High cloud size dependency of the applicability of the fixed anvil temperature (FAT) hypothesis using global nonhydrostatic simulations

Akira Noda, Tatsuya Seiki, Masaki Satoh and Yohei Yamada

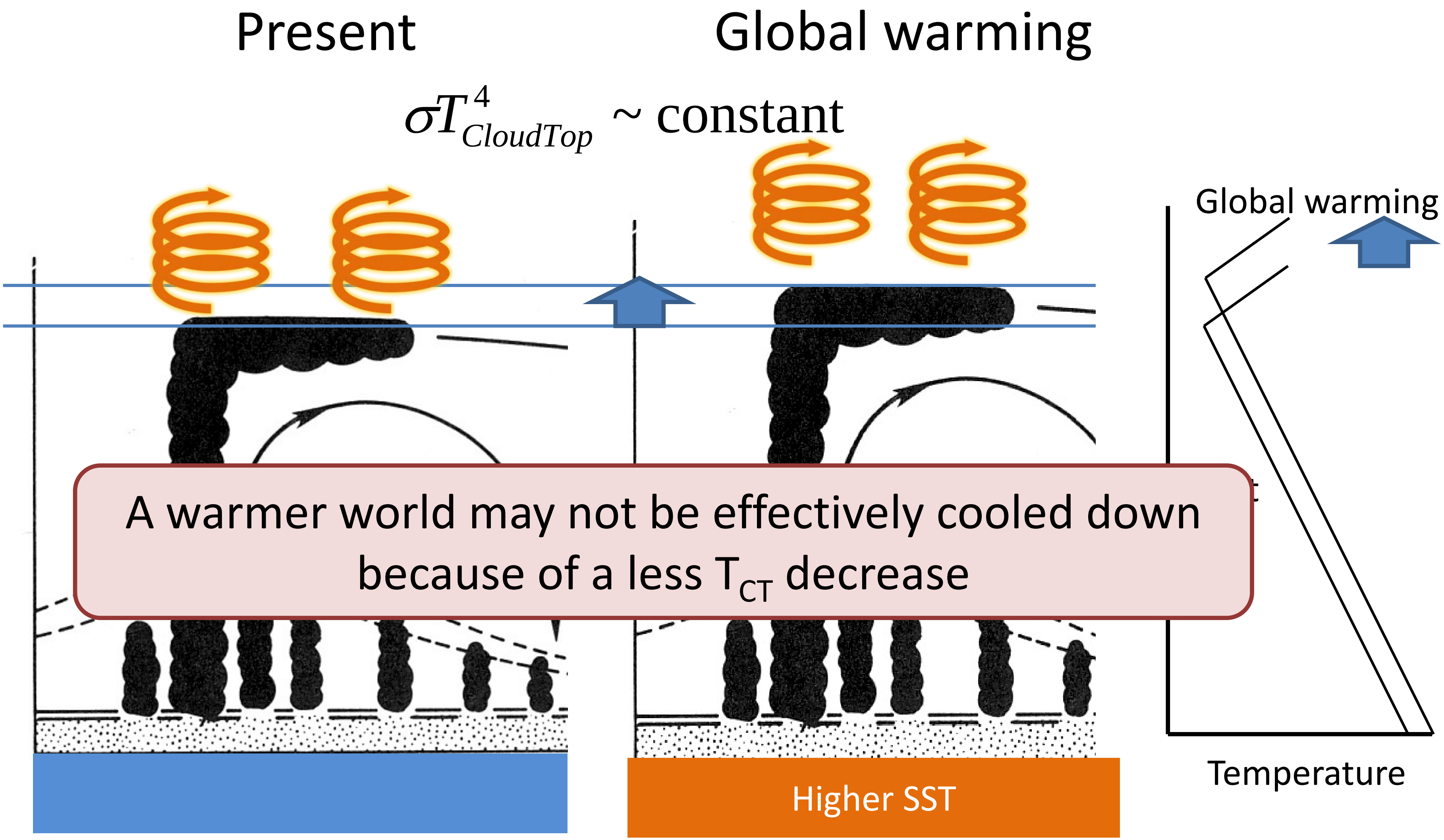
Japan Agency for Marine-Earth Science and Technology, Japan

- Noda et al. 2016: High cloud size dependency in the applicability of the fixed anvil temperature hypothesis using global non-hydrostatic simulations. Geophys. Res. Lett, doi:10.1002/2016GL067742.
- Noda et al. 2014: Responses of tropical and subtropical high-cloud statistics to global warming. J. Climate, 27, 7753-7768.

~The FAT hypothesis~

(Hartmann and Larson 2002)

Mean cloud-top temperature of tropical deep clouds is almost kept constant even in different climate states

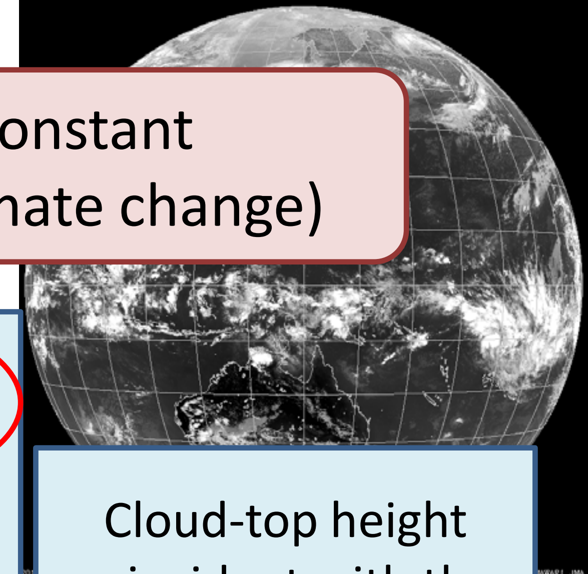


A warmer world may not be effectively cooled down because of a less T_{CT} decrease

Background

S

Cloud-top temperate is kept nearly constant
(T_{CT} not directly depend on T_{SFC} and/or climate change)

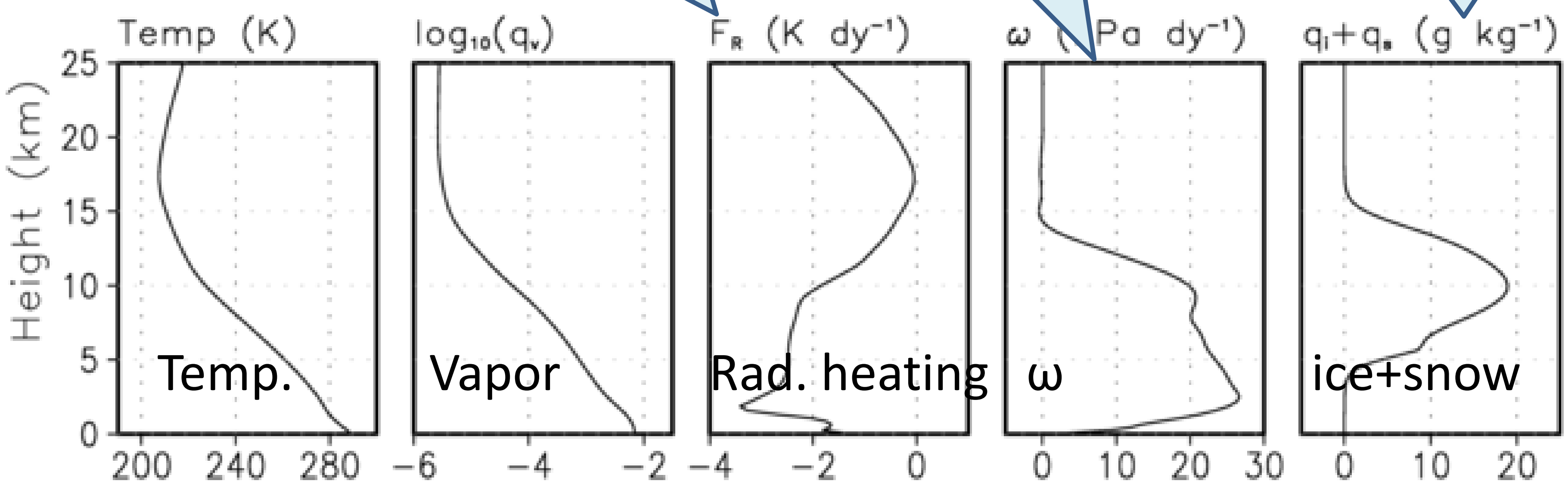


Q_V (z) ∼ T(z)
due to C-C relatio

F_R (z) ∼ Q_V (z)
due to emission by
vapor

ω(z) (and cloud-top
height (i.e.,
detrainment
height) ∼ F_R(z)
due to heat
balance
$\omega \partial\theta/\partial p \sim F_R$

Cloud-top height
coincident with the
rapid decreasing
level of qv



- Question
  - FAT hypothesis says "Change of T_{CT} is small enough not to affect the earth's radiative budget"
  - But…
    - To what extent small is small enough?
    - How about the dependence on types of clouds?
      - Scales of tropical deep clouds have wide variability…
- Data
  - 7-km mesh NICAM
  - 1-yr simulation for present and global warming climate (time-slice approach)

Experimental Design (Present climate simulation)

Initialization	NCEP Global analysis
Time Integration	1 year starting from 1 June 2004
SST	Slab mixed layer ocean model with 15m depth and 7day e-folding time, nudged to NOAA Weekly Reynolds SST
Horizontal resolution	7km
Vertical resolution	80m～2.9km (Stretched)
Cloud	One-moment, 6 categories (Tomita 2008) (cumulus parameterization not used)
Turbulence	Improved version of Mellor-Yamada Level 2 with subgrid-scale condensation (Nakanishi & Niino 2006; Noda et al. 2010) ※partial cloudiness not considered
Surface turbulent flux	Bulk parameterization by Louis (1979)
Radiation	MSTRN-X (Sekiguchi and Nakajima 2008)
Land surface	MATSIRO (Takata et al. 2003)
CO2 concentration	348 ppm

Experimental Design (Global warming simulation)

Initialization	NCEP Global analysis
Time Integration	1 year starting from 1 May 2004 / 1-month spin-up + 1 year (Time slice approach)
SST	Slab mixed layer ocean model with 15m depth and 7day e-folding time, nudged t / Present+Increase by CMIP3 ensemble
Horizontal resolution	7km
Vertical resolution	80m～2.9km (Stretched)
Cloud	One-moment, 6 categories (Tomita 2008) (cumulus parameterization not used)
Turbulence	Improved version of Mellor-Yamada Level 2 with subgrid-scale condensation (Nakanishi & Niino 2006; Noda et al. 2010) ※partial cloudiness not considered
Surface turbulent flux	Bulk parameterization by Louis (1979)
Radiation	MSTRN-X (Sekiguchi and Nakajima 2008)
Land surface	MATSIRO (Takata et al. 2003)
CO2 concentration	348 ppm / 696 ppm (twiced homogeneously over the globe)

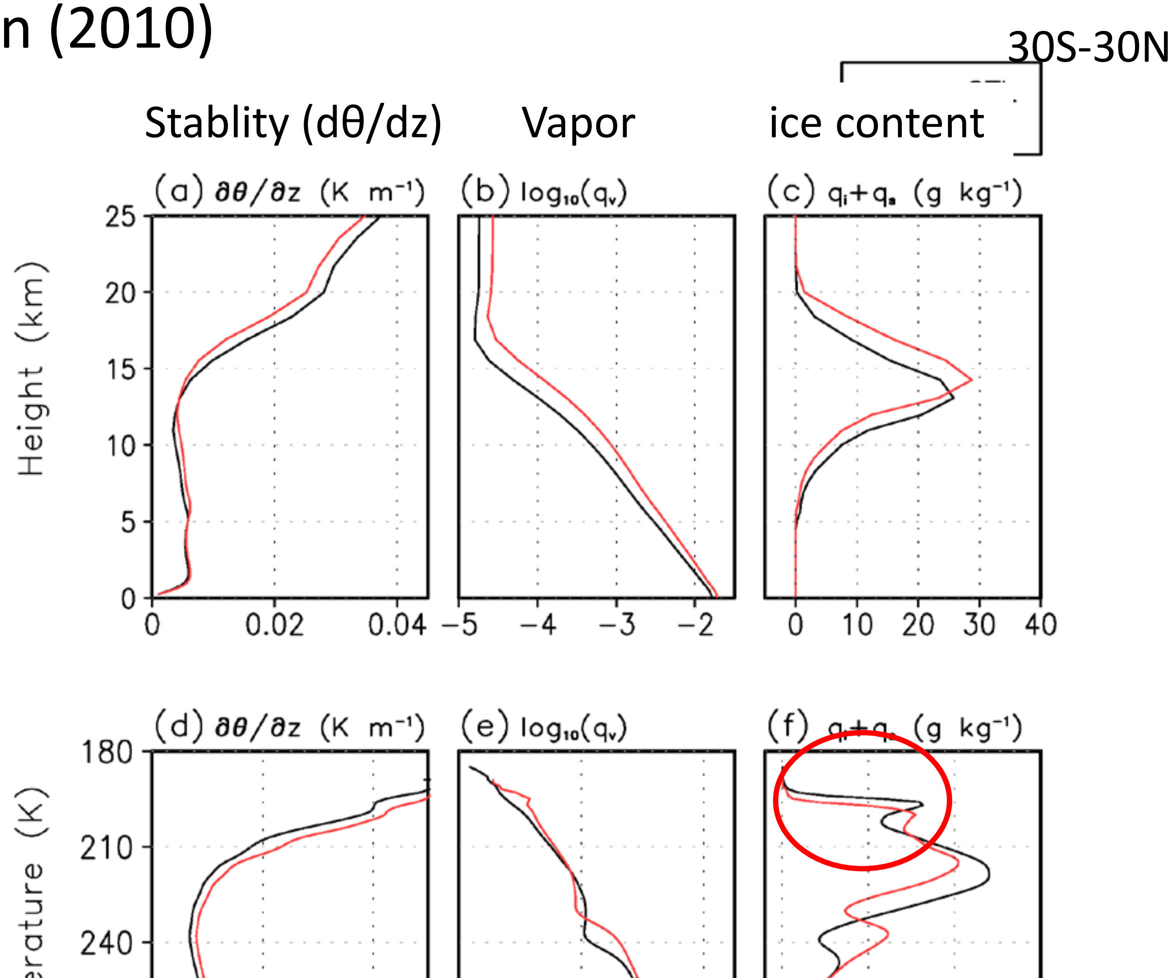
Present climate vs warmer world

- NICAM simulation result is mostly consistent with the result in Zelinka and Hartmann (2010)

Present climate
Global warming

z coordinate

Temperature coordinate



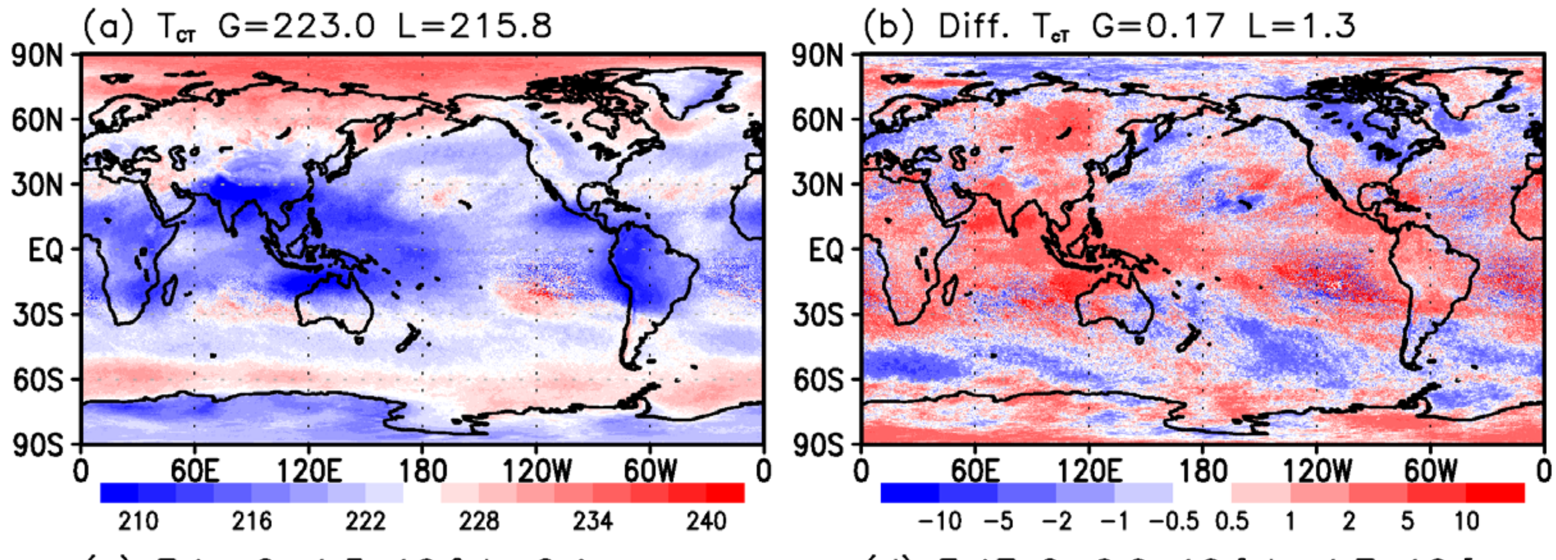
The slight increase of the cloud top temperature, which acts to increase OLR, is not important for changes of net OLR?

Year-mean Cloud top height

- T_{CT} slightly increases in the tropics. The net change of T_{CT} in low latitudes (30S-30N) is weakly positive (～1.3 K), consistent with PHAT (Zelinka and Hartmann 2010)

Present climate

Warmer - Present



Before Cloud size analysis,

Some preparation
for
Evaluation in contributions of changes of T_{CT} and other elements to that of OLR

Formulation
Decomposition by ε, T_{CT} and F^{CLR}

True
(on-line computation
by radiative module)

Diagnosed

$$F \cong \sigma\varepsilon T_{CT}^{\ 4} + F_{CB}$$
$$\cong \sigma\varepsilon T_{CT}^{\ 4} + (1-\varepsilon)F^{CLR},$$

$$\varepsilon = 1 - \exp(-a\tau), \quad \tau = \frac{3}{2}\frac{\mathrm{IWP}}{\rho_i r_e},$$

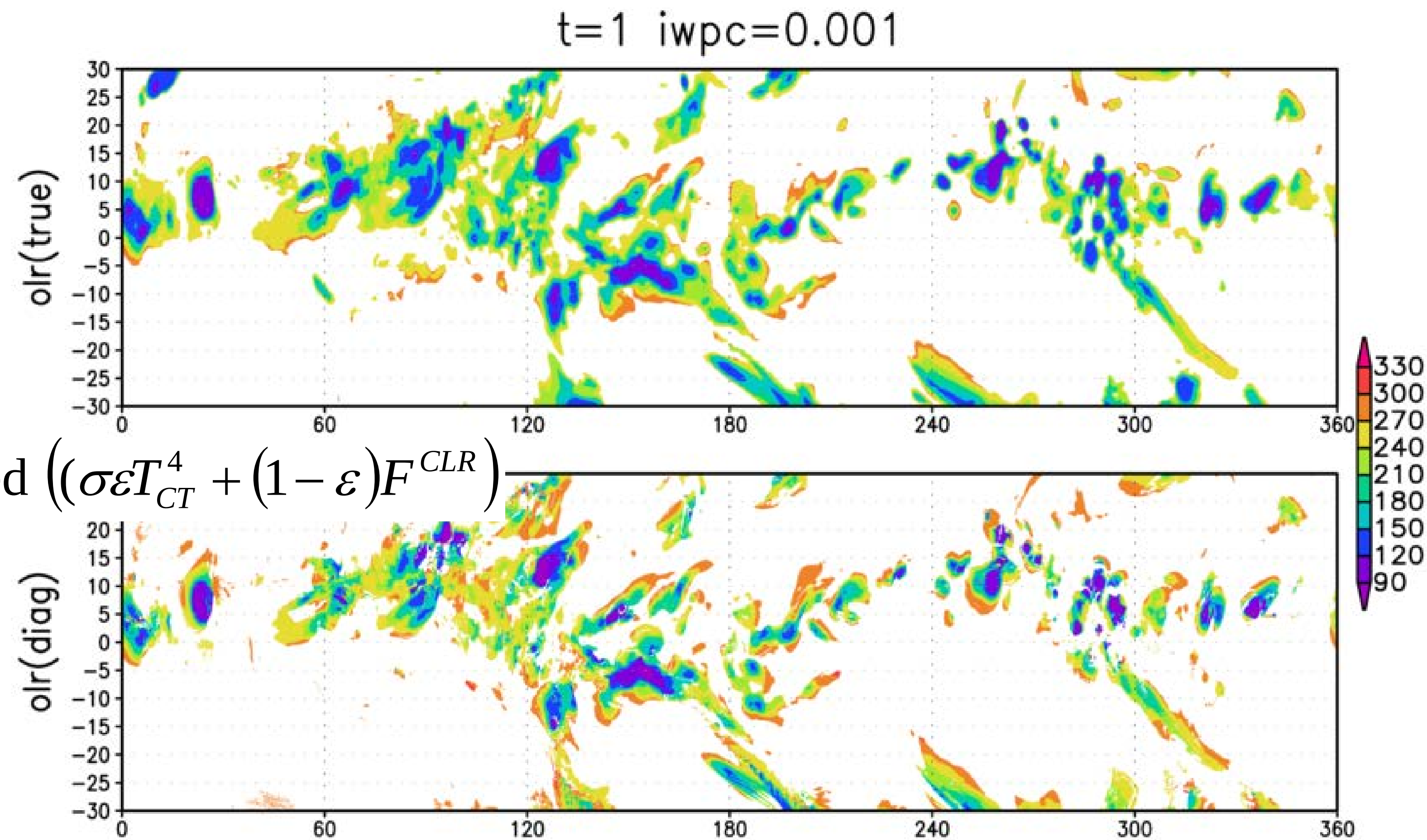
T_{CT} is defined as the height where a cloud optical depth from the toa is ~ 0.1

OLR
~True vs Diagnosis~

- Diagnosed OLR reasonably agree with true OLR (on-line computed OLR)

True

Diagnosed $\left((\sigma\varepsilon T_{CT}^{4}+(1-\varepsilon)F^{CLR}\right)$



Formulation

Decomposition into ε, T_{CT} and F^{CLR}

True (on-line computation by radiative module)

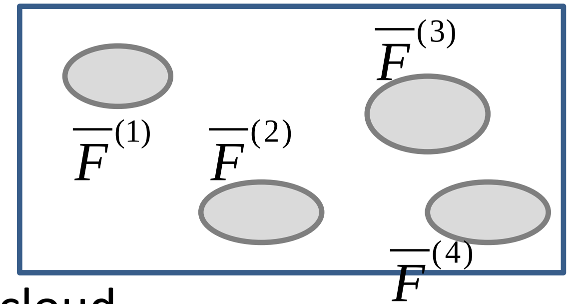
Diagnosed

$$F \cong \sigma\varepsilon T_{CT}^{4} + F_{CB}$$
$$\cong \sigma\varepsilon T_{CT}^{4} + (1-\varepsilon)F^{CLR},$$

$$\varepsilon = 1 - \exp(-a\tau), \quad \tau = \frac{3}{2}\frac{\mathrm{IWP}}{\rho_i r_e},$$

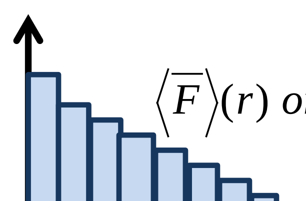
T_{CT} is defined as the height where a cloud optical depth from the toa is ~ 0.1

$$\overline{F}^{(i)} \cong \sigma\overline{\varepsilon}^{(i)}\overline{T}_{CT}^{(i)\,4} + \overline{F}_{CB}^{(i)}$$
$$\cong \sigma\overline{\varepsilon}^{(i)}\overline{T}_{CT}^{(i)\,4} + \left(1-\overline{\varepsilon}^{(i)}\right)\overline{F^{CLR}}^{(i)},$$



※ Overbar+(i) denotes cloud-area mean at i-th high cloud

$$\Delta\langle\overline{F}\rangle(r) \cong \left\langle\frac{\partial\overline{F}}{\partial\varepsilon}\right\rangle_{T_{CT},F^{CLR}}(r)\Delta\langle\overline{\varepsilon}\rangle(r) + \left\langle\frac{\partial\overline{F}}{\partial T_{CT}}\right\rangle_{\varepsilon,F^{CLR}}\Delta\langle\overline{T}_{CT}\rangle(r) + \left\langle\frac{\partial\overline{F}}{\partial F^{CLR}}\right\rangle_{\varepsilon,T_{cCT}}\Delta\langle\overline{F^{CLR}}\rangle(r)$$
$$\equiv F_{\varepsilon}\Delta\langle\overline{\varepsilon}\rangle(r) + F_{T}\Delta\langle\overline{T}_{CT}\rangle(r) + F_{F}\Delta\langle\overline{F^{CLR}}\rangle(r),$$

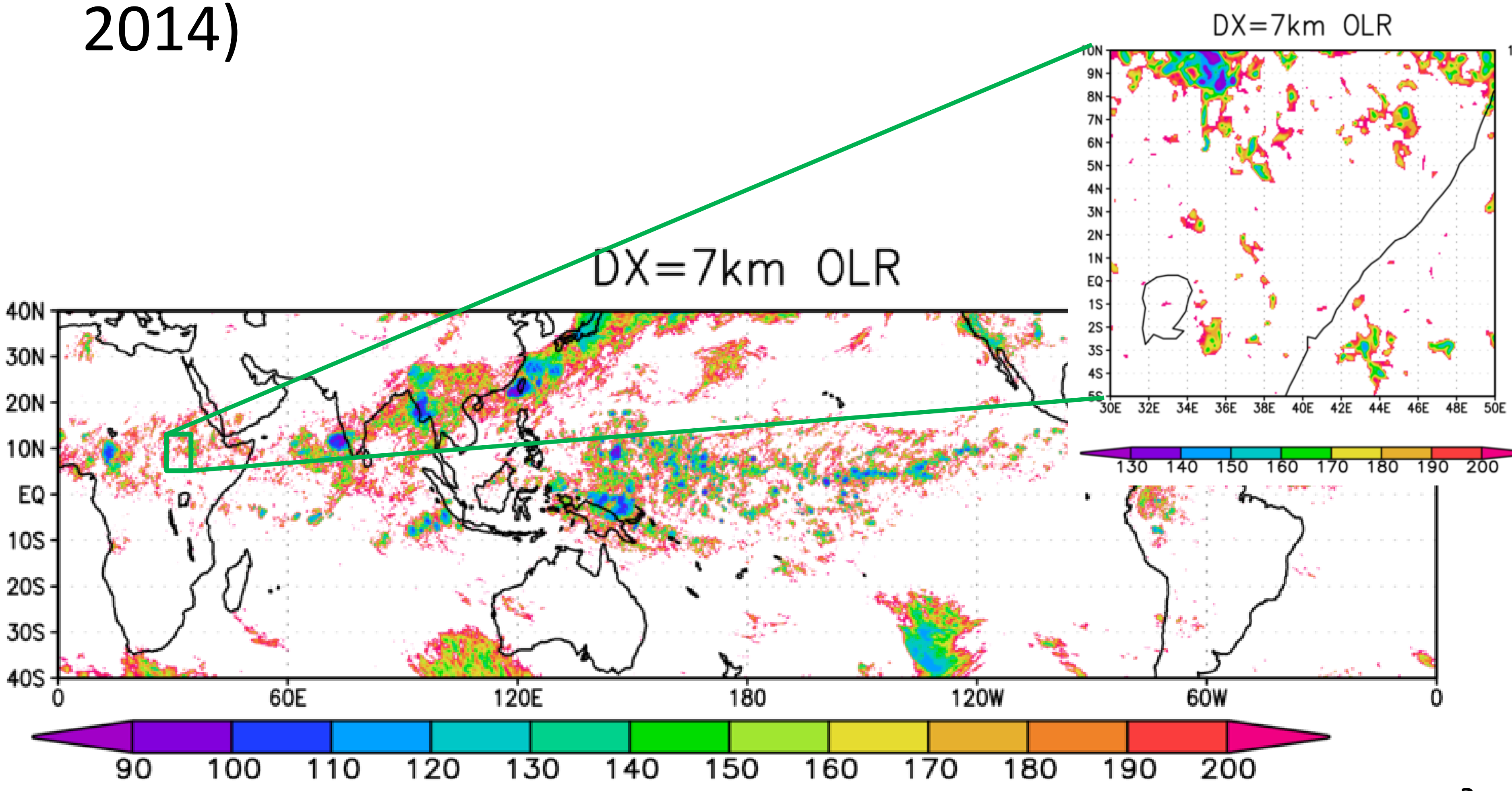


※ < > denotes a value binned to cloud radius

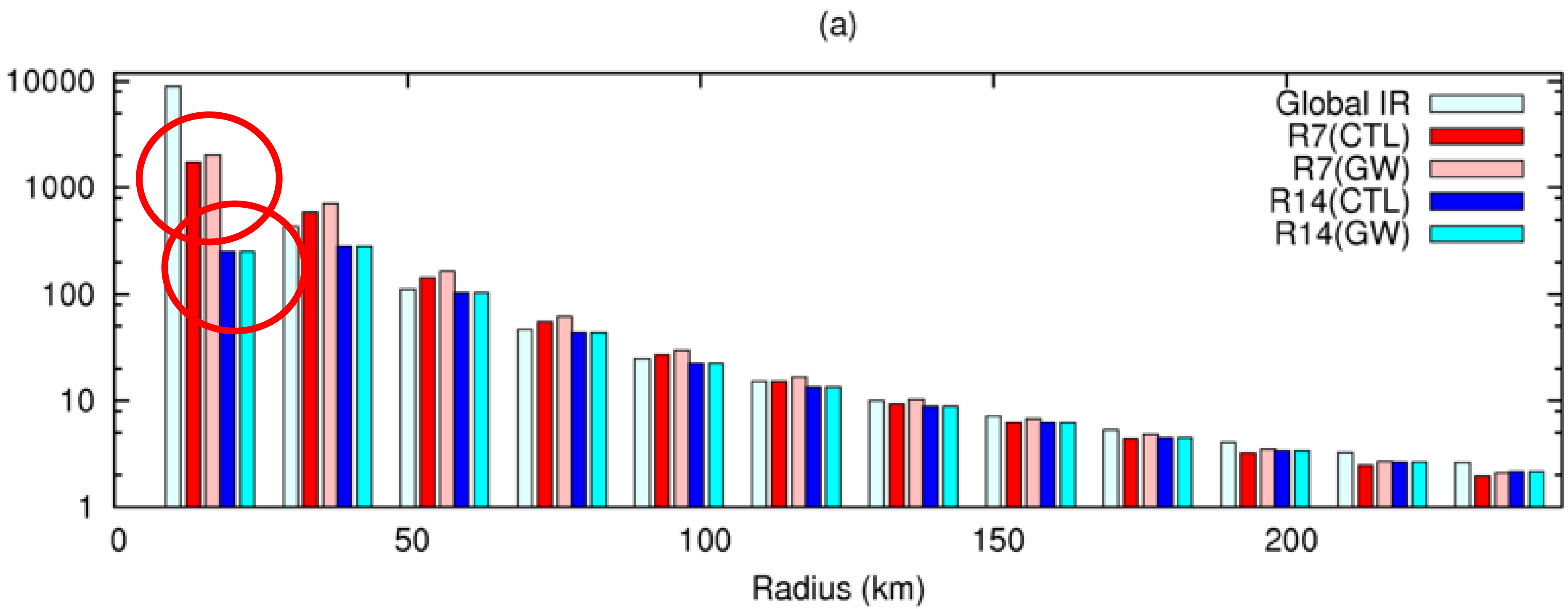
Using this diagnosis formulation, we can easily evaluate contributions of changes of ε, T_{CT}, and F^{CLR} to the net change of cloudy-OLR

Definition

- High cloud area ≦ 210 W/m^2 (～－20℃)(Mapes and Houze 1993; Inoue et al. 2008; Noda et al. 2014)



Number of high clouds

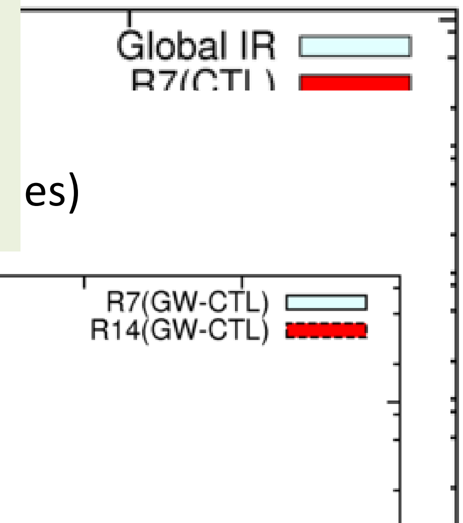


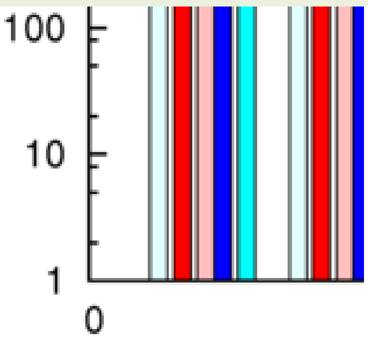
- The number of high clouds decreases with radius in a power-law.
- The 14-km mesh model underestimates smaller clouds, compared to the satellite observation.
- But this negative bias is reduced in higher resolution model, such as 7-km mesh run.

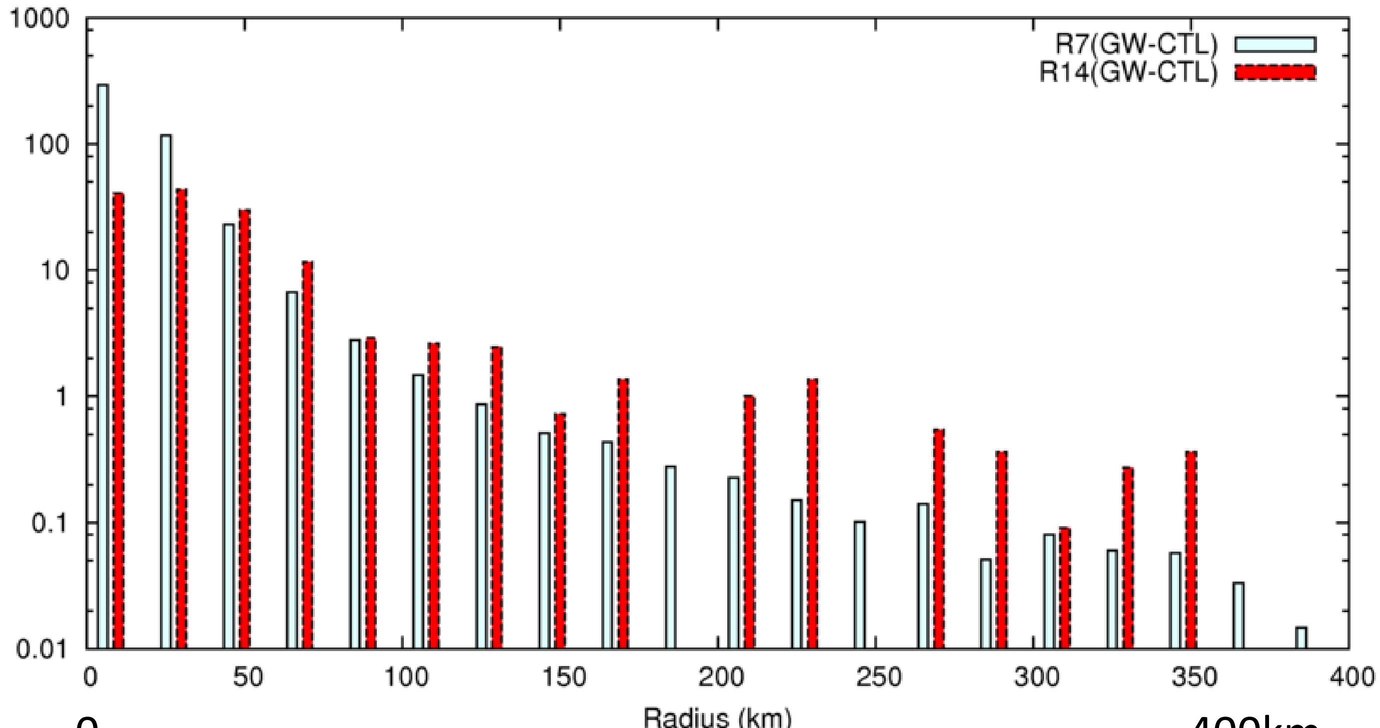
Number of high clouds (GW-CTL)

(a)

- In a warmer atmosphere, the numbers of high clouds increase in almost all radius bins both in 7-km and 14 km mesh robustly.
- The increase of high clouds contributes to the increase of LW CRF, leading to positive feedback (following slides)







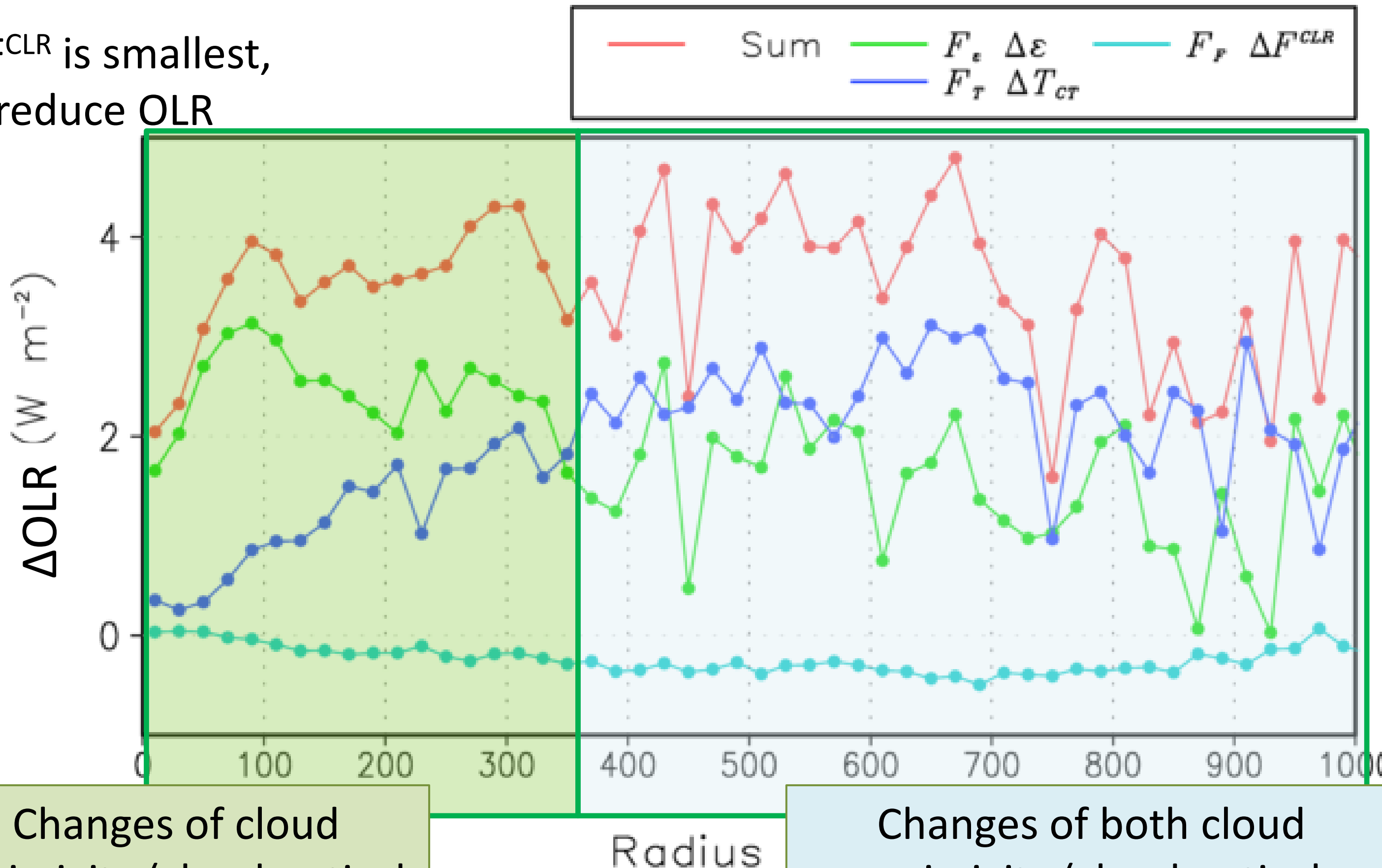
0 400km

GW-Present
7-km mesh
14-km mesh

Contributions to the OLR change

- Contributions of the r.h.s. of the 3 terms strongly differ depending on cloud radius
- Contributions of ΔF^{CLR} is smallest, but acts slightly to reduce OLR

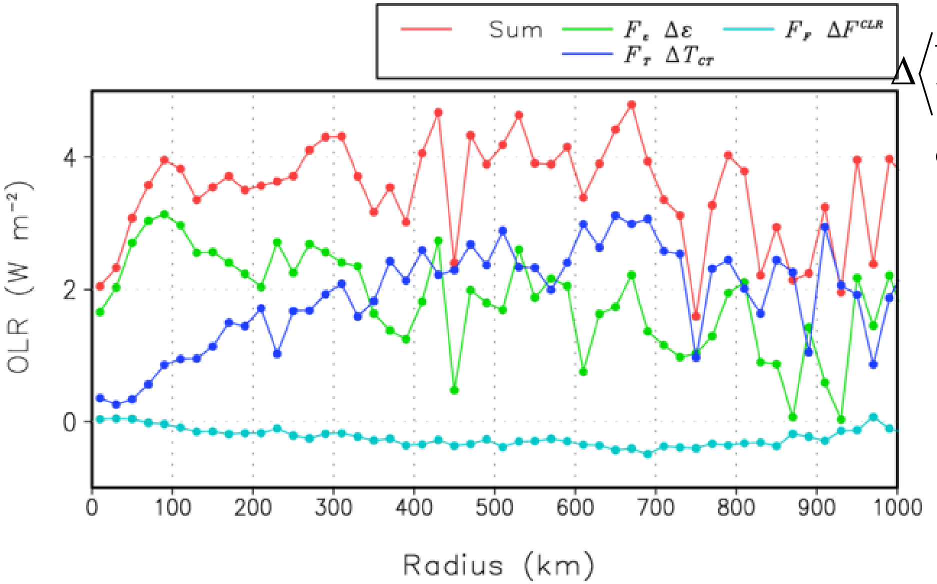
$$\Delta\left\langle \overline{F}^{(i)} \right\rangle(r) = F_{\varepsilon}\Delta\left\langle \overline{\varepsilon}^{(i)} \right\rangle(r) + F_{T}\Delta\left\langle \overline{T}_{CT}^{(i)} \right\rangle(r) + F_{F}\Delta\left\langle \overline{F^{CLR}}^{(i)} \right\rangle(r),$$



Changes of cloud emissivity (cloud optical thickness) is most important

Changes of both cloud emissivity (cloud optical thickness) and cloud top height are important

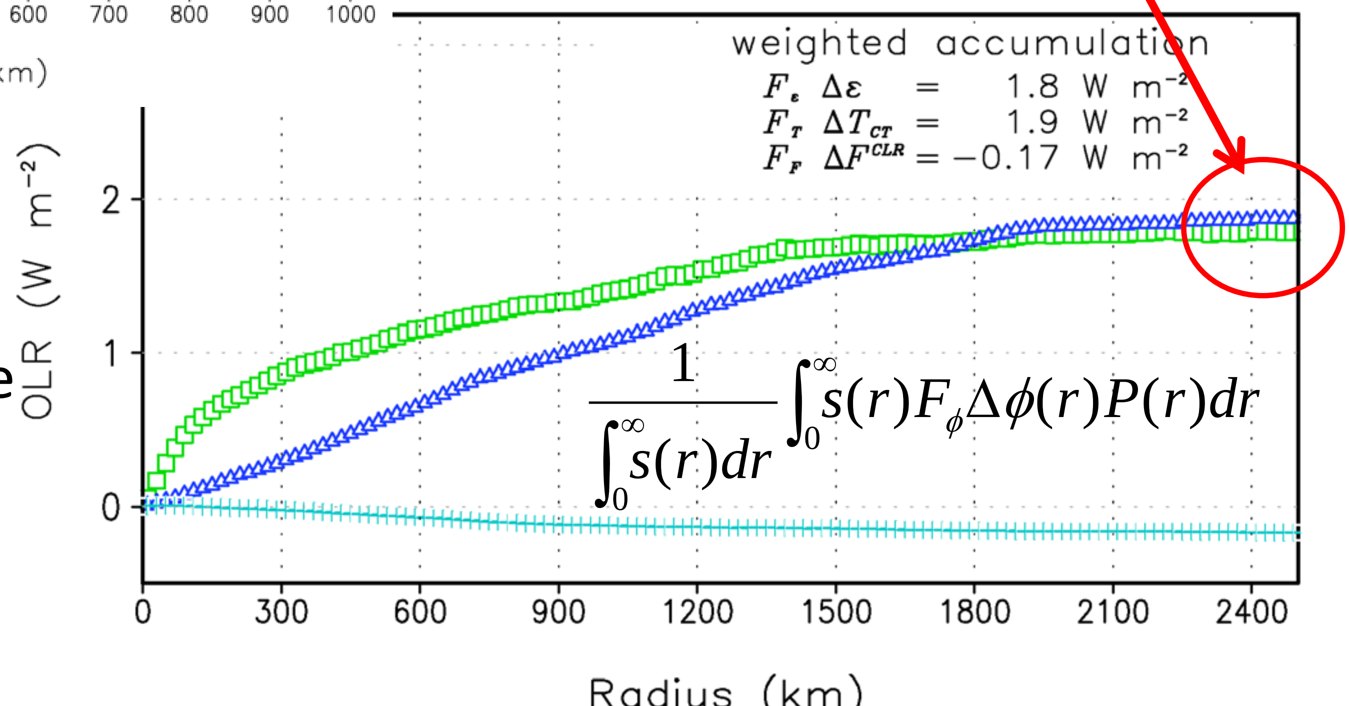
Contributions to the net OLR change



$$\Delta\left\langle\overline{F}^{(i)}\right\rangle(r) = F_\varepsilon\Delta\left\langle\overline{\varepsilon}^{(i)}\right\rangle(r) + F_T\Delta\left\langle\overline{T}_{CT}^{(i)}\right\rangle(r) + F_F\Delta\left\langle\overline{F^{CLR}}^{(i)}\right\rangle(r),$$

- Contributions by changes of emissivity and cloud top temperature are comparable!

$$F_\varepsilon\Delta\left\langle\overline{\varepsilon}^{(i)}\right\rangle(r) \cong F_T\Delta\left\langle\overline{T}_{CT}^{(i)}\right\rangle(r)$$



by ε change

by T_{CT} change

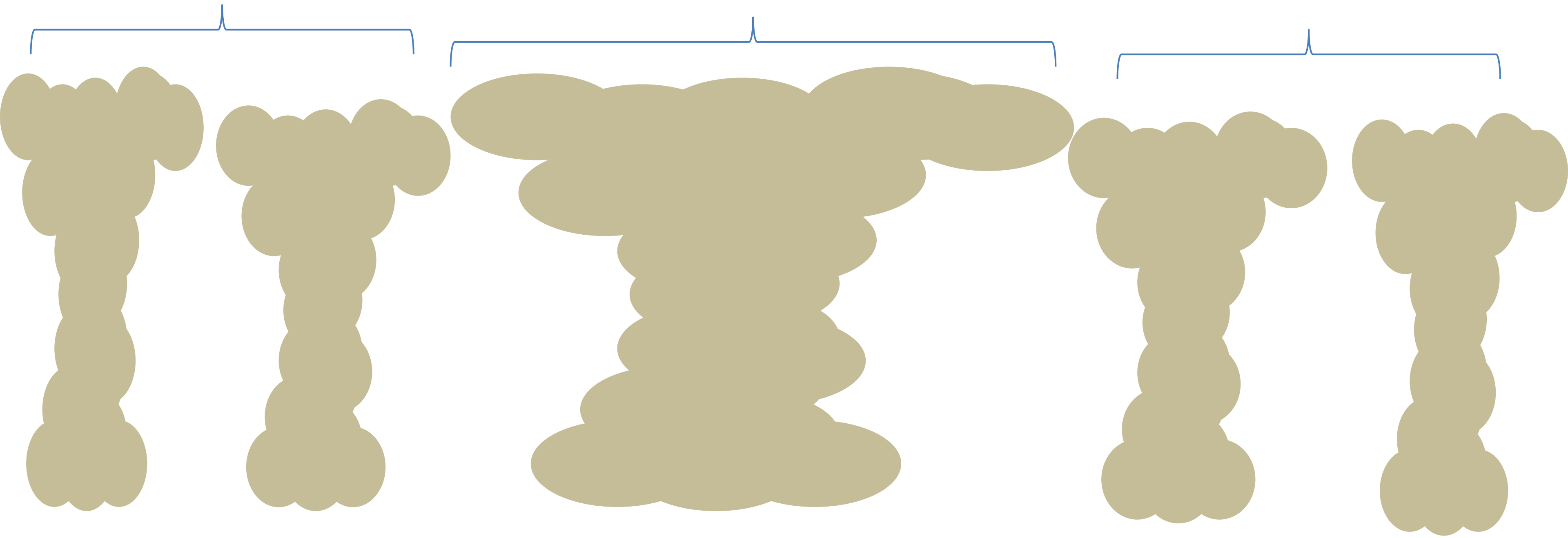
by F^{CLR} change

Conclusion (1)

Smaller clouds
Effect of $\Delta\varepsilon$

Larger clouds
Effect of $\Delta T_{CT} \sim$ Effect of $\Delta\varepsilon$

Smaller clouds
Effect of $\Delta\varepsilon$

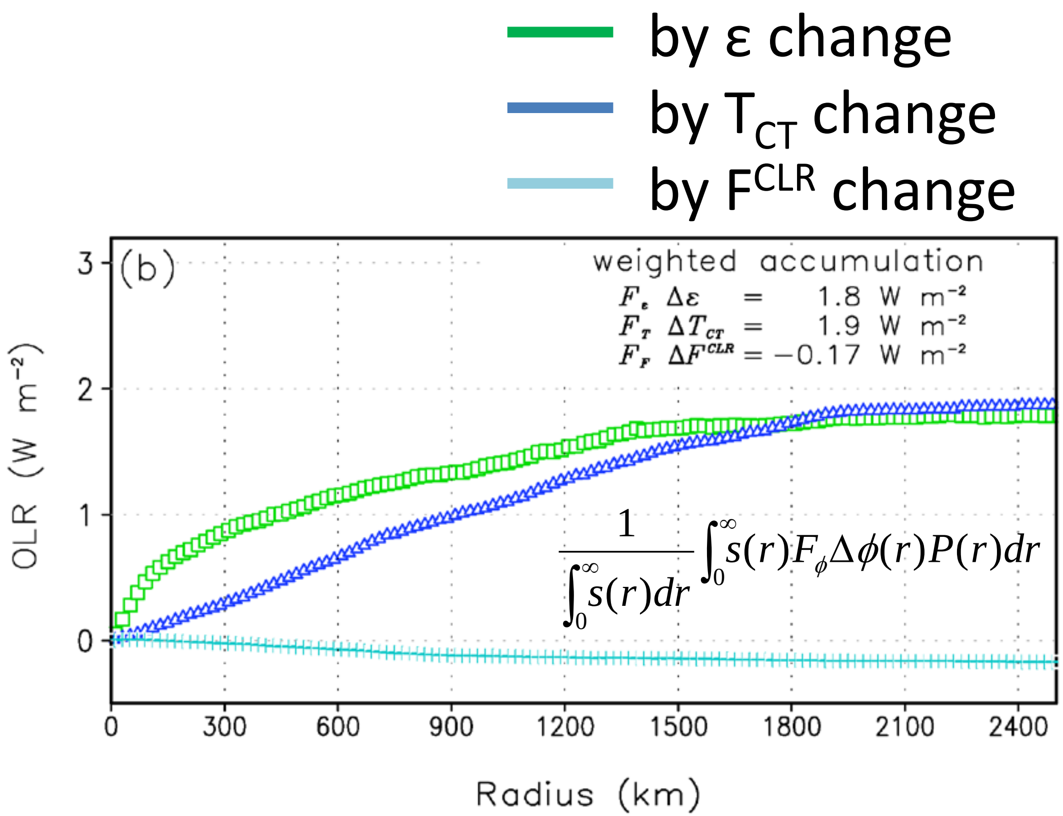


Smaller clouds Optically thinner effect $>$ Effect of T_{CT} increase
Larger clouds Optically thinner effect $\fallingdotseq$ Effect of T_{CT} increase

Frequency of occurrence Smaller clouds $\gg$ Larger clouds
Cloud coverage Smaller clouds $\ll$ Larger clouds

Both changes of ε and T_{CT} are equally important for OLR change

Conclusion (2)



- <u>The extent to what the FAT hypothesis holds can depend strongly on cloud size.</u>
- Changes of ε is important in smaller clouds while that of T_{CT} is equally important in larger clouds.
- For the net effect, changes of ε and T_{CT} are equally important
- <u>Thus, it is worth revisiting the quantification of the FAT hypothesis</u>

▪Noda et al. 2016: High cloud size dependency in the applicability of the fixed anvil temperature hypothesis using global non-hydrostatic simulations. Geophys. Res. Lett, doi:10.1002/2016GL067742.

▪Noda et al. 2014: Responses of tropical and subtropical high-cloud statistics to global warming. J. Climate, 27, 7753-7768.