AEROSOL CLIMATOLOGY OVER INDIA AND RADIATIVE IMPLICATIONS - INITIATIVES UNDER ISRO-GEOSPHERE BIOSPHERE PROGRAMME

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Why the concern on aerosols?

Role in

1. Regional radiative forcing
   Direct & Indirect Effects: Cooling or heating?!!

2. Climate perturbations
   Affect the radiation budget of earth-atmosphere
   Influence the cloud/hydrological cycle

3. Atmospheric Chemistry
   Act as surface area for ozone destruction reactions to take place at stratosphere

4. Environmental degradation
   Reduce visibility (Traffic problems)
   Problems in Remote sensing

5. Health impacts
Environmental & Health Impacts

- Visibility & Air Quality
- Respiratory disorders

Most relevant parameters:
- Abundance
- Size distribution - particularly concentration <1µm
- Composition - toxicity
Monitored by CPCB

National Ambient Air Quality Standards

- **TSP** - Air Quality
  - 360 µg m\(^{-3}\) (Industrial); 140 µg m\(^{-3}\) (Residential)

- **PM10** - RSP
  - 120 µg m\(^{-3}\) (Industrial); 60 µg m\(^{-3}\) (Residential)

- **PM2.5** -
- **PM1** -

- **Toxicity health hazard**
Climate Impact – Global & Regional

Climate impact of aerosols results from the **Radiative Forcing** of the Atmosphere by the aerosols

**Aerosols Force the Atmosphere both Directly and Indirectly**
What is forcing?

- Forcing is the change in the radiation flux, either at the top of the atmosphere (TOA) or at the surface (S) or in the atmosphere (in W m$^{-2}$) due to the presence of aerosols.

\[
(\Delta F)_{S,TOA} = (F_{NA})_{S,TOA} - (F_A)_{S,TOA}
\]

\[
(\Delta F)_A = (\Delta F)_{TOA} - (\Delta F)_S
\]
The Earth’s Radiative Budget

- Incoming solar radiation
- Absorbed at surface 51
- Absorbed in atmosphere 18
- Reflected by clouds 3
- Backscattered by atmosphere 6
- Absorbed in clouds 3
- Reflected by surface 26
- Net emission of infrared radiation from surface 21
- Sensible heat flux 4
- Latent heat flux 26
- Outgoing infrared radiation 23
- Emission by clouds 38
- Absorption in atmosphere 15

Total:
- Incoming solar radiation 100
- Absorbed at surface 51
- Absorbed in atmosphere 18
- Reflected by clouds 3
- Backscattered by atmosphere 6
- Absorbed in clouds 3
- Reflected by surface 26
- Net emission of infrared radiation from surface 21
- Sensible heat flux 4
- Latent heat flux 26
- Outgoing infrared radiation 23
- Emission by clouds 38
- Absorption in atmosphere 15

Net radiation balance: 100 - 51 - 18 - 3 - 6 - 3 - 26 - 4 - 23 - 38 - 15 = 0
Aerosols and Climate

- Aerosols influence climate:

  - Directly:
    - by back-scattering incoming sunlight to space.
    - by absorbing sunlight

  - Indirectly:
    - by modifying the properties and lifetime of the clouds.
Aerosol Indirect/ Semi-direct Forcing

- Aerosols (CCN) change the cloud droplet size distribution and hence the cloud albedo. (For a given cloud liquid water content, the increase in CCN leads to smaller drops and whiter clouds)
- Smaller droplets reduce precipitation leading to increased cloud life-times/ and hence cloud cover
- Absorbing aerosols lead to cloud burn-outs
Optical depth is the integrated extinction coefficient over a column of unit cross section and is a result of the combined effect of scattering and absorption.

High optical depth implies less atmospheric transmittance.

$$\tau_p = \int_{0}^{z} \beta_e(\lambda, z) \, dz$$
The ratio of scattering coefficient to extinction coefficient is called single scattering albedo \( (\omega) \) and is a measure of the effectiveness of scattering over absorption.

\[
\omega = \frac{\beta_s}{\beta_e}
\]

\( \omega \) is 0 for perfectly absorbing aerosol, and 1 for pure scattering aerosol.
The refractive index $m = n + ik$

<table>
<thead>
<tr>
<th>Substance</th>
<th>$n$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (liquid)</td>
<td>1.333</td>
<td>0</td>
</tr>
<tr>
<td>NaCl</td>
<td>1.544</td>
<td>0</td>
</tr>
<tr>
<td>$H_2SO_4$</td>
<td>1.426</td>
<td>0</td>
</tr>
<tr>
<td>$NH_4HSO_4$</td>
<td>1.473</td>
<td>0</td>
</tr>
<tr>
<td>$(NH_4)_2SO_4$</td>
<td>1.521</td>
<td>0</td>
</tr>
<tr>
<td>$SiO_2$</td>
<td>1.55</td>
<td>0</td>
</tr>
<tr>
<td>BC</td>
<td>1.96</td>
<td>0.66</td>
</tr>
</tbody>
</table>
Impact of absorption on Radiative Forcing

(Babu et al., 2004)
The scattering phase function $P(\theta)$ describes the angular distribution of scattered radiation with respect to the incident radiation.

$$P(\theta) = \frac{\beta_s(\theta)}{\frac{1}{4\pi} \int_0^{4\pi} \beta_s(\theta_p) d\omega}$$
Do aerosols cool/ warm?

Projected Caveats:

1. Extinction of direct solar irradiance cools the Earth’s Surface – Reduction in evaporation and water cycle + *Dimming* of the planet

2. Absorption by BC, Dust and Organics warms the lower atmosphere – All leading to
   - Reduced cloud formation; inhibition of precipitation
   - *Cloud burn-off*
   - *Reduction in crop yield and water cycle*
   - Climate Impact
Recent observations (Science 2005)
Observations differ from Models

Why?

- Aerosol Characteristics incorporated into climate models do not adequately represent the heterogeneity
- Climate feedback mechanisms are still uncertain
Current understanding

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm$^{-2}$)

- **Greenhouse gases**
  - Halocarbons
  - N$_2$O
  - CH$_4$

- **Aerosols + clouds**
  - Black carbon from fossil fuel burning
  - Mineral Dust
  - Aviation
    - Contrails
    - Cirrus
  - Solar

- **Cooling**
  - Stratospheric ozone
  - Sulphate
  - Organic carbon from fossil fuel burning
  - Biomass burning
  - Land use (albedo only)

- **Warming**
  - CO$_2$
  - Tropospheric ozone
  - Halocarbons

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

**Aerosol indirect effect**

**Level of scientific understanding**

- High
- Medium
- Medium
- Low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
Why Aerosols are Special? (unlike the GHGs)

- Heterogeneity – The Hallmark of aerosols
  - Region specific source distribution, sink characteristics and microphysics
  - Spatio-temporal heterogeneity in Physical & Chemical properties
- Large-scale Atmospheric Dynamics (for eg ITCZ)
- Long-range Transport (>1000s km – intercontinental)
- Short and highly variable life-time
- Cloud properties & Aerosol cloud interaction
Climate Impact of Aerosols

CHARACTERISTICS OF ATMOSPHERIC AEROSOLS

Spectral AOD

Size distribution

Phase Function

Altitude Profile

Composition

SSA

Radiative Forcing

Direct & Indirect

Natural Spatio-temporal variability

Large-scale Atmospheric Dynamics

Long-range Transport

Anthropogenic Activities

CLIMATE IMPACT
India – Data scarcity

- **Heterogeneous India**
  - Geography
  - Diverse Human Activities & living habits
  - Large density of population
  - Large annual excursion of the ITCZ & associated changes
  - Long, dry, winter season

- **Complex Long-range Transport**
  - Europe, west Asia, E & SE Asia, South China

- **Potential Climate and Health implications**

- **Socio-economic and geo-political implications**
  - Scarcity of Data
Satellites – Good spatial coverage; but

- **Over BoB – Port Blair**

- **Over Central Himalayas**

![Graph showing AOD over BoB and Central Himalayas](image)

![Graph showing AOD comparison for Nainital](image)
Not always the solution!

- Coastal region / TVM
  Trivandrum - Vegitated, remote - south-west coast

- Semi-arid /
  Anantapur - Semi arid - Central Peninsula

AOD

2001 | 2002 | 2003

Modis550
MWR500
ISRO’S INITIATIVES

- IMAP – Initiation (1983-90)
- I-GBP- Thrust area since 1993
  - ACE Network; Island observatories
  - I-LARC (Port Blair)
  - Campaigns
    - Land Campaigns
    - Shipboard measurements
    - Airborne experiments
- ICARB
MWR- The workhorse

**Langley Technique**

\[ \ln(V_\lambda) = \ln(V_{o\lambda}) + 2\ln\left(\frac{r_o}{r}\right) - m\tau_\lambda \]
Radiometer network under I-GBP
<table>
<thead>
<tr>
<th>Location</th>
<th>Decadal Trends in AOD (% Yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trivandrum, 1985-2001</td>
<td>3.50, 2.78, 5.12, 1.02</td>
</tr>
<tr>
<td>Visakhapatnam, 1987-2001</td>
<td>1.19, -1.12, 0.04, -6.00</td>
</tr>
</tbody>
</table>

**Decadal Trends in AOD (\% Yr\(^{-1}\))**
Heterogeneity in AOD

[Map of aerosol optical thickness for April 2003]

[Map of aerosol optical thickness for June 2003]
Long-range Transport
Minicoy – The first special station

In A/sea; 400km west off TVM

The Observatory & MWR-
Long range Transport: Minicoy

(JAMR2001)

JMAR, 2001; JATP 2000
The I-LARC
Results from I-LARC, Port Blair \textit{GRL, 2003)}
Trajectory mean AODs

East – Advection from East (East Asia, south China…)

West – From W Asia & NW India

Mixed
Field Campaigns – over oceans

- **ARMEX–II (Mar–May 2003)**
- **SO Expedition (Jan-Apr 2004)**
The ARMEX - (JAS 2005, GRL 2004)

Comparison of BC over A/Sea with TVM
Temporal heterogeneity

March

- soot: 56.5%
- tmd: 2.3%
- wsc: 19.5%
- ssc: 2.5%
- ssm: 19.2%

April

- soot: 44.6%
- tmd: 20.4%
- wsc: 18.4%
- ssc: 1.6%
- ssm: 15%

May

- soot: 23%
- tmd: 24%
- wsc: 23%
- ssc: 18.3%
- ssm: 0.8%

June

- soot: 17.9%
- tmd: 16.2%
- wsc: 41.4%
- ssc: 4.5%
- ssm: 0.5%
Radiative forcing - heterogeneity

Graph showing the radiative forcing for different months (March, April, May, June) with data from TOA, SURFACE, and ATMOSPHERE. The graph indicates the variation in radiative forcing across these categories for each month.
Impact of West-Asian transport

(Moorthy et al., JAS 2005)
I-GBP Land Campaign - 2004

- First of its Kind
- >15000 km covered
- 83 independent samples
- @ 3 to 4 spatial samples per day over peninsula
- Identical, intercompared instruments
- Common measurement protocols
Comparison with MODIS Fine mode Fraction

- $A_f$ from measurements
- $F_f$ Feb2004 from MODIS
BC Concentration & Mass Fraction
Biomass Burning – Namakal, Kodai, Theni
Aircraft measurements: Feb 2004
Instrumental setup -
ALTITUDE PROFILES (GRL 2004)
Integrated Campaign for Aerosols, gases and Radiation
Budget - ICARB

A Multi-instrumented, Multi-institutional, Multi-platform Field Campaign of ISRO-GBP
Novel Approach - Segmented & Integrated

GROUND SEGMENT
Spatially resolved Timeseries
GBP Network Stations, Island stations – MINICOY & ILARC

OCEAN SEGMENT
Snapshot
Cruises over BoB & AS

ATMOSPHERIC SEGMENT
Aircraft Profiling over Land & Ocean

Satellites
Regional ARF
Models
Unique features of ICARB

The biggest campaign ever conducted in India

- Two-month long campaign
- Longest cruise path >25000km
- Largest number of air sorties; 26 sorties from 5 bases
- Largest no. of land-based network stations – 20 nos
- Highest participation -> 26 institutions from 4 different departments & Universities
- Participation of ~100 investigators
Time-series measurements from fixed locations over the mainland and from Islands (Minicoy & Port Blair), planned from 20 stations. Out of these 18 stations could be operated successfully.
Aircraft profilings

26 Sorties from 5 Bases; BBR, CHN, TVM, GOA & HYD

Parameters:
1. Mass Concentration of BC
2. Mass Conc of composite Aerosols
3. Fine particle conc
4. Scattering Coeff
5. MPL
6. Conc of O3, CO
OCEAN SEGMENT – CRUISE SK223

ISRO-GBP
National
Integrated Campaign for Aerosols, gases and
Radiation Budget-ICARB
March-May 2006
Cruise Track

Cruise Track of SK223:
Dep Goa - 09 Mar 2006
Arr Goa - 11 May 2006

KK: ICARB-06
Some interesting results – Port effect!

- **BC Chennai**

- **NT Chennai**
AOD BoB
Altitude profile of BC

Trivandrum, ICARB

- Hyd - 2004
Aerosol Extn profile during ICARB

Extinction Coefficient Profile: Bhubhaneswar 25th March 2006

Coast to Open Sea: BHN

Open Sea to Coast: BHN

Courtesy: SKS
Effect of Elevated absorbing layer on radiative forcing
Future directions

- **I-STAG: The Indian satellite for aerosols and gases**
  - Multi-angle polarization imager
# Primary Particles

<table>
<thead>
<tr>
<th>Species</th>
<th>Production Processes</th>
<th>Present day burden compared with pre-industrial time</th>
<th>Climate change connection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Particles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral dust</td>
<td>Wind erosion</td>
<td>Land use change Industrial dust emissions</td>
<td>Changing winds and precipitation</td>
</tr>
<tr>
<td>Sea salt</td>
<td>Wind</td>
<td>Agriculture</td>
<td>Changing winds</td>
</tr>
<tr>
<td>Biological particles</td>
<td>Wind, Biochemical processes</td>
<td>Fossil fuel Biomass Burning</td>
<td>Changing winds</td>
</tr>
<tr>
<td>Carbonaceous particles</td>
<td>Vegetation fires</td>
<td>Increased carbonaceous particles</td>
<td>Changing precipitation (droughts, )</td>
</tr>
</tbody>
</table>

* * *
# Secondary Particles

## Production Processes

<table>
<thead>
<tr>
<th>Species</th>
<th>Natural</th>
<th>Anthropogenic</th>
<th>Present day burden compared with pre-industrial time</th>
<th>Climate change connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimethyl-sulfide</td>
<td>Phytoplankton degradation</td>
<td>Increased oxidation capacity</td>
<td>Increased sulfate</td>
<td>Changing winds hence air-sea exchange</td>
</tr>
<tr>
<td>SO₂</td>
<td>Volcanic emissions</td>
<td>Fossil fuel combustion</td>
<td>Increased sulfate</td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>Microbial activity</td>
<td>Agriculture</td>
<td>Increased ammonium nitrate</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>Lightning</td>
<td>Fossil fuel combustion</td>
<td>Increased nitrate</td>
<td>Change in convective activity hence lightning</td>
</tr>
<tr>
<td>Volatile organic compounds</td>
<td>Emission from vegetation</td>
<td>Increased oxidation capacity</td>
<td>Increased organic aerosol</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Industrial processes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Aerosol Sources: Fluxes

<table>
<thead>
<tr>
<th>Surface Sources</th>
<th>Tg yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Salt</td>
<td>1300 (1000 - 10,000)</td>
</tr>
<tr>
<td>Mineral Dust</td>
<td>1500 (1000 - 3000)</td>
</tr>
<tr>
<td>Volcanoes</td>
<td>30 (4 - 10,000)</td>
</tr>
<tr>
<td>Biological Debris</td>
<td>50 (26 - 80)</td>
</tr>
</tbody>
</table>

**Gas-to-Particle Conversion**

<table>
<thead>
<tr>
<th></th>
<th>Tg yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfate from Biogenic Gases</td>
<td>130 (80 - 150)</td>
</tr>
<tr>
<td>Sulfate from Volcanic SO(_2)</td>
<td>20 (5 - 60)</td>
</tr>
<tr>
<td>Nitrates from NO(_x)</td>
<td>30 (15 - 50)</td>
</tr>
<tr>
<td>Organic Compounds from Biogenic Precursors</td>
<td>60 (40 - 200)</td>
</tr>
</tbody>
</table>

**Sum of Natural Sources**

<table>
<thead>
<tr>
<th></th>
<th>Tg yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of Natural Sources</td>
<td>3100 (2200 - 23,500)</td>
</tr>
</tbody>
</table>

### Anthropogenic Sources

<table>
<thead>
<tr>
<th></th>
<th>Tg yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Dust (non-BC)</td>
<td>100 (40 - 130)</td>
</tr>
<tr>
<td>Black Carbon</td>
<td>10 (5-20)</td>
</tr>
<tr>
<td>Biomass Burning (non-BC)</td>
<td>90 (60-150)</td>
</tr>
<tr>
<td>Sulfate from SO(_2)</td>
<td>190 (170 - 250)</td>
</tr>
<tr>
<td>Nitrates from NO(_x)</td>
<td>50 (25 - 65)</td>
</tr>
<tr>
<td>Organic Compounds</td>
<td>10 (5 - 25)</td>
</tr>
</tbody>
</table>

**Sum of Anthropogenic Sources**

<table>
<thead>
<tr>
<th></th>
<th>Tg yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of Anthropogenic Sources</td>
<td>450 (300 - 650)</td>
</tr>
</tbody>
</table>
Removal Processes

1. Wet Removal Processes
   - Rainout
   - Washout

2. Dry Removal Processes
   - Gravitational settling
   - Turbulent deposition
Aerosol Lifetimes – Lower Troposphere

After Warneck, 1988
A cloud with a greater number of small droplets has more reflective surface area than a cloud of the same volume with fewer large droplets.
Therefore, aerosols increase the reflective surface area of the cloud by acting as condensation nuclei.
This is the first indirect effect, or Twomey Effect.
Indirect aerosol effect - II

Smaller droplets \rightarrow Lower Precipitation rate

Clouds are longer lived and retain higher liquid water content
Radiative Forcing over Bay of Bengal- Interlacing ground based observations with MODIS data
Flight Tracks
Smaller droplets → Lower Precipitation rate

Clouds are longer lived and retain higher liquid water content
Aerosol Forcing Mechanisms

- **Direct Effect - Light Scattering and Absorption**
  - \( \Rightarrow \) surface cooling, atmospheric warming

- **1st Indirect Effect (Twomey Effect)**
  - Decreased cloud droplet size; Increased cloud droplet concentrations
  - \( \Rightarrow \) brighter clouds

- **2nd Indirect Effect**
  - Increased cloud lifetime and/or thickness \( \Rightarrow \) suppression of drizzle

- **Semi-Direct Effect**
  - Cloud burning due to atmospheric heating
Figure 1. Schematic of the aerosol indirect effects. CDNC means cloud droplet number concentration, and LWC means liquid water content.
The semi-direct aerosol effect

Aerosols absorb solar radiation

- Evaporation of the cloud!

- Absorbing aerosols may reduce low cloud cover

- This would warm the climate as low clouds scatter solar radiation back to space.