Evaluation of Clouds and Precipitation in the ECHAM5 General Circulation Model Using CALIPSO and CloudSat Satellite Data

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ABSTRACT

Observations from Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and CloudSat satellites are used to evaluate clouds and precipitation in the ECHAM5 general circulation model. Active lidar and radar instruments on board CALIPSO and CloudSat allow the vertical distribution of clouds and their optical properties to be studied on a global scale. To evaluate the clouds modeled by ECHAM5 with CALIPSO and CloudSat, the lidar and radar satellite simulators of the Cloud Feedback Model Intercomparison Project’s Observation Simulator Package are used. Comparison of ECHAM5 with CALIPSO and CloudSat found large-scale features resolved by the model, such as the Hadley circulation, are captured well. The lidar simulator demonstrated ECHAM5 overestimates the amount of high-level clouds, particularly optically thin clouds. High-altitude clouds in ECHAM5 consistently produced greater lidar scattering ratios compared with CALIPSO. Consequently, the lidar signal in ECHAM5 frequently attenuated high in the atmosphere. The large scattering ratios were due to an underestimation of effective ice crystal radii in ECHAM5. Doubling the effective ice crystal radii improved the scattering ratios and frequency of attenuation. Additionally, doubling the effective ice crystal radii improved the detection of ECHAM5’s highest-level clouds by the radar simulator, in better agreement with CloudSat. ECHAM5 was also shown to significantly underestimate midlevel clouds and (sub)tropical low-level clouds. The low-level clouds produced were consistently perceived by the lidar simulator as too optically thick. The radar simulator demonstrated ECHAM5 overestimates the frequency of precipitation, yet underestimates its intensity compared with CloudSat observations. These findings imply compensating mechanisms in ECHAM5 balance out the radiative imbalance caused by incorrect optical properties of clouds and consistently large hydrometeors in the atmosphere.

1. Introduction

In recent decades the spread in climate sensitivity has been found to be dominated by, but not limited to, cloud–climate feedbacks (Cess et al. 1990; Soden and Held 2006; Ringer et al. 2006). The magnitude with which clouds respond to radiative forcings effectively determines the extent to which the earth’s temperature will amplify due to an increase in greenhouse gas concentrations.
provide the first global survey of the vertical structure of multilayered cloud systems, including the formation, evolution, and distribution of cloud ice and liquid water contents (LWCs) with height (Stephens et al. 2002). To consistently compare modeled clouds with those observed by satellites, the CALIPSO and CloudSat simulators, as part of the Cloud Feedback Model Intercomparison Project’s Observation Simulator Package (COSP; Bodas-Salcedo et al. 2011), are employed. Using a common definition of clouds, the comparison of modeled clouds and satellite observations will be truer.

A description of the ECHAM5 model physics is presented in section 2 along with the experimental setup. In section 3 CALIPSO and CloudSat and the corresponding satellite datasets employed are briefly described, followed by the lidar and radar satellite simulators in section 4. Based on the main results and sensitivity experiments, in section 5, conclusions are presented in section 6.

2. Model and experiment description

The ECHAM5 atmospheric general circulation model solves prognostic equations for temperature, vorticity, divergence, logarithm of surface pressure, as well as the mass mixing ratios of water vapor and cloud liquid and ice water (Roeckner et al. 2003). These equations are solved on a hybrid terrain-following sigma-pressure 31-vertical-level coordinate system (denoted as L31). A spectral transform method with triangular truncation at wavenumber 63 (T63), which corresponds to a resolution of 1.8° × 1.8° (∼200 km × ∼200 km), is used. Equations are evaluated using a semi-implicit leapfrog time integration scheme with a time step (Δt) of 12 min. At each grid point, the water vapor, cloud liquid water, and cloud ice are transported using a flux-form semi-Lagrangian transport scheme (Lin and Rood 1996). From these prognostic grid-mean variables, clouds and their properties are parameterized. ECHAM5 parameterizes clouds in two manners—convective and stratiform clouds. A brief description of the parameterizations for stratiform and convective cloud formation and cloud cover are described below. Further information regarding the radiation scheme, cloud microphysics, and parameterizations for surfaces processes, such as heat and water budget, gravity wave drag, orbit variation, and subgrid-scale orography, can be found in Roeckner et al. (2003).

a. Convective cloud scheme

The convective parameterization scheme within ECHAM5 is based on the mass flux concept and bulk cloud model of Tiedtke (1989). In this scheme, air parcels are lifted dry adiabatically to the lifting condensation level and if the parcel is positively buoyant with respect to its surrounding, then convection is activated. Convection, in the Tiedtke (1989) scheme, is divided into three types: shallow, midlevel, and penetrative convection. Shallow convection occurs when the surface evaporation is larger than the large-scale convergence of moisture into a column. Shallow convection is mainly driven by the turbulent surface moisture flux in the boundary layer. Conversely, penetrative convection occurs when large-scale convergence is greater than the surface evaporation. The representation of penetrative convection has been slightly modified according to a cloud-base mass flux adjustment closure proposed by Nordeng (1994). Nordeng (1994) determines the cloud-base mass flux from the convective available potential energy (CAPE). Midlevel convection initiates above the boundary layer and forms when large-scale convergence at low levels is inhibited by a temperature inversion.

In the current setup of ECHAM5, the fractional cover of convective clouds is assumed negligible. Convective clouds, however, contribute to the cloud fraction of a grid box via the detrainment of cloud water from convective updrafts. The detrained water, in addition to that of shallow nonprecipitating cumulus clouds, is a source term in the stratiform cloud water transport equation (Lothmann and Roeckner 1996).

b. Stratiform cloud scheme

The cloud fraction within a grid box of ECHAM5 is determined using the statistical cloud scheme of Tompkins (2002). The cloud fraction is determined by integrating over the saturated part of the subgrid-scale total water mixing ratio probability density function (PDF). The total water mixing ratio is calculated as the sum of the mass mixing ratios of water vapor, cloud liquid water, and cloud ice. These in turn are calculated prognostically using the bulk cloud microphysics scheme presented in Lohmann and Roeckner (1996). The cloud microphysics scheme accounts for phase changes via condensation–evaporation, deposition–sublimation, and freezing–melting, and precipitation via autoconversion, accretion, and aggregation. The shape of the PDF, defined by the variance and skewness parameters, is related to subgrid-scale processes such as turbulence and convection. A wider PDF implies there is a wide range of total water mixing ratios within the grid box. A positively skewed PDF implies there are areas with concentrated water contents, for example, convective cells.

Once the cloud fraction of a grid box is known, the projected 2D total cloud cover can be determined by assuming maximum-random overlap. The maximum-random overlap implies that clouds in adjacent vertical layers overlap maximally, while groups of clouds separated
by one or more clear layers are randomly overlapped. Total cloud cover, for the purposes of this study, is the area covered by clouds if one looked down on a column of atmospheric grid boxes.

c. Experiment description

In the following experiments, ECHAM5 has been run with COSP version 1.2.1 online for the year 2007 as defined by the boundary conditions, with patterns of sea surface temperature and sea ice extent prescribed from observations, starting after an initial 3-month spinup. The results presented are for June–August (JJA) 2007. The experiments use the CALIPSO and CloudSat simulators. The simulator results are compared with their respective satellite datasets provided by the L’Institut Pierre-Simon Laplace (IPSL) ClimServ group.

It was found that the period of JJA was sufficiently long to draw conclusions regarding the general model performance and to identify model deficiencies. A comparison of the JJA period with December–February (DJF) 2007 in the control experiment showed no significant difference in the conclusions drawn here and as such are not shown.

3. Satellite observations

On 28 April 2006, CALIPSO was launched along with the CloudSat cloud profiling radar satellite. As part of the A-train constellation of satellites, CALIPSO and CloudSat are in a sun-synchronous polar orbit 705 km above the sea surface with an inclination of 98.2°. They cross the equator at approximately 1330 local solar time, and have a 16-day repeat cycle providing coverage from 82°S to 82°N due to the inclined orbit (Winker et al. 2007).

The following sections provide a brief description of the lidar and radar instruments on board CALIPSO and CloudSat, respectively, as well as the satellite datasets used in this study.

a. CALIPSO

CALIPSO provides quasi-global high-resolution profiles of the vertical structure of clouds and aerosols using the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). CALIOP is a near-nadir two-wavelength polarization-sensitive lidar that uses one channel to measure the 1064-nm lidar backscatter intensity and two channels to measure the orthogonally polarized components of the 532-nm backscattered signal (Winker et al. 2007). At the 532-nm wavelength, atmospheric cloud particles and gas molecules contribute to scattering but not absorption and so the two-wavelength signals are able to provide information regarding particle size, shape (spherical vs nonspherical) and type (Chepfer et al. 2008; Winker et al. 2007). As such, CALIOP is also able to provide information regarding the microphysical and optical properties of the clouds and aerosols. In this study, though, no such observations are used, but rather the more direct measurement of the scattering ratio is employed.

The sampling resolution of CALIOP is a function of altitude. To capture the spatial variability of cloud and aerosols in the lower troposphere and weak atmospheric signals of the upper troposphere, the vertical resolution at 532 nm is 30 m below 8 km and 60 m above. Correspondingly, the horizontal resolution for 532 nm below 8 km is 333 m (along track) × 75 m (cross track) and 1 km × 75 m above. CALIOP has a pulse duration of 20 ns.

The GCM-Oriented CALIPSO Cloud Product (GOCCP) observational dataset, provided by ClimServ, is used in this study. The GOCCP dataset, hereafter referred to as CALIPSO data, has been derived from CALIOP level 1B National Aeronautics and Space Administration (NASA) Langley Atmospheric Sciences Data Center CALIPSO datasets. Level 1B data profiles have been time-referenced, geolocated, and corrected for things such as offset voltage, background signals, and instrument artifacts (Winker et al. 2006). The level 1B instantaneous profiles of the lidar scattering ratios (SR) (i.e., ratio of light scattered by particles to light scattered by molecules) are then averaged onto a GCM grid (Chepfer et al. 2008). Upscaling of CALIPSO, and similarly CloudSat, observations onto a GCM grid resolution (40 levels, 2° × 2°) is necessary as the narrow swaths of the observations represent a 2D slice within a 3D GCM grid box. Finally, cloud diagnostics are then inferred from the profiles (Chepfer et al. 2010).

b. CloudSat

CloudSat has an onboard 94-GHz, near-nadir millimeter-wavelength cloud radar that probes the atmosphere and provides a vertical profile of clouds and precipitation. Cloud and precipitation particles, as in Marchand et al. (2009), will henceforth be collectively referred to as hydrometeors. With a pulse of approximately 3.3 µs, a hydrometeor’s reflectivity can be measured from the power of the backscattered radar beam as a function of distance from the radar. The measured hydrometeor reflectivities have a vertical resolution of ∼480 m and a horizontal resolution of 1.7 km (along track) × 1.4 km (cross track).

The CloudSat data, also provided by ClimServ, are based upon the operational CloudSat Geometric Profile dataset 2B-GeoProf (GeoProf). GeoProf data contain a hydrometeor detection mask (indicating the likelihood of hydrometeor presence and the probability of false
detection), the radar reflectivity, and estimation of gas absorption due to oxygen and water vapor (Marchand et al. 2008). Because CloudSat operates at a shorter wavelength than most weather radars, it is possible for CloudSat to become fully attenuated or have the measured return power be dominated by multiple scattering by hydrometeors (Mace et al. 2007; Marchand et al. 2008). A minimum detectable signal of approximately \(-30 \text{ dBZ}_e\) and the lowest 1 km of reflectivities are discarded because of ground clutter following Tanelli et al. (2008) and Marchand et al. (2008).

4. Satellite simulators

This study employs version 1.2.1 of the COSP that includes several satellite simulators, of which only the CALIPSO lidar simulator (ACTISM; Chepfer et al. 2008) and the CloudSat radar simulator (QuickBeam; Haynes et al. 2007) are used. Satellite simulators facilitate the comparison of clouds simulated by climate models with satellite observations by using a common definition of cloud fraction (Chepfer et al. 2010). Taking atmospheric profiles of modeled variables, such as temperature, pressure, cloud water content, and cloud fraction, satellite simulators then mimic the observations, including cloud overlap and instrument sensitivity, to produce a cloud field consistent with satellite observations. Specifically, each model grid column is divided into \(n\) subcolumns (here \(n = 50\)). In each subcolumn, the hydrometeor (cloud) fraction is assigned as either zero or one, such that the average over all subcolumns equals the modeled grid-averaged hydrometeor (cloud) fraction (Klein and Jakob 1999; Chepfer et al. 2008). Among the cloudy subcolumns of each grid box, the liquid and ice are divided equally assuming a constant in-cloud water–ice content (Klein and Jakob 1999).

To identify which clouds are visible from the top of the atmosphere (TOA) from those that are obscured by higher clouds, the model’s maximum-random cloud-overlap assumption is employed. From that point, the optical properties of the clouds are derived and the lidar scattering ratio and radar reflectivities are computed.

It should be noted the QuickBeam radar simulator includes the following assumptions, which need to be taken into consideration when interpreting the results. First, all hydrometeors, including ice crystals, are assumed spherical. Ice crystals are modeled using the maximum dimension as the diameter of the sphere. To account for the highly variable nature of ice crystal shape, density, index of refraction, and existence within mixed-phase clouds, the effective density and index of refraction are reduced to represent a mixture of ice with air following Liu (2004) (Haynes 2007; Haynes et al. 2007). Second, a lognormal distribution is assumed for the hydrometeors. The distribution is defined in terms of particle radius for consistency with the CloudSat 2B-LWC algorithm (Haynes 2007). Also, multiple scattering effects are assumed to be negligible as they only play a role when the rain rate exceeds 3 mm h\(^{-1}\) (Battaglia and Simmer 2008; Marchand et al. 2009). Large errors in reflectivity may be expected when simulating precipitation intensities greater than a few millimeters per hour.

The microphysical assumptions necessary to compute the scattering ratios and reflectivities are consistent with those in ECHAM5’s radiation scheme (Boucher and Lohmann 1995; Moss et al. 1996). Aerosols are not considered for either lidar or radar simulators, and precipitation does not affect the simulated lidar signal. From the lidar scattering ratios and radar reflectivities, summary statistics comparable to the satellite products are also computed. For the CALIPSO simulator, in particular, a cloud fraction is defined as the ratio of subcolumns with scattering ratios larger than 5, relative to all subcolumns where the lidar signal is not yet attenuated.

Simply put, satellite simulators strive to diagnose the quantities as would be seen by the satellite if it were flying above an atmosphere similar to that predicted by the model (Chepfer et al. 2010). Since the definition of clouds and cloud types differ among satellite observations and climate models, a direct comparison could be misleading. One would be comparing the total environment modeled with the limited environment to which a satellite instrument is sensitive. Satellite simulators allow for a more consistent comparison. This study is the first to make use of active spaceborne lidar and radar observations, as well as their simulators, in the evaluation of ECHAM5.

5. Results

Active satellite observations now provide a global picture of the vertical structure of clouds, improving the comparison between the vertical distribution of clouds between models and observations. In this study, references to high-, mid-, and low-level clouds refer to clouds within the following intervals:

- **High**
  - \(\text{p}_{\text{top}} < 440 \text{ hPa}\)
  - \(z > 7.2 \text{ km}\)

- **Mid**
  - \(680 \text{ hPa} > \text{p}_{\text{top}} \geq 440 \text{ hPa}\)
  - \(3.5 < z < 7.2 \text{ km}\)

- **Low**
  - \(\text{p}_{\text{top}} \geq 680 \text{ hPa}\)
  - \(z < 3.5 \text{ km}\)

where \(\text{p}_{\text{top}}\) denotes cloud-top pressures and \(z\) is cloud-top height above sea level.

The total, high-, mid-, and low-level cloud covers from the CALIPSO observations are compared with those
TABLE 1. Total, high-, mid-, and low-level global-mean cloud cover (%) for JJA 2007 average.

<table>
<thead>
<tr>
<th>Cloud Layer</th>
<th>CALIPSO</th>
<th>ECHAM5 with CALIPSO simulator</th>
<th>ECHAM5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>67.1</td>
<td>62.1</td>
<td>63.7</td>
</tr>
<tr>
<td>High level</td>
<td>32.1</td>
<td>38.0</td>
<td>40.7</td>
</tr>
<tr>
<td>Midlevel</td>
<td>19.1</td>
<td>11.2</td>
<td>21.2</td>
</tr>
<tr>
<td>Low level</td>
<td>37.6</td>
<td>29.9</td>
<td>37.6</td>
</tr>
</tbody>
</table>

modeled by ECHAM5 and emulated with the lidar simulator in Table 1 in terms of global seasonal-mean values. The values for total cloud cover presented in Table 1 appear very similar; however, CALIPSO observes slightly more clouds than modeled by ECHAM5. Interestingly, the total cloud cover of CALIPSO is greater than ECHAM5 despite the fact that at each level, ECHAM5 has more clouds than CALIPSO. CALIPSO’s greater total cloud cover implies that the clouds modeled by ECHAM5 overlap one another, more so than in the observations. This is alluded to in the cloud fraction derived by the lidar simulator. When processed with the lidar simulator, the model shows fewer clouds than diagnosed without a simulator in ECHAM5, particularly so as one moves down the levels. The differences in cloud fraction between the standard model diagnostics and the one processed via the lidar simulator are likely due to a combination of two factors. The first factor is that the standard diagnostics in ECHAM5 defines a cloud wherever some condensate is present in a grid box, while the lidar simulator, consistent with the observations, defines a cloud only if the scattering ratio exceeds 5 in any subcolumn. Thus, the model-diagnosed cloud fraction can be larger than the one processed by the lidar simulator if the clouds are sufficiently optically thin. The second factor is attenuation of the lidar signal by the clouds. Excessive attenuation of the lidar signal can occur wherever the amount of high-level clouds is overestimated, as can be seen in Table 1, or if the scattering ratio exceeds 5 in any subcolumn. Thus, the model-diagnosed cloud fraction can be larger than the one processed by the lidar simulator if the clouds are sufficiently optically thin. The second factor is attenuation of the lidar signal by the clouds. Excessive attenuation of the lidar signal can occur wherever the amount of high-level clouds is overestimated, as can be seen in Table 1, or if the clouds are optically too thick. A more detailed study of the high-, mid-, and low-level clouds, presented in Table 1 will be done in the following sections.

a. Zonal-mean cloud and hydrometeor fraction

The zonal mean hydrometeor fraction, as diagnosed from the lidar and radar on board CALIPSO and CloudSat, respectively, are compared with simulation results in Fig. 1 for JJA 2007. It should be noted that both CALIPSO and CloudSat are near-nadir pointing on an inclined orbit and as such do not obtain full polar coverage. Additionally, the lowest 1.2 km of the CloudSat observations should not be taken into consideration because of ground clutter.

The analysis of the zonal hydrometeor fraction is done here separately for the lidar and radar. In the case of lidars, the hydrometeor fraction can be equated with cloud fraction as the lidar signal becomes attenuated within optically thick clouds. The threshold for cloudiness is taken, such that even optically thick aerosol layers cannot be mistakenly defined as cloud; in the model, aerosols are not considered. The lidar hydrometeor fraction is defined as ice or liquid particles with a scattering ratio >5 (Chepfer et al. 2010). Comparably, the radar hydrometeor fraction includes liquid and ice cloud particles, as well as liquid and ice precipitation, with radar reflectivities of >–27.5 dBZc following Marchand et al. (2009). The radar hydrometeor fraction in each layer is defined by the number of positive identifications with reflectivity >–27.5 dBZc, divided by the total number of measurements in that layer (Bodas-Salcedo et al. 2008).

1) LIDAR CLOUD FRACTION

The zonal hydrometeor fraction derived from the CALIPSO observations and the lidar simulator is shown in Figs. 1a and 1b, respectively. These two plots are compared with the simulated cloud fraction diagnosed without the lidar simulator (Fig. 1c).

From the CALIPSO observations, among other details, three distinct features can be identified: the high-level clouds in the intertropical convergence zone (ITCZ), the cloud-free subsiding branches of the Hadley cell, and boundary layer clouds in the subtropics (Fig. 1a). Generally, the high-level clouds observed over all latitudes, including those in the ITCZ, are sufficiently thin, or occur rarely enough, to allow the lidar to penetrate deep into the atmosphere, capturing clouds in the boundary layer. In contrast, the lidar simulator shows ECHAM5 overestimates the zonal mean cloud fraction of all high-level clouds locally by up to a factor of 2 (Fig. 1b). The overestimation of high-level clouds in ECHAM5 can be attributed to two factors. The first factor stems from the fact vertical transport of moisture in ECHAM5 is mainly due to convection. The Tiedtke (1989) convective scheme used in ECHAM5 assumes a constant moisture flux in the subcloud layer, overestimating the mass flux at cloud base, and as a result forms cumulus anvils (Neggers et al. 2004). The second factor is an underestimation of detrainment. Gehlot and Quaas (2012) concluded for tropical clouds, the convection parameterization in ECHAM5 does not sufficiently allow for the detrainment at the midlevels but rather transports an excessive amount of water vapor to the high levels before it detrains. As a result, deep convection transports up too much mass, overestimating the cirrus clouds, which take much longer to sediment and evaporate out. The global overestimation of high-level cloud cover, presented in Table 1, shows the lidar simulator finds an overestimation in ECHAM5’s
global mean by ~20% compared with CALIPSO. Evidently, areas in which high-level clouds are significantly overestimated in ECHAM5 are balanced by regions of largely underestimated cloud cover.

A comparison of the lidar-diagnosed cloud fraction and modeled cloud fraction, Figs. 1b and 1c, respectively, demonstrates the lidar simulator does not detect all of the high-level clouds modeled by ECHAM5. As previously mentioned, hydrometeors that return a SR < 5 are not diagnosed by the lidar simulator as clouds, as in the case of the stratospheric clouds in the Southern Hemisphere (Figs. 1b and 1c). Regardless, the altitude of the highest cloud tops in ECHAM5 is slightly higher than seen in the CALIPSO observations.

The overestimation in high-level clouds, as seen in Fig. 1c and Table 1, causes the simulated lidar signal to attenuate too frequently, contributing to the underestimation of mid- and low-level clouds seen in Table 1. Frequent attenuation of the lidar signal within the satellite simulator limits the analysis of low-level clouds in regions where high-level clouds are abundant. The frequency of occurrence of lidar attenuation, in comparison to satellite observations, will be studied in section 5b. As such, the radar simulator, presented in section 4, is a very useful complement to study the zonal hydrometeor fraction in ECHAM5, particularly in regard to lower-level clouds.

The midlevel clouds modeled by ECHAM5, such as those in the ITCZ and the storm tracks, vanish when processed by the lidar simulator. Here, the lack of clouds detected by the lidar simulator is most likely due to a shielding by too abundant–too optically thick overlying clouds.

Low-level clouds in ECHAM5 are underestimated in the (sub)tropics compared with the observations, particularly the marine boundary layer stratocumulus and shallow cumulus clouds. Those that are modeled are seen in both model diagnostics as occurring too low in the atmosphere (seemingly only in the two lowest model levels, whereas the observations show nonnegligible amounts up to ~2 km).

2) RADAR HYDROMETEOR FRACTION

As with the CALIPSO observations, the zonal hydrometeor fraction from the CloudSat observations clearly show the ITCZ and cloud-free subsiding branches of the Hadley cell (Fig. 1d). It is evident from the comparison of Figs. 1a and 1d that the cloud radar shows a greater fraction of hydrometeors than the lidar at lower
altitudes. This is because the radar signal does not attenuate as easily as the lidar signal, although the radar may still be attenuated by large water droplets and precipitation.

The radar simulator shows ECHAM5 captures the large-scale features, including the ITCZ and subsidence branches, within the Hadley cell. In addition, ECHAM5 is able to capture these spatial maxima, including those in the Southern Hemisphere, the ITCZ, and boundary layer (Fig. 1e). The hydrometeor fraction in ECHAM5, however, is overestimated compared with satellite observations (Fig. 1d). To determine whether the overestimation in hydrometeor fraction is due to clouds or precipitation, or a combination of both, a distinction between their contributions to the hydrometeor fraction must first be made. A comparison of Figs. 1e and 1c shows most of the hydrometeor fraction in the ITCZ below ∼4 km is due to the precipitation modeled in ECHAM5 as there are few clouds modeled in that region visible to the radar. In areas where clouds and precipitation coexist, their respective contribution to the hydrometeor fraction is not easily distinguished as radar reflectivities are dominated by the largest particles. Rain and drizzle particles with diameters on the order of ∼2 mm will easily dominate the radar signal despite the presence of numerous smaller cloud droplets, which are on the order of ∼0.02 mm in diameter. A sensitivity experiment, for the period of July 2007, was performed in which the convective and large-scale precipitation were restricted from entering the radar simulator, thereby isolating the contribution by clouds to the radar signal. The results of the sensitivity experiment show the radar simulator no longer produced reflectivities greater than −10 dBZ. Therefore, it can be concluded that radar reflectivities in ECHAM5 between −27.5 dBZ (the lower limit of radar reflectivity) and −10 dBZ (maximum reflectivity without precipitation) are predominantly clouds and very light precipitation. The fraction calculated using this definition is shown in Fig. 1f.

A comparison of Figs. 1d and 1f clearly shows ECHAM5 lacks clouds in the tropical and subtropical mid- and low levels, yet there is clearly an overestimation in the hydrometeor frequency. This indicates the overestimation in hydrometeor fraction in altitudes lower than ∼4 km is due to the contribution by precipitation. In the boundary layer, the frequency of occurrence of precipitation in the model is severely overestimated by the model, especially in the Northern (summer) Hemisphere. The precipitation belts are much too broad in the model.

A comparison of the cloud fraction derived from the radar simulator (Fig. 1f) differs from the originally modeled cloud fraction in ECHAM5 (Fig. 1c) as the radar is unable to detect the optically thinnest clouds. Regardless, the high-level cloud fraction derived from the radar simulator agrees very well with satellite observations in terms of its general shape. It is interesting to note the height of the uppermost clouds is substantially underestimated by the model (Figs. 1e and 1f) when processed with the radar simulator compared with the CloudSat observations (Fig. 1d). Very high clouds are invisible to the radar, because they consist of relatively small particles and are optically thin. A comparison of the lidar and radar satellite observations (Figs. 1a and 1d) demonstrates the radar detects cloud-top heights at lower altitudes than the lidar. This difference in cloud-top height among the lidar and radar is much more pronounced in ECHAM5. This suggests the particles in ECHAM5’s highest-level clouds are so small the radar is unable to detect the optically thinnest clouds. Regardles, the high-level cloud fraction derived from the radar simulator agrees very well with satellite observations in terms of its general shape. It is interesting to note the height of the uppermost clouds is substantially underestimated by the model (Figs. 1e and 1f) when processed with the radar simulator compared with the CloudSat observations (Fig. 1d). Very high clouds are invisible to the radar, because they consist of relatively small particles and are optically thin. A comparison of the lidar and radar satellite observations (Figs. 1a and 1d) demonstrates the radar detects cloud-top heights at lower altitudes than the lidar. This difference in cloud-top height among the lidar and radar is much more pronounced in ECHAM5. This suggests the particles in ECHAM5’s highest-level clouds are so small the radar does not detect them. The comparison of Figs. 1e and 1f shows precipitation does not play a role at these altitudes.

b. Cloud regime analysis

The lidar joint cloud altitude–scattering ratio histograms and radar joint cloud altitude–reflectivity histograms, commonly known as contour frequency by altitude diagrams (CFADs), will be studied for four different regions (Fig. 2). These regions, as defined in Webb et al. (2001), include the North Pacific frontal region (30°–60°N, 160°E–140°W), the Hawaiian trade cumulus (15°–35°N, 160°E–140°W), the California stratocumulus 15°–35°N, 110°–140°W), and the tropical west Pacific (5°–20°N, 70°–150°E). Each region has a different cloud regime affiliated with it, and as such distinct lidar and radar signals can be expected.

To avoid redundancy an in-depth analysis will be presented for the California stratocumulus regime, followed by a brief discussion of the other three regions. The California stratocumulus region, residing under large-scale subsidence conditions, generally has few high-level clouds to obscure the mid- and low-level clouds, providing an ideal scenario to maximize the depth in which the lidar and radar can penetrate the
atmosphere. Many of the conclusions found in the California stratocumulus region apply to the other regimes.

In the following section, a comparison of the lidar joint cloud altitude–scattering ratio histograms of CALIPSO observations and ECHAM5 will be presented. The lidar scattering ratio histograms allow for an evaluation of cloud properties, such as optical thickness, cloud altitude, and frequency of occurrence, in the model. Lidar scattering ratio histograms for JJA 2007 (Fig. 3) show the frequency of occurrence of clouds and aerosols within 15 different SR bins (x axis) plotted as a function of height (y axis). The SR bin intervals, as stated in Chepfer et al. (2008), indicate

\[
\begin{align*}
    \text{SR} &< 0.01 \quad \text{laser signal fully attenuated} \\
    0.01 < \text{SR} &< 1.2 \quad \text{clear sky} \\
    1.2 < \text{SR} &< 5 \quad \text{unclassified} \\
    5 < \text{SR} &\quad \text{cloudy}.
\end{align*}
\]

The scattering ratio is a function of the particle size distribution and the particle radius. Clouds with SR > 60 are associated with optically thick clouds, while clouds with SR < 20 are deemed optically thin (Chepfer et al. 2008). The two intervals of interest in this analysis are those with scattering ratios <0.01 and scattering ratios >5, which denote lidar attenuation and cloud detection, respectively. Scattering ratios between these thresholds occur frequently in reality due to the presence of aerosols and very small hydrometeors. To avoid false identification of aerosols as clouds, a threshold of SR >5 is used to differentiate between clouds and aerosols. In the model, aerosols are not considered. Since the focus of this evaluation is on the cloud and precipitation parameterizations, this simplification is justified. Frequencies of occurrence are determined by normalizing the histogram, such that the frequencies for each altitude sum to unity.

Complementing the lidar scattering ratio histograms are the radar joint cloud altitude–reflectivity histograms

Fig. 3. Lidar cloud altitude-scattering ratio histogram for JJA 2007 for (a) California stratocumulus with (left) CALIPSO data and (right) ECHAM5 with CALIPSO simulator, similarly for (b) Hawaiian trade cumulus, (c) North Pacific, and (d) tropical west Pacific. Note that scattering ratios between 0.01 and 5 in reality occur often due to the presence of aerosols, which are not considered in the model.
of CloudSat and ECHAM5, with the CloudSat simulator presented in Fig. 4. The radar is able to probe much deeper into the atmosphere before becoming attenuated in comparison to the lidar, and as such the radar reflectivity histograms offer more details in regard to the frequency of optically thicker clouds and (light) precipitation. The large-scale and convective precipitation fluxes from ECHAM5 at each grid point are passed into the radar simulator, alongside the cloud liquid and ice water content, to determine the radar reflectivity based upon a lognormal distribution.

The radar reflectivity histograms, for JJA 2007 of the four aforementioned cloud regimes, show the frequency of occurrence of clouds every 480 m from 0 to 19.2 km for specific reflectivity intervals (from $-30$ to 20 dBZ$_e$). The histograms are normalized such that the frequency of occurrence for each altitude sums to one. Each radar reflectivity histogram can be divided into four regions of interest: precipitating and nonprecipitating, liquid water, and ice hydrometeors. These four regions can be roughly divided by altitude and radar reflectivity. Above 5 km the hydrometeors are predominantly made of ice, whereas below 5 km they are mainly liquid (Marchand et al. 2009). Hydrometeors, following Bodas-Salcedo et al. (2008) and Marchand et al. (2009), are characterized as particles with radar reflectivities $> -27.5$ dBZ$_e$. Below this threshold of $-27.5$ dBZ$_e$, the likelihood of false detection increases as the limits of radar sensitivity are approached (Marchand et al. 2008). As discussed in section 5a, radar reflectivities $< -10$ dBZ$_e$ generally indicate nonprecipitating hydrometeors, while $\geq -10$ dBZ$_e$ indicate precipitating hydrometeors. Recall radar reflectivity is sensitive to large particles, as such nonprecipitating clouds may exist though the returned reflectivity is within the precipitating region of the histogram.

1) CALIFORNIA STRATOCUMULUS

In the California stratocumulus region, both CALIPSO and CloudSat observations show a clear separation of high-level, optically thin cirrus clouds and low-level, optically thick stratocumulus clouds (Figs. 3a and 4a). Very few midlevel clouds are observed. Both CALIPSO and CloudSat show the greatest frequency of clouds occur in the boundary layer. The majority of these boundary layer clouds have high scattering ratios (i.e., are optically thick), although a wide range of lidar scattering ratios is also exhibited. These same clouds produce low to moderate reflectivities, with the greatest frequency of occurrence within the nonprecipitating quadrant of the radar reflectivity histogram.
Comparison of the satellite observations with ECHAM5, processed with the lidar and radar simulators, shows the model captures the bimodal peak in high- and low-level hydrometeors, best evident in the radar reflectivity histogram. Two striking features that appear in the comparison with observations and model results include (i) the lidar scattering ratios and frequency of occurrence of high-level cirrus clouds in ECHAM5 are overestimated; and (ii) throughout most of the tropospheric column, hydrometers in ECHAM5 frequently lie within the precipitating half of the radar reflectivity histogram, compared with the nonprecipitating regime found in observations.

The clouds in ECHAM5, as diagnosed by the lidar simulator, show high-level clouds spanning a wide range of altitudes and having a large range of scattering ratios. Most of these high-level clouds have much larger scattering ratios than those observed. ECHAM5 has a peak scattering ratio of high-level clouds between 30 and 40, whereas the peak in CALIPSO, though less pronounced and higher in altitude, lies between 10 and 15. The overestimation in optical thickness of high-level clouds implies ECHAM5 either underestimates the effective radius cloud ice and liquid water droplets or overestimates the cloud water content.

It is important to ensure that the effective radius of liquid water droplets and ice crystals in ECHAM5 are realistic. For a given cloud water content, smaller particles have larger scattering cross sections. Artificially small particles would produce large scattering ratios, causing the lidar signal to attenuate high in the atmosphere, as is seen in Fig. 3a. In ECHAM5, the particle number concentration is prescribed and as such, particle size is governed by liquid and ice water content. The JJA 2007 global average of ECHAM5’s liquid water droplet effective radius ranges from \( \sim 4 \) to \( 5.5 \) \( \mu \)m and ice crystal effective radius ranges from \( \sim (10–14.5) \) \( \mu \)m. This compares to measurements from both continental and marine stratuscumulus clouds with liquid water particles with effective radii ranging from \( \sim (4 \text{ to } 12) \) (Frisch et al. 2002) and \( \sim (20 \text{ to } 100) \) \( \mu \)m for ice (Wyser 1998). The effective radii of liquid particles in ECHAM5 are within the measured range, though leaning toward the lower end. The effective radii of ice particles in ECHAM5 are much lower than those measured. The underestimation in ice crystal effective radius likely explains why the highest-altitude clouds modeled by ECHAM5 appear in abundance in the lidar scattering ratio histogram, yet remain undetected by the radar simulator. In the radar reflectivity histogram, the highest-level of clouds appear much too low in the atmosphere, as well as too frequent, compared with radar observations. A sensitivity experiment will be presented in section 5d, in which the impact of assumed ice crystal effective radii will be studied.

### Table 2. Simulated regional large-scale and convective precipitation (mm day\(^{-1}\)) for JJA 2007.

<table>
<thead>
<tr>
<th></th>
<th>California stratocumulus</th>
<th>Hawaiian shallow cumulus</th>
<th>North Pacific</th>
<th>Tropical west Pacific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective</td>
<td>0.45</td>
<td>1.86</td>
<td>0.27</td>
<td>8.86</td>
</tr>
<tr>
<td>Large scale</td>
<td>0.40</td>
<td>0.57</td>
<td>2.50</td>
<td>2.88</td>
</tr>
</tbody>
</table>

A cloud’s optical properties are also affected by the liquid and ice water content. The optical thickness in turn governs the depth in which the lidar and radar can penetrate the atmosphere. Within the lidar and radar simulator, the in-cloud water is used to determine the optical thickness of each column. The in-cloud water is determined by dividing the gridbox mean cloud ice and liquid water by the cloud fraction. Figure 1 demonstrates ECHAM5 overestimates the high-level clouds, implying an excessive amount of cloud ice fraction high in the atmosphere. The extent to which this influences the frequent attenuation of the lidar signal in ECHAM5 high in the atmosphere compared to observations, as seen in Fig. 3a, will be presented in a second sensitivity experiment. In the second sensitivity experiment, the cloud ice content of high-level clouds is reduced and the impact of high-level cloud optical thickness on the lidar attenuation will be studied (section 5d). It should be noted that within ECHAM5, the cloud liquid and ice water are multiplied by an inhomogeneity factor of 0.7 and 0.8, respectively, before they are passed into the radiation scheme. The inhomogeneity factor accounts for subgrid variability (e.g., clouds are not rectangular boxes and as such the cloud liquid and ice water are lower in some regions). The satellite simulators do not take this inhomogeneity factor into account. The simulators take the modeled liquid and ice water mixing ratio directly, accounting for subgrid variability using a sub-column generator [Subgrid Cloud Overlap Profile Sampler (SCOPS; Klein and Jakob 1999)]. Thus, the clouds seen by the radiation scheme in ECHAM5 are optically thinner than those entering the satellite simulators. One must be aware that the satellite simulator explicitly determines what is implicitly taken into account in ECHAM5. In the future, it would be important to make this consistent and determine the difference between assuming the subcolumn liquid and ice water content of a grid box compared to the inhomogeneity factor.

In the corresponding radar reflectivity histogram, Fig. 4a, ECHAM5 shows a greater frequency of precipitation compared to observations. Precipitation in ECHAM5 is separated into two forms: convective or large-scale precipitation. Table 2 presents the regional
contribution of convective and large-scale precipitation rates. Though convective precipitation dominates the surface precipitation rate, the extent to which its frequency contributes to the radar reflectivity histogram is not as obvious, since the frequency of occurrence of convective precipitation may be lower. A sensitivity experiment isolating the contribution of convective precipitation to the radar reflectivity histograms demonstrated midlevel reflectivities are mainly caused by large-scale precipitation rather than convective precipitation. Within ECHAM5, the high- and midlevel large-scale precipitation are formed via the ice phase as the result of the sedimentation of ice crystals, accretion, or aggregation processes. As previously mentioned, the moisture available to these processes stems, to a large extent, from the convective mass flux that transports moisture to the upper atmosphere in the regions investigated here (except for the North Pacific region, where synoptic circulation plays a large role as well). It is possible that an excessive amount of moisture brought up to the upper atmosphere was transported horizontally to cover the Hawaii and California regions before sedimenting out. Clearly, the precipitation flux throughout the model’s troposphere, which is not seen in observations, poses a problem.

Hagemann et al. (2006) demonstrated that the zonal and global distribution pattern of accumulated surface precipitation in ECHAM5 agrees well with the Climate Prediction Center Merged Analysis of Precipitation global annual mean precipitation climatologies from 1979 to 1999 (Xie and Arkin 1997). Thus, it can be concluded that the frequency of precipitation is too high but is balanced by an intensity of precipitation that is too low. This conclusion is consistent with the results of the study by Dai (2006), which states GCMs, including ECHAM5, generally underestimate the contribution and frequency of heavy (>20 mm day$^{-1}$) precipitation and overestimate light (<10 mm day$^{-1}$) precipitation. Stephens et al. (2010) found the surface accumulated precipitation of five different models matched CloudSat observations over the oceans; however, the frequency of precipitation occurred nearly twice as often as that in CloudSat observations.

The frequent lidar attenuation by high-level clouds in ECHAM5 imposes a caveat on conclusions drawn regarding the modeled low-level clouds. While the lidar scattering ratio histograms provide a rich source of information regarding the high-level clouds, they must be used with caution when evaluating low-level clouds until the scattering ratios of high-level clouds in ECHAM5 are improved. Nevertheless, one can still draw conclusions regarding mid- and low-level clouds by combining the lidar and radar simulator results. It is evident that the midlevel cloud amount is underestimated in ECHAM5 in comparison with the lidar observations. The few midlevel clouds modeled have lidar scattering ratios at the upper end of the spectrum, in stark contrast to the observations, which show midlevel clouds only at the low end of the spectrum. In regard to the low-level clouds in ECHAM5, the radar simulator suggests the overall amount is strongly underestimated as well as too low in the atmosphere. The scattering ratios of these low-level clouds modeled by ECHAM5 are concentrated in the largest bins, while the observations show a broad range of scattering ratios. In reality, California stratocumulus clouds obviously show a broad range in reflectivities, thus a large heterogeneity in water concentrations. Comparably, ECHAM5 has a very narrow distribution of water contents, though too much where present. To simulate clouds to better match observations, ECHAM5 must produce many more clouds with a much broader range in water contents.

2) HAWAIIAN SHALLOW CUMULUS

Similar to the California stratocumulus region, CALIPSO and CloudSat show low-level boundary layer clouds underlying high-level cirrus clouds in the Hawaiian shallow cumulus region (Figs. 3b and 4b). The high-level cirrus clouds over the Hawaii region occur in a greater abundance, as well as have larger scattering ratios and reflectivities compared to the California cirrus in Figs. 3a and 4a. The separation of high cirrus over the shallow cumulus is not as distinct as in the California stratocumulus region, particularly so in the CloudSat observations. The midlevel hydrometeors detected by CloudSat can be broken into two distinct groups: low intensity reflectivities (i.e., nonprecipitating clouds) and high intensity reflectivities (i.e., precipitation flux). In the boundary layer, CALIPSO and CloudSat show that clouds occur slightly higher in the atmosphere and are optically brighter compared to the California stratocumulus region. Although the CloudSat radar reflectivity histogram shows a greater frequency of precipitation compared with the California region, the greatest frequency of hydrometeor occurrence remains in the nonprecipitating quadrant.

In general, ECHAM5 captures the increase in cirrus cloud amount as well as the increase in brightness compared with the California stratocumulus region. The cirrus clouds in ECHAM5, however, have significantly greater lidar scattering ratios and frequency of occurrence compared with those observed. Correspondingly, the lidar signal attenuates high in the atmosphere much too often. Simultaneous evaluation of the lidar scattering ratio and radar reflectivity histograms indicated the frequent attenuation of the lidar signal in ECHAM5, around 7 km, is also likely influenced by the frequent
occurrence of precipitation evident in the radar reflectivity histogram. In contrast to the observations, the radar simulator does not identify nonprecipitating midlevel clouds in ECHAM5. The lack of midlevel clouds in the Hawaiian shallow cumulus regime may be due to midlevel clouds mainly formed by convection. As previously mentioned, ECHAM5 does not allow for sufficient detrainment at midlevels, causing convective clouds to reach high in the atmosphere before detraining and contributing to the cloud cover. The fact that only stratiform clouds contribute to the cloud cover implies all clouds seen by radiation, and thereby the lidar and radar simulator, have homogeneous cloud properties (i.e., the PDF of in-cloud water is narrow). This homogeneity factor may be why the lidar simulator finds modeled clouds generating only large scattering ratios. The satellite observations, despite the tendency toward optically thick clouds, show a wide distribution of scattering ratios. New parameterization approaches simulating a spectrum in shallow convection may improve upon the current representation of only stratiform clouds. The assignment of a cloud fraction and optical properties to shallow cumulus clouds may improve the comparison with observations.

Comparison with radar observations shows ECHAM5 captures the general reflectivity structure, although precipitation frequently dominates mid- and low-level radar reflectivities in ECHAM5. Nonprecipitating low-level clouds appear lower in the atmosphere compared with observations, and they have lower reflectivities and show a narrower range of reflectivities.

3) NORTH PACIFIC

As presented in Chepfer et al. (2010), the CALIPSO lidar scattering ratio histogram, and similarly the CloudSat radar reflectivity histogram, of the North Pacific shows optically thick, frontal clouds extending vertically throughout the atmosphere up to about 7 km along with a large amount of optically thin high-level clouds extending up to the tropopause (Figs. 3c and 4c).

In ECHAM5, clouds detected by the lidar simulator in the North Pacific have a similar scattering ratio structure as the Hawaiian clouds, though they are lower in the atmosphere. For low- and midlevel clouds, the range of scattering ratios simulated is far too narrow and biased toward high values compared to CALIPSO. Midlevel clouds in ECHAM5 are not as optically thick as those found in the distinct peak of CALIPSO’s midlevel clouds. The radar simulator shows few midlevel nonprecipitating clouds, of which the satellite observations show an abundance. Compared to the California and Hawaii regions, both CloudSat observations and ECHAM5 show a greater frequency of precipitation, though the frequency of precipitation in ECHAM5 is greatly overestimated. The radar histograms indicate future revisions of the cloud and precipitation parameterizations in ECHAM5 should include an increase in precipitation intensity, thereby reducing the frequency of precipitation while maintaining the accumulated precipitation.

4) TROPICAL WEST PACIFIC

In comparison to the other three cloud regimes, the ECHAM5 model agrees best with CALIPSO and CloudSat observations in the region of deep convection (Figs. 3d and 4d). Deep convection, as seen in the CALIPSO observations, have a substantial amount of high-level clouds with large scattering ratios. Chepfer et al. (2010) concluded that the secondary maxima in the CALIPSO observations in the midtroposphere (5–9 km) were due to the large abundance of thick congestus clouds over this region and that the low-level clouds (below 3 km) were associated with shallow cumulus clouds. Because of the abundance in high-level, optically thick clouds in the tropics, the lidar scattering ratio histograms of CALIPSO and ECHAM5 have the greatest agreement.

The radar reflectivity histogram in the tropical west Pacific has a greater vertical distribution of hydrometeors, over all reflectivities, compared with the other three cloud regimes. Similar to the CloudSat observations, ECHAM5 shows a distribution of hydrometeors over all altitudes; however, the precipitating hydrometeors dominate the radar reflectivity. This may be related to overactive convection as proposed by Marchand et al. (2009) and the excessive mass flux transport to higher levels by the Tiedtke (1989) convective scheme. Based on the ground-based observations of tropical convective precipitation used in Mather et al. (2007), simulated radar reflectivities above 0 dBZ are indicative of convective rainfall. Radar attenuation by rainfall explains the decrease in reflectivity below the freezing level, which lies at ~5 km in the tropics (Bodas-Salcedo et al. 2008).

In addition, the vertical extent to which these high-level clouds penetrate is excessively high in the atmosphere. Disregarding the highest-level clouds, which are modeled yet remain undetected by the lidar simulator, cloud tops exceed heights of 16 km in the lidar simulator—far higher than observations. These results suggest that in the tropics, which are dominated by deep convection, the model’s convection parameterization should be revised to allow for more clouds to form with tops at midlevels (up to 7 km) and to transport less water into the upper troposphere as overshooting appears excessive.
c. Cloud radiative forcing

In section 5b the clouds in ECHAM5 were shown to differ from CALIPSO and CloudSat, independent of cloud regime, in two ways. They include an overestimation of high-level, optically thin clouds and an overestimation of boundary layer cloud optical thickness. To understand the impact of these two properties on the radiative budget, the modeled cloud radiative forcing (CRF) at the top of the atmosphere for a given cloud cover interval is evaluated against observations in Fig. 5.

For the observational cloud radiative forcing, the Clouds and the Earth’s Radiant Energy System (CERES) dataset, specifically defined for the Coupled Model Intercomparison Project, phase 5 (CMIP5), has been chosen. The CERES CMIP5 radiative data are based on the level 4 Energy Balance and Filled (EBAF) product, implying the global net TOA fluxes are balanced and constrained to the ocean heat storage and the clear-sky fluxes have been spatially interpolated in nonobserved regions (Loeb et al. 2008). Using monthly averages of the CERES CRF, on a \(1^\circ \times 1^\circ\) grid, in combination with the CALIPSO total cloud cover, one can determine the average CRF at the top of the atmosphere for a given total cloud cover. In a similar manner, the CRF of the model is calculated above each modeled grid point within a given total cloud cover interval defined by the lidar simulator. In addition to studying the CRF above total cloud cover, the CRF is also calculated for “only” low-level cloud cover conditions, which are defined as points where high- and midlevel cloud cover deduced by CALIPSO and the lidar simulator are <0.05. The CRF above these points are analogous to that of low-level clouds, and as such one can draw conclusions about their optical properties. By comparing the CRF above total and only low-cloud conditions, one can identify compensating errors in the model.

Focusing on the California stratocumulus and Hawaiian shallow cumulus regions, the CRF of ECHAM5 is presented for JJA 2007 alongside the CRF of CERES for JJA from 2006 to 2010. The CERES observational dataset was extended to include several years to maintain a sufficiently large dataset for more robust statistics over the California and Hawaii regions.

Above the California stratocumulus region, CERES shows CRF strengthens with increasing total cloud cover, reaching a maximum of approximately \(-85\) W m\(^{-2}\) for a cloud cover of 1.0. ECHAM5 shows a similar strengthening of CRF with total cloud cover, however, for total cloud cover \(\leq 0.5\) ECHAM5 is stronger than CERES. This implies ECHAM5 has optically brighter clouds, as indicated by the lidar and radar histograms. For total cloud cover \(>0.5\), ECHAM5 has a weaker CRF than CERES. This may be explained by the frequent occurrence of high-level clouds overlying low-level clouds in ECHAM5, found in the lidar and radar histograms, which act to dampen the net CRF. Should the high- and midlevel clouds in ECHAM5 play a negligible role in the CRF above the California stratocumulus region, the CRF for total cloud conditions would resemble that of the only low-level experiment. This is not the case. When high- and midlevel clouds are removed, the only low-level CRF in ECHAM5 is much stronger than that for a given total cloud cover bin. Under only low-level cloud conditions, the CRF of ECHAM5 is much stronger than that of CERES, particularly as cloud cover nears 1.0. It can be concluded that the CRF of ECHAM5, over the California stratocumulus region, is too weak because of the high-level
clouds. It should be noted, over the California stratocumulus region, there were an insufficient number of occurrences of only low-level cloud cover <0.3 to include within the statistics.

Over the Hawaiian shallow cloud region, both CERES and ECHAM5 show a weaker strengthening of CRF with increasing cloud cover compared to the California stratocumulus region. A maximum of approximately $-60 \text{ W m}^{-2}$ is reached for a cloud cover of 1.0 in CERES. The weakening in CRF is due to the increased presence of high-level clouds, visible in both the CALIPSO and CloudSat histograms. For total cloud covers <0.5, the CRF in ECHAM5 is nearly identical to CERES. This, however, is due to compensating errors. Comparisons of CRF above total and only low-level cloud covers in ECHAM5 indicate that without high- or midlevel clouds, the CRF would be about $-20 \text{ W m}^{-2}$ stronger. High-level clouds compensate for the excessively strong CRF of low-level clouds in ECHAM5, raising the CRF to the observed range. As cloud cover increases above 0.5, the difference in low-level cloud CRF between CERES and ECHAM5 strengthens. For a given low-level cloud cover, CERES shows a weakening of CRF between the California stratocumulus and Hawaiian shallow cumulus regions, indicative of changing cloud optical properties. ECHAM5 does not capture the dimming of cloud optical thickness, producing low-level clouds with a significantly stronger CRF. Despite the excessive CRF of low-level clouds in ECHAM5, when total cloud covers >0.5 the CRF in ECHAM5 is weaker than observed in CERES. This implies ECHAM5 radiates more than it should when there are only low-level clouds, yet does not radiate enough when total cloud fractions are large.

The CRF sensitivity studies confirmed that low-level clouds in ECHAM5 are too bright and high-level clouds are too abundant. The low-level clouds in ECHAM5 are more reflective than those observed by CERES, consistent with the large lidar scattering ratios seen in the regional histograms. The frequent high-level clouds, seen in the lidar and radar histograms, have been shown to significantly dampen the CRF in ECHAM5. Taking into account the statistical weight of shallow cumulus and stratocumulus clouds over the globe, and assuming the California and Hawaii regions are representative of global boundary layer clouds, it can be seen that the errors in the CRF are not negligible.

d. Sensitivity experiments: Impact of cloud ice effective radius and cloud ice content

As previously mentioned, two sensitivity experiments were designed to study potential causes of (i) the excessively large lidar scattering ratios of clouds in ECHAM5, (ii) the overly frequent lidar attenuation in ECHAM5, and (iii) the exceptionally high altitude of attenuation in ECHAM5. In both sensitivity experiments, only diagnostics by the lidar and radar simulators are modified, while the model simulation itself is unaffected. The first sensitivity experiment doubles the effective radius of ice particles of ECHAM5 entering the simulator, such that they are in the lower range of ice effective radii presented in Wyser (1998). This experiment aims to decrease the scattering by particles and thereby the attenuated backscatter. The second sensitivity experiment reduces the cloud ice content by half in clouds entering the simulator with cloud tops with $P < 440 \text{ hPa}$. This experiment aims to reduce the optical thickness of high-level clouds to determine whether high-level clouds in ECHAM5 are indeed overestimated in terms of ice water content and to which extent they may obscure low-level clouds. These experiments are compared to CALIPSO observations and the scattering ratios derived from the standard model in Fig. 6 for the period of July 2007. Differences in the radar-simulated output compared to the standard model are presented in Fig. 7.

1) Doubling effective radius of ice

The first sensitivity experiment showed that doubling the effective radius of ice has quite a large impact on the lidar scattering ratios (Fig. 6b). The lidar scattering ratios of the high-level clouds are now much smaller than the originally derived scattering ratios (Fig. 6d) and closer to satellite observations (Fig. 6a). The peak frequency of occurrence, in high-level clouds, occurs between the scattering ratio ranges of 7 and 20, which is much closer to the observed scattering ratios of 10–15. In regard to the altitude of attenuation, the changes are very slight. There is also very little change in the frequency in which low-level clouds are detected, nor are there additional low-level clouds detected within the optically thin scattering ratio bins. It is possible that the low-level clouds in ECHAM5 suffer from a similar underestimation in effective radius size. The liquid water effective radii in ECHAM5 were near the lower end of those measured by Frisch et al. (2002). It would be interesting for future work to study whether the liquid water effective radii are underestimated in ECHAM5.

The changes to the ice crystal effective radius had very little effect on the lidar-derived cloud fraction (not shown). This is because while the scattering ratios shifted from the very high (SR > 30) values to the midrange values (SR ~ 15), the changes in scattering ratios, for the most part, remained above the cloud threshold (i.e., SR > 5).

Doubling the effective radius of ice particles also improved the problem encountered by the radar simulated zonal hydrometeor fraction (Fig. 7a).
high-level clouds modeled by ECHAM5 were not detected by the radar simulator, despite their abundance. This underestimated the altitude of cloud tops compared to satellite observations. Since radar reflectivity is a function of the number and size to the power of six of all the hydrometeors in the volume scanned, doubling the effective radius of ice crystals allowed the high-level clouds to have larger reflectivities and as a result they are now detected by the radar simulator. The results are comparable to the satellite observations.

2) REDUCING CLOUD ICE CONTENT

The second sensitivity experiment, which decreases the cloud ice content by half in clouds above 440 hPa, has a smaller effect than doubling the effective radius of ice particles. The lidar scattering ratio of high-level clouds improves slightly; however, it remains much larger than those determined by the satellite observations. The greatest impact of decreasing the optical thickness of high-level clouds affects the altitude of attenuation. The
frequency at which the lidar is able to penetrate further into the atmosphere improved. Low-level clouds are still found with a large frequency of occurrence at very large optical thicknesses. These sensitivity experiments suggest deficiencies identified for mid- and low-level clouds are useful to judge different parameterizations of these cloud types.

In regard to the radar simulator, the second sensitivity experiment reduced the optical thickness of high-level clouds and thereby the hydrometeor fraction (Fig. 7b).

6. Conclusions

With the advent of spaceborne active instruments, a richer dataset has become available for the evaluation of global models. As stated in Solomon et al. (2007, p. 608), “The better a model simulates the complex spatial patterns and seasonal and diurnal cycles of present climate, the more confidence there is that all the important processes have been adequately represented,” and so we endeavor to evaluate ECHAM5’s ability to simulate the present climate by comparing it to CALIPSO and CloudSat observations.

To compare the clouds in ECHAM5 with active satellite observations, it was essential to incorporate the Cloud Feedback Model Intercomparison Project’s Observation Simulator Package lidar and radar satellite simulators.

In the process of studying the vertical distribution of clouds in ECHAM5, we learned that ECHAM5 captures large-scale features well, for example, the intertropical convergence zone and Hadley circulation. The lidar and radar simulators, however, enabled us to clearly demonstrate several model errors. These errors include an overestimation of high-level, optically thin clouds; an underestimation of nonprecipitating clouds in midlevels and especially low-levels; and an overestimation of the precipitation frequency at all altitudes.

A comparison of the observed and simulated regional lidar joint cloud altitude–scattering ratio histograms was performed for four different cloud regimes. CALIPSO observations showed a distinct pattern for each cloud regime, yet this is not captured by the model results processed by the lidar simulator. ECHAM5 consistently produced clouds with much greater scattering ratios than shown in the satellite observations. The high scattering ratios in ECHAM5 for the high-level clouds could be attributed, at least partially, to an underestimation of the ice crystal effective radius, as demonstrated in a sensitivity study. A study of the cloud radiative forcing over the California and Hawaii regions has shown ECHAM5 overestimates the CRF where only low-level clouds occur and underestimates the CRF when total cloud fractions are large. In climate projections, both changes to the vertical distribution of clouds and changes to the cloud amount in ECHAM5 will have a significant impact on the radiation budget of ECHAM5 because of the compensating errors.

The radar joint cloud altitude–reflectivity histograms of the four regional cloud regimes demonstrated ECHAM5 has much a greater frequency of occurrence of precipitation compared to the satellite observations. CloudSat observations show that in all regions examined, except in the tropics, the greatest frequency of occurrence of hydrometeors lies within the nonprecipitating boundary layer. This, however, is not what is modeled. Aside from the highest levels (>9 km), the greatest frequency of occurrence of hydrometeors in ECHAM5 is generally within the precipitating half of the histogram, be it ice or liquid water. The radar simulator showed that precipitation in ECHAM5, which accounts for all radar reflectivities >−10 dBZ, is too frequent. Since previous studies showed that the accumulated precipitation compares well to observations, it can be inferred that the intensity is too low.

Both lidar and radar results show that the frequency of occurrence of nonprecipitating boundary layer clouds is far too low in the model. The observations show a broad range in reflectivities, while the model only produces optically thick (as seen in the lidar results), constantly precipitating (seen in the radar results) clouds. The boundary layer clouds, which are modeled, remain in the lowest layers of the atmosphere, unlike observations. Additionally, there is a lack of nonprecipitating midlevel clouds.

Gehlot and Quaas (2012) found the overestimate in high-level clouds stems from the excessive transport of mass into the upper atmosphere via convection, which takes longer to evaporate and sediment out. This problem, as shown in the present study, is exacerbated by the underestimation in the ice crystal effective radius, leading to artificially large scattering ratios for a given ice crystal content and causing the lidar signal to attenuate high in the atmosphere.

A sensitivity study proved doubling the ice crystal effective radius in ECHAM5 has a significant impact on the lidar scattering ratio histograms, reducing the scattering ratios to approximately the same ranges observed. In addition to improving the lidar scatter ratios, doubling the effective ice radius improved the detection of high-level hydrometeors by the radar simulator. High-level clouds, previously undetected by the radar, are now captured and the altitude of the highest-level clouds is closer to observations.

A further sensitivity study showed that the main problem with the frequency of occurrence of precipitation is for stratiform rather than convective clouds.

Our results suggest three avenues for a better representation of clouds in ECHAM5. First, it is evident from
our sensitivity study that the comparison to both lidar and radar improves if the assumed size of ice crystals is increased by about a factor of 2. Second, a broad range of cloud reflectivities should be simulated. A parameterization of the subgrid-scale variability of cloud water used for the radiative effects of the clouds may be useful. If a sensible subgrid-scale variability of cloud water is simulated, then this may also help to simulate precipitation less frequently but with greater intensities when present. Third, a revision of the convective scheme would be useful. The presence of shallow cumuli should influence radiation directly, rather than indirectly, by detraining water, which then serves as a source of stratiform cloudiness. A spectrum of convective clouds should be simulated, with more clouds detraining in the mid- and low levels, and fewer penetrating the high levels.

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