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Interactive comment on "No role for industrial black carbon in forcing 19th century glacier retreat in the Alps" *by* Michael Sigl et al.

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Commentary by T. H. Painter, M. G. Flanner, G. Kaser, B. Marzeion, R. A. VanCuren, and W. Abdalati

We are quite pleased to see testing of the hypothesis presented in our 2013 paper End of the Little Ice Age in the Alps forced by industrial black carbon. However, the paper submitted here to The Cryosphere Discussions (Sigl et al, hereafter SCD for Sigl Cryosphere Discussion) has a host of logical and interpretive errors that prevent its conclusion that it refutes the hypothesis in Painter et al 2013, let alone robustly. We describe these errors in the following three categories: (1) glaciology, (2) ice core interpretation, and (3) radiative transfer.

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Discussion paper

(1) Glaciological

The importance and magnitude of the post-1865 retreat of Alpine glaciers is not that they retreat from the LIA high stand of the early 19th century but instead that they retreat to lengths not observed in the previous several hundred years. The Little Ice Age is generally considered as spanning 1300-1870 (Grove, 2004). It is exactly because of this excursion that we used the glacier length records that we did in Painter et al (2013), which reached back hundreds of years. The specific statement in SCD, "can thus be understood as a delayed rebound back to their positions they had before the radiative perturbed time period 1800-1840 AD" (p12, lines 20-21) is inconsistent with the glacier records from the Alps going back to the 1600s. Such an abrupt Alps-wide excursion from multi-centennial glacier length equilibrium range requires a likewise abrupt and marked perturbation to energy or mass balance (Huybrechts et al., 1989; Kerschner, 1997) or potentially an intensification of subannual climate variability (Farinotti, 2013). Such do not exist in the observational record nor the HISTALP reconstruction. The excursion from the envelope of lengths did not happen until approximately 1870-1875, consistent with their interpretation of when BC emissions emerged above pre-industrial.

Note that in Painter et al (2013), we state on p2, first paragraph "As indicated by Huybrechts et al. (10) and many others, our best understanding of changes in temperature and precipitation in the 19th century indicates that there was no regional climatic anomaly coincident with the coherent retreat of glaciers in the Alps near 1865". Moreover, in our Figure 1 (Painter et al 2013), the vertical dashed line at 1875 indicates the unambiguous excursion in lengths from the previous several hundred years (Figure 1 below). We understand the appeal of the higher temporal resolution glacier length records but without the records back into several earlier centuries, one cannot address the driver of that excursion and the relevant scientific question.

An additional issue with the current document is that SCD do not address the explicit treatment of glacier mass balance in our paper. With the temperature and precipitation from HISTALP, the glacier mass balance model matches well the record of the Hintereisferner across the last ∼60 years. However, the excursion in glacier length cannot be resolved without contribution of some additional forcing, as Huybrechts et al (1989) put it, "Forcing the mass balance history [with summer and mean annual temperature anomalies] brought to light, that, in particular, the observed glacier retreat since about 1850 is not fully understood. This result and the improved model simulations that could be obtained while assuming an additional negative mass balance perturbation during roughly the last 150 years, seems to point to additional features affecting the glacier's mass balance that are not captured well in the ambient climatic records.

SCD seem to allude to some contribution from the temperatures from Buntgen et al. (2006; 2011) as being suggestive of the rising temperatures sufficient to explain the post-1865 glacier length excursion. However, these reconstructions are inconsistent with the observational record, even after it is corrected for shading.

SCD cite Gabbi et al (2015) multiple times but miss the contradictory relevance of the central points of that paper compared to their paper from a glaciological, ice core, and radiative transfer standpoint. In particular, at the Clarindenfirn, across most of the 20th century BC has ∼3X greater radiative forcing than dust, and summer radiative forcings from BC in snow were 13-16 W m-2. Gabbi et al consider this a lower limit, including this being a period of markedly lower BC emissions, deposition, and radiative forcing in snow than at the peaks of industrialization. Considering the SCD BC time series, present day radiative forcings should be relatively consistent with those in the 1880s, before the further rise in the late 1800s to that of the first decades of the 20th century. Indeed, they indicate "As a result, we obtain similar BC concentrations in the surface layer on average, and thus, a comparable impact of BC on glacier mass balance. The general agreement of our assessment with that of Painter et al. (2007) [our dust radiative forcing and melt paper] indicates the highly relevant role of BC in shaping changes in glacier mass balance over the last century."

(2) Ice Core Interpretation

In the context of ice core interpretation, this is the area of the authors' expertise. We in no way contest their analysis of the constituents that were found in the CG ice core. The issue comes with the interpretation of the results. Interpretation of poorly mixed constituents (such as BC) in complex terrain with enormous relief must be treated with caution and, as such, semi-quantitatively. In particular, ice cores from locations with such intense wind scouring and complex wind fields (Figure 2) cannot be considered to be absolute in capturing all air that has passed over and onto the surface. Moreover, their flow regimes are frequently disconnected from those in the ablation zones (as they were for the mid 19th century glaciers at 1500 to 2200 m elevation) where the increased net fluxes from impurities would have had their maximum impact on mass balance and glacier length. As such, unlike determination of well-mixed gases in ice cores, these cores should be considered as suggestive of transport to mountain systems and offering a lower bound on deposition.

Multiple sources suggest that BC emissions from industrialization on the European continent began to increase substantially in the 1850s with a quasi-monotonic growth in emissions (Bond et al., 2007; Bond et al., 2013; Lavanchy et al., 1999). SCD argue that, because such reconstructions have substantial uncertainties, that the quasi-monotonic increase must be erroneous and that the time series in the ice core more accurately represents actual emissions. This argument is posited with no argument to explain 100% excursions in BC emissions that are expressed in the ice core time series presented in SCD Figure 3a, when BC drops entirely (annual) or by ~50% (5 yr) from 1880 to 1890. Likewise, no explanation is given as to the steep drop from ~1920 and then the enormous climb beginning in 1930, coincident with the global depression. The timing of these excursions is markedly out of phase with well understood historical excursions in continental European productivity.

Regarding the non-quantitation between the core and regional emissions, the inter-annual variation in the laser-incandescence (LI) data is quite large. SCD contends that the linear interpolation between years in the Bond et al emission estimates is not credible. Here, we show European emissions data for 2000-2015 (Figure 3), which span the largest economic variation in more than half a century. Note that PM2.5 emissions still had an average interannual variation of 3 percent. This suggests that the noise in the ice core BC concentrations is in transport variation year to year, not to first order emissions. The burden needs to be put back to the authors to defend the "emergence" statistic. Indeed, the more noise, the later the lag in detection of any increase in LI-sensitive carbon. These thoughts are detailed in the four points below:

1. The use of summer-only data assumes that summer aerosols at the Col represent the operative aerosol deposition impacting the whole glacier - the strong persistent inversion in the Alps in summer disconnects the atmosphere at the Col from the atmosphere over the transport and ablation zones of the valley glaciers (Figure 4), thus the Col record is not a quantitative analog of valley conditions, and there is no evidence presented that winter and spring deposition can be inferred from the summer data. 2. The laser incandescence (LI) method is highly sensitive to carbonaceous chain aggregate particles and is usually calibrated with a pure hydrocarbon combustion soot generator. The measurement is less sensitive to "brown carbon" and mixed-component aerosols such as produced by burning low quality coal or inefficient coal combustion (Sun et al., 2017). It may be that the record reflects evolving combustion technology as much or more so than emission strength. 3. The large inter-annual variation in the LI data is inconsistent with interpreting it as a surrogate for regional or continental scale emissions. Data on modern fine particle emissions from 2000 to 2015 (Figure 3) show an average inter-annual variation of about 3%, even though this period includes the enormous economic fluctuations driven by the crisis of 2008. This suggests a large variability in the LI data due to meteorology. Hence, these data suggest noise is in transport variation year to year, not emissions. 4. The emergence test statistic is strongly influenced by the noise in the time series data - with detection of a trend delayed as noise increases. Since the noise in these data contains a large meteorological component, the inferred timing of the beginning of industrial impact in these data has a large and un-discussed time lag.

Note also that in SCD Figure 5, the climb in BC in Greenland unambiguously occurs around 1850-1860.

(3) Radiative Transfer

SCD do not address the magnitude of radiative forcing by BC that was present in the Alps at the time. For the claim of no role for BC in the retreat of European glaciers from the LIA to be valid, the radiative forcings in Painter et al (2013) estimated from the ice core BC would have to be overestimated by more than an order of magnitude. We think this is highly unlikely given the known increase in aerosol concentrations with decreasing altitude, as substantiated by SCD co-author Schwikowski (2004), among many others. From an energy balance perspective, we do not understand how SCD would explain away the 20-40 W m-2 seasonally-averaged radiative forcing by BC for April-June in the ablation zones? As described in Painter et al (2013), the melt magnitude associated with the 1880 radiative forcing of 10-20 W m-2 would have been 240-480 kg m-2 (0.6-1.2 m w.e.) and with the 1900 radiative forcing of 19-38 W m-2 would have been 450-890 kg m-2 (1.1-2.2 m w.e.). Equivalent changes in temperature to produce such radiative forcings in context of mass balance would have reached 3-4 K.

SCD state that our study suffers from not including the radiative forcing by dust in snow (p3, lines 32-35+p4, 1-2). To a degree they are correct because we did not include the description of our coupled dust+BC radiative forcings. However, the BC radiative forcings that we report were in fact (BC+Dust)-(Dust Only). Moreover, we concluded from extensive analyses of these cores that dust deposition saw no trends during the period recorded in the ice cores. Likewise, SCD also found that mineral dust had no trends (p8, 30-32), "In agreement with other dust records from Colle Gnifetti (Bohleber et al., 2018; Wagenbach and Geis, 1989), we observe no enhanced mean (or frequency) of mineral dust deposition throughout the 19th century (Supplementary Figs. S1, S4)." Either way, we are puzzled that such would be highlighted as a 'suffering'.

Summary

Again, we are enthused that our work has stimulated thought and testing of our hypothesis. However, based on the above comments, it appears to be clear that SCD does not refute the hypothesis. Ultimately, the core of the SCD paper is really to reconcile an issue with ice cores and emission scenarios, neither of which presently can be considered quantitatively robust in characterizing regional atmospheric conditions at the elevations of Alpine glacier ablation zones (today back to the high stand of the LIA). Instead, the ice cores can be considered as suggestive of BC deposition timing and magnitude but not as an absolute quantification. Likewise, to a lesser degree the paper also encounters the discrepancy between the temperature observations, HISTALP reconstructions, and the tree-ring derived temperature reconstruction of Büntgen et al (2012). Let's work as a community to resolve these particular discrepancies.

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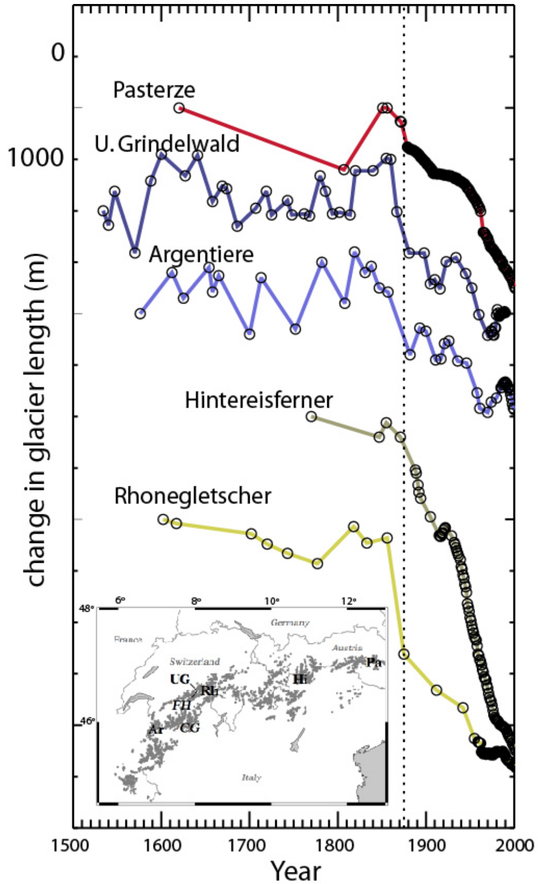

Fig. 1. From Painter et al (2013), their Figure 1 shows the vertical line plotted at 1875 to indicate the unambiguous excursion from the previous several hundred years of glacier length.

Fig. 2. Photograph of frequent wind structures in snow at the Colle Gnifetti, demonstrating that the site is subject to frequent redistribution of snow and its constituents. (Source: U. of Maine)

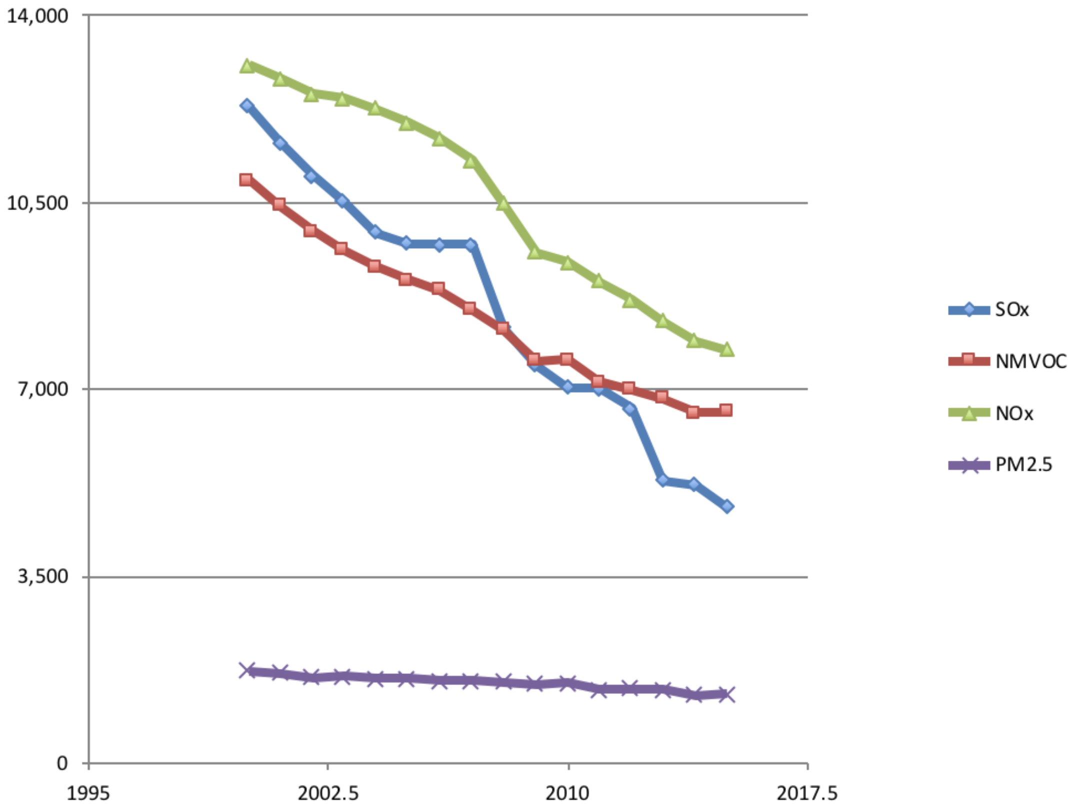

Fig. 3. European emissions of SOx, NOx, NMVOC, and PM2.5 across 2000-2015, which includes the global economic downturn. Data source: European Environment Agency.

Fig. 4. Summer looking south into the Bernese Alps shows air pollution in the Alps confined to lower altitudes, concentrating the deposition of soot and dust on the lower slopes. Credit: Peter More

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