The Contribution of Black Carbon Above Clouds to Global Average Radiative Forcing

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Colin Zarzycki (colin.zarzycki@gmail.com) and Tami C. Bond (yark@illinois.edu)
Department of Civil and Environmental Engineering, University of Illinois, Urbana, IL, USA

Introduction

- Absorption of solar radiation by black carbon (BC) aerosol has a positive direct radiative forcing on the climate system

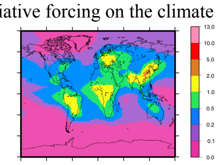

Figure 1: Annual Community Atmosphere Model (CAM) mean black carbon column load (in µg/m3). (from *Koch et al., 2009*)

- BC forcing is estimated to be either the second or third largest contributor to globally-averaged forcing
- Published direct forcing estimates range from +0.34 W/m^2 (*IPCC, 2007*) to +0.9 W/m^2 (*Ramanathan and Carmichael, 2008*).

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"… we know that short-lived carbon forcers like methane, *black carbon*, and tropospheric ozone contributes significantly to the warming of the Arctic. And because they are short lived, they also give us an opportunity to make rapid progress if we work to limit them."
– Sec. of State, Hillary Clinton

Rationale

- Causes of variability in modeled BC radiative forcing are:
  - Emission rates, optical properties, aerosol lifetime, vertical distribution
- BC over clouds plays a key role in forcing magnitude:
  - Highly reflective clouds beneath absorbing aerosol: **RF↑** (*Haywood and Shine, 1997*)
  - Elevated BC layer: **RF↑** because of cloudy layers (*Haywood and Ramaswamy, 1998*)
  - Warming effects of biomass burning aerosol may be 3x higher when spatial covariance between satellite-derived cloud cover and aerosol fields is considered. (*Chand et al., 2009*)
  - Cloud and BC fields vary in global climate models (GCM) *(Koch et al.*, 2009)
- Conclusion: ***Explore sensitivity of global BC forcing to cloud-aerosol location***

NDRF: A Measure of Black Carbon Impact

- Metric of interest is *normalized direct radiative forcing* (**NDRF**, W/g)

$$NDRF = \frac{Column\ Forcing}{Column\ Burden} = \frac{\frac{Forcing}{Area}}{\frac{Mass}{Area}} = \frac{Forcing}{Mass}$$

- Can apply to varying emission rates & lifetimes to determine total forcing

Methods

1
- 1-D radiative transfer model
- Determine RF for various cloud/BC vertical combinations

2
- Weight values from step 1 by sky coverage
- Test sensitivity of forcing by varying sky coverage

3
- Use 3-D model output to estimate covariance
- Investigate global effect of varying vertical distribution

Objective: Answer These Questions

- How much of observed model variance can result from vertical distribution?
- What is a realistic range of black carbon forcing, since vertical distribution is poorly constrained?

1 Radiative Transfer Model

- 1-D radiative transfer model (Streamer)
  - Medium spectral resolution used for calculating radiation fluxes for a wide range of surface and atmospheric inputs (*Key and Schweiger, 1998*)
- **Clouds (4 types)**
  - Defined by cloud top height (CTH) and droplet/crystal optical properties (τ, r_e, LWC)
- **Aerosol (Black Carbon)**
  - Optical properties derived from OPAC (Hess et al., 1998)
    - Used to mirror BC optical properties used in current climate models
  - Each simulated aerosol layer - constant aerosol optical depth (AOD) of 0.05 at 550 nm

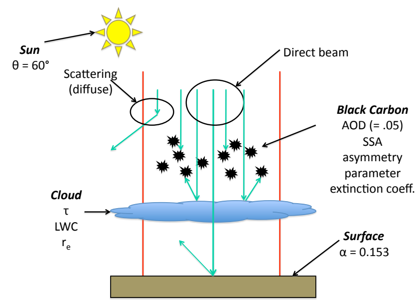

Figure 2: Basic explanation of Streamer's operation as well as the model's input parameters.

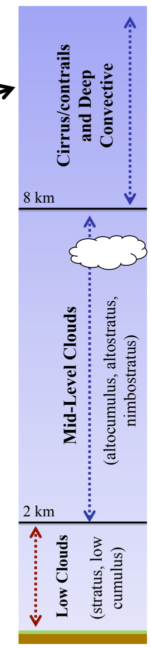

Figure 3: Vertical spans of cloud top height (CTH) used for four cloud types

1 BC Forcing by Cloud Type

- BC NDRF calculated for 9 cases: ***Above*** 4 cloud types, ***Below*** same 4 cloud types, ***Clear sky***
- RF = Difference in top-of-atmosphere (TOA) flux between aerosol and no-aerosol STREAMER runs

Sky Cover	BC Location	NDRF (W/g)
Clear Sky (CS)		1,050
Low (LC)	Below	244
	Above	2,790
Medium (MC)	Below	229
	Above	3,100
Cirrus and Cirrus-like (HC)	Below	436
	Above	2,140
Deep Convective (DC)	Below	23
	Above	5,530

- NDRF is:
  - Nearly **3x higher** than clear sky **above low clouds** and **above mid-level clouds**
  - Much lower when shielded by optically deep clouds, but still non-zero

First-Order Global Average

- **Black carbon profile** from field campaigns summarized in Koch et al., 2009

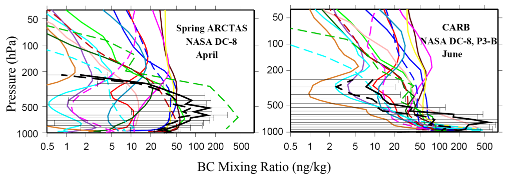

Figure 4. An example of a high-latitude (left) and mid-latitude (right) BC profiles. The black line is field campaign data that was used to estimate a global profile, the other colors are AEROCOM model-produced profiles (from *Koch et al., 2009*)

- **Sky coverage** data from the International Satellite Cloud Climatology Project (ISCCP)
  - Long-term satellite measurements to determine time-averaged clear sky and cloudy sky fractions (*Rossow et al., 1996*).

Weight each case by sky coverage and column BC above and below each cloud for a first-order estimate of NDRF:

$$NDRF_{avg} = f_{CS}NDRF_{CS} + \sum f_{xC}NDRF_{AxC}\beta_{AxC} + \sum f_{xC}NDRF_{BxC}\beta_{BxC}$$

NDRF	case-dependent normalized direct radiative forcing values
f	ISCCP-derived cloud fraction for each sky case
β	fraction of total column BC above (A) or below (B) cloud top in each case
xC (subscript)	type of cloud

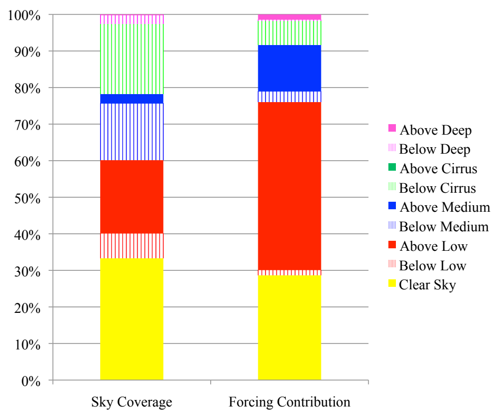

Figure 5. Normalized graphs showing global black carbon burden weighted by sky fraction (left) and the corresponding global forcing contribution predicted by the model (right). <u>Note the significant importance in the contribution of BC above mid and low-level clouds to average NDRF relative to their mass fraction</u>

Comparison with 3-D Global Climate Models

Comparison with other GCM NDRF:

- ISCCP cloud fractions
- Field-campaign derived BC profile

NDRF = **1250 W/g**

- Figure to the right shows distribution of 17 AeroCom models (*Schultz et al., 2006*). First-order estimate is shown in **green**

Test of first-order model:

- Community Atmosphere Model run:
  - Globally-averaged BC profile
  - Model sky coverage fractions

  NDRF = 1430 W/g
- Actual model NDRF = 1210 W/g

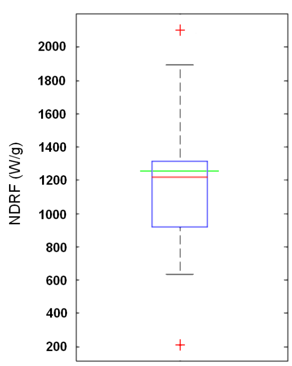

Figure 6. Boxplot showing spread of globally-averaged BC NDRF produced by 17 AEROCOM models along with an estimate produced by our weighting model in green.

Sensitivity and Range of NDRF

How much does can varying the vertical distribution affect NDRF?

- **Small perturbation example:** a +/- 5% perturbation at low cloud tops, +/-2% (mid-cloud tops), and +/- 1% (cirrus and deep convective)
- **"Real" boundary profiles:** Max/min RF produced by BC profile in a single CAM gridbox
- **Extreme boundary profiles:** Lofting *<u>all</u>* black carbon above clouds or restricting *<u>all</u>* the column burden to the surface

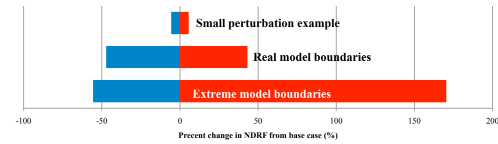

Figure 7. NDRF variation relative to the base case defined in "First-Order Global Average" for three examples of different vertical profiles desbcribed above.

- Required to double forcing: 85% of column burden > 550 hPa (4 – 5 km)

BC/Cloud Covariance and 3-D Profile Analysis

- 1st order model simplistic; doesn't consider potential BC/cloud covariance
- By using 3-D model output we can consider regional cloud and burden effects by allowing them to vary horizontally before weighting
  - NDRF ~**3% lower** than simple averaging (step 2) if we calculate BC/cloud type breakdown in each gridbox and weight by column burden
- Hold total burden and horizontal BC distribution constant (CAM) -> two vertical profiles were analyzed:
  - Direct CAM output (**CAM**)
    - High BC mixing ratios in mid-upper troposphere relative to observed (*Koch et al., 2009*) result in <u>high NDRF due to BC forcing above mid -and upper-level clouds</u>
  - Constant mixing ratio through 3.4 km (2.0 outside tropics) (**CMR**)
    - Profile used in *Ramanthan and Carmichael (2008)*, highest published BC forcing
    - Produces higher peaks of *near-surface BC* (< 600 hPa) than CAM
      - Overall NDRF <u>**increases 5%** due to *near-surface BC* over low cloud increase</u>

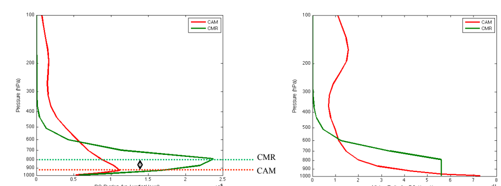

Figure 8. Figures showing the average BC level burden and mixing ratio as a function of pressure (height) between the two types of 3-D profiles employed. <u>Note the difference in the peaks of low-level BC between the CMR and the CAM runs.</u>

Summary of Results

- BC forcing is *<u>significantly higher above **any** cloud of sufficient optical depth</u>*
- All other variables equal, individual column forcing *<u>may vary +/- 50% depending on the vertical structure of BC</u>* assuming realistic profiles
- A constant mixing ratio (or similar) profile (Ramanathan and Carmichael, 2008) may result in an approximate *<u>5% increase in NDRF relative to a typical GCM due to increased BC above low-level clouds</u>*
  - While BC vertical distribution plays a role in published globally-averaged forcing differences, *<u>it is unlikely the key mechanism driving variance</u>*

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