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Aerosol transport to the high Alpine sites Jungfraujoch (3454 m asl) and Colle Gnifetti (4452 m asl)

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ABSTRACT

Atmospheric transport processes, relevant to high Alpine sites, were deduced from 2 sets of aerosol records: a 9-year record from the Jungfraujoch (3454 m) on the northern side of the Swiss Alps and a 2.5-year record from Colle Gnifetti (4452 m) on the southern side. A classification scheme for synoptic weather types was applied to separate the aerosol data into groups corresponding to different atmospheric transport conditions. For both sites, vertical aerosol transport by thermally driven convection, acting between late spring and late summer, was found to be the dominant transport process. In summer, the thermally-driven aerosol transport to both sites caused an increase of the seasonally averaged aerosol concentration between 0800 and 1800 local standard time by a factor of two. Under anticyclonic conditions, when subsidence on a synoptic scale is present, the thermally driven aerosol transport is most pronounced. Therefore, the aerosol determining thermal transport takes place within a synoptic scale vertical motion of opposite direction. Under cyclonic conditions, when lifting on a synoptic scale is present, the thermally driven aerosol transport is nearly absent. In winter, thermally driven convection does not contribute to the aerosol concentrations at both sites. Nevertheless, also in winter statistically significant differences in aerosol concentration were found between cyclonic and anticyclonic weather conditions, which can be attributed to the vertical transport acting on the synoptic scale. These differences in aerosol concentration were small compared to the corresponding differences in summer. Within the weather types, which are dominated by horizontal advection in the Alpine region, the aerosol concentrations are more difficult to interpret with respect to the effective transport process.

1. Introduction

Within the Global Atmosphere Watch (GAW) programme of the World Meteorological Organisation (WMO), measurement sites on high mountains are selected to observe the background and free-tropospheric aerosol concentration at different locations of the world (WMO, 1991). The mountain stations Jungfraujoch (3454 m, Switzerland), Zugspitze (2962 m, Germany) and Sonnblick (3106 m, Austria), which are all situated in the Alps, constitute together the European GAW baseline station.

In this context, it must be determined, to what extent these sites are representative of background, or free-tropospheric, conditions. Vertical profiles of the aerosol concentration in the troposphere have been characterised for remote continental, maritime, desert and polar locations, see Jaenicke (1993) and references therein. Until now, not much attention has been paid to the changes of these vertical distributions with time. The Alps are

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situated in the mid-latitude west wind zone, where the exchange of air masses is determined by the motion of the synoptic-scale weather systems (Holton, 1979). Therefore, considerable aerosol variability can be expected at a high altitude mountain station resulting from transport processes, even if it is not influenced by local sources. Horizontal and vertical transport to the mountain station must be distinguished in order to estimate the spatial representativity of the measurements. It is well known that the heat budget of an atmosphere above mountainous terrain differs from an atmosphere above flat topography (Whiteman, 1990). This indicates that the thermally driven vertical transport to the mountain station is particularly important, which was already recognised for Mauna Loa, Hawaii (3400 m asl) by Mendonca (1969). The understanding of the development of the boundary layer over complex terrain is still incomplete, but it is clear that the diurnal evolution of slope and valley winds provides an efficient mechanism for the vertical transport for airborne constituents such as aerosol particles. Reiter et al. (1984) investigated the annual cycle and the influence of air mass changes on the aerosol concentration at the Zugspitze. They noticed that vertical transport is a key process significantly influencing the aerosol concentration at the Zugspitze. However, the time resolution of their method was not sufficient to resolve diurnal cycles.

In this work, aerosol transport to the Jungfraujoch and to Colle Gnifetti (4452 m, Switzerland) was investigated by analysing aerosol data with a 30-min time resolution. The role of synoptic-scale vertical and horizontal transport as well as the transport associated with the growth of the convective boundary layer was analysed.

2. Experimental

2.1. *Description of the Jungfraujoch and Colle Gnifetti measurement sites*

The research station at the high Alpine site Jungfraujoch (3454 m asl, 46°33′N, 7°59′E, Fig. 1) is extensively used as a platform for research in the field of atmospheric science and astronomy. Because of its unique elevation, it is suitable for the investigation of physical and chemical characteristics of the lower part of the free troposphere over central Europe. Geographically, the Jungfraujoch is situated in the north of the main Alpine chain. The saddle position of the Jungfraujoch, between the Jungfrau (4158 m) and Mönch (4089 m) mountains, channels the local horizontal flow in a north-western or south-eastern direction. With north-westerly wind directions, air from the Swiss plateau is advected to the Jungfraujoch, while during south-easterly directions, the air comes from the inner Alpine area (Fig. 1).

The Colle Gnifetti (4452 m asl, 45°54′N, 7°52′E, Fig. 1) is a saddle in the peak area of the Monte Rosa massif (up to 4634 m), the second highest peak of the Alps. It is situated on the southern side of the Alps and exposed to northern Italy. The transition from the Alpine environment to the Po plain, lying to the south-east of the Colle Gnifetti, occurs over a distance of 40 km.

2.2. *Aerosol-monitoring with the epiphaniometer*

The epiphaniometer (Greek $\varepsilon\pi\iota\phi\alpha\nu\iota\alpha$ = surface of a body) monitors aerosol particles continuously (Gäggeler et al., 1989). Air is continuously pumped through a closed chamber containing short-lived ^{211}Pb atoms ($T_{1/2} = 36$ min) delivered by a ^{227}Ac source ($T_{1/2} = 21.8$ years). These atoms attach onto the aerosol particles. After transportation through a thin capillary to a filter and counting station the particles are detected by means of an α-detector for measuring the decay of ^{211}Pb (via ^{211}Bi). The measured signal is proportional to the exposed Fuchs surface of the aerosol particles. The Fuchs surface is the surface of the aerosol particles actually effective for the diffusional attachment process. For a detailed description of the Fuchs surface see Pandis et al. (1991). For aerosol surface area distributions prevailing in the atmosphere the epiphaniometer is most sensitive in the accumulation mode (diameter d: $0.1 < d < 1$ μm). Due to its high sensitivity it also works well at the lowest particle concentrations of less than 100 ng m^{-3} with gas flow rates as low as 1 litre min^{-1}. In the following the epi signal will also be denoted with aerosol concentration.

The epiphaniometer at the Jungfraujoch is operated in a laboratory with a mean temperature of 22(±2)°C and a relative humidity below 20%. Therefore, the sampled atmospheric aerosol is dried before it reaches the attachment vessel. At

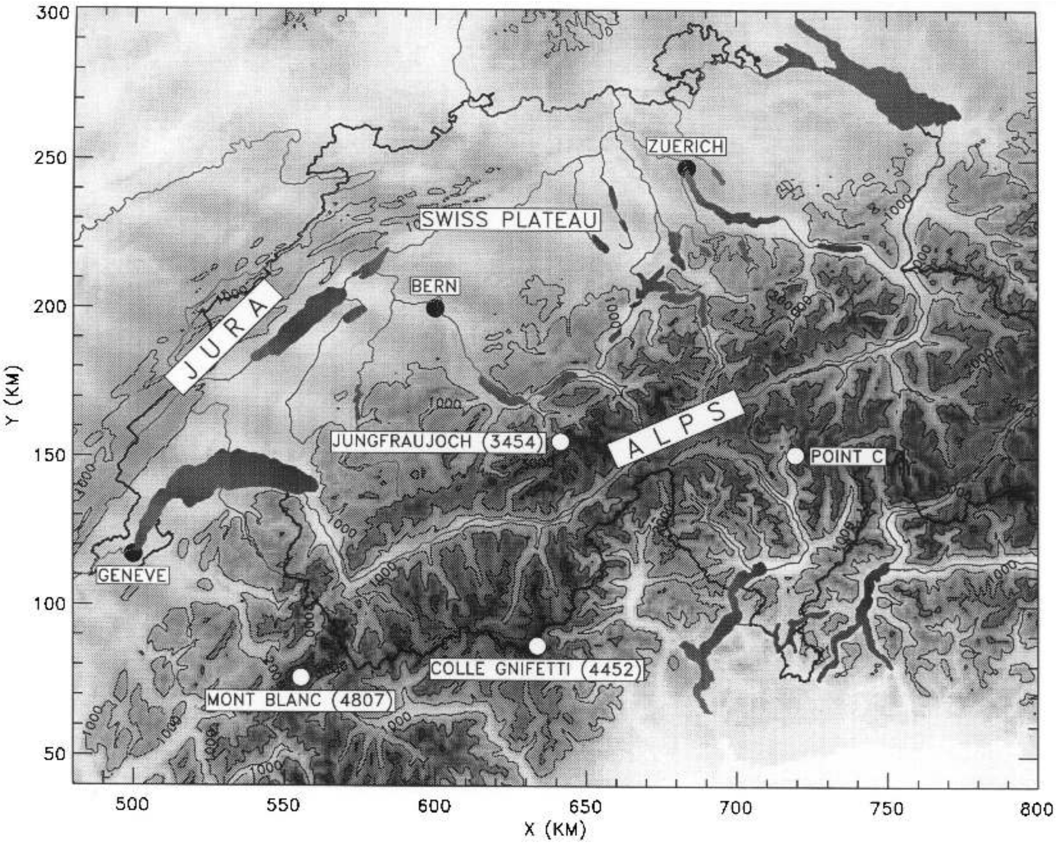

Fig. 1. Topographic map of the Alps, Swiss plateau and the Jura mountain chain between 45°30′-47°51′N and 5°52′-10°07′E. Contour lines in 1000 m intervals, major cities, lakes and rivers are included. Dark line indicates the Swiss border line. Axes show the Swiss kilometre grid. Database: DTM of Switzerland 250 m, reproduced by permission of the Swiss Federal Office of Topography, 4.2.97.

Colle Gnifetti the instrument and its batteries were only sheltered by an insulated box buried in the firn. The batteries were charged by a solar panel. Beginning in 1992, the efficiency of the batteries declined, with the consequence that the epiphaniometer often did not work from 2200 to 1000 local standard time (LST = UTC + 1 hr). The sampling temperature in the epiphaniometer varied between −11(±2)°C in December and 6(±2)°C in August. Temperature and humidity data of the ambient air were not available. However, the mean annual temperature at this site is −14°C (Oeschger et al., 1977) and thus ambient temperature was certainly lower than in the epiphaniometer during most of the measurements. Therefore, the ambient aerosol is also dried, even though to a lesser degree than at the Jungfraujoch.

The Jungfraujoch data set is nearly continuous, beginning in 1988. The Colle Gnifetti data set spans the periods from August 1988 to February 1990, July 1991 to June 1992 and October 1993 to February 1994. Both time series have a resolution of 30 minutes. Extensive field campaigns at the Jungfraujoch showed high correlation of the epi signal with the accumulation mode number concentration and with the sulphate mass concentration of the aerosol (Baltensperger et al., 1997), and also with the aerosol scattering parameters (Nyeki et al., 1997).

The diffusion of the lead atoms to the aerosol particles depends on the mean free path length of the lead atoms. The pressure decrease from the Jungfraujoch (mean pressure 663 hPa) to Colle Gnifetti (mean pressure 577 hPa) increases the efficiency of the epiphaniometer by 13%, which had been taken into account for the data presented in this paper. The measurement error of the epiphaniometer due to the counting statistics is proportional to the square root of the count rate. With a counting time of 30 min this error is about 7% for a concentration of 0.1 counts s^{-1} (cps) and below 2% for concentrations larger than 1 cps. Larger uncertainties are due to the sampling efficiency at both sites. The high correlation with sulphate, which was sampled by open face filters, suggests that most of the cloud droplets during cloud events (about 50% of the time at the Jungfraujoch) entered the system and were dried before they reached the attachment vessel, thereby reducing their surface area. In the following analysis it is assumed that the differences in operating conditions between both sites did not substantially influence the measurements. This assumption will be justified by correlation analysis of the data in subsection 3.1.

Table 1. *Alpine weather statistics (AWS): division into 3 basic and 8 extended weather types; in column 3, the weather types are characterised by means of the dominant synoptic scale motion*

Basic types	Extended, types (symbol)	Synoptic motion
(A) advective	1. east (E)	NE-SE at 500 hPa
	2. south (S)	S-SW at 500 hPa
	3. west (W)	W at 500 hPa
	4. north (N)	NW-N at 500 hPa
(B) convective	5. cyclonic (C)	lifting
	6. indifferent (I)	small-scale circulations
	7. anticyclonic (A)	subsidence
(C) mixed or vortex	8. mixed (M)	active cyclone or jet flow

2.3. *Method of data analysis*

In this contribution, the basic tool for the analysis of the aerosol data was a synoptic weather type classification system called Alpine Weather Statistics (AWS; Schüepp, 1979; SMI, 1985). This is a weather classification system based on the diurnal analysis of the pressure distribution at the surface and at 500 hPa (~5.6 km). It is defined for a circular area with a radius of 222 km (distance between 2° of latitude), centred at the point C (46°30′N, 9°E, Fig. 1), 80 km east of the Jungfraujoch. This area covers Switzerland and western Austria. In this classification, the following four key parameters are combined to define 40 Alpine weather situations (Schüepp, 1979; Wanner, H., Salvisberg, E. and Schüepp, M.: 50 years of Alpine weather statistics (AWS), submitted to Meteorol. Zeitschrift, 1997.): (1) speed of the surface wind, derived from the surface pressure gradient; (2) direction and speed of the 500 hPa wind; (3) height of the 500 hPa surface over the central point of the system; (4) baroclinicity.

These 40 weather situations can be summed into three basic and eight extended weather types (Table 1). Within the advective types the horizontal motion of the atmosphere is predominant, so that in flat terrain the vertical wind components are unimportant. However, the orography of the Alps adds vertical components to this air flow, resulting in well-marked upslope and lee phenomena (Schüepp and Schirmer, 1977), e.g., Foehn. The convective types include weather situations where the vertical motion predominantly influences the weather, either as a single effect or in connection with the effects of horizontal motion. For the latter case, where both the horizontal and vertical wind components are significant, an additional type, called the mixed weather type, was added. The eight extended weather types are further discussed in subsection 3.3.

The median value of a data sample, which consists of the AWS-grouped epi measurements, was used to characterise the average aerosol concentration, since it is a more appropriate estimator for the nearly log-normally distributed aerosol data than the arithmetic mean. Likewise, the 75th and 25th percentiles (quartiles) are given to estimate the variability within each data sample. A shift in location of the central tendency between two data samples was tested by applying the nonparametric Wilcoxon rank sum test (Gilbert, 1987). Asymptotic probability or p-values for the significance are given. For a two tailed test, the significance level of a shift in the mean concentration between two data samples is given by $100 \times (1-p)\%$. Therefore, a small p-value means that this shift is highly significant.

3. Results and discussion

3.1. *Correlations between the epiphaniometer and other aerosol data*

Besides the epiphaniometer data, other long-term aerosol data for the Jungfraujoch site are also available. Within the Swiss National Monitoring Network for Air Pollution (NABEL), described in Wunderli and Gehrig (1990) and Filliger et al. (1994), total suspended particulate matter (TSP) and the sulphur content S of TSP (mainly sulphate) are measured with two days and one day resolution, respectively. We correlated these data with the correspondingly averaged epiphaniometer data for the period from 1988 to 1994. Table 2 shows that the correlation between the epi signal and TSP as well as between S in TSP and TSP increases considerably, if the TSP values larger than the 90% percentile are disregarded, whereas the correlation between the epi signal and S in TSP is high in all cases. The highest TSP values (two-day means $>10\ \mu g\ m^{-3}$) are caused by coarse mode rather than accumulation mode particles, explaining their low correlation with the epi signal. Secondly, these large particles consist mainly of mineral dust, where the contribution of sulphate to total mass is small. Schwikowski et al. (1995) identified an episode of high TSP values as a Saharan dust event.

In the next step, we analysed the homogeneity of the epiphaniometer data between the Jungfraujoch and Colle Gnifetti. The Jungfraujoch and Colle Gnifetti are 70 km horizontally and 1 km vertically apart. Therefore spatial homogeneity involves horizontal and vertical mixing processes. We tested the homogeneity by correlation and regression analysis of the daily median values of the epi signal from both sites. The results are given in Table 3. Since both data sets are nearly log-normally distributed, we repeated the analysis for the logarithmised data. This transformation corresponds to the model equation $y=c\times x^{a}$, with $c=e^{b}$. For the linear model, the residuals increase with increasing concentrations, whereas for the non-linear model the residuals are approximately normally distributed. The correlation coefficient of the linear model is slightly lower. If aerosol concentrations at Colle Gnifetti are estimated by the regression functions, the values calculated by the linear function are higher than the values from the non-linear model. Nevertheless, the rather high correlation between both data sets

Table 2. *Correlation and regression analysis between the epiphaniometer signal (cps) total suspended particulate matter TSP ($\mu g\ m^{-3}$) and sulphur content of TSP ($\mu g\ m^{-3}$) at the Jungfraujoch*

y	TSP				TSP ⩽ 90% percentile = 10 µg m^{-3}				S in TSP			
	a	b	r	N	a	b	r	N	a	b	r	N
x = EPI	0.48	2.46	0.35	816	0.35	1.56	0.65	726	0.06	0.14	0.77	1671
S in TSP	4.89	2.71	0.3	816	3.47	1.73	0.57	726	—	—	—	—

Parameters of the linear regression $y=ax+b$, the Pearson correlation coefficient r and the number of observations N are given. Data from 1988 until 1994 are presented. TSP and S in TSP data are measured within the NABEL network and available at the Bundesamt für Umwelt, Wald und Landschaft (BUWAL), CH-3003 Bern, Switzerland.

Table 3. *Regression parameters and correlation coefficients of the daily median epiphaniometer signal between the Jungfraujoch and Colle Gnifetti; the Jungfraujoch data was viewed as the independent variable*

Model	Parameters with SD a	b	Corr. coeff. r	Samples N
$y=ax+b$	0.44(±0.02)	0.8(±0.1)	0.71	818
$\ln y=a\ln x+b$	0.67(±0.02)	−0.08(±0.002)	0.77	818

gives confidence that the differences in the epi signal represent the differences in the aerosol concentration of both sites.

3.2. The seasonal and diurnal aerosol cycles

Pronounced seasonal cycles of the aerosol concentration are characteristic for the Jungfraujoch and the Colle Gnifetti site, as can be seen from the time series of the monthly median and quartile values in Fig. 2. The highest and lowest medians differed roughly by one order of magnitude and occurred in most of the investigated years in August and December, respectively. In addition, the aerosol variability was one order of magnitude higher in summer than in winter. Since large changes on the time scale of several days (i.e., the synoptic time scale) can be expected, we analysed the epiphaniometer time series with respect to the calendar week. Fig. 3 shows the annual cycle of the epi signal at the Jungfraujoch and at Colle Gnifetti based on weekly medians. In winter the aerosol concentrations at both sites were very low, ranging from below 1 cps in December to 2 cps in February. The concentration differences between both sites were small. We conclude that in winter both sites are located in the free troposphere and are decoupled from the atmospheric boundary layer, where most of the atmospheric aerosol particle mass is found. From winter to spring the epi signal increased nearly exponentially to 7 cps on average at the Jungfraujoch until the end of April (~week 17). The concentrations at Colle Gnifetti were on average 40% lower. From May until mid July (~week 29) the aerosol concentrations showed a positive trend with large fluctuations superimposed. The local minima in aerosol concentration occurred during periods when fresh maritime air masses were advected from the Atlantic into the Alpine area. These rather regular episodes, sometimes called the European summer monsoon episodes (Schüepp and Schirmer, 1977), are accompanied by precipitation, which is enhanced by orographically forced lifting at the Alps, and subsequent cooling and stabilisation of the atmosphere. Therefore,

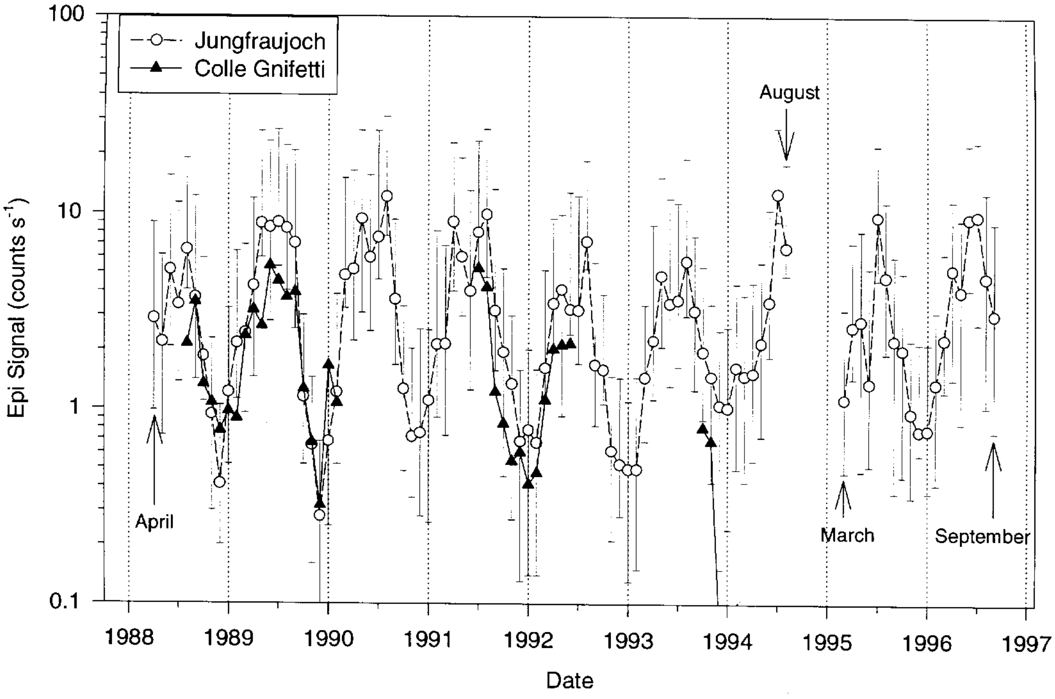

Fig. 2. Monthly median (symbol) and quartile values (whiskers) of the epi signal at the Jungfraujoch and at the Colle Gnifetti (only medians) from April 1988 to September 1996.

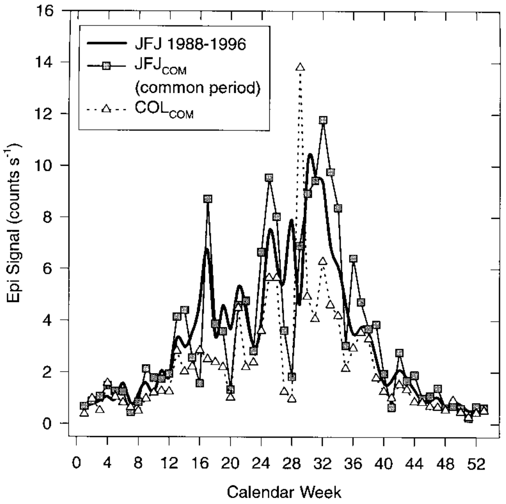

Fig. 3. Annual cycle of the aerosol concentration at the Jungfraujoch and Colle Gnifetti based on weekly medians of the daily median epi signal. The thick black curve represents all data from the Jungfraujoch from April 1988 until September 1996, whereas the curves with symbols are based only on the simultaneous measurements at the Jungfraujoch (JFJ$_{COM}$) and at Colle Gnifetti (COL$_{COM}$).

low aerosol concentrations are expected at high Alpine sites during such episodes. In the first half of summer these episodes alternate with periods in which the influence of the Azores High on the weather of the Alpine area increases, causing a flat pressure distribution (Schüepp and Schirmer, 1977). Under such conditions the horizontal advection is reduced and local circulation systems, determined by solar heating and terrain effects, develop. By these circulations, aerosol rich air from the boundary layer is transported vertically, and high concentrations can be expected at high Alpine sites. The exceptional situation of week 29, when the aerosol concentration at Colle Gnifetti exceeded the one at the Jungfraujoch by about 100%, needs further clarification. The medians for the common period of week 29 represent measurements from only 5 days (20–21/07/89 and 19–21/07/91). On the 20 July 89, a daily median of 25 cps was recorded at Colle Gnifetti but only 7 cps at the Jungfraujoch. Such an event could be an indication for long-range transport within a layer, which is decoupled from the atmosphere below by an inversion.

Between mid-July and mid-August (weeks 30–33), the aerosol concentration reached the annual maximum with 10 to 12 cps for the weekly median at the Jungfraujoch and about 50% less at Colle Gnifetti. During this period flat and high pressure distributions above the Alpine region became more persistent and disturbances by the intrusion of maritime air masses were less frequent. The exchange of air masses by horizontal advection is reduced. Vertical aerosol transport is believed to be the dominant transport process under such conditions. After this period, the epi signal decreased at both sites with only minor fluctuations. This can be explained by the stabilisation within the boundary layer in the course of autumn, which strongly reduces the vertical transport of aerosol rich air.

A clear indication for the importance of vertical aerosol transport by thermally driven convection is the pronounced diurnal variation at the Jungfraujoch (Baltensperger et al., 1991, 1997) and at Colle Gnifetti, which occurred frequently in spring and summer (Fig. 4). To allow a comparison between both sites, only data between 1988 and 1992 were used, since the night time data at Colle Gnifetti were usually missing after that period. The seasonally averaged diurnal aerosol peak was centred around 1900 LST in summer at both sites. At Colle Gnifetti, the aerosol concentration started to increase about 2 h later, but the increase was faster compared to the Jungfraujoch. In spring, the aerosol peak occurred around 1600 LST at the Jungfraujoch, while there was no corresponding peak at Colle Gnifetti. Both the absolute and the relative diurnal amplitude (diurnal amplitude divided be the diurnal average) depended on the season. At Colle Gnifetti, the duration of the afternoon aerosol peak was reduced on the diurnal and the seasonal time scale, which is probably due to the higher elevation. This is another indication that the diurnal variations shown in Fig. 4 are caused by transport processes, which will be discussed further in subsection 3.4.2.

3.3. *The AWS weather types and their seasonal cycle*

Fig. 5 shows the seasonal frequency distribution of the basic and extended weather types for the period from 1988 to 1996. The convective weather types were dominant throughout the year and

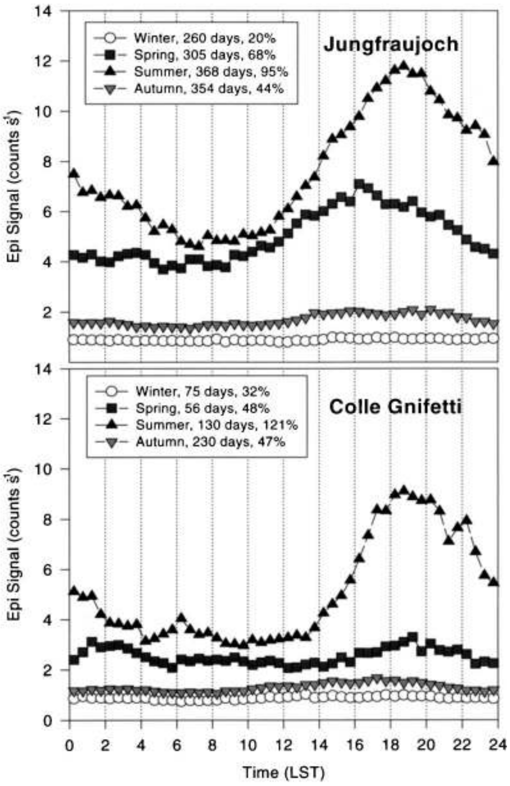

Fig. 4. Seasonal median values of the epi signal at Jungfraujoch and Colle Gnifetti as a function of time of day. In the legends the number of days with data and the relative amplitude 100 × (max-min)/mean of the diurnal variation is given for each season. Data are shown from 1988 to 1992.

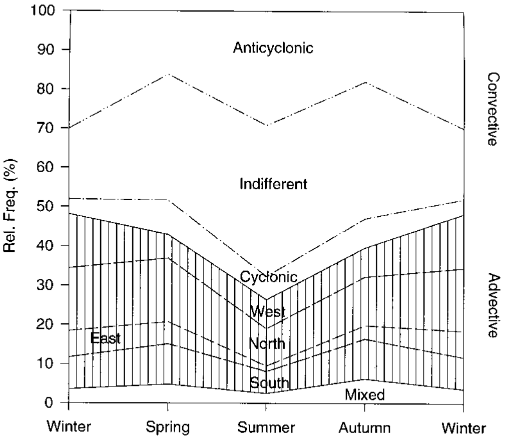

Fig. 5. Seasonal frequency distribution (stacked) of AWS weather types for the period from January 1988 until July 1996. Data from Swiss Meteorological Institute.

exhibited a pronounced summer maximum. The advective weather types were more frequent in winter, when vertical displacements are suppressed by the great static stability of the atmosphere (Schüepp and Schirmer, 1977). The mixed weather types also exhibited an annual cycle, with maxima in frequency in spring and autumn, but these types were rather seldom compared to the convective and advective types.

The differences in the synoptic scale flow also result in differences in the thermodynamic variables pressure, temperature, relative humidity and sunshine duration shown in Table 4 for the Jungfraujoch site. The three convective weather types differ by the sign of the synoptic scale vertical motion (Table 1). Subsidence caused by frictional divergence is predominant for the anticyclonic type A, resulting in adiabatic warming and cloud dissipation. On the other hand, ascent of air, caused by frictional convergence, is predominant for the cyclonic type C, resulting in adiabatic cooling and cloud formation with subsequent precipitation. The differences in the synoptic scale vertical motion of weather types A and C result in differences in the thermodynamic variables, which are considerably more pronounced than between the advective weather types E, S, W and N (Table 4). The indifferent weather type is characterised by a flat pressure distribution and therefore alternating small-scale up- and downdrafts depending on the effects of the terrain (Schüepp and Schirmer, 1977). Substantial horizontal and vertical motions occur, when an active cyclone or a front is present in the surface chart. Such conditions are classified as mixed weather types. They include characteristics of the convective and the advective weather types. The classification of the advective types is based on the wind direction at the 500 hPa level over the central Alpine area. 8 wind sectors of 45° are distinguished, where the number of sectors within each advective type are different (Table 1). Type W has only one sector, types N and S two and type E three. Wind directions from west to north were most frequent, whereas wind directions from north-east to south-east were rather seldom (Fig. 5). Weather type E represents situations when the usual zonal circulation is blocked.

Table 4. *Pressure p (hPa), temperature T (°C), relative humidity rh (%) and sunshine duration sd (hours day*$^{-1}$*) at the Jungfraujoch for the period from 1988 to 1996*

	Winter				Spring				Summer				Autumn			
AWS-group	*p*	*T*	rh	sd	*p*	*T*	rh	sd	*p*	*T*	rh	sd	*p*	*T*	rh	sd
C	637	−19	82	2	643	−14	85	1	654	−7	92	1	651	−8	88	1
I	649	−13	80	6	653	−8	88	4	662	−1	84	5	658	−5	79	5
A	660	−9	41	7	661	−7	58	10	667	+2	71	10	665	−1	57	8
M	648	−12	86	0	650	−10	84	2	659	−2	86	5	653	−6	88	1
E	651	−14	62	7	653	−8	79	8	661	−4	85	5	650	−8	75	7
S	647	−11	85	0	651	−8	90	0	662	−1	91	2	653	−5	91	0
W	649	−10	87	0	651	−10	87	2	659	−2	89	6	655	−6	84	4
N	650	−15	82	1	649	−13	84	3	659	−4	91	2	654	−9	85	3

Seasonal median values are presented for each extended weather type. Basic convective and advective weather types are indicated by brackets. Data received from the Swiss Meteorological Institute.

3.4. Aerosol concentration and basic weather types

We now turn to investigate the influences of the synoptic scale transport processes on the aerosol concentration. In Figs. 6 and 7 the median and quartile values of the seasonally and AWS grouped aerosol data are displayed. While Fig. 6 presents the Jungfraujoch data for the full period (88–96), Fig. 7 gives the results for Colle Gnifetti along with a comparison of the Jungfraujoch data for the same period. Tables 5 and 6 give the results of the Wilcoxon rank sum test for the two sites.

Firstly, we consider the differences in the median aerosol concentration between the basic convective and advective weather type. These values are represented by the horizontal lines in Figs. 6, 7. The basic convective type showed higher concentrations than the basic advective type. This concentration difference was highly significant in all seasons ($p<10^{-3}$, autumn $p=0.07$) for the whole Jungfraujoch data set, but not significant if the data from the common measurement period are considered (Fig. 7). Figs. 6, 7 also show that the main differences in aerosol concentration occurred between the extended weather types, which will now be discussed within each basic type. The mixed weather type will be discussed together with the convective types.

3.4.1. Aerosol concentrations within the advective weather types. Fig. 6 shows that flow conditions of type E and S usually accounted for above average aerosol concentrations at the Jungfraujoch within the advective types, whereas during type N and W flow, the concentrations were below average. However, Table 5 shows that in most cases the differences were not statistically significant. The aerosol data for the common measurement period of both sites (Fig. 7) exhibited remarkable differences. In summer and winter, the highest median aerosol concentration within the advective weather types occurred under type S conditions at the Jungfraujoch, whereas under this condition the lowest value was observed at Colle Gnifetti. During the advective types N and E, the median aerosol concentrations of both sites were similar.

During weather type W, maritime air masses from the Atlantic are advected towards the Alps. Typical conditions of type N occur when the Alps are influenced by cold polar air masses after a cyclone has passed to the North of Switzerland (Schüepp, 1979). The most precipitation on the southern side of the Alps occurs during weather type S. It was mentioned earlier that the Alpine orography induces vertical motions on the atmospheric flow during advective type conditions, which are often associated with cloud formation and precipitation on the upslope side. Therefore, the aerosol concentration at high Alpine sites is probably not only determined by the different origin of the air mass but also by modifications arising from the forced vertical motion. Our results suggest that, within the advective weather types, the precipitation forced by vertical motion significantly influences the aerosol concentration at both sites. If air mass differences between the

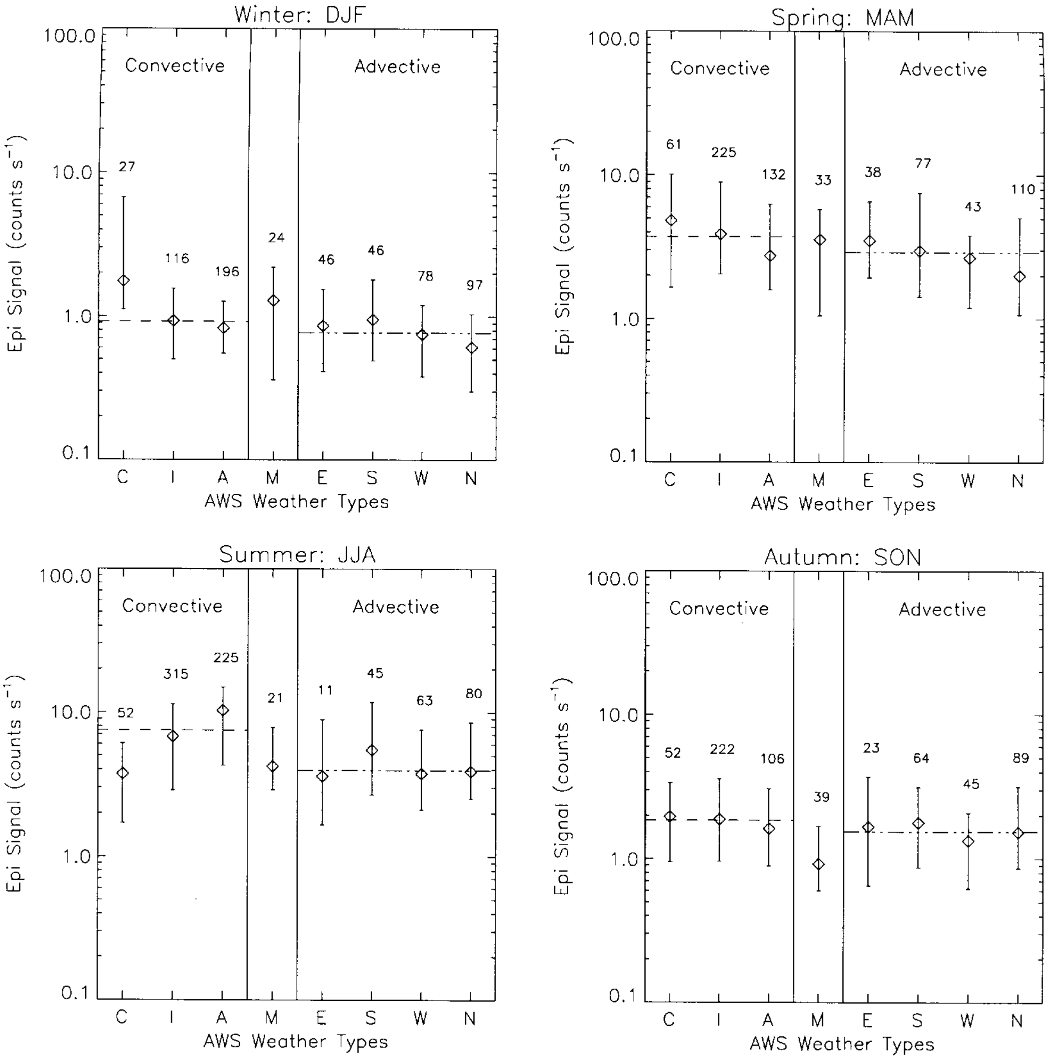

Fig. 6. Seasonal median (diamond) and quartile values (whiskers) of the daily median epi signal at the Jungfraujoch as a function of the extended AWS weather types for the period from April 1988 until September 1996. Number of days with measurements are given for each season and each weather type. The dashed line is the seasonal median for all convective weather types, the dash-dotted line that for all advective weather types. Abbreviations: DJF-December, January, February, MAM-March, April, May, etc.

advective types were dominant, more significant differences in aerosol concentrations between the advective weather types and more coherence between the Jungfraujoch and Colle Gnifetti would be expected.

3.4.2. Aerosol concentrations within the convective and mixed weather types. Within the basic convective weather type, the differences in aerosol concentrations between the extended types were large. The differences were most pronounced between the cyclonic and anticyclonic weather types (Fig. 6, Table 5). These differences changed with season. In winter, the aerosol concentration decreased significantly from the weather type C over I to A. In spring, this tendency still prevailed,

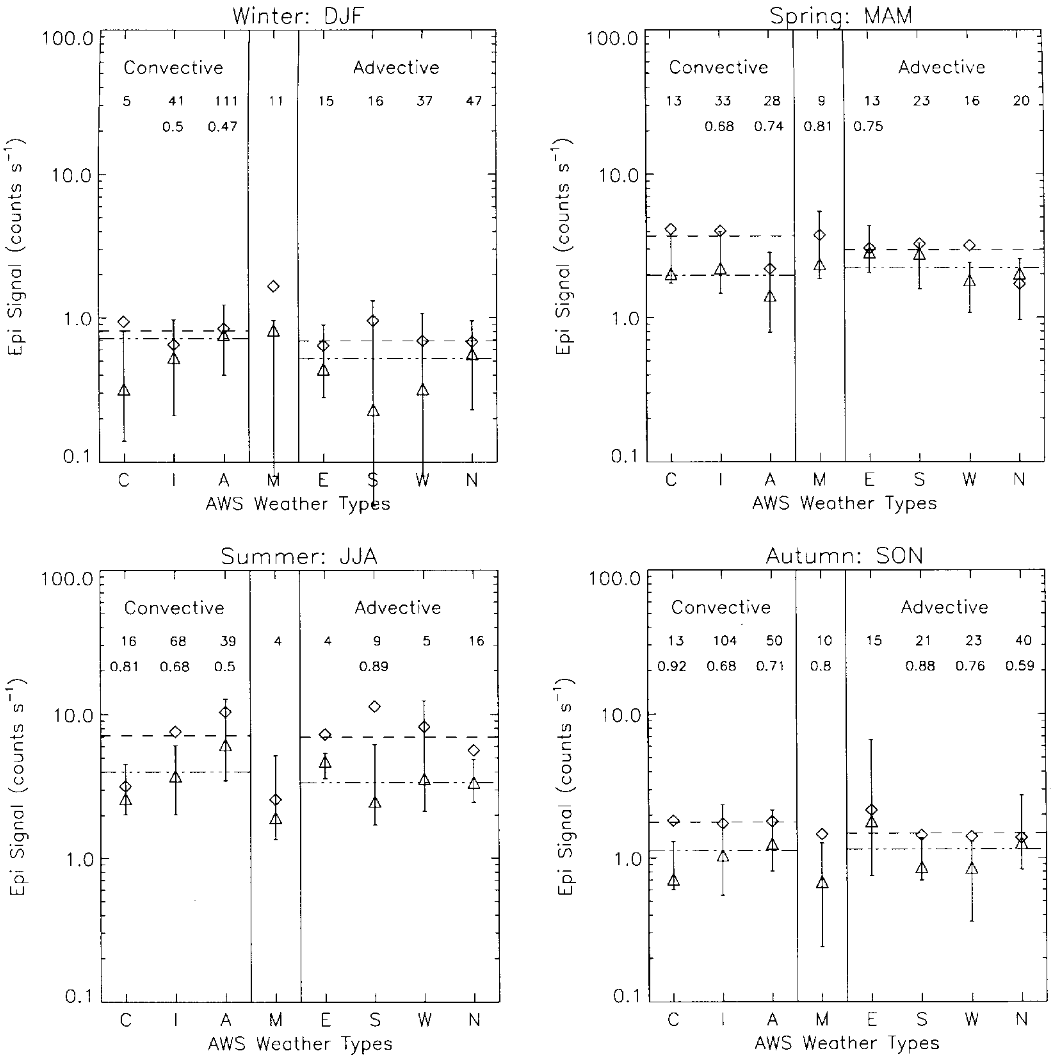

Fig. 7. Seasonal medians (triangle for Colle Gnifetti, diamond for Jungfraujoch) and quartile values (whiskers, only for Colle Gnifetti) of the daily median epi signal for the common measurement period. The number of days with epi data at Colle Gnifetti is given for each season and each weather type for comparison with the numbers given in Fig. 6. Additionally, the correlation coefficient *r* between the daily median epi signal at the Jungfraujoch and at Colle Gnifetti are given for weather types, where *r* is significant at the 99% level. The seasonal medians at Jungfraujoch are given by the dashed lines for the convective and advective weather types, respectively. The dashed dotted lines are the corresponding medians at Colle Gnifetti.

but with a lower significance. In summer, the aerosol concentration increased from the weather type C over I to A, again with high significance. Finally, the average concentrations in autumn were similar to the winter characteristics, but the differences in aerosol concentration were small. The median aerosol concentration of the mixed weather type was above average in winter and below average in summer, similar to that of weather type C. In autumn, the aerosol concentrations during periods of type M were very low. The aerosol data from Colle Gnifetti and Jungfraujoch, restricted to the common period, are shown in Fig. 7 and the *p*-values of the Wilcoxon-test for

Table 5. *Probability values for the significance of a concentration difference between the AWS grouped epi data from Jungfraujoch, shown in Fig. 6*

Winter

	C	I	A	E	S	W
C	—					
I	10^{-4}	—				
A	10^{-4}	0.34	—			
M	0.03	0.6	0.36			
E				—		
S				0.53	—	
W				0.33	0.1	—
N				0.08	0.02	0.35

Spring

	C	I	A	E	S	W
C	—					
I	0.66	—				
A	0.04	0.01	—			
M	0.07	0.07	0.63			
E				—		
S				0.67	—	
W				0.05	0.15	—
N				0.08	0.15	0.79

Summer

	C	I	A	E	S	W
C	—					
I	10^{-4}	—				
A	10^{-4}	10^{-4}	—			
M	0.06	0.42	0.02			
E				—		
S				0.21	—	
W				0.55	0.14	—
N				0.4	0.17	0.8

Autumn

	C	I	A	E	S	W
C	—					
I	0.64	—				
A	0.64	0.01	—			
M	0.01	10^{-4}	10^{-3}			
E				—		
S				0.86	—	
W				0.57	0.38	—
N				0.98	0.68	0.6

Small values indicate high significance levels, e.g. a value of 0.05 corresponds to a significance level of 95%. Analysis based on the Wilcoxon rank sum test.

Table 6. *Same as Table 5 for epi data from Colle Gnifetti, shown in Fig. 7*

Winter

	C	I	A	E	S	W
C	—					
I	0.62	—				
A	0.13	0.04	—			
M	0.8	0.82	0.15			
E				—		
S				0.68	—	
W				0.48	0.84	—
N				0.89	0.59	0.34

Spring

	C	I	A	E	S	W
C	—					
I	0.78	—				
A	0.13	0.11	—			
M	0.74	0.58	0.26			
E				—		
S				0.47	—	
W				0.02	0.03	—
N				0.03	0.12	0.79

Summer

	C	I	A	E	S	W
C	—					
I	0.17	—				
A	10^{-3}	0.01	—			
M	0.42	0.36	0.05			
E				—		
S				0.49	—	
W				0.9	0.42	—
N				0.32	0.41	0.9

Autumn

	C	I	A	E	S	W
C	—					
I	0.4	—				
A	0.04	0.1	—			
M	0.48	0.15	0.02			
E				—		
S				0.06	—	
W				0.02	0.53	—
N				0.23	0.13	0.03

the Colle Gnifetti data in Table 6. The high aerosol concentration of type A and the low concentration of type C in summer were a common feature of both sites and both time periods. Therefore, the summer observations at Colle Gnifetti and at the Jungfraujoch are likely to be explained by the same mechanism. Noteworthy also is the significant correlation between the data of both sites for the individual weather types in summer (Fig. 7). However, in winter the aerosol concentration increased on average from cyclonic to anticyclonic conditions at Colle Gnifetti, resulting in a larger aerosol gradient between the Jungfraujoch and Colle Gnifetti under type C conditions than under type A conditions. In autumn, a similar tendency was observed.

The vertical distribution of the aerosol mass in the troposphere typically shows an exponential decrease with increasing altitude up to a certain height and a rather constant profile above this height (Jaenicke, 1993). Under the assumptions of a horizontally homogeneous aerosol distribution and no sources and sinks, the aerosol concentration at a fixed altitude changes only by vertical transport. Therefore, lifting increases the aerosol concentration at a certain height, whereas subsidence reduces it. On the other hand, lifting can induce the formation of clouds and precipitation, which is an important sink for aerosol particles (Hobbs, 1993). Conversely, the evaporation of clouds during subsidence can be a source for dry aerosols (Jaenicke, 1993 and reference therein). Whether the aerosol concentration at a certain height in a vertical motion field increases or decreases depends on how much the change resulting from vertical transport is compensated by aerosol relevant cloud processes.

The decline of the average aerosol concentration from weather type C to A at the Jungfraujoch in winter (Fig. 6) is expected, if transport by the synoptic scale lifting rather than cloud processes is the dominant mechanism. The reversed tendency in aerosol concentration, observed at Colle Gnifetti, could be caused by a weakening of the vertical transport with increasing height or by height dependent aerosol scavenging, or both.

In summer, the aerosol concentrations increased roughly by a factor of 2.5–3 from cyclonic to anticyclonic conditions at both sites. This result is counter-intuitive with respect to aerosol transport by the synoptic scale vertical motion. Scavenging of aerosol particles by cloud droplets could be one reason for the low concentration values during type C conditions in summer at the Jungfraujoch and at Colle Gnifetti. It can be assumed that this process is more effective under type C than type A conditions, see the differences in sunshine duration, shown in Table 4. However, this interpretation cannot explain the differences in aerosol concentration between A and C for all the other seasons, since the presence of clouds during weather type C is a feature independent of the season (Table 4). Therefore, neither vertical aerosol transport by the synoptic scale vertical motion nor aerosol scavenging by cloud droplets can explain the observations. We conclude that aerosol transport by thermally driven convection, which was recognised as the main vertical transport process in summer (Fig. 4), must be different between the convective weather types. Fig. 8 shows the diurnal variation of the median epi signal at the Jungfraujoch and at Colle Gnifetti in summer and winter for the convective weather types. Indeed, in contrast to weather type C, the weather types A and I exhibited a pronounced late afternoon peak in the aerosol concentration. At Colle Gnifetti, the concentration peaks occurred at 2000 LST, about 2 hours after the peaks at the Jungfraujoch.

Fig. 8 illustrates not only that thermally driven aerosol transport can reach altitudes up to 4.5 km, but also that this transport mechanism depends on the direction of the synoptic-scale vertical motion above the central Alpine region. The diurnal variation of the water vapour mixing ratio, shown in Fig. 9, was similar to that of the aerosol concentration. Under the condition of weak horizontal advection, the water vapour mixing ratio is also a tracer for vertical motion. Pronounced differences within the convective weather types were also present for the sunshine duration (Fig. 9). Under cyclonic conditions, the Jungfraujoch was within clouds most of the day, whereas under anticyclonic conditions a clear sky prevailed until the afternoon.

Under anticyclonic conditions, the synoptic scale subsidence causes the dissipation of clouds in the troposphere, resulting in high radiation fluxes at the surface and subsequently a strong warming of the air near the surface. By this way, a convective boundary layer (CBL) develops, in which intense vertical mixing takes place. A

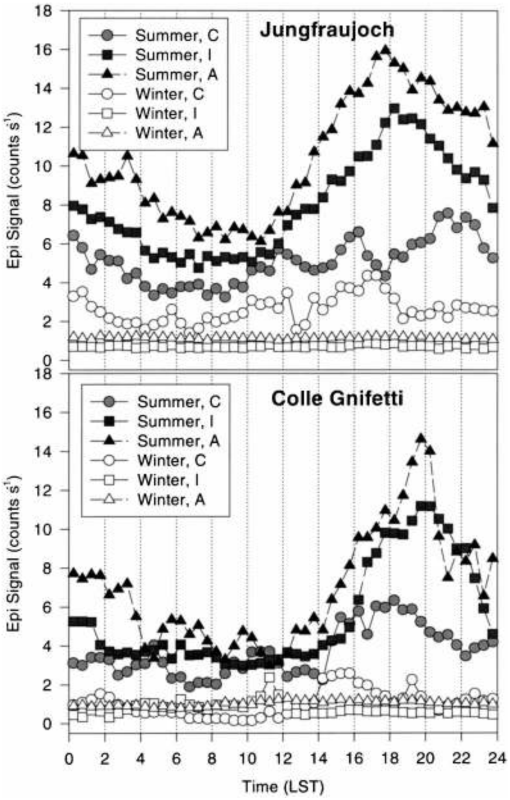

Fig. 8. Diurnal variation of the median epi signal at the Jungfraujoch and Colle Gnifetti for the 3 convective weather types. Data include the seasons winter and summer from 1988 to 1992.

detailed description of the dynamics of the CBL is given by Garratt (1992). From Fig. 8 we conclude that the Jungfraujoch and even Colle Gnifetti are influenced by the transport processes within the CBL under type A and to a lesser extent under type I conditions. Under cyclonic conditions the synoptic scale lifting causes the formation of stratiform clouds, which reduce the surface heat fluxes and therefore the potential for aerosol transport by thermally driven convection. Thus, thermal convection can reach altitudes of 4.5 km quite frequently, in contrast to the fact that mountain stations, even at much lower altitudes, are quite often considered as purely free tropospheric sites (Kley et al., 1994; Bonasoni et al., 1996).

3.4.3. Topographic amplification of the convective aerosol transport. The complex topography

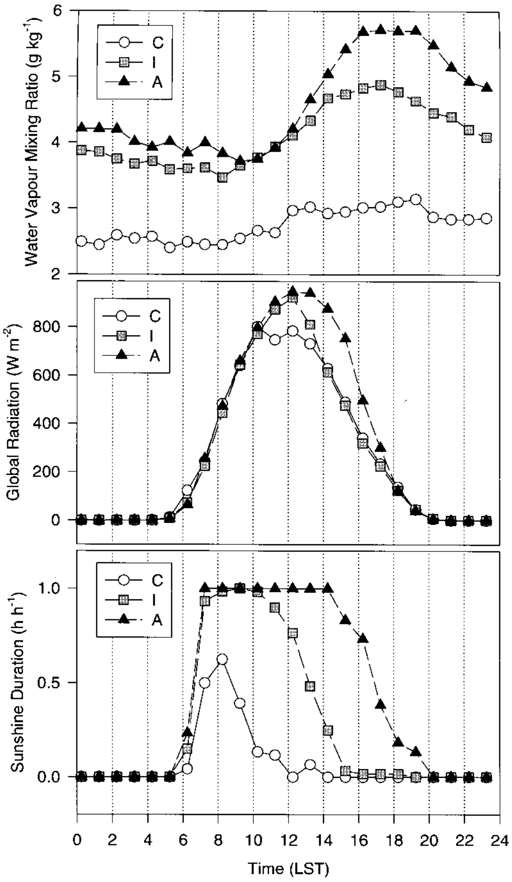

Fig. 9. Diurnal variation of the median water vapour mixing ratio, the median global radiation and the median sunshine duration at the Jungfraujoch for the three convective groups C, I and A. Summer data from 1988 to 1992 are shown.

renders the determination of the height of the CBL difficult. Topographically induced wind currents such as mountain-valley winds and slope winds, see Whiteman (1990) and references therein, will modify the structure of the CBL compared to the structure over homogeneous terrain.

We believe that the following analysis reflects an amplification of the thermally driven vertical transport of aerosols by the Alpine topography. Fig. 1 shows that during advection from northwest to north, air from the Swiss plateau reaches the Jungfraujoch, whereas during advection from south to south-west, air from a large mountainous area reaches the Jungfraujoch. If the topographical

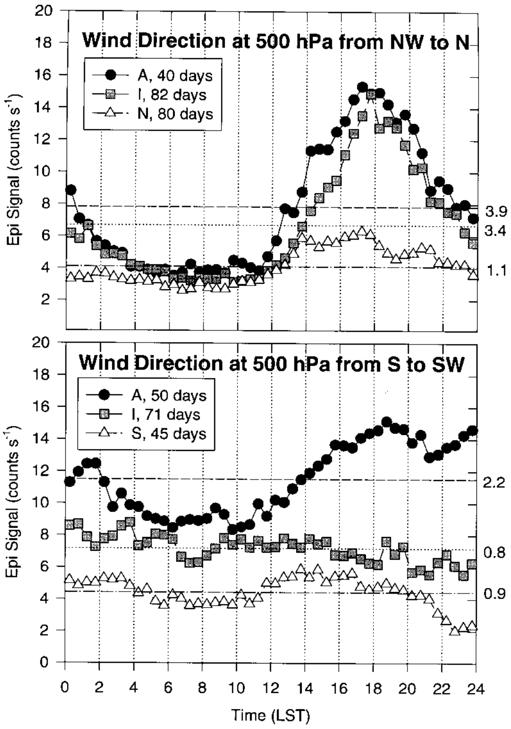

Fig. 10. Diurnal variation of the median epi signal at the Jungfraujoch during wind directions from north and south for the convective weather types A and I and during the advective weather types N and S. The total average (horizontal line) and the standard deviation (number on the right side) of the diurnal variation is given for each group. Summer data from 1988 to 1996 are shown.

differences cause differences in the vertical extent of the thermally driven transport, a distinction of the aerosol data by the wind direction should reflect these differences. A wind analysis showed that the wind direction at the Jungfraujoch is mainly from north-west, when the 500 hPa wind is within the north-western and northern sectors. Similarly, but to a smaller degree, south-easterly winds prevail at the Jungfraujoch, when the wind direction at 500 hPa is within the sectors from south to south-west. Therefore, taking the channelling of the local wind at the Jungfraujoch into account, the wind direction at the altitude of the Jungfraujoch and at 500 hPa ($\sim$5.6 km) are reasonably well correlated for our purposes.

In Fig. 10 the diurnal aerosol variations for the convective weather types A and I are shown for northerly (sector NW to N) and southerly (sector S to SW) wind directions at 500 hPa. The diurnal aerosol variations for the advective types N and S are also shown in order to emphasise the difference in concentration between the convective and advective types for the same wind directions. During northerly advection in the free troposphere of the A and I weather types low concentrations before noon and a steep increase in the afternoon was observed at the Jungfraujoch. During southerly advection, the diurnal mean concentrations were similar or even higher (weather type A) than during northerly advection, but the diurnal variations were much less pronounced. We believe that the topographical influence on differences in the thermally driven aerosol transport is most clearly visible in the diurnal variations of weather type A of Fig. 10. We interpret the pronounced afternoon aerosol peak, which occurred only with northerly winds, as caused by thermally driven transport taking place in a relatively small area in the vicinity to the north of the Jungfraujoch. After 1715 LST the aerosol rich air at the Jungfraujoch is continuously replaced by air from the free troposphere above the Swiss plateau, where the aerosol concentration at the same altitude is considerably lower. A late afternoon peak at 1845 LST occurred also during type A conditions with southerly winds, which in a similar way must be due to the convective transport taking place in the vicinity south of the Jungfraujoch. The continuously high aerosol concentrations and the other maxima at 2400 and 0200 LST during southerly advection can be understood as transport of air, in which thermal convection reached high altitudes at different locations of the mountainous terrain upstream of the Jungfraujoch. The difference in the diurnal variation suggests that thermally driven aerosol transport up to 3.5 and even 4.5 km is a phenomenon limited to the Alpine area.

4. Conclusions

Aerosol data from two high Alpine sites were analysed with respect to the annual cycles, diurnal variations and changes on a synoptic time scale. Characteristic annual and diurnal aerosol patterns were found, common to both sites. These patterns could be explained by the seasonal development of thermally driven vertical transport, which itself is controlled by the synoptic weather conditions. Synoptic scale subsidence, associated with the presence of an anticyclone above the Alps, promotes thermally driven vertical transport of aerosol rich air from the boundary layer to the high Alpine sites. During synoptic scale lifting, the thermally driven transport is absent in summer. Beyond that there is evidence that the thermally driven vertical transport is enhanced above the Alpine area.

From these observations, important implications arise regarding the question: how much does the air at a mountain station represent free tropospheric conditions? As our results suggest, a discrimination between free tropospheric and boundary layer influenced periods at a mountain observatory in the Alps cannot be based only on the restriction to a certain period of the day or on the diurnal variation of a tracer, as it is possible for an isolated mountain station, such as the Mauna Loa observatory on Hawaii. The duration of a boundary layer influenced period, caused by thermal convection, depends critically on the geographical location of the site within the Alpine body and the advection direction of the synoptic scale horizontal wind. If the horizontal scale of the Alpine topography L upstream of a flow with speed U is small, a relatively sharp peak with high concentrations over the period $\Delta T = L/U$ can be expected on days with intense thermal convection. If the horizontal scale L increases, as with southerly advection to the Jungfraujoch, ΔT increases and may extend over periods, when the local convection has already ceased. The concentrations measured during such episodes are characteristic only on a regional scale and should not be taken as representative for the free troposphere on a larger scale, even though they will probably remain in the free troposphere. The mixing process of such polluted layers within the free troposphere depends on the lifetime of the aerosol particles ($\sim$1 week) and the turbulence of the wind field. Therefore, one can imagine that distinct layers keep their identity within the free troposphere for several days, especially when mechanical turbulence is low, as under anticyclonic conditions.

Finally, we want to point out that an analysis of the height of the 500 hPa pressure surface and the horizontal pressure gradient can give valuable information to decide whether the aerosol concentration at the high Alpine site is caused by long-range or local vertical transport.

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REFERENCES

Baltensperger, U., Gäggeler, H. W., Jost, D. T., Emmenegger, M. and Nägeli, W. 1991. Continuous background aerosol monitoring with the epiphaniometer. *Atmos. Environ.* **25A**, 629–634.

Baltensperger, U., Gäggeler, H. W., Jost, D. T., Lugauer, M., Schwikowski, M., Weingartner, E. and Seibert, P. 1997. Aerosol climatology at the high-alpine site Jungfraujoch, Switzerland. *J. Geophys. Res.* **102**, 19 707–19 715.

Bonasoni, P., Colombo, T., Lenaz, R., Tesi, G., Evangelisti, F., Giovanelli, G., Ravenagni, F. and Santaguida, R. 1996. Effect of Saharan dust transport on ozone and carbon dioxide concentration. In: *The impact of desert dust across the Mediterranean* (eds. S. Guerzoni and R. Chester). Kluwer Academic Publishers, Netherlands, 313–322.

Filliger, P., Buchmann, B. and Schwarzenbach, B. 1994. Air pollution measurements at the high alpine station Jungfraujoch (3580 m asl), Switzerland, 1973–1993. In: *Proceedings of EUROTRAC Symposium '94* (ed. P. M. Borrell, P. Borrell, T. Cvitas and W. Seiler). Academic Publishing, The Hague, 259–262.

Garratt, J. R. 1992. *The atmospheric boundary layer*. Cambridge University Press, Cambridge, 145–164.

Gäggeler, H. W., Baltensperger, U., Emmenegger, M., Jost, D. T., Schmidt-Ott, A., Haller, P. and Hofmann, M. 1989. The epiphaniometer, a new device for continuous aerosol monitoring. *J. Aerosol Sci.* **20**, 557–564.

Gilbert, R. O. 1987. *Statistical methods for environmental pollution monitoring*. Van Nostrand Reinhold Company, New York, 247–250.

Hobbs, P. V. 1993. Aerosol-cloud interactions. In: *Aerosol-cloud-climate interactions* (ed. P. V. Hobbs). Academic Press, San Diego, 33–73.

Holton, J. R. 1979. *An introduction to dynamic meteorology*. Academic Press, New York, 120–145.

Jaenicke, R. 1993. Tropospheric aerosols. In: *Aerosol-cloud-climate interactions* (ed. P. V. Hobbs). Academic Press, San Diego, 1-27.

Kley, D., Geiss, H. and Mohnen, V. A. 1994. Tropospheric ozone at elevated sites and precursor emissions in the United States and Europe. *Atmos. Environ.* **28**, 149–158.

Mendonca, B. G. 1969. Local wind circulation on the slopes of Mauna Loa. *J. Appl. Meteorol.* **8**, 533–541.

Nyeki, S., Baltensperger, U., Colbeck, I. and Jost, D. T. 1997. The Jungfraujoch high-alpine research station (3454 m) as a background clean continental site for the measurement of aerosol parameters. *J. Geophys. Res,* in press.

Oeschger, H., Schotterer, U., Stau er, B., Häberli, W. and Röthlisberger, H. 1977. First results from alpine core drilling projects. *Zeitschrift für Gletscherkunde und Glazialgeologie* **13**, 193–208.

Pandis, S. N., Baltensperger, U., Wolfenbarger, J. K. and Seinfeld, J. H. 1991. Inversion of aerosol data from the epiphaniometer. *J. Aerosol Sci.* **22**, 417–428.

Reiter, R., Carnuth, W. and Sladkovic, R. 1984. Determination of physical and chemical properties of the aerosol from 1972 to 1982 at a north-alpine pure air station at 1780 m a.s.l. Part III: Aerosol size spectra. *Arch. Met. Geoph. Biocl.* **B35**, 179–201.

Schüepp, M. and Schirmer H. 1977. Climates of Central Europe. In: *Worlds survey of climatology, vol. 6: Climates of central and southern Europe* (ed. C. C. Wallen). Elsevier Scientific Publishing Company, Amsterdam, 3–73.

Schüepp, M. 1979. Witterungsklimatologie. Klimatologie der Schweiz, Band III (in German, 94 pp). *Beilage zu den Annalen 1978*. (Available from Swiss Meteorological Institute, 8044 Zürich, Switzerland)

Schwikowski, M., Seibert, P., Baltensperger, U. and Gäggeler, H. W. 1995. A study of an outstanding Saharan dust event at the high-alpine site Jungfraujoch, Switzerland. *Atmos. Environ.* **29**, 1829–1842.

SMI (Swiss Meteorological Institute) 1985. *Alpenwetterstatistik Witterungskalender. Beschreibung der einzelnen Parameter* (in German, 26 pp) (available from Swiss Meteorological Institute, 8044 Zürich, Switzerland).

Whiteman, D. C. 1990. Observations of thermally developed wind systems in mountainous terrain. In: *Atmospheric processes over complex terrain* (ed. W. Blumen). Meteorological Monographs Vol. **23** Nr. 45, American Meteorological Society, Boston, Massachusetts, 5–42.

WMO 1991. *Report on the WMO meeting of experts to consider the aerosol component of GAW.* World Meteorological Organisation, Global Atmosphere Watch, Geneva.

Wunderli, S. and Gehrig, R. 1990. Surface ozone in rural, urban and alpine regions of Switzerland. *Atmos. Environ.* **24A**, 2641–2646.