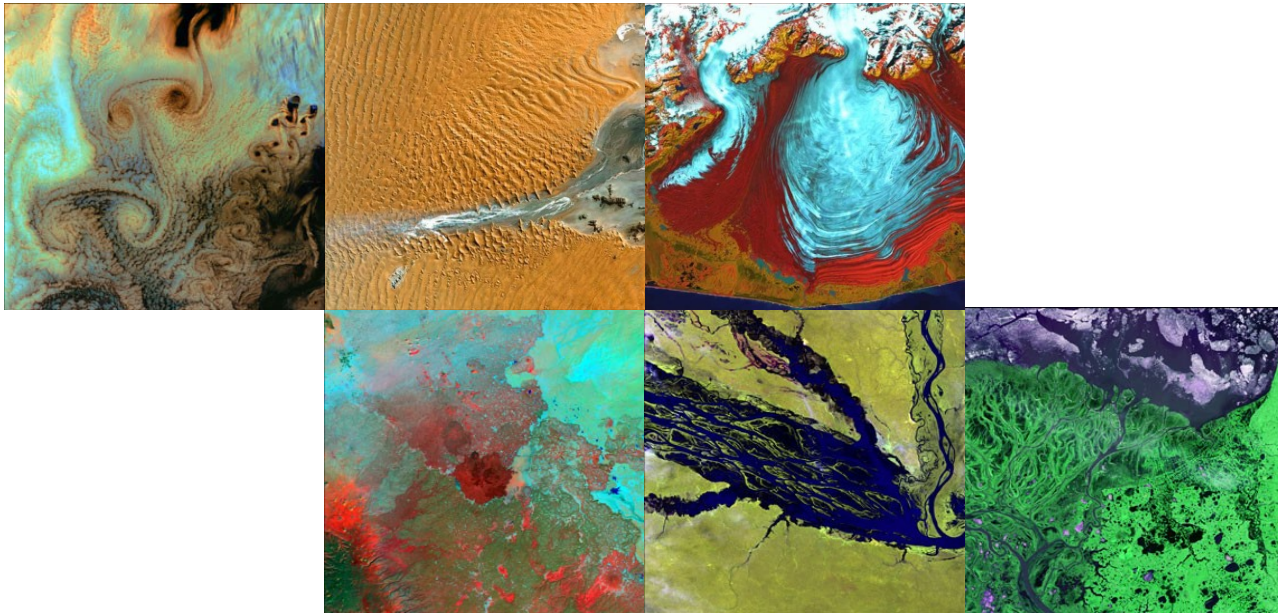


Model simulation of biomass burning aerosols and trace gases: Opportunities and challenges



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NASA Goddard Space Flight Center

Introduction (1)

- Biomass burning is one of the major sources of atmospheric aerosols and trace gases
- The large variations of spatial and temporal patterns, different causes of fire activities, and a variety of fuel conditions/types make quantitative emission estimation challenging
- Satellite observations in the past decades have led a “quantum leap” in global and regional scale fire monitoring and prediction, making emission estimation much more accurate

Introduction (2)

- To realistically simulate the biomass burning aerosols and trace gases, a model has to take into account of
 - Emission amount of species of interest
 - Altitudes of fire injection
 - Smoke transport and dispersion
 - Plume chemistry
 - Removal processes
 - Physical and optical properties of particles

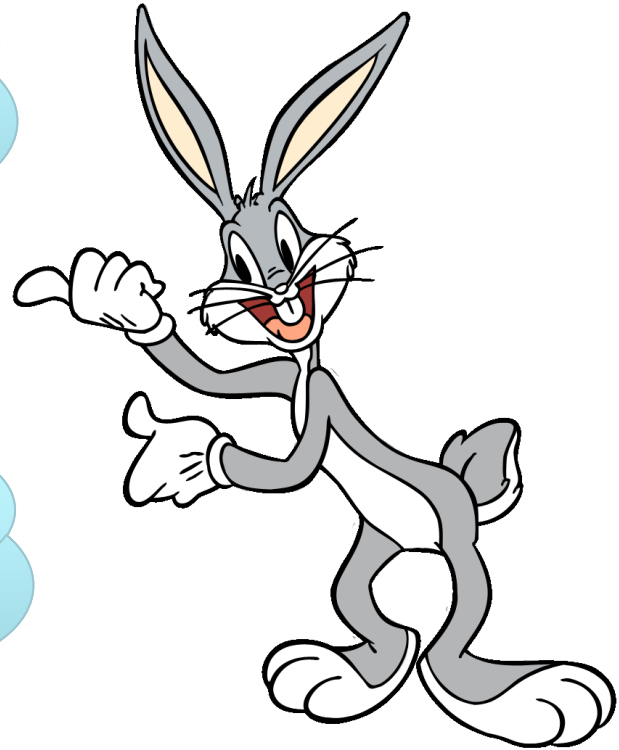
Today's talk

- I will go over each of the above aspect as used in the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model for atmospheric aerosols to provide some perspectives
 - Emission
 - Atmospheric processes (chemistry, transport, removal)
 - Optical properties
- Then I will show some of the model results and how they are being evaluated
- Lastly we should discuss uncertainties and challenges, as well as future directions

Two things to keep in mind if you are doing global modeling

All models are wrong, but some are useful.

Keep it simple, stupid!



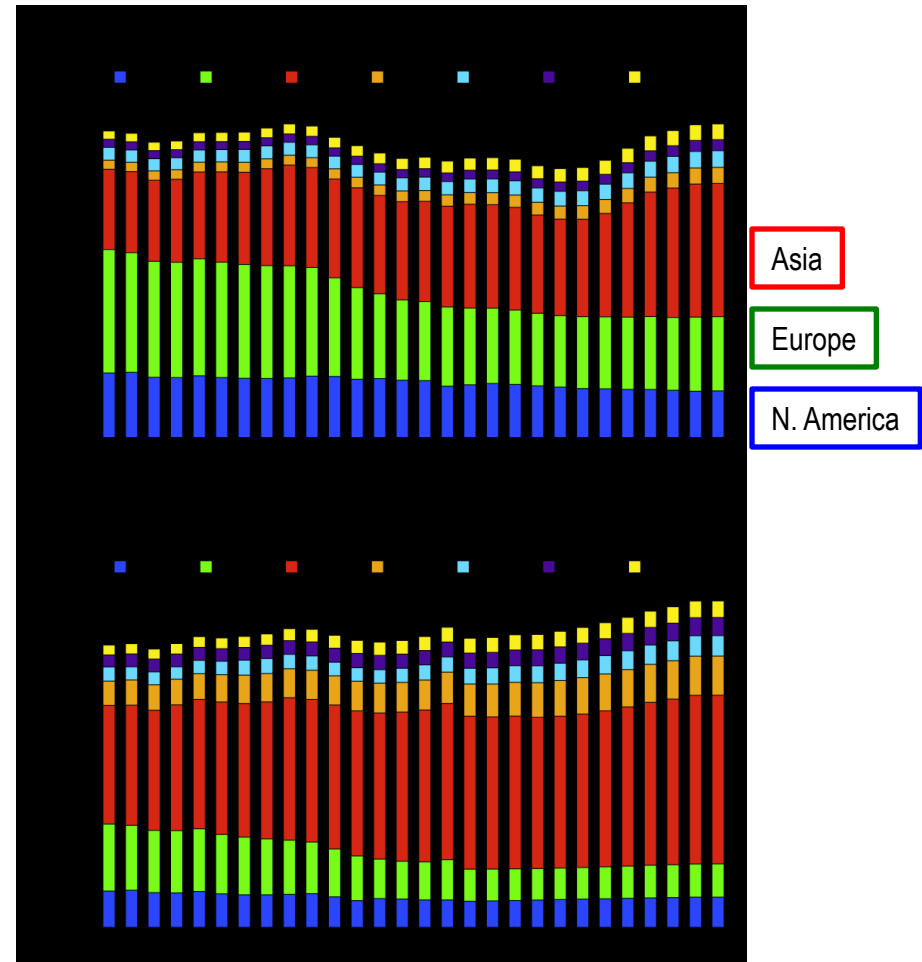
GOCART model at-a-glance

- Global chemistry and transport model using assimilated meteorological data from NASA GEOS DAS to simulate atmospheric components
- Horizontal resolution is at 1 degree latitude by 1.25 degree longitude with 30 vertical layers
- For atmospheric aerosols, the GOCART model takes into account of anthropogenic, biomass burning, and natural sources of aerosols and related gas species
- Major aerosol species: sulfate (and precursor gases SO₂ and DMS), black carbon, organic matter, dust, sea salt
- Simulating atmospheric processes (chemistry, transport, convection, dry and wet deposition)
- Aerosol optical depth (AOD), aerosol absorption optical depth (AAOD), and other optical properties are calculated from aerosol mass concentrations, particle size distributions, refractive indices of each components, and hygroscopic growth

Emission, emission, emission (1)

- Industrial emission:
 - Rely on emission inventories (e.g., GEIA, IASA, EDGAR, Streets, Bond, etc.).
 - They are relatively “constant”, i.e. they are all year long with small seasonal variations and better characterized geographic locations

In GOCART: Anthropogenic emissions of SO₂, BC, and OC from David Streets (Streets et al., 2006, 2009)



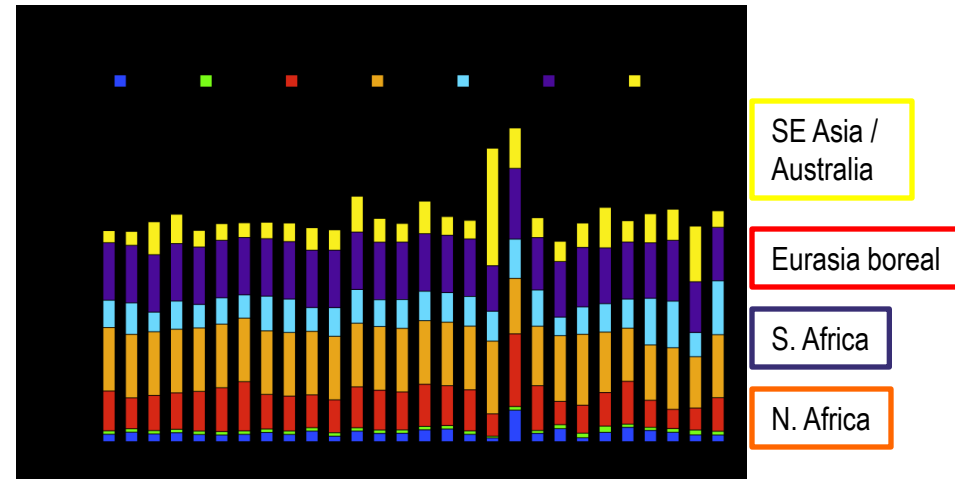
Emission, emission, emission (2)

- Biomass burning emission:
 - Default: GFED v2, monthly (or 8-day)
 - Injection height: evenly distributed within BL
 - biomass burning sources are very seasonal, and its intensity can vary in great deal from one year to another

$$E_i = A \cdot B \cdot C \cdot F = DM \cdot F_i$$

Where

- A = area burned
- B = biomass density
- C = completeness of burning
- F_i = emission factor for species i
- DM = dry mass burned = A · B · C



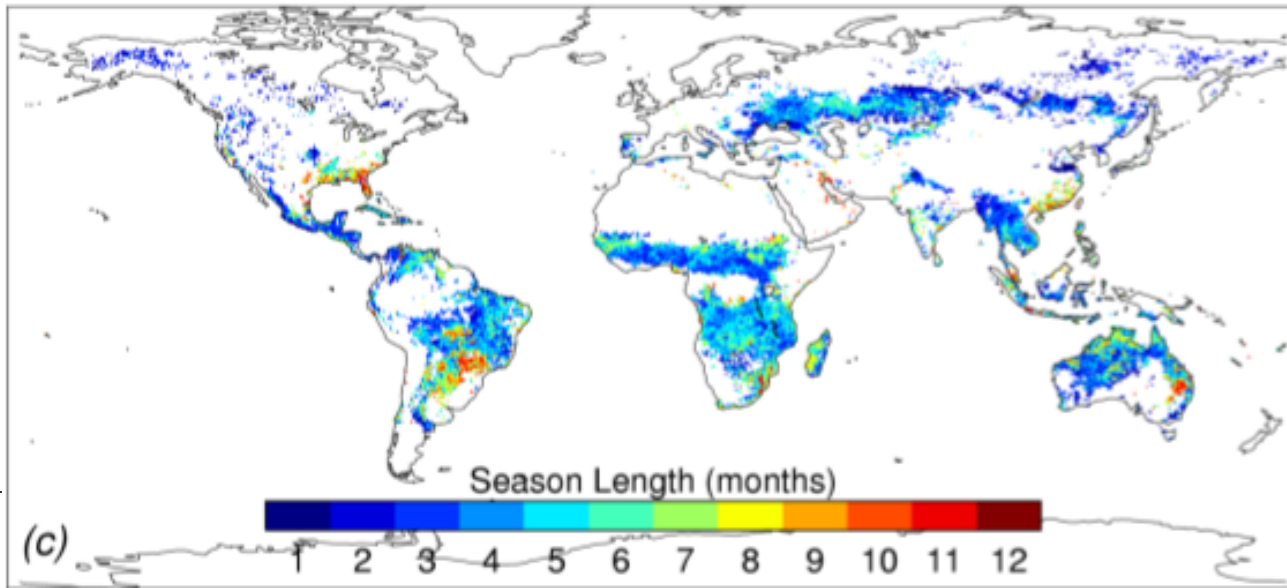
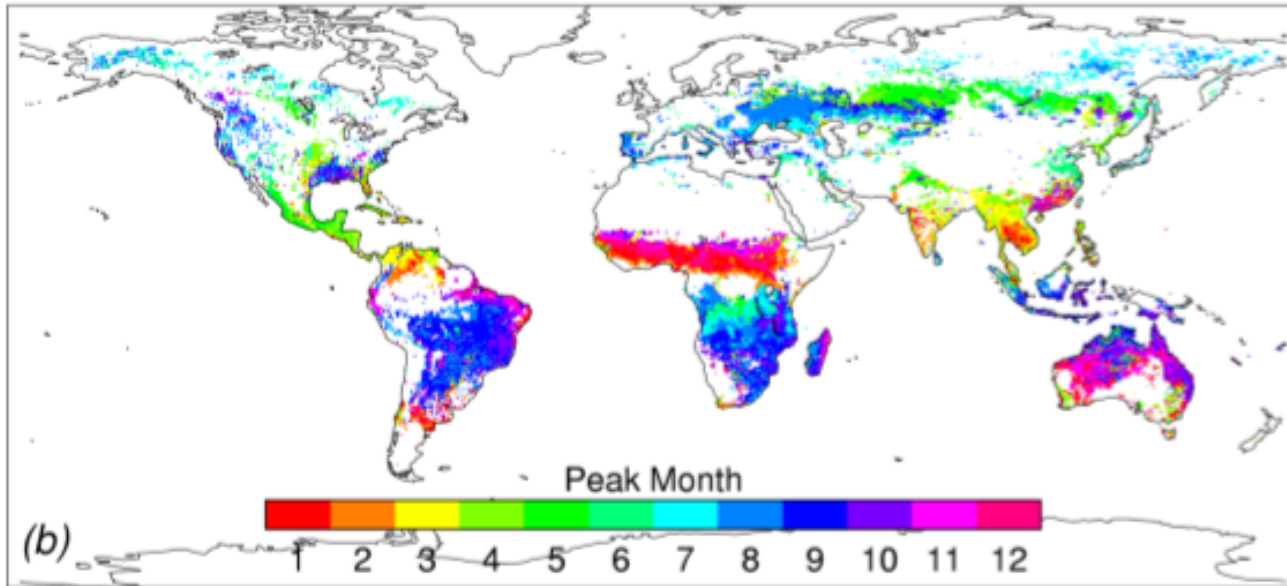
In GOCART:

Dry mass burned from GFED (van der Werf et al., 2006). Emission factors (Chin et al., 2004, 2007):

$$F_{BC} = 1 \text{g/kgDM}$$

$$F_{OC} = 8 \text{g/kgDM}$$

Fire seasonality and duration



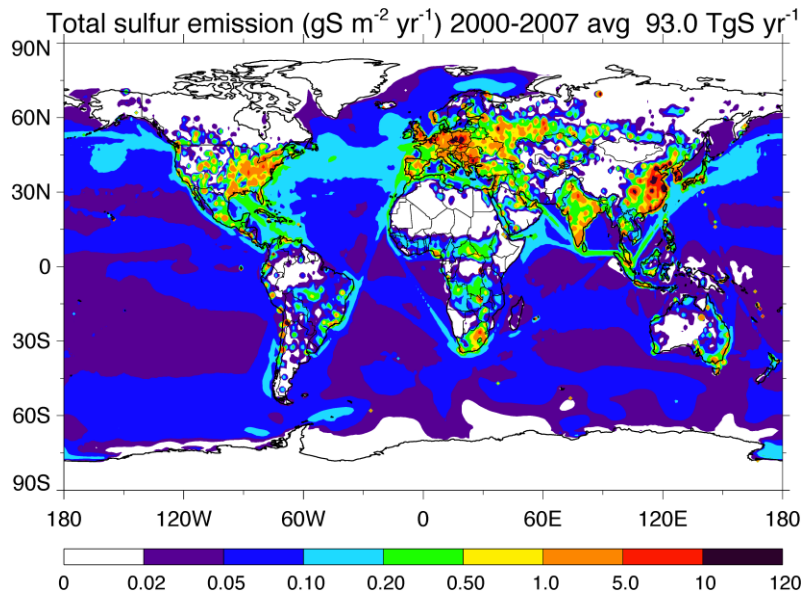
Statistics
based on 6
years of Terra
MODIS data

(Giglio et al.,
JGR 2006)

Emission, emission, emission (3)

- Other SO₂, BC, and OC emissions:
 - Transportation (aircraft, ship)
 - Volcanoes (continuously degassing and eruptive)
 - We use the Global Volcanism Program database and TOMS/OMI volcanic SO₂ data (compiled by Thomas Diehl)
 - Ocean (dimethyl sulfide as SO₂ precursor)
- Dust and sea-salt emissions:
 - Depending on winds and surface conditions – calculated in the model

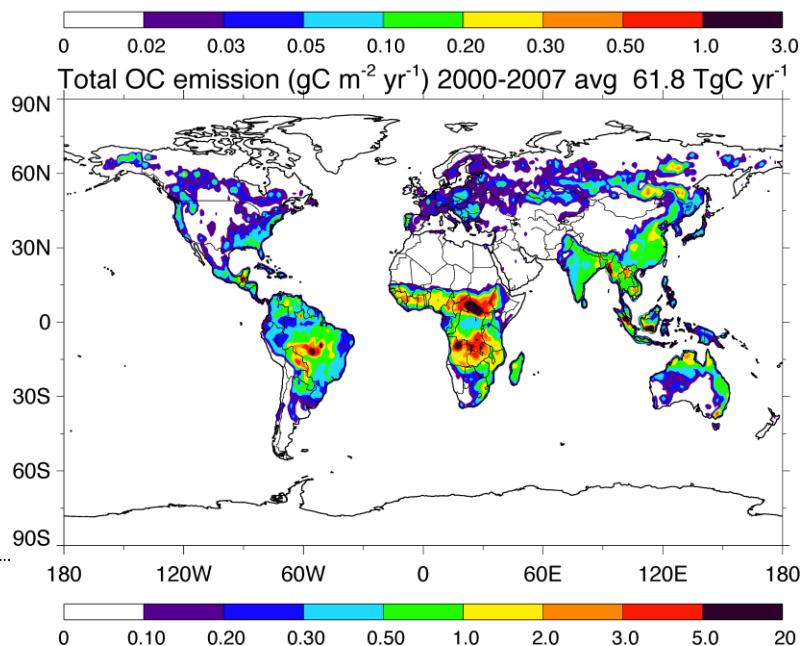
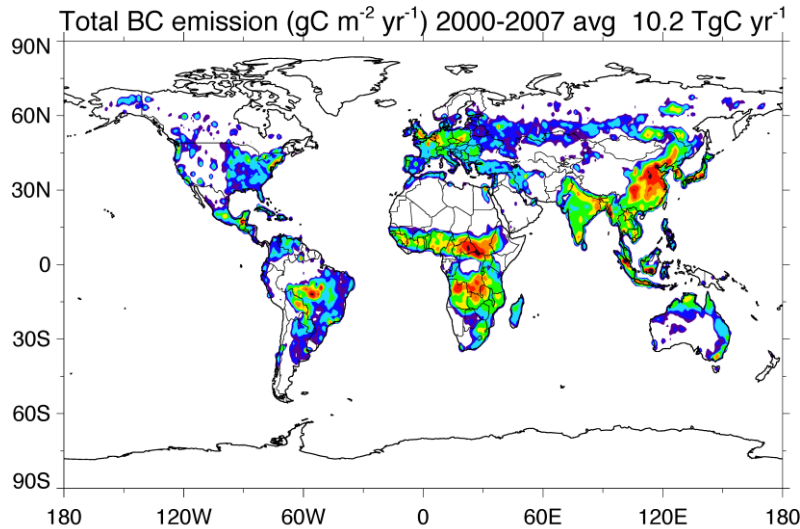
Aerosol and precursor emissions – Sulfur



Most sulfate aerosol is produced in the atmosphere by its precursor gases, both anthropogenic and natural origin.

Sulfur emission 2000-2007	TgS/yr
DMS, Ocean	15.7
SO ₂ , Fuel combustion	63.5
SO ₄ ²⁻ , Fuel combustion	2.0
SO ₂ , Biomass Burning	2.8
SO ₂ , Volcano	9.0
Total	93.0

Aerosol and precursor emissions – BC and OC

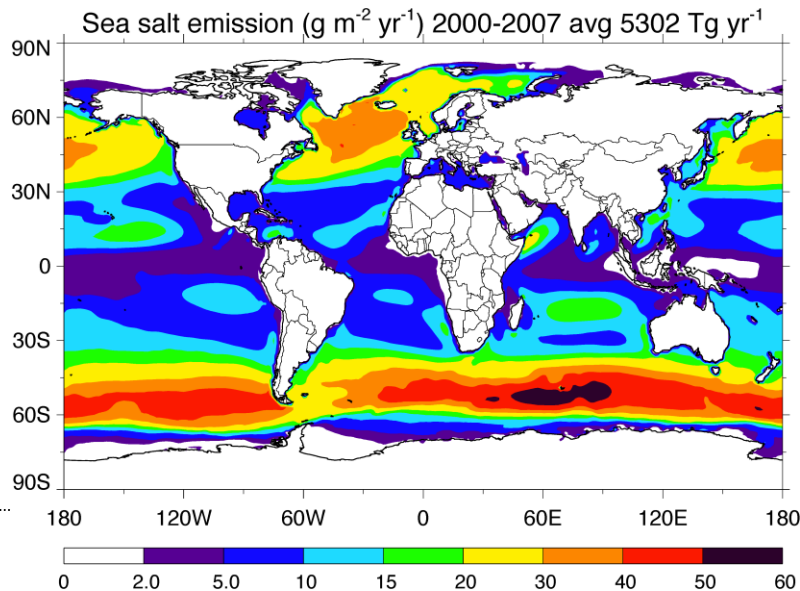
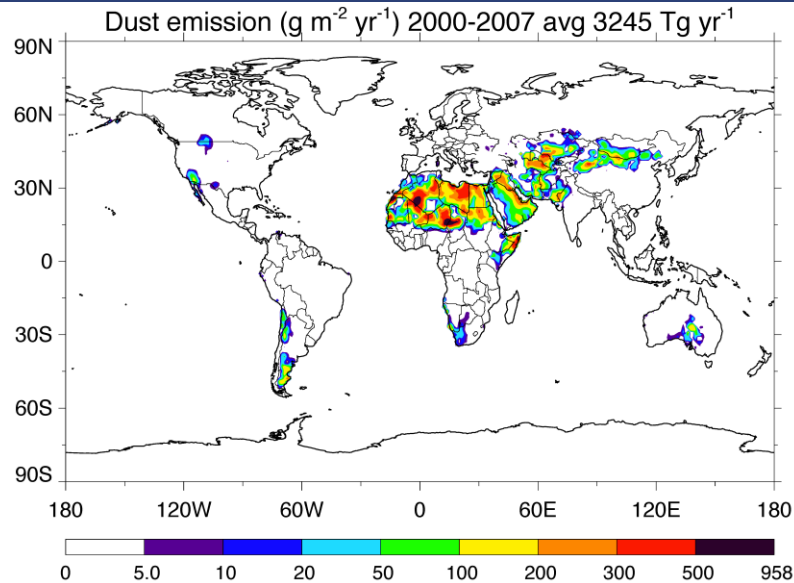


Both black and organic carbon emissions include fuel combustion and biomass burning. Terpene from vegetation is also a source of OC.

BC emission 2000-2007	TgC/yr
BC, Fuel combustion	5.2
BC, Biomass burning	5.0 (2.7)
Total	10.2
OC emission 2000-2007	TgC/yr
OC, Fuel combustion	8.9
OC, Biomass Burning	40.2 (21.5)
OC, Terpene oxidation	12.7
Total	61.8

Values in () from GFED v2

Aerosol and precursor emissions – Dust and Sea salt



Dust is emitted from permanent deserts and from other bare surfaces (dry lake beds, landuse disturbance, drought-induced bare soil). We calculate dust emission ($r_e = 0.1 - 10 \mu\text{m}$) as a function of surface type, winds, and wetness.

Dust emission 2000-2007	Tg/yr
Total	3245

Sea salt is emitted from the oceans. We calculate sea-salt emission ($r_e = 0.1 - 10 \mu\text{m}$) as a function of surface wind speed.

Sea salt emission 2000-2007	Tg/yr
Total	5302

Atmospheric processes

- Chemistry:
 - $\text{DMS} + \text{OH} \rightarrow \text{SO}_2$ (gas phase)
 - $\text{DMS} + \text{NO}_3 \rightarrow \text{SO}_2$ (gas phase)
 - $\text{SO}_2 + \text{OH} \rightarrow$ sulfate (gas phase)
 - $\text{SO}_2 + \text{H}_2\text{O}_2 \rightarrow$ sulfate (aqueous phase)
- Advection
- Convection
- Dry deposition
- Rainout/washout

Aerosol optical properties

- To convert aerosol mass concentrations to aerosol extinction, absorption, and their optical depth, one needs to know
 - size distributions and
 - complex refractive indices of aerosol particles
 - Then use Mie theory to calculate mass extinction/absorption efficiency

$$\tau = M_d \beta$$

Where τ is aerosol extinction or absorption optical depth, M_d is the aerosol dry mass, and β is the mass extinction/absorption efficiency which changes with ambient RH

Microphysical and optical parameters

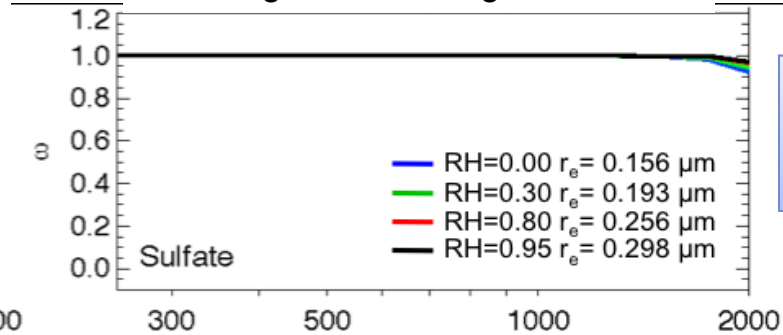
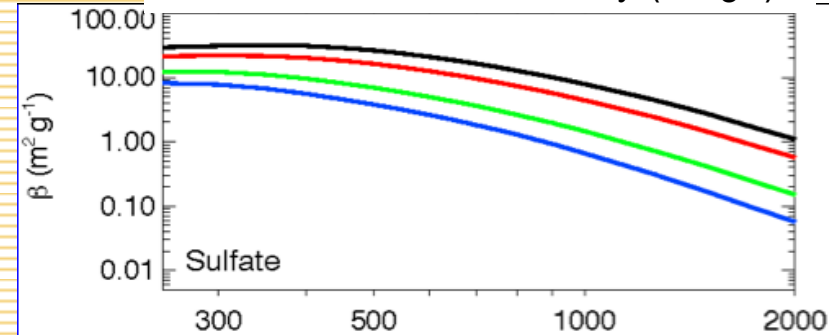
Aerosol Type	Density (g cm⁻³)	Dry r_m (μm)	Dry r_e (μm)	σ_g (μm)	Dry β (MEE) at 550 nm (m² g⁻¹)	Refractive Index at 550 nm
Sulfate	1.7	0.0695	0.156	2.03	3.143	$1.43 - 10^{-8}i$
OC	1.8	0.0212	0.087	2.20	2.668	$1.53 - 0.006i$
BC	1.0	0.0118	0.039	2.00	9.284	$1.75 - 0.44i$
Dust	2.6	0.0421	0.14	2.00	2.432	$1.53 - 0.0055i$
	2.6	0.0722	0.24	2.00	2.578	$1.53 - 0.0055i$
	2.6	0.1354	0.45	2.00	1.830	$1.53 - 0.0055i$
	2.6	0.2407	0.80	2.00	1.015	$1.53 - 0.0055i$
	2.6	0.4212	1.40	2.00	0.497	$1.53 - 0.0055i$
	2.6	0.7220	2.40	2.00	0.271	$1.53 - 0.0055i$
	2.6	1.3540	4.50	2.00	0.138	$1.53 - 0.0055i$
	2.6	2.4070	8.00	2.00	0.075	$1.53 - 0.0055i$
	Sea Salt	2.2	0.228	0.80	2.03	1.152
2.2		1.64	5.73	2.03	0.128	$1.50 - 10^{-8}i$

Based on the Global Aerosol Data Set (GADS), aka OPAC

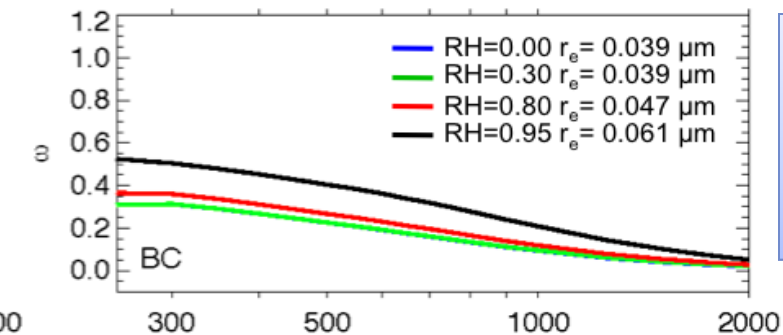
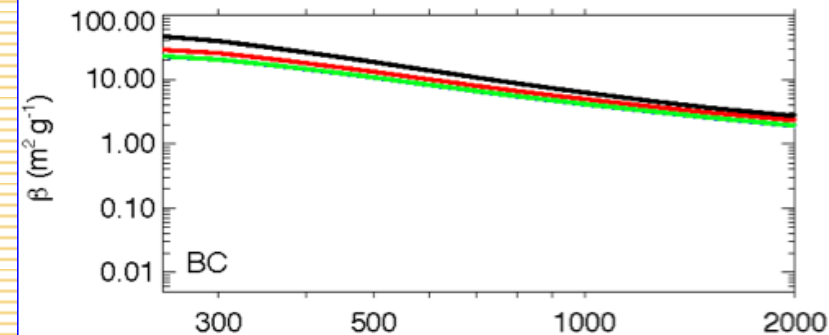
Spectral dependence of MEE and SSA

Mass Extinction Efficiency ($\text{m}^2 \text{g}^{-1}$)

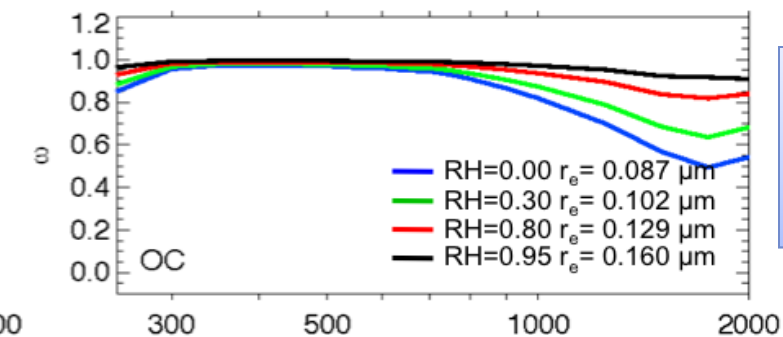
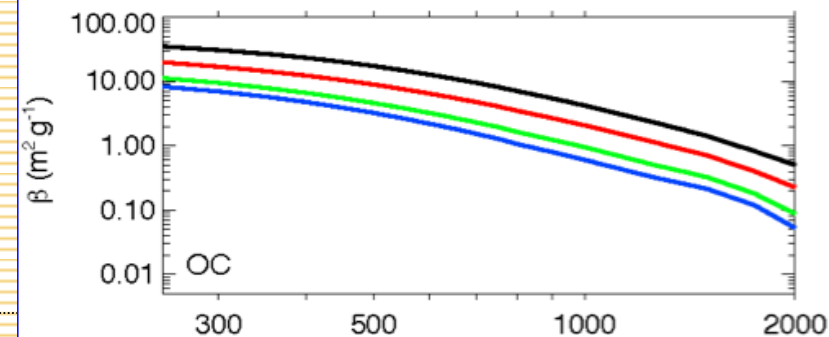
Single Scattering Albedo



Sulfate is non-absorbing in the UV-VIS-NIR



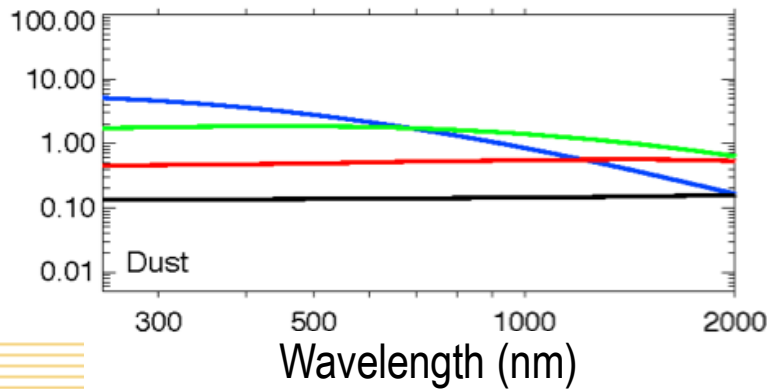
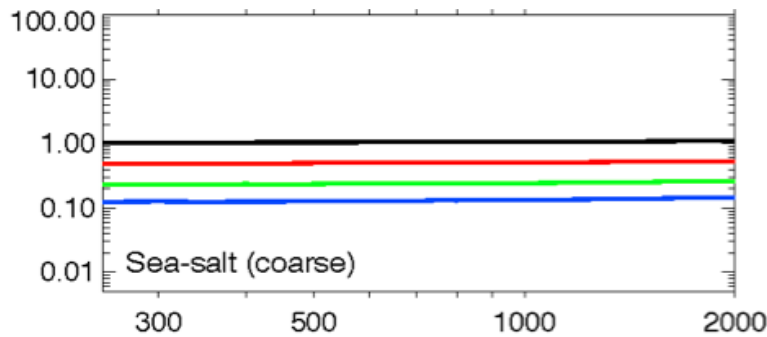
BC is very absorbing at all spectrum range, and more so at longer wavelengths



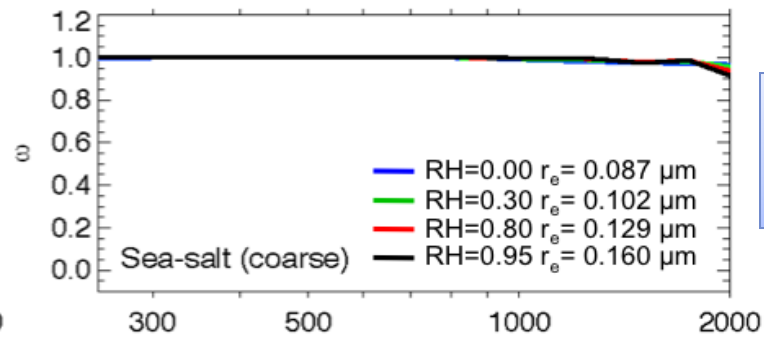
OC is slightly absorbing in the UV and more absorbing in NIR

Spectral dependence of MEE and SSA

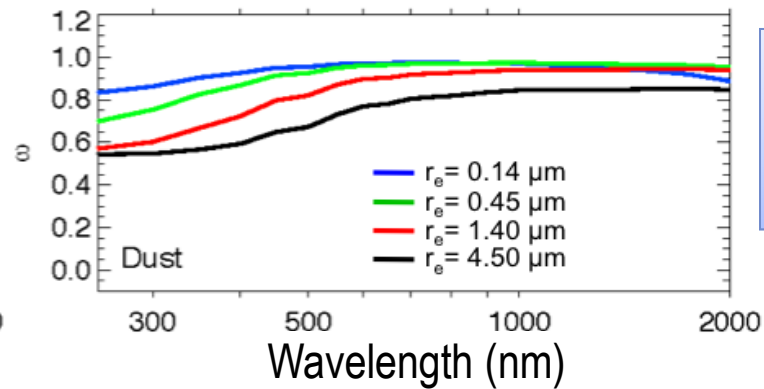
Mass Extinction Efficiency ($\text{m}^2 \text{g}^{-1}$)



Single Scattering Albedo



Sea-salt is non-absorbing in the UV-VIS-NIR



Dust is more absorbing in the shorter wavelengths with larger size

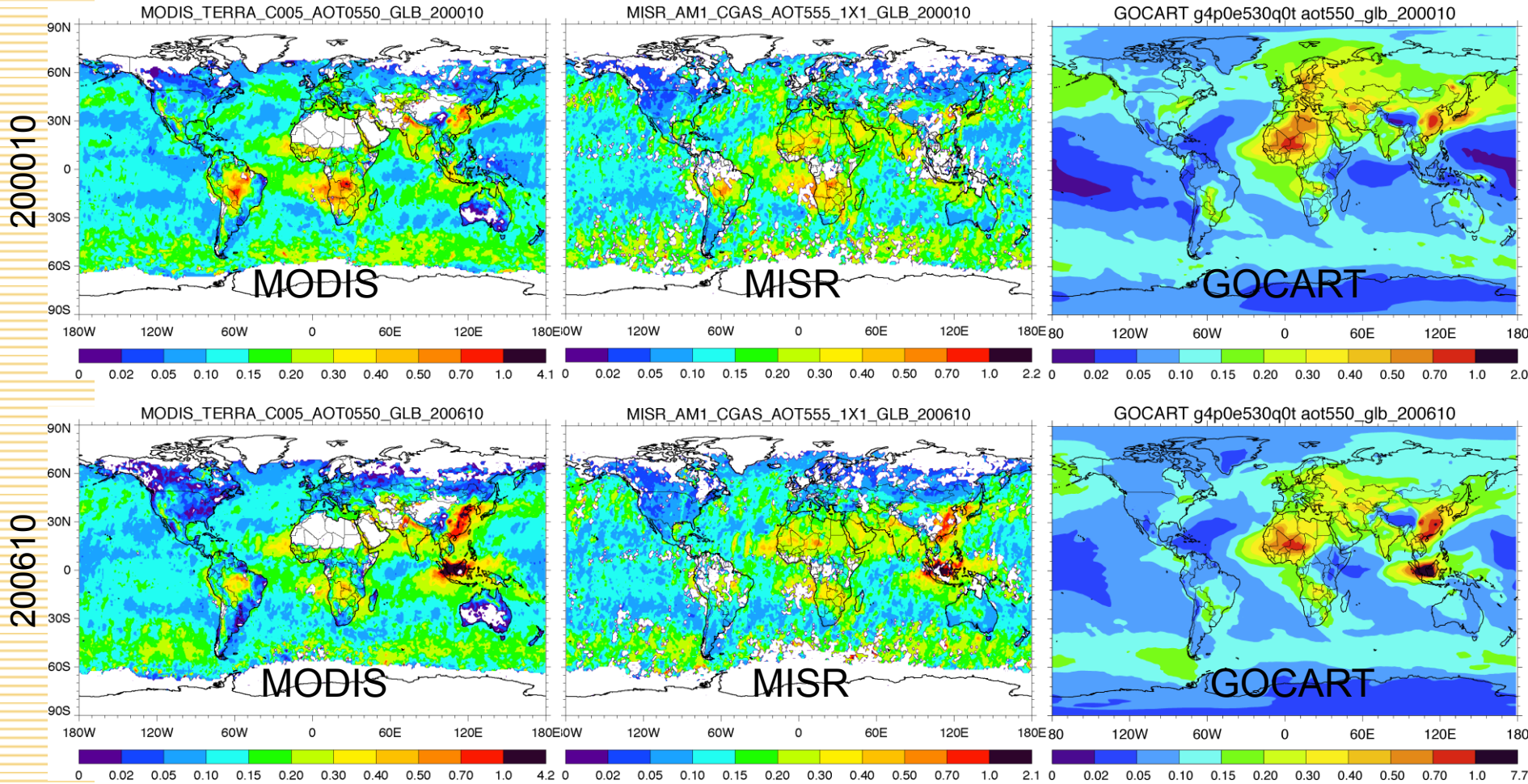
Summary points of modeling

- Choose your emission
- Crank your model (including chemistry, transport, dry and wet depositions)
- Get mass concentrations of aerosol species
- Convert the aerosol mass to aerosol optical depth
- In solar spectral region, BC and dust are the dominant absorbing species (OC absorbs in UV). BC absorbs much more efficiently than dust per unit mass, but its concentrations are much lower than dust

Evaluation

- Mass concentration: sub-orbital data from surface and aircraft
- Optical data (extinction/scattering/absorption): satellite and sub-orbital remote sensing
- Today I will concentrate on using remote sensing data

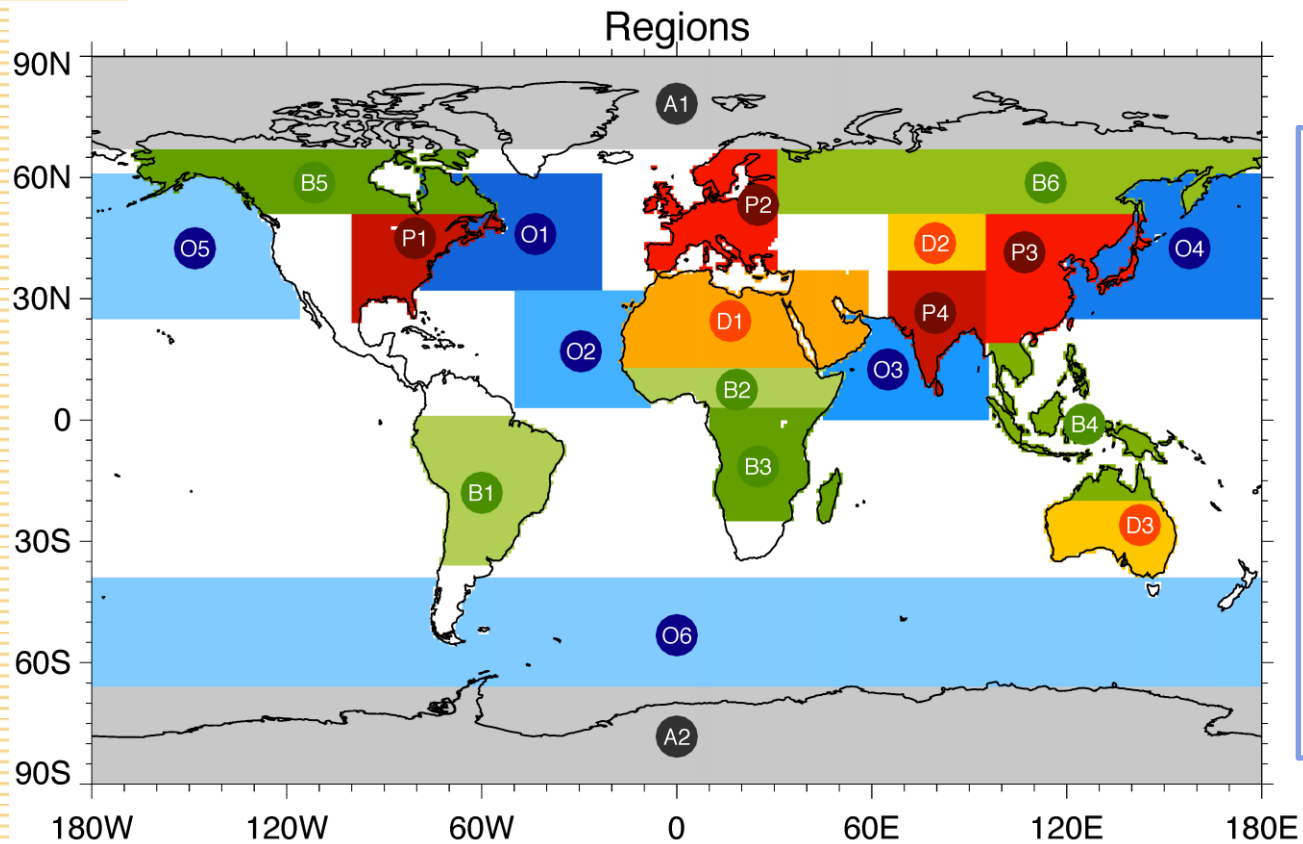
Global distribution of AOD



Comparisons between 200010 and 200610:

- Pollution regions: N. America & Europe decreased, Asia increased
- Biomass burning: Large fire in Indonesia in Oct 2006

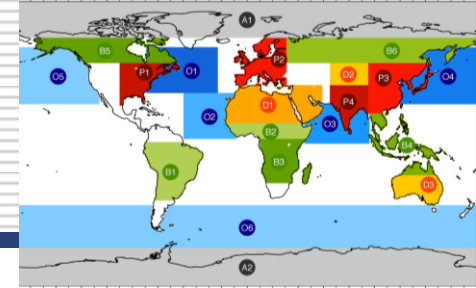
Comparisons between model, AERONET, and satellite data



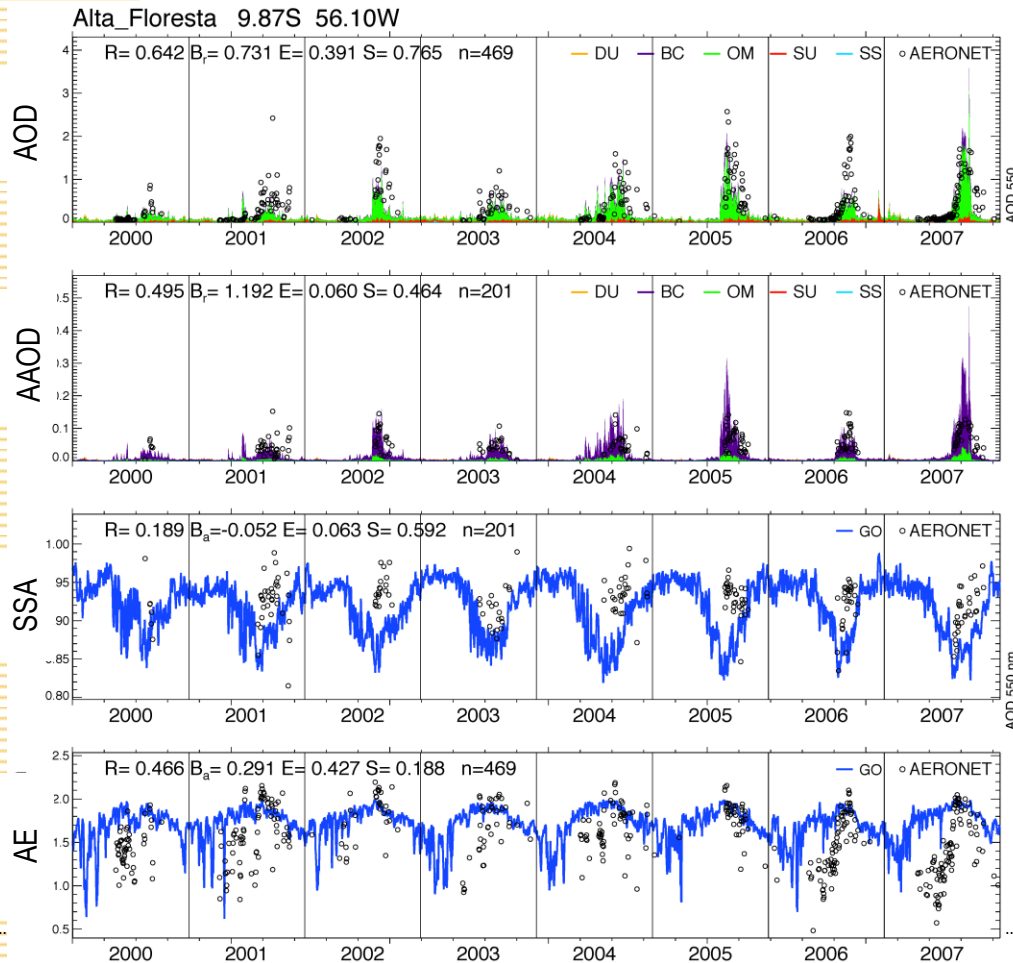
21 regions:

- 4 pollution (P)
- 6 Biomass burning (B)
- 3 Dust/mixed (D)
- 6 Oceanic (O)
- 2 polar (A)

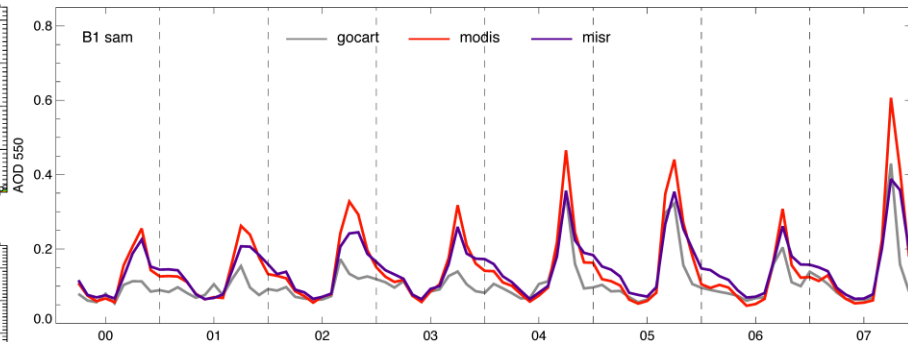
B1 – South America (SAM)



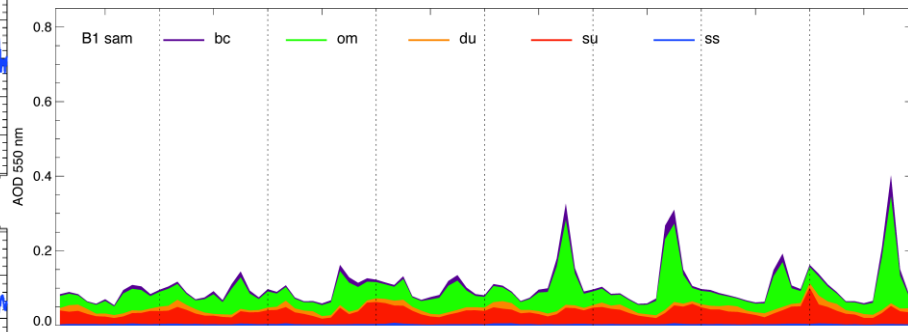
Daily variation at AERONET site – Alta_Floresta



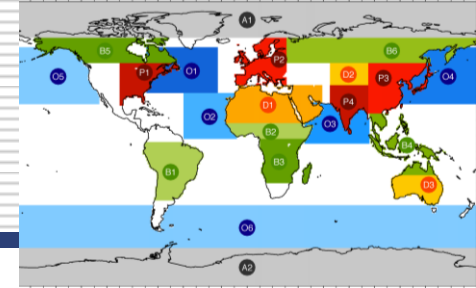
AOD – Regional, monthly average, MODIS, MISR, and GOCART



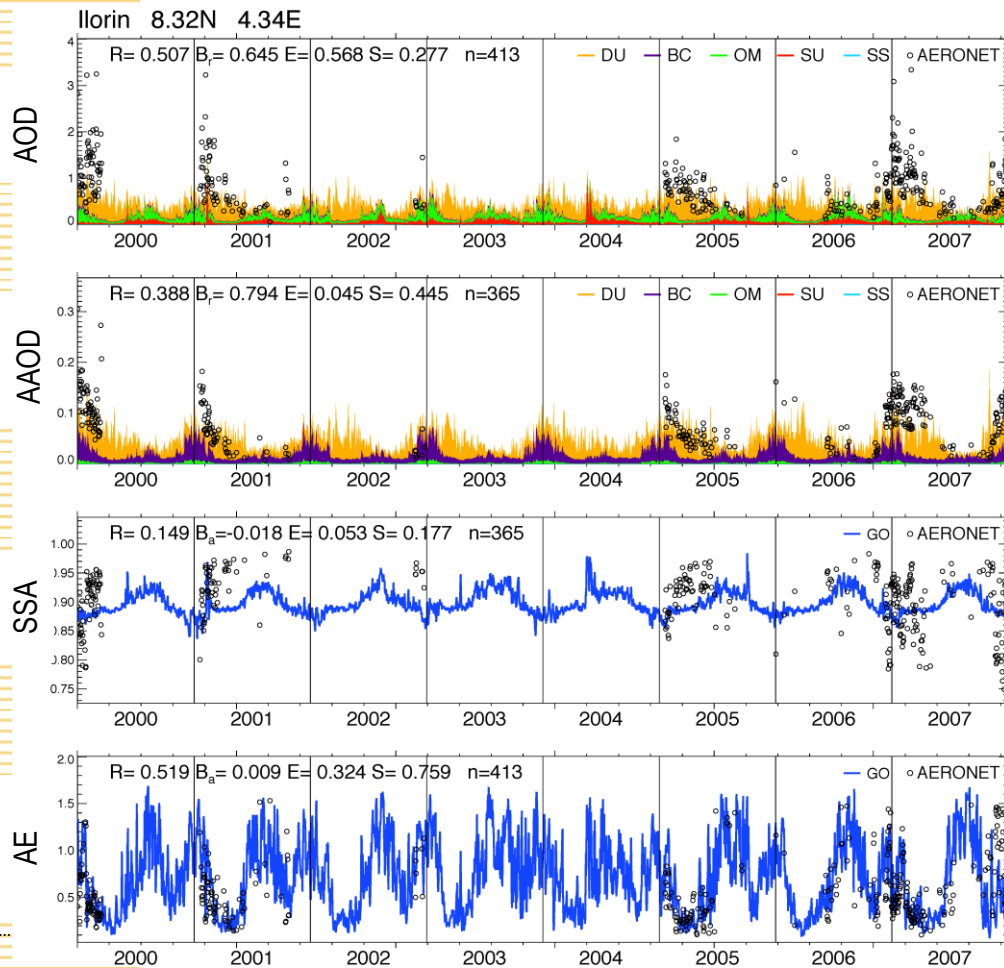
AOD – Regional composition, GOCART



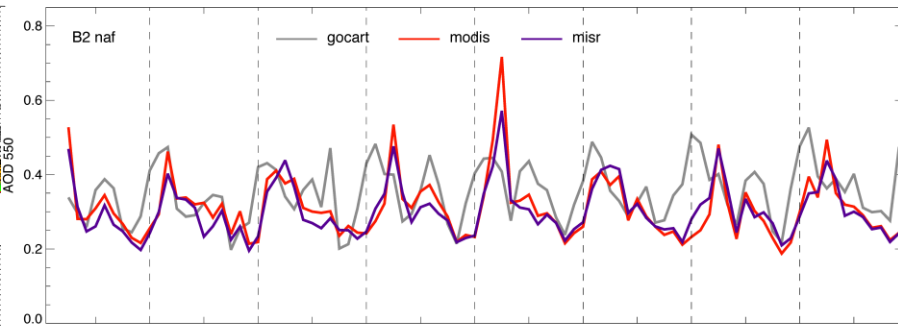
B2 – Northern Africa (NAF)



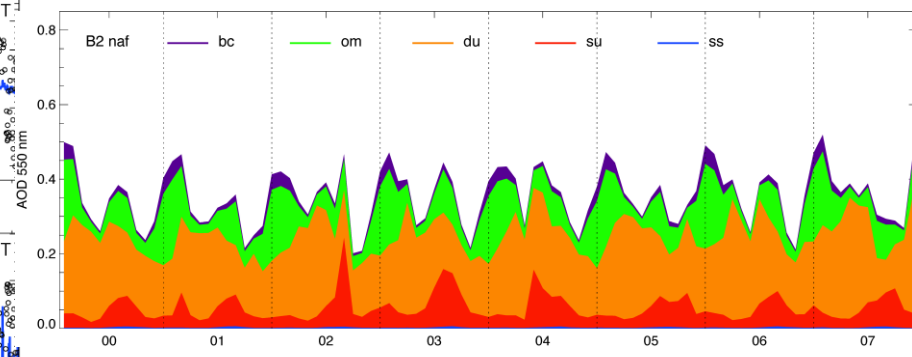
Daily variation at AERONET site – Ilorin



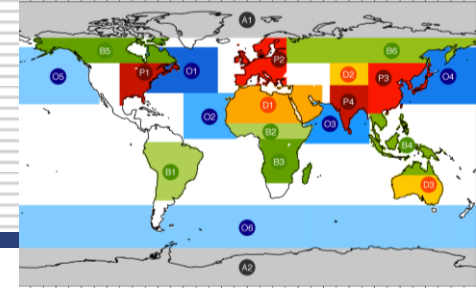
AOD – Regional, monthly average, MODIS, MISR, and GOCART



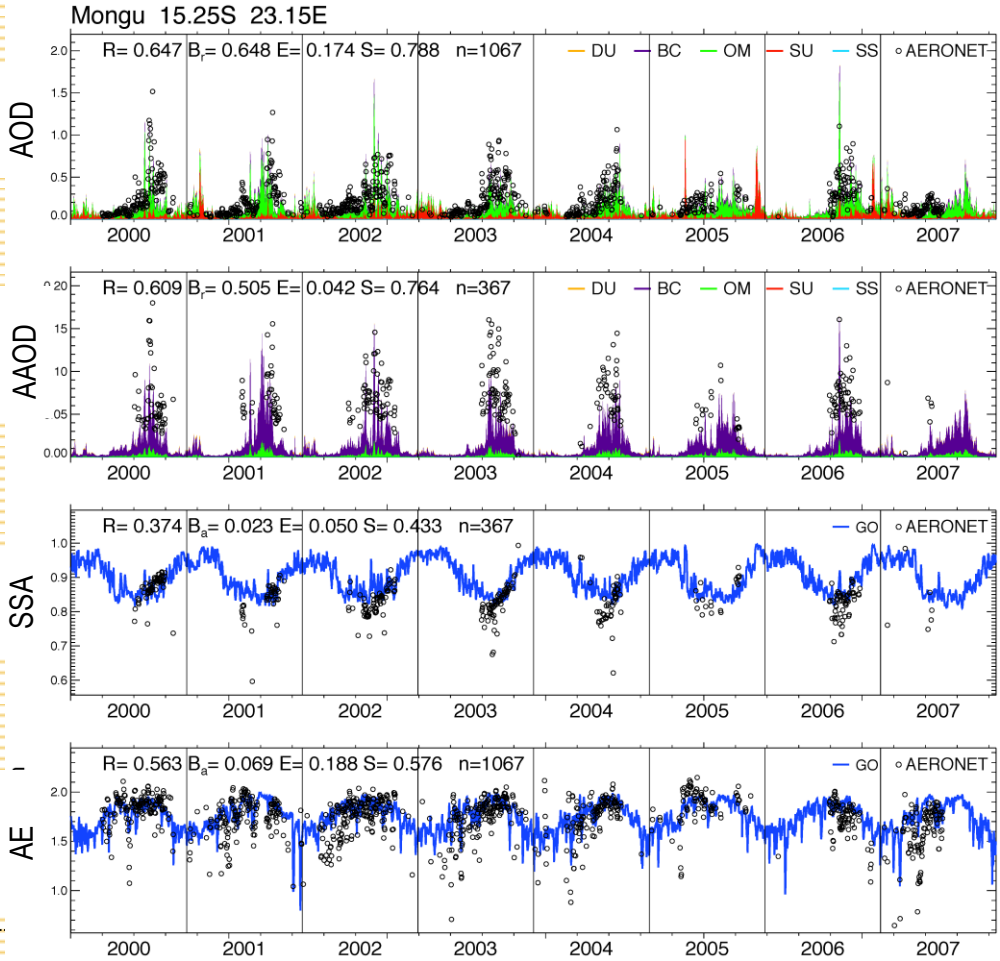
AOD – Regional composition, GOCART



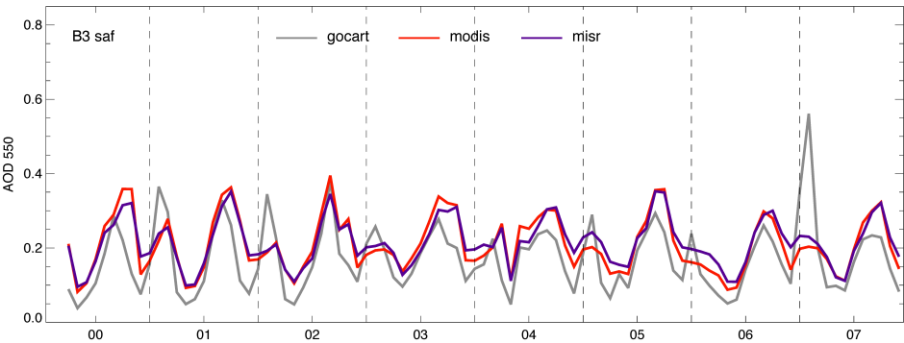
B3 – Southern Africa (SAF)



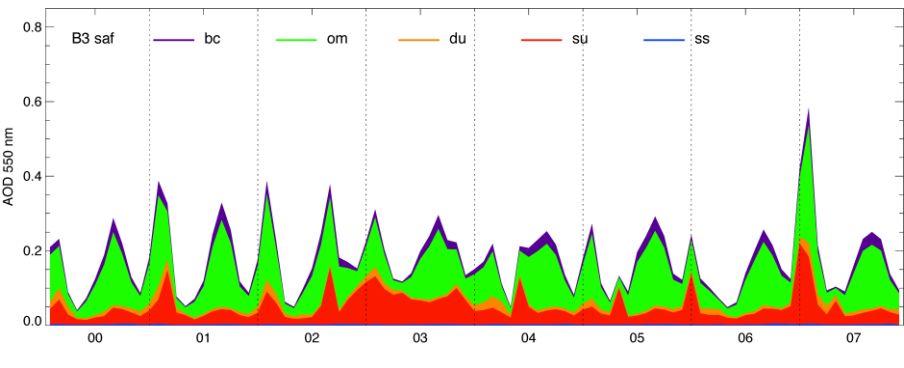
Daily variation at AERONET site – Mongu



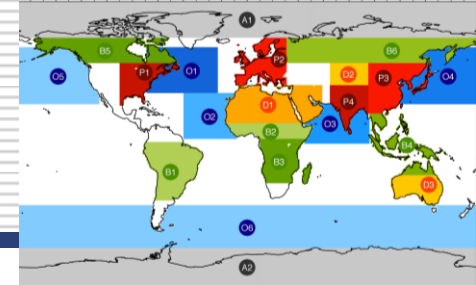
AOD – Regional, monthly average, MODIS, MISR, and GOCART



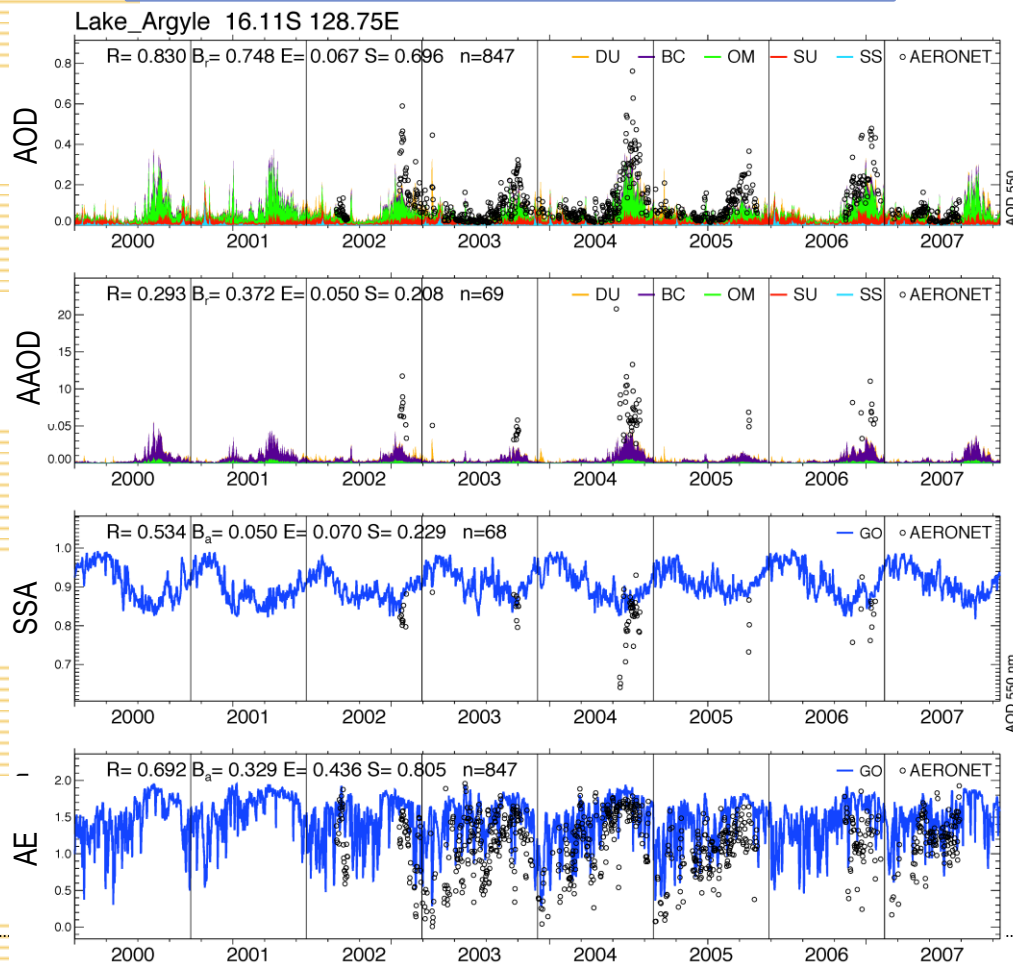
AOD – Regional composition, GOCART



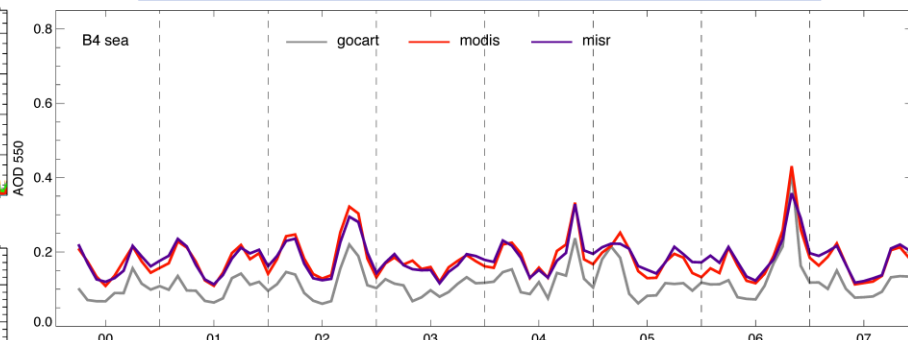
B4 – Southeast Asia (SEA)



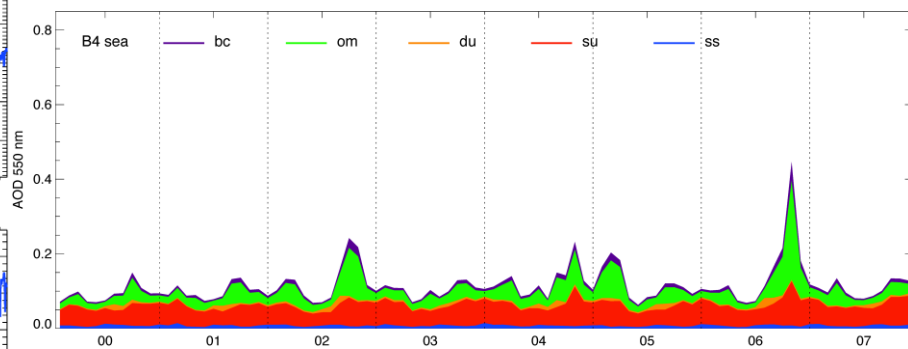
Daily variation at AERONET site – Lake Argyle



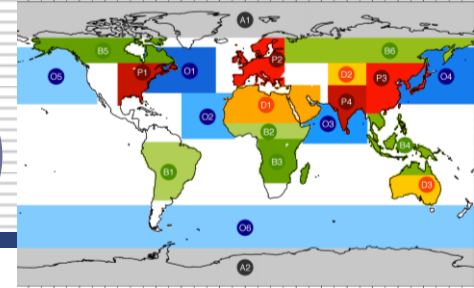
AOD – Regional, monthly average, MODIS, MISR, and GOCART



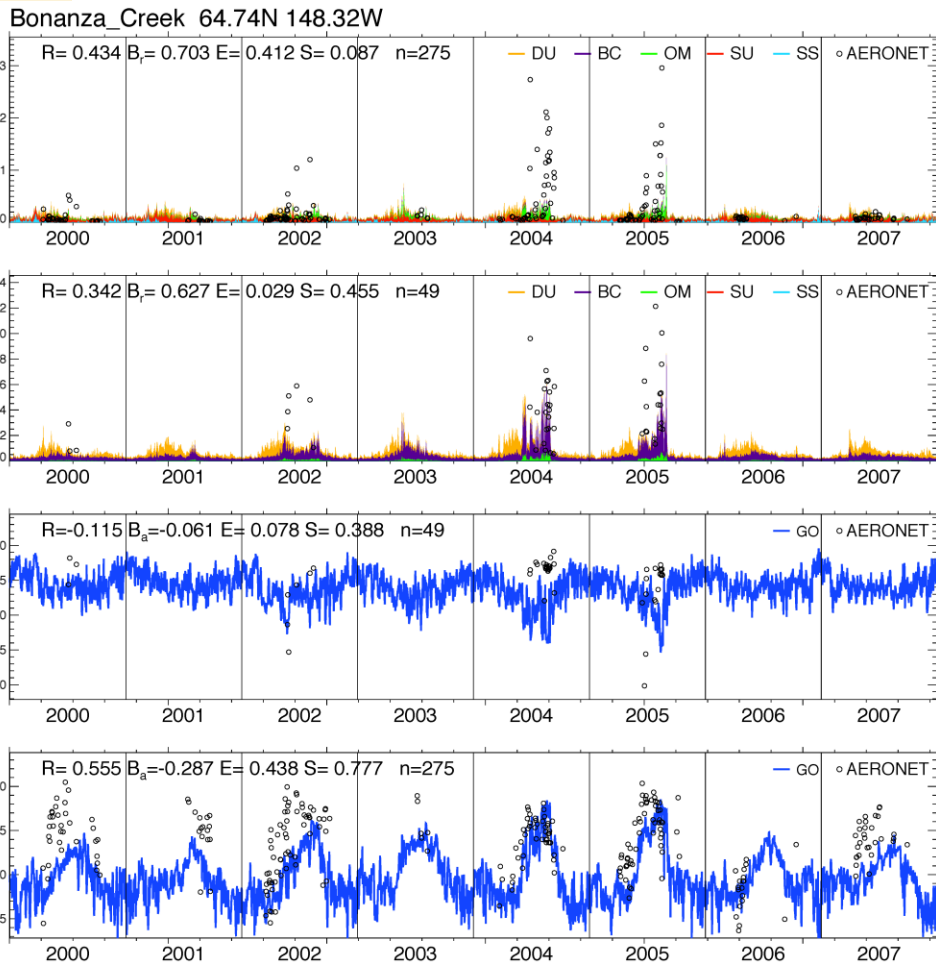
AOD – Regional composition, GOCART



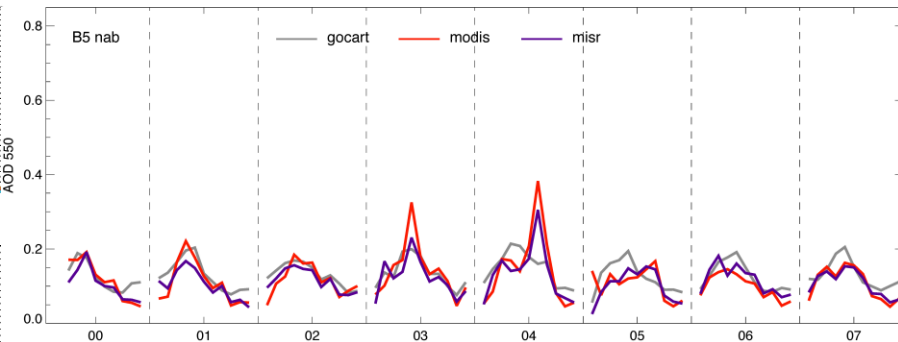
B5 – North America Boreal (NAB)



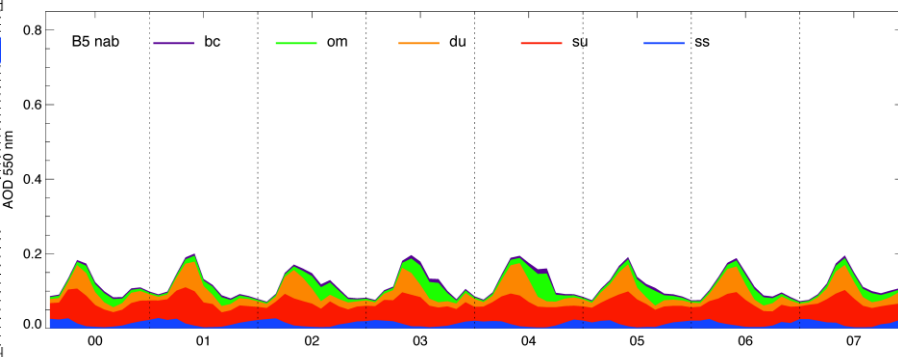
Daily variation at AERONET site – Bonanza Creek



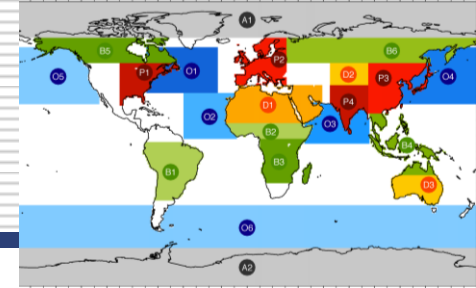
AOD – Regional, monthly average, MODIS, MISR, and GOCART



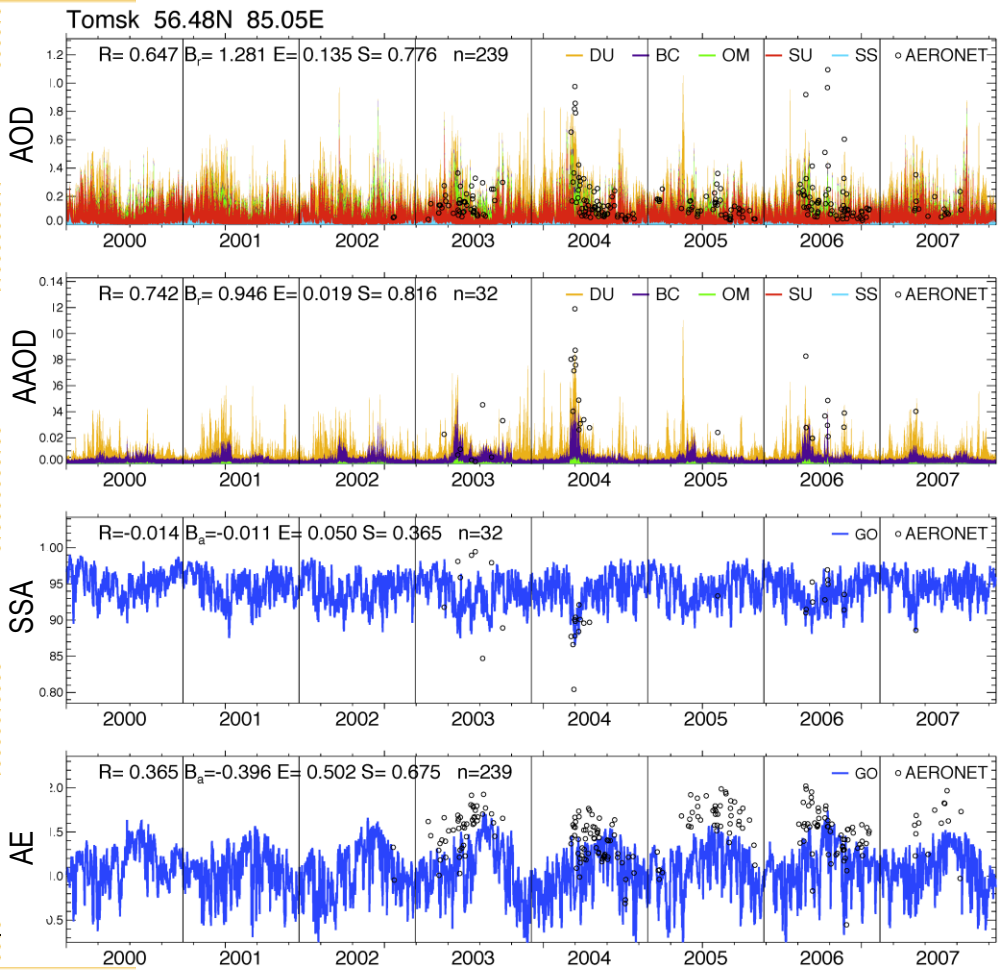
AOD – Regional composition, GOCART



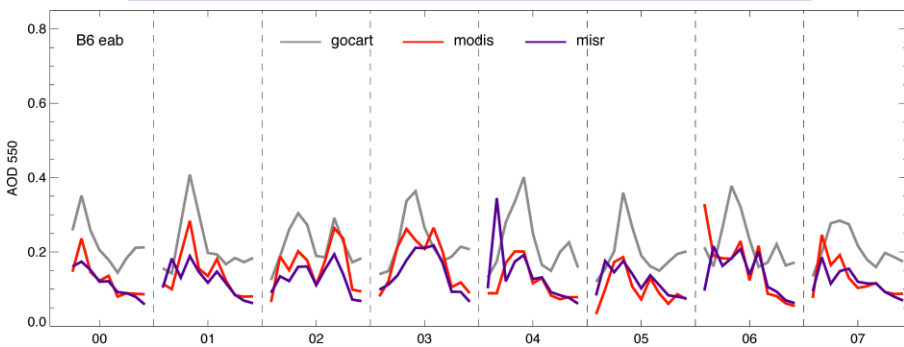
B6 – Eurasia Boreal (EAB)



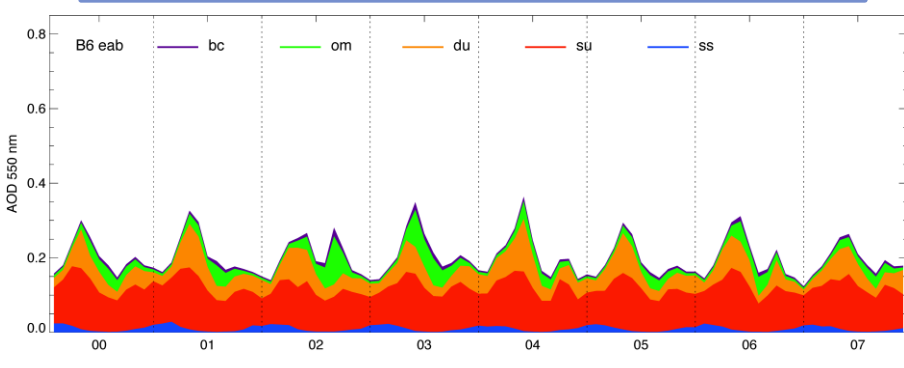
Daily variation at AERONET site – Tomsk



AOD – Regional, monthly average, MODIS, MISR, and GOCART

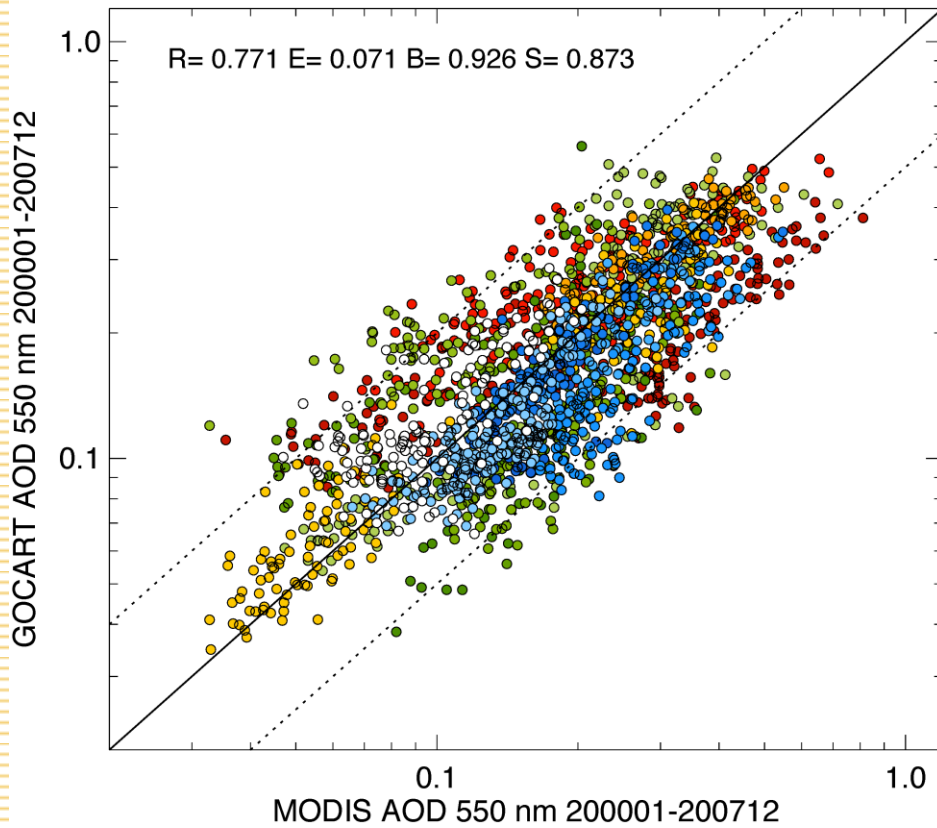


AOD – Regional composition, GOCART

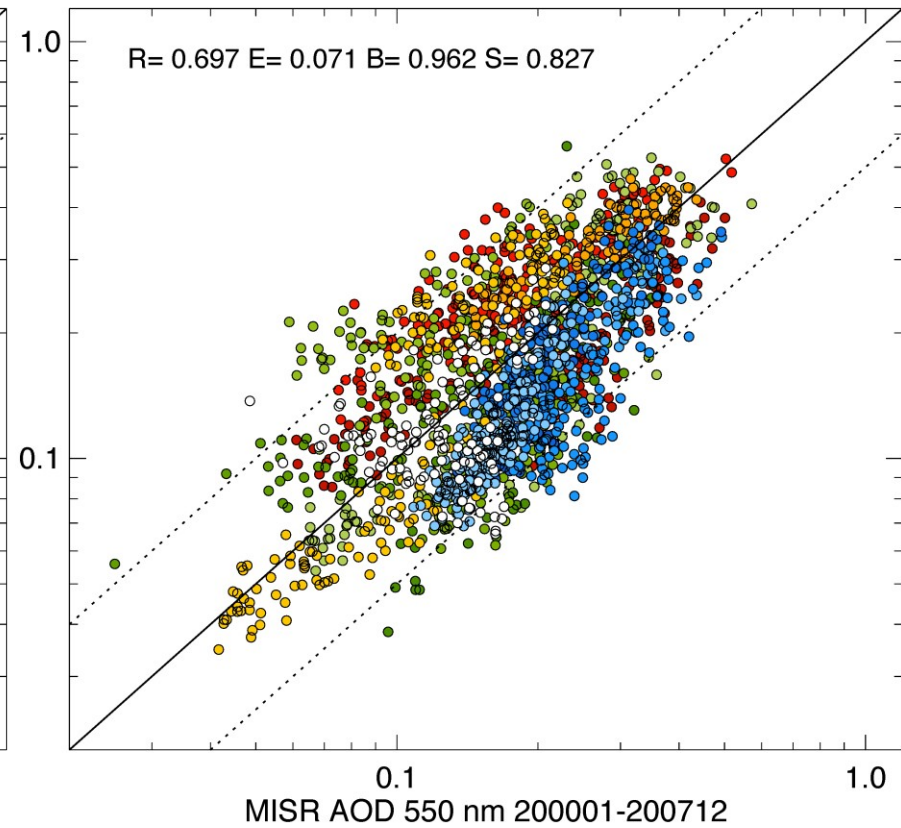


Overall scatter plot – GOCART vs Satellite

GOCART vs MODIS

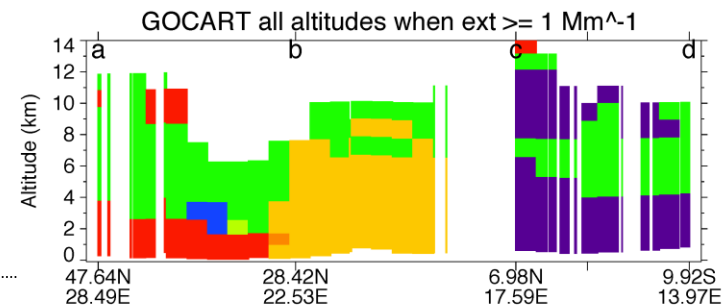
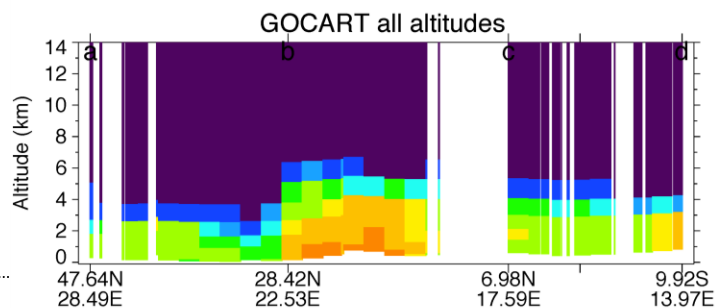
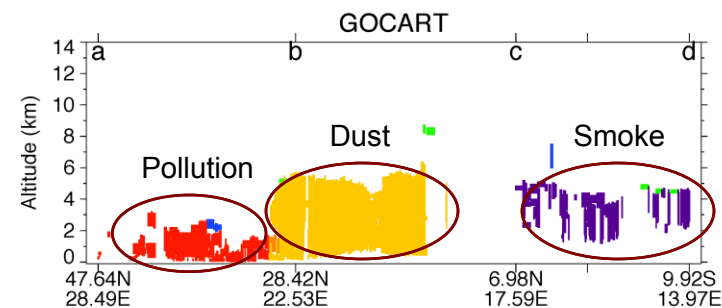
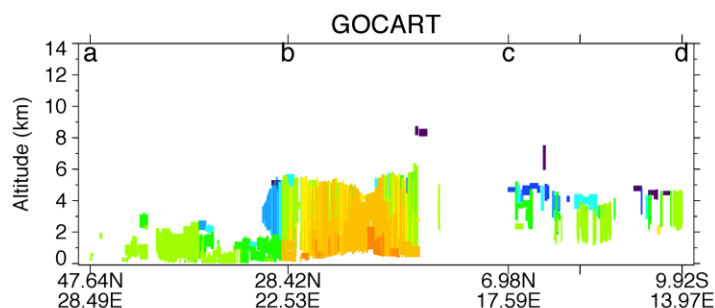
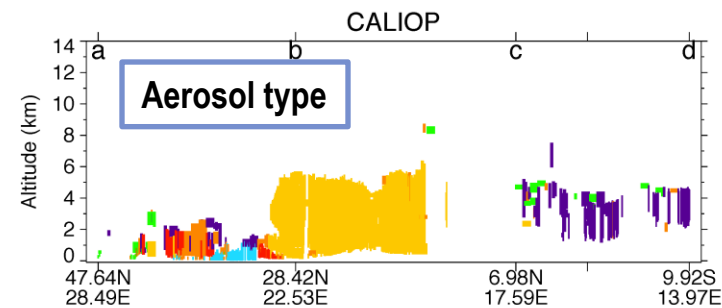
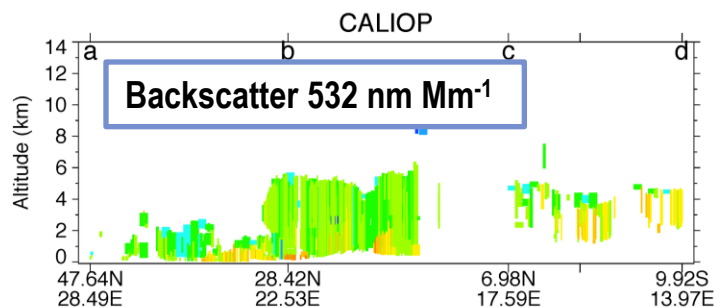
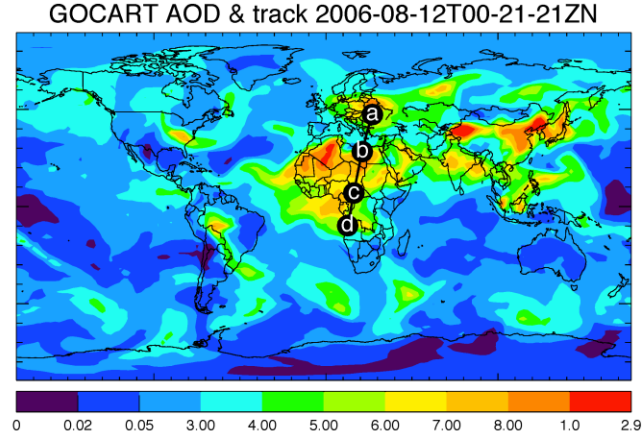


GOCART vs MISR



Aerosol plume height – GOCART vs CALIPSO

2006-08-12T00-21-21Z



Remarks

- We have been using the “imperfect” but “useful” model for data analysis, field experiment forecasts, estimating aerosol climate forcing, assessing surface air quality, studying aerosol absorption, addressing intercontinental transport
- Continuous evaluation with various measurements making model improvements an on-going process

Discussion points

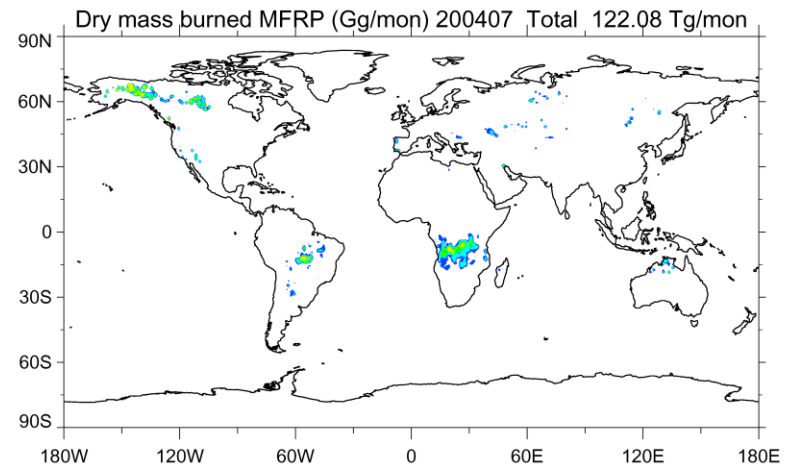
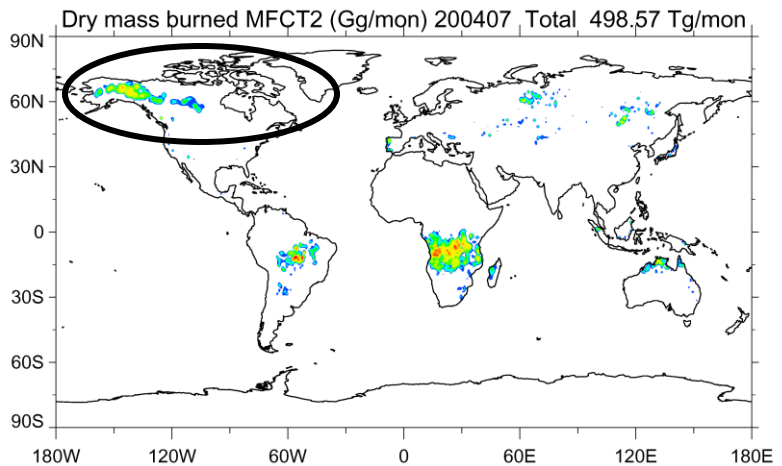
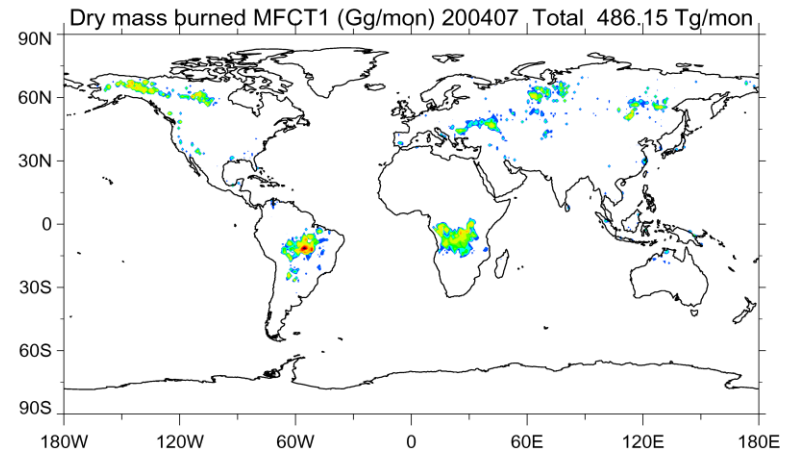
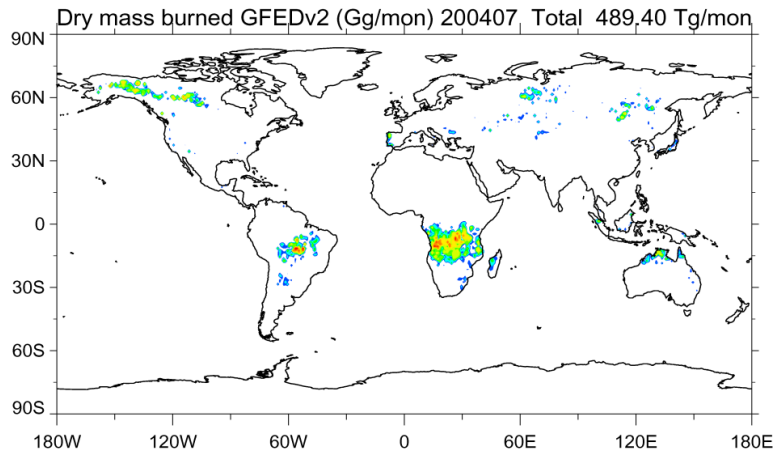
- Different approach to estimate dry mass burned
- Monthly emission vs. 8-day vs. daily emission
- Injection height

Satellite fire data-based estimation of biomass burning emissions

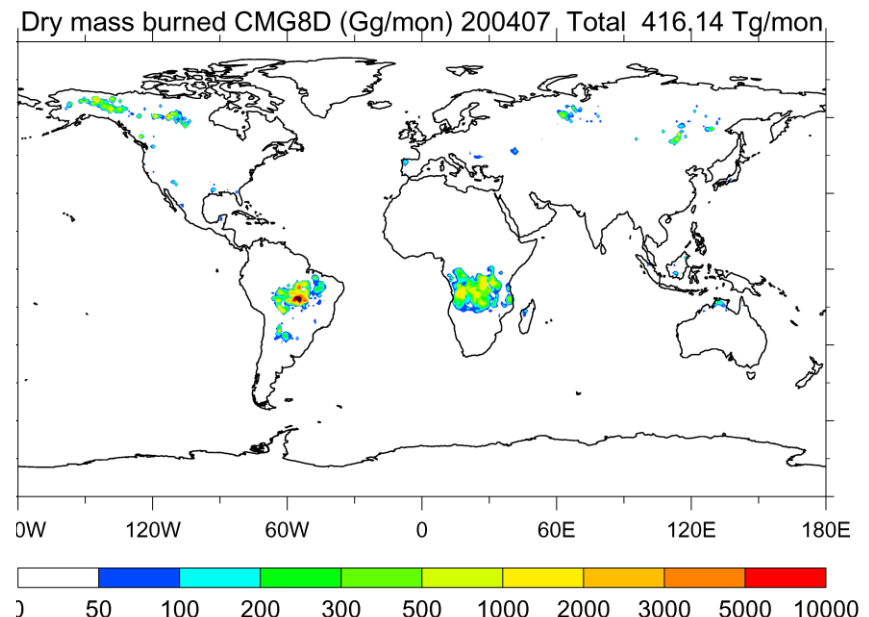
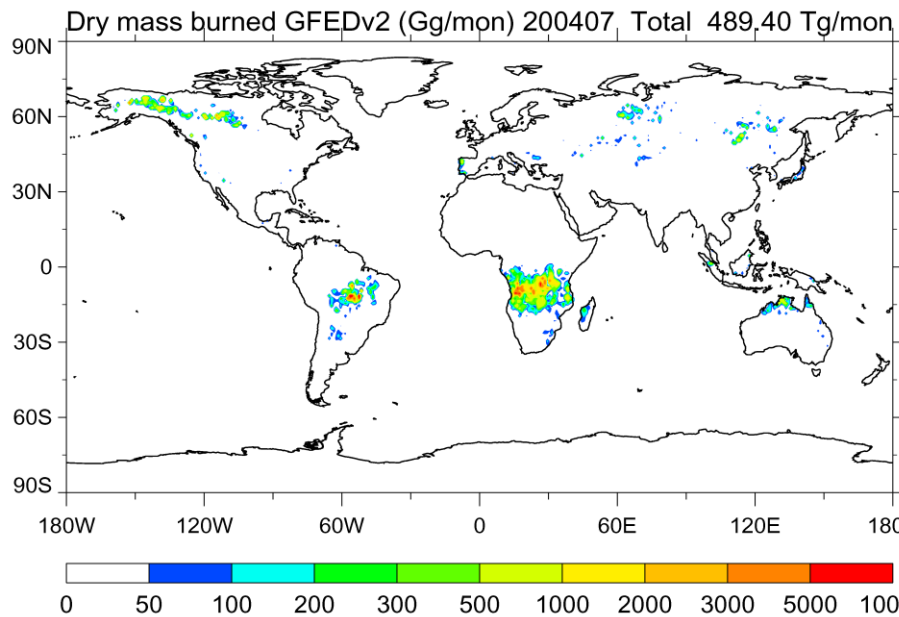
	Satellite data	Other data/tools	Emission calculated	Time resolution
Global Fire Emission Dataset (GFED)	Terra-MODIS, TRMM-VIRS, ERS-ATSR	CASA biogeochemical model	$E = ABCF$	Monthly average
MODIS Fire Counts (MFC1)	Terra- and/or Aqua-MODIS	Biomass density, completeness of burning	$E = ABCF$	Daily (Terra)
MODIS Fire Counts (MFC2)	Terra- and/or Aqua-MODIS	Biomass density, fire severity (dep. on RH and T)	$E = ABCF$	Daily (Terra)
MODIS Fire Radiative Power (MFRP)	Terra- and/or Aqua-MODIS		$E = kPF$ ($k = 0.368 - 4.37$)	Daily (Terra)
MODIS CMG-8day (CMG8D)	Terra- and/or Aqua-MODIS	Biomass density, completeness of burning	$E = ABCF$	8-day average

E = emission rate, A = area burned, B = biomass density, C = Completeness of burning, F = emission factor, k = constant converting emission rate to fire radiative power

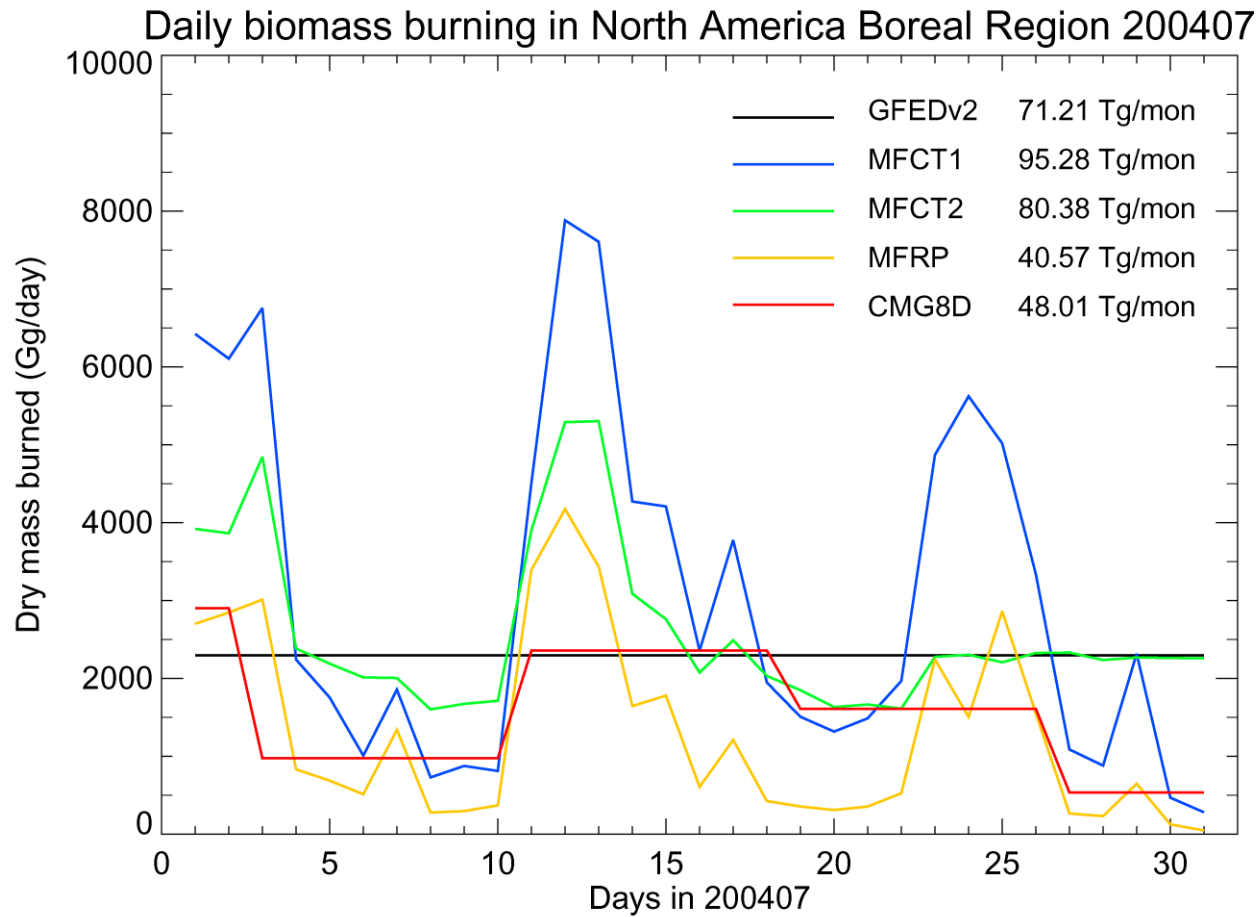
Comparison with estimated dry mass burned from different methods for 200407, global



Comparison with estimated dry mass burned from different methods for 200407, global



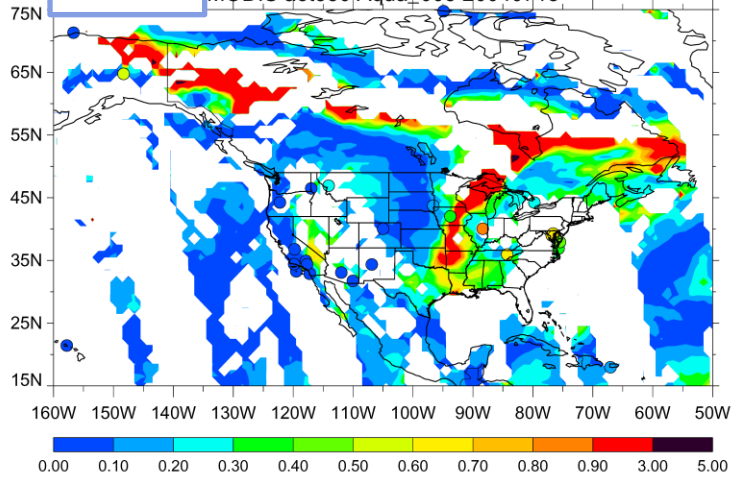
Comparison with estimated dry mass burned from different methods for 200407, North America



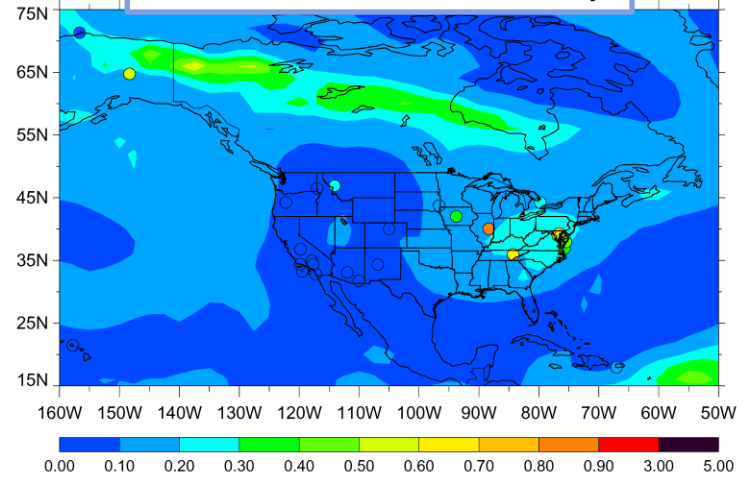
AOT: Comparison with MODIS (7/18/04)

MODIS

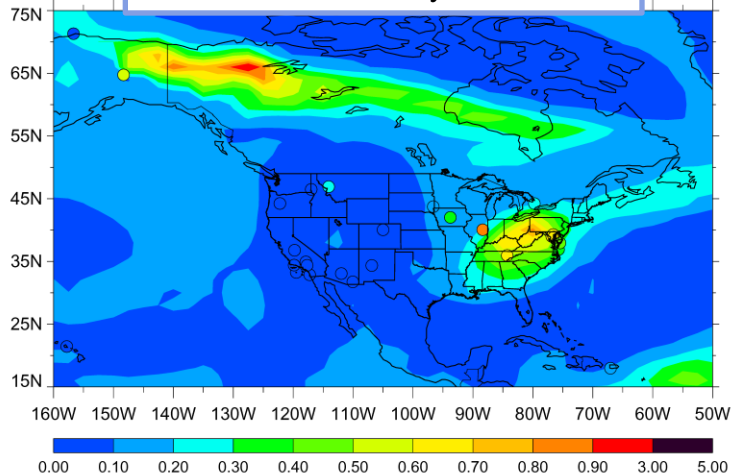
MODIS aot550 Aqua_005 20040718



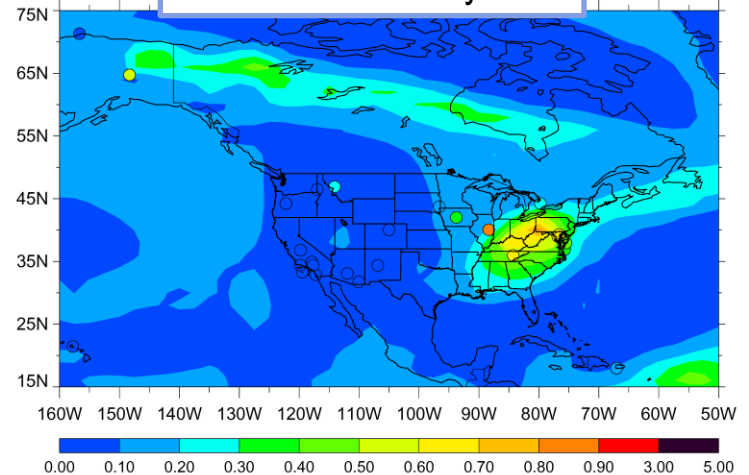
GOCART with GFED monthly



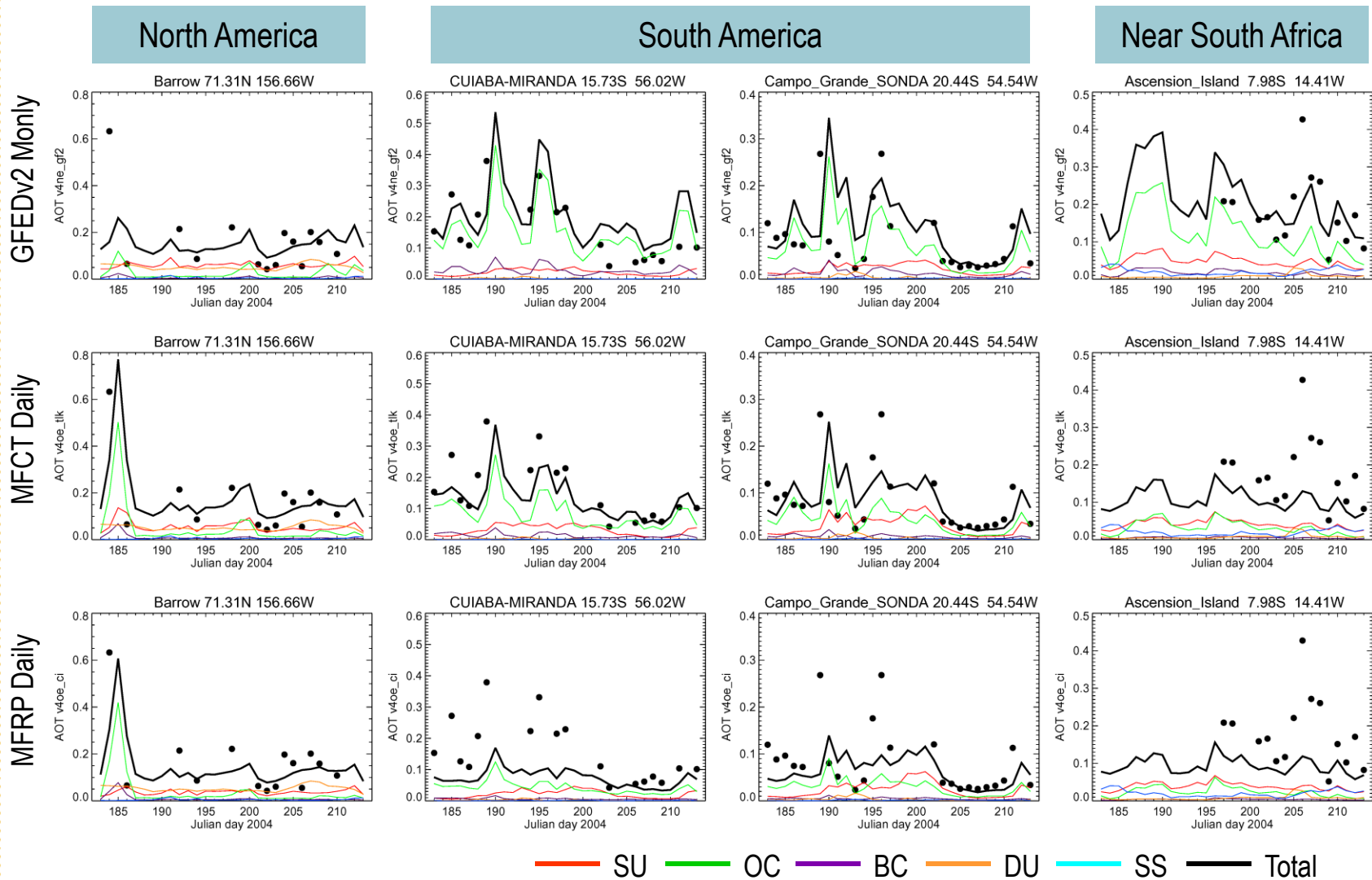
GOCART with daily fire counts



GOCART with daily FRP



AOD: Comparison with AERONET



Comments on time resolution of emission

- Monthly avg emission is not adequate for capturing large variations of aerosol near the source region, but seems not problematic for places where emission is always there (e.g., South America and Africa) during the burning season, and for places away from sources

Comments on injection height

- Biomass burning plume height in the atmosphere \neq injection height. It is the combination of convective transport and injection height
- Often, the smoke vertical distribution is determined by the atmospheric stability
- However, “pyroconvection” can put smoke to very high altitudes (e.g. stratosphere) that has to be taken into special consideration