Elucidating local pollution and site representativeness at the Jungfraujoch, Switzerland through parallel aerosol measurements at an adjacent mountain ridge

To cite this article: Nicolas Bukowiecki et al 2021 Environ. Res. Commun. 3 021001

View the article online for updates and enhancements.

You may also like

- First full dynamic range calibration of the JUNGFRAU photon detector
  S. Redford, M. Andrà, R. Barten et al.

- Operation and performance of the JUNGFRAU photon detector during first FEL and synchrotron experiments
  S. Redford, M. Andrà, R. Barten et al.

- Assessing local CO₂ contamination revealed by two near-by high altitude records at Jungfraujoch, Switzerland
  Stéphane Affolter, Michael Schibig, Tesfaye Berhanu et al.
Environ. Res. Commun. 3 (2021) 021001

LETTER

Elucidating local pollution and site representativeness at the Jungfraujoch, Switzerland through parallel aerosol measurements at an adjacent mountain ridge

Nicolas Bukowiecki\(^1\)\(^,2\), Benjamin T. Brem\(^1\), Günther Wehrle\(^1\), Griša Močnik\(^3\)\(^,4\)\(^,5\), Stéphane Affolter\(^3\)\(^,6\)\(^,7\), Markus Leuenberger\(^1\), Martine Collaud Coen\(^8\), Maxime Hervo\(^8\), Urs Baltensperger\(^1\) and Martin Gysel-Beer\(^1\)

\(^1\) Laboratory of Atmospheric Chemistry, Paul Scherrer Institute, Villigen PSI, Switzerland
\(^2\) Now at: Atmospheric Sciences, Department of Environmental Sciences, University of Basel, Basel, Switzerland
\(^3\) Jozef Stefan Institute, Ljubljana, Slovenia
\(^4\) Aerosol d.o.o., Ljubljana, Slovenia
\(^5\) Center for Atmospheric Research, University of Nova Gorica, Ajdovščina, Slovenia
\(^6\) Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
\(^7\) Now at: Department of Environmental Sciences, University of Basel, Basel, Switzerland
\(^8\) Federal Office of Meteorology and Climatology, MeteoSwiss, Payerne, Switzerland

E-mail: nicolas.bukowiecki@unibas.ch and martin.gysel@psi.ch

Keywords: aerosol long-term monitoring, equivalent black carbon, aerosol number concentration, spatial variation

Supplementary material for this article is available online

Abstract

Many long-term air pollution and climate monitoring stations face the issue of increasing anthropogenic activities in their vicinity. Furthermore, the spatial representativeness of the sites is often not entirely understood especially in mountainous terrain with complex topographic features. This study presents a 5-year comparison of parallel aerosol measurements (total particle number concentration and equivalent black carbon mass concentration) at the Jungfraujoch in the Swiss Alps (JFJ, 3580 m a.s.l.), and an adjacent mountain ridge, the Jungfrau East Ridge (JER, 3705 m a.s.l.), in 1000 m air-line distance to the main site. The parallel aerosol measurements reveal characteristic differences in the diurnal variations between the two sites under certain specific meteorological conditions. Our analysis estimates that on 20\%–40\% of the days local activities at the Jungfraujoch have a clear influence on the measured time series of the total aerosol number concentration and the equivalent black carbon mass concentration. This influence is mainly seen in form of strong isolated spikes rather than by an increase in the on-site background concentration. They can thus be flagged during the data quality assurance process and filtered from those measurement parameters available at high time resolution. Removing the spikes from the original time series results in daily mean values for the total aerosol number concentration and equivalent black carbon mass concentration that are 5\%–10\% lower compared to the original signals. During nighttime with hardly any local pollution sources that cause spikes this percentage decreases towards 0\%. The signal baselines at the Jungfraujoch and Jungfrau East Ridge correlate well during more than 50\% of the days.

1. Introduction

At the High Altitude Research Station Jungfraujoch in the Swiss Alps (Switzerland, 3580 m a.s.l., hereafter called JFJ) manifold properties of atmospheric aerosol have been continuously measured for more than 25 years. Along with the research activities at the Jungfraujoch, the site is a worldwide renowned destination for tourism. Due to its high elevation and extensive measurement activities, the research facility has been recognized as a global baseline station for the measurement of atmospheric constituents in a large number of studies (see e.g. review article by Bukowiecki et al 2016). Many of the performed long-term measurements are also embedded in
international measurement networks such as the Global Atmosphere Watch program of the World Meteorological Organization (GAW/WMO) and the European Research Infrastructure Consortia ICOS (Integrated Carbon Observation System) and ACTRIS (European Research Infrastructure for the observation of Aerosol, Clouds and Trace Gases). In the research field of atmospheric aerosols, the site also has played an important role in the mechanistic examination of aerosol-cloud interactions (e.g. Motos et al. 2019) and atmospheric nucleation (e.g. Bianchi et al. 2016).

Temporal changes in aerosol properties at the JFJ are mainly given by seasonal and diurnal variations, due to the meteorological pattern and the special geographical position of the site on a ridge. In summer, injection of air parcels by thermal convection from the atmospheric boundary layer (ABL) often reaches the site in the afternoon, and for Southeast wind directions the JFJ remains in the aerosol residual layer during the night (Lugauer et al. 1998). This leads to an increase in the aerosol loading of the air masses sampled at the JFJ. In winter, this process does not play an important role, and the JFJ is considered to be within the free troposphere most of the time (Herrmann et al. 2015, Poltera et al. 2017).

Most studies have so far been performed directly at the site, and only a few studies looked at meteorological effects around the site (Kammermann et al. 2010, Ketterer et al. 2014, Poltera et al. 2017), and their possible influence on the aerosol parameters and trace gas concentrations. This study presents a 5-year comparison of aerosol measurements with parallel measurements at an adjacent mountain ridge, Jungfrau East Ridge (3705 m a.s.l., hereafter called JER). The presented data were measured between October 2014 and December 2019, plus an additional time period in spring 2020 during the site lockdown due to the covid-19 pandemic. The time series of both sites are used to assess the relevance of local emissions at the JFJ and JER. Furthermore, the diurnal variations of the aerosol parameters available at both sites are analyzed for systematic differences that may be caused by different air masses at the two sites under certain meteorological conditions. In a companion paper to this article, CO2 measurements made at both sites are compared and discussed (Affolter et al. 2021).

2. Methods

2.1. Site description
The High Altitude Research Station Jungfraujoch (3580 m a.s.l., 46°32’N 7°59’E), is located on an exposed anticline. The Jungfrau East Ridge (JER, 3705 m a.s.l.), is in 1000 m air-line distance to the JFJ site. Both sites are interconnected via a tunnel. Figure 1 shows the topography and locations of the two sites. Further details about the two sites are given by Affolter et al. (2021).

2.2. Instrumentation
The mass concentration of equivalent black carbon (eBC) was measured at both sites using a seven-wavelength aethalometer (AE33, Magee Scientific Inc. USA) with a time resolution of 5 min. For conversion of the measured filter attenuation into eBC mass concentration (hereafter called \(m_{\text{eBC}}\)), the standard mass attenuation coefficient value and the instrument internal loading compensation was applied (Drinovec et al. 2015). The total particle
number concentration (hereafter called $N_{tot}$) was measured by a condensation particle counter (CPC) model 3772 at JFJ and a CPC model 3775 at JER, both instruments manufactured by TSI Inc., USA. The applied CPCs have different lower 50% cutoff diameters (10 nm for the CPC3772 and 7 nm for the CPC3775). The effect of this cutoff on the comparability of the data is discussed in the Results section. All the measured data were quality assured according to the recommendations given by the Global Atmosphere Watch program (GAW 2016). A comprehensive list of all parameters measured within the long-term program at the JFJ is given in Bukowiecki et al (2016). Meteorological data used in this study were obtained from the Federal Office of Meteorology and Climatology MeteoSwiss (wind direction at JFJ) and from ceilometer measurements at a nearby valley site at 2061 m a.s.l in 5.5 km distance to the JFJ site, providing the top edge of the continuous aerosol layer (TCAL) and the convective boundary layer height (CBLH). The top of the continuous aerosol layer (CAL) is defined as the uninterrupted aerosol region along the backscatter profile starting from the ground and reaching the first discontinuity in the aerosol distribution. The top of the CAL (TCAL) is defined as the height of the retrieved discontinuity (Polterra et al 2017).

2.3. Spike analysis and statistical assessment of diurnal variations
An automated algorithm was applied to flag spikes in the original $m_{eBC}$ and $N_{tot}$ time series. The applied spike detection algorithm involves several steps. First, a signal baseline is determined for the 1 min $N_{tot}$ data and the 30 min $m_{eBC}$ data, by calculating a running 10 min 5% percentile for $N_{tot}$ and a running 2 h minimum for $m_{eBC}$. The window size and the percentile value were optimized for each parameter by stepwise variation of the two quantities, leading to a set of values where the resulting baseline is minimally influenced by the signal spikes but at the same time has a minimal negative offset to the original signal. Subsequently the baseline is subtracted from the original time series to obtain the isolated spikes time series. Finally, a spike flag is applied to the data periods whenever a 1 min value of the $N_{tot}$ spikes time series exceeds the 80th percentile within a 60 min time window around it by 1000 cm$^{-3}$ or more. Equivalently, for $m_{eBC}$ the 50 min 80% percentile and a threshold of 50 ng m$^{-3}$ is used. The individual values of the applied running percentiles were varied for each instrument to optimally identify individual peaks and minimize the detection of false peaks such as random noise at low concentrations. The result of all runs was empirically inspected, to manually assess the number of ‘false’ counts and double counts. Details are provided in figure S1 of the supplementary information to this article (available online at stacks.iop.org/ERC/3/021001/mmedia).

To quantify individual features of the observed diurnal variations at JFJ and JER, several statistical measures are shown in table 1. For the $R^2$ values, only full days with all parameters available were considered (1124 out of 1929 days).
Table 1. Parameters used in this study to quantify the diurnal variations of the total particle number concentration ($N_{tot}$) and the equivalent black carbon mass concentration ($m_{eBC}$) at the Jungfraujoch (JFJ) and Jungfrau East Ridge (JER). The time resolution is 1 min for $N_{tot}$ data and 30 min for $m_{eBC}$ data.

| Parameter name | Description | Proxy for: |
|----------------|-------------|-------------|
| Sig($N_{tot}$, JFJ) | Original signal | Meteorological variation and local pollution |
| Sig($N_{tot}$, JER) | | |
| Sig($m_{eBC}$, JFJ) | | |
| Sig($m_{eBC}$, JER) | | |
| Base($N_{tot}$, JFJ) | Signal baseline | Meteorological variation |
| Base($N_{tot}$, JER) | | |
| Base($m_{eBC}$, JFJ) | | |
| Base($m_{eBC}$, JER) | | |
| Spiket($N_{tot}$, JFJ) | Number of spikes per day | Local sources (pollution and/or nucleation) |
| Spiket($N_{tot}$, JER) | | |
| Spiket($m_{eBC}$, JFJ) | | |
| Spiket($m_{eBC}$, JER) | | |
| IQR($N_{tot}$, sig/base) | Baseline or signal IQR (interquartile range) per day | Amplitude of planetary boundary layer influence (baseline) and/or spikes (signal) |
| IQR($N_{tot}$, sig/base) | | |
| IQR($m_{eBC}$, sig/base) | | |
| IQR($m_{eBC}$, sig/base) | | |
| $R^2$($N_{tot}$, JFJ/JER, sig) | Correlation ($R^2$) between JER and JFJ signal per day | General similarity of diurnal signal variation |
| $R^2$($m_{eBC}$, JFJ/JER, sig) | | |
| $R^2$($N_{tot}$, JFJ/JER, base) | Correlation ($R^2$) between JER and JFJ baseline per day | General similarity of diurnal baseline variation |
| $R^2$($m_{eBC}$, JFJ/JER, base) | | |

3. Results and discussion

3.1. Time series

Figure 2 shows daily average values of $N_{tot}$ (panel a) and $m_{eBC}$ (panel b) both for JFJ and JER, before elimination of the identified spikes. The distinctive seasonality with very low concentrations in winter ($m_{eBC} < 50$ ng m$^{-3}$, $N_{tot} < 500$ cm$^{-3}$) and higher concentrations in summertime due to injections of PBL air into the free troposphere (see Bukowiecki et al. 2016 and references therein) is observed at both sites for the diurnal averages.

Additionally, the concentration difference is shown in the bottom two panels. For the $m_{eBC}$ difference (figure 2(d)) there is a weak seasonality, with concentration differences close to zero during winter and positive concentration differences (meaning higher concentrations at JFJ than JER) during summer for days with ABL influence where 50–100 ng m$^{-3}$ are regularly reached. In contrast, there is no seasonality in $N_{tot}$ and there seems to be a long-term drift towards a more negative concentration difference (meaning lower concentrations at JFJ). The concentration difference for an identical aerosol at JFJ and JER is per se zero or negative due to the different CPC cutoffs (the JER CPC has a lower size cutoff and thus measures more particles, see section 2.2). The main hypothesis is that this observed drift may be due to decreasing number concentrations at JFJ, as a result of measures that were introduced in 2017 by the railway company to protect the air quality monitoring from local pollution. This hypothesis will be tested and assessed in section 3.3 (spike analysis).

3.2. Diurnal variations

Despite the similarity in the seasonality of the daily averages, the diurnal variations of $m_{eBC}$ and $N_{tot}$ regularly show distinctive differences between the two sites.

At the JFJ, $N_{tot}$ and $m_{eBC}$ concentrations are influenced by different sources. The aerosol number concentration (with diameter $d > 10$ nm) is sensitive to:

(a) PBL influenced air masses leading to ‘moderate’ concentrations (Herrmann et al. 2015),
(b) new particle formation with bursts/‘bananas’ up to 20’000 cm$^{-3}$, Tröstl et al. (2016),
(c) helicopter exhaust with spikes up to 10’000 cm$^{-3}$ (based on many years of on-site eye observations, helicopter gas turbine engines are known to be a very significant source of particulate number concentrations, see e.g. Cain et al. (2013)),

Consequently, the diurnal variations observed at the JFJ have a distinctive pattern, with higher concentration differences during the day and lower concentration differences during the night. This pattern is not observed at the JER, where the diurnal variations are more uniform and show a general similarity with the JFJ. The distinctive seasonality with very low concentrations in winter and higher concentrations in summertime due to injections of PBL air into the free troposphere is observed at both sites for the diurnal averages.

Figure 2 Panel a shows daily average values of $N_{tot}$ (a) and $m_{eBC}$ (b) both for JFJ and JER, before elimination of the identified spikes. The distinctive seasonality with very low concentrations in winter and higher concentrations in summertime due to injections of PBL air into the free troposphere is observed at both sites for the diurnal averages.

Additionally, the concentration difference is shown in the bottom two panels. For the $m_{eBC}$ difference there is a weak seasonality, with concentration differences close to zero during winter and positive concentration differences (meaning higher concentrations at JFJ than JER) during summer for days with ABL influence where 50–100 ng m$^{-3}$ are regularly reached. In contrast, there is no seasonality in $N_{tot}$ and there seems to be a long-term drift towards a more negative concentration difference (meaning lower concentrations at JFJ). The concentration difference for an identical aerosol at JFJ and JER is per se zero or negative due to the different CPC cutoffs (the JER CPC has a lower size cutoff and thus measures more particles, see section 2.2). The main hypothesis is that this observed drift may be due to decreasing number concentrations at JFJ, as a result of measures that were introduced in 2017 by the railway company to protect the air quality monitoring from local pollution. This hypothesis will be tested and assessed in section 3.3 (spike analysis).
(d) cigarette smoke from the tourist platform 10 m underneath the inlet with spikes up to 10'000 cm$^{-3}$ (Fröhlich et al 2015).

The eBC mass concentration on the other hand is sensitive to ABL influenced air masses (‘moderate’ concentrations), as well as to local combustion processes in general (e.g. diesel generators applied during construction work) and snow cat emissions, see Bukowiecki et al (2016) and references therein.

Figure 3(a) shows a wintertime example day with virtually identical signals at the two sites, with low absolute values. The summertime example given in figure 3(b) also shows similar but more distinct diurnal variations (larger interquartile range) for both sites and both instruments. $N_{tot}$ at JER is constantly higher compared to JFJ, due to the presence of nucleation mode particles, which are frequently and sometimes persistently present (Tröstl et al 2016) and are captured differently by the different lower size cutoffs of the two CPCs (see section 2.2). Figure 3(c) shows an example day with very frequent and intense daytime spikes in the total aerosol number concentration measured at JFJ, whereas the signal baselines are virtually identical for both instruments and both sites. This is regularly observed at fair weather days with a high number of tourists at JFJ on the various outdoor platforms near the aerosol sampling inlet. This will be quantified in section 3.4. A further example is given in figure 3(d), with clear differences in $N_{tot}$ and $m_{eBC}$ at the two sites being detected on days when the two sites do not reside in the same air mass (for example during foehn wind conditions with strong winds from

---

Figure 3. Example days exhibiting different characteristic and frequently observed diurnal patterns of the total particle number concentration ($N_{tot}$) and the eBC mass concentration ($m_{eBC}$) at the two sites JFJ and JER. The time resolution for $N_{tot}$ data is 1 min and 30 min for $m_{eBC}$ data. The interpretation of the examples is given in section 3.2.
South, see additional figure S2 in the supplementary information). Finally, distinct signal differences in $N_{\text{tot}}$ between JFJ and JER are regularly observed on days with new particle formation occurring at or near the two sites. An example for this situation is shown in figure 3(e) for a fair weather day. While $m_{\text{BC}}$ shows an almost identical diurnal variation for both sites (caused by the summertime PBL injections), new particle formation first causes a steep increase in $N_{\text{tot}}$ at JFJ and with a time lag of about an hour also at JER. Later in the afternoon, the decay of $N_{\text{tot}}$ and $m_{\text{BC}}$ first starts at JER. Figure S3 in the supplementary information shows additional meteorological data and number size distributions for this example. This typical case of new particle formation at fair weather days is regularly observed at JFJ and has been addressed in a row of studies (Bianchi et al 2016, Tröstl et al 2016).

While the examples given in figures 3(a)–(e) show selected days with an isolated occurrence of the discussed phenomena, they often occur simultaneously, as exemplified for a 4-day period in figure 3(f).

3.3. Spike analysis
The frequently occurring spikes illustrated in figure 3(c) were systematically examined applying the spike analysis presented in section 2.3. Figures 4(a)–(c) show the monthly spike frequencies for the individual instruments and the two sites (shown as monthly average of the number of spikes per day). At JFJ, the seasonal variation of the spike frequency of the individual parameters is in general similar to the seasonal pattern of the visitor numbers, i.e. with higher values in summertime compared to wintertime. In contrast, the spikes detected at JER show no clear seasonality or temporal variation, and the spikes detected for $m_{\text{BC}}$ seem more influenced by instrumental noise rather than by real spikes. This supports the basic assumption that more visitors and touristic activities results in more spikes in the aerosol parameters measured at JFJ. However, the extent of spike frequency varies between years. In March 2017, signs were mounted on the tourist platform with the voluntary invitation to refrain from smoking. For $N_{\text{tot}}$ the spike frequency clearly follows the visitor numbers for 2015, 2016 (most spikes), and also for 2018 though with a lower spike to tourist ratio, while the spike frequency in 2017 and 2019 was clearly lower for and less correlated to the seasonal tourist counts. For the $m_{\text{BC}}$ concentrations on the other hand, the highest spike frequencies at JFJ were observed in 2017, together with a good correlation to the tourist counts, while all other years show lower spike frequencies. This different year-to-year behavior of the $N_{\text{tot}}$
Figure 5. Monthly mean values of the number of identified spikes per day at JFJ and JER for $N_{tot}$ for 2019 and 2020, illustrating the decrease of spikes during the closure of the JFJ touristic activities during the Covid-19 lockdown from March to May 2020.

Figure 6. Top panels: Monthly average values of the diurnal interquartile range (IQR, panel a for $N_{tot}$, panel b for $m_{BC}$) at JFJ and JER. Bottom panels: Monthly average values of the daily correlation coefficient ($R^2$) between JFJ and JER signals and baselines, for $N_{tot}$ (panel c, based on 1-min data) and $m_{BC}$ (panel d, based on 30 min data).
Table 2. Summary statistics for frequently observed patterns in the diurnal variations of $N_{tot}$ and $m_{nc}$ measured at JFJ and JER. The respective plots of the diurnal variations are shown in figure 3. The categories were defined using the parameters shown in table 1. Statistics are shown for the geometric mean diameter (GMD) of the particle number size distribution (obtained from scanning mobility particle sizer data from JFJ), for the top of the continuous aerosol layer (TCAL) and the convective boundary layer height (CBLH, both obtained from ceilometer measurements at a nearby valley site, see section 2.2), as well as for the daily percentage of wind arriving at JFJ from the South (between 100 and 200 degree).

| Main category | Unit | Statistics | a | b | c | d | e |
|---------------|------|------------|---|---|---|---|---|
| Classification according to examples in section 3.1 | | | | | | | |
| Clean winter day (figure 3(a)) | | | | | | | |
| Summer day with high PBL influence (figure 3(b)) | | | | | | | |
| Days with strong spikes at JFJ (figure 3(c)) | | | | | | | |
| Different baselines (figure 3(d)) | | | | | | | |
| New particle formation (figure 3(e)) | | | | | | | |
| Definition according to table 1 | | IQR ↓ | IQR ↑ | Spikes ↓ | Spikes (JFJ) ↑ | IQR ($m_{nc}$, JFJ, sig)/IQR ($m_{nc}$, JFJ, base) ↑ | IQR ($N_{tot}$, JFJ, sig)/IQR ($N_{tot}$, JFJ, base) ↑ | IQR ($N_{tot}$, JFJ, sig)/IQR ($N_{tot}$, JFJ, base) ↑ | IQR ($m_{nc}$, JFJ, sig)/IQR ($m_{nc}$, JFJ, base) ↑ | IQR ($N_{tot}$, JFJ, sig)/IQR ($N_{tot}$, JFJ, base) ↑ | IQR ($m_{nc}$, JFJ, sig)/IQR ($m_{nc}$, JFJ, base) ↑ |
| Occurrence | % of Days | 5.5 | 4.5 | 31.7 | 4.7 | 5.2 |
| Number of days (of 1124 days in total) | | 62 | 51 | 356 | 53 | 59 |
| Predominant months/season | | Nov, Dec, Jan | Jul, Aug | May to Oct, Dec | Spring, Autumn | Spring, Autumn |
| Geom. Mean Diameter | [nm] | | | | | | |
| Average | 56 | 77 | 73 | 88 | 66 |
| Median | 55 | 78 | 68 | 89 | 62 |
| 1st Quartile | 45 | 62 | 55 | 73 | 50 |
| 3rd Quartile | 65 | 92 | 88 | 102 | 79 |
| TCAL | [m a.s.l.] | | | | | | |
| Average | 3017 | 3124 | 3119 | 3190 | 3090 |
| Median | 2990 | 3086 | 3075 | 3195 | 3036 |
| 1st Quartile | 2928 | 2959 | 2950 | 2975 | 2921 |
| 3rd Quartile | 3095 | 3276 | 3264 | 3343 | 3182 |
| CBLH | [m a.s.l.] | | | | | | |
| Average | 2574 | 2740 | 2710 | 2808 | 2714 |
| Median | 2503 | 2650 | 2635 | 2650 | 2637 |
| 1st Quartile | 2342 | 2415 | 2412 | 2430 | 2445 |
| 3rd Quartile | 2772 | 2951 | 2913 | 3041 | 2950 |
| S Wind per Day at JFJ | [%] | | | | | | |
| Average | 29 | 36 | 30 | 40 | 33 |
| Median | 0 | 17 | 17 | 29 | 29 |
| 1st Quartile | 0 | 0 | 0 | 0 | 4 |
| 3rd Quartile | 63 | 54 | 54 | 79 | 56 |

a: Low signal correlation due to instrumental noise at low concentrations, see text (section 3.4).
b: This category does not reflect the total number of days with new particle formation, but the number of days with significant differences between JFJ and JER due to new particle formation.
and \( m_{\text{BC}} \) spikes, along with highly variable seasonal correlations with the tourist counts, underline that the spikes are not a simple function of total tourist number but depend on their actual activities, weather and multiple local sources: for \( N_{\text{tot}} \) mainly smoking on the outside platforms, plus helicopter traffic, and for \( m_{\text{BC}} \) mainly combustion engines from on-site construction, as well as snow cats preparing the snow walks etc. For example, the probability for spikes due to smoking also depends on the weather at the site, since this has a direct influence on the possibility or willingness for the tourists to go outside, and on the likelihood that cigarette smoke actually reaches the inlet before being blown away.

Finally, the bottom panel in figure 4 shows that also CO\(_2\) exhibits the same \( N_{\text{tot}} \) spike patterns at the two sites. This is possibly due to the CO\(_2\) exhalation by the tourists visiting the visitor platform underneath the inlets, as explained in more detail in the companion paper to this article (Affolter et al. 2021).

Although this paper focuses on the 5-year period 2014–2019, the spike analysis was also performed for \( N_{\text{tot}} \) for 2020, and shows a clear decrease of spikes during the shutdown of the JFJ touristic activities from March to May 2020 during the Covid-19 pandemic, see figure 5.

The spikes detected by the algorithm were also used to address the question of how strongly daily average values are influenced by the spikes. For the considered time period, the diurnal variation of the time series with the spikes removed is between 5 and 10% lower compared to the original signal both for \( N_{\text{tot}} \) and \( m_{\text{BC}} \). During nighttime with hardly any local pollution sources that cause spikes (with exception of occasional construction work in the site tunnels), the deviation decreases towards 0%. Details are given in figure S4 in the supplementary information.

3.4. Spatial differences between the sites

While the spike analysis discussed so far gives an indication of the quantitative influence of local emission sources, it does not consider any systematic differences between the two sites that are e.g. caused by different air masses. To assess any combined effect of local sources and air mass differences at the two sites, the interquartile range (IQR) and the Pearson correlation coefficient \( R^2 \) of the parameters given in table 1 were calculated for each individual day and are shown in figure 6 as monthly mean values. While the IQR for \( N_{\text{tot}} \) is around 200 cm\(^{-3}\) in winter, it peaks up to 400–600 cm\(^{-3}\) in summer due to the increased ABL injections and the local touristic emissions. The respective values for \( m_{\text{BC}} \) are 10–20 ng m\(^{-3}\) and 40–80 ng m\(^{-3}\). The \( R^2 \) values for the daily \( N_{\text{tot}} \) JFJ/JER correlations are per definition equal or higher for the signal baselines (0.7 < \( R^2 \) < 0.8) compared to the original signals including the spikes (<0.4). In contrast, the \( R^2 \) values for the daily \( m_{\text{BC}} \) JFJ/JER correlations do not significantly differ for the baseline and the original signal but rather show a strong seasonality with \( R^2 \) < 0.3 in winter and >0.6 in summer. This is explained by the fact that a) there are much less \( m_{\text{BC}} \) spikes compared to \( N_{\text{tot}} \) (see figure 4) and b) that \( m_{\text{BC}} \) is very low in winter with 30 min values reaching the instrument noise level which transfers into a low \( R^2 \).

Based on these seasonal characteristics, threshold values were defined for the daily spike frequencies (figure 4) and the daily IQR and \( R^2 \) values (figure 6). These threshold criteria (listed in table 3) were used to calculate the percentage of days where the individual parameters show ‘increased values’ i.e. where the parameters exceed the defined threshold. These threshold values can be used to attempt a more quantitative approach to assess the example categories for typical diurnal variations shown in figure 3 and discussed in section 3.2. The results are shown in table 2 and additionally include the geometric mean diameter (GMD) of the JFJ particle number size distribution, as well as the top of continuous aerosol layer (TCAL) as well as the convective boundary layer height (CBLH) measured above a valley site at 5 km air-line distance from the two sites at 2061 m a.s.l. These parameters are used as consistency check, while the classification is exclusively based on the threshold analysis. Category (a), (clear winter days) shows that both the TCAL and the CBLH are lower compared to the other categories, confirming the reduced ABL influence in wintertime. In line with Herrmann et al. (2015), the aerosol particles are smaller (lower GMD) in wintertime compared to the other seasons, which is a combined effect of different air masses and different PBL conditions. Also for category (e) (new particle formation), the summary statistics for the GMD as expected show lower values for this category compared to the other categories (with exception of category a). Finally, the slightly increased percentage of South wind in category (d) supports the observed cases of South foehn wind that fall into this category (see also figure S2 in the supplementary information). However, while the summary statistics in table 2 help confirming the semi-quantitative characterization of the observed ‘typical’ diurnal variations at JFJ and JER, a more detailed quantification of the individual processes (Foehn wind, new particle formation, PBL influence) exceeds the scope of this paper.

Table 2 also shows that the overall percentage of the isolated occurrence of the individual categories is low, i.e. below 10% with exception of category (c) (days with high spikes at JFJ, 32%). As already discussed in section 3.2 and shown in figure 3 (f), most days throughout the year are influenced by a combination of more than one or even all of the above categories. To better quantify the co-influence of the individual categories, table 3 lists the percentage of days where the individual parameters defined in table 1 show ‘increased values’ i.e. where the parameters exceed the defined threshold. At the same time, the table also checks the ‘co-match’ of the other parameters, i.e. if the other
parameters exceed their own threshold value during these days. As an example, the diurnal interquartile range for $N_{\text{tot}}$ is higher than $400 \text{ cm}^{-3}$ for 30% of all days (purple number in column A). For 92% of these selected days also the interquartile range of $N_{\text{tot}}$ at JER is higher than $400 \text{ cm}^{-3}$ (row B in column A), and for 75% of the selected days the $R^2$ for the baseline correlation between JER and JFJ for $N_{\text{tot}}$ is higher than 0.6 (row F in column A).

Table 3 shows that virtually all threshold criteria have a co-match of one or more of the other criteria. Notably, the co-match for all of the $meBC$ related parameters with the $N_{\text{tot}}$ related parameters is rather low (<50%; lower left quadrant of the table). This indicates that most diurnal variations of $N_{\text{tot}}$ are predominantly influenced by either the $N_{\text{tot}}$ specific local sources (cigarettes, helicopters) or by new particle formation, whereas the PBL influence (which is a main driver for $meBC$) is often hidden for $N_{\text{tot}}$ by the other sources. Vice versa, the co-match for all of the $N_{\text{tot}}$ related parameters with the $meBC$ related parameters is rather low (<50%; upper right quadrant of the table), with the exception of the $N_{\text{tot}}$ base line correlation between JFJ and JER. This is likely a combined effect of instrumental behavior and PBL influence, i.e. as soon as the ABL influence both at JFJ and JER is high enough (high IQR) so that the measured 30 min averages measured by the aethalometer are clearly above the noise level, a real baseline correlation evolves ($high R^2$). Obviously, during the days with very strong ABL influence seen in $meBC$, the ABL influence is also strong enough to dominate the baseline correlation between JFJ and JER for $N_{\text{tot}}$.

Finally, table 3 also shows that the baseline correlation between JFJ and JER for $N_{\text{tot}}$ is high for 61% of the days (column F), which is an important key number to assess the spatial comparability of the two sites. The respective percentage is lower for $meBC$ (31%, column L) but cannot be used for further interpretation because it is affected by the instrumental noise during wintertime.

### 4. Conclusions

Most background air pollution monitoring stations, especially in regions accessible for tourists such as the Alps have faced or are likely to face an increased development in their vicinity (new roads, new buildings, helicopter
flights, mass gatherings). The pollutant emissions of these activities and their potential influence on the measured time series need to be carefully assessed and addressed, especially with respect to the statistical treatment of the long-term data. A second aspect to be considered is the spatial representativeness of a monitoring site. Despite the progresses made in the assessment of spatial variability through instrument miniaturization and sampling/probing technology (e.g. using unmanned aerial vehicles, UAVs), a statistically satisfying assessment of the spatial representativeness is hard to get.

This work has addressed both of these aspects for the aerosol monitoring at the JFJ and used a spike analysis as well as an analysis of the diurnal variations as an attempt to quantify the effects that are frequently observed in the visual data inspection. Our analysis estimates that on 20%–40% of the days local activities at the Jungfraujoch have a clear influence on the measured time series of the total aerosol number concentration and the equivalent black carbon mass concentration. This influence is mainly seen in form of strong isolated spikes rather than by an increase in the on-site background concentration. These spikes can thus be flagged during the data quality assurance process and filtered from those measurement parameters available at high time resolution. Removing the spikes from the original time series results in daily mean values for the total aerosol number concentration and equivalent black carbon mass concentration that are 5%–10% lower compared to the original signals. During nighttime with hardly any local pollution sources that cause spikes this percentage decreases towards 0%. The signal baselines at the Jungfraujoch and Jungfrau East Ridge correlate well during more than 50% of the days.

The presented analysis of the parallel \( N_{\text{tot}} \) and \( m_{\text{BC}} \) measurements at the two sites cannot explain the detailed mechanisms of the local aerosol transport, this will only be possibly by including an in-depth local-scale analysis of meteorological parameters. However, this study illustrates the usefulness of the additional measurements at the additional site JER, which provide highly valuable quality assurance aspects for the long-term monitoring at the JFJ.

Acknowledgments

We thank the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat (HFSJG, Bern, Switzerland) for the opportunity to perform experiments at the Jungfraujoch. Special thanks go to Christine and Ruedi Käser, Maria and Urs Otz, as well as Joan and Martin Fischer, the facility managers of the station. We also acknowledge Erik Herrmann for his support and maintenance of the aerosol measurements at JFJ and JER. Aerosol measurements at the Jungfraujoch are performed within the framework of the Swiss contribution to the Global Atmosphere Watch (GAW) program funded by MeteoSwiss. Further financial support was received through the ACTRIS2 project (EU H2020 grant no. 654109 and SERI contract no. 15.0159-1). The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government.

The ceilometer measurements discussed in this article are performed by the Swiss Federal Laboratories for Materials Science and Technology (Empa), within the framework of ICOS (Integrated Carbon Observation System). GM acknowledges the support from the Slovene Research Agency through the program ‘P1-0385 Remote sensing of atmospheric properties’. We also thank the Jungfraubahnen for their long-lasting support and partnership, and Aerosol d.o.o. for lending one of the Aethalometers. Access to the East Ridge was possible due to the large support by Swisscom, VBS and Jungfraubahnen.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Nicolas Bukowiecki https://orcid.org/0000-0002-2925-8553
Benjamin T. Brem https://orcid.org/0000-0001-6211-2815
Griša Močnik https://orcid.org/0000-0001-6379-2381
Stéphane Affolter https://orcid.org/0000-0002-6646-9018

References

Affolter S, Schibig M, Bernahu T, Bukowiecki N, Steinbacher M, Nyfeler S, Lauper J and Leuenberger M 2021 Detecting and assessing local CO₂ contamination revealed by two near-by high altitude records at Jungfraujoch, Switzerland Env. Res. Lett. in press (https://doi.org/10.1088/1748-9326/abc74a)
Bianchi F et al 2016 New particle formation in the free troposphere: a question of chemistry and timing Science 352 1109–12
Bukowiecki N, Weingartner E, Gyol M, Collaud Coen M, Zieger P, Herrmann E, Steinbacher M, Gággeler H W and Baltensperger U 2016 A review of more than 20 years of aerosol observation at the high altitude research station jungfraujoch, Switzerland (3580 m asl) Aerosol Air Qual. Res. 16 764–88
Cain J et al 2013 Characterization of gaseous and particulate emissions from a turboshaft engine burning conventional, alternative, and surrogate fuels Ener. Fuels 27 2290–302

Drinovec L et al 2015 The ‘dual-spot’ Aethalometer: an improved measurement of aerosol black carbon with real-time loading compensation Atmos. Meas. Tech. 8 1965–79

Fröhlich R et al 2015 Fourteen months of on-line measurements of the non-refractory submicron aerosol at the Jungfraujoch (3580 m a.s.l.) – chemical composition, origins and organic aerosol sources Atmos. Chem. Phys. 15 11373–98

GAW 2016 WMO/GAW Aerosol Measurement Procedures, Guidelines and Recommendations (WMO-No. 1177) 227 World Meteorological Organization 93 (https://library.wmo.int/doc_num.php?explnum_id=3073)

Herrmann E et al 2015 Analysis of long-term aerosol size distribution data from Jungfraujoch with emphasis on free tropospheric conditions, cloud influence, and air mass transport J. Geophys. Res. Atmos. 120 9459–80

Kammermann L, Gysel M, Weingartner E and Baltensperger U 2010 13-month climatology of the aerosol hygroscopicity at the free tropospheric site Jungfraujoch (3580 m a.s.l.) Atmos. Chem. Phys. 10 10717–32

Ketterer C, Zieger P, Bukowiecki N, Collaud Coen M, Maier O, Ruffieux D and Weingartner E 2014 Investigation of the planetary boundary layer in the Swiss Alps using remote sensing and in situ measurements Boundary Layer Meteorol. 151 317–34

Lugauer M, Baltensperger U, Jerger M, Gageler H W, Jost D T, Schwikowski M and Wanner H 1998 Aerosol transport to the high Alpine sites Jungfraujoch (3454 m asl) and Colle Gnifetti (4452 m asl) Tellus B: Chemical and Physical Meteorology 50 76–92

Motos G, Schmale J, Corbin J C, Modini R L, Karlen N, Bertò M, Baltensperger U and Gysel-Beer M 2019 Cloud droplet activation properties and scavenged fraction of black carbon in liquid-phase clouds at the high-alpine research station Jungfraujoch (3580 m a.s.l.) Atmos. Chem. Phys. 19 3833–55

Poltera Y, Martucci G, Collaud Coen M, Hervo M, Emmenegger L, Henne S, Brunner D and Haefele A 2017 PathfinderTURB: an automatic boundary layer algorithm. Development, validation and application to study the impact on in situ measurements at the Jungfraujoch Atmos. Chem. Phys. 17 10051–70

Tröstl J et al 2016 Contribution of new particle formation to the total aerosol concentration at the high-altitude site Jungfraujoch (3580 m asl, Switzerland) J. Geophys. Res. Atmos. 121 11692–711