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Impact of the representation of marine stratocumulus clouds on the anthropogenic aerosol effect

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Abstract

Stratocumulus clouds are important for climate by reflecting large amounts of solar radiation back to space. However they are difficult to simulate in global climate models because they form under a sharp inversion and are thin. A comparison of model simulations with the ECHAM6-HAM2 global climate model to observations, reanalysis and literature data revealed too strong turbulent mixing at the top of stratocumulus clouds and a lack of vertical resolution. Further reasons for cloud biases in stratocumulus regions are the too "active" shallow convection scheme, the cloud cover scheme and possibly too low subsidence rates.

To address some of these issues and improve the representation of stratocumulus clouds we made three distinct changes to ECHAM6-HAM2. With a "sharp" stability function in the turbulent mixing scheme we have observed, similar to previous studies, increases in stratocumulus cloud cover and liquid water path. With an increased vertical resolution in the lower troposphere in ECHAM6-HAM2 the stratocumulus clouds form higher up in the atmosphere and their vertical extent agrees better with reanalysis data. The recently implemented in-cloud aerosol processing in stratiform clouds is used to improve the aerosol representation in the model.

Including the improvements also affects the anthropogenic aerosol effect. In-cloud aerosol processing in ECHAM6-HAM2 leads in the global, annual mean to a decrease of the anthropogenic aerosol effect while using a "sharp" stability function leads to an increase. The results from the simulation with increased vertical resolution are diverse but also the anthropogenic aerosol effect is increased.

1 Introduction

Stratocumulus clouds are important for future climate predictions as they have a strong cooling effect (Bretherthon et al., 2004; Williams and Webb, 2009). In a general circulation model it is challenging to model stratocumulus clouds because of their small ver-

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tical extent. The feedback of low clouds is believed to be a major cause for the model discrepancy in the $2 \times CO_2$ climate sensitivity (Bony and Dufresne, 2005; Stephens, 2005; Williams and Webb, 2009).

Typical biases of global circulation models and numerical weather prediction models when simulating stratocumulus clouds are a too low cloud amount, a too shallow planetary boundary layer and an underestimation of the liquid water path (Hannay et al., 2009; Medeiros and Stevens, 2011). The diversity that exists among models in simulating stratocumulus clouds increases the uncertainty of the influence of aerosol particles on climate. In an intercomparison study by Stier et al. (2013) the uncertainty in the direct aerosol forcing due to the differences in simulated cloud albedo and used surface albedo among the participating models was assessed. Stratocumulus cloud regions were identified to be among the regions responsible for the largest host model uncertainty in the direct aerosol effect. As stratocumulus regions are also areas of a strong anthropogenic aerosol effect, simulations of the anthropogenic aerosol effect can be expected to depend on the representation of stratocumulus clouds. In our study we investigate the total anthropogenic aerosol effect (also referred to as the effective radiative forcing due to aerosol-cloud and aerosol-radiation interactions, Boucher et al., 2013), including the direct, semi-direct, indirect aerosol effects (cloud albedo, cloud lifetime) as well as effects on mixed-phase, ice and convective clouds.

In a recent study, Carslaw et al. (2013) systematically evaluated uncertainty sources for simulating the first indirect aerosol effect (cloud albedo effect). Uncertainties in natural emissions cause most uncertainty in cloud radiative forcing, followed by uncertainties in anthropogenic emissions and aerosol processes. International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999) D2 data for low level stratiform clouds was used in their study. Carslaw et al. (2013) have done extra simulations with a different time period of the ISCCP climatology and the sensitivity to the cloud climatology was very small. The low sensitivity may be due to the relatively high cloud droplet number concentrations in stratocumulus clouds regions in the ISCCP data.

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A number of physical processes have to be accounted for when modeling stratocumulus clouds including cloud top radiative cooling which drives turbulent fluxes in the planetary boundary layer, absorption of shortwave fluxes in the cloud layer, entrainment of warm, dry air from the free atmosphere and microphysical processes. The representation of several of these processes are addressed in the general circulation model ECHAM6 (Stevens et al., 2013) coupled to the aerosol module HAM2 (Zhang et al., 2012) and a two-moment cloud microphysics scheme (Lohmann et al., 2007) in this study.

Section 2 summarizes the methodology to evaluate stratocumulus clouds in a global climate model and observational data used. Section 3 gives a description of the model and experiments conducted, the results from which are presented in Sect. 4. The discussion of the results and conclusions follow in Sect. 5.

2 Methodology and observational data

The focus of this study lies on the representation of marine stratocumulus clouds. The analysis of the experiments is therefore confined to stratocumulus regions (and global values where appropriate). Two approaches have been used in recent years for analysis in different cloud regimes. The first one is based on cloud characteristics where a statistical cluster analysis method is used to identify cloud clusters in joint-histograms of cloud optical depth and cloud top pressure (Jakob and Tselioudis, 2003; Gordon et al., 2005; Williams and Tselioudis, 2007; Zhang, 2007; Williams and Webb, 2009; Tsushima et al., 2013). The second approach is based on dynamic and/or thermodynamic regimes (Tselioudis et al., 2000; Norris and Weaver, 2001; Tselioudis and Jakob, 2002; Bony et al., 2004; Williams et al., 2006; Medeiros and Stevens, 2011). We have used the latter approach as it is straight-forward to apply to a global climate model and provides information for the frequency of occurrence of environmental conditions favorable for stratocumulus clouds.

ACPD
14, 13681–13729, 2014

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We define the stratocumulus regime by:

$$500\,\text{hPa vertical velocity} > 10\,\text{hPa}\,\text{day}^{-1} \tag{1}$$

and to separate trade-wind cumuli from stratocumulus:

$$\text{lower tropospheric stability (LTS} = \theta_{700\,\text{hPa}} - \theta_{1000\,\text{hPa}}) > 18.55\,\text{K} \tag{2}$$

(θ is the potential temperature), following Medeiros and Stevens (2011). Another criterion for the vertical velocity closer to the inversion height e.g. 700 hPa could be used but we found that this makes little difference for defining the stratocumulus regime in ECHAM6-HAM2. Because of the known issues of satellite observations at high zenith angles and over bright surfaces (see e.g. Zygmuntowska et al., 2012) stratocumulus clouds at high latitudes ($> 60^\circ$ N and $> 60^\circ$ S) have been excluded in this analysis. We also exclude all land areas as we focus on marine stratocumulus clouds. Monthly mean values of potential temperature and vertical velocity were used to compute the stratocumulus regime.

For model evaluation we use satellite data and ERA-Interim reanalysis data (Dee et al., 2011). To take into account limitations in satellite observations (e.g. detection thresholds), different definitions of model variables vs. variables in satellite retrievals and different scales of model grids vs. satellite pixels we use the Cloud-Aersol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; Winker et al., 2010) simulator from the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP; Bodas-Salcedo et al., 2011). This simulator also separates cloud cover into high, mid and low cloud fractions according to the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999) definition.

CFMIP also provides satellite data products for the evaluation of climate and weather prediction models (CFMIP-OBS; http://climserv.ipsl.polytechnique.fr/cfmip-obs/). We used the CFMIP-OBS ISCCP, CALIPSO-GOCCP (Chepfer et al., 2010) and Clouds and Earth's Radiant Energy System (CERES) data products. The CFMIP-OBS ISCCP data product is derived from ISCCP (Rossow and Schiffer, 1999) D1 data. Only daytime

ACPD
14, 13681–13729, 2014

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observations are used and averaged over one month. We extended the CFMIP-OBS ISCCP data product using D1 data to cover the time period January 2006 to December 2009. From the cloud top pressure/optical thickness histograms we derived high, mid and low cloud cover by integrating the cloud fraction over the optical thickness at each pressure level. The CFMIP-OBS CALIPSO data product we used covers the time period June 2006 to December 2010. The CERES-Energy Balanced and Filled (EBAF; Loeb et al., 2009) data product covers the time period March 2000 to October 2005.

The total anthropogenic aerosol effect (AAE) is calculated using effective radiative forcing (also called the radiative flux perturbation method) that takes fast feedbacks and interactions into account (cloud lifetime effect, semi-direct effect or aerosol interactions with mixed-phase and ice clouds). Effective radiative forcing is computed as the difference in the top of the atmosphere radiation budget between simulations with and without anthropogenic aerosol emissions using the same sea surface temperatures (Hansen et al., 2005; Haywood et al., 2009; Lohmann et al., 2010; Boucher et al., 2013):

$$\mathrm{AAE} = \Delta F_{\mathrm{all}} = F_{\mathrm{all,PD}} - F_{\mathrm{all,PI}}, \tag{3}$$

where Δ represents the difference between present-day (PD) and pre-industrial (PI) aerosol emissions and F_{all} is the all-sky net radiation flux at the top of the atmosphere.

On the one hand using only grid boxes in the analysis where the environmental conditions are suitable for stratocumulus clouds provides additional information and allows to focus on one cloud regime. Where and when the stratocumulus conditions occur depends on the temporal evolution of the modelled atmospheric conditions. Such a conditional sampling is therefore on the other hand a source of internal variability when comparing different simulations. Global differences by model changes or the anthropogenic aerosol effect are typically much larger than internal variability. In the stratocumulus regime however due to the conditional sampling internal variability can become comparable to model changes or the anthropogenic aerosol effect. Furthermore differences in the stratocumulus regime between simulations cannot be computed as a difference

ACPD
14, 13681–13729, 2014

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of each grid box at each month as it is typically done for global differences. Due to the conditional sampling an averaging step is necessary before two simulations can be compared. Therefore the statistical significance of model changes or the anthropogenic aerosol effect in the stratocumulus regime is highly relevant. Statistical significance is assessed by applying an unpaired two tails t test with unequal variances to yearly mean values over all or specific stratocumulus regions of two simulations which are compared. The null hypothesis is rejected for p values < 0.1 (i.e. differences between the simulations are statistical significant). Results are presented in the Supplement Tables S1 and S2. For differences by model changes (see Sect. 3) the mean values over all stratocumulus regions are computed at once as these were found to be statistically significant (or in the case of including aerosol processing too small to be statistically significant independent of the averaging method). Differences due to anthropogenic aerosol were found to be smaller. We therefore did not average over all stratocumulus regions at once but computed yearly mean values in six stratocumulus regions (see Fig. 4) and compared the differences in these six regions between simulations with present day and pre-industrial aerosol emissions and then took a weighted average (Nam and Quaas, 2013 used a similar approach to evaluate boundary layer clouds in satellite and model data). This raises the statistical significance of some model variables globally as the difference in the simulations in some stratocumulus regions can be larger than the internal variability. When computing the spatial average the different size of the grid boxes is taken into account as a weighting factor. The frequency of occurrence of stratocumulus conditions in the six different stratocumulus regions is used as a weighting factor to compute global values from the values in the six regions.

ACPD
14, 13681–13729, 2014

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3 Model and experiment description

3.1 Model

The general circulation model ECHAM6 (Stevens et al., 2013) coupled to the latest version of the aerosol module HAM2 (Zhang et al., 2012) is used in this study. It includes a two-moment cloud microphysics scheme for cloud droplets and ice crystals where prognostic equations are computed for cloud water, cloud ice, cloud droplet number concentrations and ice crystal number concentrations (Lohmann et al., 2007). The latest version, HAM2.2 includes a size dependent in-cloud scavenging parameterization (Croft et al., 2010) and optionally orographic cirrus clouds (Joos et al., 2010). Hereinafter for the sake of brevity we will refer to it as HAM2. The impact of aerosols on warm, mixed-phase and ice clouds can be studied using ECHAM6-HAM2. In all experiments we use a fractional cloud cover scheme that diagnoses fractional cloud cover from relative humidity when a critical relative humidity is reached (Sundqvist et al., 1989).

The vertical turbulent diffusion scheme uses a 1.5 order turbulence closure scheme, which includes a simplified prognostic equation for turbulence kinetic energy (TKE) with moist Richardson number (Brinkop and Roeckner, 1995).

We made three distinct changes to ECHAM6-HAM2 for this study:

1. Sharp stability function (STAB):
   In the TKE scheme used in ECHAM6, the turbulent diffusivities (K_{Turb}) are the product of the turbulent mixing length (l), a stability function (S) and the square root of TKE:

   $$K_{\text{Turb}} = l \cdot S \cdot \sqrt{\text{TKE}} \tag{4}$$

   The stability function used in ECHAM6 is a so-called "long-tail" function, which decays slowly with increasing Richardson number (see Fig. 1). "Long-tails" functions, also used in numerical weather prediction models, are known to result in

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ACPD

14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

excessive mixing at high stabilities. This artificial increased mixing was introduced to offset a cold bias in the near-surface temperature and too active synoptic cyclones (see Sandu et al., 2013 and references therein). In the European Centre for Medium-Range Weather Forecasts (ECMWF) numerical weather prediction model the mixing at stable conditions was later relaxed to avoid the erosion of capping inversions of the planetary boundary layer and thereby dissipation of stratocumulus clouds (Köhler et al., 2011; Holtslag et al., 2013). Brown et al. (2008) have found improvements of the operational verification scores in a numerical weather prediction model by changes to the boundary layer scheme that included the use of a "short-tail" or "sharp" stability function over the ocean. They also noted that in the Met Office Hadley Centre climate model (HadGEM2; Martin et al., 2011) the "sharp" stability function cloud be used everywhere (ocean and land). Pithan and Mauritsen (2012) have found an increase in subtropical stratocumulus cloud cover and a decrease in trade wind cumulus when using ECHAM6 with a "sharp" function. No near-surface temperature cold bias was apparent with the "sharp" stability function (F. Pithan, personal communication, 2013). In a recent study Possner et al. (2014) have shown that reducing the mixing at high stability improves the simulation of inversions in the regional climate and weather prediction model COSMO.

2. Increased vertical resolution (VRES):
   The low vertical resolution used in global climate models (GCMs) results in numerical artifacts such as numerical entrainment (Lendering and Holtslag, 2000) and spurious radiative-dynamical interactions at the cloud top interface of stratocumulus clouds (Stevens et al., 1999). We therefore increase the vertical resolution in the lower troposphere in ECHAM6-HAM2 (see Fig. 2). Grenier and Bretherton (2001) have shown that a 1.5 order turbulence closure model can provide good simulations of dry convective boundary layers. With 15 hPa vertical resolution also in stratocumulus-capped boundary layers mixing was simulated properly. The performance of the model simulations of Grenier and Bretherton (2001), especially

ACPD
14, 13681–13729, 2014

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at coarser resolution, were depending on further details of the model like the implementation of the entrainment closure and the vertical advection scheme. In the current study we use two new vertical grids: L47bl and L95bl. In both grids the new layers are inserted primarily in the boundary layer/lower atmosphere. To avoid numerical instabilities the time step needs to be increased at higher vertical resolution. From the standard 31 vertical layers (L31) to L47bl the vertical resolution is approximately doubled and the time step is reduced from 720 s to 300 s. With L95bl the vertical resolution is approximately doubled again compared to L47bl or quadruplicated compared to L31 and the time step is reduced to 180 s.

3. Aerosol processing (AP):
Aerosol processing in stratiform clouds by uptake into cloud particles, collision-coalescence, chemical processing inside the cloud particles and release back into the atmosphere changes the aerosol concentration, size distribution, chemical composition and mixing state. By modeling aerosol processing the representation of the mixing state and the size distribution of particles released by evaporation of clouds and precipitation is more realistic. These changes in the aerosol can influence cloud droplet and ice crystal number concentrations and subsequently cloud liquid and ice water paths as well as cloud lifetime and cloud radiative forcing. HAM2 uses seven modes to describe the total aerosol. We adapted the scheme from Hoose et al. (2008a, b) to ECHAM6-HAM2, to extend the seven modes by an explicit representation of aerosol particles in cloud droplets and ice crystals in stratiform clouds, which are each represented by 5 tracers for sulfate (SO_4), black carbon (BC), organic carbon (OC), sea salt (SS) and mineral dust (DU). Aerosol mass transfers by nucleation and impact scavenging, freezing and evaporation of cloud droplets and melting and sublimation of ice crystals are treated explicitly (see Fig. 3). Aerosol particles from evaporating precipitation are released to modes, which correspond to their size.

ACPD
14, 13681–13729, 2014

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3.2 Experiments

The simulations, summarized in Table 1, were conducted with sea surface temperatures and sea ice cover fixed to observed values (AMIP simulations) at T63 spectral resolution using 31 vertical layers (L31) except for the simulations using the new vertical grids. The length of the simulations was 5 years for L31 after 3 months spin-up. Due to the increased computational demand of the higher vertical resolution the VRES simulations were run only for 1 year (+3 months spin-up). Present day (year 2000) greenhouse gas concentrations were used in all simulations. Each experiment is a pair of runs with present day (year 2000) and pre-industrial (year 1850) aerosol emissions from the AeroCom Phase II dataset (ACCMIP by Angelika Heil, Martin Schultz and colleagues, see http://aerocom.met.no/emissions.html; Lamarque et al., 2010). For the evaluation of stratocumulus clouds in the reference experiment and the experiments for the changes above (Sects. 4.1 and 4.2) present day aerosol emissions have been used. For the evaluation of the anthropogenic aerosol effect the experiments where repeated with climatological values for sea surface temperatures and sea ice cover (CLIM simulations) too decrease the internal variability in the experiments (see also Sect. 2).

In addition to the standard experiments a sensitivity simulation with the reference configuration was performed where the precipitation in stratocumulus regions was turned off and another simulation where the parameterization for shallow convective clouds was turned off. Both simulations were run in free mode with climatological sea surface temperatures and sea ice cover for 1 year with present day greenhouse gas and aerosol emissions.

The changes described in Sect. 3.1 lead to an imbalance of the radiative fluxes on top of the atmosphere. The model was therefore re-tuned for the different experiments. Most parameters are kept to the values of the reference simulation and changes are kept to a minimum. Although this may result in being not the optimal parameter settings to be used, the comparison between the different experiments is facilitated. In most

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experiments only the tuning parameter for the autoconversion rate is changed (see Table 1), which by itself has a small effect on AAE (Lohmann and Ferrachat, 2010). The tuning of the experiments with the new vertical grids L47bl and L95bl is described in more detail in Sect. 4.2.2).

4 Results

4.1 Stratocumulus clouds in reference simulation

The stratocumulus conditions (see Sect. 2) are met in ECHAM6-HAM2 in similar areas as in ERA-Interim but less frequently (Fig. 4). This is because large values of LTS occur less often in ECHAM6-HAM2 than in the reanalysis data (the same is true for other GCMs, see Medeiros and Stevens, 2011). The criterion for subsidence is met approximately as frequent in ECHAM6-HAM2 as in ERA-INTERIM. As the conditions of strong LTS and subsidence together are less frequently met in ECHAM6-HAM2, stratocumulus clouds form less often than in ERA-Interim. Cloud properties like cloud cover, liquid water path or cloud radiative effect will therefore be too low compared to observations. The regime based analysis allows to investigate cloud properties only when the environmental conditions for stratocumulus clouds are met (see Sect. 2.) and therefore to separate between in-regime uncertainties and total uncertainties (in-regime plus frequency of occurrence uncertainty). We therefore differentiate in the following between cloud properties in stratocumulus areas (total uncertainty) and stratocumulus regime cloud properties (in-regime uncertainty). As values in the stratocumulus areas include the average frequency of occurrence (≤ 1) of stratocumulus in a model grid they are typically smaller than values in the stratocumulus regime.

In Fig. 5 a clear underestimation of low level cloud fraction (LCC) in stratocumulus cloud regions in the reference simulation compared to CALIPSO/ISCCP satellite data is visible. When looking only at in-(stratocumulus)regime values the underestimation is less severe: on average 48 % of the stratocumulus regions are cloud covered in

ACPD
14, 13681–13729, 2014

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the reference simulation compared to 65 % in CALIPSO data. The low cloud cover is significantly lower in ISCCP compared to CALIPSO, whereas it is vice versa for mid cloud cover (see Supplement Fig. S1) indicating a problem with the cloud top height in stratocumulus regions in the ISCCP data.

Similar to the cloud fraction also the liquid water path (LWP) is too low in the reference simulation as compared to observations in stratocumulus areas (see Fig. 6). ERA-Interim reanalysis data agrees fairly well with Moderate Resolution Imaging Spectroradiometer (MODIS; MYD08_D3 daily mean level 3 cloud product; King et al., 2003) data and the LWP climatology of the University of Wisconsin (UWisc; O'Dell et al., 2008). On the other hand when looking only at the LWP in the stratocumulus regime, the values for LWP are higher in the reference simulation than in ERA-Interim. The apparent underestimation of LWP is therefore due to the less frequent simulation of large LTS in ECHAM6-HAM2.

The shortwave and longwave cloud radiative effects (SWCRE/LWCRE) are too low (see Fig. 7) in the ECHAM6-HAM2 reference simulation compared to CERES data (Loeb et al., 2009). The in-regime value for the shortwave cloud radiative effect of the simulation agrees quite well with the observational data. The LWCRE on the other hand is underestimated also when only grid points that meet stratocumulus conditions are considered. This is not associated with stratocumulus clouds but due to a lack of mid level and high clouds in stratocumulus regions in the reference simulation (see Supplement Figs. S1 and S2). The net cloud radiative effect is therefore too negative in stratocumulus regions in ECHAM6-HAM2.

In Fig. 10 vertical profiles of relative humidity, potential temperature, cloud cover and liquid water content in stratocumulus regions for the reference simulation, the STAB-simulation and ERA-Interim are shown. The inversion in temperature and humidity is not represented well in the reference simulation, which is due mostly to the coarse resolution used in the reference simulation.

ACPD
14, 13681–13729, 2014

The cloud cover and liquid water content profiles show that stratocumulus clouds form too low in the atmosphere and are too shallow in ECHAM6-HAM2. The liquid water content is too high resulting in the observed overestimation of LWP.

The mean diurnal cycle of liquid water path (LWP) in all stratocumulus regions from one month of a ECHAM6-HAM2 simulation is displayed in Fig. 8. Also shown is the diurnal cycle in different regions from Wood et al. (2002) who examined two years of TMI (Tropical Rainfall Measuring Mission Microwave Imager) satellite microwave radiometer data. Wood et al. (2002) found that the diurnal cycle was more pronounced in the SE Pacific and in the SE Atlantic. We therefore chose for a comparison the month of October (2006) when in the SE Pacific and in the SE Atlantic the stratocumulus cloud cover is large. The mean LWP is lower in this particular month as the multiyear average (see Fig. 6). The difference in the morning maximum and the afternoon minimum of LWP, normalized to the mean LWP, in ECHAM6-HAM2 (26 %) agrees quite well with the TMI data (20–28 %, depending on the region).

To summarize, ECHAM6-HAM2 has cloud biases in stratocumulus cloud regions that are typical for GCMs: the cloud form too low and are too shallow, low cloud cover, liquid water path and the shortwave cloud radiative effect are underestimated. When looking only at data points where the environmental conditions are favorable for stratocumulus clouds (in-regime values) these biases are reduced. The simulated diurnal cycle of stratocumulus clouds with ECHAM6-HAM2 agrees well with observations.

4.2 Changes for stratocumulus clouds

4.2.1 Reduced turbulent mixing in stable conditions (STAB)

In Fig. 9 changes in cloud properties are shown when the "long-tail" stability function of ECHAM6-HAM2 is replaced by a "sharp" stability function. Both the cloud cover and the liquid water path increase in the stratocumulus regime whereas in other regions the changes are small. The in-regime low cloud cover increases by 5.3 % and the LWP increases by 8.2 $\mathrm{g\,m^{-2}}$. This leads to a more negative SWCRE by $-2.5\,\mathrm{W\,m^{-2}}$. The

ACPD
14, 13681–13729, 2014

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frequency of occurrence of stratocumulus regions is too low in the STAB experiments compared to reanalysis data and even lower than in the REF experiment (Fig. 4). The global changes in cloud properties by using a "sharp" stability function are rather patchy (see Supplement Fig. S3). In some regions there is an increase in cloud cover and LWP, whereas in other regions there is a decrease. On average these changes almost cancel each other and the averaged change in total cloud cover and liquid water path between the simulation with a "sharp" stability function and the reference simulation is small.

The vertical cloud properties shown in Fig. 10 in the stratocumulus regime reveal subtle changes by using a "sharp" stability function. While stratocumulus clouds still form too low and their vertical extension seems to be limited, cloud cover and liquid water content are reduced above the inversion and reduced below as would be expected by a reduction of mixing at cloud top.

Two one year free simulations with climatological sea surface temperatures and sea ice cover and otherwise the same setup as REF and STAB were conducted to diagnose vertical profiles of the turbulent diffusion coefficients (K_m, K_h), turbulent kinetic energy (TKE) and the stability function in the stratocumulus regime. The results are shown in Fig. 11 and indeed the stability function is decreased above the inversion with the "sharp" stability function. The turbulent kinetic energy (TKE) increases slightly in the cloud layer with the "sharp" stability function and decreases above. Due to the coarse vertical resolution TKE is produced in the cloud layer rather than at its top.

4.2.2 Increased vertical resolution (VRES47, VRES95, VRES47 + STAB)

An increase of the vertical resolution leads to a degradation of the simulations as parameters used in the parameterization of sub grid processes may depend on the resolution. In a sensitivity simulation an autoconversion rate parameter (ccraut) of 12 was necessary to achieve a balance of radiative fluxes at the top of the atmosphere. This large autoconversion rate leads to more precipitation in the stratocumulus regime as well as strong reductions in cloud cover and liquid water path. For the experiments with increased vertical resolution we used therefore tuning parameters that have no strong

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effect on stratocumulus clouds in the model if possible. For L47bl ccraut was kept as in the reference simulation and a parameter for the entrainment rate of deep convection was adjusted instead. For L95bl ccraut = 12 was necessary in addition to the adjustment in the entrainment rate of deep convection to achieve radiation balance. Mean zonal winds, surface pressure and ocean surface stress are very similar to reanalysis data and the reference simulation in the VRES experiments. For L95bl the zonal winds are weaker in the Pacific storm-tracks but this small difference should not affect stratocumulus regions.

The increase of the vertical resolution has an ambiguous impact on stratocumulus clouds. Figure 12 shows that with L47bl the already small low cloud cover and the LWP in stratocumulus regions decrease and the net cloud radiative effect is less negative compared to L31 in the reference simulation. The decrease in low clouds is compensated partly by an increase in mid-level clouds but the total cloud cover decreases with L47bl in stratocumulus regions (not shown). The cloud cover in regions of shallow convective clouds increases and compensates the decrease in stratocumulus regions whereas other regions show only small changes. The vertical profiles of relative humidity and potential temperature do not change significantly with L47bl in the stratocumulus regime compared to the reference simulation (see Fig. 13). The clouds seem to form higher up in the atmosphere but the cloud cover and the liquid water content are reduced. Increasing the vertical resolution further has a somewhat different effect. With the highest vertical resolution grid L95bl used in this study there is an increase in cloud cover and liquid water path in the stratocumulus regime (Fig. 12). This increase in cloud cover and LWP is in areas where also shallow cumulus clouds may appear and not in the “core” stratocumulus regions, which show the same decrease of cloud cover and LWP as in the VRES47 simulation. In VRES95 the vertical cloud properties are improved further i.e. the clouds form higher up in the atmosphere and their vertical extent agrees better with reanalysis data. That there is no clear improvement in ECHAM6-HAM2 when increasing the vertical resolution is in agreement with other studies. Stevens et al. (2007) have shown that LWP and the planetary boundary layer

ACPD
14, 13681–13729, 2014

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(PBL) depth are underestimated in ERA-40 (Uppala et al., 2005) and ERA-15 (Gibson et al., 1997) although the vertical resolution was increased from ERA-15 to ERA-40. With the Köhler (2005) PBL scheme the representation of stratocumulus clouds was improved in the ECMWF model without increasing the vertical resolution. Although increasing the vertical resolution in single column models often improves the representation of stable/cloudy boundary layers (Grenier and Bretherton, 2001; Zhu et al., 2005; Wyant et al., 2007; Gettelman and Morrison, 2014) the same must not necessarily be true in a global model. Feedbacks between the dynamics and the physical parameterizations can cause differences in the biases of a parameterization in a global model and a single column model (Petch et al., 2007; Zhang et al., 2013).

The vertical profiles of relative humidity and cloud properties improve with the L95bl-resolution and are quite similar to reanalysis data. The clouds are forming higher up in the atmosphere and have a larger vertical extent (see Fig. 13). The higher cloud cover and LWP at higher altitudes in the VRES experiments compared to ERA-Interim and the lower cloud cover and LWP at lower altitudes indicate too much turbulent and convective vertical transport at the cloud top in the VRES experiments. There are still too few stratocumulus clouds even with L95bl in ECHAM6-HAM2 as only the cloud cover in stratocumulus regions increases whereas the frequency of occurrence of those regions is still too low or even lower in the VRES experiments compared to reanalysis data (Fig. 4). The increased stratocumulus cloud height and height of the humidity inversion are not due to changes in the depth of the PBL. The PBL depth actually decreases slightly with increased vertical resolution globally and in the stratocumulus regime compared to the reference simulation. A comparison of the frequency of 500 hPa vertical velocities of the REF experiment and ERA-Interim data revealed a higher fraction of small subsidence velocities ($> 10\,\text{hPa}\,\text{day}^{-1}$) in the REF experiment. As there is almost no change in the frequency of subsidence velocities at higher vertical resolution compared to the reference simulation the decrease in PBL depth does not seem to be due to changes in subsidence. As the Richardson number based PBL depth diagnosed in ERA-Interim is biased low compared to radiosonde data (von Engeln and Teixeira,

ACPD
14, 13681–13729, 2014

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2013), we have compared the PBL depth diagnosed in ECHAM6-HAM2 to a PBL depth climatology derived from ECMWF reanalysis data (von Engeln and Teixeira, 2013). The PBL depth diagnosed in ECHAM6-HAM2 agrees qualitatively well with this climatology (not shown).

In the VRES47 + STAB experiment the clouds in the stratocumulus regime are even further reduced as in the VRES47 experiment. The low cloud cover is lower by −11.4 %, LWP decreases by $-9.7\,\mathrm{g\,m^{-2}}$ and SWCRE by $11.5\,\mathrm{W\,m^{-2}}$ in the stratocumulus regime compared to the REF experiment (not shown). The vertical cloud properties are less similar to reanalysis data in the VRES47 + STAB experiment than in the VRES47 experiment. The cloud cover is further reduced around 900 hPa but too high around 800 and 1000 hPa. The vertical profile of liquid water content changes similar to the cloud cover when the "sharp" stability function is used together with the L47bl vertical grid. The liquid water content is reduced around 900 hPa but larger close to the surface in the VRES47 + STAB experiment than in VRES47. Around 800 hPa the liquid water content in the VRES47 + STAB and VRES47 experiments is too large compared to reanalysis, irrespective of the stability function used. This indicates that convective transport is too large around 800 hPa in the stratocumulus regime.

4.2.3 Aerosol processing in stratiform clouds (AP, STAB + AP)

The cloud condensation nuclei concentration at 0.1 % supersaturation roughly doubles in the AP experiment compared to the reference simulation in the stratocumulus regime while the cloud droplet number concentration only increases by 13 %. Although the aerosol load, aerosol size distribution and mixing state change when using in-cloud aerosol processing (not shown), this hardly affects cloud properties in stratocumulus cloud regions. In a simulation with aerosol processing the cloud cover is lower by 0.3 %, LWP increases by $0.4\,\mathrm{g\,m^{-2}}$ and NETCRE by $0.8\,\mathrm{W\,m^{-2}}$ in the stratocumulus regime. The frequency of occurrence of stratocumulus regions is similar to the REF experiment (see Fig. 4). Also the vertical profiles of relative humidity, potential temperature, cloud cover and liquid water content in stratocumulus regions are similar to the reference sim-

ACPD
14, 13681–13729, 2014

ulation. In-cloud aerosol processing seems to alter only the aerosol in stratocumulus regions not the clouds.

In the experiment STAB + AP where the "sharp" stability function and aerosol processing are used together the stratocumulus clouds are very similar to the STAB experiment. The low cloud cover is higher by 4.8 %, LWP increases by 15.5 $g\,m^{-2}$ and SWCRE by $-4.4\,W\,m^{-2}$ in the stratocumulus regime compared to the REF experiment (not shown). Turbulent mixing at the top of the boundary layer also affects the aerosol. The AOD is slightly lower in the STAB + AP experiment than in the AP experiment.

4.3 Anthropogenic aerosol effect

In Fig. 14 the total anthropogenic aerosol effect (AAE) is shown globally. Stratocumulus regions are regions of a strong negative AAE as are regions close to the industrial centers of the world and biomass burning regions. Table 2 lists AAE and other parameters for all experiments globally and in the stratocumulus regime. For the computation of the change in the aerosol effect in the stratocumulus regime (AAE_{Sc}) the stratocumulus conditions have been computed for the present day and pre-industrial aerosol simulations separately. There are differences in the appearance of these conditions in both space and time between present day and pre-industrial aerosol simulations due to internal variability. This variability can be comparable to the anthropogenic aerosol effect. Regionally averaged values for the stratocumulus regime were therefore computed (see Sect. 2; Table 2).

Figure 15 shows the change in AAE between the reference simulation and simulations with the "sharp" stability function (STAP), aerosol processing (AP) and increased vertical resolution (VRES47, VRES95) respectively. In the experiment with the "sharp" stability function the change in LWP between the simulation with present day and pre-industrial aerosol and the change in cloud cover are comparable to the reference experiment (see Table 2). AAE increases globally ($-0.25\,W\,m^{-2}$) and in the stratocumulus regime in the STAB experiment. The global increase in AAE is actually due to a stronger decrease of the longwave aerosol forcing than the shortwave aerosol forcing. Aerosol

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

number and mass are reduced by approx. 10 % in the stratocumulus regime with the "sharp" stability function whereas global mean values of aerosol number and mass are similar for the STAB and REF experiments. The reduction in background aerosol load in the stratocumulus regime with the "sharp" stability function and the accompanied increased susceptibility of AAE_{Sc} to anthropogenic aerosol (Carslaw et al., 2013) as well as the larger changes of LWP_{Sc} and LCC_{Sc} can explain the increase in AAE_{Sc} in the STAB experiment compared to the reference experiment.

There is a reduction in AAE compared to the reference simulation in the experiment with aerosol processing i.e. in regions of a negative AAE in the reference simulation, AAE becomes less negative; in regions of a positive AAE in the reference simulation, AAE becomes less positive and in the global average AAE is less negative. In the AP experiment the background aerosol is increased. This leads to a reduced susceptibility of the clouds to anthropogenic aerosol. The reduction occures everywhere on the globe in the simulation with aerosol processing. Both shortwave and longwave forcings are weaker but on average the forcing becomes less negative ($-1.08\,\mathrm{W\,m^{-2}}$ compared to $-1.19\,\mathrm{W\,m^{-2}}$ in the reference simulation globally).

Running the model with the "sharp" stability function and aerosol processing together (STAB + AP) further amplifies the reduction in AAE. In the stratocumulus regime AAE_{Sc} also seems to decrease in the STAB + AP experiment but the differences between present day and pre-industrial aerosol simulations are too small to be significant compared to internal variability.

In the VRES47 experiment both shortwave and longwave aerosol forcing increase compared to the REF experiment. The resulting AAE is stronger in VRES47 than in REF. The change in the shortwave and longwave aerosol forcing comes probably from changes in cloud regimes due to the increased vertical resolution and different entrainment rates for deep convection. In the stratocumulus regimes there is a similar strong increase in AAE_{Sc} in the VRES47 experiment as globally.

Combining the increased vertical resolution with the "sharp" stability function (VRES47 + STAB) leads to a more negative AAE globally compared to the reference

ACPD
14, 13681–13729, 2014

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experiment and similar AAE compared to VRES47. This is due to decreased shortwave and longwave aerosol forcing that compensate each other compared to the VRES47 experiment. The shortwave aerosol forcing is smaller in the stratocumulus regime in VRES47 + STAB but AAE_{Sc} is quite similar to VRES47 and STAB.

In the VRES95 experiment AAE is strongly increased. This is due to a lower aerosol load in the present day and pre-industrial aerosol simulations at this high vertical resolution and the subsequent increased susceptibility to anthropogenic aerosol. In the stratocumulus regime a similar strong increase compared to REF in AAE_{Sc} is observed.

5 Discussion and conclusions

We have identified several reasons for the cloud biases in regions with high stratocumulus cloud cover in ECHAM6-HAM2. The biases are typical for global models: the clouds form too low and are too shallow, low cloud cover, liquid water path and the shortwave cloud radiative effect are underestimated. In the stratocumulus regime (diagnosed by environmental conditions) these biases are reduced. Reasons for these biases are a too strong turbulent mixing at stable conditions, a too "active" shallow convective scheme, the relative humidity based cloud cover scheme, a lack of vertical resolution and possibly too low subsidence rates.

Environmental conditions suitable for stratocumulus clouds appear not frequent enough in ECHAM6-HAM2 compared to reanalysis data mainly due to a too low LTS. The underestimation of the frequency of stratocumulus conditions appears in all simulations conducted in this study, in particular also in the simulations with reduced turbulent mixing at the top of the stratocumulus clouds and increased vertical resolution. Subsidence rates are lower in ECHAM6-HAM2 than in ERA-Interim which might explain the lack of inversions.

At high vertical resolution the vertical cloud properties indicate a too strong mixing at the top of stratocumulus clouds in ECHAM6-HAM2 and too much convective transport. The turbulent mixing at stable conditions can be reduced by using a "sharp" stability

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function in the TKE scheme of ECHAM6. This improves stratocumulus cloud cover and liquid water path but changes the vertical cloud properties only modestly. The stratocumulus cloud cover in ECHAM6-HAM2 at high vertical resolution goes higher up but is smaller at lower altitudes than in ERA-Interim. This may be explained by too strong entrainment of warm, dry free tropospheric air into the PBL, which is reduced with the "sharp" stability function, and too much convective transport of moisture to higher levels.

The improvement by using a "sharp" stability function is not enough to reconcile the simulated low cloud cover with that of satellite observations. Improving the simulation of stratocumulus clouds in ECHAM6-HAM2 would require multiple changes to different parts of the model that are causing the model biases in the stratocumulus regime.

Another reason for the lack of stratocumulus clouds appears to be the over-active shallow convection scheme in ECHAM6-HAM2. Isotta et al. (2011) have shown that the Tiedtke-shallow-convection scheme (Tiedtke, 1989) used in ECHAM5-HAM (Roeckner et al., 2003; Stier et al., 2005; also used in ECHAM6-HAM2) activates too frequently compared to large eddy simulations and observations of the frequency of cumulus clouds. Their transient shallow-convection scheme decreased the frequency of shallow convection which was compensated by increased stratus and stratocumulus (a similar decrease of shallow-convection frequency and increase of LWP in the stratocumulus regime was observed in the VRES95 experiment, see Supplement Fig. S4). In a recent study Nam et al. (2014) compared three boundary layer cloud schemes in ECHAM5 to CALIPSO and CloudSat satellite observations and found that two schemes, that separately calculate shallow convection, reduced its frequency. All three schemes improved low cloud cover and precipitation in the (sub)tropics (note that their ECHAM5_Trig model is similar to what is used in ECHAM6).

By turning off shallow convection completely in a sensitivity study we found stratocumulus clouds are forming higher up and are thicker. The improvement is almost as large as by increasing the vertical resolution. Turning off shallow convection also increased the low cloud cover in the stratocumulus regime. Changing the shallow con-

ACPD
14, 13681–13729, 2014

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vection scheme in ECHAM6 would probably be beneficial for representing stratocumulus clouds.

A sensitivity study where precipitation in the stratocumulus regime was turned off showed an impact mainly on liquid water path, cloud optical properties and cloud radiative effects. LWP and cloud optical depth (COD) approximately double in the stratocumulus regime without precipitation compared to the reference simulation and SWCRE is increased by 21 % resulting in a more negative net cloud radiative effect (NETCRE). The low cloud cover increases only by 3 % from 47.7 % to 50.7 %. As the LWP in the stratocumulus regime is already larger in the reference experiment than in observations this strong increase in LWP by turning off precipitation which hardly affects low cloud cover indicates that the relative humidity based cloud cover scheme used for the simulations produces not enough cloud cover in the stratocumulus regime (see also Fig. 5).

The diurnal cycle of stratocumulus clouds modeled in ECHAM6-HAM2 agrees well with observations.

Stratocumulus clouds in ECHAM6-HAM2 form too low and are too shallow. With an increased vertical resolution the clouds are forming higher up and are quite similar too the clouds in the ERA-Interim stratocumulus regime. A simple increase of the vertical resolution (at unchanged horizontal resolution) improves the vertical cloud properties in the stratocumulus regime but affects other parts of the model and leads to a degradation of the simulation. Diagnosing the actual inversion height (cloud top) in stratocumulus regions as in the schemes of Grenier and Bretherton (2001; applied to ECHAM5-HAM in Siegenthaler-Le Drian, 2010) could improve stratocumulus clouds while keeping the interaction with other parts of the model at a minimum.

The cloud droplet number concentration is quite stable in the stratocumulus regime as it increases only by 23 % in the sensitivity study with precipitation turned off in the stratocumulus regime and it also increases only by 13 % in the aerosol processing experiment where the cloud condensation nuclei concentration (CCN) approximately doubles. The CCN concentrations did not increase by turning off precipitation in the

ACPD
14, 13681–13729, 2014

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stratocumulus regime so we observed no indication of the bistability of CCN concentrations as hypothesized by Baker and Charlson (1990). Aerosol processing in stratiform clouds has a small impact on cloud properties in ECHAM6-HAM2 but it reduces the anthropogenic aerosol effect. Including aerosol processing and all other changes made affect the anthropogenic aerosol effect (AAE) globally and in the stratocumulus regime. Aerosol processing decreases AAE globally compared to the reference simulation. The "sharp" stability function and VRES47 lead to an increase in AAE and VRES95 strongly increases AAE globally. AAE in the stratocumulus regime is generally stronger than in the global mean and so are typically the changes between the different experiments. For simulations of the anthropogenic aerosol effect it is therefore of importance to have a good representation of stratocumulus clouds.

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ACPD
14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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ACPD
14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

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Table 1. Description of experiments conducted in this study.

Label	Vertical Resolution	Tuning factor of the auto-conversion rate (ccraut)	Description	Sea surface temperature and sea ice cover	Other changes
REF	L31	4	control simulation	AMIP/CLIM	
STAB	L31	3.5	modified stability function	AMIP/CLIM	
VRES47	L47bl	4	additional model layers (47 layers in total)	AMIP/CLIM	Reduced entrainment deep convective clouds
VRES95	L95bl	12	additional model layers (95 layers in total)	AMIP/CLIM	Reduced entrainment deep convective clouds
AP	L31	5	in-cloud aerosol processing	AMIP/CLIM	
STAB + AP	L31	5	STAB + AP	AMIP/CLIM	Tuning as STAB
VRES47 + STAB	L47bl	4	VRES47 + STAB	AMIP/CLIM	Tuning as VRES47
NOPRECIP	L31	4	Sc-precipitation turned off	CLIM	
NOSHCV	L31	4	shallow convective cloud parameterization turned off	CLIM	

ACPD
14, 13681–13729, 2014

Table 2. Changes in aerosol, cloud and forcing parameters between simulations with pre-industrial and present day aerosol for all experiments. Global values and values in the stratocumulus regime are given. Note that the results with L47bl and L95bl are from one year simulations. LWP is liquid water path, CC is cloud cover, AAE is the anthropogenic aerosol effect, τ_{anth} the anthropogenic aerosol optical depth, $\Delta\tau$ the change in aerosol optical depth and Δ precip the change in large scale precipitation. The subscript $_{Sc}$ represents values in the stratocumulus regime. Values marked by * are not statistically significant or could not be tested for statistical significance.

Variable	Experiment (PD-PIaer)						
	REF	STAB	AP	STAB + AP	VRES47	VRES95	VRES47 + STAB
ΔLWP ($g\,m^{-2}$)	6.5	6.4	5.0	4.4	8.3	7.4	8.5
ΔCC	0.5	0.4	0.3	0.2	1.2	0.9	0.7
AAE ($W\,m^{-2}$)	−1.19	−1.34	−1.08	−0.90	−1.84	−2.30	−1.89
AAE_{SW} ($W\,m^{-2}$)	−2.12	−2.09	−1.72	−1.36	−3.41	−3.51	−3.03
AAE_{LW} ($W\,m^{-2}$)	0.94	0.75	0.65	0.46	1.33	1.19	0.88
τ_{anth} (@550 nm)	0.019	0.018	0.026	0.012	0.013	0.012	0.018
ΔLWP_{Sc} ($g\,m^{-2}$)	6.6	9.5	5.3	2.8*	9.9*	12.6*	10.5*
AAE_{Sc} ($W\,m^{-2}$)	−2.95	−3.55	−2.90	−2.17*	−3.60*	−7.78*	−3.52*
$AAE_{Sc/SW}$ ($W\,m^{-2}$)	−2.95	−4.49	−2.69*	−1.81*	−5.08*	−7.48*	−4.01*
$\Delta\tau_{Sc}$ (@550 nm)	0.006	0.009	0.010	0.000	0.000*	−0.009*	0.025*

ACPD
14, 13681–13729, 2014

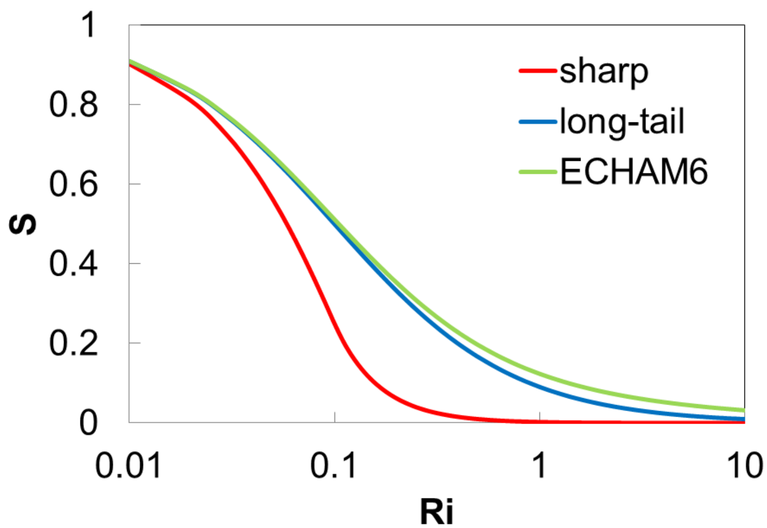

Figure 1. Comparison of "sharp", "long-tail" and ECHAM6 stability function S (Eq. 4; dimensionless) as a function of Richardson number (Ri).

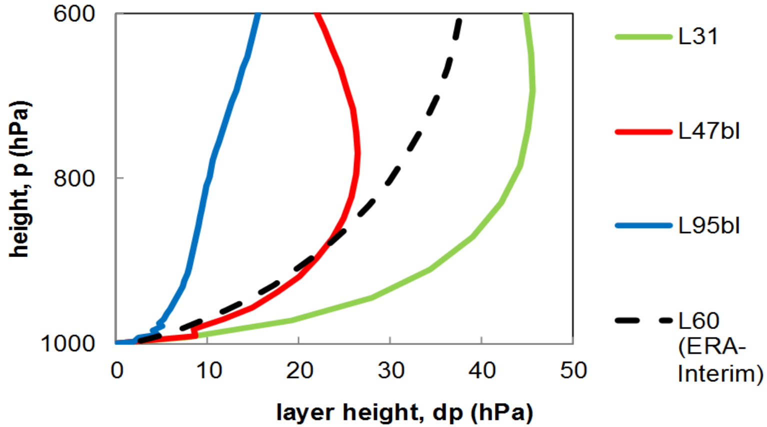

Figure 2. Vertical resolution of the reference L31 vertical grid and new L47bl and L95bl grids as well as the L60 vertical grid used in ERA-Interim. The (pressure) height of the model layers is shown as a function of the height above the surface for a surface pressure of 1000 hPa.

ACPD
14, 13681–13729, 2014

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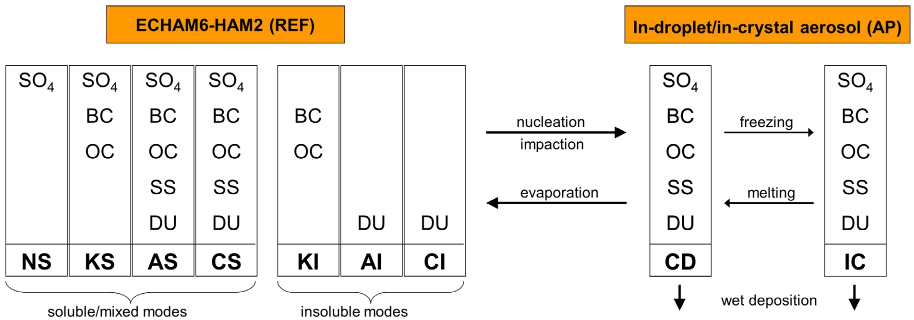

Figure 3. Processes and tracers used in the aerosol processing scheme. To the tracers for the soluble/mixed modes of HAM2 (nucleation (NS), Aitken (KS), accumulation (AS), coarse (CS)) and insoluble modes (Aitken (KI), accumulation (AI), coarse (CI)) new tracers for aerosol particles in cloud droplets (CD) and ice crystals (IC) are added.

ACPD
14, 13681–13729, 2014

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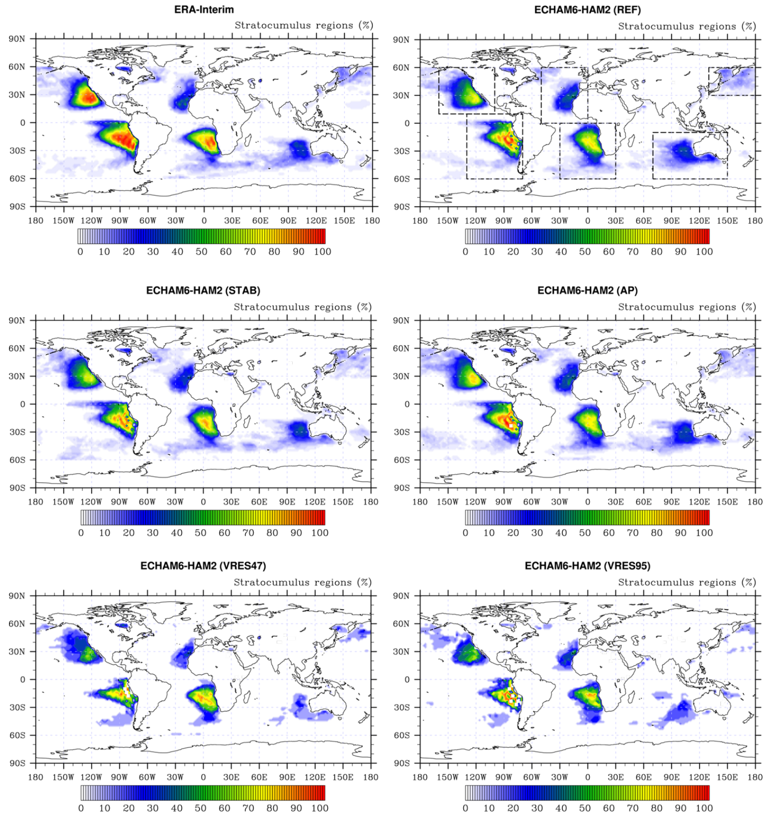

Figure 4. Frequency of occurrence of stratocumulus conditions in ERA-Interim and ECHAM6-HAM2 in the REF, STAB, AP, VRES47 and VRES95 experiments. In the panel for the REF experiment are also the six stratocumulus regions shown which are used in assessing the effect of anthropogenic aerosol.

ACPD
14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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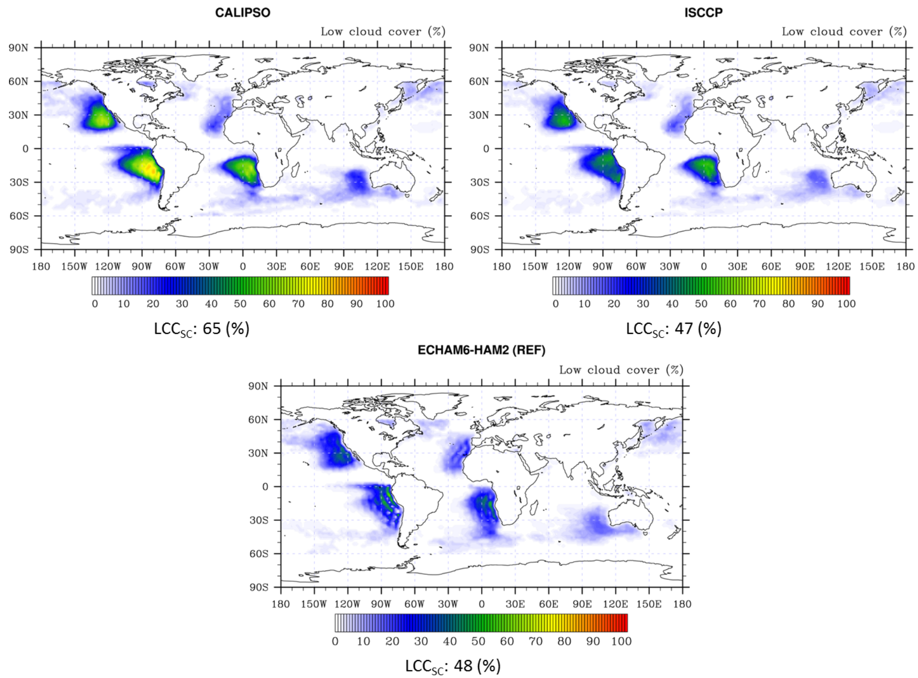

Figure 5. Low level cloud cover in stratocumulus cloud regions in the reference simulation and the CALIPSO and ISCCP satellite data. Values below each panel show in-regime values (subscript $_{\mathrm{Sc}}$). Note that in-regime values are larger than the mean over the stratocumulus cloud regions.

ACPD
14, 13681–13729, 2014

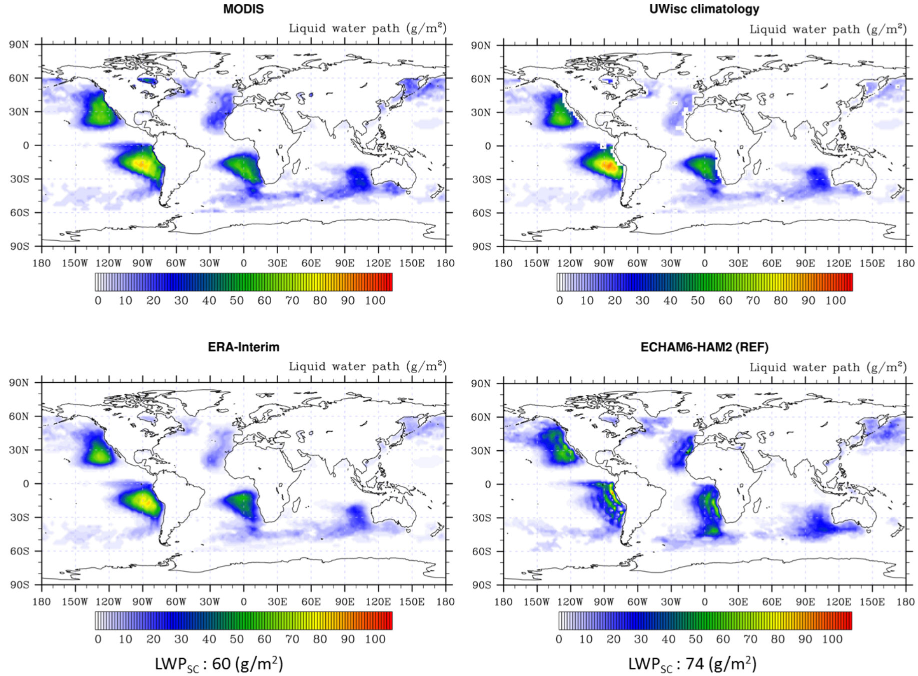

Figure 6. Liquid water path in stratocumulus cloud regions in the reference simulation, MODIS, ERA-Interim and a climatology from the University of Wisconsin. Values below the panels are in-regime values.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

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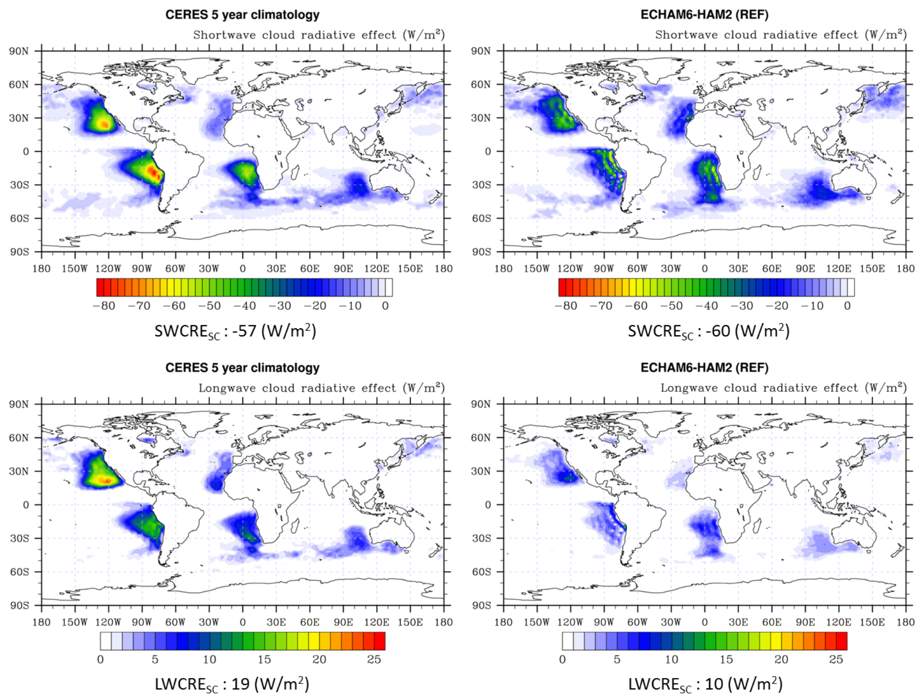

Figure 7. Shortwave and longwave cloud radiative effect in stratocumulus cloud regions in the reference simulation and a 5 years CERES climatology. Values below each panel are in-regime values.

ACPD
14, 13681–13729, 2014

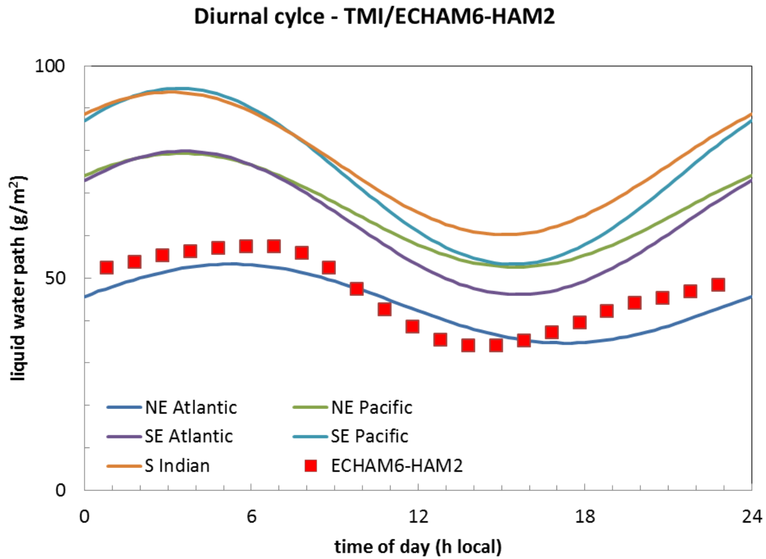

Figure 8. Diurnal cycle of liquid water path from TMI microwave radiometer data in different regions in 1999–2000 and ECHAM6-HAM2 in the stratocumulus regime in October 2006.

ACPD
14, 13681–13729, 2014

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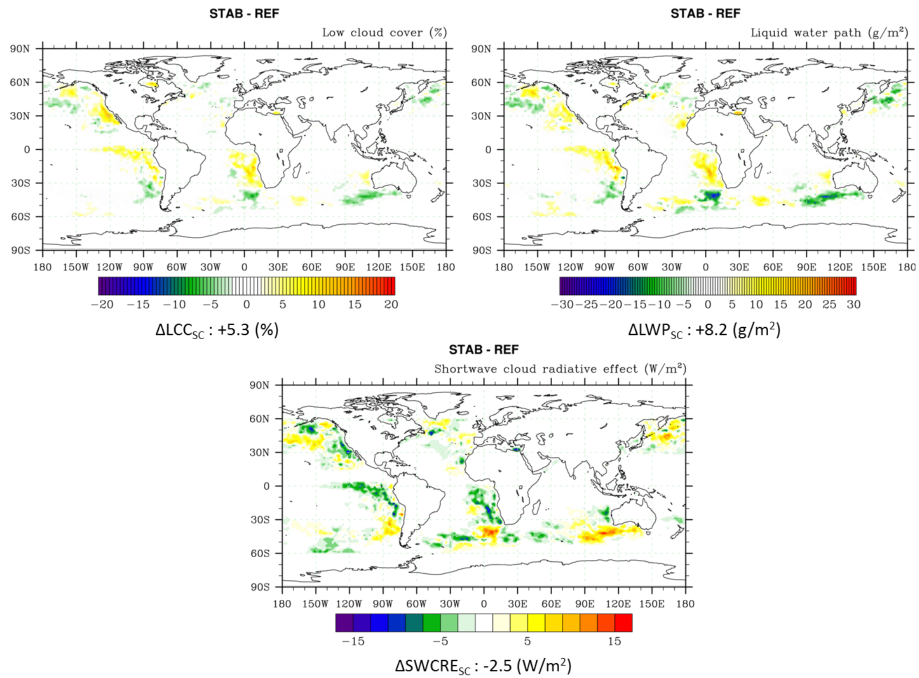

Figure 9. Difference in low cloud cover, LWP and SWCRE in stratocumulus regions between a simulation with a "sharp" stability function and the reference simulation. Values below each panel are in-regime values.

ACPD
14, 13681–13729, 2014

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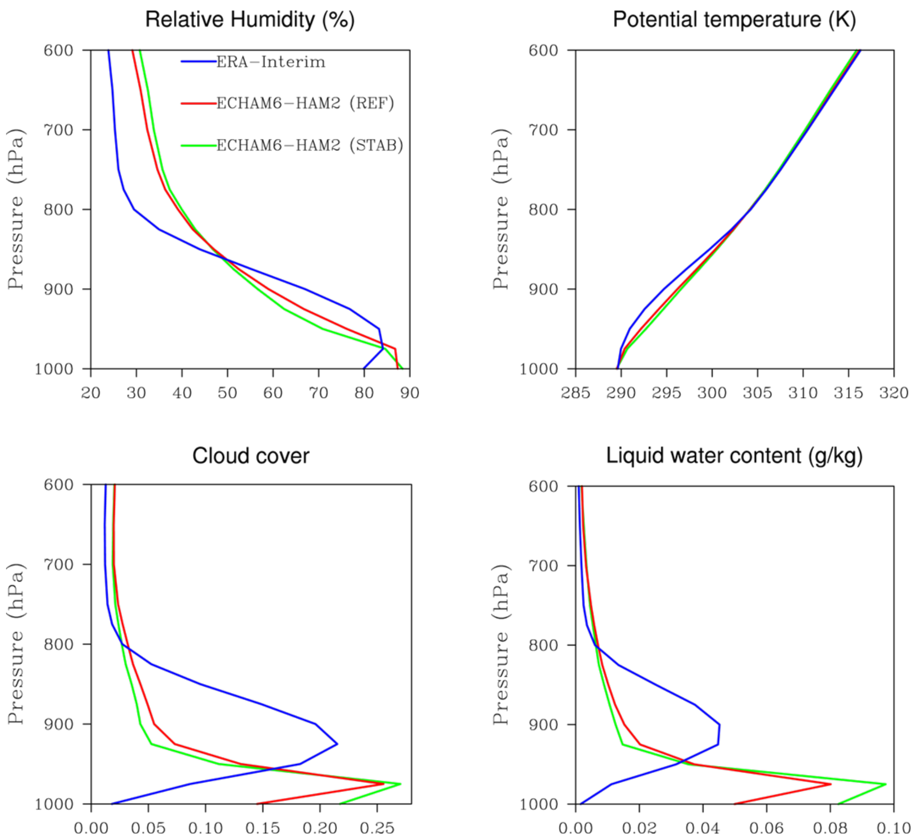

Figure 10. Vertical profiles of relative humidity, potential temperature, cloud cover and liquid water content in the stratocumulus regime. The red line is for the ECHAM6-HAM2 reference simulation, the green line for the STAB-simulation and the blue line for ERA-Interim data.

ACPD
14, 13681–13729, 2014

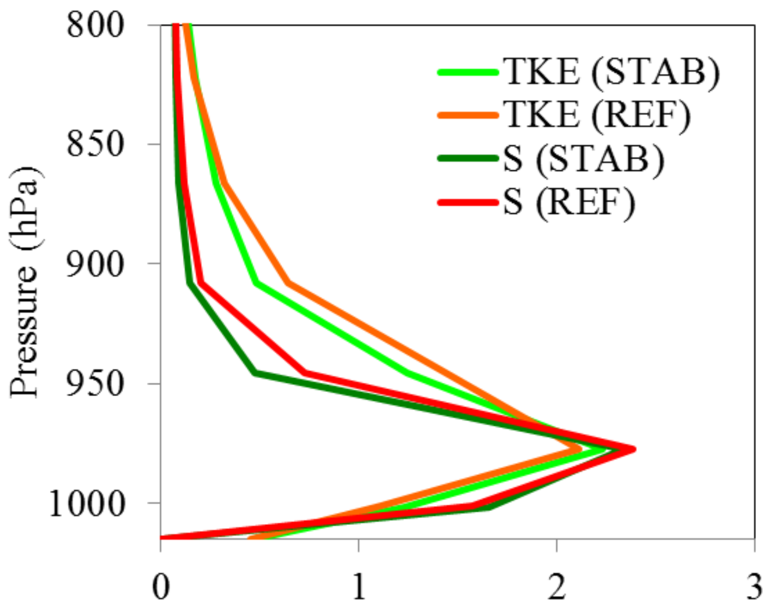

Figure 11. Vertical profiles of turbulent kinetic energy (TKE in $m^2\,s^{-2}$) and the stability function (dimensionless) are shown in the stratocumulus regime. The red and orange lines are for the ECHAM6-HAM2 reference simulation, the light and dark green lines for the STAB-simulation.

ACPD
14, 13681–13729, 2014

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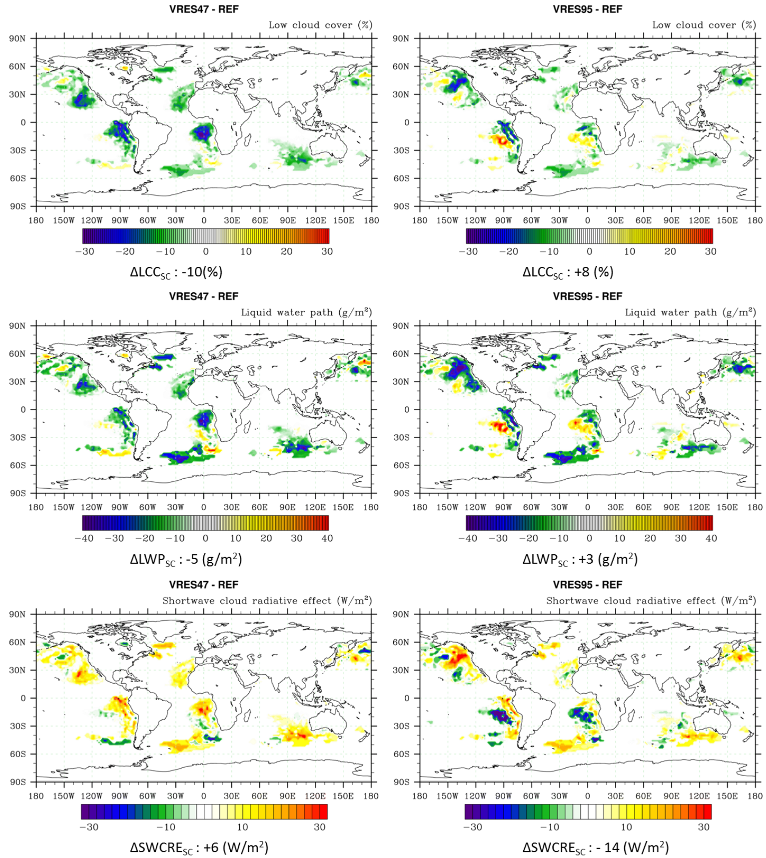

Figure 12. Same as in Fig. 9 but for increased vertical resolution (L47bl and L95bl). Values below each panel are in-regime values.

ACPD
14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▌ | ▶▌
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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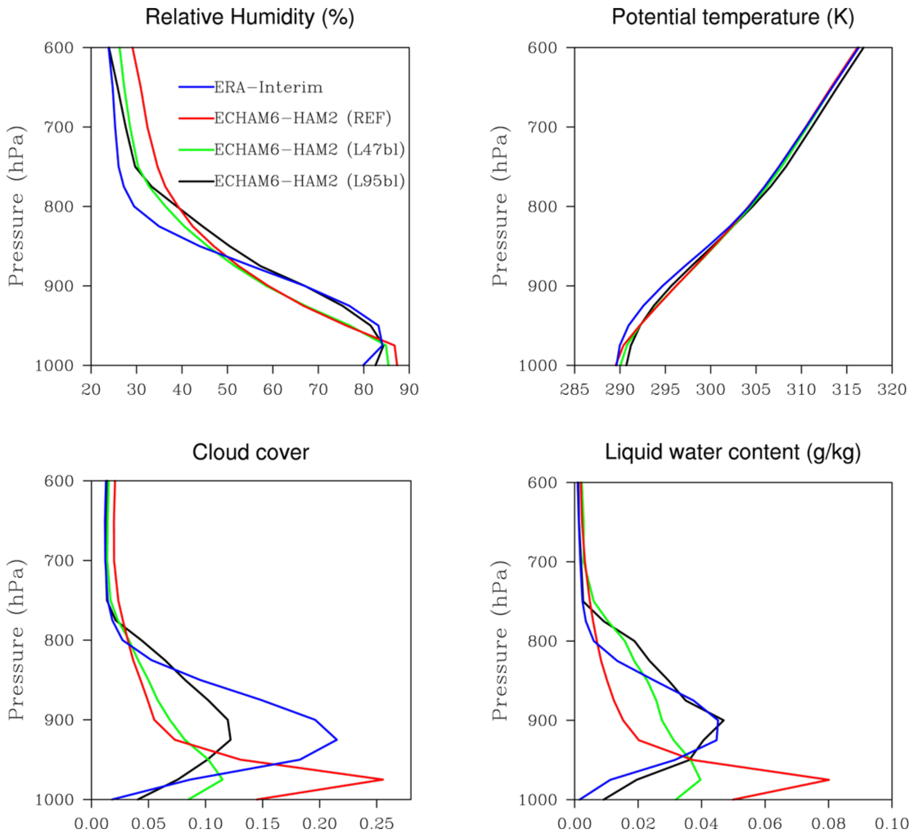

Figure 13. Vertical profiles of relative humidity, potential temperature, cloud cover and liquid water content in stratocumulus regions (in-regime values). The green line is for a simulation with the L47bl vertical grid, the black line for L95bl, the red line is for the ECHAM6-HAM2 reference simulation and the blue line for ERA-Interim data.

ACPD
14, 13681–13729, 2014

Impact of the representation of marine stratocumulus clouds on the AAE

D. Neubauer et al.

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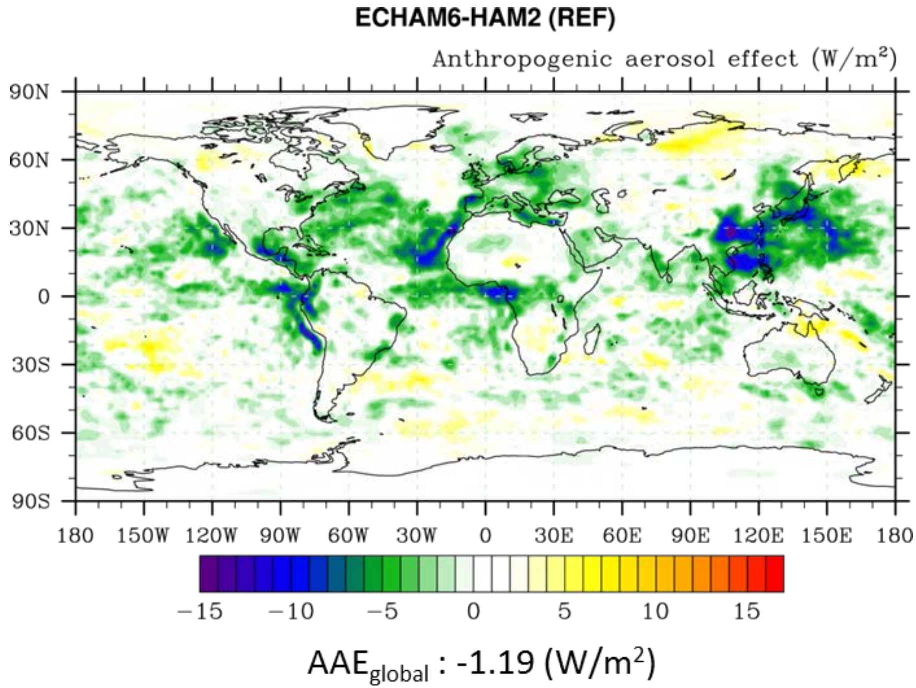

Figure 14. The total anthropogenic aerosol effect (AAE) is shown globally. Below the panel the average value is shown.

ACPD
14, 13681–13729, 2014

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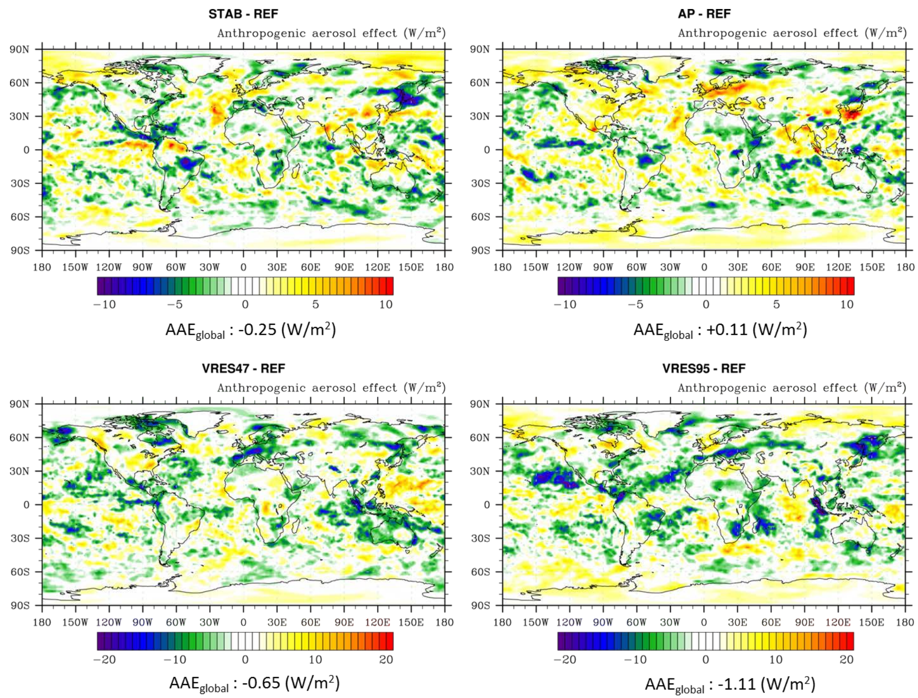

Figure 15. The change in AAE between the STAB, AP, VRES47 and VRES95 simulation and the reference simulation is shown globally. Values below each panel are average values for the areas above.

ACPD
14, 13681–13729, 2014

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