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Brown Clouds over South Asia: Biomass or Fossil Fuel Combustion?

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Carbonaceous aerosols cause strong atmospheric heating and large surface cooling that is as important to South Asian climate forcing as greenhouse gases, yet the aerosol sources are poorly understood. Emission inventory models suggest that biofuel burning accounts for 50 to 90% of emissions, whereas the elemental composition of ambient aerosols points to fossil fuel combustion. We used radiocarbon measurements of winter monsoon aerosols from western India and the Indian Ocean to determine that biomass combustion produced two-thirds of the bulk carbonaceous aerosols, as well as one-half and two-thirds of two black carbon subfractions, respectively. These constraints show that both biomass combustion (such as residential cooking and agricultural burning) and fossil fuel combustion should be targeted to mitigate climate effects and improve air quality.

The radiative effects of carbonaceous aerosols constitute one of the largest uncertainties in climate modeling (1–6). Combustion-derived carbonaceous aerosols have traditionally been associated with pollution in urban areas, but research over the past decade has revealed that the haze they cause may envelop entire subcontinents and ocean basins (3, 7–9). The extensive atmospheric brown cloud (ABC) over South Asia and the Indian Ocean persists during the winter season, and its cooling effect may regionally balance and even surpass the warming effect of greenhouse gases (GHGs) (3, 4, 8), with predicted effects including changed circulation and monsoon patterns with amplified droughts and floods (10, 11), as well as increased melting of Himalayan glaciers (4). A conspicuous feature of the Asian ABC is its unusually high content of airborne black carbon (BC) particles (4, 7, 12, 13). This highly condensed carbonaceous residue of incomplete combustion is the “dark horse” in the current climate debate as sub-

stantial uncertainties exist about its atmospheric longevity (1), aerosol mixing state (14), measurement (15–18), and sources (12, 19–25). Because it is becoming clear that BC represents a continuum of light absorbing carbon (LAC) forms (16–18), exploiting differences in BC analytical techniques may improve the characterization of atmospheric BC. The primary motivation for the ABC BC Radiocarbon (¹⁴C) Campaign (ABC-BC14), the results of which are reported here, was the observational determination of the relative contribution of contemporary biomass versus fossil fuel combustion to both the total carbonaceous aerosols and to two different atmospheric BC isolates.

Though it is now established that there is an unusually high mass fraction of BC in the Asian ABC (4, 7, 12, 13, 23–25), there is a notable discrepancy in source apportionment of this BC between top-down studies relying on measured ratios of BC to total carbon or other aerosol components (12, 24, 25) as compared with bottom-up emission inventories based on fuel consumption and laboratory-derived emission factors (19–23) (Table 1). Several top-down studies conclude that 50 to 90% of the South Asian BC originates from fossil fuel combustion (12, 24, 25). However, employed end-member ratios were from other regions and may not be representative of South Asian combustion processes (21, 23). Further, the BC:organic carbon

(OC) ratio is nonconservative if there is substantial formation of secondary organic aerosols (13, 26). In contrast, bottom-up approaches suggest that only 10 to 30% of the BC loadings originate from fossil fuel combustion (19–23) while recognizing that emission factors (particularly those for biomass combustion) are difficult to constrain because of strong dependency on fuel type and efficiency of combustion (22, 23). This current dichotomy is addressed in the ABC-BC14 Campaign by using radiocarbon abundance (half life $\tau_{1/2} = 5730$ years) as a tool to distinguish between fossil (radiocarbon “dead”) and contemporary biomass (radiocarbon “alive”) combustion sources of the Asian ABC.

The ABC-BC14 Campaign was conducted with identical sampling at two sites (Fig. 1) of the international ABC-Asia project. Aerosol samples for microscale ¹⁴C measurements were collected at the Maldives Climate Observatory at Hanimaadhoo island (MCOH) (6.78°N, 73.18°E) from 31 January to 16 March 2006 and at the mountain top site of the Indian Institute of Tropical Meteorology located at Sinhadag, West India (SIN) (18.35°N, 73.75°E, 1400 meters above sea level) from 27 March to 18 April 2006 (27). The ABC-BC14 Campaign thus overlapped with the previously reported Maldives Autonomous Unmanned Aerial Vehicle Campaign (4) that reported on the vertically resolved aerosol solar heating, and the meteorological context is detailed therein.

Back-trajectory analyses illustrate the typical winter monsoon circulation, with most of the first half of the MCOH samples (31 January to 18 February 2006) reflecting a predominant low-level air mass transport during the preceding 10 days from central India (including the Gangetic Plain) flowing southward along the western Bay of Bengal 2 to 5 days before arrival (fig. S1A). During subsequent collections (19 February to 16 March 2006), most 10-day trajectories originated from the northern Arabian Sea and adjacent land areas in northwest India and Pakistan with transport along the Indian west coast margin (fig. S1B). Most of the surface air masses sampled at SIN were arriving from a sector west and north, originating from Arabian Sea, Arabic peninsula, Pakistan, and northwest India (fig. S1C). Satellite-retrieved optical signals suggest that study locations were

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influenced by aerosols, presumably brown clouds (Fig. 1).

Ground-based particle soot absorption photometer (PSAP) (550 nm) measurements confirm high abundances of LAC at MCOH and SIN (Fig. 2A). Absorption coefficients of $1 \cdot 10^{-5} \text{ m}^{-1}$ at the onset of the MCOH Campaign increased to a maximum above $3 \cdot 10^{-5} \text{ m}^{-1}$ toward the end of the Gangetic Plain influenced period, followed by a consistent decrease to $5 \cdot 10^{-6} \text{ m}^{-1}$ as trajectories shifted toward the western side of India. The lower-temporal-resolution PSAP data for the SIN campaign varied from 0.3 to $3 \cdot 10^{-5} \text{ m}^{-1}$.

The temporal evolutions of the mass-based carbonaceous aerosol concentrations were broadly consistent with the PSAP data (Fig. 2B). The highest MCOH total organic carbon (TOC) values were associated with air from northern India (4 to $5 \mu\text{g}\cdot\text{m}^{-3}$) decreasing to $1.4 \mu\text{g}\cdot\text{m}^{-3}$ with Arabian Sea origin. Similarly, the elemental carbon (EC), measured using a thermo-optical technique (17, 18, 27, 28), varied from 1.2 to $0.2 \mu\text{g}\cdot\text{m}^{-3}$ (Fig. 2B) for MCOH. The soot carbon (SC) fraction, measured by chemothermal-oxidation (18, 27–29) and representing a more recalcitrant portion of the BC spectrum (15, 16, 18), was lower but followed a similar temporal trend (table S1). The TOC, EC, and SC were all closely coupled ($r^2 = 0.84$ for EC versus SC) (fig. S2), indicating a strong contribution of combustion processes to the total carbonaceous aerosols.

Each of the three carbon isolates exhibited a marked temporal uniformity in radiocarbon signal and hence between the contributions from fossil and contemporary biomass sources. The measured $\Delta^{14}\text{C}$ content of TOC ranged from -239 ± 3 to -145 ± 2 per mil (‰) in MCOH samples and from -235 ± 2 to -187 ± 2 ‰ in SIN samples (Fig. 2C and table S1). This consistency attests to the ability of the series of week-long samples to capture the broader-scale source contributions. Because the optical techniques used to quantify LAC-BC do not physically isolate a carbon mass fraction, a prerequisite for ^{14}C measurement, two techniques commonly used to quantify the combustion-derived carbon mass were employed to isolate carbon (27).

The EC isolate was more fossil-rich than the TOC and ranged from -379 ± 4 to -319 ± 3 ‰ in India and from -595 ± 12 to -430 ± 5 ‰ over the Indian Ocean (Fig. 2C). The more recalcitrant SC fraction had more modern $\Delta^{14}\text{C}$ values, indistinguishable between Indian and Maldivian sites, with averages of -227 ± 37 versus -167 ± 70 ‰, respectively. Hence, there is a component included in the EC isolate but excluded from SC—that is, less recalcitrant but more ^{14}C depleted. We hypothesize that this is fossil “brown carbon” (17) from either domestic coal combustion or fine coal dust released from pulverization of coal for the many coal-fired power plants in India (21, 22). Coal has been one key replacement of wood as domestic fuel (22), and it is conceivable that the BC produced by such small-scale and inefficient coal burning

is escaping detection as SC (16, 18) but is included in EC (24). Further, uncombusted fine coal dust yields larger false positives for EC than SC (18), consistent with differences in $\Delta^{14}\text{C}$ dur-

ing the ABC-BC14 study. Sensitivity model calculations explored inclusion of up to 30% of the instrument-inherent pyrolyzed OC in the isolated EC and found that the potential effect

Table 1. Apportionment of Indian carbonaceous aerosols between fossil fuel and biomass combustion. The characteristics of different carbonaceous particle fractions (TOC, BC, EC, SC) are discussed in the text and SOM.

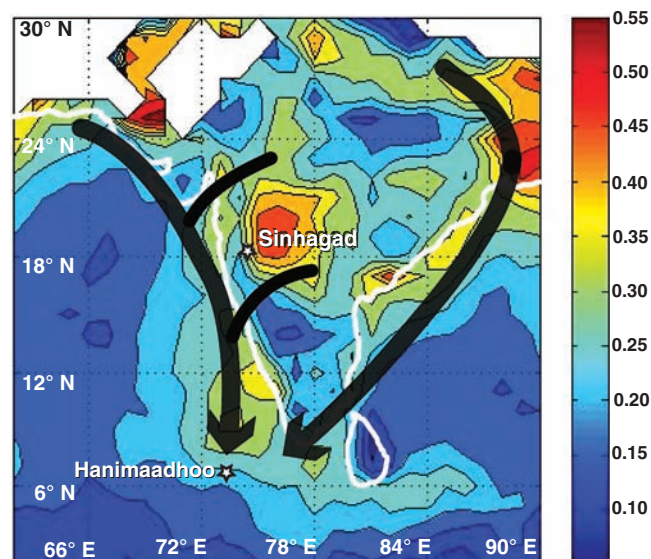
Study	BC from fossil fuel combustion	BC from biomass combustion	Methods/comments
<i>Emission inventories</i>			
India inventory (19, 20)	29%	71%	0.1 Tg/year fossil fuel and 0.25 Tg/year biomass
South Asia inventory (21)	12–45%	55–88%	0.059–0.37 Tg/year fossil fuel and 0.45 Tg/year biomass for India
Global inventory (22)	~30%	~70%	0.18 Tg/year fossil fuel, 0.33 Tg/year biofuel, 0.087 Tg/year open burning for India
South Asia biofuel study (23)	25%	75%	India-specific emission factors and fuel usage
<i>Ambient measurements</i>			
INDOEX* flights over the tropical Indian Ocean (24)	80%	20%	EC:TC ratio for three flights
INDOEX flights over the tropical Indian Ocean (12)	60–90%	10–40%	EC:TC ratio for 13 flights
ABC monitoring in the Maldives (25)	40–50%	30–40%	Positive matrix factorization with EC and multiple elements
Maldives + India (this study)	$32 \pm 5\% \dagger$	$68 \pm 6\%$	Radiocarbon analysis of ambient filter-based SC, range \dagger of 66–76% for biomass
Maldives + India (this study)	$54 \pm 8\%$	$46 \pm 8\%$	Radiocarbon analysis of ambient filter-based EC, range of 45–52% for biomass

*INDOEX is the Indian Ocean Experiment. analysis detailed in the SOM text.

\dagger Standard deviation of 9 samples.

\ddagger Ranges calculated from sensitivity

Fig. 1. Regional distribution of aerosol optical depth at 550 nm derived from a moderate resolution imaging spectroradiometer (MODIS) instrument aboard the Terra satellite (average for March 2006). The black arrows denote dominant air mass transport patterns in the region during the winter monsoon. The two aerosol sampling sites are shown.



would be within the uncertainty of the reported isotope values [table S2 and supporting online material (SOM) text].

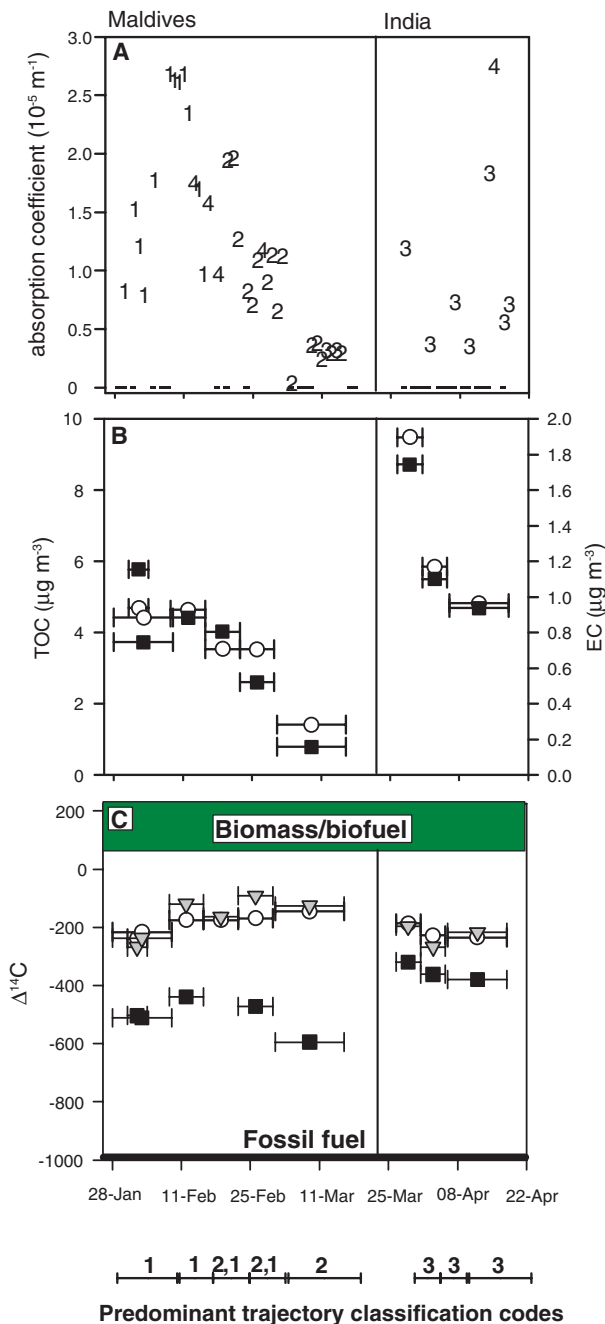
To afford a detailed comparison with earlier bottom-up and top-down source apportionment estimates of carbonaceous aerosols, a simple isotopic mass balance equation (28, 30), based on the $\Delta^{14}\text{C}$ data, was applied to apportion between the fractional contributions of biomass (f_{biomass}) and fossil fuel ($f_{\text{fossil}} = 1 - f_{\text{biomass}}$)

combustion sources to the carbonaceous aerosol components in the investigated samples, as illustrated for EC

$$\Delta^{14}\text{C}_{\text{EC}} = \Delta^{14}\text{C}_{\text{biomass}} \cdot f_{\text{biomass}} + \Delta^{14}\text{C}_{\text{fossil}} \cdot (1 - f_{\text{biomass}}) \quad (1)$$

where $\Delta^{14}\text{C}_{\text{EC}}$ is the measured radiocarbon content of the EC component and $\Delta^{14}\text{C}_{\text{fossil}}$ is

Fig. 2. Concentration and radiocarbon-based source apportionment of carbonaceous aerosols over the Maldives and western India. The ABC-BC14 Campaign is divided into two periods with sampling at Hanimaadhoo (Maldives) 31 January to 16 March 2006 and at Sinhagad (India) 27 March to 18 April 2006. (A) Optical measurement (PSAP) of LAC. The data symbols are numbered 1 to 4, which corresponds to the four different source trajectory classes listed below the figure. The dashed symbols at the bottom of the panel represent days with no data. (B) Carbon-mass based concentrations of total organic carbonaceous aerosols (TOC) (open circles) and EC (black squares). (C) Radiocarbon content of TOC, EC, and SC (gray inverted triangles). The radiocarbon end-member ranges are shown for both contemporary biomass/biofuel (upper green field) and for fossil fuel (lower black line) and are further detailed in the text. The predominant air mass source regions over the past 10 days are summarized at the bottom. Horizontal range bars in (B) and (C) represent the collection and integration period for each sample.



-1000‰ . The $\Delta^{14}\text{C}_{\text{biomass}}$ end member is between $+70$ and $+225\text{‰}$. The first $\Delta^{14}\text{C}$ value corresponds to contemporary CO_2 (31), and thus freshly produced biomass, whereas the second $\Delta^{14}\text{C}$ end member is for combustion particles emanating from the combustion of wood (28, 32, 33). The latter $\Delta^{14}\text{C}$ value is higher because it is reflecting the $\Delta^{14}\text{C}$ of biomass that has accumulated over the decades-to-century-long life span of trees, which includes the period after the atmospheric nuclear bomb testing that nearly doubled the $\Delta^{14}\text{C}$ value of CO_2 by the early 1960s. For India, there are several important contemporary biofuel types, including wood fuel and cow dung; additionally, crop residue burning is believed to be an important source of atmospheric BC. To regionally parameterize the contemporary $\Delta^{14}\text{C}_{\text{biomass}}$ end member, the relative contributions of fuel wood (83%) and dung + crop waste (17%) provided by C. Venkataraman *et al.* were employed (23). Hence, an India-tailored $\Delta^{14}\text{C}_{\text{biomass}}$ end member of $+199\text{‰}$ was used in the model calculations. The sensitivity of the source apportionment results toward this end-member selection is low (Table 1, table S3, and SOM text).

Application of this isotopic mass balance model to these Asian aerosol $\Delta^{14}\text{C}$ values revealed that bulk carbonaceous aerosols (TOC) were $67 \pm 3\%$ (1 SD) of contemporary origin. The EC and SC isolates of the BC continuum were 46 ± 8 and $68 \pm 6\%$ from biomass combustion (Table 1). Although there are not yet any other reports of $\Delta^{14}\text{C}$ for EC isolates, the biomass combustion fraction of SC was 63% for northwest African dust intercepted in the northeast Atlantic Ocean (34), 70 to 88% in wintertime Scandinavia (28), and an averaged 35% in a Swiss alpine valley in the winter (33).

Our ^{14}C -based constraint thus indicates a much larger role for biomass and biofuel burning, compared with earlier top-down studies, while attenuating the biofuel influence relative to bottom-up suggestions. In contrast to the two earlier approaches, the ABC-BC14 results also provide a much tighter source constraint. Dual isotopic probing, combining $\Delta^{14}\text{C}$ with $\delta^{13}\text{C}$ (fig. S3), further underscores biomass combustion. The $\delta^{13}\text{C}$ suggests that wood fuel and other C3 plants are complemented by C4 sources (such as from agricultural slash-and-burn practices) as substantial contributors.

This work demonstrates that both fossil and biomass combustion processes can be blamed for the extensive ABC over South Asia. Improved constraint on the sources is the first step toward enacting effective abatement strategies. The much shorter atmospheric longevity for BC aerosols (approximately days to weeks) compared with GHGs raises the hope of a rapid response of the climate system. However, a consequence of thus decreasing the ABC “global dimmer” would also be to remove its counterbalancing effect on anthropogenic GHGs (1).

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SOM Text

Figs. S1 to S3

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Genetic Interactions Between Transcription Factors Cause Natural Variation in Yeast

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Our understanding of the genetic basis of phenotypic diversity is limited by the paucity of examples in which multiple, interacting loci have been identified. We show that natural variation in the efficiency of sporulation, the program in yeast that initiates the sexual phase of the life cycle, between oak tree and vineyard strains is due to allelic variation between four nucleotide changes in three transcription factors: *IME1*, *RME1*, and *RSF1*. Furthermore, we identified that selection has shaped quantitative variation in yeast sporulation between strains. These results illustrate how genetic interactions between transcription factors are a major source of phenotypic diversity within species.

Understanding the molecular basis of natural phenotypic diversity is a major challenge in modern genetics (1–6). Knowing how individual genetic polymorphisms combine to produce phenotypic change could strengthen evolutionary theory and advance applications such as personalized medicine (7, 8). Many loci that contribute to variation have been identified across taxa, but only a small fraction has been resolved to the nucleotide level (9, 10). Examples of complex traits in which causative

polymorphisms have been identified at multiple contributing loci are even rarer (11). As a result, the interactions between nucleotide changes in nature, and thus the genetic mechanisms of phenotypic change, are largely unknown.

Table 1. Significant QTL for sporulation efficiency.

Chromosome	Nearest marker	lod score	Variance explained (%)	Additive effect (%)
7	L7.9	86.42	41	20
7	L7.17	4.7	2	4
10	L10.14	68.2	29	16
11	L11.2	3.9	1	–3
13	L13.6	28.7	10	10

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