Emission and climate forcing of Black Carbon (BC)

Current Progress in global BC modeling at PKU/LSCE

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Motivations

A well know fact: Emission is the basement for assessing BC’s forcing.

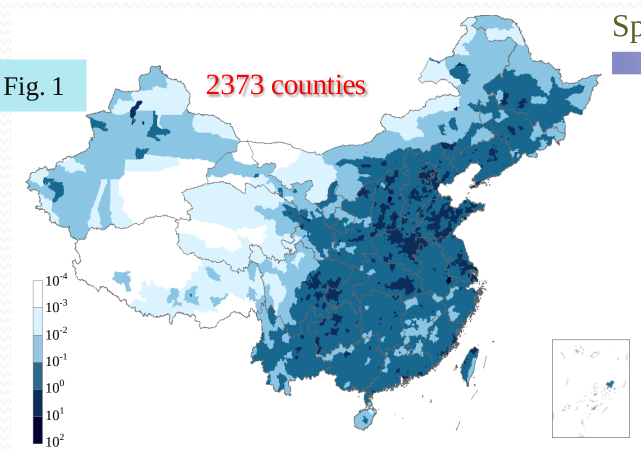
Emission of pollutants = ∑(Fuel consumption/activity) × (Emission factor)

Emission Factor (EF), defined as mass of the pollutant emitted per fuel consumed/activity.

Up-bottom approach:

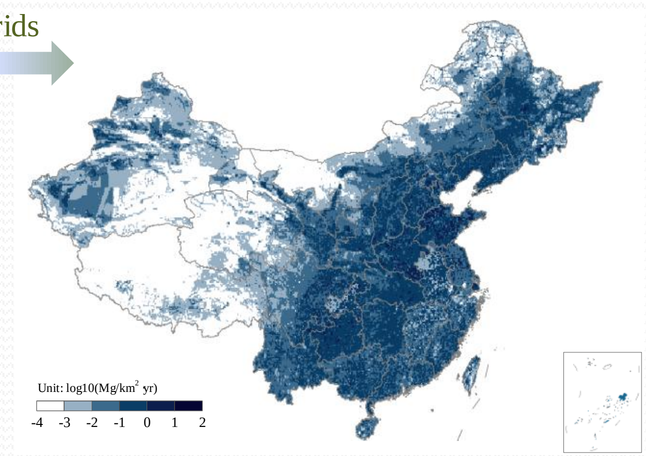
Emission by country/province/county => 0.1°×0.1° gridded emission

Fig. 1



Spatial allocation to 0.1°×0.1° grids

using various proxies



Emission Map by County

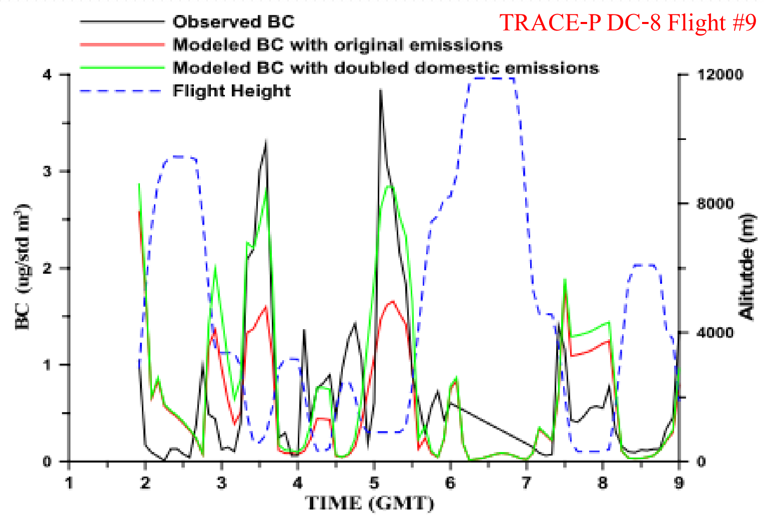
Emission Map by 0.1°×0.1° grids

Atmospheric BC in the area was underestimated!

Carmichael et al.,2003

Emission inventory: TRACE-P inventory (*Streets, 2001*)

Regional transport model: CFORS/STEM-2K1



Koch et al.,2008

Emission inventory: a global BC inventory (*Bond, 2004*)

Model: 17 AeroCom aerosol models

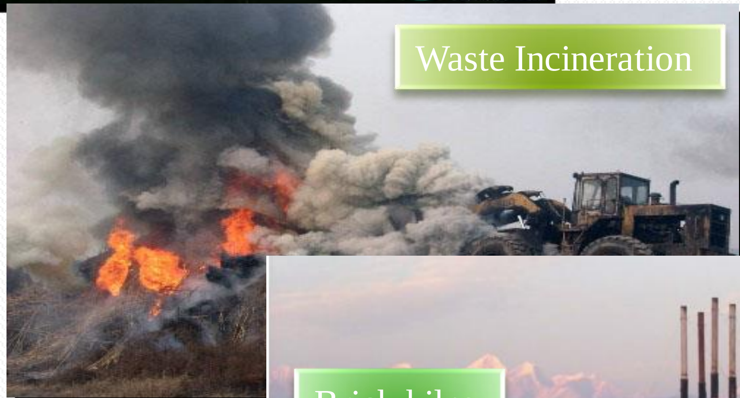
Average model biases	N Am	Eur	Asia	S Am	Afr	Rest
Surface concentration	1.6	2.6	0.50	NA	NA	1.4
BC burden	0.42	0.58	0.64	0.42	0.64	0.40
AERONET AAOD	0.86	0.81	0.67	0.68	0.53	0.55
OMI AAOD	0.52	1.6	0.71	0.35	0.47	0.26

Ratio of modeled BC to observed BC

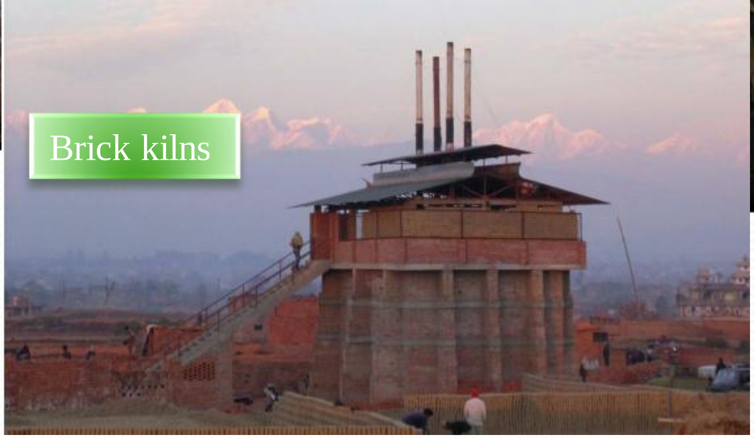
Similar results for the underestimation in the region were reported in other studies (*Uno,2003; Hakami,2003; Chung,2010; Kondo,2011*).


Power plants & industry


Residential Coal Stoves


Waste Incineration


Residential biomass Stoves


Brick kilns

Emission and climate forcing of BC

Part 1: Present-day emission of BC

Emission of BC in 2007

In 2007, 6.27 and 2.23 Tg/yr were from anthropogenic and natural sources.

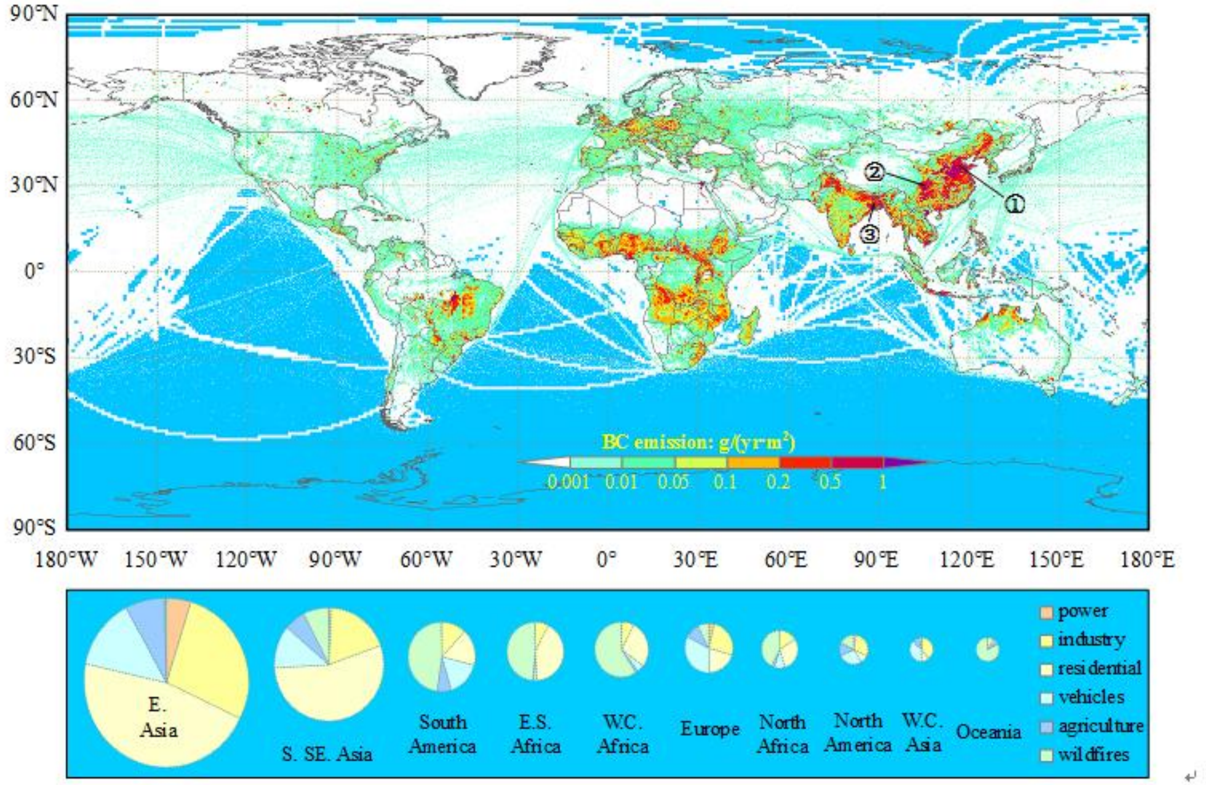


Fig.1. Geographic distribution of total BC emissions at 0.1°×0.1° resolution in 2007. Ocean grids with no emission was shown as blue. Three hot-spot emission regions were shown: ① North China Plain, ② Chengdu Plain, ③ Ganges Delta region. For the total emission, the relative contributions of the 6 economic sectors in 10 regions are shown as pie charts at the bottom, and the total areas of the pies are proportional to the total emissions in the regions. The total emissions in North Africa and Caribbean/Central America are too small to be shown as pie charts.

Comparison between the PKU-BC inventory with previous ones

E: global total emission;

var: variation of gridded emission density for all land grids;

F_1 and $F_{0.5}$: percentage of area with emission density over a criteria (for a criteria of 1 and 0.5 $g/yr/m^2$)

Inventory	resolution	year	*E*, Gg	*var*, $g/yr/m^2$	F_1, %	$F_{0.5}$, %
Anthropogenic Inventory						
PKU-BC	0.1°×0.1°	2007	**6274**	**0.387**	**0.674**	**1.734**
ACCMIP	0.5°×0.5°	2007	5279	0.107	0.218	1.162
by Dentener	0.5°×0.5°	2005	5410	0.105	0.208	1.144
by Junker	1°×1°	2003	5360	0.095	0.125	0.852
by Bond	1°×1°	2000	4531	0.087	0.132	0.702
IPCC-RCP	1°×1°	2005	5335	0.108	0.198	1.173
PKU-BC_noEF	0.1°×0.1°	2007	5379	0.325	0.557	1.455
PKU-BC_noSDM	0.1°×0.1°	2007	6274	0.314	**0.741**	1.919
PKU-BC_noEF&SDM	0.1°×0.1°	2007	5379	0.279	0.580	1.580
Wildfire Inventory						
PKU-BC	0.1°×0.1°	2007	**2225**	**0.387**	**0.674**	**1.734**
ACCMIP	0.5°×0.5°	2007	2643	0.109	0.137	0.505
IPCC-RCP	0.5°×0.5°	2005	2577	0.065	0.072	0.411
GFEDv3	0.5°×0.5°	2007	2143	0.065	0.097	0.271
GICC	0.5°×0.5°	2005	3876	0.089	0.184	0.865
PKU-BC_noEF	0.1°×0.1°	2007	2096	0.109	0.132	0.355

Major improvements for the PKU-BC inventory: Update of emission factors (EF):

Update of **EF,** especially for transportation, residential and industrial sectors

Effect : **a decrease of emission in developed countries, and an increase of emission for developing countries**

1) 80% of countries and 96% of emissions in developing countries were estimated higher than that by ACCMIP

2) 79% of countries and 87% of emissions in developed countries were estimated higher than that by ACCMIP

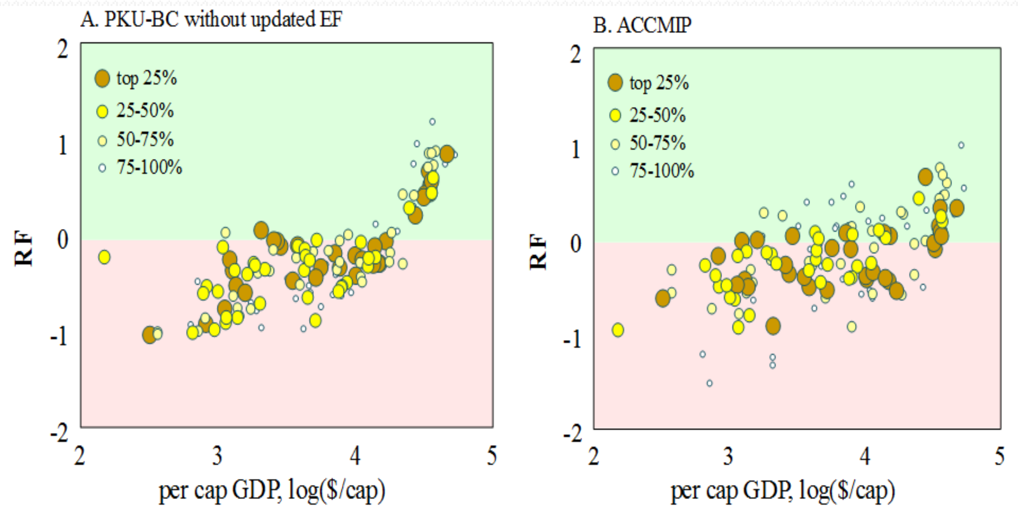


Fig. 2. Plot of relative different (RF) between the PKU-BC emission and that in other inventories (A: the PKU-BC without updated EF; B: ACCMIP) and PKU-BC against per cap GDP by country. A positive/negative RF indicates the higher/lower emission by the inventory to be compared than that in PKU-BC. The three inventories compared here are all for the year of 2007.

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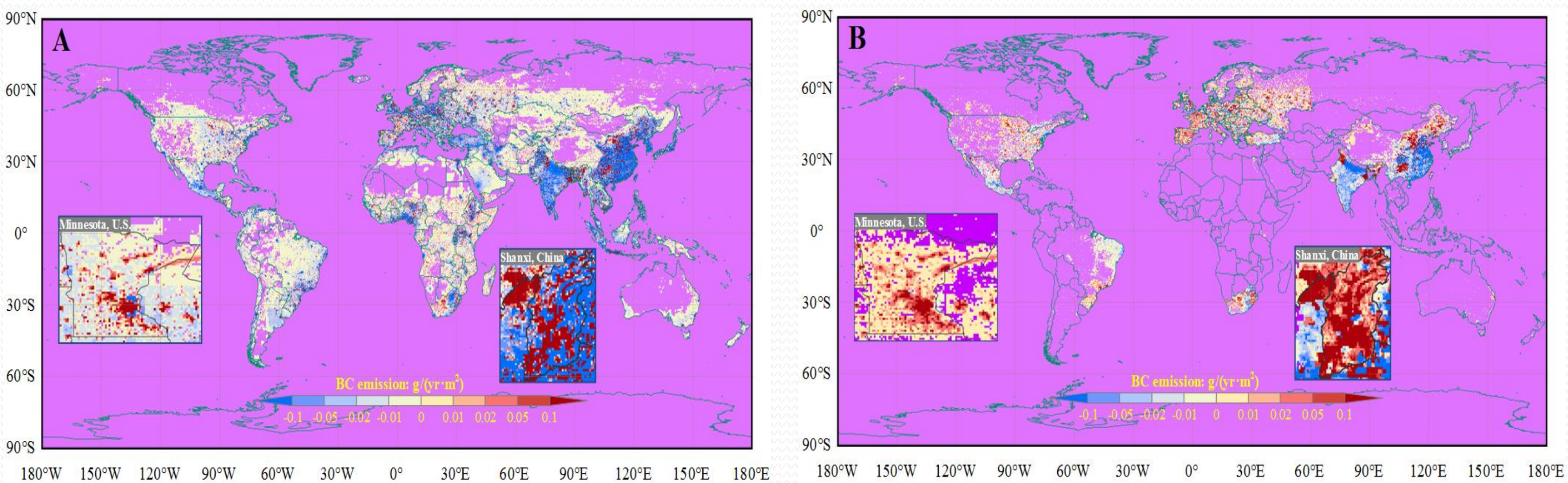
Major improvements for the PKU-BC inventory: sub-national disaggregation method (SDM)

- ✓ County-level inventory in China, Mexico and US
- ✓ Province or state -level inventory in India, Brazil, Canada, Australia, Turkey, and South Africa
- ✓ 0.5° ×0.5° in 37 European countries

Map of relative difference (RD) between PKU-BC and ACCMIP (A) and the PKU-BC without SDM (B)



Uncertainty of emissions

1) Based on the uncertainty of EF_{BC} and fuel data, global total BC emission varied from 4.86 to 14.5 Gg/yr as R_{50}, in which 91% of the uncertainty was from the variation of EF_{BC}.

Reason for the high uncertainty: the lack of enough measurement of EF_{BC}, like brick kilns and coke production.

2) By considering the uncertainty of emission estimations as well as spatial disaggregation, the uncertainty of gridded emission was derived.

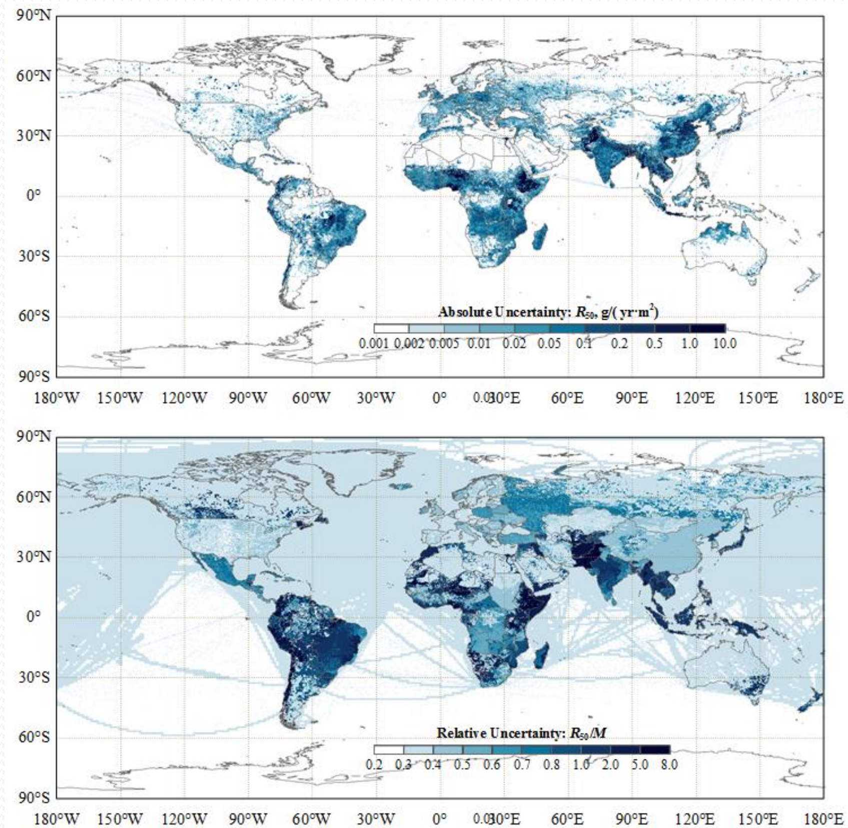


Fig. 4. Geographical distributions of absolute and relative uncertainties of BC emissions from combustion sources, excluding shipping and aviation at 0.1°×0.1° resolution. (a) absolute uncertainties as R_{90} and (b) relative uncertainties as R_{90}/M, where R_{90} and M are the 95th minus 5th percentile range and median value obtained in each grid-point calculated from Monte Carlo simulations (500 runs) with randomly varied input data, respectively.

Emission and climate forcing of BC

Part 2: Radiative forcing of BC using the new inventory

Methodology

General circulation model with aerosols and chemistry: LMDZORINCA (LOA)

Two version of the model:

1) LOA-zAsia: LOA zoomed over Asia with a resolution 0.51° ×0.66° (lat,lon)
2) LOA-Reg: LOA using regular grid with a resolution of 1.25° ×2.50° (lat,lon)

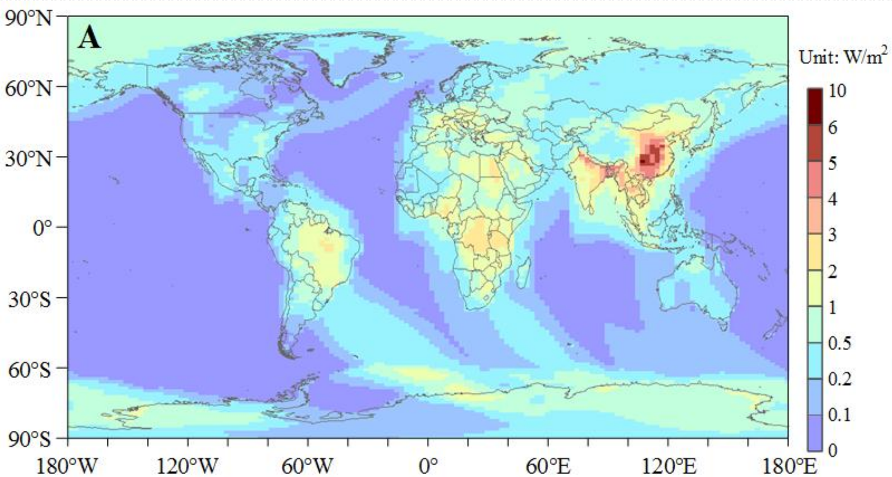
Emission inventory to compare with PKU-BC

1) PKU-BC_noEF, without updating emission factors (EF) (using EF by Bond, 2004);
2) PKU-BC_noSDM, without sub-national disaggregation methods (SDM);
3) PKU-BC_noEF&SDM, without updating EFs and SDM;
4) the 0.5° ×0.5° ACCMIP inventory (anthrop + natural fires).

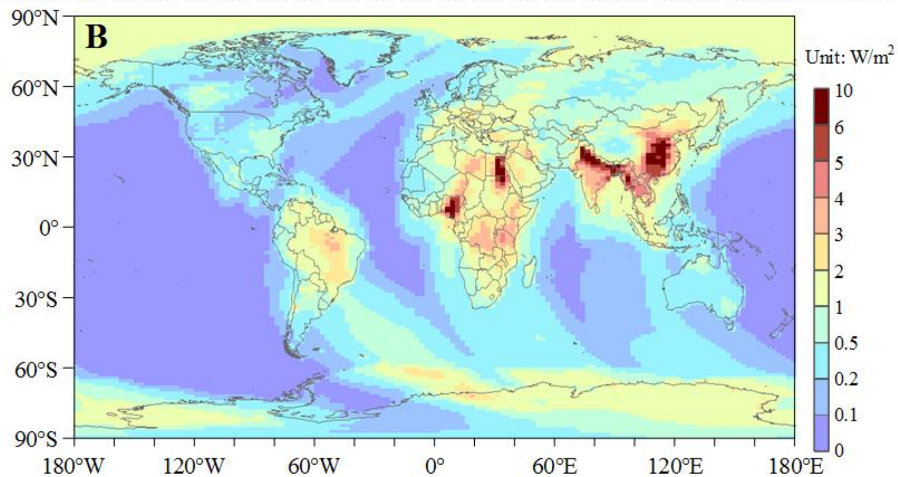
Results: radiative forcing of BC

Global forcing of BC as well as the uncertainty due to emission

Median Estimates: 0.46 W/m2



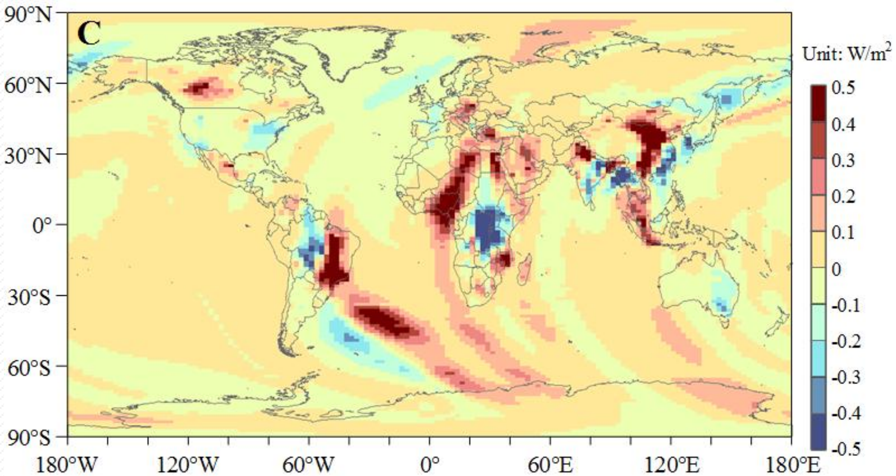
High Estimates: 0.77 W/m2



Comparison within this study

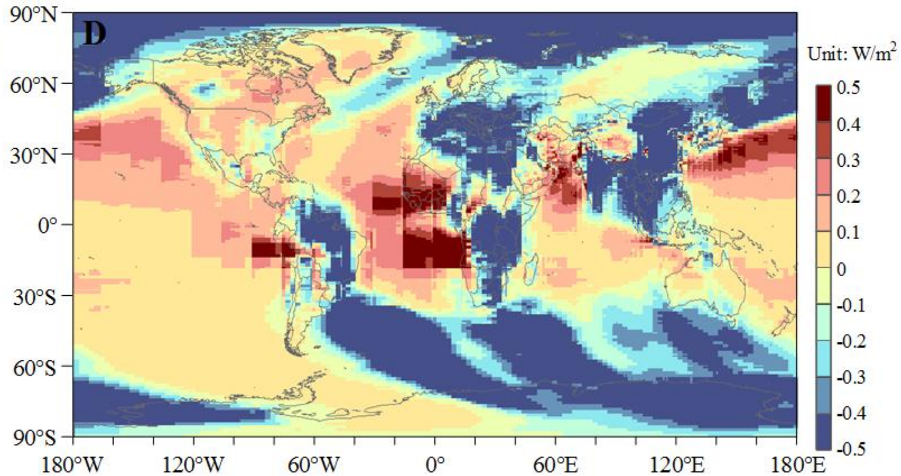
Difference between using PKU-BC and ACCMIP

by the LOA-REG



Difference between using LOA-zAsia and LOA-Reg

both using the PKU-BC inventory



Comparison to other studies

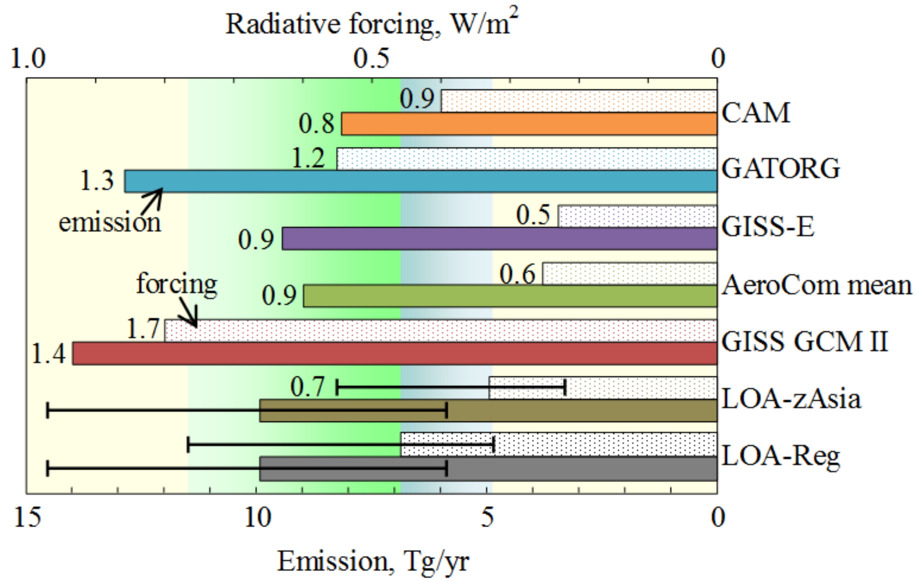


Fig. 7. Comparison of the radiative forcing as well as prescribed emission in different studies. The LOA-Reg and LOA-zAsia are corresponding to the LOA-Reg and LOA-zAsia model using the PKUBC inventory. GISS GCM II is by Chung et al. (Chung,2002); AeroCom mean is by Schulz et al. (Schulz,2006); GISS GCM II is by Koch et al. (Koch, 2011); GATORG is by Jacobson (Jacobson,2001); CAM is by Bond et al. (Bond,2011). The ratio of radiative forcing and prescribed emission by different models to that in LOA-Reg is marked.

Conclusions:

Compared to IPCC-AR4, the estimated direct radiative forcing of BC (0.40 W/m^2 as the mean by the LOA-Reg and LOA-zAsia, and 0.21 - 0.77 W/m^2 as the uncertainty including uncertainty in emission) is close to CH_4 (0.48 W/m^2), and contributes about 30% relative to CO_2 (1.66 W/m^2), but is higher than N2O (0.16 W/m^2) and tropospheric O_3 (0.35 W/m^2).

Emission and climate forcing of BC

Part 3: Model Evaluation by using the new inventory

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Surface concentrations: spatial distribution (measurement in 2003-2008)

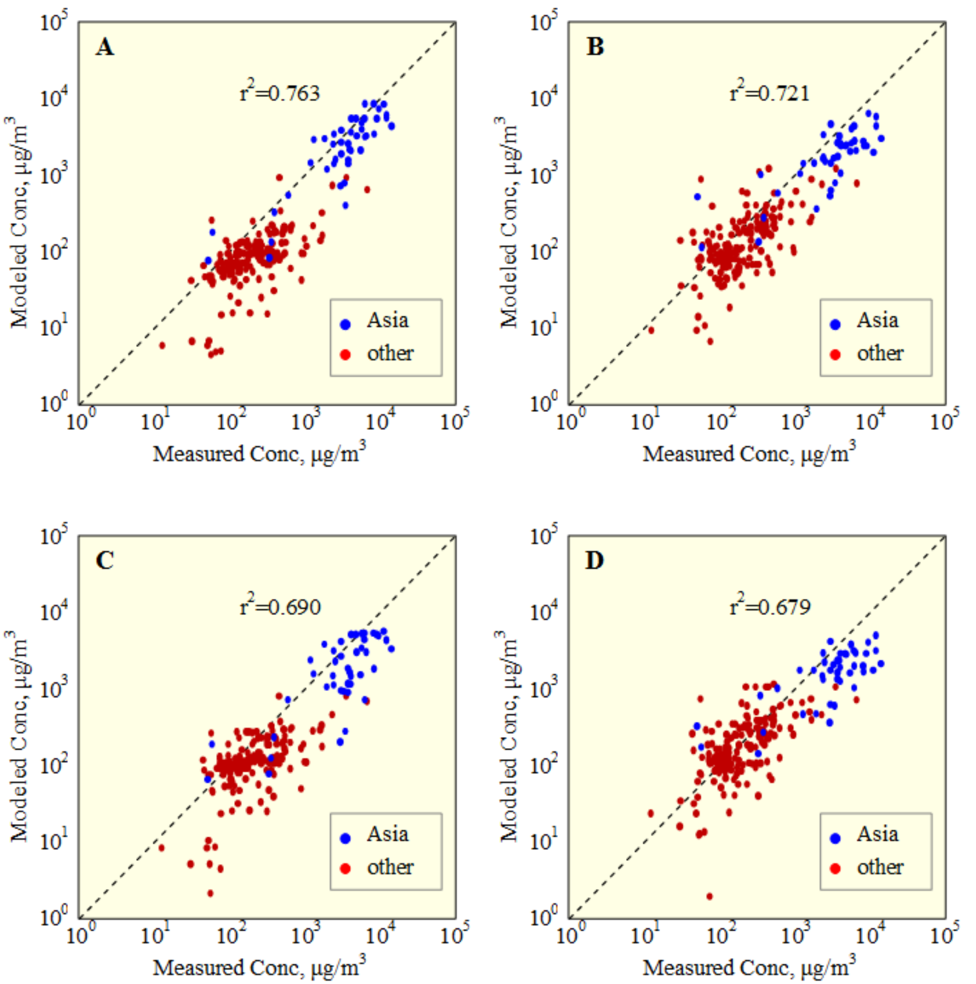


Fig. 10. Comparison between the modeled and measured surface BC concentrations (n=221). A) results from LOA-zAsia model using the PKU-BC inventory; B) results from LOA-Reg model using the PKU-BC inventory; C) results from LOA-zAsia model using the ACCMIP inventory; D) results from LOA-Reg model using the ACCMIP inventory.

Surface concentrations: seasonal variation

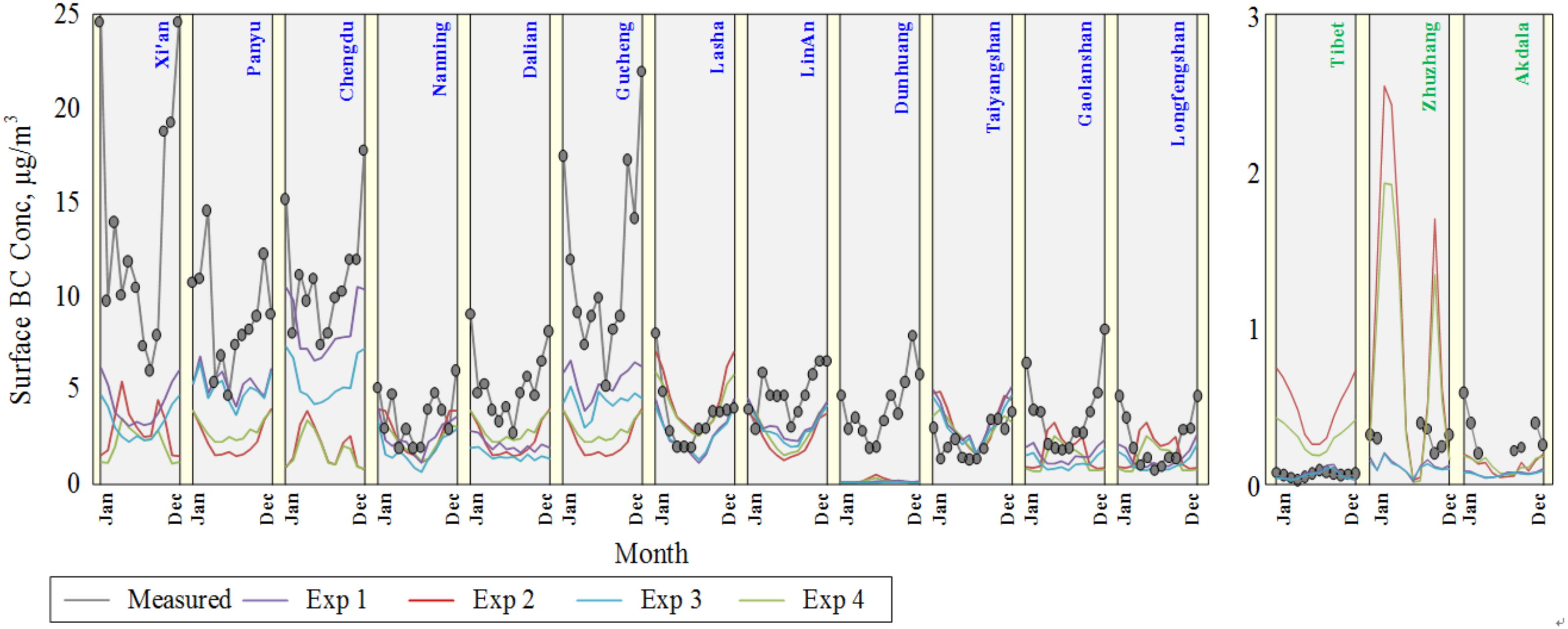


Fig. 13. Comparison of measured and modeled surface BC concentrations by month. Model results are corresponding to the experiments of: 1) LOA-zAsia model using the PKU-BC inventory; 2) LOA-Reg model using the PKU-BC inventory; 3) LOA-zAsia model using the ACCMIP inventory; 4) LOA-Reg model using the ACCMIP inventory. Normal sites are marked in blue font, while background sites are marked in green font.

Vertical Profiles of BC concentrations: comparison to aircraft measurements

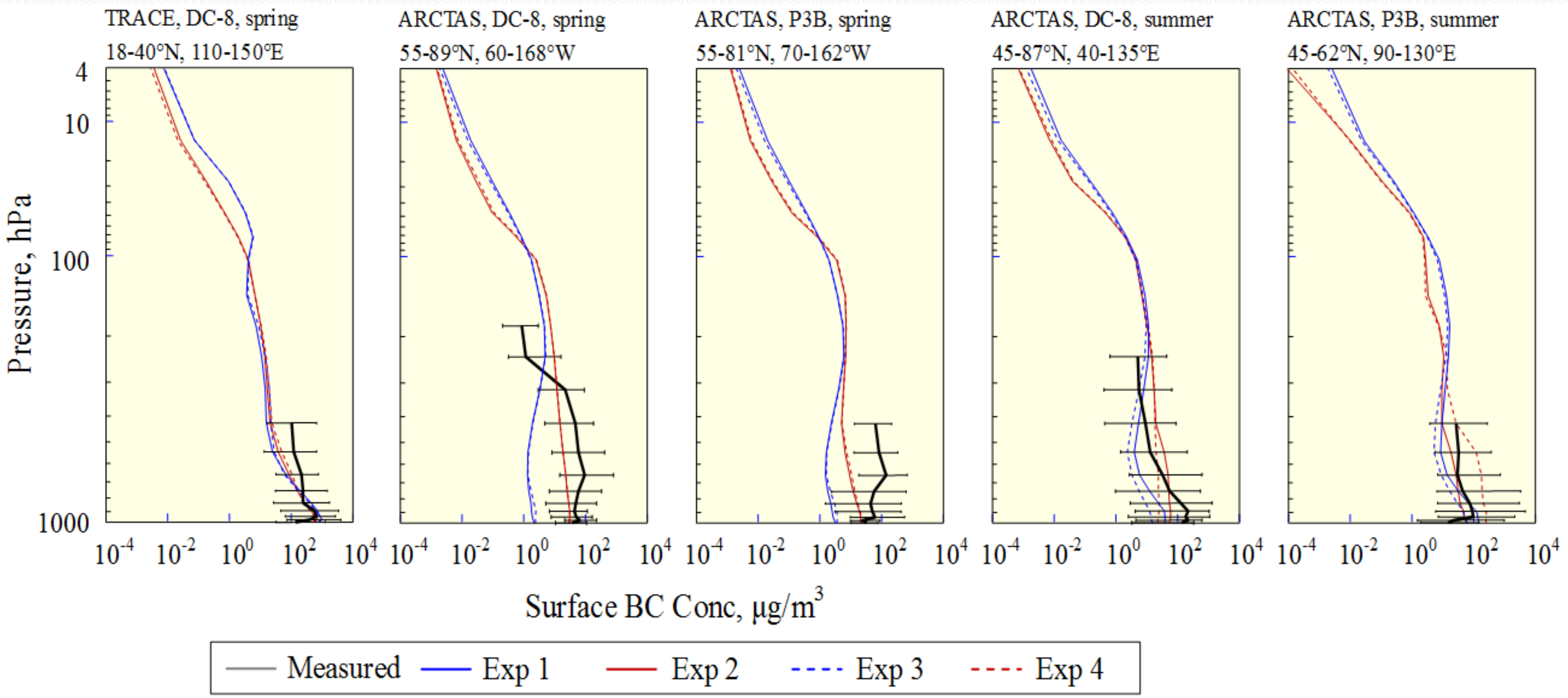
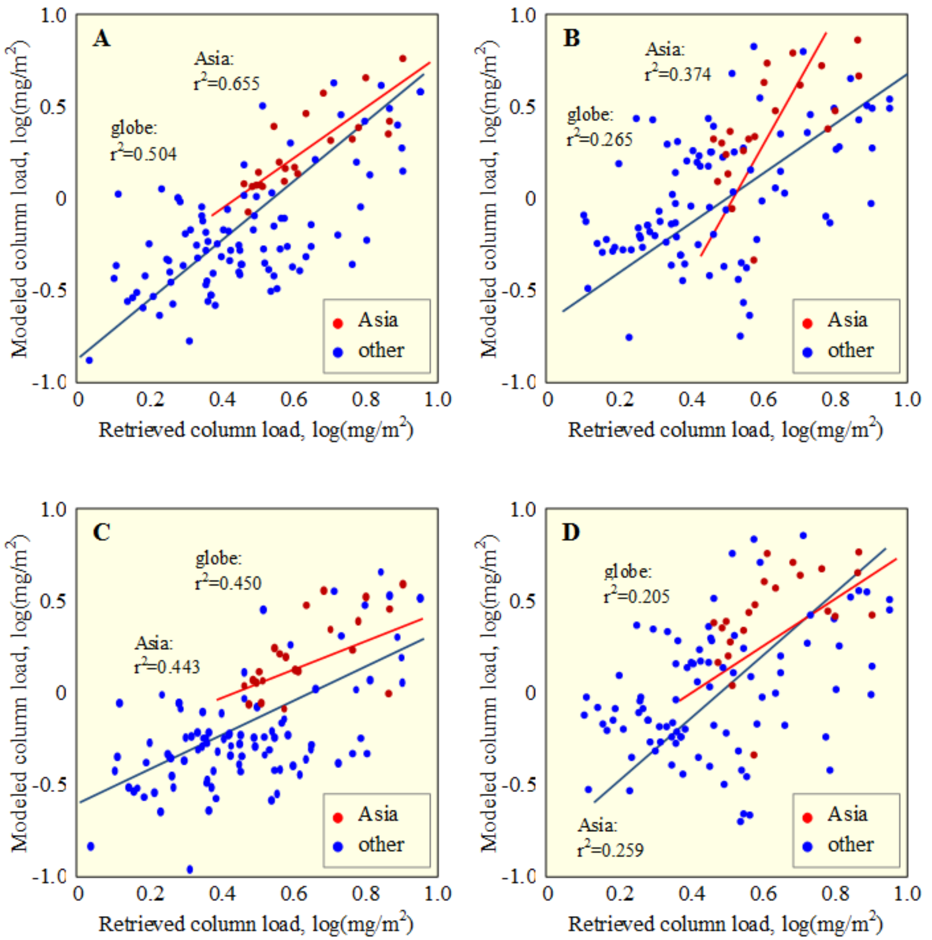


Fig. 14 Comparison of aircraft-measured and modeled vertical distribution of BC concentrations. Model results (monthly mean) are corresponding to the experiments of: 1) LOA-zAsia model using the PKU-BC inventory; 2) LOA-Reg model using the PKU-BC inventory; 3) LOA-zAsia model using the ACCMIP inventory; 4) LOA-Reg model using the ACCMIP inventory. Measured results are the means for all campaigns, with the semi-interquartile range shown as the error bar.

BC Column Load: spatial distribution



It's to be noted that all AERONET data (level 2.0) are only available when AOD(440) > 0.4, indicating the retrieved BC column loads (monthly means) were the means for high-pollution days. Therefore, we focused on comparing the seasonal and spatial patterns by using this product.

Fig. 16. Plots of the modeled against the retrieved annual mean column load of BC at 116 AERONET sites. A) results from LOA-zAsia model using the PKU-BC inventory; B) results from LOA-Reg model using the PKU-BC inventory; C) results from LOA-zAsia model using the ACCMIP inventory; D) results from LOA-Reg model using the ACCMIP inventory.

BC Column Load: seasonal variations

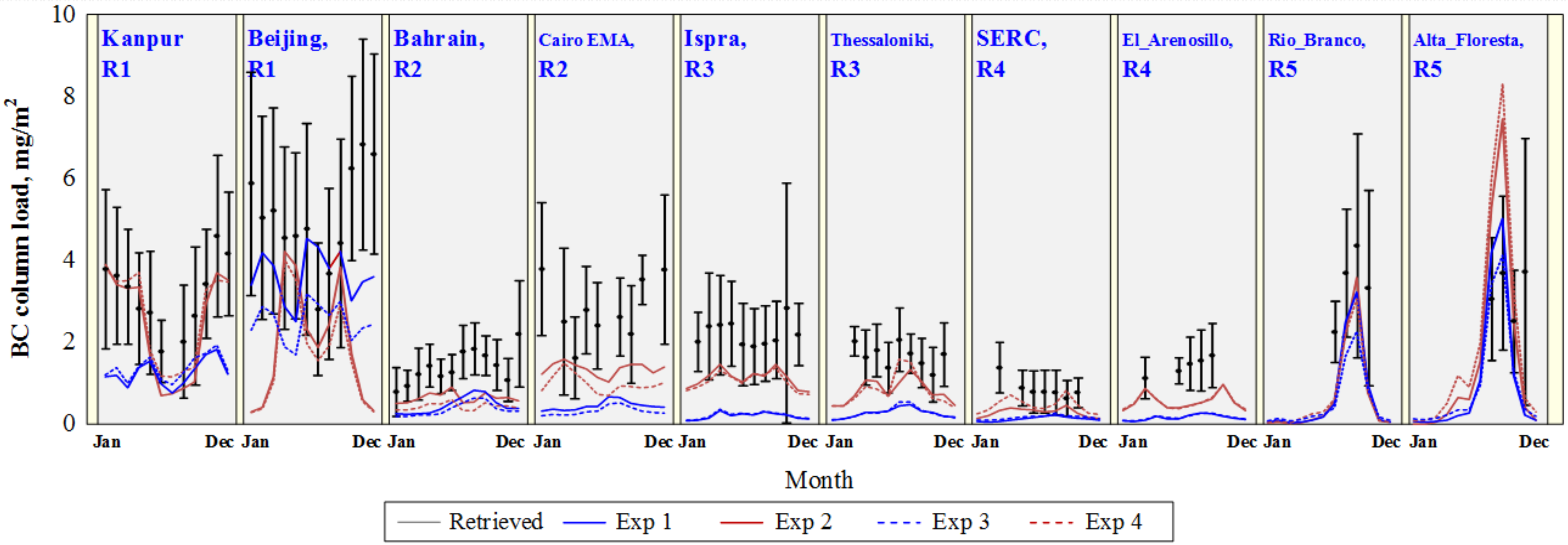


Fig. 17. Comparison between the modeled and retrieved monthly column load of BC at 10 AERONET sites. Model results are corresponding to the experiments of: 1) LOA-zAsia model using the PKU-BC inventory; 2) LOA-Reg model using the PKU-BC inventory; 3) LOA-zAsia model using the ACCMIP inventory; 4) LOA-Reg model using the ACCMIP inventory. The standard variations at each site are shown as the error bars. To reduce the influence of low-AOD(440) days on the retrieved BC column loads, the two highest modeled AOD(443) sites among the monitor sites in each region (R1 for Asia; R2 for Africa and Middle East; R3 for Europe; R4 for North America; R5 for South America) were selected to evaluate modeled seasonal variations of BC column loads.

Emission and climate forcing of BC

Part 4: Climate mitigation in Asia

A discussion on details after the conference

Mitigation in China and India

By cutting off all anthropogenic BC emission in China/India, the effect on forcing:

- Global forcing: China - 0.09 W/m^2, and India - 0.04 W/m^2
- Asian forcing: China - 0.45 W/m^2, and India - 0.22 W/m^2

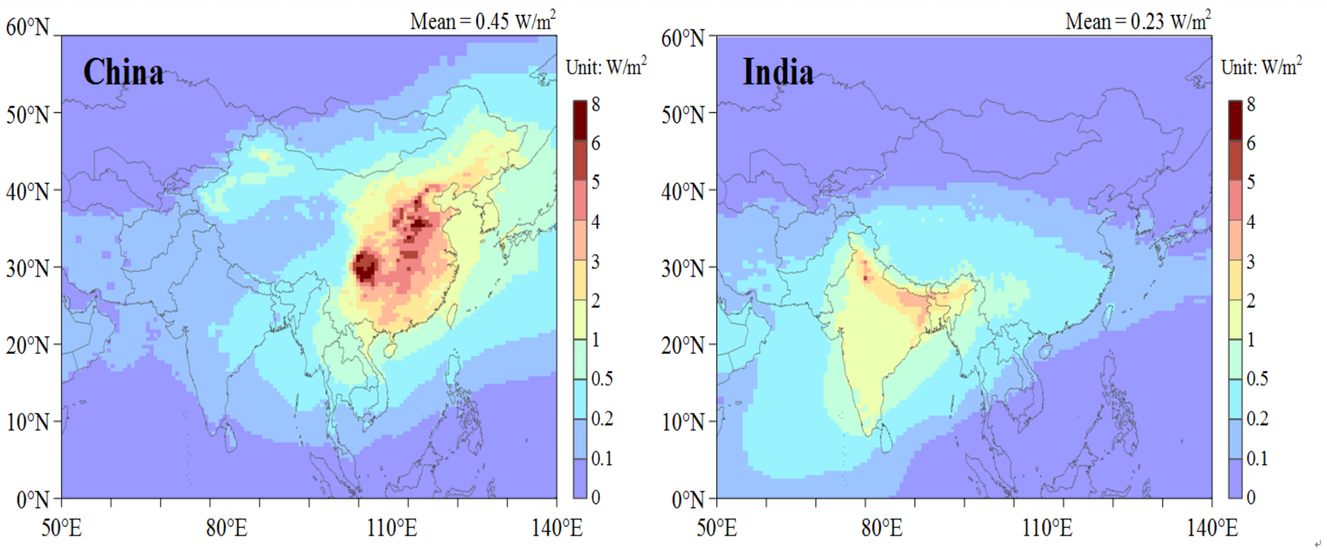


Fig. X. Regional radiative forcing of BC emission from China and India by LMDzAsia model using the PKU-BC inventory.

Investigation of the effect of mitigation policies on climate forcing of BC

China:

1) cM1: solid biofuels (straw, firewood, and dung cake) were replaced by clean fuel
2) cM2: residential coal fuels were replaced by clean fuel
3) cM3: diesel vehicles were applied by DPF (diesel particulate filters)
4) cM4: small-scaled brick kilns were replaced by tunnel kilns in Asia
5) cM5: open burning of crop residue were controlled
6) cM6: all the 5 mitigations above were realized at a percentage of 100% at the same time

India:

1) iM1: solid biofuels (straw, firewood, and dung cake) were replaced by clean fuel

	Costs		Mit. Emission		Mit. RF in Asia		Mit. RF in Globe		ΔRF/ΔE[1]	ΔRF/cost[2]
	10^9 \$	cost/GDP[3]	Gg	ratio[4]	mW/m^2	ratio[5]	mW/m^2	ratio[6]	W/m^2/Tg	W/m^2/(10^{12}\$)
cM1	352.6	6.14%	433	5.1%	96.6	8.9%	19.0	4.9%	0.0437	0.054
cM2	115.8	2.02%	516	6.1%	114.2	10.5%	21.8	5.7%	0.0423	0.188
cM3	45.6	0.79%	239	2.8%	52.5	4.8%	10.2	2.7%	0.0427	0.224
cM4	2.4	0.04%	116	1.4%	24.9	2.3%	4.9	1.3%	0.0423	**2.033**
cM5	2.3	0.04%	101	1.2%	20.2	1.8%	4.0	1.0%	0.0394	**1.732**
cM6	518.7	9.04%	1405	16.5%	318.9	29.2%	61.0	15.9%	0.0434	0.118
i M1	322	22.55%	346	4.1%	130.4	11.9%	26.1	6.8%	**0.0756**	0.081

1. ratio of mitigated global RF and emission
2. ratio of mitigated global RF and cost
3. ratio of the cost to the national GDP in 2010
4. ratio of the mitigated emission to global total emission
5. ratio of mitigated Asian RF to that by cutting off all anthropogenic emissions
6. ratio of mitigated global RF to that by cutting off all anthropogenic emissions

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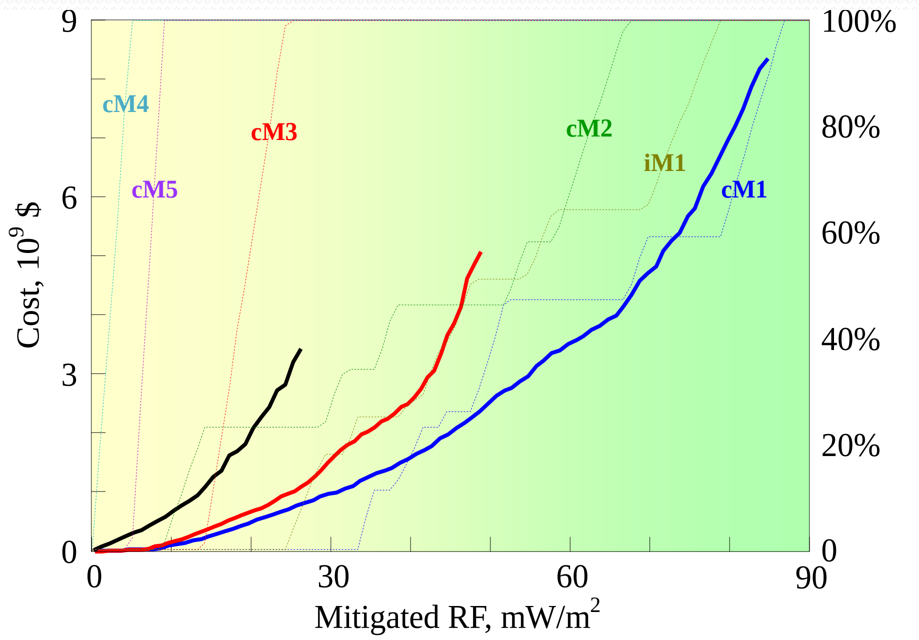
Comparison between Single-strategy and Multi-strategy mitigation

Cost-effect curves of different strategies:



- Mitigation only in China: red lines
- Mitigation only in India: black line
- Mitigation together with China and India: blue line
- Dotted lines are showing the ratios of each mitigation in the combined mitigation.

A question:

Is it possible to compare the cost-effect curve of BC to that of CO_2 and compare them to give the suggestion for regional mitigation policies?

Emission and climate forcing of BC

Work undergoing

Part 5: Climate forcing in the Arctic

- **Using the LMDZ-INCA zoomed in Europe**

Part 6: Inter-continent transport and global forcing of BC

- **Using the regular-grid LMDZ-INCA**

Part 7: Contribution of BC forcing by region and sectors

- **Using the regular-grid, Asia-zoomed, Europe-zoomed LMDZ-INCA model together**

Part 8: Long-term emission and forcing of BC: 1960-2050