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

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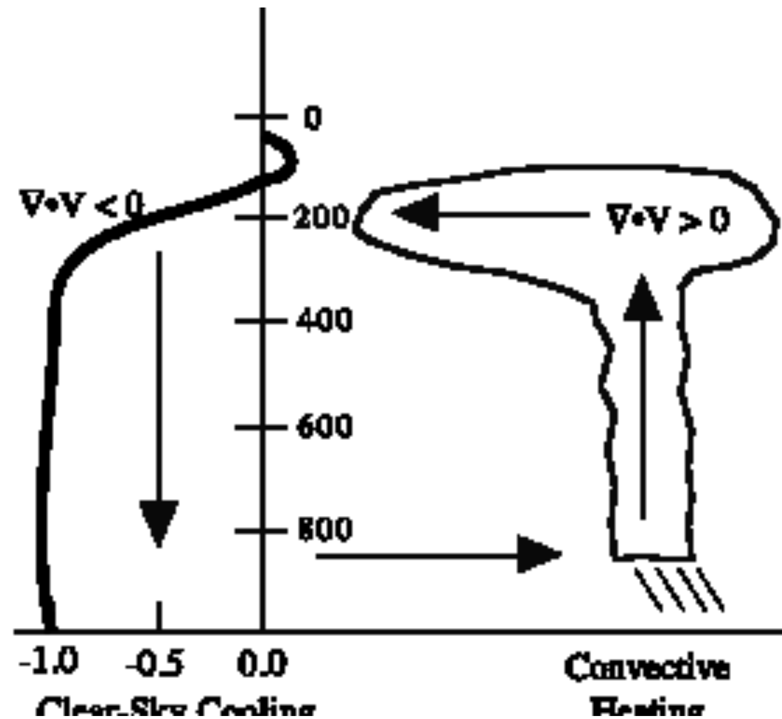
Background (1)
FAT hypothesis

- $Q_v(z)$ strongly constrained by $T(z)$ through the C-C relation
- $F_R(z)$ strongly constrained by $Q_v(z)$
- $\omega(z)$ (and detrainment height) strongly constrained by F_R (z)
- T_{CT} corresponds to detrainment height

- $T_{CT} \sim$ const
- (T_{CT} not directly depend on T_{SFC} and/or climate change)

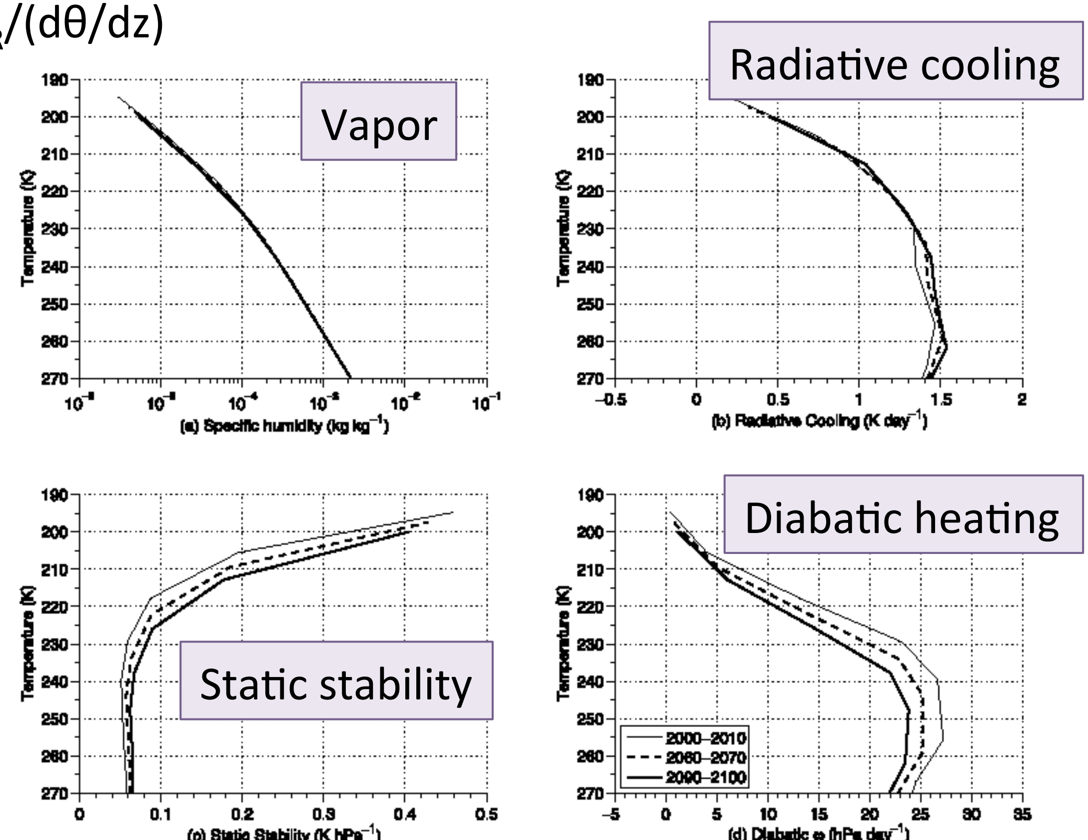
- FAT hypothesis suggests that a warmer world may not be effectively cooled down because of a less T_{CT} increase



Hartmann and Larson (2002)

Background (2)
GCM result

- In the temperature coordinate, zonal means of Q_v and F_R do not vary, showing strong constraint of Q_v by Temperature ($Q_v \propto \exp(-a(T-T_0)/(T_0-b)$ if relative humidity does not change even in a warmer world)
- $d\theta/dz$ depends on a vertical gradient of temperature, rather than its absolute value
  - $\Rightarrow d\theta/dz$ increases at given temperature
  - $\Rightarrow \omega$ decreases, since $\omega \sim F_R/(d\theta/dz)$



Temperature (K)

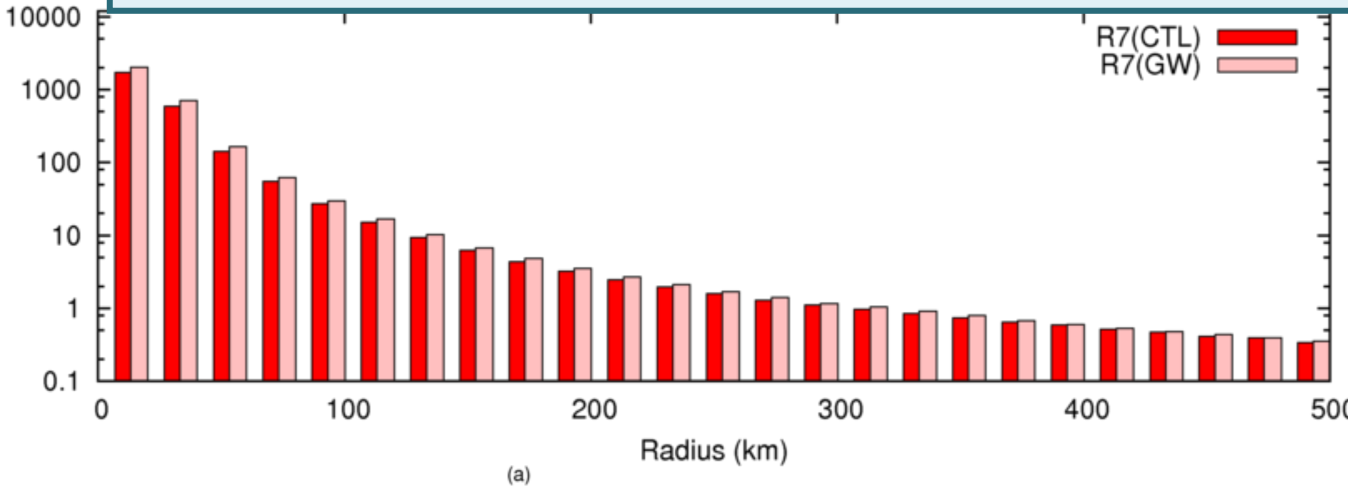
2000-2010
2060-2070
2090-2100

Zelinka and Hartmann (2010)

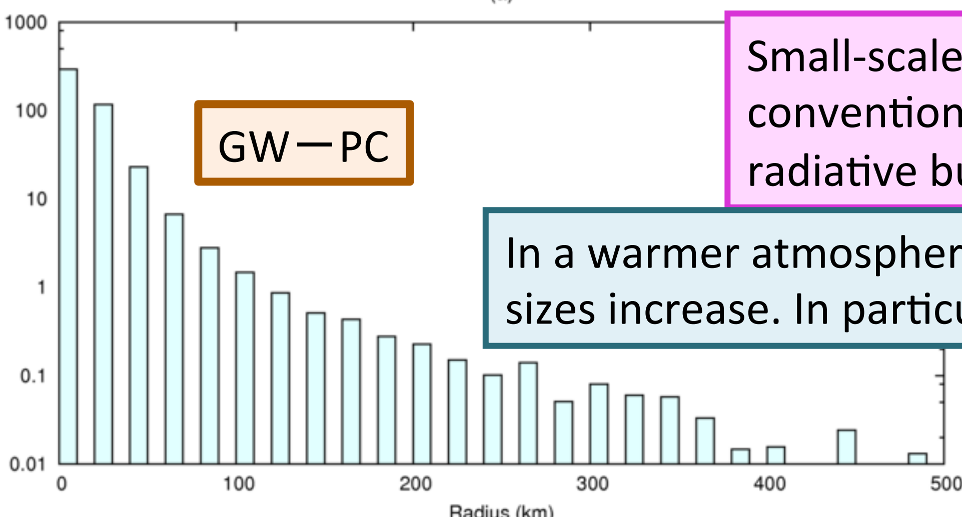
- Question
  - What is the mean of “FAT hypothesis holds”?
    - Change of T_{CT} is small enough… How small is small enough? and compared with what?
    - Relations of changes of cloud types have not been argued well
      - e.g., dependency on changes of cloud size

Responses of cloud size to global warming (7km mesh NICAM)

Number of clouds exponentially decreases with increasing cloud radius



Present climate
Global warming

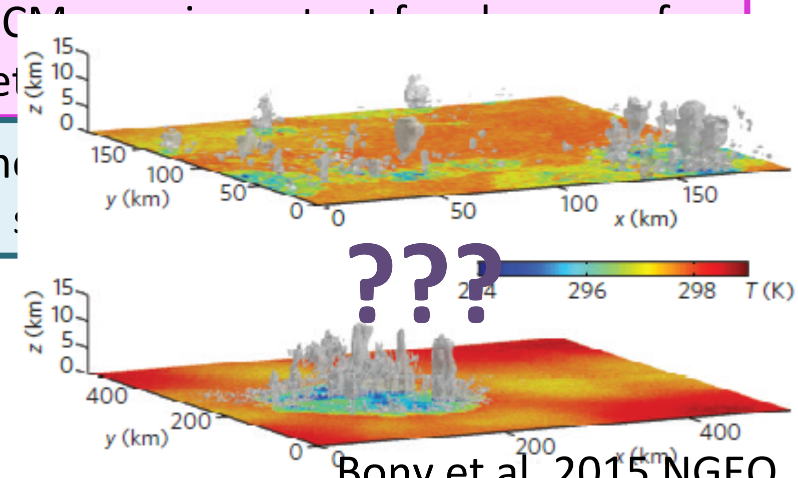


GW－PC

Small-scale clouds, which cannot be resolved in
conventional GC
radiative budget

In a warmer atmosphere, th
sizes increase. In particular,

Noda et al. (2014, JCLI)



Bony et al. 2015 NGEO

- Question
  - What is the mean that “FAT hypothesis holds”?
    - Change of T_{CT} is small enough… How small is small enough? and compared with what?
    - Relations of changes of cloud types are unclear
      - e.g., dependency on changes of cloud size)
    - Furthermore, how strong is their quantitative dependency?
  - In addition,
    - To what extent changes of cloud properties (e.g., cloud optical depth, precipitable water, etc) depend on cloud size
- Method
  - 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 to NOAA Week	Pseudo-Global warming
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)	
CO_2 concentration	348 ppm	696 ppm (twiced homogeneously over the globe)

Present climate vs warmer world

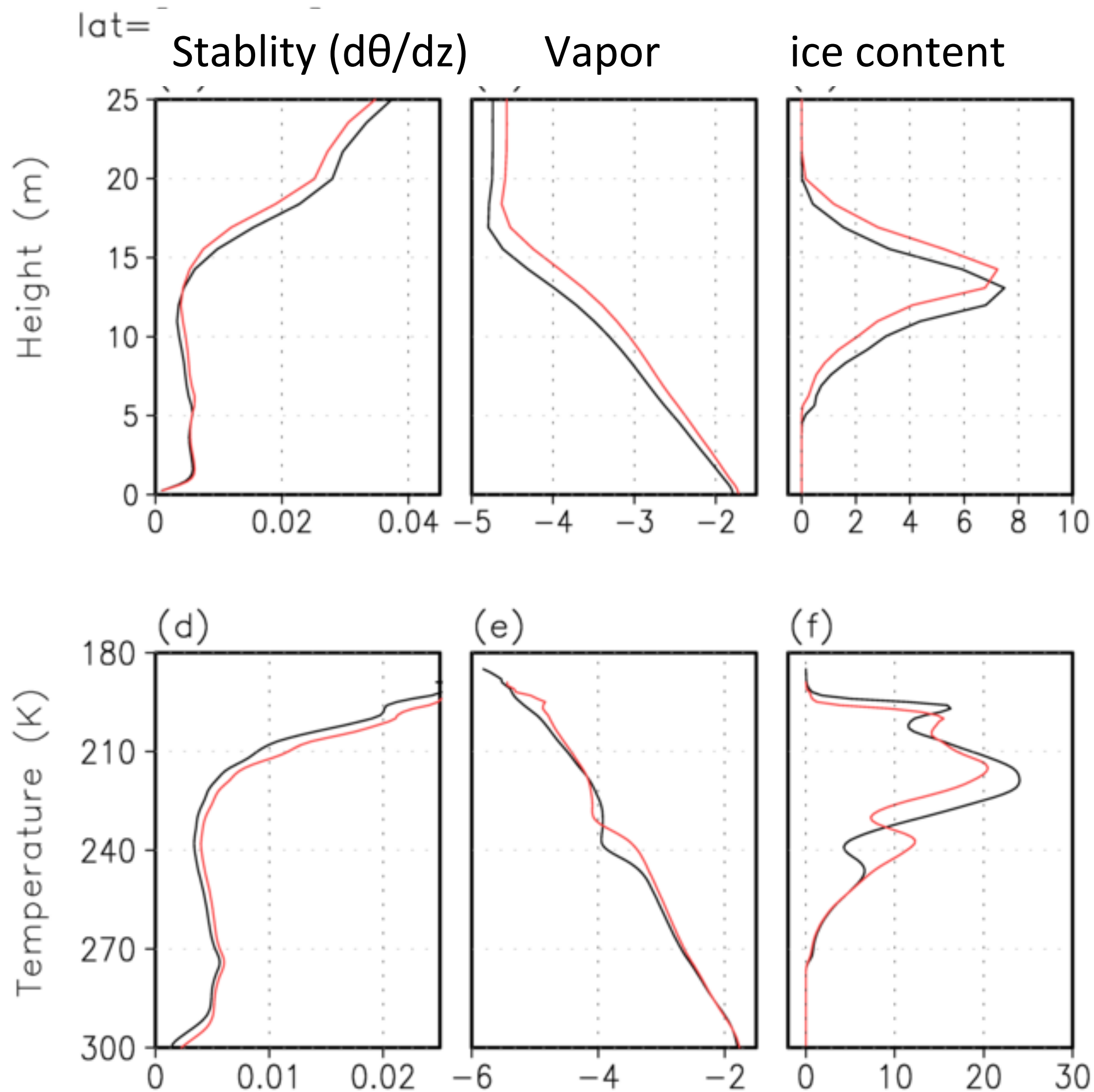
- NICAM simulation result is mostly consistent with the result in Zelinka and Hartmann (2010)

30S-30N

Present climate
Global warming

z coordinate

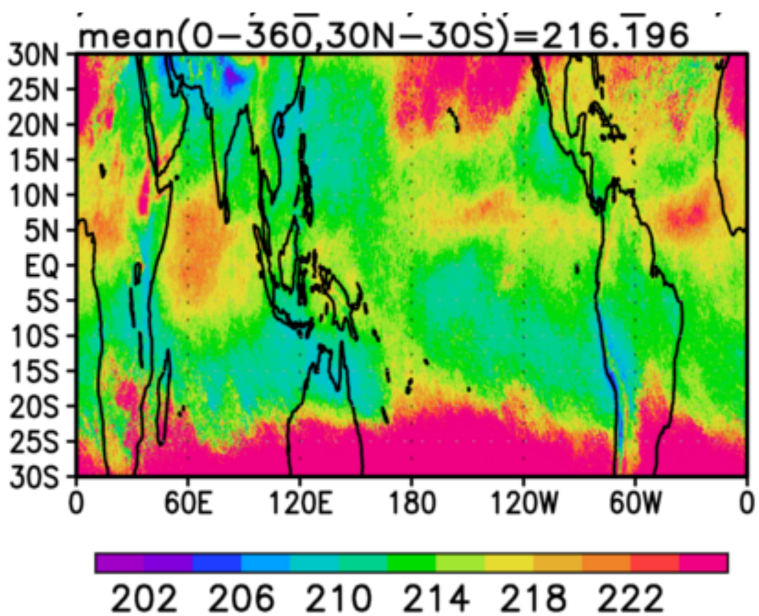
Temperature coordinate



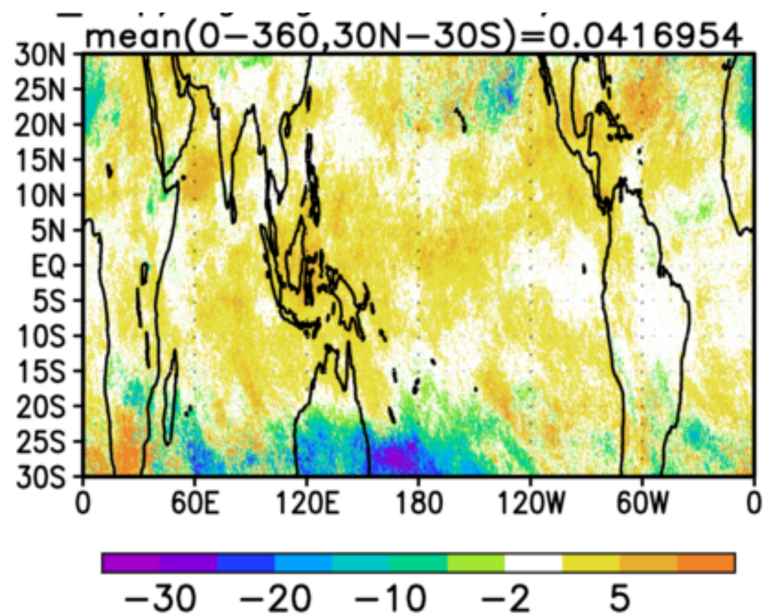
Year-mean Cloud top height

- T_{CT} slightly increases (ca. 1.5 K) in the tropics, while it decreases in higher latitudes. The net change of T_{CT} in low latitudes is weakly positive (ca. 0.4 K), consistent with PHAT (Zelinka and Hartmann 2010)

Present climate



Warmer - Present

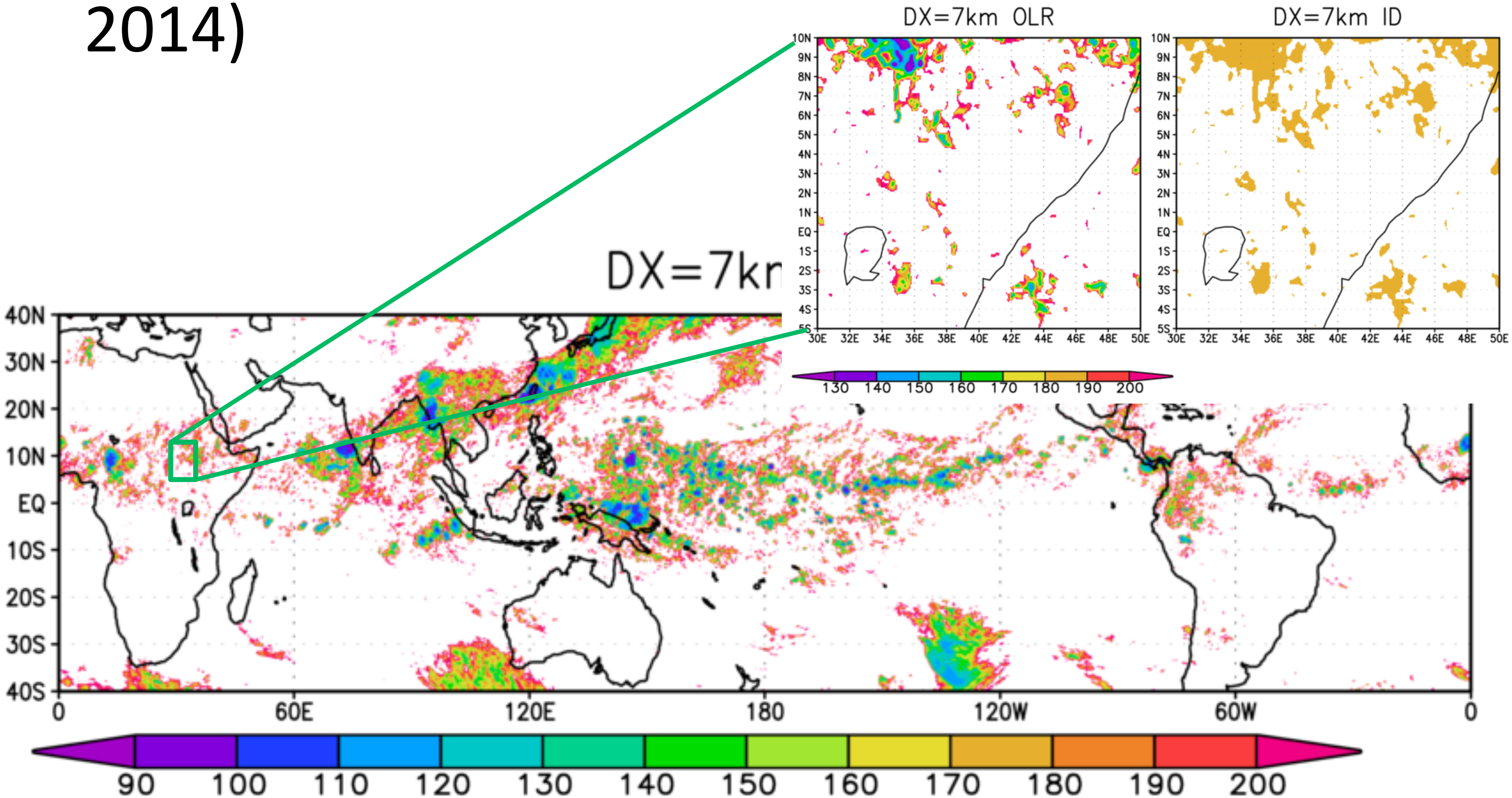


Cloud size analysis

Definition of high cloud area

Definition

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



Cloud size analysis

Some preparation

Formulation

True
(on-line computation
by radiative module)

Diagnosed

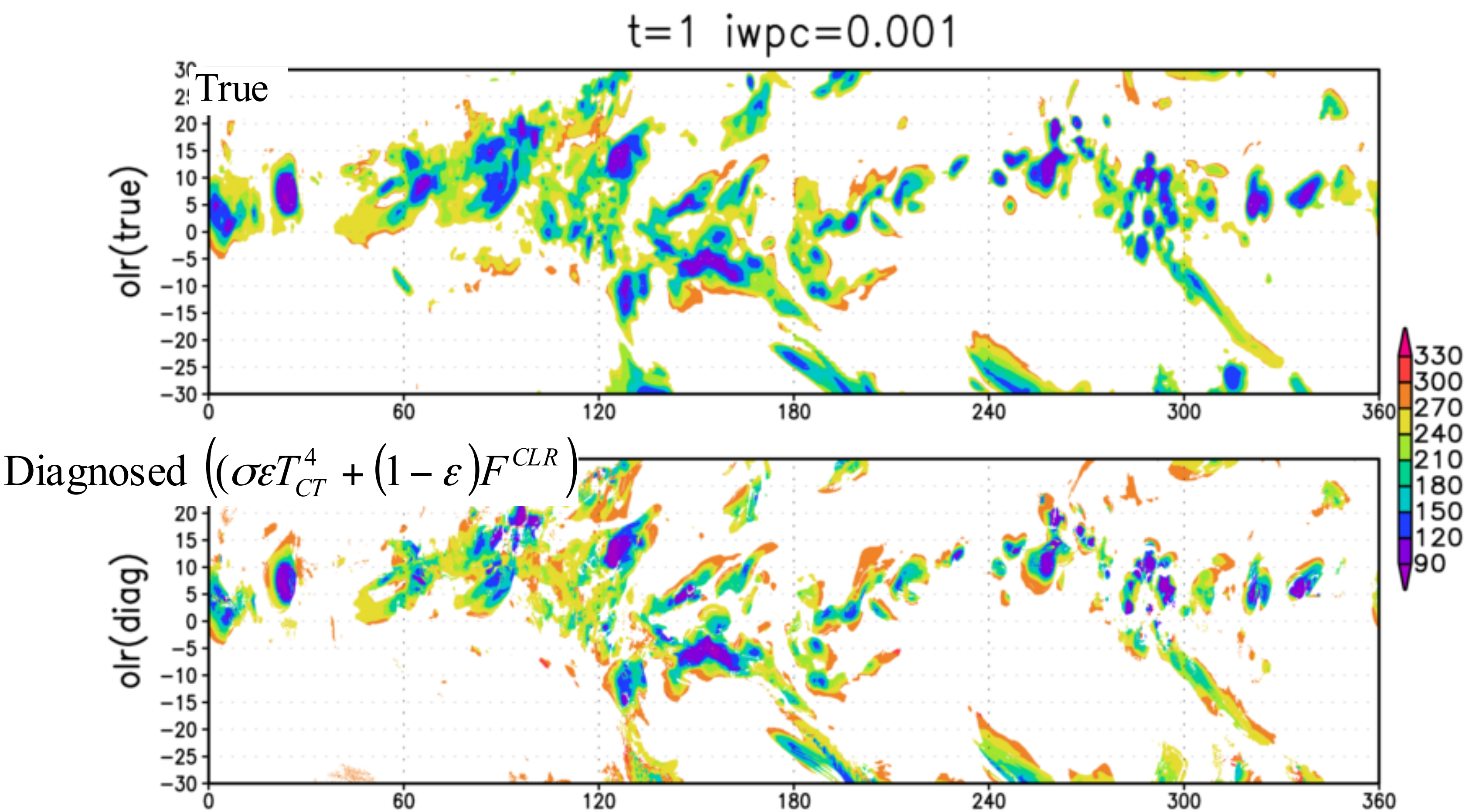
$$F \cong \sigma\varepsilon T_{CT}^{\ 4} + F_{CB}$$
$$\cong \sigma\varepsilon T_{CT}^{\ 4} + (1-\varepsilon)F^{CLR},$$

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

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

OLR
True vs Diagnosed

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



Formulation

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

True
(on-line computation
by radiative module)

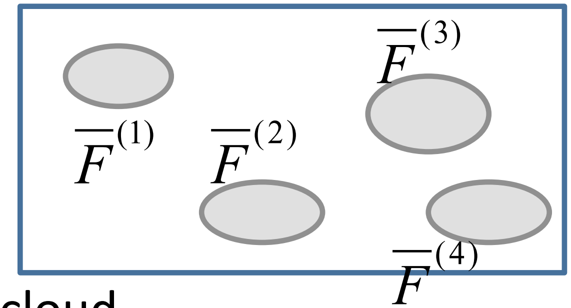
Diagnosed

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

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

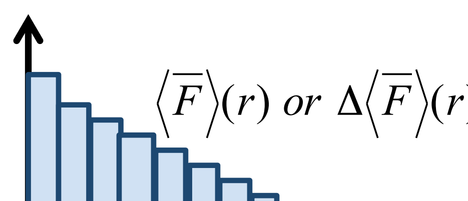
T_{CT} is defined as the height where a cloud optical depth from the toa is ~ 0.1

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



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

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



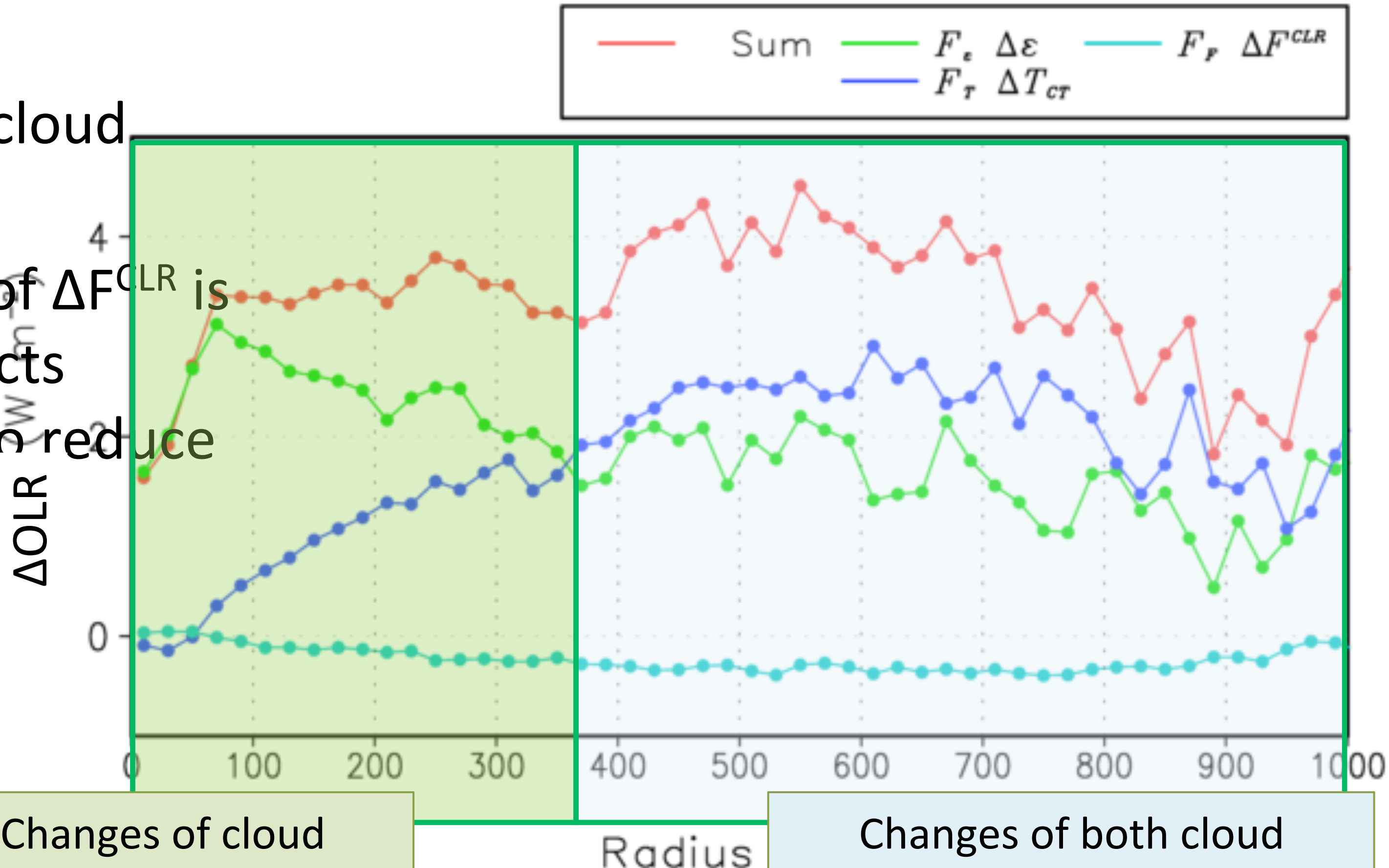
※ < > denotes a value binned to cloud radius

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

Contributions of each change to net 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 substantially 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

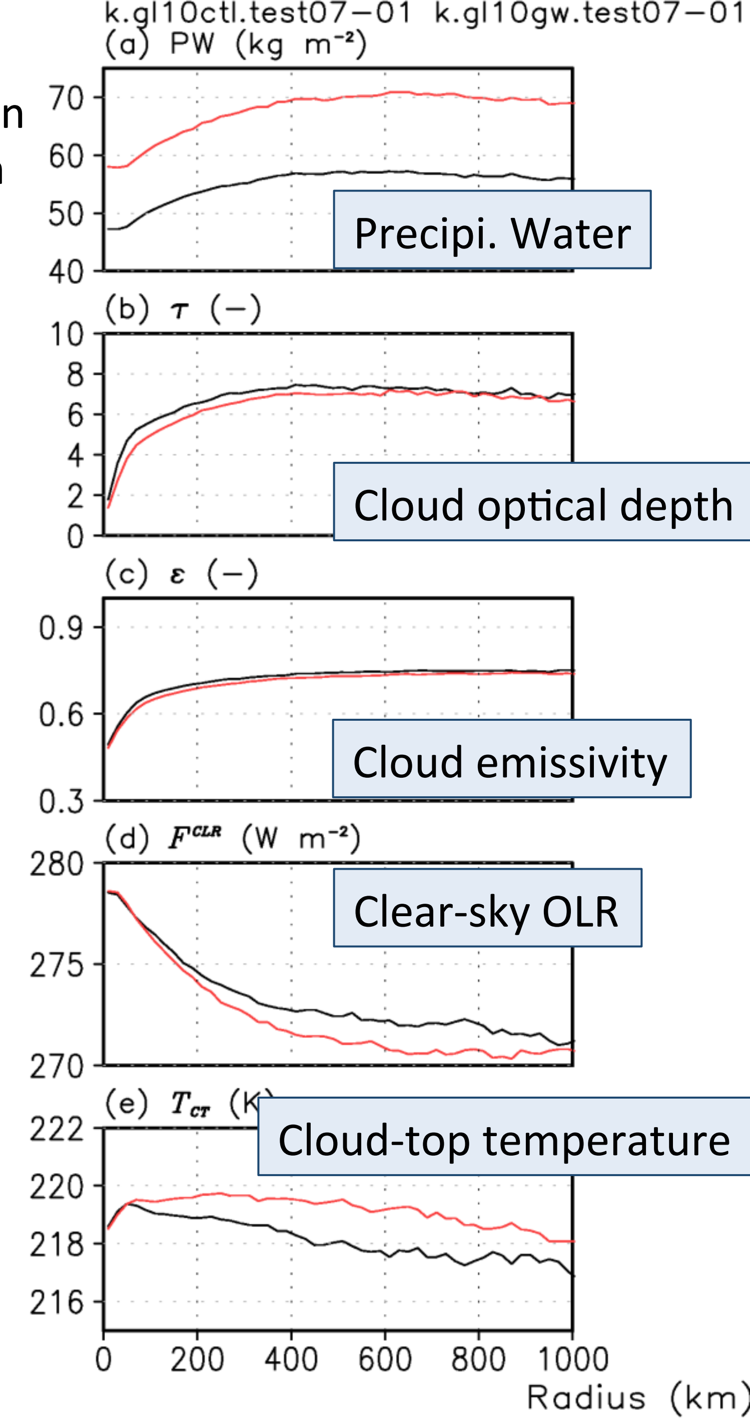
Changes of both cloud emissivity (cloud optical thickness) and cloud top height are important

Other changes of Cloud properties

Present run
Future run

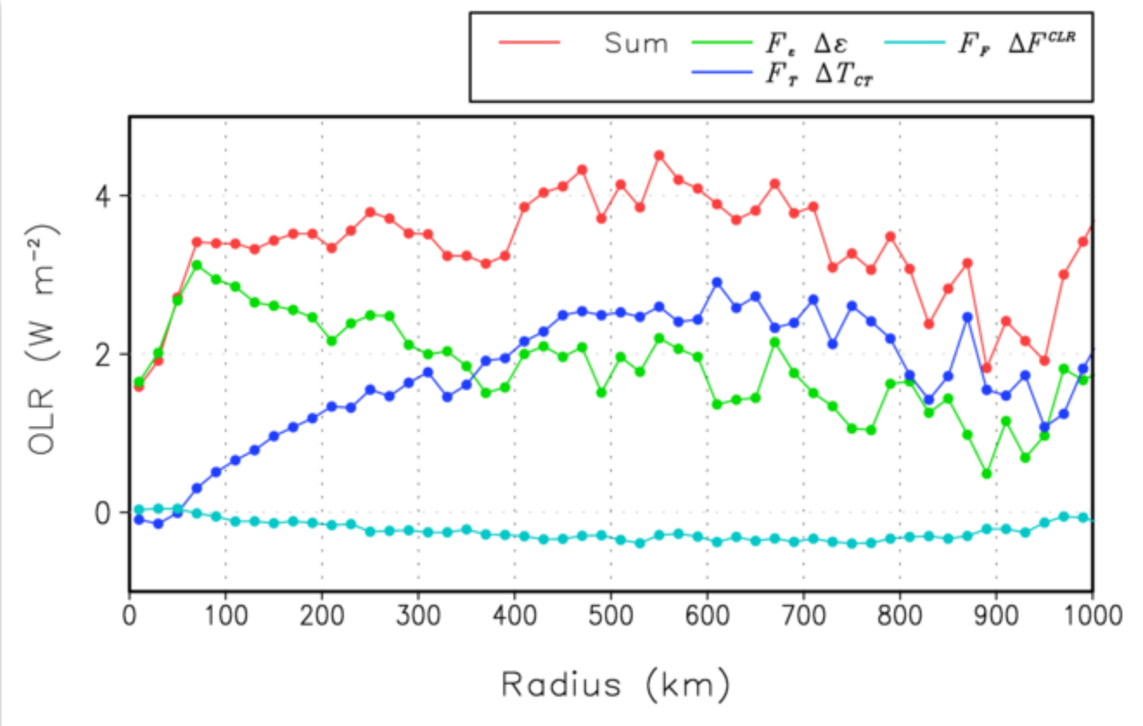
- Precipitable water generally increases with radius in both climate states. Responding to global warming, the increase rate becomes greater by r=400 km.
- τ becomes smaller especially in smaller clouds. τ becomes decreasing in a warmer world
- According to the decrease of τ, ε changes negatively, and the changes of the amplitude is greater in smaller clouds.
- F^{CLR} decreases with radius, and its reduction rate becomes greater with radius; this change in F^{CLR} is consistent with the gradual increase of precipitable water. The change of T_{CT} is positive for r > 60 km and it becomes gradually larger for 100 km < r <600 km.

- F^{CLR} is systematically related to cloud size, suggesting that an estimation error of F^{CLR} could also depend on cloud size.



Conclusion

- <u>The extent to what the FAT hypothesis holds can depend strongly on cloud size.</u>
- For smaller cloud sizes less than about 400 km, the contribution of changes of T_{CT} is secondary importance, and the contribution of changes of cloud emissivity is more important.

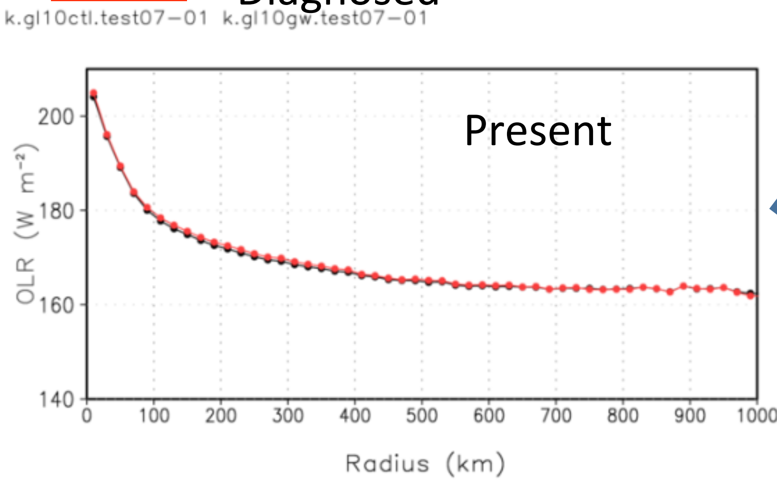


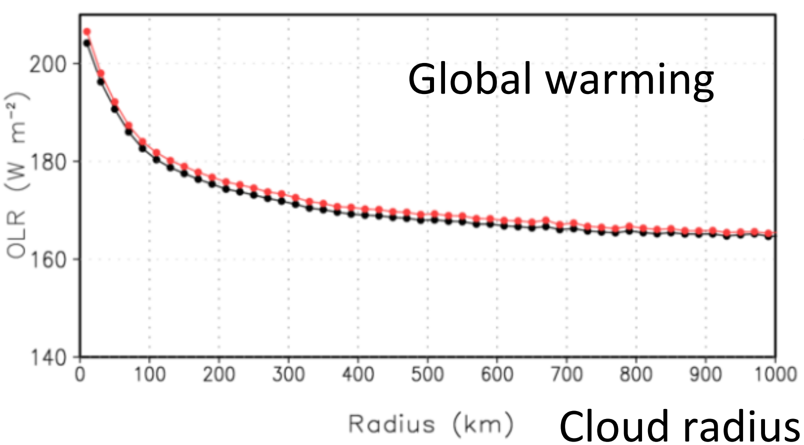
- In contrast, for high clouds larger than 400 km, the contribution of changes of cloud emissivity is comparable to that of T_{CT}, and thus both Δε and Δ T_{CT} are equally important.

Noda et al, High cloud size dependency of the applicability of the fixed anvil temperature hypothesis using global nonhydrostatic simulations (to be submitted)

Estimation of Diagnosis Error

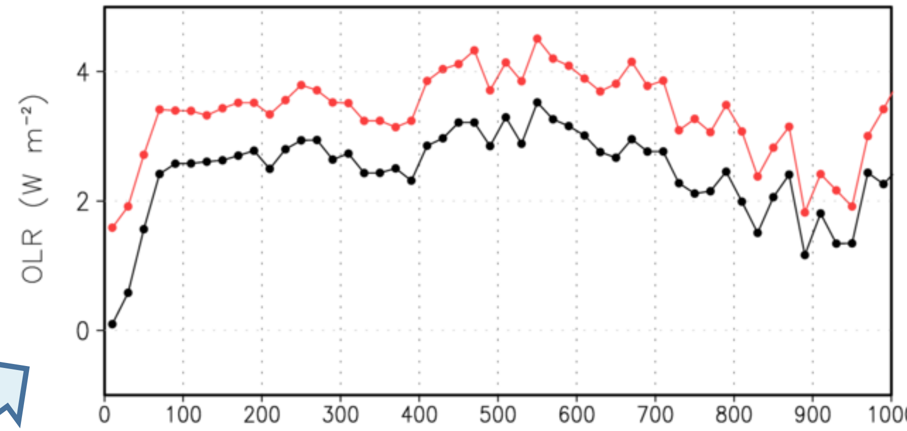
True
Diagnosed





Cloud radius (km)

Δ(OLR) (=Global warming − Present)



Cloud radius (km)

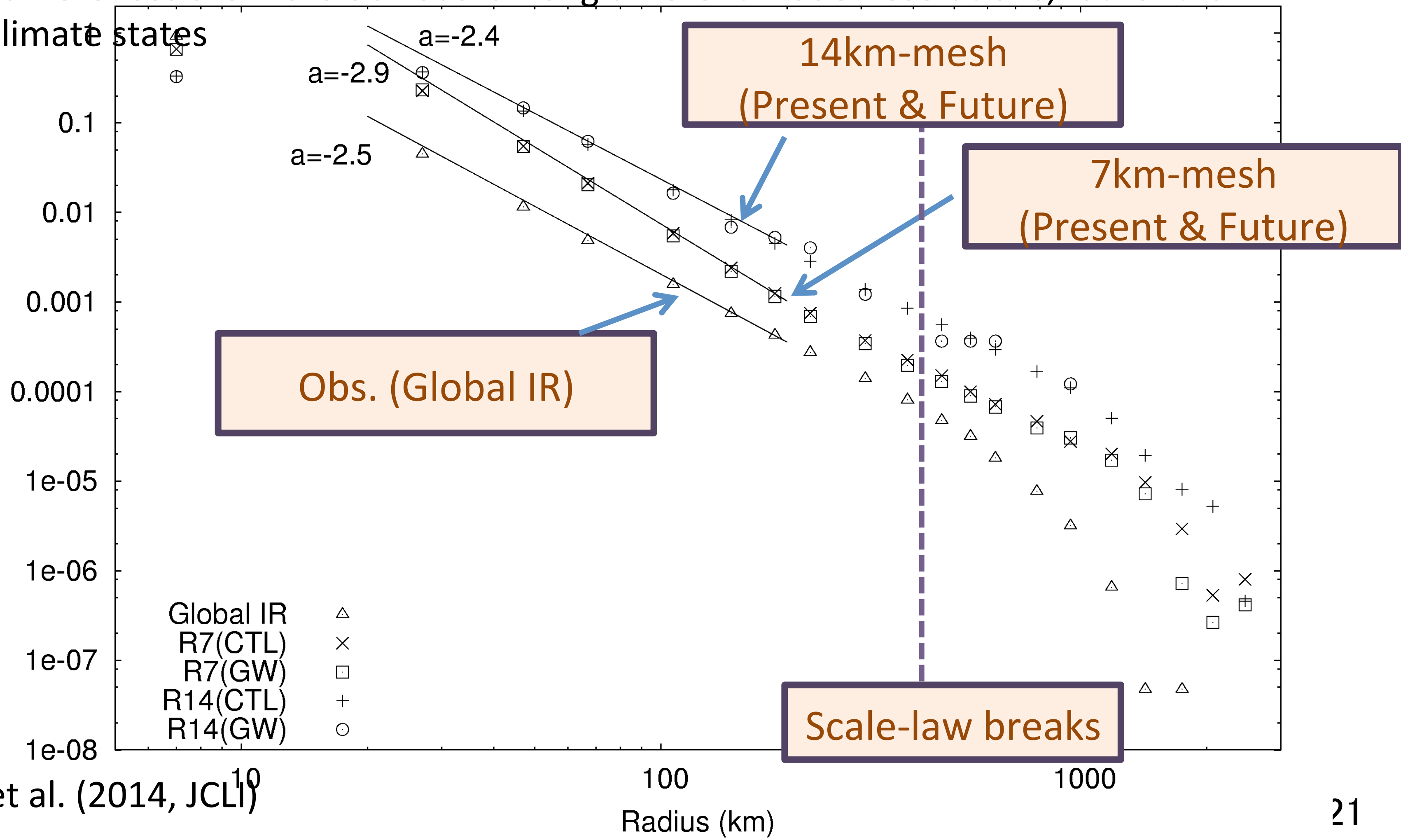
Error (red minus black)
∼ 1.7W/m^2 for r ≦ 80km
∼ 1W/m^2 for r > 80km
Need care about interpretation for smaller clouds (next slide)

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

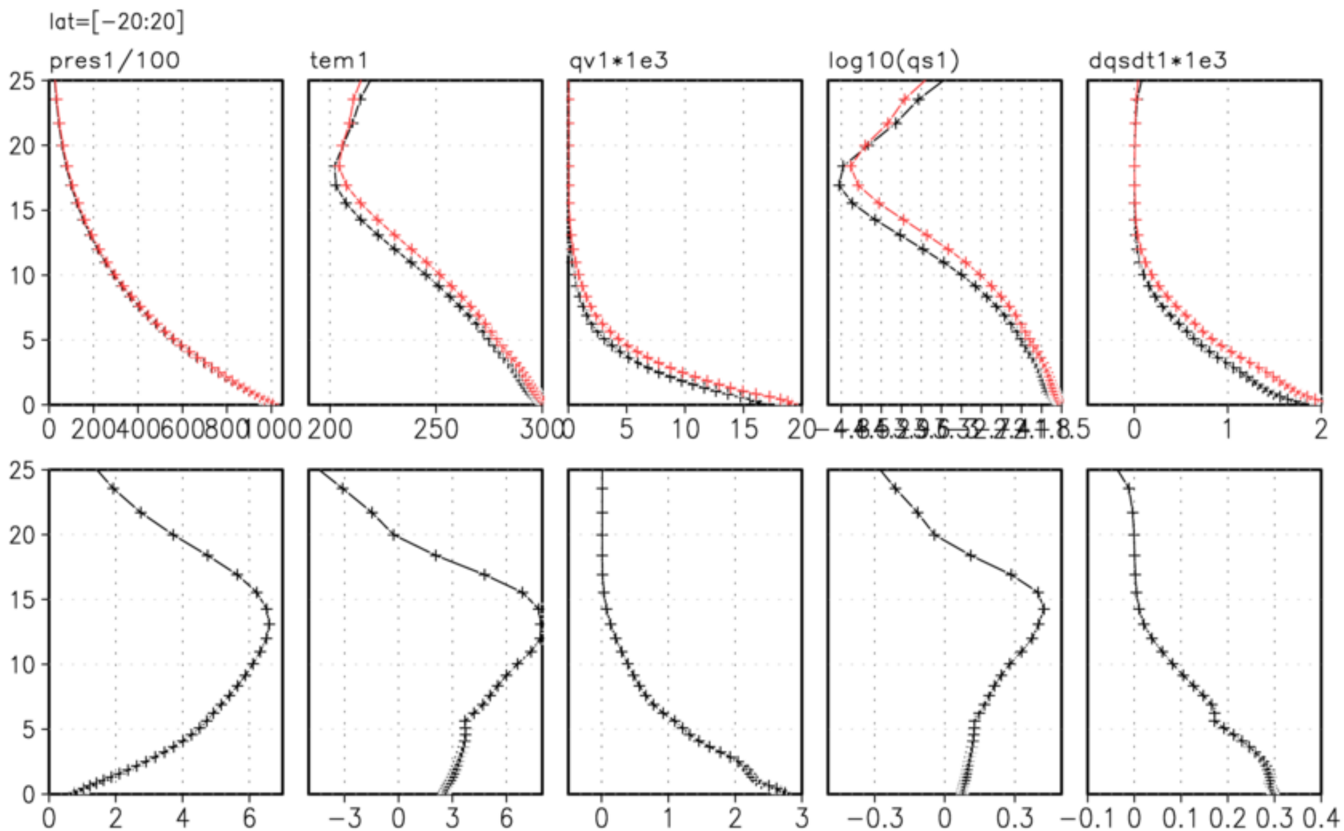
$$\cong \sigma \overline{\varepsilon}^{(i)} \overline{T}_{CT}^{(i)\,4} + \left(1-\overline{\varepsilon}^{(i)}\right)\overline{F^{CLR}}^{(i)},$$

Self-similarity in cloud size

- ✓ Slopes of all results is about $r^{-2.4} \sim r^{-2.9}$
  - ✓ Slope in both 7km and 14km is similar to obs.
- ✓ Much more dependency on grid size, compared to that on climate change
- ✓ Scale law breaks across 500-1000km radius
- ✓ Mainly differences are more obvious among different model resolutions, rather than in different climate states



Noda et al. (2014, JCLI)



qvsは特に200hpaで急に小さくなるわけでもないので200hpaで水蒸気がほぼ0になり、放射冷却も0に近づくというわでもない

Analysis Error
(example for present climate case)

True

Diagnosed

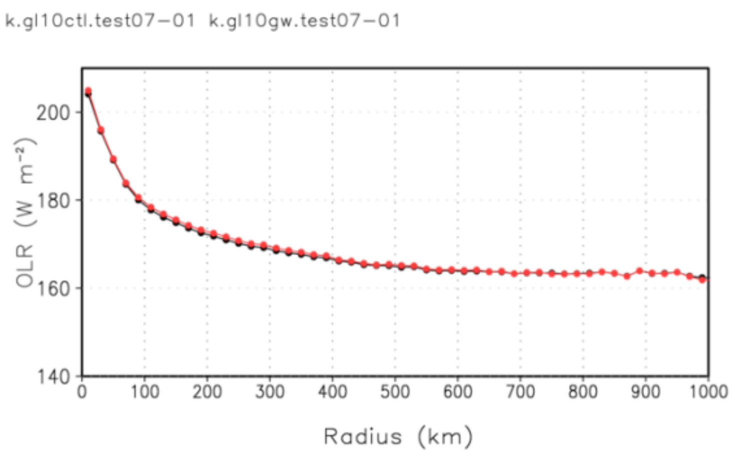
$$\overline{F}^{(i)} \cong \sigma \overline{\varepsilon}^{(i)} \overline{T}_{CT}^{(i)\,4} + \overline{F}_{CB}^{(i)}$$

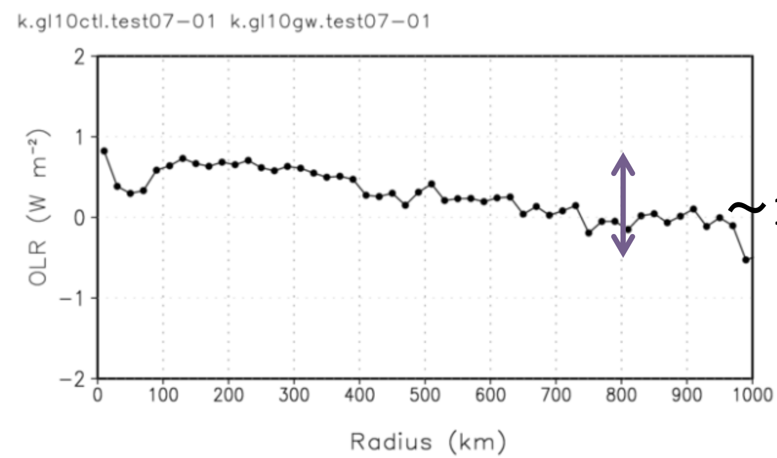
$$\cong \sigma \overline{\varepsilon}^{(i)} \overline{T}_{CT}^{(i)\,4} + \left(1-\overline{\varepsilon}^{(i)}\right)\overline{F^{CLR}}^{(i)},$$

Diagnosed − True

Error

Present





~1W/m^2

It maybe difficult to discuss a budget for r < ca.80km because the net error in ΔF (i.e., sum of the errors of present + future) is larger in a smaller radius range (1.7W/m^2 r～80km)

Error in each climate

True

Diagnosed

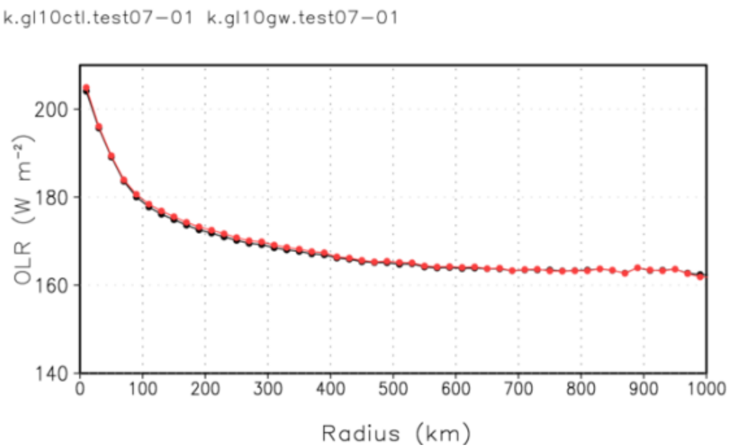
$$\overline{F}^{(i)} \cong \sigma \overline{\varepsilon}^{(i)} \overline{T}_{CT}^{(i)\,4} + \overline{F}_{CB}^{(i)}$$

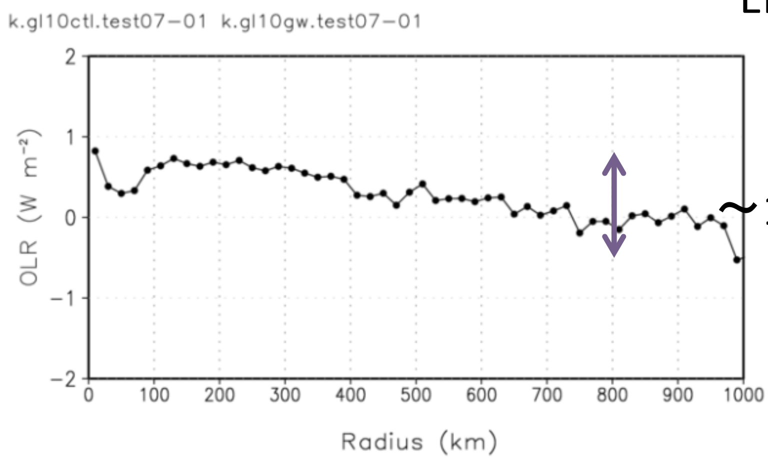
$$\cong \sigma \overline{\varepsilon}^{(i)} \overline{T}_{CT}^{(i)\,4} + \left(1 - \overline{\varepsilon}^{(i)}\right) \overline{F^{CLR}}^{(i)},$$

Diagnosed − True

Error

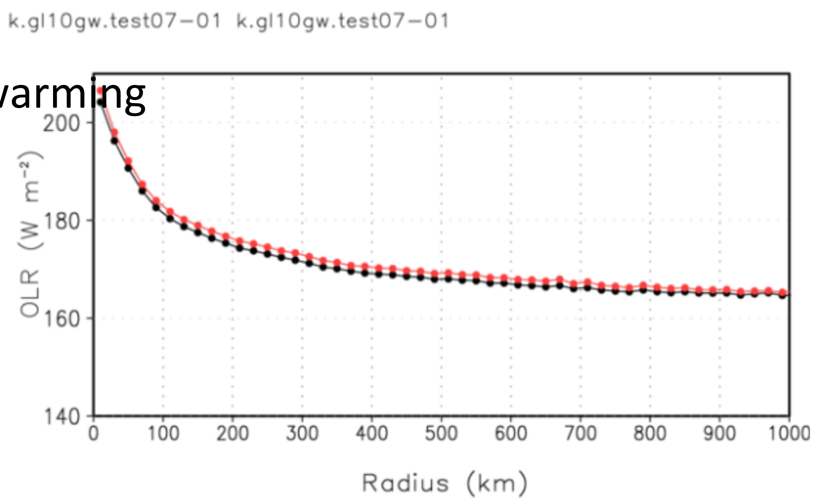
Present

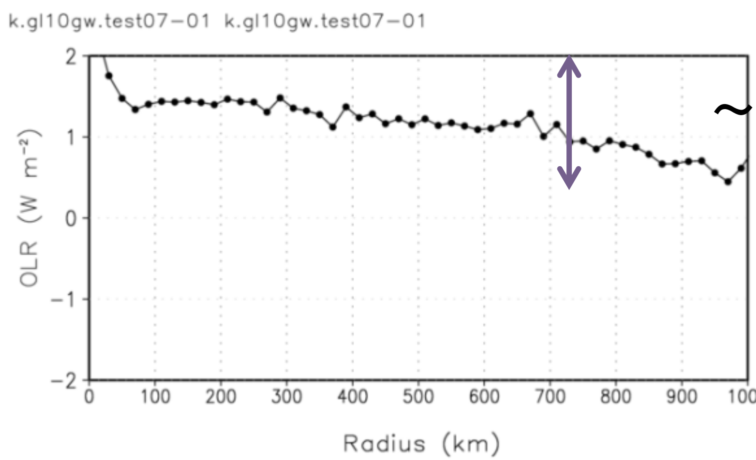




~1W/m^2

Global warming

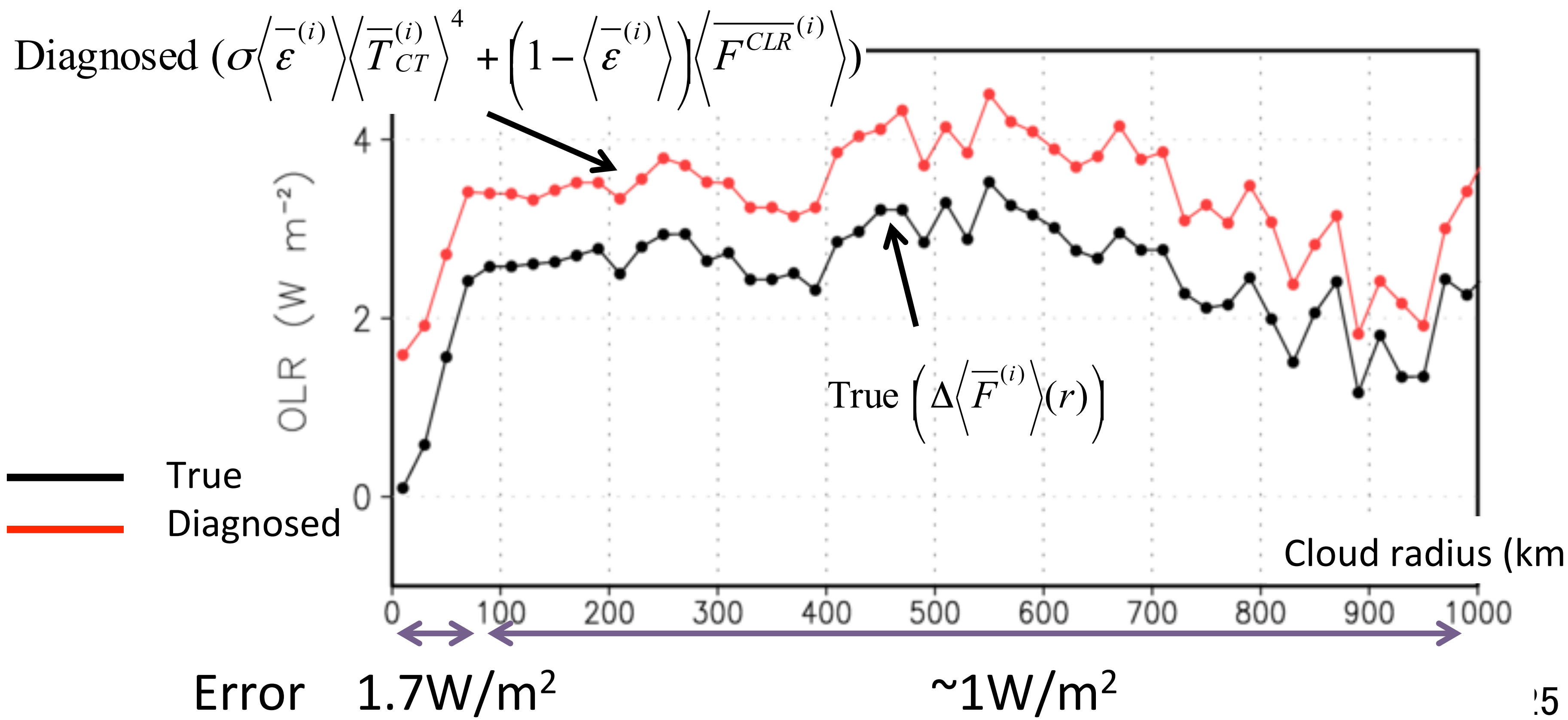




~2W/m^2

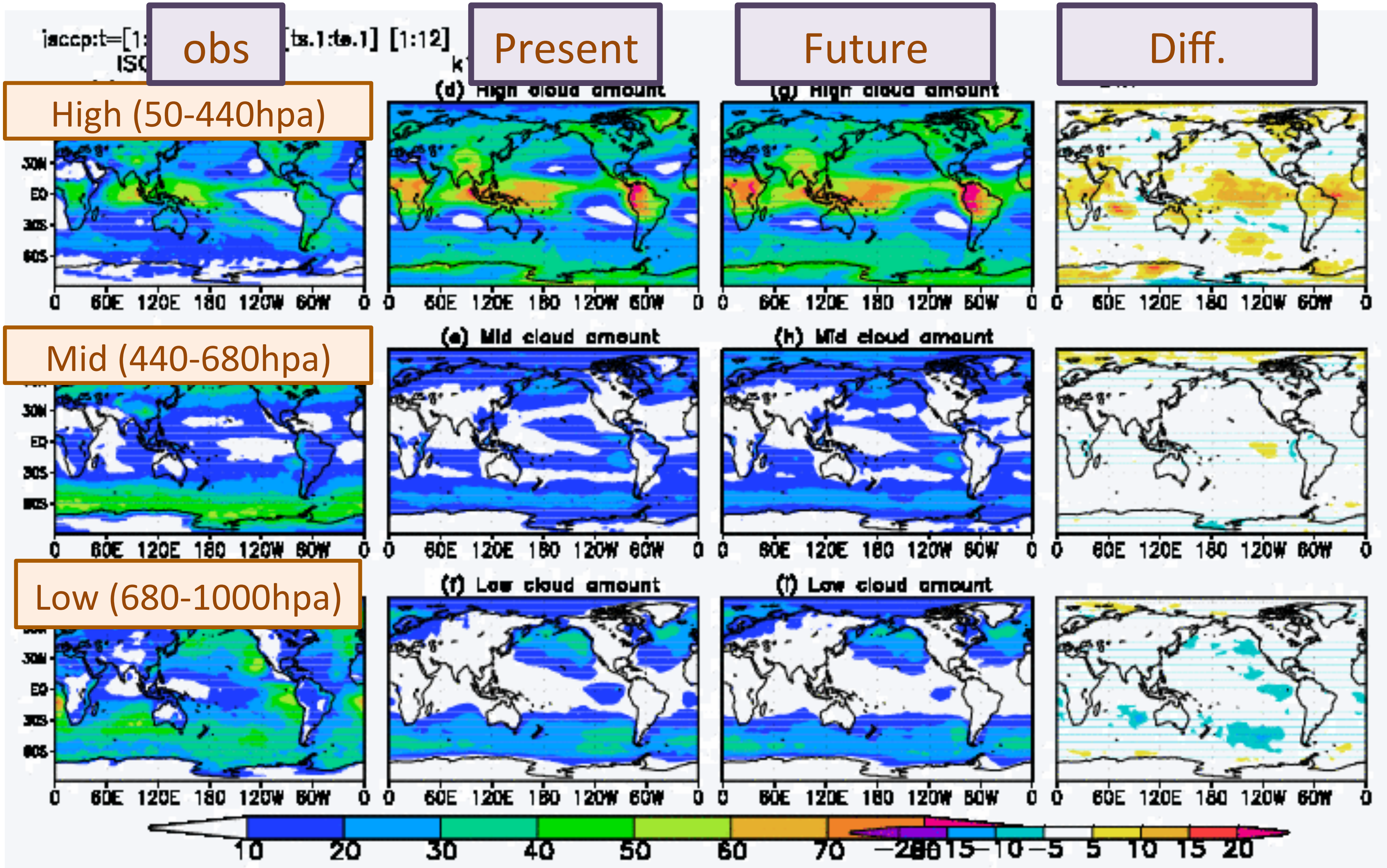
Error evaluation
True vs Diagnosed

- Diagnosed ΔF (red line) overstimates especially in the smaller clouds $r \leqq 80$ km.
- Therefore, we cannot discuss the changes for the result in ranges of $r \leqq 80$ km, where the error in the diagnosed OLR is large



Cloud cover (7km mesh)

1-yr simulation



High cloud response to warmer climate

- Clouds in global warming experiment with NICAM
  - High cloud amount increases (positive feedback) but accumulated ice amount decreases (Satoh et al. 2012)