Aerosol Distributions and Direct Radiative Forcing – Estimates from a Global Aerosol Analysis with MODIS Assimilation

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Aerosols are particles in the atmosphere that can absorb and reflect solar radiation.

"It is unlikely that satellites can directly supply the required aerosol information; rather success will depend upon appropriate combinations of satellite data, models, field measurements and surface monitoring. These considerations apply to investigation of the effect of aerosols on clouds, that is, the ‘indirect’ aerosol climate forcing, as well as the direct aerosol forcing."

Executive Summary of the NASA Global Aerosol Climatology Project
Aerosol Optical Depth (AOD) Assimilation is a method of blending model simulated aerosol fields with satellite observations.

Constraining a global transport model in this way may lead to improved estimates of aerosol radiative forcing.
Chemical Transport Models

Dust Aerosol Example

Winds from Weather Forecasts/Analyses advect tracers in the transport model.

Dust Emissions

kg m$^{-2}$ day$^{-1}$

0.0003

0
AOD Assimilation

**AVHRR** Advanced Very High Resolution Radiometer

**MODIS** Moderate Resolution Imaging Spectrometer

AOD

\( \lambda = 630 \text{ nm} \)

OR

\( \lambda = 550 \text{ nm} \)

Optimal Interpolation

1° by 1° gridded aerosol product

Stowe et al 1997

Kaufman et al 1998

Meteorological fields

**NCEP/NCAR Reanalysis**

resolution T62 ~ 1.9°, 28 levels

OR **NCEP Aviation Analysis**

resolution T126, 42 levels

OR **CAM** (NCAR Community Atmosphere Model)

resolution T42, 28 levels

SO\(_2\)/DMS/Carbon Aerosol Emission Inventories

monthly climatologies

Benkovitz et al 1996

Cooke et al 1999

Lioussse et al 1996

**MATCH**

Model for Atmospheric Transport and Chemistry

Rasch et al 1997
MATCH Configuration

Sulfur Cycle/ Sulfate Aerosol
Gas phase/aqueous chemistry
Barth et al 2000
  tracers DMS, SO₂, SO₄, H₂O₂
  monthly climatologies for O₃, OH, HO₂, NO₃
  from MOZART (Model for Ozone and its Precursors in the Troposphere)

Carbon Aerosol
Black Carbon (Soot)
Organic Carbon  hydrophobic → hydrophilic
Cooke and Wilson 1996

Hydrological Cycle
Prognostic cloud water
  Rasch and Kristjansson 1997
Vertical convection
  Zhang and McFarlane 1995
Precipitation - bulk microphysical
  Flatau 1989

Aerosol Optics
Sulfate*, Sea-Salt, Organic Carbon, Soot
  Optical Properties of Aerosols and Clouds
  Hess et al 1998
  Dust
  Zender et al 2003
*Currently based on (NH₄)₂SO₄

Dust Aerosol
Mobilization and deposition
  Zender et al 2003
  Mahowald et al 2003
  4 size categories
  0.005 – 0.5 µm (radius), 0.5 – 1.25 µm,
  1.25 – 2.5 µm, 2.5 – 5.0 µm

Diagnosed sea-salt aerosol
  Blanchard and Woodcock 1980
No nitrate aerosol
How does AOD assimilation work?

Assimilation adjusts model aerosol mass so that model AOD more closely matches satellite observed AOD.

\[ \tau_\lambda = \Sigma_s \Sigma_k \left[ \frac{\Delta p_k}{g} k_\lambda(RH) \right] q_{sk} \]

Single wavelength assimilation scales aerosol mass mixing ratios independent of vertical level and species \( q_{sk} \rightarrow \alpha q_{sk} \) through *Optimal Interpolation*, with a spatial correlation length of \( \sim 100 \text{ km} \).

An example illustrates the subsequent model propagation of this mass correction …
Aerosol Assimilation Example

Saharan Dust Storm
March 2, 2003

MODIS AOD at MATCH 1.9° resolution
March 2

MATCH AOD

AOD Difference

MATCH with MODIS Assimilation (on March 2 only)

MATCH
Aerosol Optical Depth 2001

MATCH with MODIS Assimilation
Aerosol Optical Depth    MATCH/MODIS Correlation   2001

5-day running mean

with Assimilation
AOD Assimilation Correction  2001

AOD Difference

MATCH with MODIS Assimilation
- MATCH
June - July - August  2001

MATCH AOD

Assimilation Correction

0.6
0.3
0.2
0
-0.2
September - October - November 2001
Dust Mass Budget

MATCH

Mass ~ 18.6 Tg
Emissions ~ 2.7 Tg day\(^{-1}\)
Dry Deposition ~ 1.2 Tg day\(^{-1}\)
Wet Deposition ~ 1.5 Tg day\(^{-1}\)

\(\tau \sim 7.0\) days

MATCH with MODIS Assimilation

Mass ~ 16.8 Tg
Emissions ~ 2.7 Tg day\(^{-1}\)
Assimilation ~ -0.3 Tg day\(^{-1}\)
Dry Deposition ~ 1.1 Tg day\(^{-1}\)
Wet Deposition ~ 1.3 Tg day\(^{-1}\)

\(\tau \sim 7.0\) days
**Sulfate Mass Budget**

**MATCH**

- Mass ~ 0.6 Tg(S)
- Emissions ~ 0.005 Tg(S) day\(^{-1}\)
- Gas Phase ~ 0.02 Tg(S)
- Aqueous Phase ~ 0.125 Tg(S)
- Dry Deposition ~ 0.02 Tg(S) day\(^{-1}\)
- Wet Deposition ~ 0.13 Tg(S) day\(^{-1}\)

\[ \tau \approx 3.9 \text{ days} \]

**MATCH with MODIS Assimilation**

- Mass ~ 0.73 Tg(S)
- Emissions ~ 0.005 Tg(S) day\(^{-1}\)
- Gas Phase ~ 0.02 Tg(S)
- Aqueous Phase ~ 0.125 Tg(S)
- Assimilation ~ 0.02 Tg day\(^{-1}\)
- Dry Deposition ~ 0.025 Tg(S) day\(^{-1}\)
- Wet Deposition ~ 0.145 Tg(S) day\(^{-1}\)

\[ \tau \approx 4.3 \text{ days} \]
Organic Carbon Mass Budget

MATCH

Mass ~ 1.7 Tg
Emissions ~ 0.24 Tg day$^{-1}$
Dry Deposition ~ 0.06 Tg day$^{-1}$
Wet Deposition ~ 0.18 Tg day$^{-1}$

$\tau$ ~ 7.2 days

MATCH with MODIS Assimilation

Mass ~ 2.2 Tg
Emissions ~ 0.24 Tg day$^{-1}$
Assimilation ~ 0.04 Tg day$^{-1}$
Dry Deposition ~ 0.06 Tg day$^{-1}$
Wet Deposition ~ 0.22 Tg day$^{-1}$

$\tau$ ~ 7.6 days
Black Carbon Mass Budget

MATCH

Mass ~ 0.19 Tg
Emissions ~ 0.03 Tg day\(^{-1}\)
Dry Deposition ~ 0.01 Tg day\(^{-1}\)
Wet Deposition ~ 0.02 Tg day\(^{-1}\)

\(\tau\) ~ 6.6 days

MATCH with MODIS Assimilation

Mass ~ 0.25 Tg
Emissions ~ 0.03 Tg day\(^{-1}\)
Assimilation ~ 0.005 Tg day\(^{-1}\)
Dry Deposition ~ 0.01 Tg day\(^{-1}\)
Wet Deposition ~ 0.025 Tg day\(^{-1}\)

\(\tau\) ~ 7.1 days
Aerosol Radiative Forcing
National Centers for Environmental Prediction

NCEP T62

MODIS AOD
1 x 1 deg

MATCH

Moderate Resolution Imaging Spectrometer

Mar 2000 – Feb 2003

Aerosol Climatology

3-year monthly cyclic

CAM (Community Atmosphere Model) T42

MODIS Surface Albedo

CERES
2.5 x 2.5 deg

Mar 2000 – Feb 2003

Clouds and the Earth’s Radiant Energy System

Fluxes
Top-of-Atmosphere Net Shortwave Flux (Clear-Sky)

CAM

CERES*
Satellite

*ERBE-Like Algorithm
(Earth Radiation Budget Experiment)

380.0

150.0
W m^{-2}
TOA Net SW Flux Bias over Oceans

CAM - CERES
No Aerosol

CAM - CERES
with MATCH/MODIS Aerosol
Diffuse Land Surface Albedo Differences

CAM with MODIS Surface Albedo - CAM

SW

NIR
TOA Net SW Flux Bias over Land

CAM - CERES

CAM with MODIS Surface Albedo - CERES

$W m^{-2}$
Aerosol TOA SW Radiative Forcing (Clear-Sky)
from CAM with MATCH/MODIS Aerosol Climatology
Aerosol Atmospheric Absorption

Dust

Carbon Aerosol

W m\(^{-2}\)
Change in Forcing  CAM Surface Albedo ➔

MODIS/CAM Surface Albedo

Dust

Sulfate

Carbon

-5.0

W m⁻²

5.0
Dust TOA Forcing $> 0$ over Sahara?

Change in Dust Absorption

Dust TOA Forcing with MODIS Surface Albedo
Global Mean TOA Aerosol Forcing

-2.5
-2
-1.5
-1
-0.5
0
0.5

W / m²

Sulfate Dust Carbon Sea-Salt

Clear-Sky
with Sfc
All-Sky
with Sfc
IPCC +
IPCC
IPCC -
Conclusions/Future Work

- The MATCH/MODIS Aerosol Dataset provides estimates of aerosol mass and radiative forcing directly constrained by satellite observations.

- Validation of this Dataset will occur in the next few weeks through the AEROCOM (Aerosol Inter-Comparison) project.

- The CERES (ERBE-Like Algorithm) for satellite measured fluxes does not detect regional aerosol signatures over oceans.

- However, this Dataset will be an integral part of the NASA CERES-SARB (Clouds and the Earth’s Radiant Energy System – Surface Atmosphere Radiation Budget) project, which will estimate top and in-atmosphere fluxes constrained by the CERES measurements using improved CERES/MODIS cloud and scene algorithms.
MISR (Multi-Angle Imaging Spectro-Radiometer) flux and radiance assimilation.
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