Improved Low-cloud Simulation from the Community Atmosphere Model with a Third-order Turbulence Closure

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Introduction

The representation of clouds, especially low-level clouds, is the largest source of uncertainty in climate simulation. Low level clouds associated with turbulent circulations of small spatial scales (meters to kilometers) cannot be adequately resolved even by a multiscale modeling framework (MMF) despite its successes in simulating phenomena associated with deep convective clouds. In an MMF a cloud resolving model (CRM) is embedded in each grid column of the host general circulation model (GCM) to represent cloud physical processes.

Cheng and Xu (2011) and Xu and Cheng (2013) demonstrated that the application of a third-order turbulence closure (TOC) in the CRM component of an MMF results in substantial improvements in the representation of the global distributions of low-level clouds in the subtropics and middle-level clouds in mid-latitude storm track regions as compared with those from an MMF with a first-order turbulence closure in its CRM component.

This study evaluates a TOC in Community Atmosphere Model version 5.3 (CAM5) and a comparison among the results from the default CAM5, CAM5 with the TOC, and the MMF with the TOC.

Model Description

The intermediately-prognostic higher-order turbulence closure (IPHOC) is implemented in CAM5 (hereafter, CAM5-IP). IPHOC assumes a joint double-Gaussian distribution of liquid water potential temperature, total water, and vertical velocity. The distribution is inferred from the first-, second-, and third-order and is used to diagnose cloud fraction and grid-mean liquid water mixing ratio, as well as the buoyancy terms and fourth-order terms in the equations describing the evolution of the second- and third-order moments.

The IPHOC used in CAM5 has been simplified with six prognostic equations, instead of the twelve used in the IPHOC in the MMF (hereafter SPCAM-IPHOC). They include the three first-order moments and the second-order moment of vertical velocity and the fluxes of total water mixing ratio and liquid-water potential temperature. The rest of the higher-order moments are diagnosed. A diagnosed planetary boundary-layer (PBL) height is implemented in the simplified IPHOC so that the strong inversion above PBL can be resolved despite the coarse vertical grid-spacing used. The simplified IPHOC replaces PBL, shallow convection, and cloud macrophysics parameterizations in CAM5. The CAM5-IP represents a more unified treatment of boundary layer and shallow convective processes than the default CAM5.

Experiment Design

Three sets of experiments were made: 1) a five year and three month simulation using CAM5 with a finite-volume (fv-) 1.9°X2.5° dynamic core starting from September 1, 1997; 2) Same as 1) except using CAM5-IPHOC, and 3) Same as 1) except using SPCAM-IPHOC. In all experiments, 12 vertical levels below 700 hPa were used in order to better resolve boundary-layer clouds, compared with 10 levels in the standard CAM5. The results from the last five years are analyzed in this study.

Global Distributions

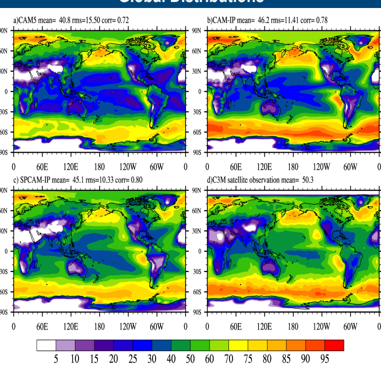

Fig. 1. Global distribution of boreal winter annual **mean low-level (below 700 hPa) cloud amounts** (%) from CAM5 (a), CAM5-IP (b), SPCAM-IPHOC (c), and C3M (CERES, CALIPSO, CloudSat and MODIS) observations (d).

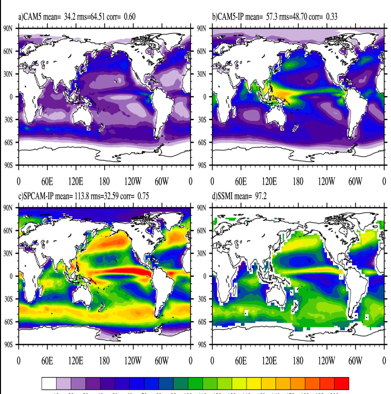

Fig. 2. Same as Fig. 1 except for **liquid water paths** (LWPs; g m^{-2}) and (d) from SSM/I (Special Sensor Microwave/ Imager) observations.

Global Distributions (cont.)

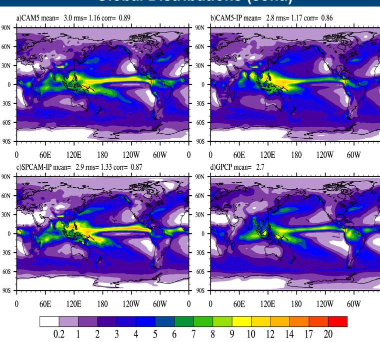

Fig. 3. Same as Fig.1 except for **surface precipitation rate** (mm day^{-1}) and (d) from Global Precipitation Climatology Project (GPCP).

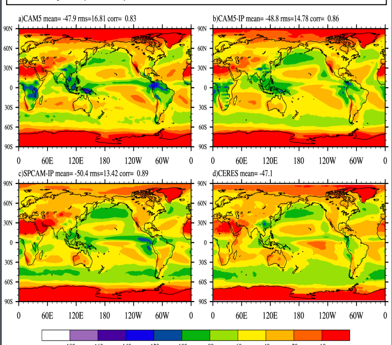

Fig. 4. Same as Fig.1 except for **shortwave cloud radiative forcing** (W m^{-2}) and (d) from CERES EBAF.

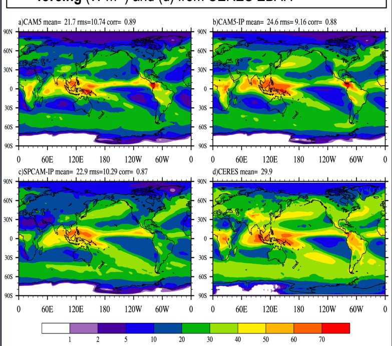

Fig. 5. Same as Fig.4 except for **longwave cloud radiative forcing** (W m^{-2})

Vertical Cross Section along Southeast Pacific

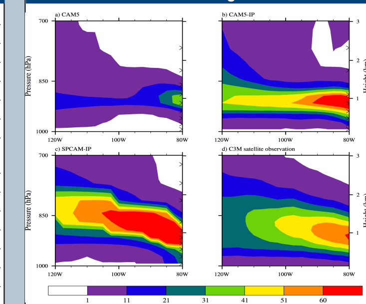

Fig. 6. Seasonal-mean **cloud fraction** (%) along 15°S over the southeast Pacific from CAM5 (a), CAM5-IP (b), SPCAM-IPHOC (c), and C3 (CERES, CALIPSO, CloudSat and MODIS) observations.

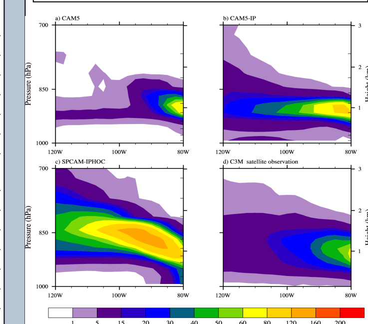

Fig. 7. Same as Fig. 6 except for **cloud liquid water content** (mg kg^{-1}).

Summary and Conclusions

- The low cloud amounts near the west coast of the subtropical continents are well produced in CAM5-IP and are more abundant than in other two models.
- There are some improvements in shortwave and longwave cloud radiative forcing compared with SPCAM-IPHOC and CAM5.
- The cloud structures from CAM5-IP, represented by the cloud fraction and cloud water content at 15°S transect, compare well with the C3M observations. The shallow cumulus clouds from CAM5 are shallower and have less liquid, while those from SPCAM-IPHOC are deeper and have more liquid than from the C3M observations.
- Challenges: the global and annual mean liquid water path (LWP) is still underestimated and the correlation of LWP and surface precipitation between CAM5-IP and observations decreases.