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Report

Preliminary report of "Arctic Airborne Measurement Program 2002" (AAMP 02)

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Abstract: The Arctic Airborne Measurement Program 2002 (AAMP 02) campaign was carried out in March 2002 as one of the sub programs of the project "Variations of atmospheric constituents and their climate impact in the Arctic". The main goal of the project was to investigate the transport, transformation and radiative effect of trace gases and aerosols, and their role in the global climate. An instrumented jet plane, Gulfstream II (G-II), was flown from Nagoya, Japan *via* Barrow, Alaska to Longyearbyen (78°N, 15°E), Svalbard, crossing the Arctic Ocean in the lower stratospher. Three local flights were made over the Greenland Sea around Svalbard and two profile flights near Barrow. The plane was equipped with CO_2 and ozone analyzers, gas and aerosol sampling systems, aerosol particle counter, nephelometer, absorption photometer, PMS particle probes, sunphotometer, dew point hygrometer and dropsonde system. During the campaign, intensitive surface operations were also conducted at Ny-Ålesund (79°N, 12°E), Svalbard. Vertical profiles of several trace gases gave information about transport, a new observation by sunphotometer derived an aerosol optical depth in the stratosphere, and another new observation by dropsonde gave information on the polar vortex.

key words: Arctic, trace gases, aerosols, transport, airborne observation

1. Introduction

The Arctic is expected to be greatly affected by global warming and environmental change, and the Arctic in turn may exert strong feedback on global climate (Morison *et al*., 1998; Heintzenberg, 1989). Many of the linkages between the Arctic system and global climate involve cycling of atmospheric constituents, such as the distribution and transport of greenhouse gases and aerosols, and their radiative effects. Concentrations of greenhouse gases at several Arctic stations have shown a noticeable deviation from the normal seasonal variation parallel to that of aerosols. This indicates the importance of the transport process (Engardt and Holmén, 1999; Higuchi *et al*., 2001). Occurrence of "Arctic haze" phenomena also strongly depended on the aerosol long-range transport in the atmosphere from anthropogenic source regions (Yamanouchi *et al*., 2003).

In order to clarify the transport, transformation and radiative effect of trace gases and aerosols and their climatic impact, the Arctic Airborne Measurement Program 2002 (AAMP 02) campaign was conducted in March 2002 as one of the sub projects of "Variations of atmospheric constituents and their climatic impact in the Arctic" (Special Scientific Research Program of the Ministry of Education, Culture, Sports, Science and Technology, No. 11208201). The project was carried out by the National Institute of Polar Research (NIPR) under the cooperation of the Alfred-Wegener Institute for Polar and Marine Research (AWI) and several other institutions. An instrumented jet plane, Gulfstream II (G-II; commercially leased from Diamond Air Service Co., Nagoya), was used and flown from Nagoya, Japan through Barrow (71°N, 157°W), Alaska to Longyearbyen (78°N, 15°E), Svalbard, crossing the Arctic Ocean at 12–13 km height, and three local flights over the Greenland Sea around Svalbard for profile observations connected to Ny-Ålesund ground-based observations. During the campaign, intensive surface operations were also conducted at Ny-Ålesund (79°N, 12°E), Svalbard by NIPR, AWI and others. Two additional vertical profile measurements have been performed near Barrow connected to the regular ground-based observations by NOAA/CMDL. The airborne measurements are also compared with SAGE-III satellite measurements by NASA Langley Research Center. This airborne campaign was a follow on of AAMP 98 (Shiobara *et al*., 1999) with similar operation and of ASTAR 2000 (Arctic Study of Tropospheric Aerosol and Radiation; specially focused on Arctic haze; Yamanouchi and Herber, 2001; Yamanouchi *et al*., 2003). The present paper gives a brief report on the campaign.

2. Status of research projects in the Arctic

The following specific research has been conducted during the current year related to the project, "Variations of atmospheric constituents and their climatic impact in the Arctic":

(1) Long term observations of greenhouse gases: At the Rabben observatory in Ny-Ålesund, Svalbard, long term air sampling for greenhouse gases and stable isotope analysis, and continuous measurements of surface ozone and meteorological parameters have been continued (Yamanouchi *et al*., 1996; Morimoto *et al*., 2001). We also

accumulated data concerning exchange of carbon dioxide between ocean and atmosphere, in collaboration with the oceanographic group (*e.g.* CONVECTION; Hashida *et al*., 2001).

(2) Aerosol and cloud observations: Measurements of aerosol number concentrations, optical depth, vertical distributions, composition and precursor gases (Hara *et al*., 2002); and observations of precipitable water, cloud liquid water, ice water amount and precipitated snow particles, have been continued at Ny-Ålesund to determine the relationship among aerosols, clouds and precipitation (Wada and Igarashi, 1998). Doppler radar observations were also conducted at Bear Island.

(3) ASTAR 2000: Coordinated airborne and ground-based observations of aerosols and radiation were carried out in the Svalbard area through March and April 2000 (Yamanouchi and Herber, 2001). A German aircraft Polar 4 (Dornier 228) was used to measure vertical distributions of aerosols and radiation, while remote sensing and sampling were conducted on the ground. In addition, SAGE-II satellite observations were compared with our data (Thomason *et al*., 2003), and the radiative forcing of aerosols over a wide area was evaluated by incorporating the observational results into an Arctic regional climate model (HIRHAM; Dethloff *et al*., 1996).

(4) AAMP 98: Similar campaign to AAMP 02, of airborne observations using a jet plane (the G-II), was carried out in March 1998 with long range stratosphere flights over the Arctic Ocean and local profiling flights in the vicinity of Svalbard (Shiobara *et al*., 1999).

3. Instrumentation

The plane, the G-II, was equipped with CO_2 and ozone analyzers, gas sampling systems (for CO_2, CH_4, N_2O, CO, SF_6, O_2/N_2 and the isotope; for COS), aerosol filter sampler and impactor, aerosol particle counter, nephelometer, absorption photometer, PMS particle probes, sunphotometer, dewpoint hygrometer and dropsonde system. Instruments are listed in Table 1, and the configuration on the plane is shown in Fig. 1.

Atmospheric concentrations of CO_2 and ozone were measured on board continuously (NDIR CO_2 analyzer, Machida *et al*., 1995, 2002; Dasibi ozone monitor, Morimoto, 2002, Morimoto *et al*., 2003), and also concentrations of CO_2 and other trace gases were analyzed from sampled air after return to the home laboratory. Sampling of air for O_2/N_2 was done with 24 glass flasks of 800 m*l*, and for other gases except for COS was done by 41 stainless steel cylinders of 600 or 1000 m*l* (Sugawara *et al*., 2002). CO_2 concentration was analyzed by an NDIR analyzer and O_2 concentration was analyzed by a mass spectrometer (Ishidoya *et al*., 2003). Samples for carbonyl sulfide (COS) measurement need a large amount of air so a large 1 L sampling cylinder was used, the total number of samples was 41 (Inomata *et al*., 2002a,b, 2003).

Filter samples for aerosols were analyzed for ion concentration by an ion chromatograph (Yamagata *et al*., 2002; Yamazaki *et al*., 2002). Impactor samples were analyzed by electron microscope to derive chemical compositions of aerosols (Hara *et al*., 2003). It was intended to use two optical particle counters to measure the size distribution of particle number concentration larger than 0.1 μm; however, the operation suffered a problem. *In-situ* scattering and absorption coefficient were measured with an

Table 1. Instruments for airborne observation by G-II.

Instrument	Type	Reference
CO_2 NDIR analyzer	Li-COR LI-6262	continuous measurement of CO_2 concentration
Ozone monitor	Dasibi model 1100	continuous measurement of O_3 concentration
Air sampler with pump	0.6 and 1 L cyclinder	samples for analysis of CO_2, CH_4, N_2O, CO and SF_6
	0.8 L glass flask	samples for analysis of O_2/N_2 and isotopes
Air sampler with pump	1 L cylinder	samples for analysis of COS
Aerosol filter sampler	NILU type	ion chromatograph analysis for ionic components
Aerosol impactor	special made	electron micro-scope analysis for chemical constituents
Optical particle counter	MetOne 237 H	particle number concentration D > 0.1, 0.2, 0.3, 0.5, 1.0 μm
Optical particle counter	MetOne 237 B	particle number concentration D> 0.3, 0. 5, 1.0, 5.0 μm
Integrating nephelometer	M 903	scattering coefficient at 530 nm
Absorption photometer	Radiance Research PSAP	absorption coefficient at 565 nm
PMS probe	FSSP-300	aerosol number concentration 0.3 – 20 μm
PMS probe	FSSP-100	cloud particle concentration 2 – 47 μm
PMS probe	OAP-2D-GA2	particle 10 – 620 μm
PMS probe	OAP-2D-GB2	particle 50 μm – 3.1 mm
Sunphotometer	SP1A	349 to 1065 nm, 17 channel
Dew point hygrometer	Buck research CR-2	dew point temperature by mirror system
Drop sonde	Vaisala AVAPS	temperature, humidity and wind profile
Basic flight data		temperature, humidity, pressure, wind, position, attitude and speed of plane
Data acquisition system		

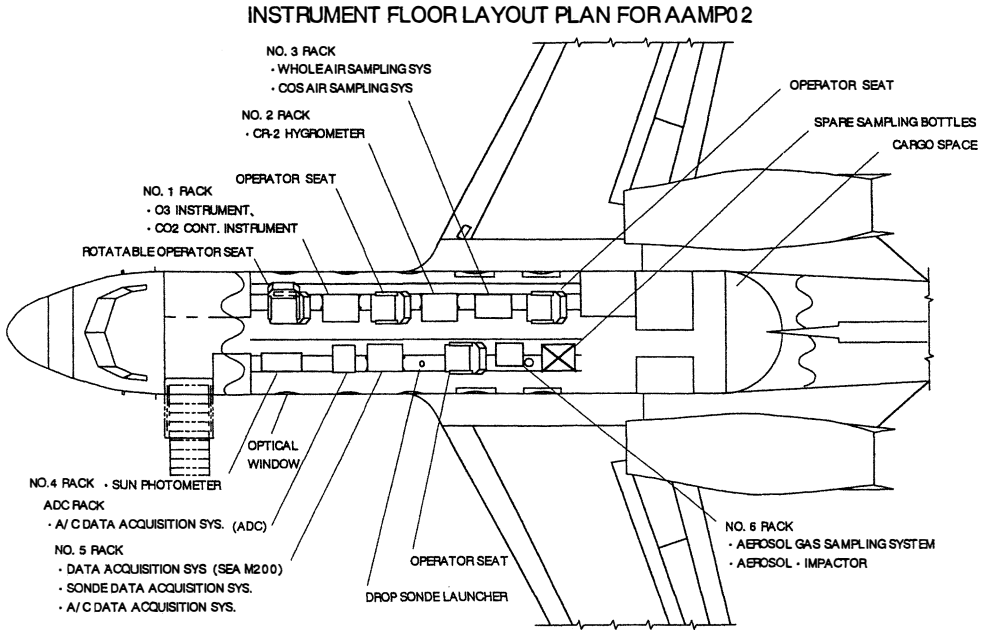

Fig. 1. Instrumentation of Gulfstream II for theAAMP 02 campaign.

integrating nephelometer and a particle soot absorption photometer. All these instruments measured the air introduced into the diffuser set inside the plane. PMS probes measured aerosol particles and cloud particles outside the plane by sensors set under the wing (Asuma *et al*., 2002a, b).

A sunphotometer was used for the measurement of solar radiance to derive height dependent optical depth and extinction coefficients. For this optical measurement, a window of the plane was replaced by a special quartz glass window 375 mm in diameter and 40 mm in thickness; special care had to be taken since the cabin of the plane was pressurized. From the position of the sunphotometer set inside the plane, measurements were possible for solar elevation in the range from 3 to 25 degrees.

For the measurement of basic meteorological fields, a dewpoint hygrometer, CR-2, designed for airborne measurement was installed. The CR-2 was capable of measuring the dew point down to -90°C. A dropsonde system, the Vaisala AVAPS (Hock and Franklin, 1999), also newly designed for a fast flying jet plane, was used in addition to the normal meteorological sensors on the plane. The dropsonde was shot through a shooter by the power of pressure difference between inside and outside the plane. This shooting of the sonde was the most critical part of the operation (Wada *et al*., 2002). Some of the shooting was not successful, resulting in the sonde falling down without a parachute and making wind observation difficult. The basic meteorological sensors for air temperature, humidity (dew point) and static and dynamic pressures were installed on the aircraft and these data together with other flight information from an inertial reference system and the global positioning system were recorded in the data recording system.

4. Airborne observation flight

The Arctic airborne observations were conducted during 5–14 March 2002. The flight schedule, total 49.2 hrs, is shown in Table 2, and the general route in Fig. 2. The

Table 2. Flight hours (UT), route and altitude.

Date	Hour	Route	Flight altitude
March 4	23:20 – 03:05	Nagoya – Petropavlovsk	00:00 – 01:07 37000 ft; – 02:35 36400 ft
March 5	04:15 – 08:55	Petropavlovsk – Anchorage	04:41 – 06:32 36400 ft; – 07:40 37000 ft; – 08:40 35000 ft
March 5	23:20 – 02:40	Anchorage – Barrow	23:50 – 00:29 39000 ft; 01:20 – 02:14 profile (5000 – 45000 ft; 71°N, 156°W)
March 6	03:35 – 09:05	Barrow – Longyearbyen	04:29 – 07:01 37000 ft; – 08:10 43000 ft
March 7	10:50 – 13:50	Longyearbyen – local flight	11:25 – 14:38 profile (500 – 43000 ft; 79°N, 9°E)
March 10	09:45 – 14:40	Longyearbyen – local flight	11:18 – 12:21 profile (6000 – 45000 ft; 74°N, 15°E); 13:23 – 14:11 profile (45000 – 1000 ft; 79°N, 10°E)
March 11	11:05 – 15:30	Longyearbyen – local flight	11:55 – 12:56 37000 ft; 12:56 – 14:02 polar low profile (37000 – 3000 ft; 72°N, 19 – 29°E)
March 12	14:45 – 19:40	Longyearbyen – Barrow	15:28 – 18:39 39000 ft
March 12	20:45 – 00:20	Barrow – Anchorage	21:19 – 22:34 profile (1600 – 43000 ft; 72°N, 152°W); - 00:03 37000 ft
March 13	23:20 – 03:50	Anchorage – Petropavlovsk	23:40 – 23:59 28000 ft; - 01:28 31500 ft; - 03:21 38000 ft
March 14	04:55 – 09:15	Petropavlovsk – Nagoya	05:09 – 06:47 37000 ft; - 08:28 36400 ft

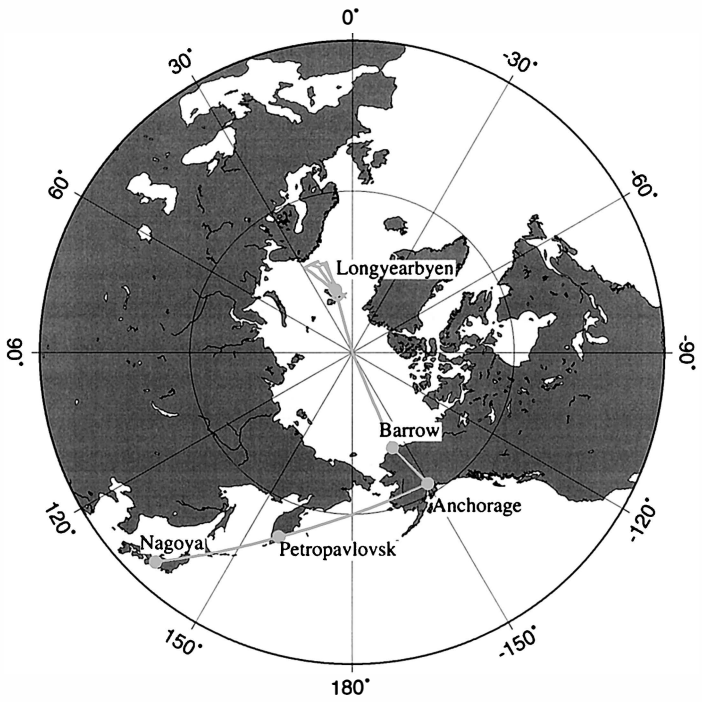

Fig. 2. Map showing the flight route.

flight was from Nagoya, Japan, via Petropavlovsk and Anchorage to Barrow. After a short stop at Barrow, vertical flights were done before the trans-Arctic flight. The trans-Arctic flight from Barrow to Longyearbyen crossing the North Pole was made on March 6, wih the return flight on March 12. Due to the strict limitation on flight operation by the regional air control, a constant flight level could not be kept during the trans-Arctic flight. Three local flights were made also from Longyearbyen in the Greenland Sea and Norwegian Sea for vertical profile observations corresponding to Ny-Ålesund ground-based observations, and for polar low observations. Finally, the return flight ended at Nagoya on March 14.

5. Ground based observations

The airborne measurements were complemented by comprehensive ground-based measurements at Ny-Ålesund. At NIPR Rabben Station, air sampling for greenhouse gases, continuous measurements of surface ozone and aerosol particles, remote sensing by sky radiometer, microwave radiometer, micro-pulse lidar and radar were made (Shiobara, 2000; Wada *et al*., 1996). At AWI Koldewey Station (Gernandt *et al*., 2001), sunphotometer, lidar and FTIR remote sensing together with balloon launchings have been performed. Instruments used in the campaign are listed in Table 3.

Table 3. Instruments for ground-based observation at Ny-Ålesund.

Instrument	Type	Reference
(NIPR)		
Surface ozone monitor	Dasibi	continuous measurement of O_3 concentration
Air sampler	0.8 L cylinder	samples for analysis of CO_2, CH_4, N_2O and isotopes
Low pressure impactor	Dylec LP-20Z	aerosol sampling in 0.06 – 12 μm, 12 stage
Optical particle counter	Rion KC-01C	particle number concentration in 0.3 – 5.0 μm, 5 channel
Integrating nephelometer	TSI 3563	scattering coefficient at 450, 550 and 700 nm
Absorption photometer	Radiance Research PSAP	absorption coefficient at 565 nm
Sampling photometer	Satsunan Y-01	aerosol sampling
Micro Pulse Lidar	SESI MPL	backscatter at 523 nm, Dh = 30 m
Sky radiometer	Prede POM-01	sky radiance at 368 – 1045 nm, 7 channel
Microwave radiometer	Radiometrics WVR-1100	water vapor and liquid water amount from 23.8, 31.9 GHz
Vertical pointing radar	JRC X-band	cloud and precipitation from radar echo at 9.4 GHz
Precipitation sensor	Andrew POSS	precipitation type, intensity, rate and size distribution (X-band bi-static radar)
Infrared thermometer	Minolta	brightness temperature of the atmosphere (cloud)
(AWI)		
Tropospheric lidar	KARL	backscatter and depolarization ratio at 532, 1064 nm
Sun photometer	SP1A	aerosol optical depth at 349 – 1065 nm, 17 channel
Star photometer	Star 01	aerosol optical depth at 400 – 800 nm, 10 channel
2 & 8 stage impactor	Kaskade impactor	size dependent (0.3 – 16 μm) heavy metal concentration
FTIR Spectrometer	Bruker FTS	trace gas concentration from 10 – 100 μm
Ozone sonde	ECC 6a	ozone concentration profile (0 – 30 km)
BSRN radiometers	CM-11 and Eppley	short and longwave radiation

6. Preliminary results

The polar vortex shifted to the European side and its center was around the north of Greenland during the outward flight as shown in the 200 hPa height field (NCEP/NCAR analysis), Fig. 3. The shift of the polar vortex might correspond to the existence of a blocking high seen west of Alaska, over Bering Straight. Dropsonde observations were made at about every 5 degrees during the trans-Arctic flight (Wada *et al.*, 2002). The dropsonde profile shows that, along the route, on the Alaskan side the tropopause was high, around 250 hPa, and the flight route was outside the polar vortex (mid-latitude airmass), while on the European side the tropopause became low, close to 400 hPa and the route was in the core of the polar vortex (Fig. 4). Temperature in the troposphere gradually decreased along the route from 75°N on the Alaskan side to 85°N on the European side, profiles were almost parallel except for the lowest layer below 850 hPa, and the total difference from 75°N on the Alaskan side to 85°N on the European side in the mid-troposphere was about 13 degrees. Close to the surface, a large temperature inversion, more than 10 degrees, was seen at 80°N on the Alaskan side and 85°N on the European side.

This atmospheric condition affected greenhouse gases, and different vertical profiles were seen at Barrow and Longyearbyen as shown in Fig. 5. Large gaps of the CO_2 concentrations in the troposphere and stratosphere are seen at the different height levels corresponding to the different tropopause heights. The gap was especially clear at Barrow and the concentration changed drastically crossing the tropopause; however, at Longyearbyen the gap was not so clear and the concentration gradually changed from

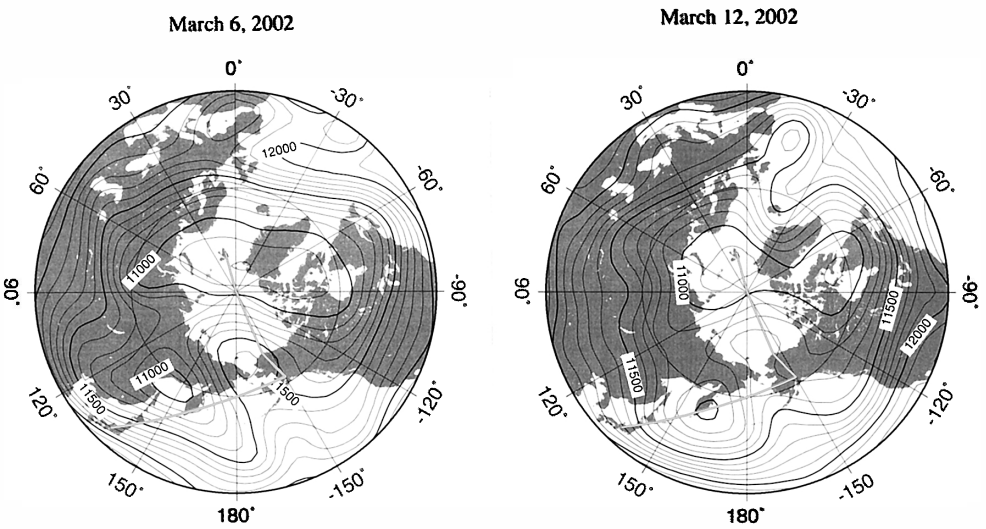

Fig. 3. 200 hPa height field (gpm) at March 6, 06 UT, and March 12, 18 UT, 2002, when the trans-Arctic flights were performed (NCEP/NCAR analysis), with the flight path (thick line).

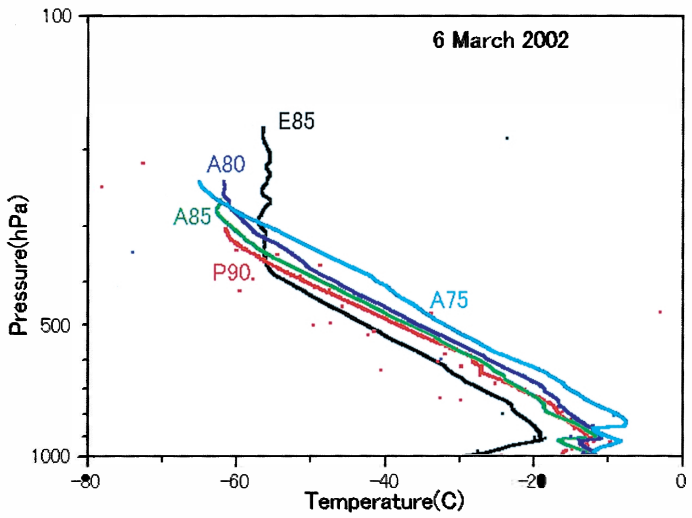

Fig. 4. Temperature profiles by dropsonde observations at 75, 80, 85°N on the Alaskan side (A75, A80, A85), North Pole (P90), and 85°N on the European side (E85), March 6, 2002.

the troposphere to the stratosphere. At Longyearbyen, also, a gradual decrease of concentration in the troposphere from the surface to the tropopause was seen, while at Barrow, a rather constant vertical distribution was seen from 1000 m height to the tropopause, though both concentrations were similar at the surface. The difference in the vertical profile might be due to the difference in mixing process or transport process within the troposphere and stratosphere, and troposphere-stratosphere exchange between the inside and outside of the polar vortex. The increase of CO_2 concentration in

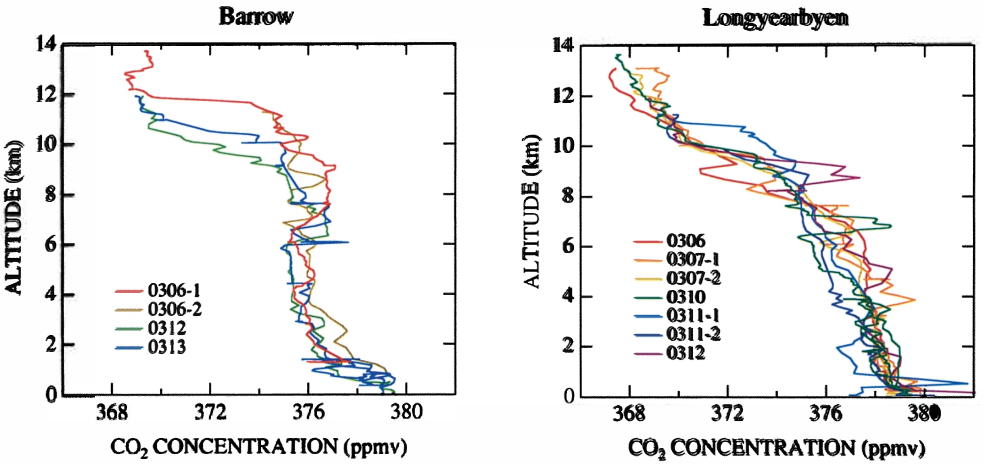

Fig. 5. Vertical profiles of CO_2 concentration near Barrow and Longyearbyen; numbers correspond to the date and profile number; March 6 (0306), 7 (0307), 10 (0310), 11 (0311), 12 (0312) and 13 (0313).

the lower stratosphere (around 12 km) during March 1998 (Shiobara *et al.*, 1999) and 2002 was about 6–8 ppmv.

From the sampled air, O_2 concentration was analyzed by a mass spectrometer together with concentrations of other trace gases and isotopes. The vertical profile of O_2 concentration up to the stratosphere was obtained as the first result in the Arctic atmosphere. $\delta(O_2/N_2)$, defined as the relative difference from the standard, gives information on the source and sink of CO_2, just as $\delta^{13}C$. $\delta(O_2/N_2)$ showed a gradual increase in the troposphere, -180 per meg at the surface near Longyearbyen, and -130 per meg just below the tropopause. $\delta(O_2/N_2)$ in the stratosphere showed a higher value than in the troposphere, and was about -80 per meg at 13 km height. $\delta(O_2/N_2)$ and CO_2 concentration showed a negative correlation (Ishidoya *et al.*, 2002).

Also, a concentration of SF_6 was analyzed from the sampled air. Since SF_6 has an ultra long life time and negligible exchange between atmosphere and biosphere or ocean, SF_6 could be treated as a tracer of atmospheric transport. SF_6 concentration, which was almost constant in the troposphere and decreased with height in the stratosphere, was about 4.5 pptv between 11 and 13 km height. Comparing the vertical profile near Barrow and Ny-Ålesund, SF_6 concentration in the stratosphere at Ny-Ålesund was systematically lower by about 0.2 pptv than at Barrow. The difference in the tropopause height or the difference in the age of the air between the inside and outside of the polar vortex might explain this concentration difference (Kawahara *et al.*, 2002).

Carbonyl sulfide (COS) was analyzed as the major precursor of stratospheric sulfur aerosols. COS was analyzed by gas-chromatograph (GC-FPD) at Nagoya University. Vertical distribution of COS concentration in the troposphere was almost constant, reflecting a long life time in the troposphere and negligible source and sink in the Arctic. In the stratosphere, COS distribution showed a quick decrease with height at Barrow; however, only a weak decrease with height was seen at Svalbard. This difference might be due to the difference in the atmospheric circulation field, inside and outside of the

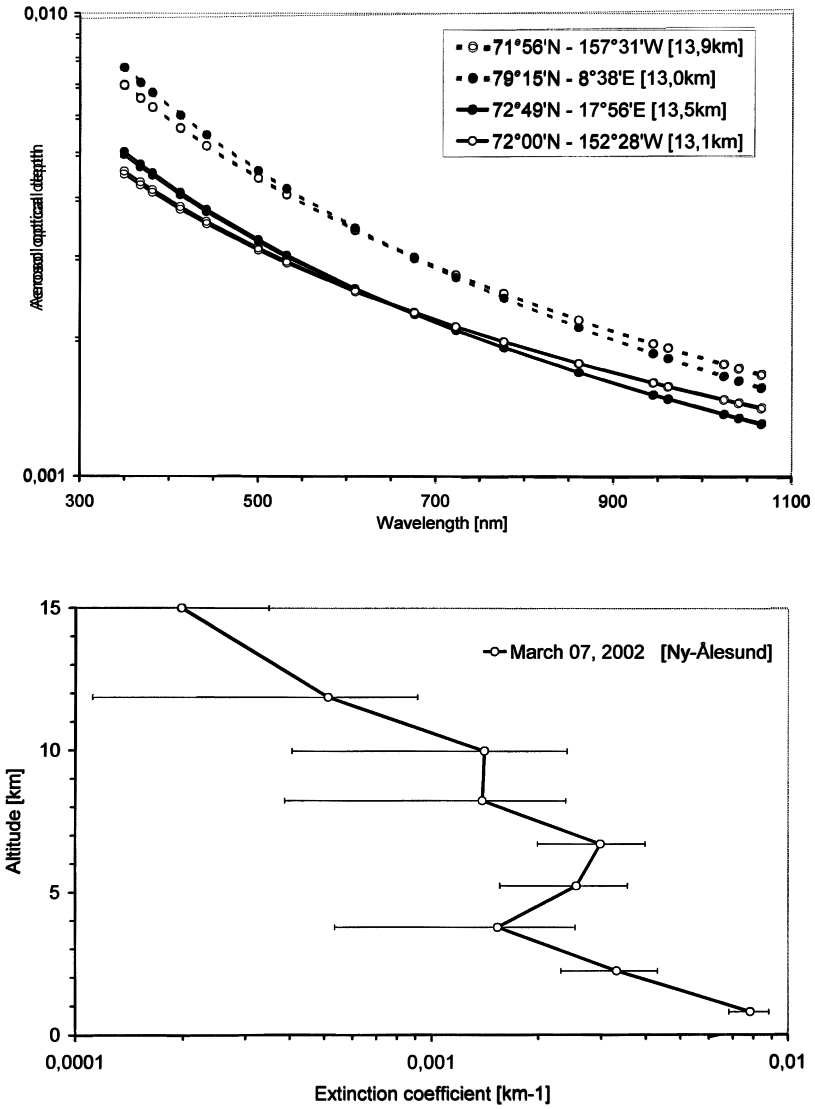

Fig. 6. Aerosol optical depth of the stratosphere from 13–14 km height (upper panel), and vertical profile of extinction coefficient at 532 nm with standard deviations close to Ny-Ålesund, March 7, 2002 (lower panel).

polar vortex (Inomata *et al.*, 2002b).

Aerosol samplings were performed and 34 filter samples were obtained. They were analyzed for their ionic components with ion-chromatography. Although the main part of ionic components in the stratosphere was occupied by sulfate (SO_4^{2-}), other ions such as Na^+, Ca^{2+}, K^+, Mg^{2+} and NO_3^- were also detected (Yamazaki *et al.*, 2002). Total ionic mass for each filter was compared with particle number concentrations measured by PMS particle probe outside the plane. Optical parameters, *i.e.*,

scattering coefficient and absorption coefficient of aerosol particles were also measured inside the cabin. Aerosols were sampled on an impactor and chemical constituents were analyzed with an electron microscope.

From sunphotometer measurements, the optical depth of the atmosphere above flight level was derived and an extinction coefficient for the layer was obtained from the differences of two optical depths above and below the layer. The optical depth of the stratospheric aerosols showed good agreement over a wide area of flight, at 500 nm, as in Fig. 6: 0.003 to 0.004 in the range 13–14 km. The extinction coefficient profile at Ny-Ålesund was expanded from the mid-troposphere (Nagel *et al*., 1998; Yamanouchi *et al*., 2003; Treffeisen *et al*., 2003) to the lower stratosphere, up to 15 km (see the profile for 532 nm in Fig. 6), and also extremely good agreement of extinction profile with the SAGE-III satellite measurement was found between 3 to 15 km height at 72°N, off Barrow.

Ground-based measurements were continued during the campaign; however, conditions to compare with airborne measurements was not ideal due to the short window of airborne operation near the station and weather condition. At Ny-Ålesund, it was cloudy during most of the local flight close to the station, and it was difficult to look at the same airmass with remote sensing observation.

One flight observation was intended to investigate a polar low developing; however, the weather was rather calm and we could not find a developed disturbance within the flight range except for a weak system. The flight was conducted on March 11 to search for weather disturbances associated with a vortex in the lower boundary layer off the Norwegian Peninsula. Although these disturbances were decayed at the time of measurement, we obtained environmental data related to the disturbances (Asuma *et al*., 2002b).

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