A Novel Back-trajectory Analysis of the Origin of Black Carbon Transported to the Himalayas and Tibetan Plateau during 1996–2010

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Background & Objective

Background

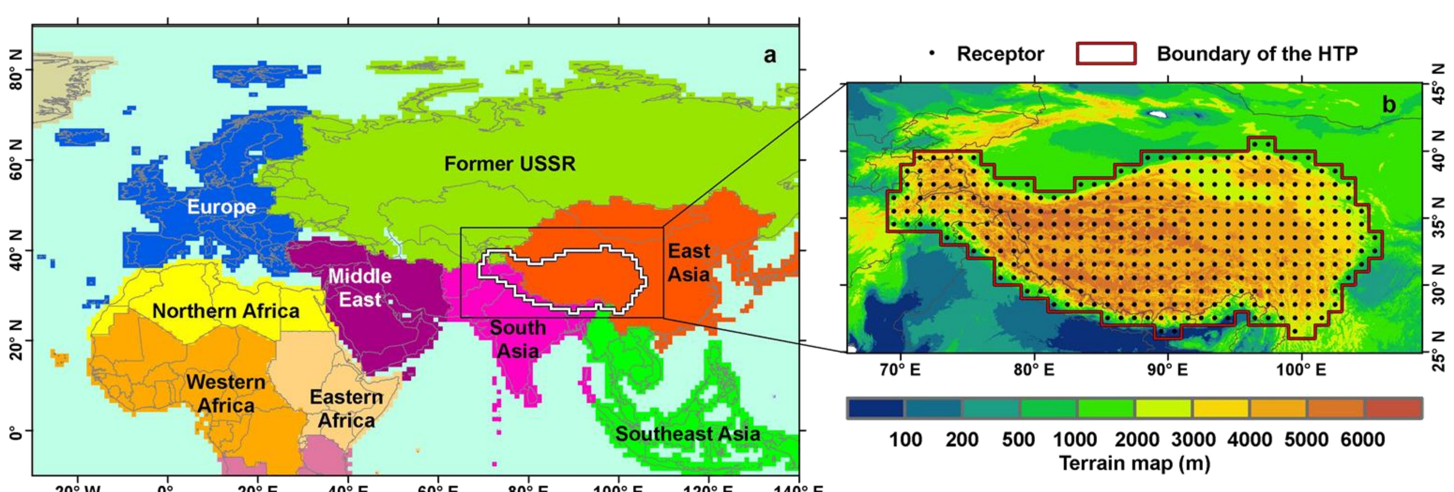
- Himalayas and Tibetan Plateau (HTP)…
  - *is also known as the Earth's "third pole"*
  - *is surrounded by the world's two largest black carbon (BC) generating regions, South Asia and East Asia*
- BC in the air or deposited at the surface…
  - *affects public health, air quality, and the Earth's energy budget*
  - *reduces surface albedo and accelerates glacier melting*
  - *is a major reason for the rapid climate change and glacier retreat of the HTP*
  - *has been shown to influence the weather, hydrological cycles, and ecosystems at regional and global scale since the mid-1990s*
- The origin of BC on the HTP is insufficiently studied
  - *Traditional back-trajectory approaches only identify the possible source regions by tracking air mass flow and cannot give any quantitative results* [Ming et al., 2008, 2009]
  - *The GEOS-Chem adjoint model only provides information for limited locations and time periods due to the heavy computational requirements, the absence of reliable multi-year emissions data, and the coarse model resolution* [Kopacz et al., 2011]

Objective

- Develop a novel back-trajectory approach that takes into account transportation, emissions, hydrophilic-to-hydrophobic conversion, and removal processes of BC to study the origin of BC on the HTP

Methodology

Back-trajectory Calculations



- Model — *HYSPLIT ver. 4.9*
- Receptor — *367 points covering the whole area of the HTP*
- Run time — *7 days (BC atmospheric lifetime ~1 week)*
- Frequency — *4 times daily at UTC 00:00, 06:00, 12:00, and 18:00*
- Arrival height — *500 m a.g.l. (within the typical PBL height over the HTP)*
- Met. Fields — *NCEP GDAS for 2005−2010 (3 h, 1º, 23 levels)*; *NCEP/NCAR reanalysis for 1996−2004 (6 h, 2.5º, 18 levels)*

Global Monthly BC Emissions

- *0.5º×0.5º, 9 sectors, period 1996−2010*

Sectors	Gridded emissions		Monthly information	
	China & India	Other regions	China & India	Other Regions
Power generation	Lu et al., 2011	IPCC RCP4.5	Lu et al., 2011	No seasonality
Industry	Lu et al., 2011	IPCC RCP4.5	Lu et al., 2011	No seasonality
Residential	Lu et al., 2011	IPCC RCP4.5	Lu et al., 2011	Assumed*
Land transport	Lu et al., 2011	IPCC RCP4.5	Lu et al., 2011	No seasonality
International shipping	IPCC RCP4.5	IPCC RCP4.5	No seasonality	No seasonality
Aviation	IPCC RCP4.5	IPCC RCP4.5	No seasonality	No seasonality
Agricultural waste burning	Lu et al., 2011	IPCC RCP4.5	Lu et al., 2011	GFED3.1
Open forests burning	GFED3.1	GFED3.1	GFED3.1	GFED3.1
Open savanna burning	GFED3.1	GFED3.1	GFED3.1	GFED3.1

* The residential emissions in winter (or summer) over northern Europe (latitude > 45º N) are assumed to be 30% higher (or lower) than the annual average value

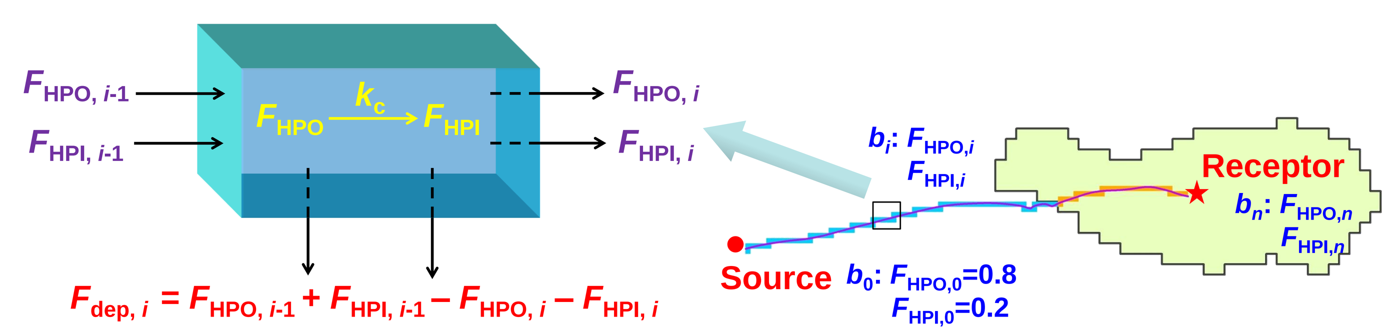
Hydrophilic-to-hydrophobic Conversion

- Follow the scheme developed by *Cooke et al.* [1999]
  - *Fresh emitted BC aerosols: 80% hydrophobic, 20% hydrophilic*
  - *Hydrophobic BC* $\xrightarrow{k_c}$ *Hydrophilic BC* $k_c = 1.01 \times 10^{-5}\ s^{-1}$

Removal Processes

- Follow the scheme developed by *Liu et al.* [2001]
- Dry deposition $k_d = 4.25 \times 10^{-7}\ s^{-1}$
- Wet deposition k_w *(monthly 3-D global fields)*
  - k_w *fields were generated from the hydrological data in the GEOS met. archive*
  - *Is applied only to the hydrophilic part of the aerosol*
  - *Includes rainout and washout of both convective and large-scale precipitation*

Effective Emission Intensity (EEI)



- The fraction of hydrophobic BC (F_{HPO}) and hydrophilic BC (F_{HPI}) in box b_i can be calculated as

$$\begin{cases} F_{HPO,i} = F_{HPO,i-1} \cdot \exp[-(k_d + k_c)t_i] \\ F_{HPI,i} = \left(F_{HPI,i-1} - \dfrac{k_c F_{HPO,i-1}}{k_{w,i} - k_c}\right) \cdot \exp[-(k_d + k_{w,i})t_i] + \dfrac{k_c F_{HPO,i-1}}{k_{w,i} - k_c} \cdot \exp[-(k_d + k_c)t_i] \end{cases}$$

- Define the transport efficiency of trajectory *l* at box *b* as

$$\mathrm{TE}_{b,l} = (F_{HPO,n} + F_{HPI,n}) + (\sum_j F_{dep,j})$$

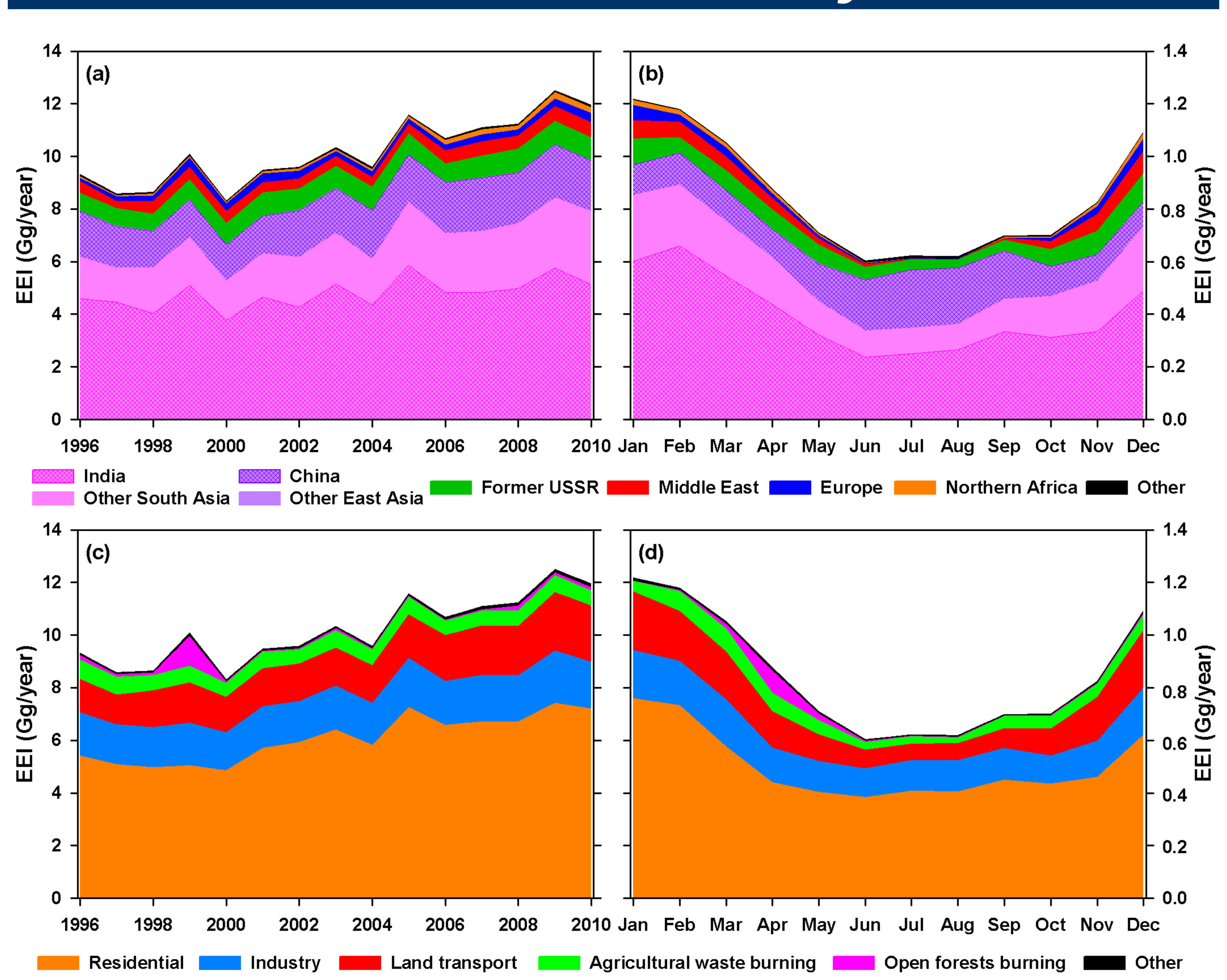
TE represents the transport ability of BC from the source region to the HTP

- Define the EEI of a surface grid *h* in month *g* as

$$\mathrm{EEI}_{h,g} = E_{h,g} \cdot [(\sum_{l=1}^{m_{h,g}} \mathrm{TE}_{h,l,g}) / \mathrm{TNT}_g]$$

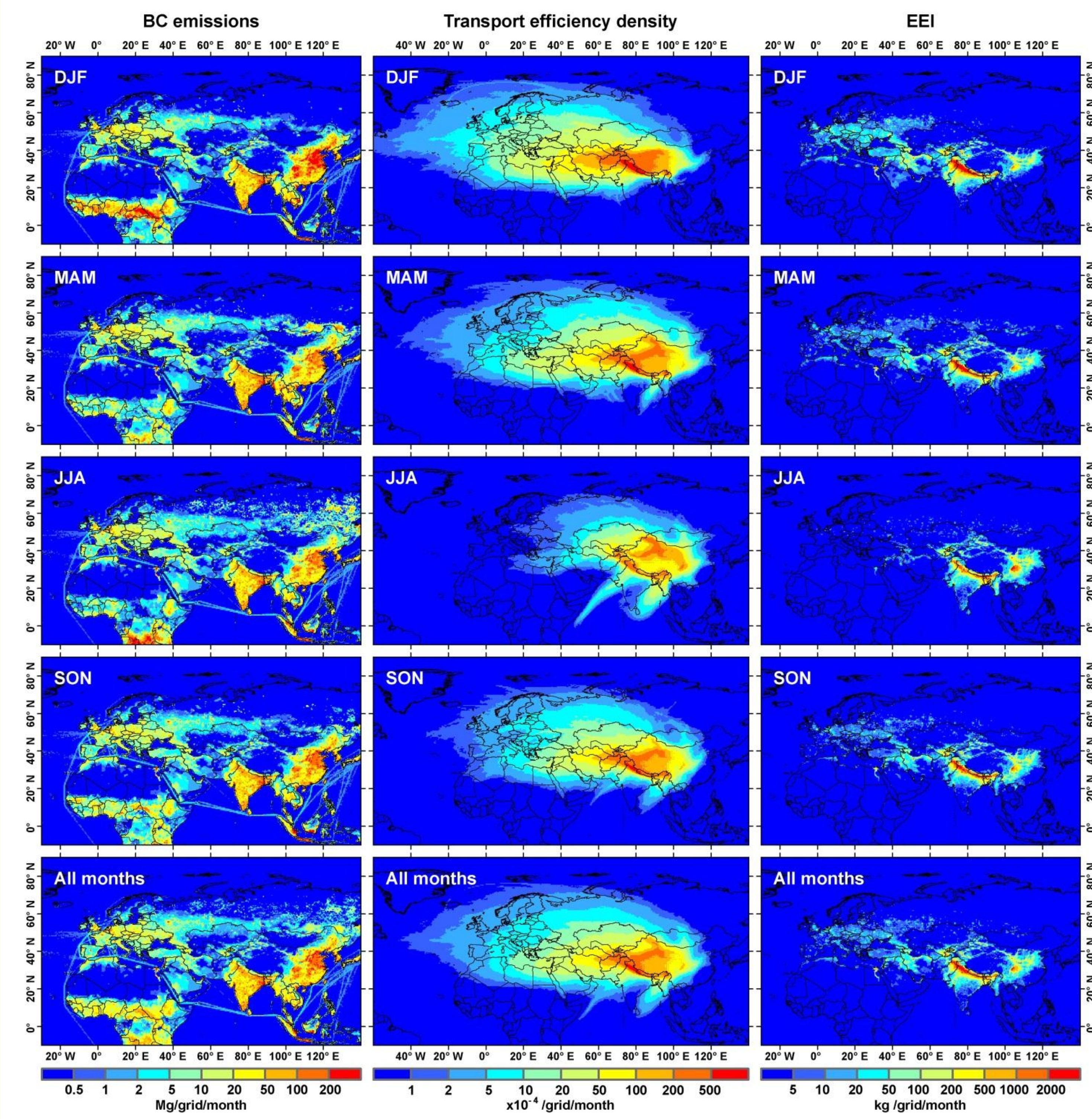
EEI represents TE weighted BC emissions

Trends and Seasonality of EEI



- BC transported to the HTP increased by 41% during 1996–2010
- Sectoral contributions
  - *Residential 60±5%*, *Land transportation 15±5%*
  - *Industry 17±3%*, *Agricultural waste burning 6±3%*
- The amount of BC transported to the HTP is high in winter and low in summer because of the effective wet scavenging of BC during the summer monsoon season

Spatial Origin of BC



- Two hotspots of BC origin
  - *Northern South Asia (e.g., the Indo-Gangetic Plain)*
  - *Southwestern China (e.g., the Sichuan Basin)*
  - *Reflect the intensive BC emissions and high transport efficiencies*
- BC sources that influence the HTP vary with seasons
  - *In January: South Asia ~70%, East Asia ~9%, Former USSR ~8%, Middle East ~6%, Europe ~5%, Northern Africa ~2%*
  - *In July: South Asia ~56%, East Asia ~36%, Former USSR ~6%*
- India and China are the two largest contributing countries
  - *Winter: India ~50%, China ~9%*
  - *Summer: India ~40%, China ~34%*

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Acknowledgments

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