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Cloud representation in General Circulation Models over the Northern Pacific Ocean: A EUROCS intercomparison study.

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SUMMARY

The EUROCS (EURopean Cloud Systems Study) project aims to improve the treatment of cloud systems in regional and global climate and weather prediction models. This paper reports an intercomparison study of cloud representation over the Pacific Ocean for 9 climate and weather prediction models. The study consists of an analysis of a June/July/August 1998 period along an idealized trajectory over the Pacific Ocean that encompasses both the ascending and descending branch of the Hadley Circulation. The three cloud types that are studied by EUROCS, stratocumulus, shallow cumulus and deep convective cloud systems, do all occur in a persistent and geographically separated way, along this trajectory.

The main focus of this study is on processes related to the hydrological cycle within the Hadley Circulation. These include the large scale dynamics, i.e. the strength of the up- and down-welling branches of the Hadley cell, the cloud processes, i.e. cloud cover, cloud amounts and precipitation, and the impact of these processes on the radiation budget both at the top of the atmosphere and at the ocean's surface.

In order to make a quantitative assessment, special care has been taken to select reliable observational data sets. The main conclusions are that i) almost all models strongly under-predicted both cloud cover and cloud amount in the stratocumulus regions while ii) the situation is opposite in the trade wind region and the tropics where cloud cover and cloud amount are over-predicted by most models. This deficiencies result in a over-prediction of the down-welling surface shortwave radiation of typically 60 W m^{-2} in the stratocumulus regimes and a similar under-prediction of 60 W m^{-2} in the trade wind regions and in the Inter Tropical Convergence Zone (ITCZ). Similar biases for the shortwave radiation were found at the top of the atmosphere while discrepancies in the outgoing longwave radiation (OLR) are most pronounced in the ITCZ.

KEYWORDS: clouds convection radiation

1. INTRODUCTION

The representation of clouds in general circulation models (GCM's) remains one of the most important and yet unresolved issues in atmospheric modeling. This is partially due to the overwhelming variety of clouds observed in the atmosphere and even more so due to the large number of physical processes governing cloud formation and evolution as well as the great complexity of their interactions. Model improvement necessarily begins with an assessment of current model performance and the identification of model shortcomings. For cloud parameterizations a number of assessment techniques have been developed and applied ranging from broad model climate evaluation to detailed process case studies.

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The EUROCS (EURopean Cloud Systems Study) project aims to improve the treatment of cloud systems in regional and global climate and numerical weather prediction (NWP) models. The strategy used in EUROCS is based on the use of a hierarchy of models and observations to integrate cloud studies across the full range of scales: improved parameterizations of cloud processes are developed by comparing single column model (SCM) simulations to cloud resolving models (CRM) and large eddy simulation (LES) models for a number of well documented cases. This technique has been pioneered by the GEWEX Cloud System Study (GCSS) (Browning 1993; Randall *et al.* 2003) and is now considered a well established approach to model evaluation and improvement. It relies on results of a small number of isolated case studies carried out for various cloud types such as stratocumulus, shallow cumulus and deep convective clouds. While extremely useful in identifying flaws in the formulation of parameterizations, it is not immediately obvious how to transfer findings of those studies to the full GCM. This is partly due to the (desired) absence of feedback processes onto the large scale in SCM/CRM/LES studies, but also results from the possibility that the large-scale conditions prescribed in the SCM/CRM simulations might be non-representative for both the real and model atmospheres.

Jakob (2003) has argued that a better link between the "mean" results of a GCM and case studies need to be established by evaluating GCM results in terms of cloud regimes. Techniques for such a cloud-regime driven model analysis have been developed and used in a variety of studies (e.g. Klein and Jakob 1999; Tselioudis *et al.* 2000; Webb *et al.* 2001; Norris and Weaver 2001; Tselioudis and Jakob 2002; Williams *et al.* 2003). While very useful, the complexity of the techniques used in these studies has usually limited their application to either a single or a small number of models. Since it is the aim of EUROCS to evaluate cloud and convection parameterizations in a large number of GCMs and for a variety of cloud types, the application of complex techniques to all of the participating models is difficult. Hence, in this study we aim to develop and apply a simpler approach to cloud-regime oriented model evaluation.

The cloud types studied by EUROCS include stratocumulus, shallow cumulus and deep convective cloud systems (Duynkerke and co authors 2004; Lenderink and co authors 2004; Guichard and co authors 2004). Fortunately, these cloud types do occur in nature in reasonable geographic separation as the predominant regimes in the ascending and descending branches of the Hadley circulation. It is therefore possible to isolate regimes geographically by following an idealized trajectory along the inflow into the Inter Tropical Convergence Zone (ITCZ). For that purpose model simulations with nine large-scale models are carried out for June/July/August 1998 and the quality of their results are assessed along a cross section in the sub-tropical and tropical North Pacific ranging from 235E, 35N to 187.5E ,1S. The main goals we hope to achieve through this assessment are

- To document the state of the art in modeling the first-order characteristics of sub-tropical and tropical cloud systems in state-of-the-art GCM's
- To provide an additional simple test-bed for parameterizations in GCM's by establishing a reference observational data set for the evaluation of cloud systems contained in the Hadley circulation
- To establish a broader context for the results of the SCM studies that form a main part of EUROCS

TABLE 1. Key characteristics of the participating models

Model	Type	Model reference	Scientist	Hor. Res.	Ver. Lev.
ARPEGE 3.22a	climate/global	(Gibelin and Déqué 2003)	Grenier Marquet	T42	45
ECHAM 5.0.9	climate/global	(Roeckner *et al.* 1996)	Chlond Muller	T42	19
Speedy 7	climate/global	(Molteni 1996)	Severijns	T30	7
ECMWF 23r4	weather/global	(Gregory *et al.* 2000)	Koehler	T159	31
MetO	weather/global	(Webster *et al.* 2003)	Lock	2.5 × 3.75 deg	38
JMA gsm0103	weather/global	(Matsumura *et al.* 2002)	Kitagawa	T106	40
RACMO 2	climate/regional	(Lenderink *et al.* 2003)	Lenderink	0.5 × 0.5 deg	40
RCA 2	climate/regional	(Jones 2001)	Jones	0.5 × 0.5 deg	40
HIRLAM 5.1.4	weather/regional	(Unden *et al.* 2002)	Calvo	0.5 × 0.5 deg	40

It is worthwhile pointing out that, as for all multi-model studies, the aim of the model evaluation carried out here needs to remain broad. Studies like this cannot and will not solve all problems in all participating models. They will, however, provide guidance as to where major efforts need to be directed both in individual modeling groups and the wider research community and will provide a reference point for future work. The identification of specific errors in individual models usually requires more sophisticated analysis techniques and is consequently left to the individual model development groups. An example for such individual model assessment using the approach developed here can be found in the study of Lock (2004) in this issue.

Section 2 will provide a description of the participating models and the setup of the experiments. Section 3 summarizes the various observations used in the study. Section 4 contains the main results of the comparison followed by a discussion and resulting conclusions in Section 5.

2. Case set up and participating models

The intercomparison is based on simulations by 9 different models. These include three global climate models (ARPEGE, ECHAM, SPEEDY), three global numerical weather prediction models (ECMWF, MetO, JMA) and three regional models (RACMO, RCA: climate, HIRLAM: weather). For a short description of the models we refer to the Appendix. Table 1 lists responsible scientists, the model names, versions and types, references to full model descriptions and model resolution. It is sufficient here to note that all three regional models (RACMO, RCA, HIRLAM) use the same dynamics. Differences between these models can thus be completely attributed to differences in the physics parameterization. ECMWF and RACMO on the other hand use exactly the same physics parameterization package. Differences between these models therefore reside in the dynamics.

Figure 1 shows the 13 locations along the cross section used throughout this study along with the observed cloud cover averaged over the selected three months period. The observed cloud cover fields are obtained from the International Satellite Cloud Climatology Project (ISCCP, see Rossow *et al.* 1991). It starts in the North-East off the coast of California where the down-welling branch of the Hadley circulation over a cold Pacific Ocean causes persistent solid stratocumulus decks (between 35 and 25 N). Subsequently the cross section enters the trade wind region in which the stratocumulus breaks up into scattered shallow cumulus fields (between 25 and 15 N) and finally ends in the ITCZ that is characterized by deep convective cumulus towers. The transect therefore encompasses three areas, each dominated by a cloud type that has been subject of isolated case studies within the EUROCS project (Duynkerke and co authors 2004; Lenderink and co authors 2004; Guichard and co authors 2004).

All participating modelers were asked to send in model output for 13 locations, starting at 35N, 235E and moving southwestwards with steps of 4 deg longitude and 3 deg latitude until 1S, 187.5E. As all modelers were free to choose their model resolutions, the model output should simply originate from model grid points that are closest to the requested locations. The only imposed restrictions were that the models had to run in a climate mode (i.e. without data assimilation) and with a prescribed sea surface temperature (SST). All three participating regional models used the same lateral boundary fields that were obtained from the ECMWF model.

As the Hadley cell is a well-defined circulation we consider it sufficient to use a relative short period for the analysis of model deficiencies. June/July/August 1998 was selected as that period, largely because the Sea Surface Temperature (SST) anomaly along the cross section for that period was less than 1K. Therefore the monthly mean deviations from climatology for most of the cloud parameters are expected to be small.

Merely as a check whether all models were subjected to similar boundary conditions we show in Fig. 1 the JJA-averaged prescribed SST's used by all 9 models along with AVHRR satellite data using the Optimum Interpolation (OI) version 2 method (Reynolds *et al.* 2002). Basically three regimes can be identified: (i) an almost linear rise of the SST along the trades from about 290 K, typical of stratocumulus situations at 35 N to values of around 301 K at about 10 N, (ii) an almost constant value from 10 N to 5 N (the ITCZ) and (iii) a slight decrease toward the equator. There is some scatter between the different models, but the standard deviation is within the range of variability in the observations. Only the SST's used by the JMA and Speedy are systematically too warm up to values close to 1 degree

Participants were requested to send in monthly mean results for 0,3,6,...,21 UTC. This way model data are available for both the month to month variability and the (monthly averaged) diurnal cycle. Two types of model data were requested for the 13 locations: i) vertical profiles for a number of atmospheric fields and ii) single level parameters for several vertically integrated fields, fluxes at the top of the atmosphere fluxes and fluxes near the surface. A complete list of fields, data and results can be found on the web †. In this paper we will only present and discuss the main results.

3. Observational datasets

A number of different satellite based observational data sets have been used for this intercomparison. As spaceborn remote sensing techniques have not (yet) reached the level of providing reliable data with vertical structure they are restricted to three types of observations:

- top of the atmosphere (radiative) fluxes.
- vertically integrated fields (cloud cover, liquid water path etc.) and precipitation

† http://www.knmi.nl/samenw/eurocs

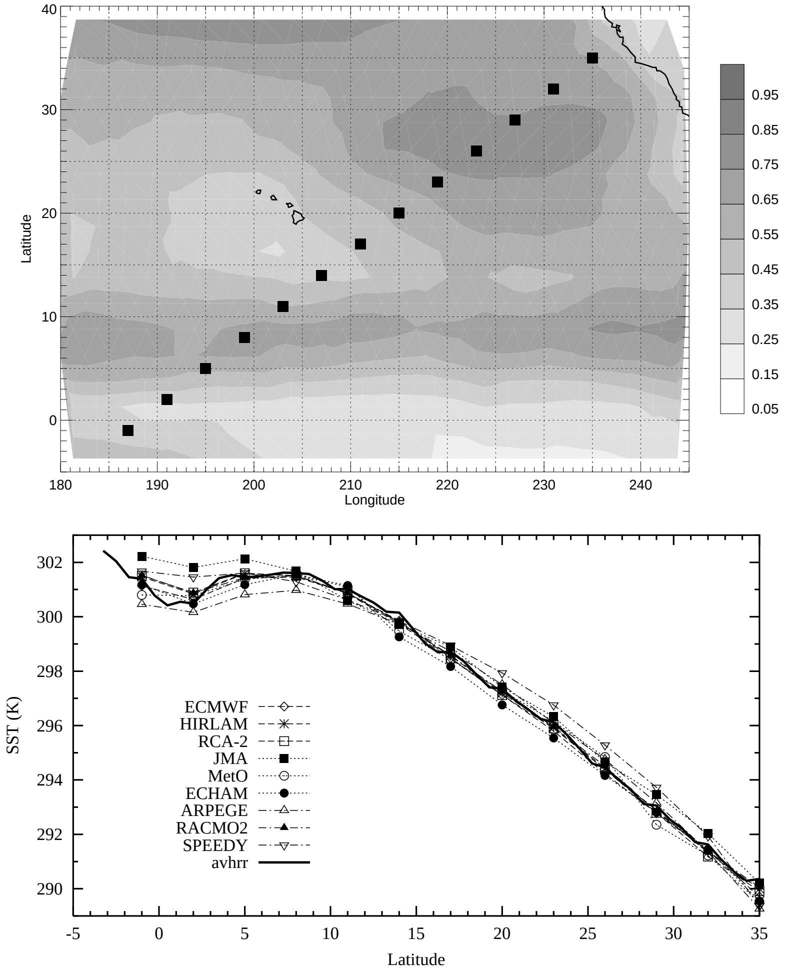

Figure 1. top panel: Proposed cross section with the 13 locations from which model output is requested. The same figure also shows the ISCCP observed cloud cover for the JJA 1998 period. lower panel: The prescribed Sea Surface Temperatures (SST's) used in the models along with observations based on AVHRR.

- surface fields and surface radiative fluxes.

It should be noted that there is an increasing level of uncertainty for these types of observations. The top of the atmosphere fluxes are almost direct measurements and are as such the most reliable. For the second class of observations various assumptions on, for instance the effective droplet size, needs to be made while for the third class even further additional assumptions on the vertical structure are used in conjunction with a radiative transfer model in order to assess the radiative surface fluxes (Wielicki *et al.* 1996).

Most of the used observational data in the rectangular that spans the prescribed cross section has been made easily accessible by the GEWEX Cloud System Study Data Integration for Model Evaluation (GCSS-DIME) on the web

Archive	Datasets	Platforms	$\Delta x \Delta y$ (deg), Δt	Parameters
NASA Langley ASDC	CERES ES9	TRMM	2.5x2.5, ..	TOA Radiative fluxes Surface SW fluxes
RSS, GCSS-DIME	SSMI	DMSP F11, F12, F14	0.25x0.25, 2/day	Liquid water path Water vapour column
ISCCP, GCSS-DIME	D1	based on DX	2.5x2.5, 3hr	Cloud cover
NASA GSFC, GCSS-DIME	GPCP v.2	NOAA, gauges	1.0x1.0, dayly	Precipitation rate
NASA GSFC	TRMM 3B42	TRMM	1.0x1.0, dayly	Precipitation rate
NCEP	OI	AVHRR	1.0x1.0, monthly	Sea surface temperature

TABLE 2. The various archives, the observational data sets and their specifics, and the measured parameters used in this study. The acronyms are explained in the text.

‡. Table 2 provides an overview of the used satellite products and the archives where the data can be found. Monthly averages are calculated of all data sets. The horizontal resolutions may differ, as each instrument or merged group of instruments has its/their own precision. However, similar to the model data no interpolation is used in the calculation for the average values of the various fields on the 13 points of the cross section on the diagonals: the values are taken from the grid points closest to the points on the diagonal.

Top of the atmosphere radiative flux observations used in this study are provided by the Clouds and the Earth's Radiant Energy System (CERES, see Wielicki *et al.* 1996). The instruments are carried by the Tropical Rainfall Measurement Mission satellite (TRMM, see Simpson *et al.* 1996; Kummerow *et al.* 1998), launched November 1997. Dataset ES9 contains monthly regional averages on a 2.5x2.5 grid of the TOA fluxes, of which we used the outgoing longwave radiation (OLR), the net shortwave radiation and the cloud radiative forcing.

Cloud cover fields are obtained from ISCCP (Rossow *et al.* 1991). A hierarchy of geostationary (GOES, GMS, METEOSAT) and polar orbiting (NOAA) satellites are used by ISCCP to produce a number of cloud products. In the present study the D1 data set is used for cloud cover estimates on a 3 hourly time and a 2.5 deg. spatial resolution.

Liquid water path and water vapour column are derived from measurements by the Special Sensor Microwave/Imager (SSM/I, see Hollinger 1987). The SSM/I data and images are produced by Remote Sensing Systems (RSS) and sponsored by the NASA Pathfinder Program for early Earth Observing System (EOS) products. SSM/I is situated on polar orbiting satellites flown by the Defense Meteorological Satellite Program (DMSP), the first of which was launched in June 1987. RSS generates SSM/I data products using a unified, physically based algorithm to simultaneously retrieve ocean wind speed (at 10 meters), water vapor, cloud water, and rain rate (Wentz 1997; Wentz and Spencer 1998). Three DMSP satellites carrying SSM/I (F11, F13 and F14) were operational during our period of interest.

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‡ http://gcss-dime.giss.nasa.gov/index.html

The surface precipitation rate was obtained from the Global Precipitation Climatology Project (GPCP, see Huffman *et al.* 1997; Huffman 1997). The general approach of GPCP is to combine the precipitation information available from each of several sources into a final merged product, taking advantage of the strengths of each data type. Microwave estimates are based on SSMI, infrared (IR) precipitation estimates are obtained from geostationary satellites and polar-orbiting satellites, and gauge data are assembled and analyzed by the Global Precipitation Climatology Centre (GPCC). The GPCP Version 2 combination includes precipitation estimates from TOVS and NOAA OPI data, permitting filling data voids at high latitudes that occurred in Version 1. One degree daily product (1DD) in the band 40degN-40degS was used. Another source for precipitation measurements is TRMM. Dataset 3B42 contains daily-averaged adjusted merged-infrared (IR) estimates, generated by combining measurements by the TRMM Visible and Infrared Scanner (VIRS) and the TRMM Microwave Imager (TMI) (e.g. Huffman *et al.* 1995).The TRMM 3B42 dataset were provided by the Distributed Active Archive System (DAAC) of the NASA Goddard Space Flight Center (GSFC).

Surface radiative fluxes (both longwave and shortwave) were derived using the CERES instrument data in conjunction with a radiative transfer model (Wielicki *et al.* 1996). As no reliable observations of latent and sensible surface fluxes are available we use the climatology based on da Silva *et al.* (1994) and model reanalysis results of ECMWF and NCEP.

Finally we will use ECMWF reanalysis products for evaluation of the vertical structure of various fields although we are well aware that reanalysis fields are not real observations. Nevertheless, at present, these are the only products that are available for analyzing vertical structure.

4. Results

In this section we discuss the fundamental results of this intercomparison. We will therefore limit ourselves to 3-months averages for the whole simulation period JJA 1998.

First we will present cross sections of vertical velocity, relative humidity and cloud cover in order illustrate the model to model variability in the spatial structure of these fields. As a reference we also show the ECMWF reanalysis results. Because of the very coarse vertical resolution we exclude results from SPEEDY for this part. Secondly we will evaluate single level model fields that are relevant for the hydrological cycle with observations and finally we explore the implications on the radiation budget.

(*a*) *Cross Sections*

Cross sections with the vertical velocity are displayed in Fig. 2. All models seem to produce a reasonable qualitative picture of the Hadley circulation, with a narrow area of upward vertical velocities in the deep convection region and a large area of downward motion in the subtropical free troposphere cumulating in a maximum of the subsidence values at around 35 N. In practice, however, the models show substantial differences. Only the ECMWF and MetO vertical velocity fields are similar to the ECMWF reanalysis, which has a strong and narrow upward branch with velocities up to 0.1 Pa/s in the ITCZ between 5 and 10 N and the strongest subsidence values in the Stratocumulus regions.

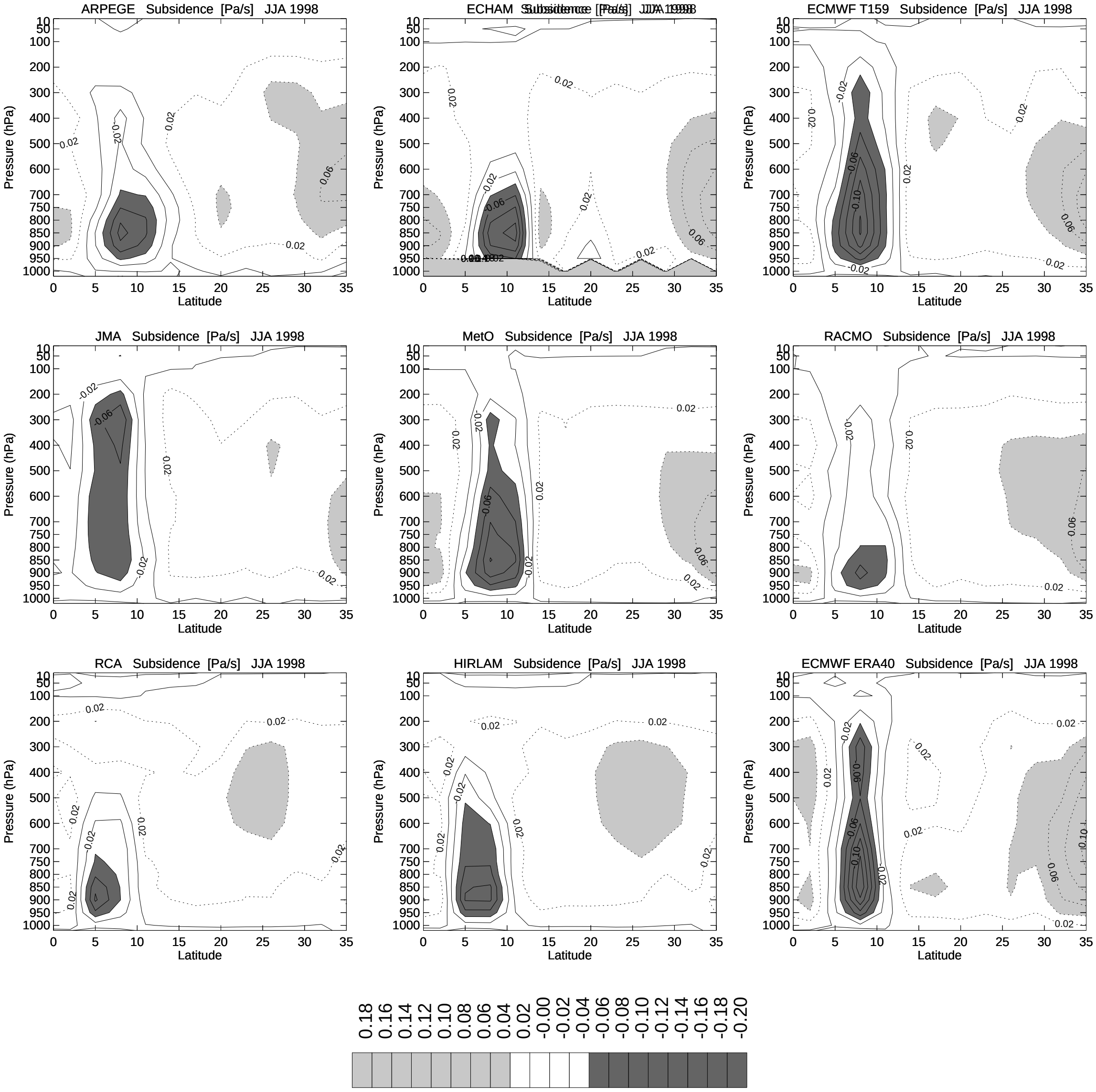
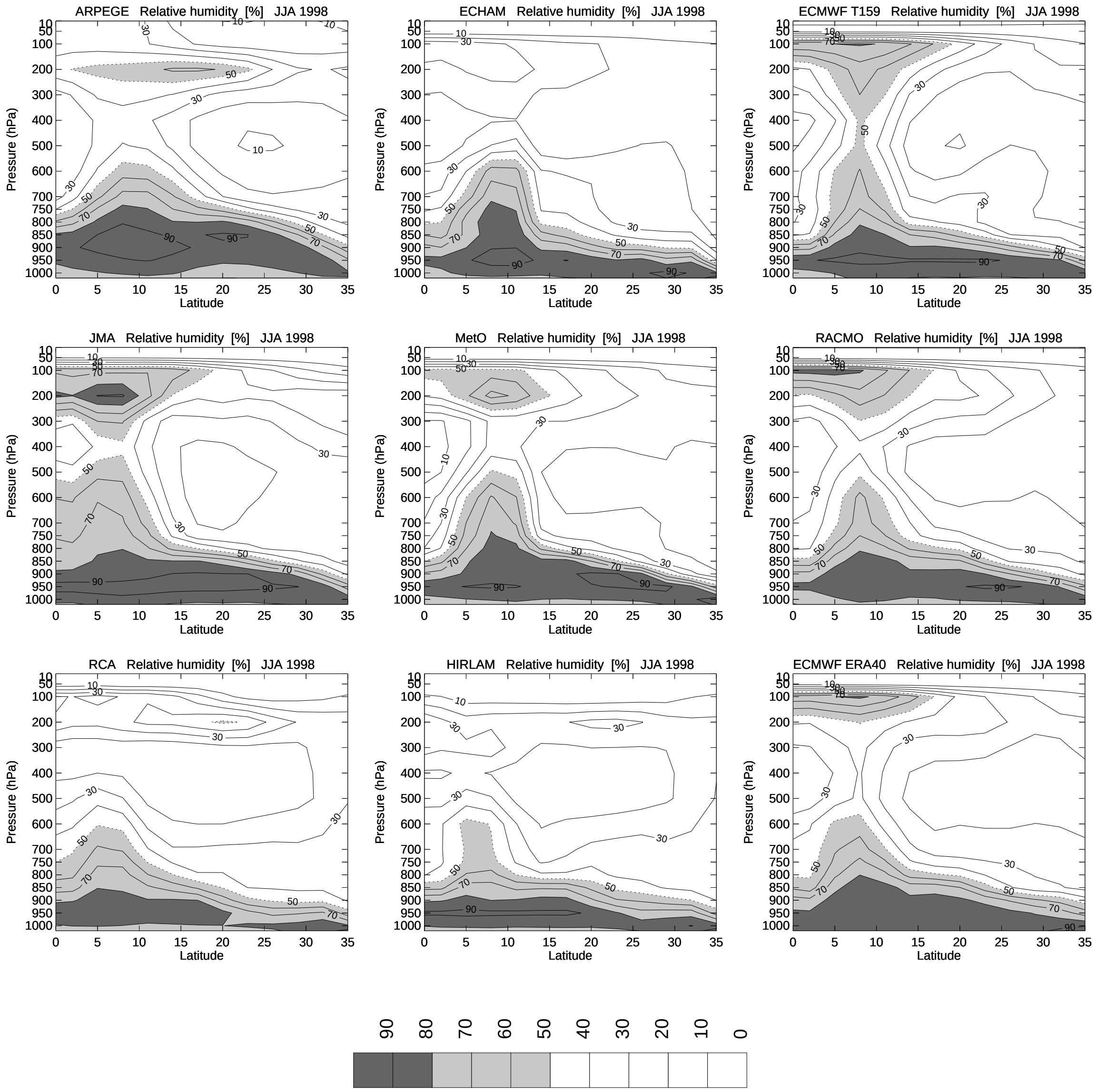


Figure 2. JJA averaged cross sections of vertical velocity. Top panel left to right shows: ARPEGE, ECHAM and ECMWF. Middle panel left to right shows: JMA, MetO and RACMO. Bottom panel shows left to right: RCA, HIRLAM and, as a reference, the ECMWF analysis

The other models show either weaker and/or shallower upward branches. In the Stratocumulus (Sc) region between 35 N and 25 N, the subsidence velocity in ECMWF, ECHAM, MetO and RACMO is on average around 0.04 Pa/s in the free atmosphere just above the observed Sc cloud tops (approximately 900 hPa). This value is close to what one would expect from assuming background radiatively driven subsidence (Betts and Ridgway 1988). Arpege and JMA have slightly lower subsidence values of around 0.02∼0.03 Pa/s while HIRLAM and RCA have virtually no subsidence.


ARPEGE Relative humidity [%] JJA 1998

ECHAM Relative humidity [%] JJA 1998

ECMWF T159 Relative humidity [%] JJA 1998

JMA Relative humidity [%] JJA 1998

MetO Relative humidity [%] JJA 1998

RACMO Relative humidity [%] JJA 1998

RCA Relative humidity [%] JJA 1998

HIRLAM Relative humidity [%] JJA 1998

ECMWF ERA40 Relative humidity [%] JJA 1998

Figure 3. As in Fig. 2, but now for relative humidity

It is difficult to argue about the reasons for these differences since the vertical velocity field is the result of a complex interplay between physics and dynamics. It does show however that there is a strong feedback of the physics on to the dynamics; for instance RACMO, RCA and HIRLAM show significant differences in the vertical velocity field, while they are all limited area models using identical dynamics and the same ECMWF boundary fields. In other words, the displayed differences for these three models are due to the different physics parameterization packages.

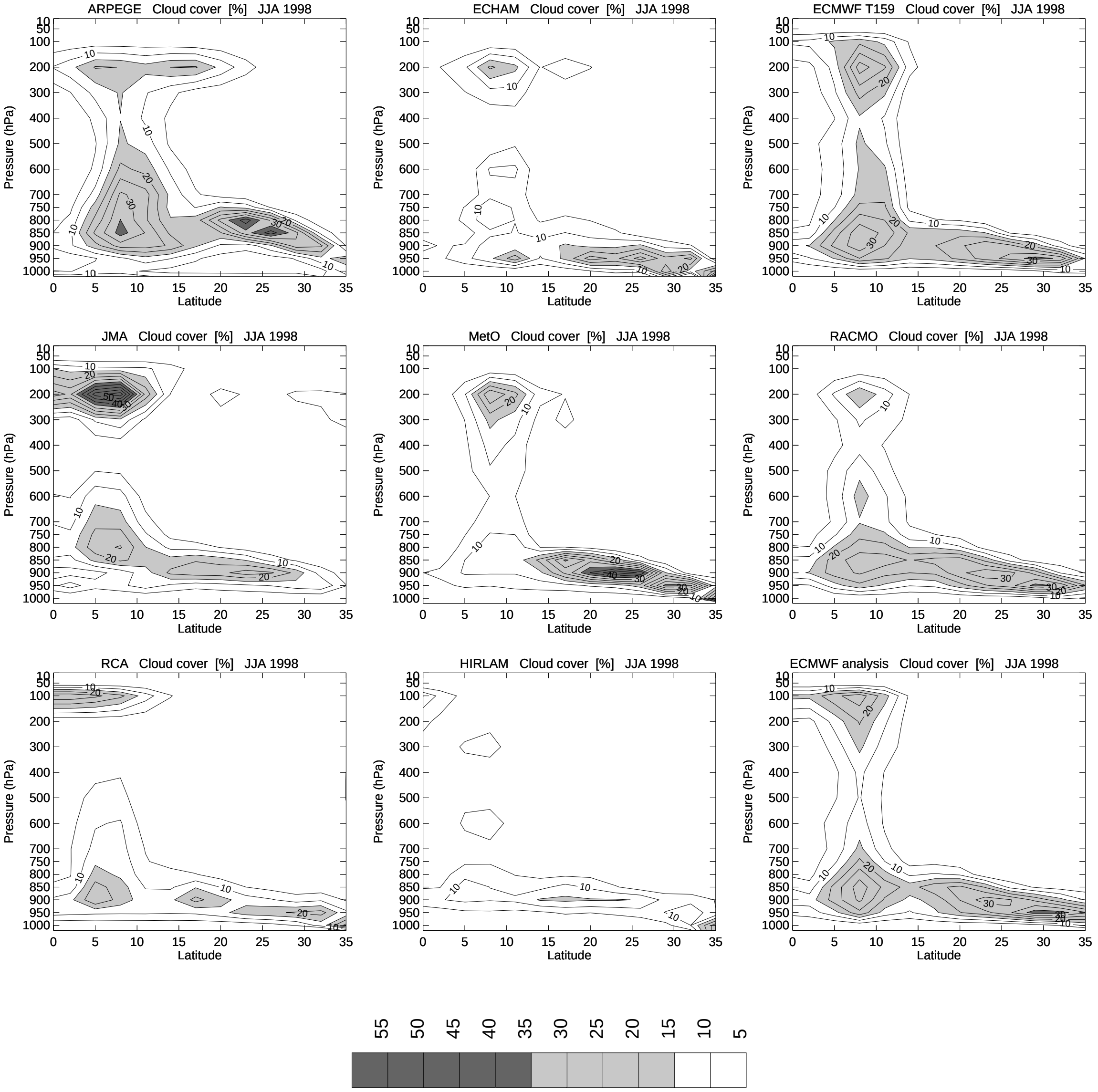

ARPEGE Cloud cover [%] JJA 1998
ECHAM Cloud cover [%] JJA 1998
ECMWF T159 Cloud cover [%] JJA 1998
JMA Cloud cover [%] JJA 1998
MetO Cloud cover [%] JJA 1998
RACMO Cloud cover [%] JJA 1998
RCA Cloud cover [%] JJA 1998
HIRLAM Cloud cover [%] JJA 1998
ECMWF analysis Cloud cover [%] JJA 1998

Figure 4. As in Fig. 2, but now for cloud cover

The cross sections of relative humidity are shown in Fig. 3. Some care has to be taken here as the models use different methods to determine this variable. Arpege and MetO simply calculate the relative humidity with respect to the saturation specific humidity of water above 273K and with respect to the saturation specific humidity of ice below 273K. All other models assume a mixed phase between in the interval between 273K and $238 \sim 258K$ and use different types of combinations of the saturation specific humidity of ice and water within this temperature interval. Again all models seem to capture the general characteristics relatively well. In the subtropics, all models show moist

PBL air capped by a strong inversion and dry atmosphere above. The inversion height increases from the Sc regions to the deep tropics over increasing SST. The growth of the boundary layer height, however, proceeds in different ways in the different models, and this has important consequences in terms of clouds and the radiative balance that will later be explored in more detail. If we loosely define the boundary layer height as the 50% relative humidity level for the Sc and the trade wind region, it can be observed that the ECMWF analysis indicates a boundary layer top at 910 mb at 35N that is increasing with latitude with 500 m/1000 km. Most models have a similar behaviour in the range $400 \sim 600$ m/1000 km. Only ARPEGE is an outlier with a boundary layer that is typically 100 *mb* deeper and is also stronger deepening with latitude as 700 m/1000 km. In the ITCZ all models show relatively high values of relative humidity extending to the upper troposphere; however, the differences between the models are very significant. There is a clear relationship between the depth of the upward velocity field and the vertical structure of the relative humidity field. The models with relative humidity below 50% in the upper troposphere (ECHAM,RCA, HIRLAM) are all models with a shallow updraft branch. Only RACMO is a bit of an outlier since it also has a rather weak updraft coinciding with a high relative humidity in the upper troposphere. While both the vertical velocity and the intensity of convective mixing are determining the relative humidity fields, it seems that the latter is most important, and that the velocity field mainly responds to the intensity of the convective mixing. For example, ECMWF and RACMO have very similar relative humidity fields, whereas they differ significantly with respect to the velocity field. Since RACMO and ECMWF share the same convection scheme, this also suggests that the dynamics in RACMO responds differently to the intensity of the convection scheme than the dynamics of the ECMWF model.

Figure 4 shows the cross sections of model cloud cover. Similar to the boundary layer height it can be seen that cloud top height grows with increasing SST. Not surprisingly, the cloud top height in ARPEGE is too high; at 20 N the ECMWF analysis (and most other models) show a PBL top of around 800 mb while in ARPEGE the cloud top is around 700 mb. The erroneous rapid growth of the boundary layer height in ARPEGE is consistent with results of a single column model version (Lenderink and co authors 2004). Furthermore MetO seems to have too high cloud cover values in the trades up to values of 45 %, even larger than values found in the Sc-region. In the deep tropics HIRLAM and to a lesser extent RCA and ECHAM stand out as they produce low values of cloud cover above 500 mb in the ITCZ compared to the other models. The differences in cloud cover between the models are especially large in the ITCZ near the tropopause where cloud cover value range between 0 and 50 %.

(*b*) *Hydrological fields and fluxes*

An important requisite for having realistic cloud fields in any model, is to have reliable estimates for the total column water vapour (TCWV). The results for TCWV along with SSM/I observations are shown in Fig. 5a. As can be seen the relative scatter between the different models and around the observations appears to be small at first sight. This is not surprising since the TCWV is a fundamental integral quantity that models should be able to simulate correctly if claims of a realistic simulation of the Hadley circulation are to be made. All models show the correct qualitative behaviour of going from a low value between 15 and 20 kg m^{-2} in the Sc regions to around 50 kg m^{-2} in the ITCZ. In absolute sense however, the errors in some models are large. ARPEGE overestimates TCWV over the whole with an typical value of 10 kg m^{-2}. This bias is most likely related with the overestimation of the boundary layer depth of ARPEGE, since it is the boundary layer where most of the humidity resides in. ARPEGE, MetO and JMA overestimate the peak value in the ITCZ with $5 \sim 10$ kg m^{-2} while HIRLAM and RCA underestimate this peak with a similar value and also position the peak too much to the South. In the trades all models except ARPEGE do give approximately the correct results while in the Sc regions the TCWV is overpredicted by HIRLAM, RCA, and to a lesser extend by JMA and ARPEGE. The overestimation of TCWV by JMA might be related to the slightly biased prescribed SST by this model.

Figure 5b shows the latitude variation of the total cloud cover (TCC) for each model along with observations from ISCCP. There is a general pattern followed by most models. Most models, with the exception of the MetO and RCA, strongly under-predict the stratocumulus cloud cover. On the other hand most models over-predict cloud cover associated with the deep convection in the ITCZ. As a result, since most models also over-predict the cloud cover of the shallow trade wind cumuli, only few models exhibit the characteristic minimum of the cloud cover in the trades between 15 and 20 N that is so clearly present in the observations. Note that the errors are large; in the Sc region cloud fraction is underestimated by 30 to 50 % while the overestimation in the trades and the ITCZ is of the order of 20 %.

The consequences in terms of cloud water are investigated by analyzing the latitude variation of the liquid water path (LWP) that is shown in Fig. 5c for the different models along with SSM/I estimates from three different satellites. In general, the results confirm the previous findings: the models underestimate LWP in the Sc areas and overestimate LWP in the equatorial regions. Observations in the Sc regions indicate typical values for LWP of typically 90$\sim$100 g m^{-2}. Only MetO and ECHAM predict similar values while the other models underpredict LWP with negative biases up to 80 and 90 g m^{-2}. Some of these low values are similar to the differences reported by Duynkerke and Teixeira (2001). Note that some models (e.g. RCA) that predict reasonable values for cloud cover in the Sc regions still fail to give realistic values for LWP. On the other hand ECHAM underestimates cloud cover but gives reasonable values for LWP in the Sc region. In general, models that use liquid water as a prognostic variable but estimate cloud fraction diagnostically in a rather independent way may show these unrealistic features. Most models overestimate the LWP in the trades around 15 N which is consistent with the systematic over-estimation of cloud cover of most models in these regions. In the ITCZ ECMWF and RACMO strongly overpredict the observed LWP peak value of around 200 g m^{-2} while MetO completely misses the LWP peak and underestimates LWP therefore by 150 g m^{-2}.

The impact on the mean precipitation can be seen in Fig. 5d. Precipitation observed by TRMM and GPCP peaks in the ITCZ at around 8 N with values of $10 \sim 11$ mm day^{-1}. ECMWF and MetO have positive biases of around 5 mm day^{-1}, which confirms previous results of Teixeira (1999). Only RCA and especially SPEEDY underestimate the peak intensity in the tropics and also fail to model the correct position of the precipitation maximum. Speedy and ARPEGE predict a too broad precipitation peak causing too much precipitation in the trades. Much of the findings concerning the location of the precipitation maximum and the width of the tropical precipitation peak are in line with the

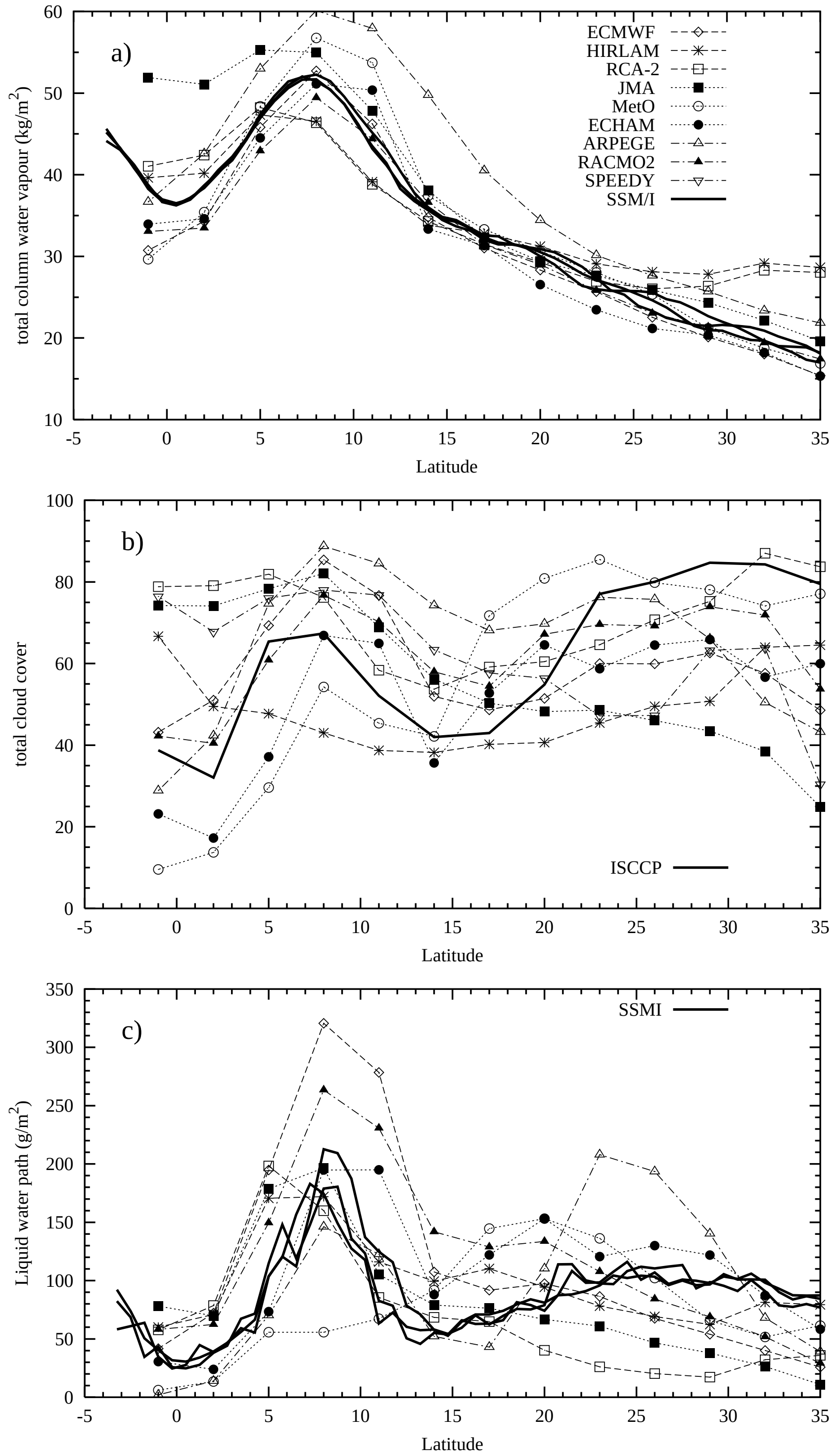


Figure 5. JJA averaged fields for all models of a) integrated water vapour column along SSM/I observations, b) total cloud cover along with ISCCP observations, c) integrated liquid water path (LWP) along with SSM/I observations, d) precipitation rates along with GPCP and TRMM observations, e) latent heat surface fluxes along with climatology and ECMWF analysis and finally f) precipitation minus surface evaporation.

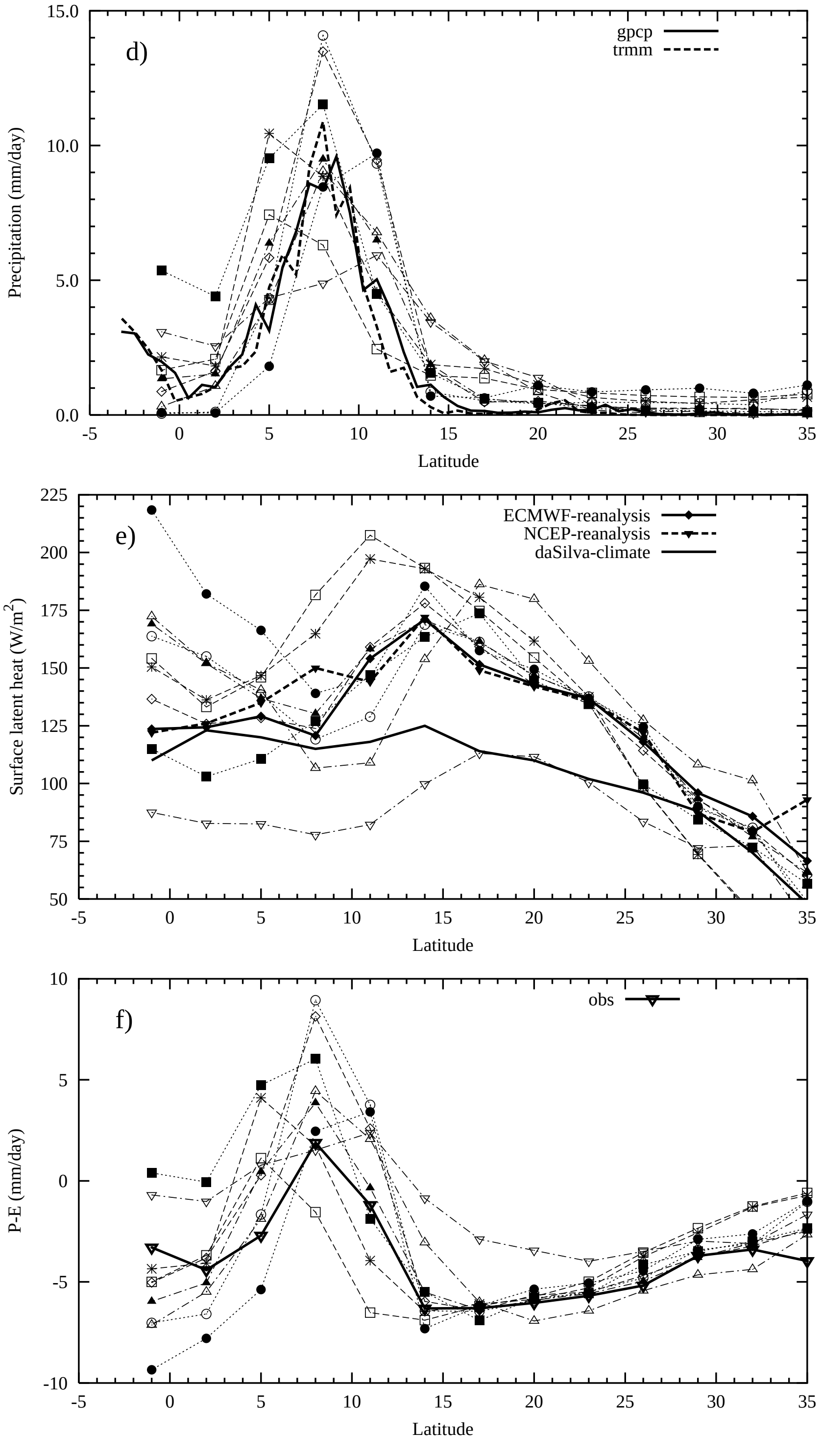


Figure 5. continued

results of LWP and the vertical velocity. In the Sc regions the models produce values homogeneously scattered between 0 and 1 mm/day. Observations show basically no precipitation but the used satellite observations are not very reliable for these low drizzle rates and precise data on drizzle rates on this seasonal scale are lacking. However, recent observational campaigns (Stevens and co authors 2003) suggest that stratocumulus may drizzle more than previously accepted.

An important parameter for the hydrological cycle is the surface latent heat flux. Unfortunately there were no reliable measurements available for this parameter so that we used three surrogates: i) climatology as determined by da Silva *et al.* (1994) ii) ECMWF reanalysis and iii) NCEP reanalysis. Results are shown in Fig. 5e. Both reanalysis results indicate an increase of the latent heat fluxes from the Sc regions with values of $80 \sim 90$ W m^{-2} to peak values of around 170 W m^{-2} in the trades. Further toward the ITCZ the fluxes decrease again to values of around 125 W m^{-2}. These reanalysis results are in sharp contrast with the da Silva climatology (see Fig. 5e)

Most models show qualitatively a similar behaviour as the ECMWF and NCEP reanalysis with maximum values in the trades. However, since the observations that actually go into the analysis are sparse, differences between the reanalyses and the "true" surface fluxes can be large. Outliers are HIRLAM and RCA with too high peak values of around 200 W m^{-2} and SPEEDY with too low values in especially the deep tropics. Furthermore it is surprising to see that almost all models have substantially higher fluxes than the reanalysis and climatology at the equator with biases up to 100 W m^{-2} (ECHAM).

We finally show in Fig. 5f precipitation minus the surface evaporation (P-E). In the Sc and the trade wind regions all models (except SPEEDY) agree reasonably well with a negative P-E decreasing from -1 mm day^{-1} at 35 N to -6 mm day^{-1} at 15 N. In the ITCZ all models show a positive P-E but the absolute values range from marginally positive (RCA: 1 mm day^{-1}) to values of as much as 9 mm day^{-1}.

(*c*) *Radiative fluxes*

We finally want to explore the impact of the modelled hydrological cycle on the radiative fluxes of the models, both at the top of the atmosphere as well as near the surface. The global energy balance of the atmosphere is to a large extend determined through the top of the atmosphere radiative fluxes and the uncertainty in these fluxes can for a large part be attributed to uncertainties in the predicted cloud amounts. On the other hand, especially the Sc regions do have a significant cooling effect on the underlying ocean. Therefore an under-prediction of the Sc amounts causes an over-prediction of the net heat surface flux into the ocean that can lead to positive SST biases in coupled atmosphere-ocean models. In this section we will quantify the typical biases in the modelled radiative fluxes.

Figure 6a shows the corresponding results for the JJA averaged outgoing longwave radiation (OLR) along with observations from CERES. The OLR of HIRLAM, RCA and SPEEDY have such deviant behaviour that it is likely not only due to the biases in the cloud amounts but also due to flaws in the radiation scheme formulation. In the rest of the discussion we will exclude these models. In the Sc regions the differences between the other models and the observations are relatively small (and roughly the same number of models is above and below the observations), mainly because the OLR is not so sensitive to low level cloud amount as it is to high and medium level clouds. However, it is a somewhat disturbing that these differences although quite low when compared to the biases in the ITCZ, can reach values of up to almost 20 W/m2. In the deep tropics most models underestimate the OLR, with the exception of ECHAM and RACMO. The negative biases range from 10 W m^{-2} (MetO, Arpege) up to 30 W m^{-2} (JMA, ECMWF). These results are consistent with the amounts of high cloud cover predicted by the models.

The net shortwave radiation at the top of the atmosphere (SWTOA) is shown in Fig.6b along with CERES observations. It can be seen clearly that in general most model's atmospheres are not reflective enough in the Sc regions and are too reflective in the deep tropics. This confirms again that the models have in general a lack of clouds in the Sc areas and too many clouds in the ITCZ. In the Sc regions ECMWF, RCA, JMA, ARPEGE and RACMO over-estimate SWTOA the most, which is consistent with under-prediction of cloud cover and LWP in these models. They all overestimate TOASW by 60∼80 W m^{-2}. In the ITCZ, negative biases ranging from 20 to 80 W m^{-2} of SWTOA is clearly visible for all models except MetO.

The downward shortwave fluxes at the surface are shown in Fig. 6c. along with observations from CERES. These results are somewhat the mirror image of the TOA short wave radiation results: the model's atmospheres are too transparent in the Sc regions and reflect (and/or absorb) too much in the trades and the tropics. Again this is directly related with the under-estimation of clouds and LWP in the Sc regions and an overestimation of these fields elsewhere. The positive biases of the shortwave radiation in the Sc region are typically of the order of 60 W m^{-2}. Only MetO and ECHAM give correct fluxes in these regions. On the other hand, under-prediction of the order of 60 W m^{-2} for the surface SW fluxes can be seen in the trades and the tropics are.

Although the prime suspect for the high shortwave transmissivity in the Sc regions is most likely the under-prediction of LWP, it can not be ruled out that also biases due to the formulation of the radiation schemes in the models contaminate the results. One way to address this issue is to examine correlations between LWP and the downward shortwave fluxes at the surface $F_{r,sw,down,srf}$. In order to eliminate trivial dependencies of $F_{r,sw,down,srf}$ on the top of the atmosphere (TOA) incoming shortwave radiation $F_{r,sw,down,toa}$, we consider the shortwave transmissivity. Since we want to analyse only model output with stratocumulus clouds, only model output for the 4 grid points between 25 and 35 N with a total cloud cover larger than 40 % were selected. For each of these grid points the monthly averaged transmissivity is calculated between 18 UTC and 00 UTC which is a six hour time interval around local noon. In formula

$$\langle T\rangle = \frac{\langle F_{r,sw,down,srf}\rangle}{\langle F_{r,sw,down,toa}\rangle\,.} \tag{1}$$

where the brackets denote a time average. The 6 hour time interval has been used since some models supplied their radiative fluxes only as 6 hour averages. In Fig. 7a LWP versus the transmissivity is displayed for all models. If all models would use an identical radiation scheme that would treat clouds in an identical way, one would expect that the the points would scatter around one single curve, irrespectively whether the models do predict the LWP amount correct or not. The results show that ECMWF, RACMO, RCA, HIRLAM and Arpege do scatter around one imaginary curve. It should be noted however that ECMWF

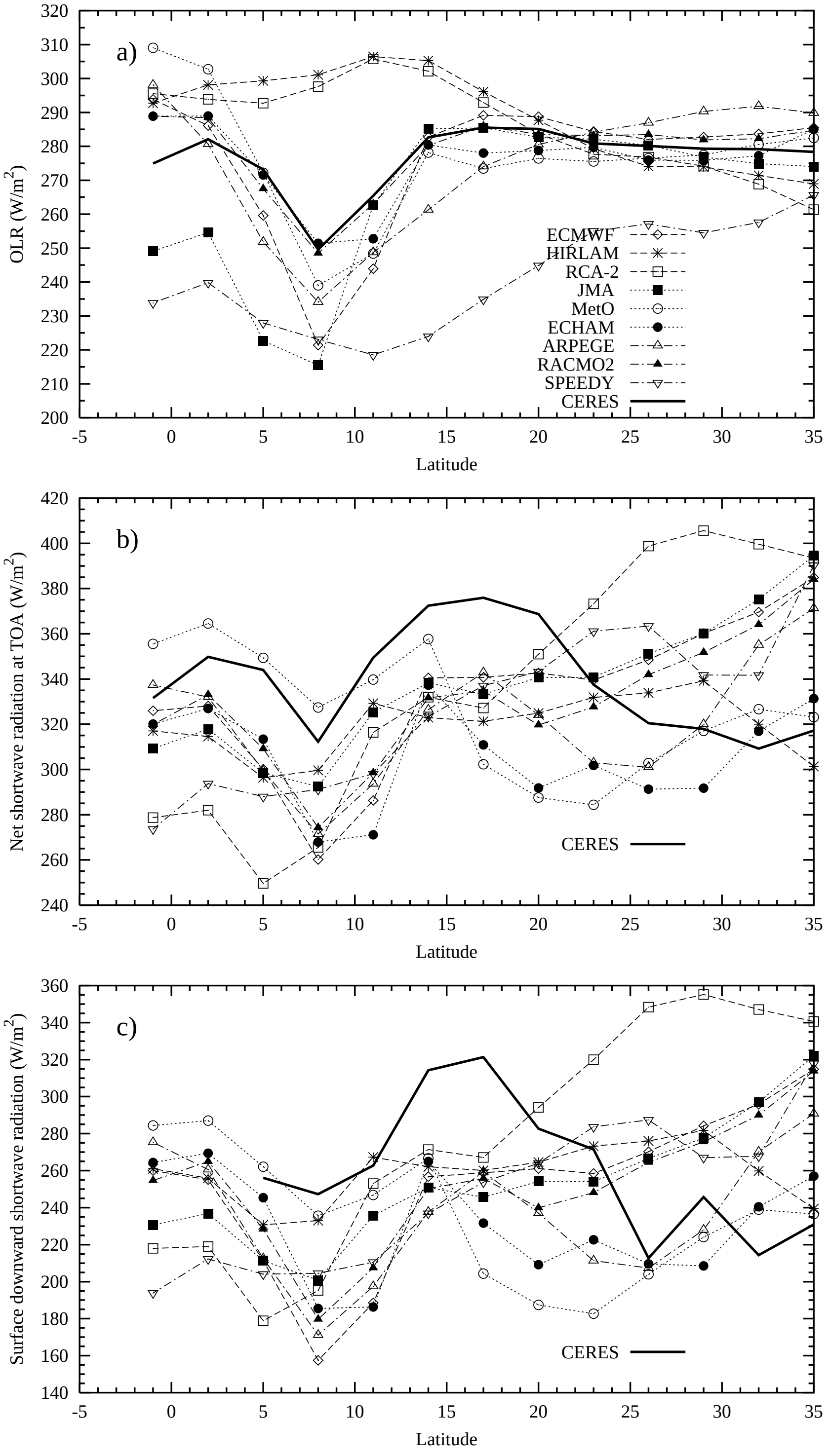


Figure 6. JJA averaged fields for all models of a) outgoing longwave radiation along b) net shortwave radiation at the top of the atmosphere, c) downward surface shortwave radiation, along with observations from CERES

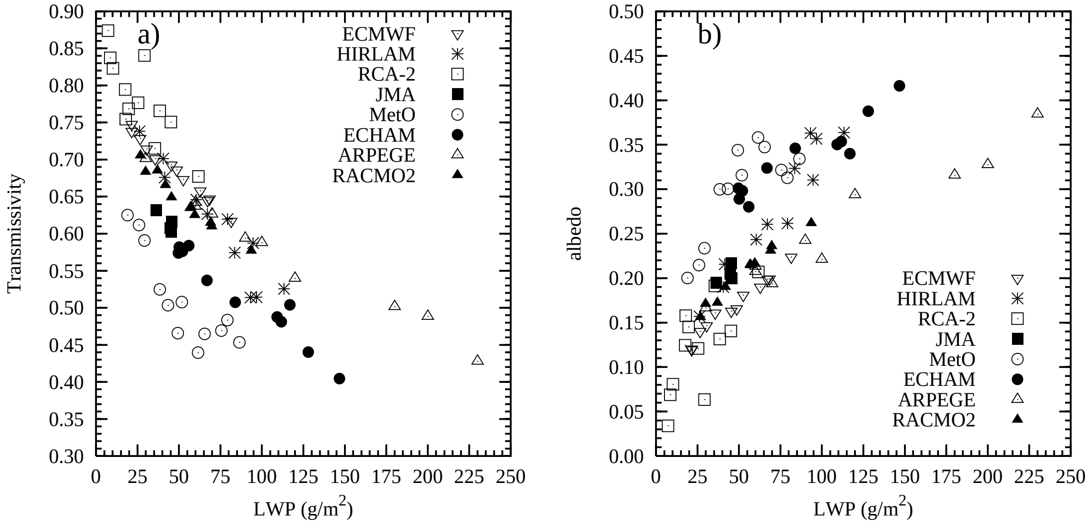


Figure 7. scatter plot of the transmissivity (left panel) and planetary albedo (right panel) as a function of liquid water path for grid points with stratocumulus

and RACMO use an identical radiation scheme. The points of JMA, ECHAM and especially MetO demonstrate that these models have a substantially smaller transmissivity. A similar message is contained in the planetary albedo

$$\langle A\rangle = \frac{\langle F_{r,sw,up,toa}\rangle}{\langle F_{r,sw,down,toa}\rangle}\,. \tag{2}$$

where the brackets denote the same time average as for the transmissivity; MetO and ECHAM exhibit a systematically larger reflectivity than the other models for a given LWP. It is difficult to make speculations on the cause of these differences. However one option could reside in how cloud inhomogeneity is treated in the various models; ECMWF and RACMO reduce their cloud albedo by a factor 0.7 with respect to the plane parallel calculations which enhances the cloud transmissivity considerably. This has to be contrasted with the MetO and ECHAM that treats their clouds simply as plane parallel. A careful analysis of these data with observations is left to future studies.

5. Discussion and Perspectives

In general it can be seen that all models seem to reproduce the broad qualitative properties of the Hadley circulation in a relatively realistic way. However, many of physical characteristics studied vary widely from model to model. All the quantities analysed are directly or indirectly linked to cloud properties, and the results show that although there is a large spread in the results of the different models, some typical behaviours are common among most models: (i) most models underestimate clouds in the stratocumulus regions with the inevitable consequences in terms of shortwave radiative fluxes; (ii) most models overestimate clouds in the ITCZ and the trades with important connections in terms of longwave radiative properties and precipitation.

It is encouraging to see that the only model result (MetO) that included improved parameterizations for stratocumulus and shallow cumulus developed during the EUROCS project, turned out to have the best cloud representation for these cloud types. Thus, it is to be expected that the other participating models will improve similarly when they will rerun this case, since a number of the observed deficiencies were also present in the individual case studies with SCM's and LES models. Especially the case study of diurnal cycle of shallow cumulus convection (Lenderink and co authors 2004) also reported a collective overestimating of cloud cover and cloud liquid water. Also some of the individual model deficiencies, such as the unrealistic deep PBL of the ARPEGE model, were present in this study. Apparently these problems can be isolated to a single case with prescribed conditions and for the causes and solutions of these deficiencies we refer to Lenderink and co authors (2004).

The under-prediction of clouds in the Sc regions can be due to errors in at least three physical mechanisms: i) incorrect large scale forcings, ii) too intense drizzle and iii) too much entrainment. It is difficult to point out which one is the prime suspect. However since the subsidence rates of most models is quite close to what one would expect from assuming background radiatively driven subsidence it is most likely due to one of (or a combination of) the last 2 mechanisms. Since the LES EUROCS stratocumulus case study (Duynkerke and co authors 2004) studied only non-drizzling stratocumulus and concentrated mainly on entrainment it can not resolve this issue. However the fact that SCM simulations for the non-drizzling stratocumulus in that study do not show a systematic under-estimation of cloud amounts, suggests that the use of a too active drizzle parametrization is likely one of the reasons of the low simulated LWP values in most model runs. In any case, drizzle is probably a key process in the whole stratocumulus riddle. In a short Note in this special issue (Lenderink and Siebesma 2004) it is argued that the extreme sensitivity between LWP and subsidence (Duynkerke and co authors 2004; Chlond *et al.* 2004) can be strongly reduced by introducing drizzle. In this same Note it is also argued that steady state stratocumulus fields are possible with realistic subsidence rates of around 0.05 Pa/s if, again, drizzle is taken into account. Nevertheless some important conclusions can be drawn from the EUROCS LES stratocumulus case study (Duynkerke and co authors 2004). First, it is important to control the entrainment process in any turbulence mixing parameterization, either by a prescribed entrainment rates (Lock 2004) or by using a TKE scheme that is formulated in moist conserved variables and has a high enough vertical resolution (Lenderink and Holtslag 2000). Furthermore activation of the convection scheme might cause extra turbulent mixing and hence, extra entrainment that might erode the stratocumulus clouds. It is therefore important that the turbulence and the convection scheme in any parameterization package operate in a coherent way. Finally. care needs to be taken with the numerical discretisation effects in the parameterizations especially near the top of the stratocumulus layer. It should be noted that the improved version of the MetO has taken into account all these three points with a positive impact on the representation of stratocumulus (Lock 2004).

Many of the findings in the case studies for deep convection (Guichard and co authors 2004) need to be evaluated in a 3D GCM context and the present case offers an excellent and simple test. A recent study on a new trigger function in the ECMWF model (Jakob and Siebesma 2003) shows that the cloud climatology in the ITCZ is extremely sensitive to the used trigger mechanism.

The present initial analysis has been rather superficial. Only averages over the whole JJA period have been analysed. However, much more detailed model and observational data is available to analyse, like for instance, the monthly averaged diurnal cycle. More profound studies of the physical details of the models are left to the future. The special strength of these type of studies is that different aspects (in this case clouds and radiation and to a lesser extent dynamics) are evaluated in a coherent way. Especially since remote sensing techniques are advancing fast, model evaluations like the present one, will put more constraints on the parameterizations of clouds and radiation. It will become increasingly more difficult to have a correct radiative energy balance in a climate model along with an incorrect cloud climatology. Through these type of constraints and through critical evaluations, the scientific community will be forced to further develop physically sound parameterizations that ultimately results in models that are capable of simulating our climate system with increasing realism.

Let us finally stress that this type of model development and evaluation is only possible because modelers are brought together through international networks and projects such as EUROCS and GCSS and through initiatives such as GCSS-DIME that are indispensable in helping to close the gap between models and observations.

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Appendix A

The three participating global climate models (ECHAM, ARPEGE, SPEEDY) all are spectral models. SPEEDY (Simplified Parameterizations, primitivE-Equation DYnamics) is intermediate complexity model with a parameterization package that has been specially designed to work in models with just a few vertical levels. It is the model with the most coarse resolution with only 7 levels in the vertical and a spectral truncation at total wave number 30 (T30L7). ECHAM and Arpege are state of the art climate models. A brief description of the physics package can be found in the appendix of an accompanying paper in this special issue (Lenderink and co authors 2004) that deals with an intercomparison case study with one-column versions of these models. However, note that Max Planck Institute in comparison with the one-column version intercomparison study is using a newer model version (ECHAM 5) in this present study. One of the main differences with respect to ECHAM-4 is the use of a new statistical cloud scheme (Tompkins 2002).

The three participating global numerical weather forecast models (ECMWF, MetO, JMA) operate typically at a higher resolution (see Table 1). The Met Office model is the only model from which results were submitted for both the standard version and one for an improved version. In this paper we will only show results of the improved new model version such as described in Lock (2004). The ECMWF model uses version 23r3 (Gregory *et al.* 2000), which is essentially the same physics package as in the cumulus single column model intercomparison study (Lenderink and co authors 2004). The JMA (Japan Meteorological Agency) employs the level 2 turbulence closure scheme of Mellor and Yamada to determine effects of vertical diffusion. For convection an economical version of the Arakawa-Schubert scheme is used to simulate penetrative (deep) convection. Cloud fraction and cloud water determined using a statistical scheme.

The three regional models (HIRLAM5, RCA-2 and RACMO-2) are grid point models and operate on the highest resolution and use identical dynamical cores. They also use the same ECMWF operational analysis as boundaries. Therefore the models only differ from each other through the use of different physics packages. The physics package of the RACMO-2 model is identical to the one in the ECMWF model version 23r4 (Gregory *et al.* 2000). The HIRLAM5 physics package is briefly described in (Lenderink and co authors 2004). The RCA-2 model uses a (Kain and Fritsch 1990) scheme for convection, clouds are diagnosed using a cloud scheme based on relative humidity and condensation, microphysics and precipitation are estimated according to (Rasch and Kristjánsson 1998)

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