N the increase in RH occurred when the aircraft entered

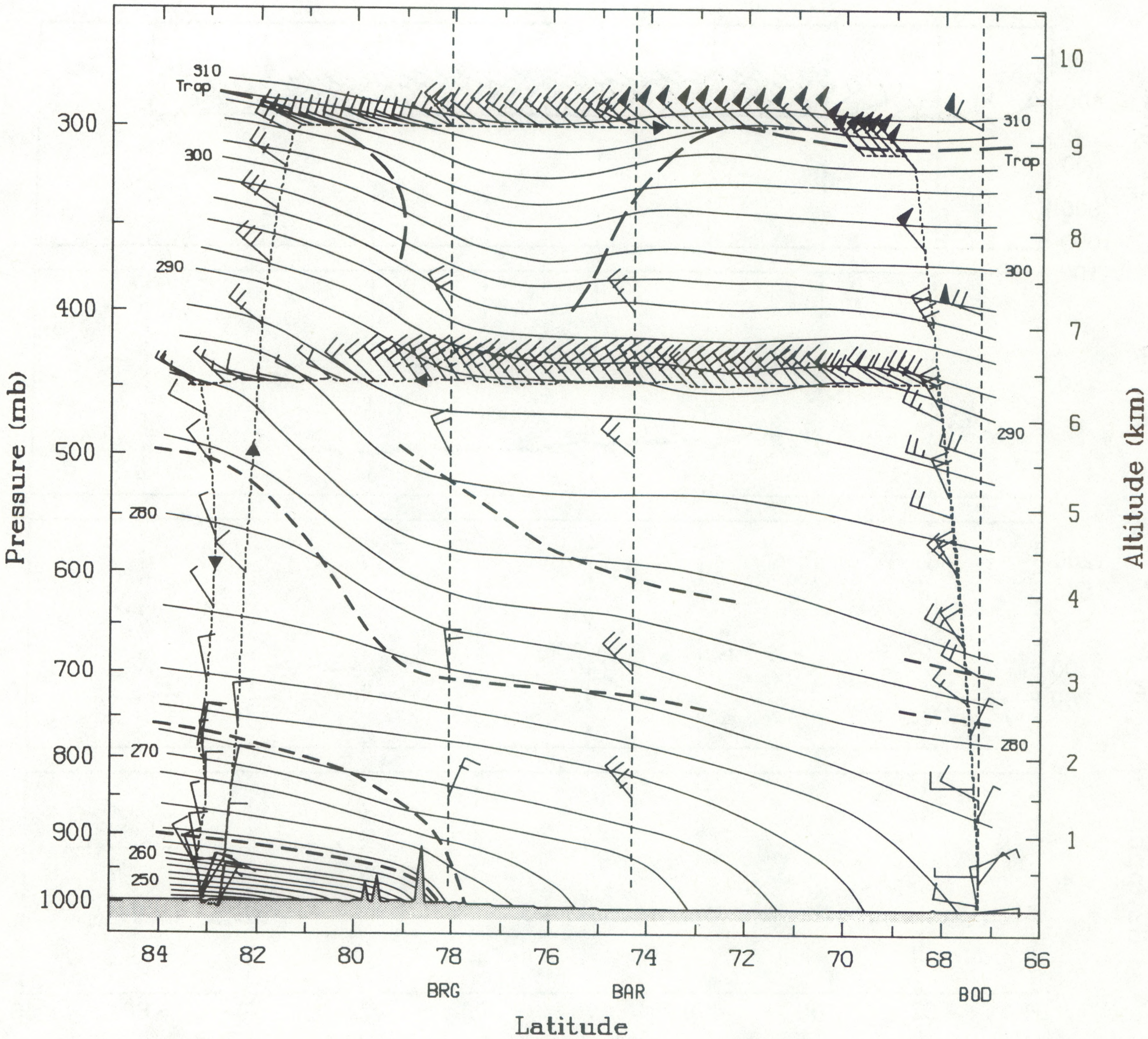

Figure 7.4. Latitude-altitude cross section of potential temperature (K) and wind (1 barb = 10 knots) between Bodø and 84°N, 0926-1923 UTC, March 30, 1989. The tropopause is indicated by a thick long-dashed line; stable layers, frontal zones, and the top of the Arctic boundary layer by thick short-dashed lines; and the aircraft flight track by thin-dashed lines. Arrows are placed at the beginning of each hour to indicate the direction of the aircraft . Vertical dashed lines show the rawinsonde location (BOD, BAR, and BRG).

the baroclinic zone that was analyzed at 76°N 24 hours earlier in Fig. 6.5. The minor variations in the CN concentration from 74° to 79°N were at the same latitudes but 400 km to the west of elevated CN concentrations observed 24 hours earlier at this same altitude (Fig. 6.5). Ozone concentrations also increased slightly to 50 ppb at about 79°N. After a brief period of increased RH from 80° to 82°N the atmosphere was dry again.

Three distinct changes in air mass occurred during the descent at 83°N (Fig. 7.6). The first was the transition from a stable baroclinic region that the aircraft entered on the northward

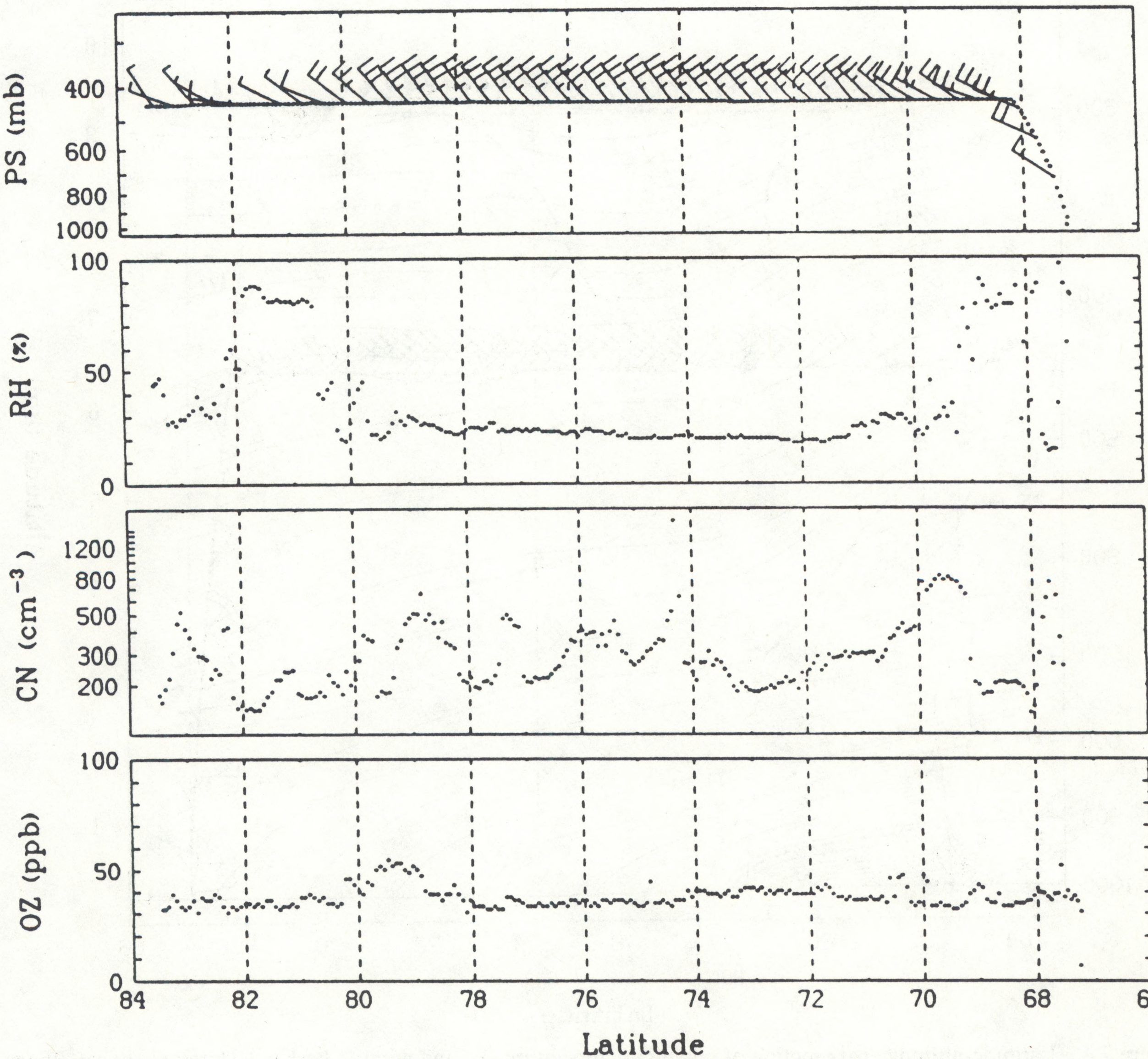

Figure 7.5. Aircraft transect, northbound leg, 0927-1314 UTC, March 30, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

traverse at 500 hPa, according to the potential temperature and wind shift (Fig. 7.4). The RH profile indicates the top at 470 hPa. The layer from 500 to 720 hPa was more unstable, having a higher RH, especially in the upper half of the layer. As was the case for the flight on March 27, the stable layer at 720-780 hPa separated a dryer region in the middle troposphere from a more humid layer below. The RH increased from 30 to 80% in the 780 to 880 hPa layer, and remained above 70% throughout the boundary layer. The top of the Arctic PBL was at about 880 hPA (Fig. 7.4). The primary wind shift did not occur until 980 hPa, where the direction changed from the prevailing northwesterly direction aloft to a northeasterly direction in the surface layer.

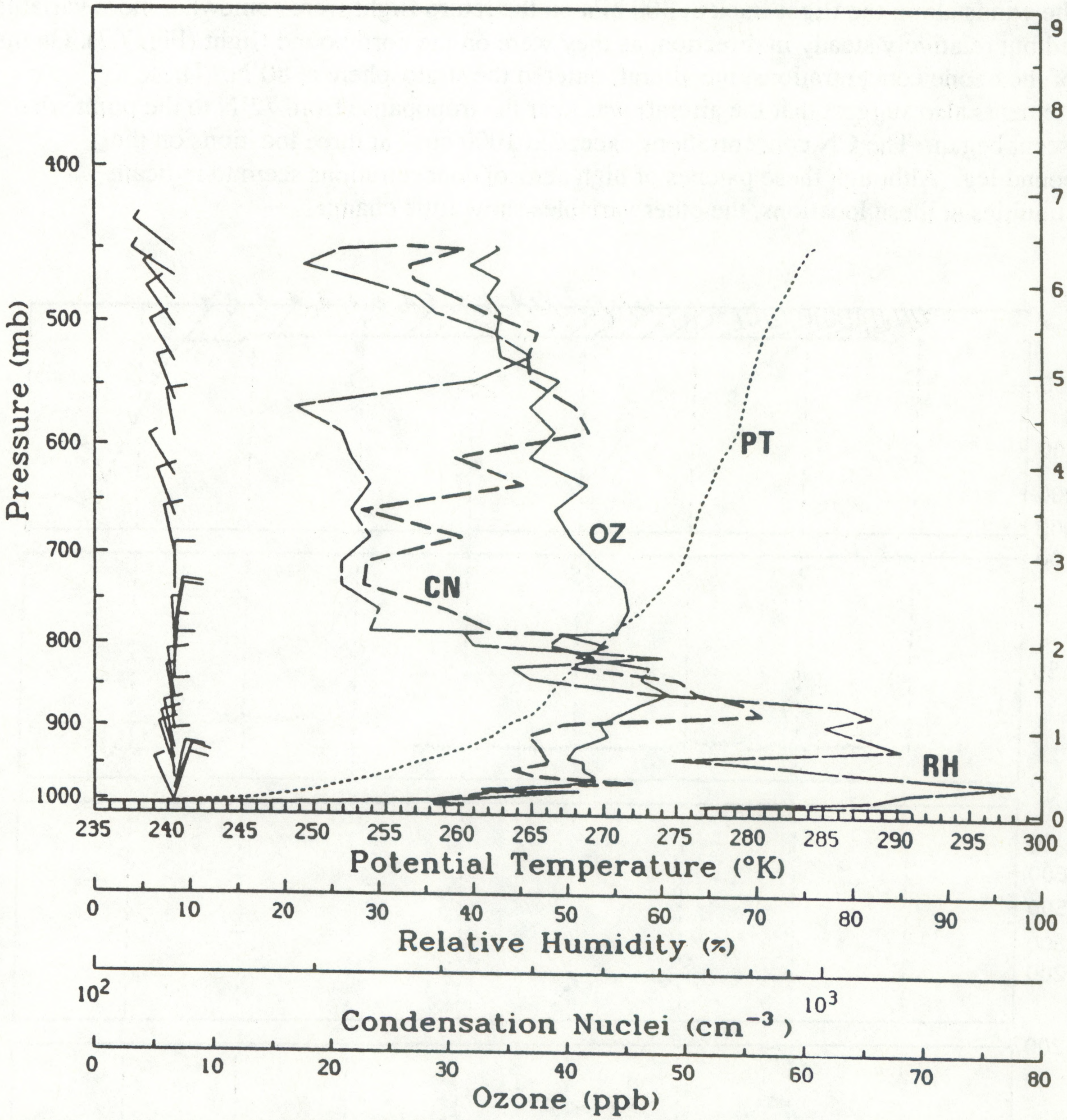

Figure 7.6. Aircraft sounding, 1320-1427 UTC, March 30, 1989. Profiles of potential temperature (PT), relative humidity (RH), condensation nucleus concentration (CN), and ozone concentration (OZ) are shown.

The CN concentrations were in the range that is typical of background midtropospheric conditions, 250-450 cm^{-3}, above the 720-780 hPa layer (Fig. 7.6). Below this layer CN concentrations increased, indicating a weak, elevated haze layer. The increase was in the same layer that the RH increased. The CN concentrations in the PBL returned to background levels. The ozone concentration showed little variation in the midtroposphere with values in the range of 30-50 ppb. The decrease in concentration in the surface layer, below 1004 hPa, indicates significant ozone destruction at the surface.

The winds along the flight track at 300 hPa on the return flight were somewhat more variable in speed but relatively steady in direction, as they were on the northbound flight (Fig. 7.7). On the basis of the ozone concentrations, the aircraft entered the stratosphere at 80°N. These measurements also suggest that the aircraft was near the tropopause from 72°N to the point where the descent began. The CN concentrations exceeded 1000 cm^{-3} at three locations on the southbound leg. Although these patches of high aerosol concentrations seem to indicate discontinuities at these locations, the other variables show little change.

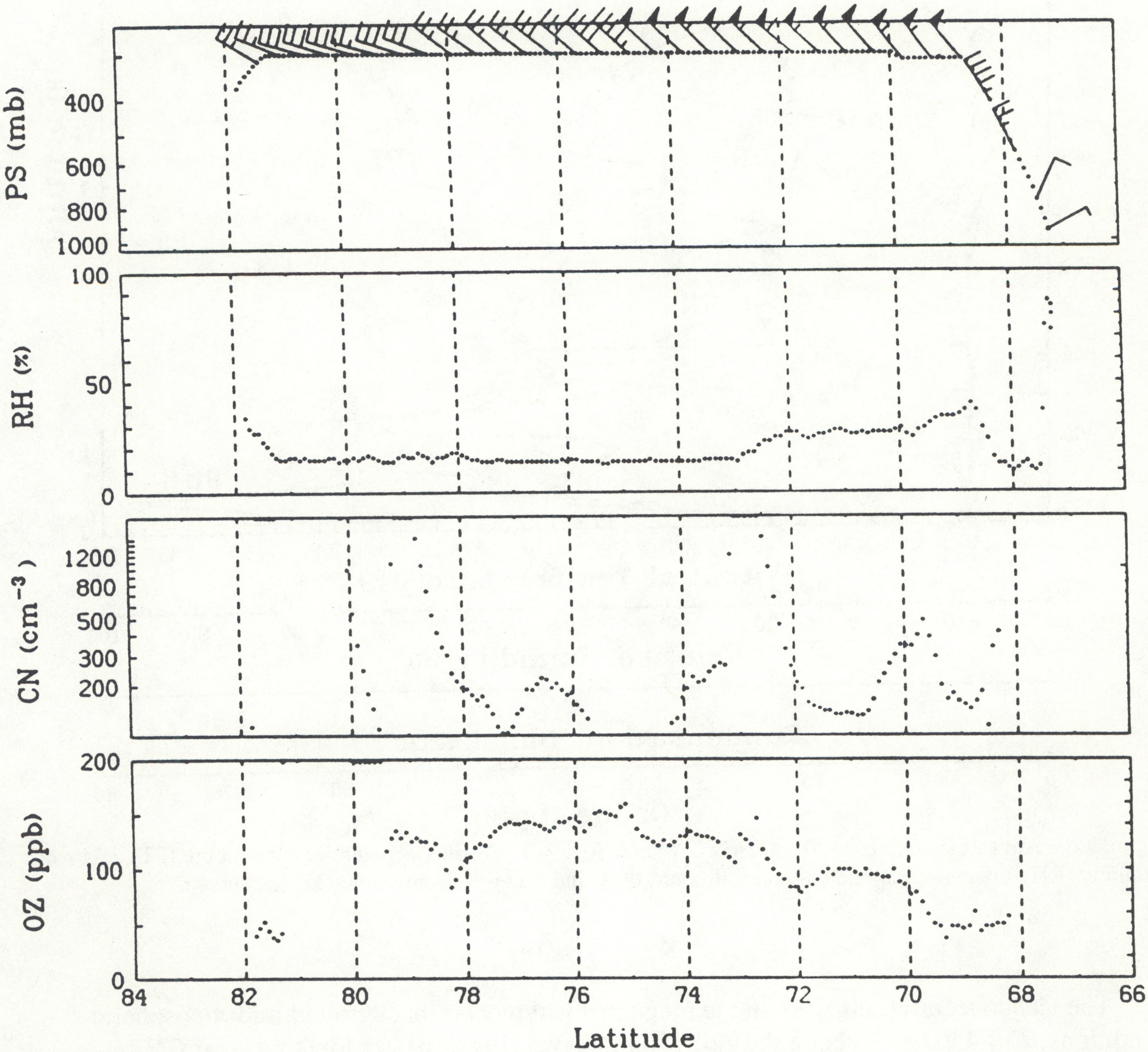

Figure 7.7. Aircraft transect, southbound leg, 1640-1920 UTC, March 30, 1989. Aircraft flight-level pressure (PS) and winds (speeds are indicated in knots, single flag = 10 knots), relative humidity (RH) condensation nucleus concentration (CN), and ozone concentration (OZ) are shown in respective panels.

7.4 Discussion

On the basis of the measurements obtained along the trancepts, there were five distinct air masses sampled during this midtropospheric leg of the flight. The first was moist, relatively aerosol-free, air in the vicinity of Bodø. The surface observation for Bodø indicated a broken cloud condition consisting of low and middle cloudiness, and northwesterly winds. The second was dry, upper-tropospheric air encountered at 69°N, shortly after the aircraft reached cruising altitude. The transition was marked by an abrupt decrease in the RH (Fig. 7.5). The aircraft left the dry upper-tropospheric air at about 80°N. The baroclinic zone at 79°-81°N, separated the dry, upper-tropospheric air to the south from more humid air. The slight increases in CN concentration at 76° and 79°N correspond to reports of light haze being visible from the aircraft (see Appendix A). The measurements suggest that subsidence was greatest in a narrow zone immediately to the south of the baroclinic zone. The subsidence, which accounts for the low RH from 69° to 80°N, occurred in conjunction with dynamic forcing on the west side of the trough at 500 hPa and the influence of Greenland to the west over which this air has passed. The increase in RH at 80.5°-82°N suggests a third air mass of lower-tropospheric origin.

A fourth was the relatively dry polar air, having low CN concentrations at 83°N between 470 and 760 hPA. The fifth was the Arctic PBL, the top of which was at about 760 hPa (Fig. 7.4). The aircraft passed through the polar air again before entering the stratosphere at 300 hPa at 80°N on the southbound flight. With the exception of the region below the Arctic inversion, where the winds were more northerly, at all other locations on this flight they were northwesterly.

Meteorological analysis suggests that with the exception of the maritime air south of 69°N, over Bodø, the history of the air encountered from south of 80°N was of high-tropospheric origin with a path over Greenland within the preceding 2-4 days. Between 80.5° and 82°N the RH increased, indicating air of midtropospheric origin that was possibly associated with the low-pressure region to the east, yet there were no reports of cirrus clouds. The wind flow was such in the region of elevated CN concentrations in the 760-900 hPa layer as to suggest transport off the Arctic basin. Although the values were not large compared with observations of sulfate aerosols near the tropopause on this flight and earlier missions, they were nevertheless high compared with the observations in the 600-760 layer. With the high RH in the surface layer, condensation processes may have depleted the CN population in the surface layer.

8. SUMMARY

Table 1 contains an hourly summary of meteorological conditions encountered during the six WP-3D CEAREX flights that constituted the AGASP-III haze flights. In the table the first two rows for each flight contain the ranges of latitude and of pressure altitudes in which the aircraft operated during the hour specified. The third row contains the location of the air mass in terms of the portion of the atmosphere. Vertical positioning of the flight segments was largely based on the water vapor and ozone concentrations. The fourth and fifth rows contain estimates of the local transport (1-2 days) and the long-range transport (3-5 days). A key to the contents is positioned in the upper right-hand corner of the table.

For more than half the flight hours (60%), the aircraft was operating in the troposphere. The stratosphere was sampled about 16% of the time, and the Arctic PBL was sampled 24% of the time. During those hours that the aircraft was climbing or descending, and more than one region was sampled, the exact position can be determined by consulting the flight log (Appendix A).

The large number of indications of North Atlantic sources is attributable to the fact that for much of the time (37%) the winds along the flight track were light, less than 10 m s^{-1}. This would lead to transport distances of less than 600 km in 2 days. For 1-2 days tranport, when the winds were less than 3 ms^{-1}, the term local was used. Thus "N Atlantic" indicates in many cases the Berents Sea or the Norwegian Sea, depending on the flight. The designation "Sov Arctic" means that the air passed over the eastern Barents Sea. For 3-5 day transport, the indication is that the air was from the North Atlantic or from over Greenland (56%). The percentage of time the long-range transport was from Europe was <10%, and from the high Arctic was about 18%.

Significant haze events in the lower troposphere, as denoted by extensive layers of CN concentrations in excess of 1000 cm^{-3}, were encountered during three periods: 1200-1300 UTC March 21, 1200 UTC March 23, and 1600-1700 UTC March 23. The meteorological conditions indicate that the first resulted from pollution that is traceable to Soviet Arctic sources. The second and third were off the Norwegian coast and may have been remnants of the large polluted air mass sampled east of Svalbard 2 days earlier, or they may have been of Fennoscandia origin, or both. Other than brief encounters with local pollution shortly after takeoff, these were the only significant periods encountered. For the most part, the three missions to sample north of Svalbard at 82°N yielded CN concentrations in the 400-800 cm^{-3} range, which may be considered the background levels in the eastern Arctic at that time of year. Only for very brief periods, 1200-1400 UTC March 29 and 1300 UTC March 29 at the top of the PBL in a very thin layer, did the concentrations at 82°N exceed 1000 cm^{-1}.

Brief episodes of high CN concentrations were also encountered in the vicinity of the tropopause. In two instances the concentrations exceded 20,000 cm^{-1}, 1600 UTC March 29 and 1600 UTC March 30, indicating active gas-to-particle conversion. In these cases the excessive CN concentrations occurred immediately below the tropopause, and the events were often associated with regions of strong wind shear.

Compared with earlier studies of the distribution of aerosol concentrations with height in the Alaskan Arctic (*Raatz et al.*, 1985*b*; *Herbert et al.*, 1989*b*), the haze layers showed less vari-

Table 1. Hourly (UTC) summary of air masses encountered during the six WP-3D haze flights. The key is given in the upper right corner and further discussed in the text.

Date 1989, Flight	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	KEY
March 16, # 303		67.3-68.9 987-445 Troposphere Local Scan. N Atlantic	68.9-73.9 446 Troposphere N Atlantic N Atlantic	73.9-78.3 446-437 Upper Trop Scan Arctic Greenland	78.3-80.0 437-439 Trop/Strat Scan Arctic Arctic	80.3-79.7 439-982 Trop/ArctBL Sov Arctic Sov Arctic	80.1-77.8 848 Arctic BL Local N Atlantic	77.8-75.7 848-496 ArcBL/Trop N Atlantic W Europe	75.7-72.8 496-974 Troposphere N Atlantic Sov Arctic	72.8-68.4 423-343 Troposphere N Atlantic Sov Arctic	68.4-67.2 473-987 Troposphere N Atlantic N Atlantic			LAT, deg N ALT, hPa Air mass 1-2 days 3-5 days
March 21, # 306			67.3-70.0 988-446 Troposphere Local/Scan	70.0-74.9 448-448 Upper Trop W Europe N Atlantic	74.9-78.6 446-709 Upper Trop W Europe N Atlantic	78.3-78.5 414-968 Trop/Strat W Europe N Atlantic	78.5-78.9 1009-835 Arctic BL Sov Arctic Cent Europe	78.4-77.9 835-1007 Troposphere Sov Arctic Cent Europe	77.9-76.6 1007-599 Upper Trop Sov Arctic Cent Europe	76.6-74.9 599-328 Upper Trop N Atlantic Greenland	74.9-70.7 328-300 Trop/Strat Greenland Polar	70.7-67.3 300-989 Strat/Trop N Atlantic N Atlantic		
March 23, # 307		67.4-71.2 844-448 Troposphere Local/Scan	71.3-75.5 447 Troposphere W Europe N Atlantic	75.5-78.2 447-376 Tropospher e N Atlantic N Atlantic	78.2-78.6 406-794 Troposphere Scan Arctic Sov Arctic	78.6-78.9 794-1004 Arctic BL Sov Arctic Sov Arctic	77.6-74.3 699-920 Trop/ArctBL Sov Arctic E Europe	74.0-70.7 860-311 Trop/Strat N Atlantic N Atlantic	70.7-71.3 306-658 Strat/Trop N Atlantic N Atlantic	71.3-70.1 658-974 Troposphere N Atlantic N Atlantic	70.1-67.2 723-986 Troposphere N Atlantic N Atlantic			
March 27, # 309	67.3-70.3 1018-446 Troposphere N Scan N Atlantic	70.3-75.0 447 Troposphere N Atlantic Greenland	75.0-79.9 447-451 Troposphere N Atlantic Greenland	79.9-83.1 447-747 Tropospher e N Atlantic Greenland	83.1-83.7 751-1015 Arctic BL N Atlantic Greenland	83.0-82.7 992-1015 Arctic BL N Atlantic Greenland	82.7-83.3 987-1015 Arctic BL N Atlantic Greenland	83.3-79,2 1009-307 ABL/T/Strat N Atlantic Greenland	79.2-74.4 307-293 Strat N Atlantic Unknown	74.4-69.6 293 Strat N Atlantic Unknown	69.6-67.3 293-1014 Troposphere N Atlantic Unknown			
March 29, # 310		67.3-70.2 992-409 Troposphere N Atlantic N Atlantic	70.3-75.4 410 Trop/Strat N Atlantic N Atlantic	75.4-80.5 413 Tropospher e N Atlantic N Atlantic	80.5-82.7 413-750 Troposphere Greenland Greenland	82.7-82.6 750-991 Arctic BL Scan Arctic Greenland	82.6-79.7 996-748 Arctic BL Svalbard Scan Arctic	79.7-77.6 960-989 Arctic BL Sov Arctic Unknown	77.6-74.5 965-307 Trop/Strat N Europe N Atlantic	74.5-70.1 307-300 Strat N Atlantic N Atlantic	70.1-67.3 300-1002 Strat/Trop N Atlantic N Atlantic			
March 30, # 311			67.3-69.3 1005-447 Troposphere N Atlantic NA Polar	69.3-73-6 447 Tropospher e Greenland NA Polar	73.7-77.9 447 Trop/Strat Greenland W Arctic	78.0-82.4 447 Troposphere Greenland W Arctic	82.5-83.3 446-943 Trop/ArcBL Local Greenland	83.2-83.3 946-1003 Arctic BL Local Cent Arctic	83.3-83.1 1007-971 Arctic BL Local Cent Arctic	83.0-80.1 1008-300 Arctic BL Local Greenland	80.1-74.0 300 ArcBL/Trop Greenland W Arctic	74.7-68.8 300-313 Strat Greenland W Arctic	68.7-67.3 314-1010 Troposphere N Atlantic N Atlantic	

ability with height in the Svalbard region. The background values were considerably less than were found from the Alaskan samples.

Because of the predominantly zonal nature of the flow over northern Europe in March 1989, there were only brief periods of significant meridional transport of pollutants. Coupled with this flow pattern was the occurrence of record warm temperatures over the western Soviet Union. Therefore, the sources of pollution were reduced. Thus with the exception of the intrusion of northern European air over the Barents Sea on March 20-21, there were no significant long-range transport events in March to study.

9. ACKNOWLEDGMENTS

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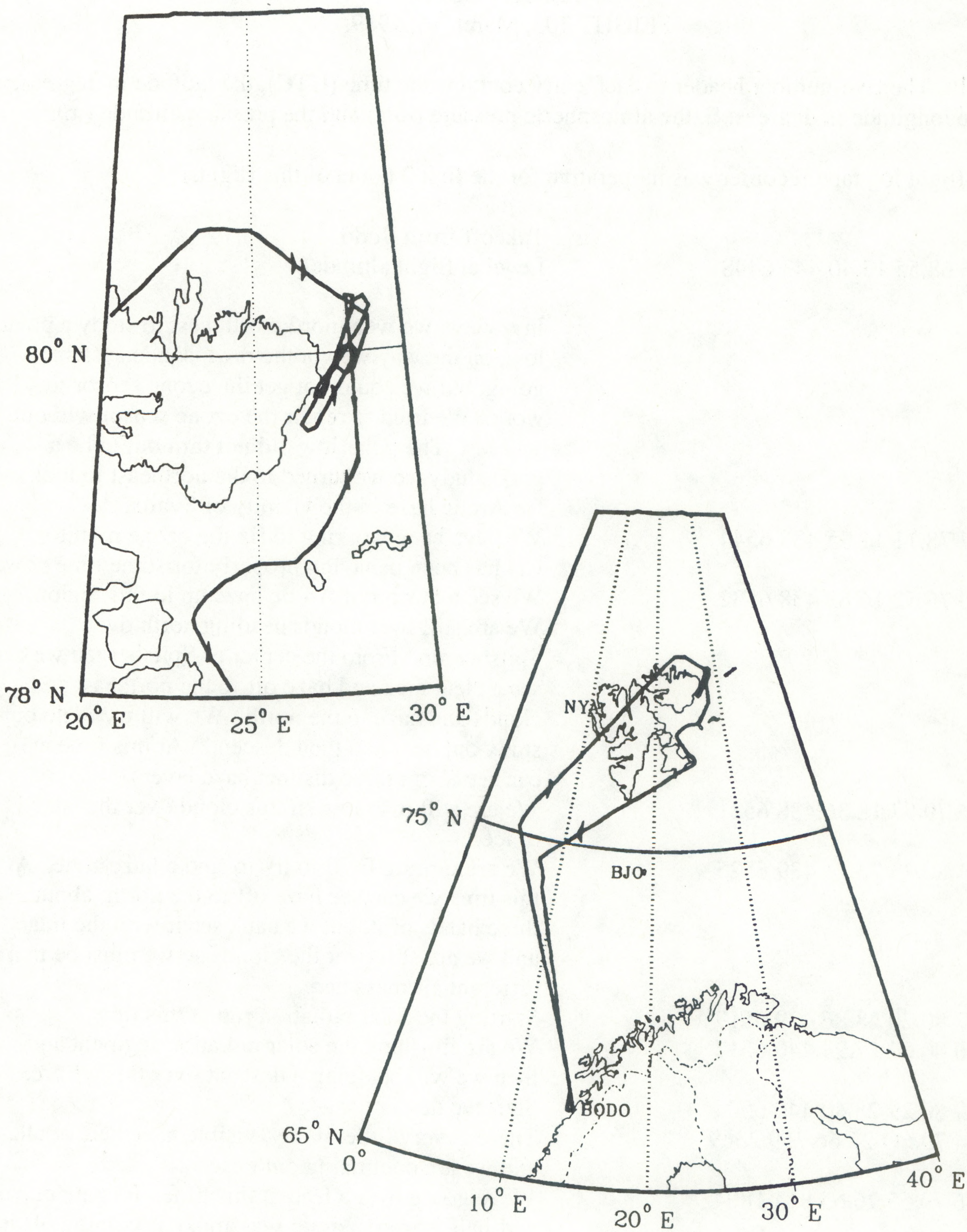
11. APPENDIX A



Horizontal projection of the aircraft flight track on a latitude - longitude grid,
Flight 303, March 16, 1989.

FLIGHT LOG
FLIGHT 303, March 16, 1989.

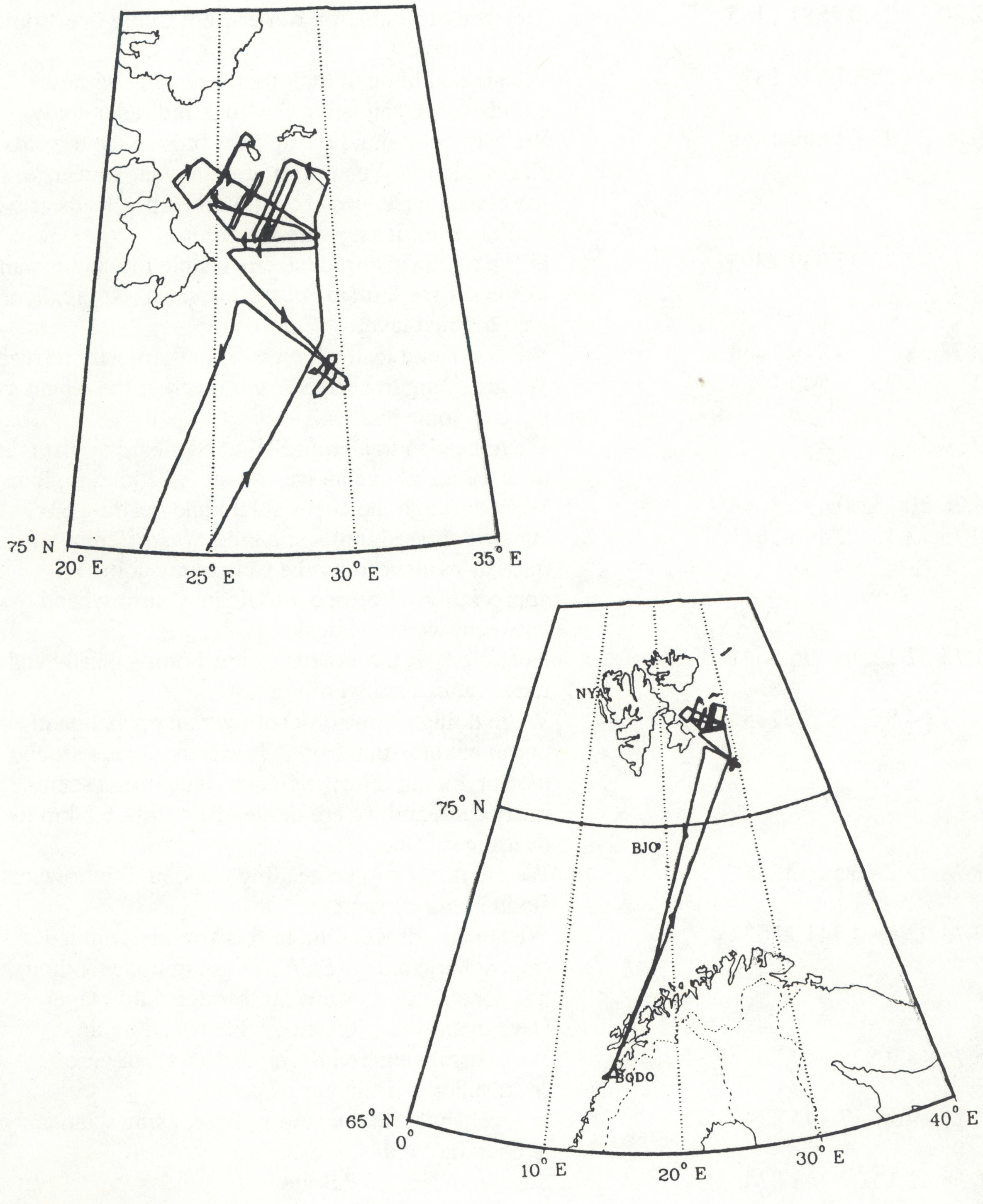
NOTE: The five-number header to each entry contains the time (UTC), the latitude in degrees, N, the longitude in degrees, E, the atmospheric pressure (hPa) and the pressure altitude (m).

(The flight log tape recorder was inoperative for the first 2 hours of this flight.)

08:24	Takeoff from Bodo.
08:56 68.55 13.40 443 6448	Level at flight altitude.
	In review, we went north northwest to study a polar low, on the way we got the rawinsonde system going, but we could not get the ozone sensor to work. We tried to repair the ozone sensor without success. The polar low did not turn out to be a good study, so we turned to the northeast to look for Arctic haze in the vicinity of Svalbard.
10:57 78.11 11.35 438 6544	We have been working to fix the ozone monitor. CN has been behaving properly for some time now.
11:20 79.52 16.63 438 6532	We see a fair bit of Arctic haze up in this region. We are still over clouds heading north over Spitsbergen. From the center of Spitsbergen we can see a clear area and haze off to the northeast and clouds and haze to the north. We will try to do our study out here and then descend. At this time we can see about three distinct haze layers.
11:26 79.87 18.36 438 6531	We are still over low stratus cloud over the island or ice.
11:41 80.73 23.11 439 6525	We are turning ENE to try to find a haze zone. At this time we can see haze off to the north, about three bands of it, but we can't see it with the lidar and we are still over the clouds so we must be in a different air mass here.
11:57 80.20 28.86 439 6519	Starting the solar radiation run at this time.
12:06 80.07 27.94 440 6512	We are finishing the solar radiation segment and then we will be doing a descent over this ice area.
12:09 80.29 28.40 440 6504	Start the descent.
12:24 79.6O 26.6o 759 2369	There is very little, if any, visible haze here at all, and we are continuing our descent.
12:26 79.55 26.63 814 1804	We're going over a lead at this time. It is about half-and-half frozen. Arctic sea-smoke is coming off it.
12:32 79.84 27.84 905 941	We just went through the inversion. The CN count is very clean and we are going to continue our descent.
12:42 79.84 27.18 982 265	We are flying back and forth over the ice and broken leads doing a radiation run in an area that is

	very clean. In this area the ice does not have any large pressure ridges. It is mostly just cracks.
12:52 80.13 28.05 881 1165	Finished our radiation run and are flying over some small clouds.
12:58 80.23 28.17 848 1473	We are southbound looking for an area without clouds so we can begin the lidar and radar study.
13:20 79.20 27.67 849 1469	We are southbound flying over broken ice towards King Karl's Island. We are flying with what appears to be an ice-crystal haze, possibly from the open leads as we fly into the sun. It's a white-ish color.
13:32 78.78 25.85 849 1465	Diffuse brownish-red haze is visible looking toward to sun off the left side of the airplane. Not really a well defined layer.
13:40 78.68 23.99 849 1464	We are over a lead which is actually mostly refrozen.
14:02 77.75 25.35 849 1464	We are going to head SW to go across the island to get into some haze.
14:39 76.53 17.37 495 5643	We're headed to a point SW of Svalbard and at this time we are above an ice crystal and cloud region.
14:48 76.20 15.50 495 5643	We're through the cirrus shield and heading SW.
15:00 75.73 13.20 496 5641	We just crossed into some kind of a different air mass as evidenced by the CN counts going up appreciably. We appear to be in a narrow band between two cloud decks.
15:04 75.57 12.43 496 5641	Heading SW, CN counts jumped momentarily and temperatures are warming now.
15:26 74.64 8.53 525 5215	We're doing a slow descent over an open area of ocean behind this front. There are clouds around us, but not big billowing ones. The ocean seems fairly calm and we are descending from 5.5 km to near the surface.
15:31 74.43 7.76 598 4235	We are turning to be heading back straight towards Bodø in our descent.
15:39 73.92 8.44 741 2562	We are still descending in this slightly polluted tropospheric air. B-SCAT is going up. CN though has gone down as we went through a thin layer. Over open water; no ice visible for some time.
16:05 72.48 9.87 434 8253	We possibly entered the stratosphere, or air of stratospheric origin at this point.
16:22 71.19 11.17 344 8247	In level flight, in the stratosphere, using wind and temperature indications.
16:56 68.62 13.27 344 8240	Start of descent for Bodø.
17:25	Landing in Bodø.

In review it would appear the Arctic haze was west of Spitsbergen behind the front, not much found to the north.



Horizontal projection of the aircraft flight track on a latitude - longitude grid,
Flight 306, March 21, 1989.

FLIGHT LOG

FLIGHT 306, March 21, 1989

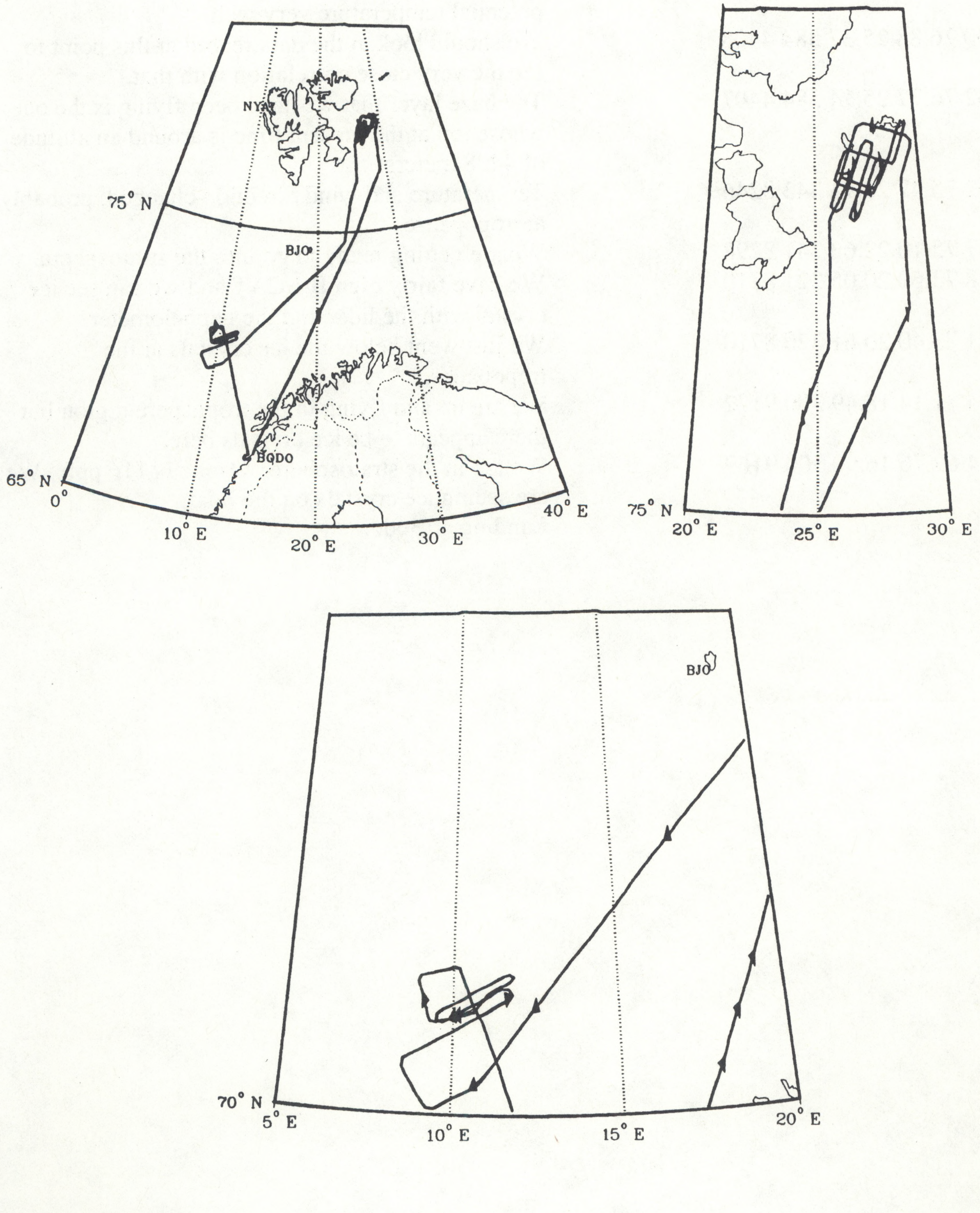
09:20	Takeoff.
09:32 67.73 14.84 574 4544	Still in clouds, climbing to 22k ft.
09:42 68.45 15.61 460 6192	We just broke out of cloud which is very evident on the nephelometer.
09:53 69.40 16.63 446 6414	Level at 6.4 km, just at top of clouds.
10:05 70.41 17.88 446 6407	Ice crystals at top of cloud layer. Clouds 1.5 km above patchy.
10:08 70.66 18.19 446 6405	We have been flying over a large cirrus deck. Ice crystals are below the plane, by visual observations. CN and Nephelometer are picking up increasing aerosol concentrations, which must be the ice crystals.
10:15 71.26 18.95 446 6401	Northbound. We are starting to break out of this higher level cirrus. We have a mid-level stratus with breaks in it.
10:21 71.76 19.63 447 6398	Ci aloft, pathy 1.5 km, mid layer open, lower level clouds lkm.
10:32 72.68 20.83 447 6392	We are flying in patches of haze. We are getting high CN counts.
10:33 72.76 20.95 447 6392	First haze obs, some turbulence, haze layer aloft.
10:55 74.51 23.80 448 6380	Broad diffuse haze indicated to NW. Big BSCAT jump 10 min. ago.
10:58 74.74 24.23 448 6379	Two layer indicated with bright band in between.
11:01 74.96 24.68 448 6376	We are flying into a huge layer of aerosols. It may be mixed with ice crystals but it has the appearance of haze. CN counts are climbing.
11:02 75.04 24.84 448 6376	We are getting a change in the wind direction. Wind direction and CN are dropping off fast.
11:05 75.26 25.29 448 6376	Sharp layer, temperature just dropped. Very muddy, brownish view below.
11:10 75.64 26.05 448 6372	Upper layer gone.
11:11 75.71 26.22 448 6371	We are in a high-level haze layer.
11:15 76.00 26.90 449 6357	CN up to approximately 1200 cm-3, B-SCAT up also. Visual Ice edge is visible - clouds free over ice as well.
11:20 76.37 27.76 450 6349	A couple of good haze bands visible due north. We are going to descend slowly to sample them.
11:22 76.51 28.10 450 6348	View of ice is not as sharp now - either fuzzy due to clouds or haze.
11:23 76.58 28.28 450 6347	We have been in haze for the last 10 minutes and we are now getting ready to descend because we Just came out of this layer.
11:24 76.65 28.46 451 6336	We are just in the top of the haze.

11:26 76.80 28.83 453 6297	We are still in this haze.
11:28 76.99 29.27 459 6202	Turned toward north.
11:33 77.35 29.27 470 6029	We are climbing back up again to see if we can go through these layers.
11:34 77.42 29.25 466 6096	Began climb to 7 km.
11:37 77.64 29.23 435 6585	We are entering that second haze layer on our descent.
11:42 78.01 29.26 409 7035	Began radiation segment, we did not quite reach the stratosphere before starting radiation legs.
11:43 78.09 29.27 409 7031	We are setting up a radiation run, then we are going to do a sunphotometer run on the left wing and then we are going to fly into the sun and begin our descent.
11:47 78.35 29.81 409 7028	We are over broken ice and haze. We are in our solar radiation run and now we are going to do our sunphotometer run.
11:48 78.41 29.94 409 7030	We are turning for a sun photometer run coming back into a little bit of haze.
12:03 78.06 26.86 437 6556	Haze above and below.
12:08 77.98 26.99 487 5767	We just went through another thin haze layer.
12:13 78.27 27.66 540 5008	Dense layer ahead.
12:18 78.51 28.43 560 4259	Good haze, we've been going through a haze layer here.
12:23 78.24 28.03 660 3476	We are in another haze layer. Second layer at 663 hPa, gap in between.
12:27 78.03 27.54 713 2867	Dense haze at 700 hPa.
12:31 77.94 27.00 768 2271	Began level leg heading 25°.
12:37 78.24 27.35 770 2252	We are still in a haze layer.
12:43 78.23 26.04 771 2249	We are getting into another B-SCAT layer which maybe ice crystals. The lidar sees the top of the layer at about 1.2 km.
12:48 78.00 25.74 787 2081	We are in some kind of a layer that is giving us a very high B-SCAT but not much CN. Began descent again 500'/m to 500', high B-Scat low layer CN. A shallow layer at 770 hPa.
12:51 78.15 26.07 826 1692	We just passed through a very dry haze layer. With the highest B-SCAT we have seen today.
13:02 78.36 26.77 1006 64	As we go beneath the inversion B-Scat disappears. Ozone is disappearing.
13:09 78.20 25.43 1009 34	Ozone is reading 18 ppb. The CN are fairly low and B-SCAT is very low as we do our run over the ice at 30 feet. I just did a Ras Gas in this boundary layer at 13:06.
13:12 78.28 24.77 993 172	We are doing our last leg of our solar radiation run. We've climbed up to turn.
13:14 78.37 24.92 1009 36	We are flying low over the ice beneath the

13:14 78.37 24.92 1009 36	We are flying low over the ice beneath the inversion again at 30 feet. B-SCAT is down, ozone is down, and we are going to finish this solar radiation run and then come up and do a filter. Ice is solid - no clouds.
13:35 78.52 25.39 829 1659	Level at 830 hPa.
13:55 78.59 24.52 843 1612	Elevated aerosols. End radiation run.
14:13 78.07 28.42 1001 106	Begin low level run.
14:14 78.04 28.60 1000 109	We're in the planetary boundary layer run at 250 feet. Ozone is holding steady at 25-26 ppb, down from 45 ppb higher up.
14:16 77.99 29.17 1000 108	Shadow on the horizon are a puzzle. It seem to vary as we fly along.
14:20 77.90 29.09 972 348	We are going back down to 250 feet to do a survey of the ice.
14:21 77.9 28.83 986 232	Down to 200 ft again.
14:22 77.90 28.48 1000 108	We're flying over the ice under a very thin cloud layer just above us that we had noticed in the inversion before.
14:23 77.90 28.43 1000 109	Clouds at 1500-2000 ft. I believe that is the moist layer at 900 hPa. I see light clouds above us. This is that wispy layer at 1000 feet that has been there most of the day. I don't think we are going to be able to avoid that. It has a little wave-like structure in it and we are going to keep at this level for 45 minutes.
14:25 77.90 27.79 1000 108	We appear to be away from the clouds. I have not seen an unfrozen lead in this area yet. All of them are ice skimmed. Out of clouds. High Athelometer values.
14:29 77.89 26.78 1000 108	Even though we are seeing a lot of refrozen leads and water that was open a while ago, we are not seeing any that are fresh open water.
14:30 77.89 26.53 1000 109	We are still flying into the sun and we have not seen any open leads and we do not have ice crystals between us and the sun and there are no visible clouds above.
14:32 77.89 26.04 1000 108	We are climbing and there are little clouds above. These little clouds are at about 1000 feet. They are the ones that we have been seeing occasionally during the day.
14:36 78.01 25.38 1000 108	We are going to continue this radiation leg in a semi-cloud free condition. On this whole run I have not seen one lead that doesn't have ice on it.
14:37 78.05 25.23 1000 108	Sun setting over Svalbard, clouds over islands.
14:38 78.09 25.07 1000 109	We are back in little patchy clouds, in and out again.

14:43 78.19 25.17 1001 104	We are heading away from the sun. Still looking for open leads and doing a chemistry run. Have yet to find one open lead.
14:49 78.12 26.56 1000 109	Still cloud free. Leads all seem to be covered with grease ice.
14:53 78.07 27.44 1000 113	We are traveling on a track of 106 degrees, and all of the snow indicates flow from slightly south of this line and it looks like it has been fairly persistent for a while.
14:57 78.02 28.33 1000 111	Ozone sounding near surface between 1006 and 1007 hPa, winds 60° at 9 ms^{-1}.
14:58 78.00 28.54 997 133	We are doing a little ozone sounding here down a slow as he'll go and hold it for a minute and then comeback up.
15:03 77.82 29.29 955 490	We are climbing up out of the boundary layer.
15:15 77.80 25.75 671 3348	The B-SCAT is increasing. I think we are in the bottom of this haze layer.
15:23 77.43 26.80 532 5113	We are going to drop back down into this layer that we just went through and see what we can find. It is a very well-defined layer.
15:25 77.34 27.18 557 4766	We are coming back into that haze layer where were going to do our multiple sampling. Trying to stay in an elevated layer for the chemist, heading 138 degrees, winds 80° at 9 ms^{-1}.
15:42 76.51 29.28 570 4598	We went out of this haze layer for just a minute. We dropped down and now we are back in it.
15:46 76.56 29.00 570 4596	We are holding in this plume doing samples. We are also going over a lead area that the lidar is looking at.
15:51 76.81 29.75 573 4562	We are going to turn around and go back over this lead with the lidar.
15:55 76.65 28.91 583 4420	We're going to go over the ice edge to see what is happening here. We can see roll clouds forming as we go along.
15:58 76.66 29.10 599 4214	We are right at the ice edge.
16:01 76.54 29.72 599 4214	We are heading from the open water towards the ice and we can see little clouds forming right at the edge of the ice. There is a little roll structure to them and we will head back over the ice to obtain lidar observations. We're turning to go back in over the ice at this time.
16:29 76.94 25.47 571 4585	We have been flying at a constant potential temperature surface. While the temperature has been going down we've increased our altitude 700 feet. Potential temperature and equivalent potential temperature are the same. As we go down in

	SCAT goes up indicating that it's following the potential temperature very well.
16:30 76.88 25.37 584 4408	We should look at the data record at this point to see the very close correlation with that.
16:32 76.77 25.14 584 4407	The haze layer that we have been flying is the one whose top at the present time is around an altitude of 4408 meters.
16:52 75.47 23.13 343 8246	Temperature and wind direction changed, probably at tropopause.
16:57 75.10 22.63 341 8298	We are getting ready to go into the stratosphere.
17:18 73.60 20.05 321 8710	We have fairly high B-SCAT and we can see ice crystal with the lidar and the nephelometer.
17:21 73.40 20.61 320 8710	We just went below the ice crystals at the tropopause.
17:54 71.14 18.49 300 9172	We are up and flying in the tropospere region but there appears to be ice crystals here.
18:14 69.76 16.90 300 9169	We are in the stratosphere. Ozone is 116 ppb. We are seeing ice crystals on the lidar.
19:00	Landing at Bodø.



Horizontal projection of the aircraft flight track on a latitude - longitude grid, Flight 307, March 23, 1989.

FLIGHT LOG
Flight 307, March 23,1989.

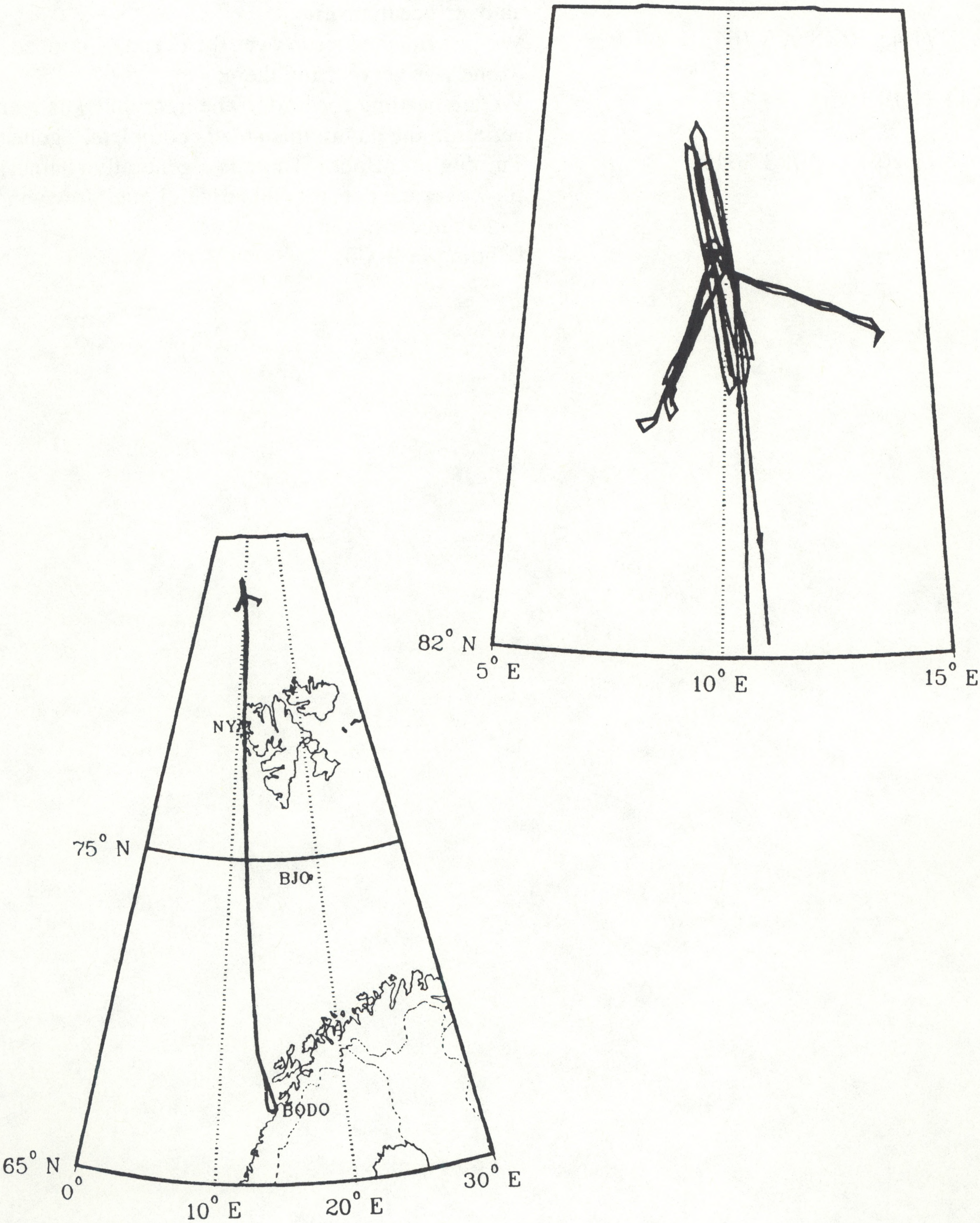
08:04	Take off from Bodø, Norway.
08:14 67.91 14.98 526 5203	As we pull out, north of Bodø, we're in some kind of local pollution.
08:22 68.43 15.53 445 6413	We're flying through haze and pollution layers just north of Bodø.
08:33 69.28 16.46 447 6399	We are still encountering various haze layers.
08:34 69.35 16.55 447 6398	We flew through another layer of pollution over Andoya and we're heading northward. There is another layer or two above us and we are just scraping along in one.
08:40 69.80 17.10 447 6392	This haze is south of a warm front so it must be coming from the U.K. or Europe.
08:42 69.95 17.29 447 6391	There appears to be a slightly darker layer of aerosol just above us. We can't get to it because we are still too heavy.
08:46 70.24 17.65 447 6389	We now seem to be getting out of this haze layer.
09:00 71.25 18.92 448 6382	Approaching a frontal zone, clouds below and ahead, some high clouds ahead as well. Slight turbulence.
09:04 71.54 19.28 445 6420	Into a cloud, light turbulence.
09:12 72.10 20.00 445 6416	Stratosphere, wind shift, 4°C jump.
09:13 72.18 20.08 445 6419	We're near the tropopause.
09:15 72.32 20.31 446 6414	We're flying immediately below the tropopause and getting the appropriate ozone and aerosol signatures.
09:18 72.52 20.63 446 6414	Looking up with the lidar, we can see a cirrus layer above us.
09:20 72.67 20.85 446 6414	We are seeing lots of little ice crystals in the lidar. B-SCAT just went off scale, sampling ice crystals.
09:24 72.95 21.28 446 6411	We are seeing aerosol layers above us. We are at the bottom of the stratosphere, so these are polar-stratospheric clouds.
09:29 73.30 21.82 446 6409	Stratospheric Ci above us, CN steady.
09:32 73.51 22.16 446 6405	View is obscured by clouds, above and below.
09:37 73.86 22.75 446 6401	Very big drop in B-SCAT.
09:45 74.42 23.75 447 6398	Haze and/or cloud layer visible in front of and above.
09:50 74.76 24.48 447 6396	View opened, Ci above, low Cu, open area ahead. Big ozone drop, B-SCAT down.
09:58 75.33 25.55 447 6391	We are northbound, approaching the ice edge. The clouds seem to terminate about ice edge or there abouts. We can see about five haze layers in front of us as well as a cirrus cloud. We are going to do a descent over a fairly clear area where we can find it.

10:01 75.55 25.94 447 6390	We are northbound and we can see streaks coming out of the ice in an east-southeast wind. White caps at surface. Ice edge visible to West.
10:04 75.76 26.34 447 6387	Ice turning brown.
10:08 76.05 26.88 442 6467	We are going to climb a thousand feet to get above this area of haze so we can do a profile. We can see in front of us, one, two, three, four, very good layers and a possible fifth.
10:26 77.36 29.06 383 7501	We are climbing. We went through a thin haze layer and then we went up and hit another one.
10:31 77.76 29.11 376 7628	Large leads still visible.
10:38 78.33 29.15 376 7623	We are in the radiation run and then we are going to do a radiation profile. Kong Karls Land visible to NW.
10:44 78.74 29.49 376 7617	This is going to be a haze run.
10:49 78.86 27.79 376 7613	The haze is much lighter here than it was farther to the south.
10:55 78.57 26.60 376 7611	Clouds visible above Ice.
10:56 78.59 26.49 377 7607	Began descent.
11:00 78.21 25.96 406 7083	We are now descending in our radiation profile.
11:03 78.02 25.97 430 6671	Big jump in B-SCAT, lots of structure to B-SCAT.
11:07 78.24 26.57 464 6116	We just went through a very thin layer of haze.
11:14 78.66 27.33 528 5173	Right to 200 at 78.37 27.19, Kong Karls Land.
11:22 78.30 27.22 613 4039	The haze is very thin in this area. We are getting very little structure. Clouds below heading south.
11:29 77.92 26.80 691 3114	Turning to 23 degrees number of open leads below.
11:43 78.46 28.29 793 2017	Level at 793 hPa, elevated B-SCAT, CN in thin layers, lots of variability.
12:00 78.55 26.37 795 2003	Begin descent again.
12:02 78.62 26.66 821 1743	We are descending. We will do a radiation run when we get to the bottom.
12:09 78.50 28.28 929 722	We are into the planetary boundary layer.
12:15 78.62 29.10 1002 96	At a radar altitude of 28m.
12:20 78.85 29.51 968 382	Headed into island. Leads at end of this run.
12:25 78.65 28.82 994 163	We see ozone destruction, ice crystal present underneath the boundary layer. In Ice crystals at 997 hPa, patchy clouds.
12:31 78.33 28.16 982 261	Open lead on left side.
12:34 78.24 27.55 987 216	At very low altitude.
12:40 78.38 26.24 963 431	We are going to line up and do a lidar run on the ice.
12:42 78.41 26.85 913 870	We are going over an area of recently refrozen leads. They do not have any open, rippling water on them.
12:42 78.43 26.91 913 869	We're crossing right over the lead.
12:47 78.40 26.86 913 866	We've passed over that open lead with the lidar operating, southbound.

12:52 78.11 26.08 824 1705	We've decided to go southbound and we are going to look for a haze layer, fly it south and then go back to Bodø and do the haze layer seen on departure.
13:01 77.53 25.64 699 3022	We're trying to find the haze layer now that we were in a little while ago.
13:04 77.35 25.62 733 2646	We're descending as we head southbound looking for that haze layer around 850 hPa. We did try one just over 700 hPa. While it was there, it was not too dense.
13:14 76.76 25.51 882 1160	We're still descending. We're going to go through this layer and then come back up and fly a potential temperature line. Sounding at this time. Haze at 700 hPa, clean at 750 hPa, haze at 800 hPa, picked 870 hPa for a haze run south.
13:20 76.39 24.99 869 1274	We are southbound. We are going to fly a potential temperature surface in this haze.
13:21 76.37 24.96 869 1273	We are flying in a haze layer around 870 hPa, and we are going to try to stay in this layer as we head south.
13:30 75.86 24.27 893 1056	In and out of haze layer.
13:42 75.17 23.72 901 977	In the previous 10 minutes we've been flying Arctic haze on an potential temperature surface. Now we are out over the open water. The insentropic surface went into the water, and we followed the haze for a while. Now we are continuing south, doing a solar radiation profile.
13:43 75.11 23.67 901 976	We have a very interesting relationship between B-SCAT and ozone right in the break in the clouds where it was sunny. B-SCAT went down and then ozone came up and now they are both going up, now they are going opposite to each other.
13:44 75.05 23.63 902 972	We are back in the haze layer.
13:46 74.93 23.54 902 971	We are still heading south just over the clouds, and we are getting back in the haze layer. We flew along the isentropic surface and got back in the haze layer. We are presently flying in it.
13:50 74.70 23.38 902 973	We are flying into the sun trying to stay above the cloud layer. We are in a fairly good haze layer here. White caps visible at the ocean surface.
13:51 74.65 23.29 898 1007	We are flying in a haze layer above the cloud tops about 500 to 1000 feet above them.
13:59 74.26 22.08 859 1366	We just climb up through the clouds on this last pollution leg.
14:03 74.07 21.51 860 1366	We are going to climb up out across the front, at 25,000 feet.

14:07 73.87 20.88 662 3451	We are climbing out over this frontal zone. We should go up to the south to find these high-level haze layers.
14:10 73.73 20.38 533 5093	We are climbing at a very fast rate.
14:27 72.74 16.98 375 7636	Southbound. We see a very strong haze layer south of the front. The same place as we found it before. We'll be flying over it and then doing a haze profile and a solar radiation profile.
14:32 72.41 15.95 375 7634	We're in the high troposphere or in the lower stratosphere. The polluted air north of Bodø is visible.
14:38 72.03 14.96 328 8573	We are in the stratosphere.
14:41 71.86 14.48 322 8688	We are in the stratosphere. Ozone is 127 ppb.
14:46 71.57 13.66 322 8687	The lidar doesn't show any good ice crystals at this time.
14:52 71.21 12.78 322 8686	We are well into the stratosphere. We have a nice high aerosol B-SCAT at this time which must be ice crystals and we also have an interesting high ozone, though CN is fairly low.
14:57 70.92 12.08 322 8684	We are going to try to climb higher to get more stratospheric air.
15:04 70.49 11.13 306 9023	In a few minutes we are going to do a radiation run and then do a descent over this area.
15:05 70.42 10.99 306 9022	We're still in the stratosphere and we're getting ready for a profile.
15:06 70.36 10.86 307 9021	We are going to do a radiation run.
15:12 70.10 9.71 307 9018	We are in a radiation run. We are still fairly high in the stratosphere and we are going to be doing a descent over this ocean area.
15:26 70.77 9.56 307 9000	Start descent from stratosphere.
15:28 70.85 9.99 318 8769	We are in the descent. We are going to go down at 500 feet per minute until we get out of the stratosphere and then we may increase the descent rate after that.
15:30 70.93 10.41 331 8510	We are descending in this radiation profile over open ocean for the most part with some small thin cumulus. We are going to descend in this haze layer and change filters accordingly.
15:42 71.17 10.92 416 6905	We are going to increase to 750 feet per minute to get a little more air.
15:51 71.02 9.52 527 5183	Ice crystals are present, at the same time as we sample for Ras Gas.
15:59 71.28 10.86 646 3611	We are still descending at 750 feet per minute over the ocean.
16:03 71.40 11.53 712 2882	We just went through a little haze layer; the one that we had seen just previously.

16:13 71.13 10.84 908 919	There is not much haze in this area so we're doing an over-ocean profile.
16:38 71.43 10.18 925 766	We just finished a run over the ocean. I noticed the ozone was very steady there.
16:43 71.19 10.50 723 2752	We are heading for Bodø. The haze that was seen earlier in the day in this area is completely gone.
17:42 71.26 10.43 733 2645	Turning into Bodø. There is a generally southerly flow over the ocean at this time, though low winds and whitecaps.
17:48	Landing in Bodø.



Horizontal projection of the aircraft flight track on a latitude - longitude grid,
Flight 309, March 27, 1989.

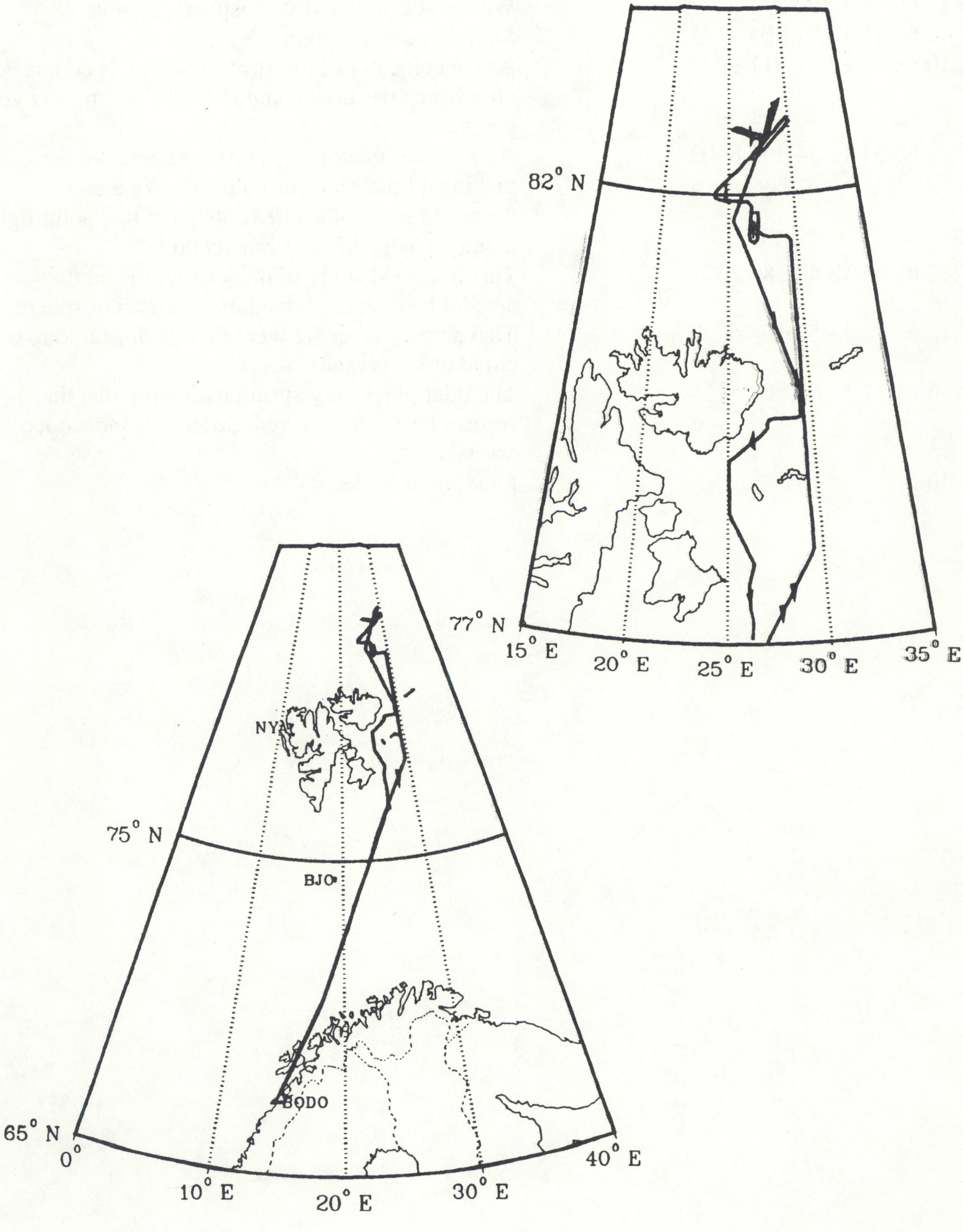
FLIGHT LOG

Flight 309, March 27, 1989

07:12	Takeoff.
07:22 67.75 14.18 569 4603	Climbing toward the north, we went through a haze layer, one that we could see from the ground. It was a fairly fragmented layer, but fairly extensive. We went through too fast to really analyze it. We may hit another one as we go higher.
07:41 68.94 13.07 446 6408	We are flying northwest and there is fair bit of haze out here below us. With easterly winds it is possibly from the Murmansk region.
07:55 70.30 12.79 446 6401	Northbound. We can see five separate haze layers in this region probably coming from Murmansk.
08:00 70.41 12.71 447 6399	We are still seeing good haze layers off to the front and left of the aircraft, fairly dense layers well above the cloud level which is not much below our altitude at this time.
08:19 71.84 12.44 447 6380	I can see six layers of haze off to the northwest, varying degrees of thickness.
08:35 73.11 12.15 448 6378	Still northwest bound. Haze layers are getting noticeably thinner in front of us, more compact and lower down and fewer of them.
08:55 74.65 11.81 449 6367	The haze is noticeably thinner as we move north.
09:15 76.25 11.51 449 6354	As we approach the ice edge west of Svalbard, we have lost the haze layers.
09:26 77.41 11.37 450 6347	Over ice edge.
09:31 77.54 11.24 450 6344	We're seeing a medium to light haze bands from our altitude, the band stretches across the horizon. There appears to be a second, slightly diffused layer beneath this. This band is above the thin cloud layer laying above the open ocean.
09:32 77.62 11.22 450 6343	We are over a haze layer so we will run one in here as Arctic slightly polluted background.
09:35 77.86 11.18 450 6342	Eight minutes ago, we must have gone into a new airmass because the CN counts went up, potential temperature went down, and the moisture went down. We are now north of the front and in that Arctic high pressure area.
09:57 79.68 10.95 451 6329	We are north of Svalbard and went through a frontal zone, the air is clearing up considerably now, though we do have some very light haze layers out there.
10:14 81.10 10.71 452 6318	We are flying north about 30 minutes from the ice camp, over open leads with slight haze visible on the horizon.

10:38 83.10 10.23 447 6393	We are over the ice. We see clouds to the right near the surface and we are beginning our descent shortly.
10:42 83.40 9.87 447 6389	We are in the high troposphere over the ice camp in our radiation run. We are about to descend over the snow covered ice.
10:45 83.51 9.16 447 6387	Current track is 169 degrees.
10:50 83.19 9.70 456 6249	Started slow descent.
11:08 83.55 9.48 751 2376	We are descending over the ice camp. At this time, we are in hold for a radiation profile. We have only encountered one thin haze layer of any consequence.
11:09 83.61 9.39 758 2377	The ice is clearly visible below us. It's a very even, unbroken ice pack, any ridging is old.
11:10 83.65 9.17 758 2377	We went into a sharp turn to the left which is very much inevidence on the aerosol as measured by the nephelometer, observe this later on when we go to correct the data.
11:26 83.85 10.25 913 873	We are turning in the region of the camp. It is a slightly hazy area in here. Ice is very thick and we see no ice crystal effects.
12:13 82.91 8.90 1010 26	Passed over very large open lead. At 50 m, ozone dropped to a low of ~10 ppb for a brief time.
12:34 82.96 9.17 1011 18	Ozone depression observed by both Dasibi and Gilmer Ozone instruments.
13:00 82.73 7.94 995 151	For the last hour we have been flying at 50 ft. and going up to 450 ft. to see the ozone depletion. We saw an ozone depletion when we got below 50 ft. and then as we went up, it disappeared. We are getting ready to do another profile now.
13:45 82.99 9.02 1009 37	We appear to have some ice crystals in the air.
13:47 82.90 8.65 1000 115	We just crossed over a lead. We appear to have ice crystals in the area.
14:40 80.66 11.05 307 9008	Start descending to lower altitude because of strong headwinds in the stratosphere.
14:48 79.99 11.01 412 6969	Winds did not diminish during the descent, so we are going backup to previous altitude.
15:57 74.63 11.93 293 9323	Southbound. From this position I can see one very thin haze layer, high up, east of the aircraft, but nothing to the west. The haze layer is at an exceptionally high altitude, equivalent to our aircraft altitude.
16:43 71.02 12.63 293 9321	The neph is showing indications of ice crystals at this point.
16:44 70.94 12.65 293 9320	There is no indication that the lidar is seeing ice crystals at this point.

16:58 69.78 12.90 293 9320	We are getting good stratospheric sample.
17:09 68.82 13.21 301 9145	Start descent for Bodø.
17:10 68.72 13.27 311 8921	As we come out of the stratosphere, CN counts go up, ozone goes down, and B-SCAT jumps all over the place.
17:12 68.54 13.54 355 8003	As we enter the top of the troposphere we are picking a little bit of turbulence. We are descending out of a 110 knots jet at this point right along the edge of the stratosphere.
17:13 68.45 13.49 389 7377	This is a good study of the jet stream and the aerosol layer at the boundary of the stratosphere.
17:15 68.28 13.59 466 6090	That aerosol layer we went though appeared to be cloud or ice crystals.
17:16 68.21 13.61 508 5451	The lidar gives very strong indication that the aerosol layer we just went through is indeed ice crystals.
17:36	Landing in Bodø.



Horizontal projection of the aircraft flight track on a latitude - longitude grid,
Flight 310, March 29, 1989.

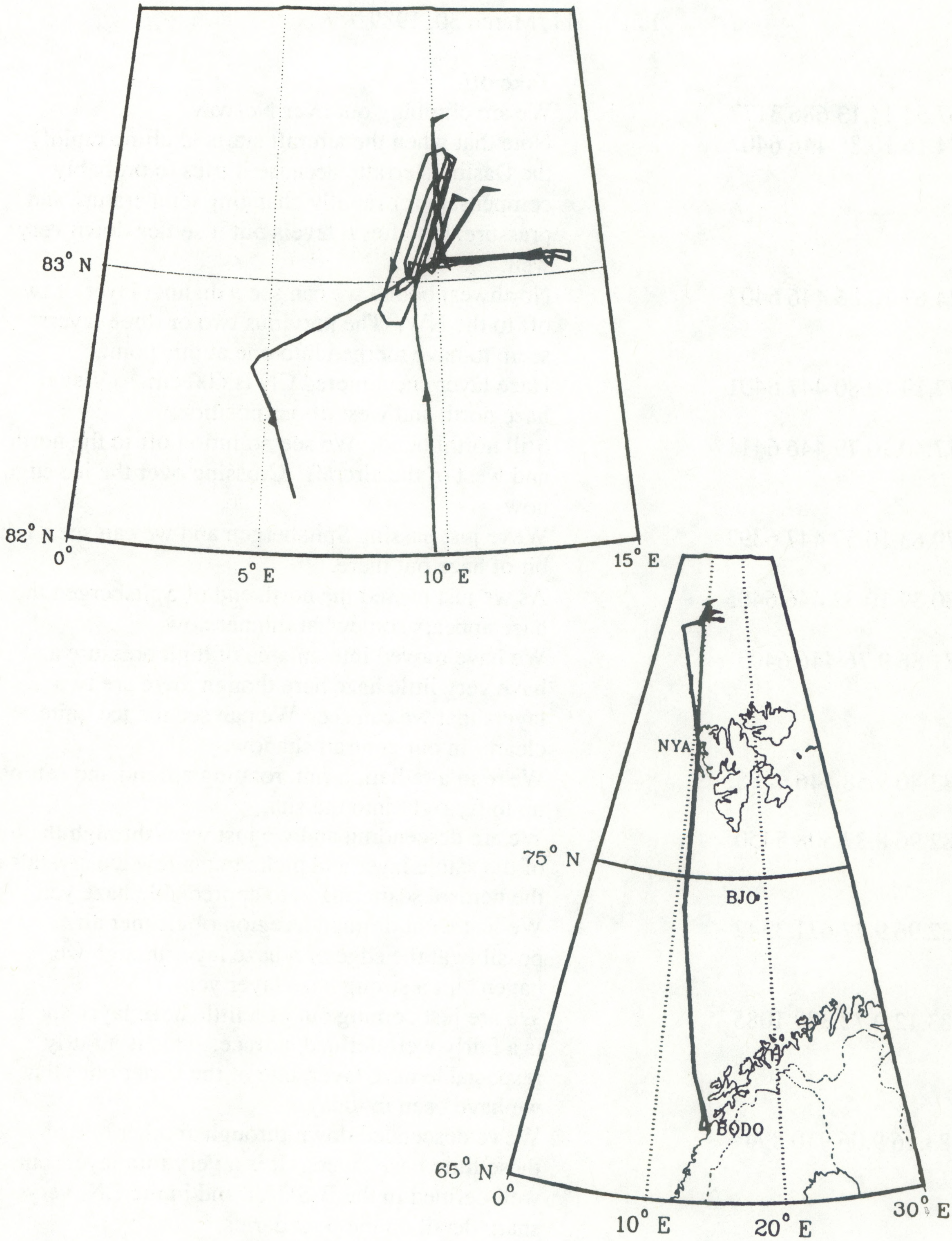
FLIGHT LOG
Flight 310, March 29, 1989

08:15	Takeoff on haze flight 310.
08:28 67.86 14.95 510 5435	CN increasing.
08:40 68.72 15.81 446 6403	Haze present.
08:45 69.11 16.22 428 6709	No visible haze.
08:47 69.26 16.39 410 7019	On climb out we notice a fair bit of high CN and B-SCAT which must indicate polluted air. That tends to be stabilizing a little bit now, but is quite a bit higher than we'd expect. UK air appears to be coming up and behind the low which makes sense.
08:49 69.41 16.56 408 7043	We are going in and out of little layers of CN behind this low pressure system. We really don't know what is causing this.
08:54 69.80 17.01 410 7037	High B-SCAT for 1 min. at this time.
09:01 70.34 17.71 409 7035	The CN is dropping off very dramatically. We must have gone though some kind of a frontal zone here.
09:03 70.50 17.93 409 7034	Cleaner now.
09:06 70.74 18.17 409 7033	We're flying northward over this low pressure system. We can see fairly good wind activity on the sea surface as we head northward towards Spitsbergen. We are above most of the clouds and it is a very clear day with good visibility. There are lower CN counts than we experienced a few minutes ago. The boundary was associated with a wind shift and we should look at this fairly carefully.
09:16 71.62 19.01 409 7026	Entered the stratosphere.
09:19 71.88 19.27 409 7023	Aerosols increasing.
09:30 72.83 20.36 410 7012	Turbulence at 23 k ft.
09:38 73.52 21.21 410 7010	Light turbulence, note ozone maximum at 09:12. Down now, I think we went through a fold from 09:05 to 09:25.
09:50 74.54 22.60 410 7003	Light turbulence, Clouds below.
09:51 74.62 22.72 411 7001	We've gone into the jet stream of the stratosphere. About 5 minutes ago we had a very strange aerosol signal which looked like a power outage, though things seemed to have come up and are running well now.
09:54 74.88 23.06 411 6999	CN Jump
09:55 74.97 23.18 411 6997	We've got an incredible peak of condensation nuclei at this time which is the stratospheric aerosol just at the bottom of the stratosphere.
10:00 75.41 23.77 411 6995	SO layer moist, high CN low.

10:10 76.28 25.29 411 6988	Into Ci cloud.
10:14 76.62 26.01 411 6987	Light turbulence.
10:24 77.43 27.92 412 6980	Still light turbulence. CN and steady B-SCAT tracking the cloud.
10:25 77.50 28.12 412 6976	For the last 15 minutes we have been having very high ice crystal counts as we fly through a cirrus cloud as evidenced on the B-SCAT.
10:27 77.66 28.52 412 6976	Light turbulence still, B-SCAT decreasing.
10:36 78.42 29.51 412 6970	Still in Ci layer all parameters are steady.
10:59 80.42 29.55 413 6955	Northbound. Still in Ci, ice crystals in the air. We are going to have to decide if we are going to do a descent here.
11:03 80.74 29.53 413 6953	Still in Ci layer all parameters are steady.
11:20 81.73 26.62 367 7782	Area free of clouds.
11:25 81.61 27.18 368 7700	B-SCAT variable. CN steady. Relatively cloud free.
11:27 81.49 27.12 368 7778	Large B-SCAT variation, ice crystals.
11:32 81.71 26.63 368 7776	We are in the radiation run over a clear area. No clouds above us, no clouds below us. Ice surface clearly visible.
11:41 81.96 23.96 370 7578	Began descent 1000'/min 045 heading big B-SCAT variable.
11:49 82.39 26.68 520 5275	Haze layers visible out the front of the aircraft.
11:57 82.76 29.47 700 3016	Turned to 225° 500'/min. descent starts.
12:03 82.61 28.87 791 2041	Descending in a haze-free and spot cloud-free. Essentially very steady CN and no appreciable B-SCAT.
12:12 82.47 27.10 927 747	Horizon to N looks grayish brown.
12:14 82.53 27.68 958 469	In the planetary boundary layer.
12:26 82.94 29.19 1005 72	Radiation run into the sun at 50 ft.
12:28 82.84 28.87 1005 68	We are doing the radiation run at the bottom of this layer. We notice a good ozone depletion down to zero on the systems and this occurred very rapidly around 950-960 mb.
12:31 82.69 28.41 1005 67	We are in the boundary layer still doing our radiation run and essentially zero ozone.
12:33 82.62 27.97 989 201	We are flying over a lead area with some sea fog coming off of it.
12:38 82.70 26.06 1005 67	We are approaching an open lead. There are a lot of open leads in this area.
12:41 82.67 25.72 1001 98	Gust probe run.
13:02 82.55 27.72 982 262	At 500 feet over the ice we came through a very sharp ozone boundary.
13:09 82.21 26.70 955 492	We are climbing slowly to get through this inversion layer and see where the ozone peaks out. Note that this is a very sunny day over the ice.

13:29 81.22 26.68 760 2361	We are going to do a descent now heading north under light clouds to get down into this ozone depleted region. I am taking Ras Gas samples above this.
13:47 80.35 28.46 945 586	We're under clouds at this time heading down doing samples to see if there is any destruction of the ozone.
13:53 80.06 28.98 995 153	We are under clouds heading south and we do not find any ozone depletion in this area, open leads.
14:10 79.57 29.32 959 461	In clouds heading south, We are going to go down, around and out and then go down underneath the inversion so we can see what the ozone is doing down there and put this thing in perspective.
14:14 79.52 28.38 970 364	We are finding lots of clouds and ice crystals in this area and no ozone destruction. At 700 ft (215 m) altitude. Ozone is 29 ppb at it's lowest point.
14:24 79.29 26.53 989 206	In clouds, turbulence.
14:37 78.60 25.08 961 440	As we head south we can barely see the surface.
14:43 78.32 25.40 968 380	In a brief snow shower that we were out of by 1446 UTC.
14:53 77.90 26.37 967 396	We are still flying at a pressure altitude of 392 m and sampling in this cloud or whatever it is as a comparative study of the bright sunshine ozone depletion.
15:00 77.55 26.12 963 424	We are over a fair bit of broken ice in this region.
15:08 77.18 26.26 964 414	We are slowly coming into this open area and there's more open and broken ice. We have the radar on so that we can get some indication of what's happening over it.
15:11 77.05 26.23 964 414	We are flying through snow and the B-SCAT is low. We have had some discussion of what this could mean and it appears that if you have large ice crystals they can't make it in the inlet, so we are really reading the insitu aerosol, but if you have small ice crystals, they can get in and you see them.
15:14 76.91 26.21 965 413	We are now starting to go over broken pan ice where there are little quarter-acre squares which are quite different than what we have had earlier on.
15:18 76.72 26.20 964 423	As we move south, B-SCAT is decreasing slowly, indicating a cleaner air mass.
15:19 76.68 26.20 963 430	We're climbing out at 200 feet a minute. When we get above this system, we will head home.
15:22 76.54 25.96 946 540	The flight director tells us that we were in the inversion all this time.

15:41 75.59 24.23 631, 3825	It appears that we went into small ice crystals because we got a very high peak in B-SCAT We can see in under the sun so that was definitely ice crystals.
15:49 75.12 23.47 371 7705	We are coming on the stratosphere so we are going to run a couple of samples here.
16:20 73.06 20.70 299 9185	We have just gone into the high CN in the stratosphereic. layer and very high sulfuric acid at this point. We had an incredibly high stratospheric sulfuric acid peak (i.e. CN).
16:24 72.77 20.36 300 9172	We went into a very high CN peak in the stratosphere. This is sulfuric acid. Ozone at this time is 190 ppb.
16:29 72.41 19.91 300 9173	We are checking to see if we happened to have passed a jet airway and maybe reading the exhaust of another aircraft.
16:35 71.98 19.14 299 9179	That high CN peak we saw in the stratosphere did not have any aethalometer carbon signals so we assume that it probably was not a signal from an aircraft exhaust.
17:05 69.98 16.97 300 9170	We are still flying in the stratosphere, but we don't have much ozone at this point. Ozone is still at 175 ppb, but we don't have much CN.
17:07 69.53 16.79 299 9183	We hit some turbulence. We must be coming in or around the edge of a jet stream.
17:17 68.74 15.08 299 9182	Ozone is coming down and aerosol light scatter is going up. CN is constant as we begin to move out of the stratosphere.
17:21 68.41 15.58 313 8870	We are starting to come out of the stratosphere at a fairly high descent rate and the CN counts are starting to go up.
17:24 68.18 15.34 356 7441	We are coming through this sulfuric acid layer again. Nothing visual outside.
17:29 67.85 14.95 519 5295	We are getting a nice edge on this sulfuric acid layer as the ozone drops down to tropospheric values.
17:33 67.58 15.02 697 3050	We are inbound to Bodø. We've come into the top of a local haze layer at this time.
17:47	Touchdown at Bodø.



Horizontal projection of the aircraft flight track on a latitude - longitude grid,
Flight 311, March 30, 1989.

FLIGHT LOG

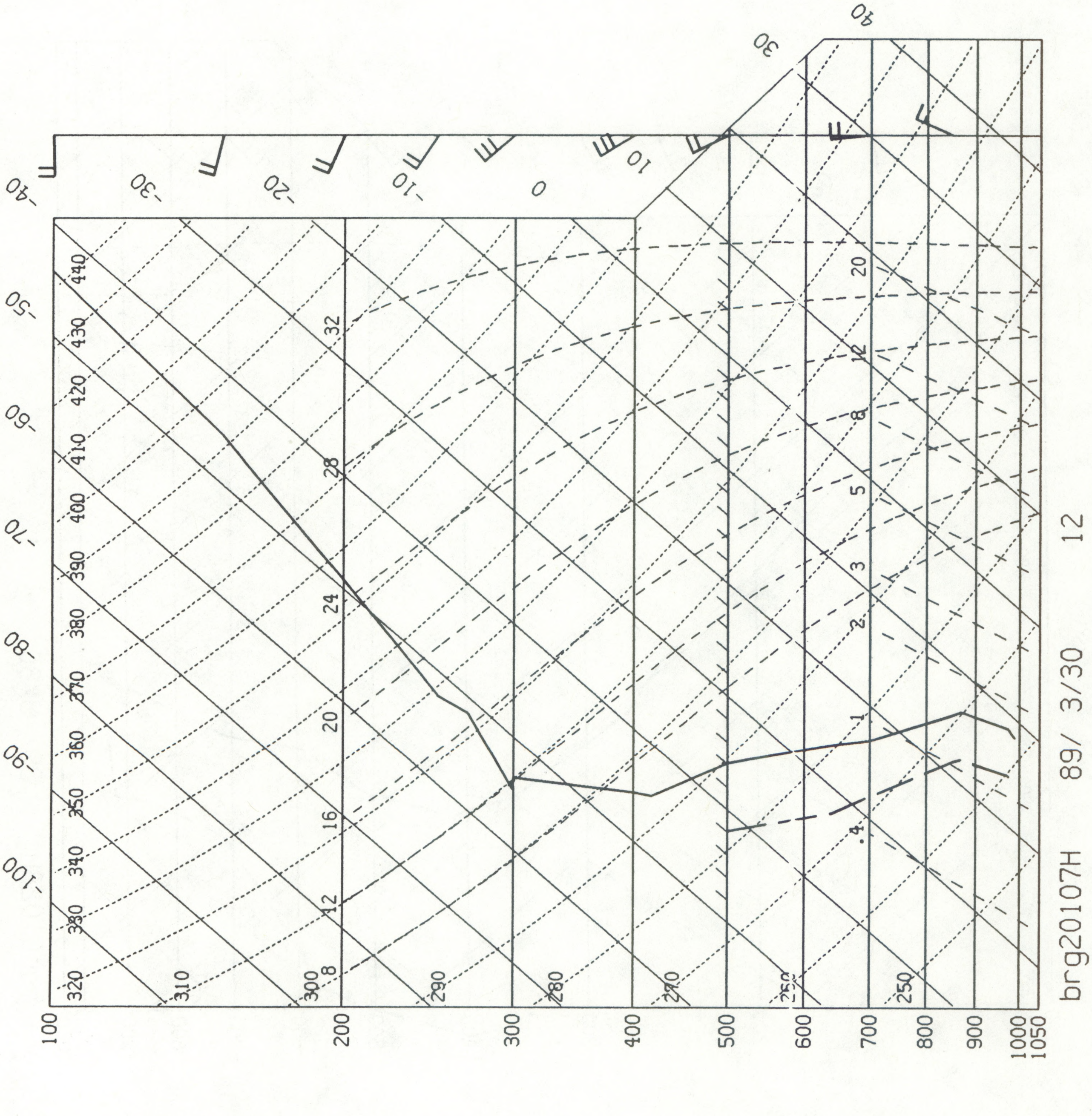
Flight 311, March 30, 1989

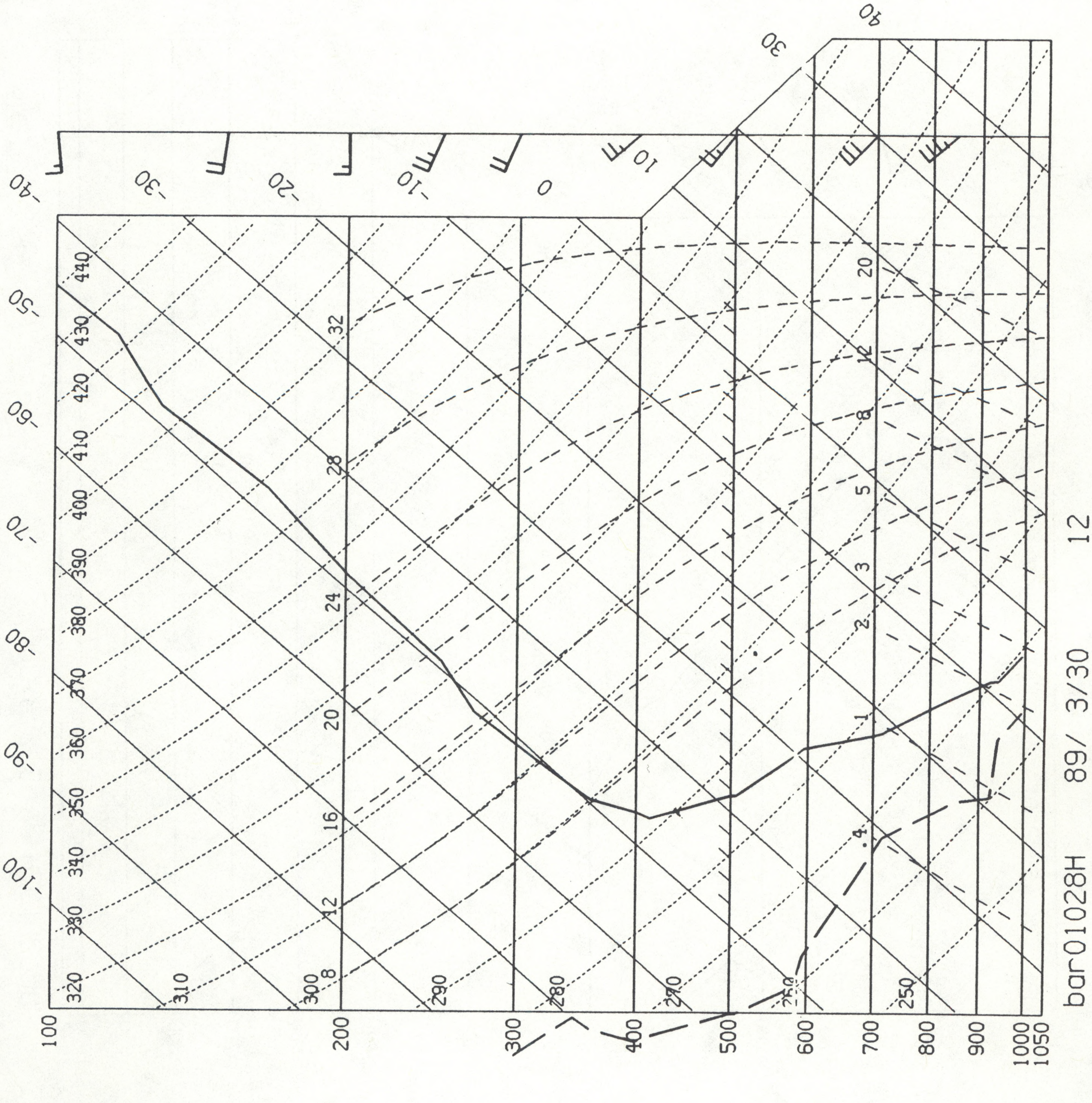
09:26	Take off.
09:33 67.54 14.13 686 3177	We are climbing out over Norway.
11:07 74.16 10.88 446 6407	Note that when the aircraft starts to climb rapidly the Dasibi is erratic because it tries to probably compensate for rapidly changing temperature and pressure, but after it levels out it settles down very well.
11:14 74.67 10.86 446 6402	Northwest bound we can see a distinct layer or two off to the NW. The previous two or three layers seem to have merged into one at this point.
11:49 77.19 10.80 447 6401	Haze layer encountered CN is 600 cm^{-3}. Visual haze north and west of our position.
11:52 77.40 10.79 446 6411	Still northbound. We see pollution off to the north and west of the aircraft. Crossing over the ice edge now.
12:23 79.63 10.59 447 6392	We're just passing Spitsbergen and we can see a fair bit of haze out there.
12:33 80.39 10.32 446 6405	As we just passed the north end of Spitsbergen the haze appears somewhat thinner now.
12:52 81.86 9.76 446 6405	We have moved into an area of high pressure and have very little haze here though there are two layers that we can see. We can see the ice quite clearly in our contrail shadow.
13:16 83.40 9.58 446 6488	We're in a radiation run, rotating around and setting up to fly right into the sun.
13:23 82.96 8.37 508 5450	We are descending and we just went through the top of the stable layer and picked up a few ice crystals on the perosol scattering. No appreciable haze yet.
13:28 82.96 9.27 671 3342	We just went through a region of cleaner air, possibly at the edge of a haze layer though we haven't hit a strong haze layer yet.
13:47 83.12 9.72 889 1085	We are just coming out of a little haze layer and it is a fairly well-defined surface. This is a fairly respectable haze layer, one of the better ones that we have been in today.
13:48 83.16 9.06 910 894	We've descended down through another one of these little haze layers. It is a very thin layer, but well defined in the B-SCAT and in the CN; very sharp detail on the boundaries.
13:55 83.46 10.44 943 601	At ~1500 ft. and descending.
14:06 82.96 8.72 984 246	We are descending. We don't notice any great ozone change yet.
14:18 83.26 10.43 987 222	We sniffed our own plume for just a second.

14:22 83.07 9.96 986 225	I note that when we make a right 90, left 270 turn, level at 225 that we have a change in our nephelometer signal. It goes down and then comes back up.
14:34 83.26 11.26 1004 76	The ozone decrease is very rapid at radar altitude of about 50 ft.
14:39 83.09 10.07 987 219	The base of the ozone increase or the depletion area is just over 100 meters pressure altitude indicated at this time.
14:45 83.49 9.97 1006 59	Ozone is now down to very low levels again as we fly along under the inversion.
15:52 83.08 10.28 998 124	We are still wondering around over the ice here. This day should be a good day to be able to do the gradient because we've flown at 50, 100, 150, etc., up to 600 ft with level legs in there so the ozone systems would have stabilized.
16:15 82.96 8.36 1007 51	Back to 50 ft. Flew over several open leads - felt turbulence.
16:20 82.84 6.55 1007 53	We notice a peak of CN a few seconds after we crossed a lead which we could feel shake the aircraft.
16:22 82.79 5.82 1008 40	The signal that we had before was a B-SCAT signal just down wind of the open lead so it must have been ice crystals.
16:24 82.74 5.11 1007 49	We are southbound and as we go southbound, ozone is slowly going up and down, very close to what we see on the CN count.
16:44 81.49 7.44 320 8730	Richard Gilmer is showing me his chart on the ozone and temperature and there are occasional times when you get a little spike of colder air coming up from below when we are flying at just above the inversion and the ozone changes, the temperature changes, and the water vapor increases. I will let Dick tell you in his words. "When we hit these little bursts when we are above the inversion, cold air comes in from below, drier or less ozone comes up and the air is much more moist, but these are just little bursts intermittent, every so often." We should make a note at this time to look to see if that is occurring over leads where there is a little bit of turbulence.
18:18 72.95 11.49 300 9155	We appear to have gone through the sulfuric acid layer as we begin to descend out of the stratosphere.
18:51 69.66 12.80 313 8880	Descending through tropopause.
19:18 67.26 13.72 933 692	We are preparing to land at Bodø and this ends flight number 311 and end of AGASP-III.
19:23:30	Landed in Bodø.

12. APPENDIX B

Rawinsonde observations made at the times corresponding to AGASP-III flights are plotted on skew T, log P diagrams. The stations represented are Barentsburg, Svalbard, (brg) (78°04'N, 14°00'E); Bear Island, Norway (bar) 74°25'N, 19°00'E); and Bodø, Norway (bod) (67°17'N, 14°23'E). Temperatures are in Kelvins; full-length wind barbs equal 10 knots.


brg20107H 89/ 3/30 12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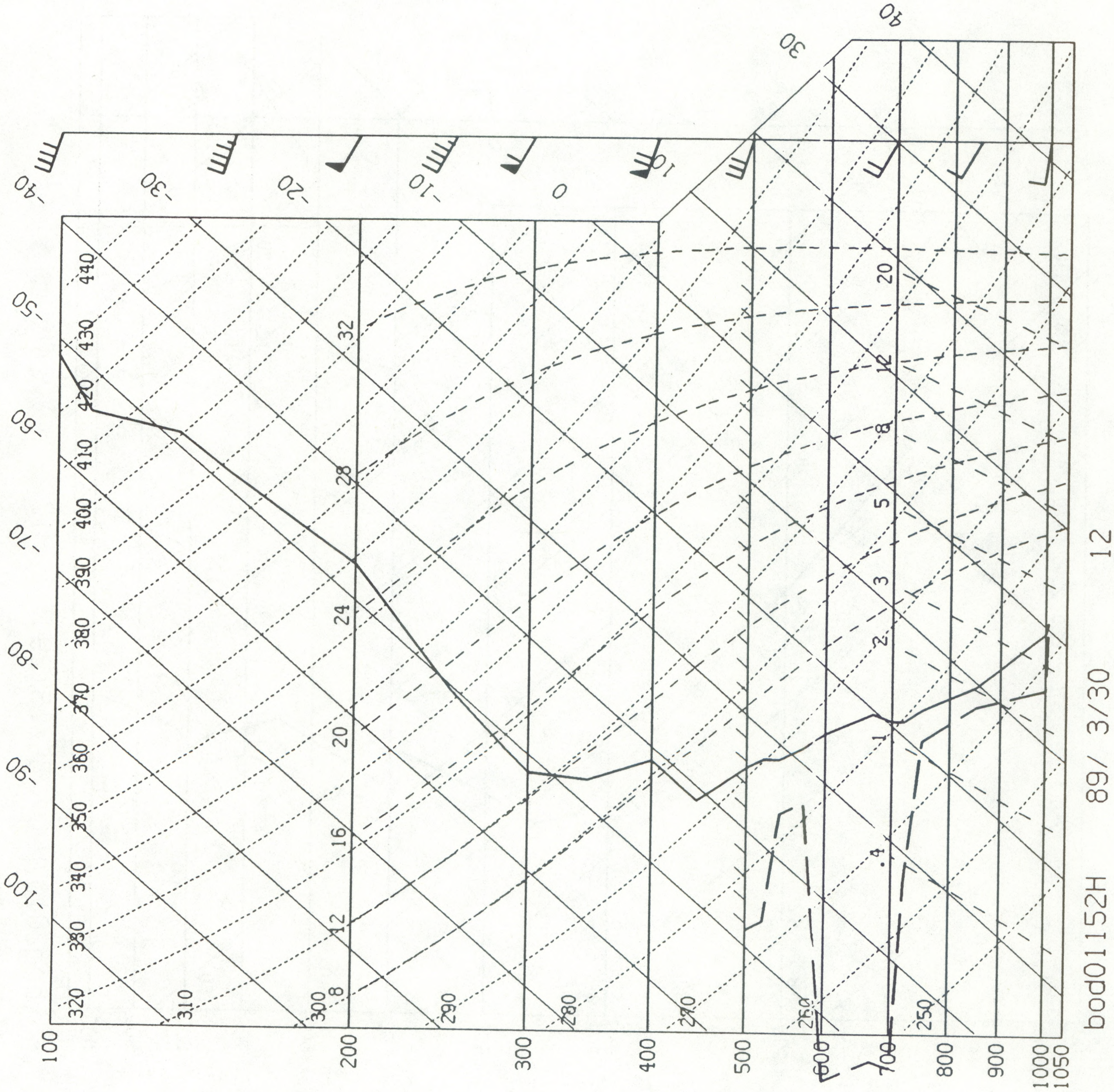

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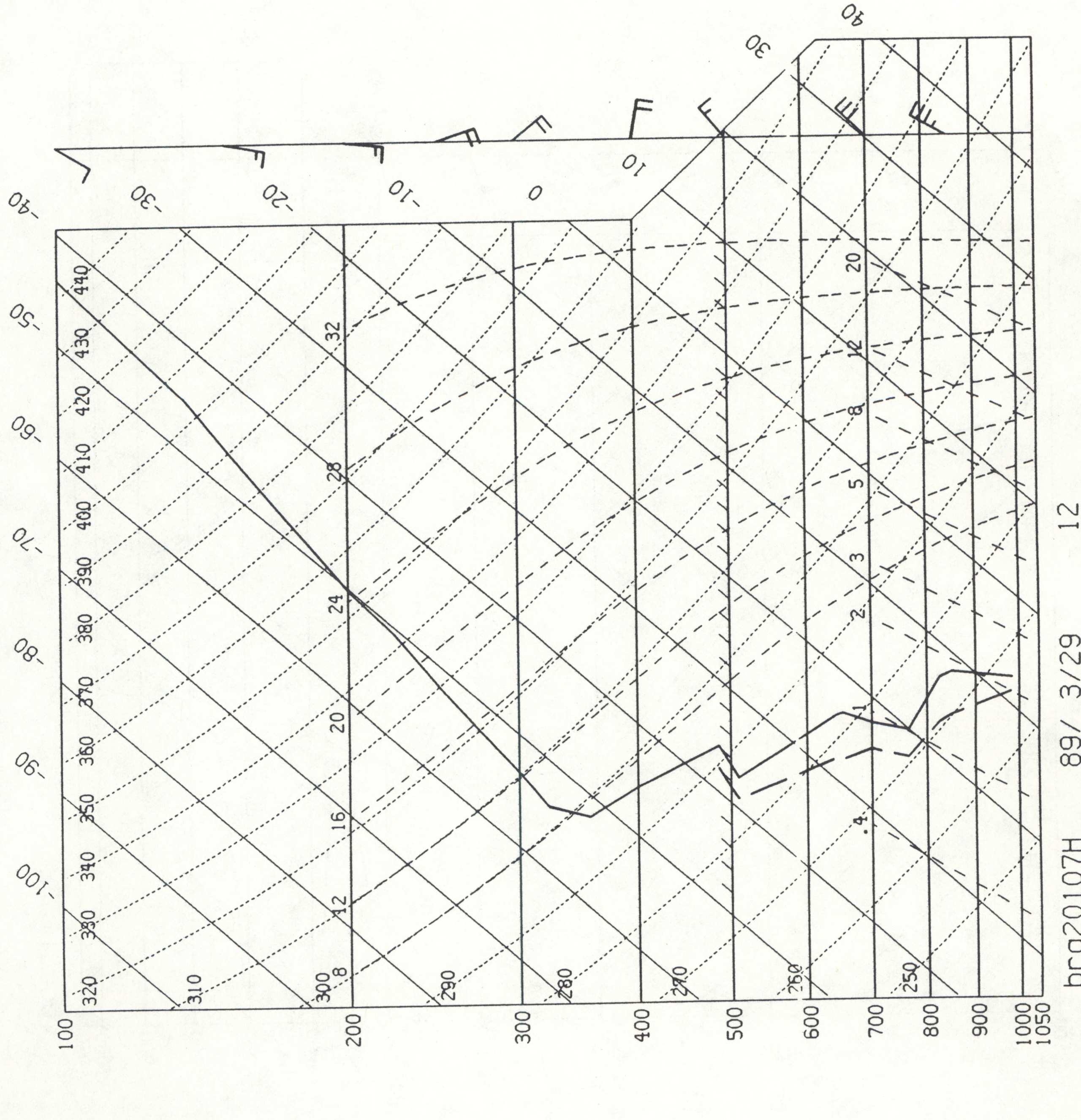
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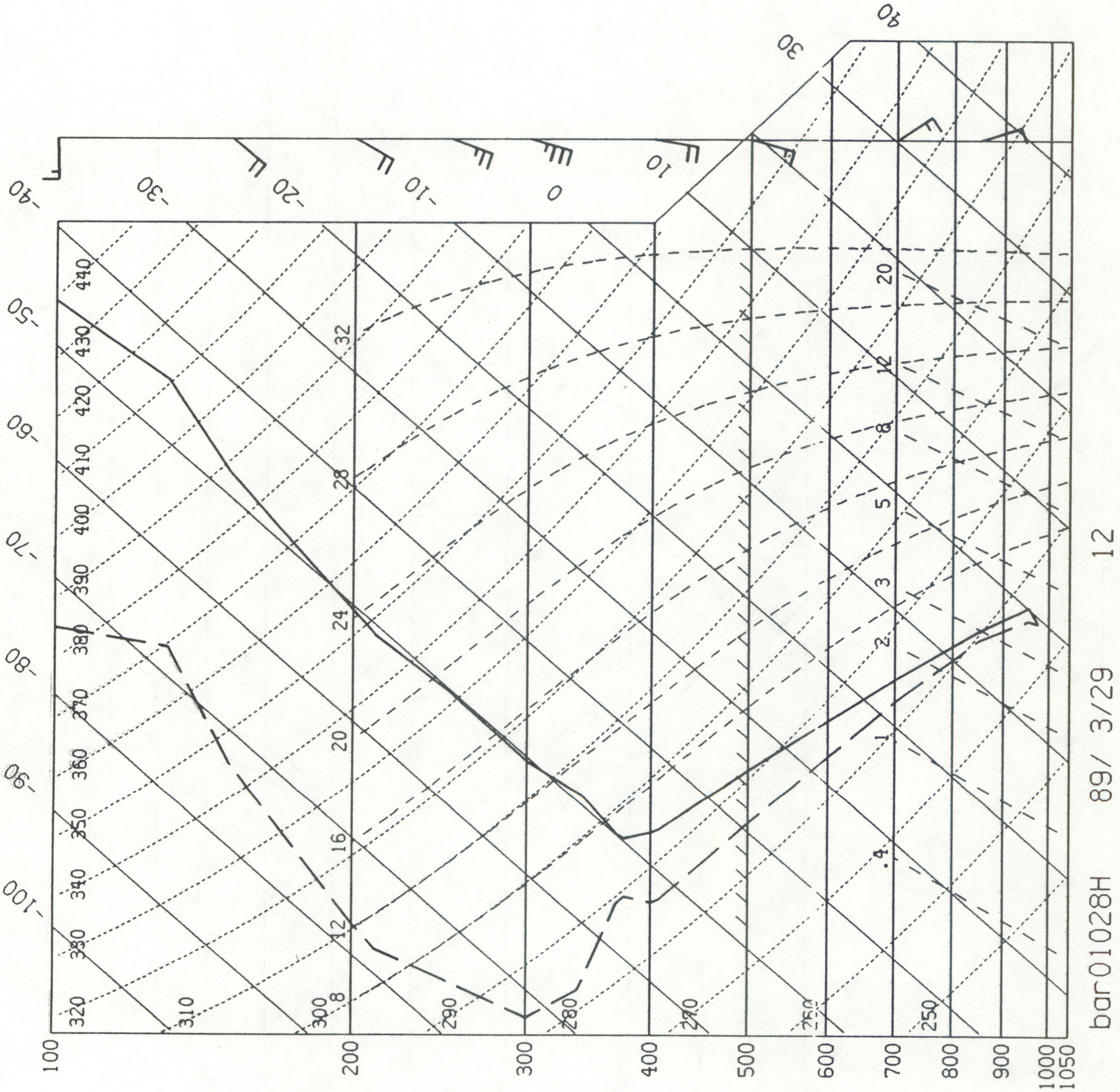
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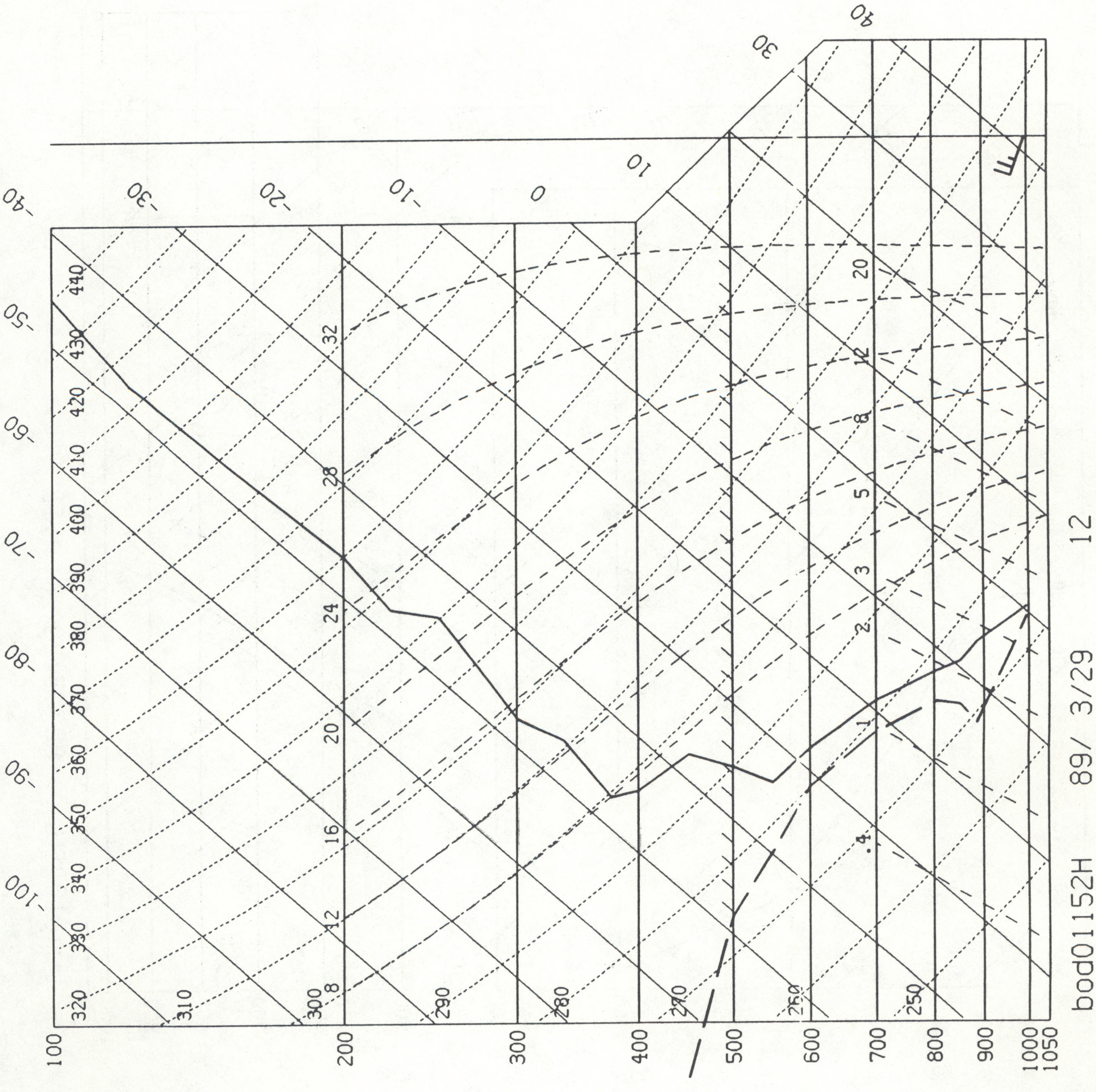
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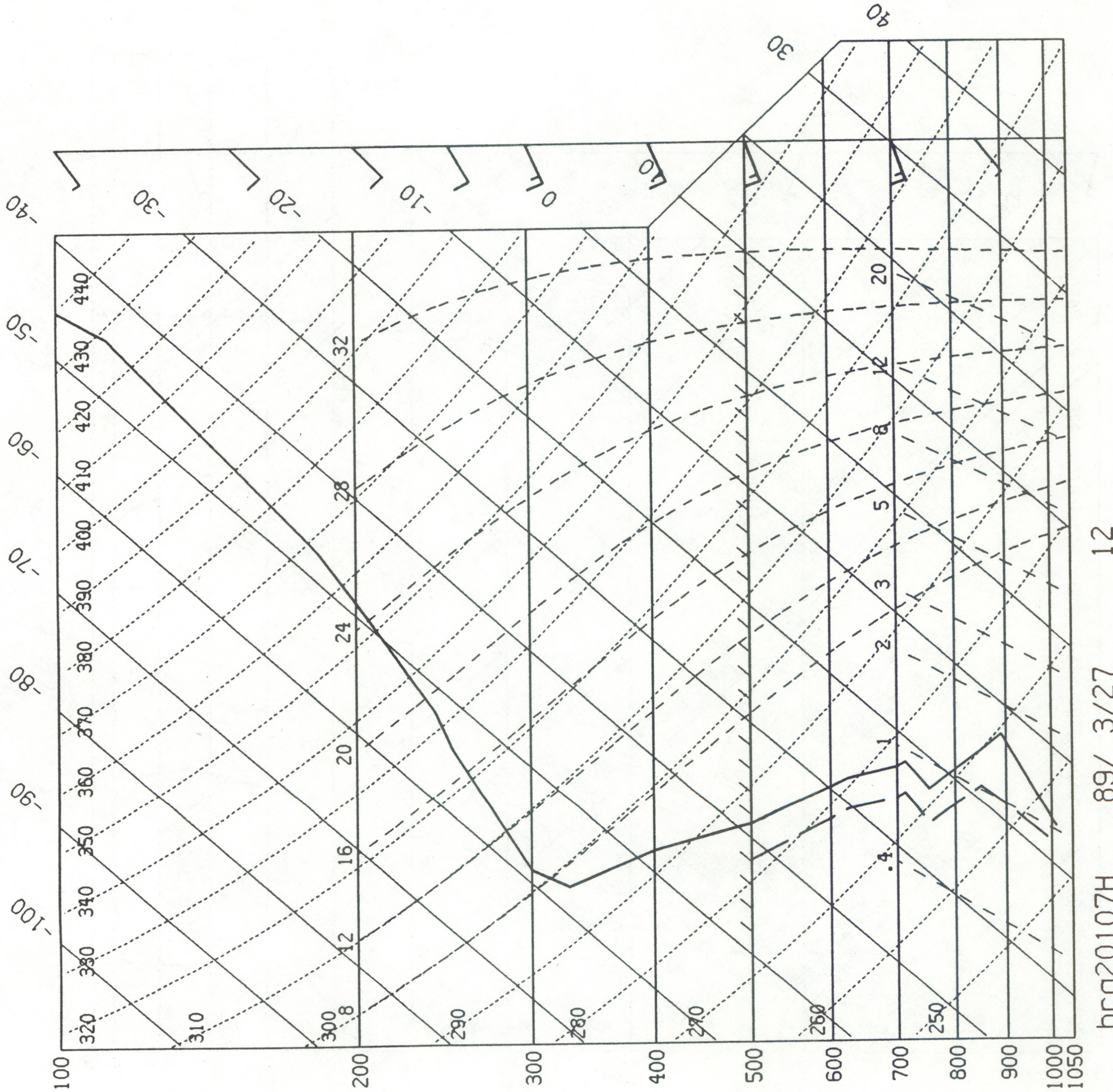
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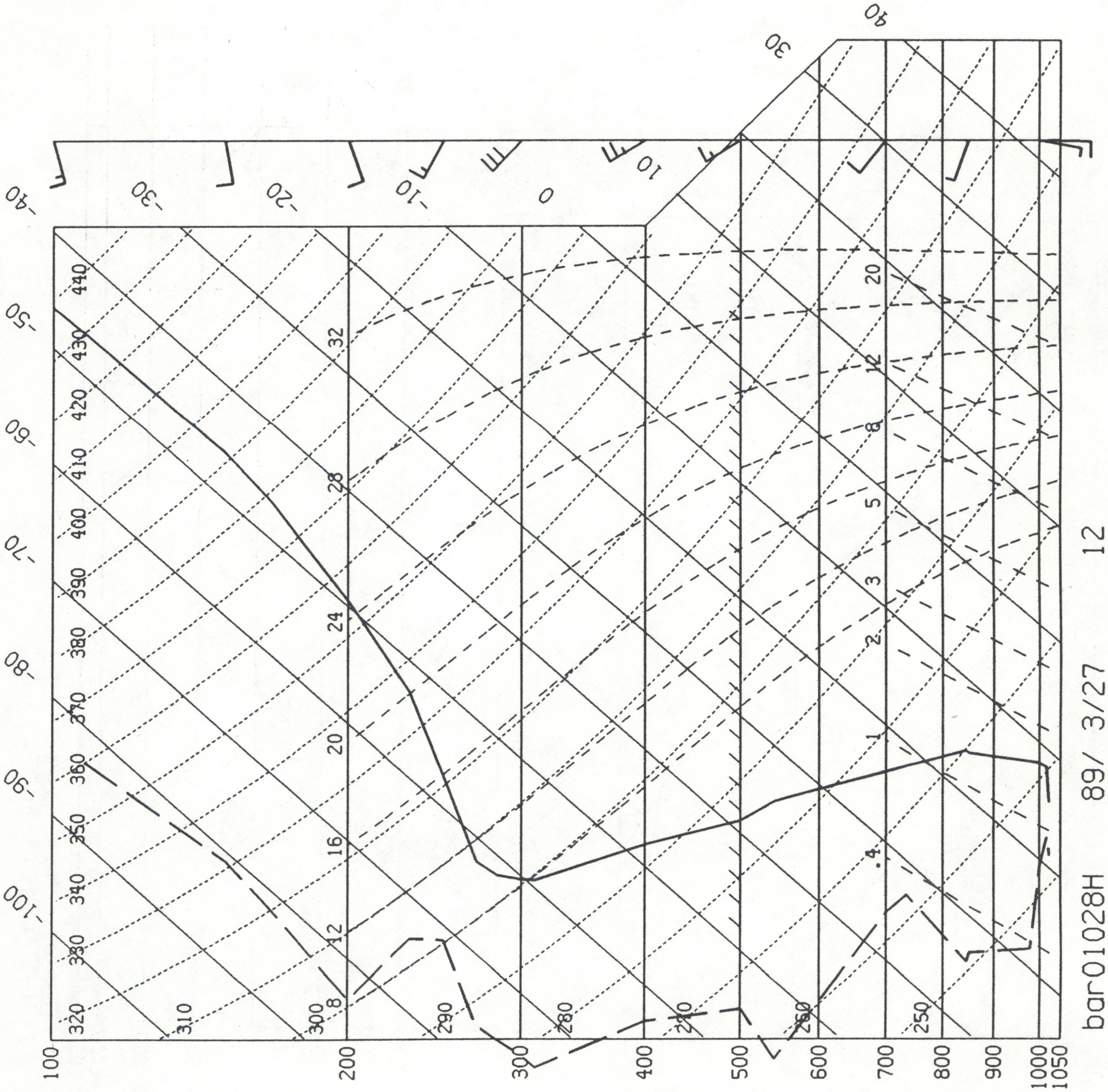
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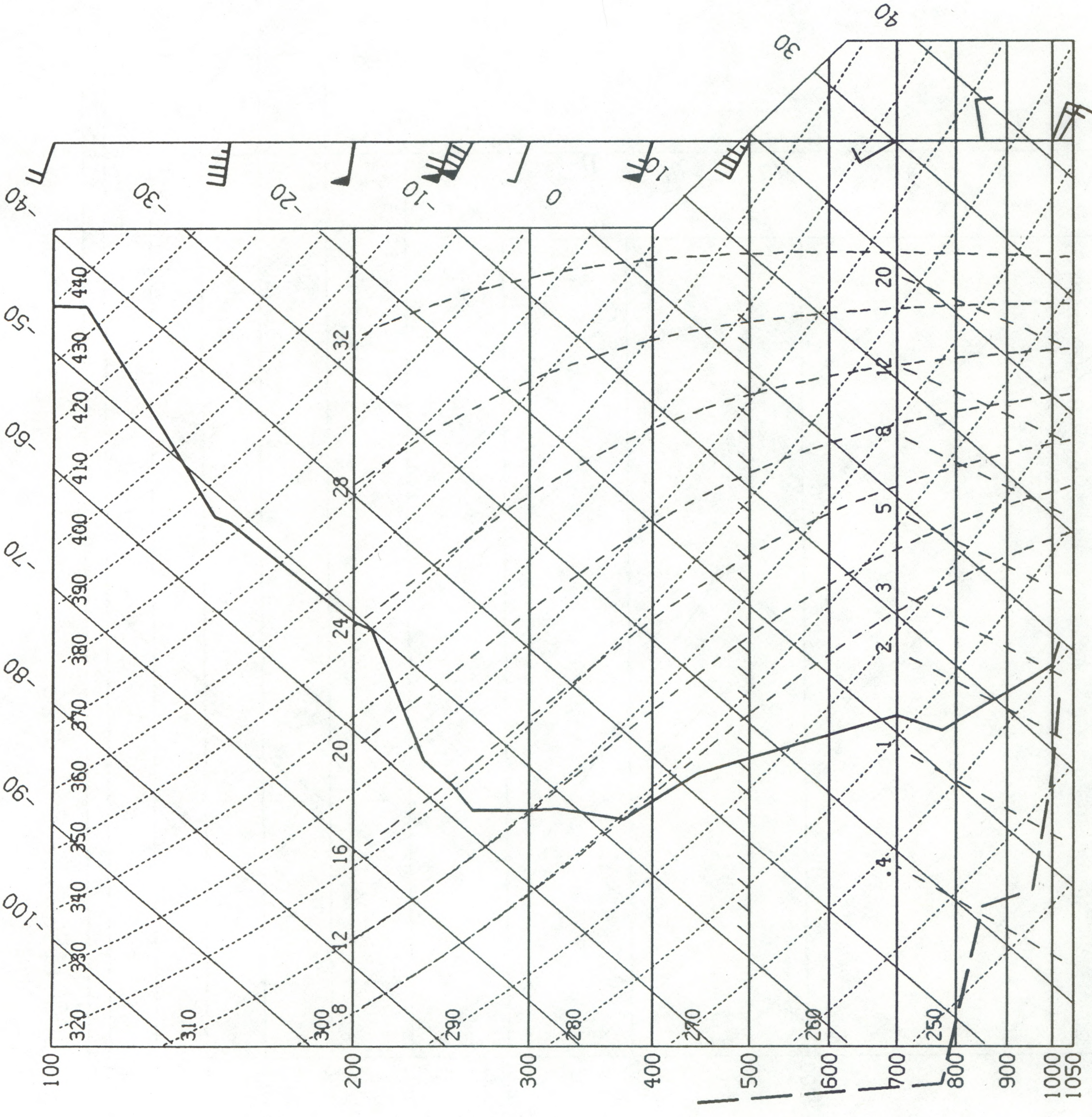
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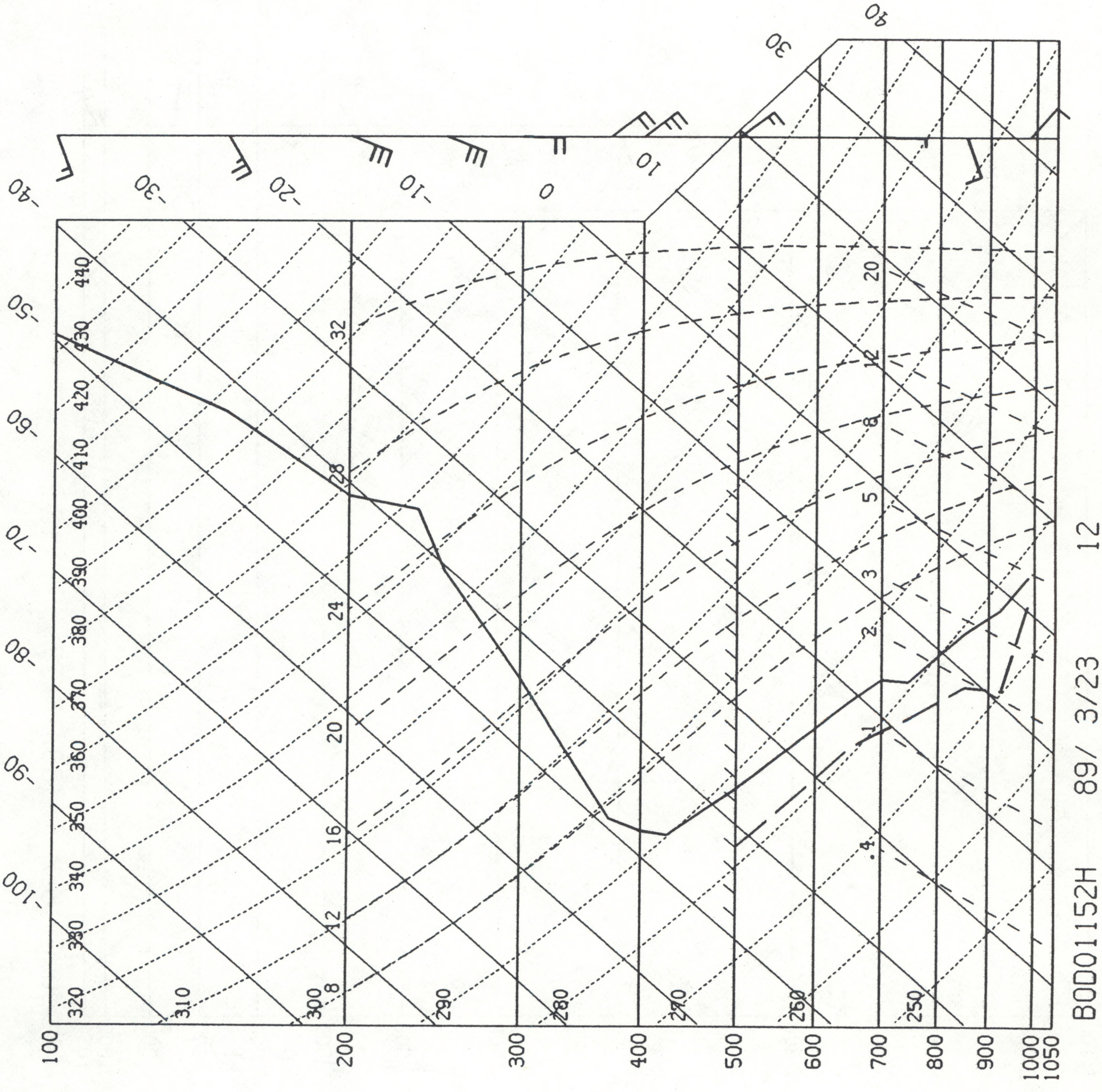
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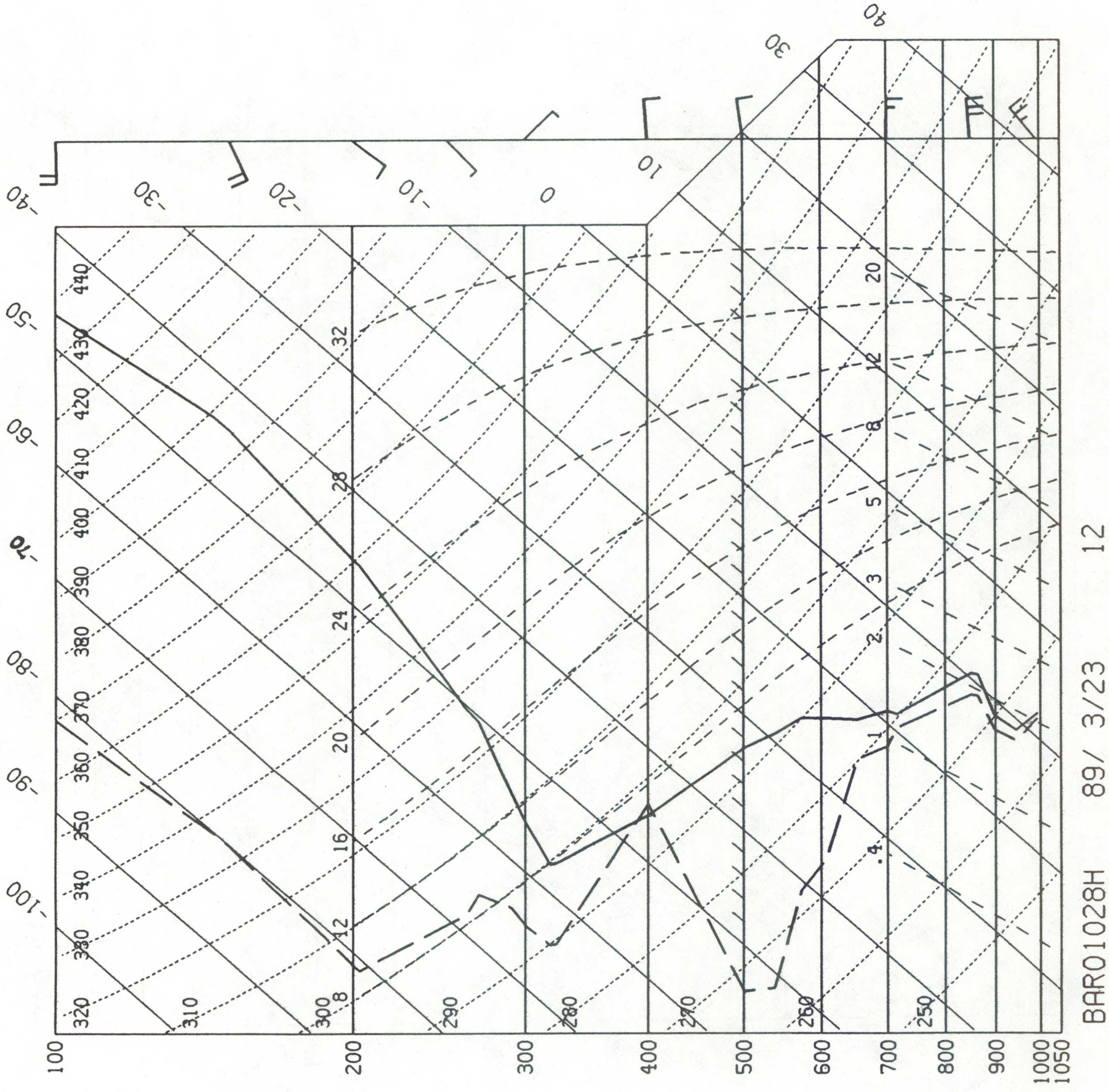
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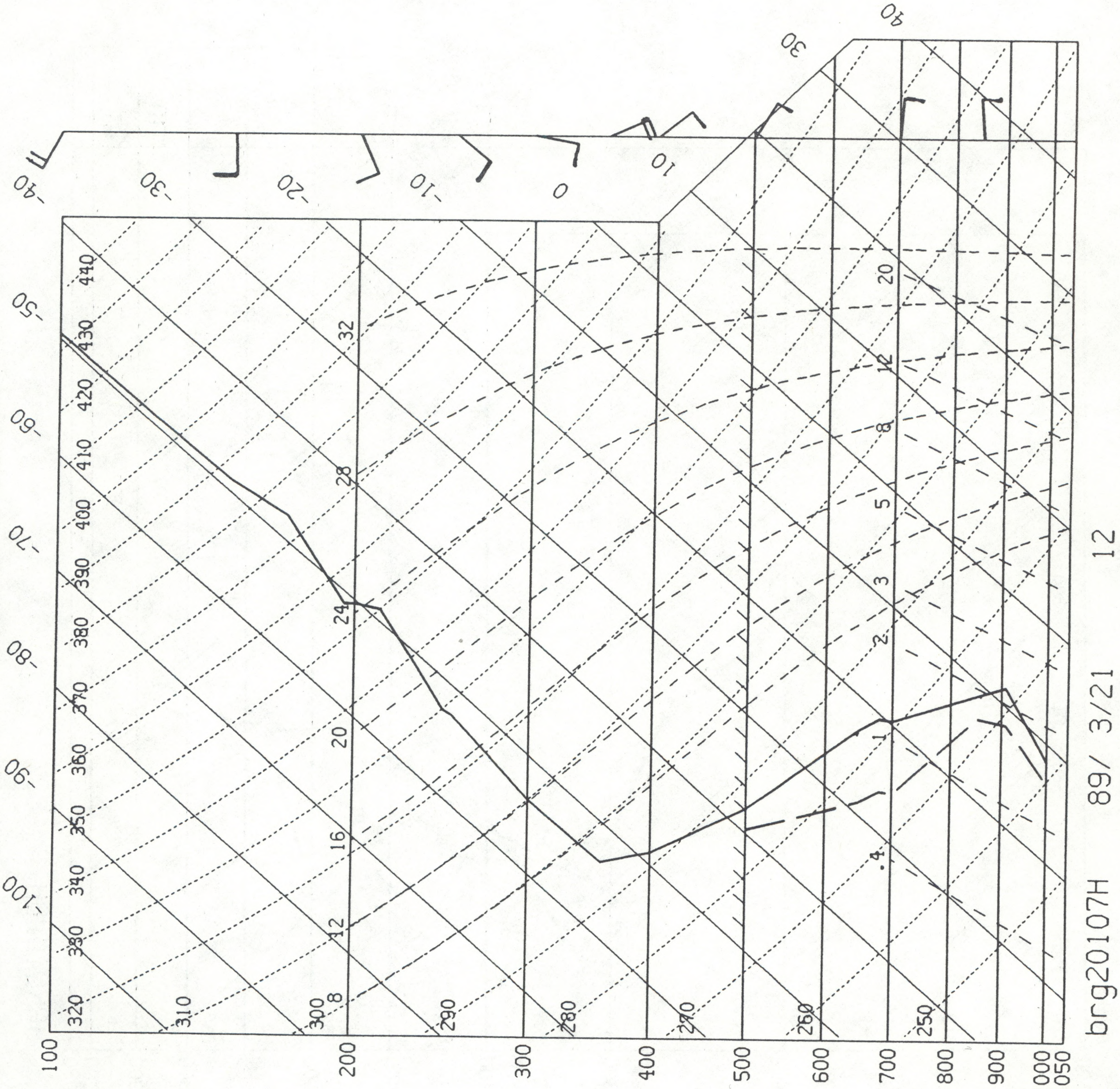
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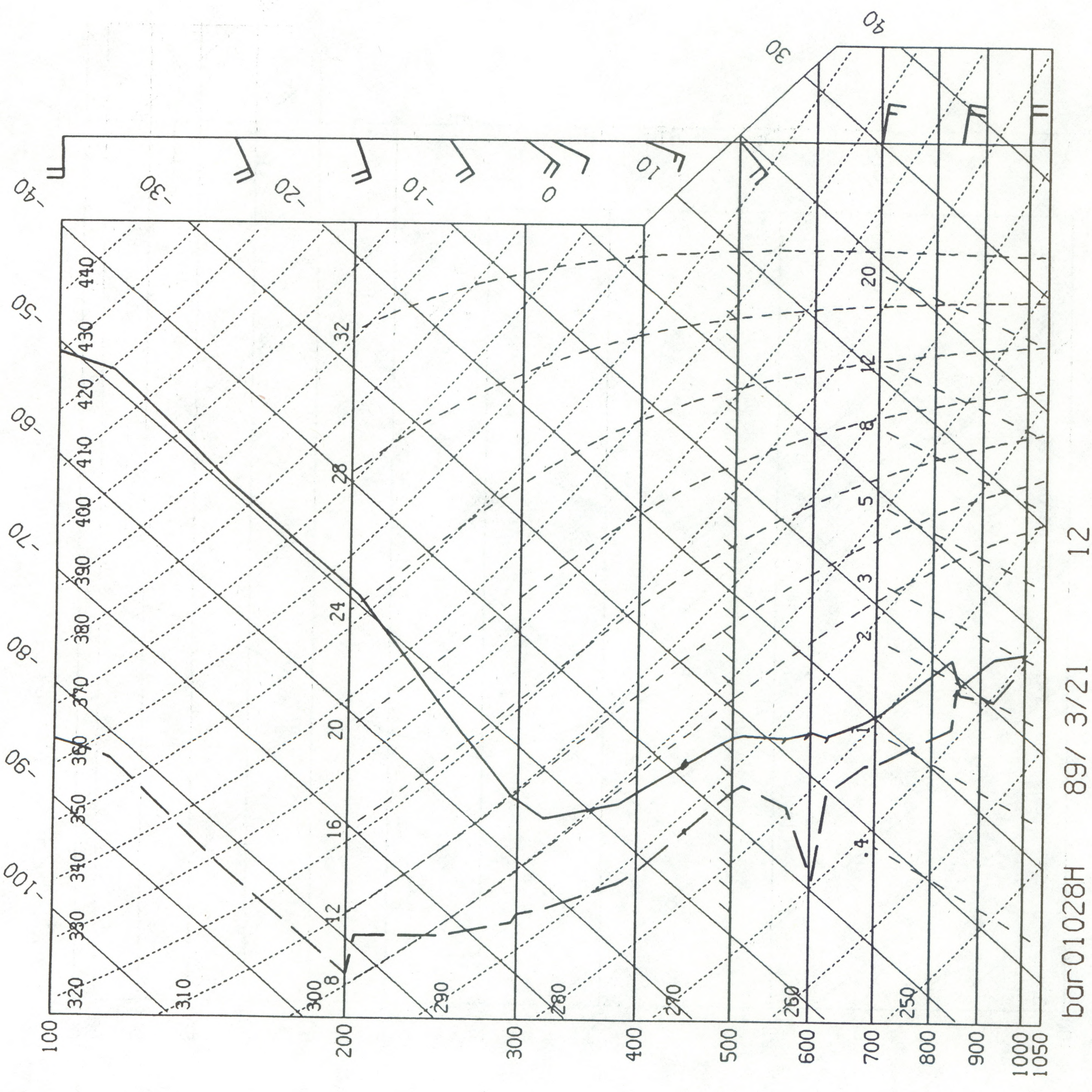
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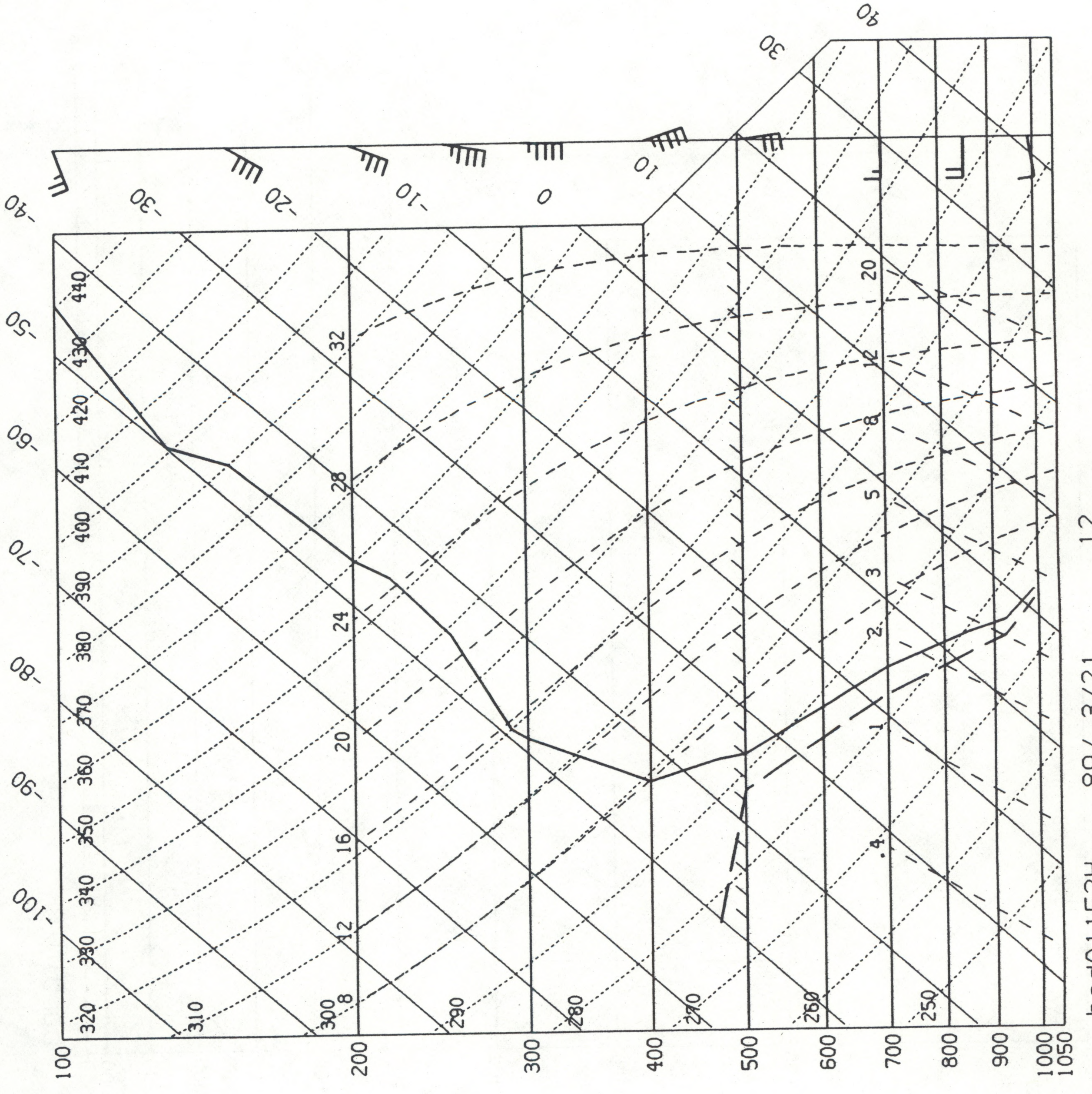
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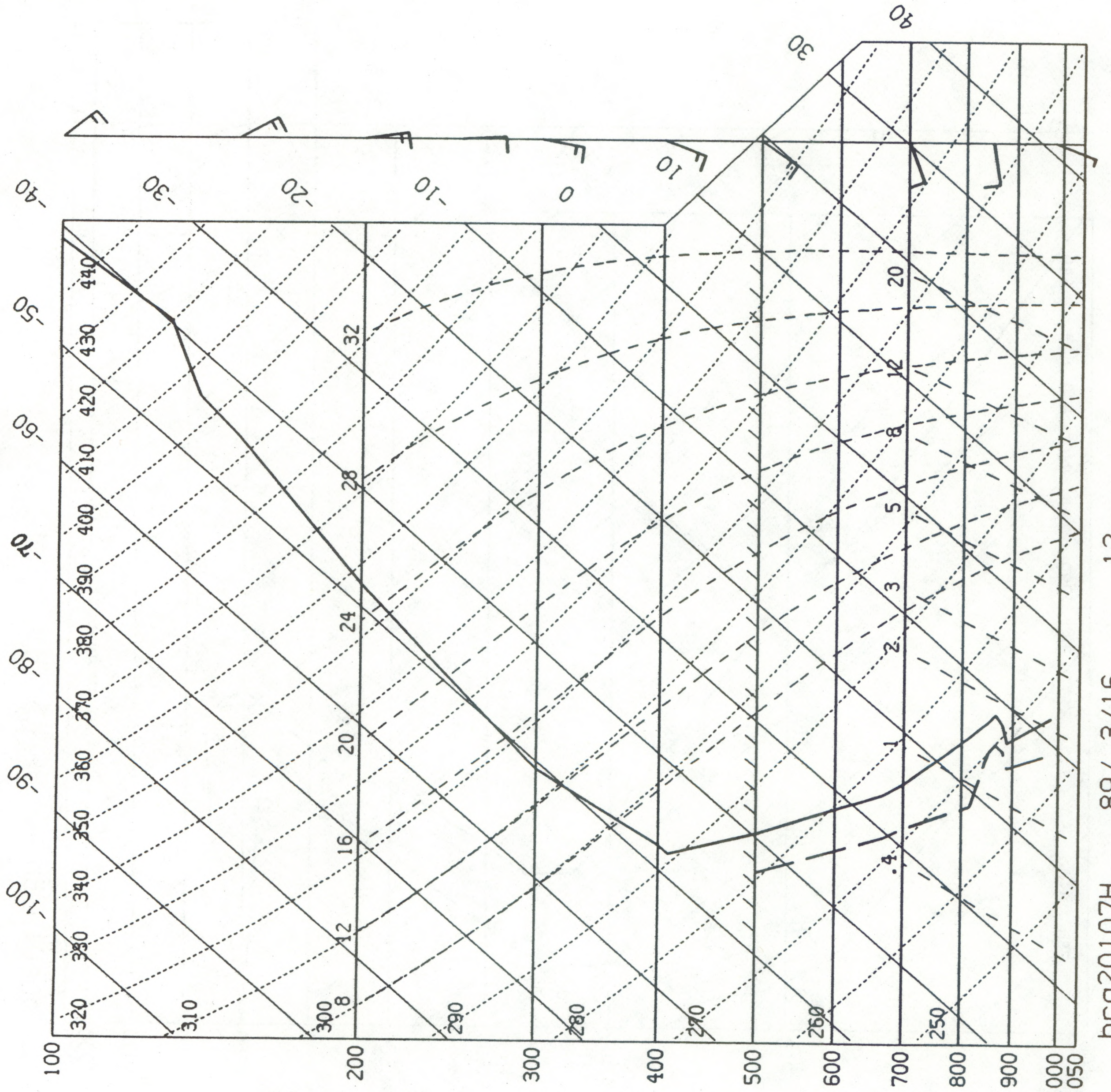
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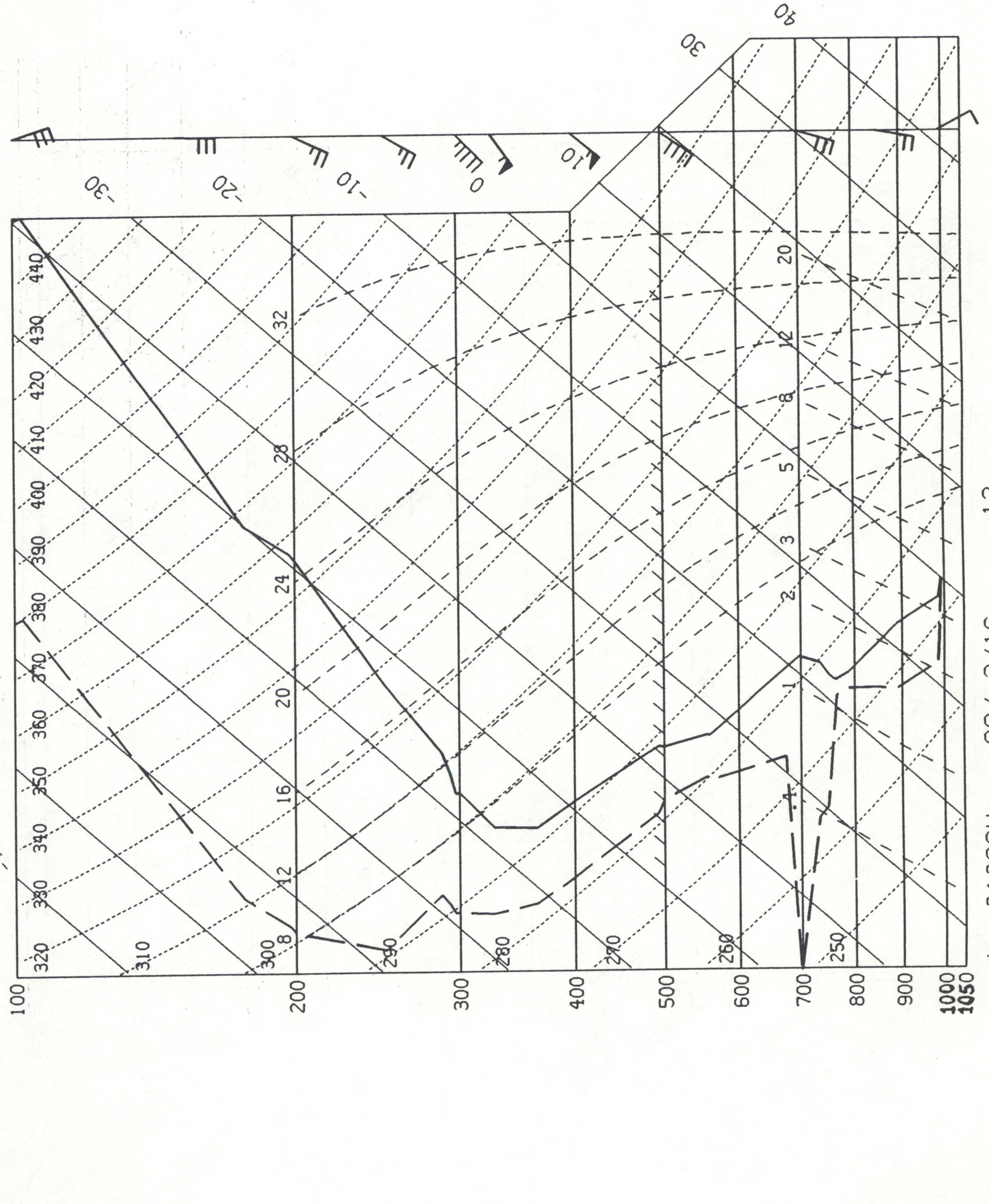
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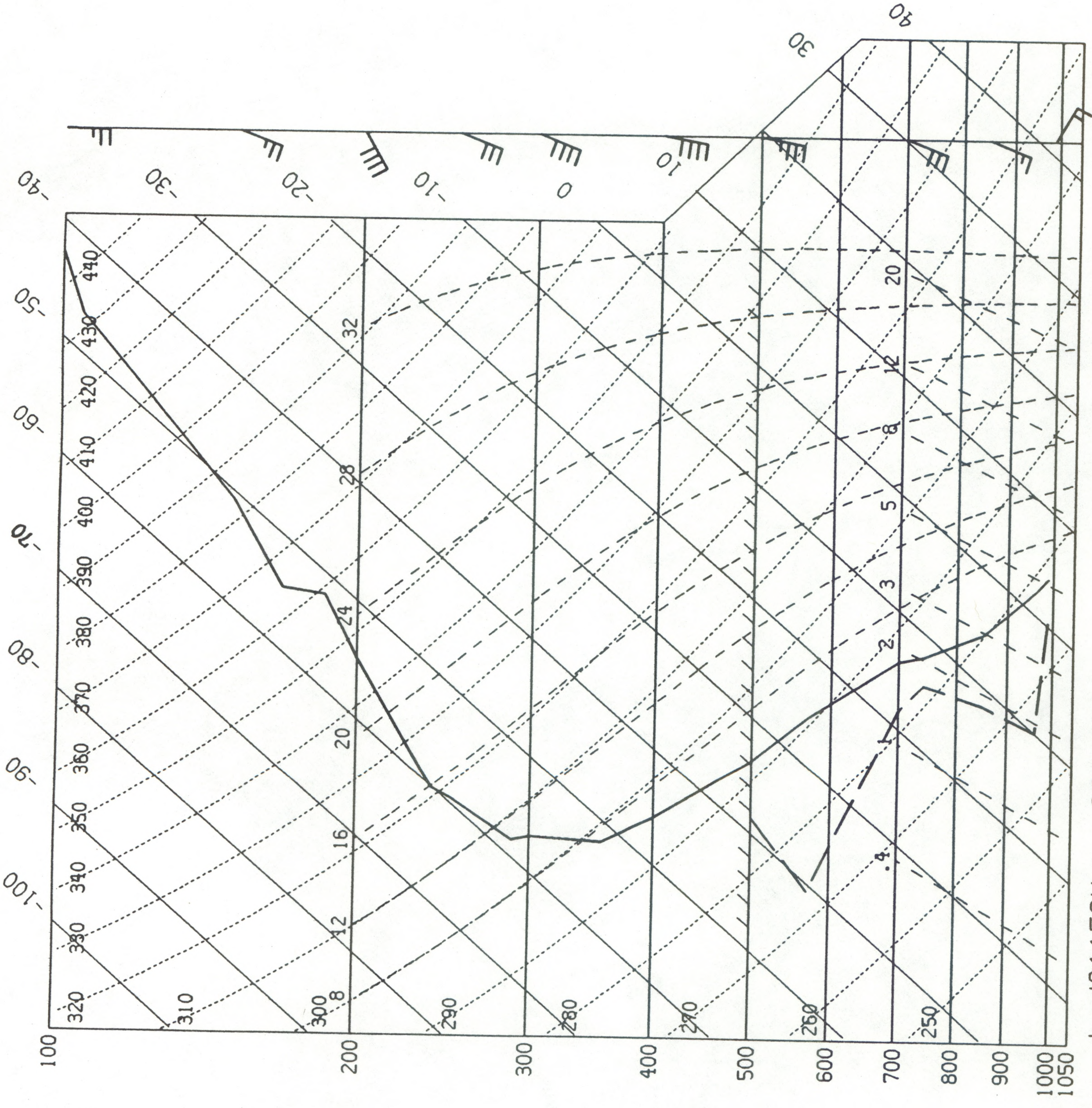

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