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Satellite remote sensing of aerosols – Past, present and future

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Aerosol impact on the earth’s climate

Yamamoto & Tanaka (JAS 72)

Ångström’s law

\[ \tau_\lambda = \beta \lambda^{-\alpha} \]

\( \alpha \) : exponent

\( \beta \) : turbidity factor

Yamamoto et al. (JMSJ 68): IGY data

\( \beta = 0.05-0.075 \) -> doubling

\( -\Delta T_s = 1.3-1.8 \text{C for } n_i=0.01; 1.0-1.2 \text{ for } n_i=0.02 \)

Hansen et al. (JGR 97)

Global modeling result:

\( \omega_0 > 0.9 \): cooling

\( \omega_0 < 0.9 \): warming

Ramanathan et al. (Science 01)

\( R_A > 0 \)

\( R_A < 0 \)

Planetary albedo

\[ 0.4 \quad 0.3 \quad 0.2 \quad 0.1 \quad 0.0 \]

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \]

Temperature change

\[ 5 \quad 0 \quad -5 \quad -10 \quad -15 \]

Absorption

TOA forcing (W m\(^{-2}\))

SSA=0.85

SSA=0.95

Land

Ocean
- Emission sources?
- Gas to particle conversion?
- Particle size ($r$) ? Size distribution ? $n(r)$
- Shape?
- Mixing state (internal, external, heterogeneous...?)?
- Stratification?
- Scattering cross section ($C_s$) ? , absorption cross section ($C_a$) ?
- Extinction cross section? ($C_e = C_s + C_a$)
- Optical thickness: AOT= $\Sigma C_e(z) \Delta z$ ?
- Single scattering albedo (SSA, $\omega$)= $C_s/C_e$ ?
- Wavelength dependence?
Angular coress section of aerosols

- **Grams et al. (JAM 74):** Polar nephelometer
- **Tanaka, Takamura, Nakajima (JCAM 83):**
- Large absorption by aerosols
- Rejected by JAS

\[ P(\theta) = \frac{P_1(\theta) + P_2(\theta)}{2} \]

\[ sP(\theta) L dx \]

Phase function

Complex refractive index

Data: 1978-78, Sendai, Japan
Sun and sky photometry

Aureole-meter in early 1980s

CiMel sun/sky photometer with Brent Holben in 1993

- SW sun&sky photometry: Smithsonian Institute ('23-'52) (Roosen & Angione, BAMS'84)
- Sunphotometer: Ångström (Tellus'61), Voltz (AO'74)
- Spectral sun&sky: Nakajima et al. (AO’83), Nakajima, Tonna, Rao, Kaufman, Holben (AO'96)
- Aeronet: Holben et al. (Atmos. Environ 98)
- Dubovik and King (JGR 00); Dubovik et al. (JAS 02)
- Hashimoto, Nakajima and Dubovik (AMT’12)

Skynet PREDE skyradiometer

NASA/AERONET
Sky-sunphotometry measurement: Optical properties of various aerosol types

- Dubovik and King (JGR 00)
- Dubovik et al. (JAS 02)

A man from Minsk to NIES and GSFC in IRS2000
New BC and BrC DRF estimates

Table 2. Empirical estimates of global average annual mean optical depths and DRE

<table>
<thead>
<tr>
<th></th>
<th>CA</th>
<th>BC</th>
<th>OM</th>
<th>BrC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption optical depth (550 nm)</td>
<td>0.0095 (0.008 ~ 0.01)</td>
<td>0.0077 (0.006 ~ 0.009)</td>
<td>0.0018 (0.001 ~ 0.003)</td>
<td>0.0018 (0.001 ~ 0.003)</td>
</tr>
<tr>
<td>Optical depth (550 nm)</td>
<td>0.022 (0.015 ~ 0.03)</td>
<td>0.0095 (0.007 ~ 0.015)</td>
<td>0.012 (0.007 ~ 0.02)</td>
<td>0.005 (-0.2 ~ +0.2)</td>
</tr>
<tr>
<td>TOA DRE (Wm$^{-2}$)</td>
<td>0.75 (0.5 ~ 1.0)</td>
<td>0.75 (0.6 ~ 0.9)</td>
<td>0.0 (-0.2 ~ +0.2)</td>
<td>0.0 (-0.2 ~ +0.2)</td>
</tr>
<tr>
<td>TOA clear-sky DRE</td>
<td>0.6 (0.4 ~ 0.8)</td>
<td>0.7 (0.6 ~ 0.8)</td>
<td>-0.1 (-0.3 ~ +0.1)</td>
<td>-0.1 (-0.3 ~ +0.1)</td>
</tr>
<tr>
<td>Atmosphere DRE</td>
<td>3.8 (3.3 ~ 4.3)</td>
<td>2.75 (2.3 ~ 3.2)</td>
<td>1.1 (0.8 ~ 1.4)</td>
<td>1.1 (0.8 ~ 1.4)</td>
</tr>
<tr>
<td>Surface DRE</td>
<td>-3.05 (-2.7 ~ -3.6)</td>
<td>-2.0 (-2.3 ~ -1.7)</td>
<td>-1.1 (-1.50 ~ -0.75)</td>
<td>-1.1 (-1.50 ~ -0.75)</td>
</tr>
</tbody>
</table>

The baseline value (for optical depth) or central value (for forcing) is shown along with the range stemming from parameter uncertainties and observational errors (Tables S3 and S4 and SI Text, Uncertainty of Our Global Estimates). The global average AOD and AAOD are 0.153 and 0.0104, respectively.

- AERONET data used
- Large absorption (DRE~+0.7 Wm$^{-2}$) by BC and brown aerosols
- $AAOD = (1-SSA)AOD$
Passive aerosol remote sensing

Herman et al. (JGR 97): TOMS AI
Nakajima and Higurashi (GRL 98): 2ch over ocean
Kaufman, Tanre, et al. (GRL01) Dust SSA
Deuze et al. (JGR01): Polarization and directional
Higurashi and Nakajima (GRL 02): sulfate, OC, dust, salt
Remer et al. (2005): MODIS collection 5
Hsu et al. (IEEE TGRS 04, 06): Deep blue algorithm

Reflectance (%)

0.3um 0.4um 0.5um 0.6um 0.7um 0.8um 0.9um

SSA

1

Dust aerosol

Carbon aerosol

grass(dry)

deciduous trees

sea water

0 10 20 30 40 50 60

wavelength[um]

30km resolution

1km

polarization/direction

0.3um 0.6um 0.9um 0.4um 0.5um 0.7um 0.8um

MODIS DT
(Kaufman 2001)

2ch method (NH1998) ocean

MODIS DB
(Hsu 2004)

4ch method (HN2002) ocean

(GLI, CAI 380nm)

(Herman 1997)

TOMS AI
Aerosol from high spatial resolution 1km in 380nm channel

Biomass burning in Asia captured by ADEOS2/GLI

<table>
<thead>
<tr>
<th></th>
<th>Wavelength</th>
<th>μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>13</td>
<td>0.678</td>
</tr>
<tr>
<td>Green</td>
<td>8</td>
<td>0.545</td>
</tr>
<tr>
<td>Blue</td>
<td>5</td>
<td>0.460</td>
</tr>
</tbody>
</table>

Appeared in “Nature”
GOSAT XCO2, XCH4, aerosols

Cloud and Aerosol Imager (CAI)
380, 670, 860, 1600nm
FOV 500m 750m
Push-broom imager, Cheap!
GOSAT/CAI ground reflectance

2009/05 Ag(band1) 380nm

2009/05 Ag(band2) 670nm

2009/05 Ag(band3) 860nm

2009/05 Ag(band4) 1.6 μm
Various remote sensing methods for aerosols

GOSAT/CAI (380nm, 1km) 
MODIS Dark Target

CALIPSO (lidar) 
MODIS Deep Blue

S. Fukuda (PHD 2011)
Volcanic Plume from Mt. Oyama, Miyakejima

SeaWiFS True-color Image

Aerosol Types
- Sulfate
- Carbon
- Soil Dust
- Salt

Particle Size
- Small
- Large

Two-channel algorithm
(Higurashi and Nakajima, JAS 1999)

Large
- Blue absorbing
- UV algorithm
(Herman, JGR 1997)

Small
- Non-absorbing

4,365 ton/day sulfate, 23% of SO2 gas

Four channel method (ocean)

412, 443nm

36°N 32°N

670 and 865nm

138°E 142°E

May 5, 2001

Higurashi and Nakajima (GRL02)
Dust optical properties
by Neutral (critical) reflectance method of Kaufman (JGR 87)
extended by Yoshida et al. (ACPD 12)

- 9 year mean (2003-2011), OMI prescreen
- Lower SSA in Asia: Dust and soot mixed
- SSA related with land albedo

Africa MODIS band 9 (443nm)

- Single scattering albedo
- Aerosol optical depth
- Surface reflectance

SSA

AOT

Asia

RE>0

RE=0

RE<0

Google earth
TOA SW DRF for total aerosol from CALIOP

- COT from MODIS; aerosol and cloud layering from CALIPSO
- Good agreement between satellite and model; but large uncertainty in layer classifications
- Large uncertainty in model values

T. L’Ecuyer: -1.6
W. Su: GOCART -1.9
M/M : -3.0

(Oikawa, Nakajima, Winker, JGR 13)
**CALIOP aerosol optical models (Omar et al., JAS 09)**

<table>
<thead>
<tr>
<th>Parameters @532nm</th>
<th>Desert dust</th>
<th>Smoke</th>
<th>Background</th>
<th>Polluted continental</th>
<th>Marine</th>
<th>Polluted dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>alfa</td>
<td>0.940</td>
<td>1.408</td>
<td>0.276</td>
<td>1.604</td>
<td>-0.137</td>
<td>1.154</td>
</tr>
<tr>
<td>ssa</td>
<td>0.919</td>
<td>0.833</td>
<td>0.904</td>
<td>0.935</td>
<td>0.986</td>
<td>0.851</td>
</tr>
<tr>
<td>sratio</td>
<td>42.3</td>
<td>74.9</td>
<td>38.2</td>
<td>69.2</td>
<td>23.6</td>
<td>62.0</td>
</tr>
</tbody>
</table>

**Underestimation of SSA for dust?**
- Large uncertainty in polluted dust SSA (Chinese region)
- No validation of SSA over ocean (SODA, POLDER)

**Graphical Data**

- ARF\textsubscript{anth, direct} = -0.2 : SPRINTARS
- ARF\textsubscript{total, direct} = -0.61 Wm\textsuperscript{-2} : CALIPSO
- -0.58 Wm\textsuperscript{-2} : SPRINTARS

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Yoshida & Murakami, AO08

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Our study
- Haywood et al
- Kaufman et al
- Fouquart et al
- Carlson and Benjamin
- D'Almeida
- WMO
For separation of coarse and fine particles

- Use of TIR spectral region for coarse particle detection

\[ \varepsilon T(z) \quad \text{and} \quad \varepsilon_g T e^{-\tau m} \]

\[ \text{AOT}_{\text{coarse}} \quad \text{Height}_{\text{coarse}} \]

\[ \text{AOT}_{\text{fine}} \ll 1 \text{ in TIR} \]

*Courtesy: Hyojin Han & B.J. Sohn (2013)*
Next generation satellites

GOSAT, GOSAT-II
2009~

2015~
EarthCARE

GOSAT2/FTS-SWIR

2014~
GCOM-C

Current 2nd generation
2015~ 3rd generation
Himawari-8&9

AHI specs, JMA/HIMAWARI-8/9
16 bands (1km, 2km)
Full disk scan every 10min
Rapid scan every 2.5 min

Aerosol and cloud monitoring

CGOM/C-SGLI
imager
back/forward view
with polarization

250m, 11ch
500m, 2 ch
1km, 4 ch

GOSAT2/FTS-SWIR

FTS-TIR

CAI2

Coarse aerosol correction

ESA-JAXA/EarthCARE

Aerosol forcing

XCO₂, XCH₄

Dynamics with aerosol

Radar Echo

Doppler velocity

NASA/LARC
MEXT/RECCA Programme
AssimiLation System and its Application for Atmospheric Environmental Materials
(Project SALSA)

Stretched-NICAM +SPRINTARS+CHASER

Diamond-NICAM

Fukushima simulation

PM2.5 excess deaths (persons/km²)

Cloud, dust, fine particle

CO₂

1970s Temp. 2000s 2030s

Temperature from NICAM-SPRINTARS (August 2007)

CO₂

δ¹⁸O

Rain
Conclusions

• Awareness of absorbing aerosols for environmental and climate issues
• Man-made and dust aerosol mixture
• Information from NUV to TIR wavelength / multi-view and polarization useful
• Combined active/passive remote sensing for aerosol and cloud interaction
• Observation and modeling synergy in progress