Revisit of the fixed anvil temperature hypothesis from nonhydrostatic global simulations

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1. Introduction

Hartmann and Larson [2002] proposed a constraint of a response of high clouds to global warming, termed the fixed-anvil-temperature (FAT) hypothesis. The hypothesis states that cloud-top temperature, T_{CT}, remains nearly constant despite the increase in surface temperature due to global warming. The validity of the FAT hypothesis depends on the magnitude of the changes of cloud-top temperature. However, it has not been well recognized the extent to which changes can be regarded as *small* or *large* enough. We investigate the relative components of the changes of outgoing-longwave radiation (OLR) at the top of the atmosphere (TOA) by decomposing the contributions into T_{CT}, cloud optical thickness (or cloud emissivity, ε), and clear-sky OLR, F^{CLR}.

2. Data

NICAM is used in the present study. The model configuration used was the same as Noda et al. [2014, JCLI, 2015, JMSJ], with mesh intervals of approximately 7 km and a time integration period extended to a full year (1 June 2004-31 May 2005). In the following analysis, we defined a high-cloud region as one where the modeled OLR at TOA was less than 210 W m^{-2}, and cloud sizes are shown as an equivalent radius of a circle, and thus the minimum radius is approximately half of the model grid size [Noda et al., 2012, JCLI]. We focus mostly on the tropical and subtropical regions between 30°S and 30°N, which will be referred to as ‘low latitudes’ hereafter.

3. Diagnosis of OLR

To evaluate what factors contribute to the net OLR change, we derive a diagnostic equation of OLR at the TOA, F (W m^{-2}), in terms of T_{CT} (K), ε, and F^{CLR} (W m^{-2}). We begin with an approximation of OLR as

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

where F_{CB} (W m^{-2}) is the upwelling longwave radiation from the bottom level of a high cloud, and $\sigma(= 5.67 \times 10^{-8}\mathrm{Wm^{-2}K^{-4}})$ is the Stefan-Boltzmann constant. We calculated ε using an approximation proposed by *Fu and Liou* [1993] as

$$\varepsilon = 1 - exp(-a\tau) \quad (2)$$

where a=0.79. τ is an optical depth. Thus, OLR at TOA is approximately diagnosed from equation (1) by determining the cloud top temperature T_{CT}. Conventionally, the T_{CT} value is often defined at the level where optical depth from cloud top τ_c reaches 0.1 [e.g., *Hartmann and Larson*, 2002]. In this study, however we use an empirical formula instead of the constant value of 0.1 as

$$\tau_c = \max\left(min\left(\frac{\tau_2-\tau_1}{F_2-F_1}(F-F_1), \tau_2\right), \tau_1\right) \quad (3)$$

where (F_1, τ_1)=(200, 0.1) and (F_2, τ_2)=(185, 0.4). These values are derived from a trial-and-error approach to diagnose a simulated relation between OLR and cloud radius. The response of OLR to global warming, Δ , can be approximated as

$$\Delta \bar{F}^{(i)} \simeq \left(\frac{\partial F}{\partial \varepsilon}\right)_{T_{CT}, F^{CLR}} \Delta \bar{\varepsilon}^{(i)} + \left(\frac{\partial F}{\partial T_{CT}}\right)_{\varepsilon, F^{CLR}} \Delta \overline{T_{CT}}^{(i)} + \left(\frac{\partial F}{\partial F^{CLR}}\right)_{T_{CT}, \varepsilon} \Delta \overline{F^{CLR}}^{(i)}$$

$$\equiv F_{\varepsilon} \Delta \bar{\varepsilon}^{(i)} + F_{T} \Delta \overline{T_{CT}}^{(i)} + F_{F} \Delta \overline{F^{CLR}}^{(i)}. \quad (4)$$

An overbar with a prefix, i, denotes an average over i-th cloud area. Those values are hereafter shown with being binned at cloud radius. Using the above formula, one can evaluate the contributions of ε, T_{CT}, and F^{CLR} to changes of F.

4. Results

Figure 1 shows each contribution of the terms in Eq. 4 on OLR as a function of cloud size. From CTL to GW (Fig. 1a), OLR changes positively by 1.0–3.5 W m^{-2} for the clouds with r>50 km for the actual ΔF. The contribution of the three terms to the net OLR change clearly varies depending on the radius. The change of cloud emissivity is largest at approximately r=90 km, and then decreases with increasing radius. In contrast, the effect of the changes of T_{CT} becomes stronger with increasing radius. In particular, for r>340 km, the contribution magnitude becomes comparable to that of cloud emissivity (blue and green lines, respectively). In contrast to the above two terms, the F^{CLR} contribution is very small: the term is negative at every radius, and its amplitude increases slightly with increasing cloud radius by r=700 km.

Considering the net contributions (Fig. 1b), the changes in ε strongly contribute to the net OLR change by r=1800 km due to changes of smaller clouds. In contrast, the contribution of T_{CT} increases gradually, nearly constantly with radius, eventually slightly exceeding that of ε. The effects of changes in ε and T_{CT} are nearly comparable with each other, and the changes in F^{CLR} have a much weaker effect.

5. Summary

We have argued for the importance of the FAT hypothesis based on the high-resolution GCM data, in which cumulus parameterization was not used, particularly focusing on the dependency on high cloud size. The present study suggests that the extent to which the FAT hypothesis holds true can depend on cloud size. That is, for smaller cloud sizes (e.g., less than approximately 340 km in the present case), the contribution of T_{CT} is of secondary importance, and the contribution of cloud emissivity is more important. In contrast, for clouds larger than 340 km, the contribution of cloud emissivity is comparable to that of T_{CT}, and thus, both of the two components become equally important. The role of F^{CLR} is smaller than those of the two previous factors over the low latitudes. The changes of F^{CLR} depend weakly on cloud radius. In addition, we also showed dependency of the responses of precipitable water, τ, ε, F_{CLR}, and T_{CT} to global warming on cloud radius.

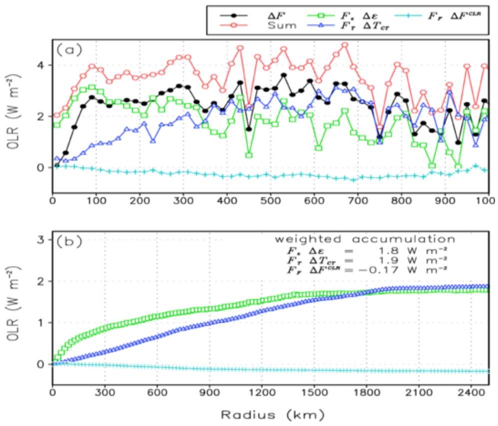

Figure 1. Budget analysis of OLR changes due to global warming binned by cloud size (20 km bins), showing (a) mean values for each cloud size, and (b) their area-ratio-and-frequency-of-occurrence-weighted accumulation in the x (radius) direction. The original OLR values (black), diagnosed values from Eq. 4 (red), and the contributions of each RHS term (green, blue and sky blue) are plotted.