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Feedbacks between convection and climate: Analysis with global modeling and satellite observations

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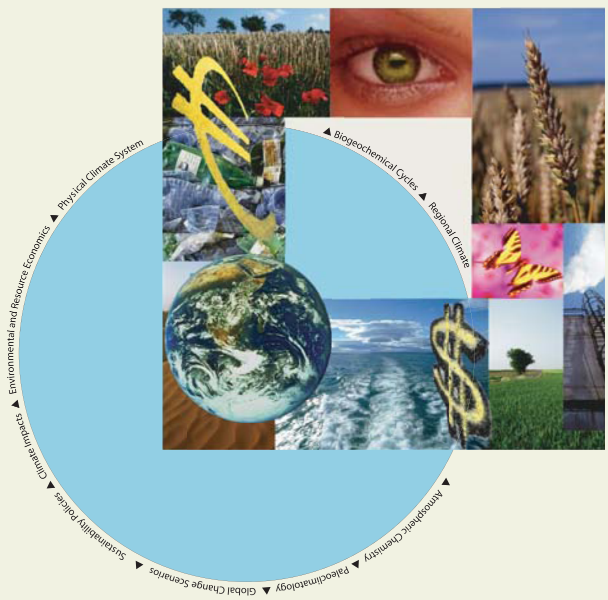

Abstract

Clouds are one of the most important components of the climate system, regulating the radiation budget of the Earth. In the simulation of the global climate using General Circulation Models (GCMs), cloud feedbacks contribute to a major uncertainty on account of poorly represented cloud processes. Satellite observations provide the most comprehensive view of cloud related quantities at a global scale, and are an important data source for evaluation of cloud representations in GCMs. The International Satellite Cloud Climatology Project (ISCCP) simulator is a valuable tool for analyzing GCM cloud distributions. This research focuses on diagnostic applications of the ISCCP simulator to pinpoint the ECHAM5 model deficiencies related to the cloud processes. Subgrid-scale cloud variability information using the probability density function of total water mixing ratio, is incorporated in the ISCCP simulator diagnostics to characterize the cloud property distributions. The simulator diagnostics serve as a primary tool in the model evaluation studies performed in this work.

The analysis of global average cloud distributions of ECHAM5 model reveals that high-level clouds are overestimated in the tropics, which is compensated by an underestimation of low- and mid-level clouds. The analysis suggests that convection in the model transports too much moisture to higher levels of upper troposphere, not allowing detrainment at mid-levels. High-level clouds over tropical land areas have a major contribution from this model deficiency due to large amount of convection. Evaluation of global average histograms reveal that most of these high clouds over land are optically thin clouds, which are less abundant in the observations. Land and sea diurnal cycles in the simulated cloud types are compared with ISCCP observations for four tropical test-case areas. In general, the model shows a weak diurnal behavior for deep-convective clouds and low-level clouds. In the observations, the diurnal cycle in total cloud cover is dominated by the latter in most land as well as sea areas. The diurnal peak of cloud fractions are diagnosed too early in the model compared to the ISCCP observations both for the land and sea areas.

A clustering technique for cloud regime categorization in the model output is performed in order to compare the model behavior with other model inter-comparison studies. For the tropics and the ice-free extratropics, the ECHAM5 model simulates shallow cumulus clouds as the most frequent cloud regime with qualitative agreement to the ISCCP observations, but a substantial underestimation in quantitative terms. ECHAM5 produces an excess of tropical convective and extra-tropical frontal clouds in comparison to the observations. The total climate change response of clouds to an SST perturbation, when measured by change in net cloud radiative forcing, is calculated for each cloud regime and averaged over tropics, ice-free extratropics and snow or ice-covered extratropics. The stratocumulus and stratocumulus-cumulus transition cloud regimes are responsible for 2/3 of the feedbacks, with stratocumulus alone responsible for $\sim$50%. The tropics in turn dominate the global cloud-climate feedbacks from change in net radiative cloud forcing.

The ISCCP simulator diagnostics are further used in characterizing the processes highly relevant for convection-climate feedbacks. A Lagrangian trajectory analysis is performed to track the transitions of deep-convective clouds to cirrus clouds (cirrostratus and cirrus) within the ISCCP observations and the ECHAM5 model. Forward trajectories for the ISCCP observations and model are created over which the ISCCP histograms are used for tracking the cirrus life cycle associated with deep convective events in a period of 5 days. The cloud evolutions over trajectory paths suggest that the deep-convective clouds detrain over time and gradually thin-out by the first day after the convective event. The evolution of cirrostratus and cirrus clouds begin from the convective detrainment and stay for next 3 to 4 days in relation to the convective events. We also separate the cirrus clouds formed due to convection and the ones formed in-situ due to large scale dynamics. This study reports that the detrainment cirrus in the ECHAM5 model lasts for 20±15 hrs compared to the in-situ cirrus life time of 17±12 hrs. Finally, the effect of these transitions in a changing/warmer climate is analyzed, in order to understand the climate feedbacks due to deep-convective cloud transitions. A perturbed model simulation with +2 K warmer SST is performed. The Lagrangian trajectory analysis suggests that more and too thick cirrostratus and cirrus clouds occur in the warmer climate compared to the present day climate. Stronger convection is noticed in the perturbed climate which leads to an increased precipitation, especially on day-2 and -3 after the convective event. The shortwave and the longwave cloud forcings increase in the warmer climate which results in an increase of net cloud radiative forcing (NCRF), leading to a positive feedback of the increased cirrostratus and cirrus clouds from a Lagrangian transition perspective.

The evaluation studies using different approaches focusing on different processes and features show consistent problems in the current model. The findings of the present day climate evaluations also persist in the simulated convection and cloud behavior in a warmer climate. This research study overall points to ways for improving the representation of convection and convection-related clouds in the GCM and thus a more reliable simulation of the climate feedbacks.