Improvement and Implementation of a Parameterization for Shallow Cumulus in the Global Climate Model ECHAM5-HAM

FRANCESCO A. ISOTTA, P. SPICHTINGER, AND U. LOHMANN
Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

K. VON SALZEN
Canadian Centre for Climate Modelling and Analysis, Environment Canada, Victoria, British Columbia, Canada

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ABSTRACT

A transient shallow-convection scheme is implemented into the general circulation model ECHAM5 and the coupled aerosol model HAM, developed at the Max Planck Institute for Meteorology in Hamburg. The shallow-convection scheme is extended to take the ice phase into account. In addition, a detailed double-moment microphysics approach has been added. In this approach, the freezing processes and precipitation formation are dependent on aerosols. Furthermore, in the scheme, tracers are transported and scavenged consistently as in the rest of the model. Results of a single-column model simulation for the Barbados Oceanography and Meteorology Experiment (BOMEX) campaign are compared with previously published large-eddy simulation (LES) results. Compared to the standard version, the global ECHAM5-HAM simulations with the newly implemented scheme show a decreased frequency of shallow convection in better agreement with LES. Less shallow convection is compensated by more stratus and stratocumulus. Deep and especially midlevel convection are markedly affected by those changes, which in turn influence high-level clouds. Generally, a better agreement with the observations can be obtained. For a better understanding of the scheme’s impact and to test different setting parameters, sensitivity analyses are performed. The mixing properties, cloud-base vertical velocity, and launching layer of the test parcel, respectively, are varied. In this context, results from simulations without shallow convection are also presented.

1. Introduction

General circulation models (GCMs) are an important tool in climate studies, both for analyses of past climate and projections of future changes. The representation of convection and its interaction with the rest of the model (such as large-scale cloud parameterization and radiation) is of crucial importance. Convection spanning over vast areas of the world is a fundamental component of weather and climate, affecting the moisture and energy budgets and transports tracers. Despite the increasing complexity of parameterization, cloud effects and related feedbacks are the largest contribution to uncertainty in climate sensitivity (Randall et al. 2007).

Shallow cumuli are one of the most common cloud types in the troposphere (Rauber et al. 2007) and the most abundant of tropical clouds (Johnson et al. 1999). The relevance of these clouds for large-scale atmospheric dynamics is evident in trade wind areas in the subtropical belts above the oceans. Shallow cumuli transport humid air from the surface layer to the free atmosphere (Stull 1985; Bélair et al. 2005), influencing temperature, humidity, winds, cloud cover, and depth of the planetary boundary layer (PBL; Bretherton et al. 2004). They contribute fundamentally to the moisture and energy balance in the lower troposphere. Quantitative evidence for this on the global scale has been provided by von Salzen et al. (2005). Since deep convection is suppressed in the trade wind regions, the maximum evaporation rates from the ocean originate from fluxes of moisture associated with updrafts in shallow cumulus clouds, which root deeply in the sub-cloud layer. Part of the detrained moisture in the environment is transported to the intertropical convergence zone (ITCZ) by the trade winds at low altitudes (e.g.,
Shallow cumuli have a short lifetime (from minutes to up to one hour) with active mixing with the environment both at the sides and the top of the cloud, leading to a strong dilution, as can be seen in observations (e.g., Stommel 1947; Warner 1955; Holland and Rasmusson 1973; Albrecht 1981; Raga et al. 1990; Rangno and Hobbs 2005) and simulations (e.g., Stevens et al. 2001; Brown et al. 2002; Siebesma et al. 2003). Although shallow cumuli are often defined as nonprecipitating clouds, Short and Nakamura (2000) and others found evidence for light precipitation from shallow convection, which is dominated by warm rain processes (Rauber et al. 2007). For cloud droplet formation in warm and mixed phase clouds, aerosols acting as cloud condensation nuclei (CCN) are needed. The composition of aerosols acting as CCN depends on the source regions. Typically CCN are sulfates, sea salt, nitrates, and organics and their activation depends on ambient supersaturation, size, and chemical composition. Once the aerosols pass a critical radius, they can grow to form cloud droplets. Depending on processes such as emissions, growth, scavenging, sedimentation, and mixing, the concentration of aerosols in the atmosphere varies.

The cloud-top temperature for small clouds in the subtropics and tropics is often below the 0°C level, but at higher latitudes the relative amount of shallow convection that extends to colder levels increases, giving rise to supercooled liquid droplets. Ice crystals can be formed as well, through homogeneous freezing at very low temperatures (\(<-238 \text{ K}\)) and through heterogeneous freezing of supercooled cloud droplets at higher temperatures. Aerosols involved in heterogeneous freezing are called ice nuclei (IN), consisting of mainly insoluble particles such as mineral dust, metallic material, and also biogenic material (e.g., Rosinski and Morgan 1991; Vali 1996; Diehl et al. 2001; Morris et al. 2004; Richardson et al. 2007). Four freezing processes are commonly distinguished: condensation freezing (condensation of a liquid layer on a particle, before initiation of freezing), immersion freezing (initiated by an ice nucleus within a supercooled droplet), contact freezing (collision of a supercooled droplet with an ice nucleus, normally the most efficient for slight supercooling), and deposition freezing (water vapor is deposited on the IN) (Vali 1985). The importance of the different freezing modes is still a topic of ongoing research.

In mixed phase clouds, where the liquid and ice phases coexist, precipitation formation is more efficient than in warm clouds (Rogers and Yau 1989). Liquid and ice particles can both grow or ice particles can rapidly grow at the expense of liquid droplets, which evaporate. The latter is called the Wegener–Bergeron–Findeisen process (Findeisen 1938), which derives from the fact that if unrefrozen droplets are present, the air inside the cloud is saturated with respect to water and consequently supersaturated with respect to ice. Finally, the relevance of each process in clouds depends on the local vertical velocity, temperature, and concentrations and mean radii of the particles of both phases (Korolev 2008).

A number of convection parameterizations have been developed in the past and are mostly based on a plume or a thermal since these have counterparts in laboratory studies that help formulate equations to represent the plume–thermal. The mass flux scheme, currently the most used cumulus parameterization (e.g., Arakawa and Schubert 1974; Tiedtke 1989; Zhang and McFarlane 1995; Emanuel and Zivkovic-Rothman 1999; von Salzen and McFarlane 2002, hereafter SF02), was first introduced by Yanai et al. (1973). Despite various attempts (e.g., Siebesma and Cuijpers 1995; Carpenter et al. 1998), the representation of entrainment and detrainment in mass flux schemes remains uncertain. Recently, further developments in convection schemes take into account new insights on the nature of cumulus clouds. The scheme of SF02 introduced a life cycle, resulting in an ensemble of transient shallow cumuli. This scheme, like others (e.g., Bretherton et al. 2004), is developed explicitly for shallow convection and is able to successfully simulate the thermodynamics of the shallow-cumulus-topped planetary boundary layer.

This paper describes the implementation of the shallow-convection scheme by SF02 in ECHAM5-HAM, which replaces the scheme of Tiedtke (1989) except for deep and midlevel convection. The scheme is extended to take into account the ice phase, precipitation, transport, and scavenging of tracers in the ECHAM5 model. The freezing process and precipitation formation are coupled to the double-moment aerosol scheme HAM (Stier et al. 2005).

The paper is organized as follows: in section 2 the model is described, with special emphasis on the convection scheme by Tiedtke (1989; i.e., the standard scheme) and on the new scheme implemented. Additionally, further developments of the shallow-convection scheme are described. The results of the single-column model (SCM) simulations used as a first validation of the scheme are presented in section 3. Thereafter, global simulations are discussed. Sensitivity tests are performed to show the impact of varying, for example, the mixing intensity and the launching layer of the test parcel. The summary concludes the paper.
2. Model description

In this study we use the general circulation model ECHAM5 described in Roeckner et al. (2003). The Hamburg aerosol model, HAM, has been coupled to ECHAM5 (Stier et al. 2005). ECHAM5-HAM contains a detailed two-moment microphysics scheme with prognostic equations for cloud droplets and ice crystal mass mixing ratios and number concentrations as well as aerosol mass and number concentrations (Lohmann et al. 1999, 2007). The aerosol mixing state is calculated from the included aerosol microphysical processes. With the microphysics, the phase changes and the precipitation processes, namely autoconversion, accretion, and aggregation, are calculated. The aerosols included are sulfate, black carbon, particulate organic matter, sea salt, and mineral dust. The statistical cloud cover scheme (Tompkins 2002) assumes a beta distribution for the probability density function (PDF) of \( r_T \) (total water mixing ratio) of a grid cell to describe the subgrid variability. The cloud cover is the supersaturated part of the PDF.

The resolution used is T63 in the horizontal, corresponding to 192 \( \times \) 96 grid points with a grid size of 1.875° \( \times \) 1.875°, and 31 levels in the vertical, with the top of the model located at 10 hPa. Climatological sea surface temperatures and sea ice extent are used. The time step for GCM simulations is 5 min and the simulation period lasts 5 yr after a 3-month spinup, except for the sensitivity simulations, which are interpreted only over 3 months (winter) to reduce computing time but nevertheless gain insights into the performance of the model with different settings. Tests with longer periods show that the results of the first winter are representative. For the reference simulation we use the model version as described in Lohmann (2008), with a balanced radiation budget at the top of the atmosphere. Note that the simulations in Lohmann (2008) were conducted in T42 horizontal resolution with only 19 vertical levels, which explains differences, for instance, in the ratios between convective and stratiform precipitation discussed below. The new versions are not tuned to achieve radiative balance so as to see the effective changes resulting from the modifications.

a. ECHAM5-HAM and the Tiedtke scheme

Convection in the standard version of ECHAM5-HAM is parameterized using the mass flux scheme of Tiedtke (1989, hereafter T89), with modifications from Nordeng (1994) for deep convection. It distinguishes between deep, shallow, and midlevel convection, but only one type of convection is allowed in a grid box at a certain time step. The entrainment and detrainment consist of an organized part, associated with large-scale convergence, and a turbulent part, caused by turbulent eddies at the cloud edges.

The cloud model is a simple entraining–detraining single plume, where the updraft and downdraft bulk properties are treated separately. The plume is assumed to have properties identical to those obtained after averaging over all cloudy parcels. Bulk values are calculated and downdrafts are parameterized assuming that they originate from the mixing of cloudy and environmental air that has been cooled by evaporation of precipitation. The downdraft mass flux is directly proportional to the upward mass flux. Deep and shallow convection are mainly distinguished by different fractional turbulent entrainment and detrainment rates and by the absence of precipitation in shallow clouds. The closure is based on a moisture balance for the subcloud layer to calculate the cloud-base mass flux, as described in T89. For shallow convection the moisture supply is largely through surface evaporation, which balances the shallow-cloud moisture flux. The modifications of Nordeng (1994), which only apply to deep convection, do not change the bulk concept, but introduce organized detrainment from clouds with different top heights (spectrum of clouds) based on Yanai et al. (1973).

Note that there is no cloud fraction associated with convective clouds. The detrained cloud water and ice is a source for the large-scale water and ice content in the stratiform cloud routine. This permits simulation of long-lived anvils at the top of the updraft. In some models the interactions of stratiform clouds on convective clouds are also taken into account (e.g., Fowler and Randall 2002), but not in the case of ECHAM5-HAM.

In the convection scheme of the standard model (ECHAM5std), the same two-moment cloud microphysics scheme as implemented for stratiform clouds was recently added (Lohmann 2008). It is coupled to the HAM aerosol scheme. In this way, liquid and ice water mixing ratio and number concentrations of cloud droplets and ice crystals are calculated and the aerosols influence the warm and ice phase formation and thus precipitation. The detrained number concentrations are then also an output from the convection scheme handed over to the stratiform clouds scheme.

Although the T89 scheme was an important step forward in convection parameterization, there are some unresolved aspects. Tiedtke (1989), Gregory and Rowntree (1990), and others discuss the critical importance of entrainment and detrainment rates in a mass flux scheme. The scheme of T89 has, for example, fixed fractional entrainment and detrainment rates, which are rather low to permit convection to penetrate to high altitudes. In subsequent studies it was found that those values are about an order of magnitude smaller (e.g., Siebesma...
and Cuijpers 1995). Consequently, shallow-convection mass flux is overestimated and the clouds are mainly composed of undiluted air coming from the cloud base. Moreover, the assumption of equal fractional entrainment and detrainment rates is criticized in Siebesma and Cuijpers (1995).

b. The transient shallow-convection scheme

Von Salzen and McFarlane (2002) developed a bulk parameterization for an ensemble of transient shallow cumuli. The fundamental set of equations consists of continuity equations for mass, general scalar properties, and vertical momentum in the convectively active region. The equations are time dependent because of the inclusion of a fractional cloud cover. A life cycle of cumuli is considered (Fig. 1). At time \( t_a = 0 \) s, turbulent processes and favorable conditions can permit the lifting of air parcels until the lifting condensation level (LCL) is reached, and condensation occurs. Once the level of free convection (LFC) is reached a cloud is formed and reaches the LNB at time \( t_a = \tau \). Here, \( M_b \) is the cloud-base mass flux, \( E \) is the entrainment, \( D \) is the detrainment at cloud edges (subscript \( s \)) and at cloud top (subscript \( t \)), and \( D_f \) is the lateral detrainment in the final stage of the cloud.

\[
\left( \frac{E_s}{D_s} \right) = \rho a_o w_e \left( \frac{e}{\partial z} \right) = \rho a_o w_e \frac{\partial B_u}{\partial z} \left[ \max \left( \frac{\partial B_u}{\partial z}, 0 \right) \right],
\]

where \( \rho \) is the density of air, \( a_o \) the fractional cloud cover, \( w_e \) the vertical velocity, and \( \mu \) the mixing rate scaling factor that needs to be determined from, for example, large-eddy simulation (LES) as in SF02.

In the SF02 scheme, inhomogeneities in the horizontal distribution of in-cloud properties due to mixing at cloud top are accounted for. After the cloud top has passed a certain layer, its properties remain constant. This is also valid for the fractional cloud area, defined as the portion of the layer with liquid water content (LWC). Conserved quantities inside the cloud (total water and moist static energy) are represented as linear mixtures of environmental air and in-cloud air from lower levels. The approach of the standard version (labeled DECORE_B in SF02) is used because it best approximates LES results of the Barbados Oceanography and Meteorology Experiment (BOMEX) and is based on the assumption that the probability of dilution increases with time during the evolution of the cloud.

A closure is necessary to link the actual amount of convection to gridbox mean model variables. The closure in the scheme of SF02 following Grant (2001) is based on a simplified turbulent kinetic energy (TKE) budget for the convective boundary layer to connect the cloud-base mass flux with the convective vertical velocity scale. Neggers et al. (2004) evaluated different closures for diurnal cycles of shallow cumuli over land, comparing the resulting cloud-base mass fluxes with results from LES, showing a good performance of the one presented above.

c. Further developments of the shallow-convection scheme for ECHAM5-HAM

In ECHAM, the shallow-convection scheme replaces that of the T89 scheme, but the T89 scheme is still used for midlevel and deep convection. Given that shallow cumuli are often in the starting stage of a day with convective activity, it was decided to first allow the shallow-convection scheme to produce a cloud. If it is not able to trigger a cloud or if the LNB is above \( 0^\circ C \), deep or midlevel convection of the T89 scheme has the possibility of being active. This model version is hereafter called ECHAM5sh-noice.

The scheme is further developed, resulting finally in the version ECHAM5sh (see Table 1 for a summary of the different model versions used). First, the three levels of the model near and at the surface are analyzed. The one with highest moist static energy is chosen as the
launching layer for the test parcel, which is used to simulate the ascent of the cloud, avoiding the choice of a fixed layer. The biggest change affecting large parts of the scheme is the introduction of the ice phase and cloud microphysics. Including the ice phase requires adjusting the moist static energy. This quantity is of fundamental significance for moist convection processes since it is conserved for adiabatic, saturated, and unsaturated transformation in which the pressure change is hydrostatic and mass is conserved. In ECHAM5sh-noice it is calculated according to SF02:

\[ h = c_{pd} T + gz + L_v r_v, \]  

(2)

where \( h \) is the moist static energy, \( c_{pd} \) is the heat capacity at constant pressure for dry air, \( T \) is the temperature, \( g \) is the gravitational acceleration, \( z \) is the height, \( L_v \) is the latent heat of vaporization, and \( r_v \) is the water vapor mixing ratio. The frozen moist static energy is chosen to include the ice phase in the shallow-convection scheme (Emanuel 1994; Bretherton et al. 2005):

\[ h_T = (c_{pd} + r_T c_{pv}) T + L_v r_v - L_i r_i + (1 + r_T) gz, \]  

(3)

where \( c_{pv} \) is the heat capacity of water vapor at constant pressure, \( r_T \) is the total water mixing ratio \( (r_v + r_i + r_L) \), \( L_i \) is the latent heat of freezing, and \( r_i \) is the ice mixing ratio. In the last term the simplification \( 1 + r_T \approx 1 \) is applied. This is reasonable since \( r_T \) is very small. The term \( r_T c_{pv} \) has been neglected in Eq. (2).

In the ECHAM5-HAM model version used, the two-moment microphysics scheme for cloud droplets and ice crystals in stratiform clouds (Lohmann et al. 2007) is implemented into the shallow-convection scheme consistently, the same way as was done for the T89 scheme (Zhang et al. 2005; Lohmann 2008). The aerosol activation is parameterized following Lin and Leaitch (1997). In the current study we have the advantage of calculating vertical velocity explicitly using the new shallow-convection scheme instead of estimating it via TKE and convective available potential energy (CAPE) as done before (Lohmann 2002).

The cloud droplet number concentration (CDNC) is calculated at cloud base, and is constant over the whole vertical extent of the clouds as suggested by Rogers and Yau (1989). Between 273 and 238 K, liquid cloud droplets can freeze via heterogeneous nucleation and water droplets can exist as supercooled droplets. Below 238 K, homogeneous freezing sets in. Two heterogeneous freezing modes are taken into account between 273 and 238 K, namely contact nucleation and immersion freezing (Lohmann and Diehl 2006; Hoose et al. 2008, and references therein). Deposition nucleation is assumed to be negligible in mixed phase clouds (Hoese et al. 2008). Black carbon and mineral dust aerosols are taken into account. For contact freezing, aerosols must be uncoated and solid whereas for the immersion freezing only the internally mixed mineral dusts and black carbon are involved. The processes change the mixing ratio and number concentrations of liquid water drops and ice crystals. If the ice mixing ratio exceeds a threshold value of 0.5 mg kg\(^{-1}\) because of heterogeneous freezing, the Wegener–Bergeron–Findeisen process is activated and the water mixing ratio is transferred to the existing ice crystals (Lohmann et al. 2007).

After freezing takes place, the formation of precipitation from ice and liquid water is computed following Lohmann and Roeckner (1996, and references therein), except for autoconversion and accretion of cloud droplets to rain, which is computed as in Khairoutdinov and Kogan (2000). Ice crystals generate snow by aggregation. After formation, rain droplets grow by accretion (collision and coalescence) of cloud droplets and snow by accretion of cloud droplets and ice crystals. Feedbacks of microphysical processes on moisture and energy fluxes in the shallow-cumulus scheme are omitted. Including the ice phase means that restricting the LNB below the 0°C level is no longer necessary. A new criterion must be applied for the artificial but necessary division between shallow and other types of convection, with the ideal case being a scheme that is suitable for treating all types of convection, permitting a smooth transition. The criterion chosen is the depth of the cloud and depends on the processes that are taken into account in the different parameterizations. The shallow-convection scheme, for example, does not take downdrafts into account. Also, the life cycle changes for other types of convection and the assumption of clouds

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**Table 1. Abbreviations and descriptions of the model versions.**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ECHAM5std</td>
<td>Standard version, without any modification</td>
</tr>
<tr>
<td>ECHAM5sh-noice</td>
<td>As in ECHAM5std with the scheme of SF02 in which only the precipitation formation rate has been changed to Khairoutdinov and Kogan (2000)</td>
</tr>
<tr>
<td>ECHAM5sh</td>
<td>As in ECHAM5sh-noice, but with all developments (triggering, ice phase, detailed microphysics, and tracer transport) described in section 2c</td>
</tr>
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Lf is the latent heat of freezing, and \( r_T \) is the ice mixing ratio.
collapsing after reaching the LNB would not be justified for deep convection. In ECHAM5sh, a critical cloud depth of 300 hPa was chosen. For a vertical extension of convection below this threshold shallow convection is triggered. The choice is somewhat arbitrary, thus sensitivity tests are presented later.

Tracers are transported inside the clouds and are entrained and detrained. Furthermore, the wet deposition for shallow convection is implemented consistently with the parameterizations in ECHAM5-HAM. For in-cloud scavenging, Henry’s law is used for the partitioning of gases between air and cloud water and for aerosols a prescribed scavenging parameter (size and composition dependent) is used. In an updraft, tracer mixing ratios are attributed to the liquid and ice phase in proportion to the presence of the respective phase and then tendencies due to in-cloud scavenging are calculated. Finally, below-cloud scavenging due to rain and snow is also taken into account. A detailed description of the parameterization of scavenging processes can be found in Stier et al. (2005).

### 3. Experiments and results

#### a. Validation of the scheme

Single-column model analyses are a powerful first test of the performance of the model. In this section, results from the BOMEX case during the period from 22 to 26 June 1969 are used. Only nonprecipitating trade wind cumulus clouds were observed during this time period (Siebesma and Cuijpers 1995; Siebesma and Holtslag 1996; Siebesma et al. 2003). In the lowest 500 m, a well-mixed layer is present, followed by a conditionally unstable layer topped by a stable inversion layer, as can be seen in the profiles (Fig. 2).

The simulation is run for 20 min forced every 5 min with soundings based on observations (temperature, moisture, and horizontal wind velocities) followed by a free run for 10 h. However, the results are not that sensitive to the lengths of the forced and following period. A detailed analysis of the BOMEX case and the shallow-convection scheme can be found in SF02. Here we present briefly the findings using ECHAM5-HAM SCM. For the BOMEX study, the vertical velocity at the cloud base ($w_{cb}$) is increased from 0.25 to 0.4 m s$^{-1}$ in the shallow-convection scheme. Velocity $w_{cb}$ is in most schemes (e.g., Nober and Graf 2005) a tuneable variable and is set between 0.1 and 2 m s$^{-1}$. The slight increase of $w_{cb}$ in this case was necessary to avoid the formation of stratiform clouds. Figure 3 shows mean simulated cloud properties. Results for the standard and the ECHAM5sh versions are plotted in addition to averages from 10 LES reported by Siebesma et al. (2003), which show little spread. For the grid mean liquid water content and the mass flux, the results using the standard model with the T89 scheme (ECHAM5std) are also included.

The ECHAM5sh mass flux and liquid water content are in much better agreement with the LES simulation results than ECHAM5std. The cloud fraction and the vertical velocity are also in good agreement with the LES results. This confirms the effectiveness of the newly implemented scheme with its additional modifications. The mass flux and the cloud fraction are decreasing monotonically with height. The LES results suggest that detrainment of cloud mass occurs over the whole cloud layer (Siebesma and Cuijpers 1995; Siebesma and Holtslag 1996). This could be interpreted as numerous small clouds with different tops. The cloud fraction, like the other variables in the figure, is computed inside the convection scheme. Although with the new shallow-convection scheme we can calculate the cloud fraction, it is not used further in the model. The cloud cover calculated with the Tompkins (2002) scheme does not correctly represent the BOMEX case either in the standard or in the ECHAM5sh version (not shown). This is analogous to the results of Park and Bretherton (2009). The disagreement is the subject of ongoing investigations.

The LWC is overestimated with respect to LES results, similar to Park and Bretherton (2009), but the overall structure is captured with a maximum near-cloud base. The T89 scheme in ECHAM5std has a very low LWC with the maximum at higher levels than the LES models and the mass flux is drastically underestimated. An improvement of the representation of shallow convection using the modified SF02 scheme is clear for this SCM case.
The fractional detrainment rates, in agreement with results described in Siebesma and Cuijpers (1995), are larger than the fractional entrainment rates, leading to a cloud with decreasing mass flux with height as shown in Fig. 3. Typical values are around $2 \times 10^{-3}$ m$^{-1}$ for the fractional detrainment rate and $5 \times 10^{-4}$ m$^{-1}$ for the fractional entrainment rate, thus lower than the values from the LES models ($2.5 \times 10^{-3}$ and $1.5 \times 10^{-3}$ m$^{-1}$, respectively) but higher than those fixed in the scheme of T89 ($3 \times 10^{-4}$ m$^{-1}$ for both). In SF02 evidence is provided for overestimation of the entrainment rates in LES models. In general the findings from the SCM are comparable to the good performance of the results of the SCM presented by Park and Bretherton (2009).

b. Discussion of GCM simulations

The implementation of the modified SF02 scheme in the GCM changes simulated clouds and the energy and water budgets considerably. Figure 4 shows the frequencies of occurrence for the three different convection types in the ECHAM5std, ECHAM5sh-noice, and ECHAM5sh versions. In addition the interpolated observational data of cumulus and cumulonimbus clouds from ships (1954–97) and land (1971–96) are plotted. The raw data come from Warren and Hahn (2002) and the online version (www.atmos.washington.edu/CloudMap/).

The sum of midlevel and deep convection is added to permit an easier comparison with the observations, where the two convection types are not distinguished but appear as “cumulonimbus.” Shallow convection can be compared to the cloud type “cumulus” in the observations.

Shallow convection occurs far too often in ECHAM5std and is a consequence of the triggering and the low entrainment and detrainment rates in T89, but the pattern is captured well. The versions ECHAM5sh-noice and ECHAM5sh are similar, but the inclusion of the ice phase permits the shallow-convection scheme to be active also when the LNB is above $0^\circ$C level, particularly in mid-latitudes but also in the subtropics, where there is a clear increase of frequency. Both versions are now in better agreement with observations. A negative aspect in the versions with the modified SF02 scheme is the lack of shallow convection over continents, especially over the northern part of South America, the Mediterranean region, and the mid-south of Africa. It is possible that the simplified formulation of the closure may not be appropriate for convection over land or that the PBL may not be well resolved over land. The higher frequencies in ECHAM5sh over the Roaring Forties and toward the North Pole compared to the observations are of lesser concern because of the lower confidence in the sparse ground observations in the vicinity of the Antarctic and Arctic regions.
The frequency of midlevel convection is much higher in ECHAM5std than in the other two versions. In particular, the high values in the midlatitudes that did not correspond to the observations are not present anymore. From ECHAM5sh-noice to ECHAM5sh there is further reduction due to the increase of frequency of shallow convection, partly because only one convection type can be active at each time step in one grid cell. The resulting pattern in ECHAM5sh is in good agreement with the observations for cumulonimbus (see the sum of midlevel convection in Fig. 4, first to fourth row) Frequency of appearance of shallow, midlevel, deep convection, and the sum of midlevel and deep convection in (left) ECHAM5std, (middle) ECHAM5sh-noice, and (right) ECHAM5sh. (fifth row), (left) Cumulus, to be compared with shallow convection in first row, and (right) cumulonimbus, to be compared with fourth row, surface-based cloud climatology from ships (1954–97) and land (1971–96) observational data (from www.atmos.washington.edu/CloudMap; Warren and Hahn 2002). Data interpolated on the whole grid.
and deep convection). The frequency of appearance of cumulonimbus over mid-Africa and some parts of Asia (China and Russia) is underestimated in the ECHAM5sh-noice and ECHAM5sh versions, in contrast to ECHAM5std. Interesting is the change over the ocean in the tropics, where the midlevel convection appears quite often as compared to the standard version. In the latter, midlevel and deep convection was a rare occurrence over the ocean. The version without ice has higher frequencies of midlevel convection in the tropics, corrected in ECHAM5sh by the increase of shallow convection, which avoids the fast onset of deeper convection. Differences in the effects on deep convection between the three simulations are less pronounced. However, they still have a big impact on overall results, as discussed later.

The changes in frequencies have a strong and complex effect on the whole model. Figure 5 shows the total cloud cover for ECHAM5std, ECHAM5sh-noice, and ECHAM5sh and satellite observations from the International Satellite Cloud Climatology Project (ISCCP; e.g., Rossow and Schiffer 1999) and the Moderate Resolution Imaging Spectroradiometer (MODIS; Minnis et al. 2002; March 2000–February 2001). Besides the poles, where the data from ISCCP and MODIS are not reliable because of the poor retrieval from the satellite over ice and snow surfaces (Drake 1993), the midlatitudes are well represented in all three model versions. In ECHAM5sh-noice there is an increase in cloud cover over the Roaring Forties, which is slightly decreased in ECHAM5sh, closer to satellite data. In the Southern Hemisphere the performance of ECHAM5sh is in good agreement with ISCCP and MODIS in the Indian Ocean, but the cloud cover is too high in the Atlantic and Pacific trade wind regions, where the results of ECHAM5sh-noice are better. Also in the Northern Hemisphere the cloud cover is too high, especially over the Pacific Ocean. ECHAM5std has a strong negative bias over the subtropics.

Several mechanisms are responsible for changes in cloud cover in different parts of the globe. The increase in cloud cover over the subtropics and, to a lesser extent, in the midlatitudes for the new model versions is due to a reduction in vertical mixing of moisture because of the lower frequency of shallow convection (see Fig. 4). The associated increase in moisture at lower levels results in an increase of stratocumuli and stratus. This was found in a detailed analysis using the same criterion as in the ISCCP satellite retrieval to distinguish between the different cloud types according to cloud optical thickness and cloud-top pressure (not shown). The vertical mixing of moisture is slightly increased from ECHAM5sh-noice to ECHAM5sh because of the increase of shallow-convection frequency.

The largest discrepancies between ECHAM5sh and ISCCP are in the tropics, where the simulated cloud cover is too high, in particular over Indonesia and the western tropical Pacific. This is due to the strong increase in the frequency of midlevel convection in the tropics as compared to ECAHM5std (see Fig. 4). With the cloud-type classification described above, it was found that the increase of cloud cover in the tropics is
due to increasing deep convection producing cirrus, and
cirrostratus. The appearance of these clouds is connected,
because more high-level clouds can develop because of
increased deep and midlevel convection and thus stronger
detrainment at the cloud top, which is typical for the T89
scheme, given its small entrainment and detrainment
rates. A small increase is also found for cumuli and is more
pronounced for stratocumuli. The MODIS data differ
from the ISCCP data in the Roaring Forties and in the
subtropics and tropics, where the cloud cover is higher.
ECHAM5sh results are in better agreement with the
MODIS data than the ISCCP observations. The afore-
mentioned problems in convection frequencies over the
continents do not seem to affect cloud cover considerably
because of the complex interactions between convection,
stratiform clouds, and the cloud cover scheme. The global
values over the 5 yr are summarized in Table 2. The total
cloud cover increases significantly from the standard ver-
sion to ECHAM5sh-noice and is slightly reduced in
ECHAM5sh, but is still much higher compared to ISCCP
(67.0%) or MODIS (66.7%). Stubenrauch et al. (2009)
found a total cloud cover using different satellite data of
70% ± 5%. The high values found in this study thus still
fall within the uncertainties of the measurements.

Figure 6 shows the annual mean precipitation as com-
pared to the Global Precipitation Climatology Project
(GPCP) data (Adler et al. 2003). The changes between
ECHAM5std and ECAHM5sh are small with main devi-
ations from the observations at the same locations and
only small changes in intensity. An improvement is the
decrease of positive bias over mid- and southern Africa.
On the other hand, the positive bias east of the Philip-
pines is increased because of the increase of midlevel
and deep convection (see Fig. 4). The relatively similar
patterns between the simulations of ECHAM5std,
ECHAM5sh-noice (not shown), and ECHAM5sh suggest
that fundamental changes in the convection are not strong
enough to considerably change the precipitation. Other
aspects, such as circulation and the constant sea surface
temperature assumed here, maintain the bias of the
model. The zonal means in Fig. 6 show the simulated
contributions from convective and stratiform pre-
cipitation. The general reduction of shallow and mid-
level convection, especially in midlatitudes for the
latter (see Fig. 4), results in increasing stratus and
stratocumulus clouds, as mentioned before, which in-
creases the stratiform precipitation. For shallow con-
vection in contrast to midlevel and deep convection,
the convective precipitation is not changing signifi-
cantly because shallow convection only produces small
amounts of precipitation mostly on the order of $5 \times 10^{-3}$
to $10^{-1}$ mm day$^{-1}$ in the annual mean (not shown). Thus,
the increase of midlevel convection near the Philippines,
for example, can be seen in the increase of convective and
decrease of stratiform precipitation.

The differences in the contribution from convective pre-
cipitation between ECHAM5sh-noice and ECHAM5sh
are predominantly near the equator, where the increase of
shallow convection from the version without ice to
ECHAM5sh decreases midlevel convection. For the
stratiform precipitation, stratus and stratocumulus are
less abundant around 50°N/S because of shallow con-
vection in ECHAM5sh and ECHAM5sh-noice. The global
mean precipitation (see Table 2) decreases slightly
from 3.12 mm day$^{-1}$ in ECHAM5std to 3.07 mm day$^{-1}$
in ECHAM5sh-noice and 2.98 mm day$^{-1}$ in ECHAM5sh.
The ratio of convective precipitation to the total amount
changes from 0.30 to 0.27 and 0.25. This is quite low and
may be an artifact of this particular model version. It will
be investigated in a future study.

The liquid water path (LWP) from ECHAM5std and
ECHAM5sh, accompanied by the observations of MODIS
and the Special Sensor Microwave Imager (SSM/I)
(Greenwald et al. 1993; Weng and Grody 1994), is shown

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Table 2: The 5-yr global annual means of selected variables for the three simulations ECHAM5std, ECHAM5sh-noice, and ECHAM5sh.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ECHAM5std</th>
<th>ECHAM5sh-noice</th>
<th>ECHAM5sh</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cloud cover (%)</td>
<td>66.4</td>
<td>72.2</td>
<td>72.0</td>
<td>62–75a</td>
</tr>
<tr>
<td>Total precipitation (mm day$^{-1}$)</td>
<td>3.12</td>
<td>3.07</td>
<td>2.98</td>
<td>2.74b</td>
</tr>
<tr>
<td>Convective precipitation (mm day$^{-1}$)</td>
<td>0.93</td>
<td>0.82</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Stratiform precipitation (mm day$^{-1}$)</td>
<td>2.18</td>
<td>2.26</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>LWP (oceans) (g m$^{-2}$)</td>
<td>113.9</td>
<td>144.2</td>
<td>140.7</td>
<td>50–85c</td>
</tr>
<tr>
<td>IWP (g m$^{-2}$)</td>
<td>19.8</td>
<td>19.6</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>SWCRF (W m$^{-2}$)</td>
<td>−50.4</td>
<td>−61.9</td>
<td>−62.1</td>
<td>−50d</td>
</tr>
<tr>
<td>LWCRF (W m$^{-2}$)</td>
<td>27.0</td>
<td>27.5</td>
<td>27.3</td>
<td>22–30d</td>
</tr>
</tbody>
</table>

a From surface observations (Warren and Hahn 2002), ISCCP, MODIS, and Stubenrauch et al. (2009).
b From GPCP.
c From SSM/I and ISCCP.
d From Kiehl and Trenberth (1997).
in Fig. 7. However, there are huge discrepancies between different observations due to difficulties in retrieving the LWP from satellite measurements. In the tropics, the overestimated values are slightly increased in ECHAM5sh, both over the oceans and over the continents. The increase in the amounts of stratus and stratocumulus already described before increases the LWP at midlatitudes. The same is true in the subtropics, where the values in ECHAM5std are too low over the Atlantic and Pacific in the Southern Hemisphere. From ECHAM5sh-noice (not shown) to ECHAM5sh, the slight increase in shallow convection leads to a decrease in low-level clouds and LWP, particularly at midlatitudes. This again shows the importance of the interaction of convection with the stratiform part, as also noticed by Park and Bretherton (2009). The analysis is reflected also in the global mean of the LWP (Table 2), with a large increase from ECHAM5std to ECHAM5sh-noice and a slight reduction to ECHAM5sh.

Ice is not frequently formed in shallow convection in the GCM and does not significantly affect the ice water content in the atmosphere. Low amounts of ice are present in the zones between 40° and 70°N/S. The major changes in ice water path (IWP) shown in Fig. 8 are an indirect effect of the substitution of the convection scheme, which affects the formation of other clouds, in particular, stratus and stratocumulus, deep and midlevel convection, and related cirrus or cirrostratus clouds. In general, the patterns are the same in the three simulations, as also the global annual average shown in Table 2 remains almost constant. Figure 9 shows the shortwave and longwave cloud radiative forcing (SWCRF and LWCRF) from the simulations and the observations from the Earth Radiation Budget Experiment (ERBE; Kiehl and Trenberth 1997). In ECHAM5std the SWCRF is in good agreement with the observations. There is clear successive deterioration of the performance from ECHAM5std to ECHAM5sh-noice to ECHAM5sh. Recall that the standard model is tuned to have a balanced top of atmosphere radiation budget. With the new developments, the global values (see Table 2) of SWCRF increase strongly from ECHAM5std to ECHAM5sh-noice to ECHAM5sh whereas LWCRF does not show large differences between the simulations. The radiative budget for the versions with the new convection scheme is not balanced anymore. The main changes in SWCRF occur in the subtropical regions over the oceans where shallow convection is prominent. The increase in SWCRF is the result of an increase of stratus and stratocumulus clouds there. LWCRF remains nearly the same in all three simulations, as mainly low-level
clouds are affected by the introduction of the modified SF02 scheme. LWCRF is in good agreement with ERBE except in the tropics, where there is a negative bias. The results show the necessity of a detailed review of the stratiform cloud scheme in the future. A change in one part of the model, especially if it has global effects, such as shallow convection, will influence the interplay with other parts of the model and therefore the improvement of shallow convection cannot be treated in isolation.

c. Sensitivity studies

The implementation of the modified SF02 scheme is accompanied by decisions about the settings of few parameters that have a plausible range, but not a precise value. Furthermore, the competition between the different convection types must be considered. Sensitivity tests were performed to investigate the effects of uncertainties in different parameters on the results. Figure 10a shows zonal mean differences in frequency of occurrence of shallow convection for the sensitivity simulations with ECHAM5sh over one winter [December–February (DJF)] after 2 months of spinup. In the ECHAM5sh version, shallow convection can only span maximally over a depth of 300 hPa. If it is not fulfilled, then deep or midlevel convection can be active. Simulations with 200 and 400 hPa are labeled with $D_p = 200$ and $D_p = 400$, respectively. It is not surprising that a reduced critical depth results in reduced shallow-convection frequency. As a reaction (which appears frequently in the different simulations), midlevel convection increases over wide regions of the oceans. With 400 hPa the increase of shallow-convection frequency is
moderate and more concentrated in smaller areas as compared to the decrease with 200 hPa. In a detailed analysis (not shown) on the frequency of the different cloud types and on the properties of the PBL in the simulations, it was found that the reasons for the described shallow-convection frequencies are manifold, such as the change of the structure and profiles of the PBL, the different low-level clouds appearing in the experiments, and the shift in place of midlevel and deep convection. At and near the tropics, midlevel convection behaves opposite to the shallow convection, but this is not the case in the midlatitudes, where they are in phase (not shown).

In ECHAM5sh the starting layer of the test parcel in the shallow-cumulus scheme is set to the one with the highest moist static energy in the lowest levels. Different constant starting layers from the surface (“lev1”
in Fig. 10a) to the fourth level above surface (‘‘lev2’’–‘‘lev5,’’ around 10, 40, 100, and 250 m, respectively) are tested, although it is evident that a too high starting level is not appropriate. In effect, by increasing the launching layer, the frequency of shallow convection is reduced to very low values. For the first and the second level above ground the reduction is particularly strong in the Southern Hemisphere, where the starting layer in ECHAM5sh changes frequently between the lowest layers. The fact that the simulation with a constant starting layer at the surface is very close to the ECHAM5sh version demonstrates that in the latter simulation the test parcel is frequently launched from the surface.

The shallow-convection scheme needs a prescribed cloud-base velocity, which is set to a low value (0.25 m s$^{-1}$) as compared to other models. The decrease to 0.1 m s$^{-1}$...
(\(w\downarrow\) in Fig. 10a) reduces the shallow-convection frequency while the increase to 1.0 m s\(^{-1}\) (\(w\uparrow\)) increases it and more clouds can develop.

There are two parameters that must be chosen to define the mixing properties of the shallow-convection clouds and are tuned with observations in SF02. The first is the mixing-rate scaling factor, \(\mu\), which is multiplied with the vertical derivation of the undiluted buoyancy of the parcel initiating the cloud to determine the fractional entrainment and detrainment rates [see Eq. (1)]. These are used in calculations of organized lateral entrainment and detrainment. An increase in \(\mu\) means more lateral mixing. The second parameter, \(\phi\), is related to the magnitude of the cloud-top mixing (see SF02), which increases as higher values of \(\phi\) are chosen. In ECHAM5sh and ECHAM5sh-noice, the values are set to \(\mu = 4.5\) s\(^2\) m\(^{-1}\) and \(\phi = 4 \times 10^{-3}\) s\(^{-1}\) and correspond to the numerical experiment labeled DECORE_B in SF02, which was found to best approximate analysis results for the heat and moisture sinks in the atmosphere during BOMEX according to Nitta and Esbensen (1974).

Sensitivity studies are performed with \(\mu = 14\) and 2 s\(^2\) m\(^{-1}\) (\(\mu\uparrow\) and \(\mu\downarrow\) respectively Fig. 10b) and \(\phi = 1 \times 10^{-3}\) and \(8 \times 10^{-5}\) s\(^{-1}\) (\(\phi\uparrow\) and \(\phi\downarrow\) respectively). The choice of the higher values of \(\phi\) and \(\mu\) corresponds to the one in SF02 that gave good results as compared to the LES intercomparison of the BOMEX case (Siebesma et al. 2003). For higher \(\phi\) the frequency of shallow convection increases in ECHAM5-HAM. The increase is stronger if \(\mu\) is also higher; otherwise it is weaker. The opposite is the case for lower \(\phi\), where a lower \(\mu\) results in a stronger decrease of the frequency between 40°S and 40°N. Note that the changes in the results have different magnitudes also due to the choice of the parameters, which are not symmetric around the standard value. For example, the effects of the changes in \(\mu\) are much larger for \(\mu = 14\) s\(^2\) m\(^{-1}\) than for \(\mu = 2\) s\(^2\) m\(^{-1}\).

In summary, the higher both parameters are, the more frequent shallow convection is, and the opposite is true for lower values. With less mixing the cloud can more often exceed the threshold of 300 hPa and cannot be stopped by the inversion, which is not well represented in ECHAM5. Thus the shallow-convection activity is terminated, leading to less shallow convection in these simulations. To improve the PBL, there are plans to couple ECHAM5sh to the developments in PBL in ECHAM5-HAM described in Siegenthaler-Le Drian et al. (2011, manuscript submitted to Atmos. Chem. Phys.). The introduction of moist instead of dry variables and the increase of resolution in the PBL ameliorate the structure of the PBL.

A closer look at the geographical distribution provides some interesting insights. The major changes in the frequency of shallow convection are in the areas where deep convection is very active, namely in the ITCZ and over the mid-Pacific branch over Kiribati and French Polynesia. In other areas there are mostly weak positive or negative changes. This can be seen in Fig. 10c, which is the sensitivity simulation with \(\mu = 4.5\) s\(^2\) m\(^{-1}\) and \(\phi = 8 \times 10^{-3}\) s\(^{-1}\), representative of the behavior of the other simulations. Also from the same simulation, the frequency of midlevel and deep convection is plotted in Figs. 10d,e. The midlevel convection reacts mostly opposite to the shallow-convection frequency besides some spots in higher latitudes, especially in the Roaring Forties. Changes for deep convection are less coherent. The effects of changing cumuli on the convection in the ITCZ are complex, as suggested by Neggers et al. (2007). For a detailed analysis the coarse resolution is not appropriate and a statistical analysis did not yield significant changes in the frequency of deep convection.

Figure 10f shows the total cloud cover of the model for a case where there is no shallow convection at all (neither from the newly implemented scheme nor from the T89 scheme). The trade cumulus boundary layer is now occupied by stratocumulus and stratus clouds similar to the results reported by von Salzen et al. (2005). The cloud cover shows a strong increase in the subtropics, but also areas of decrease or no change in the tropics. This is different from the results of von Salzen et al. (2005) and can be linked to the strong increase of midlevel convection over the whole of the oceans, which partly inhibits the occurrence of other low-level clouds instead of shallow convection.

4. Summary and conclusions

In this paper we implemented the shallow-convection scheme by SF02, replacing T89 with shallow convection in the ECHAM5-HAM model. Further developments to take into account the ice phase and precipitation in the form of rain and snow have a strong impact, in particular permitting the formation of shallow convection at higher latitudes, but also in some cases in the subtropics and tropics, where the LNB is located above the 0°C level. The implemented two-moment microphysics scheme for cloud droplets and ice crystals is consistent with the stratiform scheme and the other types of convective clouds. The ice phase permits one to alter the criterion to distinguish between shallow and the other two types of convection, namely deep and midlevel, which are still calculated by the T89 scheme.

As a first test of the performance of the new scheme and the interaction with the rest of the model, the BOMEX case was run in single-column mode and the results were compared with LES from Siebesma et al. (2003). The
resulting profiles correspond better to LES simulations even when compared to the standard version.

There are a lot of changes in the results between the ECHAM5std and ECHAM5sh, as described below. The frequencies of appearance of the different convection types in the GCM are in much better agreement with observations, except for some regions over the continents. The amount of shallow convection is generally decreased, in particular in the version without the ice phase. The midlevel convection appears in completely different areas and also decreases in frequency, except in the tropics. The deep convection changes are also significant, although lesser pronounced than the other convection types.

The cloud cover increases in ECHAM5sh compared to ECHAM5std, especially over the tropics and subtropics. This results from the reduction of the vertical mixing of moisture of shallow cumuli in ECHAM5sh, increasing stratus and stratocumulus. The increase of icy high-level clouds in some areas of the tropics is the result of more midlevel and modified deep convection with the corresponding detrainment at these altitudes.

Precipitation does not differ largely between the standard and the ECHAM5sh simulations. This is also the case for the ratio between convective and stratiform clouds, except in some areas where the decrease in shallow convection and the increase of stratiform low-level clouds and midlevel convection changes the ratio. LWP is generally strongly increased, increasing the discrepancy between model and observations, in particular in the tropics. In the subtropics the increase ameliorates low values in some areas; in others the positive bias compared to observations is further increased from ECHAM5std to ECHAM5sh. More stratus and stratocumulus in ECHAM5sh and the changes in convection frequencies are the main causes. Ice is not frequently formed in shallow cumuli; however, the IWP is modified especially by the indirect effect due to the reaction of other clouds as deep and midlevel convection to the new conditions.

The shortwave cloud radiative forcing (SWCRF) increases largely because of more stratus and stratocumulus. Longwave cloud radiative forcing (LWCRF) remains similar in the different simulations except in regions where deep and midlevel convection, and thus high-level clouds, are increased.

Sensitivity tests were performed to evaluate the effects of some choices and parameter settings that do not have a well-defined value. A higher cloud-base vertical velocity, a lower constant starting level of the test parcel, or a higher critical depth, which defines the artificial transition between shallow and the other two types of convection, increase the amount of shallow cumuli. Increasing the mixing of the clouds increases the frequencies of occurrence, because the less they are diluted the more they surpass the inversion and reach depths higher than the critical depth (300 hPa), above which shallow convection is not permitted any longer. Finally, without any shallow convection at all, the cloud cover is increased in the subtropics because of of an increase in otherlow-level clouds; but in other regions the increase of midlevel convection partly counteracts this tendency. There are some recurring patterns in the different sensitivity simulations. The diminishing of shallow convection increases stratus, stratocumulus, and midlevel convection, except in the midlatitudes.

As a general conclusion, the modification of the shallow-convection scheme has considerable effects on the climatology of the model and also has global effects indirectly due to the modification of the other clouds. The results show an improvement in the performance although the complexity of the interactions makes the analysis difficult. After implementing and testing the scheme, the interactions with the rest of the convection types and with the stratiform scheme should be revised. At the moment the interaction is only unilateral without the direct influence of stratiform clouds on convection. A further development could consist of having a separate cloud cover for convective clouds and permit the interaction of stratiform clouds with convection. The shortcomings experienced during the analysis require an effort to ameliorate the convection over the continents and the structure of the PBL.

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REFERENCES


clouds over the warm pool of the tropical Pacific Ocean. 


