Observing the Earth's Atmosphere

Environment Monitoring & Research Centre
India Meteorological Department, New Delhi

Atmosphere

Gases

Non-Changing Gases

Gas	Symbol	Percent (by volume) Dry Air
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	Ar	0.92
Neon	Ne	0.0018
Helium	He	0.0005
Hydrogen	H_2	0.00006
Xenon	Xe	0.000009

Variable Gases

Water Vapor	H_2O	0 to 4
Carbon Dioxide	CO_2	0.037
Methane	CH_4	0.00017
Nitrous Oxide	N_2O	0.00003
Ozone	O_3	0.00000002
Sulfur Dioxide	SO_2	
Nitrogen Dioxide	NO_2	

- Water vapor (~0 to 4%). Critically important!
  - Clouds and precipitation
  - Important way to move energy around
  - Major greenhouse gas!
- Major GHGs

Non-Gas Constituents

- Hydrometeors – rain, clouds, hail
- Aerosol (Particulate Matter)
  - liquid or solid dispersed in a gas, usually air
- Aerosol can be
  - Inorganic- soil, smoke, dirt, sea salt, volcanic dust, surface acid aerosol
  - Organic- seeds, spores, pollen, bacteria

Sources: Natural, Anthropogenic

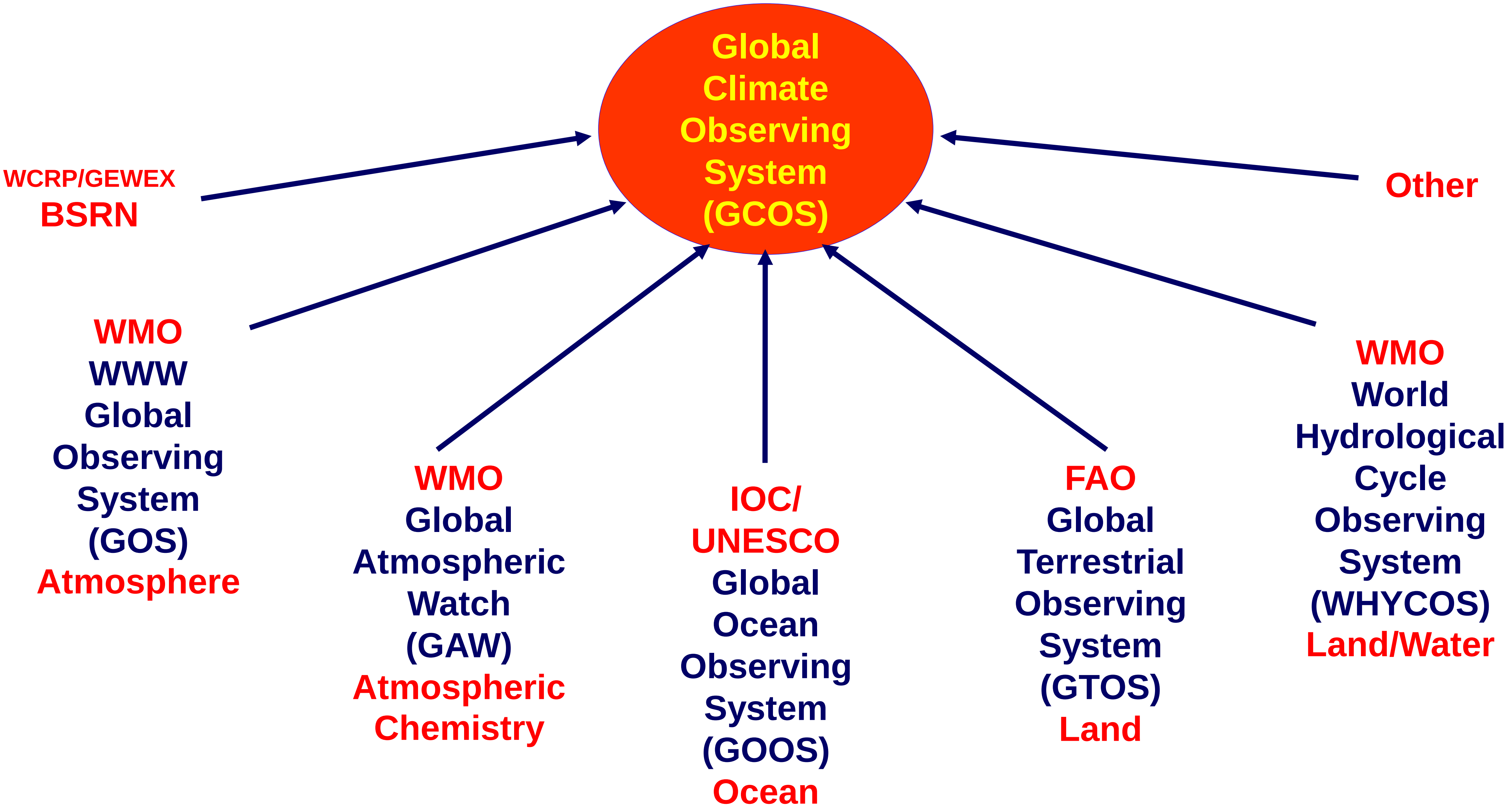
Why are Aerosols important?

- Act as condensation and freezing nuclei!
  - Water likes to condense on or freeze on to particles
- Can absorb or scatter radiation
  - Reduce visibility
  - Can scatter solar radiation to space: cool planet
- Can impact human health.
  - Can irritate lungs, initiate asthma, heart disease

Climate Communication: The Global Climate Indicators

Temperature and Energy	Atmospheric Composition	Ocean and Water	Cryosphere
Surface Temperature	Atmospheric CO_2	Ocean Acidification	Glaciers
Ocean Heat		Sea Level	Arctic and Antarctic Sea Ice Extent

GCOS is comprised of climate components of various global observing systems including both satellite and *in situ* observations



Essential Climate Variable

An Essential Climate Variable (ECV) is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth’ s climate. GCOS currently specifies 54 ECVs.

ECV are identified based on the following criteria:

- **Relevance**: The variable is critical for characterizing the climate system and its changes.
- **Feasibility**: Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.
- **Cost effectiveness**: Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

Essential Climate Variables

Atmosphere

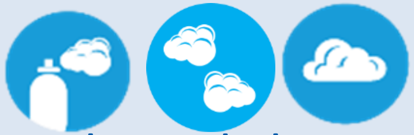
Surface

1. Precipitation
2. Pressure
3. Radiation budget
4. Temperature
5. Water vapour
6. Wind speed and direction

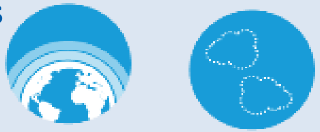
Upper-air

1. Earth radiation budget
2. Lightning
3. Temperature
4. Water vapor
5. Wind speed and direction

Atmospheric Composition



1. Aerosols
2. Carbon dioxide, methane and other greenhouse gases
3. Clouds
4. Ozone
5. Precursors for aerosols and ozone



Land

Hydrosphere

1. Groundwater
2. Lakes
3. River discharge

Cryosphere

1. Glaciers
2. Ice sheets and ice shelves
3. Permafrost
4. Snow

Biosphere

1. Above-ground biomass
2. Albedo
3. Evaporation from land
4. Fire
5. Fraction of absorbed photosynthetically active radiation (FAPAR)
6. Land cover
7. Land surface temperature
8. Leaf area index
9. Soil carbon
10. Soil moisture

Anthroposphere

1. Anthropogenic Greenhouse gas fluxes
2. Anthropogenic water use

Ocean

Physical

1. Ocean surface heat flux
2. Sea ice
3. Sea level
4. Sea state
5. Sea surface currents
6. Sea surface salinity
7. Sea surface stress
8. Sea surface temperature
9. Subsurface currents
10. Subsurface salinity
11. Subsurface temperature

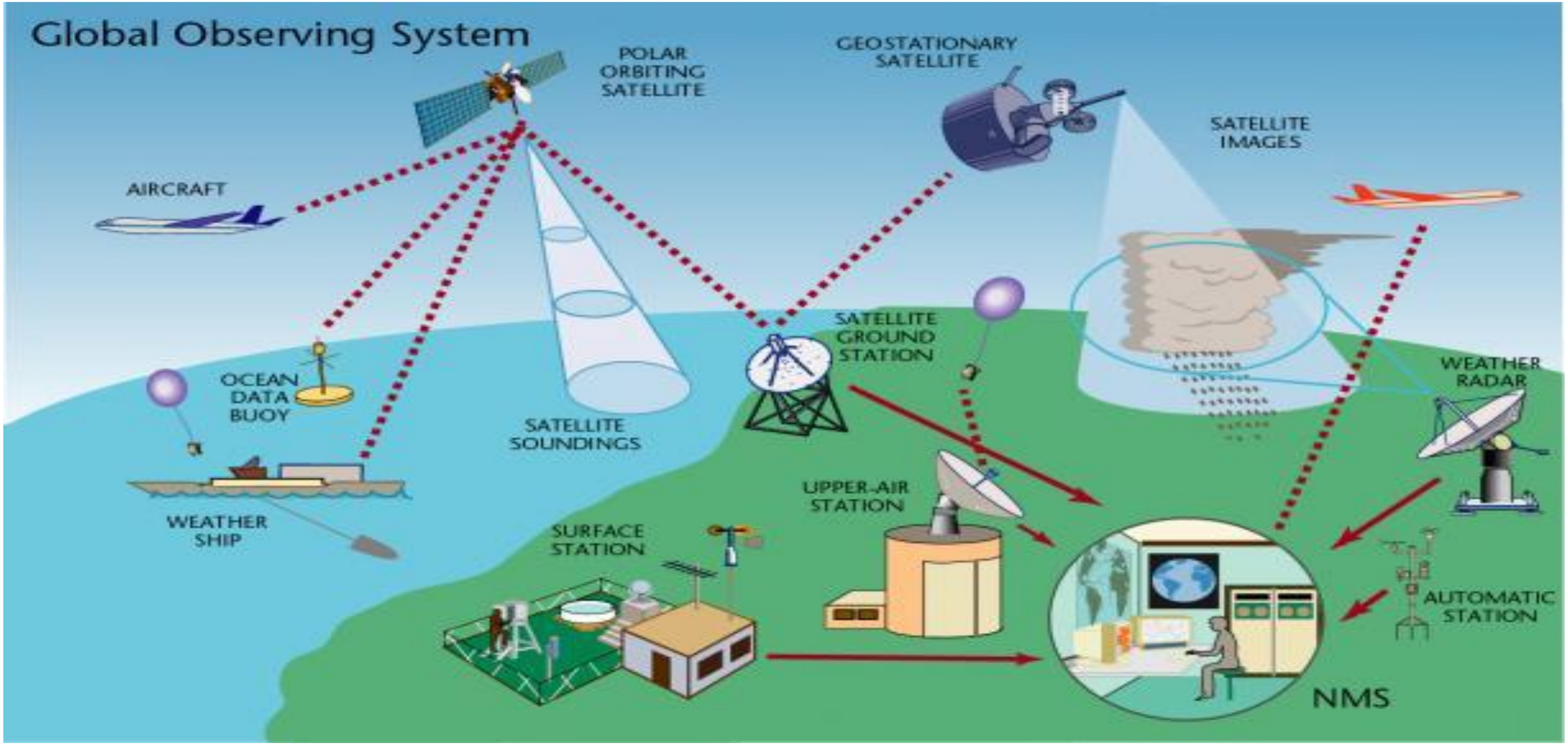
Biogeochemical

1. Inorganic carbon
2. Nitrous oxide
3. Nutrients
4. Ocean colour
5. Oxygen
6. Transient tracers

Biological/ecosystems

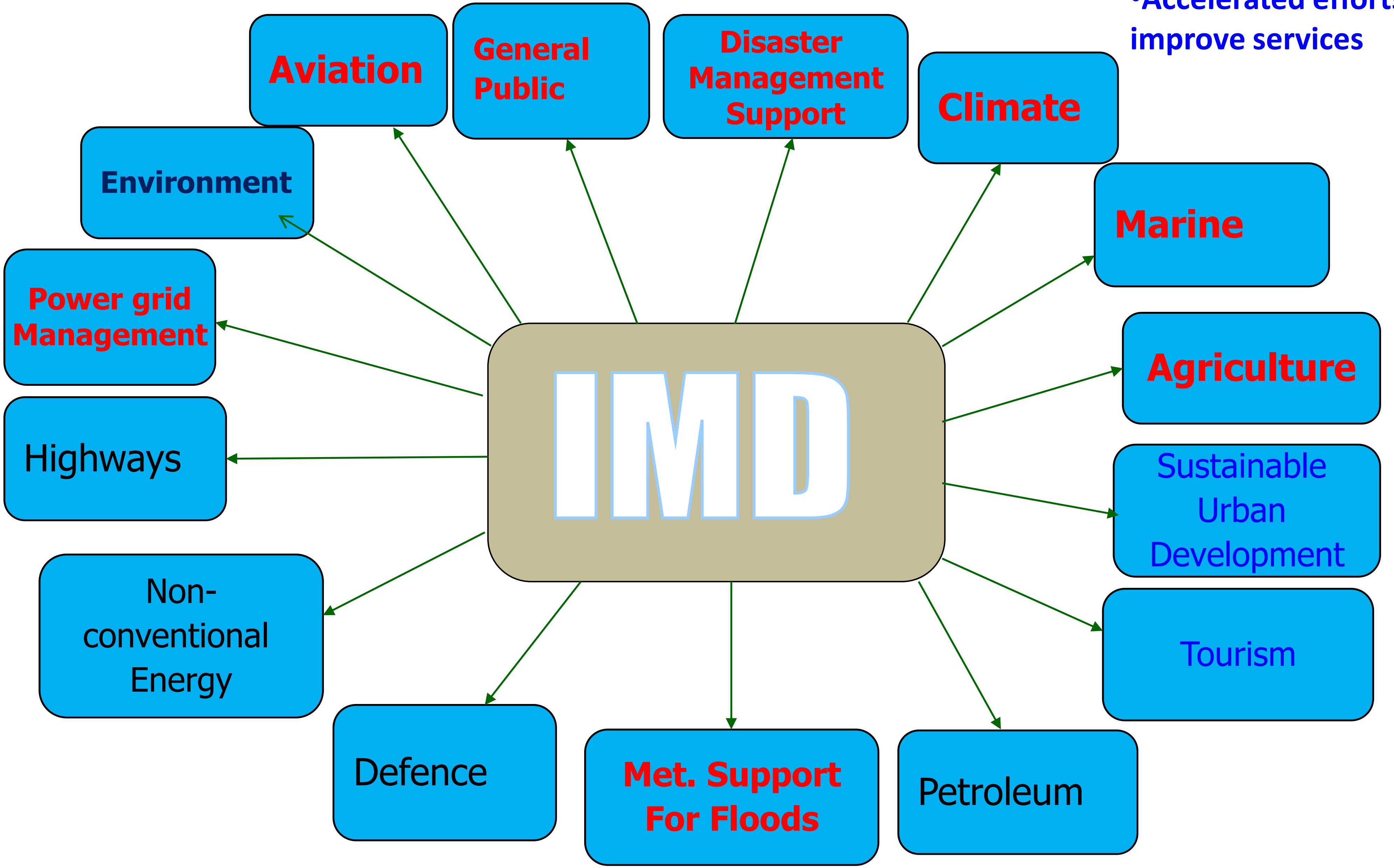
1. Marine habitats
2. Plankton

Global Earth Observation System

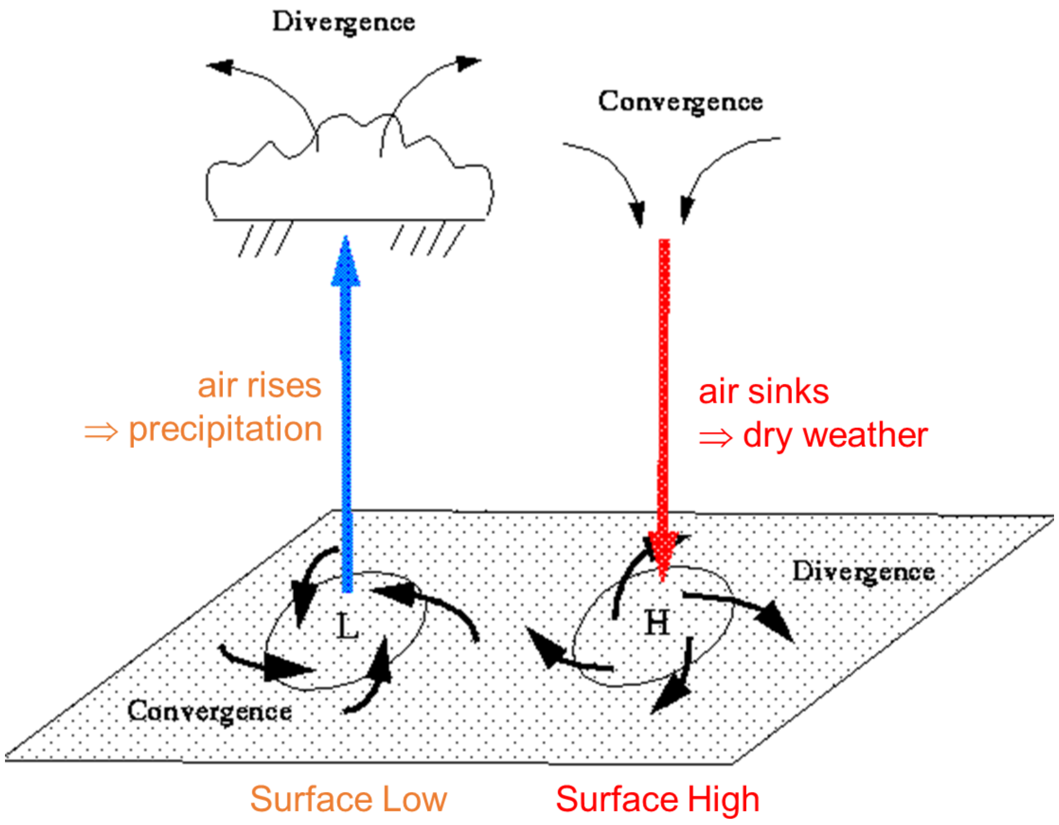


Major science themes/applications/services of IMD

- Core Services
- Accelerated efforts to improve services



How Highs and Lows affect surface weather



Cyclonic conditions

- Areas of Low pressure are generally
  - fast moving,
  - associated with strong winds and
  - upward motion, clouds and precipitation

  → **all result in low pollutant concentrations**

Anticyclonic conditions

- High pressure areas have the opposite conditions:
  - Often slow moving and stagnant
  - Associated with weak pressure gradients and light winds
  - Downward motion – clear skies and no precipitation
  - Formation of a subsidence inversion that stabilizes the atmosphere and limits vertical mixing

  → **Conditions that lead to stagnation and high pollutant concentrations**

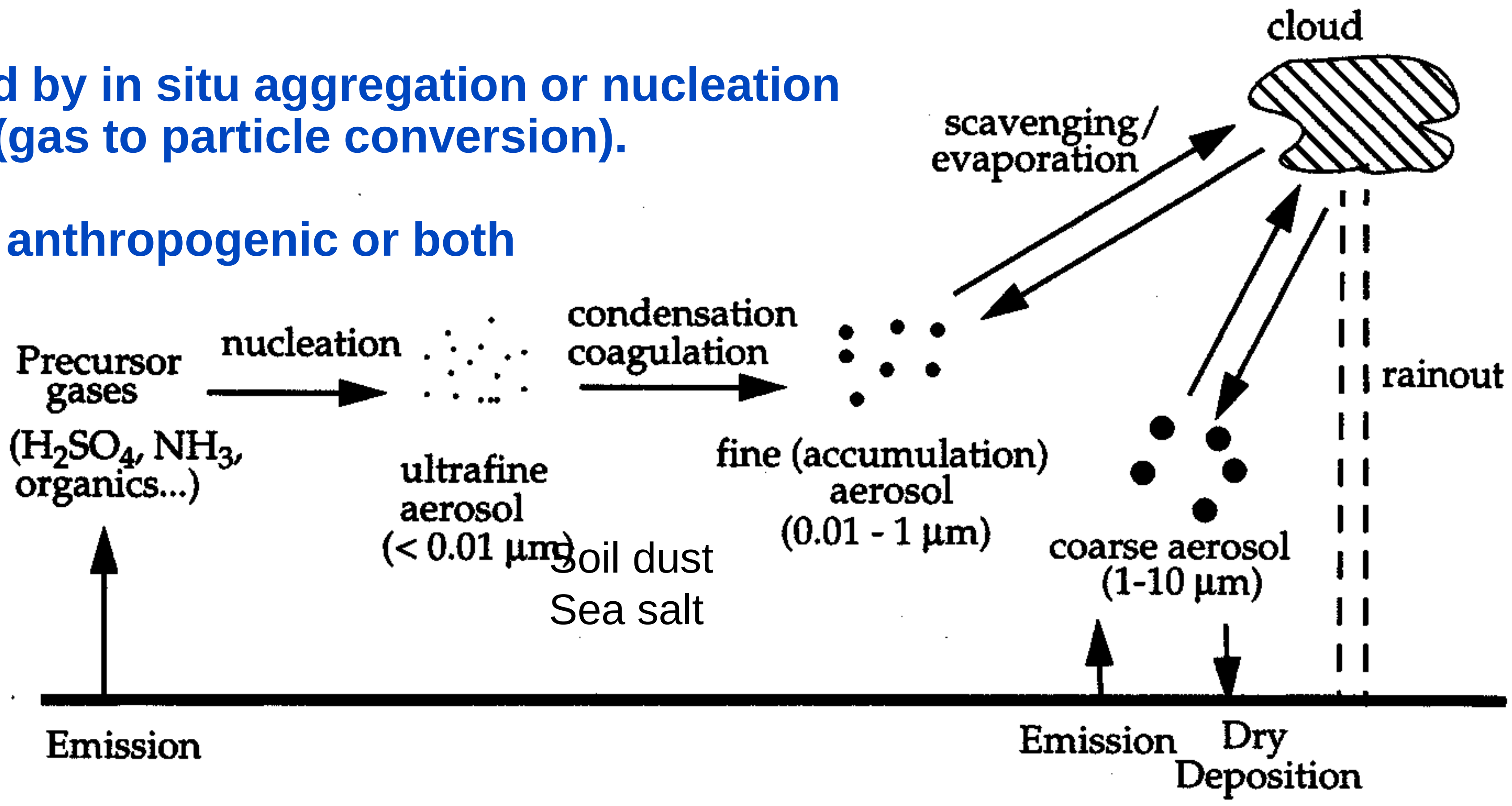
ATMOSPHERIC AEROSOL

Aerosol: Solid, liquid or combination of thereof suspended in a air

Size range: 0.001 μm (molecular cluster) to 100 μm (small raindrop)

- **Primary aerosol – emitted or injected directly into the atmosphere.**
- **Secondary aerosol - created by in situ aggregation or nucleation from gas phase molecules (gas to particle conversion).**

Either type may be natural or anthropogenic or both



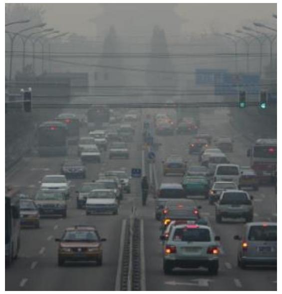
Environmental importance: health (respiration), visibility, radiative balance, cloud formation, heterogeneous reactions, delivery of nutrients…

Types and Sources of Aerosols

Type	Sources
Dust	Desert, bare soil
Sulfuric aerosol	Fossil fuel burning, ocean phytoplankton
Sea salt	Ocean spray
Smoke	Forest fires
Organic carbon	Fossil fuel burning, forest fires

Natural Sources

Anthropogenic Sources



Lifetimes are ….

Distribution of aerosols around the globe is heterogeneous and they have a short residence time

- Aitken nuclei – hours to days (diffusion/coagulation)
- Accumulation mode – weeks
- Coarse mode – hours to days (deposition)
- Ultrafine – minutes to hours

Direct Aerosol Effect

There are three processes causing the direct aerosol effect:

(i) the absorption of the longwave radiation and incoming solar radiation.

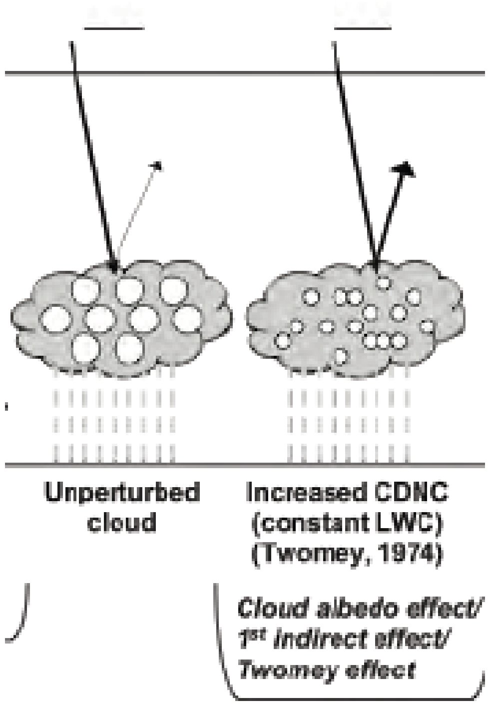
(ii) the longwave radiation emitted by the Earth surface is backscattered by the mineral dust particles.

(iii) incoming shortwave radiation is backscattered as well (global dimming).

All three processes result in reductions of the surface temperature (surface cooling), which leads to a decrease of the net surface radiation forcing of about 1 Wm^{-2}, at the same time with a increase in lower atmospheric heating of about 1 K day^{-1} due to absorption.

Cloud Albedo and Life Time Effect

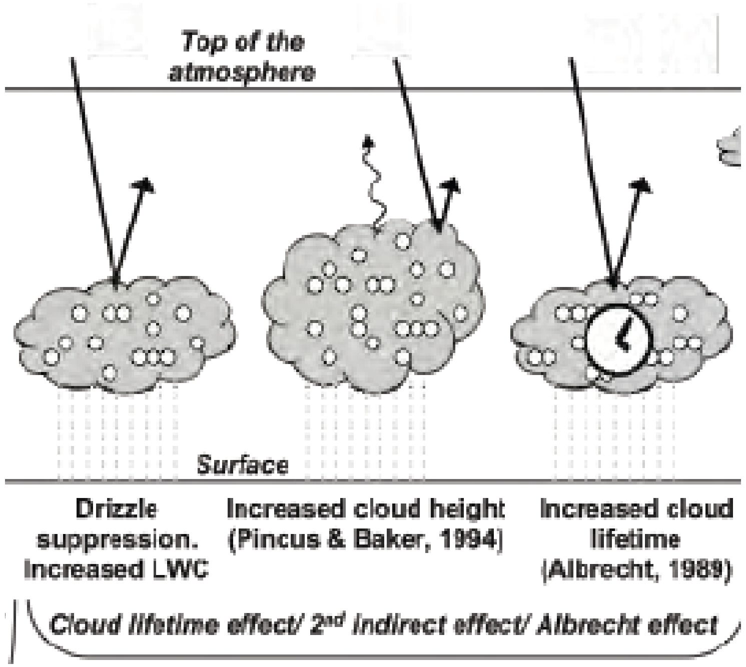
The indirect effect corresponding to radiative forcing is called cloud albedo effect or Twomey effect, the one corresponding to the hydrological cycle is called cloud lifetime effect.



A "contaminated" cloud has more numerous but smaller cloud droplets as a "clean" cloud, which leads to different properties.

Cloud Albedo Effect: the reflectivity/the optical depth of the contaminated cloud is enhanced- the cloud is brighter, which causes an increased albedo.
This means that more radiation is backscattered into the space, so that the net solar radiation at the top-of-the atmosphere is reduced and it gets cooler.

Cloud Albedo and Life Time Effect

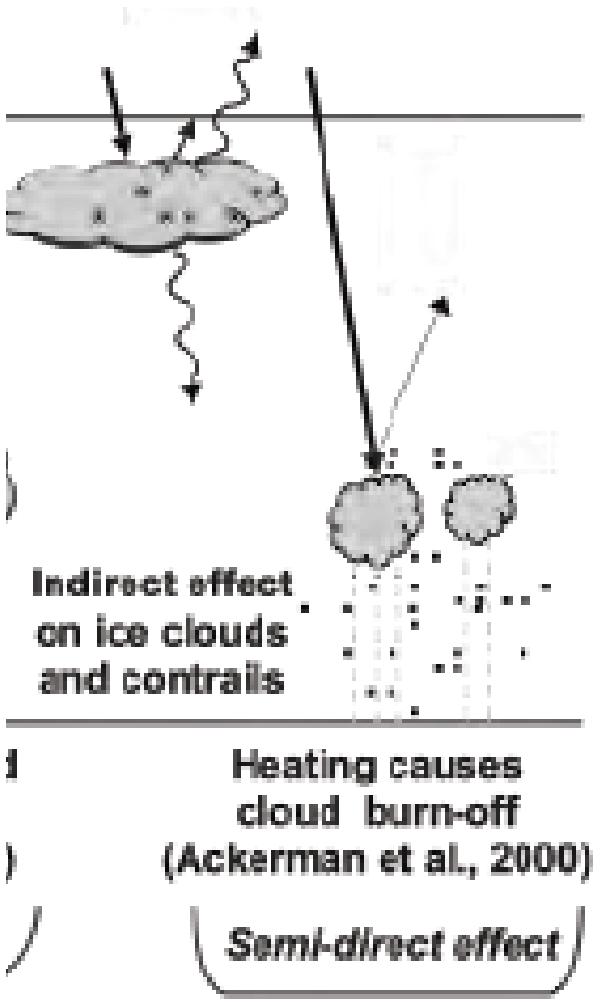


Cloud Life Time Effect

Small droplets are growing less probable by coalescence than bigger ones, so that precipitation could be diminished or suppressed depending on environmental conditions, cloud types and the stage in the storm's lifecycle. **By diminishing or suppressing rainfall the lifetime of the cloud changes, it takes longer until the cloud rains and disappears.** A longer lifetime of contaminated clouds leads to an overall increased cloud cover, which reduces the net solar radiation at the surface, it gets cooler again.

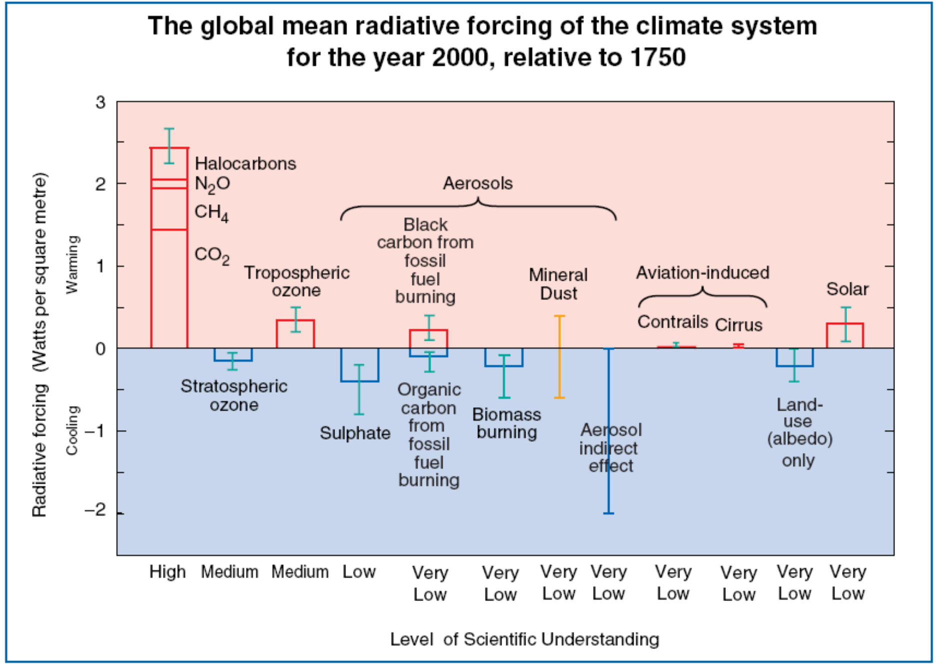
Additionally the total amount of precipitation is reduced, so that aerosols reduce vital water resources in semi-arid regions. This can cause drier soil, which in turn raises more dust (feedback loop).

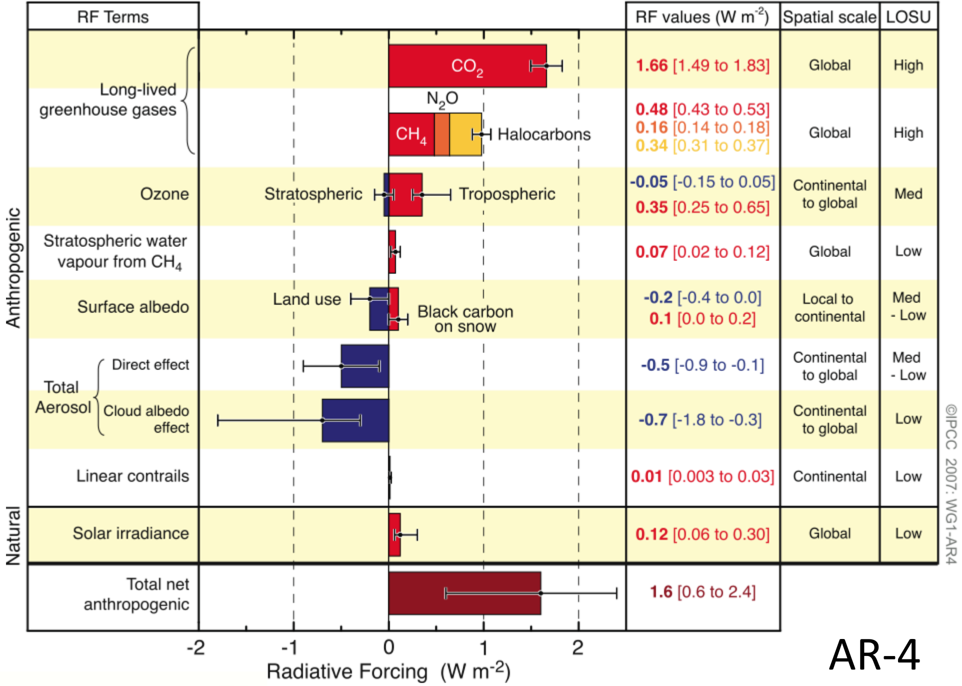
Aerosol Semi-direct Effect



The absorption of solar radiation in clouds leads to another effect- the so called semi-direct effect. Due to this absorption the evaporation of cloud droplets within the clouds is increased, which may lead to a decrease in cloud cover.

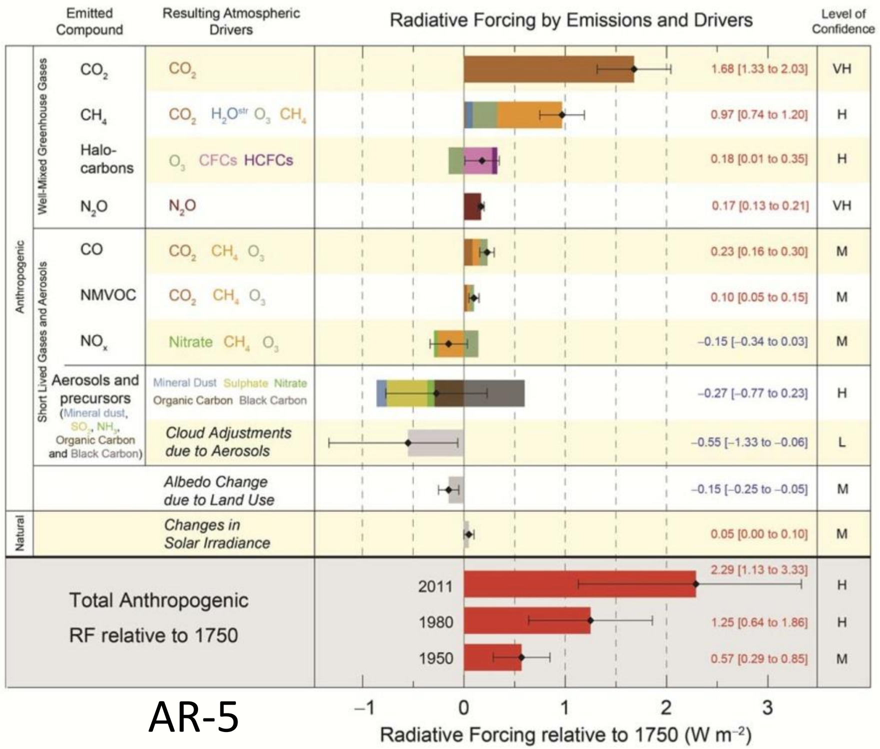
Secondary, followed by the temperature increase the relative humidity is reduced. These affect the thermal atmospheric structure and dynamics and in contrast to the other aerosol effects amplify warming of the Earth-atmosphere system





AR-4

Radiative Forcing Estimates



AR-5

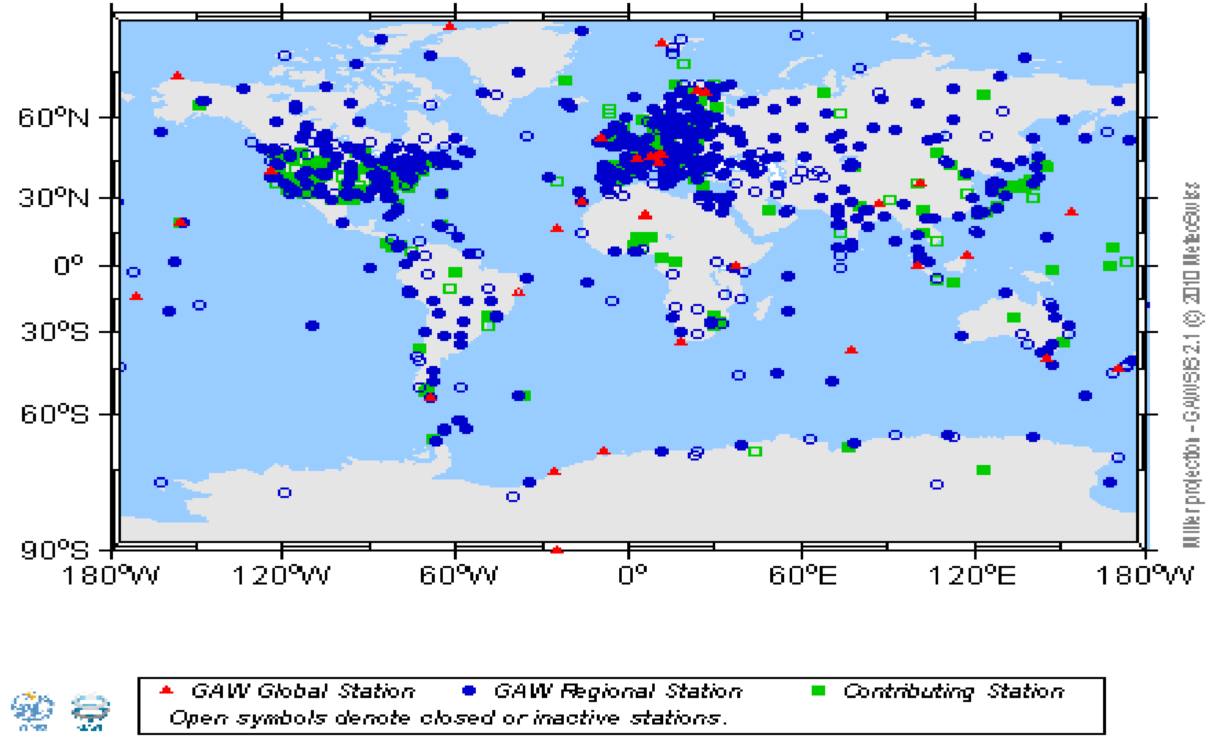
The RF of the total aerosol effect in the atmosphere, which includes cloud adjustments due to aerosols, is –0.9 [–1.9 to −0.1] Wm^{-2} (medium confidence), and results from a negative forcing from most aerosols and a positive contribution from BC absorption of solar radiation. (Source: IPCC, AR5)

Aerosol Networks

- Worldwide, there are many aerosol networks, regional or global in scope. Mainly of two types:

(1) Networks driven by project-based research, and

(2) Networks driven by environmental policy frameworks



WMO Global Atmosphere Watch Network

WMO Global Atmosphere Watch (GAW) Programme

The mission of GAW is to:

- Reduce environmental risks to society and meet the requirements of environmental conventions.
- Strengthen capabilities to predict climate, weather and air quality.
- Contribute to scientific assessment in support of environmental policy.

WMO GAW focuses on six groups of variables (also called focal areas):

- Greenhouse Gases
- Ozone
- Aerosols
- Reactive Gases
- Total Atmospheric Deposition
- Solar Radiation

Aerosol measurements

Long-term Aerosol measurements recommended by the WMO-GAW SAG on Aerosols:

Continuous Measurement

Column and Profile:

Aerosol Optical Depth (multi-wavelengths)

Vertical Profile of Aerosol Backscattering Coefficient

Vertical Profile of Aerosol Extinction Coefficient

Optical Properties:

Particle Light Scattering and Absorption Coefficient (multi-wavelengths)

Particle Light Hemispheric Backscattering Coefficient (multi-wavelengths)

Physical Properties:

Particle Number Concentration (size-integrated)

Particle Number Size Distribution

Particle Mass Concentration (two size fractions)

Cloud Condensation Nuclei Number Concentration (at various super-saturations)

Chemical Properties:

Particle Mass Concentration of Major Chemical Components (two size fractions)

Intermittent or Continuous Measurement

Particle Size-segregated Chemical Composition

Dependence of aerosol properties on relative humidity

Ancillary measurements

- **Meteorology**
- **Upper Air Observation**
- **Solar Radiation**

Ground-based remote sensing

- Passive technique:
  - Sunphotometer measurements of column AOD, such as those measured by AERONET, SKYNET, WMO-PFR
  - Data are usually considered to be "ground truth" that are used for satellite retrieval validation and model evaluation
- Active technique:
  - LIDAR measurement of aerosol vertical profiles such as those measured by GALION, MPL-NET

Laboratory measurements

- Measuring chemical reaction rates and products in well controlled conditions
- Measuring physical and chemical properties
- Analyzing samples collected in the fields
- Testing and calibrating instruments

Aerosol Monitoring Network of IMD

Angstrom’s Turbidity Coefficient
1957-2010

Volz’s Sunphotometer
1973-2004

Microtops-II
2004-2012

Skyradiometer
2012 -

Some stations are part of Global Atmosphere Watch Program of WMO (formarly known as Background Air Pollution Monitoring Network (BAPMoN)

Sun Photometer

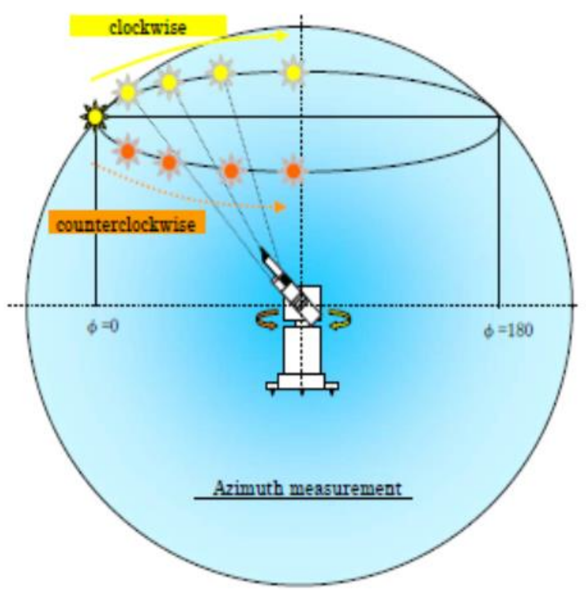
- Sun Photometers absorb *direct* sunlight energy and convert the intensity into a quantified voltage to measure aerosols in the atmosphere.

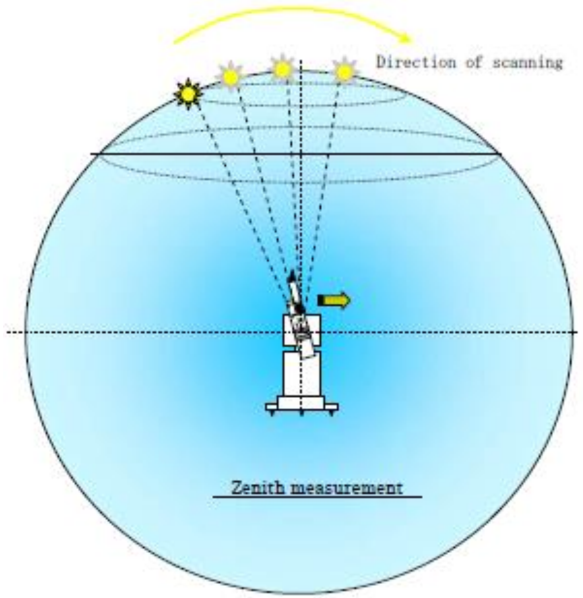
- The intensity of sunlight at the top of the earth's atmosphere is constant. While the sunlight travels through the atmosphere, though, aerosols can dissipate the energy by scattering (Rayleigh) and absorbing the light. More aerosols in the atmosphere cause more scattering and less energy transmitted to the surface.

- Knowing the sunlight's energy at the top of the atmosphere, the thickness of the atmosphere, and the amount of sunlight transmitted to the earth's surface and can allows us to determine the amount of scattering, and thus, the amount of aerosols.

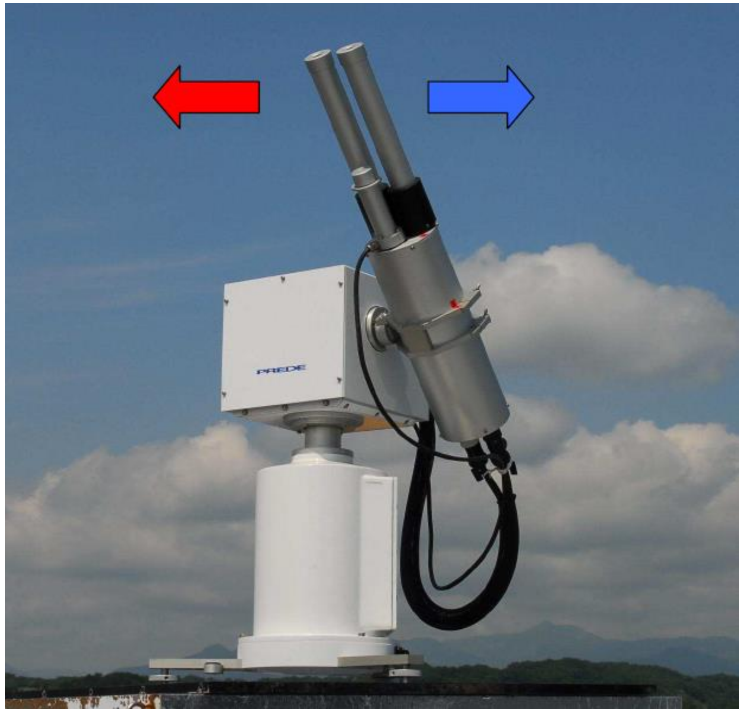
Skyradiometer Specifications

Half view angle	**0.5°**	
Min scattering angle	**3°**	
Wavelengths	**315, 340, 380, 440, 500, 675, 870, 940, 1020, 1640, 2200nm, 940nm is channel for water vapor**	
Detector	**Short wave（315nm～1020nm）**	**Si photodiode**
	Long Wave（1627nm， 2200nm)	**InGaAs photodiode**
Temperature control	**20°C, option ： cooler, built-in Heater**	
Tracking control	**Stepping Motor：2 way, Azimuth and Zenith, Stepping angle 0.0036° /pulse**	
Sun sensor	**Si photodiode**	
Potential tracking area	**Azimuth ±300° （South 0° ）**	
	Zenith -60 ～ 170° （Horizon 0° ）	





POM-02 Zenith Measurement for clouds



Azimuth Scanning

Sky-radiometer Network of IMD
Skynet-India

Online Data Transfer on real time

Data processing at Central Data Processing System, EMRC, New Delhi

- Aerosol Optical Depth (AOD),
- Angström exponent,
- Single Scattering Albedo,
- Aerosol Size Distribution,
- Asymmetry Parameter,
- Columnar Water Vapor,
- Complex Refractive Index of aerosols,
- **Aerosol Radiative Forcing**

Aerosol Parameters measured and Estimated

- Direct and Diffuse Spectral fluxes (Wm^{-2}) measured

- Aerosol Optical Depth

  (Columnar load of Aerosols)

- Ångström's Exponent (α)

  a large Ångström exponent indicates more fine mode aerosol events. (α generally range from greater than 2.0 for particles near combustion sources to values close to zero for coarse-mode-dominated desert dust aerosols).

- Single Scattering Albedo

Inversion products of Sun/sky radiometer

Inversion algorithm provides the aerosol retrievals by fitting the entire measured field of Sun radiances and the angular distribution of sky radiances to a radiative transfer model that results in estimation of the

Retrieved Parameters

Aerosols size distribution,

Spectrally dependent complex Refractive Index,

Partition of spherical/non-spherical particles

Calculated Parameters (on the basis of the retrieved aerosol properties)

Phase Function

Asymmetry Parameter.

Extinction efficiency

Radiative Forcing

Radiative Forcing Efficiency

In addition to the detailed size distribution, the retrieval provides the following standard parameters for total (t), fine (f) and coarse (c) aerosol modes:

C_v – ($\mu m^3/\mu m^2$) volume size distribution (t, f, c)

r_v- volume median radius (t, f, c)

σ - standard deviation (t, f, c)

r_{eff} - effective radius (t, f, c)

Log-normal distributions

Number distribution →
$n_n(\log D_p) = dN/d \log D_p$

Surface area distribution →
$n_s(\log D_p) = dS/d \log D_p$

Volume distribution →
$n_v(\log D_p) = dV/d \log D_p$

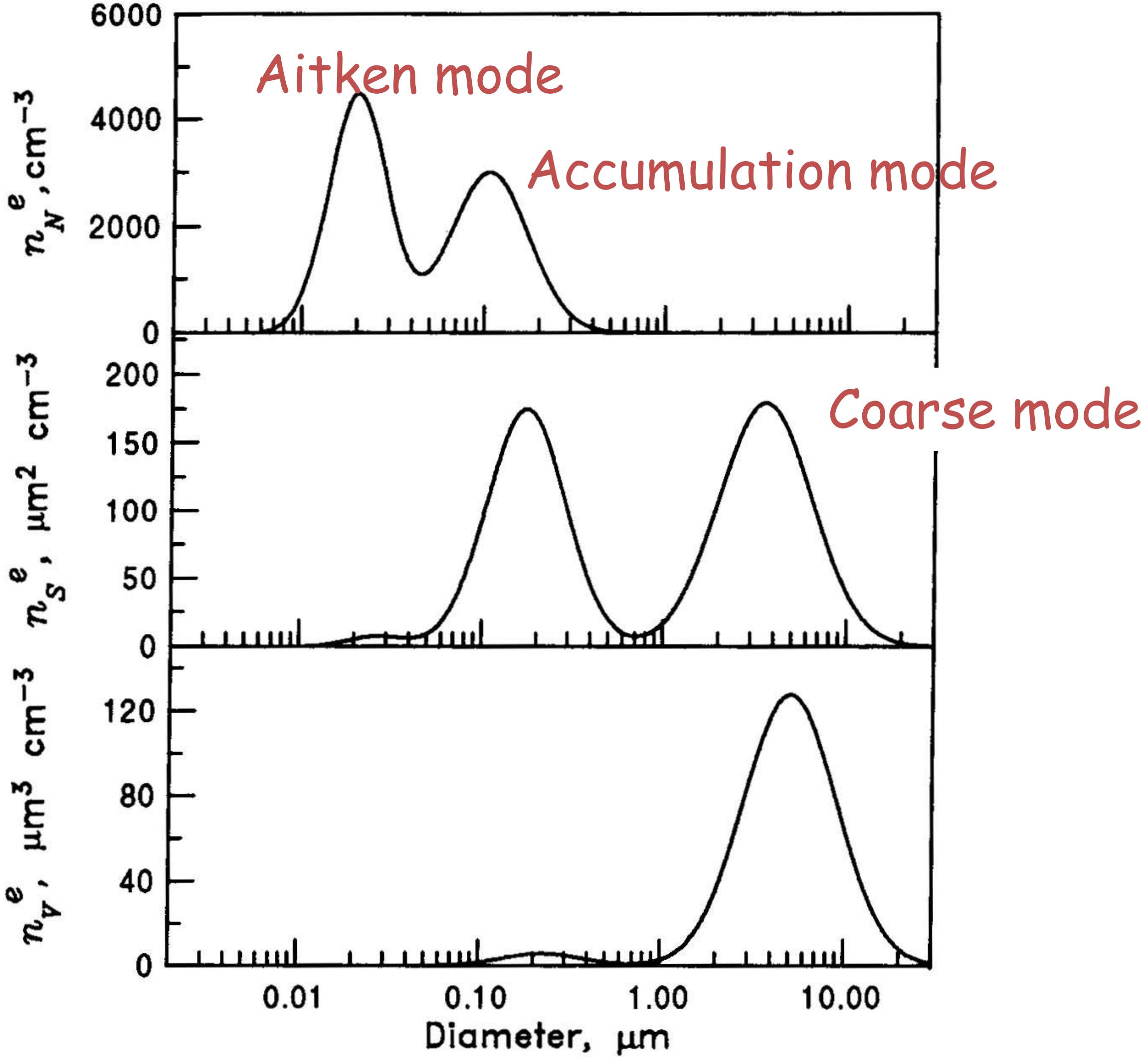


FIGURE 7.6 The same aerosol distribution as in Figures 7.4 and 7.5 expressed as a function of log D_p and plotted versus log D_p. Also shown are the surface and volume distributions. The areas below the three curves correspond to the total aerosol number, surface, and volume, respectively.

Aerosol Optical Thickness

AOT is a measure of spectral extinction of extra-terrestrial solar irradiance and is computed from ratio of irradiance measured to the corresponding extra-terrestrial values. Hence, the AOT can be computed for any arbitrarily chosen unit of radiation, may it even be the voltage recorded by the sensor.

Principles and theory of measurement

Solar radiation heading toward the earth decays due to scattering and absorption by atmospheric elements such as air molecules, aerosols, water vapor, carbon dioxide and ozone. Solar irradiance at a specific wavelength of λ is represented by the following equation according to the Lambert-Beer Law:

$$I(\lambda) = I_0(\lambda)\exp(-m_r * \tau(\lambda))$$

$I(\lambda)$: solar irradiance at a wavelength of λ at the earth's surface

$I_0(\lambda)$: extra-terrestrial solar irradiance at a wavelength of λ

$\tau(\lambda)$: atmospheric optical depth when the optical air mass is 1

m_r: relative air column length of zenith angle θ at that of zenith direction 1 (optical air mass)

τ at a certain wavelength can be expressed as follows:

$$\tau = \tau(air) + \tau(aro) + \tau(gas)$$

τ(air): optical depth of air molecules

τ(aro): aerosol optical depth(AOD)

τ(gas): optical depth of the absorbing atmosphere element (e.g., water vapor, carbon dioxide, ozone)Thus, AOD is determined as follows:

$$\tau(aro) = (1/m) * \ln(I_0 / I) - (\tau(air) + \tau(gas))$$

τ(air) is calculated from local pressure and τ(gas) is eliminated by selecting the specific wavelength where there is no radiation absorption by water vapor, carbon dioxide and so on. Additionally, absorption by ozone is calculated using the total ozone amount and its absorption coefficient at the relevant wavelength.

$$AOT = \left[\frac{Ln\left(\frac{Vo}{V * S}\right) - mr * \delta R * \left(\frac{P}{Po}\right)}{mr} \right]$$

P = station pressure

Po = standard atmospheric pressure (= 1013.25 mb)

S = mean sun-earth correction factor

mr = relative optical airmass

δR = Rayleigh scattering factor for wavelength λ1

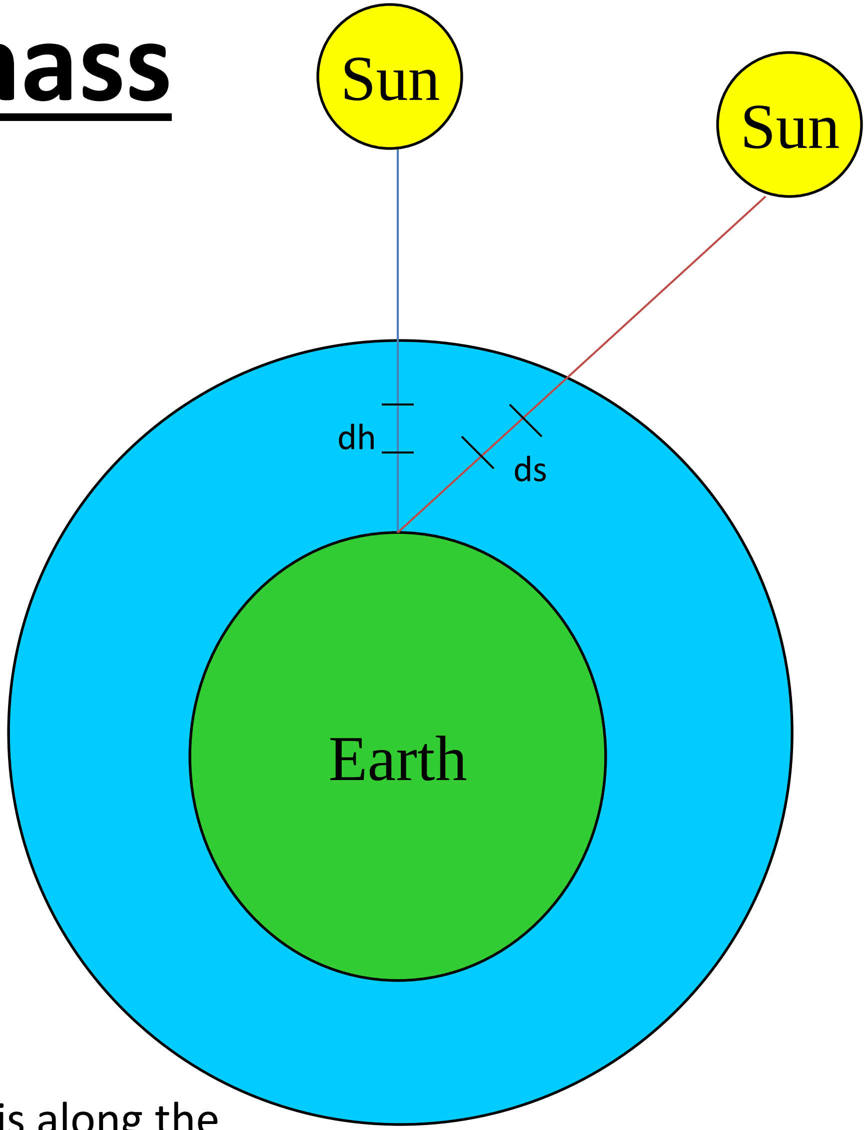
Vo = Extraterrestrial constant for channel-1 (wavelength λ1) in mV

V = signal in mV (meter value) for channel-1

Relative Optical Airmass

Relative Optical Airmass is the relative path length of the direct solar beam radiance through the atmosphere. It represents the actual path as a multiple of the shortest vertical path and computed from the relation:

$$mr = \frac{\int_0^{\infty} \rho \, ds}{\int_0^{\infty} \rho \, dh}$$



where ds is the length element along the actual path, while dh is along the local vertical. ρ is the density of air.

Airmass

When the sun is directly above a sea-level location the path length is defined as airmass 1.0 (AM 1.0). AM 1.0 is not synonymous with solar noon because the sun is usually not directly overhead at solar noon in most seasons and locations. When the angle of the sun from zenith (directly overhead) increases, the airmass increases approximately by the secant of the zenith angle. Considering the geometry of the curved surface of earth and atmosphere and the effects of refraction (an average refractive index of atmosphere for the entire visible range being taken), the following Kasten's empirical formula (Kasten, 1966) can be used to evaluate airmass (m_r) for standard pressure:

$$m_r = [\ \cos(Z) + 0.15 * (93.885 - Z)-1.253]^{-1}$$

$$m_r = [\ \sin(\gamma) + 0.15 * (3.885 + \gamma)-1.253]^{-1}$$

A better calculation *(Kasten, and Young (1989). Revised optical air mass tables and approximation formula.* ***Applied Optics 28*** *(22), 4735-4738)* follows:

$$m_r = [\ \cos(Z) + 0.50572 * (96.07995 - Z)-1.6364]^{-1}$$

where Z is the solar zenith angle. γ = 90-Z

Or

$$m_r = [\ \sin(\gamma) + 0.50572 * (6.07995 + \gamma)-1.6364]^{-1}$$

where γ is the elevation angle of the Sun in degrees (solar altitude)

This airmass should be corrected for any deviations from the standard pressure. The airmass duly modified by station pressure is:

$$m_a = m_r(P/Po)$$

Scattering Phase Function

The angular distribution of light intensity scattered by a particle at a given wavelength is called the *phase function,* or the *scattering phase function;* it is the scattered intensity at a particular angle relative to the incident beam and normalized by the integral of the scattered intensity at all angles.

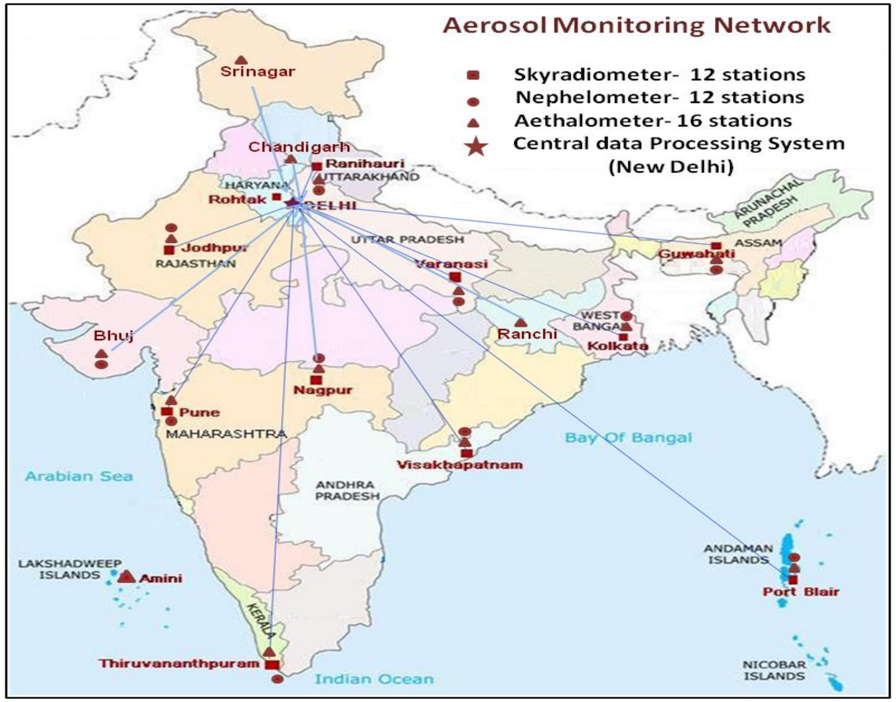
The **asymmetry parameter (g)** is the normalized angular distribution of the scattered radiation (the so-called *scattering phase function*) and is the
angle between the incident radiation and the scattered radiation.
The asymmetry factor is zero for isotropic radiation and ranges from -1 to +1, with positive values indicative of a predominance of forward scattering. Typical values of *g* range from 0.5 for aerosols to 0.80 for ice crystals and 0.85 for cloud droplets. Because of the predominance of forward scattering, a cloud of a given optical depth consisting of spherical cloud droplets reflects much less solar radiation back to space than a "cloud" of isotropic scatterers having the same optical depth.

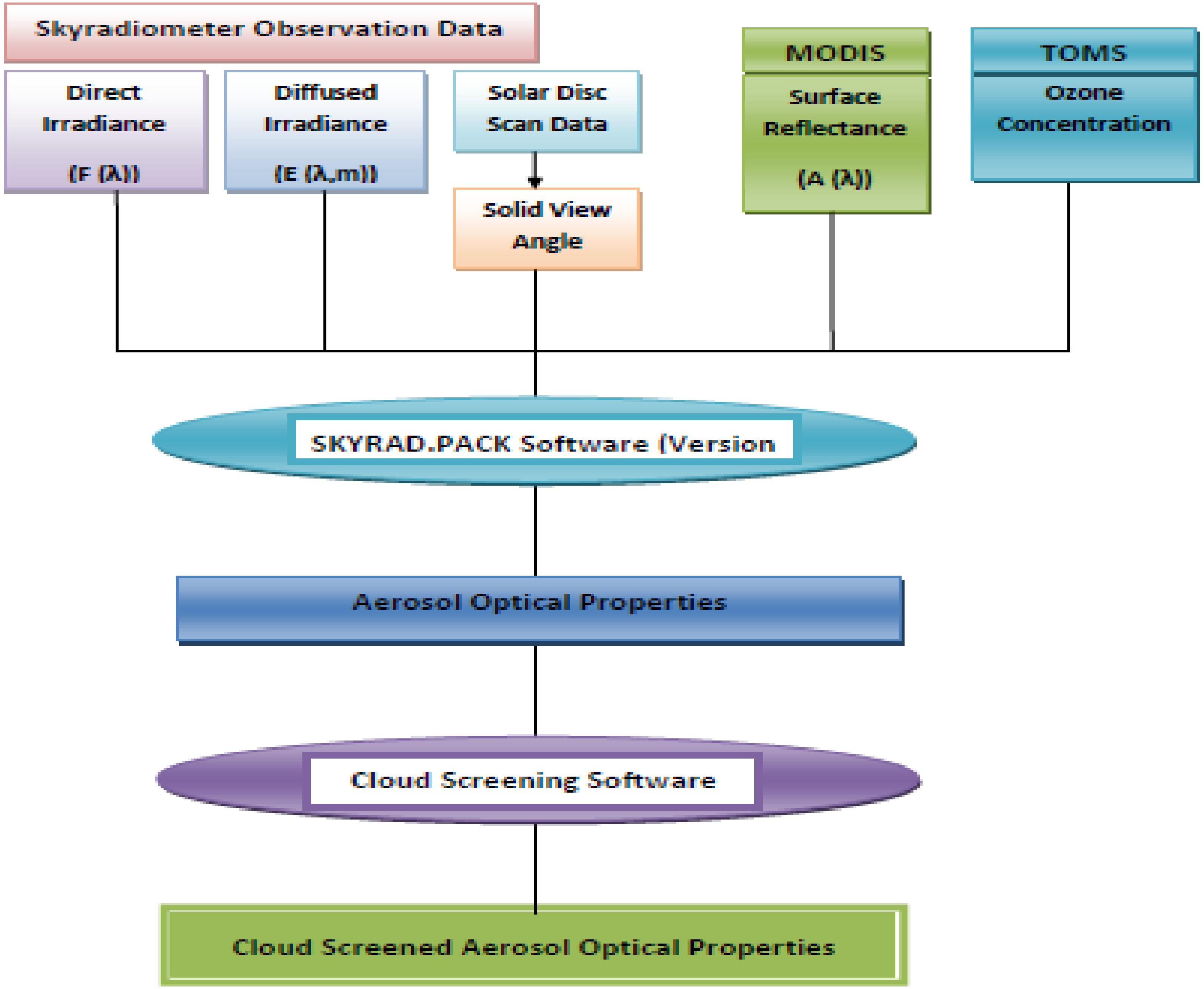
Single Scattering Albedo

The single scattering albedo (ω), defined as a measure of the relative importance of scattering and absorption. Values of single scattering albedo range from 1.0 for nonabsorbing particles to below 0.5 for strongly absorbing particles.

$$\omega = \frac{\text{Scattering Coeff.}}{\text{Scattering Coeff.} + \text{Absorption Coeff.}}$$

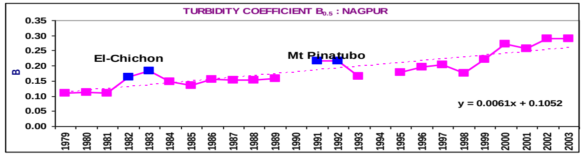
Schematic diagram of data analysis sky-radiometers

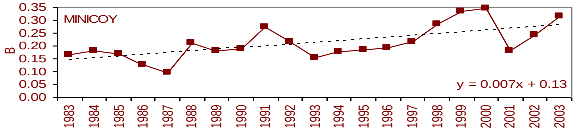


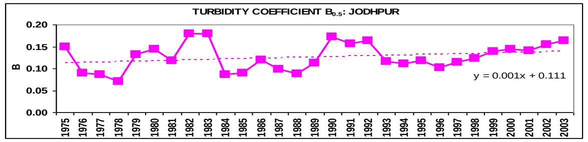


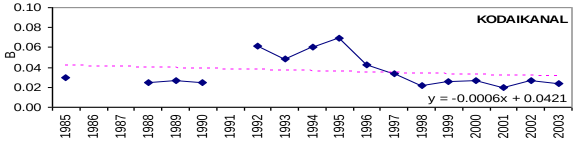
Early Aerosol Research

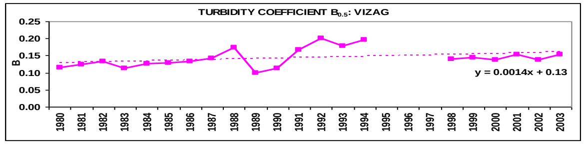
- Atmospheric turbidity
- Linke turbidity factor and Angstrom's turbidity coefficient from Pyrheliometric measurements have been determined at a number of stations in India since the IGY (1957-58).
- Volz Sunphotometer (1970s till 2004)
- Microtops-II sunphotometer (2001-2012)

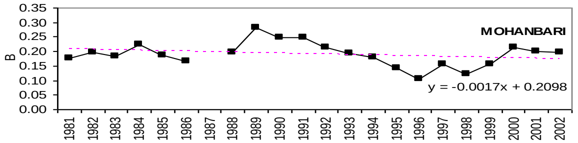


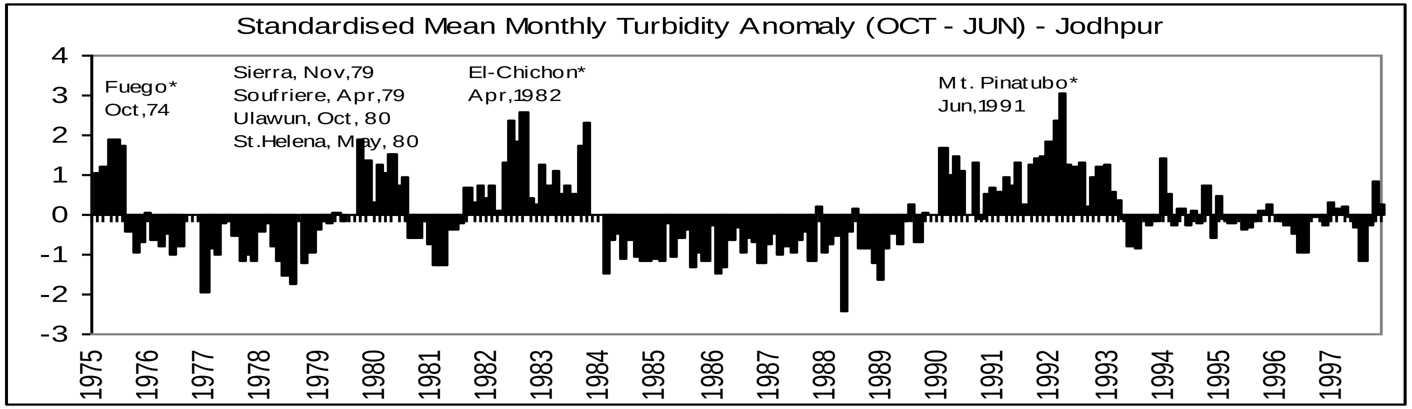


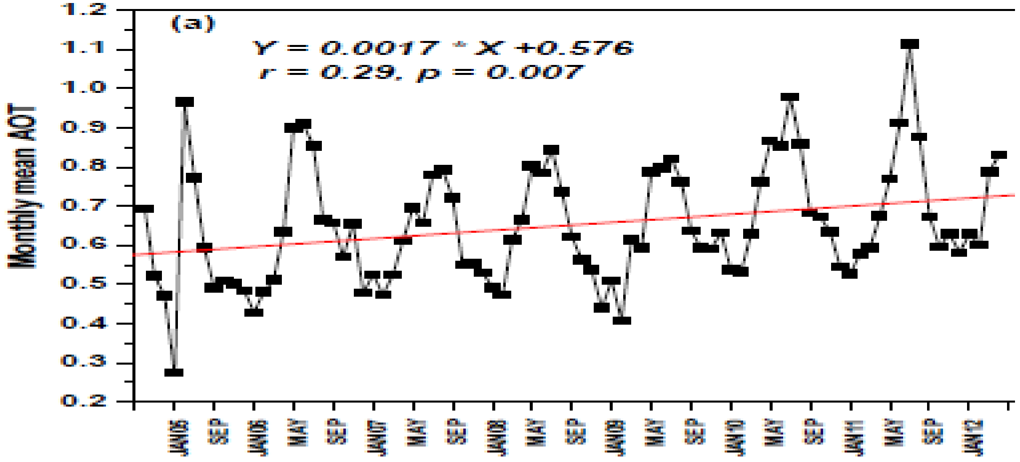


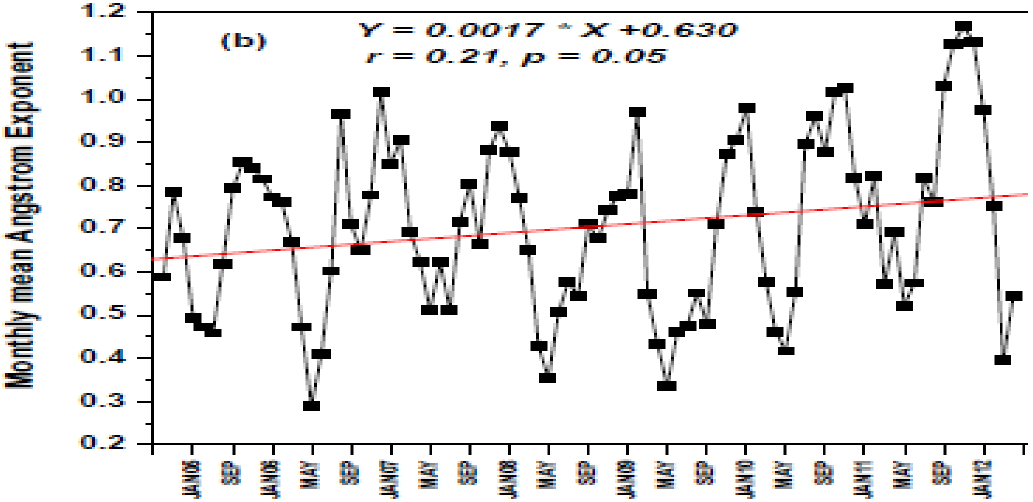




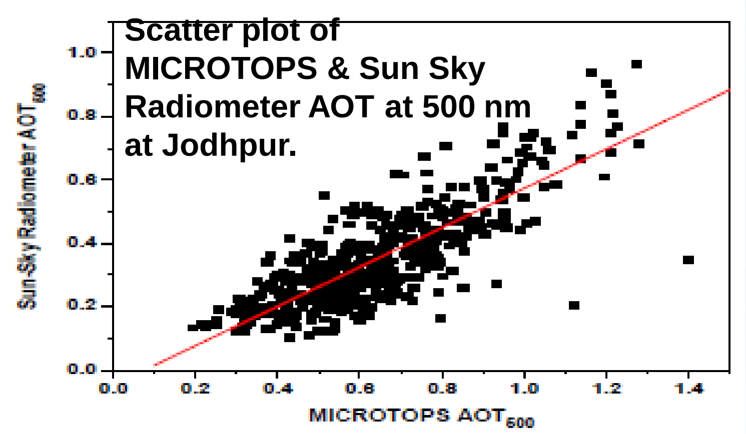


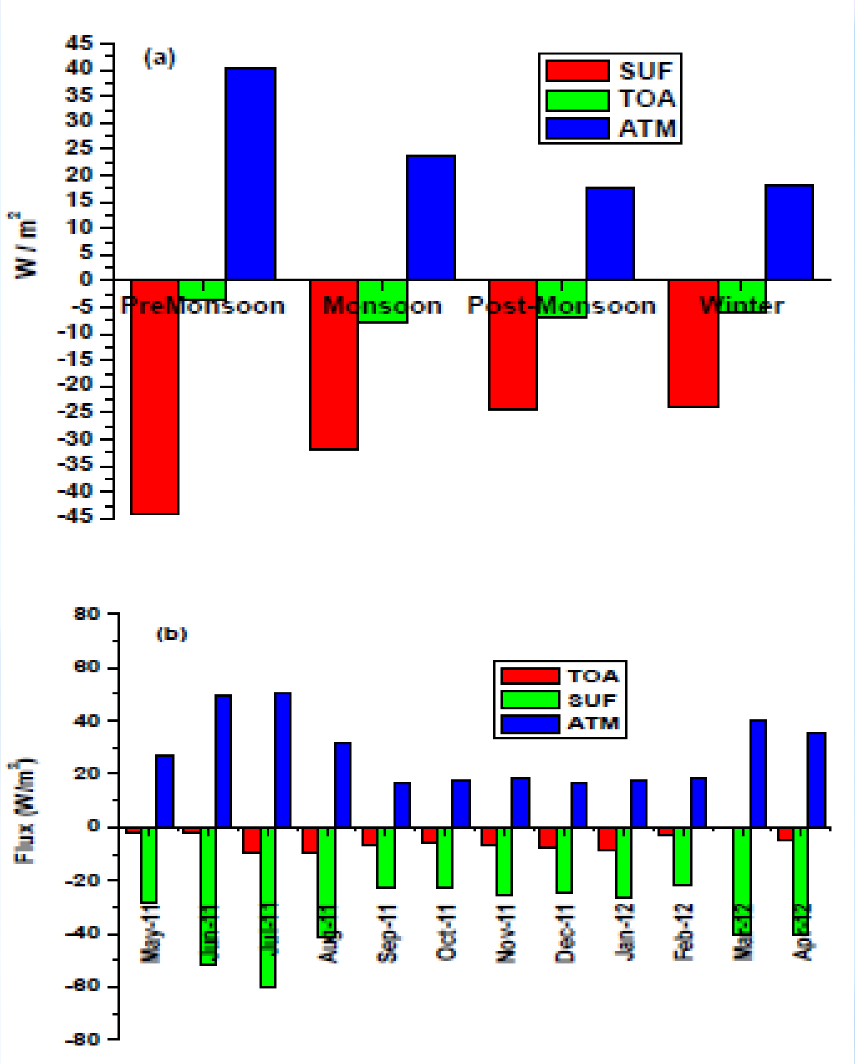




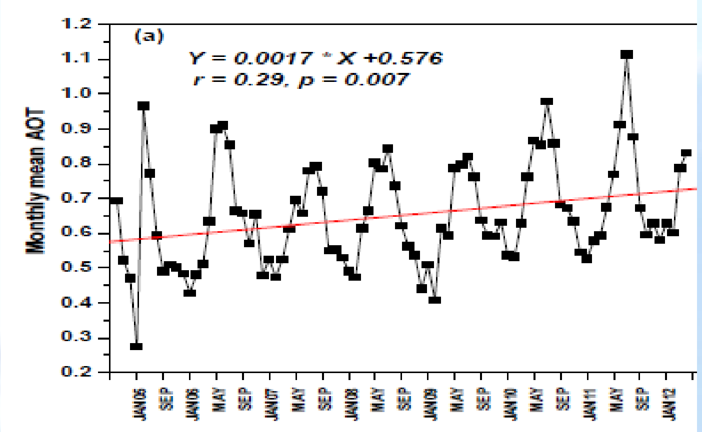


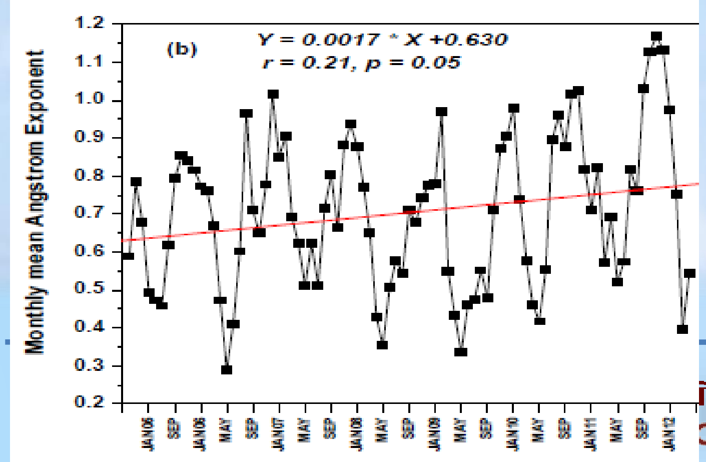
Jodhpur

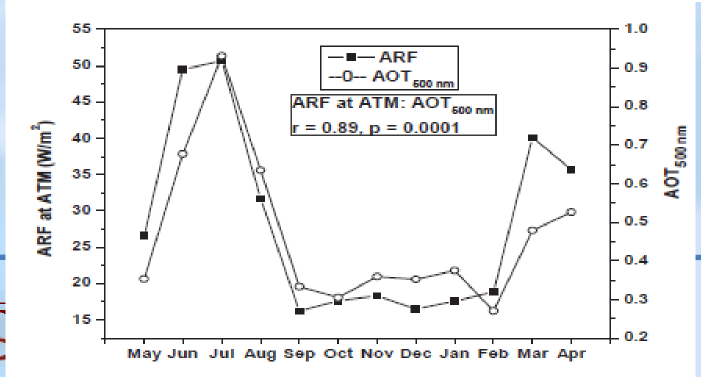


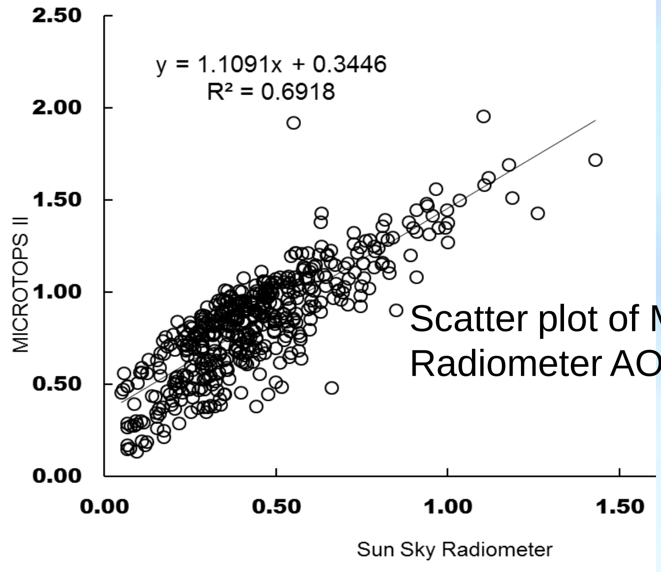


Long Term Variation of (a) Microtops AOT at 500 nm and (b) Angstrom Exponent 2004-12



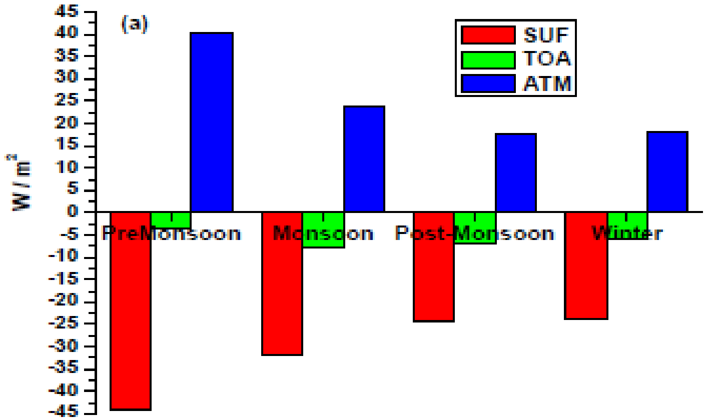


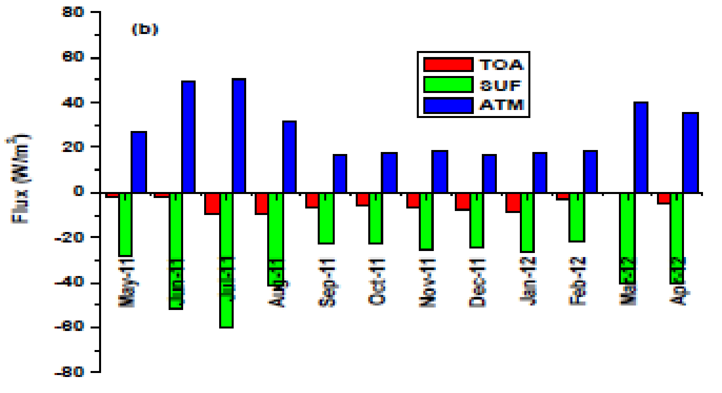


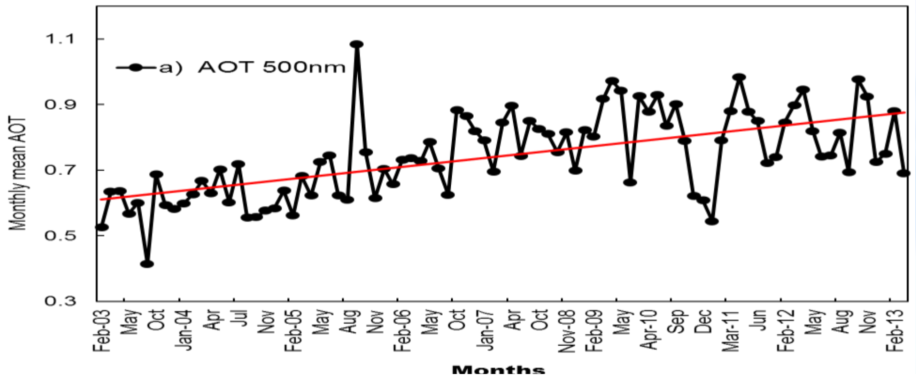


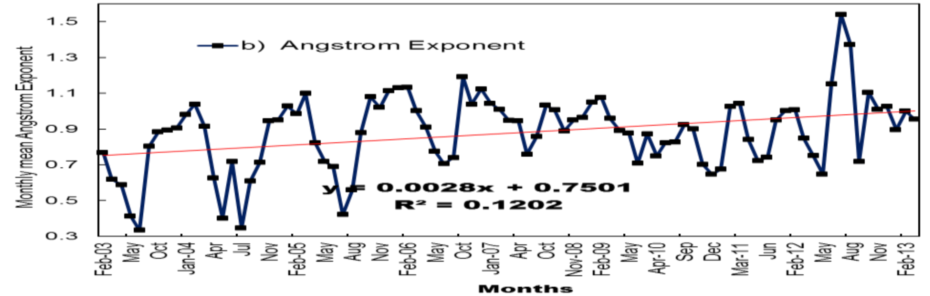
PUNE

Scatter plot of Microtops & Sun Sky Radiometer AOT at 500 nm at Pune.









Variation of (a) Microtops AOT at 500 nm and (b) Angstrom Exponent during 2003-13