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Black carbon record based on a shallow Himalayan ice core and its climatic implications

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Abstract

A continuous measurement for black carbon conducted on a shallow ice core extracted from the East Rongbuk glacier beside Mt. Qomolangma recovers the first historical record of black carbon 13 deposition in the past ~50 years in the high Asian cryosphere.

5 Fast increasing trend of BC concentration is revealed since the mid-1990s. Backward air trajectory analysis indicates that South Asia's emission has significant impacts on the BC deposition in the East Rongbuk glacier. The estimated atmospheric BC concentration over the East Rongbuk glacier is about 80 ngC m^{-3} . This suggests black carbon from South Asia's emission might penetrate into the Tibetan Plateau by 18 climbing over
10 the elevated Himalayas. Considering the consequent extra solar radiative absorption over the glacier, it is suggested that this amplitude of BC concentration in the atmosphere over the Himalayas could not be neglected when assessing the warming effect on the surface of the glaciers on the Himalayas.

1 Introduction

15 Black carbon (hereafter "BC") plays an important role in the earth climate system. BC particles suspended in the atmosphere could result in very complex radiative effects acting as the light absorber and veil (e.g. Jacobson, 2004a). Although there are many uncertainties on this issue, negative impacts of short term cooling but long term warming the atmosphere dominate the popular views (e.g. Jacobson, 2004b). A recent high-
20 light on BC climate effect is that BC deposited on the snow and ice surface could absorb the sunlight largely and reduce the albedo intensely so as to accelerate the melting of snow cover and sea ice (e.g. Hansen and Nazarenko, 2004; Jacobson, 2004a).

Cold glaciers and polar ice sheets are excellent archives for documenting dry and wet depositing constituents in the atmosphere. BC measurements in snow and ice
25 have been conducted by some previous studies since the 1980s (e.g. Chýlek et al., 1987; Chýlek et al., 1995; Cachier and Pertuisot, 1994). These papers focus on the

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issue of the Arctic haze and therefore its consequent climatic and environmental significances, while the historical records of BC recovered from the ice cores in mid-low latitude regions are very few. Up to now there are only two reports on the historical records of carbonaceous particle concentrations in ice cores both extracted from Mt. Alps. One suggests that mean concentration of BC have increased by a factor of 3.7 from $22 \mu\text{gC kg}^{-1}$ in preindustrial time (1755–1890) to $82 \mu\text{gC kg}^{-1}$ in modern time (1950–1975) (Lavanchy et al., 1999), and the other shows that BC concentration increased from $15 \mu\text{gC kg}^{-1}$ in preindustrial time (1650–1870) to $27 \mu\text{gC kg}^{-1}$ in the transition era (1870–1940) (Jenk et al., 2006).

The Himalayas is located on the south margin of the Tibetan Plateau (hereafter “TP”) and stretches 2500 km from west to east, spanning the middle and upper layers of the troposphere. Himalayas may be an effective barrier to restrict the exchange of air masses carried by monsoons and by westerly between TP and the Indian subcontinent in summer and winter (Nieuwolt, 1977). The East Rongbuk Glacier (hereafter “ERG”) is located on the northern slope of Mt. Qomolangma in central Himalayas. Previous studies on the ice core records extracted here have revealed plenty of credible information on climate change and environment (e.g. Kang et al., 2002a; Qin et al., 2002). Both East Asia and South Asia are fast-developing regions with strong BC emissions in recent years (e.g. Streets et al., 2003; Venkataraman et al., 2005). This region is known as a home to the Asian Brown Cloud (hereafter “ABC”) (e.g. Ramanathan et al., 2001a). As the hinterland surrounded by the Central, East, and South Asia, the TP may be under the impacts of the polluted air masses coming from these regions. The deposition information could be archived frozen in ERG. And yet no data on BC deposition were obtained from this site till now. In this work, we try to reconstruct a BC history recorded in a shallow ice core (hereafter “ERIC2002C”) from ERG in 2002 for the first time.

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2 Experimental methods

2.1 Ice core recovery

ERIC2002C was drilled in the summer of 2002. The drilling site is located on the Re-
pula Col (28°01'12 N, 86°57'36 E, and 6500 m a.s.l.) of ERG near Mt. Qomolangma
(Fig. 1). At the saddle of ERG, the present average annual net accumulation is about
500 mm water equivalent as determined from snow pits and a stake accumulation net-
work established during a reconnaissance in May of 1998. Prior to drilling, a 1.5-m
deep snow pit was dug to remove the snow/firn above the borehole. The ice core was
40.8 m long and 9.4 cm in diameter and was sealed in polyethylene bags in sections
of 50 to 115.5 cm length at the site. At the same time, the other two ice cores with
the lengths of 108.83 m and 95.80 m (named “ERIC2002A” and “ERIC2002B”, respec-
tively) were extracted together at very near sites, not more than 1 m far away from each
other. The borehole temperature of ERIC2002A ranged from a minimum of -9.6° at
20 m and -8.9° at the bottom. The low temperature throughout the borehole indicated
that the information of atmospheric depositing here can be preserved. We maintained
the ice core in frozen condition during the transportation and storage time.

The deepest section of ERIC2002C was used to analyze culturable bacteria (Zhang
et al., 2007). Each section of the left was split into two halves axially. One half was
analyzed for $\delta^{18}\text{O}$ isotope and soluble major ions (Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Cl^- , NO_3^- ,
and SO_4^{2-}). The measurements for $\delta^{18}\text{O}$ and ions of ERIC2002C were performed at
the State Key Laboratory of Cryospheric Sciences (Chinese Academy of Sciences,
Lanzhou) following the methods of previous studies (e.g. Tian et al., 2003; Xiao et al.,
2004). And in this work the left half was used to analyze black carbon.

2.2 Ice core dating

In the Mt. Qomolangma region, the seasonality of $\delta^{18}\text{O}$ exhibit an amount effect,
namely high $\delta^{18}\text{O}$ value in the precipitation occurs in non-monsoon season in win-

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ter, while low $\delta^{18}\text{O}$ value occurs in the monsoon season in summer (Kang et al., 2000, 2002b; Tian et al., 2003). Calcium is suggested to be the most definitive ion for precise dating due to the striking differences in its concentrations occurring between monsoon and non-monsoon seasons based on snow chemistry data from both fresh snow and snow pit samples (Kang et al., 2004). Therefore, we dated ERIC2002C by counting the seasonal variability of $\delta^{18}\text{O}$ and Ca^{2+} profiles, simultaneously considering the annual net water accumulation. The result was further verified by the β activity horizon produced by the atmospheric thermonuclear test in the early 1960s (Fig. 2). Subtracting one year of the snow pit covering ERIC2002C, the ice core was dated to be 50 years old (1951–2001 AD). We estimate a dating error of ± 1 year throughout the whole ice core.

2.3 Sample preparation

Although BC measurement requires rather large amounts of ice, sufficient sample guarantee we could perform a continuous measure for BC concentration on this half of ERIC2002C. Four testing samples sectioned randomly from ERIC2002C were measured for BC beforehand to consider what was the proper volume needed for each sample. The BC amounts of these testing samples gave us a clue that 70 to 500 g per sample is the best volume for carbon analysis, giving 5 to 10 μg BC on the filtration deposit. Then the sections of the ice core were sectioned to the expected weight, and 143 samples were obtained aggregately.

A series of scraping operations would be performed on the ice core. A lathe was used to peel the outermost layer of 1 to 2 cm thickness of each section of the ice core. All the ice samples were prepared in the laminar flow cabinet of the inner clean room of 100-class in a low-temperature room (-20°). The next outer layer of approximate 1 cm thickness and the two ends of each sample were removed by scraping manually with a stainless steel blade. Then the ice samples were stored in pre-cleaned glass jars with covers and kept at low temperature until filtration.

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Filtering was operated in the warm clean room of 100-class. Warm water bath was used to shorten the time of melting. Once there was some melted water of around 1-cm depth in the container, the sample would be allowed to melt at room temperature and manual stirring of the container may further favor the process. This process was limited within 4 h to avoid developing extra bacteria. Prior to filtration, these bottles were submitted to ultra sounding for 15 min in order to avoid loss of particles which may have attached to the walls of the containers. After filtration, a cylinder (± 1 ml) was used to measure the volume (weight) of every sample. Quartz fiber filters (Whatman QMA) of 2.5 cm diameter, of which effective filtering size was 12 mm diameter, were used to recover particles after filtration. They were pre-heated (24 h at 600°) to remove any carbon content. A hand vacuum pump was used to accelerate filtering the melted samples. After filtration, hydrochloric acid (2–4%) was put on the filter and passed through. Acidification step duration of 15 min at least is necessary to remove carbonates which might if any, overestimate BC contents. Finally, the filters would be moved to clean Petri-slides (Millipore), and set in clean cabinet to let them dry. In addition, blank filters were made by filtering washing water of the blank bottles with ultra-pure water and HCl solution as mentioned above.

2.4 BC measurement

Filters were analyzed at Laboratoire des Sciences du Climat et l'Environnement (LSCE). Pre-combustion is necessary to eliminate the organic particles and minimize any “cross-over” effect between organic compounds and BC. BC and OC separation was obtained following the analytical protocol set up for aerosols (Cachier et al., 1989) and adapted for snow and ice samples (Cachier and Pertuisot, 1994). According to the apparent grey level of the filter color, samples were divided into two batches, the filters loaded lightly and the filters loaded heavily, which will be committed to either a coulometric titration-based analysis (using the Ströhlein Coulomat 702C) or to a thermo-optical analysis (using the Sunset thermo-optical transmission carbon analyzer System (Sunset Lab., OR, USA).

3 Results and discussion

3.1 General trend of BC concentration

Bond et al. (2007) presented a historical record of BC emission, which indicated an increasing trend of BC emission worldwide, including the case in India as an adjacent region to the south of the Himalayas. As a very close site by India, the variation of BC concentration in ERIC2002C is presented in Fig. 3a. The BC concentration throughout the core could be divided into three stages, 1951–1976, 1976–1994, and 1995–2002 (Fig. 3b). During 1951–1976, BC concentrations with the mean of $16.5 \pm 10.8 \mu\text{gC kg}^{-1}$ show large fluctuations, especially for the later part (1966–1976) in which a significant bump appears in the smoothed curve. From 1977–1994, BC concentrations with the mean of $11.8 \pm 5.5 \mu\text{gC kg}^{-1}$ are quite low and stable, while from 1995–2002 there is a significant increasing trend, and rises over $50 \mu\text{gC kg}^{-1}$ in 2001.

3.2 Estimated BC concentration in the atmosphere over ERG

The BC deposition in ERIC2002C could provide us the first approach to estimate the atmospheric BC concentration level over ERG in the past 50 years. We use a transformed equation from Davidson et al. (1993),

$$C_a = \rho_a \times C_s / \omega,$$

to estimate BC concentration in air, where C_a is species concentration (ng m^{-3}) in air, ρ_a is air density (g m^{-3}) after correcting for the standard temperature and pressure, C_s is species concentration (ng g^{-1}) in snow, and ω is the scavenging ratio of snow fall. The scavenging ratio of ω was estimated by several previous studies, for example, at 160 by Clarke and Noone (1985) and at 97 ± 34 by Noone and Clarke (1988) at several different locations on earth. The work of Jacobson (2004a) used a three-dimensional global model to estimate ω at ~ 125 as a worldwide mean. This numerical value (125) is adopted for our estimation. We obtain a time series of air pressure at the drilling site

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from 1951 to 2001 after interpolating 6500 m a.s.l. between the geo-potential heights of NCEP/NCAR Reanalysis data at 400 hPa and 500 hPa, and then we estimate a time series of air density at the drilling site from 1951 to 2001. And therefore we use the above equation to estimate BC concentration in air over ERG during the past half century. Mean atmospheric BC concentration over ERG is $77 \pm 45 \text{ ngC m}^{-3}$ in the past 50 years (Fig. 4).

3.3 The relationship between the atmospheric BC over ERG and its transport pathways

Air masses over the TP are mainly dominated by polar air masses from the Arctic, continental air masses from central Asia, and maritime air masses from the Pacific and Indian Ocean (Bryson, 1986). And with the alternation of seasons, dominant air masses vary. During summer monsoon seasons, the Indian monsoon dominates the synoptic regime over ERG, while the westerly takes its power in non-monsoon seasons (Ye and Yang, 1979).

The transport patterns for monsoon and non-monsoon seasons are largely different as indicated by the different synoptic circulation mentioned above. For example, air masses over ERG are transported by the Indian monsoon dominantly and next by westerly during the monsoon seasons, and yet they are completely transported by westerly in non-monsoon seasons. No matter what season it is in, ERG is located in the downwind direction of South Asia. We use the HYbird Single-Particle Lagrangian Integrated Trajectory model (in brief "HYSPLIT", version 4.8) to investigate the transport of aerosols arriving at our drilling site. The Climate Diagnostics Center -1 (CDC1) Meteorological Data (reproduced by Air Resources Laboratory, NOAA) provides the global reanalysis grid data of $2.5^\circ \times 2.5^\circ$ from 1948 to date. This dataset will allow us to calculate the daily backward trajectories ending at our drilling site from 1951 to 2002, when covers the whole time period of ERIC2002C. The clustering tool integrated in the model is applied to calculate the mean trajectories each year (Fig. 5). We counted the number of the trajectories contained in the mean trajectory of non-long-distance transport

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each year, and obtained a time series of this number from 1951–2001. Co-variability is found between this number and estimated atmospheric BC concentration over ERG (Fig. 6), and the correlation coefficient between them is 0.435 ($N=51$, $\alpha=0.01$).

3.4 The climatic implications: the influence of the BC emitted from South Asia on the Himalayan glaciers

South Asia is well known for heavy BC emissions, including ABC blanketing its sky (Ramanathan et al., 2001a). And ABC, which covers most of the Arabian Sea, the Bay of Bengal, and South Asia, occurs every year and typically extends from November through May. The brownish haze is composed of a 3-km-thick mixture of anthropogenic sulfates, nitrates, organics, black carbon, dust and fly ash particles, and natural aerosols such as sea salt and mineral dust (Ramanathan and Ramana, 2003). In-situ measurements of aerosol chemistry from aircraft, ships, and surface stations found that anthropogenic sources (e.g., biomass burning, fossil-fuel combustion) contribute as much as 75% to the observed aerosol concentration (Ramanathan et al., 2001b; Lelieveld et al., 2001).

As discussed in Sect. 3.3, estimated atmospheric BC concentration seems to be more related to the annual number of the southerly trajectories travelling over South Asia of non-long-distance transport, compared with the annual number of the westerly trajectories of long-distance transport. This suggests that South Asia's emission has more influence on the BC concentration in atmosphere over ERG. A recent study on ABC over South Asia displayed a north-south profile of lidar backscatter signal showing the vertical distribution of ABC from the TP to the Indian Ocean (see also Fig. 2 in Ramanathan et al., 2007), indicating there is outflow of ABC from South Asia climbing over the elevated Himalayas. In Sect. 3.2, the mean estimated BC concentration in atmosphere over ERG is nearly 80 ngC m^{-3} in the past 50 years. A result revealed by a numeric simulation model shows atmospheric BC of $40\text{--}100 \text{ ngC m}^{-3}$ over the Arctic could accelerate the melting of ice significantly (Koch and Hansen, 2005). Compared with this amplitude of BC concentration, the ERG's BC concentration (80 ngC m^{-3}) in

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air could not be neglected to consider its consequent climate effect after taking its enhancing atmospheric solar absorption over snow and ice surface into account. For the scarcity of data, it is difficult to assess what is the exact forcing on the ice body from atmospheric BC over Himalayan glaciers. However, this level of BC concentration in atmosphere and therefore black carbonaceous particles deposited in snow and ice could be fatal to the Himalayan glaciers. Since the 1960s the average retreat rate of the glaciers on the north slope of Mt. Qomolangma and of those on Mt. Xixiabangma (Fig. 1) are 5.5–9.5 m a⁻¹ and 4.0–5.2 m a⁻¹ (Ren et al., 2006), respectively. Dasuopu ice core records from Mt. Xixiabangma suggested a weakening of Indian monsoon since the 1920s should be responsible for the declining net accumulating rate of Dasuopu glacier (Duan et al., 2004). We suggest BC particles in atmosphere and the surface snow over the Himalayan glaciers might be another factor to reduce the net accumulation, as well as the weakening of the monsoon. A simulation estimated that, since 1950 South Asia's atmosphere has warmed by 0.25° per decade due to Asian Brown Cloud at altitudes ranging from 2000 to 5000 m a.s.l. – precisely the height where thousands of Himalayan glaciers are located, and this amplitude of warming might be sufficient to account for the observed retreat of the Himalayan glaciers (Ramanathan et al., 2007).

4 Conclusions

BC concentration is continuously measured based on a 50-year ice core (ERIC2002C) extracted from the ERG beside Mt. Qomolangma. General trend of BC concentration indicates a significant increase since the mid-1990s. The result of backward trajectory analysis indicates that South Asia's emission has significantly impacted on the BC deposition on ERG. The estimated average atmospheric BC concentration over ERG is about 80 ngC m⁻³ during the last 50 years. This suggests BC from South Asia's emission might penetrate into the high Himalayas. Considering the consequent extra solar radiative absorption over the glacier, we suggest that this amplitude of BC concentra-

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tion in atmosphere could not be neglected to assess the warming effect on the surface of the glaciers on the Himalayas, and is also suggestive to our future observations on ERG and other Himalaya glaciers.

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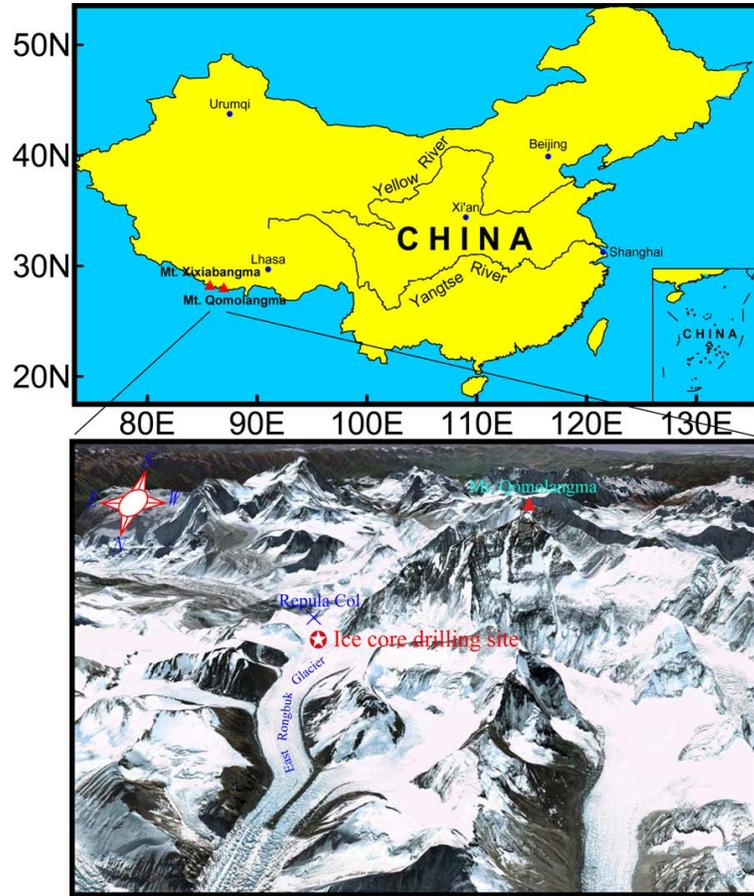


Fig. 1. Location map of ERIC2002C drilling site.

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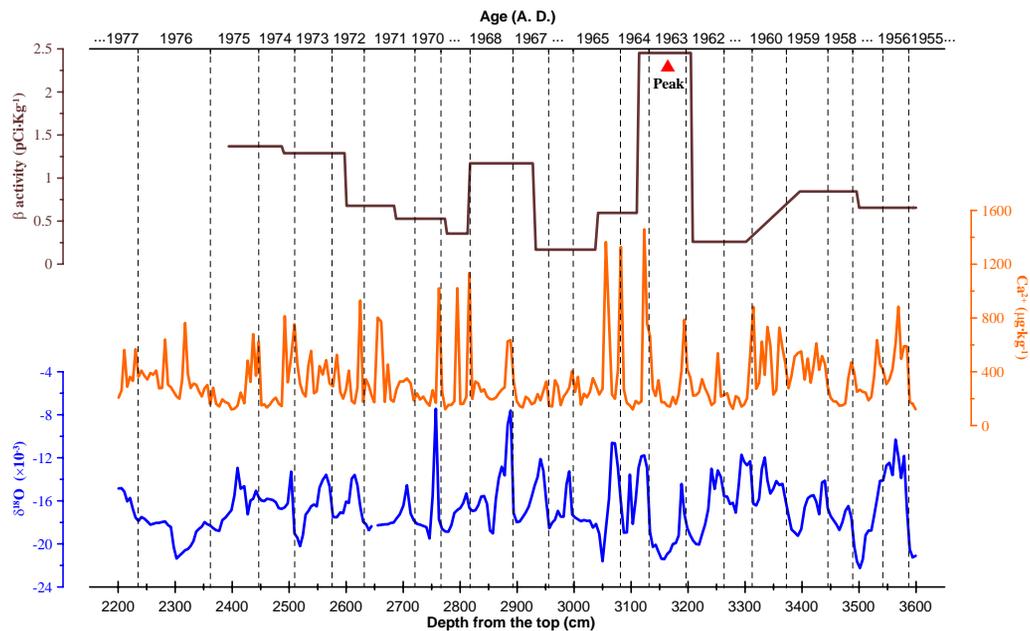


Fig. 2. The dating of ERIC2002C, in which the β activity peak value shows a year of 1963.

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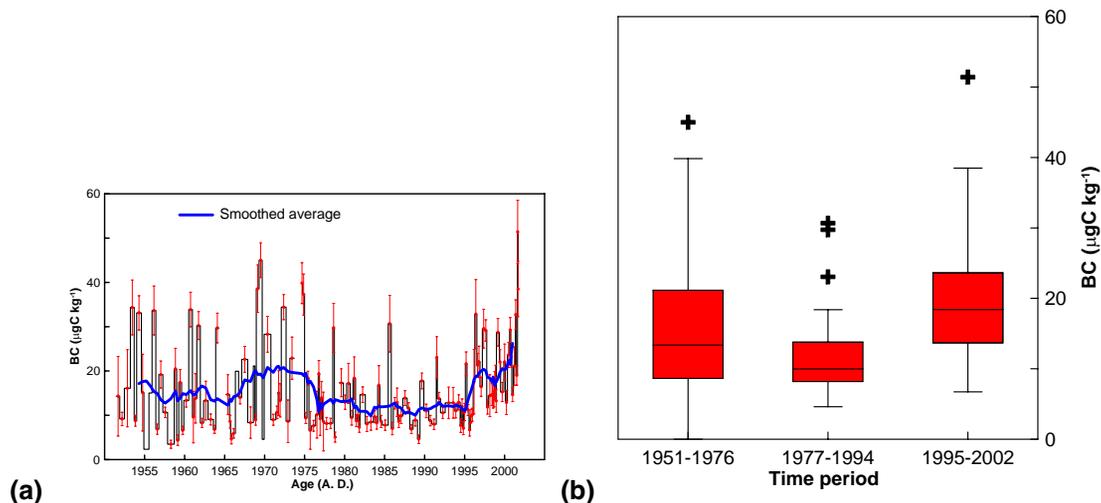


Fig. 3. (a) the time series of BC concentration profile for sections in ERIC2002C, error bars are presented as solid red lines with middle dots, and the thick solid blue curve is smooth average; (b) the box plot of BC concentration in ERIC2002C for the time periods of 1951–1976 (N=58), 1977–1994 (N=47), and 1995–2002 (N=35), and some outliers as well as 95%, 75%, 50%, 25%, and 0% percentiles of BC concentrations are shown as cross symbols. Dramatic increase could be seen since the mid-1990s.

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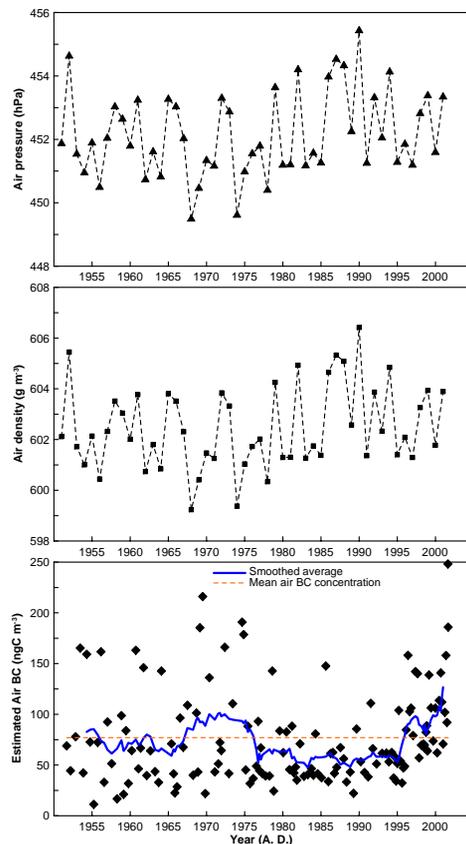


Fig. 4. (a) the variability of estimated air pressure over ERG from 1951–2001; (b) the variability of estimated air density over ERG from 1951–2001; (c) the variability of estimated atmospheric BC concentration (ngC m^{-3}) in the past 50 years, where the thick solid blue curve represent 11-point running average, and the dashed orange line represent the mean level of atmospheric BC concentration ($\sim 80 \text{ ngC m}^{-3}$).

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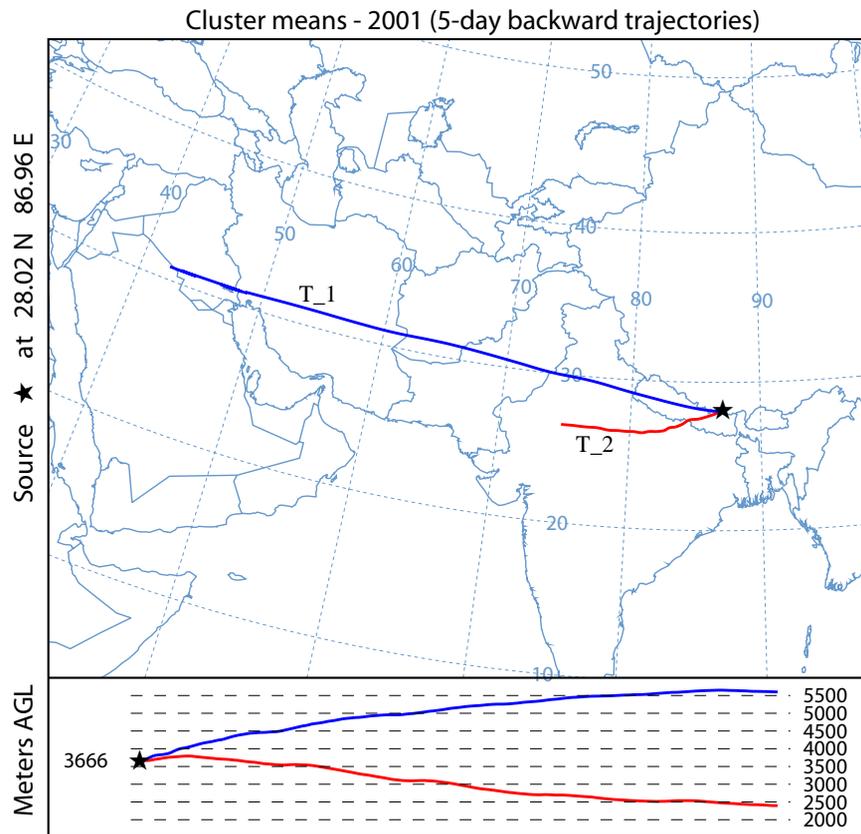


Fig. 5. Typical results of two mean trajectories in 2001 by HYSPLIT 4.8 model. 5-day backward air trajectories each year are calculated with a daily resolution. For each year from 1951-2001, they are clustered using the integrated tool in the model. Generally, two mean trajectories could be obtained, one in for long-distance transport (T₁) and the other for non-long-distance transport (T₂). The latter trajectory indicates the air masses transported from South Asia.

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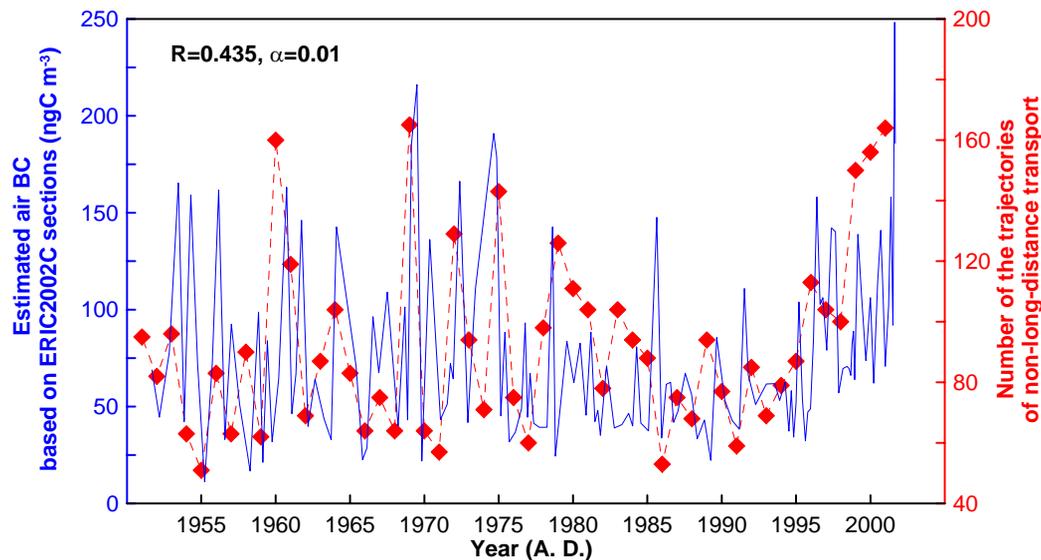


Fig. 6. The co-variability of the estimated atmospheric BC concentrations and the annual number of T₂ covering the period 1951–2001 counted from the results of HYSPLIT model. Good positive correlation between them indicates the BC emission from South Asia has a significant impact on the BC deposition on ERG.

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