We thank the referees and colleagues for their time and energy to review our manuscript. Please find below our responses to the points and comments raised by the reviewers and peers and the changes in the manuscript.

Reviewer #1 (RC1):

This paper sets out to challenge the hypothesis that an increase in industrially produced black carbon (refractory black carbon; rBC) is responsible for glacier retreat in the Alps during the latter half of the 20th century due to a decreasing albedo feedback mechanism. The authors use data acquired from 2 new ice cores from the Colle Gnifetti and to derive the timing of an increase in rBC deposition above preindustrial levels and compare it to the timing and rates of glacial retreat, finding that most of the glacier retreat in the Alps had occurred prior to the onset of higher rBC. Another notable finding of the study is a discrepancy in modelled and reported rBC emissions and what is actually reported in the ice cores.

I think that this is an excellent manuscript. The authors do a great job in tying their observations from a single site to observations from other rBC records in the region as a validation of the regional scope of their conclusions and using a multi-proxy approach to documenting potential rBC source. The time of emergence analysis is novel for this application and was useful for deriving the emergence of "industrial" rBC as an aerosol. I thought that Figure 7 was particularly effective because it showed how glacier advance/retreat was functioning independently of rBC concentration where glaciers retreated when rBC concentration is high and advance when it is low.

Minor editorial comments are as follows:
Abstract, line 19: should be "The basis. . ." Pg 1, line 7: why "already"? Pg 1, line 8: should it be "cloud forming processes"? Pg 1, line 26: "hampering to attribute" is awkward., Pg 7, line 9: missing a period Pg 11, line 26: "forced by the latter" is awkward Pg 12, line 8: "documentaries"? Pg 13, line11: delete "towards" Pg 14, line 13: maybe change "Much understanding" to "Much of the understanding"?

We kindly acknowledge this positive and constructive evaluation. We carefully considered all the suggested technical corrections and revised the manuscript accordingly.

Pg 4, line 18: why is it summer biased?

Due to preferential wind erosion of winter snow as stated in line 15 and in the cited references

Short Comment by T. H. Painter, M. G. Flanner, G. Kaser, B. Marzeion, R. A. VanCuren, and W. Abdalatiet al (SC1):

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.

We acknowledge the comments by the authors of Painter et al., 2013; PNAS (hereafter PP13) and, in the following, address them point-by-point. Our main conclusions stand untouched.
1) At the time when BC deposition values from multiple state-of-the-art ice-core reconstructions exceeded its natural variability, the vast majority of glacier length reductions had already occurred.
2) During 1910-1920, when industrial BC deposition reached peak values exceeding three times values from 1875-1885 AD, many glaciers in the Alps were advancing.
Both these observations are inconsistent with the hypothesis that industrial BC forced the end of the Little Ice Age in the Alps. The end of the Little Ice Age, we argue, was primarily due to the absence of the radiative forcing agents that produced the Little Ice Age in the first place (Miller et al., 2012; Schurer et al., 2014) – clusters of large volcanic eruptions and solar minima, both more abundant between 1600-1840 AD compared to the long-term mean (Toohey and Sigl, 2017; Usoskin, 2017).

(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.

We argue that the glaciers were not within their equilibrium range, neither from 1800-1840 nor from 1600-1840 due to the repeated radiative perturbations during the late LIA. The glacier length records Mer de Glace and Bossons provide both: 1) a long-term perspective extending before 1600 AD and 2) high-resolution observations since the mid-1850s that allow to identify precisely the timing of increased glacier retreat rates (Nussbaumer and Zumbühl, 2012; Zumbühl et al., 2008). Glacier lengths of Bossons were equal to that of 1870 in 1580, 1700, 1730 and 1760 AD (see Figure below). In 1742 AD the length was less than at any time between 1880-1930 AD. The glacier length positions of Mer de Glace during the late 16th century had not been reached before 1878 AD. The 16th and 18th century are characterized by lower volcanic activity, whereas the early 17th and early 19th century experienced strong volcanic perturbations. Mean Stratospheric Aerosol Optical Depth for the time window 1600-1840 AD was 40% larger than during the entire Common Era (Sigl & Toohey, 2017). Long-term glacier length records (e.g. from Great Aletsch and Gorner Glacier; (Holzhauser et al., 2005)) clearly show that glacier lengths less than in the 1880 AD have frequently occurred throughout the Common Era (e.g., in the 16th and 14th century and during most of the 'Medieval Quiet Period' and 'Roman Quiet Period', without the presence of industrial BC. See also review paper by Solomina et al. (2016).

This aspect is now considered in the "Discussion" section of the revised manuscript, where the following sentence was added: "*The stratospheric aerosol burden for the time window 1600-1840 AD was 40% larger than during the entire Common Era (Sigl & Toohey, 2017) with volcanic eruptions frequently forcing cold spells and glacier advances (e.g., in 1600s, 1640s, 1820s, 1840s) in the Alps (Fig. 9) and elsewhere (Solomina et al., 2016).*"

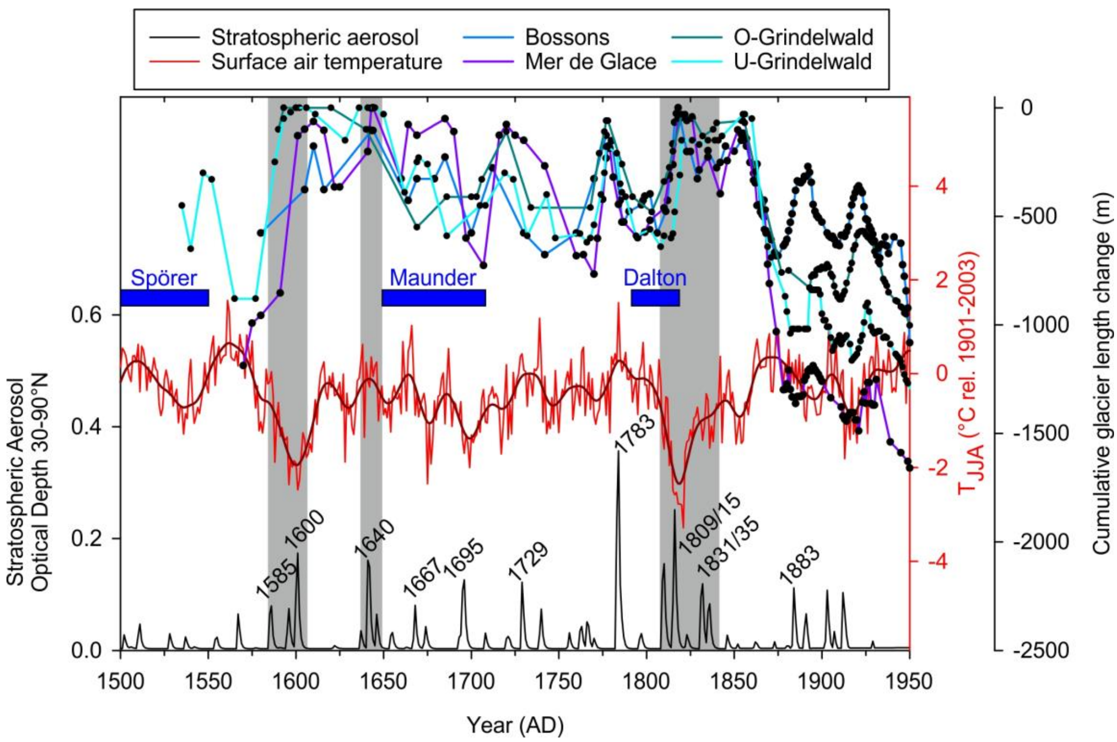

Figure 9: Cumulative length changes of four Alpine glaciers (Nussbaumer & Zumbühl 2012), tree-ring reconstructed Alpine summer temperatures (Büntgen et al., 2011), minima in solar activity (Usoskin 2017) and volcanic aerosol forcing (Revell et al., 2017; Toohey and Sigl, 2017) from 1500 to 1950 AD. Grey shading marks time periods with increased volcanic aerosol forcing.

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.

It appears the authors here suggest that the Alpine glacier retreat (accelerating in the 1860s, based on high-resolution glacier length records) was well within the range of natural variability until 1875 AD (keeping in mind that climate was generally very cold since 1600 AD). We agree. The glacier retreat until 1875, however, makes up over 80% of the entire 1850-1900 length reduction (see Table below) visualizing the "*End of the Little Ice Age*" (PP13). For the remaining 19th century we stated: "*Only after 1870 AD, when BC emissions started to strongly increase, snow-albedo impurity effects may have potentially contributed to the glacier length reductions, although the magnitude of such a feedback must be considered small given that glaciers were advancing during the coal-burning era of peak air pollution with BC in Central Europe (1910-1920)*"; p.14, l.9).

In the revised manuscript, following suggestions of Reviewer #2 we changed the title to "*No **leading** role for industrial black carbon in forcing 19th century glacier retreat in the Alps*".

Table: Glacier length variability, and BC concentrations in the Alps (Colle Gnifetti) and Greenland (4 ice-core stack) during the mid-19th to early 20th century.

Year	BC_{Alps} (ng/g)	$BC_{Greenland}$ (ng/g)	Bossons (m)	Mer de Glace (m)	O. Grindelwald (m)	U. Grindelwald (m)
1850	2.5	1.4	-200	-149	-63	-72
1875	4.1	1.6	-682	-1099	-696	-780
1900	4.9	3.4	-527	-1261	-734	-950
1915	10.8	5.1	-549	-1419	-777	-1070

*ice core concentrations are 10-yr means (e.g., 1846-1855 AD)

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.

Using the glacier records going back several hundreds of years the dominant role of volcanic eruptions in driving summer temperature variability and thus glacier excursions becomes even more evident. Our new Figure 9 shows that all major glacier advances since 1600 AD (e.g., in 1600s, 1640s, 1820s and 1850s) followed closely clusters of large stratospheric eruptions which has also been pointed out in several other recent studies (Lüthi, 2014; Solomina et al., 2016). The Huybrechts study from 1989 was long before the "*instrumental warm bias*" entered the scientific discussion (Böhm et al., 2010; Frank et al., 2007) and also dates back to two years prior to the eruption of Pinatubo 1991 when the global-scale cooling impact of volcanic eruptions was demonstrated (Robock and Mao, 1995).

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 Büntgen 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.

Since the work from Huybrechts et al. (1989), almost thirty years ago, a number of new studies have focused on the issue of an early 19th century instrumental warm bias producing an apparent cooling trend in the 19th century (see PP13 Fig. 2). Early instrumental station measurements prior to the 19th century were specifically prone to error and scarce in high-alpine environments. Correcting this bias and reconstructing early 19th century temperatures and precipitation rates in high-alpine regions thus remain areas of ongoing research (Böhm et al., 2010; Frank et al., 2007). Biases due to unshaded temperature readings are difficult to correct and likely result in an overall net warming influence on early station data (Böhm et al., 2010).

A recent multi-proxy reconstruction shows a mean 19th century JJA warming trend for Europe of 0.4°C (Luterbacher et al., 2016). The Alpine-wide tree-ring reconstruction from Büntgen et al., (2011) shows a 19th century warming trend of 1.5°C. With no apparent 19th century cooling trend in state-of-the-art Alpine climate reconstructions, there is no need to invoke additional feedbacks to produce glacier retreat. The fact that modelling with HISTALP data give reasonable agreement with observations during the past 60 years, does not mean that HISTALP data must be correct for the early 19th century (Böhm et al., 2010).

Finally, Lüthi (2014), by using a macroscopic model of glacier dynamics, derived a history of glacier equilibrium line altitude changes since 400 AD that strongly resembles reconstructions of Alpine summer temperatures. He concluded that *"the glacier advances during the LIA, and the retreat after 1860, can thus be mainly attributed to temperature and volcanic radiative cooling."*

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 20^{th} 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."

We cite Gabbi et al (2015), because, in this study, the annual BC record from Fiescherhorn was for the first time reported. The Gabbi et al. study showed that in the 20th century, the peak period of the industrialization in Central Europe with the highest BC concentrations in the Fiescherhorn ice core, annual melt was amplified by maximal 19% due to the combined effect of BC and mineral dust. Thus, the effect must have been much lower in the mid-to late 19th 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.

We acknowledge (and have acknowledged throughout the manuscript) the inherent limitations arising from transport and snow conservation on the mean aerosol concentrations on small temporal and spatial scales. Our main conclusions are, however, drawn from long-term trends ("emergence") that are observed at multiple different sites (two from the Alps, four from Greenland) using multiple different methods and proxies (e.g. BC, EC, Bi) for industrial pollution. The consistency of results across multiple sites indicates that local and site-specific deposition/preservation factors have not substantially altered the long-term signals of black carbon in these ice cores.

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.

The glacier sites from which the ice-cores were drilled are almost certainly more frequently above the planetary boundary layer, but they are by no means decoupled from the lower elevations where the emissions take place. The diurnal cycle as well as the annual cycles of aerosol deposition resulting from convective transport have been tracked and analysed at Colle Gnifetti and Jungfraujoch over many years using remote sensing and high-resolution in-situ aerosol monitoring (Lugauer et al., 1998; Nyeki et al., 2000). Sulphate records from Colle Gnifetti also closely mirror emission estimates over the past 100 years (Engardt et al., 2017). Ice cores from Colle Gnifetti are, in fact, dated by counting the summer peaks of maximum aerosol concentrations for many hundred years back in time (Bohleber et al., 2018). Aerosols from mining emissions during Roman times have been detected in two ice cores as far away as Greenland (Hong et al., 1994; McConnell et al., 2018). In other words, if there were any significant industrial BC emission sources from Central Europe present during the 1850-60s, they would have left detectable traces in the two ice cores from the Alps as well as in the ice cores from Greenland.

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).

This statement is hardly true. Bond et al. (2013) is a review paper. The Bond et al., (2007) paper discusses the development of a global emission inventory. Therein, Table 1 lists a single primary data source prior to 1923 AD – fossil fuel production and consumption estimates derived from Andres et al. (1999). We reviewed all these papers and we discuss in our manuscript, that there is scarcely any primary input data available from Central Europe and thus BC estimates from these inventories closely resemble energy consumption estimates taken from countries with more abundant data (i.e., the U.S.), a caveat already discussed by Bond et al. (2007).

Lavanchy (1999), in the first attempt to quantify BC and EC in Colle Gnifetti ice cores, defined the preindustrial as 1740-1889 AD (see Figure below) which is in close agreement with the best estimates given for Greenland for a "*rapid increase in ~1888*" (McConnell et al., 2007) and in many subsequent studies that we have cited in our manuscript.

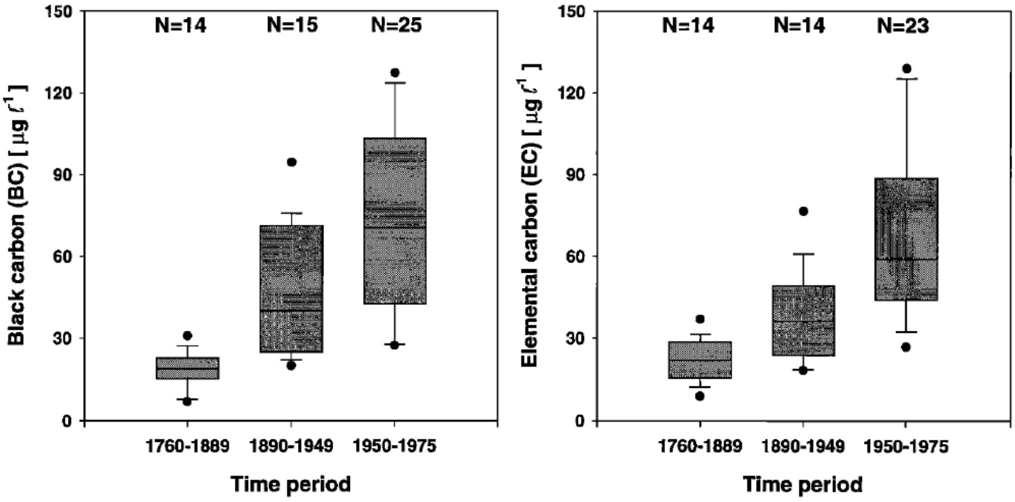

Figure. Minimum and maximum as well as 95th, 75th, 50th, 25th, and 5th percentiles of BC and EC from Colle Gnifetti (from Lavanchy et al., 1999).

SCD argue that, because such reconstructions have substantial uncertainties, that the quasimonotonic 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 low concentrations in the 1890s may represent an artefact of the kind we summarized in the section "Ice-core drilling site": "*On inter-annual timescales, the summer-biased and irregular snow deposition contributes to the observed variability of the proxy records, with occasionally preserved winter snowfall typically having low impurity concentrations*". This is a site-specific characteristic resulting most likely from increased preservation of winter snow in the 1890s with strongly depleted d^{18}O values and overall low impurity content that has been previously discussed for other ice cores from Colle Gnifetti (Wagenbach et al., 2012). On the basis of conservative aerosol proxies (such experiencing no major trends; e.g. dust, sea-salt) and the ratio of stable isotopes in water we can identify that this glacio-chemical anomaly is unique in the context of the record discussed here (starting in 1741 AD).

Low BC concentrations are centred on 1930 before BC starts to increase again in 1933. Similar trends have been previously described for lead and were explained with the Great Depression starting in 1929 and lasting into the 1930s (Gabrieli and Barbante, 2014).

We added the Wagenbach et al. reference describing that the 1890 AD period experienced anomalous high winter snow preservation at Colle Gnifetti.

The timing of these excursions is markedly out of phase with well understood historical excursions in continental European productivity. Regarding the nonquantitation between the core and regional emissions, the interannual 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.

It is obvious that any measurement of a variable at a single given location experiences more variability than emissions integrated over all of Europe. There is some additional noise in the ice-core data due to inter-annual variability of transport, but the long-term trend is not affected as illustrated by the agreement between emission estimates and ice core data for sulphate (Engardt et al., 2017).

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:

We have performed ToE analyses explicitly after removing forest fire related BC peaks during the pre-industrial in order to reduce the "noise" from non-industrial sources. Performing BC on the original dataset identifies 1895 or 1906 depending on the choice of the method as "time-of-emergence" (Supplementary Fig. S7). We also repeated ToE analyses for the four ice cores from Greenland and identified "time-of-emergences" in the range of 1864 to 1878 AD (1886-1892 AD using the Bayesian changepoint method). No matter which proxy and parameters we used to infer industrial BC emissions we found no evidence that "*BC emissions increased dramatically after 1850*" (Painter et al., 2013) which is the key assumption in the PP13 hypothesis.
We now report the results of ToE analyses performed for Greenland ice cores and added a new Supplementary Figure S7.

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.

This photograph is neither representing typical conditions prevailing throughout summer nor is this claim above substantiated by any robust data. Only Colle Gnifetti has a summer bias, whereas the Fiescherhorn ice core contains snow from all seasons. Yet, both records show overall similar long-term trends with BC concentrations at pre-industrial levels until 1875 AD. As shown in the Figure below, every summer, BC and other aerosols from the lowlands get frequently deposited at sites as high as Colle Gnifetti (Lugauer et al., 1998). Unless one argued that the industrialization in the regions surrounding Colle Gnifetti produced emissions only during winter-spring, we don't see a pathway in which valley glaciers should have experienced a different long-term history of BC deposition than the sites where we extracted the ice cores.

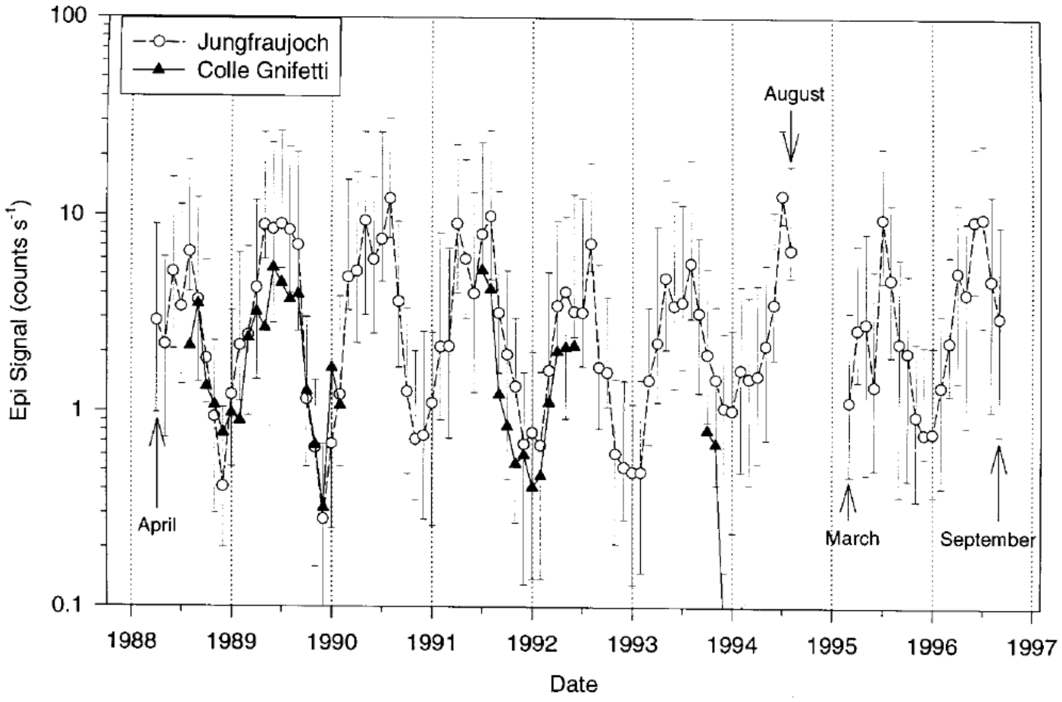

Figure. Monthly median (symbol) and quartile values (whiskers) of the epiphaniometer signal monitoring aerosol particles at the Jungfraujoch and at the Colle Gnifetti (only medians) from April 1988 to September 1996. (Lugauer et al., 1998)

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.

We used both "elemental carbon" and "black carbon" each determined with different instrumentation and also other elemental coal burning proxies (e.g. Bi), but none of the measurements indicate significant increases before 1870. We cannot disentangle the relative importance of evolving combustion technology versus emission strengths since both parameters are largely unconstrained during the 19th century.

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.

We do not recommend to interpret interannual BC variability from a single ice-core site as a quantitative reconstruction of large-scale emissions but notice that the absence of any significant increases of BC between 1850 AD and 1875 AD in virtual all ice cores in Greenland and the Alps are inconsistent with 1) the idea of linearly rising BC emissions in North America and Europe between 1850 and 1900; and 2) with the hypothesis of BC constituting the main driver of Alpine glacier recession on the assumption that "*black carbon concentrations increased abruptly in the mid-19th century*" (Painter et al., 2013)

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 undiscussed time lag.

While there are limitations in any methodology to estimate break-points in time-series depending on the noise and also other factors we have tried to estimate a lower (i.e. older) bound by "cleaning" the BC data for occasional forest fire peaks (to reduce the noise) and by including conservative age error estimates. Mean BC concentrations for the time period 1850-1875 AD are less than 20% elevated compared to the long-term preindustrial mean (1790-1850 AD) at Colle Gnifetti, Fiescherhorn and four different Greenland ice core sites, respectively.

The time of emergence results that we present are based on a distribution of results that assess the sensitivity of the ToE to methodological choices in the reference window length. We also further verify that similar late 19th Century changepoints are produced for the GC and Greenland ice core data using a Bayesian changepoint method (Ruggieri 2013).

Further, even assuming that deposition processes affect the BC preserved in the ice cores resulting in a "noisier" signal than for European-wide emissions (which we would expect), this "noise" would equally apply to the albedo effect of BC acting upon an individual glacier. The time when the concentration of BC in the ice core rose above the level of pre-industrial natural variability is thus a relevant measure for assessing when an unusual forcing by BC on the glacier could have become a plausible driver of glacier length changes.

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

In Figure 5, the unambiguous climb above background variability occurs only after 1870 AD. The period 1850-1860 was characterized by numerous forest fires (e.g. 1854, 1863, 1868, 1871) as can be proven for D4 using vanillic acid (VA) as a distinctive forest fire tracer (McConnell et al., 2007). For clarification, we repeated ToE analyses for all four individual ice cores: D4: 1878 [1865-1885; 5-95%], Summit2010: 1873 [1865-1878], NEEM: 1872 [1830-1882], TUNU: 1864 [1857-1869]. McConnell et al. (2007) give 1888 AD as their best estimate for industrial BC emergence at D4 which closely matches the dates determined

using the Bayesian changepoint method (1883-1893 AD, 5-95% range of all four ice cores).
We added a new figure Supplementary Fig. S7 showing the ToE analysis results for the D4 ice core – the only ice-core with annual dating accuracy, and a clear-cut proxy (vanillic acid) for forest-fire activity, respectively (McConnell et al., 2007) allowing discrimination of forest-fore BC.

(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.

Basis of these calculations were 1) not reproducible BC concentration estimates from an earlier study (Thevenon et al., 2009) which used an analytical setup that has not been used by any other research group since, and 2) largely unconstrained estimates of altitudinal gradients between valley glaciers and ice-core glaciers in the order of a factor of 10-20. If these previous estimates (e.g. 10-20 W/m^2; 0.6-1.2 m weq) were indeed realistic representations of the actual radiative forcing in 1880 AD, the radiative forcing from 1910-1920 AD (when industrial BC content was three times that of 1875-1885 AD) and the resulting glacier melt rates would have been extreme, but overall glaciers advanced during this time period.

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'.

We agree that dust has no long-term trends in the 19th century but this had not been explicitly addressed in the PP13 paper. In hindsight, we consider this a minor issue in the PP13 paper.

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.

The last sentence excluded, we respectfully disagree with this interpretation. The basis of the BC forcing hypothesis was that increased glacier retreat rates were coinciding with abrupt increases of industrial BC since 1850 based on model experiments using ice-core records, whereas temperatures appeared to have shown a declining trend throughout the 19th century. Using new measurements, we demonstrated that glacier melt accelerated before industrial BC emissions started to rise and highlighted the role of natural glacier variations resulting from global-scale radiative forcing from volcanic eruptions between 1600 and 1840 AD. We agree that detection and attribution of individual drivers of climate and glacier variability requires a community effort but also more and better observations and proxies. With the data at hand we, however, cannot identify a leading role in industrial BC in ending the "Little Ice Age". Previous *'Little Ice Age'*-type events (e.g., the *Late Antique Little Ice Age*) also ended, eventually (Büntgen et al., 2016).

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Reviewer #2 (RC2):

This paper evaluates the hypothesis that black carbon deposition could play a dominant role in European glacier dynamics. The paper presents black carbon concentrations found in ice cores at Colle Gnifetti along with other tracers of different kinds of combustion. Authors examine the role of mineral dust in possible forcing; since it absorbs light, mineral dust can be a possible confounding factor. They also compare their measurements with those of other ice cores. Finally, they compare the trends of black carbon deposition with those of black carbon emission and point out discrepancies between measured tracers and bottom-up inventories. The work is supported by a careful treatment of timing and uncertainties to interpret the ice core measurements.

We kindly acknowledge this positive and constructive evaluation. We carefully considered the improvements suggested below and we have revised the manuscript accordingly.

Overall, this part of the paper is a quite thorough and welcome contribution to the discussion of black carbon (and other species) emissions and influence during the industrial era. I commend the authors on their careful work.
The next part of the work– and the origin of the paper's title– compares the timing of glacial retreat with the timing of black carbon increase. These glaciers are frequently observed, making them good candidates for such an analysis. Authors identify retreat and advance periods and compare them with time-of-emergence of black carbon above pre-industrial periods, finding no relationship. Finally, on page 11, authors posit that volcanic forcing, and not change in albedo caused by black carbon deposition, is the cause of glacial retreat. The glaciers analyzed (four in a "glacier stack") begin to retreat before the increase in black carbon emissions, so it is unlikely that black carbon, alone, caused the current retreat. Despite this good point, this part of the work appears less supported by the evidence presented. An important question is on what time and spatial scales one respects a response between a forcing and a regional response. Attribution of climate response typically involves some kind of large-scale pattern matching, considering more factors than given here. One doesn't expect an increase in black carbon emission to correlate neatly with the glacier retreat– although certainly the fact that glaciers retreated first indicates that other causes are at work. If there were such neat correlations, we should have much less trouble identifying the causes of climate change, overall. So the following questions would have to be answered in order to confidently state the "No role for black carbon" as in the title: What other factors could contribute to glacial retreat; How much do they vary and on what temporal and spatial scales (i.e. what noise could confound the signal and must be averaged out); and then how much black carbon does contribute and whether it has a significant effect. The authors also considered volcanic forcing, which they suggest to be much more relevant than black carbon forcing, yet they did not provide any quantification of or data behind the volcanic forcing, but only some discussion. That quantification would be needed in order to make the statements in this paper with confidence.

We fully agree with the reviewer. We did not intend to perform a classical *Detection-and-Attribution* study delineating the changing contributions of natural and anthropogenic climate forcers on European glacier dynamics through time. With growing emissions of greenhouse gases and anthropogenic aerosols starting in the 19th century a monocausal relationship between glacier dynamics and any single forcing is inherently difficult to detect, let alone to quantify. However, there is also growing scientific evidence of the strong influence of natural forcing (e.g., from volcanic eruptions) on regional climate (temperature, precipitation) a fact that had been largely ignored by Painter et al., (2013) who argued in favour of an exclusive role of anthropogenic snow-albedo forcing from industrial soot.

To better reflect that we did not quantify relative contributions of forcing to glacier variability we changed the title to "*No **leading** role for industrial black carbon in forcing 19th century glacier retreat in the Alps*"

The four glaciers we used in our manuscript have mean "reaction times" of the glacier tongue to a climate perturbation of on average less than 10 years, whereas the "response time", the time required for a glacier to adjust from one "steady-state" to another, following a change in the mass balance may be two to three times longer (Nussbaumer & Zumbühl. 2012). However, the reaction to atmospheric conditions at the glacier front can also be more immediate in some situations, e.g. after runs of cool summers as becomes evident by maximum glacier advances in 1602, 1644, 1821 following "volcanic winters" with 5 years delay or less. To err on the side of caution, we have, in the interpretation of our "time-of-emergence" assessment, assumed that glacier fronts would have reacted immediately to increased rates of BC deposition.

In the revised manuscript, we put volcanic aerosol forcing from 1600-1840 AD in a long-term perspective. We quantified that Northern hemisphere (30-90°N) stratospheric aerosol optical depth (SAOD) was during this time 40% higher than the mean of the Common Era. Strong aerosol forcing culminated in a cluster of large eruptions during the early 19th century that was followed by Alpine glacier advances until the mid-19th century (new Fig. 9). New paleo-reanalyses covering the past 400 years confirm the large-magnitude, large-scale cooling impact of explosive eruptions Franke et al., (2017).

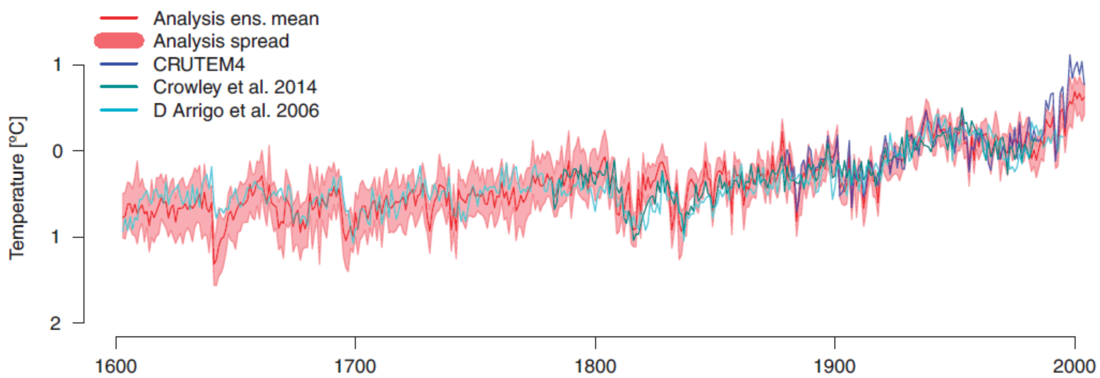

Figure. Northern hemisphere temperature evolution over the past centuries (Franke et al., 2017)

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