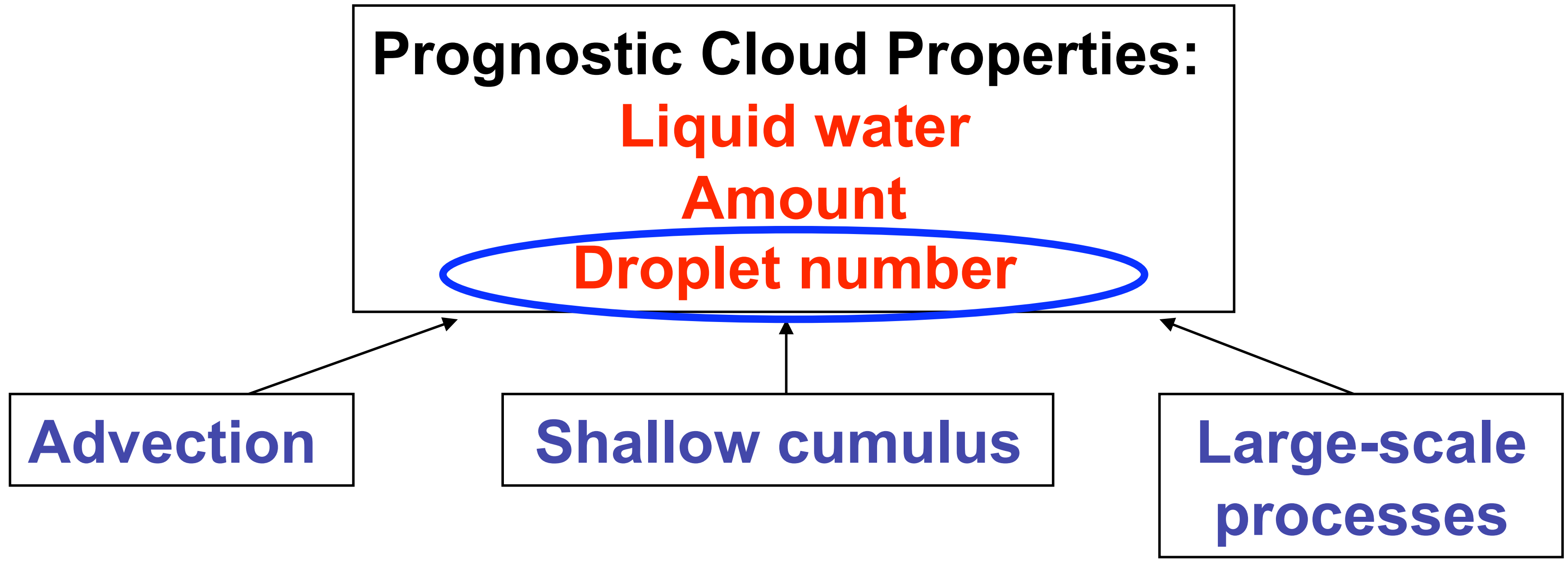
Dissecting Aerosol Indirect Effects on the Process Level

Yi Ming

Geophysical Fluid Dynamics Laboratory/NOAA

Princeton, New Jersey

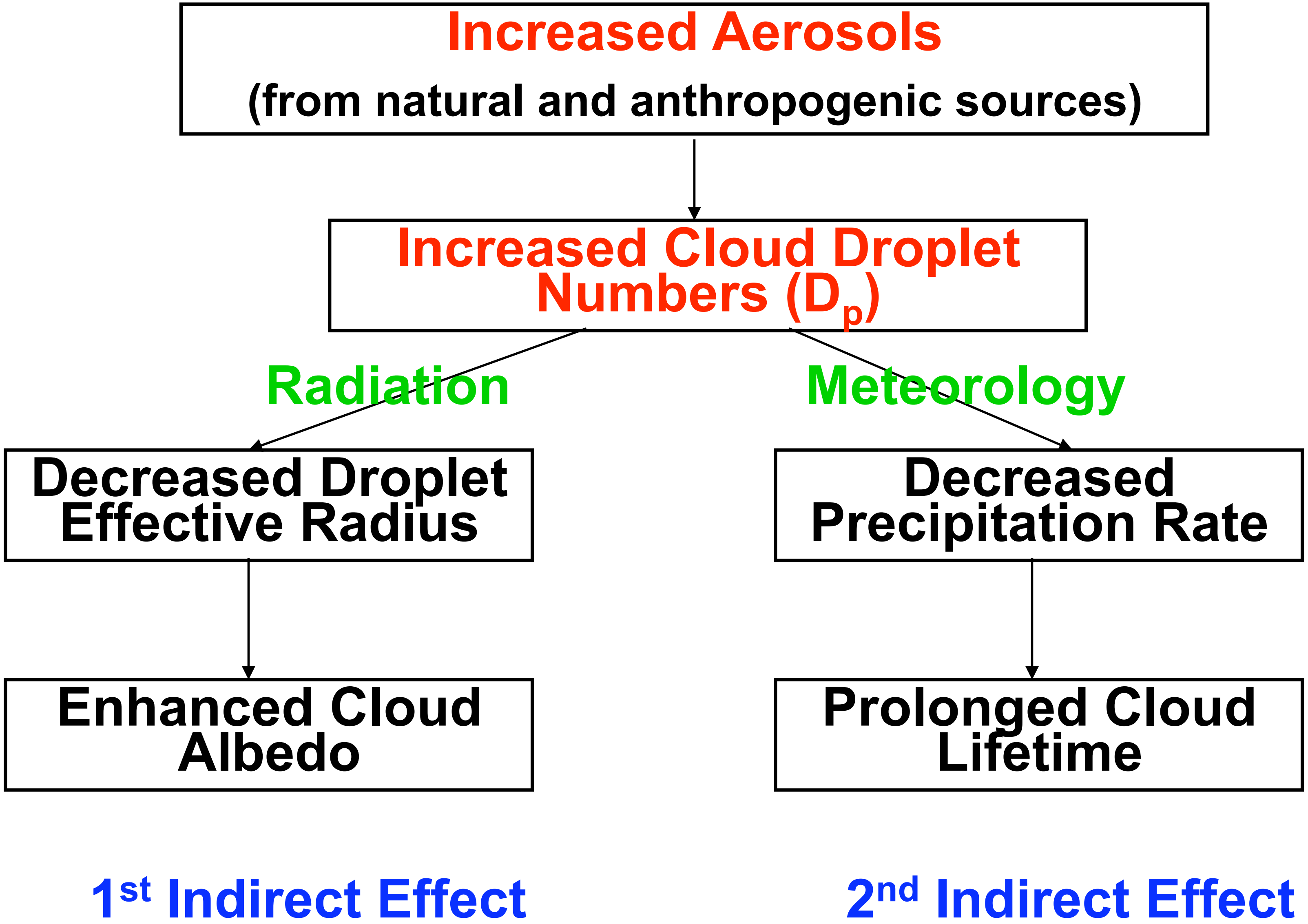
A primer on the model representation of aerosol-liquid cloud interactions



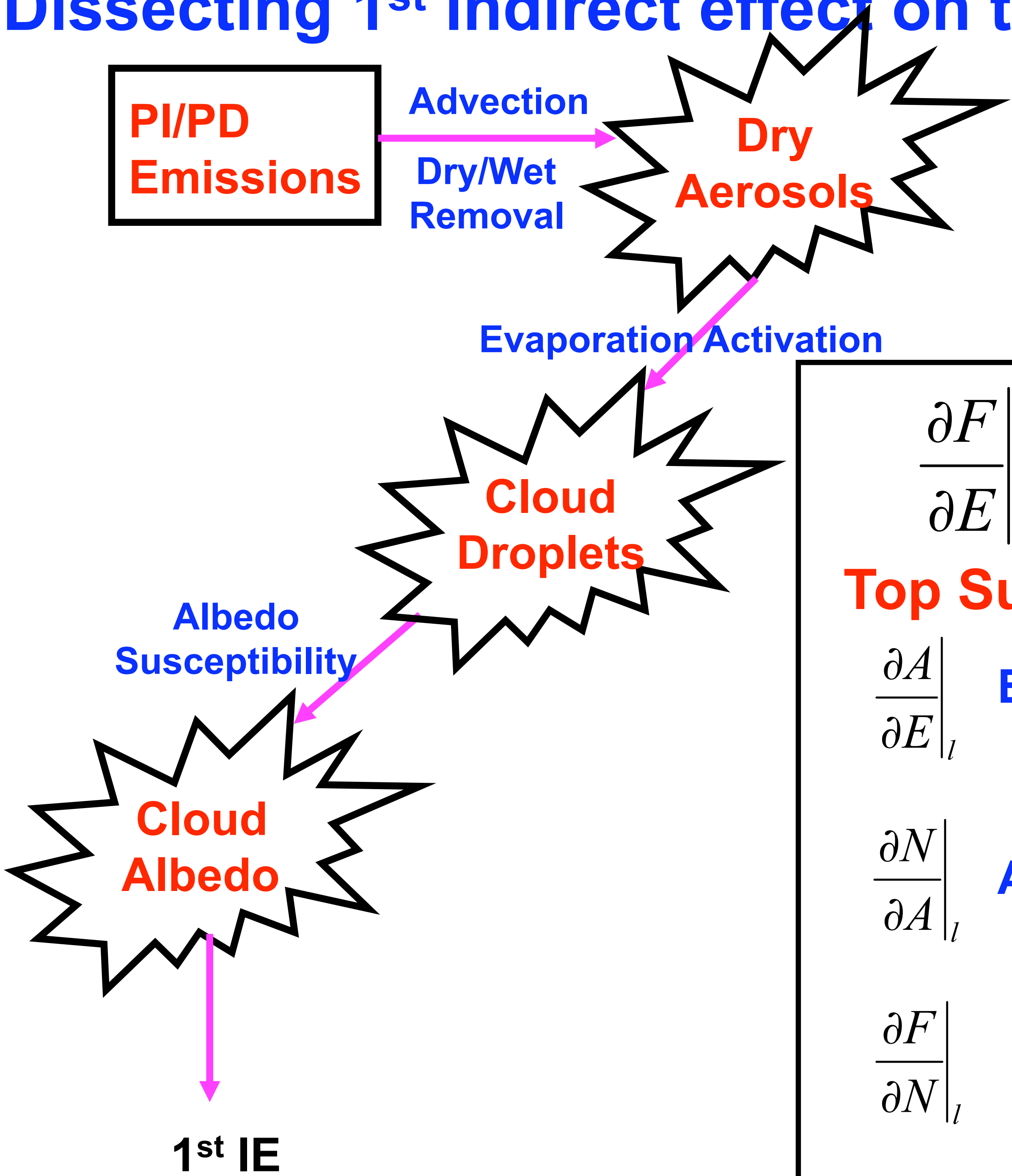
- Source and sink terms are fully consistent;
- Multiple aerosol species (i.e., sulfate, organic carbon and sea salt) are activated;
- Droplets evolve freely with model meteorology.

Ming et al. JAS (2006, 2007)

1st and 2nd indirect radiative effects of aerosols



Dissecting 1st indirect effect on the process level



$$\left.\frac{\partial F}{\partial E}\right|_l = \left.\frac{\partial A}{\partial E}\right|_l \left.\frac{\partial N}{\partial A}\right|_l \left.\frac{\partial F}{\partial N}\right|_l$$

Top Suspects:

$\left.\frac{\partial A}{\partial E}\right|_l$ Emissions, Wet Removal

$\left.\frac{\partial N}{\partial A}\right|_l$ Activation

$\left.\frac{\partial F}{\partial N}\right|_l$ Cloud Distribution

$\left.\frac{\partial F}{\partial N}\right|_l$ How cloud forcing varies with droplet number?

Revisiting Twomey's Cloud Susceptibility:

$$\left.\frac{\partial R}{\partial N}\right|_l = \frac{R(1-R)}{3N}$$

In discrete form, the relative cloud susceptibility can be written as:

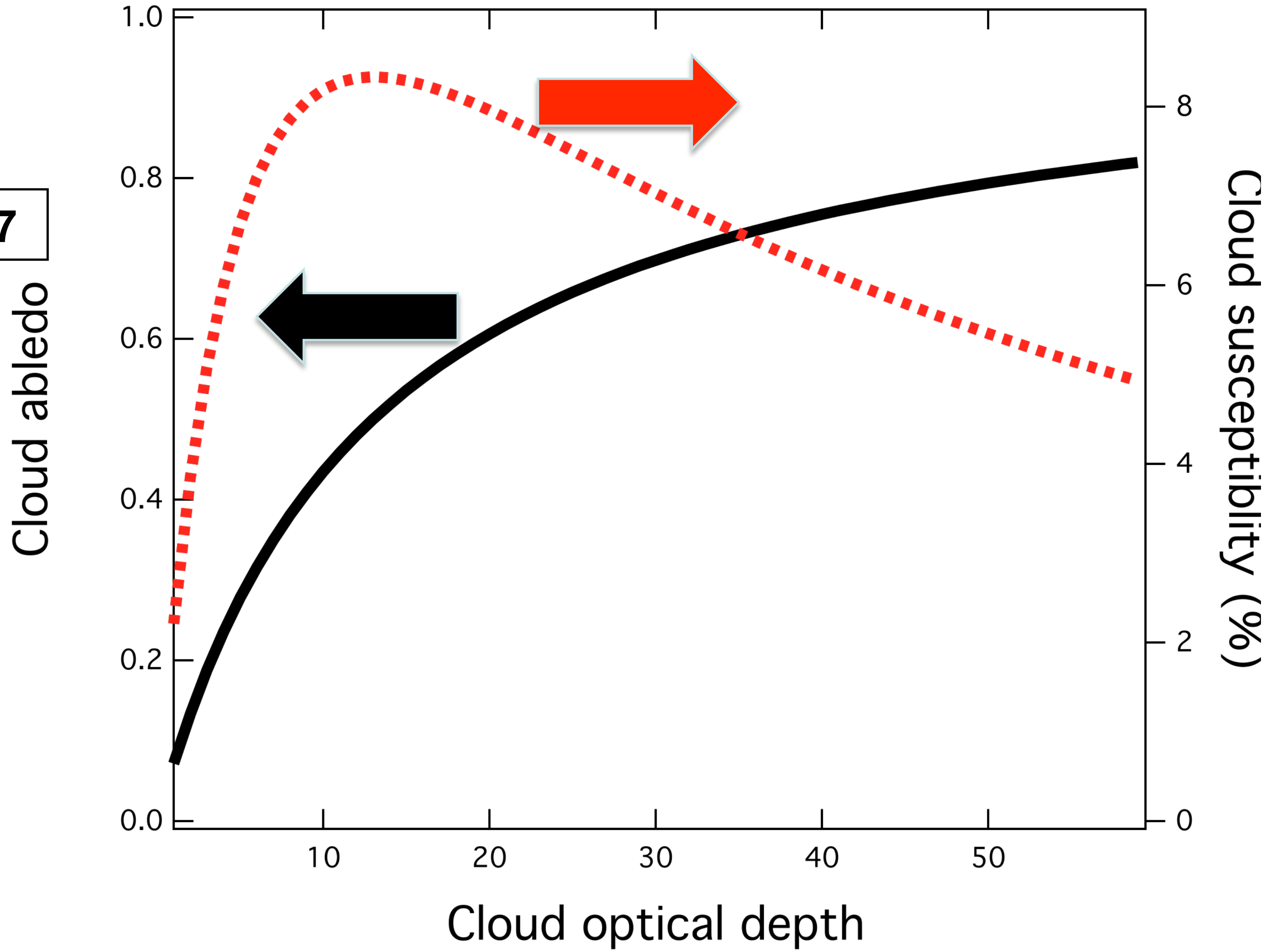
$$\left.\frac{\Delta R}{\left(\frac{\Delta N}{N}\right)}\right|_l = \frac{R(1-R)}{3} \longrightarrow \left.\frac{\Delta R}{\left(\frac{\Delta N}{N}\right)}\right|_{l,\max} = \frac{1}{12} = 8.3\%$$

when $R = 0.5$

Cloud susceptibility is highly nonlinear w.r.t. cloud optical depth.

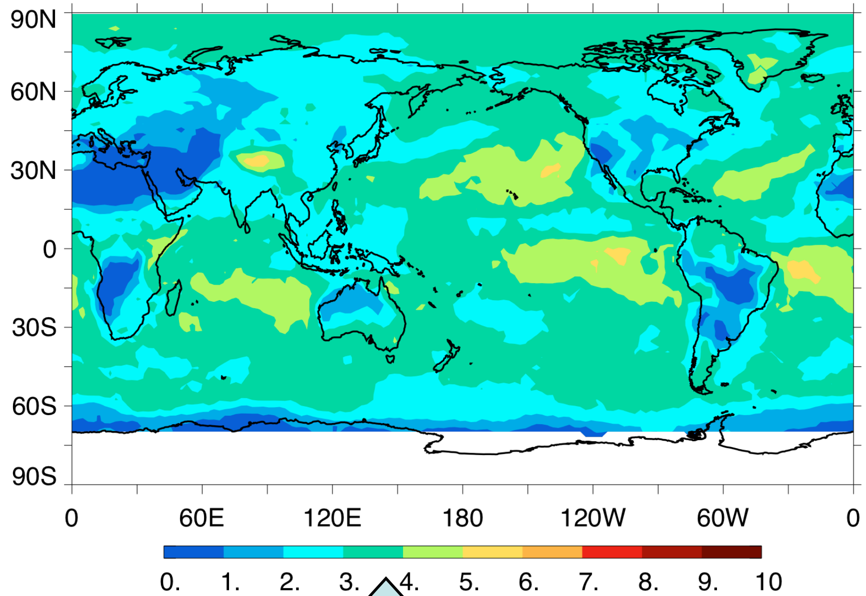
$$R = \frac{\tau}{\tau + 13}$$

Bohren, 1987

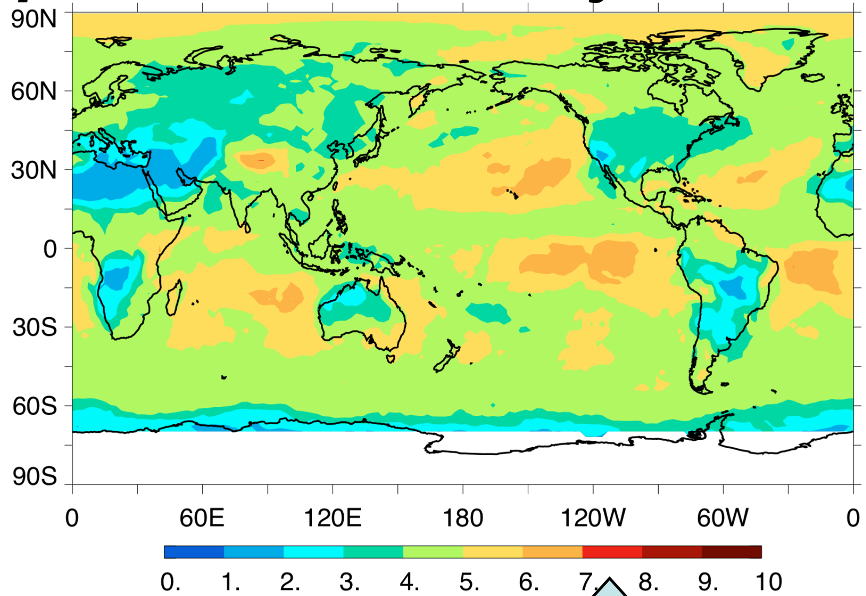


Cloud susceptibility to droplet number concentration

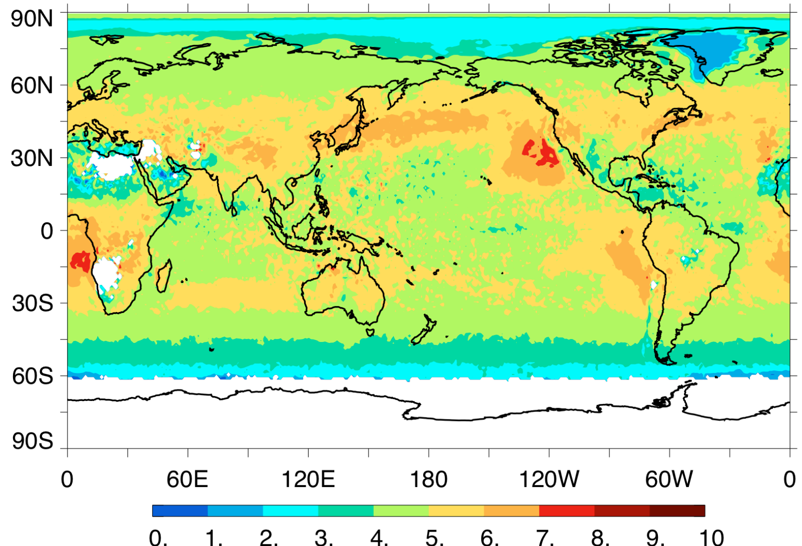
Difference in planetary albedo (x1000) caused by a uniform 10% increase in droplet number in July.



AM3



AM3+1.5



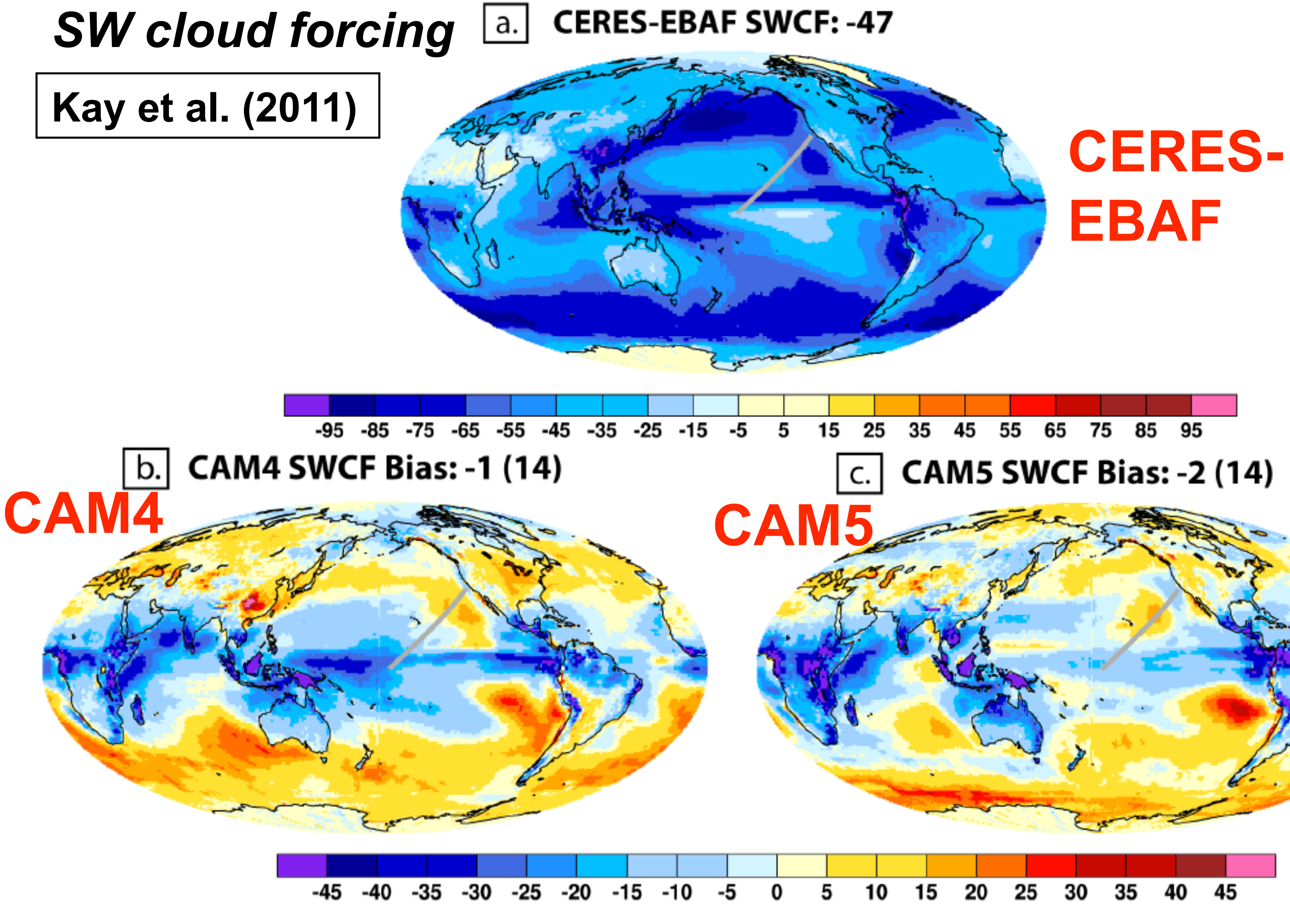
MODIS

Oreopoulos & Platnick (2008)

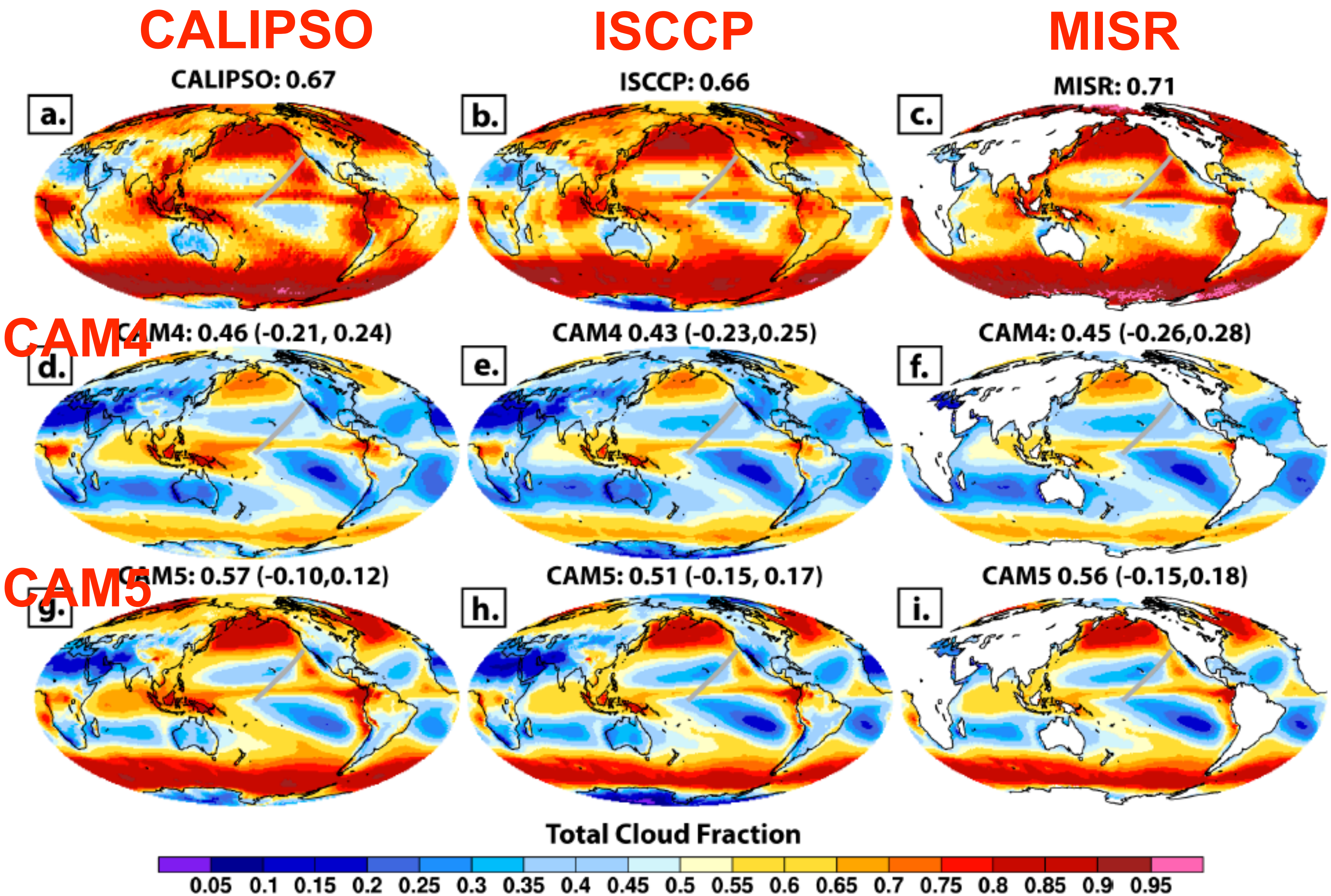
Why the susceptibility could be very different across models?

SW cloud forcing

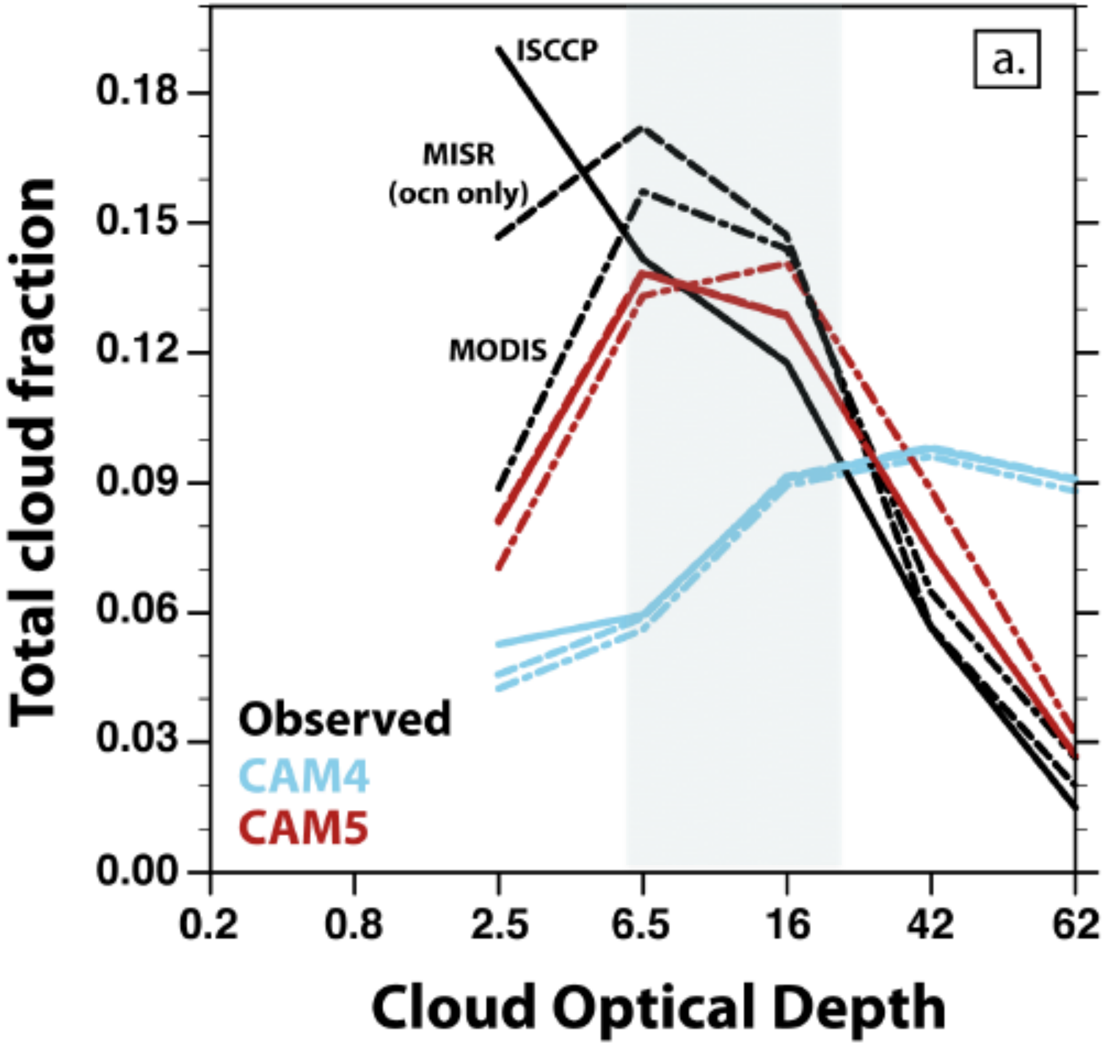
Kay et al. (2011)

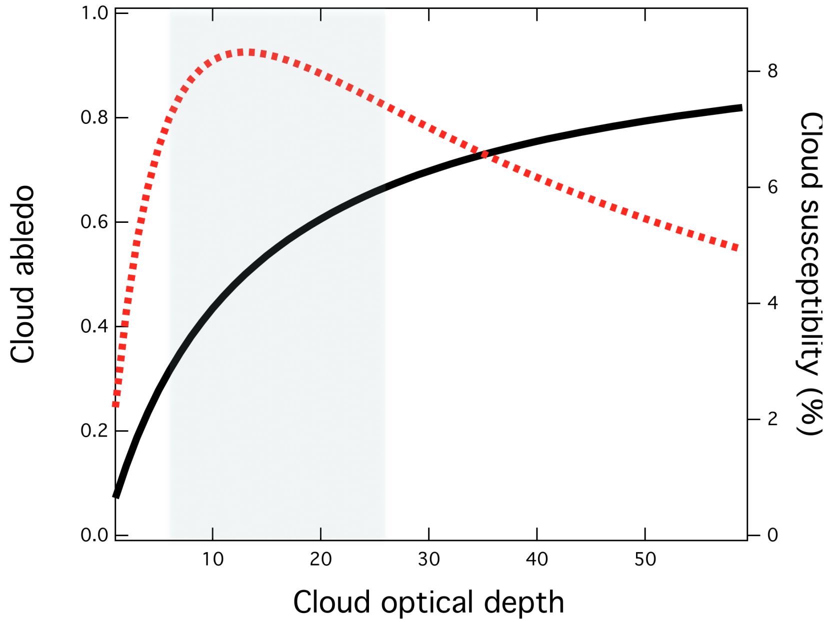


Total cloud amount

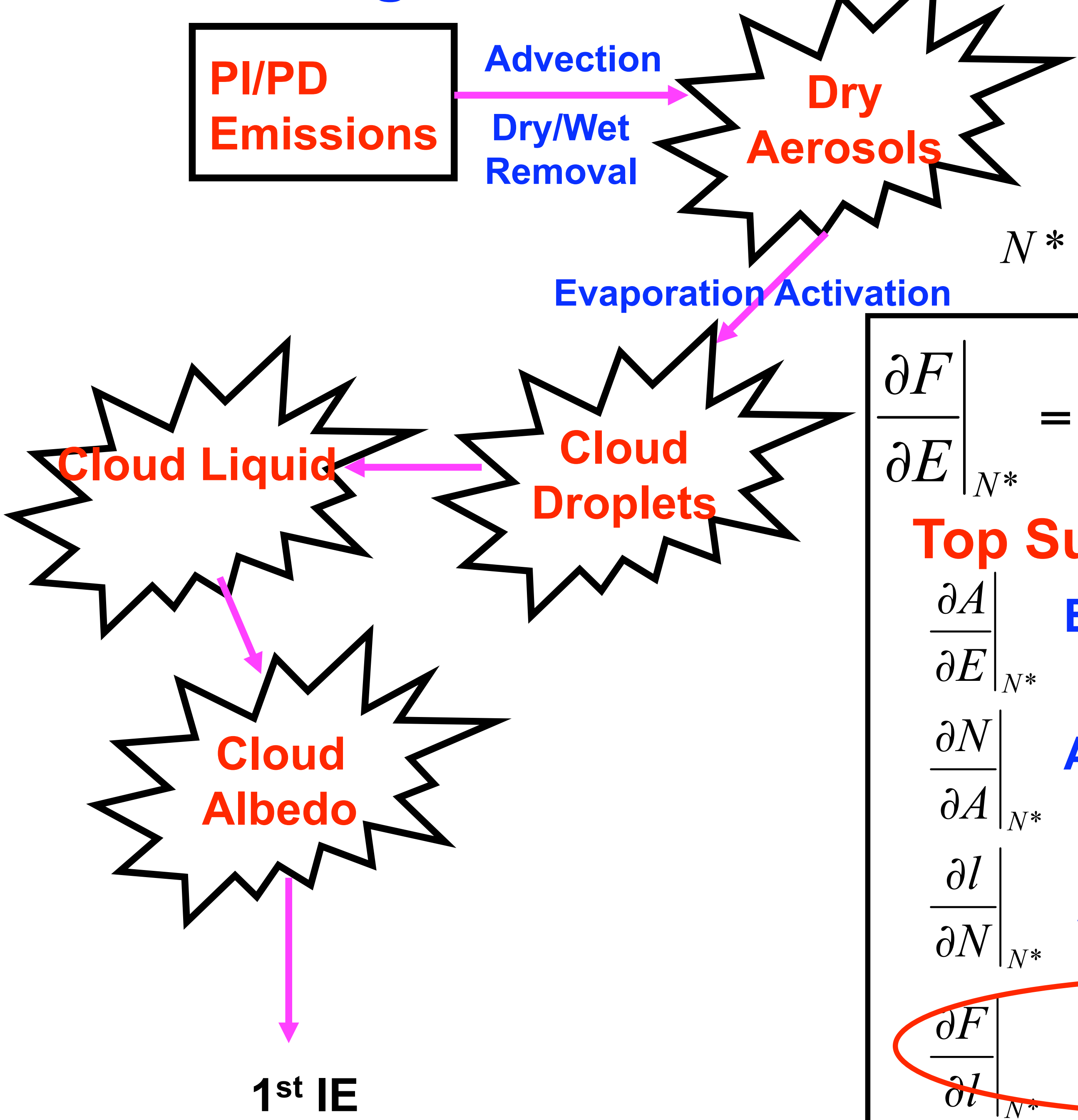


Similar cloud forcing, but different cloud amount. Why?





Dissecting 2nd indirect effect on the process level



$N*$ ***Droplet number used in calculating cloud albedo***

$$\left.\frac{\partial F}{\partial E}\right|_{N*} = \left.\frac{\partial A}{\partial E}\right|_{N*} \left.\frac{\partial N}{\partial A}\right|_{N*} \left.\frac{\partial l}{\partial N}\right|_{N*} \left.\frac{\partial F}{\partial l}\right|_{N*}$$

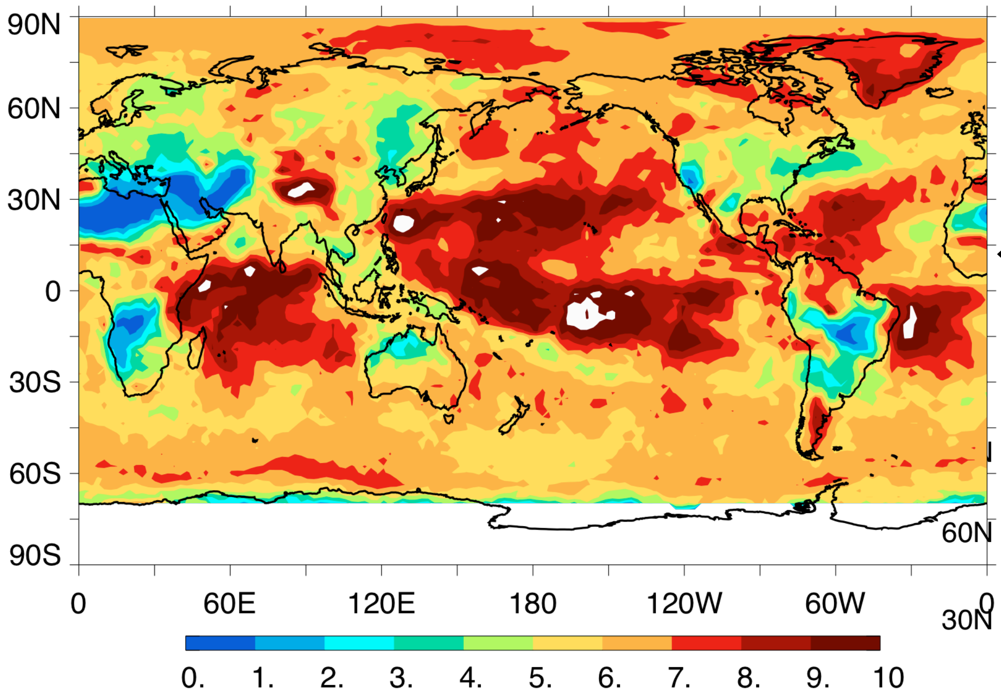
Top Suspects:

- $\left.\frac{\partial A}{\partial E}\right|_{N*}$ **Emissions, Wet Removal**
- $\left.\frac{\partial N}{\partial A}\right|_{N*}$ **Activation**
- $\left.\frac{\partial l}{\partial N}\right|_{N*}$ **Autoconversion**
- $\left.\frac{\partial F}{\partial l}\right|_{N*}$ **Cloud Distribution**

Cloud susceptibility to cloud liquid condensate

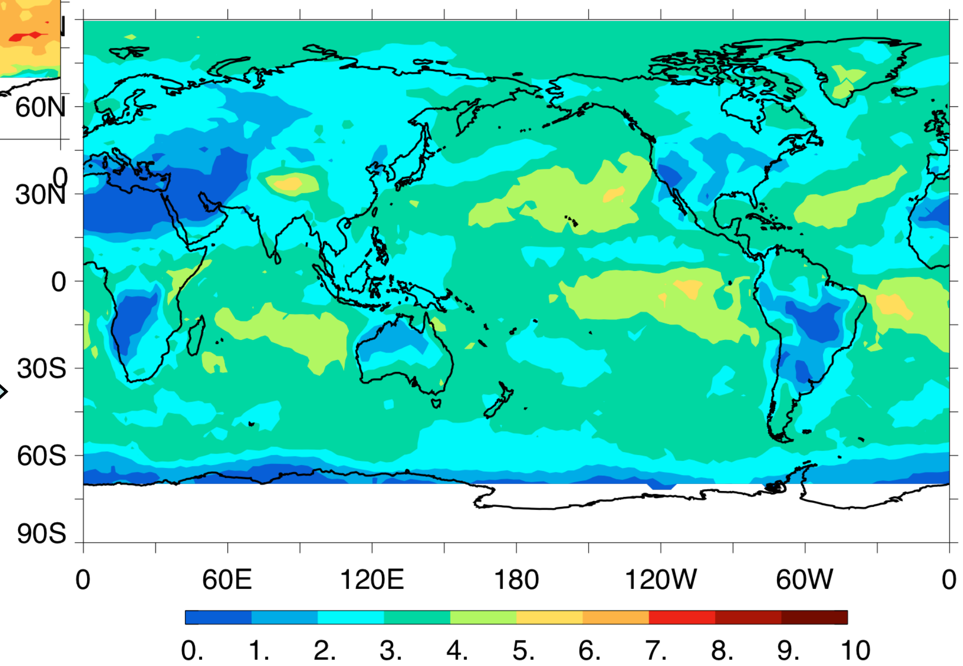
Difference in planetary albedo (x1000) caused by a uniform 10% increase in cloud liquid in July.

$$\tau \propto L^{2/3} N^{1/3}$$

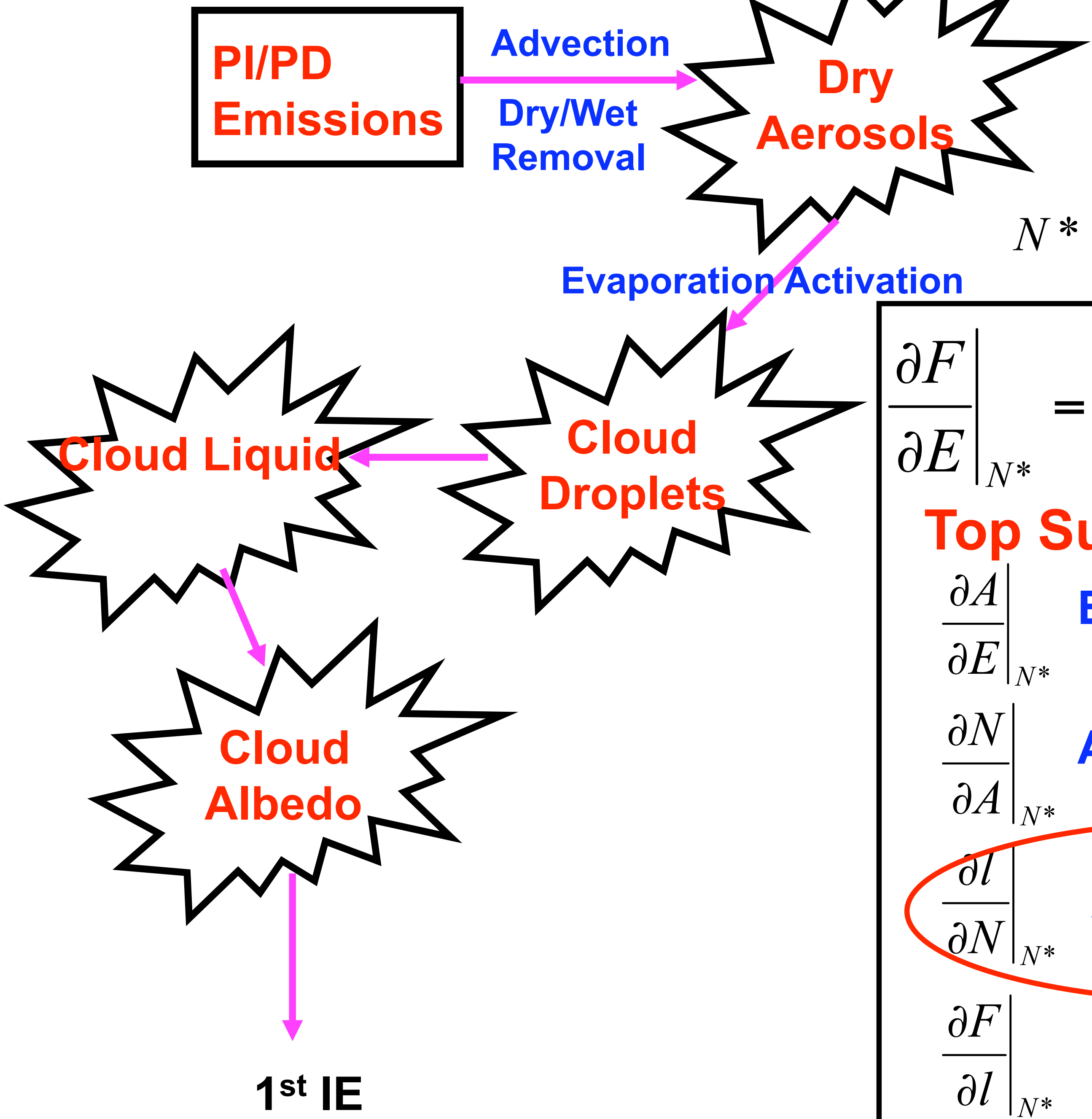


Cloud liquid

Cloud droplet number



Dissecting 2nd indirect effect on the process Level



$N*$ ***Droplet number used in calculating cloud albedo***

$$\left.\frac{\partial F}{\partial E}\right|_{N*} = \left.\frac{\partial A}{\partial E}\right|_{N*} \left.\frac{\partial N}{\partial A}\right|_{N*} \left.\frac{\partial l}{\partial N}\right|_{N*} \left.\frac{\partial F}{\partial l}\right|_{N*}$$

Top Suspects:

- $\left.\frac{\partial A}{\partial E}\right|_{N*}$ **Emissions, Wet Removal**
- $\left.\frac{\partial N}{\partial A}\right|_{N*}$ **Activation**
- $\left.\frac{\partial l}{\partial N}\right|_{N*}$ **Autoconversion**
- $\left.\frac{\partial F}{\partial l}\right|_{N*}$ **Cloud Distribution**

$\left.\frac{\partial l}{\partial N}\right|_{N*}$ How Droplet Number Affects Cloud Liquid?

The governing equation for cloud liquid can be simplified into

$$\frac{\partial l}{\partial t} = S - \frac{\partial l}{\partial t}_{auto} = S - a\frac{l^m}{N^n}$$

$\uparrow$

Sources/Sinks except autoconversion; assumed to be constant w.r.t. droplet number (?).

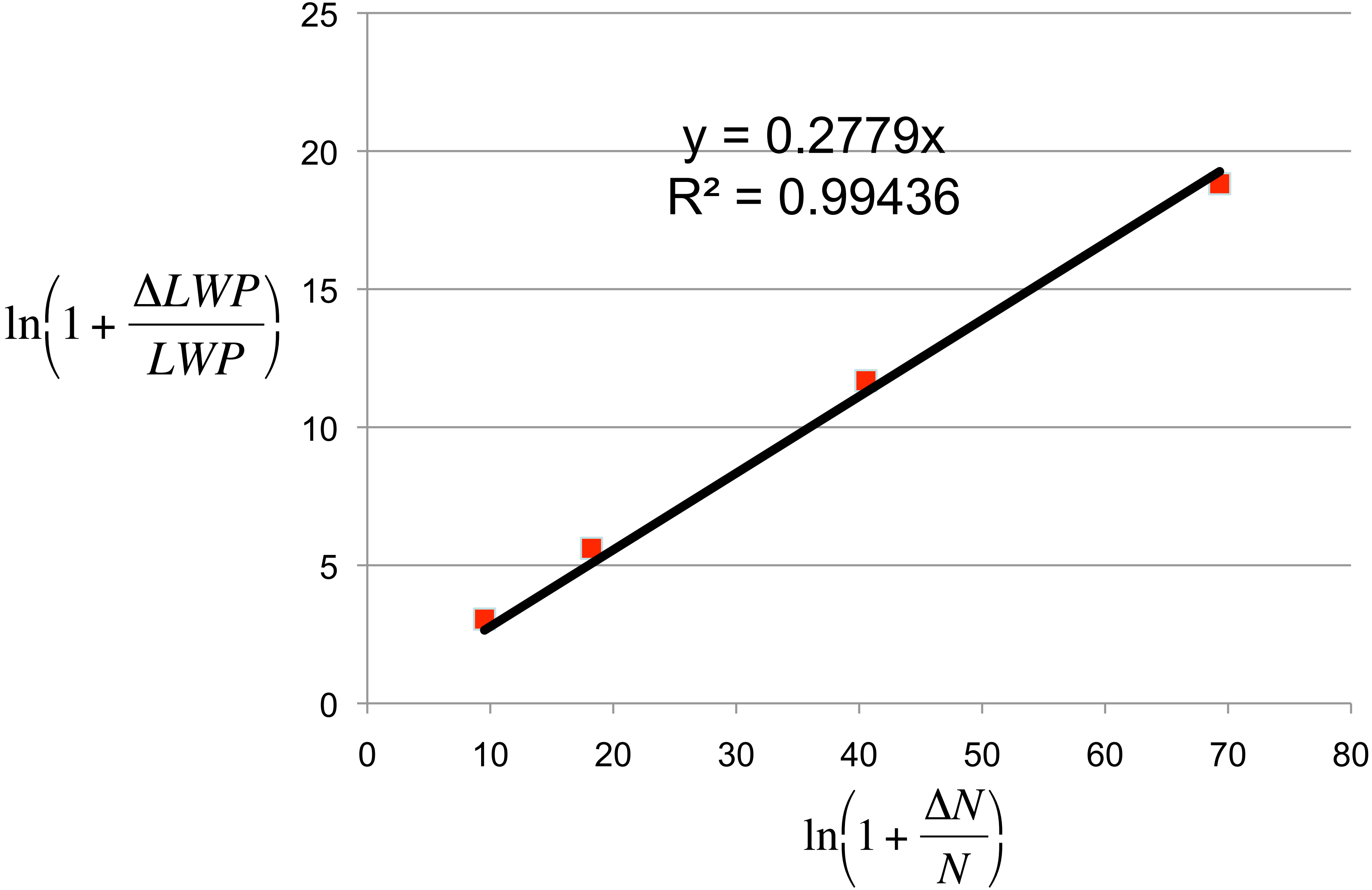
At steady state, $\frac{\partial l}{\partial t} = 0$

Then,

$$\ln\left(1 + \frac{\Delta l}{l}\right) = \frac{n}{m}\ln\left(1 + \frac{\Delta N}{N}\right)$$

$\left(\frac{\partial q_r}{\partial t}\right)_{\text{auto}} = 1350 q_c^{2.47} N_c^{-1.79}$ ***Khairoutdinov & Kogan suggests 0.72.***

Model-Simulated Dependence of Cloud Liquid on Droplet Number



Conclusions

•To reduce the uncertainties of indirect effects, one may choose to examine the underlying processes individually, as opposed the effects as a whole;

•The model representation of the processes should be checked carefully against theories and satellite observations.

Cloud effective radii