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Article

Backscatter lidar observation of the aerosol stratification in the lower troposphere during winter Bise: a case study

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Abstract

This work presents observations of the aerosol mixed layer in the planetary boundary layer and aerosol layers in the lower troposphere during a case of winter Bise wind. The Bise wind event occurred from December 5 till December 18, 2001. The observations were performed above Neuchâtel, Switzerland, 47.00°N, 6.95°E, 488 m asl, using a ground-based backscatter lidar, operating at a wavelength of 532 nm. The height of the aerosol mixed layer was found to extend up to 0.6–0.8 km agl. Another aerosol layer centred around 1.5 km and 2.5 km agl was also observed. The combination of the lidar-observed profiles with radiosonde measurements from Payerne station shows a coincidence of the altitudes of the observed aerosol layers with the altitudes of the Bise wind layer. Back trajectories were used to trace the incoming Bise air masses showing a likely origin from North America.

Zusammenfassung

Diese Studie präsentiert Beobachtungen von Aerosolen in der planetaren Grenzschicht und in der freien Troposphäre während Bise-Bedingungen. Das diskutierte Bise-Ereignis fand in der Periode vom 5.–18. Dezember 2001 statt. Die Aerosol-Beobachtungen wurden mit einem bodengestützten Rückstreulidar bei einer Wellenlänge von 532 nm in Neuchâtel, Schweiz (47,00°N, 6,95°E, 488 m über NN), gemacht. Die Höhe der Mischungsschicht, abgeleitet aus den Aerosolbeobachtungen, betrug etwa 0,6–0,8 km über NN. Eine weitere Aerosolschicht wurde zwischen 1,5 und 2,5 km über Grund beobachtet. Der Vergleich der Lidar-Profile mit Radiosondenmessungen aus Payerne belegt, dass die Höhe der Aerosolschichten mit der Höhe der Bise-Winde übereinstimmt. Rückwärtstrajektorien zeigen, dass die Aerosole in den Bise-Luftmassen ihren Ursprung vermutlich in Nordamerika gehabt haben.

1 Introduction

Recently a number of studies combined backscatter lidar data with back trajectory analysis of the probed air masses to present the aerosol backscatter altitude profiles with respect to long-range aerosol transport. Examples for such studies are KREIPL et al. (2000), MATTIS et al. (2000), HEINTZENBERG et al. (2003), ANSMANN et al. (2003) and WANDINGER et al. (2004). The objective of this work is to present observations of the altitude profile of the aerosol backscatter coefficient (further "aerosol backscatter" or ABC) in the Planetary Boundary Layer (PBL) and the free troposphere during one case of winter Bise. This objective is motivated by previously expressed hypothesis that the Bise wind may transport air pollutions (FURGER et al., 1989; WANNER and FURGER, 1990).

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The synoptic conditions leading to Bise wind and Bise climatology are well described elsewhere (WANNER and FURGER, 1990; WEBER and FURGER, 2001). The 'Bise' is a synoptically induced regional northeastern wind system in Switzerland. It affects the Swiss Middleland (SM) and is channelled between the Alps and Jura. The basic cause of Bise is a northeast-southwest (NE–SW) pressure gradient of the order of 1 hPa / 100 km or more at the 850 hPa pressure level. The Bise substantially decreases the surface temperature along its pathway. The highest frequency of Bise winds occurs during winter (Nov–Dec–Jan–Feb) when the synoptic-scale forcing is strongest, followed by spring (Mar–Apr–May), summer (Jun–Jul–Aug) and autumn (Sep–Oct). Bise events typically last for about 3–4 days but sometimes can persist for more, if the synoptic situation remains unchanged. The observations presented here were performed during the case of Bise wind between December 5 and December 18, 2001. The measurements of the ABC profile and the aerosol

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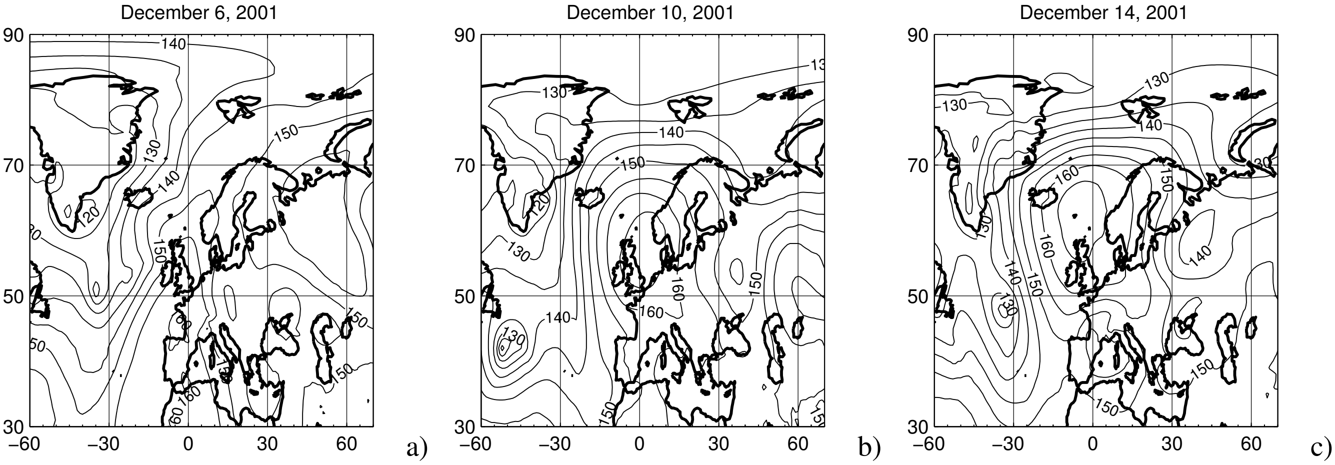

Figure 1: Maps of geopotential height in gpdm at 850 hPa based on ECMWF reanalysis data with 1° by 1° resolution: (a) December 6, 2001/1200 UTC, (b) December 10, 2001/1200 UTC, (c) December 14, 2001/1200 UTC. Black contour lines are drawn every 5 gpdm.

mixed layer height were performed by a backscatter lidar, based in Neuchâtel (47.00°N, 6.95°E, 488 m asl). Surface weather parameters from Neuchâtel and Chasseral (47.13°N, 7.06°E, 1607 m asl) were used to identify the period of Bise. The altitude profiles of meteorological parameters were determined from radiosonde data from Payerne station (46.82°N, 6.95°E, 491 m asl, situated at about 20 km south of Neuchâtel). Ten-day back trajectories were used to show the path of the observed air masses.

2 Lidar and lidar data

The backscatter lidar used in this study is described in previous studies (Frioud et al., 2003, 2004). It operates with the second harmonic (532 nm) of an Nd:YAG laser, having a pulse energy of 20–40 mJ and a pulse repetition rate of 20 Hz. In its present configuration the lidar has a receiver telescope with 25 cm diameter. Photomultipliers and two digital oscilloscopes are used for signal detection and acquisition. The full overlap altitude of the lidar starts at about 0.5 km above ground level (agl). The received backscattered signal is divided into two polarization components that are independently detected: one is parallel to the polarization of the transmitted beam and the other is perpendicular to it. The vertical and the temporal resolutions of the measured single lidar signal profile are, respectively, 6 m and 50 s.

To obtain the aerosol backscatter coefficient (further referred as "backscatter"), the backscatter lidar signal is processed using an inversion method (Fernald, 1984). The processing assumes a constant extinction-to-backscatter ratio (or "lidar ratio") of 50 sr, as it is obtained by numerical study in Ackermann (1997). This value of the lidar ratio is close to the value obtained statistically from lidar measurements in Mattis et al. (2004). The uncertainties in the backscatter profile, associated with the difference between the assumed altitude profile of constant lidar ratio, instead of the actual varying one, are discussed in Frioud et al. (2003). It is shown there that such uncertainties are in the order of 10 % in PBL and 3–5 % in the lower troposphere for difference of 10 sr in the lidar ratio. The top of the PBL is defined determined as height of the aerosol mixed layer, i.e., the altitude of the sharp drop of the aerosol backscatter. This altitude coincides with the altitude of the minimum of the log-derivative of the range-and noise corrected lidar signal (Menut et. al., 1999; Frioud et. al., 2003). All presented results for backscatter and the log-derivative of the lidar signal are given with a height resolution of 60 m and a temporal resolution of 60 min. The lidar used in the reported study operated in the frame of the European project EARLINET and underwent the inter-comparison procedures in this lidar network (Boesenberg et al., 2002; Matthias et al., 2004).

3 Synoptic situation

The reported backscatter lidar measurements were performed during a period of winter Bise lasting from December 5 till December 18, 2001. During this period the wind direction was almost constantly 60 deg (from approx NE) at Neuchâtel and Chasseral. The mean wind speed during this period was predominantly 5–10 m/s at Neuchâtel and between 10–25 m/s at Chasseral, with temperatures respectively in the range of –5°C to +5°C at Neuchâtel and 0°C to –15°C at Chasseral. From December 5 to 7, Northern Europe was under the influence of an Icelandic low-pressure system, while a ridge was situated over Spain and Great Britain (see Figure 1a). On December 8, the ridge extended northwards and developed into a high-pressure system with a centre over Great Britain. At the same time, a cut-off low pressure

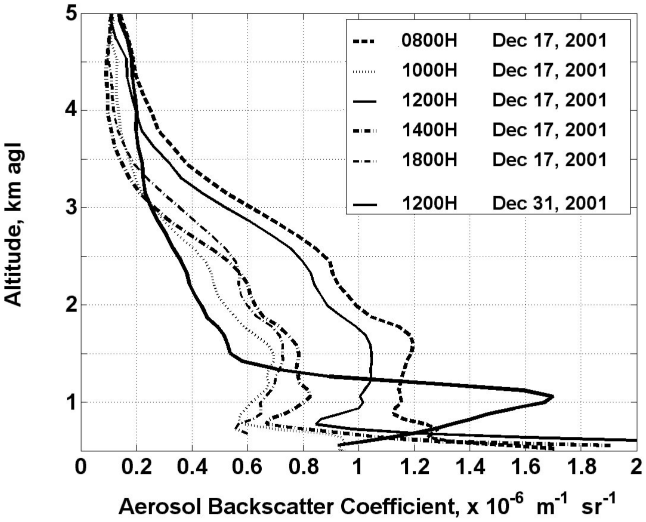

Figure 2: Altitude profiles of the aerosol backscatter coefficient for one day (Dec 17, 2001) together with one profile of aerosol backscatter coefficient for one non-Bise day (Dec 31, 2001). The time for the individual measurements are shown in the legend in local time. The uncertainty for ABC is around 10 % at altitudes 1.3–1.4 km (error bar is not shown).

over the Atlantic Ocean, and another low-pressure system north of the Black Sea developed, leading to an “Omega"-type weather pattern, which was fully established on December 10. This large-scale synoptic situation persisted with little change till the end of the study period (see Figures 1b and 1c). On the south-eastern edge of the anticyclone with centre over Great Britain, the north-easterly flow lead to the Bise wind system. It was temporarily disturbed by a low pressure system over the Mediterranean around December 14 (Figure 1c), but re-established soon after.

4 Observations

Figure 2 presents five successive profiles with 2-hours intervals observed during the Bise day of December 17, 2001. For a comparison in the same figure we present one backscatter profile measured during the non-Bise day of December 31, 2001. The altitudes for the sharp decrease in the ABC value on the profiles from December 17 show a low PBL top with a small variation, between 0.6 km and 0.8 km agl. No increase during afternoon hours is noticed. Aerosol layers above the PBL top are observed for the entire day, with slight maxima around 1.5 km agl and 2.5 km agl. The aerosol backscatter values for these maxima vary between $0.7 - 1.2 \cdot 10^{-6}$ (m sr)$^{-1}$ at 1.5 km agl and $0.4 - 0.9 \cdot 10^{-6}$ (m sr)$^{-1}$ at 2.5 km agl. This gives values for the aerosol extinction coefficient of $35 - 60 \cdot 10^{-6}$ m^{-1} at 1.5 km agl and $20 - 45 \cdot 10^{-6}$ m^{-1} at 2.5 km agl. The PBL height for December 31, 2001 (1200 local time) appears at about 1.4 km agl above an aerosol accumulation layer. Above this altitude and at altitudes where the aerosol layers during December 17 were observed, the ABC values drop sharply below $0.5 \cdot 0^{-6}$ (m sr)$^{-1}$. Figures 3a, 3b, and 3c show the altitude profiles of the aerosol backscatter and the log-derivative of the lidar signal, together with temperature and potential temperature, wind, humidity, and water vapour mixing ratio. The values are for three days during the Bise period: December 7, 14 and 17, 2001, at local noon. For comparison, Figure 3d presents the same parameters for one non-Bise day, on December 31, 2001, at local noon. The profiles of the meteorological parameters are derived from regular radiosonde measurements at Payerne station, also at noon. The profiles of the meteorological parameters in Figs 3a, 3b, and 3c present a typical Bise wind situation. Evidenced by the wind speed and direction, the Bise was fully established with a layer depth of about 3 km and more above the PBL. The log-derivative shows a low altitude of the PBL top, in the range of 0.6–0.8 km. In Figs 3a, 3b and 3c, the PBL top corresponds to the altitude of the temperature inversion, as well as to the altitude with the drop in the water vapour mixing ratio. In the case of the non-Bise day in Fig. 3d, the PBL top appears higher, at about 1.4 km altitude agl. Aerosol layers above the PBL top are seen in Figs 3a, 3b and 3c extending from around 1.0 km agl to 3–3.5 km agl, with maxima centred at around 1.5 km agl and 2.5 km agl. These aerosol layers occur above the temperature inversion and coincide with the layer of the strong north-easterly Bise wind, as well as with a small increase in RH above the PBL top. During the non-Bise day December 31, 2001, the aerosol layers above the PBL top are absent. Values for the aerosol depolarisation ratio are also determined from the lidar measurements, following the definition in BROWELL et al. (1990). The aerosol depolarisation values for the aerosol layers observed in the Bise days are below 1 %. This is around the uncertainty in our determination. Such low values of the aerosol depolarisation indicate that the observed aerosol particles are non-polarizing. I. e., they likely consist of fine-size aerosol particles (below 0.3–0.5 micrometers) or/and aerosol having spherical, or near-spherical shape (CHEN et al., 2002; BROWELL et al. 1990; TOON et al., 1990). We shall note, that depolarisation ratio smaller than 1 % indicates also the absence of desert dust particles (GOBBI et al. 2003; ANSMANN et al., 2003).

5 Backward trajectories

To relate the enhanced particle concentrations to possible source regions, arrays of three-dimensional 10-day backward trajectories were calculated ending at the lidar station at every 0.25 km up to 5.25 km asl. The trajectory model FLEXTRA (version 3.5; STOHL et al.,

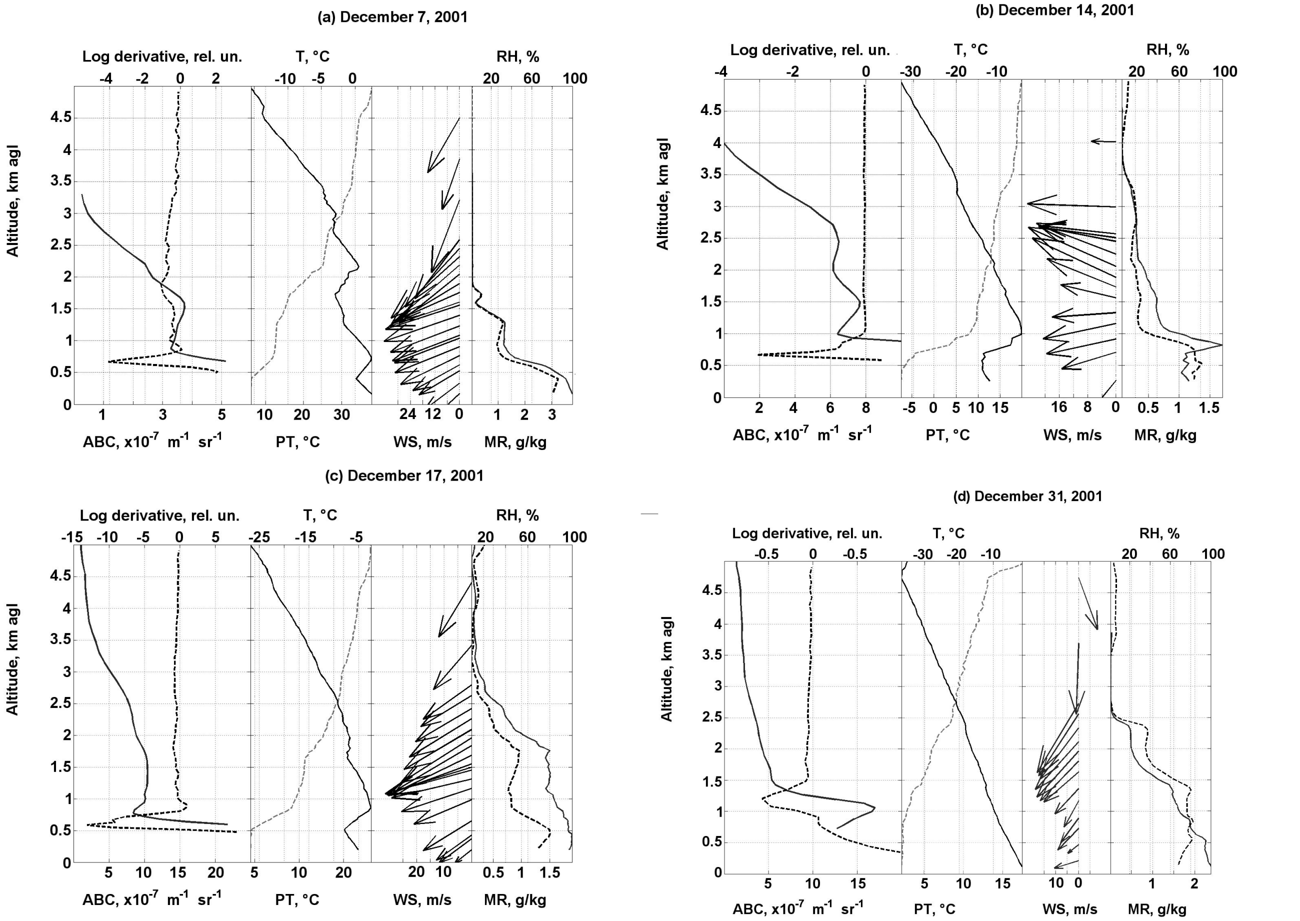

Figure 3: Altitude profiles of the aerosol backscatter coefficient (ABC) and log-derivative of the signal, derived from the lidar measurements, and meteorological parameters from radiosondes for Bise days (7, 14, 17 December 2001) and for a non-Bise day (31 December 2001). First panel from left: ABC (solid line) and log-derivative of range-corrected lidar signal (dashed line). The uncertainty for ABC is about 10 % at altitudes 1.3–1.4 km (error bar is not shown). Second panel from left: Radiosonde derived temperature (T, solid line) and potential temperature (PT, dashed line). Third panel from left: Wind speed (WS) and wind direction (WD). WS is shown by the length of the vector with a scale given on the horizontal axis. WD is given by the vector orientation. Fourth panel from left: Water vapour mixing ratio (MR, solid line) and relative humidity (RH, dashed line). a): Observations for 1200 local time, December 7, 2001. b): Observations for 1200 local time, December 14, 2001. c): Observations for 1200 local time, December 17, 2001. d): Observations for 1200 local time, December 31, 2001.

1995; STOHL and SEIBERT, 1998) was used with global meteorological input fields from the European Center for Medium-Range Weather Forecasts (ECMWF, 1995). Trajectories were calculated every 3 hours during the investigated period. The horizontal resolution of the wind fields was 1° x 1°, and all 60 model levels were used. The time resolution of the ECMWF data was 3 hours (analyses at 0000, 0600, 1200, 1800 UTC; 3-hour forecasts at 0300, 0900, 1500, 2100 UTC). Bicubic interpolations in the horizontal, quadratic interpolation in the vertical and linear interpolation in time were used to interpolate data from the model grid points to the actual trajectory positions.

Figures 4a and 4b show the backward trajectories arriving above Neuchâtel for December 7 and December 17, 2001, at 1200 local time. For clarity, only every second trajectory is shown. During the considered days the back trajectories at the altitudes of the observed aerosol layers above Neuchâtel are starting from various places, but almost all are passing over the Atlantic Ocean. After crossing the North Atlantic, they subsequently follow a common anticyclonic path to the Swiss Plateau. On December 7, 2001 (Fig. 4a). The air masses arriving between 3 and 5 km above Neuchâtel originated from the western parts of North America according to the 10-day backward trajectories. The trajectories were at rather low heights over this area so it is likely that uptake of aerosol occurred. One of the lower trajectories also ends at low altitude in the Arctic. On December 17 (Fig. 5b), all back trajectories spiral around the high-pressure region over Great Britain. Only the lowest trajectory, arriving at 1.25 km above sea level at Neuchâtel (i.e., approx 0.75 km agl), is located in the PBL during the entire 10-day period. Some of the other back trajectories have a

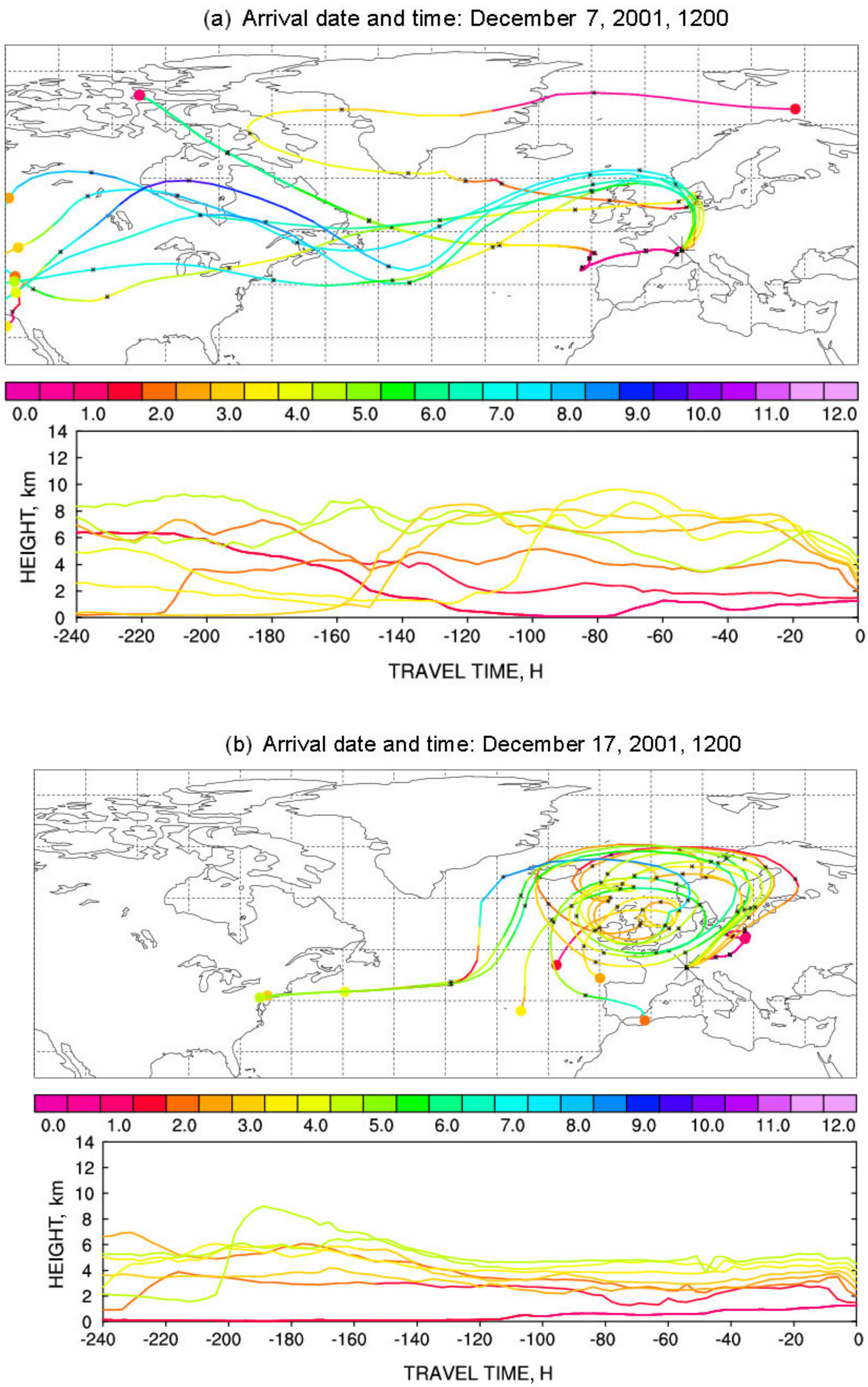

Figure 4: 10-day back trajectories for the air masses arriving above Neuchâtel at 12 UTC respectively on December 7, 2001. (a) and on December 17, 2001 (b). The distance from one dot to another is equal to one day travel. The colour scale gives the altitude of the trajectory in km asl.

part of their travel path at low altitudes over the North Sea and northern Europe, before they ascend to their arrival height above Neuchâtel. Such back trajectories suggest air masses containing aged aerosol, likely from more than one source. Also, the backtrajectories corresponding to the layers at altitudes 1.5–3.5 km agl, appear to be above ML height during their travel above Europe. There may be a possibility that the observed layers contain also finer sea-salt aerosols from the top of ML and the lower troposphere above the ocean (JAENICKE, 1993; HESS et al., 1998). Anyway, the probability for this is low, due to the low altitude of the winter maritime ML. Also, the observed low depolarisation ratio (less than 1 %, section 4) excludes desert dust particles. This is again consistent with the hypothesis that the observed aerosol layers likely contained predominantly aged aerosol particles possibly advected from North America, similarly as observed in KREIPL et al. (2000); CARNUTH et al. (2002); HEINTZENBERG et al. (2003).

6 Conclusions

Aerosol layers are observed during the studied Bise event, starting at altitudes just above the PBL top till 3–3.5 km height agl. The aerosol depolarisation ratio in these layers is found to be very low, suggesting that the particles in these layers were rather small and have spherical shape. The conditions of Bise wind lead also to a low PBL top – till 0.6–0.8 km agl. The 10-days back trajectory study for the pathway of the air masses observed above Neuchâtel, suggest that layers advected from North America and containing particles of fine size, likely aged aerosol, were observed. The variety of sites of the backward trajectories origin shows that in such Bise synoptic situation, the effect of Bise is in the collection of the contribution from the possible sources in a large area and from long ranges, and channelling it at altitudes of the lower troposphere above Swiss Middleland or more generally, over Central Europe. It shall be noted that high-pressure systems over the North Atlantic shall be expected to favour such long-range transport of aerosol particles, because the probability for washing out by precipitation is relatively low.

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