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# Convective Boundary Layer Evolution to 4 km asl over High-Alpine Terrain: Airborne Lidar Observations in the Alps

S. Nyeki,[1,2] M. Kalberer,[1] I. Colbeck,[2] S. De Wekker,[3] M. Furger,[1] H. W. Gäggeler,[1]
M. Kossmann,[4] M. Lugauer,[1] D. Steyn,[3] E. Weingartner,[1] M. Wirth[5], and U. Baltensperger[1]

**Abstract.** Mountain ranges have important influences on the structure and composition of the convective boundary layer (CBL) and free troposphere (FT). Evolution of the summer CBL, measured over the European Alps using airborne lidar, was clearly observed to attain a near-uniform height up to 4.2 km asl by early afternoon. A climatology of in-situ high-alpine aerosol measurements suggests that such substantial growth, corresponding to ~ 0.3 of the mid-latitude tropopause height, often occurs during summer months. Subsequent nocturnal collapse of the CBL was estimated to result in the venting of ~ 0.8 ± 0.3 ($SO_4$) Gg day$^{-1}$ into a FT residual layer, leeward of the Alps.

## 1. Introduction

Atmospheric structure in the lower troposphere over high-alpine terrain is still poorly defined [*Blumen*, 1990], despite the importance of the European Alps, Rocky mountains, Andes and Tibetan plateau on synoptic and global-scale circulation of the atmosphere [*Barry*, 1992]. Exchange of airmasses from the convective boundary layer (CBL) into the free troposphere (FT), or venting, is aided by mountain ranges [*Kossmann et al.*, 1999] and may thus affect the spatial and temporal distribution of aerosol properties. Hence CBL depth is a fundamental variable in boundary layer (BL) research. While airborne aerosol lidar is being increasingly used to investigate CBL evolution, most investigations have so far only considered flat terrain [*Cooper and Eichinger*, 1994], coastal mountainous regions [*McElroy and Smith*, 1986] or pre-alpine terrain [*McElroy and Smith*, 1991]. In order to study CBL evolution over high-alpine terrain, an airborne campaign was conducted over the Jungfraujoch (JFJ) research station (46.55°N, 7.98°E; 3580 m; Switzerland). Favorable conditions for an observational case study were encountered on July 30, 1997, when a nadir-pointing aerosol lidar (wavelength $\lambda$ = 532 nm) aboard the German Aerospace Establishment (DLR) Falcon 20 jet aircraft [*Kiemle et al.*, 1995] obtained a dataset with high temporal and spatial resolution of atmospheric structure below 8 km.

## 2. Meteorological Conditions

Synoptic conditions were such that a high-pressure ridge extended from Scandinavia to southern France. Airmass back-trajectory analyses using the 48-hour mesoscale model of the Swiss Meteorological Institute suggested an origin from over the north Atlantic. Airborne measurements from stacked vertical profiles (4.5 - 12 km) above the JFJ in the morning and afternoon [*Nyeki et al.*, 1999] indicated a uniform wind direction from the north-west (305 - 315°) with a moderate wind strength (7 - 15 m s$^{-1}$). The middle and upper FT was stably stratified, where $\Delta\theta/\Delta z$ ~ 4.1 K km$^{-1}$ ($\theta$ = potential temperature). Although profiles below 4.5 km were not available in the inner Alps, 1200 UTC radiosonde data windward of the Alps (Payerne, Switzerland; Lyon, France; Munich, Germany) indicated a CBL top capped by a subsidence inversion at 2000 – 2500 m, while leeward profiles (Milan and Udine, Italy) showed the subsidence to reach to 3000 m.

## 3. Results and Discussion

Lidar measurements consisted of a morning and afternoon flight pattern (Figure 1) over the JFJ massif at 8 km, oriented parallel and orthogonal to the regional mountain divide (NE-SW). Six similar transects (labeled P3) were flown during the day and are shown in Figure 2, where atmospheric structure is depicted by the aerosol backscatter ratio, $B$ (i.e. (Rayleigh + aerosol scatter)/ Rayleigh scatter)). Transect P3 represents the sharp transition in topography from the pre-alpine foothills in the Emmental region (up to ~ 2000 m), through the JFJ and the surrounding massif (3000 - 4000 m),

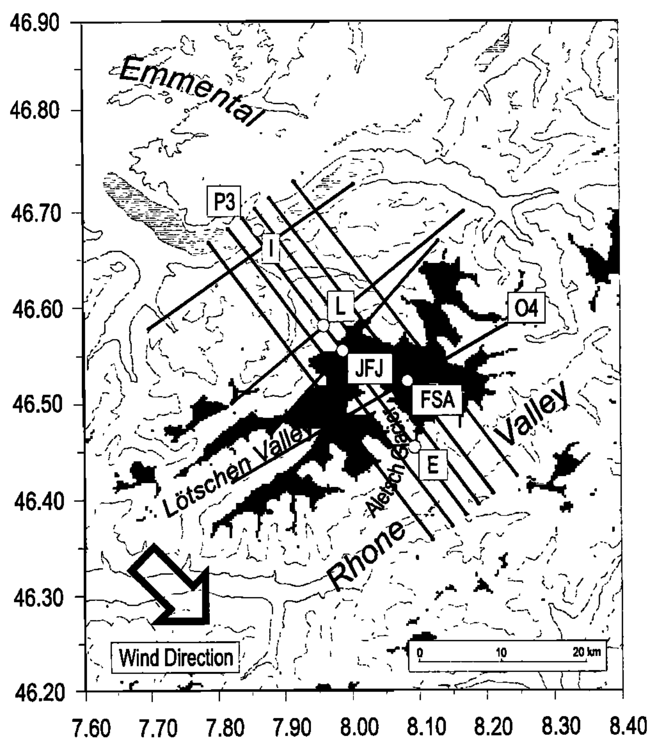


**Figure 1.** Nominal lidar pattern over the JFJ region at 8000 m. Topographic intervals at 1000 m, darkest = 3000 - 4000 m. Abbreviations: I = Interlaken town (563 m), L = Lauberhorn (2472 m), JFJ = Jungfraujoch station (3580 m), FSA = Finsteraarhorn (4274 m), and E = Eggishorn (2927 m).

[1] Paul Scherrer Institute, Villigen, Switzerland.
[2] University of Essex, Colchester Essex, England.
[3] University of British Columbia, Vancouver, Canada.
[4] University of Canterbury, Christchurch, New Zealand
[5] DLR, Oberpfaffenhofen, Germany.



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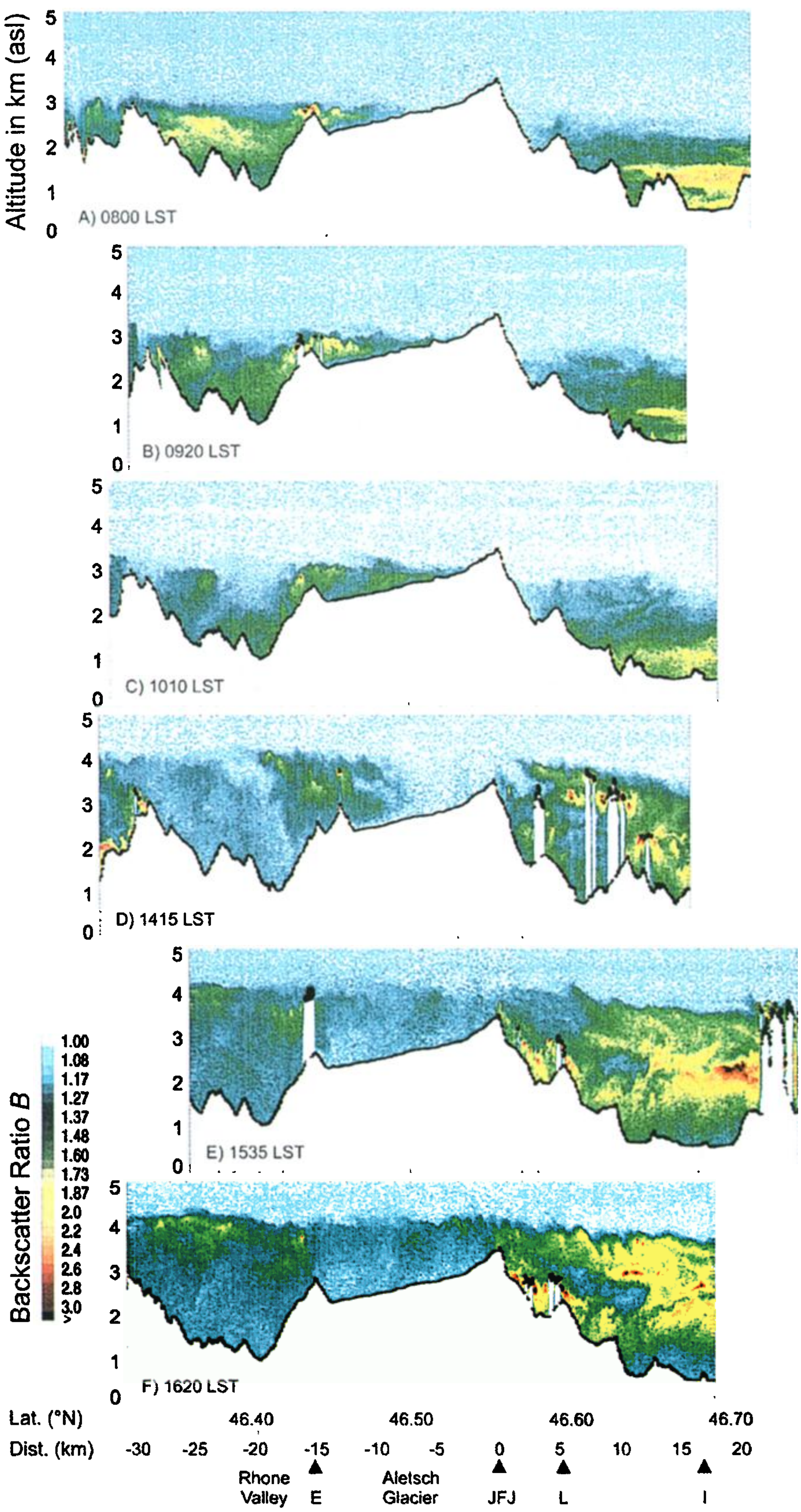


**Figure 2.** Lidar transects (transect P3) illustrating CBL temporal evolution over the JFJ massif. Details same as in Figure 1.

and down over the Aletsch glacier towards the inner Swiss and Italian Alps. Pre-alpine landuse consists largely of urban, agricultural and forested areas, which changes to snow and glaciated cover above the snowline at ~ 2500 m in late summer. Transect times at 0800 LST (= UTC + 1), 0920, 1010, 1415, 1535 and 1620 in Figure 2, correspond to average BL heights of ~ 2.5 km, 2.7, 2.8, 3.9, 4.0 and 4.0, respectively. In the early morning (Figure 2A-C), the growing CBL is hard to distinguish from the residual layer, with the latter most probably forming the upper boundary of the BL. However, CBL growth occurs fairly rapidly thereafter, until the last two transects illustrate a quasi-stationary average CBL height of ~ 4.0 km, which is substantial as it corresponds to ~ 0.3 of the tropopause height at ~ 12.5 km.

A number of dynamical features are evident in Figure 2 and include: Cloud formation above south-facing slopes (e.g. Fig. 2D-F, 46.59°N), cloud-forming thermals that reach to the CBL top (e.g. Figure 2E, 46.73°N), and maximum growth of the CBL to ~ 3.1 km agl (above ground level) above some valleys which is comparable to strong CBL growth over flat terrain. It should be noted that enhancements in *B* are partly due to aerosol humidity growth above a relative humidity ~ 85% and not only to increased aerosol concentrations from natural or anthropogenic activity. Among the interesting aspects in Figure 2, two main features are discussed in greater detail: Uniformity or "levelness" of the CBL top, and katabatic flow of FT air down the JFJ massif.

Transects in Figure 2 exhibit no significant terrain-following behavior of the CBL top, at least over a spatial scale of 20 - 25 km. Similar observations of CBL levelness were recently made in an investigation over the Black Forest region (< 1500 m) of southern Germany [*Kossmann et al.*, 1998, *Kalthoff et al.*, 1998]. However, terrain-following behavior was observed to occur during the morning, and only changed in the afternoon when the CBL depth exceeded the characteristic scale of the obstacle, given by $Z = (H\,L)^{0.5}$, where $H$ and $L$ are the characteristic height and length of the mountain, respectively [*Kalthoff et al.*, 1998]. When applied to the JFJ massif ($H$ ~ 2500 m and $L$ ~ 40 km), this results in $Z$ ~ 10 km, and is ~ 3 times the maximum observed CBL depth of 3100 m over the Rhone valley (Figure 2D-F, 46.41°N). While elementary concepts exist for the description of CBL levelness over smooth hilly terrain below the snowline [*Stull*, 1992], concepts for high-alpine mountainous terrain and the influence of high snow/ice albedo on CBL evolution have yet to be developed.

Characterization of the CBL top largely depends on the horizontal scale of investigation. Over scales similar to transect P3 (~ 45 - 50 km), an inclination of the CBL top towards the Emmental region is seen in Figure 2. The residual layer over the Rhone valley lies ~ 700 m higher than over the Emmental region at 0800 LST, and is a feature that remains throughout the day, reducing to a height differential of ~ 400 m by 1620 LST. This may partly be explained by the different average altitude both windward (500 - 2000 m) and leeward (2500 - 3500 m) of the mountain divide. On a scale larger than 100 km, results in Figure 2 and radiosonde profiles suggest that the CBL top follows the large-scale topography of the Alps.

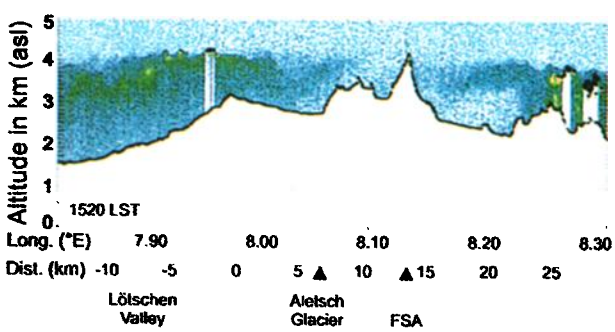


**Figure 3.** Lidar transect O4 (1520 LST), illustrating katabatic flow down the JFJ massif.

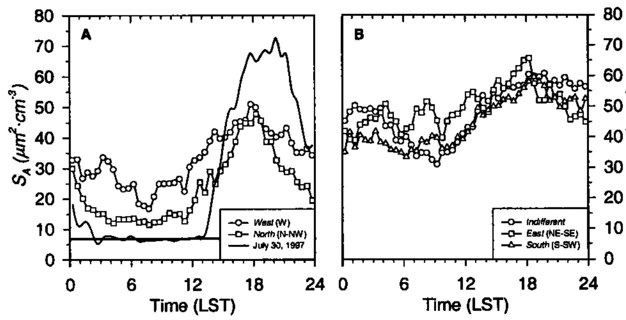


**Figure 4.** JFJ diurnal cycle of the median aerosol surface area concentration ($S_A$). Anticyclonic conditions for June – August (1988 – 1997) for the following categories: (A) *North* and *West*, and (B) *South*, *East* and *Indifferent*. Horizontal line indicates mean FT conditions on July 30, 1997.

Several events, in which cleansing flows of FT air penetrate into the CBL, are seen at various times and locations in Figure 2. High-resolution analysis of transects in Figure 2A-B reveals the flow of FT air down the Aletsch glacier in a surface layer 50 - 80 m agl. Similar glacier winds up to 100 m agl have been observed on the Pasterze glacier in Austria [*van den Broeke*, 1997]. However, a more significant feature is the large katabatic intrusion of FT air onto the Aletsch glacier and down the northface of the JFJ massif in Figure 2D, which persisted to a lesser extent for at least two hours until the last transect. Further evidence of the spatial extent of the intrusion is seen at 1520 LST in transect O4 (Figure 3), oriented orthogonal to transect P3. Based on these results and other lidar transects (not shown), only one large intrusion was observed to occur, whose horizontal spatial extent (~ 15 x 25 km) corresponded approximately to that of terrain above the snowline. These katabatic intrusions arise from the cold air directly above ice/snow surfaces resulting in the sinking of FT air. Aerosol and meteorological records at the JFJ (discussed below) and the Eggishorn automatic station (Fig, 1; point E) confirm this intrusion, but also indicate that such occurrences are not common.

Evidence of substantial CBL growth and a diurnal variation in CBL height also appears in the long-term, in-situ JFJ and airborne aerosol records. Measurements of the aerosol surface area concentration ($S_A$) have been conducted since 1988 at the JFJ and intermittently from 1988 - 1994 at Colle Gnifetti (4452 m; 45.90°N, 7.87°E, Switzerland) [*Baltensperger et al.*, 1997; *Lugauer et al.*, 1998]. Figure 4 exhibits the distinct diurnal cycle at the JFJ from 1988 - 1997 during summer months, and indicates the arrival of CBL airmasses at 1200 - 1300 LST, reaching a maximum at 1800 LST and a minimum after 0200 - 0300 LST. The time period during which FT conditions prevail is therefore provisionally defined here as 0300 - 0900 LST, and the remaining period as BL conditions. A similar diurnal cycle, beginning 2 hours later under similar synoptic conditions, also occurs at Colle Gnifetti and suggests CBL growth to above 4500 m, but would require confirmation with for instance an aerosol airborne lidar. While the onset of CBL conditions is evident in the aerosol record, the time at which the CBL "collapses" and a new nocturnal BL forms is more difficult to estimate. Due to the presence of residual CBL layers windward of the JFJ, which attain a maximum height of 3800 m over the Emmental region (Figure 2E-F), FT conditions are only restored once these layers have been advected away.

Transects in Figure 2 indicate that the transport mechanism of airmasses to the JFJ depends mainly on CBL growth, rather than on local thermally-induced winds. Although some evidence for these winds are seen in Figure 2E-F, on the northern flank of the JFJ massif (46.56 - 46.58°N) as a local increase in *B*, they are expected to be less significant due to the aspect and snow/ice-cover of the incline [*Baltensperger et al.*, 1997].

Long-term results have also been analyzed according to the synoptic Alpine Weather Statistics (AWS) scheme [*Schüepp*, 1979]. Figure 4A and B illustrates that winds in the i) *North* and *West* categories during FT conditions exhibit a lower mean value of $S_A$ (18.5 $\mu m^2\ cm^{-3}$; STP conditions unless stated) than in ii) the *South*, *East* and *Indifferent* categories (40.5 $\mu m^2\ cm^{-3}$). The higher mean elevation and areal extent of the inner Alps (2500 - 3500 m) south of the JFJ massif, in comparison to the Emmental region, results in this behavior [*Lugauer et al.*, 1998]. The JFJ diurnal variation in $S_A$ on July 30 resembles and corresponds to the AWS anticyclonic *North* category in Figure 4. A sharp increase was observed to begin at ~1300 LST, and agrees with lidar transects which indicate growth of the CBL to JFJ altitude between 1010 and 1415 LST (Figure 2C-D). Airborne measurements in the lower troposphere (4.5 - 5.5 km) indicated that $S_A$ = 8.7 - 9.0 $\mu m^2\ cm^{-3}$ during both morning and afternoon vertical descents over the JFJ [*Nyeki et al.*, 1999], illustrating that the CBL top was below 4.5 km.

An alternative method to determine CBL height is through in-situ JFJ aerosol and column-integrated aerosol optical depth (AOD) measurements on July 30. Reasonable assumptions include a well-mixed CBL above the JFJ and that the increase in AOD during the daytime is due to CBL aerosols. Using the 1620 LST lidar transect (Figure 2F), for which the CBL is more fully-developed and homogeneous than other transects, an AOD-derived depth of 370 ± 80 m agl gives a total CBL depth of 3950 ± 80 m and compares well with the lidar value of 4000 - 4100 m.

A final issue of importance concerns the relevance of the JFJ data record on mountain venting of CBL airmasses into the FT. Recent evidence suggests that once pollutants have been transported to high elevations, horizontal advection then plays an important role in the formation of FT residual layers [*Kossmann et al.*, 1999]. This is also observed here in radiosonde profiles. The water vapor mixing ratio (*r*) profile from the Milan 0000 UTC radiosounding on July 31, exhibited a layer of enhanced *r* above the CBL up to 4 km, a feature not seen in the windward 1200 UTC Payerne radiosounding on July 30. Similar findings were also observed for locations windward (Munich and Lyon) and leeward (Udine) of the Alps, and suggest that the source of this humidity was vertical transport in the Alps.

Based on this evidence and the JFJ aerosol record, a simple box model was used to estimate the CBL aerosol mass concentration vented into the lower troposphere, leeward of the Alps. The aerosol sulfate mass concentration (*M*) in the accumulation mode range ($d$ = 0.1 - 1.0 $\mu m$) has been shown to correlate well with $S_A$ at the JFJ (see *Baltensperger et al.*, 1997). Hence, it is estimated that $M = 3.30 \pm 0.33$ ($SO_4$) $\mu g\ m^{-3}$ during CBL conditions on July 30, 1997 (Fig. 4A), which compares well with the corresponding AWS *North* value of $M = 2.90 \pm 0.30$ ($SO_4$) $\mu g\ m^{-3}$. Dimensions of the residual aerosol layer appearing leeward of the Alps were estimated from: i) radiosoundings (depth = 2000 ± 100 m), ii) windward breadth of the Alps (width = 630 ± 50 km) and iii) duration of CBL conditions and the average windspeed (to give length = 197 ± 28 km). Results gave 0.8 ± 0.3 ($SO_4$) Gg $day^{-1}$ for July 30, and compares with 18.6 ($SO_4$) Gg $day^{-1}$ (yearly average) for CBL airmass exchange with the FT over Europe [*Chin and Jacob*, 1996]. These translate into a vertical flux of ~ 6.5 ± 2.7 kg $km^{-2}\ day^{-1}$ over the Alps and a yearly average value of ~ 1 kg $km^{-2}\ day^{-1}$ for Europe using the horizontal dimensions given above. As this estimate for aerosol export to the FT via residual layers is based on a number of assumptions (point measurements at the JFJ, well-mixed CBL), interpretation should be restricted to the specific meteorological conditions encountered on July 30, 1997. Applicability of our results on a spatial alpine-wide scale is suggested by radiosoundings, while on a temporal scale, further airborne lidar data during different seasons and meteorological situations are required. However, as a first-order estimate, mountain-induced venting may only be an important mechanism under certain synoptic conditions during summer months.

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U. Baltensperger, M. Furger, H. W. Gäggeler, M. Kalberer, M. Lugauer, S. Nyeki, and E. Weingartner, Paul Scherrer Institute, CH-5232 Villigen, Switzerland. (email: nyeki@psi.ch)

I. Colbeck, Institute for Environmental Research, University of Essex, Colchester/Essex, CO4 3SQ, England.

S. De Wekker, and D. Steyn, Dept. Geography, University of British Columbia, 217-1984 West Mall, Vancouver BC, V6T 1Z2, Canada.

M. Kossmann, Dept. Geography, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.

M. Wirth, Institute for Atmospheric Physics, DLR, Oberpfaffenhofen, D-82234 Wessling, Germany.

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