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Recent increase in black carbon concentrations from a Mt. Everest ice core spanning 1860–2000 AD

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[1]   A Mt. Everest ice core spanning 1860–2000 AD and analyzed at high resolution for black carbon (BC) using a Single Particle Soot Photometer (SP2) demonstrates strong seasonality, with peak concentrations during the winter-spring, and low concentrations during the summer monsoon season. BC concentrations from 1975–2000 relative to 1860–1975 have increased approximately threefold, indicating that BC from anthropogenic sources is being transported to high elevation regions of the Himalaya. The timing of the increase in BC is consistent with BC emission inventory data from South Asia and the Middle East, however since 1990 the ice core BC record does not indicate continually increasing BC concentrations. The Everest BC and dust records provide information about absorbing impurities that can contribute to glacier melt by reducing the albedo of snow and ice. There is no increasing trend in dust concentrations since 1860, and estimated surface radiative forcing due to BC in snow exceeds that of dust in snow. This suggests that a reduction in BC emissions may be an effective means to reduce the effect of absorbing impurities on snow albedo and melt, which affects Himalayan glaciers and the availability of water resources in major Asian rivers. **Citation:** Kaspari, S. D., M. Schwikowski, M. Gysel, M. G. Flanner, S. Kang, S. Hou, and P. A. Mayewski (2011), Recent increase in black carbon concentrations from a Mt. Everest ice core spanning 1860–2000 AD, *Geophys. Res. Lett.*, *38*, L04703, doi:10.1029/2010GL046096.

1. Introduction

[2]   Black carbon (BC, the absorbing component of soot) produced by the incomplete combustion of biomass, coal and diesel fuels can significantly contribute to climate change by altering the Earth's radiative balance. BC in the atmosphere absorbs light and causes atmospheric heating, whereas BC deposited on snow and ice can significantly reduce the surface albedo, hasten melt, and trigger albedo feedback [*Flanner et al.*, 2009; *Hansen and Nazarenko*, 2004; *Ramanathan and Carmichael*, 2008]. BC is estimated to have 55% of the radiative forcing effect of CO_2 [*Ramanathan and Carmichael*, 2008], yet BC remains one of the largest sources of uncertainty in analyses of climate change.

[3]   Records of BC mass concentration and spatial and temporal distribution in the atmosphere are needed to determine the role of BC in climate change. BC has a mean atmospheric residence time of several days, thus the global distribution is inhomogeneous and strongly correlated to sources. As a result, BC measurements are needed from many locations. Modern measurements of BC have been made on aerosol and precipitation samples, however historical records of BC are scarce. Thus, studies assessing the role of BC in climate change have relied on inventories of carbonaceous particle emissions based on wood and/or fossil fuel consumption data [*Bond et al.*, 2007; *Novakov et al.*, 2003]. However, many important BC sources such as residential emissions from cooking and heating are very difficult to estimate in the present, even more difficult to estimate for the past, and can vary greatly through time and with location. Thus, more quantitative measurements of BC emissions and atmospheric concentrations as a function of time are needed to estimate climate change related to BC forcing [*Hansen and Nazarenko*, 2004; *Novakov et al.*, 2003]. Ice cores from ice sheets and mountain glaciers provide a means to reconstruct historical BC concentrations.

[4]   Reconstructing BC concentrations in the Himalayas is particularly important because this region is influenced by some of the largest BC sources globally [*Bond et al.*, 2007], with negative impacts on climate, water resources, agriculture and human health [*Auffhammer et al.*, 2006; *Chameides et al.*, 1999; *Menon et al.*, 2002; *Ramanathan and Carmichael*, 2008]. Furthermore, it is estimated that the largest climate forcing from BC in snow occurs over the Himalayas and Tibetan Plateau [*Flanner et al.*, 2007, 2009; *Ramanathan and Carmichael*, 2008], and modeling studies suggest that BC is contributing to glacier retreat via atmospheric heating and BC deposition on glacier surfaces [*Lau et al.*, 2010; *Qian et al.*, 2010]. Herein we present a high-resolution BC record from a Mt. Everest ice core spanning 1860–2000 AD. This provides the first pre-industrial to present record of BC concentrations from the Himalayas.

2. Site Description and Methods

[5]   In 2002 a 108 m ice core was collected from the col of the East Rongbuk glacier located on the northeast ridge of Mt. Everest (28.03 N, 86.96 E, 6518 m) on the north slope

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of the Himalaya. The ice core was analyzed for BC using a Single Particle Soot Photometer (SP2, Droplet Measurement Technologies), a BC analytical technique first applied to ice cores by [*McConnell et al.*, 2007]. The SP2 uses laser-induced incandescence to measure the BC mass in individual particles quantitatively and independent of particle morphology and coatings with light scattering material [*Schwarz et al.*, 2006; *Slowik et al.*, 2007; *Stephens et al.*, 2003]. Specifically, the SP2 detects only the mass concentration of refractory black carbon (sometimes referred to as rBC; the term BC is used here for simplicity), while other absorbing aerosol components such as brownish carbon or mineral dust are not detected by the SP2. The high sensitivity and small required sample volume enables ice cores to be analyzed at much higher resolution than thermal-optical methods. Additional information about the ice core processing, chemical analyses, dating, SP2 calibration and BC mass size distribution are discussed in the auxiliary material.[1]

3. Results and Discussion

[6] The high-resolution BC data demonstrates strong seasonality, with peak concentrations during the winter-spring when atmospheric circulation is dominated by the westerlies, and low concentrations during the summer monsoon season, when southerly winds are dominant at the surface. The BC seasonality is illustrated by comparing the BC record with: 1) dust source elements (e.g., Fe) that peak during the winter and spring due to unstable atmospheric conditions and strong winds [*Kaspari et al.*, 2009], and 2) the more negative hydrogen stable isotope ratio (δD) due to strong monsoon activity during the summer [*Tian et al.*, 2003] (Figure 1). The ice core BC seasonality is consistent with previous findings, including: soot particles measured in snow pits at the same site [*Cong et al.*, 2009]; atmospheric measurements in the Khumbu Valley, Nepal (5079 m asl) [*Marinoni et al.*, 2010]; and other atmospheric measurements in the region [*Adhikary et al.*, 2007; *Ram et al.*, 2008; *Ramanathan et al.*, 2007; *Stone et al.*, 2010].

[7] Factors controlling BC seasonality include variations in emissions, atmospheric transport, and precipitation. For example, in the Kathmandu valley brick kilns that utilize coal and other biofuels only operate in the dry months between December and April, and biomass burning emissions from regions in South Asia peak during spring [*Adhikary et al.*, 2007; *Streets et al.*, 2003; *Venkataraman et al.*, 2006]. The winter-spring in this region of the Himalayas is particularly dry, thus the lifetime of BC and other aerosols in the atmosphere can be prolonged. Conversely, the majority of precipitation occurs during the summer monsoon season, resulting in the wet removal of BC and other aerosols from the atmosphere. As a result, summer precipitation in this region typically has low BC concentrations.

[8] To investigate changes in BC since 1860, the high-resolution data were re-sampled to 4 samples/year to correct for differences in sampling resolution with depth in the ice core. Average BC concentrations from 1860–1975 and 1975–2000 were 0.2 ± 0.3 $\mu g/L$ and $.7 \pm 1.0$ $\mu g/L$, respectively, indicating a threefold increase in BC concentrations from

pre-industrial to industrial times (Figure 1b) (herein reported BC concentrations and radiative forcing estimates represent lower limit values due to potential particle losses in the nebulizer). The increase is most apparent in peak BC concentrations (maximum BC = 32 $\mu g/L$ in 1984), however background concentrations also rise from ~0.05 $\mu g/L$ prior to 1960 to ~0.10 $\mu g/L$ post 1960. Higher BC concentrations in recent decades indicate that BC from anthropogenic sources is being transported to high elevation regions of the Himalaya.

[9] The increase in Everest BC during the 1970s is simultaneous with a rise in BC emissions as estimated from historical records of energy-related combustion in South Asia and the Middle East [*Bond et al.*, 2007] (Figure 1b). Based on dominant atmospheric circulation patterns and previous back-trajectory research [*Kaspari et al.*, 2009], these regions are likely sources of BC that is deposited at Mt. Everest. BC emissions in South Asia are substantially higher than the Middle East, particularly in recent decades, and northern regions of India may be a dominant source of BC transported to Everest via the westerlies. However, BC emissions from South Asia continue to increase throughout the record, whereas BC in the Everest record does not increase post ~1990. The Everest BC record likely represents trends in BC emissions from both regional and long-range sources, potentially including the Former USSR and Eastern Europe, where BC emissions have decreased in recent decades (Figure 1b). Western Europe and China are likely not important sources of BC transported to the Everest ice core site, as Western European sources peaked in 1960 and have since decreased, and BC emissions from China are downwind from the Himalaya. In addition to changes in BC emissions, deposited BC is also controlled by variations in the strength and pathways of winds that transport the BC from source regions to high elevations. Due to the extreme topography in this region, the mountain meteorology is complex and it is difficult to constrain inter-annual variability in vertical transport processes that allow BC from relatively low elevation source regions to be transported to the high elevation ice core drill site.

[10] BC deposited at Everest likely has both fossil and biofuel sources. BC fossil fuel sources include coal, petrol and diesel used in power generation, transportation, domestic uses and steel and cement manufacturing, whereas major BC biofuel sources include cattle manure, fuel wood, agricultural residue burning and forest fires [*Reddy and Venkataraman*, 2002a, 2002b]. Previous attempts to apportion BC to biomass and fossil fuel sources have produced varying results depending on the approach used (e.g., ratios of BC to total carbon; emission inventories based on fuel consumption), with recent radiocarbon measurements from India indicating that one half to two thirds of BC emissions result from biomass combustion [*Gustafsson et al.*, 2009].

[11] In addition to providing a record of historical BC concentrations in the atmosphere, the Everest BC and dust records supply information about absorbing impurities that can contribute to glacier melt by reducing the albedo of snow and ice. Notably, the Everest Fe record, used as a proxy for dust [*Kaspari et al.*, 2009] (Figure 1b), and dust number and mass records [*Xu et al.*, 2010] do not show an increasing trend since 1860. This is significant because it suggests that if the recent retreat of glaciers in the region is due, at least in part, to the effect of impurities on snow albedo, the reduced

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL046096.
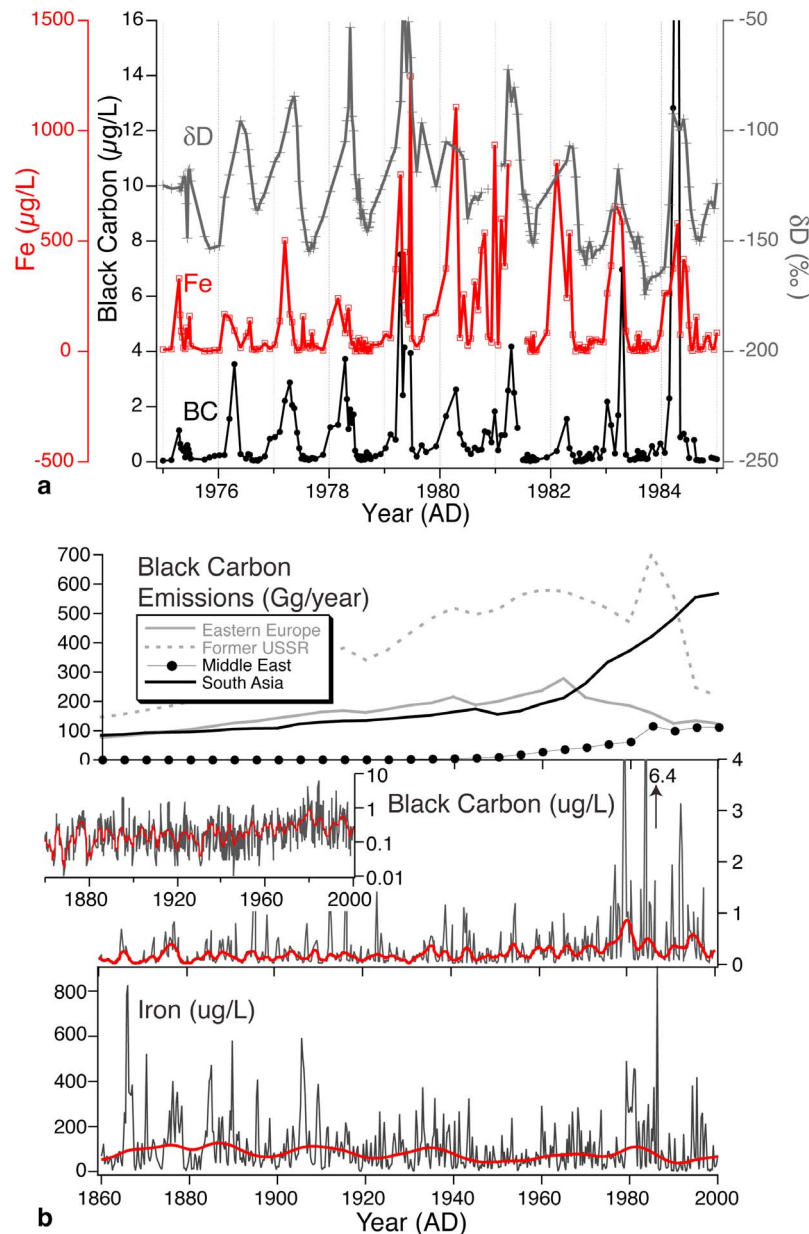
Figure 1. (a) High-resolution BC, Iron (Fe) and δD from the Everest ice core spanning 1975–1985 AD. (b) BC emission data [*Bond et al.*, 2007]; Everest ice core BC (including inset with logarithmic scale to show changes in background concentrations), and iron (used as a proxy for dust) [*Kaspari et al.*, 2009]. The Everest ice core data are re-sampled to 4 samples/year (black) due to differences in sampling resolution over time, and smoothed with a robust spline (red).

albedo is more likely due to increased BC deposition rather than dust.

[12] BC is estimated to be fifty times more effective than dust at reducing the visible snow albedo [*Warren*, 1984], although dust absorptivity is highly variable. Due to the prevalence of dust in this region, the relative importance of BC versus dust in reducing snow albedo has not been clear. A recent modeling study estimated that the Eurasian spring radiative forcing (RF) from dust and BC in snow is 1.2 and 2.7 W/m2, respectively [*Flanner et al.*, 2009]. We used the Snow, Ice, and Aerosol Radiative (SNICAR) model [*Flanner et al.*, 2007] to estimate the RF from BC and dust in snow. We assume that BC is internally mixed with scattering aerosol

components and thus use a mass absorption cross section of 11.3 m^2/g [*Flanner et al.*, 2007]. Average (466 ppb) and peak (3388 ppb) dust mass concentrations and size distribution are from measurements made on the same ice core [*Xu et al.*, 2010] and dust optical properties are derived from [*Clarke et al.*, 2004]. Surface RF measurements were calculated with varying snow effective radii, with 250 μm representing a central estimate, and 100 and 1000 μm bracketing the plausible range associated with variable snow grain size (Table 1).

[13] The average spring (March–April) BC RF in the presence of average dust concentrations increased from $0.11_{250\mu m}$ ($0.07_{100\mu m}$; $0.22_{1000\mu m}$) W/m^2 from 1860–1974 to $0.36_{250\mu m}$ ($0.22_{100\mu m}$; $0.69_{1000\mu m}$) W/m^2 from 1975–2000, indicating

Table 1. BC and Surface Radiative Forcing Average From 1860 to 1974 and 1975 to 2000, Increase Factor From 1975 to 2000/1860 to 1974, and Maximum Values From the Mt. Everest Ice Core[a]

	1860–1974[b]	1975–2000[b]	1975–2000/1860–1974 Increase Factor	Maximum[c]
Black Carbon (μg/L)	0.23	0.69	3	32.42
Mar–Apr Surface Radiative Forcing (W/m²)				
r = 250 μm, no dust	0.11	0.36	3.15	6.12
r = 100 μm, dust = 466 ppb	0.07	0.22	3.17	3.85
r = 250 μm, dust = 466 ppb	0.11	0.35	3.16	6.05
r = 1000 μm, dust = 466 ppb	0.22	0.69	3.15	11.46
r = 100 μm, dust = 3388 ppb	0.06	0.20	3.20	-
r = 250 μm, dust = 3388 ppb	0.10	0.31	3.20	5.69
r = 1000 μm, dust = 3388 ppb	0.19	0.60	3.19	-
r = 250 μm, no BC, dust = 466 ppb (constant)	0.11	0.11	constant	0.15
r = 250 μm, no BC, dust = 3388 ppb (constant)	0.77	0.77	constant	1.01
Jul–Sep Surface Radiative Forcing (W/m²)				
r = 100 μm	0.02	0.03	1.95	-
r = 250 μm	0.02	0.05	1.95	-
r = 1000 μm	0.05	0.09	1.95	-

[a]Surface radiative forcing (based on SNICAR [*Flanner et al.*, 2007]) is due to BC in snow in the presence of dust, unless specifically noted as no BC, in which case the radiative forcing is due to dust in snow. Here r is snow effective radius; dust is dust mass concentration [*Xu et al.*, 2010].
[b]Average based on 4 samples/year data.
[c]Based on high resolution data.

a threefold increase in RF from BC in snow (Table 1 and Figure 2a). Despite higher incoming solar radiation during the summer, the BC RF in snow is considerably lower during the summer monsoon season (July–September) due to much lower BC concentrations during this time (Figure 2b). Nevertheless, average summer monsoon RF from 1975–2000 is twofold higher than 1860–1974. As mentioned previously, the 1860–2000 timeseries is re-sampled to 4 samples/year. This results in a smoothing of the record, precluding examination of RF from peak impurity concentrations. Thus, the high-resolution record from 1975–1985, representing the time period with peak impurity concentrations, was re-sampled at monthly resolution (12 samples/year) to further examine BC RF peak values and seasonality. Monthly mean RF is highly seasonal, with a peak BC RF of $6.05_{250\mu m}$ ($3.85_{100\mu m}$, $11.46_{1000\mu m}$) W/m² occurring during the spring (Figure 2c).

[14] The previous analyses consider the BC RF in the presence of average dust levels. Because we are interested in the relative contributions of BC and dust to the RF and reductions in snow albedo, we also ran SNICAR for r = 250 μm with BC and varying dust concentrations, and without BC. The average spring BC RF in the presence of peak dust concentrations (3388 ppb) is less than that with average dust concentrations because the dust captures some of the solar absorption that the BC would receive under less dusty conditions (Table 1). Omission of dust results in the highest BC RF. Conversely, the dust RF in the absence of BC is highly dependent on dust concentrations, with a spring dust RF of .11 and .77 W/m² for average and peak dust concentrations, respectively. This peak dust RF is still considerably less than peak BC RF from the high-resolution record, supporting the conclusions from previous studies suggesting that a reduction in BC emissions would be the most effective means by which to reduce the impact of absorbing impurities on albedo and snow melt [*Hansen and Nazarenko*, 2004]. Full snowpack/glacier modeling would be needed to assess impacts on snowmelt of specific BC reductions. Additionally, our current analyses do not address other absorbing impurities in the snowpack that also can contribute to reductions in albedo such as additional sources of light absorbing carbon (colored organics) from biomass burning, humic-like substances, snow algae and bacteria [*Andreae and Gelencser*, 2006; *Takeuchi*, 2002].
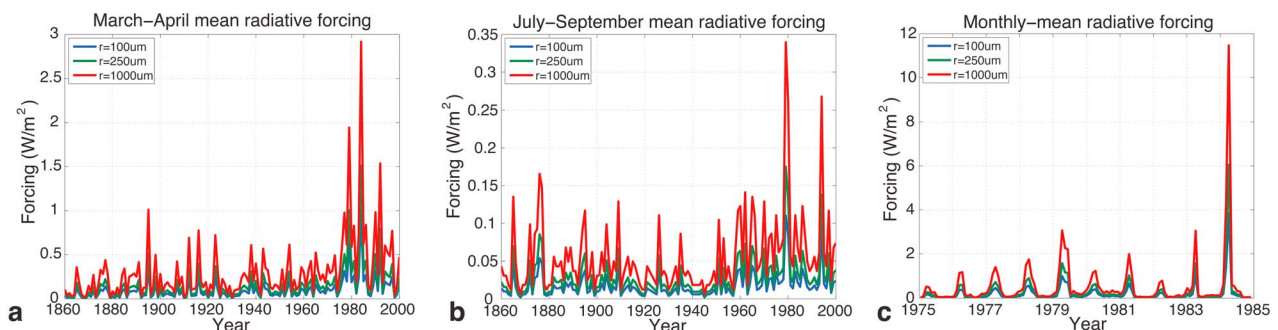
Figure 2. BC radiative forcing (W/m²) in the presence of average dust mass concentration (466 ppb) as determined using SNICAR [*Flanner et al.*, 2007] for snow effective radii (r) = 150 (blue); 250 (green) and 1000 μm from (a) March–April (b) July–September, and (c) monthly mean. Additional model parameters are discussed in the text.

[15] Spatial heterogeneity in BC concentrations due to differences in BC sources and transport is evident when comparing the results of this study with BC ice core records from other regions of the Himalaya and Tibetan Plateau spanning ~1950 to recent time: cores from the Tibetan Plateau have relatively high BC concentrations during the 1950s–1960s, whereas peak BC concentrations in a core from Zuoqiupu in the Eastern Himalaya occurred post 1990 [*Liu et al.*, 2008; *Ming et al.*, 2008; *Xu et al.*, 2009]. The BC spatial variations, combined with differences in the amount and seasonality of precipitation and dust deposition, results in a heterogeneous pattern of snow and glacier melt across the region.

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