The use of satellite data-based "critical relative humidity" in cloud parameterization and its role in modulating cloud feedback

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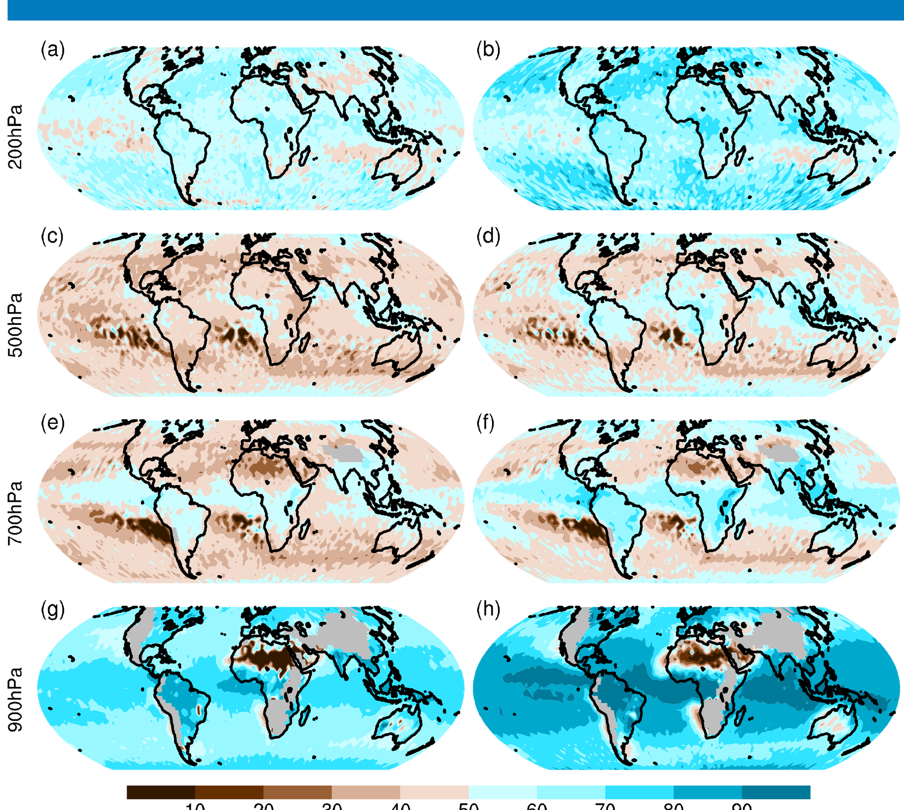
1. Introduction

The critical relative humidity (RHc), which approximately measures the subgrid-scale variability of moisture, is important to cloud parameterization. Based on the diagnostics from CloudSat/CALIPSO satellite data, we propose an improved RHc formula that incorporates geographic dependence and allows for non-monotonic variations in the vertical direction. With the parameterized RHc, a cloud macrophysics scheme is constructed in which fractional cloudiness and subgrid-scale condensation are synergistically solved, with the latter being calculated using two different approaches. Cloud feedback is analyzed under the new scheme.

2. Diagnosis of RHc



$$\mathrm{RH_c} = 1 - \frac{1-\mathrm{RH}}{(1-C)^2}$$

RH: grid-mean relative humidity
C: cloud fraction

- Lower values in subtropics
- higher ones in inner tropics

Fig. 1. Geographical distribution of CloudSat/CALIPSO diagnostic $\mathrm{RH_c}$ (%) at selected pressure levels using the temporal average (left) and least-squares method (right).

3. Parameterization of RHc

In each region, RHc has the general form:

$$\mathrm{RH_c} = \beta_1 + \beta_2 \times \exp\left[1-\left(\frac{P}{P_s}\right)^{\beta_3}\right] + \beta_4 \times \exp\left[1-\left(\frac{P_s-P}{P_s}\right)^{\beta_5}\right]$$

The coefficients βj are determined by minimizing the cost function, as follows:

$$g = \sqrt{\frac{1}{N}\sum\left(\beta_1 + \beta_2 \times \exp\left[1-\left(\frac{P}{P_s}\right)^{\beta_3}\right] + \beta_4 \times \exp\left[1-\left(\frac{P_s-P}{P_s}\right)^{\beta_5}\right] - \mathrm{RH_c^{obs}}\right)}$$

The separated RHc is then combined into a single latitude-dependent formula as:

$$\mathrm{RH_c}(\phi) = \frac{1-\alpha_{\mathrm{idx}(\phi)-1}}{2}\mathrm{RH_c}(\mathrm{idx}(\phi)-1) + \frac{1+\alpha_{\mathrm{idx}(\phi)-1}}{2}\mathrm{RH_c}(\mathrm{idx}(\phi))$$

where ϕ stands for latitude, and "idx" is the index of the region corresponding to latitude ϕ. $\alpha_{\mathrm{idx}(\phi)}$ are weighing coefficients satisfying $\alpha_{\mathrm{idx}(\phi)} = \tanh\left(\frac{\phi-\phi_0}{D_0}\right)$, where ϕ_0 and D_0 are tunable parameters

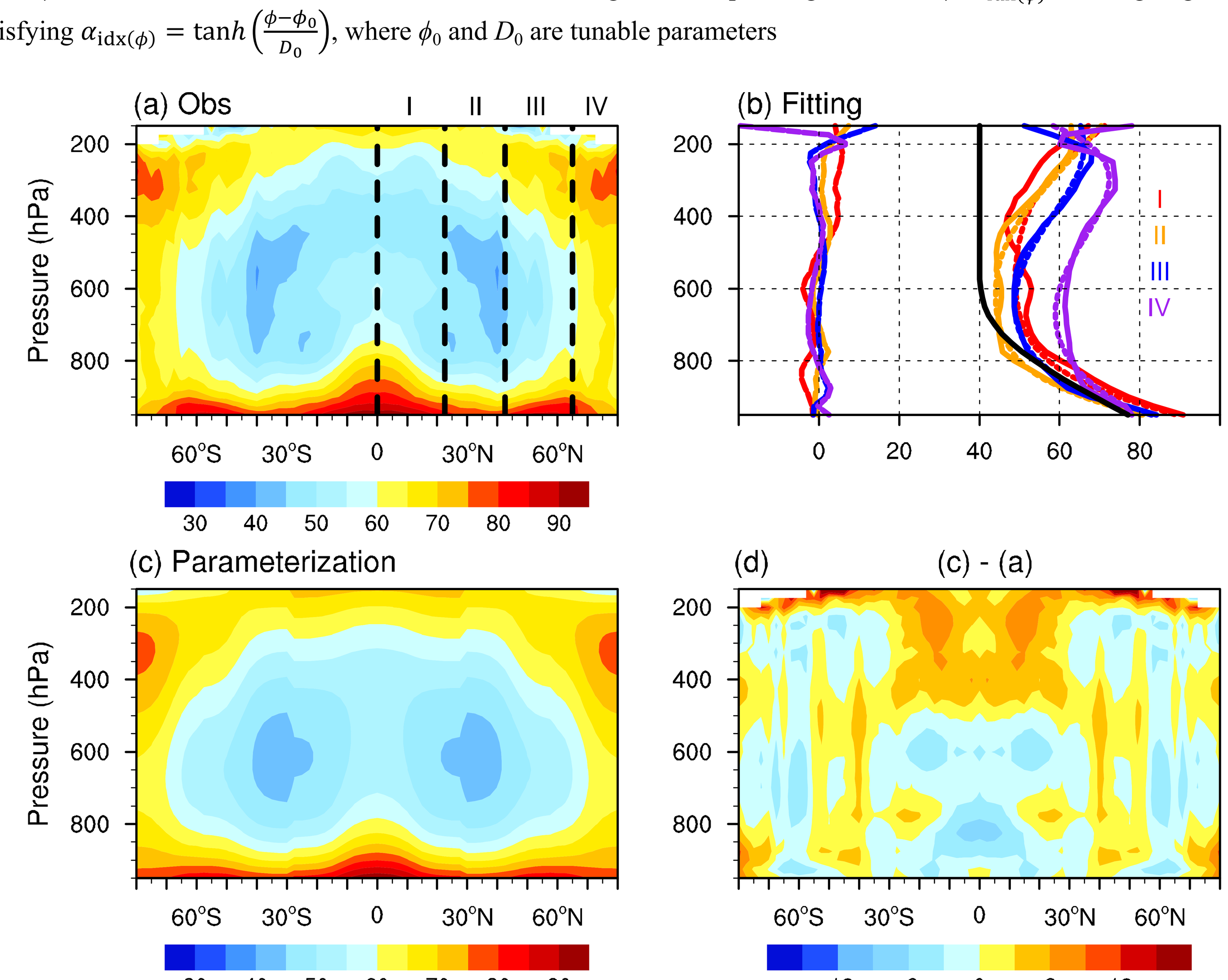


Fig. 2. (a) Observed $\mathrm{RH_c}$ (%) after symmetrization in the Northern Hemisphere and Southern Hemisphere. (b) Observed (dashed) and parameterized (solid) $\mathrm{RH_c}$ profiles in four representative regions, with the differences marked by long-dashed lines. The parameterized $\mathrm{RH_c}$ of Quaas (2012) is also superimposed in the figure (solid black). (c, d) Latitude–pressure cross-section of (c) the new parameterized $\mathrm{RH_c}$ and (d) its deviation against the observation.

Reference:
X Wang, et al. The use of satellite data-based "critical relative humidity" in cloud parameterization and its role in modulating cloud feedback, *Journal of Advances in Modeling Earth Systems*, 2022, 14(10): e2022MS003213

4. Calculation of subgrid condensation

✓ **Prognostic method (_prog)**

This method retains the property of cloud condensate as a prognostic variable in models. The prognostic equation for relative humidity U is expressed in terms of total water q_t, liquid water temperature T_l, and liquid water q_l:

$$\frac{\partial U}{\partial t} = \alpha\frac{\partial q_t}{\partial t} - \beta\frac{\partial T_l}{\partial t} - \gamma\frac{\partial q_l}{\partial t}$$

Noting $\frac{\partial U}{\partial t} = 0$ in the cloudy portion, together with the use of $\frac{\partial q_l}{\partial t} = C\frac{\partial \hat{q_l}}{\partial t} + c_m\hat{q_l}\frac{\partial C}{\partial t}$, equation (8) is further expanded in the following form:

$$\left(1 + C\frac{L}{C_p}\frac{\partial q_s}{\partial T}\right)\frac{\partial \hat{q_l}}{\partial t} + c_m\hat{q_l}\frac{L}{C_p}\frac{\partial q_s}{\partial T}\frac{\partial C}{\partial t} = \frac{\partial \hat{q_t}}{\partial t} - \frac{\partial q_s}{\partial T}\frac{\partial T_l}{\partial t}$$

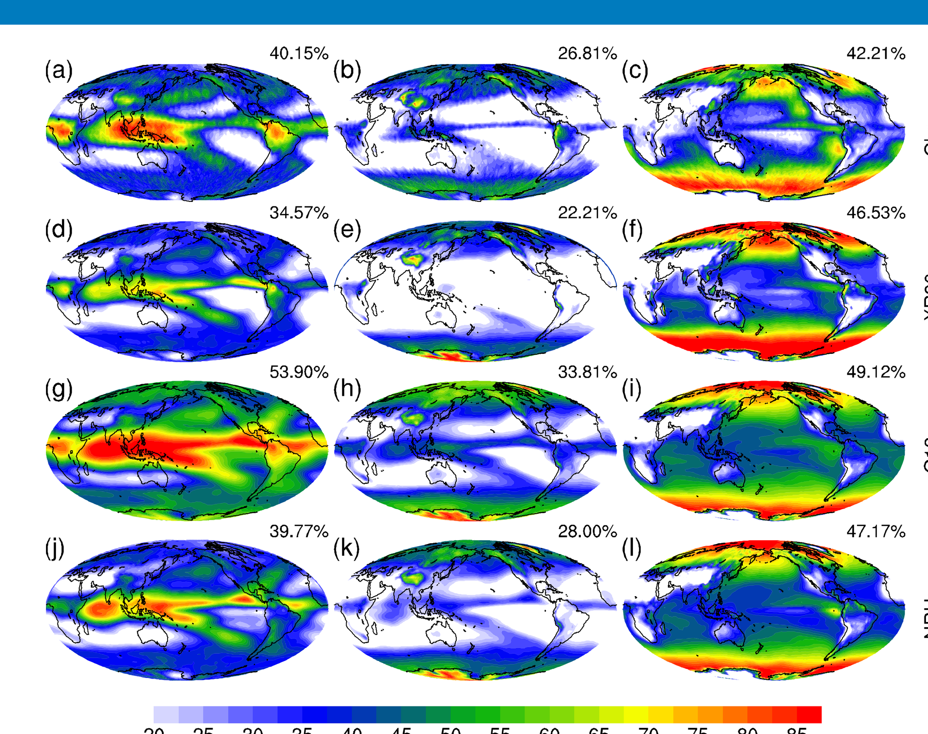
✓ **Diagnostic method based on PDF (_pdf)**

With a uniform PDF assumed for total water, one can also obtain a diagnostic formula for cloud condensate,

$$q_l = \int_{q_s}^{q_t+\Delta q}(q-q_s)\frac{1}{2\Delta q}dq$$

which is further expanded as: $q_l = \frac{(q_t+\Delta q)^2 - q_s^2}{4\Delta q} - \frac{1}{2\Delta q}(q_t+\Delta q-q_s).q_s$

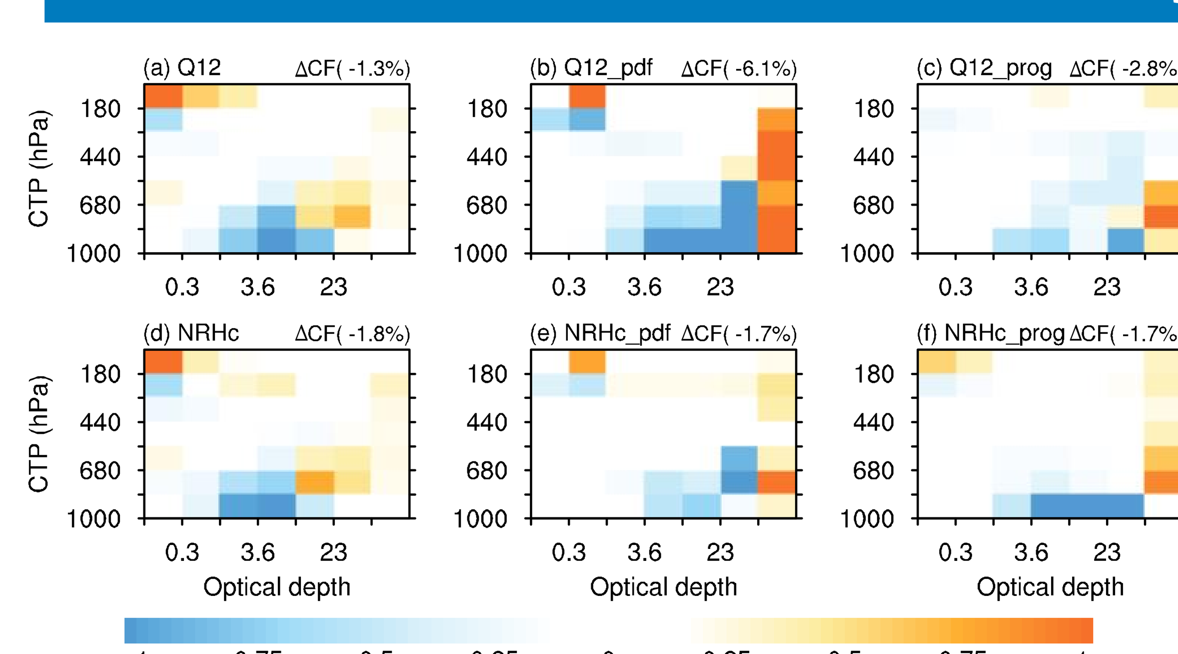
5. Performance on AMIP simulation



- XR96 and Q12 underestimates clouds
- NRHc scheme performs better

Fig. 3. Geographical distribution of high (left column), mid (middle column) and low (right column) cloud cover (%) from (a–c) CloudSat/CALIPSO and simulations using the cloud scheme of (d–f) XR96, (g–i) Q12, and (j–l) $\mathrm{NRH_c}$. The global mean value is shown in the top right of each figure.

6. Cloud feedback analysis



- All simulations show a reduction in globally-averaged cloudiness
- The sensitivity to RHc is smaller in simulations applying RHc in cloud cover alone

Fig. 4. Globally averaged changes in cloud fraction in CTP-τ histograms between the +4 K and control experiments in simulations with different $\mathrm{RH_c}$ configurations. The sum of each matrix is shown in the top right of each panel.

- Large discrepancies of cloud feedbacks are found in a single model
- The way to calculate subgrid condensation and the choice of RHc are both important

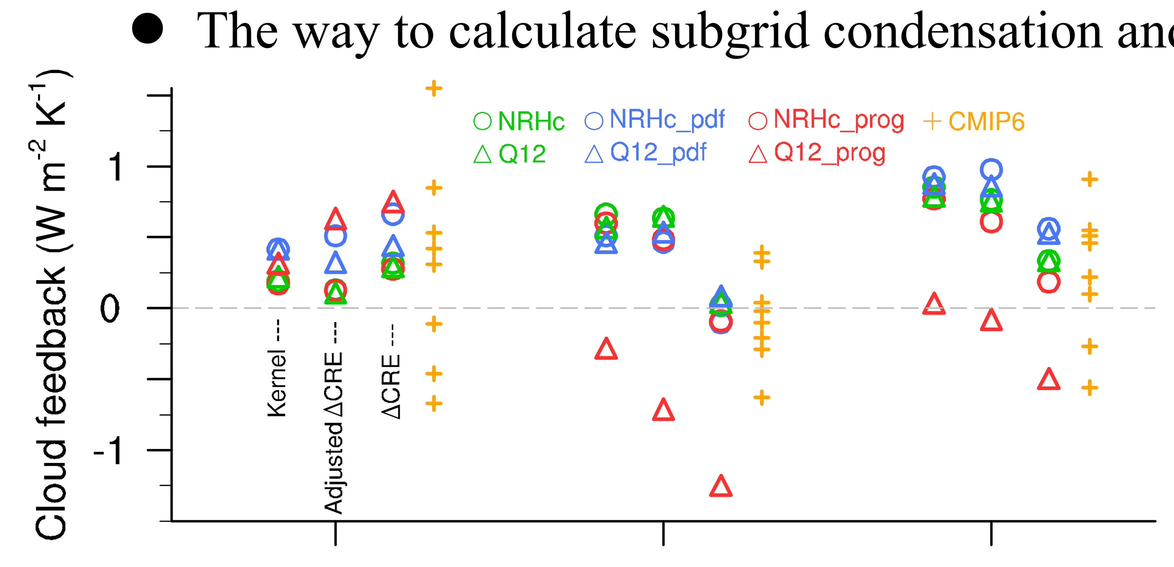


Fig. 5. Global- and annual-mean cloud feedbacks estimated by three different methods in simulations with different $\mathrm{RH_c}$ configurations. The multimodel cloud feedbacks estimated by ΔCRE from the CMIP6 APE experiments are also overlaid, with each model represented by a plus sign.

7. Conclusion

- We propose an improved RHc formula that incorporates geographic dependence and allows for non-monotonic variations in the vertical.
- Varying RHc and techniques in calculating subgrid condensation replicates the range of uncertainty found in CMIP6 cloud feedback estimates.
- Varying RHc and its implementation in models leads to the diversity of cloud feedback being mainly due to optically thick clouds