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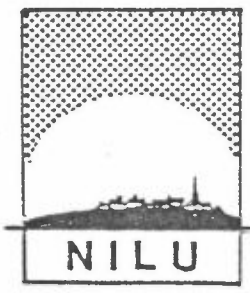

NORWEGIAN INSTITUTE FOR AIR RESEARCH
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NORWEGIAN INSTITUTE FOR AIR RESEARCH
P.O.BOX 130, N-2001 LILLESTRØM
NORWAY

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ABSTRACT

Physical properties, particle size distribution, and chemical composition of the arctic aerosol aloft have been studied to assess the origin of polluted layers of the arctic air. Four measurement campaigns were made with the NILU aircraft during the period March 1983 - July 1984. Evidence of very long range transport of air masses to the Arctic is presented for summer and winter conditions. These polluted air masses are observed at higher altitudes (>1.5 km). The layers of polluted air at lower altitudes are believed to be due to episodes of air mass transport from emission areas with a temperature similar to that in the Arctic in winter, and from local sources in summer. However, further aircraft measurements are needed to support these preliminary results.

LIST OF CONTENT

AIRCRAFT MEASUREMENTS OF AIR POLLUTION IN THE NORWEGIAN ARCTIC

1 INTRODUCTION

The occurrance of turbid layers in the Arctic air was first described by Mitchell in 1956 (Mitchell, 1956). In the 1970s the light reflection and chemical composition of these layers were examined (Shaw and Wendler, 1972; Rahn and Borys, 1977). Later, the trace element composition of aerosol samples has often been used to identify emission areas (e.g., Rahn and MacCaffrey, 1980; Lowenthal and Rahn, 1984; Hopper, 1984; Heidam, 1984). Recently, aircraft measurements have shown that well defined layers of polluted air occur at different altitudes throughout the Arctic troposphere.

These data indicate that the pollution layers are at least partly due to an episodic transport of air pollutants to the Arctic. Based on the measurement campaigns carried out in the Norwegian sector of the Arctic, including aircraft measurements, in August 1983 and March 1984, the origin of the aerosols within the pollution layers is examined. The study is based on the light scattering of the particles, the particle size distribution, the chemical composition, and wind trajectory analyses.

2 EXPERIMENTAL

During the period August 16-26, 1983, 13 flights were made at various altitudes over the Svalbard Archipelago. During the period February 29-March 12, 1984, 12 flights were made.

The NILU aircraft, a 2-engine Piper Navajo, with 7 hours endurance and a travelling speed of 250 km h^{-1}, was equipped with a nephelometer constructed by Heintzenberg and Bäclin at

the Meteorological Institute of Stockholm University, a Knollenberg particle mass spectrometer (PMS) for measuring aerosol number-size distributions (0.09-3.0 μm), a TSI condensation nuclei counter, low and high volume samplers of aerosols, as well as instruments for measuring height, temperature, and dew point. The measured data are reduced and stored in a specially designed computer onboard the aircraft. Using an Omega navigation system, all data are automatically referred to time and position in space. By playing back the memory unit, data displays were produced shortly after each flight.

The chemical composition of the aerosol samples was analyzed for several trace elements by instrumental neutron activation analysis (INAA) at the Instituut voor Nucleaire Wetenschappen, Rijksuniversiteit, Gent. Details about the INAA procedure are given by Schutyser et al. (1978).

Two flights from the August 1983 measurement campaign and one flight from the February/March 1984 campaign have been selected for detailed presentation in this paper. The flight routes are shown in Fig. 1. Wind trajectories at 850, 700 and 500 mb for the flights in August 1983 are given in Fig. 2 (calculated by Harris of the National Oceanic and Atmospheric Administration, USA). Vertical profiles constructed from the nephelometer measurements of σ_{sp} are given in Fig. 3. The particle size distribution was measured each minute along the flight. The measurements cover 4 size ranges: 0.09- 0.195 μm (R_3), 0.15-0.30 μm (R_2), 0.24-0.84 μm (R_1) and 0.60-3.0 μm (R_0). The data are used in two ways. The four size ranges can be joined to form size distribution curves as in Fig. 4 A,B,C. Also vertical profiles can be constructed for the different size ranges (Fig. 5-7), and compared with the corresponding nephelometer data. This information may be used to examine variations in the aerosol composition along the flight route.

Further information was obtained from the measurements of temperature and dew point. Condensation nuclei were measured by the aircraft only in the March 1984 compaign.

3 RESULTS

3.1 Measurements on August 18, 1983

During the August 1983 aircraft measurement campaign only one episode of elevated air pollution concentration was observed. On August 17-18 very high concentrations of Cd and Zn were observed at the Ny Ålesund ground station (NYA). The air trajectories had all passed over the Soviet Union. Of the 10 day back trajectories the 500 mb trajectory started somewhere in Canada, the 850 mb trajectory in the North Atlantic, while the 700 mb trajectory started in the USSR, see Fig. 2

The flight pattern on August 18 is shown in Fig. 1. Measurements were made up to an elevation of 4400 m NW of Spitsbergen. In Fig. 8 some of the measured values have been plotted as functions of time along a vertical projection of the flight track against the land profile. The mountains in this area reach a level of about 1000 m, and generally they end rather steeply in the sea. The short valleys leading out to the sea are often filled with glaciers which have a pronounced effect on the local circulation of the air (glacier wind).

Each 10 min. from take off the position of the aircraft is indicated by a number, which works as a reference to the measured data given in other figures.

The flight started from Longyearbyen (LYR) at 11.55. The wind at LYR was from 270^0 and the wind speed was 12 m/s. The temperature was about $+5^0$C, with a relative humidity (RH) of 80-90%.

The flight profile in Fig. 8 shows values for σ_{sp} and the concentration of the aerosol fractions R_0 (0.6-3.0 µm) and R_2 (0.15-0.30 µm). These are the two fractions which show the most pronounced variation along the track. The elevated aerosol concentrations measured at LYR are due to local sources, and it is characteristic that these also show high concentrations of the finest particles R_3 (0.09-0.195 µm).

Climbing across the Kongsbreen glacier the concentration of R_0 starts to increase at 1500 m, and haze is reported. This situation persists up to 3900 m. The high R_0-values are not, however, observed by the nephelometer which is mainly sensitive to particles in the size range 0.1-1.0 µm. At 1800 m also the R_2-values increase, and this is noted by the nephelometer. Above 3000 m the R_0-values become lower, i.e., there are less particles in the size range 0.6-3.0 µm. The variations of temperature and RH during this ascent are shown in Fig. 9. The mean temperature gradient of 6.5^0C/km shows a stable structure. Passing the Isfjord and climbing to 1600 m, the RH-value decreases from 93% to 83%, indicating a gradually reduced influence from the open sea. At 1600 m the RH-value increases again and reaches 100% at 2500 m, indicating a different air mass, in agreement with the aerosol measurements. Above 3300 m the RH-value rapidly decreases to about 50-60%, indicating that the top of this layer has been reached.

Passing NYA and descending to 2400 m, the RH-value remains low until the level of 3000 m. Then it increases to 70-75% at 2400 m. Flying over the sea northwest of NYA at 2400 m the R_0-values (0.6-3.0 µm) showed a remarkable structure with high peak values on top of a background value close to zero.

At positions 13-14-15 an ascent was made up to 4200 m. The nephelometer shows a very large peak at 3300 m, which is not reflected in the PMS data. Returning to NYA at 1900 m, the R_0

peak values are less pronounced. Descending from 1900 m and landing at NYA, the number of particles is reduced, but increases locally near NYA.

While ascending to 4200 m, see Fig. 9, the RH-value increased to 100%, and the nephelometer gave very high values which were not reflected in the PMS data (Fig. 8). Haze was observed and the nephelometer used is known to react on fog droplets, while the PMS is insensitive to water vapour.

Descending, the RH-value decreased to 60% at 3300 m. At 1900 m it increased again to 70-80%, while the aircraft turned towards land. Approaching NYA from the north and landing, the RH-value and the temperature indicated the lower boundary of the polluted air layer at 1600 m, in accordance with the aerosol measurements.

The aircraft observations show that on August 18 the area was covered by an elevated layer of polluted air. The lower boundary was at about 1600 m, and pollutants from the local emissions in LYR and NYA stayed well below this level. The layer seems to have a more diffuse upper boundary at about 3300 m. Above this boundary the RH-value over the land becomes low, about 50%. Over the sea the RH-values above 2400 m varied. On ascending to 4200 m through haze it showed 100%. On descending to 3300 m, it dropped to 60%. The temperature profiles in Fig. 9 were, however, very similar.

The chemical analysis of samples collected at the station in NYA and the trajectories indicated an intrusion of polluted air from the Kola Peninsula. The NYA station is situated 1.5 km away from the local settlement, and the sampler was turned off when wind direction and the condensation nuclei counts indicated local contamination. These analyses may therefore be representative also for the air above 1600 m, and one would expect the smaller particles to be representative of the long range transport. The particles in the R_0-group (0.6-3.0 µm) may, however, be of a different origin. The R_0-values in Fig.

8 show a patchy structure with high values for 1-2 minutes, i.e., over a distance of 5-10 km. This patchy structure can hardly be the result of agglomeration processes during these long range transport of the layer. It is also remarkable that when the R_0 value increases, this is always due to an increase of the number of particles larger than 2 µm. There is no similar increase of the number of R_0 particles between 0.60 and 2 µm.

A possible explanation may be that these larger particles have been formed by agglomeration of particles which originally were brought into the Arctic at a higher altitude, and now are in the process of being deposited by sedimentation. Admittedly, the sedimentation rate of particles with an equivalent aerodynamic diameter 2-3 µm is low. However, the pronounced stability of the arctic atmosphere and the general subsidence of the air may make a slow deposition of this type possible. Furthermore, the observations indicate that the sedimentation of these larger particles is held up by the polluted layer above 1600 m. Below this level the R_0 value is very low. This may possibly be explained by the radiation ballance. A slight upwards directed radiation is sufficient to establish the necessary lift. The temperature profile around 1600 m supports this view. The boundary at about 1600 m separates 2 air masses of different history. The upper layer which extends to a height of 3500-4000 m represents a polluted air mass. The chemical analysis and the trajectories indicate that most of the pollution has been picked up from industrial sources in the northern USSR. In the course of 4-5 days this air has been transported over a distance of 3000-4000 km, passing north of Spitsbergen to Greenland and back to NYA. During this transport it has retained the moisture picked up outside the northern coastline of the USSR. When passing the polar front, it has been brought up to an altitude above 1600 m. When the air mass arrives in the Spitsbergen area, haze and a RH value of 100% is observed in parts of the layer above 2400 m. Below 2400 m the RH value within this layer varies between 60 and 90%.

When comparing the observed temperature variations in Fig. 9 with the dry adiabat, it is evident that the layer of air below 1600 m has a stable structure. The temperature gradient between 2400 m and 3600 m is close to the dry adiabat, but considering the scattered observations of haze and 100% RH, a moist adiabat seems to be more applicable. This means that the air mass above 2000 m probably has a neutral or even unstable layering. This picture is further complicated by possible influences of topographical features. Thus, the measurements during the ascent in Fig. 9a were made over the Kongsbreen glacier which goes up to 1000 m, while the ascent in Fig. 9b was made off the northern coastline.

This lack of stability in the layer between 2000 and 3500 m does, however, help to explain the possibility of an intrusion of old particles in the size range 2-3 μm from still higher altitudes.

A closer examination of the lower boundary of this layer (Fig. 9b) shows that the temperature first drops, while the RH value increases strongly at 1600 m. Then the temperature increases, while the RH value shows a minimum. A similar shift but less well developed, is observed in Fig. 9a. This temperature variation may be explained by adopting a moist adiabat for the upper layer and a dry adiabat for the lower layer. Although the RH value for the upper layer is less than 100% (no condensation) the layer is polluted with particles which may pick up and give off water at a RH value around 90%. The situation is illustrated in Fig. 10.

If "a" represents the moist adiabat in the polluted and slightly unstable upper layer and "b" the dry adiabat in the cleaner air below, then an air parcel which is moved adiabatically downwards from "p_1", will follow the moist adiabat to "p_2" where it will stop. As the RH value at p_2 is less than at p_1, water will evaporate from the particles. The result is a reduced temperature and an increased RH value just below the

interface. If a particle at p_2 is moved adiabatically into the upper layer it will, however, fall back to its original position. The resulting shape of the temperature and RH curves are indicated in Figure 10. The RH curve is explained by the same mechanism. This explanation is tentative, and further measurements are required to show definitely that this represents a significant feature of the arctic deposition of aerosols.

The size distribution curves in Fig. 4A are all from the polluted layer between 1600 m and 4000 m. They show enhanced volume concentrations for the 0.15-0.25 and >1.5 µm diameter fractions of the particles. Below 1500 m also an increase of the number of the smallest particles is observed, see Fig. 5D.

Generally the size distribution of particles in industrial and urban areas is bimodal, with a minimum at about 2.5 µm diameter (Whitby, 1978; Lee and Goranson, 1976). The size distribution of particles emitted from industrial processes may, however, be different. Thus, the fly ash from coal combustion boilers contains at least two distinct modes, particles of about 0.1 µm diameter, and larger particles with a diameter greater than 0.5 µm (McElroy et al., 1982). About 20 percent of the particulate mass in the stack emissions may be contained in the <0.1 µm mode. Other industries, such as non-ferrous metal smelters and iron foundries also emit particles in these size ranges.

Particles derived from natural sources may also exist in both modes, but are usually found in the larger mode (>2.5 µm). During long-range transport, these particles are to a large extent deposited. Their occurance is therefore usually ascribed to local sources (soil components, sea spray). During air transport over sea surfaces gaseous components from biological activity may, however, be converted to particles and result in a growing of the finest particles by coagulation. This process will be much more important in summer than in winter when the ice is a natural obstacle for emissions from the sea.

The very high volume concentrations observed in the vicinity of LYR and NYA are due to local emissions. Above 1500 m the concentration of the very smallest particles is low, indicating little production of new particles. The increasing number of particles in the size range 2-3 μm is probably, as explained earlier due to an intrusion of old material from higher levels.

3.2 Measurements on August 25, 1983

The purpose of this flight was to examine the influence of local sources at Spitsbergen on the Arctic air pollution and the flight was made at altitudes not exceeding 1500 m.

The emission sources at Spitsbergen consist of the five towns Longyearbyen (LYR), Barentsburg, (BBG), Pyramiden (PYR), Sveagruva (SVA) and Ny Ålesund (NYA) (see Fig. 1). The last is now a research center. LYR is the administration center with an international airport. In summer the traffic of fishing vessels, supply ships, and tourist liners also represent significant sources of air pollution.

The flight on August 25, 1983 started from LYR at 11.28. The temperature was about + 8.5^0C at LYR and the atmospheric stabiity was $\approx 6^0$C/km. The wind had a strength of 3 m/s from 330^0. The flight route is shown in Fig. 1b. The wind trajectories in Fig. 2b show that the trajectories at 500 and 700 mb had passed Alaska 6 days earlier, while the 850 mb trajectory has used 4-5 days from the eastern part of the USSR.

In Fig. 11A and B the nephelometer values and the R_0 and R_3 fractions have been plotted along the flight track in a vertical projection.

The highest nephelometer values were measured just after take off at about 70 m above sea level. This value is no doubt due

to emission of particles from LYR. The PMS data, however, indicated a peak only for the R_0 range of particles, (0.60-3.00 μm). The sources may be (1) the coal separation plant at LYR (2 chimneys of 35 m and 10 m), (2) the coal fired power plant (rather less significant because the plant is equipped with scrubbers and multicyclones), and (3) sea salt particles. The RH-value was almost 100%. The highest value of the nephelometer data and the highest concentration of the R_0 particles were observed when the aircraft was passing over the Isfjorden between LYR and PYR.

Climbing to an altitude of 1200 m a temperature inversion was observed indicating the upper limit of the boundary layer, (see Fig. 12). Turning back, descending and passing PYR at altitude 950 m, the nephelometer, the R_0 and the R_3 values show small peaks, probably due to the emissions from PYR (a coal mine with a production of 0.25×10^6 t/y), see Fig. 6 and the particle size distribution C in Fig. 4b.

The aircraft then made 3 passes along the Isfjord (to and from). The first pas was made out the fjord at elevation 950 m on the northern side. The RH value was about 75%. The first flight in the fjord went along the southern side and showed RH values close to 100%. The wind direction of 330^0 (across the fjord) may explain this by a descent of the air on the northern side and an ascent on the southern side. The nephelometer values were low, but the particle size spectrum showed enhanced concentrations of particles for R_0 and R_3. The second flight, back in the Isfjord was made at 500 m. The nephelometer data were low, no indication of peaks. The temperature was rather constant and the RH values were 70-80%. The particle size spectrum showed a high concentration of the smallest particles R_3 and the R_0 value showed some peaks, probably due to emission from the coal fired power plants at BBG, LYB and PYR. The last passing out the Isfjord was at 240 m. The nephelometer data were extremely low. The temperature was somewhat higher, and the RH value slightly lower. Enhanced concentrations of the smallest particles R_3 were noticed, but

lower than during the second flight (at 500 m). The R_0 values showed peaks when passing the mining towns.

Passing reference point 15, the aircraft turned in the direction of Bellsund at constant level 250 m, see Fig. 11b. The flight was continued at this level to the area of SVEA. The R_0 and R_3 values peaked when passing over van Mijenfjorden. Elevated concentrations were also noticed for fraction R_0 when passing the SVEA area (mining, diesel oil power plant using 2000 m^3/year). The RH value was around 90%.

Ascending to 550 m, the aircraft turned back over SVEA and passed out the van Mijenfjord. The nephelometer and all particle fractions except R_1, showed peaks when passing south of BBG.

For the first time during the flight high values were observed for the R-2 fraction. The RH increased to about 95%. Turning back to LYR across the inland, peak values of R_0 were observed at BBG and LYR.

The sharp maxima in the σ_{sp} values of Fig. 3b represent thin layers of polluted air from the local sources indicated. Generally, the air is very clean and the σ_{sp} values were approximately 3 times lower than the σ_{sp} values measured during the the flight on 18 August.

The size distribution curves in Fig. 4b show the familiar characteristics, large local production of the smallest particles in group R_3, a maximum in the range 0.15-0.25 µm, and considerable production of particles in the largest group (R_0) near the sources.

3.3 Measurements on March 3, 1984

During the flight on March 3, 1984, measurements were made at various altitudes up to 5000 m. During this flight high volume

samples were collected at three different altitudes: 800, 2200 and 4700 m. (Unfortunately, no high volume samples were collected during the August 1983 measurements). The vertical profiles of σ_{sp} in Fig. 3c show an elevated pollution layer between 1300 and 2700 m with a peak concentration at 2000 m. A second layer of polluted air was observed below 1000 m. This was at least partly due to local sources.

The flight pattern is shown in Fig. 1c. The aircraft started from LYB at 12.28. The temperature was about -26^0C at LYR and the atmospheric stability was $\approx 6^0$C/km. The wind had a strenght of 0.7 m/s from 300^0.

In Fig. 13 the nephelometer values and the R_3 fractions have been plotted along the flight track in a vertical projection.

Temperature inversions were observed between the altitudes 130-280 m and 850-1500 m when climbing over Isfjorden to 5000 m, see Fig. 14.

While climbing, the RH value increased from 22% after the second inversion layer, to 50% at the level of 3900 m (reference point 3).

The nephelometer showed 2 marked peaks, at 130 m just after start and at 2200 m. The first peak was reflected in all size fractions of particles, even for R_1 which is unusual, and indicates local emissions from LYR (2 minutes after start). The second peak at 2200 m was clearly reflected in the size fractions R_0 and R_2. It also showed up with a small peak in fraction R_3, the smallest particles.

When the aircraft reached the level of 5000 m, reference point 4, the RH had increased to 62%, but no peakes were observed. It must be admitted, however, that the DP temperature at this level has reached the lowest value to be measured by our equipment. There is good reason to believe that the real DP

temperature at the level of 5000 m was lower resulting in lower RH values. Passing over Wijdefjorden at constant level 5000 m, enhanced nephelometer values, but rather low particle concentrations in all fractions, were observed. The RH value was constant. When the aircraft turned westward at the end of Wijdefjorden in northern Spitsbergen and descended to 1800 m, the RH value decreased to 22%. Then it increased to 45% at 870 m, and decreased again to 28% at a level close to the sea (ice). Later it went up again to 45% at the level at 870 m.

This shows that the inversion layer between 180-870 m was similar to that over Isfjorden. The nephelometer data peaked at the level of 2100 m. This peak is also seen in the 2 smaller particle size fractions R_2 and R_3. The two other fractions showed enhanced concentrations, but no peaks.

Then the aircraft continued westward over northwestern Spitsbergen and further out over the sea (ice) at a constant level of 870 m. The RH values were rather constant, and very high nephelometer values were observed all the time, with a peak quite far from the shore (point 14). The size spectrum showed very clear peaks in all fractions, even R_1, which is unusual in winter. These observations indicate that there was a pollution layer at 800-900 m. The chemical composition indicated pollution of anthropogenic origin from an area with non-ferrous metal production. The large particles (R_0) at this altitude, are probably due to natural sources, not too far away. One possibility may be a coagulation of ice nuclei with co-existing primary particles of anthropogenic origin.

Then the aircraft first descended to 200 m, then it climbed to 5200 m and went back at this level to the end of Woodfjorden. The nephelometer showed rather low values as did the concentrations of the size fraction R_0, R_2 and R_3. Analysis of the HV-sample collected, showed a mixture of natural and anthropogenic pollutants, which could be due to very long range transport of pollutants from several emission areas.

Then the aircraft turned back again, descended to 2300 m, and passed at this level to the islands Nordvestøyene. The RH value decreased to 45%, and the nephelometer data show clearly elevated values, as observed earlier at this altitude over Wijdefjorden. Elevated concentrations were also noticed for the fractions R_3, R_2 and R_1.

The last part of the flight back to LYR was made at a constant level of 2300 m. The RH values over the land were between 45-50% and increased to 60% when approaching LYB. The nephelometer data were quite constant and enhanced. Elevated concentrations were measured for the fractions R_3, R_2 and R_1.

Some particle size distributions from the 3 March flight are shown in Fig. 4c. The absence of particles in the size range R_3 indicates that there is little or no production of new particles in the winter aerosol (Joranger & Ottar, 1984). The high particle concentrations at altitudes below 2700 m (curves a, b and c) are probably due to long range transport of air pollutants, at low level from source areas with about the same potential temperature as the Spitsbergen area (e.g., Iversen, 1984; Ottar and Pacyna, 1984).

An examination of the meteorological maps on March 3, 1984 indicates transport of polluted air from the Kola Peninsula to the Norwegian Arctic. As the thermal coagulation process is less effective in winter, the arctic winter aerosols may have a similar size distribution as the particles in the source area. Indeed, the size distribution of the arctic aerosol below 2700 m (Fig. 4c) shows concentration peaks in the 0.15-0.5 µm range, which likely are due to the emissions of pollutants from fuel combustion and copper-nickel smelters in the Kola Peninsula. The enhanced concentrations in the >1.5 µm fraction may be due to emissions from natural sources, such as a windblown dust from the Eurasian continent.

The contribution to the 0.15-0.5 µm fraction of the arctic winter aerosol is less significant at high altitudes (see curve d in Fig. 4c). The different size distribution of particles measured at 4700 m suggests that the aerosols measured during the 3 March 1984 flight at altitudes below 2700 and at 4700 m have different origins. The size distribution of the latter is similar to that of the aerosol at high altitudes during summer. Thus, the concentration peak at 4700 m shown in Fig. 3c may be due to very long range transport of pollutants over several thousands of kilometer.

Chemical composition of the aerosols

The chemical composition of aerosols measured during the 3 March flight is presented in Fig. 15. The sample collected at 800 m consists of several pollutants of anthropogenic and natural origin. The antropogenic group includes V, As, Cd, Sb, Au, Cu and partly Mn, Co, and Zn. A very high concentration of 1270 ng/m^3 was observed for Cu. For comparison, Wiersma and Davidson (1984) have reviewed trace metal concentrations in the atmosphere of remote areas and found the value of 110 ng/m^3 in the rural area of Arizona as the highest one (after Mayers et al., 1977). The average concentration in Sudbury, Ontario was 371 ng/m^3 but fell to 120 ng/m^3 in 1973 after the installation of a very tall stack at the largest smelter in the area (Barton et al., 1975). Kretzschmar et al. (1977) have indicated a mean concentration of 130 ng Cu/m^3 (range 20 to 3925 ng/m^3) in Liege, Belgium.

The Cd concentration was higher than the highest level previously observed at the NYA during episodes with air pollution from the Soviet Union.

The Au concentration was higher than the levels observed in the air over several industrial areas, see Rahn (1976), and similar to the Au concentrations in the air over the heavily polluted Katowice region in Poland (Tomza, 1984).

When enrichment factors for the elements presented in Fig. 15 were calculated with Sc as reference element and crustal rock as reference material, unusually high values were again obtained for Cu, Au and Cd, being 6400, 14300 and 10000, respectively.

The high concentrations and enrichment factors of Cu, Au and Cd measured at 800 m during the 3 March 1984 flight, indicate transport of polluted air from areas with copper smelters to the Arctic. Two large complexes of copper-nickel metallurgy are located on the Kola Peninsula with an annual production of 65.10^3 tons Ni and 75.10^3 tons Cu (NILU, 1984). This strongly supports the idea that low-level transport of air pollutants from the sources on the Kola Peninsula to the Norwegian Arctic takes place during the winter. Concentrations of other elements emitted during the copper-nickel production, such as, As and Sb were also high.

The naturally derived elements Cl, Sc, and Fe were at the same levels as observe during the March 1983 episode of long range transport of pollutants from the Soviet Union to the Norwegian Arctic (Pacyna et al., 1984).

The concentrations of anthropogenic trace elements measured at 2200 m were lower than these at 800 m. The elements As, Sb, Sm and Au were at the level of detection limit.

The chemical composition of aerosols measured at 4700 m differs significantly from that of the aerosol collected at 800 m. Aerosols at higher altitudes consist mainly of elements from natural sources, such as Cl and Br from sea sprays and Sc, Ti and Fe from windblown dust erosion. The concentrations of these elements are higher in samples at 4700 m than in samples at 800 m (except Sc). The anthropogenic pollutants are found in the former sample, however, their concentrations are very low.

The chemical composition of the aerosols at 800, 2200 and 4700 m seems to support the suggestion that the layers of polluted arctic air observed at higher altitudes during winter are due to very long range transport of pollution. This transport may originate somewhere on the North American continent, pass over Europe, the USSR and continue to the Arctic. As in summer, these warm air masses will be lifted to higher altitudes when passing the polar front. As the temperature difference between air masses from lower latitudes and the arctic air is larger in winter, the pollution layers in winter can be expected at higher altitudes. The present data seem to confirm this explanation.

4 CONCLUSIONS

Information on the scattering coefficient, the particle size distributions, and the chemical composition of the arctic aerosol, obtained from the NILU aircraft measurements, has shed light on the origins of the pollution layers in the arctic air. Very long range transport of air masses over several thousand kilometers, seems to affect the quality of the arctic air both in summer and winter. Polluted air masses carrying a mixture of anthropogenic pollutants from various sources in different locations, has been identified in the Arctic at altitudes from 1.5 to 4-5 km. The altitude of these polluted air layers is higher in winter than in summer, due to the larger temperature gradients between the arctic air and the air at lower latitudes in winter.

The layers of polluted air at altitudes below 1.5 km can be related to episodes of air mass transport from sources situated in areas with temperatures similar to that of the Arctic, e.g. in the Northern Soviet Union. Also the effect of local sources are observed within this layer. The long range transport is a dominating feature in winter, but less so in

summer. Both anthropogenic and natural pollutants from local sources may contribute to the layers of contaminated air at lower altitudes.

The results obtained from the three flights discussed here, are supported by the data from other flights during the August 1983 and February/March 1984 measurement campaigns. The key to our understanding of the arctic air pollution situation is the high thermal stability and lack of turbulance throughout much of the arctic atmosphere in winter, the reduced influence of natural sources due to the ice and snow cover, and the radiation conditions.

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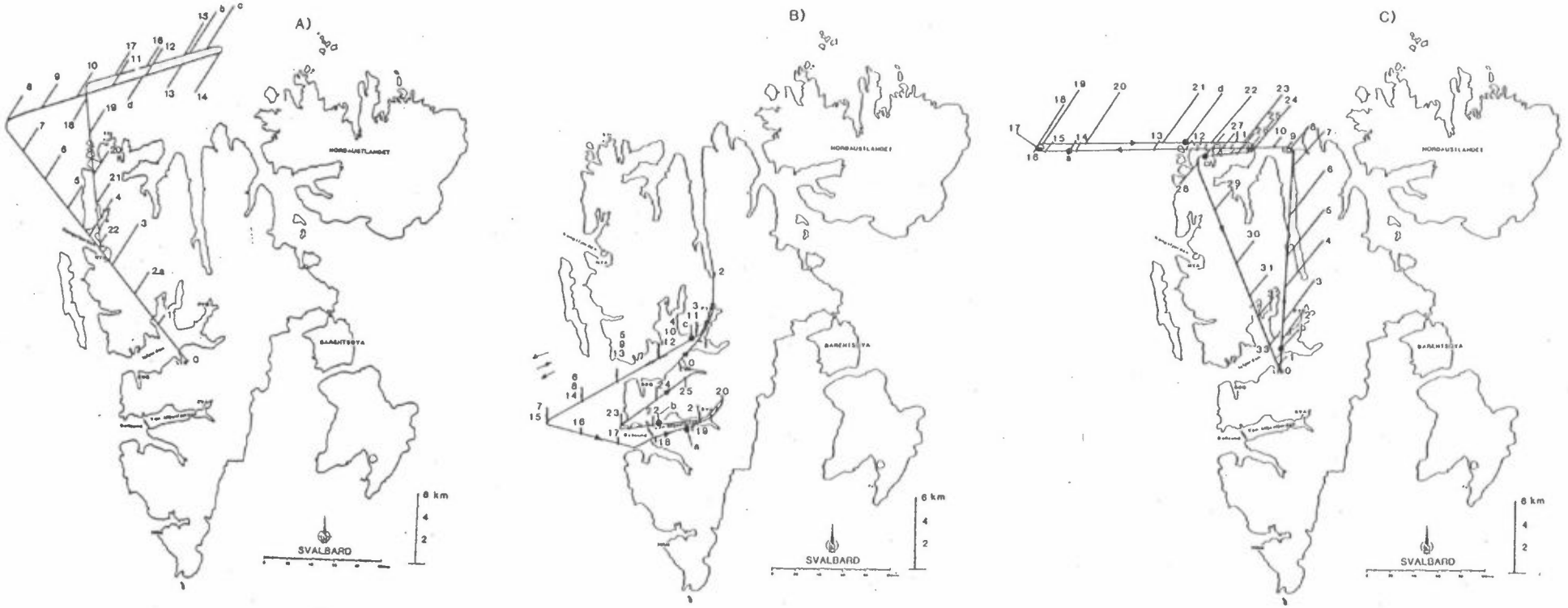

Fig. 1: Aircraft routes in the Norwegian Arctic during the NILU measurement campaigns.
A) 18.08.1983
B) 25.08.1983
C) 03.03.1984

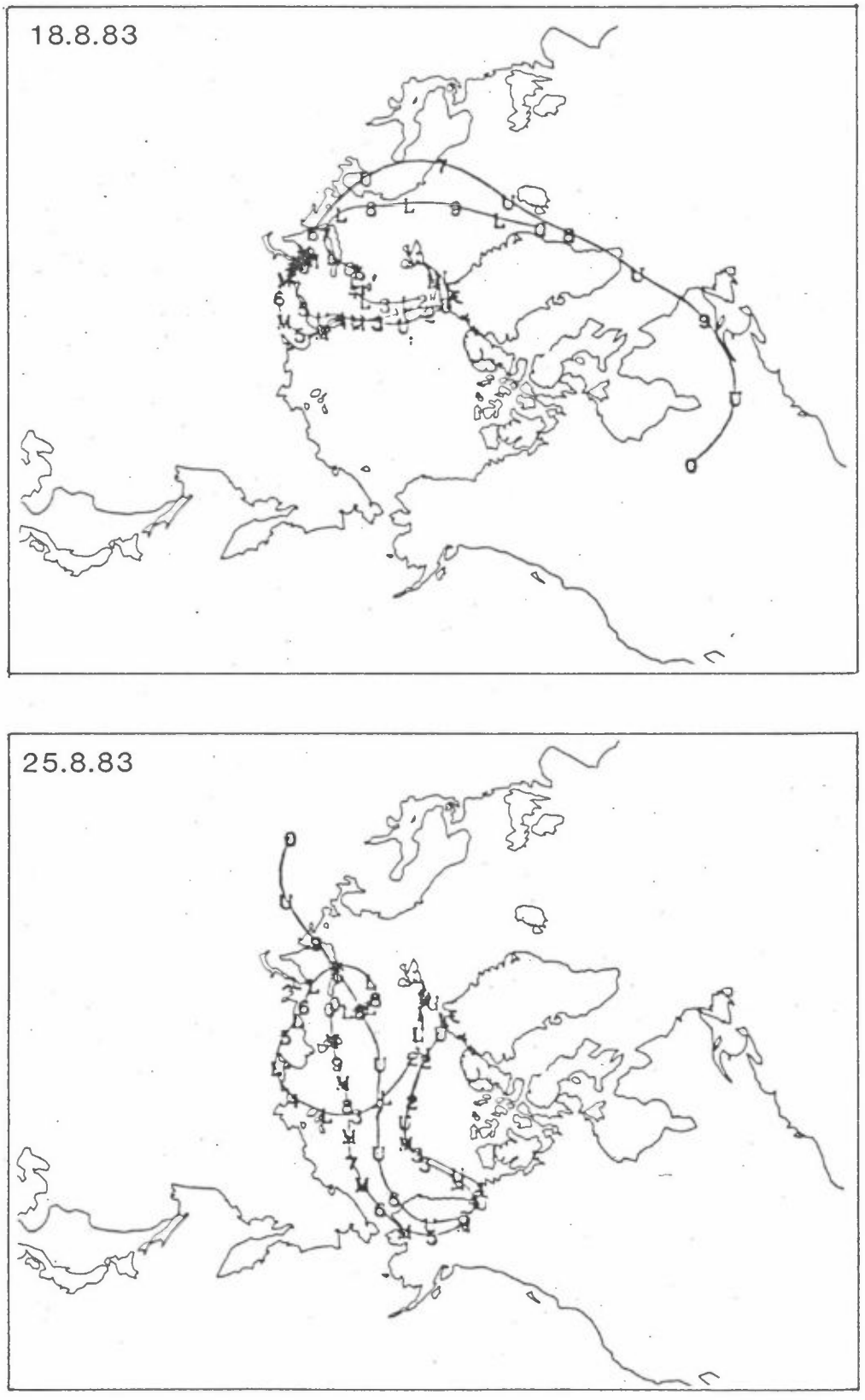

Fig. 2: Trajectories arriving at Ny Ålesund (78.93N, 11.88E)
L: 850 mb M: 700 mb U: 500 mb

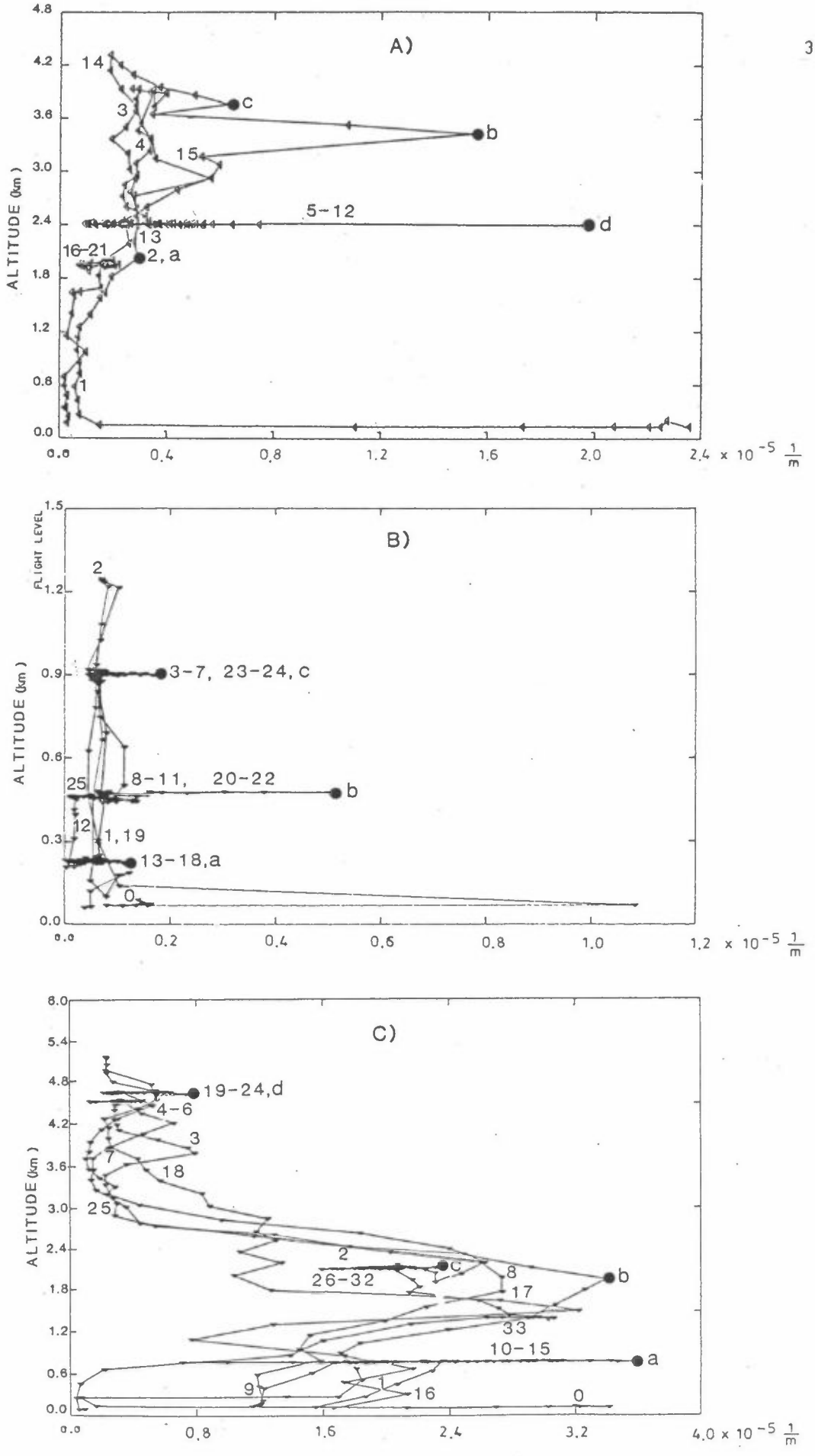

Fig. 3: The σ_{sp} values vs. flight levels during the flight in August 18, 1983 (A), August 25, 1983 (B), and March 3, 1984 (C).

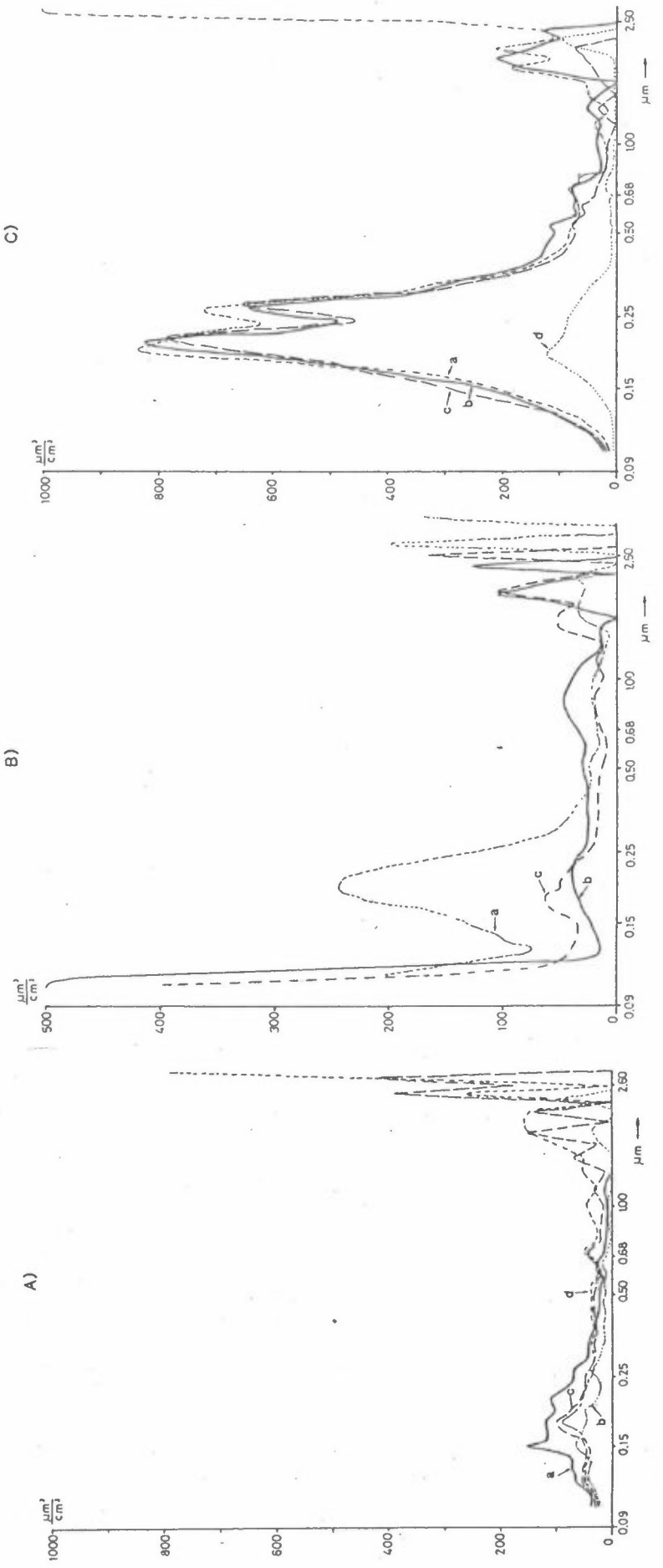

Fig. 4. Volume concentration of particles vs. particle size at different layers during the flights in August 18, 1983 (A), august 25, 1983 (B), and March 3, 1984 (C).

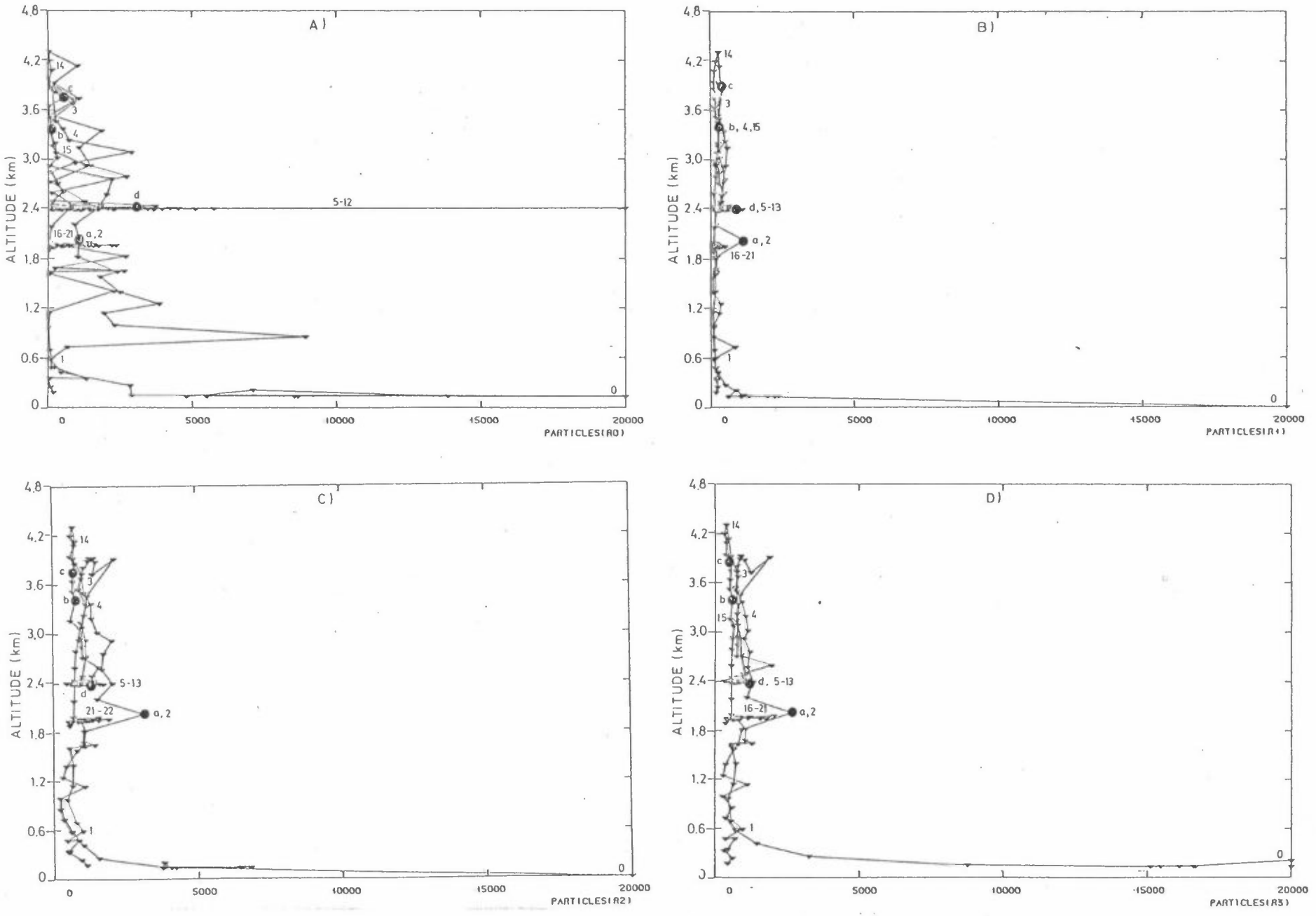

Fig. 5. Vertical profile of number concentrations of particles $(\frac{1}{cm^3})$
A) particles in the range 0.60-3.0 μm (R_0)
B) particles in the range 0.24-0.84 μm (R_1)
C) particles inthe range 0.15-0.30 μm (R_2)
D) particles in the range 0.09-0.195 μm (R_3)

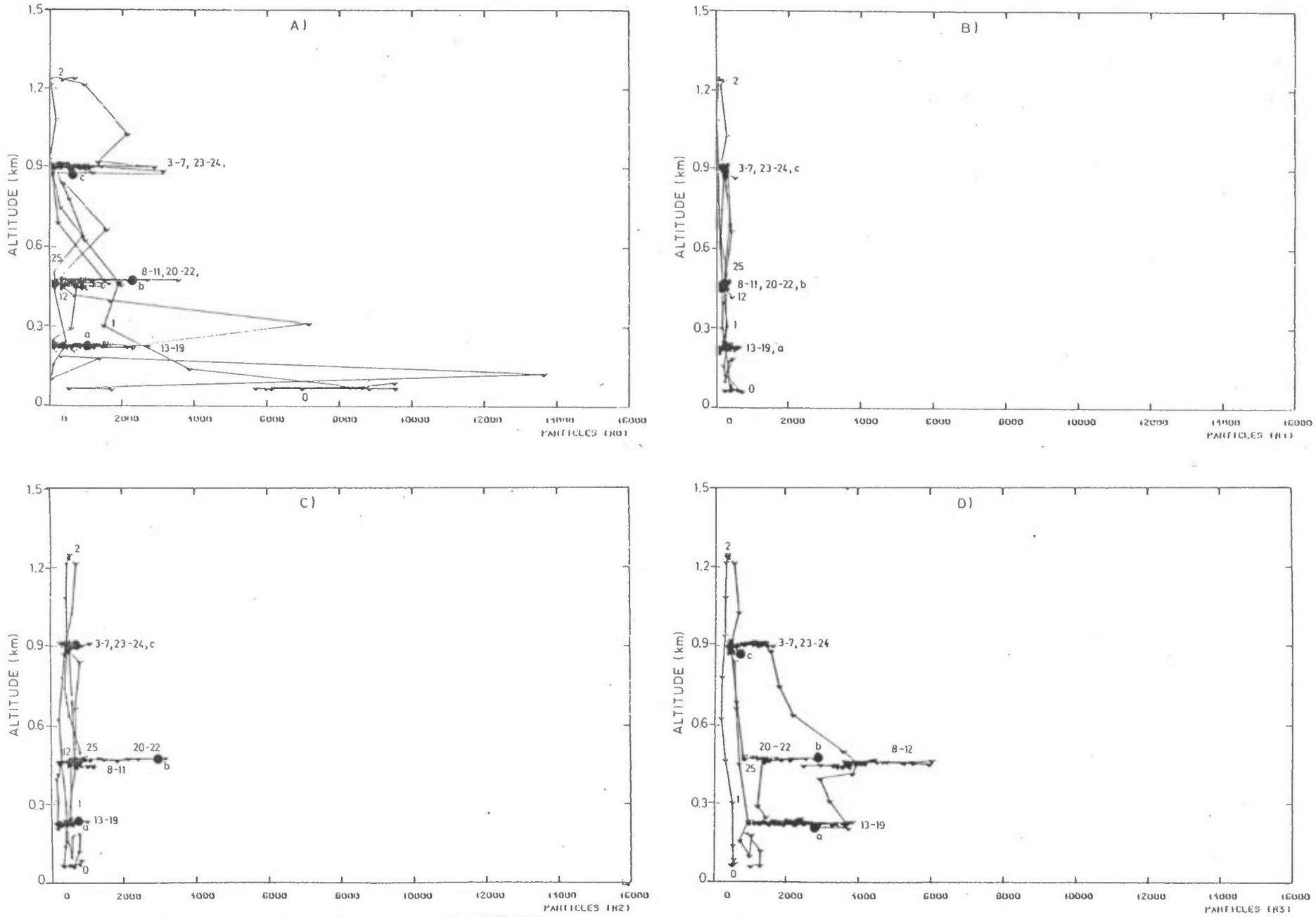

Fig. 6. Vertical profile of number concentrations of particles $(\frac{1}{cm^3})$ during the flight on August 25, 1983.
A, B, C, D as in Fig. 5

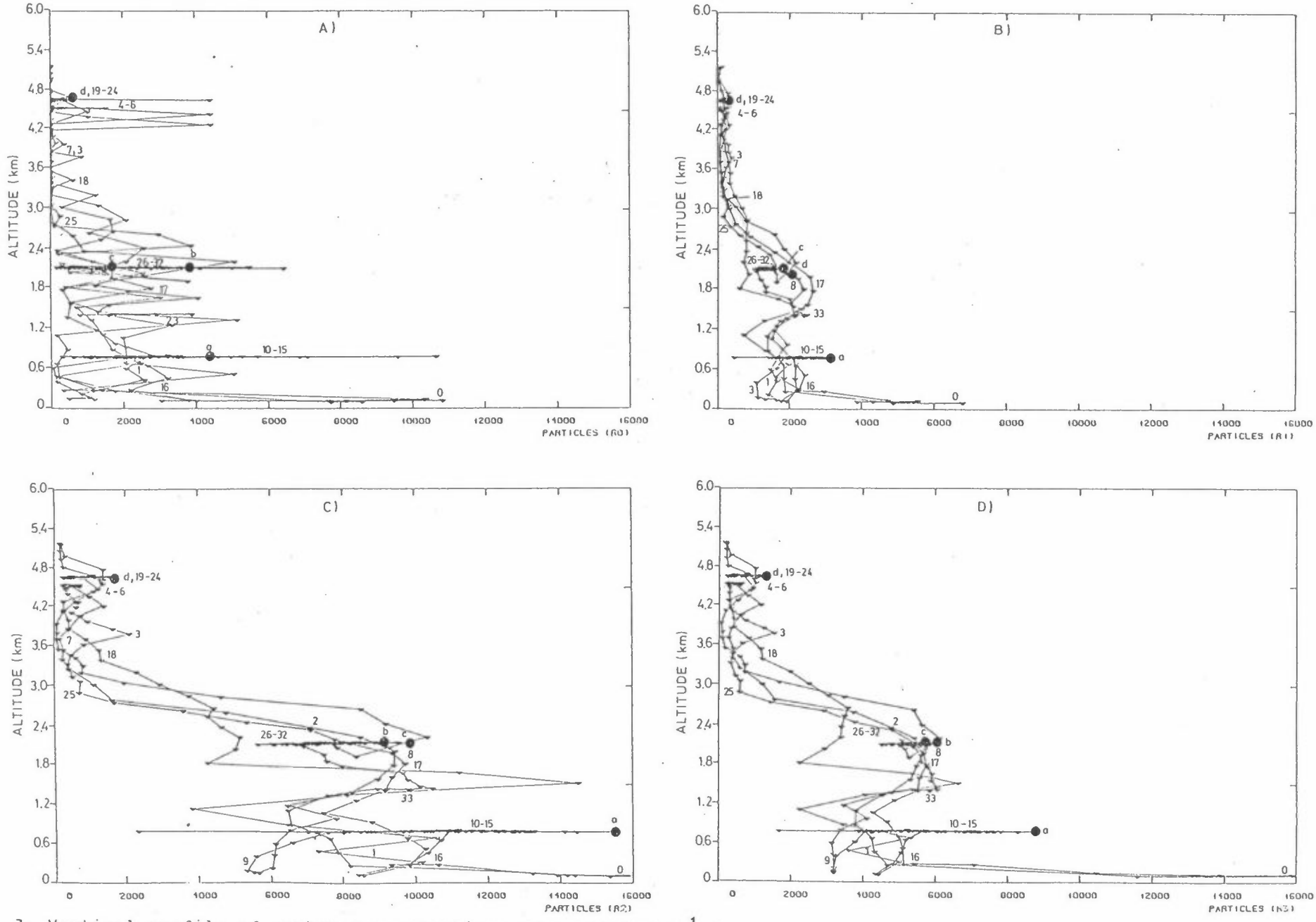

Fig. 7. Vertical profile of number concentrations of particles ($\frac{1}{cm^3}$)

during the flight on March 3, 1984.

A, B, C, D as in Fig. 5

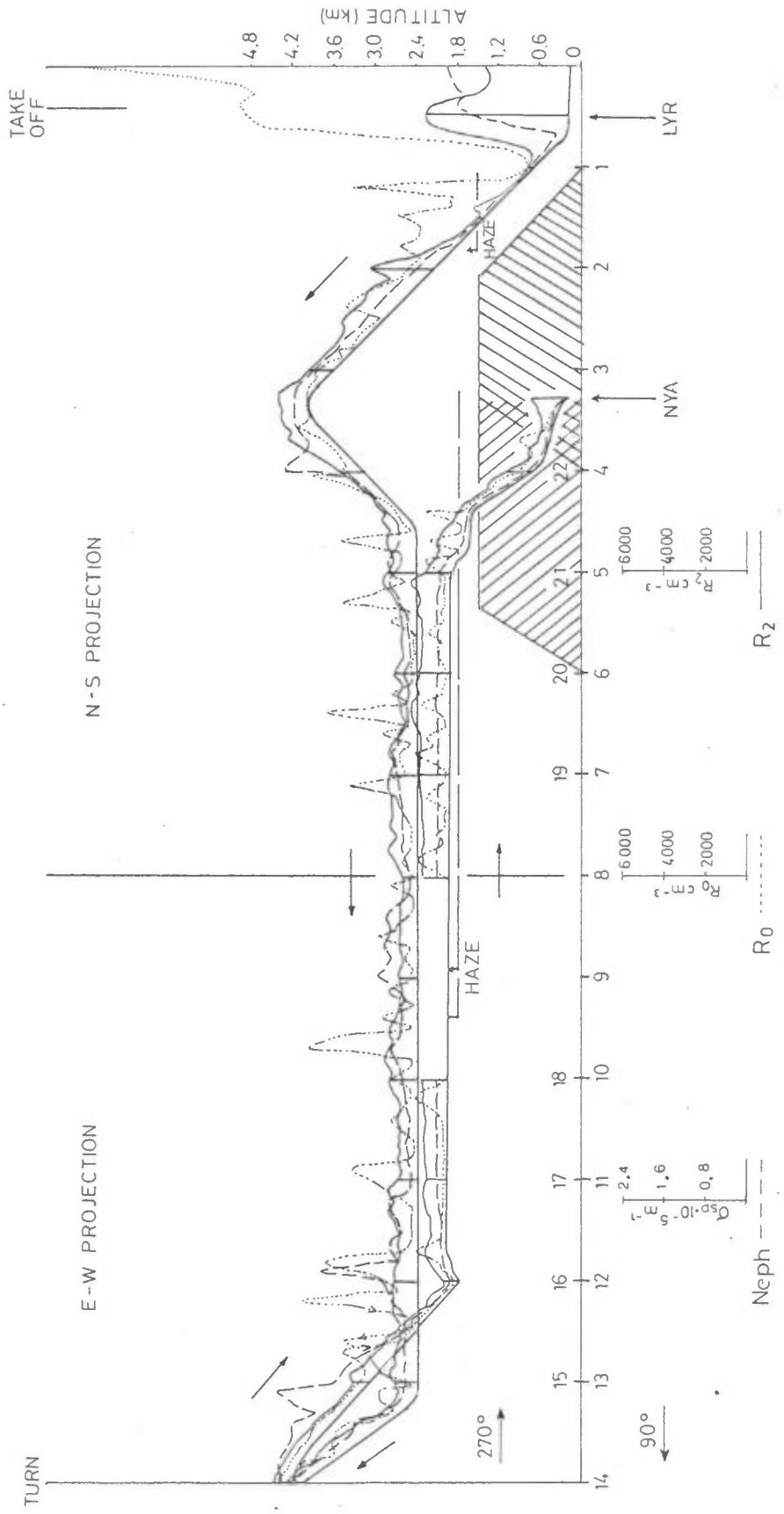

Fig. 8. Vertical projection of the August 18 flight track vs. the land profile.

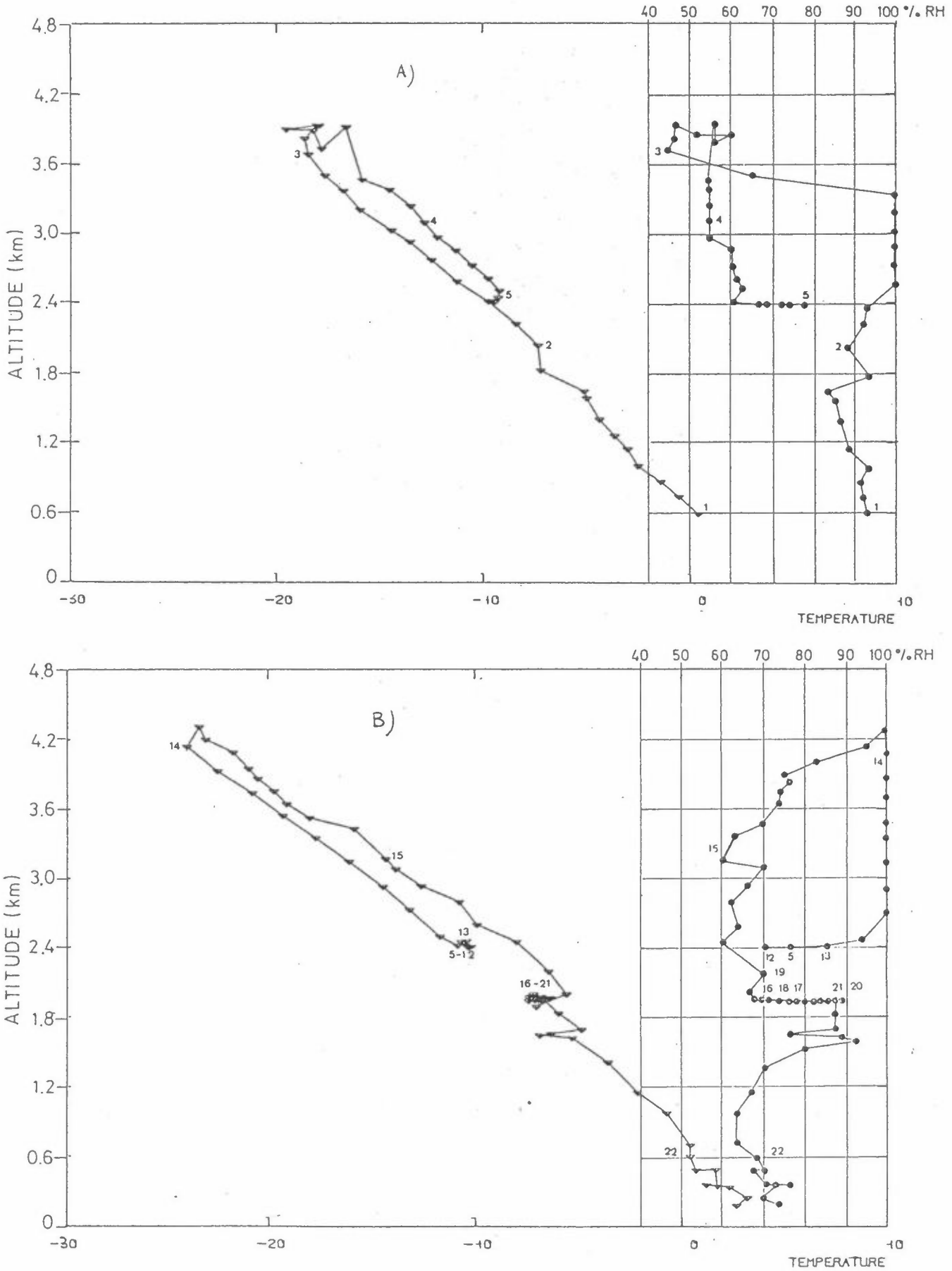

Fig. 9. Vertical profile of air temperature and relative humidity during the flight on August 18, 1983.

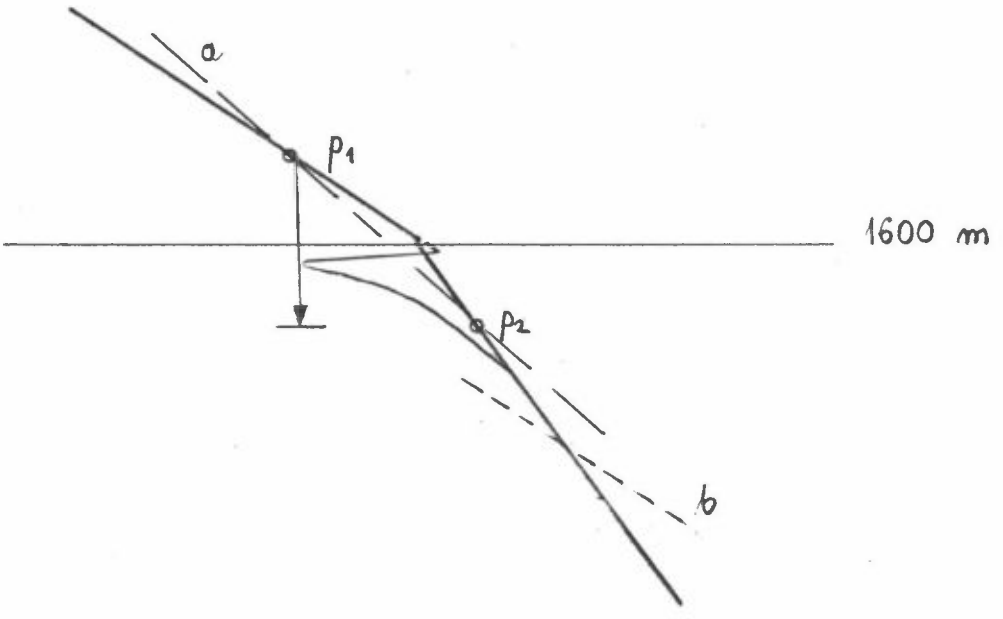

Fig. 10. The temperature curve at the lower boundary of the layer of polluted air during the August 18, flight.

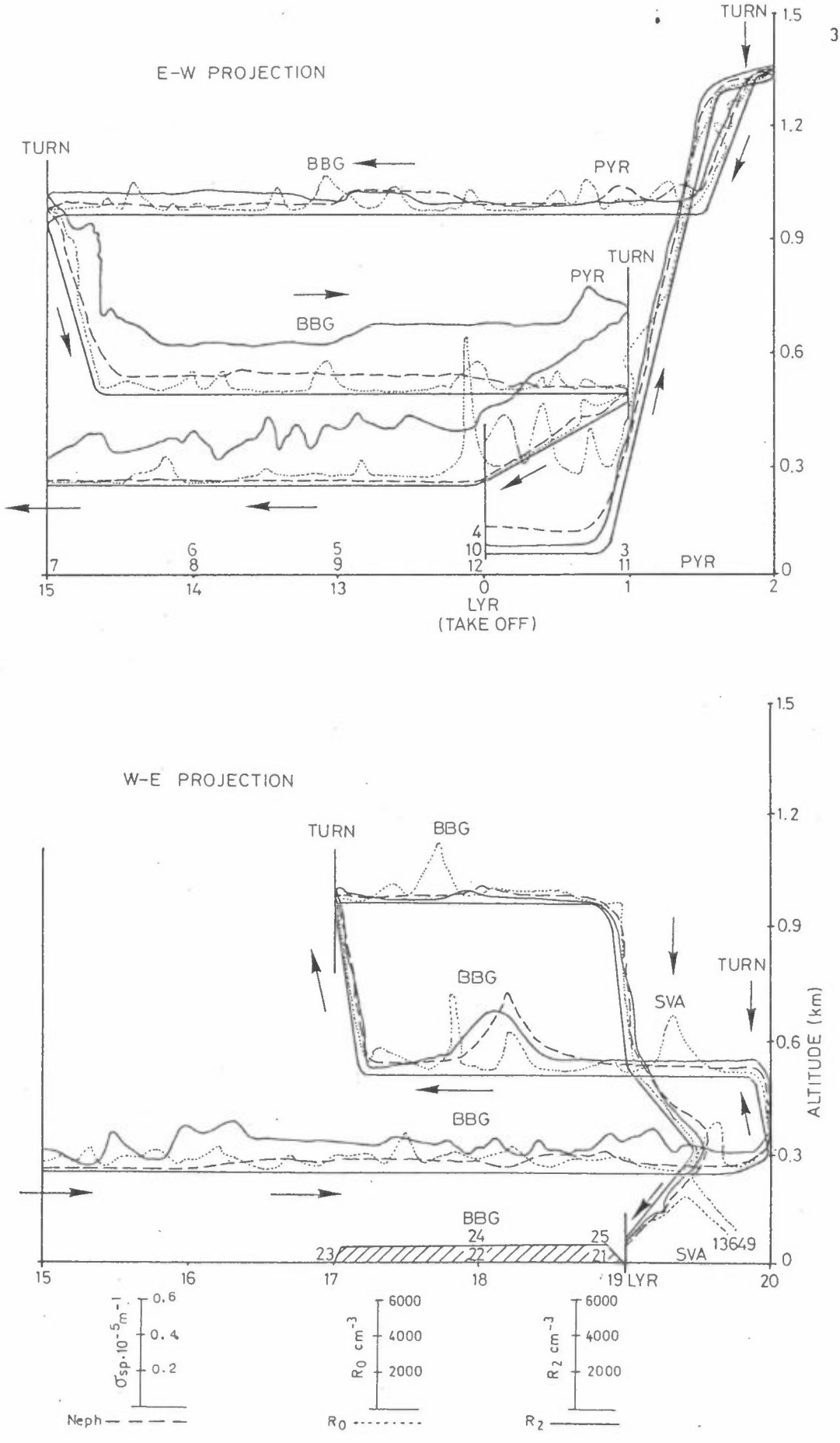

Fig. 11. Vertical profile of the August 25 flight track vs. the land profile.

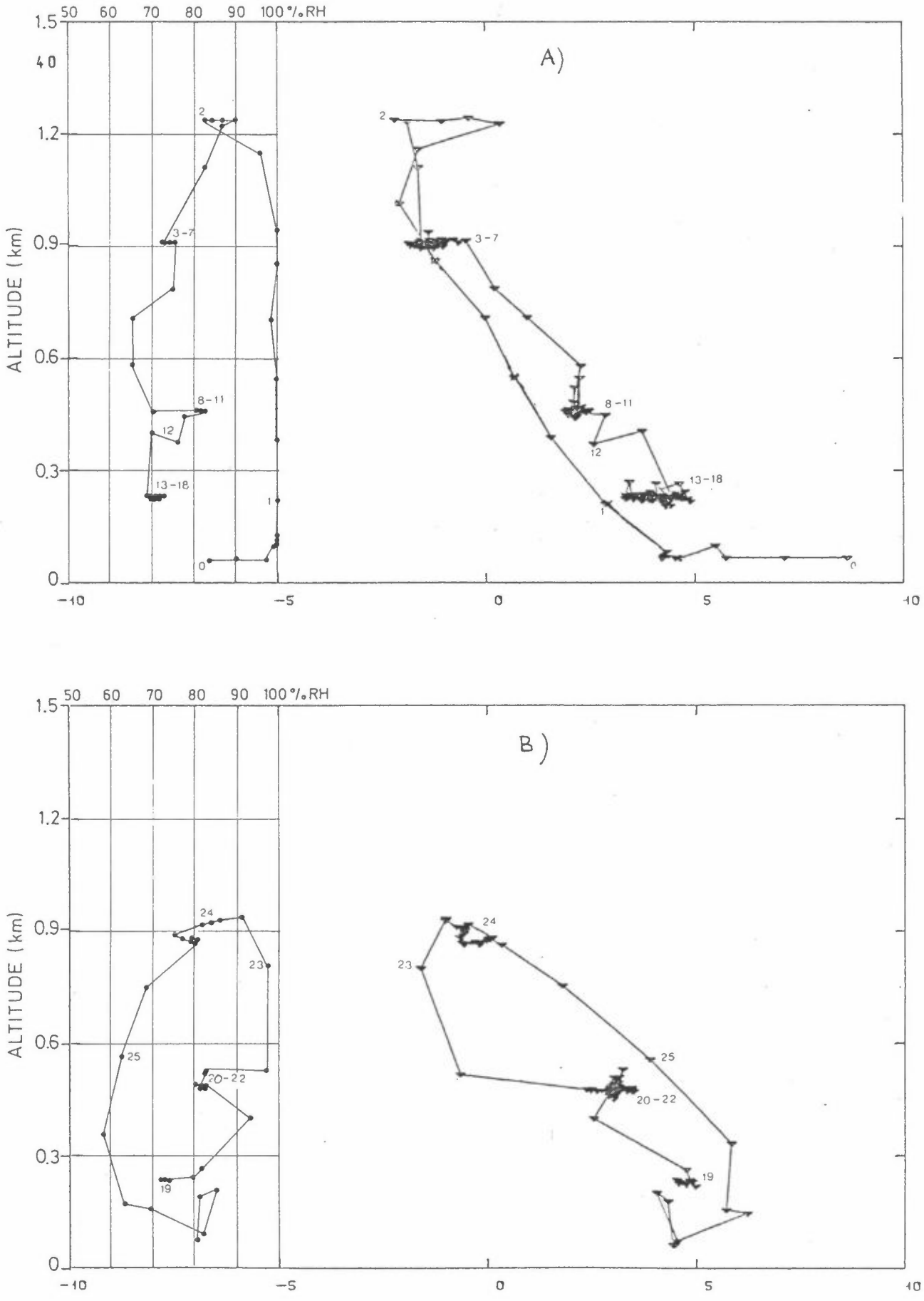

Fig. 12. Vertical profile of air temperature and relative humidity during the flight on August 25, 1983.

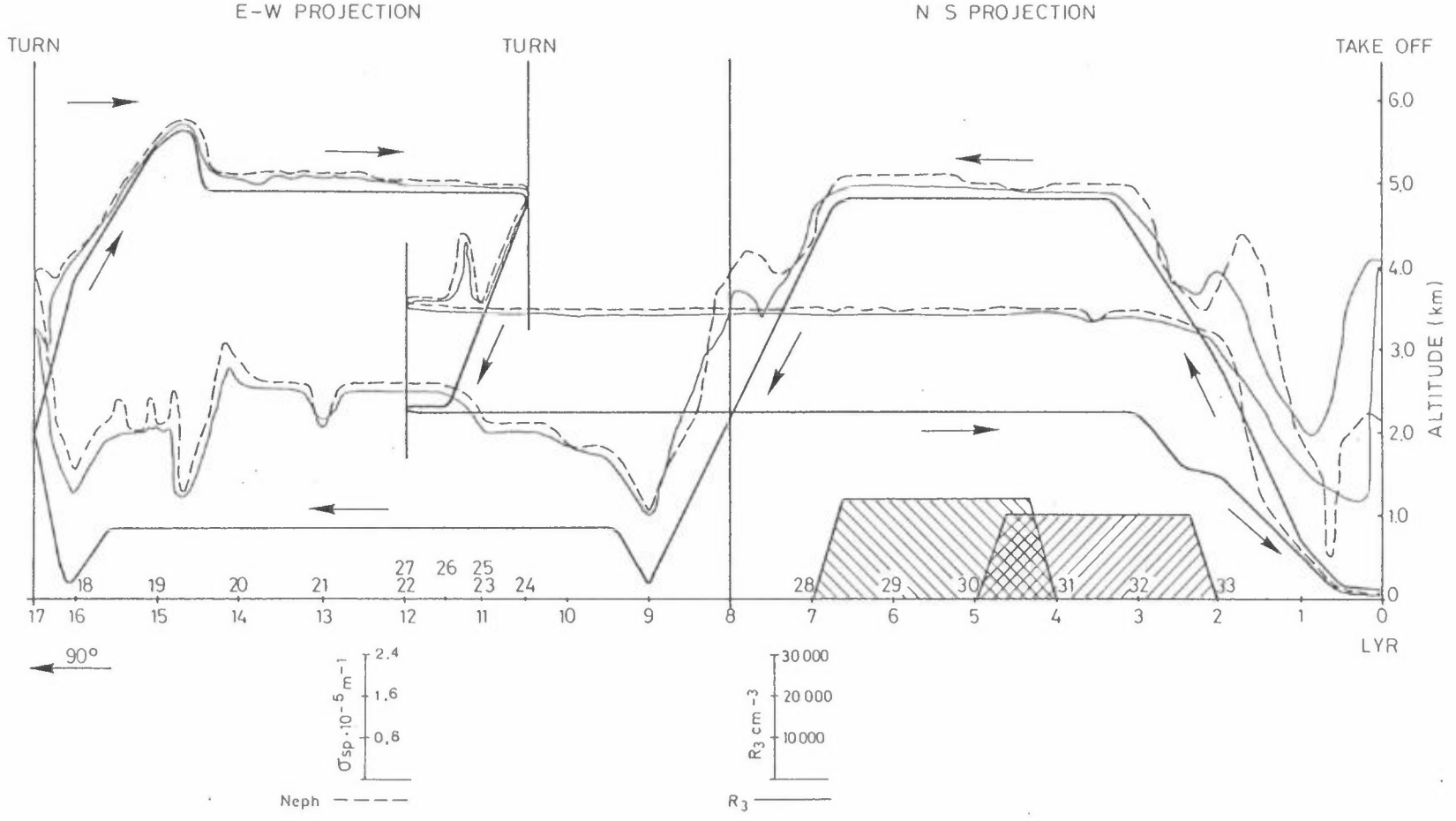

Fig. 13. Vertical profile of the March 3 flight track vs. the land profile.

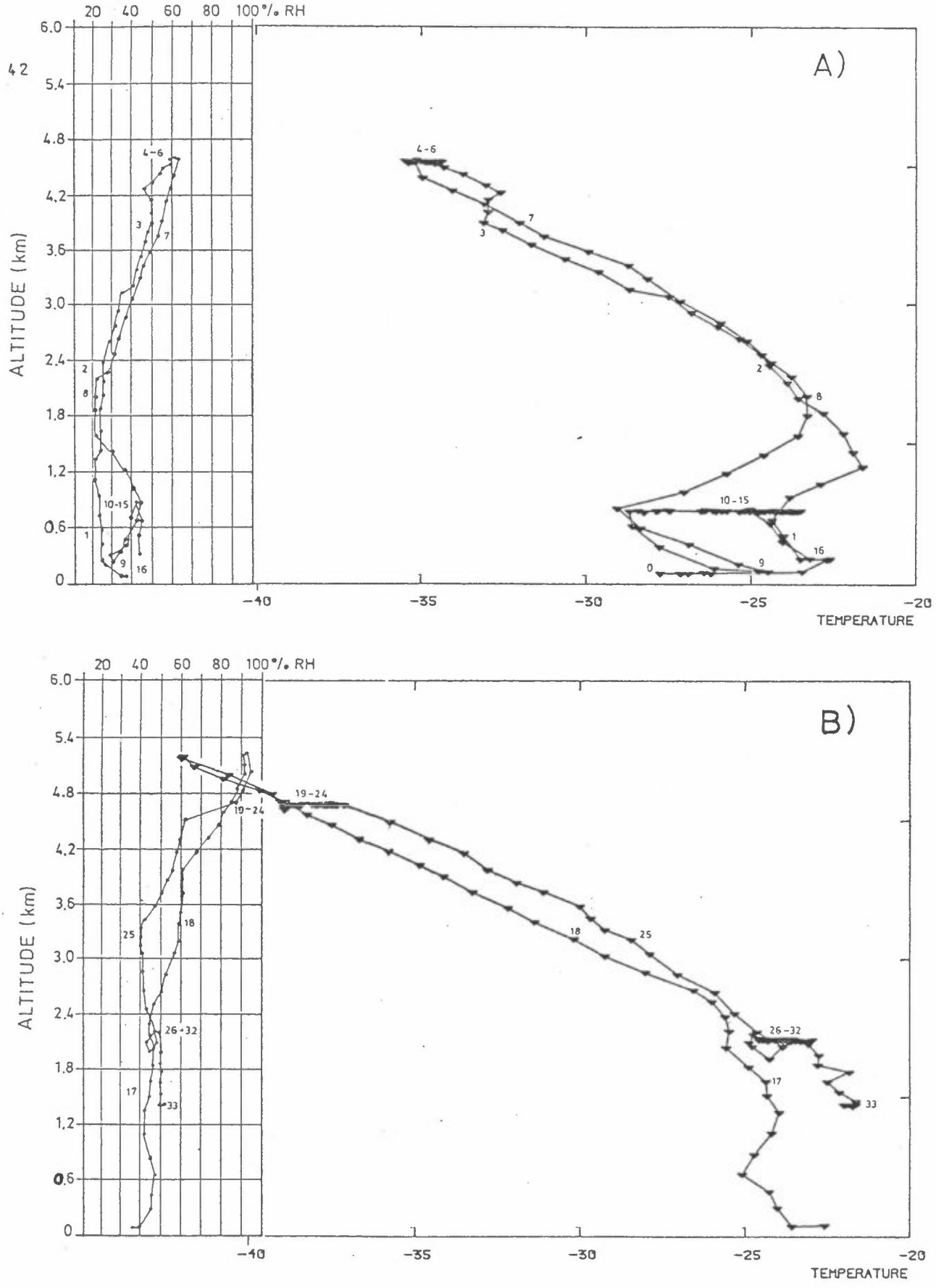

Fig. 14: Vertical profile of air temperature and relative humidity during the flight on March 3, 1984.

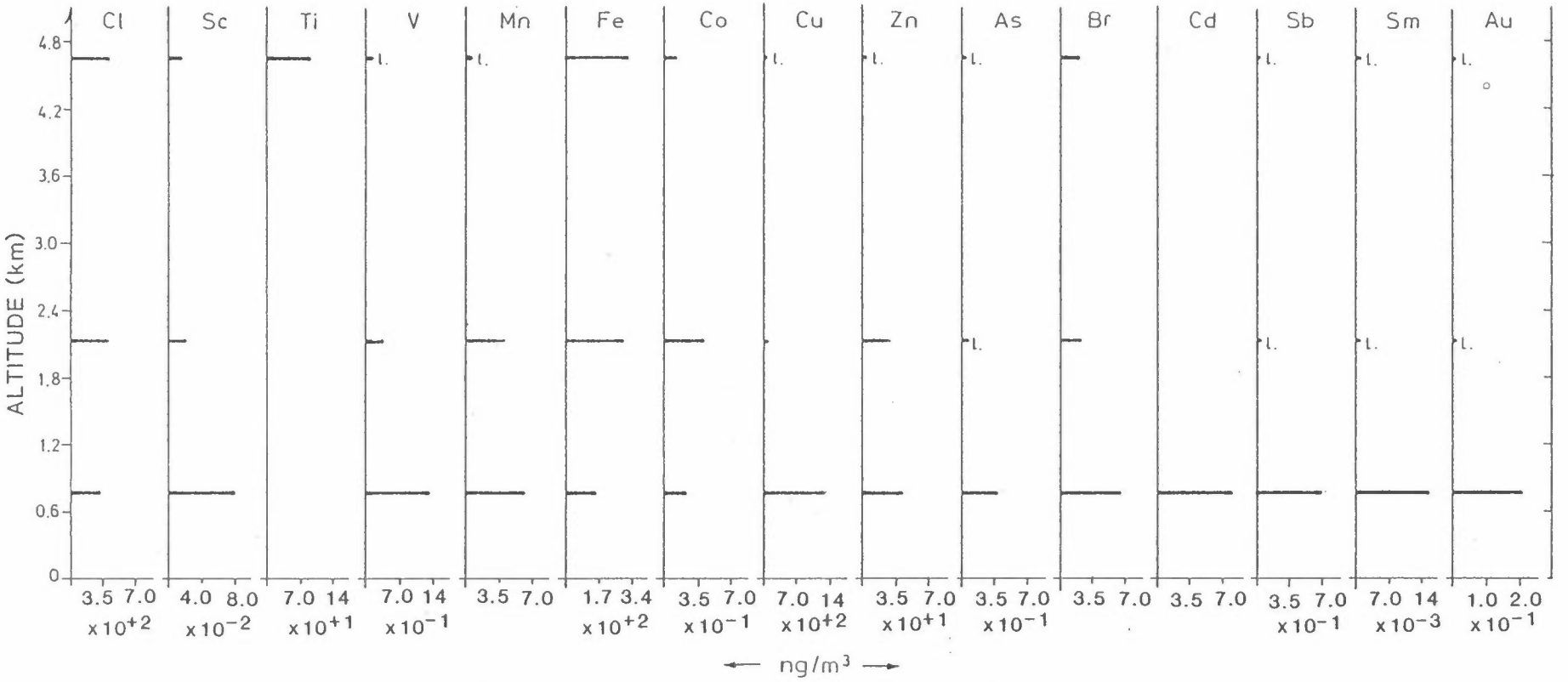

Fig. 15. Chemical composition of aerosols measured at different altitudes during the March 3 flight.

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Aircraft measurements of air pollution in the Norwegian Arctic.

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B. Ottar

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FORFATTER(E)

B. Ottar, J.M. Pacyna and T.C.Berg

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Physical properties, particle size distribution, and chemical composition of the arctic aerosol aloft have been studied to assess the origin of polluted layers of the arctic air. Evidence of very long range transport of air masses to the Arctic is presented for summer and winter conditions. These polluted air masses are observed at higher altitudes (> 1.5 km).

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