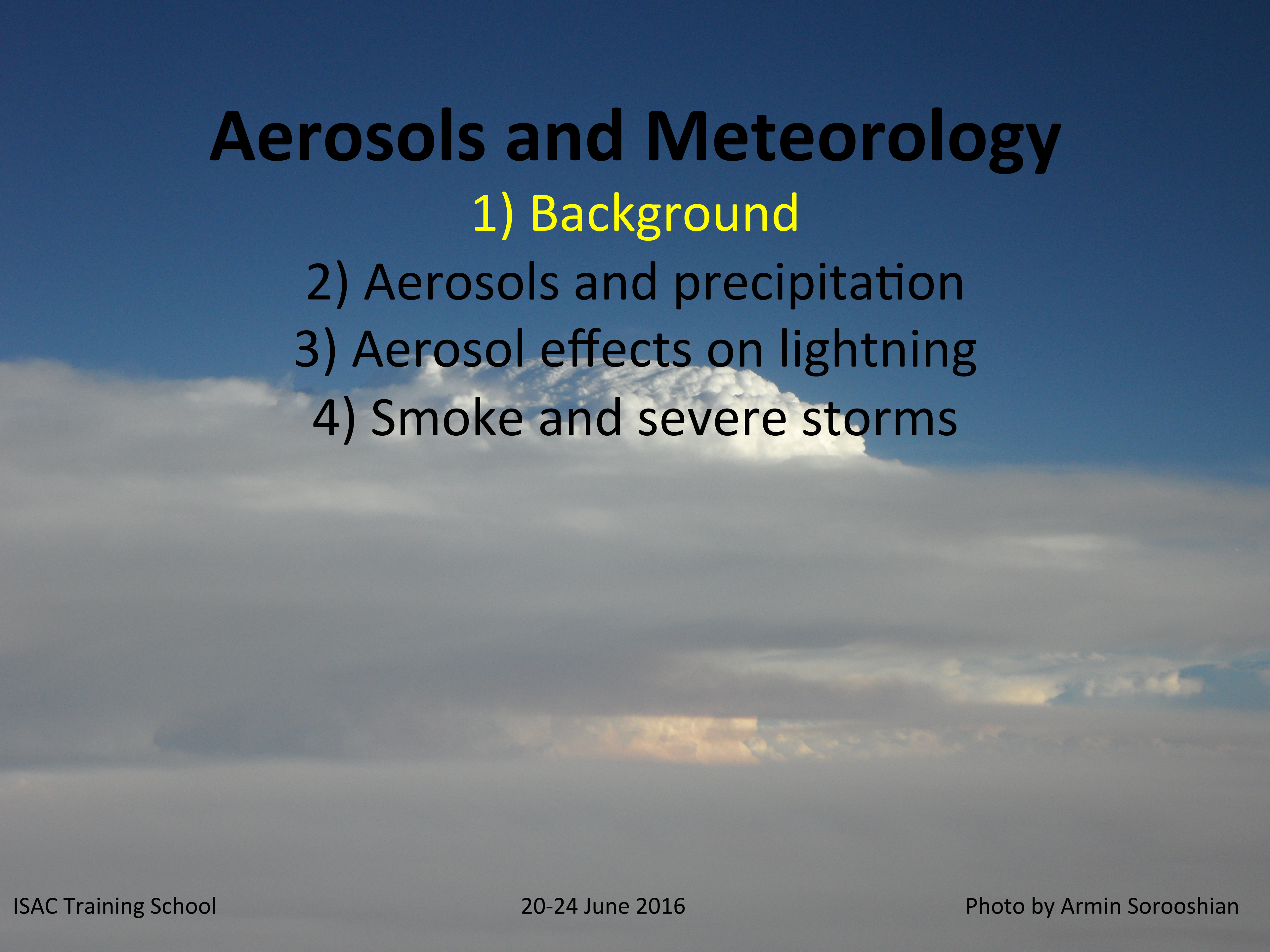
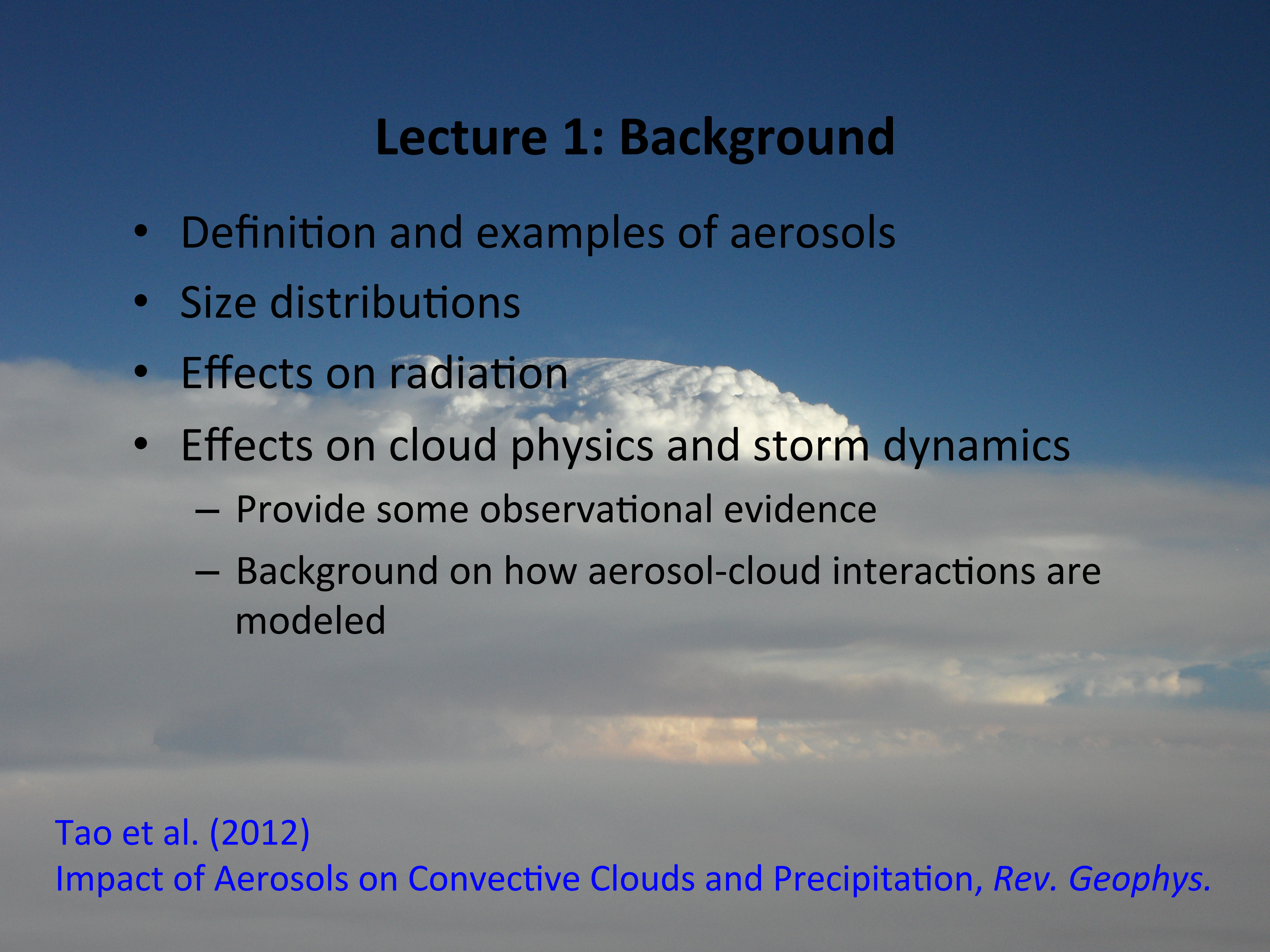


Aerosols and Meteorology

1) Background
2) Aerosols and precipitation
3) Aerosol effects on lightning
4) Smoke and severe storms

Photo by Armin Sorooshian



Lecture 1: Background

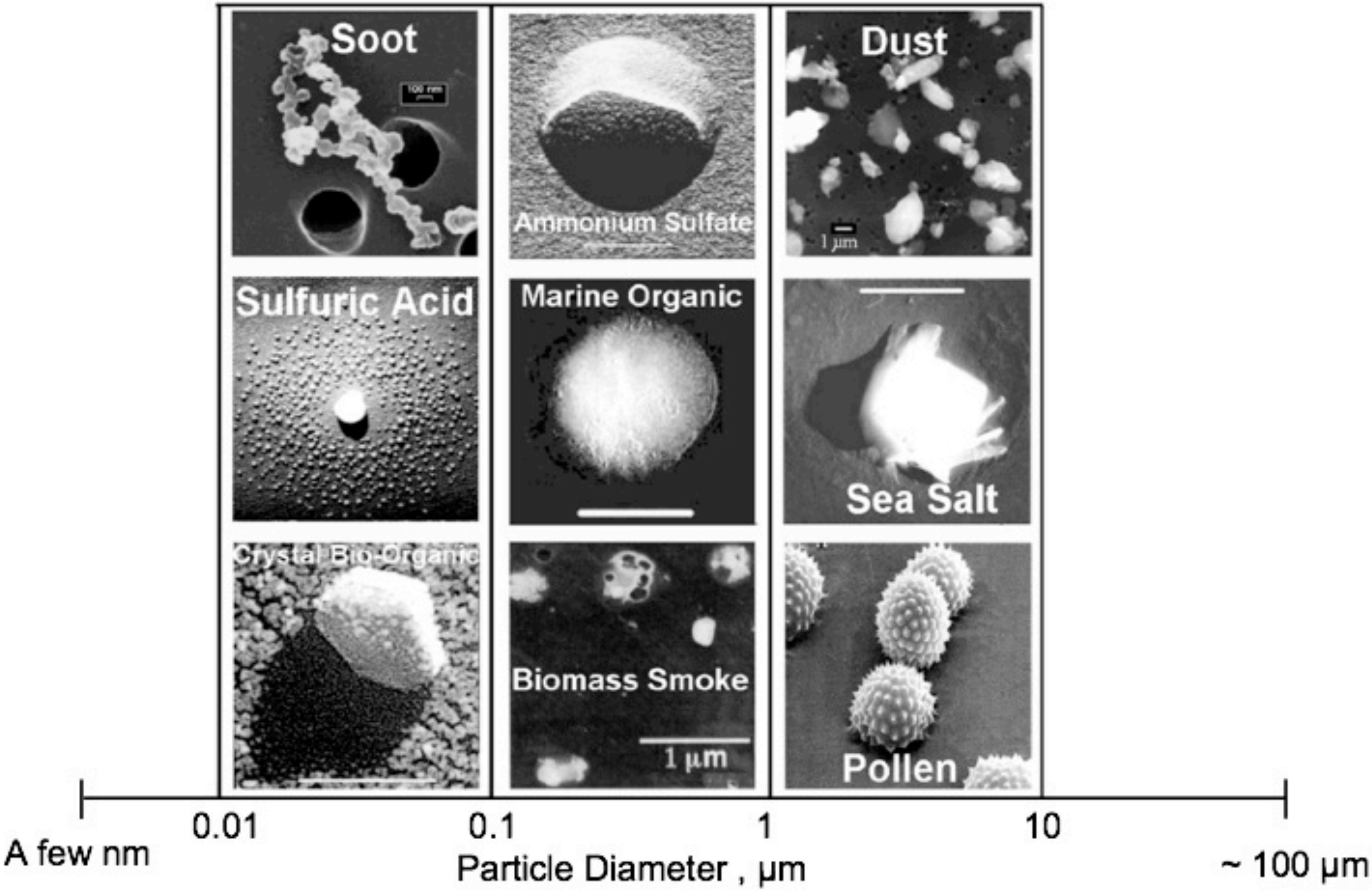
- Definition and examples of aerosols
- Size distributions
- Effects on radiation
- Effects on cloud physics and storm dynamics
  - Provide some observational evidence
  - Background on how aerosol-cloud interactions are modeled

Tao et al. (2012)
Impact of Aerosols on Convective Clouds and Precipitation, *Rev. Geophys.*

What are aerosols?

- An aerosol is defined as a colloidal system of solid or liquid particles in a gas. An aerosol includes both the particles and the suspending gas, which is usually air.

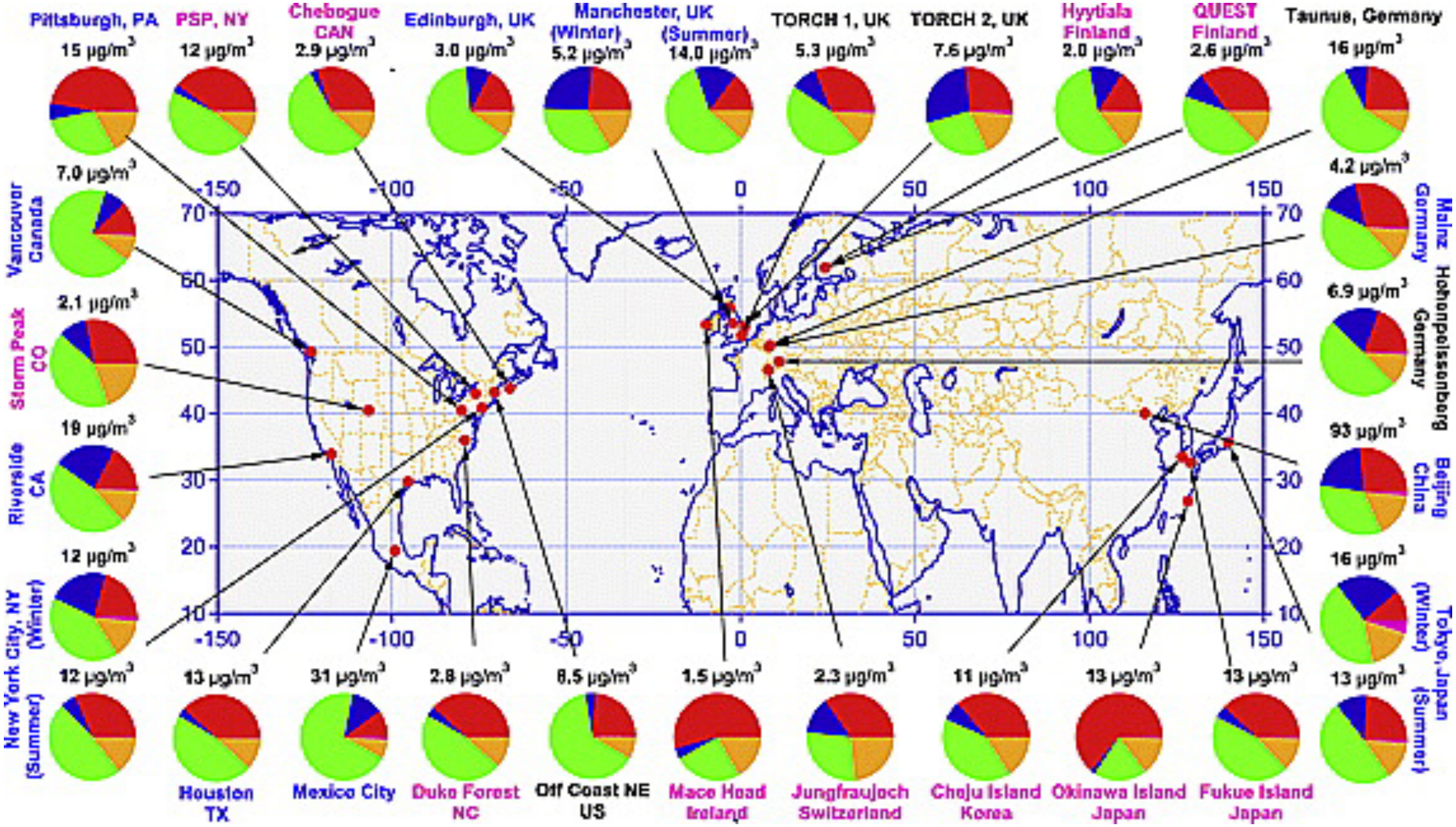
What are aerosols?



http://www.esrl.noaa.gov/research/themes/aerosols/pdf/AerosolIntro.pdf

What are aerosols?

Aerosol Composition at Urban and Rural Locations (Zhang et al., 2007)



Sulfate, nitrate, ammonium, organics

Not included: black carbon, dust, sea salt, water

Measurements from Aerosol Mass Spectrometer which analyzes aerosols < 1000 nm

What are aerosols?

- An aerosol is defined as a colloidal system of solid or liquid particles in a gas. An aerosol includes both the particles and the suspending gas, which is usually air.

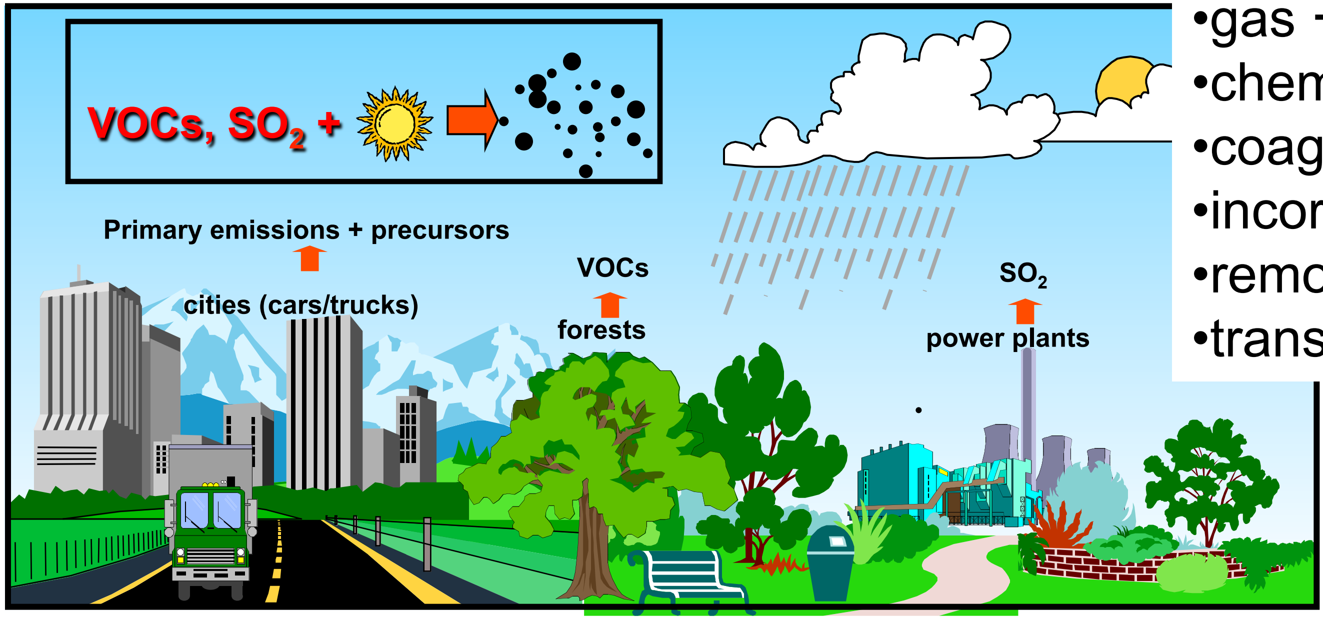
- *Primary aerosols* contain particles introduced directly into the gas;
- ***Secondary aerosols*** form through gas-to-particle conversion.

Secondary (produced in atmosphere) sources of particles:

- vehicles (organics, nitrates)
- industry (sulfate, organics, nitrates, ammonium)
- plants (organics)
- agriculture (ammonium, nitrate)

Atmospheric processes:

- gas → particle conversion
- chemical reactions
- coagulation
- incorporation into clouds
- removal by precipitation
- transport



Primary (directly emitted) sources of particles:

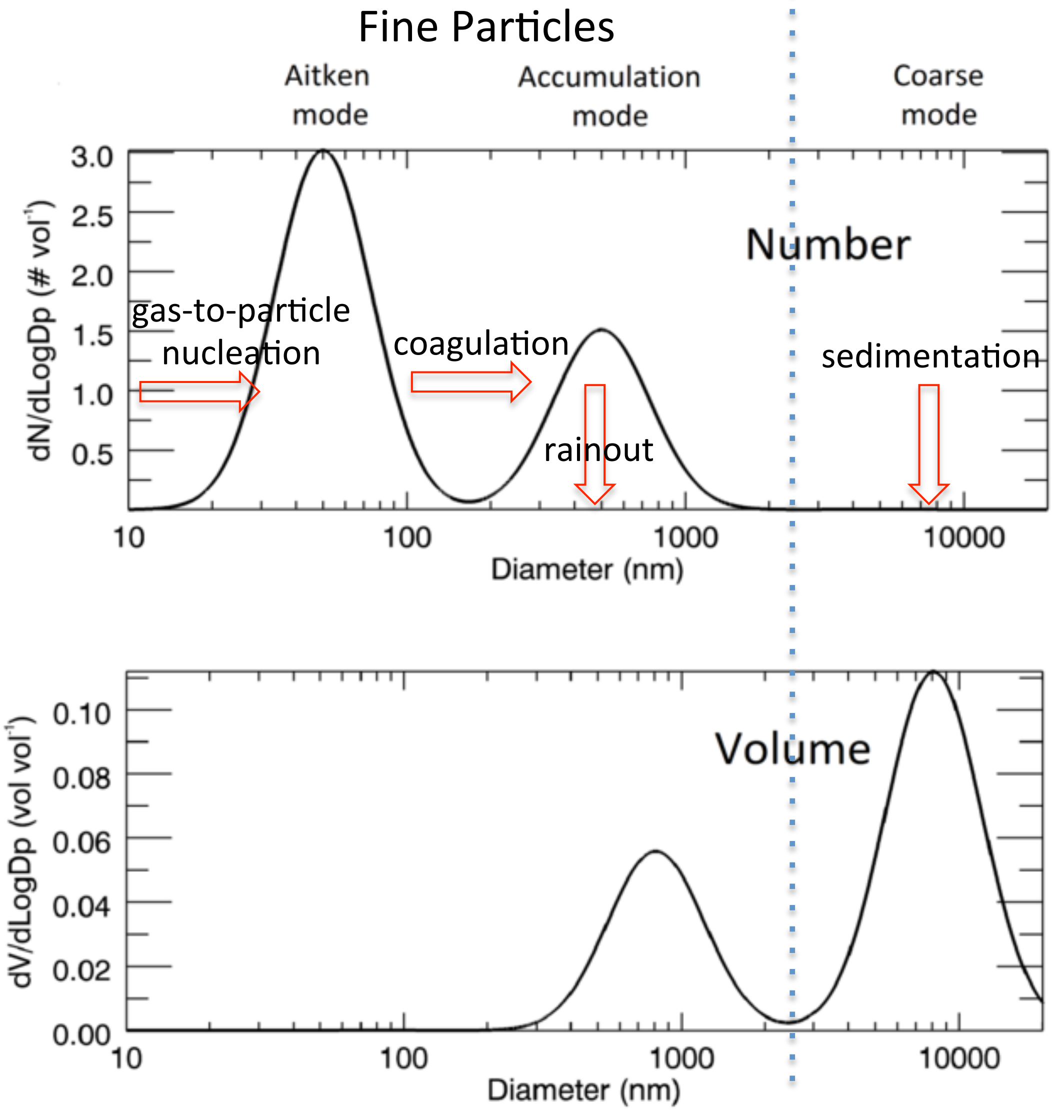
- vehicles (soot, organics)
- industry (soot, sulfate, organics, metals)
- construction & agriculture (soot, soil)
- sea-spray (salt)
- fires (soot and organics)

From: http://www.esrl.noaa.gov/research/themes/aerosols/pdf/AerosolProcesses.pdf

Aerosol Size Distribution

<u>Chemical Processes</u>

- Sulfate
- Nitrate
- Ammonium
- Organics
- Black carbon



Fine Particles

Aitken mode

Accumulation mode

Coarse mode

gas-to-particle nucleation

coagulation

rainout

sedimentation

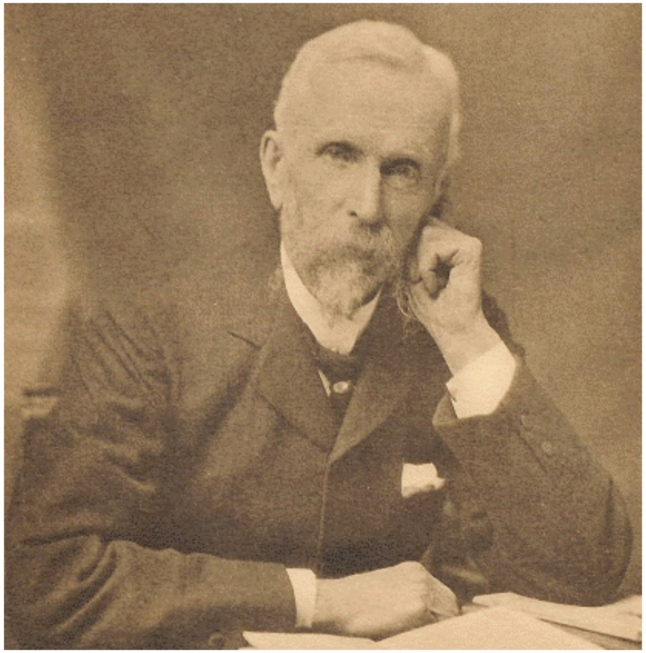
<u>Mechanical Processes</u>

- Dust
- Sea salt
- Pollen
- Spores
- Ash (volcanos)

CC0, https://en.wikipedia.org/w/index.php?curid=37039318

"We have in this fine dust a most beautiful illustration of how the little things in the world work great effects by virtue of their numbers."

-John Aitken, 1880



http://www.iara.org/AerosolPioneers.htm

Why are aerosols important?

- Aerosols affect the energy budget of the atmosphere by scattering and/or absorbing radiation
- Aerosols play a key role in forming cloud droplets and ice crystals

➢ Aerosols affect cloud properties, e.g. albedo, lifetime, precipitation

Aerosols and Radiation

- Aerosols scatter solar radiation cooling the atmosphere
- Aerosols absorb solar radiation heating regions of the atmosphere

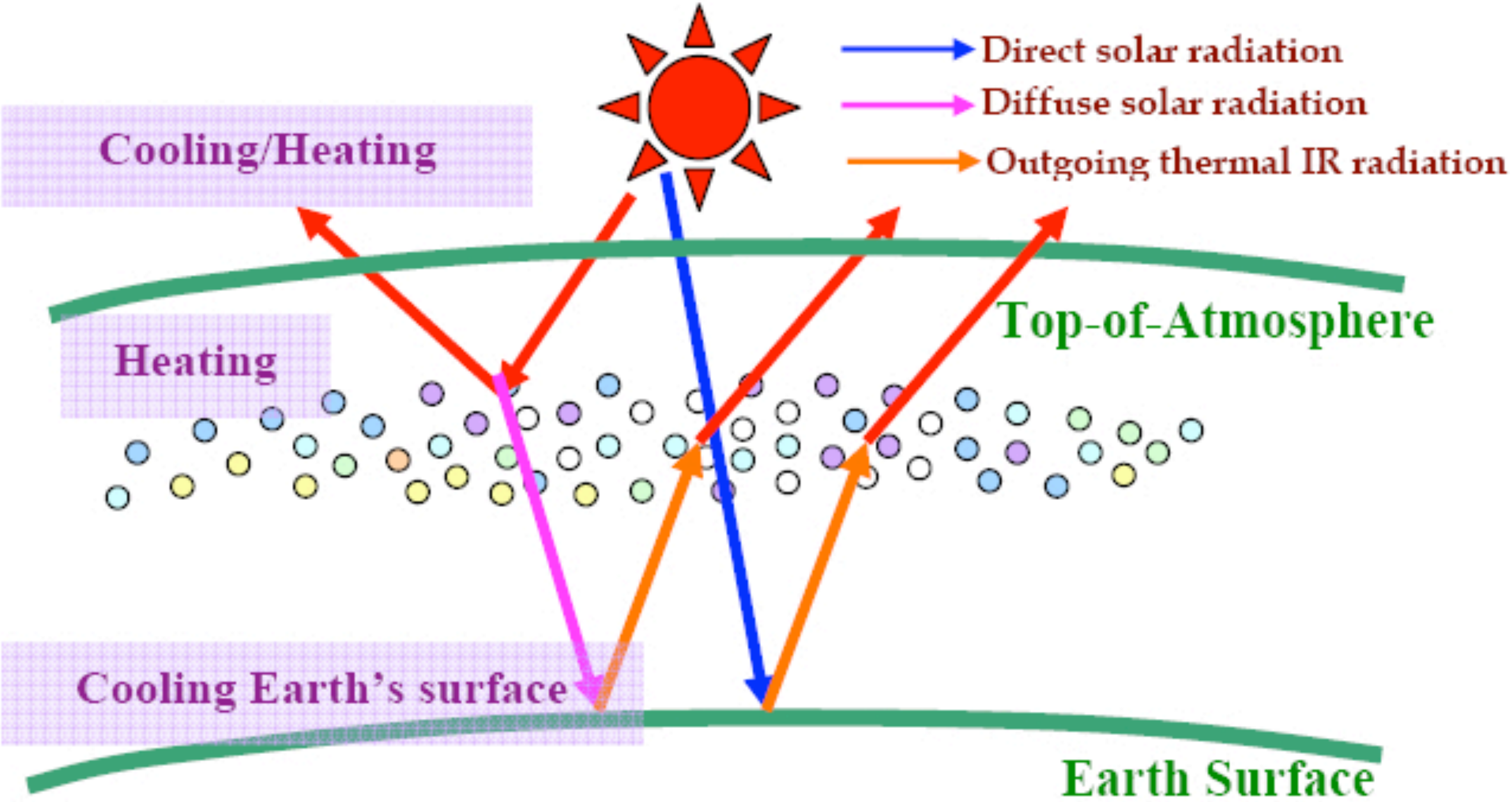


Image from S. Tripathy, IIT-Kanpur

Aerosols and Radiation

- Aerosols scatter solar radiation cooling the atmosphere **(sulfate, nitrate, sea salt)**
- Aerosols absorb solar radiation heating regions of the atmosphere **(BC, dust, BrC)**

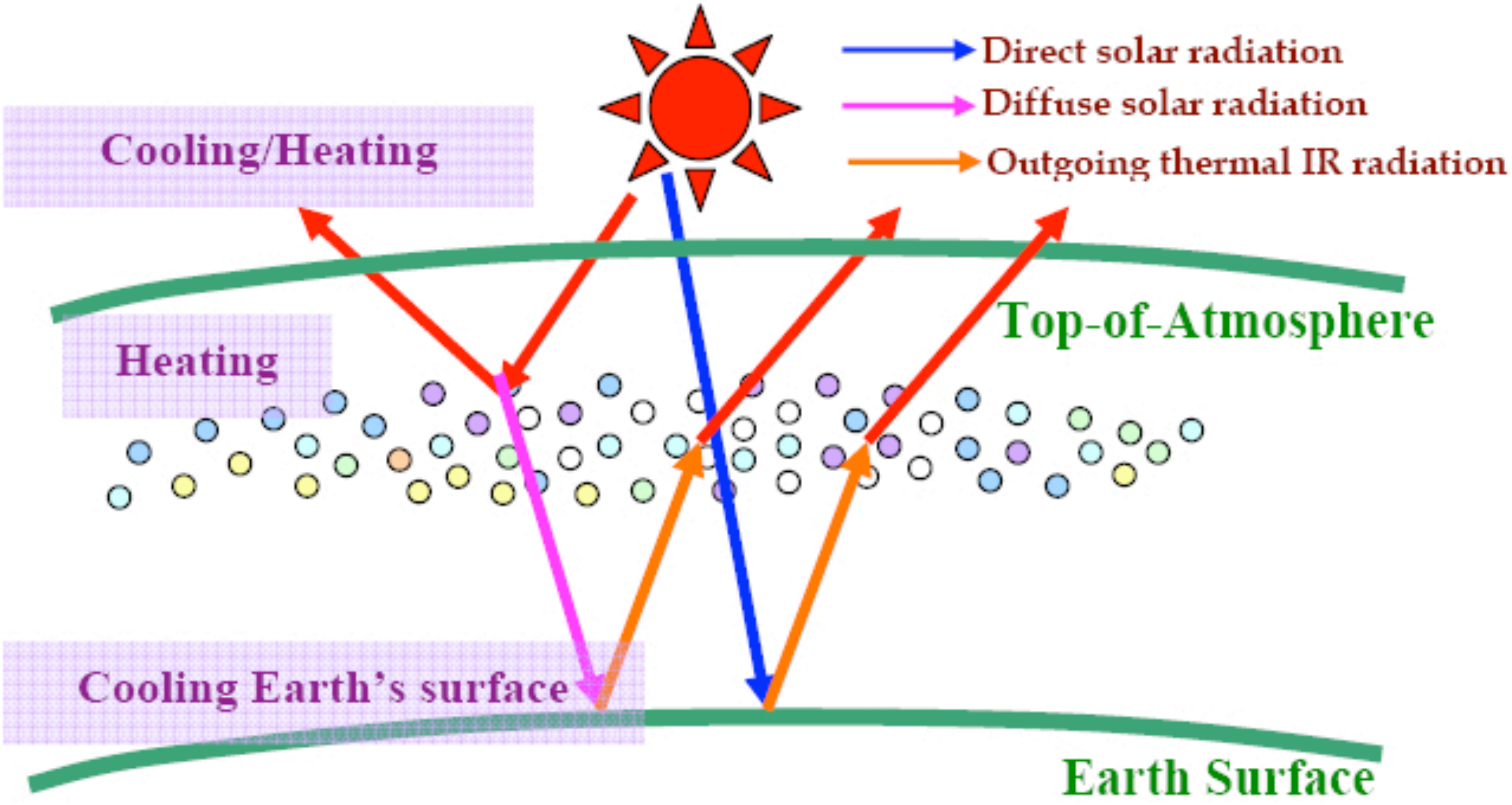
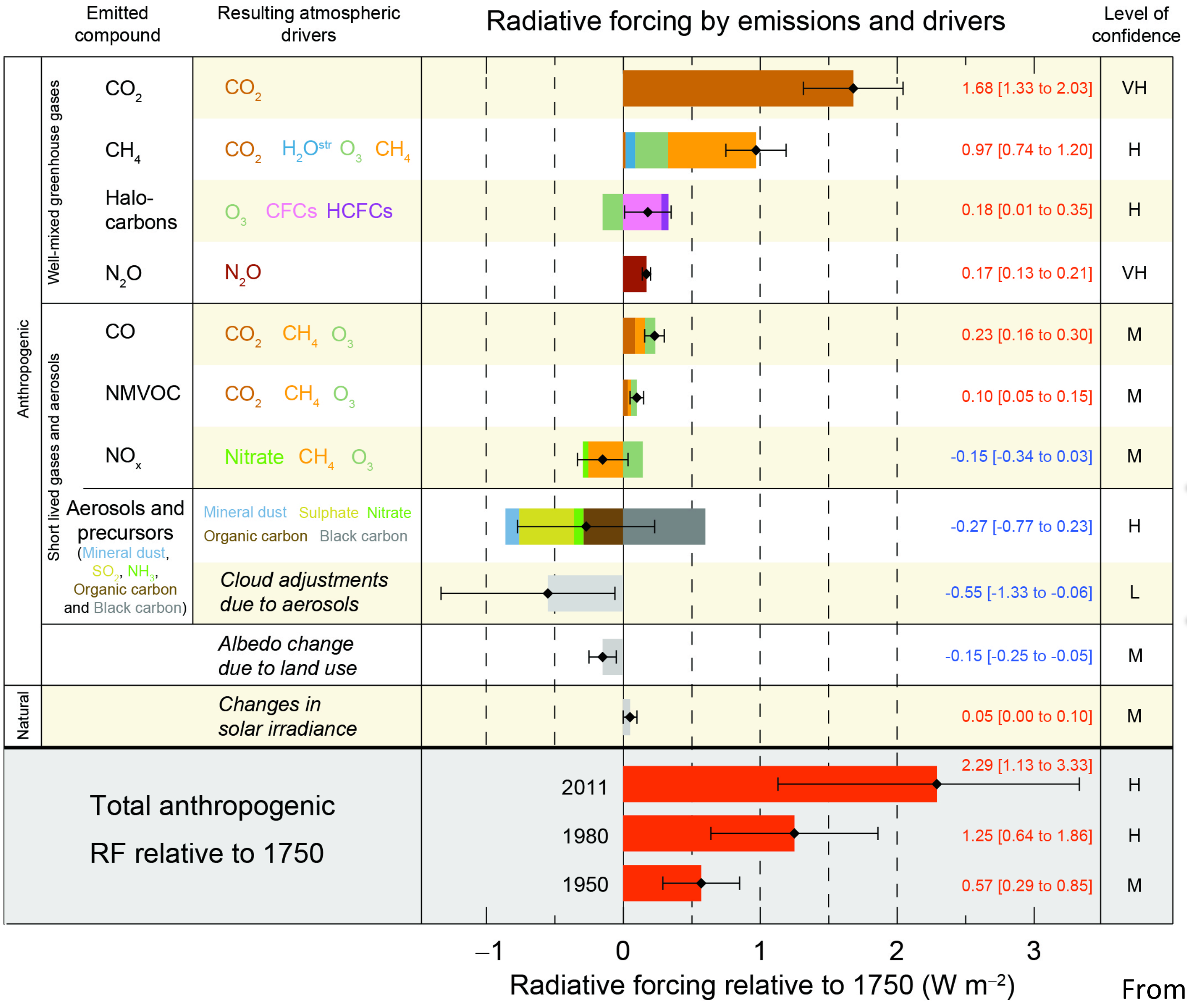


Image from S. Tripathy, IIT-Kanpur

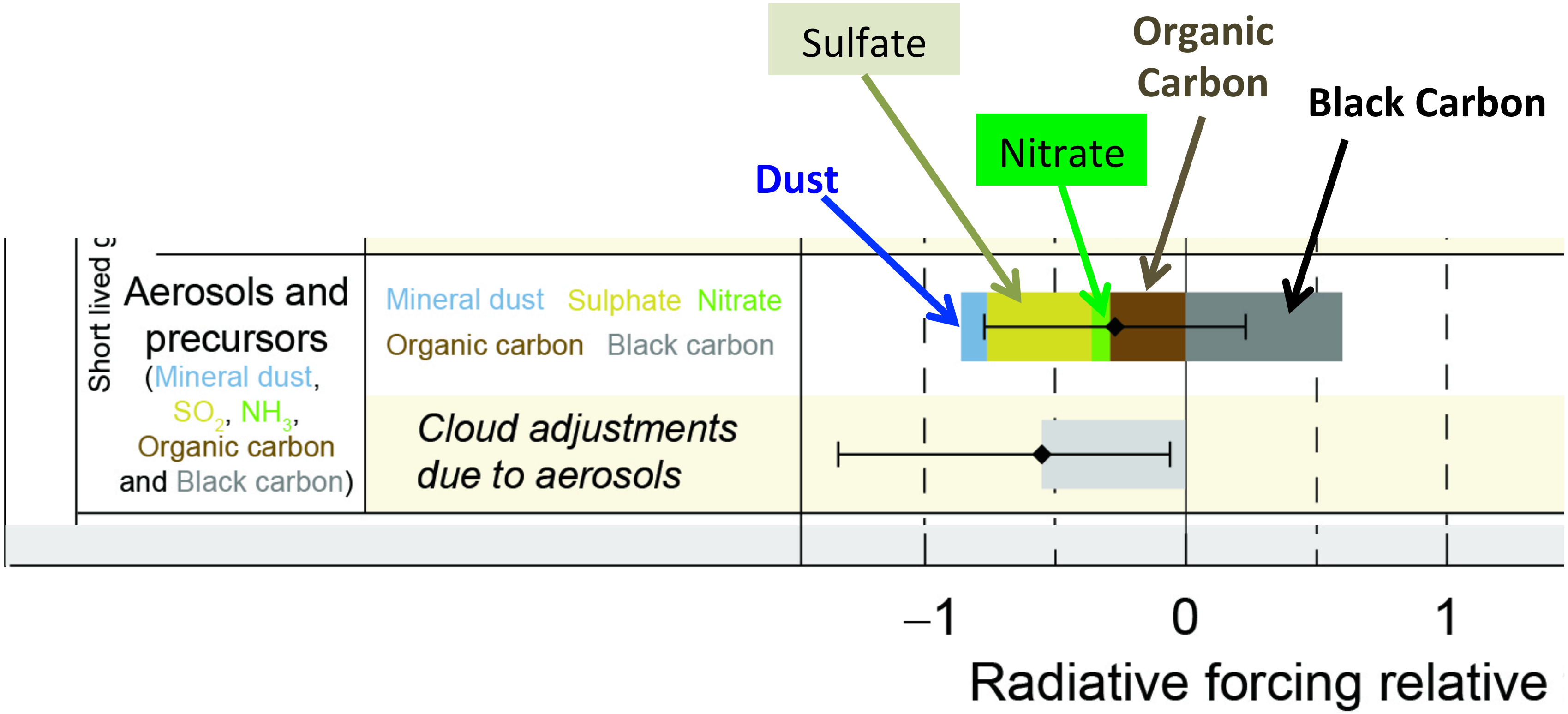
Aerosols and Climate



Aerosols

From IPCC 5th Assessment

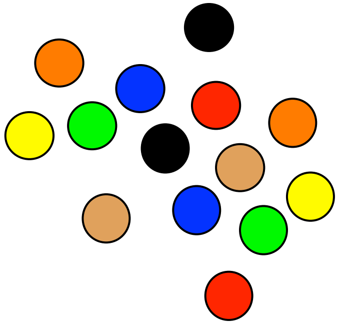
Aerosols and Climate

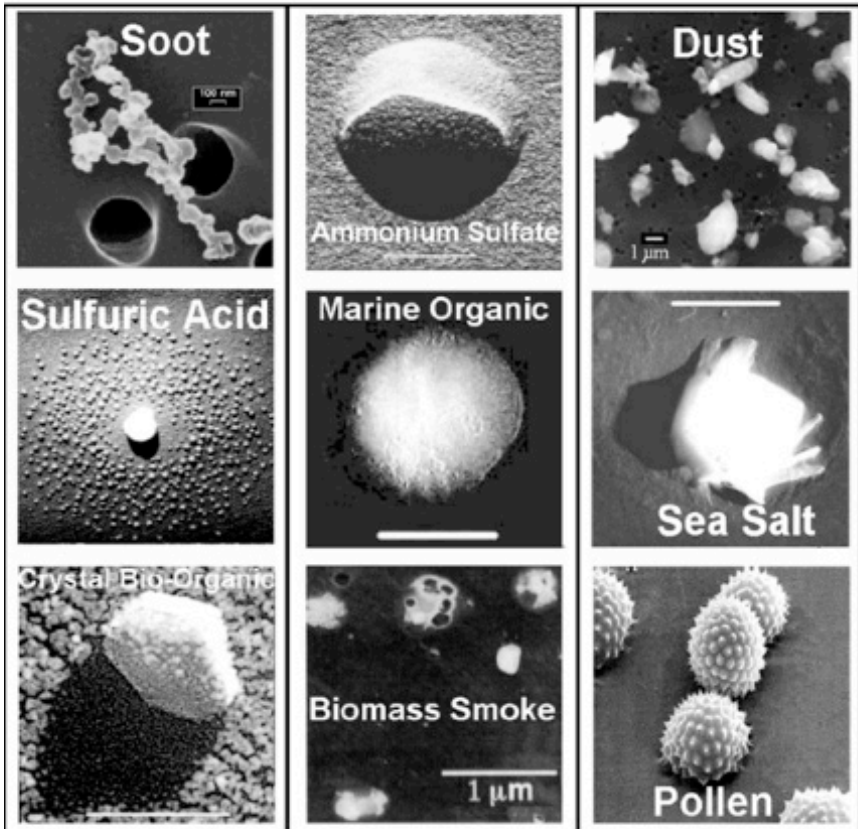


From IPCC 5th Assessment

Aerosol Mixtures

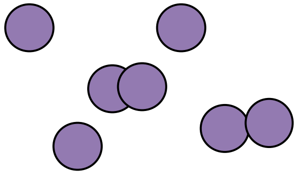
External Mixture:
Each particle is separate in composition: BC, sulfate, sea salt



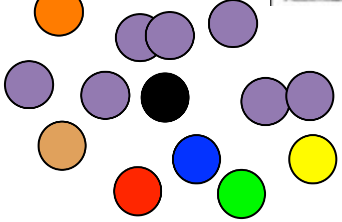


No combinations, e.g. sulfate coating BC aerosol

Internal Mixture:
Each particle is same composition:
BC+sulfate+sea salt



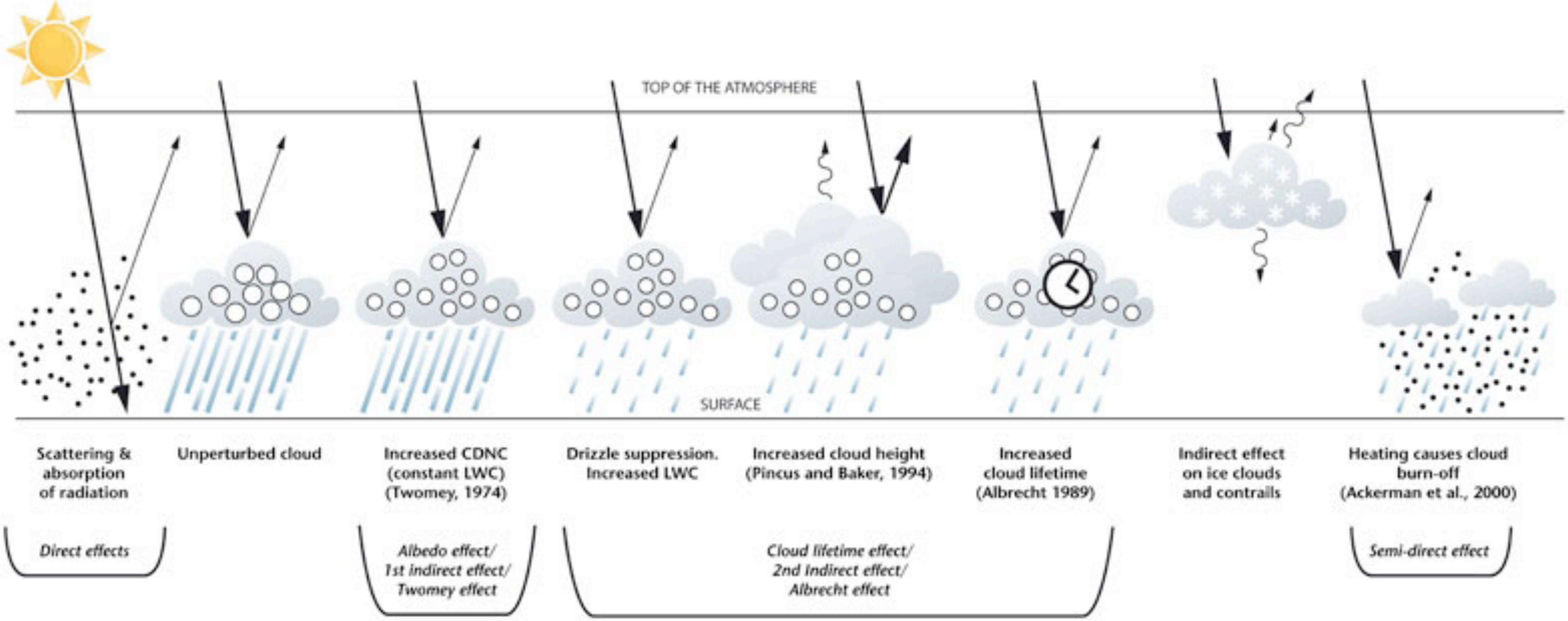
Reality:
Have aerosols that are both external and internal mixtures



Composition is important in affecting radiation – extent of scattering vs absorbing

Aerosol Effects on Clouds and Radiation

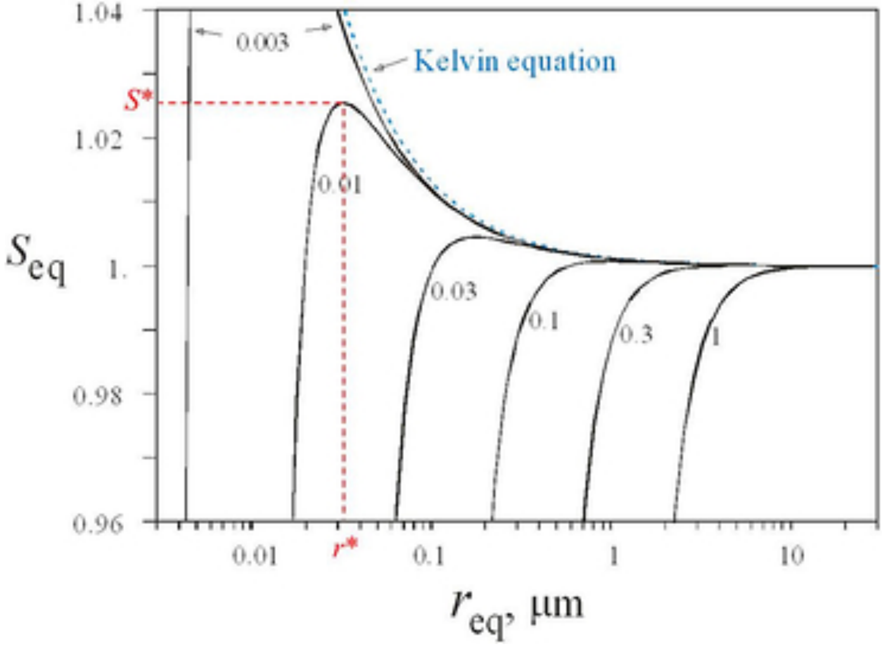
Background



Met Office

http://www.metoffice.gov.uk/research/areas/chemistry-ecosystems/aerosols

Aerosols and Clouds



Cloud drops form on aerosols:
Cloud Condensation Nuclei (CCN)

Köhler curves show relation between the equilibrium saturation ratio over the solution drop surface as a function of drop radius

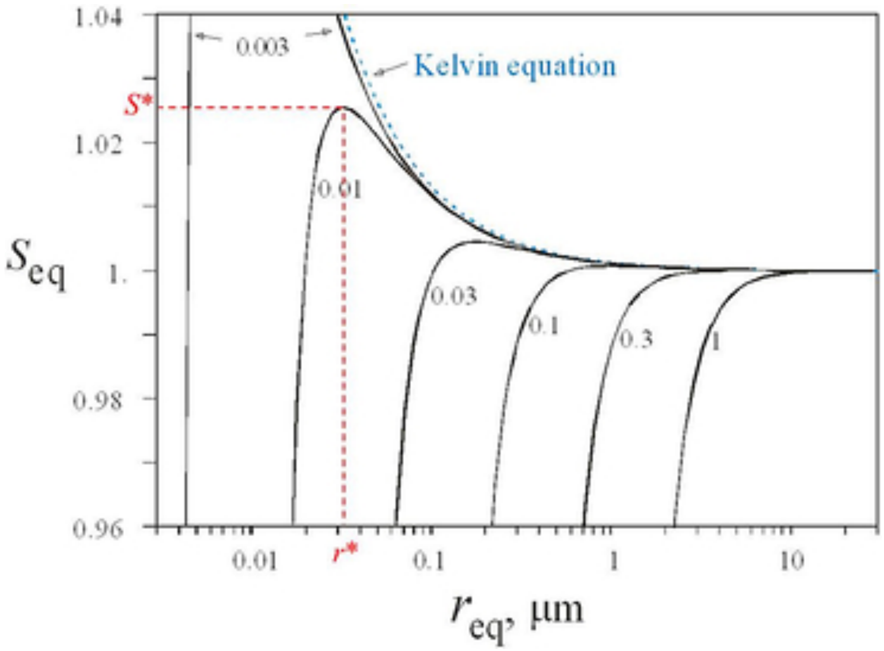
Drops contain dissolved salt causing a solute effect (Raoult) reducing surface vapor pressure

Curvature effect (Kelvin) increases saturation ratio

Peak saturation ratio at a unique critical radius

Tao et al. (2012) *Rev. Geophys.*

Aerosols and Clouds



Important Factors for Drop Formation:

Supersaturation (RH > 100%)

Particle Size

Particle Chemical Composition
-- alters Raoult (via water activity) and Kelvin effects (via surface tension)

Temperature
-- aerosol temperature (e.g. warmed by latent heating, or solar radiation absorption) affects saturation vapor pressure, surface tension, solution activity

How is this represented in cloud-resolving to global models?

Tao et al. (2012) *Rev. Geophys.*

Aerosols and Clouds

$$N_{CCN} = C\,\mathbf{S}^{k}$$

- Simple and effective formulation
- But N_{CCN} is always increasing – unrealistic
- No dependence on chemical composition

Important Factors for Drop Formation:

Supersaturation (RH > 100%)

Particle Size

Particle Chemical Composition
-- alters Raoult (via water activity) and Kelvin effects (via surface tension)

Temperature
-- aerosol temperature (e.g. warmed by latent heating, or solar radiation absorption) affects saturation vapor pressure, surface tension, solution activity

Tao et al. (2012) *Rev. Geophys.*

Aerosols and Clouds

- Köhler theory to find supersaturation
- Hygroscopicity parameter, ***κ***, used to represent the aerosol population's affinity for water and how readily the aerosols will activate to cloud drops

Important Factors for Drop Formation:

Supersaturation (RH > 100%)

Particle Size

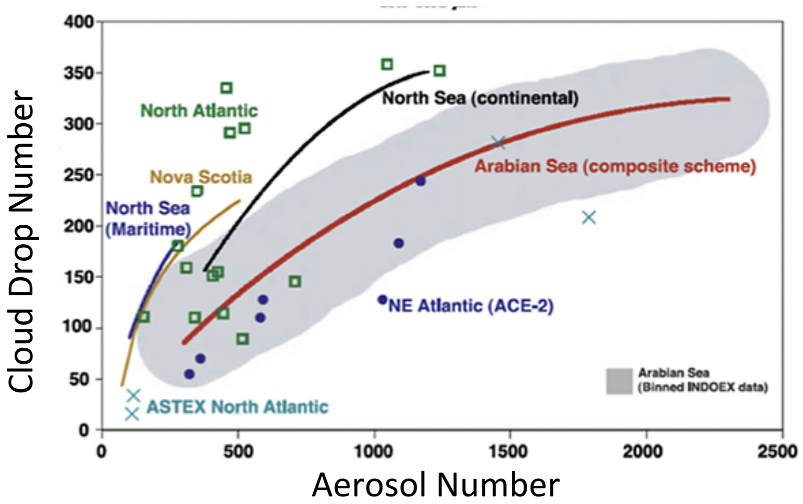
Particle Chemical Composition
-- alters Raoult (via water activity) and Kelvin effects (via surface tension)

Temperature
-- aerosol temperature (e.g. warmed by latent heating, or solar radiation absorption) affects saturation vapor pressure, surface tension, solution activity

Tao et al. (2012) *Rev. Geophys.*

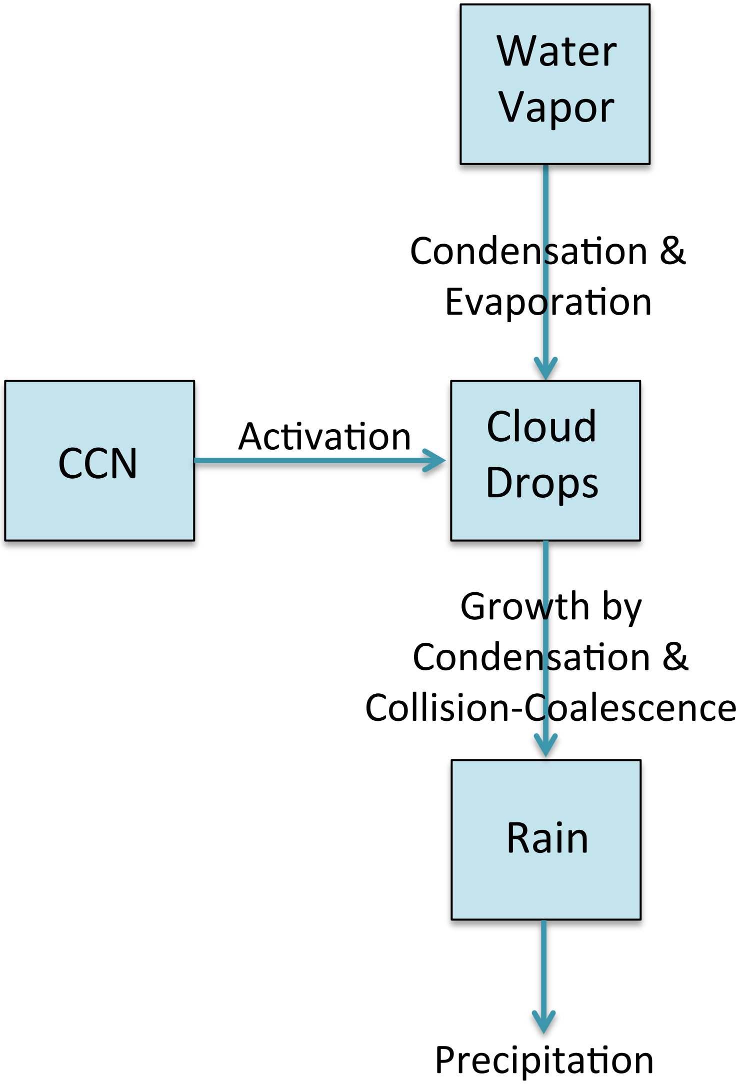
Modeling Cloud Drop Formation

- Many cloud resolving models (CRMs) predict supersaturation **S** using Köhler theory with the hygroscopicity parameter κ
- Many global models and regional cloud models use a saturation adjustment assumption and do not predict **S** explicitly
- Because peak supersaturation occurs within the first 50 m of cloud base, many CRMs under-predict supersaturation
- One solution is embedding Lagrangian parcel model or using a look-up table produced from a Lagrangian parcel model



Observations of N_{CN} and N_d summarized by *Ramanathan et al.* (2001) *Science*

Warm Rain Formation



Water Vapor

Condensation & Evaporation

CCN

Activation

Cloud Drops

Growth by Condensation & Collision-Coalescence

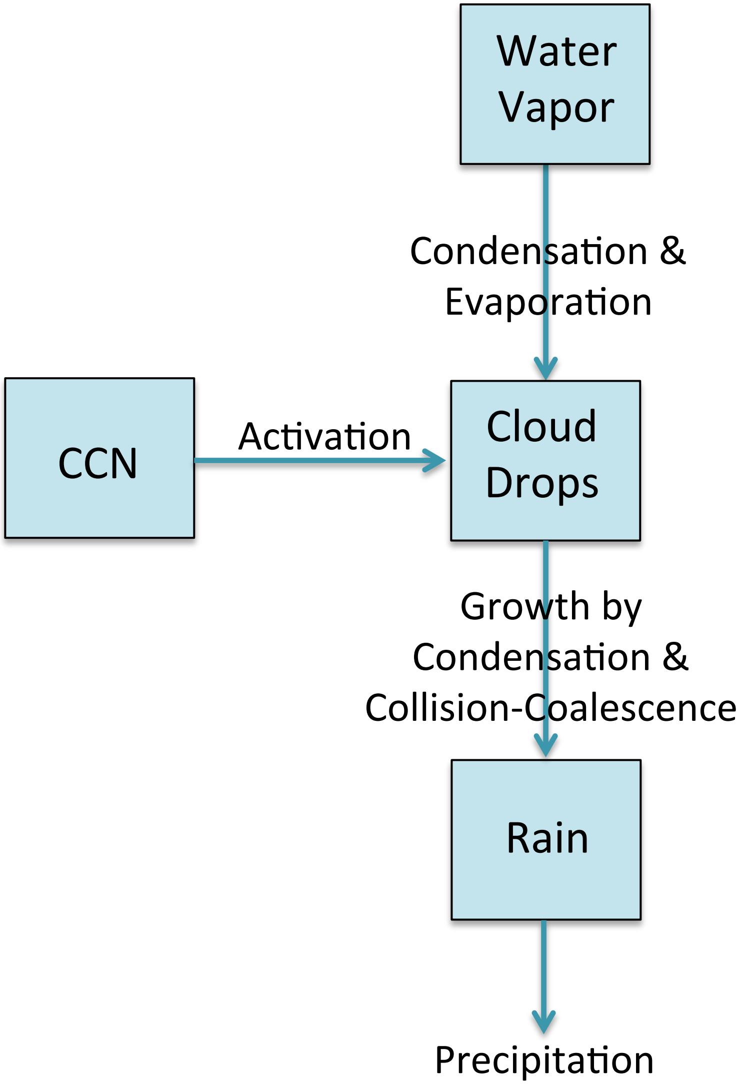
Rain

Precipitation

Rain formed by

- growing cloud drops,
- collision-coalescence of cloud drops,
- collection of cloud drops by rain drops

Warm Rain Formation



- When N_{CCN} increase, N_{drop} increase
- Higher N_{drop} leads to smaller cloud drops → collision-coalescence becomes less efficient → difficult to form rain (i.e., drops > 24 µm diameter)
- Higher N_{drop} leads to narrow cloud drop size spectrum → less difference in fall speeds leads to suppression of rain

Warm Rain Formation

- When N_{CCN} increase, N_{drop} increase
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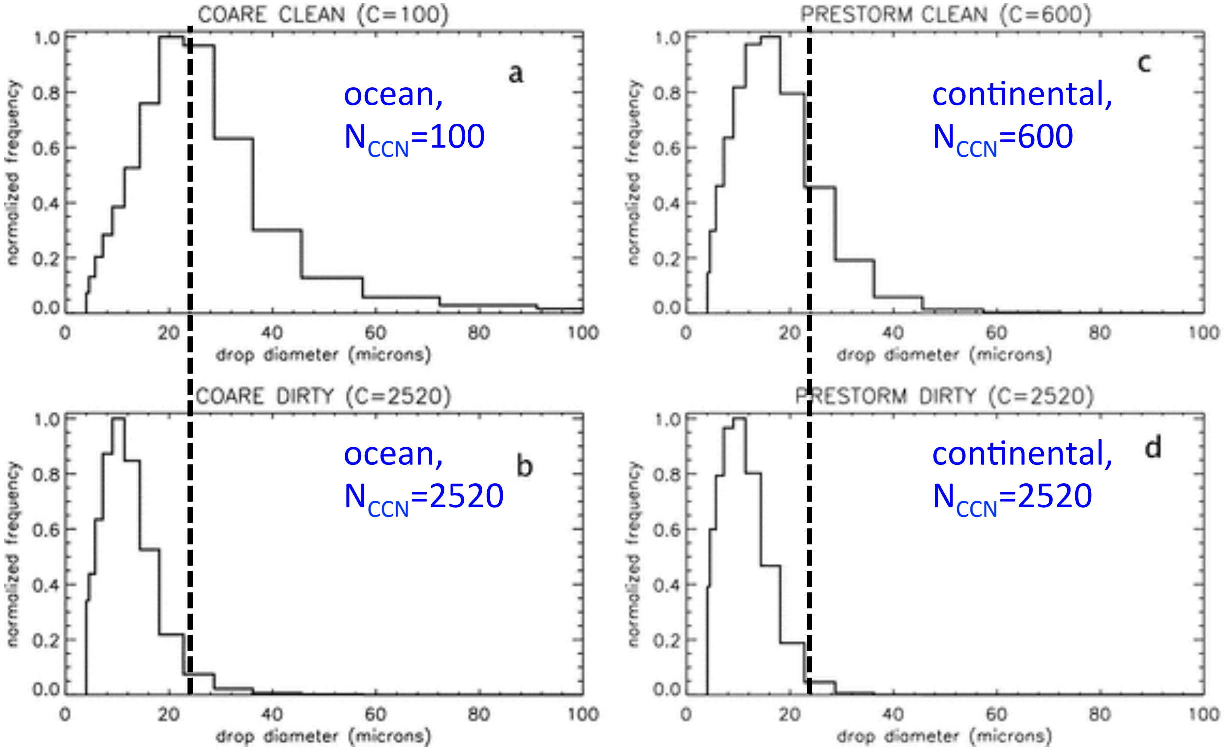
- **Higher N_{drop} leads to narrow cloud drop size spectrum** → less difference in fall speeds leads to suppression of rain

Compare drop size distributions in top panel to bottom panel

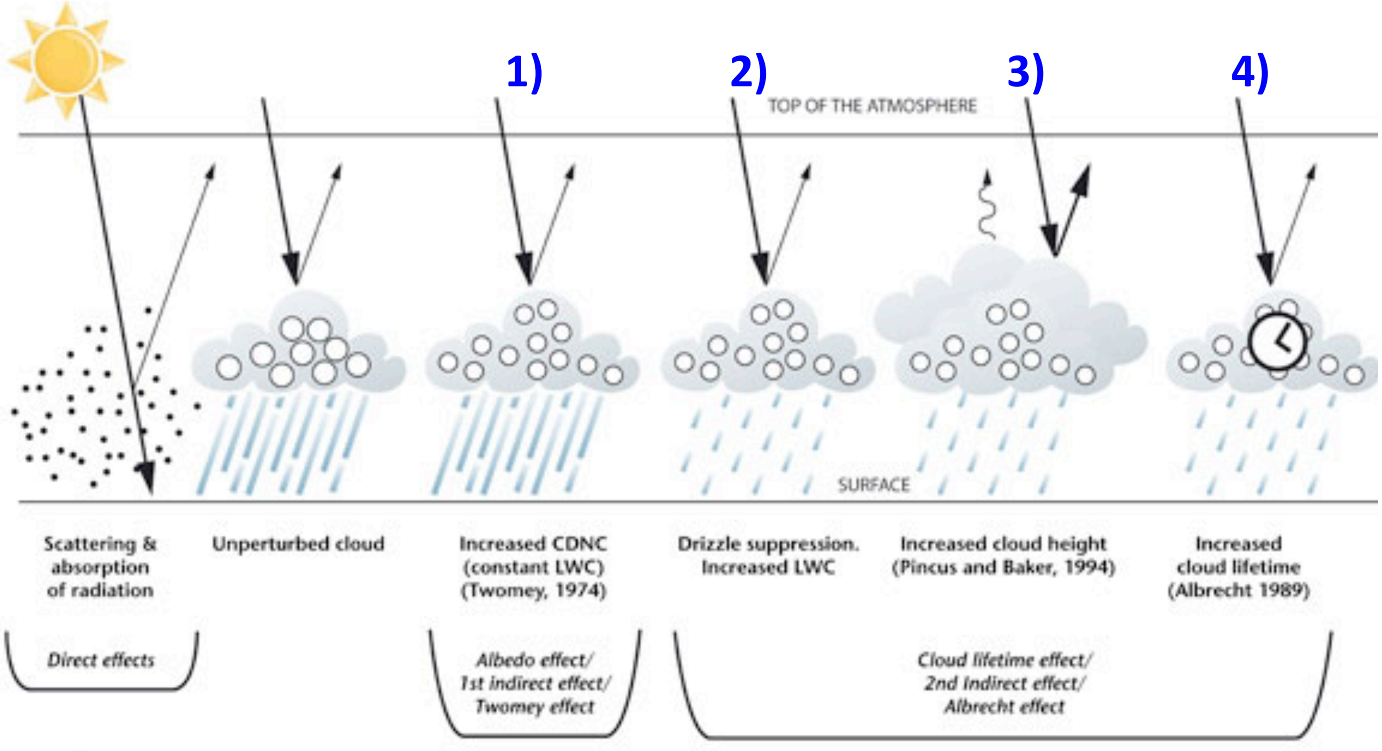


Tao et al. (2012) *Rev. Geophys.*

Aerosol Effects on Clouds and Radiation

Increased number of aerosols with same liquid water content:

1) → increased cloud drop number and cloud albedo
2) → less drizzle, increased LWC in cloud 3) → increased cloud height 4) → increased cloud lifetime



Met Office

http://www.metoffice.gov.uk/research/areas/chemistry-ecosystems/aerosols

Ice Formation

Homogeneous Ice Nucleation: freezing of aerosol or cloud drops

- Occurs at T < -40°C
- Number of ice crystals controlled by number of CN entering clouds

Heterogeneous Ice Nucleation: Ice nuclei aids freezing

- Occurs at T > -40°C
- Water vapor directly depositing onto ice nuclei
- Cloud drops collide with aerosol at below freezing temperatures
- Cloud drops collected by ice, snow, graupel, or hail (riming)

- N_{CN} affects ice nucleation because it affects N_d
- CN affect growth of ice particles via Wegener-Bergeron-Findeisen process (water evaporating from cloud drops in order to deposit on ice) → higher N_d causes faster WBF process
- Riming is often suppressed with more CN (similar to collision-coalescence)

Changes in the cloud physics affect the latent heating and therefore dynamics of the storm

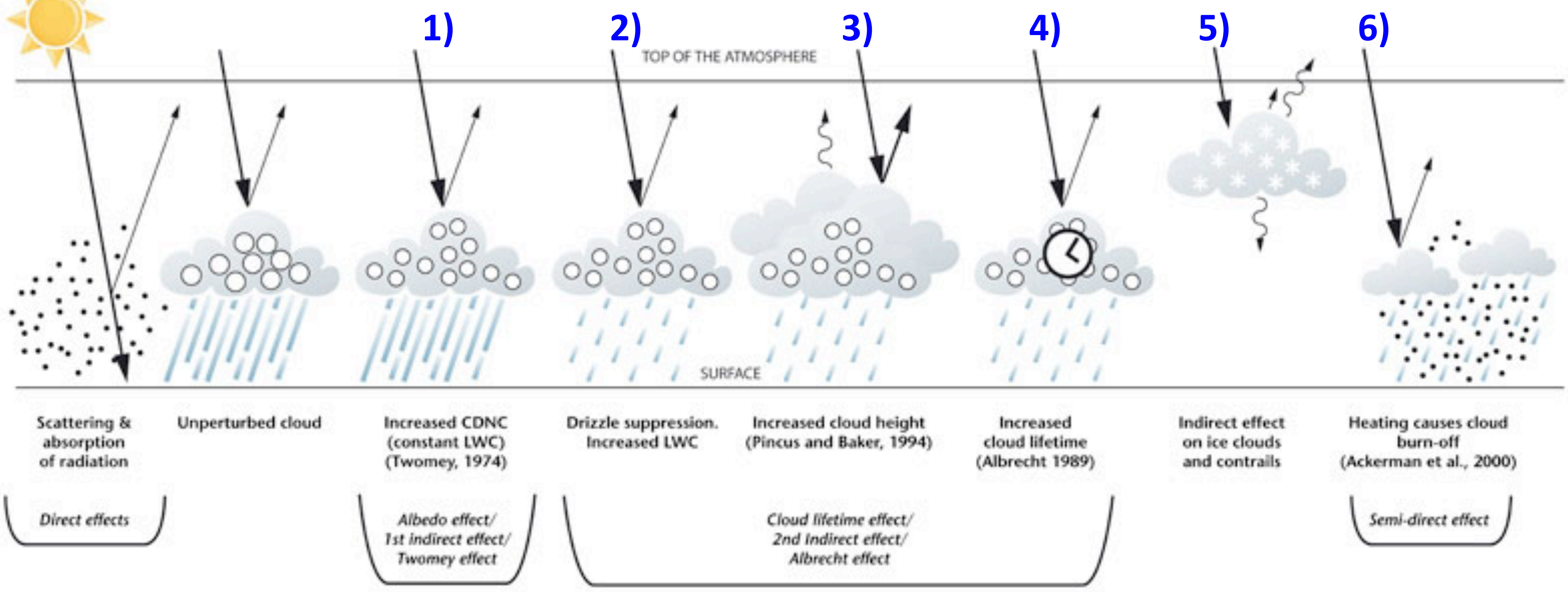
Aerosol Effects on Clouds and Radiation

Increased number of aerosols with same liquid water content:

1) → increased cloud drop number and cloud albedo
2) → less drizzle, increased LWC in cloud 3) → increased cloud height 4) → increased cloud lifetime

5) Increased number of aerosols affect cloud ice number and radiation

6) Absorbing aerosols cause heating → burn-off of clouds



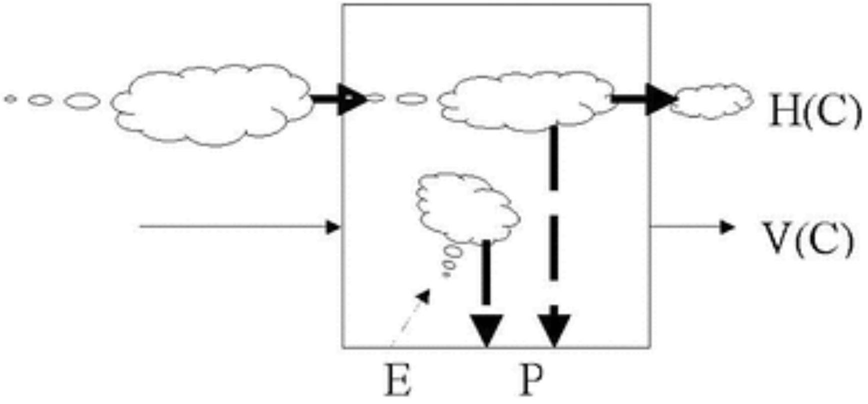
Met Office

http://www.metoffice.gov.uk/research/areas/chemistry-ecosystems/aerosols

Observing Aerosol Effects on Clouds and Radiation

Challenge of decoupling influences of atmospheric dynamics and thermodynamics

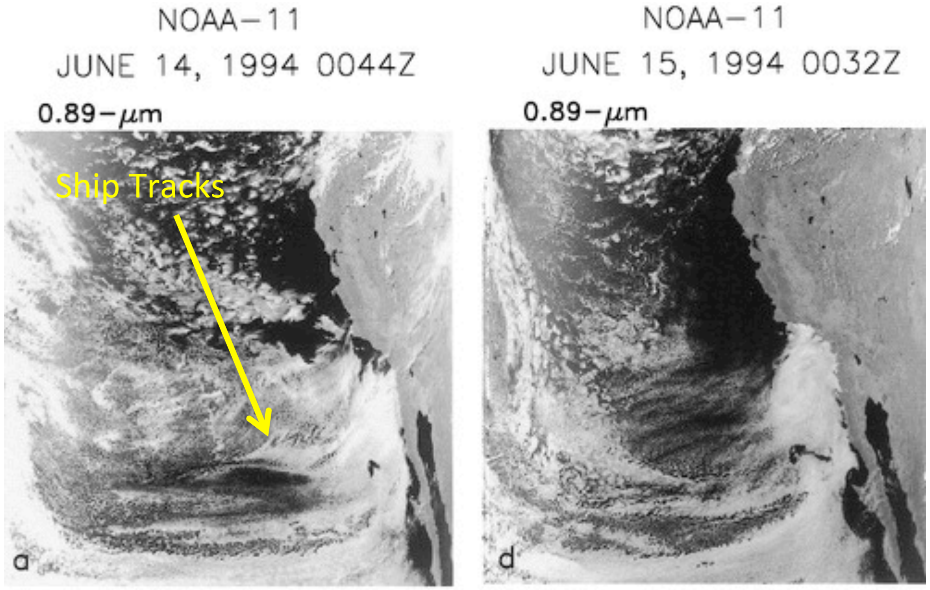
Major water processes occurring in an atmospheric column



- Observations have snapshots of aerosols, clouds, precipitation
- Satellite retrievals cannot see aerosols below clouds
- What is seen in the snapshot is a result of processes over a larger spatial-temporal domain (advection of cloud, water vapor, etc)

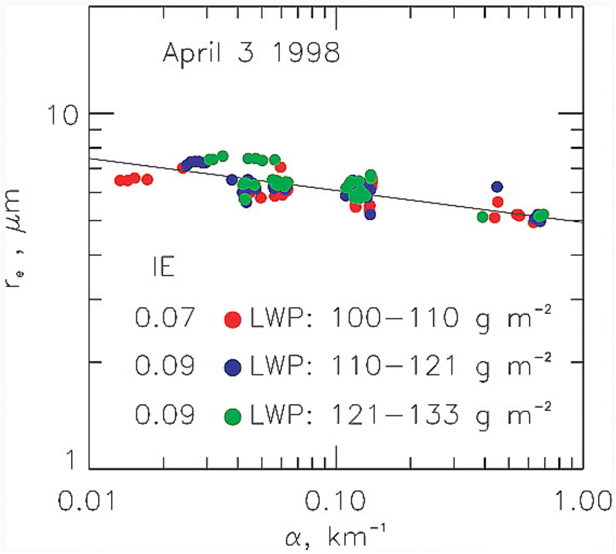
- Extreme cases enhance the aerosol-cloud signal: ship tracks, smoke, heavy air pollution, dust storms
- Time periods when aerosol loading goes up and down along with cloud properties
- Large ensemble of cases suppress the dynamics signal

Observing Aerosol Effects on Clouds and Radiation



Coakley et al. (2000) *J. Atmos. Sci.*

Cloud drop effective radius from ground-based remote sensors and aerosol extinction coefficient from Raman lidar.



Feingold et al. (2003) *Geophys. Res. Lett.*

- Extreme cases enhance the aerosol-cloud signal: ship tracks, smoke, heavy air pollution, dust storms
- Time periods when aerosol loading goes up and down along with cloud properties
- Large ensemble of cases suppress the dynamics signal

Aerosol Effects on Clouds and Precipitation

- Do increased aerosol number concentrations increase or decrease precipitation in storms?
- In convective clouds?
- Severe convection?   hurricanes, tornadoes

➢ Combining cloud physics and storm dynamics

Aerosol Invigoration Effect

Changes in the cloud physics affect the latent heating and therefore dynamics of the storm

Aerosol Invigoration Effect

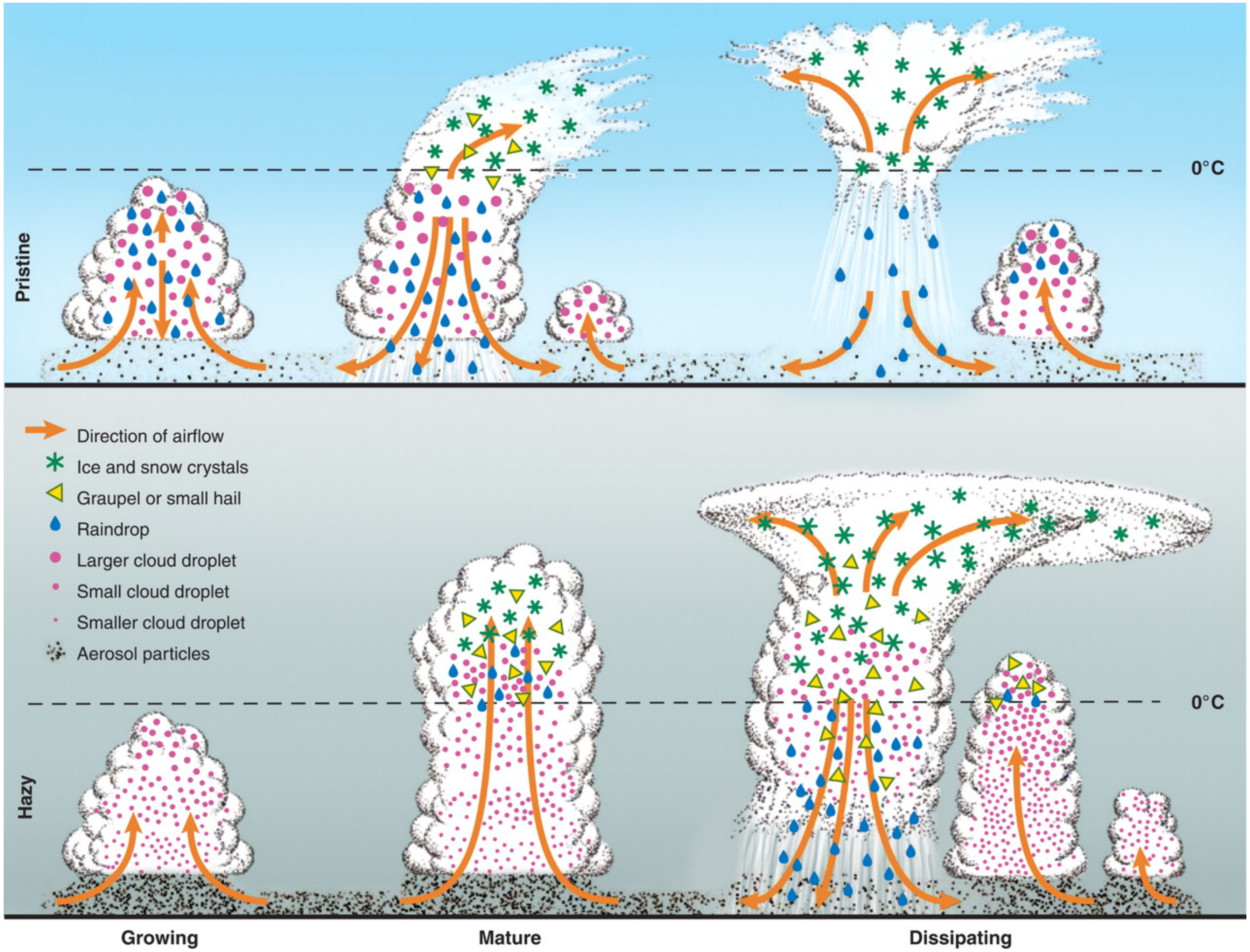
Changes in the cloud physics affect the latent heating and therefore dynamics of the storm

- More CCN → more cloud droplets, suppresses coalescence and warm rain formation
- Insufficient growth below the freezing level allows more cloud drops to be lofted above the freezing level (into the mixed phase region)
- Evidence of sustained supercooled liquid water at $T \geq -37.5°C$ in continental convection
- More freezing of cloud drops and associated latent heat release, enhances the growth of large hail and cold-rain processes
- Onset of precipitation is delayed; model results suggest greater intensity of rain later in life cycle of cloud
- Latent heat release increases updraft speeds
- Melting and evaporation cause more cooling; enhancing the cold pool

Aerosol Invigoration Effect

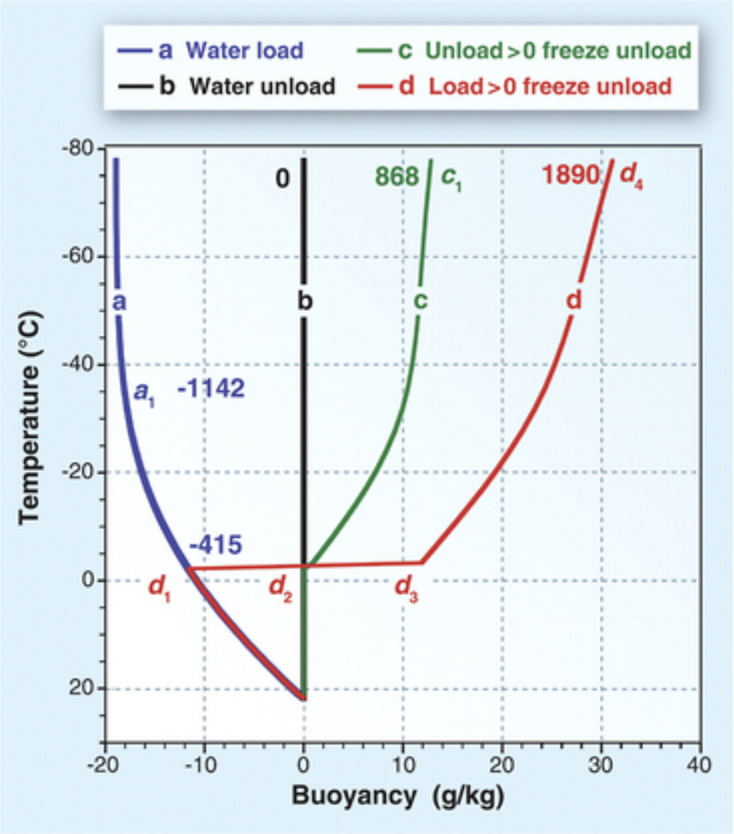
Low aerosol number concentrations

High aerosol number concentrations



Rosenfeld et al. (2008) *Science*

Aerosol Invigoration Effect – buoyancy



a. Suppressing rainfall and keeping all condensed water without freezing
b. Precipitating all condensed water without freezing
c. Precipitating all condensates with freezing at T < -4°C
d. Suppressing precipitation until T = -4°C and then freezing and precipitating all condensed water

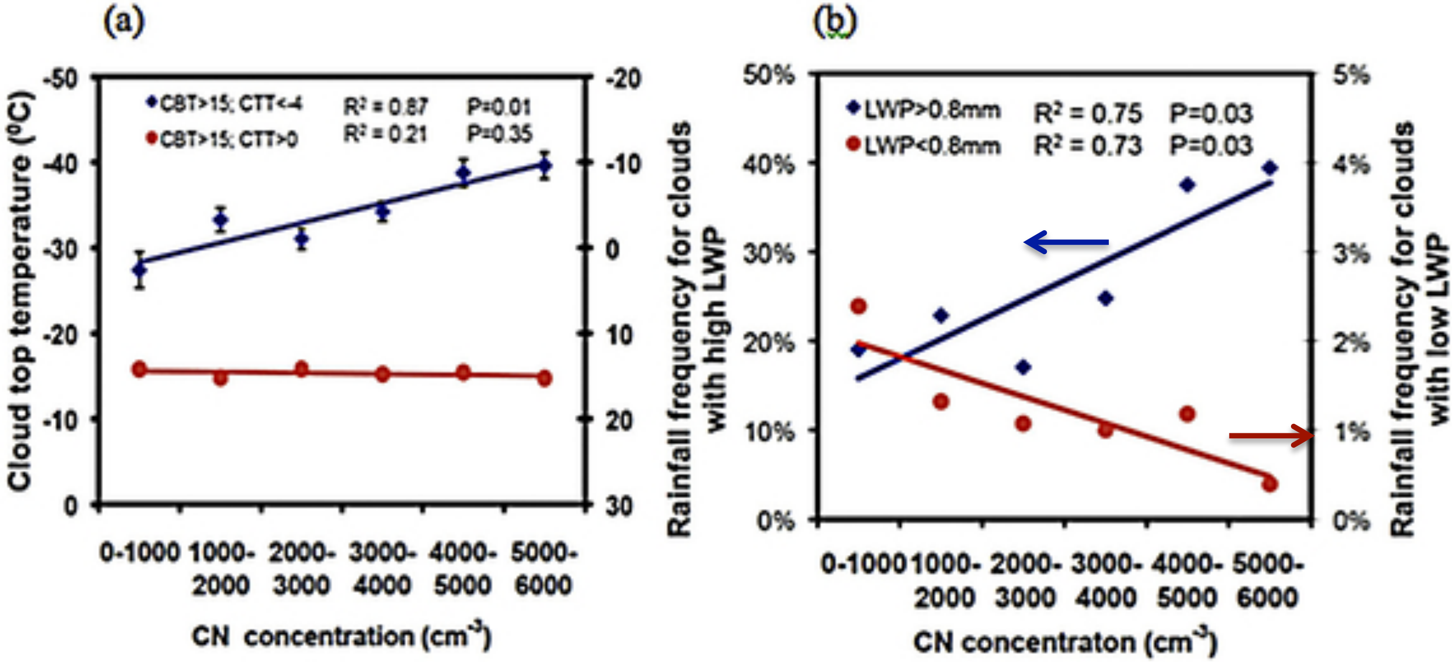
Released static energy (J/kg) with respect to scenario b is given for a, c, d

Latent heat release increases updraft speeds

Rosenfeld et al. (2008) *Science*

Evidence of Aerosol Invigoration Effect

10 years of data from DOE ARM Southern Great Plains site



- As CN increases cloud top temperature decreases (i.e. cloud top height increases) when cloud top temperature is < -4°C
- No effect for warmer clouds
- As CN increases frequency of rainfall increases when LWP > 0.8 mm
- As CN increases frequency of rainfall decreases when LWP < 0.8 mm

10 years of data from DOE ARM Southern Great Plains site

Li et al. (2011) *Nature Geosci.*

Role of Warm Cloud Depth

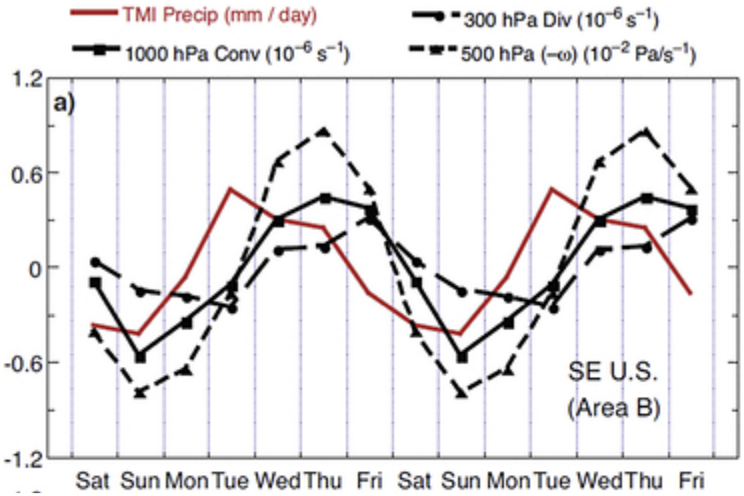
- For higher cloud bases, the warm cloud depth is shorter and there will not be very much liquid water to release latent heat
- For lower cloud bases, the warm cloud depth is deeper and the liquid water has time to grow via collision-coalescence causing drops to rain out before lofting above the freezing level

➢ Aerosol invigoration occurs in regions with the right environmental conditions

Do Aerosols from Urban Centers Affect Precipitation?

- High concentrations of hygroscopic aerosols
- Warmer temperatures in urban center compared to outside urban center
- Moist, hot air providing high CAPE

- Satellite data analysis points to a weekly cycle in precipitation in summer over the southeastern U.S.
- Controversial result – other studies show lack of weekly cycle or need for better statistical analysis (Schultz et al., 2008; Murphy et al., 2008; Kim et al., 2010; Tuttle and Carbone, 2011)



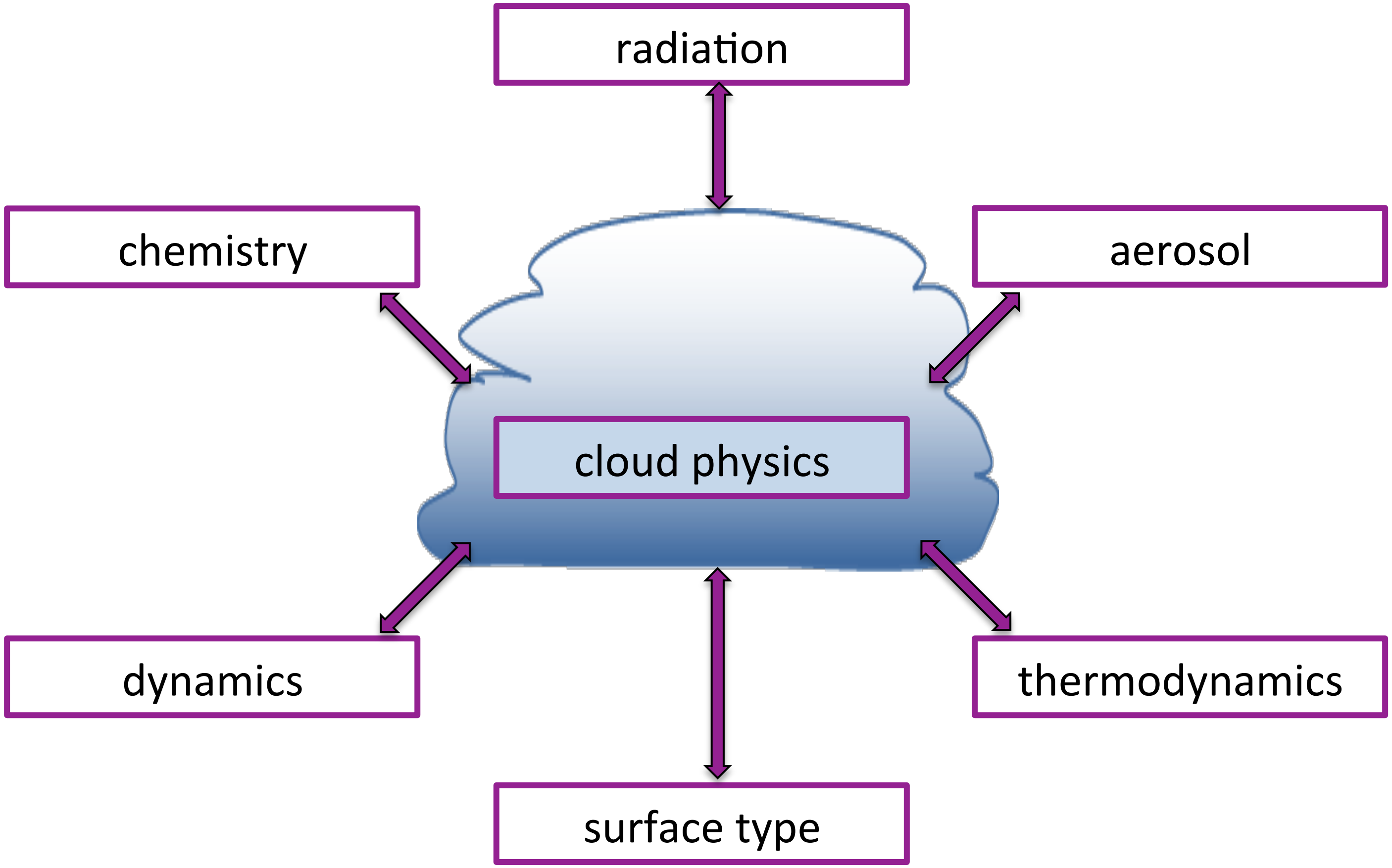
Bell et al. (2008) *J. Geophys. Res.*

Absorbing Aerosols and Clouds

- Thermodynamics of the atmosphere is altered through heating by the absorbing aerosols (black carbon, smoke)
- Depending on the height of the aerosols, the atmospheric stability is enhanced, reducing moisture content from evaporation and inhibiting formation of clouds and precipitation (Ackerman et al., 2000)

- Smoke aerosols affect clouds via CCN and via heating – two competing processes causing increases in cloud top height for aerosol optical depth < 0.4 and decreases in cloud top height at higher AOD

Modeling Aerosol Effects on Clouds and Precipitation



radiation

chemistry

aerosol

cloud physics

dynamics

thermodynamics

surface type

From Levin and Cotton, 2006