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Airborne aerosol and black carbon measurements over the East Siberian Sea, Spring 1992

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Abstract

In April 1992 we performed measurements of Arctic aerosol properties from an aircraft flying over the East Siberian Sea from Cherskiy (69°N, 161°E) to Bennett Island (76.5°N, 149°E). Eight round-trip flights were made over this 1000 kilometer path, with each flight incorporating several profiling descents from approximately 4.2 km altitude to the surface. On a 10-second time base were recorded measurements of aerosol black carbon (BC), condensation nuclei (CN), air temperature and absolute barometric pressure, from which altitude was deduced. Some profiles showed considerable vertical structure with numerous temperature inversions and stratified aerosol layers. Peak BC and CN concentrations exceeded 1000 ng m^{-3} and 1000 cm^{-3} respectively. Occasionally, extremely clean air was found in some layers. Other descents showed stable temperature profiles, with aerosol BC and CN distributed throughout the lower 4 km of the atmosphere. In most cases, the surface temperature-inversion layer contained high concentrations of aerosol species. We conclude that the atmosphere in this remote area is strongly affected by anthropogenic emissions from distant source regions, and that the meteorological and aerosol concentration profile structures were similar to those regularly observed in the western sectors of the Arctic in springtime. © 1997 Elsevier Science B.V.

1. Introduction

The phenomenon of Arctic Haze has been extensively studied in the Western sectors of the Arctic (e.g. Rahn and McCaffrey, 1980; Schnell, 1984; Herbert et al., 1989;

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Leaitch et al., 1989; Albritton, 1989; Bridgman et al., 1989; Davidson and Schnell, 1993; Barrie et al., 1994). In the late winter and spring months, anthropogenic emissions are transported into the north polar airmass, reaching concentrations that are occasionally comparable to those measured in US cities (Rosen and Hansen, 1984). Aircraft studies showed that the concentrations of these species are highly stratified in layers whose air temperatures may show numerous transitions, in addition to the usual surface temperature inversion (Schnell and Raatz, 1984). The concentrations of pollutants may be an order of magnitude greater in a layer at an altitude of a few hundred meters than in the surface atmosphere. Thus, aircraft studies are essential to determine the overall atmospheric burden of these species, in addition to providing geographic coverage. Surface measurements are routinely made at the NOAA/CMDL observatory at Barrow, Alaska (Bodhaine, 1989); at Alert, Canada (Worthy et al., 1994); at Ny Alesund, Spitzbergen (Iversen, 1989); and at other locations at lower latitudes. Starting in 1988, aerosol samples have been collected at the Ushakovskoye Polar Station on Wrangel Island, Russia (71°N, 178°W) (Hansen et al., 1991). Trace element signatures in aerosol samples collected from the surface at Barrow, Alaska (Lowenthal and Rahn, 1985) show that about 70% of the air pollution passing Barrow had origins in the then Soviet Union. The results reported in this paper represent the first airborne measurements of aerosol BC and CN over the East Siberian Sea that are available in the open literature.

In April 1992, an aircraft mission was organized to collect gas and aerosol samples from the vicinity of Bennett Island (76.5°N, 149°E) in the New Siberian Islands group. (Schnell et al., 1992). Unexplained plumes of unknown origin and composition arising from the vicinity of Bennett Island had been observed on satellite photographs for a number of years (Kienle et al., 1983; Matson, 1986). One explanation hypothesized that these plumes were due to the release of methane from hydrate deposits in the shallow ocean floor. Samples of the air from around the island and in one plume were conducted over the period of a month. The results of these analyses will be published elsewhere. The aircraft used in this work was based at Cherskiy, on the north coast of Russia, and the necessary 1000 km transit flight provided the opportunity to perform aerosol studies in the same program, the results of which form the basis of this paper. These measurements paralleled similar studies in the fourth Arctic Gas and Aerosol Sampling Program (AGASP-IV), based in Anchorage, Alaska and working in an area north of Barrow, Alaska during the same time period (Herbert et al., 1993).

2. Experimental details

The measurements were performed from a Russian 'Antonov-26'. This is a twin-turboprop aircraft with an airspeed of from 350 to 440 km/h (approximately 100 to 120 m/s), an operational ceiling of approximately 6 km altitude, and a load capacity of 4 to 5 tons. The particular aircraft that we used was modified for long-range work by the addition of extra fuel tanks, allowing for flights of 8 to 10 hours' duration with adequate reserves. This aircraft is routinely used for supply and reconnaissance in the Arctic. It does not require heated hangaring, and is normally operated from a cold soak at the prevailing ambient temperature (down to −30°C in the period of this program). Thus,

scientific equipment installed on the aircraft must either be able to withstand these temperatures, or must be removed at the end of each flight. It was not possible to interface the aircraft navigational systems to the data acquisition system in the instrument package, and so the latitude and longitude were recorded manually and subsequently transcribed. Altitude aboard the aircraft was deduced from a barometric pressure sensor. The equipment package included a similar sensor whose output was continuously recorded, and the altitude recording was constructed by intercomparison.

The air inlet to the aerosol measurement package was constructed from a length of stainless steel tubing of inside diameter 0.75 in. (1.9 cm), bent in a smooth S-curve and passing through a plate inserted in the window opening of the forward passenger door. The centerline of the inlet probe was approximately 15 cm from the aircraft fuselage. This was the maximum extension possible that also allowed the door to open. Inboard, the steel probe tube was connected to the aerosol instrument package by a length of 0.875 in. ID polypropylene tubing. The instrument rack was located in the forward cabin as close to the door as was practical. Aerosol sampling was sub-isokinetic, leading to a possible artifact over-sampling of particles of large aerodynamic diameter. However, in this remote region, we did not anticipate large concentrations of large particles. At the side of the inlet probe tip, a thermistor sensor was attached to provide a measure of air temperature. This sensor was not calibrated in flight but was laboratory calibrated prior to the flight program. An additional inlet of 0.375 in. diameter stainless steel tubing was connected to the trace-gas system that compressed samples into glass and stainless steel flasks for subsequent analysis.

The aerosol equipment package consisted of an Aethalometer to measure the concentration of aerosol BC (Hansen et al., 1982) and a TSI Model 3760 condensation nucleus counter. The Aethalometer could resolve 10 ng m^{-3} on a 10 second response time and the CN counter could resolve 10 CN cm^{-3} with a response time of 1 second. All BC and CN data were averaged with a 30 second running mean for plotting presentations. The thermistor sensor was connected to a linearizing circuit to give an output voltage proportional to the external ambient temperature. The Aethalometer and the CN counter both used positive-displacement pumps to draw sample air: the Aethalometer flow rate varied from approximately 30 SLPM at high altitudes to 65 SLPM at low altitudes, and was continuously measured with a mass flow meter. The CN counter flow rate was a nominal 1.4 l min^{-1}. The entire system had to operate at (or close to) ambient pressure, limiting our measurements to a maximum altitude of approximately 5 km, the limit considered safe for operations.

During measurements, the aircraft pressurization system was set to zero pressure boost, and a vent (designed for emergency depressurization) was opened to the outside atmosphere. At constant airspeed, the cabin pressure maintained a fixed differential with respect to the true external pressure due to the forward velocity of the aircraft. The fact that the aerosol inlet probe was sub-isokinetic insured that ram pressure would provide sufficient pressure boost to cause a slight positive pressure and hence a large airflow through the very small flow resistance of the sampling duct, aspirated downstream of the equipment by a fan. The fan exhaust was vented through a port on the side of the equipment rack, and it was easy to check at all times that a large positive airflow was maintained through the system.

The Aethalometer and CN counter inputs were connected to the sampling duct by shallow-angle catheter probes. These were thermostatically heated to insure that those instruments would not be affected by large changes in ambient air temperature, and also so that the sample streams would be warmer than the −30°C ambient temperatures. A barometric pressure sensor was mounted in the equipment rack to measure cabin pressure. The airspeed-induced cabin pressure offset was determined by comparing its output with the aircraft's external barometric pressure sensor. We observed that the aerosol system's pressure sensor was able to accurately reproduce the true barometric pressure, enabling us to use its output as an altitude indicator.

Data from the instruments was recorded by a portable computer equipped with a 16-bit analog-digital converter. The computer controlled the cyclic functioning of the aethalometer, and a multiplexer allowed for the acquisition of signals from the nephelometer, condensation nucleus counter, temperature and pressure sensors. Data was acquired continuously, and averaged over a 10-second time base. The data was recorded on magnetic disk, and also printed out as a backup. The entire package operated from the 27-volt DC power available on the aircraft, with low-voltage pumps, DC–DC converters and DC–AC inverters to power the equipment. Total current consumption was approximately 30 amperes, well within the limit available from an auxiliary power circuit on the aircraft. The equipment package was mounted in a single steel rack cabinet. By request, hot air was blown onto the cabinet for an hour or two prior to each flight to raise the temperature of the pumps and equipment from the overnight cold soak at −10 to −30°C before reapplying power. Nevertheless, it was our experience that the equipment required up to an hour of power-on time before stabilizing and working satisfactorily.

3. Flight profiles

Fig. 1 shows a map of the project area: the flight track indicates the usual locations of aerosol measurement regions. The research flights typically departed Cherskiy at 11 am local time (i.e. 2300 Z of the previous standard calendar day). The flight plan was a straight vector to the north-west in the direction of Bennett Island. This path passed over no significant habitation in the short distance to the coast, and there were very few local aerosol sources other than the town of Cherskiy. We do not believe that any of the data were affected by local emissions. The first portion of the flight was a climb to 4–5 km altitude followed by the start of the first slow outbound descent profile, at which point aerosol measurements were started. Each profile was maintained at a constant airspeed of 360 km/h with a 1 m/s rate of descent. When the lowest altitude of 100 m was reached, the aircraft flew level for 5 minutes before climbing back to the top for the second descent. By the end of the second straight descent profile, we were approaching Bennett Island. The aircraft then climbed to an altitude specified for observation of Bennett, and performed a slow spiral descent around the island at the same airspeed and vertical velocity as before. When a low altitude was reached, it was usual to spend some considerable time collecting gas samples over the ice pack, over the island, and over any

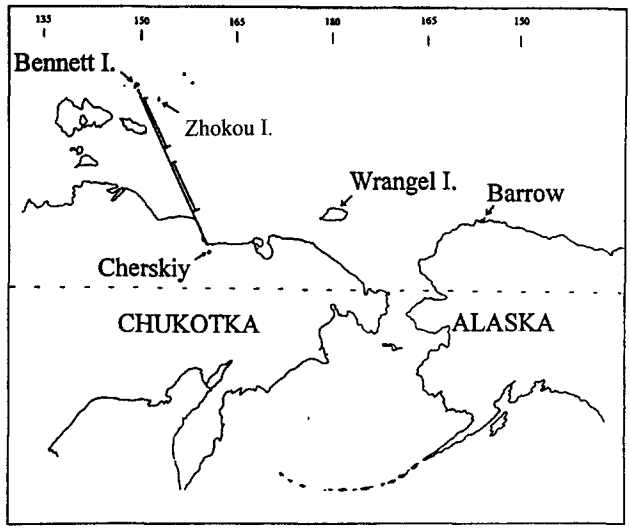

Fig. 1. Outline map showing the study area. The approximate locations of the aerosol sampling profiles are indicated along the flight paths.

open water. The aerosol system collected data at 100 m altitude for this period, and this was combined with the data from the spiral descent.

When we had completed the gas sample collection, the aircraft climbed rapidly again to the top of the first inbound descent profile. Two such profiles could be made on the inbound transit before reaching the coast and the approach to Cherskiy. Each flight therefore usually yielded five profiles: one over and around Bennett Island, and two pairs along the flight track at comparable geographic locations, although separated in time by several hours. On some flights this plan was changed, but we were able to collect data over 33 profiles in this region between the surface and a maximum altitude of 4 to 5 km in the program period of 16 days.

4. Results

We report on data from the air temperature sensor (T), the condensation nucleus (CN) counter, and the Aethalometer measuring aerosol (BC). These three quantities are studied as a function of barometric pressure (P, from which altitude may be deduced) and geographic location along the flight tracks.

4.1. Temperature profiles

The temperature profiles usually fell into four categories: (1) a surface inversion of delta-T approximately 5°C at pressure levels of 950 to 1000 hPa; (2) one or more strong inversions (delta-T from 7 to 12°C) at higher levels up to 800 hPa pressure; (3) a mixed

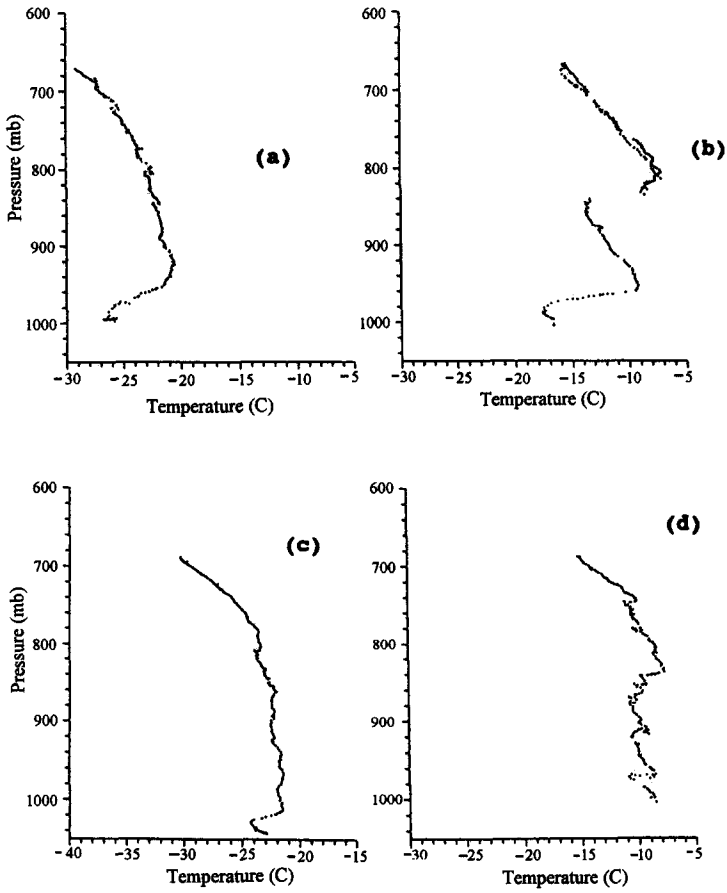

Fig. 2. Examples of air temperature profiles observed over the East Siberian Sea: (a) Surface temperature inversion, then stable lapsing profile above; first outbound descent profile, flight 7, 16 April 1992. (b) Two strong temperature inversions, one near the surface (960–980 hPa level) and the other at a higher altitude (810–830 hPa level); first outbound descent profile, flight 5, 11/12 April 1992. (c) Mixed-layer temperature profile showing a weak inversion close to the surface with little temperature change between the 1010 and 780 hPa levels; first inbound descent profile, flight 3, 8 April 1992. (d) Complex vertical structure showing a number of minor inversions superimposed on a generally well mixed atmosphere, second inbound descent profile, flight 5, 12 April 1992. Up to eight small inversions may be counted in this profile.

temperature profile showing very little decrease from 950 to 750 hPa; and (4) a complex vertical structure showing many smaller inversions at a number of altitudes. Examples of these four categories are shown in Fig. 2(a)–(d).

4.2. Aerosol profiles

The aerosol profiles showed a wide degree of variability. Layers of 'clean' air were sometimes detected, in which CN and BC concentrations were quite low. However, in

the vast majority of profiles the Arctic air was distinctly polluted throughout the column from ground level to the 5-km operational ceiling. Examples of different categories of vertical profiles of T, CN and BC are shown in Figs. 3–6.

4.2.1. Well mixed column

Fig. 3 shows an example of a situation in which the vertical column is almost uniformly polluted from ground level to 5 km altitude. The CN count varied only a little, from approximately 250 to 400 cm^{-3}. The BC concentration showed lower values near the surface, down to 150 ng m^{-3} in the surface temperature inversion layer that was capped at the 960 hPa level. BC values then ranged from 300 to 600 ng m^{-3} from this level up to the top of the profile. The temperature profile shows an version at 840 hPa, which was reflected in a moderate change in BC concentration and a slight change in the CN concentrations. The BC data may be interpreted as showing the presence of as many as eight stacked polluted layers, from 1000 to 720 hPa. The many small (but distinct) peaks in the CN record may indicate even finer vertical structure. Note that the values of the BC and CN data were not unusually high, but that their constancy throughout the vertical column implies a large total atmospheric burden.

4.2.2. Polluted layer aloft

Fig. 4 shows two profiles through an airmass that displayed relatively clean air at lower altitudes, but substantially polluted air aloft. Fig. 4(a)–(c) show the T, CN and BC profiles for the second vertical sounding on the outbound transit on 15 April 1992. Fig.

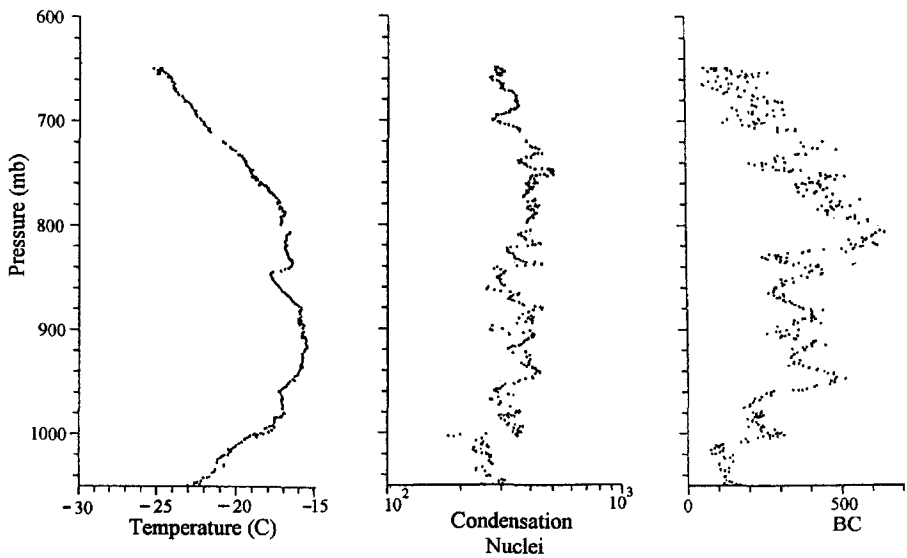

Fig. 3. Vertical profiles of (a) air temperature, (b) CN concentration and aerosol BC concentration (c) for the second outbound descent profile in the vicinity of the New Siberian Islands, flight 4, 10 April 1992. Up to eight layers may be apparent in the BC profile.

4(d)–(f) show the corresponding data for the first profile of the return trip (i.e. in the same general geographic area), taken 200 minutes later. The aerosol data show relatively low concentrations below the 840 hPa level, with a substantial increase above that level up to the top of the profile. Aerosol BC increases from 100–200 ng m^{-3} below, to 800–1000 ng m^{-3} above 850 hPa. The CN count varies by a factor of two to three between these two regimes. The situation is one in which a thick layer of heavily polluted air overlies a deep surface layer of relatively clean air. Note in Fig. 4(d) that a small temperature inversion is displayed at the 930 hPa level, and is reflected in Fig. 4(f) in a small peak in the BC data at that altitude. This may suggest that an intrusion of a

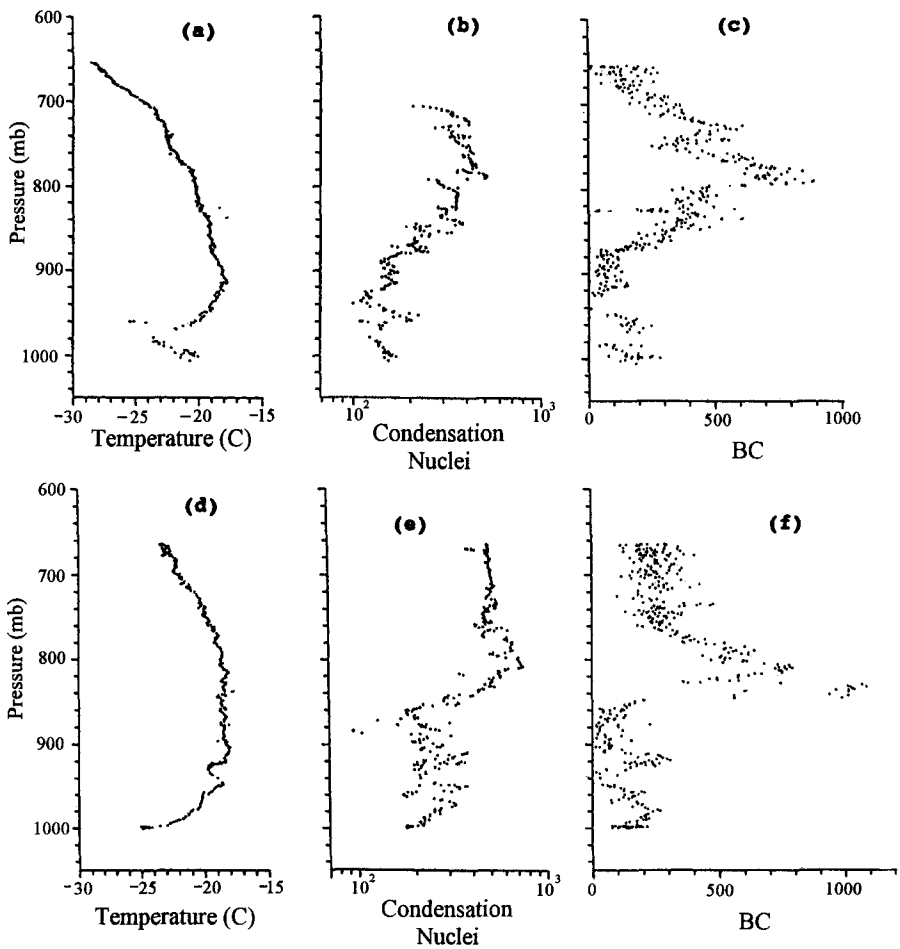

Fig. 4. Two profiles through an air mass exhibiting substantial pollution aloft, taken in the same region (approx. 74°N, 152°E) but separated in time by about 3 hours. The first three panels (a, b, c) are data from the second outbound vertical profile of flight 6 starting at 01:25 Z on 15 April 1992. The second three panels (d, e, f) are data from the first vertical profile of the inbound transit starting at 04:43 Z on the same day.

low-level layer of polluted air had occurred by the time of sampling on the return journey.

4.2.3. Well defined layers

Fig. 5 shows a situation in which there appear to be three or four distinct layers of different aerosol characteristics within the profile. The temperature profile, shown in Fig. 5(a), shows two strong inversions separating the column into three portions: below the 970 hPa level, from 970 to 900 hPa, and above 900 hPa. Closer examination suggests the possibility of a weak inversion at 800 hPa that is reflected in BC, but not in CN. Between the 900 and 800 hPa levels BC concentrations are relatively high (from 300 to 400 ng m^{-3}), and the CN counts range from about 80 to 180 cm^{-3}. Above this altitude, BC concentrations are quite low, while the CN data show variations but no obvious general trend. From 900 to 970 hPa, the CN counts are very low, as are the BC concentrations. From 970 hPa to the surface, the CN counts are below detection while the BC data show a recovery to approximately 150–200 ng m^{-3}. This suggests that these overlaying air masses may have had distinctly different histories, as discussed below.

The lowest layer may be well-aged polluted air in which the remnants of soot remain, while the CN have coagulated and been greatly reduced. The second layer, from 970 to 900 hPa, is cleaner with a few CN and little BC. The layer from 900 to 800 hPa is a deep layer of moderately polluted air, typically 100 CN cm^{-3} and 350 ng m^{-3} BC. Within this layer there is a dearth of larger particles which is coherent if BC is expressing larger particles in a general sense. With fewer large particles there are fewer

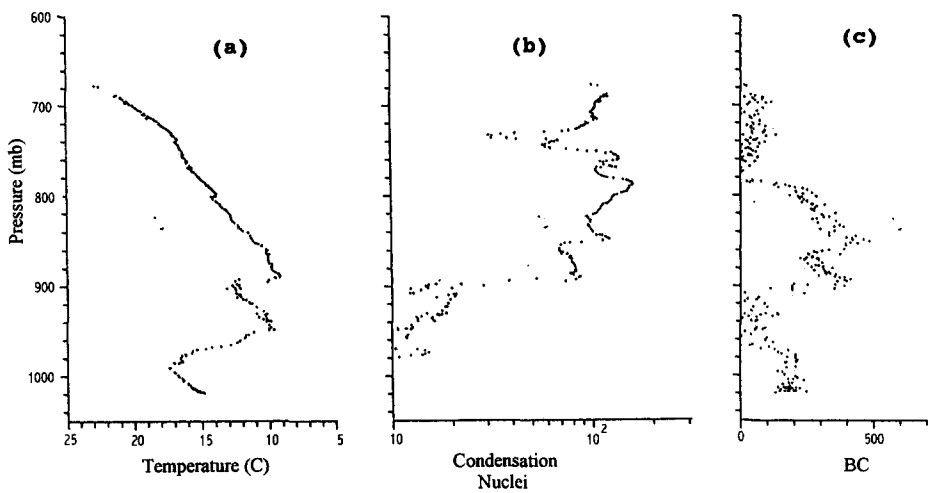

Fig. 5. Data from first vertical profile on inbound transit on flight 5, 12 April 1992, in the vicinity of the New Siberian Islands: (a) air temperature; (b) condensation nuclei concentrations; (c) aerosol BC concentrations. The temperature data show the presence of strong inversions which appear to separate layers of different aerosol characteristics (see text).

collision partners for small particles in coagulation processes and hence relatively high CN concentrations. The uppermost layer, above 790 hPa to the 5 km ceiling, shows similar levels of CN but very low values of BC. This layer might be, for example, a layer of clean marine air rapidly advected from lower latitudes. The temperature data show that the lower air masses are definitely not in equilibrium with a 'standard' mixed scenario, while the uppermost layer (above the 790 hPa level) conforms more closely to the adiabatic lapse rate.

4.2.4. Polluted layer near surface

Fig. 6 shows an observation of polluted air at the very surface, over the ice, 1000 km from the nearest significant habitation. This data represents about 100 minutes of observation starting with a descent from 5 km altitude near Jeannette Island (approximately 200 km to the east of Bennett Island), followed by low-altitude flight to Henrietta Island and thence to Bennett. All three of these islands are uninhabited. The descent profile shows a fairly constant concentration of aerosol species, with small peaks in the BC data at the 880 and 790 hPa levels, possibly mirrored in the CN data. The CN counts are moderate, at around 300 cm^{-3}, and the BC is generally low, at around 150 ng m^{-3}.

The temperature profile shows a conventional adiabatic lapse with a surface inversion below about 1000 hPa. The aerosol data do not show any correlation with the onset of the inversion, but they do show a large range of values at the lowest altitudes, represented by points almost on the x-axes of the plots. In this lowest surface layer, the air temperature showed a range of values from −21 to −25°C, probably representing

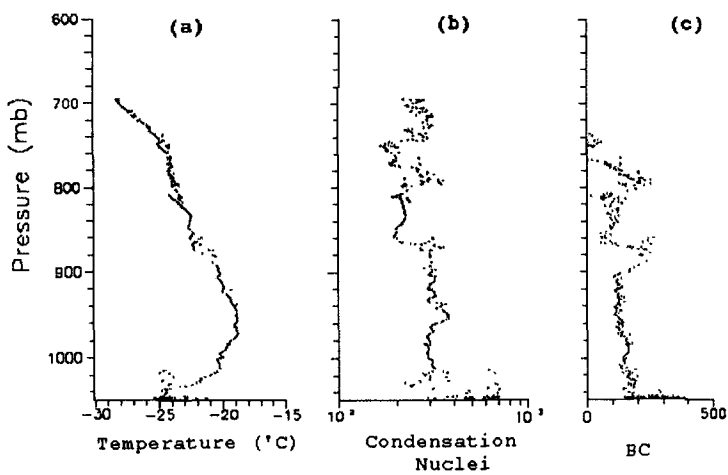

Fig. 6. Illustration of a shallow layer of polluted air right at the surface: (a) air temperature; (b) CN concentrations; (c) aerosol BC concentrations. The data were taken during flight 3, 8 April 1992, combining a descent profile over Jeannette Island (about 200 km east of Bennett Island), followed by low-altitude flying from Jeannette Island, past Henrietta Island, to Bennett Island. The lowest-altitude data accounts for about one-half of the data points in this set. While the higher altitudes are moderately polluted with some slight vertical structure, the surface data show concentrations of CN and BC that are two to three times larger. The closest significant habitation to this region is approximately 1000 km distant.

the variations due to flight over fast pack ice (colder air) or broken ice with leads (warmer air over open water). The CN count ranged from the upper-level median value of around 300 cm^{-3} to a maximum of more than 700 cm^{-3}: the BC concentrations ranged from 150 ng m^{-3} to almost 400 ng m^{-3}. Although these maximum values are not as great as those shown earlier for stronger haze layers (Fig. 4, for example), the data show an example of a very shallow polluted layer right at the surface on the Arctic ice pack. The aircraft was flying at an altitude of approximately 100 m at this time, and we can estimate that this surface layer was probably no more than one to two hundred meters thick.

5. Discussion

The results presented above illustrate the various categories of temperature and aerosol profiles that we observed on this project. In general, the Arctic atmosphere was distinctly polluted. Given the experience of AGASP and other programs in the Arctic, this fact is no longer surprising. However, we note that 'AGASP-IV', operating over the west Beaufort Sea at the same time as this work, encountered relatively little haze. The meteorological situation prevailing in the AGASP-IV study area frequently included an intrusion of marine air in a low-pressure system moving up from the Aleutian Islands through the Bering Strait, effectively displacing the 'haze front' to the north and east of the Alaskan Arctic. These marine intrusions contained less haze aerosol than the air over the Siberian Arctic which was flowing out of continental regions where combustion had recently injected its products.

A value of 300 ng m^{-3} of aerosol BC for the tropospheric column from sea level to 5 km altitude is representative of the data gathered during this project. This yields a total column burden of 1.5 mg m^{-2}. If deposited on the ice, the BC optical absorption cross – section of approximately 10 m^2 g^{-1} would lead to an optical absorption of 0.015 per deposition cycle. Aerosols in the Arctic are believed to have a lifetime on the order of one to three weeks, implying that this deposition cycle is repeated several times during the winter and spring 'Arctic Haze' season. The deposition of BC ('soot') to the ice surface may therefore lead to an accumulated absorption coefficient as high as 0.1 over the season. This is large enough to substantially perturb the surface albedo, and lead to an accelerated absorption of solar radiation when the sun rises in springtime. Similar values for soot deposition from snow measurements were reported by Clarke and Noone (1985). More accurate modeling is needed to determine whether this deposition of black aerosol onto the formerly white snow and ice cover across the entire Arctic north of the average position of the Polar Front (one-sixth of the area of the planet) may lead to a forcing term for global climate change.

We conclude by restating what is now becoming an accepted fact: the spring time Arctic Basin atmosphere is both a transport pathway and a reservoir for high levels of anthropogenic Eurasian air pollution, much of the pollution containing significant concentrations of BC. This pollution may be observed at altitudes from the surface to the stratosphere (AGASP flight data) in concentrations approaching those observed in and near the urban source regions 2000–8000 km upwind.

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It is possible to telephone directly from Anchorage to Cherskiy, via dedicated lines across the Bering Strait connecting Alaska with Chukotka and Yakutia. In this way, a scheduled daily call informed us of conditions as seen by satellite over the Bennett Island area, and allowed for the coordination of sampling between the two aircraft programs. We thank ALASCOM for providing this service.

We thank the NOAA Working Group 8 coordinators, Mr. R. Etkins and Ms. R. Tatusko, for considerable assistance with planning, international arrangements and visas. We thank the pilots and staff of Bering Air, especially Ms. T. Horvath, for extra efforts in transporting us and the equipment between Nome, Alaska and Provideniya, Russia.

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References

Albritton, D.L., 1989. Arctic Haze (combined issue). J. Atmos. Chem., 9 (1–3) (23 papers on Arctic aerosols and air chemistry).

Barrie, L.A., Bottenheim, J.W. and Hart, W.R., 1994. Special section: polar sunrise experiment (PSE 1992). Polar sunrise experiment 1992 (PSE 1992): preface. J. Geophys. Res., 99, No. D12: 25313–25314.Sch

Bodhaine, B.A., 1989. Barrow surface aerosol: 1976–1986. Atmos. Environ., 23 (11): 2357–2370.

Bridgman, R.C., Schnell, G.A., Herbert, G.A., Bodhaine, B.A. and Oltmans, S.J., 1986. Meteorology and haze structure during AGASP-II. Part 2: Canadian Arctic Flights, 13–16 April 1986. J. Atmos. Chem., 9 (1–3): July–October 1989.

Clarke, A.D. and Noone, K.J., 1985. Soot in the Arctic snow pack: a cause for perturbations in radiative transfer. Atmos. Environ., 19 (12): 2045–2054.

Davidson, C.I. and Schnell, R.C., 1993. Introduction: the special issue of 'Atmospheric Environment on Arctic air, snow, and ice chemistry', Atmos. Environ., 27A (17/18): 2695–2702.

Hansen, A.D.A., Rosen, H. and Novakov, T., 1982. Real-time measurement of the absorption coefficient of aerosol particles. Appl. Opt., 21: 3060–3062.

Hansen, A.D.A., Kapustin, V.N. and Polissar, A.V., 1991. Measurements of carbonaceous aerosols in the Eastern Arctic. Izvestiya Akad. Nauk SIR, Fizika Atmosfery I Okeana, 27: 614–620 (in Russian).

Herbert, G.A., Schnell, R.C., Bridgman, H.A., Bodhaine, B.A., Oltmans, S.J. and Shaw, G.E., 1989. Meteorology and haze structure during AGASP-II. Part 1: Alaskan Arctic Flights, 2–10 April 1986. J. Atm. Chem., 9 (1–3) July–October.

Herbert, G.A., Sheridan, P.J., Schnell, R.C., Bieniulis, M.Z., Bodhaine, B.A. and Oltmans, S.J., 1993. Analysis of meteorological conditions during AGASP-IV: March 30–April 23, 1992, NOAA Tech Memo ERL CMDL-5, April.

Iversen, T., 1989. Some statistical properties of ground level air pollution at Norwegian Arctic stations and their relation to large scale atmospheric flow systems. Atmos. Environ., 23 (11): 2451–2462.

Kienle, J., Roederer, J.G. and Shaw, G.E., 1983. A volcanic event in the Soviet Arctic? EOS, 64 (20): 377.

Leaitch, W.R., Hoff, R.M. and MacPherson, J.I., 1989. Airborne and lidar measurements of aerosol and cloud particles in the troposphere over Alert, Canada in April 1986. J. Atm. Chem., 9 (1–3): July–October 1989.

Lowenthal, D.H. and Rahn, K.A., 1985. Regional sources of pollution aerosol at Barrow, Alaska during winter 1979–80 as deduced from elemental tracers. Atmos. Environ. 19 (12): 2011–2024.

Matson, M., 1986. Large plume events in the Soviet Arctic. EOS, 27 (48): 1372–1373.

Rahn. K.A. and McCaffrey, R.J., 1980. On the origin and transport of the winter Arctic aerosol. Ann. N.Y. Acad. Sci., 338: 486–503.

Rosen, H. and Hansen, A.D.A., 1984. Role of combustion-generated carbon particles in the absorption of solar radiation in the Arctic haze (Paper 4L6046). Geophys. Res. Lett., 11 (5).

Schnell, R.C., 1984. Arctic haze and the Arctic gas and aerosol sampling program (AGASP). Geophys. Res. Lett., 11 (29 papers on Arctic haze).

Schnell. R.C. and Raatz, W.E., 1984. Vertical and horizontal characteristics of Arctic haze during AGASP: Alaskan Arctic. Geophys. Res. Lett., 11 (5).

Schnell, R.C., Hansen, A.D.A., Dlugokency, E., Conway, T.J., Polissar, A.V. and Golitsyn, G.S., 1992. Airborne investigation of the Bennett Island Plume, Proc. 5th Symposium on Arctic Air Chemistry Copenhagen, Denmark, Sept. 8–10, 1992.

Worthy, D.E.J., Trivett, N.B.A., Hopper, J.F., Bottenheim, J.W. and Levin, I., 1994. Analysis of long-range transport events at Alert, Northwest Territories, during the polar sunrise experiment. J. Geophys. Res., 99, No. D12: 25315–25329.