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Ground-based aerosol optical depth trends at three high-altitude sites in Switzerland and southern Germany from 1995 to 2010

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[1] Ground-based aerosol optical depth (AOD) climatologies at three high-altitude sites in Switzerland (Jungfraujoch and Davos) and Southern Germany (Hohenpeissenberg) are updated and re-calibrated for the period 1995–2010. In addition, AOD time series are augmented with previously unreported data, and are homogenized for the first time. Trend analysis revealed weak AOD trends (λ = 500 nm) at Jungfraujoch (JFJ; +0.007 decade^{-1}), Davos (DAV; +0.002 decade^{-1}) and Hohenpeissenberg (HPB; $-$0.011 decade^{-1}) where the JFJ and HPB trends were statistically significant at the 95% and 90% confidence levels. However, a linear trend for the JFJ 1995–2005 period was found to be more appropriate than for 1995–2010 due to the influence of stratospheric AOD which gave a trend $-$0.003 decade^{-1} (significant at 95% level). When correcting for a recently available stratospheric AOD time series, accounting for Pinatubo (1991) and more recent volcanic eruptions, the 1995–2010 AOD trends decreased slightly at DAV and HPB but remained weak at +0.000 decade^{-1} and $-$0.013 decade^{-1} (significant at 95% level). The JFJ 1995–2005 AOD time series similarly decreased to $-$0.003 decade^{-1} (significant at 95% level). We conclude that despite a more detailed re-analysis of these three time series, which have been extended by five years to the end of 2010, a significant decrease in AOD at these three high-altitude sites has still not been observed.

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1. Introduction

[2] Long-term measurements of ground-based aerosol optical depth (AOD) serve as an important validation of satellite-based and modeling studies of AOD. One area of recent interest in Europe has been to what extent aerosols play a role in the solar dimming/brightening debate [*Streets et al.*, 2009; *Wild et al.*, 2009; *Chiacchio et al.*, 2011]. These studies suggest that the contribution from anthropogenic aerosol emissions to the overall AOD reached a peak value in 1988–1990 and was partly responsible for dimming and consequent brightening over Europe. A reduction in European aerosol emissions was estimated to have resulted in a steady decrease of AOD (λ = 550 nm) from 0.31 in 1980 to a stable value of ~0.26 in 2000–2006 [*Streets et al.*, 2009]. European ground-based [*Weller and Gericke*, 2005; *Ruckstuhl et al.*, 2008] and MODIS satellite observations [*Papadimas et al.*, 2008] support these findings of a significant reduction in long-term AOD which has largely been attributed to a significant rationalization of heavy industries, mainly in specific regions of eastern Europe. However, other sites on mainland Europe exhibit small or no decreases in long-term AOD [*Gröbner and Meleti*, 2004; *Ruckstuhl et al.*, 2008]. In the latter study, ground-based AOD trends at six sites in Switzerland and Germany were reported in brief. A significant negative AOD trend at three low-altitude sites, variously spanning the 1986–2005 period, was observed which then appeared to level off after about 2000 until 2005. These trends were shown to be statistically significant at the 95% confidence level. However, a statistically significant decrease in AOD at the three high-altitude sites from 1995–2005 was not observed. The question then arises whether the observed significant decrease in AOD over Europe is/was only restricted to certain regions, to low-altitude sites or even to specific periods. Unfortunately too few ground-based AOD time series exist to even partly

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answer this question, and those that are available have been somewhat overlooked.

[3] In this study, we therefore apply a number of important improvements in determining the AOD time series at the three high-altitude sites reported by *Ruckstuhl et al.* [2008]. One aim is to establish a well-characterized climatology at each of these 3 sites, and to ascertain whether AOD trends, if any, can now be determined with greater certainty. AOD time series have been: 1) updated to the end of 2010, 2) Langley re-calibrated with stricter criteria, 3) augmented with previously unreported data, and, 4) homogenized for the first time with the same AOD algorithms. A recently available stratospheric AOD time series [*Vernier et al.*, 2011] is used to more accurately correct for the Pinatubo volcanic eruption in 1991 than in *Ruckstuhl et al.* [2008]. Robust statistical analysis techniques are then used to examine data homogeneity and to determine AOD trends.

2. Methods

[4] Sun photometer measurements have been continuously conducted at three high-altitude sites in Switzerland and southern Germany since the 1990s. Data from 1995–2010 are analyzed for: 1) Jungfraujoch (JFJ; 3580 m; 46.55°N, 7.98°E; Switzerland), 2) Davos (DAV; 1590 m asl; 46.82°N, 9.85°E; Switzerland), and 3) Hohenpeissenberg (HPB; 995 m; 47.80°N, 11.02°E, Germany). All three sites belong to the international GAW-PFR (Global Atmosphere Watch - Precision Filter Radiometer; www.pmodwrc.ch/worcc) program of the WMO.

[5] Measurements at HPB began in late 1993 with the Schulz SP1A Sun photometer which has 18 wavelengths in the range 353 to 1064 nm. Measurements at JFJ and DAV began in 1991 and 1993 with SPM2000 Sun photometers [e.g., *Ingold et al.*, 2001] as part of the national SACRaM network (Swiss Alpine Climate Radiation Monitoring, MeteoSwiss). These instruments were finally retired in 2003 after they had been measuring alongside PFRs since 1999. SPM2000s measure at 16 wavelengths in the range 368 to 1024 nm. Calibration was conducted using Langley calibrations, which occur on an average of 16 and 32 exceptionally perfect days per year at DAV and JFJ, respectively.

[6] GAW-PFR measurements with PFRs (λ = 368, 412, 500 and 862 nm) [*Wehrli*, 2000] began at all three sites in 1999. Daily calibration constants for the JFJ PFR were interpolated from semi-annual statistical analyses of in situ Langley calibrations. Standard errors of the statistical analysis are approximately 0.25% [*Schmid and Wehrli*, 1995] at all four wavelengths and the mean annual drift rates since 1999 are less than 0.1% /year. PFRs used at DAV were Langley calibrated at high-altitude stations (JFJ, Mauna Loa (3397 m), or Izaña (2371 m)), of which three of them comprise the GAW-PFR primary reference standard. Their calibration uncertainty is estimated at 0.5% based on Langley uncertainty and annual drift rates. PFRs at HPB were calibrated at DAV against the reference standards, and their calibration uncertainty is estimated at less than 1% based on pre- and post-deployment calibrations. The GAW-PFR reference standards have also been validated in international filter radiometer comparisons held at DAV in 2000, 2005, and 2010 (C. Wehrli, manuscript in preparation, 2012). PFR data have a 1-min resolution which is flagged for the presence of clouds, and when the solar pointing and sensor temperature reach threshold limits.

[7] In order to homogenize our diverse time series, only GAW-PFR algorithms [*McArthur et al.*, 2003] were used for the determination of AOD. The efficacy of GAW-PFR procedures to determine AOD has been previously verified in a network comparison with AERONET (Aerosol Robotics Network; aeronet.gsfc.nasa.gov) [*Holben et al.*, 1998; *McArthur et al.*, 2003]. Of the three sites discussed here, only DAV has a co-located AERONET Cimel Sun photometer. A comparison of the instantaneous AOD difference between AERONET and GAW-PFR (λ = 500 nm) in 2007–2010 at DAV resulted in a mean AOD difference of −0.0024 and a root-mean square error of 0.0071. As such, the difference is within the U95 uncertainty of AOD = 0.015 units for finite field-of-view instruments [*Baltensperger et al.*, 2005].

[8] Once determined, GAW-PFR AOD data are used to construct 1-h mean values if a minimum of 6 data-points are available (10% coverage). Furthermore, outliers are removed if the 1-h standard deviation >10% of the mean or >0.05. Daily and monthly mean values require a minimum of N = 50 and 100 data-points, respectively. The combined uncertainty related to instruments and retrieval algorithms is estimated to result in an AOD uncertainty <0.010 at λ = 500 nm. All AOD time series were quality assured (GAW-PFR level 3). If available, monthly data from co-located stations were then used to give the weighted monthly mean. GAW-PFR AOD data are openly available at the World Data Center for Aerosols (WDCA; ebas.nilu.no) archive managed by NILU (Norsk Institut for Luftforskning), Norway.

[9] Several other aspects were improved since the *Ruckstuhl et al.* [2008] study. SPM2000 data were re-calibrated using stricter GAW-PFR criteria for the Langley calibrations. A second aspect was the availability of data from both the SACRaM and GAW-PFR networks as opposed to just the former. This has allowed AOD since 1999 at JFJ and DAV to be merged from the weighted mean of 1–4 Sun photometers instead of a single Sun photometer. While AOD time series from other high-altitude stations in central Europe were sought, none of a suitable length were found. AERONET have Cimel Sun photometers at DAV and Laegeren (735 m; Switzerland) but the AOD time series are somewhat fragmented, and only began in 2006 and 2003, respectively.

[10] In order to check for homogeneity in the time series three statistical tests were applied: the Pettitt test, the Buishand test and the standard normal homogeneity test (SNHT) [*Wijngaard et al.*, 2003]. The null hypothesis is that the values of the testing variable are independent and identically distributed. Under the alternative hypothesis, a stepwise shift in the mean is present. These tests are capable of locating the time when a possible shift occurred but require correct usage and interpretation. First, the SNHT and Buishand tests assume that variables are normally distributed, while the Pettitt test does not. Second, the SNHT test is more sensitive to shifts near the beginning and end of a time series, whereas the Buishand and the Pettitt tests are more sensitive to shifts in the middle. In order to meet the normality assumption, AOD values were log-transformed.

[11] Trend analysis was performed using the seasonal Kendall test, and Sen's slope estimator. The seasonal Kendall test is an extension of the Mann-Kendall test, a non-parametric technique which determines whether a monotonic increasing

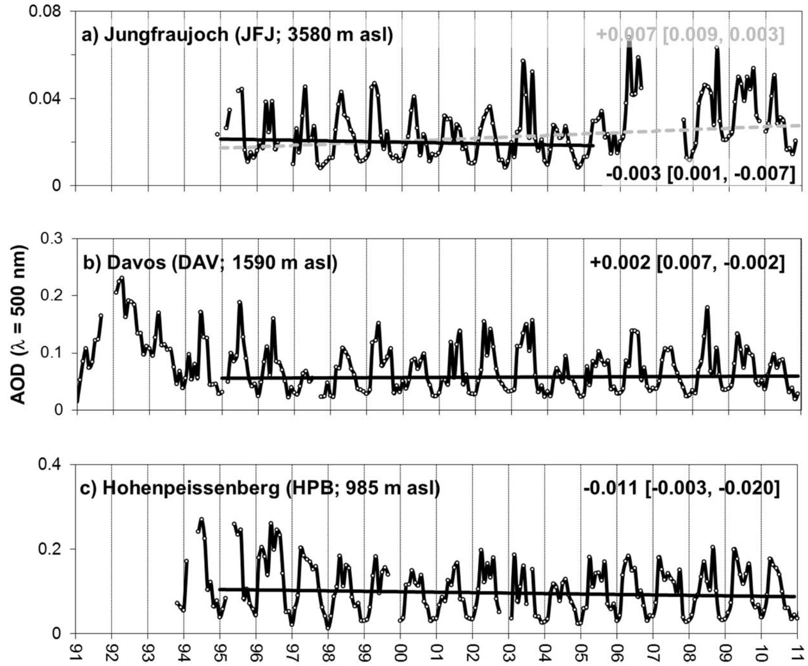

Figure 1. Time series of monthly AOD average values at (a) JFJ, (b) DAV, and (c) HPB. Although the full available AOD time series is shown for DAV (since 1991) and HPB (since 1994), linear trends only relate to data from 1995–2010 and to 1995–April 2005 for the JFJ only. Trends in AOD units are shown per decade. Square brackets denote the 95% confidence interval. The ±1 standard deviation range is not shown for clarity but averaged ±10% of the mean value.

or decreasing long-term trend exists [*Gilbert*, 1987]. It was decided to use this test to estimate trends as opposed to the Weatherhead method [*Weatherhead et al.*, 1998] used by *Ruckstuhl et al.* [2008] as it is generally considered to be more robust to missing data.

3. Results

3.1. AOD Time Series

[12] The monthly AOD time series at the JFJ, DAV and HPB sites are shown in Figures 1a–1c. The full 1991–2010 DAV time series is shown in Figure 1b to illustrate the Pinatubo eruption where a peak value ~0.23 was observed in April 1992. AOD then decreased to typical values in about 1997–1998 as determined by an exponential fit to the de-seasonalized time series. Figures 1a–1c displays several other prominent features. The first is the clear annual cycle of maxima in summer and minima in winter at all three stations. AOD mean values for the 1995–2010 time series at JFJ was 0.026 (±0.013; ±1 stdev), 0.068 (±0.036) at DAV and 0.104 (±0.058) at HPB. An interesting feature in these results is an increase in mean AOD with decreasing station altitude which is due to the varying influence of planetary boundary layer (PBL) and lower free troposphere (FT) air masses at each station. Previous airborne lidar and in situ studies have shown that the JFJ at 3580 m is mainly influenced by lower FT air masses except on occasion in summer during convective weather situations when the station is influenced by the PBL [*Nyeki et al.*, 1998, 2000; *Collaud Coen et al.*, 2011]. DAV and HPB are likely to be more influenced by the PBL than JFJ due to their lower altitude except in the winter half-year when FT conditions may predominantly occur.

[13] A second prominent feature in Figures 1a–1c is that enhanced AOD values are observed in summer 2003 and 2006 at JFJ, which is also observed at DAV and HPB to some extent. Western Europe experienced a prolonged photochemical smog episode in these summers as a result of stable and persistent anti-cyclonic weather conditions. POLDER satellite measurements indicated that AOD was a factor 2 higher than during other summer months in 2003 [*Hodzic et al.*, 2006].

[14] A further feature at JFJ is an apparent increase in AOD during the 2008 to December 2010 period, as defined by the envelope of maximum and minimum monthly values. Mean AOD was ~0.032 during this period as opposed to ~0.022 for 1995–2006. Unfortunately the JFJ time series was interrupted in August 2006–October 2007 due to a faulty observatory-dome hence making it difficult to define when the increase occurred. As the two on-site GAW PFRs were not exchanged until January 2010 an instrument artifact or change in calibration can be ruled out. Furthermore, JFJ in situ aerosol measurements of the scattering and absorption coefficients show no such increase (M. Collaud Coen, personal communication, 2012). A plausible explanation is an observed increase in stratospheric AOD in early 2005 to 2010 [*Vernier et al.*, 2011] which may also account for the September 2008 peak in Figures 1a–1c. A similar enhancement in AOD at DAV or HPB is not observed due to the greater influence of the PBL which results in a larger annual variance in AOD. These aspects concerning stratospheric AOD are discussed later in greater detail. For the

moment, application of the homogeneity tests was first investigated. Results indicate that the DAV and HPB time series are homogeneous ($p > 0.121$ for all tests), while a shift in the mean is found for JFJ (K and Q statistics for Buishand and Pettitt tests are 30,561 and 2932, respectively; T_o statistic for SNHT test is 27.44; $p < 0.0001$ for all tests). Both the Buishand and the Pettitt tests suggest that a shift in the JFJ time series began as early as April 2005. As the SNHT test found a shift in July 2006, probably due its sensitivity to the end-points of time series, it was not further considered here. The Kolmogorov-Smirnov test, a non-parametric test to determine whether two data sets differ significantly, was then applied to the JFJ pre- and post-April 2005 sub-series. Both sub-series were found to differ significantly (D statistic = 0.404, $p < 0.0001$), further strengthening the view that a change in the JFJ time series occurred in about April 2005.

[15] Before results from the trend analysis are discussed it would be appropriate to examine how well the seasonal Kendall test and Sen's slope estimator compare with the *Weatherhead et al.* [1998] method in *Ruckstuhl et al.* [2008]. A comparison using the 1995–2005 AOD time series from the latter study was therefore conducted. Apart from JFJ, DAV and HPB, *Ruckstuhl et al.* [2008] also included AOD analyses for the low-altitude stations at Lindenberg (LIN; 126 m) and Zingst (ZGT, 5 m) in Germany, and Payerne (490 m) in Switzerland. Statistically significant negative decadal trends (95% confidence level) of −53%, −54% and −34% were obtained for LIN, ZIN and PAY, respectively, and compared reasonably well with values in *Ruckstuhl et al.* [2008] of −63%, −60% and −26%. Non-statistically significant negative trends were also obtained for the high-altitude stations HPB, DAV and JFJ.

[16] Application of the seasonal Kendall test and Sen's slope estimator to the current 1995–2010 AOD time series gave the following trends at JFJ, DAV and HPB (shown in Figures 1a–1c): +0.007 decade^{-1} (statistical significance p = 0.03), +0.002 (p = 0.4), and −0.011 (p = 0.1). Although only the JFJ trend is statistically significant at the 95% confidence level, the 90% level at HPB is also an acceptable result. Similar trends were also found at other PFR wavelengths. With the above homogeneity discussion in mind it is visible in Figure 1a that the JFJ linear trend is not appropriate for the whole 1995–2010 period but rather for the 1995–April 2005 period. Re-application of the trend tests then gave a JFJ trend = −0.003 decade^{-1} (p = 0.03), statistically significant at the 95% level. Our results contrast weak negative trends at JFJ, DAV and HPB of −0.002, −0.006 and −0.015 decade^{-1} for 1995–2005 in *Ruckstuhl et al.* [2008] which were not statistically significant at the 95% confidence level. While our study has extended the available time series length from 10 to 15 years, it can be seen that the AOD trend directions are still sensitive to the length of time-intervals under consideration. The weak trends found here suggest that a significant decrease in AOD has still not occurred at our three high-altitude sites over the 1995–2010 period. *Ruckstuhl et al.* [2008] summarized their observations of a significant decrease in AOD as occurring in the "lower troposphere." However, it should be emphasized that this observation applied to their three low-altitude sites which are representative of the PBL, but not to the high-altitude sites JFJ, DAV and HPB which are more representative of the lower FT. We therefore suggest that a distinction between PBL and lower FT sites may be more appropriate for the future application of these time series. This may or may not have an impact on the conclusions from a number of studies which have modeled significant decreases in AOD over Europe since the 1990s [*Streets et al.*, 2009; *Wild et al.*, 2009; *Chiacchio et al.*, 2011].

3.2. Annual Cycles

[17] As mentioned above, a distinct annual cycle in AOD occurs at all three stations, and is illustrated in Figure 2 as box-and-whisker plots. The cycle at JFJ exhibits a maximum ~0.04 in April–May after which AOD decreases steadily to attain a minimum in December ~0.014. The late spring maximum in column AOD contrasts in situ JFJ measurements of the aerosol scattering coefficient (λ = 550 nm) in 1995–2008 which show a maximum in July as the result of convectively transported PBL air masses [*Collaud Coen et al.*, 2011]. The maximum at DAV occurs about one month later with a broad maximum centered on June (~0.118) but with a minimum in December as well (~0.034). The annual cycle at HPB is qualitatively similar to DAV except for a maximum in April (~0.166), although it should be mentioned that the inter-quartile range is the largest of any month. Similar maximum and minimum cycles in AOD have been found in the U.S. at elevated SURFRAD (Surface Radiation Budget Network) stations [*Augustine et al.*, 2008].

[18] The basic features of the annual cycle at all three stations depend foremost on the synoptic climatology of central Europe as this determines the type of air masses and amount of wet precipitation. The European Alps are located on the southern side of the extra-tropical westerlies. In winter, the Iceland low and Azores sub-tropical high pressure systems result in a higher occurrence of advective weather situations. Cyclonic weather systems then result in the removal of aerosols through wet deposition. In summer, both pressure systems move to the northwest, and convective weather situations increase in frequency over the European Alps. Combined with the photochemical production of sulfate aerosols, decreased wet deposition, and a deeper PBL, aerosols are therefore higher in concentration in the rural PBL and FT in summer than in winter [e.g., *Nyeki et al.*, 2000; *Collaud Coen et al.*, 2011].

3.3. Ångström Exponent

[19] The Ångström exponent (α) is a qualitative indicator of the relative dominance of fine mode aerosols (diameter d < 1000 nm; mainly smoke and/or urban sources) and coarse mode aerosols (d > 1000 nm; dust and/or sea-salt). It is calculated here using linear regression of log(AOD) versus log(λ) with all four PFR wavelengths. Values $\alpha > \sim 1.5$ indicate a higher fine mode fraction. The annual cycle in α at JFJ is exhibited in Figure 3 and displays an interesting structure which is absent at DAV or HPB (not shown). Mean values for the 1995–2010 period were α = 1.49 at JFJ, 1.48 at DAV and 1.54 at HPB, implying a slightly larger fraction of fine mode aerosols at HPB. Figure 3 displays a broad minimum at JFJ ~1.3 in March to June which happens to coincide with the April to May maximum in AOD. This contrasts a broad, shallow maximum of ~1.7 at DAV and HPB in June to September which can be explained by the abundance of small aerosols in PBL air masses. However, a March to June minimum in α at JFJ is more likely

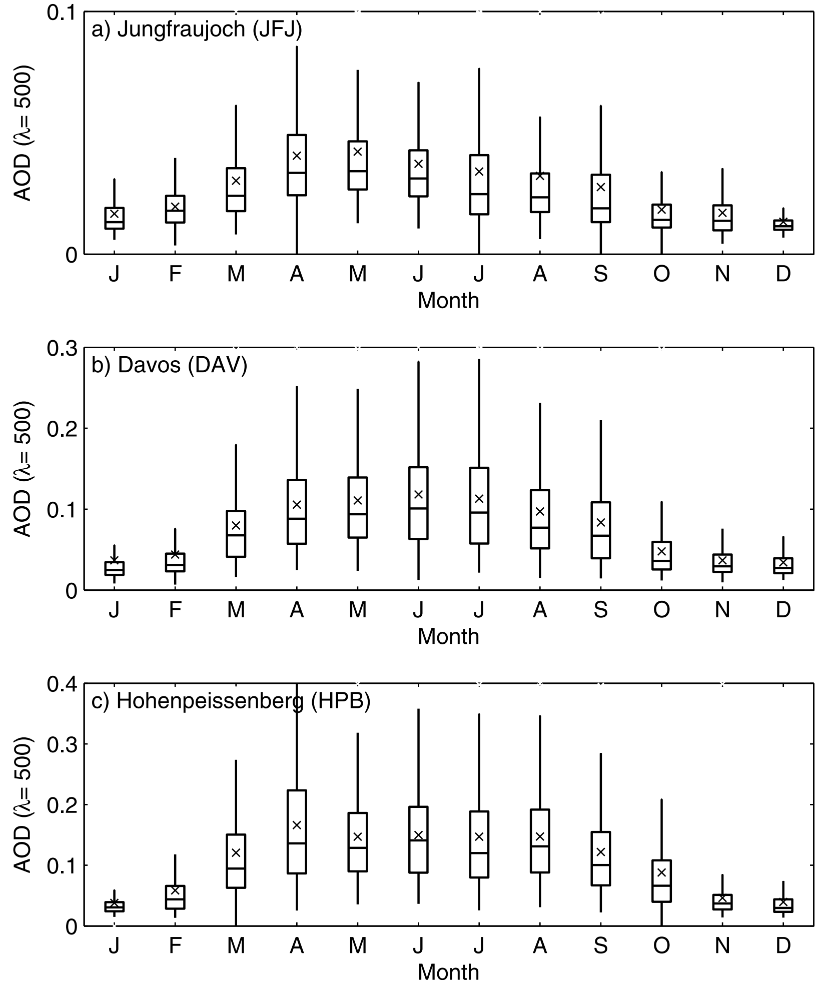

Figure 2. Monthly box-and-whisker plots (crosses are mean values; whiskers and boxes show 5, 25, median, 75, 95 percentiles) of 1-h AOD for the study period at all three high-alpine sites. Note the different AOD scales.

linked to annual circulation patterns and the long-range transport of larger aerosols.

[20] A trend analysis of the α time series gave a statistically significant negative trend for JFJ (-0.20 decade^{-1}; p = 0.05; upper and lower bound of 95% confidence interval = -0.29 and -0.10 decade^{-1}). Negative smaller trends were obtained at DAV and HPB (-0.04 and -0.02 decade^{-1}), but were not statistically significant. Interestingly, a negative trend in α (calculated only from λ = 650 and 850 nm) was also observed over the northern hemisphere oceans in a recent satellite study [*Cermak et al.*, 2010]. It was suggested that a reduction in the fine mode fraction may be due to a reduction in anthropogenic aerosol emissions.

4. Discussion and Conclusions

[21] The observed AOD trends at our three sites may be affected by a number of long-term as well as short-term

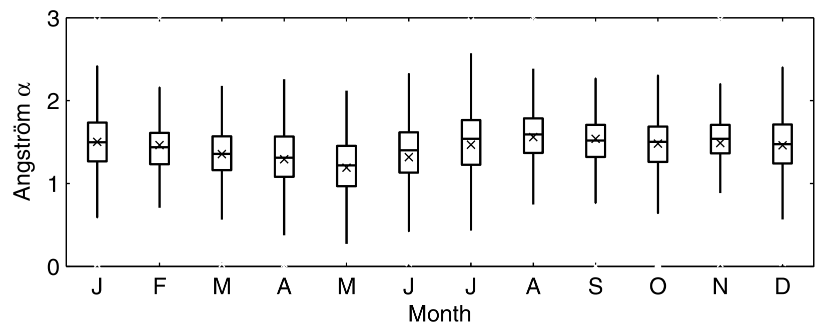

Figure 3. Monthly box-and-whisker plots of 1-h Ångström α values for the study period at JFJ.

influences which could mask the underlying trends. Several long-term influences include the effect on AOD of possible changes in relative humidity [*Bian et al.*, 2009], and the effect of the North Atlantic Oscillation (NAO) on atmospheric circulation over Europe [*Chiacchio et al.*, 2011]. However, as these influences are beyond the scope of the present study, the effect of short- to mid-term influences will be further discussed. One such influence may have been a bias due to changes in the frequency of sunny periods. Trend analysis of the number of data points in 1995–2010 showed no statistically significant trends as p values were 0.35, 0.29 and 0.89 for DAV, JFJ and HPB respectively. A further short-term influence is the effect of PBL versus FT air masses on the AOD time series. As the JFJ is the highest of our three high-altitude stations, and hence least influenced by the PBL, it should be less complicated to remove PBL-influenced periods from the AOD time series. An established method was therefore used to screen AOD data. Initially we used CO background concentrations in order to characterize each record of our time series during 2005, according to data reported by *Balzani Lööv et al.* [2008]. The NO_y/CO ratio was then calculated and the 95th percentile that corresponds to these background values (=0.015) was taken as a threshold value where lower (higher) values are indicative of FT (PBL) conditions. The removal of PBL-influenced data resulted in a slightly smaller mean AOD at JFJ (0.026 $\pm$ 0.014 as opposed to 0.027 $\pm$ 0.014), while the trend ($p < 0.05$) decreased by only 1%.

[22] In Section 3 we mentioned the possible influence of stratospheric AOD on our time series. A recent study on stratospheric AOD in 1985–2010 based on homogenized satellite data showed that the global peak due to Pinatubo occurred in spring 1992 with values as high as AOD $\sim$0.10 (λ = 525 nm) [*Vernier et al.*, 2011]. After an exponential decay, AOD only reached a quiescent "background" value of $\sim$0.004 in about 1998–2004. A subsequent increase to 0.005–0.006 in early 2005 to 2010 was argued to be due to an increase in strong volcanic eruptions rather than due to increasing SO_2 emissions in southeast Asia. Although our trend analysis only begins in 1995, stratospheric AOD was still $\sim$0.01 and represented >40% of the JFJ January 1995 value. In addition, the increase in stratospheric AOD since early 2005 appears to be reflected in the JFJ time series (see Figure 1a). Hence various statistical tests were applied to the stratospheric AOD time series. Satellite data for the 15–35 km altitude range and the 50°N–20°N zone, were converted from λ = 525 to λ = 500 nm using a post-Pinatubo Ångström exponent $\alpha \sim 1.5$ (J.-P. Vernier, private communication, 2012). When the Buishand and Pettitt homogeneity tests were applied a shift in the mean was found in March and May 2005, respectively (K and Q statistics are 62.27 and 7551 respectively; $p < 0.0001$). Application of the Kolmogorov-Smirnov test to the pre- and post-April 2005 sub-series, indicated that both sub-series differed significantly ($D = 1$, $p < 0.0001$). This coincides with the volcanic eruption of Manam (end Jan. 2005; 4°S, 145°E; Papua New Guinea) and a series of other eruptions throughout 2005–2010 which are evident in SAGE II, CALIPSO and GOMOS space-based observations [*Vernier et al.*, 2011]. The similarity of these homogeneity results and those for the JFJ strongly suggests that the post-April 2005 AOD time series at JFJ is influenced by stratospheric AOD. The small inconsistency in the times when a shift was found in stratospheric and JFJ AOD could perhaps be attributed to the large spatial coverage of the stratospheric AOD time series compared to the point measurements at JFJ.

[23] After having established that the trend in stratospheric AOD changed in about April 2005, the time series was then subtracted from the 1995–2010 JFJ, DAV and HPB time series. AOD trend results gave +0.004 decade^{-1} ($p = 0.05$), +0.000 ($p = 0.92$) and -0.013 ($p = 0.05$) for JFJ, DAV and HPB, respectively. Although only a small reduction in the decadal trends was observed, the JFJ trend remained statistically significant at the 95% level while the HPB trend increased from the 90% to the 95% level. Despite correction of the JFJ time series, the influence of stratospheric AOD is still slightly visible in the time series graph (not shown) during the 2005–2010 period, and illustrates the difficulty in correcting point measurements with zonal average measurements. Hence, the shorter JFJ period, 1995–April 2005, trend was corrected with stratospheric AOD. The trend increased only slightly to -0.002 decade^{-1} ($p = 0.07$) while the confidence level decreased to 93%. The consideration of stratospheric AOD at high-altitude sites with a low annual average is thus an important aspect.

[24] In conclusion, the above analyses show that the reported trends at all three sites were not significantly affected by any confounding effects except for stratospheric AOD to a certain degree. In an earlier study [*Ruckstuhl et al.*, 2008] a small negative trend in AOD was observed at high-altitude sites in central Europe from 1995–2005, with indications of stabilization after about 2000. Despite a more detailed re-analysis of these time series, which have been extended by five years to the end of 2010, a significant decrease in AOD at these three high-altitude sites has still not been observed.

[25] **Acknowledgments.** We kindly thank (1) EMPA, Dübendorf, Switzerland for use of CO/NOy data from the WDCGG website and (2) the SAGE II, GOMOS and CALIPSO science teams for use of stratospheric AOD data.

References

Augustine, J. A., G. B. Hodges, E. G. Dutton, J. J. Michalsky, and C. R. Cornwall (2008), An aerosol optical depth climatology for NOAA's national surface radiation budget network (SURFRAD), *J. Geophys. Res.*, *113*, D11204, doi:10.1029/2007JD009504.

Baltensperger, U., L. Barrie, and C. Wehrli (Eds.) (2005), WMO/GAW Experts Workshop on a global surface-based network for long term observations of column aerosol optical properties, *WMO TD 1287*, World Meteorol. Organ., Geneva, Switzerland.

Balzani Lööv, J. M., S. Henne, G. Legreid, J. Staehelin, S. Reimann, A. S. H. Prévôt, M. Steinbacher, and M. K. Vollmer (2008), Estimation of background concentrations of trace gases at the Swiss Alpine site Jungfraujoch (3580 m asl), *J. Geophys. Res.*, *113*, D22305, doi:10.1029/2007JD009751.

Bian, H., M. Chin, J. M. Rodriguez, H. Yu, J. E. Penner, and S. Strahan (2009), Sensitivity of aerosol optical thickness and aerosol direct radiative effect to relative humidity, *Atmos. Chem. Phys.*, *9*, 2375–2386, doi:10.5194/acp-9-2375-2009.

Cermak, J., M. Wild, R. Knutti, M. I. Mishchenko, and A. K. Heidinger (2010), Consistency of global satellite derived aerosol and cloud data sets with recent brightening observations, *Geophys. Res. Lett.*, *37*, L21704, doi:10.1029/2010GL044632.

Chiacchio, M., T. Ewen, M. Wild, M. Chin, and T. Diehl (2011), Decadal variability of aerosol optical depth in Europe and its relationship to the temporal shift of the North Atlantic Oscillation in the realm of dimming and brightening, *J. Geophys. Res.*, *116*, D02108, doi:10.1029/2010JD014471.

Collaud Coen, M., E. Weingartner, M. Furger, S. Nyeki, A. S. H. Prévot, M. Steinbacher, and U. Baltensperger (2011), Aerosol climatology and planetary boundary influence at the Jungfraujoch analyzed by synoptic weather types, *Atmos. Chem. Phys.*, *11*, 5931–5944, doi:10.5194/acp-11-5931-2011.

Gilbert, R. (1987), *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold, New York.

Gröbner, J., and C. Meleti (2004), Aerosol optical depth in the UVB and visible wavelength range from Brewer spectrophotometer direct irradiance measurements: 1991–2002, *J. Geophys. Res.*, *109*, D09202, doi:10.1029/2003JD004409.

Hodzic, A., R. Vautard, H. Chepfer, P. Goloub, L. Menut, P. Chazette, J. L. Deuzé, A. Apituley, and P. Couvert (2006), Evolution of aerosol optical thickness over Europe during the August 2003 heat wave as seen from CHIMERE model simulations and POLDER data, *Atmos. Chem. Phys.*, *6*, 1853–1864, doi:10.5194/acp-6-1853-2006.

Holben, B. N., et al. (1998), AERONET—A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, *66*, 1–16, doi:10.1016/S0034-4257(98)00031-5.

Ingold, T., C. Mätzler, N. Kämpfer, and A. Heimo (2001), Aerosol optical depth measurements by means of a Sun photometer network in Switzerland, *J. Geophys. Res.*, *106*, 27,537–27,554, doi:10.1029/2000JD000088.

McArthur, L. J. B., D. H. Halliwell, O. J. Niebergall, N. T. O'Neill, J. R. Slusser, and C. Wehrli (2003), Field comparison of network photometers, *J. Geophys. Res.*, *108*(D19), 4596, doi:10.1029/2002JD002964.

Nyeki, S., U. Baltensperger, I. Colbeck, D. T. Jost, and E. Weingartner (1998), The Jungfraujoch high-alpine research station (3454 m) as a Background clean continental site for the measurement of aerosol parameters, *J. Geophys. Res.*, *103*, 6097–6107, doi:10.1029/97JD03123.

Nyeki, S., et al. (2000), Convective boundary layer evolution to 4 km asl over high-alpine terrain: Airborne lidar observations in the Alps, *Geophys. Res. Lett.*, *27*, 689–692, doi:10.1029/1999GL010928.

Papadimas, C. D., N. Hatzianastassiou, N. Mihalopoulos, X. Querol, and I. Vardavas (2008), Spatial and temporal variability in aerosol properties over the Mediterranean basin based on 6-year (2000–2006) MODIS data, *J. Geophys. Res.*, *113*, D11205, doi:10.1029/2007JD009189.

Ruckstuhl, C., et al. (2008), Aerosol and cloud effects on solar brightening and the recent rapid warming, *Geophys. Res. Lett.*, *35*, L12708, doi:10.1029/2008GL034228.

Schmid, B., and C. Wehrli (1995), Comparison of Sun photometer calibration by Langley technique and standard lamp, *Appl. Opt.*, *34*, 4500–4512, doi:10.1364/AO.34.004500.

Streets, D. G., F. Yan, M. Chin, T. Diehl, N. Mahowald, M. Schultz, M. Wild, Y. Wu, and C. Yu (2009), Anthropogenic and natural contributions to regional trends in aerosol optical depth, 1980–2006, *J. Geophys. Res.*, *114*, D00D18, doi:10.1029/2008JD011624.

Vernier, J.-P., et al. (2011), Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade, *Geophys. Res. Lett.*, *38*, L12807, doi:10.1029/2011GL047563.

Weatherhead, E. C., et al. (1998), Factors affecting the detection of trends: Statistical considerations and applications to environmental data, *J. Geophys. Res.*, *103*, 17,149–17,161, doi:10.1029/98JD00995.

Wehrli, C. (2000), Calibrations of filter radiometers for determination of atmospheric optical depths, *Metrologia*, *37*, 419–422, doi:10.1088/0026-1394/37/5/16.

Weller, M., and K. Gericke (2005), Long-term observations of aerosol optical depths at the Meteorological Observatory Lindenberg, *Meteorol. Z.*, *14*, 651–662, doi:10.1127/0941-2948/2005/0070.

Wijngaard, J. B., A. M. G. Klein Tank, and G. P. Können (2003), Homogeneity of 20th century European daily temperature and precipitation series, *Int. J. Climatol.*, *23*, 679–692, doi:10.1002/joc.906.

Wild, M., B. Trüssel, A. Ohmura, C. N. Long, G. König-Langlo, E. G. Dutton, and A. Tsvetkov (2009), Global dimming and brightening: An update beyond 2000, *J. Geophys. Res.*, *114*, D00D13, doi:10.1029/2008JD011382.