Cloud Aerosol Effects: too cool to be true?

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This NASA satellite image shows a dust storm, hundreds of thousands of square miles in size, moving from the Saharan Air Layer over Africa into the eastern Atlantic Ocean. The image was captured by the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) instrument on February 26, 2000. (Courtesy SeaWiFS/Ocean Color Team)

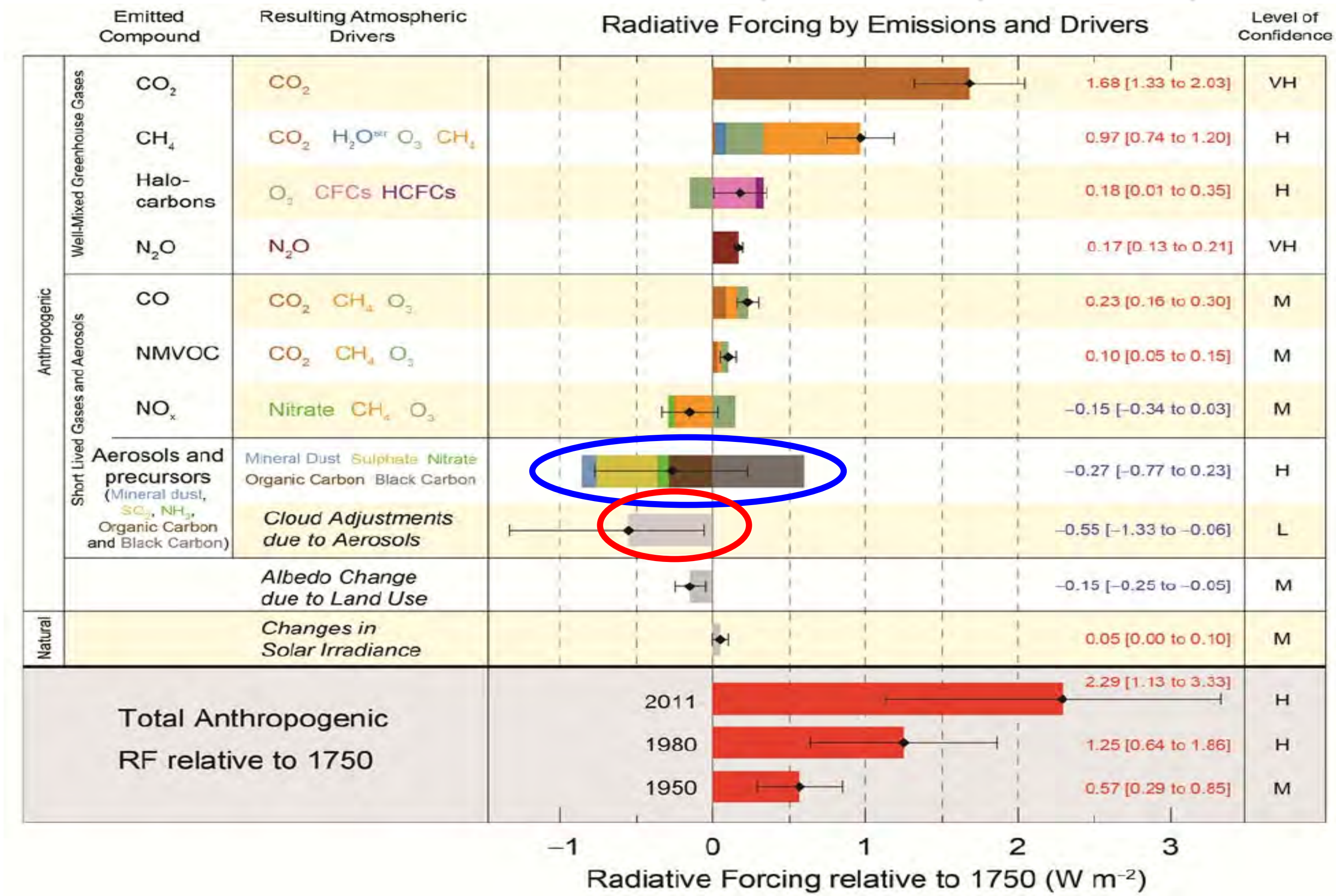
Climate Effects of Aerosol

Radiation Budget and Hydrological Cycle

- direct effect ⇨ net cooling
  aerosols scatter and absorb radiation
- first indirect effect ⇨ cooling
  aerosols increase number concentration of cloud droplets and ice particles
- second indirect effect ⇨ cooling
  aerosols decrease precipitation efficiency
- other indirect and semi-direct effects
  ⇨ cooling or warming

2011 Global Average Radiative Forcing Estimates

from IPCC fifth assessment report - http://www.ipcc.ch



- anthropogenic greenhouse forcing (~3.3 W/m^2)
- aerosols cool atmosphere => total anthropogenic ~ 2.3 W/m^2

Climate Effects of Aerosol

2005 Global Average Radiative Forcing Estimates

from IPCC fifth assessment report - http://www.ipcc.ch

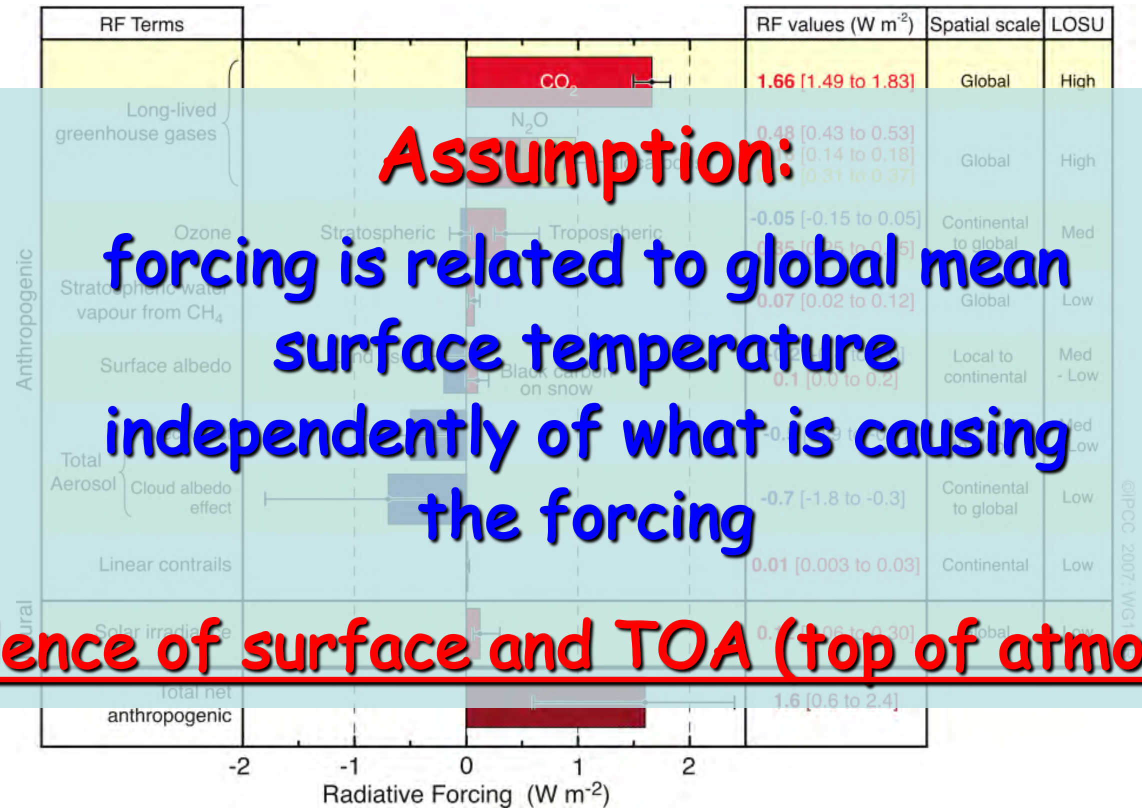
- aerosol direct effect: +0.23 to -0.77 W/m^2
  (AR4: - 0.1 to - 0.9 W/m^2)
- 1st aerosol indirect effect: -0.06 to - 1.33
  (AR4: - 0.3 to - 1.8 W/m^2)
- 2nd aerosol indirect effect: - 0.3 to - 1.4 W/m^2
  - not included in IPCC since treated as feedback
- aerosol cooling (-3.5 W/m^2 max) can not be larger than greenhouse warming! (+3.3 W/m^2 all GHG combined)

Aerosol effects on climate: too cool to be true?

Aerosol Direct Effects

- believed to be fairly well understood
  - as more observations become available
  - models become more sophisticated
- active research areas:
  - vertical aerosol distribution
  - role of absorbing aerosols
  - feedbacks with atmospheric circulation

Radiative Forcing and Surface Temperature Change



IPCC 4th Assessment Report

Figure SPM 2

Assumption:

forcing is related to global mean surface temperature independently of what is causing the forcing

equivalence of surface and TOA (top of atmosphere)

Non-absorbing Aerosol and Surface Temperature Change

non-absorbing aerosol reflects solar radiation back to space

- ⇨ cooling of atmosphere
- ⇨ surface albedo important for TOA forcing
- ⇨ reduction at surface ≈ increase in outgoing radiation
- ⇨ change in surface temperature can derived from TOA forcing thus observable from satellite
- ⇨ TOA forcing from non-absorbing aerosol and greenhouse gases affect surface temperature in the same way

Absorbing Aerosol and Surface Temperature Change

absorbing aerosol (partially) absorbs solar radiation

- ⇨ absorbed radiation cannot be reflected elsewhere
- ⇨ less solar radiation reflected back to space
- ⇨ <u>warming of the atmosphere</u>
- ⇨ absorbed radiation does <u>not</u> reach surface
- ⇨ <u>surface cooling</u>
- ⇨ reduction in surface downward radiation much larger than reduction in outgoing TOA radiation
- ⇨ change in surface temperature cannot be derived from TOA forcing in the same way as for non-absorbing aerosols and greenhouse gases

INDOEX – Indian Ocean Experiment
Ramanathan et al. (2001)

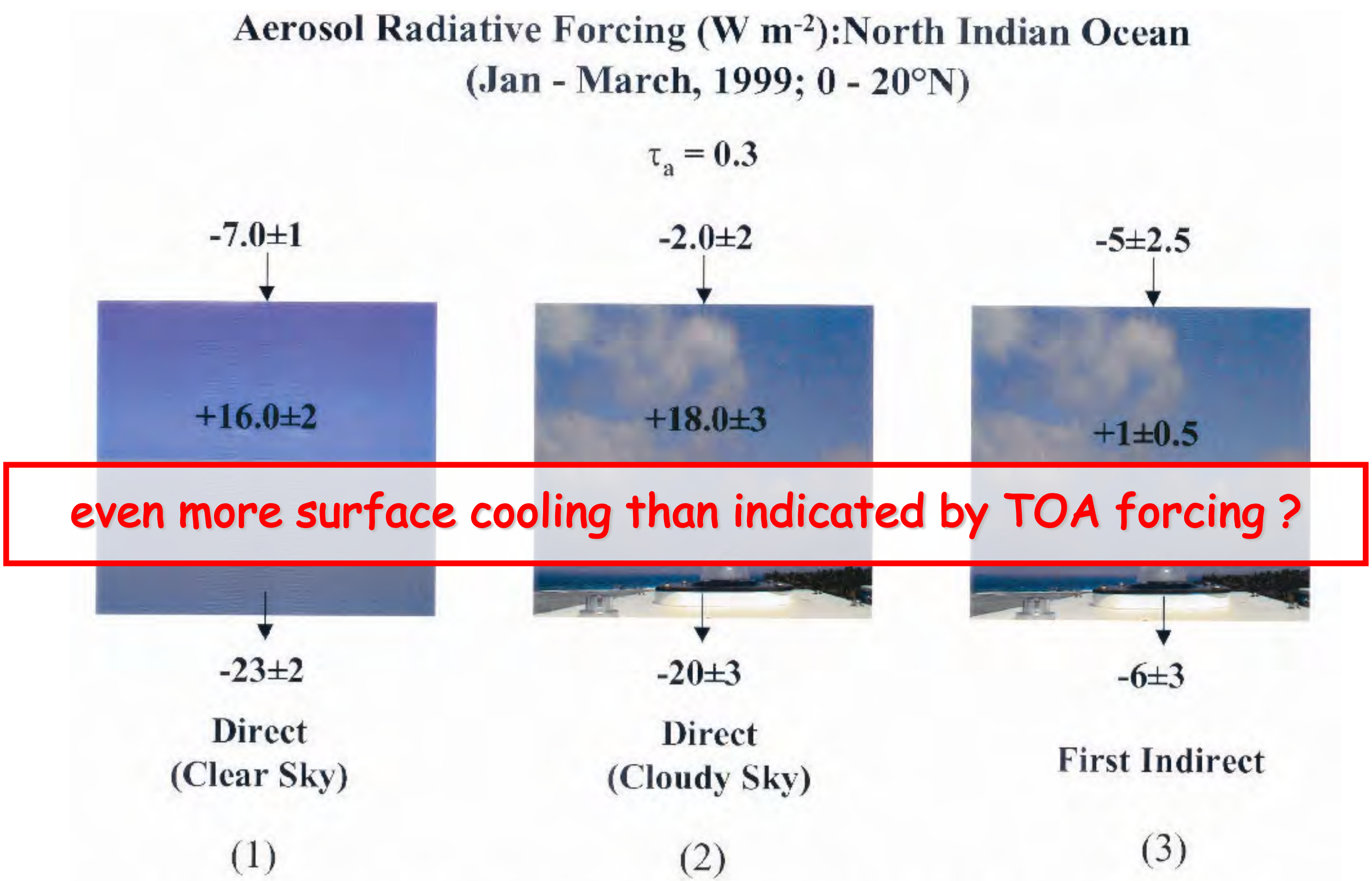


Plate 13. Aerosol direct radiative forcing for the North Indian Ocean (0° to 20°N; 40° to 100°E). The values include the effects of natural and anthropogenic aerosols. The values on top of each panel reflect TOA forcing; those within the box show the atmospheric forcing, and below the box is the surface forcing.

Semi-direct Aerosol Effect

Absorbing aerosol warms the aerosol layer and cools the surface

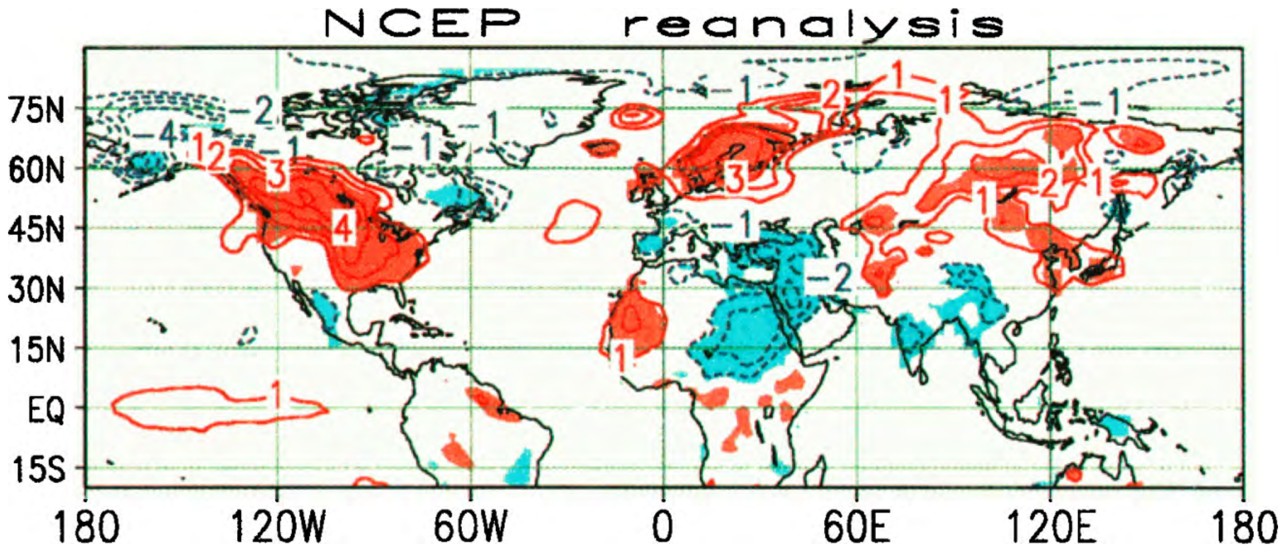
- ⇨ leading to a stabilization of the atmosphere
- ⇨ leading to a reduction in low-level cloud cover and liquid water path
- ⇨ semi-direct effects leads to surface warming (positive forcing, however, considered as feedback by IPCC)
- ⇨ semi-direct effect can be several times larger than the direct effect (even for a weakly absorbing aerosol layer)

Aerosols and Large Scale Atmospheric Circulation

- In contrast to well-mixed greenhouse gases aerosols are highly variable in space and time.
- Aerosol forcing comes in patterns with forcing values much larger in source regions than the global average.
- Aerosol pattern alter large scale gradients in temperature and pressure leading to additional circulation changes, e.g.
  - winter warming after a volcanic eruption
  - potential drying of the Sahel zone due to anthropogenic sulfate aerosol

Winter Warming following the 1991 Mt. Pinatubo volcanic eruption

- Volcanic aerosol in stratosphere excites positive phase of North Atlantic Oscillation (NAO)
  - differential heating between low and high latitudes in stratosphere
  - strengthening of polar vortex in winter
  - planetary waves reflected back to troposphere
  - circulation pattern with warm air advection over NH continents
- response to volcanic aerosol has a spatial pattern
- despite overall tropospheric cooling warming possible in some regions



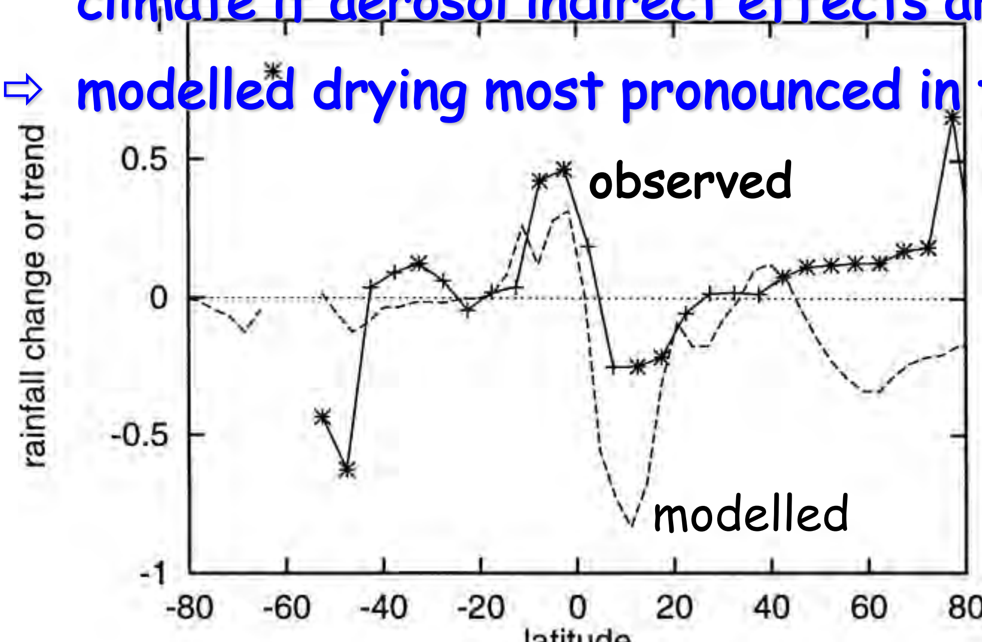
surface air temperatures anomalies [K] in DJF 1991/2

Kirchner et al. (1999)

Potential Drying of the Sahel Zone due to Anthropogenic Sulfate Aerosol

Most of the source regions for anthropogenic sulfate aerosol are in the Northern hemisphere.

- ⇨ creating a hemispherical SST difference
- ⇨ leading to a significant southward shift in tropical precipitation in the CSIRO climate model between pre-industrial and present day climate if aerosol indirect effects are included
- ⇨ modelled drying most pronounced in the Sahel in North Africa



zonally averaged trend in annual-mean precipitation over land for the period 1901–98 in mm day–1 century-1

by Rotstayn and Lohmann (2002)

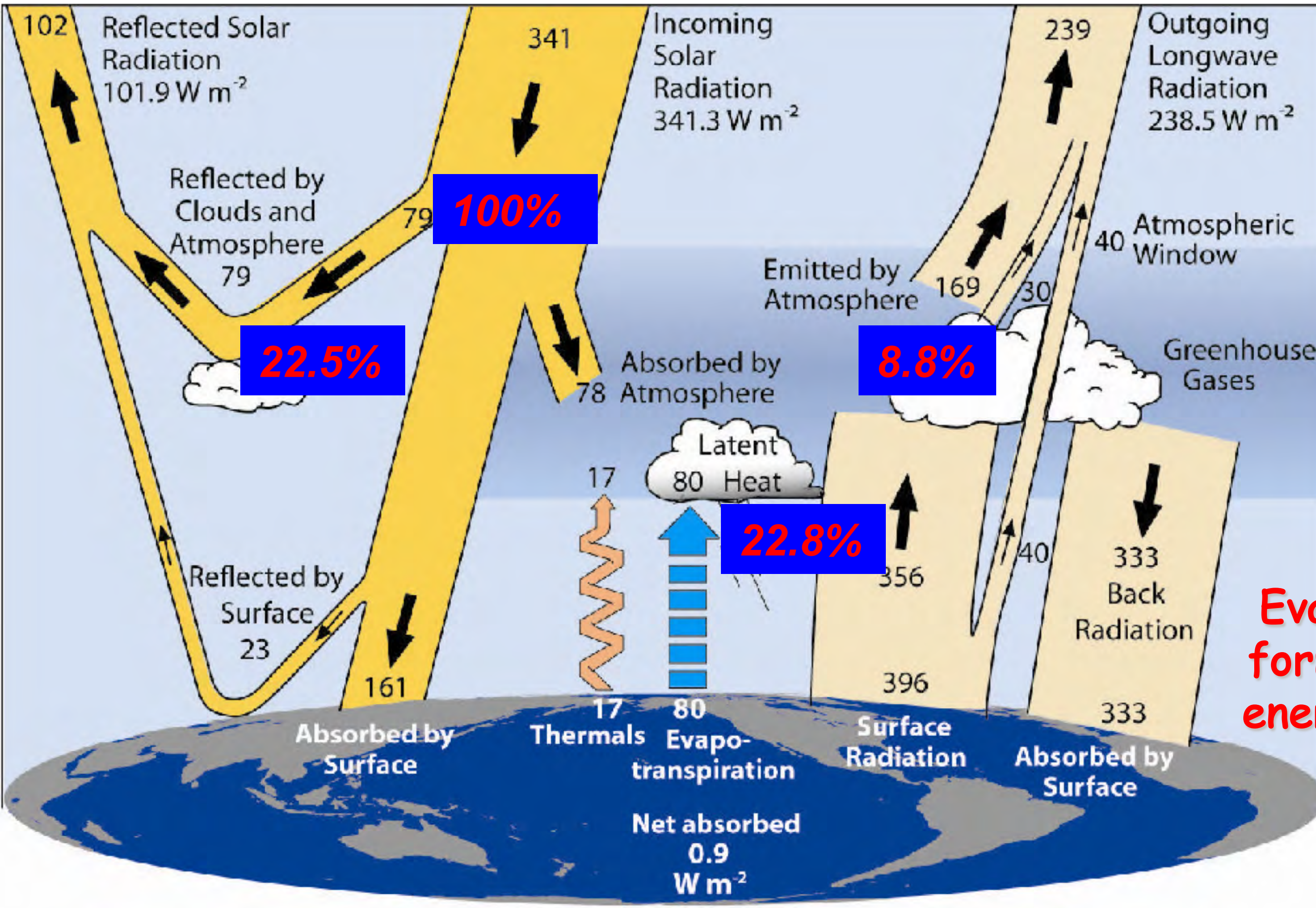
Aerosol Indirect Effects

- Consequence of interactions between aerosols and clouds

  ⇨ Let's have a look at clouds first

Cloud forcing is difference of two large numbers.

Small changes can cause big changes in net forcing!



Cloud Forcing:

Short wave: -48.4 W/m^2

Long wave: +31.1 W/m^2

Net: -17.3 W/m^2

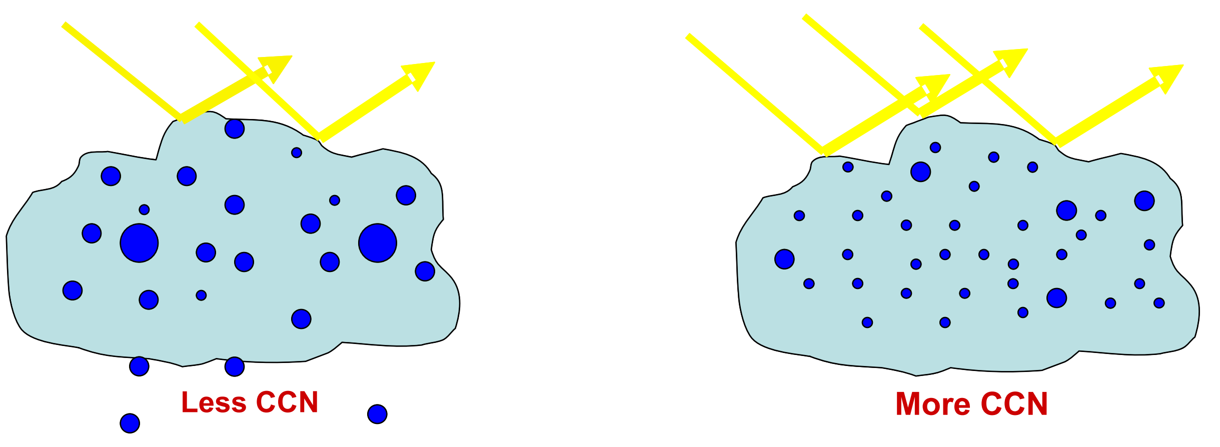
Evaporation and cloud formation redistribute energy from surface to atmosphere

Cloud Formation

- Cloud Condensation Nuclei (CCN) needed for cloud formation
  - homogeneous cloud formation requires RH>400%
- aerosol particles can act as CCN
- many aerosol particles are of anthropogenic origin
- changes in aerosol composition and concentration affect cloud properties

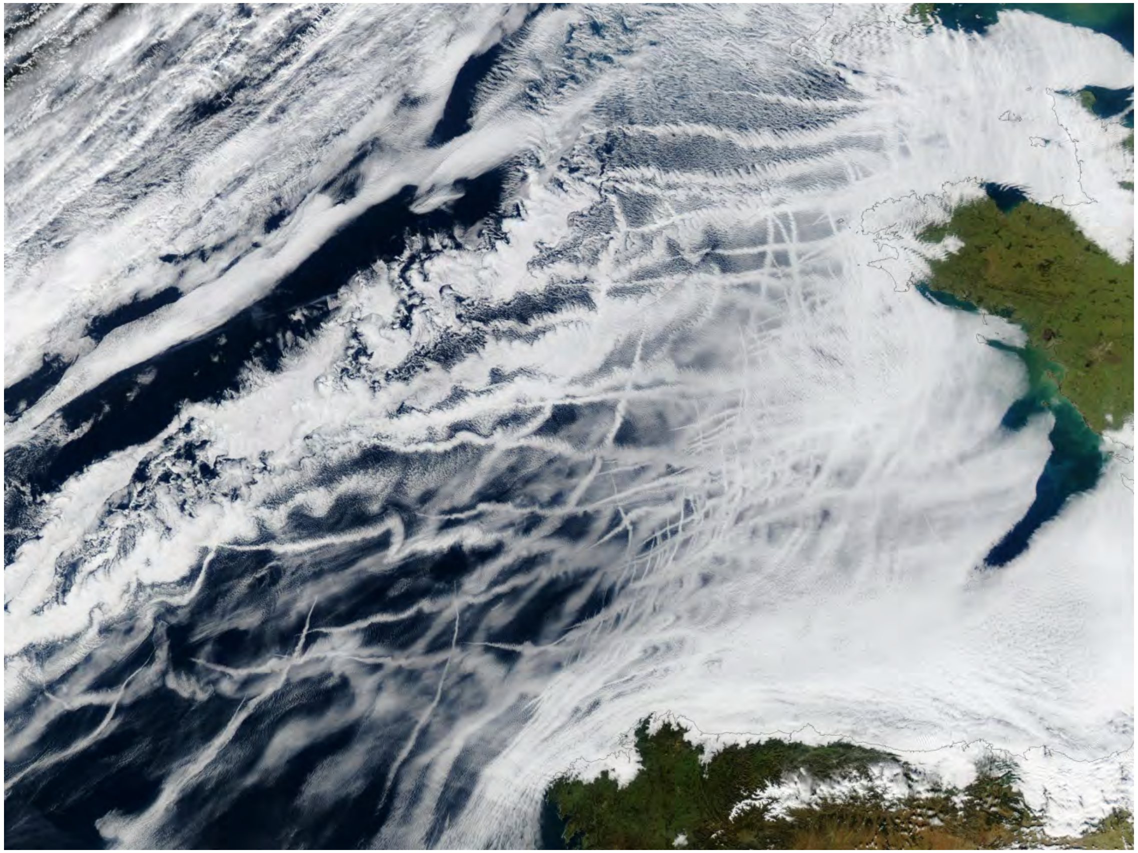
Aerosol - Cloud Interaction

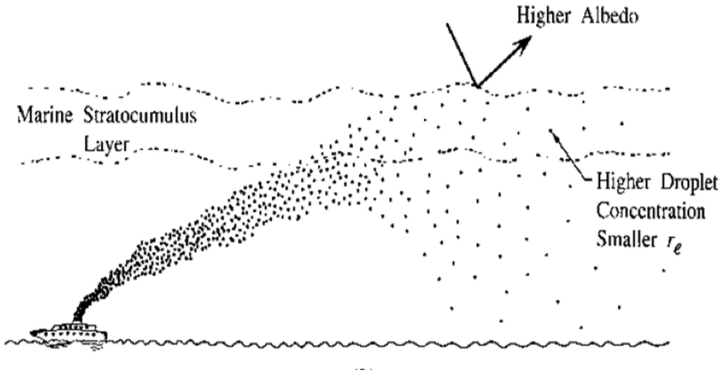
- 1st aerosol indirect effect (AIE):
  more aerosol particles result in more and smaller cloud droplets => brighter more reflective clouds
- 2nd aerosol indirect effect:
  smaller cloud droplets lead to reduced precipitation efficiency => more clouds
- aerosol cooling can offset greenhouse gas warming



Ship Tracks: observed 1st AIE

Courtesy: NASA's Earth Observatory

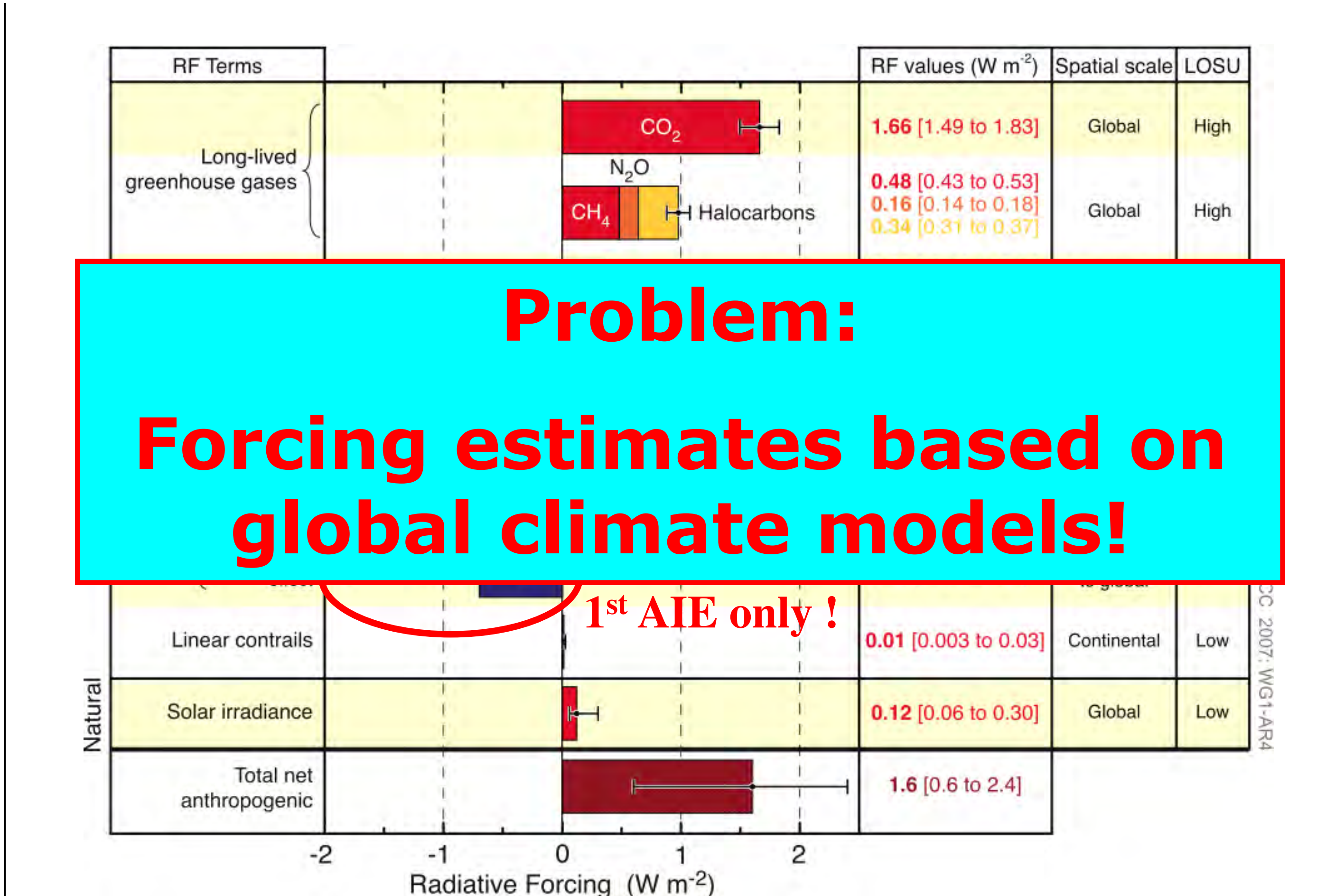




- Particles from exhaust plumes act as CCN => brighter clouds => 1st aerosol indirect effect

2005 Global Average Radiative Forcing Estimates

from IPCC fourth assessment report - http://www.ipcc.ch



Problem:

Forcing estimates based on global climate models!

- 2nd aerosol indirect effect: -0.3 to -1.4 W/m^2
- aerosol cooling can not be larger than greenhouse warming!

Clouds in Climate Models

- **Global Climate Model:**
  - spatial resolution: 2 degree (~ 200 km)
  - time scales: decadal to centennial
  - results aggregated in space and time:
    seasonal / annual and global / regional
  - main shortcoming: clouds unresolved,
    shallow and deep convection parameterized
- **clouds and precipitation poorly represented**
  - clouds are biggest uncertainty in climate sensitivity
- **estimates of aerosol indirect effects highly uncertain**

➔ **use cloud resolving model
to find missing physics**
(Guo et al., 2007)

UM in 2.5 x 3.75 resolution - climateprediction.net

Field Experiment - ACE-2:
Second Aerosol Characterization Experiment

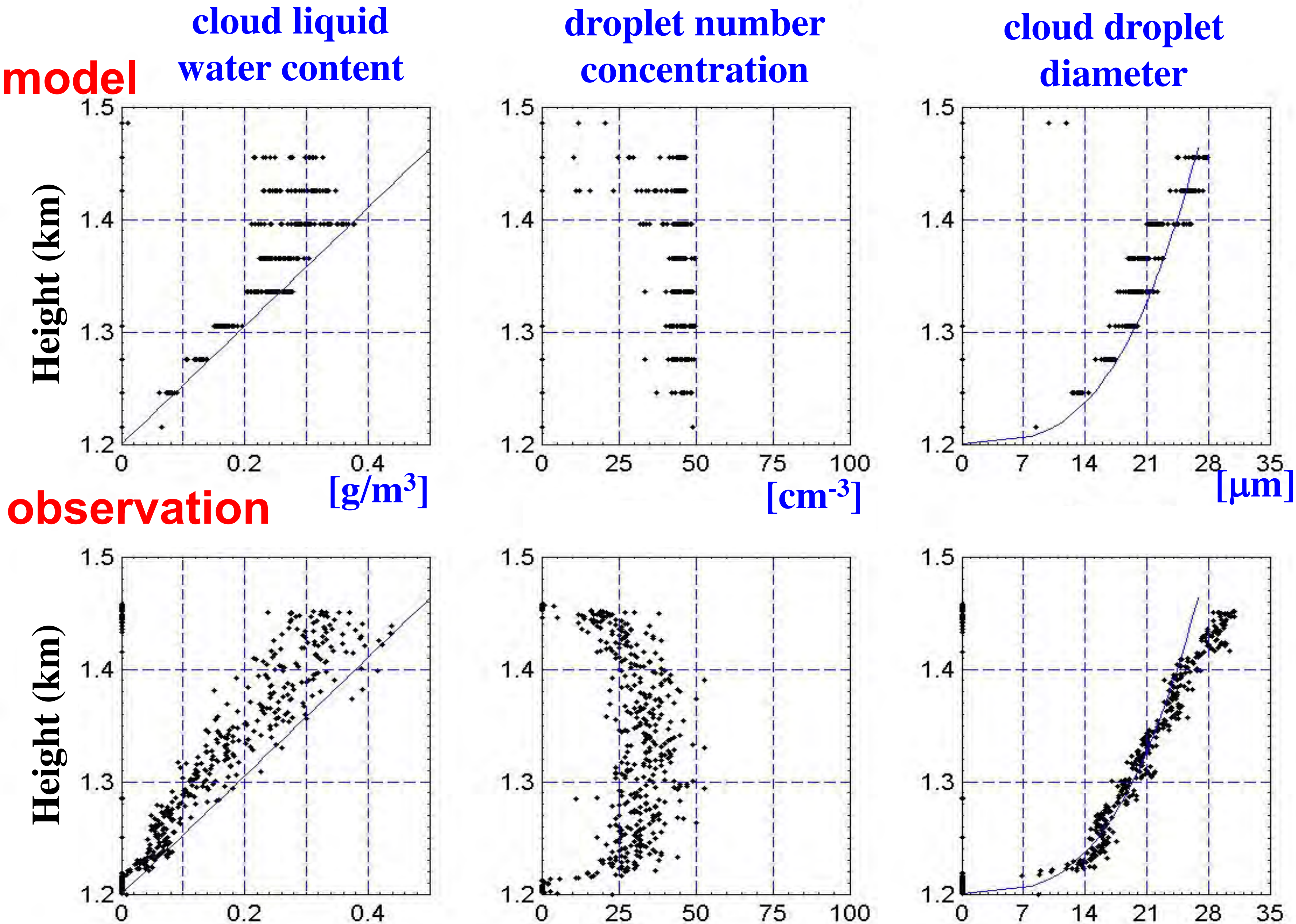
Field Experiment - ACE-2:
Second Aerosol Characterization Experiment

- marine stratocumulus over sub-tropical northeast Atlantic (Canary Islands)
- influenced by marine (clean) or continental (polluted) air
- airborne measurements in June/July 1997 of cloud and aerosol properties
- effects of meteorology and aerosols on cloud can not be distinguished
- apply cloud resolving model to investigate aerosol indirect effects

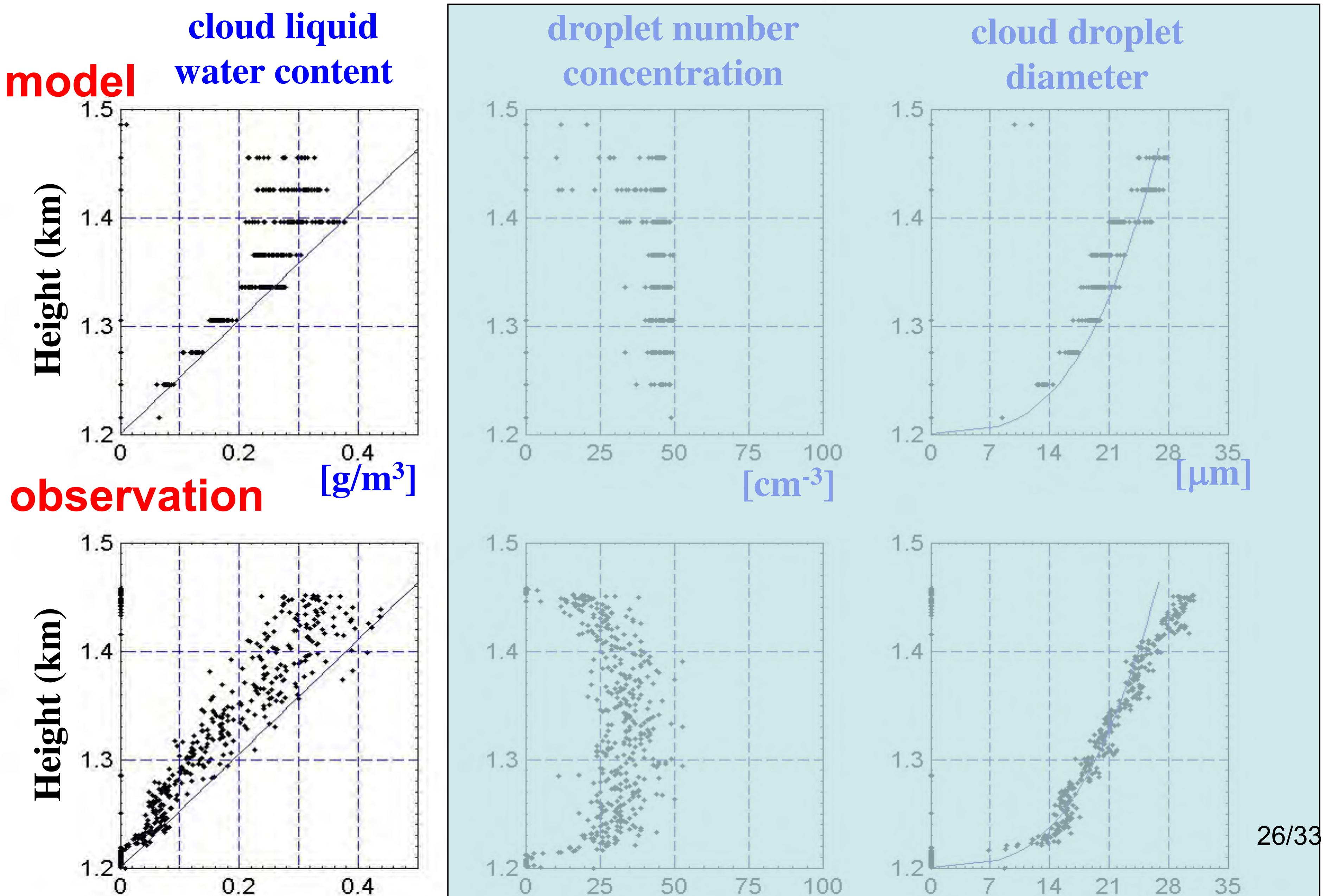
Modelling Approach

- use ATHAM as cloud resolving model
  (Active Tracer High Resolution Atmospheric Model)
  - non-hydrostatic, fully compressible
  - modules for sub-grid turbulence, cloud microphysics, radiation, and surface fluxes
- 3d cartesian, dx=100m (uniform), dz=30m (stretched)
- cyclic boundary conditions
- nudge horizontal mean flow to large scale flow, pressure to large scale pressure
- large scale forcing for temperature and humidity
- start from zero clouds (unforced, missing obs)
- predict cloud droplet number for AIE

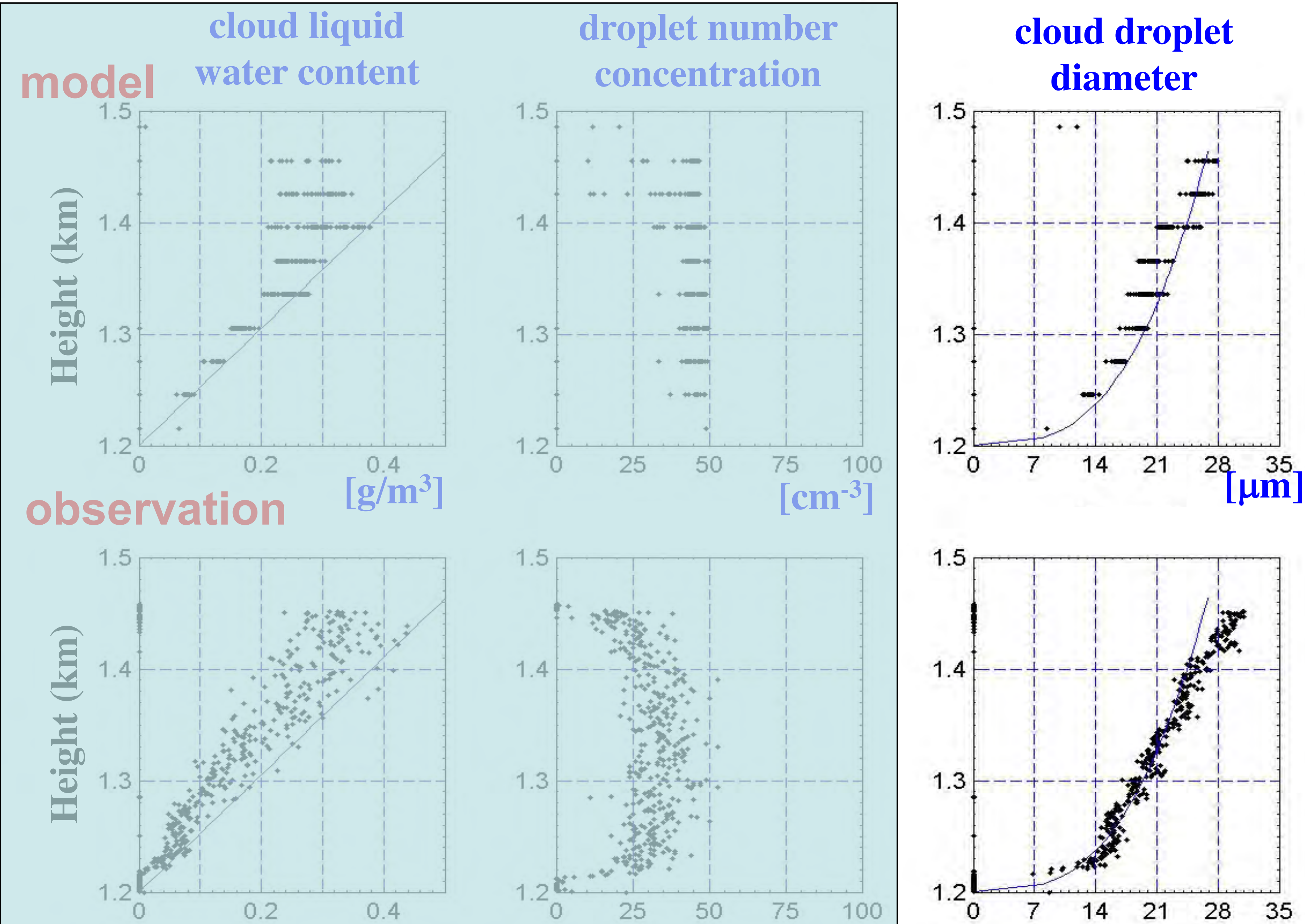
Clean Case: Comparison with Observations



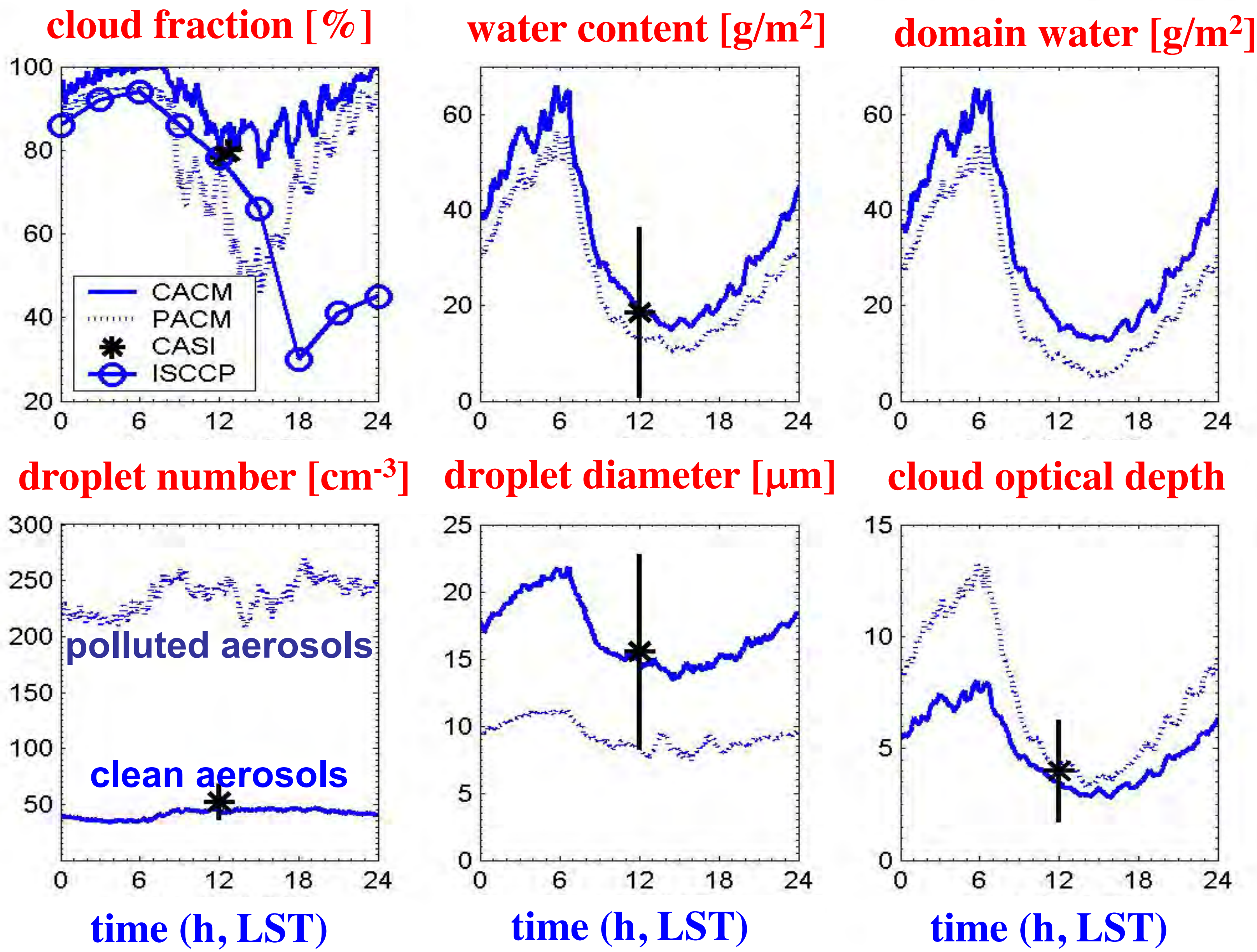
Clean Case: Comparison with Observations



Clean Case: Comparison with Observations



Modeled Aerosol Effects



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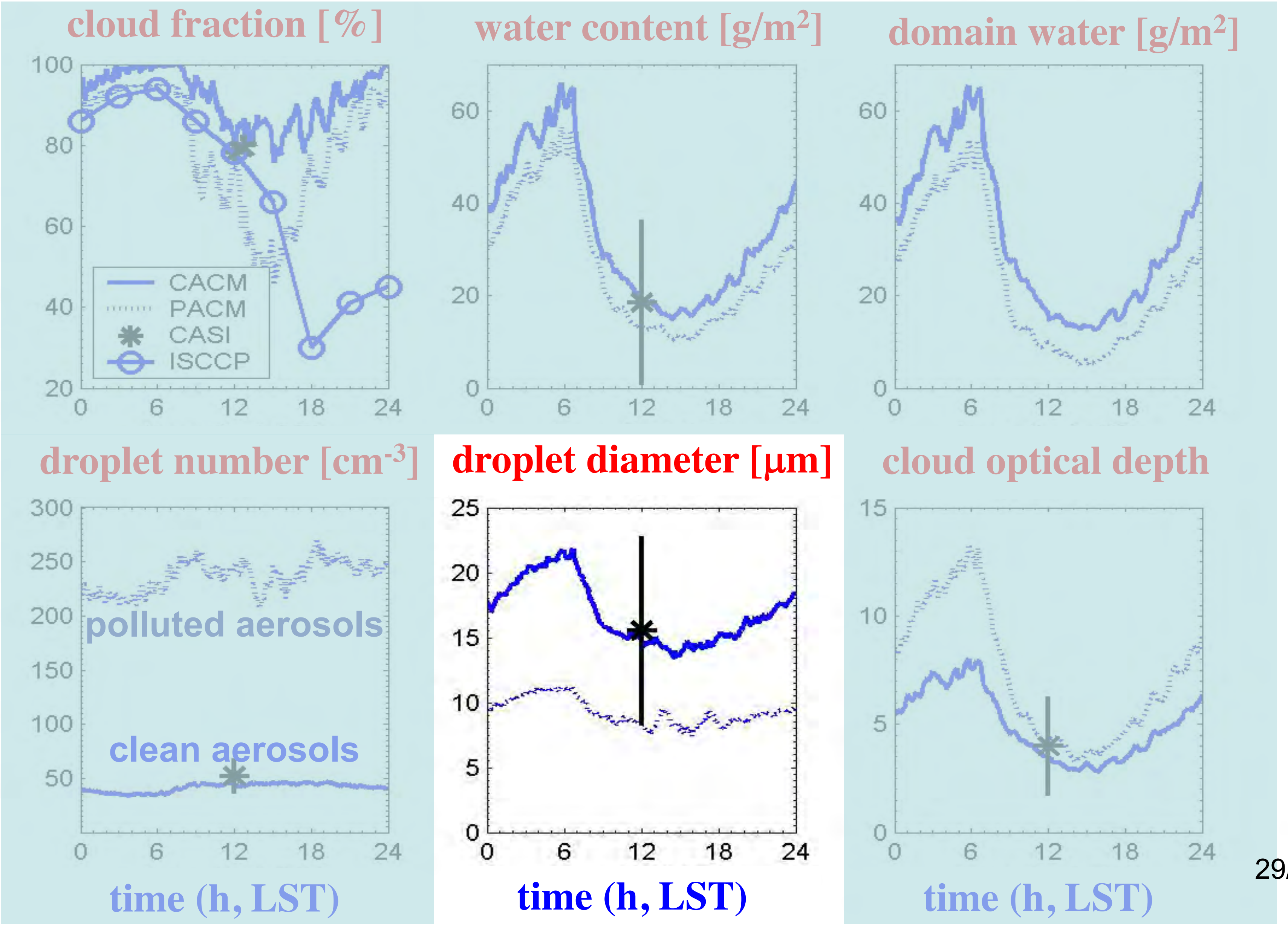
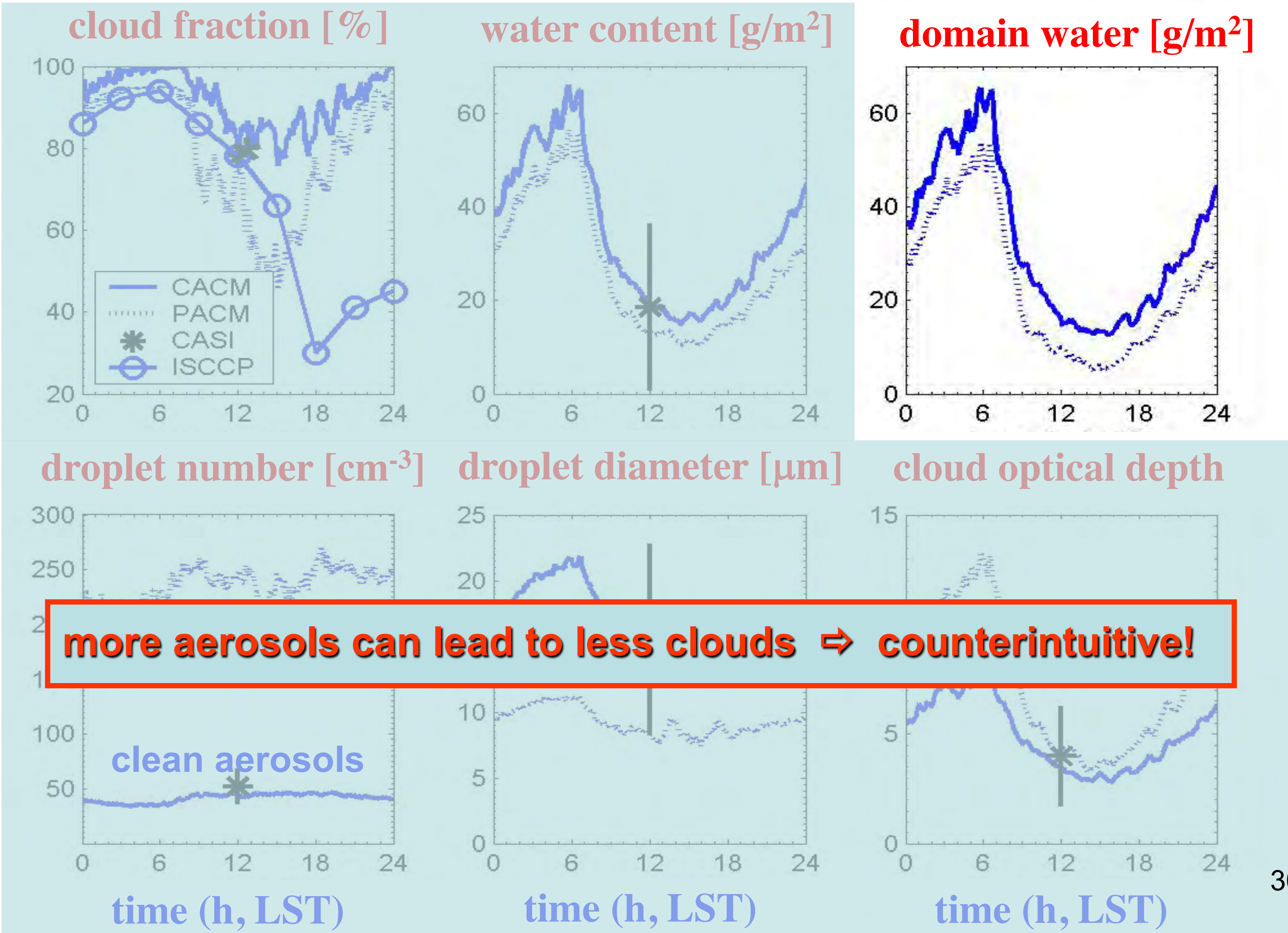
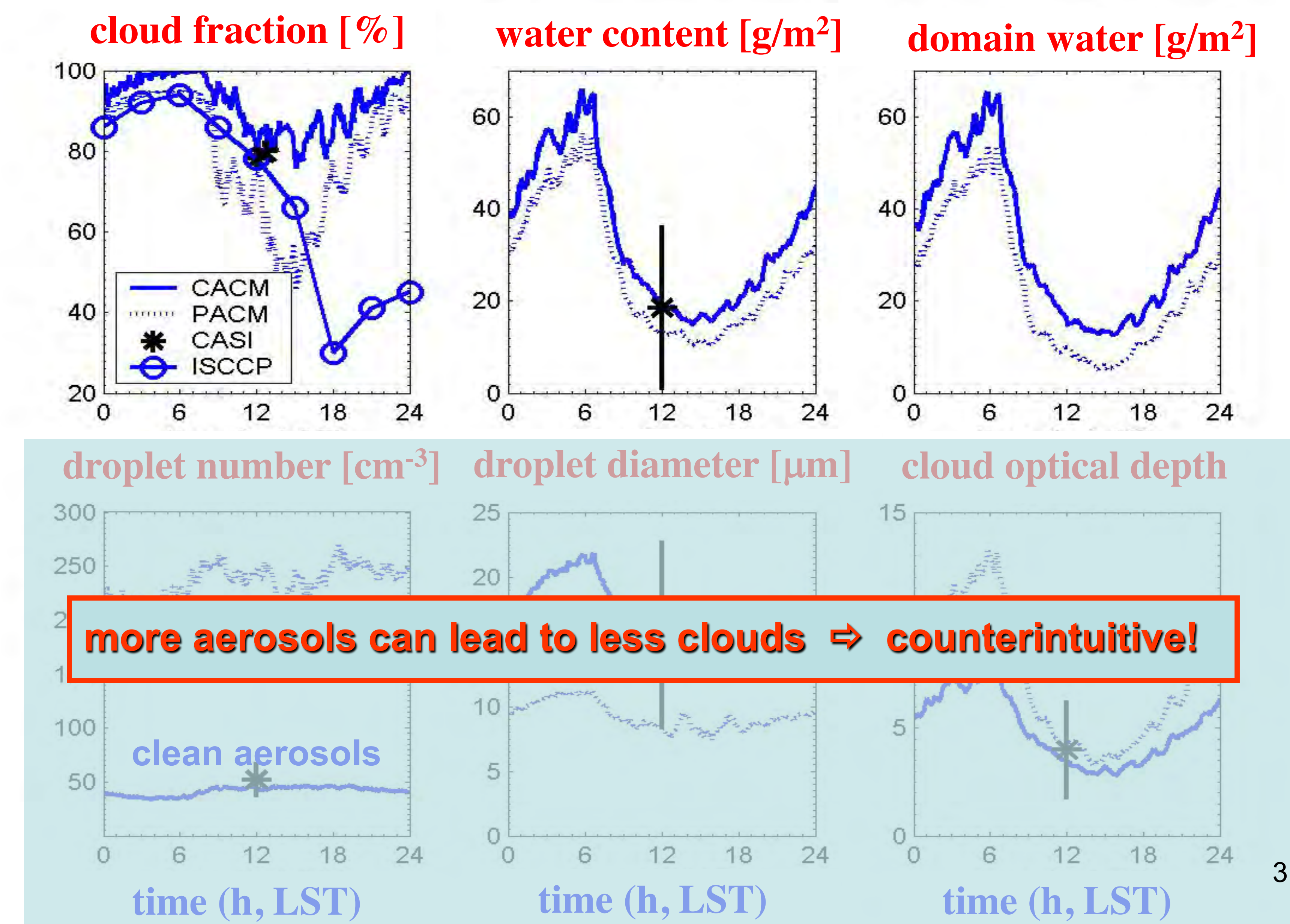


Modeled Aerosol Effects



more aerosols can lead to less clouds ⇨ counterintuitive!

Modeled Aerosol Effects



more aerosols can lead to less clouds ⇨ counterintuitive!

TOA Aerosol Forcing Estimates for Clean Case

- AIE = aerosol indirect effect
  - total AIE (PACM-CACM): -8.8 W/m^2
  - 1st AIE (N_d^{PA}-N_d^{CA}): -19.5 W/m^2
  - 2nd AIE (total – 1st): +10.7 W/m^2
- 2nd AIE positive (warming!) because of decrease in liquid water path and cloud fraction
  - changes in cloud properties lead to enhanced cloud top entrainment
- AIE can not be separated from cloud dynamical processes and meteorological conditions
- case dependent
  - problem of scale in global modelling framework used for IPCC

Summary

- Aerosols are suspended particles in the atmosphere.
- Aerosol cooling can partially offset greenhouse warming (parasol effect ⇨ potential for geo-engineering?).
- Aerosols are necessary to form clouds.
- Aerosol indirect effects result from aerosol cloud interactions.
- Quantification of aerosol forcing and feedbacks require global models.
- By design global models cannot adequately capture all relevant processes including direct, semi-direct, indirect effects and other dynamical feedbacks.
- More work is necessary to understand the role of aerosols and clouds in present and future climate.
- Mixed and ice phase clouds and their interactions with aerosols are even less well understood.