A Perspective on Radiative Transfer and Cloud Microphysics in Climate Models

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- Some Physical Understanding of Clouds Based on Observations
- Climate Models: Uncertainties
- Aerosol-Cloud-Radiation Interactions
- BC and Mountain-Snow-Albedo Feedback
- A Proposed Ice Crystal Mission

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* With contributions from Cenlin He (NCAR), Yu Gu (JIFRESSE), Jonathan Jiang (JPL/NASA), ...

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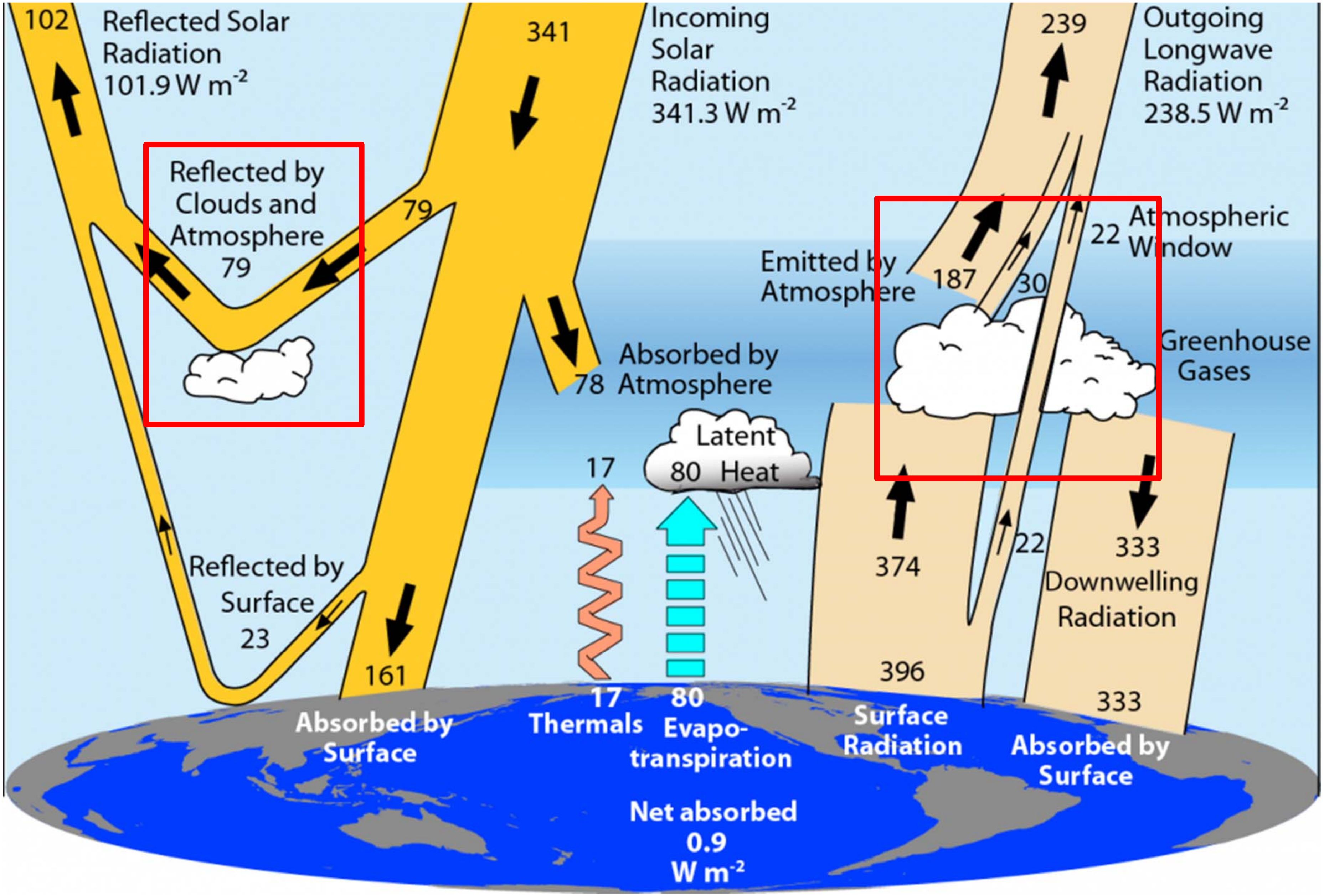
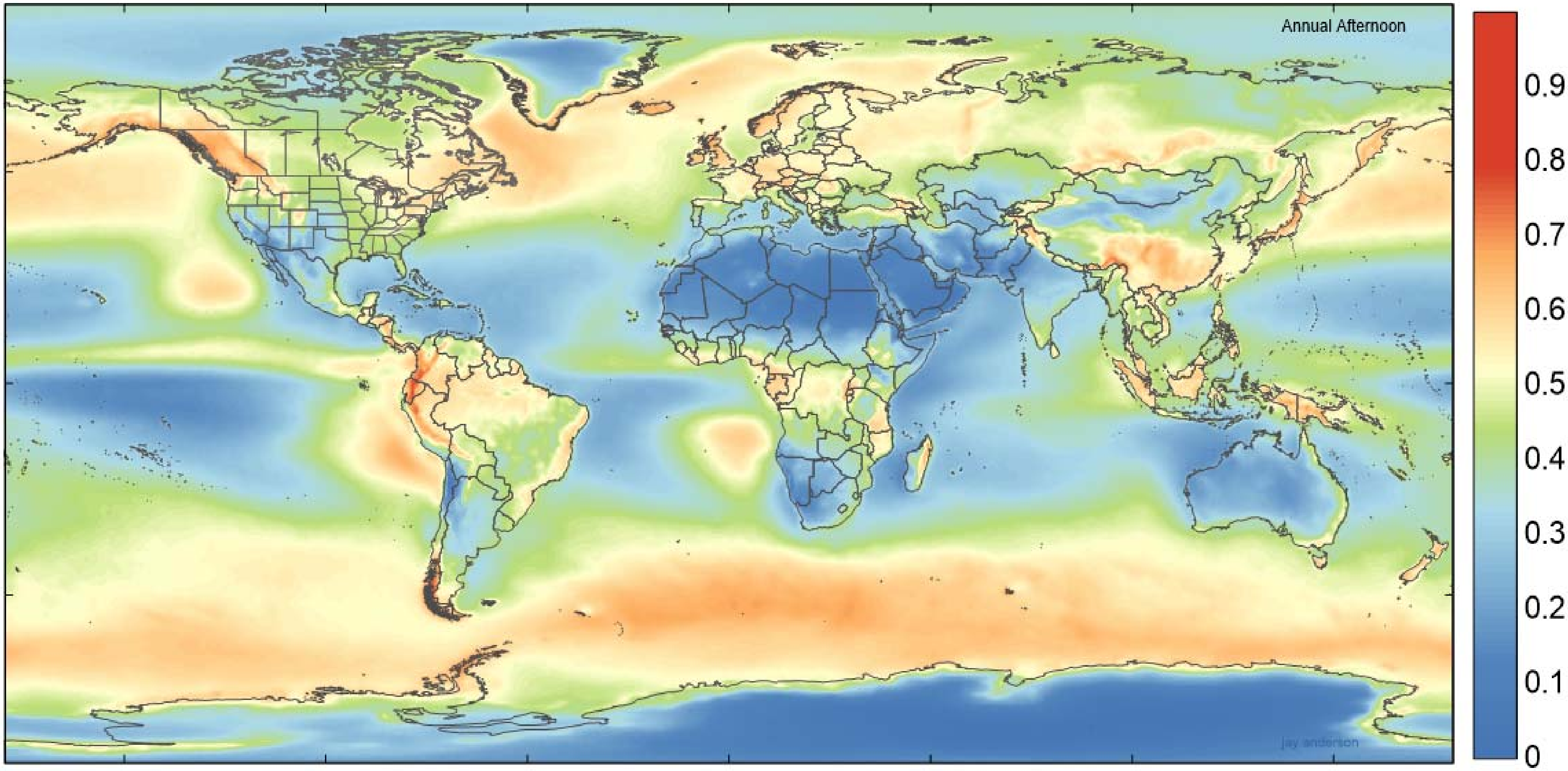
Global Energy Budget: Importance of Clouds



(After Trenberth et al. 2011); See also Liou (1992, 2002)

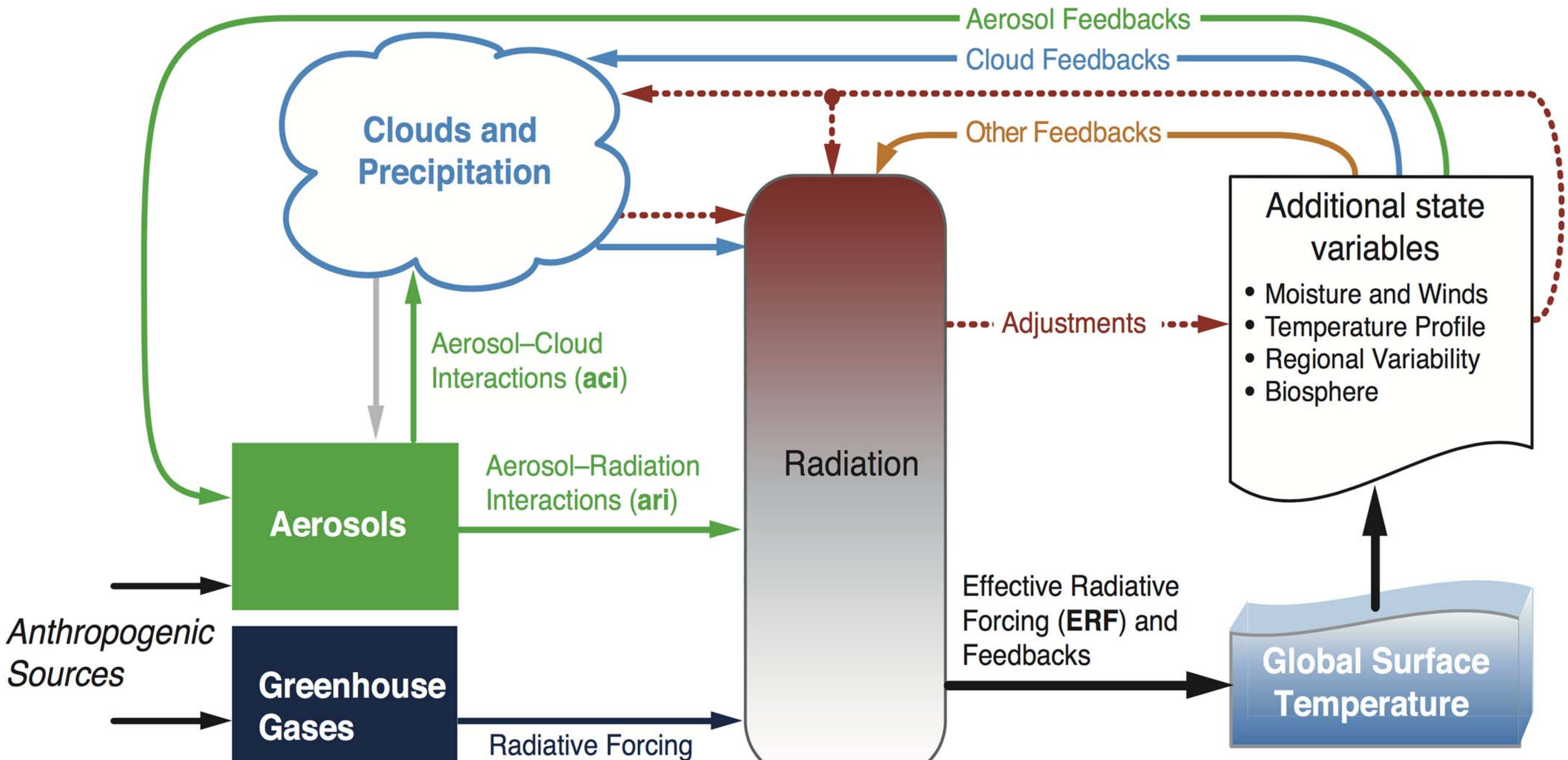
Annual Global Cloud Cover



(Data Sources: NASA MODIS-Aqua 2002–2015; Image: http://eclipsophile.com/global-cloud-cover/)

- Clouds cover approximately two thirds of the globe.
- Midlatitude oceanic storm tracks and tropical precipitation belts are particularly cloudy.
- Continental desert regions and central subtropical oceans are relatively cloud-free.

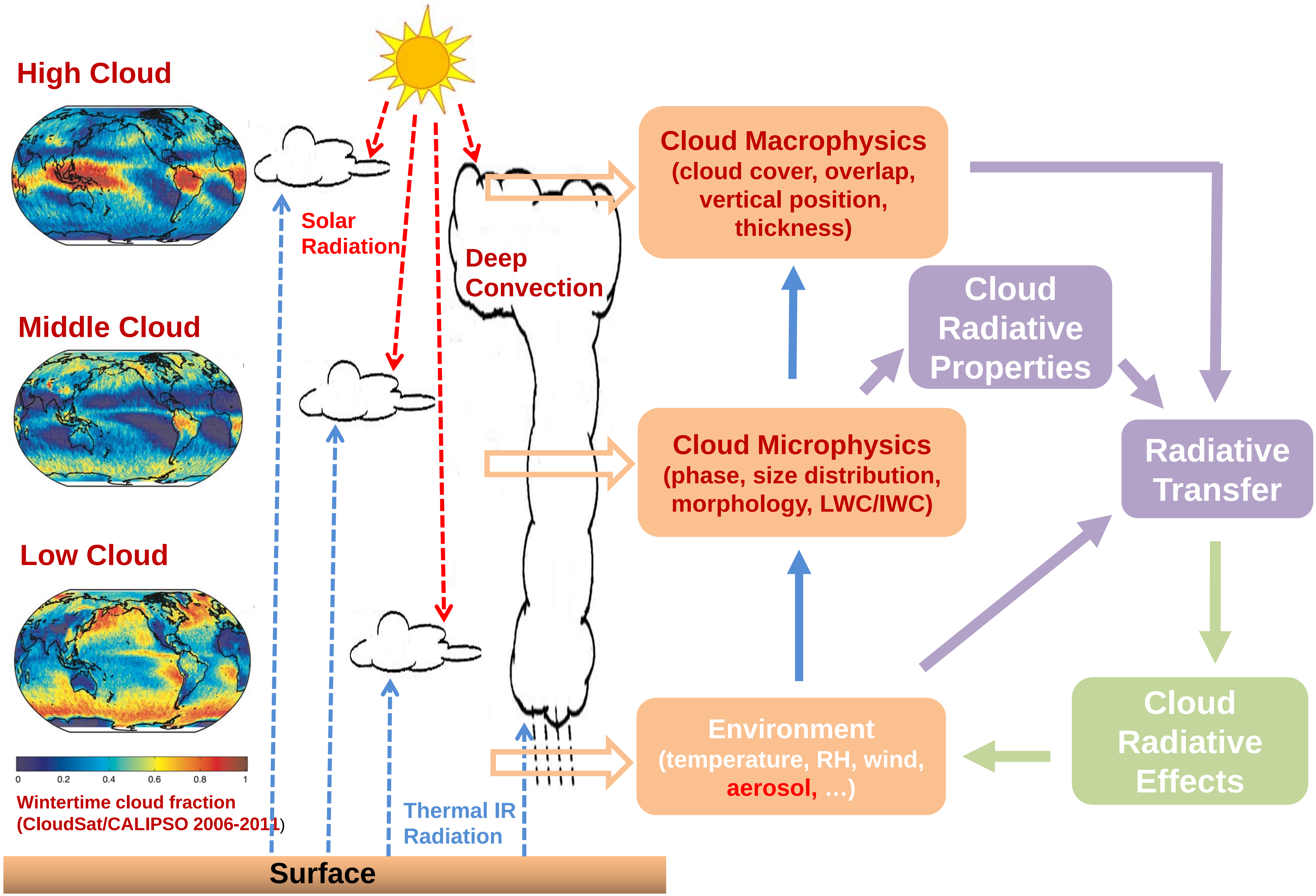
Cloud-Radiation Interactions in the Climate System



R. E. Dickinson
D. L. Hartmann

(After IPCC AR5)

Factors Affecting Cloud-Radiation Interactions

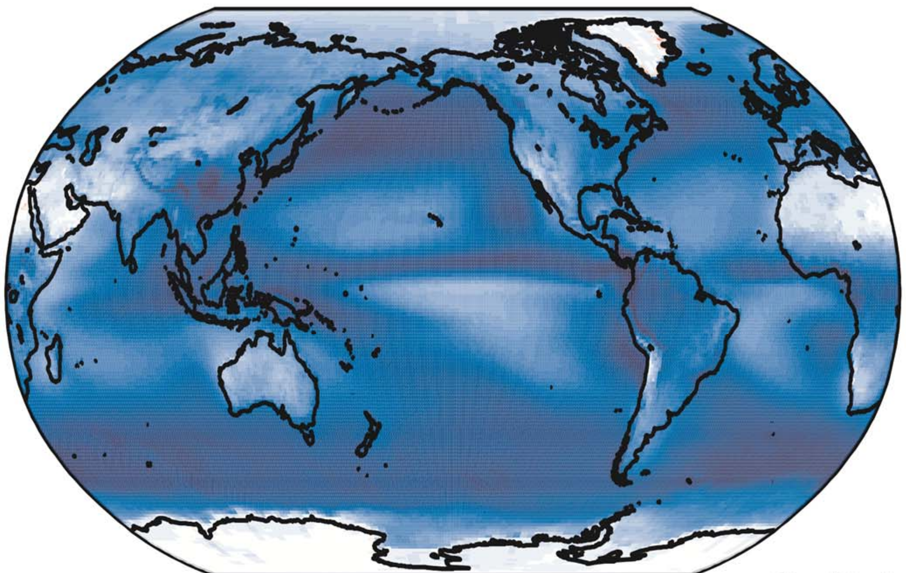


Cloud Radiative Effects Inferred from Satellite Observations

Shortwave

Global mean: -47.3 W m^{-2}

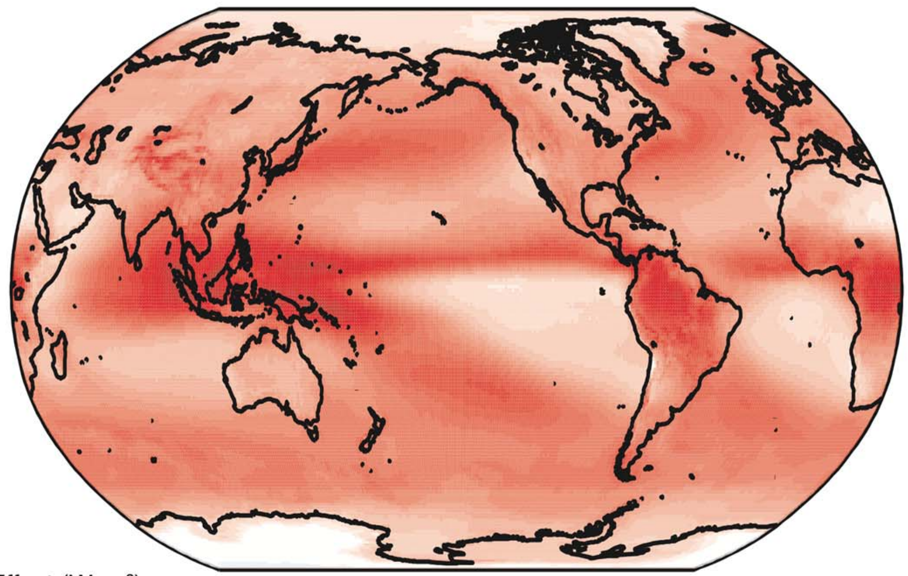
CERES 2001–2011

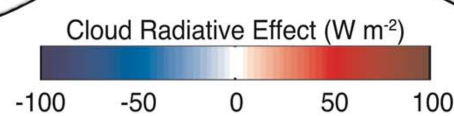


Longwave

Global mean: 26.2 W m^{-2}

CERES 2001–2011





(After Loeb et al. 2009, IPCC AR5)

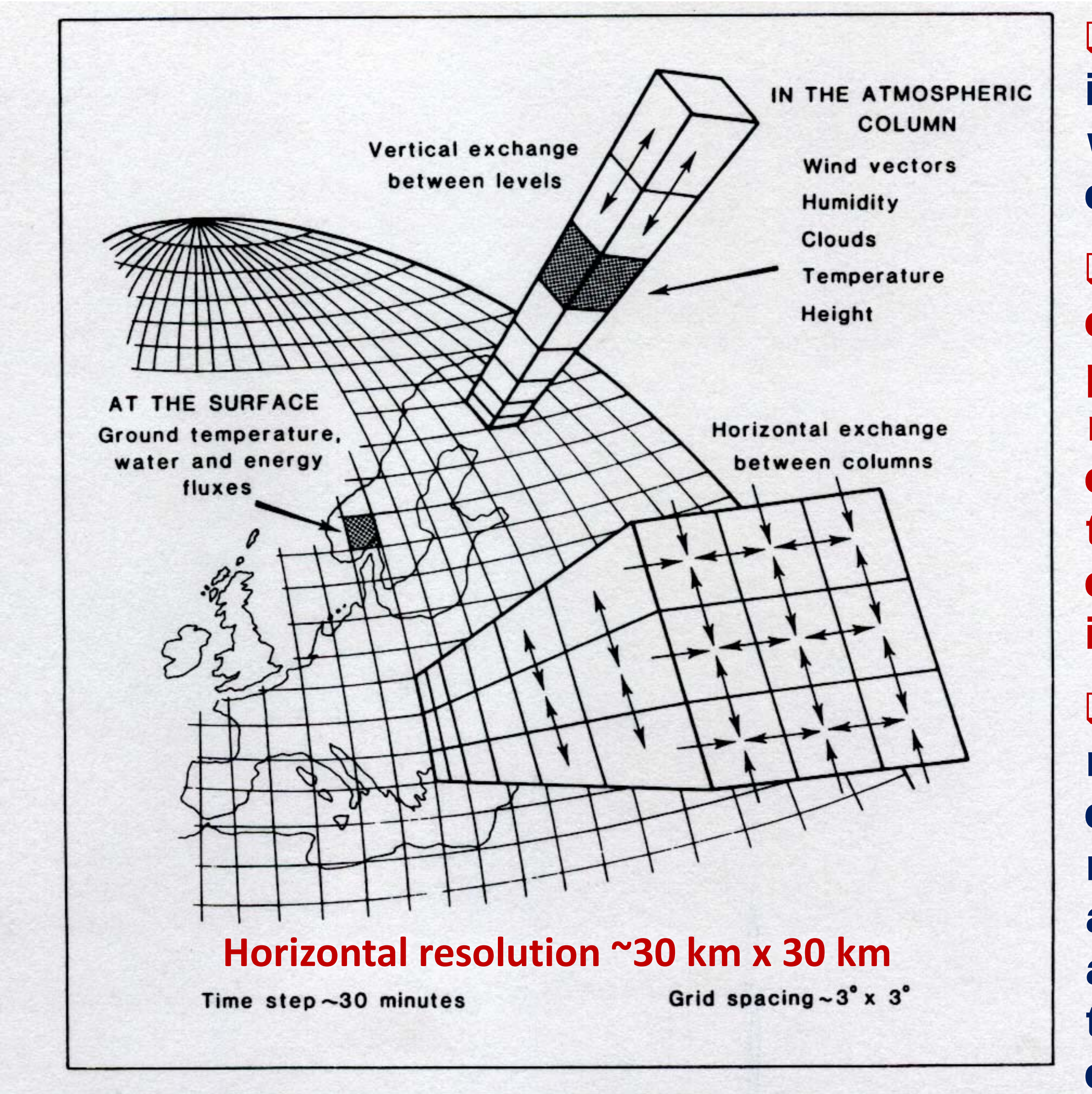
Reflect incoming solar radiation

Albedo Effect: Cooling

Trap outgoing longwave radiation

Greenhouse Effect: Warming

Parameterization of Clouds in Climate Models



- Small-scale variability in cloud properties within one grid of climate models
- Representations of cloud microphysical processes in climate models are particularly challenging due in part to stochastic nature of clouds, e.g., involving ice crystals
- Cloud formations also relate to turbulence, cumulus convection, radiative transfer, cloud amount, vertical overlap, and sub-grid scale transport of aerosol and chemical species

NCAR Community Atmosphere Model (CAM 5)

Prognostic equations for temperature (T), water vapor mixing ratio (q_v), mixing ratios of cloud droplets (q_c) and cloud ice (q_i) and number concentrations (N_c, N_i) :

$$\frac{\partial q_v}{\partial t} = -\vec{V} \cdot \nabla q_v + \sum_{i=1}^{N} \left(\frac{\partial q_v}{\partial t} \right)_{proc(i)}$$

water vapor

$$\frac{\partial q_{c/i}}{\partial t} = -\vec{V} \cdot \nabla q_{c/i} + \sum_{i=1}^{N} \left(\frac{\partial q_{c/i}}{\partial t} \right)_{proc(i)}$$

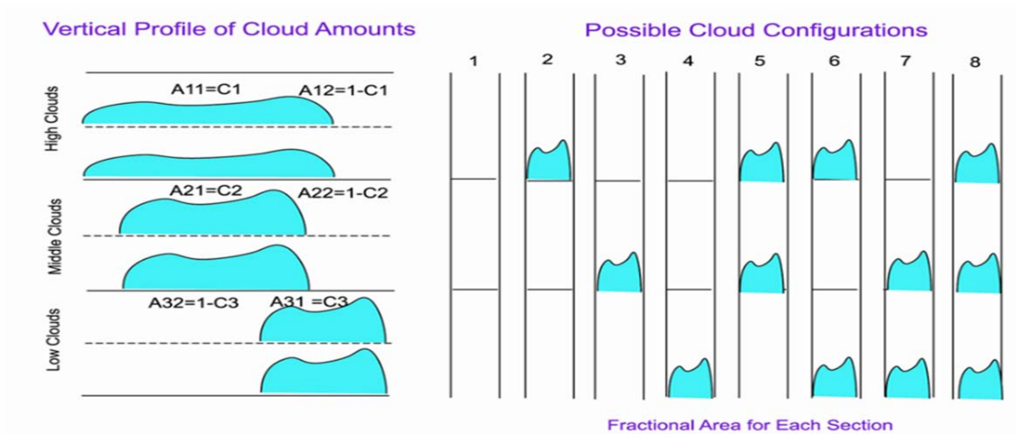
cloud droplets/ice particles

$$\frac{\partial N_{c/i}}{\partial t} = -\vec{V} \cdot \nabla N_{c/i} + \sum_{i=1}^{N} \left(\frac{\partial N_{c/i}}{\partial t} \right)_{proc(i)}$$

Nc/Ni concentrations

$$\frac{\partial T}{\partial t} = -\vec{V} \cdot \nabla T + Q$$ **(heating due to radiation and phase change)**

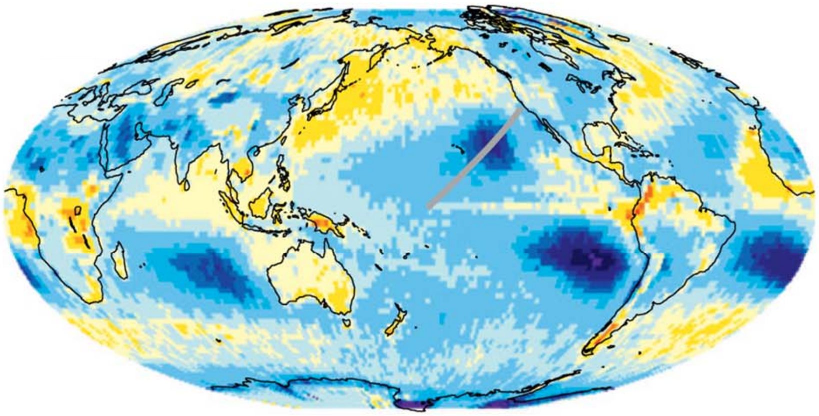
Cloud Macro-physics (Cloud Cover / Fraction)



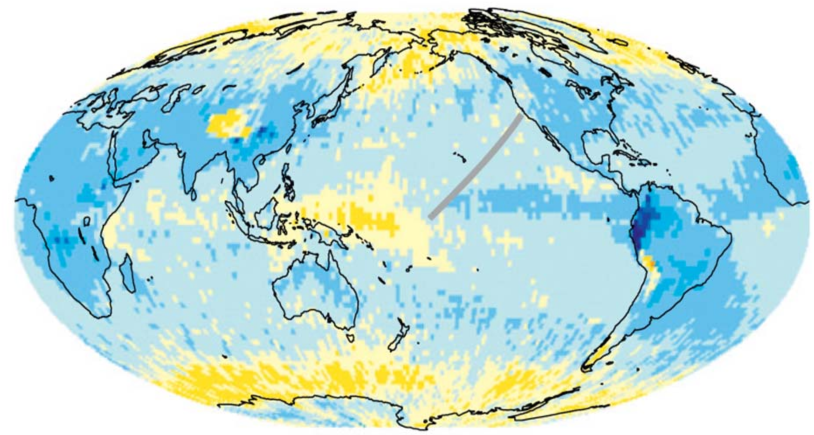
- Two types of clouds: stratus and cumulus
- **Cloud Fraction:** is a **diagnostic** para., depending on relative humidity, atmospheric stability and convective mass fluxes. (validation and calibration?)
- **Horizontal Overlap**
  - shallow and deep cumulus fractions are non-overlapped with each other
  - liquid and ice stratus fractions are maximally overlapped
  - stratus only fills the non-cumulus areas, i.e., a higher occupancy priority is given to the cumulus over stratus in each layer
- **Vertical Overlap for Radiation Calculations: Maximum / Random Overlap** (Liou & Zheng 1984)
  - compute one single cloud fraction and LWC / IWC in each layer by combining cumulus and stratus cloud properties through a simple cloud area weighting
  - 3 regimes representing lower (p>700 hPa), middle (400 hPa<p<700 hPa) and upper (p<400 hPa) atmospheres
  - **maximum** vertical overlap in each of the regime
  - **random** vertical overlap between these three regimes

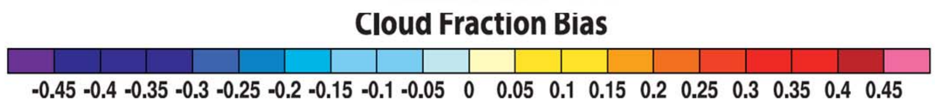
Global Cloud Fraction Computed from Climate Models vs. Satellite Observations (Model Biases)

CESM – CALIPSO (low cloud)

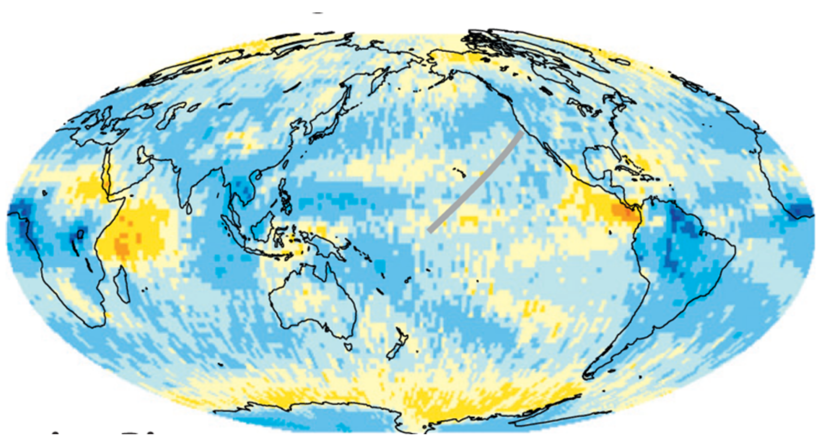


CESM – CALIPSO (middle cloud)



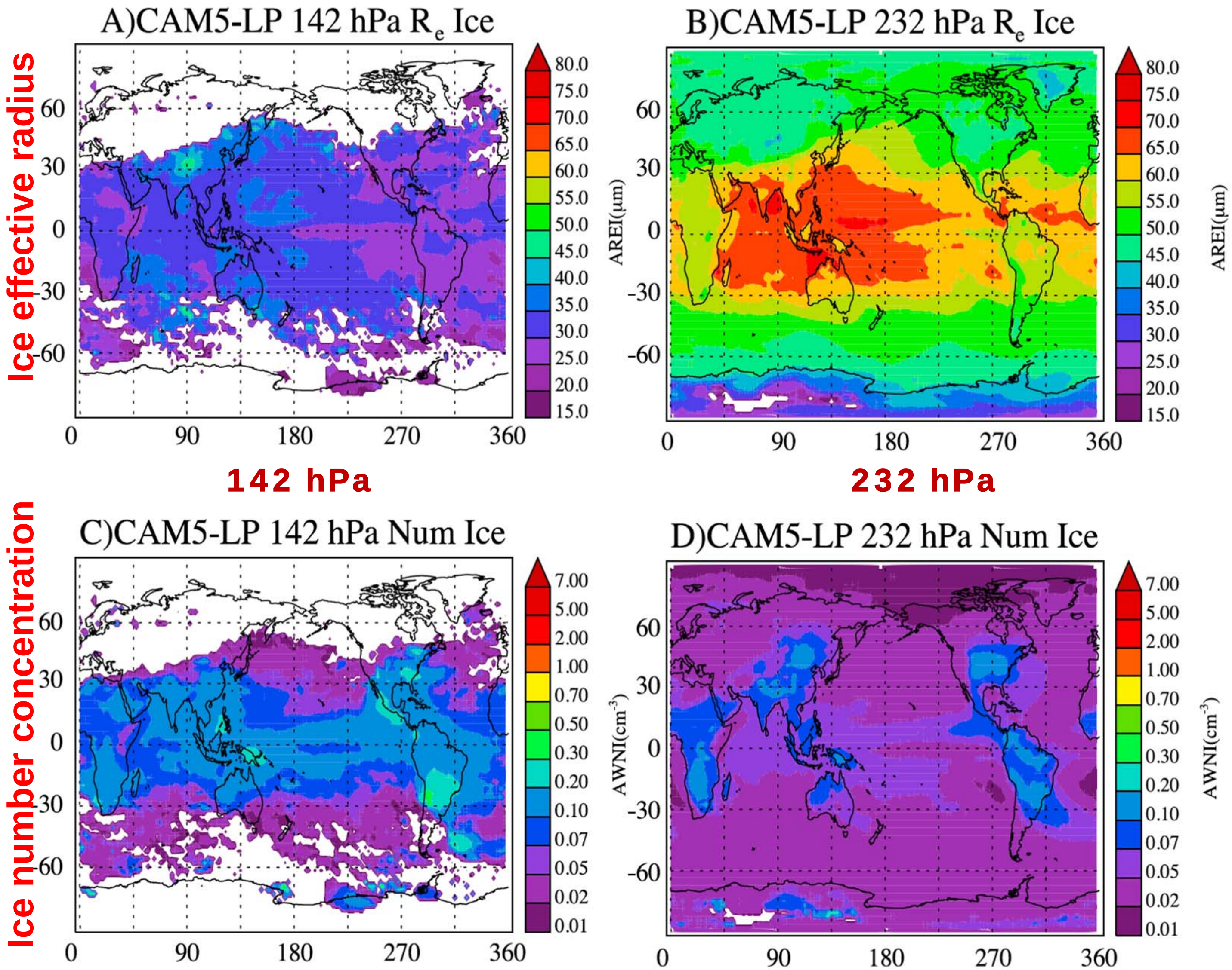


CESM – CALIPSO (high cloud)



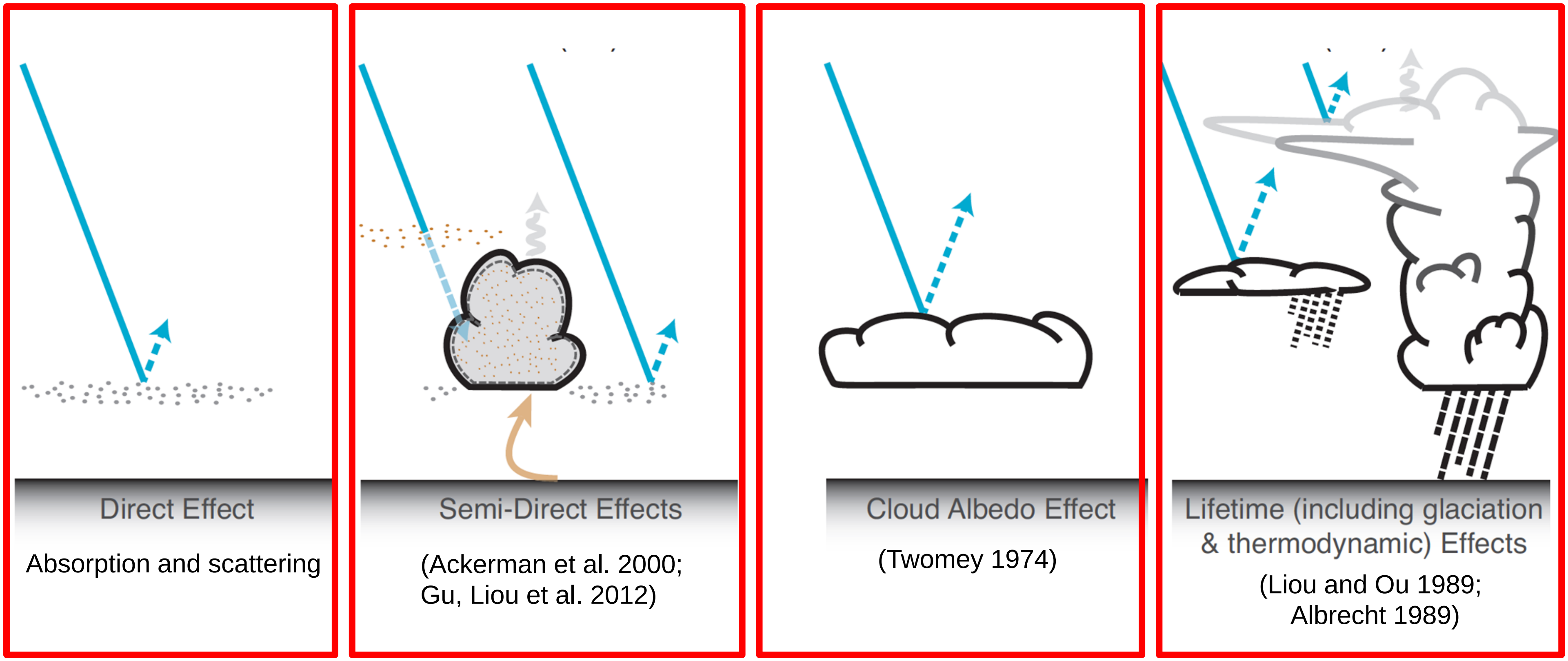
Model biases in cloud cover: CESM simulations – CALIPSO observations. Global annual values are averaged from 2006 to 2010 with a spatial resolution of ~1°x1°. As a result of cloud fraction **underestimates**, the shortwave cooling effect of clouds in CESM is too strong in the tropics & too weak in the mid-latitudes - common in climate models: **model biases in radiation fields.** The longwave cloud radiative effect bias in CESM may be partly due to cold and moist biases in the middle and upper troposphere (after Kay et al. 2012).

Ice Cloud Vertical Properties Simulated by Climate Models (CAM)



(1) **Annual mean ice effective radius and ice # concentration simulated by CAM (1.9°x2.5°). Left columns: 142 hPa features tropical cirrus in the tropopause. Right columns: 232 hPa includes cirrus in middle and high latitudes. (2) For the former, simulated ice # ranges from 0.1~0.3 /cm3, while at lower altitudes and warmer temp, ice # is generally lower. (3) Simulated ice effective radius is larger and peaks at 70 um in the tropics, and 45 um in midlatitudes (after Gettelman et al. 2012).** **See Slide 18.**

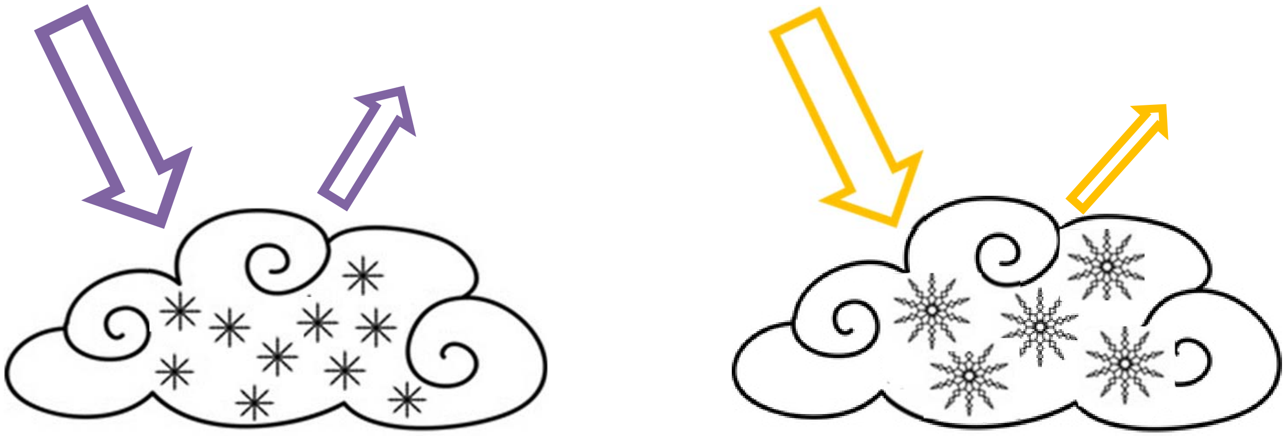
Aerosol Effects on Cloud-Radiation Interactions: Cloud Micro- & Macro-Physical Properties



Direct Effects **Semi-direct Effects** **1st Indirect Effects** **2nd Indirect Effects**

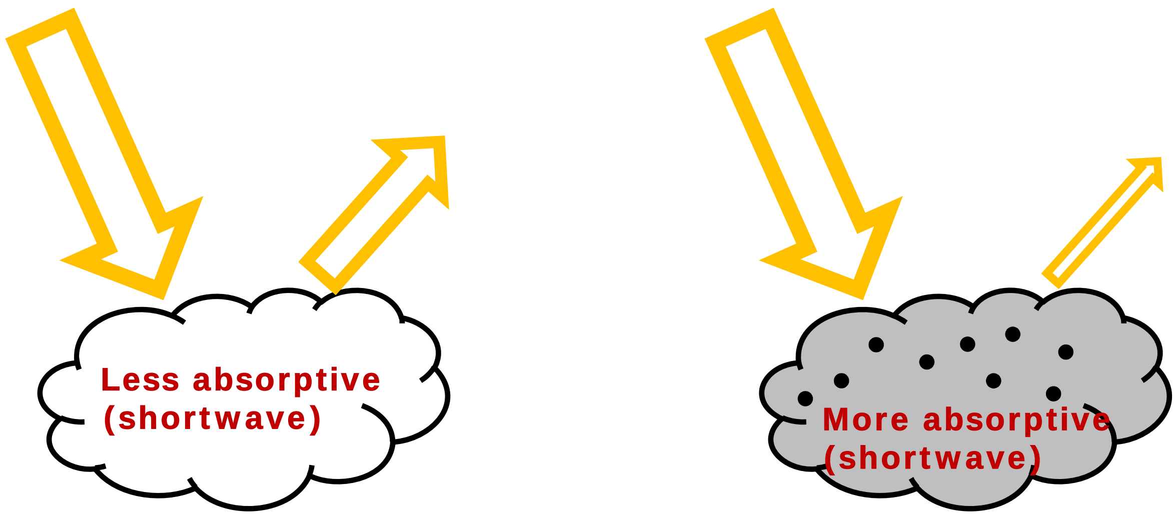
Absorbing Aerosols in High Cirrus Clouds

1. Microphysics: Possible Negative Twomey Effects



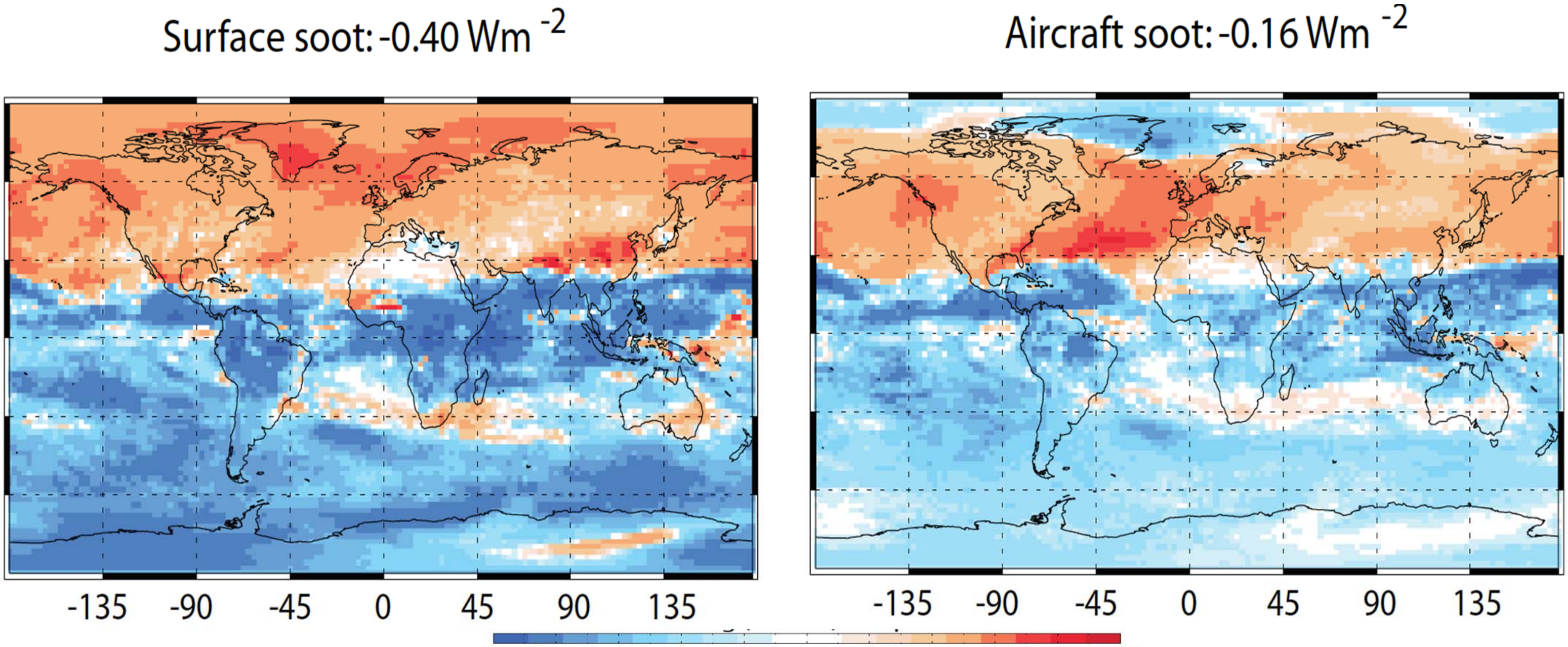
Clean clouds   Polluted (BC, Dust …) clouds

2. Radiation: Enhanced Cloud Absorption



Clean clouds   Polluted (BC, Dust …) clouds

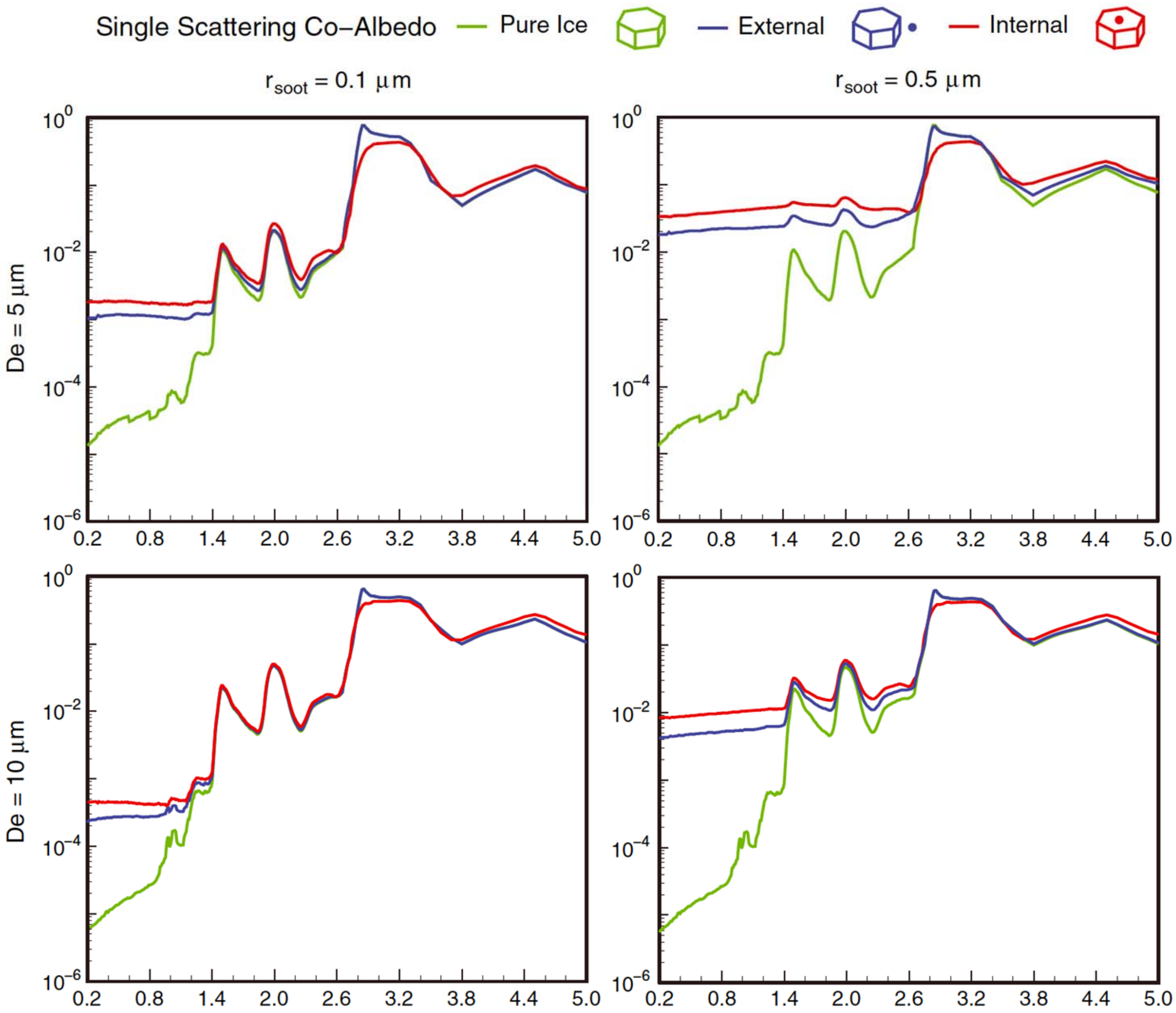
Radiative effects by including anthropogenic BC as IN



(After Penner et al. 2009)

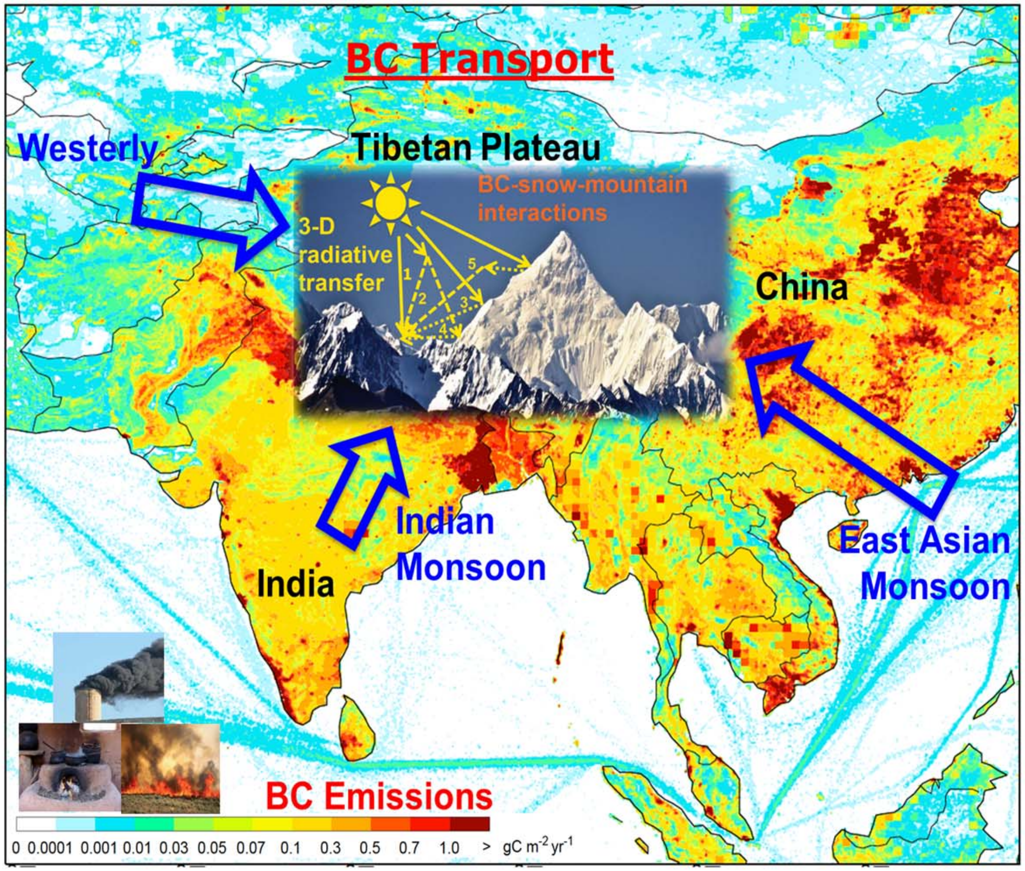
- Global annual net TOA radiative forcing (SW+ LW) of high clouds induced by BC from surface (left) and aircraft (right) emissions in CAM3.
- In the pre-industrial atmosphere, homogeneous nucleation dominates in ice clouds between 100 and 250 hPa and in Polar Regions, while heterogeneous nucleation dominates between 250 and 500 hPa at northern mid-latitudes.
- In most tropical regions, ice # conc. decreases when anthropogenic BCs are added (negative Twomey effect), so that SW forcing is positive and LW forcing is negative.
- In NH mid-latitudes below 200 hPa, an increase in ice # conc. occurs (positive Twomey effect), so that SW forcing is negative and LW forcing is positive.
- Because LW is dominant for cirrus, the net forcing pattern is similar to that of the LW forcing, i.e., negative in tropical areas and in SH, and positive north of ~30N.

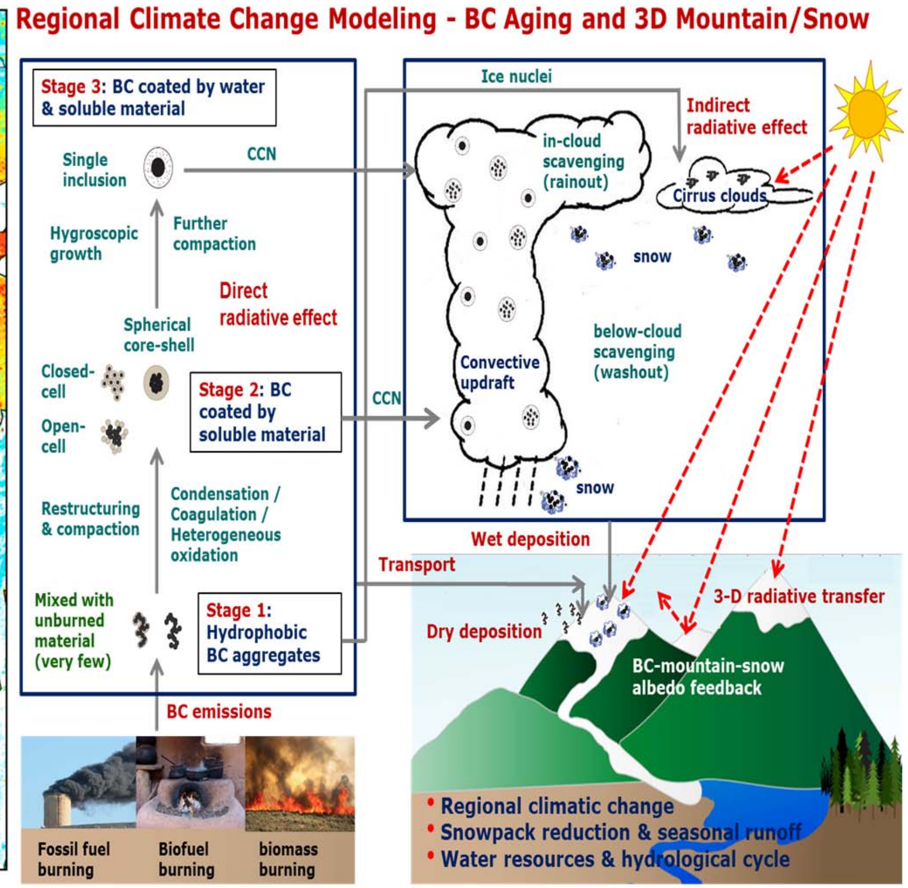
BC Contamination Enhances Ice Cloud Absorption



Spectral single-scattering co-albedo for pure ice plate and external and internal mixing cases as a function of wavelength from 0.2 to 5 um for mean effective ice crystal sizes of 5 and 10 um (Liou et al.2013).

Mountain Radiation-Snow-BC Interactions

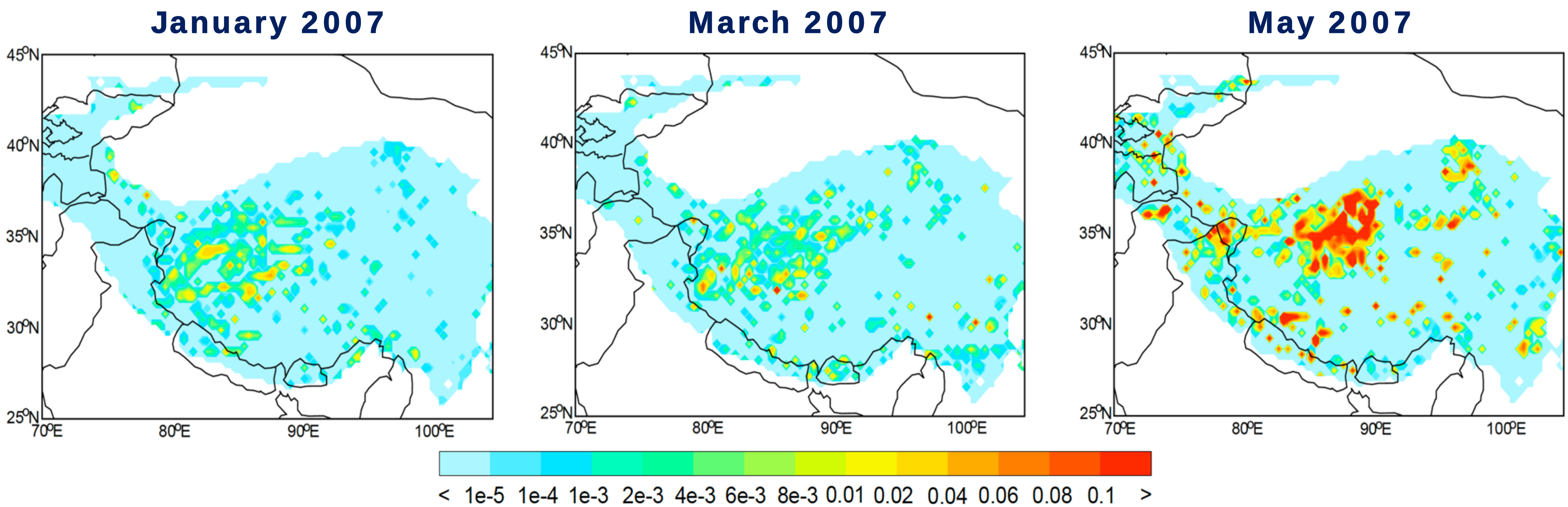




Left: BC emissions and transport over the TP areas. **Right:** BC aging processes. The left-side box shows resulting uncoated BC aggregates and coated core (BC)-shell spheres. The right-side box illustrates wet deposition, by means of aerosol-cloud-precipitation processes (washout and rainout), and dry deposition. Also shown is a graphic illustration of 3-D solar radiative transfer over intricate and complex mountain/snow regions.

BC-induced snow albedo reduction over the Tibetan Plateau from January to May: WRF-Chem Simulations with Noah-MP LSM

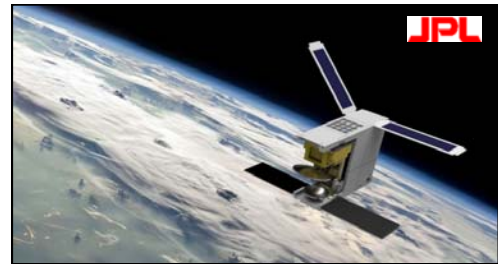
- 30km x 30km resolution for the Plateau nested in 180km x 180km for Asia; 30 vertical layers.
- Snow albedo with BC effect: the snow albedo scheme modified to couple with BC deposition based on a parameterization for BC-snow interactions. Snow albedo reduction as a function of wavelength, BC concentration in snow, snow grain size, and shape (*He et al.* 2014, 2017).
- Multiple BC stochastically mixed in snowflakes internally (*Liou et al.* 2014; *He et al.* 2016).
- Updated global BC emission inventory (2007) developed by *Wang et al.* (2014).



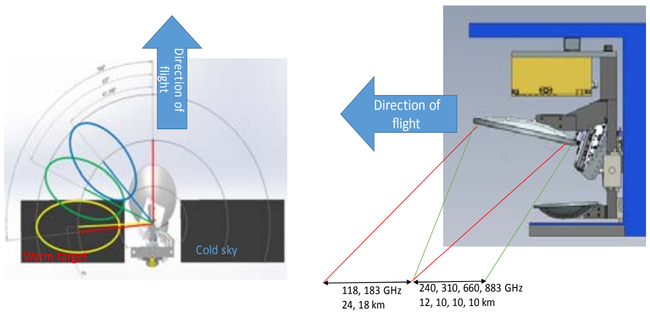
- Using the snowflake shape, BC deposition leads to a significant snow albedo reduction in the northwestern Tibetan Plateau and along southwestern regions with scattered hotspots elsewhere.
- The BC-induced snow albedo reduction is much stronger in late spring (>10%) than in winter and early spring due to smaller snowfall and stronger emissions from northern India. **Work in progress.**

A Proposed Ice Crystal Mission

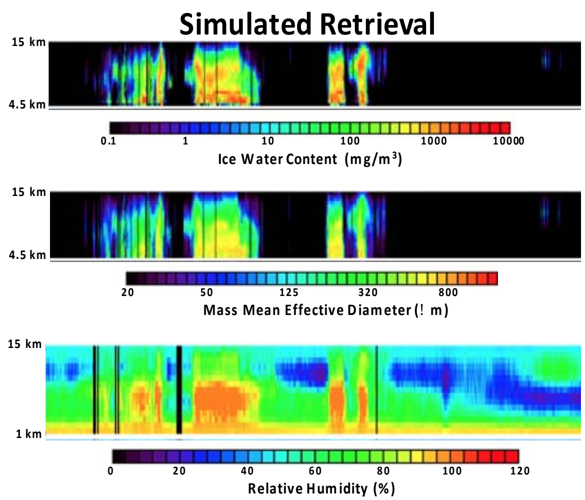
ENTICE: Earth's NexT-generation ICE mission

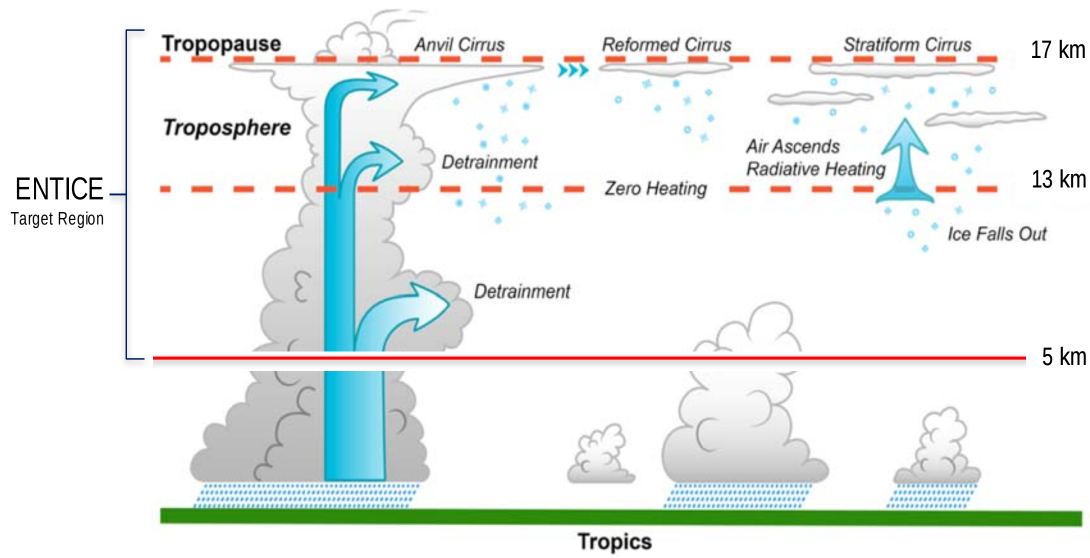


Principal Investigator: **Jonathan Jiang**; **Project Scientist**: Hui Su; **Instrument Lead**: Pekka Kangaslahti



ENTICE is a proposed JPL satellite mission that will provide the first-ever global measurements of ice cloud particle size and density profiles, together with atmospheric temperature and humidity, which will enable accurate quantification of ice cloud radiative effects and advance our understanding of ice cloud microphysical processes.





To all the happy ice crystals in planetary atmospheres.

Let there be light.

Let there be beautiful ice crystals in the air and mountain ranges.

And here come the reindeers and Santa Claus carrying Maxwell's equations, and light rays are shining in the wonderlands.

Let the glory of Geometric Optics for ice crystals, Newton's optics, and sun's light rays rise again from the horizon.

Let ice crystals' old friends – black carbon and dust – be not forgot for Auld Lang Syne.

And ice crystals are carried by the ceaseless winds; and

After travelling thousands of miles up and down, the sky looks very blue.

Let there be space missions to tender ubiquitous light rays in the sky,

And all things considered, let light scattering by ice crystals in remote sensing and climate change be a delight.