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EVALUATION OF REGIONAL CLOUD CLIMATE SIMULATIONS OVER SCANDINAVIA USING A TEN-YEAR NOAA AVHRR CLOUD CLIMATOLOGY

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1. INTRODUCTION

The validation of cloudiness in climate simulations is a challenging task given the great importance of clouds in climate modelling experiments. The large sensitivity to the detailed cloud description has been demonstrated in many papers (e.g., Zhang et al., 1995, Wild and Ohmura, 1999, Chen et al., 2000, Hu and Stamnes, 2000, Colman et al., 2001, Mason, 2002 and Murphy et al., 2004). From this it naturally follows that high requirements must also be set on the cloud observations that are used for validating models. Consequently, not only further cloud modelling development efforts are needed but also substantial efforts in establishing an accurate description of current and past global and regional cloud conditions from various observation sources.

This paper presents a method to evaluate cloud fields simulated by the SMHI Rossby Center regional climate simulation model by use of a ten-year satellite-derived cloud climatology. The cloud dataset is derived from satellite imagery provided by the Advanced Very High Resolution Radiometer (AVHRR) instrument on the polar orbiting NOAA satellites.

A central problem in any model evaluation study is how to compare with the observations in the most appropriate way. This is particularly problematic if the observed quantities are not taken from direct observations but are instead indirectly derived. This is the case for most cloud datasets derived from satellite measurements since satellites measure radiation and not clouds. Thus, such cloud information is indirectly interpreted from radiances and this introduces specific constraints and restrictions on the results. Accounting for these effects and the associated error characteristics of the used observation data set is problematic but absolutely necessary. Another aspect is that special adaptations of the model data set is required to take into account the special observation geometry that is realised from a space-based platform.

This study has used several satellite-to-model and model-to-satellite adaptation techniques to reduce as much as possible any biases caused by obvious *a priori* differences in the cloud datasets generated from satellite observations and from model simulations. A central aspect here has been an attempt to account for limitations for the satellite observation concerning the detection of optically very thin clouds.

Concerning the modelling of clouds it is well-known that the use of different cloud overlap assumptions has great importance for the achieved impact of modelled clouds, e.g. for the results produced by the model radiation scheme. Consequently, this study also looked at results based on different cloud overlaps.

In the following sections 2 and 3, the cloud datasets from the regional climate model and from the satellite are introduced in more detail. Comprehensive descriptions of the model evaluation method as well as a description of all the applied adaptations of the satellite and model datasets are then given in section 4. Results are presented in section 5 followed by a discussion and conclusions in sections 6 and 7.

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2. THE CLOUD DATASET FROM THE ROSSBY CENTRE REGIONAL CLIMATE SIMULATION MODEL

In this study, the third version of the SMHI Rossby Centre Regional Climate Model (RCA3) has been evaluated. An overall description of the modelling concept is given in Jones et al. (2004a and 2004b) and a more detailed description is presented by Kjellström et al. (2006).

RCA3 has a cloud description that could be characterised as a *prognostic process-oriented* cloud parameterisation according to the classification proposed by Jakob (2002). This means that cloud condensate (or here cloud condensate mixing ratio q_c) is carried as a prognostic variable with separate equations for its temporal evolution. The cloud fraction is basically diagnosed using a relative humidity threshold but the diagnostic method varies with height and cloud type.

In RCA3 cloud processes are basically separated into two types: large-scale clouds/processes and convective clouds/processes. Large-scale clouds (or large-scale condensation processes) are described using the scheme of Rasch and Kristjansson (1998). Convective clouds and convective processes are described using the approach of Kain and Fritsch (1990). This latter scheme assumes that meso-scale circulations are basically resolved (or being of large-scale type) in the model and that only cloud scale fluxes have to be parameterised. A consequence here is that Cirrus anvils in deep convective systems can in some sense now be seen as large-scale clouds and that only the inner cores of the clouds with areas of active vertical ascent are parameterised. The diagnosis of the cloud fraction in a grid volume follows the ideas of Slingo (1987) but various modifications of the methods for treating the large-scale and convective cloud types have been introduced.

The RCA3 radiation scheme is based on the formulation originally described by Savijärvi (1990) but slightly modified by Räisänen et al. (2000). To compensate for some deficiencies of the plane-parallel homogeneous cloud approach (not truly representative of real clouds, especially concerning the case of broken clouds which is often observed in satellite images of high horizontal resolution) some minor modifications were introduced according to Cahalan et al. (1994) leading to a reduction in albedo for short-wave calculations. A separate treatment of ice and liquid clouds is made in the radiation code, where an effective radius is diagnosed based on local air temperature for ice clouds and on cloud water amounts for water clouds (Wyser et al., 1999). The effective radius and cloud water amounts are then used in the calculation of cloud emissivity and cloud reflectivity and transmissivity. The partitioning of cloud water into liquid and solid fractions is varied non-linearly in the temperature range 250.2-273.2 K.

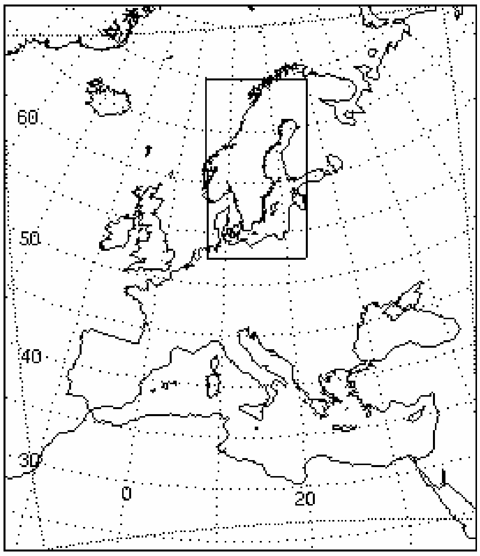

Figure 1. The geographical domain of the RCA3 model (dotted lines) used in the present study together with the coverage of the SCANDIA cloud climatology in the northern section.

Noteworthy and of great importance for this study is that in the radiation scheme cloud information is principally treated with a Maximum cloud overlap between vertical cloud layers in both short-wave and long-wave calculations.

For this particular study, RCA3 results covering the European region in the 1991-2000 period have been produced in a perfect boundary climate simulation experiment (i.e., a simulation of the present climate with analysed fields at the lateral boundaries). The model was run using ECMWF re-analysis fields (ERA-40 – described by Uppala, 2001) for specifying the boundary conditions. Figure 1 illustrates the full model domain where the indicated sub-region defines the coverage of the used cloud climatology and where the model evaluation was carried out (see next section for more details about the satellite dataset).

The RCA3 model had a horizontal resolution of approximately 44 km in this experiment and the number of vertical levels was 24. The basic cloud information from RCA3 consisted originally of only two specific cloud parameters available for each model grid layer: Cloud condensate mixing ratio q_c (prognostic variable) and fractional cloud cover f (diagnostic variable). From these basic model-simulated parameters other cloud parameters more suitable for the comparison to the satellite-observed quantities were calculated and these calculations are specified further in section 4.

3. THE 1991-2000 SCANDIA CLOUD CLIMATOLOGY

The SMHI Cloud ANalysis model using DIgital AVHRR data (hereafter denoted SCANDIA) is described in detail by Karlsson (1996 and 1997). SCANDIA uses the full five-channel NOAA AVHRR data set at the maximum horizontal resolution of 1.1 km. However, the cloud climatology results presented here have been based on a data set with a reduced resolution of 4 km in order to take into account uncertainties in the geographic navigation of individual pixels. The covered region is the Nordic region (Sweden, Norway, Denmark and Finland) including the entire Baltic Sea and nearby coastal areas and also some parts of the Norwegian Sea.

SCANDIA results from four daily overpasses over the area (observing approximately at night, in the morning, in the afternoon and in the evening under minimum satellite zenith angles) have been used to define a daily mean of cloud cover over the area. Results have then been accumulated to define monthly, seasonal and yearly climatologies for the studied time period. Since SCANDIA separates many different cloud types, the data set permitted also studies of different cloud groups in addition to the central parameter total fractional cloud cover. Of importance here is the definition used to separate the vertical cloud groups Low-level, Medium-level and High-level clouds. Since there is no standard definition to use here, it was decided to use the pressure levels at 700 hPa and 500 hPa as the reference for this separation. Notice that this definition is close but not exactly the same as the definition used by the International Satellite Cloud Climatology Project (ISCCP, see Rossow and Schiffer (1999)). Cloud top temperatures, as estimated from brightness temperatures of the AVHRR infrared channels, were compared to corresponding temperatures of the two pressurel levels from standard meteorological analyses used for numerical weather prediction (NWP).

The method for compiling climatologies based on SCANDIA results was first described by Karlsson (1997) and a complete description of the full 10-year dataset can be found in Karlsson (2003).

The quality of the SCANDIA climatology has been extensively examined (Karlsson, 2001, 2003) through comparisons with corresponding climatologies derived from surface cloud observations (SYNOP), from the ISCCP D2 dataset and from the ECMWF ERA-40 reanalysis dataset. In general, cloud amount deviations from corresponding surface observations were smaller than 10 % in cloud cover units except for some individual winter months when the separability between medium- and high-level clouds and snow-covered cold land surfaces was often poor which introduced a considerable overestimation of SCANDIA cloud amounts over land areas (close to 10 % in cloud cover units). Some problems in detecting boundary layer clouds during night and at twilight were also noticed, especially in cold winter situations with mixed cloud phases (i.e., both water droplets and ice crystals).

The comparison with the ISCCP cloud climatologies revealed much larger seasonal cloud amount variability in the SCANDIA climatology as well as on the average lower cloud amounts. However, a substantial part of this difference is most likely explained by differences in the detectability of very thin clouds due to differences in satellite viewing geometries (discussed more in detail in section 4). The agreement with the ERA-40 cloud dataset was remarkably good except for the winter season when ERA-40 cloud amounts were found to be even higher than SCANDIA over land areas (as mentioned earlier, SCANDIA was known to overestimate cloudiness in winter). This means that this winter-time deviation between SCANDIA and ERA-40 is likely to be even larger in reality.

Finally, it should be said that SCANDIA was found to underestimate cloud amounts by 5-10 % in cloud cover units in the summer season when compared with sur-

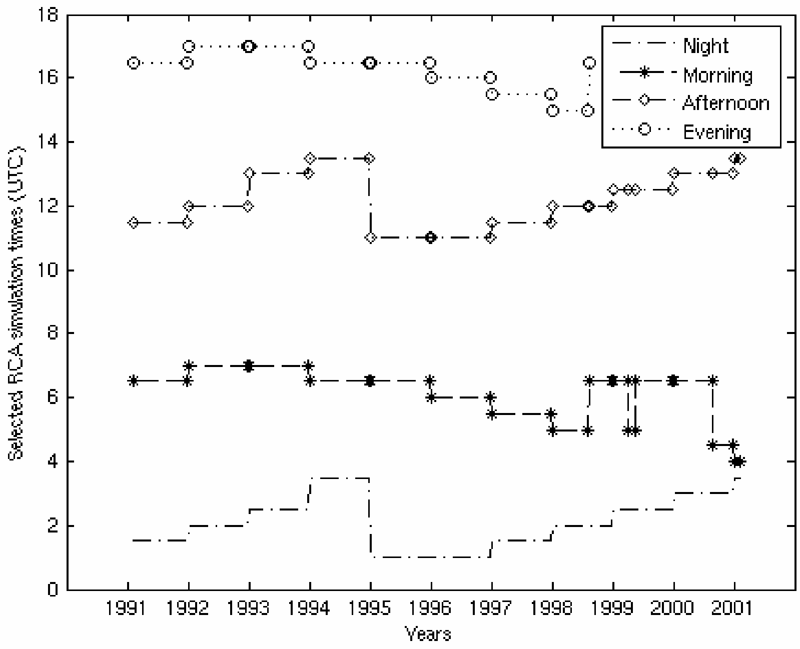

Figure 2. Visualisation of the valid times for the extracted results from RCA3 simulations in the period 1991-2000. This can be compared to corresponding NOAA overpass times presented by Karlsson (2003).

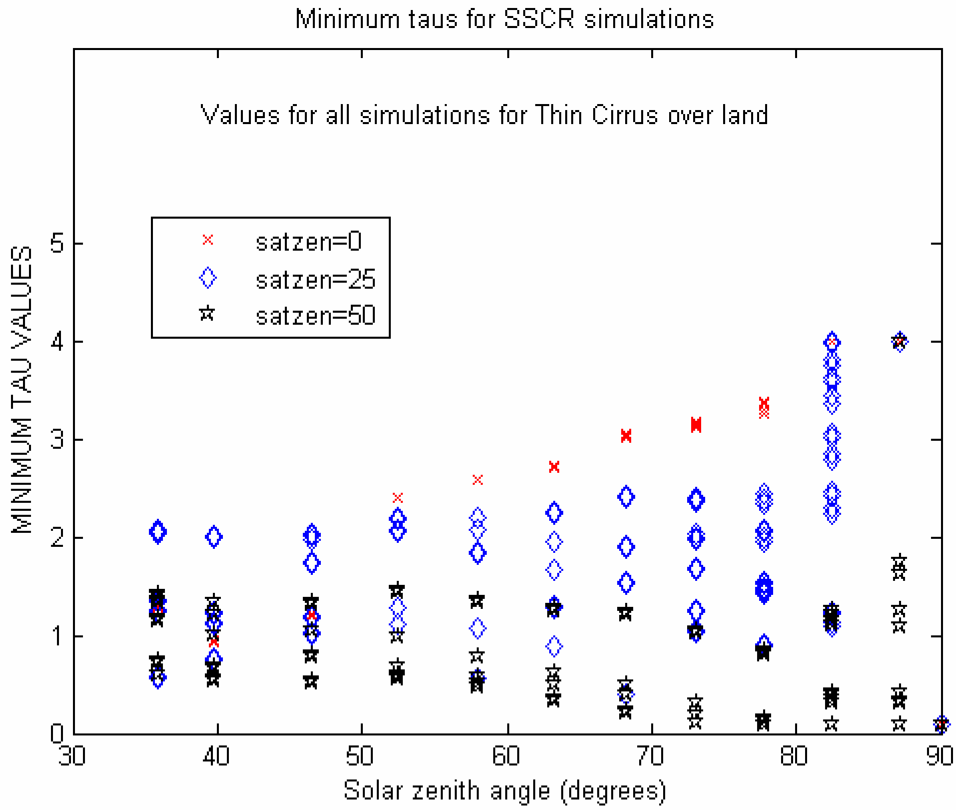

Figure 3. Extracted values of the minimum optical thickness for the thinnest Cirrus cloud categories of SCANDIA as simulated by the radiative transfer model SSCR. Simulations were made for an ice cloud over a land surface having a surface reflectivity of 5 %. Results for three different satellite zenith angles (satzen - in degrees) are highlighted.

face observations. However, this deficiency is not believed to be a true weakness of the SCANDIA observation but instead an indication of problems for the surface observer to correctly estimate cloud amounts in cases with convective cloud elements with large vertical dimensions. Experiments based on the use of additional satellite observations with large satellite zenith angles supported the view that this deviation is most probably caused by pure differences in geometrical viewing conditions (Karlsson, 1996).

4. METHODOLOGY

4.1 *General principles and basic set up for the validation experiment*

In this study we have focussed on the evaluation of the following three fundamental cloud parameters:

- Fractional total cloud cover f_{TOT}
- Vertical distribution of clouds as described by the amount of low-level clouds f_L, medium-level clouds f_M and high-level clouds f_H
- Optical thickness of clouds τ

We believe that this is a minimum set of cloud parameters that must be studied jointly for making firm conclusions about how clouds are modeled and how this might influence important physical processes like radiative transfer. Also other cloud parameters would be of interest but these are unfortunately not available in the SCANDIA cloud climatology.

The first parameter, f_{TOT}, is fundamental in that it determines the partitioning of cloudy and cloud free parts of model grid columns which has large implications for e.g. the overall radiation calculations. The second group of parameters, f_L, f_M and f_H, is decisive for longwave radiation calculations (in particular the calculation of outgoing longwave radiation – OLR - and the longwave radiation balance at the earth's surface). Finally, the third parameter, τ, determines in combination with fractional cloud cover the amount of reflected shortwave radiation, i.e., basically the cloud contribution to the planetary albedo. It is also strongly linked to the effective emissivity of clouds which has great implications for longwave calculations.

4.2 *Various model-to-satellite and satellite-to-model adaptations*

A number of adaptations of the used datasets were made to get a more justified comparison concept.

The most important Satellite-to-Model adaptation in this study was naturally the transfer of results from the high-resolution satellite-image representation into the coarse resolution representation of the RCA3 model having a horizontal grid resolution of 44 km. Also for the cloud optical thickness categories estimated from the SCANDIA results (to be described further in section 4.4), a transformation into an equivalent resolution similar to the RCA3 grid was made. For the grid averaging of in-cloud optical thicknesses from individual pixel values we have here applied a non-linear averaging (i.e., first averaging cloud transmissivities) rather than a linear averaging.

Further, we have applied the following Model-to-Satellite adaptations:

1. Matching of selected model-simulation times to satellite overpass times
2. Computation of the fractional cloud cover parameters f_{TOT}, f_L, f_M and f_H using a top-down approach (satellite perspective)
3. Restriction of the evaluation of vertical cloud groups and optical thickness categories to the following three seasons:
   SPRING (March,April,May) – denoted MAM in result figures
   SUMMER (June,July,August) – denoted JJA in result figures
   AUTUMN (September,October,November) – denoted SON in result figures
4. Calculation of typical effective cloud optical thickness categories for each cloud altitude group using the top-down approach (satellite perspective).

The first aspect here is important for avoiding possible errors or differences due to potential diurnal changes in cloudiness. One problem with the NOAA satellites is unfortunately that they are not stable in their sun-synchronous orbits. Especially, the afternoon satellites (i.e., with equator crossing times close to noon) have shown considerable orbital drifts through the years. For example, a shift (delay) in overpass times of more than three hours was gradually built up for NOAA-14 during the period 1995 to 2000. Thus, if not compensating for this in the used model datasets (e.g., if using fix times for simulating the afternoon observation) differences might occur due to diurnal changes in cloudiness. Here, we have extracted results from the model-simulation at the times indicated in Figure 2. This corresponds in an approximate way to the valid overpass times for SCANDIA as shown by Karlsson (2003).

The second mentioned Model-to-Satellite adaptation is required for taking into account the fact that from the satellite perspective it is impossible to make a correct estimation of the true coverage of clouds at lower altitudes if upper level clouds are present. What is observed is only the visible contribution to the total fractional cover f_{TOT}. Thus, we require for the model contributions from the three cloud groups; f_L, f_M and f_H, that the following relation is fulfilled:

$$f_{TOT} = f_L + f_M + f_H \qquad (1)$$

This also means that we can only expect to find a good estimate of the true cloud cover for the individual cloud altitude group of high clouds (f_H). For the other two groups we will normally get a lower value than the true cloud cover since there will be a fraction of the clouds that are obscured by upper level clouds. The top-down approach and Eq. 1 have thus been used to calculate these quantities preparing for a proper comparison with the satellite estimates. Consequently, the same criteria as in SCANDIA have been used here when defining the corresponding cloud altitude groups in the RCA3 model dataset.

Concerning the SCANDIA-retrieved thin high clouds (semi-transparent Cirrus), we also assume them to represent clouds above the 500 hPa level even if their measured brightness temperatures naturally are warmer than the temperatures at this level due to their semi-transparency. Their detection is based on brightness temperature differences in the split-window channels at 11 and 12 µm and not by direct comparison of brightness temperatures to the 500 hPa level temperature. In connection to the estimation of vertical cloud groups, it should also be remarked that a small fraction (1-2 % in cloud cover units) is defined by SCANDIA as Fractional clouds (thus, not assigned to any vertical group) and this has to be taken into account when relating the vertical cloud group contributions to total cloud amount figures.

The third mentioned adaptation of the model-simulated dataset is a consequence of the documented cloud classification problems for the SCANDIA method over land surfaces during cold winter periods as reported by Karlsson (2003). This often led to erroneously high cloud amounts over land areas in the northern parts. Furthermore, strong near-surface temperature inversions also led to problems in correctly separating Low-level clouds from Medium-level clouds using the mentioned temperature criteria above. Yet another problem was that sub-pixel convective cloud elements over ocean surfaces (e.g. Norwegian Sea) were often misinterpreted as thin Cirrus clouds during the winter season. This was caused by the introduction of artificial brightness temperature differences for channels at 3.7, 11 and 12 µm. Such differences in the radiance-to-temperature relation for the involved AVHRR channels appear if there (14)
are strong sub-pixel temperature gradients present within individual pixels. A similar effect was also seen over land areas in summer for sub-pixel cumulus clouds but not as strong as for the winter case over ocean areas. Consequently, because of these problems we do not attempt any evaluation of cloud amount contributions from the vertical cloud groups during the *WINTER* season (December-February). Similarly, we also avoid any evaluation of optical thickness categories during this season due to the very small number of useful cases because of the required minimum sun elevation for SCANDIA optical thickness retrieval.

Lastly, the fourth mentioned adaptation above was introduced for the purpose of enabling the generation of model-simulated frequency histograms describing the co-occurrence of any particular cloud altitude group with any particular optical thickness category. In this way it would be possible to describe in a compact form typical dynamic cloud regimes e.g. as demonstrated previously in a study by Tselioudis and

Jakob (2002). For this application we will apply a restricted version of this methodology for studying mean conditions over the entire SCANDIA domain (see Figure 1). More details on the exact methodology are given later in section 4.4.

4.3 *Compensating for model contributions from non-detected or non-observed thin clouds*

The most important model-to-satellite adaptation in this study (besides those mentioned in the previous section) is the removal of cloudiness contributions from clouds judged to be non-detectable in the satellite observation. This was found necessary since the RCA3 model has no lower limits for either the value of the simulated total cloud condensate or the cloud fraction that is simulated for a given model grid volume or column. The idea of a preventive filtering of the modelled dataset was first proposed by Wyser and Jones (2005) and we have adapted this concept here.

The examination of the cloud detection limits of the SCANDIA cloud classification model was made by the use of complementary radiative transfer simulations using the Signal Simulator for Cloud Retrieval (SSCR) radiative transfer code introduced by Nakajima and King (1992) and Nakajima and Nakajima (1995). SSCR is based on the previous work of Nakajima and Tanaka (1986) and is basically a discrete-ordinate method (DISORT – Stamnes and Swansson, 1981) solving the transfer equation for diffuse solar radiation in a plane-parallel scattering atmosphere. The method allows for simulation of clouds by inserting them as homogeneous sub-layers with certain specified characteristics (water phase, volume size distribution and vertically integrated optical thickness). SSCR has been extended to include thermal radiative transfer as proposed by Stamnes et al. (1988). SSCR has recently become an integral part (included in the RAD.PACK component) of a general RTM tool library available at http://www.ccsr.u-tokyo.ac.jp/~clastr/.

A large number of simulations were carried out for two selected standard cloud types (water cloud with effective radius 10 µm and ice cloud with effective radius 40 µm) in order to study the variability of the SCANDIA cloud detection limit. Simulations were made for four different standard atmospheres (mid-latitude summer and winter plus sub-arctic summer and winter – McClatchey et al., 1972), two earth surfaces (land or ocean), three satellite zenith angles (0, 25 and 50 degrees), twelve solar zenith angles (corresponding to SCANDIA sun elevation categories) and five relative sun-satellite azimuth differences (0, 45, 90, 135, 180 degrees). Figure 3 shows a summary overview of the SSCR-interpreted minimum optical thicknesses for thin Cirrus clouds over land surfaces according to SCANDIA AVHRR 0.6 µm reflectance thresholds. Results have been produced by interpolating reflectance simulations for various optical thicknesses to match corresponding SCANDIA thresholds. Each individual symbol shows the result from one specific case of all the possible simulation conditions.

Based on these results, we have here used the following concept for filtering of the modelled cloud dataset:

- For daytime conditions (here defined as for solar zenith angles below 80.2 degrees), cloud amount contributions from clouds with optical thicknesses smaller than 1.0 are removed.
- For the remaining cases (at night and at twilight), the same optical thickness limit is used for High-level clouds and Medium-level clouds while for Low-level clouds the limit is increased to 3.0 (basically due to the noisy appearance of AVHRR channel 3 data for some periods which imposed more restrictive radiance thresholds for SCANDIA).
- Since these values of minimum optical thicknesses are only approximatively defined and influenced by a large number of uncertainties and dependencies, sensitivity tests are also performed using the full range of estimated minimum optical thickness values within the interval 0.5 and 2.5.

The calculation of the effective optical thickness of a cloud layer from modelled cloud variables is based on the original formulation by Stephens (1978) giving the approximate relation between the density of water (or ice) $\rho_{w/i}$, optical thickness τ, effective radius r_e and columnar total liquid water path *LWP* (kgm^{-2}) as

$$\tau = \frac{3}{2} LWP \Big/ \rho_{w/i} r_e \qquad (2)$$

Since we are specifically interested in the cloud-representative value here (i.e, in-cloud values) instead of grid averages, we systematically multiply results from Eq. 2 with the factor *1/f* to get corresponding in-cloud values. If we ignore this aspect we would risk filtering out too many clouds in cases of small fractional cloud cover *f* in individual grid volumes. Furthermore, we also know that the use of average grid volume quantities would not be appropriate since we would then significantly underestimate (overestimate) effective cloud transmissions (optical thicknesses) as pointed out by e.g. Scheirer and Macke (2001) and Schröder et al. (2006).

We will concentrate on the most interesting cloud overlap in this context, the Maximum overlap, in this study due to its direct use in the RCA3 radiation scheme. Here, we use the approach introduced by Stubenrauch et al. (1997) and which is also in principle the one used in RCA3 radiation calculations. It is based on the use of normalised contributions from individual model layers (f/f_{Max} where f is the fractional cloud cover of a layer and f_{Max} is the maximum cloud cover of all layers within a grid column) to calculate the effective optical thickness τ_{eff} . Thus, for a case with N vertical layers we get for the effective optical thickness $\tau_{eff,Max}$ and the total cloud cover $f_{TOT,Max}$

$$\tau_{eff,Max} = \frac{\sum_{i=1}^{N} f_i \tau_i}{f_{TOT,Max}} \qquad (3)$$

$$f_{TOT,Max} = \max(f_i) \qquad (4)$$

Notice here that we are using in-cloud estimations for τ_i according to Eq. 2. An obvious limitation of this approach is that it will inevitably give an overestimation of the resulting optical thickness since the normalisation procedure is equivalent to a linear averaging of optical thicknesses over the area defined by the total cloud cover. A more accurate calculation is unfortunately not possible since it would indeed require an exact knowledge of the actual location of individual cloud layers within each grid box.

We can compare these results to results for the other extreme concerning cloud (1)
overlap, namely the Random overlap. Here we can make a more exact calculation utilising the expression for the total effective transmission T_{Ran} in a grid column

$$T_{Ran} = 1 - f_{TOT,Ran} E_{eff} \qquad (5)$$

where E_{eff} is the total extinction due to clouds. The same quantity can in the Random overlap case be calculated as the product of individual transmittances for individual layers as

$$T_{Ran} = \prod_{i=1}^{N} 1 - f_i \left(1 - \exp(-\tau_i)\right) \qquad (6)$$

Since the effective cloud transmittance is given by the expression 1-E_{eff} we can combine Eqs. 5 and 6 to finally give an expression for the effective optical thickness τeff,Ran of the cloudy fraction of the grid column.the grid column. Thus, we have the following equations for Random overlap to be compared to previous Eqs. 3 and 4 for Maximum overlap:

$$\tau_{eff,Ran} = -\ln \left\langle \frac{f_{TOT,Ran} - 1 + \prod_{i=1}^{N} 1 - f_i \left(1 - \exp(-\tau_i)\right)}{f_{TOT,Ran}} \right\rangle \qquad (7)$$

$$f_{TOT,Ran} = 1 - \prod_{i=1}^{N} \left(1 - f_i\right) \qquad (8)$$ (5)

However, since we have quite substantial observational evidence that true clouds tend to behave more like a mix between Maximum and Random overlap (e.g. as reported by Tian and Curry, 1989, and Willén et al., 2005), we will also examine results if using the Maximum-Random approach (i.e., clouds in adjacent layers are treated with Maximum overlap, other clouds are treated as Random). Due to the previously mentioned ambiguity in the calculations for the case of Maximum overlap, we will use a compromise solution also here. First we identify for each column the number of cloud blocks, N*, using the same terminology as Stubenrauch et al. (1997). Each individual cloud block is defined as either a single cloud layer (if having no adjacent cloud layers) or a group of adjacent cloudy layers. For each cloud block we calculate an effective optical thickness τ_i* according to Eq. 3 above but now only applied within an individual cloud block and not to all cloudy layers of grid column (i.e., using the maximum cloud cover f_i* of the sub-set of layers and not the maximum cloud cover for all layers in the grid column). When this is done, we finally apply the Random approach described above but now based on the reduced set of cloud blocks instead of on all individual cloud layers. Thus, we get for the Maximum-Random overlap case

$$\tau_{eff,M-R} = -\ln\left\langle \frac{f_{TOT,M-R} - 1 + \prod_{i^*=1}^{N^*} 1 - f_{i^*}\left(1-\exp\left(-\tau_{i^*}\right)\right)}{f_{TOT,M-R}} \right\rangle \tag{9}$$

$$f_{TOT,M-R} = 1 - \prod_{i=1}^{N} \frac{1-\max(f_i, f_{i-1})}{1-\min(f_i, 0.99)} \tag{10}$$

where the star-marked values indicate that these are values representing individual cloud blocks rather than individual cloud layers.

4.4 *Preparing cloud altitude - optical thickness histograms from satellite and model datasets*

For the evaluation of the third of the cloud parameters listed previously in section 4.1 (the optical thickness), we have applied a post-processing approach to the original SCANDIA cloud classification results since the original SCANDIA method did not include retrieval of optical thicknesses. The SSCR radiative transfer model was once again used to interpret SCANDIA thresholds in the visible AVHRR channel at 0.6 μm. But this time the interpretation included all SCANDIA cloud types and not only those representing thin clouds. To enable this, new SSCR simulations were made for the two standard cloud types but now for a much wider range of optical thicknesses. After matching simulation results to the threshold values, approximate values of typical optical thicknesses for each cloud type category could be extracted and grid-averaged values for the average in-cloud optical thickness were calculated.

In the next step, histograms were created which listed the frequency of co-occurring vertical cloud groups (any of Low, Medium or High) and optical thickness categories. For the latter originally eight different optical thickness categories were defined but in order to simplify visualisation of the results and partly also for acknowledging the fact that only approximate values are retrievable from satellite data we will here only use the following three optical thickness categories:

THIN CLOUDS: 1.0< τ<14.8
THICK CLOUDS: 14.8< τ<28.6
VERY THICK CLOUDS: 28.6< τ

However, it was found more complicated to extract the corresponding information from the model-simulated dataset. The reason is that we do not know exactly where the three vertical cloud groups are located horizontally due to the sub-grid scale character of the cloud fields. For example, we know that we will definitely get different results if applying different cloud overlap techniques. We are thus forced to make some assumptions here to find a way forward and we have to study the three possible overlap approaches separately. For finding the representative mean optical thickness category for each of the present categories of Low, Medium and High clouds within a grid column, we use the following approach:

Low-level clouds: The calculation of the effective optical thickness for the satellite-observed (using the top-down perspective) part of the Low-level clouds, τ_{eff_LOW} , is straight-forward. We apply Eqs. 3, 7 and 9 from pressure level 700 hPa (i.e., the first model level below this pressure level) down to the surface but in this case we substitute the f_{TOT} values with the corresponding true total amounts of low-level clouds (which now has to be calculated from the model parameters in addition).

Mid-level clouds: The calculation here requires that we also take into account that some fraction of all observed mid-level clouds are superposed over low-level clouds. Thus, we first calculate the exclusive mid-level effective optical thickness value using the true total amount of mid-level clouds and the effective in-cloud value optical thickness for mid-level cloud layers. Then we calculate the fraction of low-level clouds that is overlapped by medium-level clouds and finally we get a total effective optical thickness of satellite-observed medium-level clouds by combining the two vertical groups. In these calculations we get different results depending on the applied cloud overlap assumption.

High-level clouds: Here, we carry out the calculations following the same principle as for medium-level clouds. However, in this case we have in addition to calculate the total true amount of the combination of low-level and mid-level clouds in order to be able to add the contribution from lower level clouds (both at Low and Medium levels).

5. RESULTS

5.1 *SCANDIA-RCA3 comparison of total fractional cloudiness fields*

Figure 4 shows the unfiltered and filtered RCA3 results for the Maximum cloud overlap approach separated into four seasons and compared to the corresponding SCANDIA climatologies. The SCANDIA results show a pronounced seasonal cycle in cloudiness with a distinct minimum in the summer season. The largest yearly amplitude is shown over the Baltic Sea while the Scandinavian mountain range and the visible part of the Norwegian Sea show much smaller seasonal amplitude in cloudiness. The unfiltered RCA3 results give generally somewhat higher cloud amounts than SCANDIA, especially over the Scandinavian mountain range. The seasonal variation is much less than for SCANDIA but also here the highest amplitude is seen over the Baltic Sea. An interesting feature is the pronounced minimum in cloudiness that is seen over the Skagerrak Sea and in south-eastern Norway (near Oslo). This feature is only vaguely confirmed in by SCANDIA and the amplitude of the minimum is much lower. Also further to the north a minimum in cloudiness is seen for RCA3 on both sides of the Scandinavian mountain range. The minimum along the Norwegian coast is also found by SCANDIA (especially for spring) while the cloud pattern eastward of the mountain range is very different from RCA3 results. The SCANDIA climatology does not show the in-land minimum that is seen for RCA3.

After filtering it is seen that clouds are removed especially for the two seasons winter and spring while the other two seasons are only marginally affected. This means that we do not anymore see generally higher RCA3 cloud amounts for most seasons. Otherwise the features mentioned above basically remain the same and similar geographical variations were also seen for the two other cloud overlaps.

In Table 1 RCA3 results are summarised as area means of the difference from SCANDIA for all three cloud overlap approaches. We find that on a yearly basis the filtering removed 2.82 % in cloud cover units for Maximum overlap, 5.04 % for Maximum-Random overlap and 9.21 % for Random overlap. The best fit with SCANDIA results is seen for Maximum-Random overlap (-0.76 %) while results for Random overlap show an overestimation (+5.27 %).

	Max-Ran	Max	Ran
WINTER	**-6.09** (0.34)	**-7.16** (-2.72)	**-2.29** (8.82)
SPRING	**-4.27** (1.80)	**-4.93** (-1.40)	**0.49** (12.00)
SUMMER	**5.41** (8.90)	**2.83** (3.88)	**14.7** (21.20)
AUTUMN	**1.97** (6.16)	**-0.17** (2.09)	**8.19** (15.90)
YEAR	**-0.74** (4.30)	**-2.36** (0.46)	**5.27** (14.48)

Table 1. Area mean of seasonal and yearly differences in total cloud cover (%) between RCA3 and SCANDIA for filtered and unfiltered (in brackets) results and for different cloud overlap approaches.

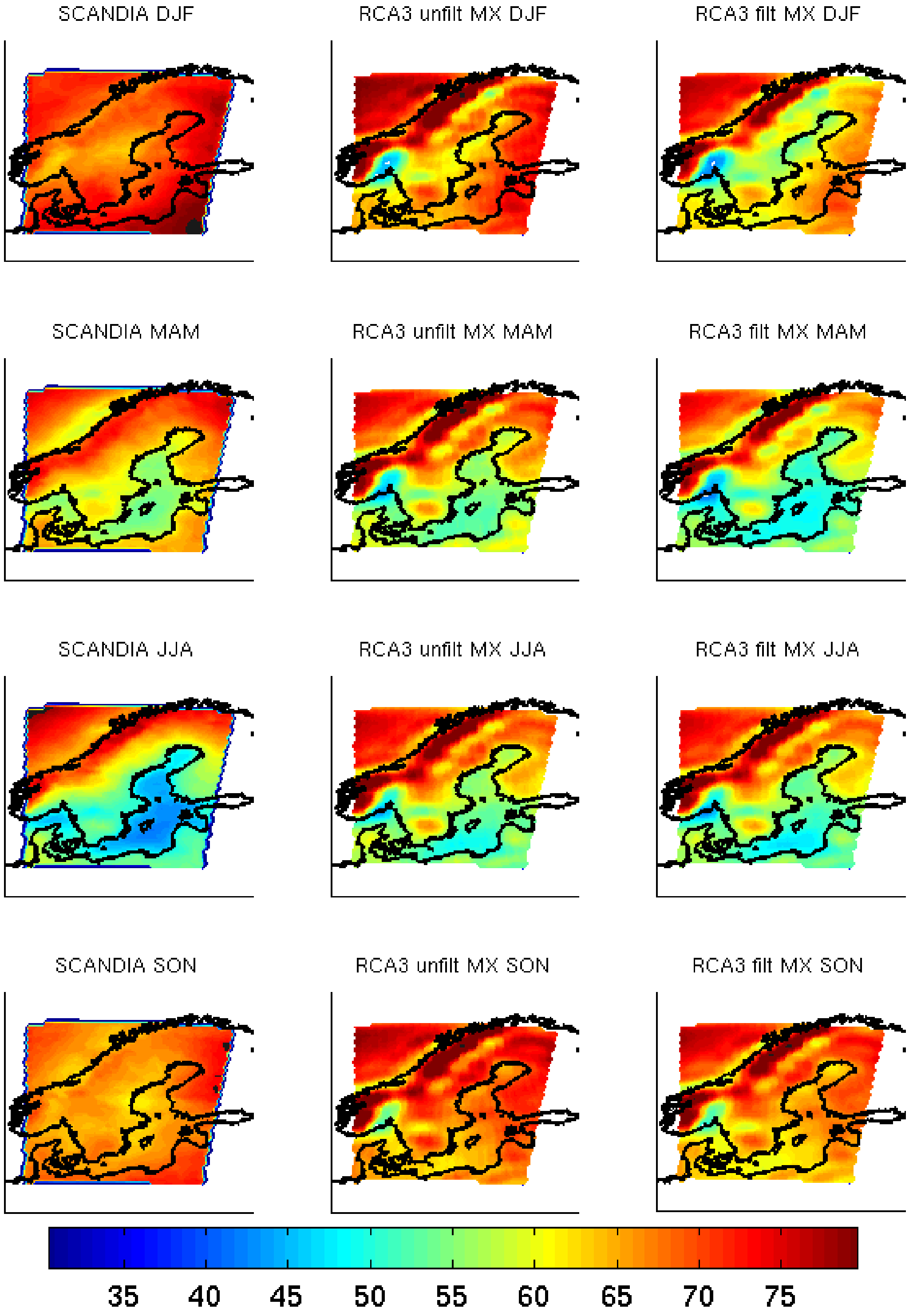

Figure 4. Seasonal means (winter,spring,summer and autumn from top to bottom) 1991-2000 of total cloud cover (%) for SCANDIA (left column) compared with original (central column) and filtered (right column) RCA3 results using the **Maximum** cloud overlap.

To notice here is that all overlaps give higher RCA3 values than SCANDIA in the summer season while the opposite is seen for winter. For Random overlap RCA3 cloud amounts are especially high during summer and autumn seasons.

5.2 *RCA3 performance concerning the vertical distribution of clouds*

Figures 5-7 show the corresponding unfiltered and filtered seasonal RCA3 means for the groups of high-level, medium-level and low-level clouds in comparison to SCANDIA and for Maximum cloud overlap. Results for the winter season are not shown here for reasons explained earlier.

RCA3 amounts of high-level clouds in Figure 5 are generally higher than SCANDIA but the difference is slightly reduced after filtering. Especially over the Scandinavian mountain range and over land areas we find higher values for RCA3. The in-land minimum in the northern part of Scandinavia that was seen for total cloud cover is seen also for the high-level clouds.

As a contrast, RCA3 amounts of medium-level clouds in Figure 6 show consistently lower values than the corresponding satellite observations. Some strange features of high cloud contributions are seen in the satellite observation, especially in the northern part in spring. This is considered to be caused by problems for SCANDIA in making a correct classification in the morning due to unfavourable illumination conditions and satellite viewing angles (enhanced forward-scattering effects from wet snow-covered ground and low-level clouds with cold cloud tops). Notice again the tendency to have higher RCA3 cloudiness in the Scandinavian mountain range.

The corresponding results for the contribution from low-level clouds are given in Figure 7. We notice that values are generally low in the SCANDIA climatology, mostly as an effect of that we only look at the exclusive contribution from that part of all low-level clouds where no upper level clouds are already present. However, cloud amounts over the Norwegian Sea are quite high in summer showing the dominance of low-level cloud presence here. Interestingly, RCA3 results show higher cloud contributions for all seasons and also after filtering. The Norwegian Sea maximum is well captured but results differ from SCANDIA over many land areas (e.g. generally higher cloud amounts but with the same in-land minimum in northern Scandinavia as for total and all vertical cloud groups).

Results for all three vertical cloud groups are summarised in Table 2 for Maximum cloud overlap. However, regardless of overlap approach, we find the same pattern: Higher values than SCANDIA for high-level clouds and low-level clouds, and lower values than SCANDIA for medium-level clouds. The difference due to cloud overlap is basically only seen in the range of differences (largest for Random overlap and smallest for Maximum overlap).

To be noticed here is that the sum of the three vertical cloud categories does not agree exactly with the results for total fractional cloud cover given earlier in Table 1. The missing cloud amount contribution (about 2 % in cloud amount units) is explained by the existence of the additional SCANDIA category of Fractional clouds (not possible to assign to any of the vertical cloud groups).

	Difference high-level clouds	Difference medium-level clouds	Difference low-level clouds
SPRING	**3.39** (5.69)	**-7.01** (-6.55)	**0.61** (1.21)
SUMMER	**5.58** (6.39)	**-5.71** (-5.70)	**4.92** (5.04)
AUTUMN	**-1.84** (-0.54)	**-2.86** (-2.70)	**6.48** (6.87)
YEAR excluding Winter	**2.38** (3.85)	**-5.19** (-4.98)	**4.00** (4.37)

Table 2. Area mean of seasonal differences (excluding Winter season) between RCA3 and SCANDIA for filtered and unfiltered (in brackets) high, medium and low cloud amount contributions (%) using the **Maximum** cloud overlap assumption.

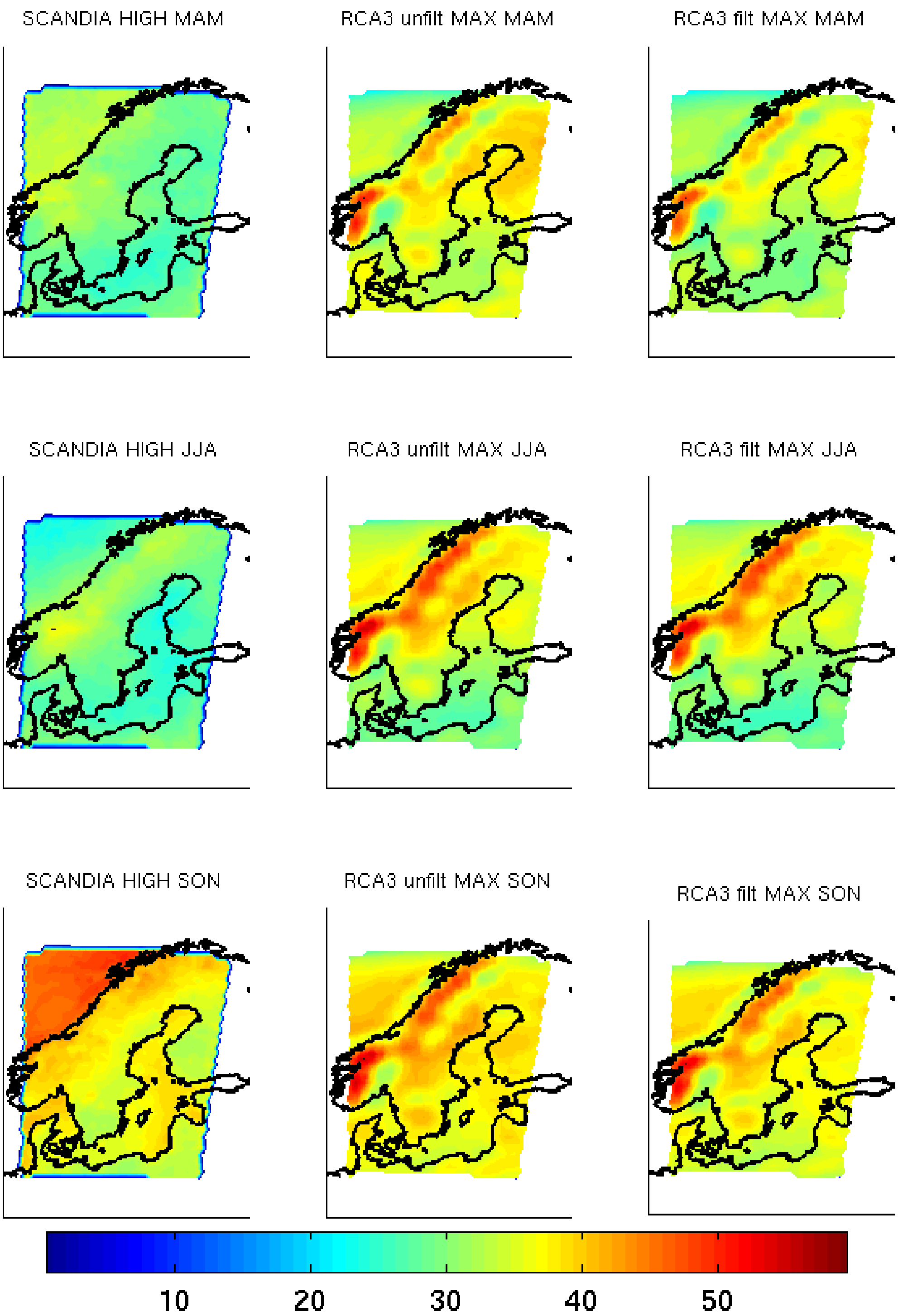

Figure 5. Seasonal means (spring, summer and autumn from top to bottom) 1991-2000 of high-level cloud cover contribution (%) for SCANDIA (left column) compared with corresponding original (central column) and filtered (right column) RCA3 results using the **Maximum** cloud overlap assumption.

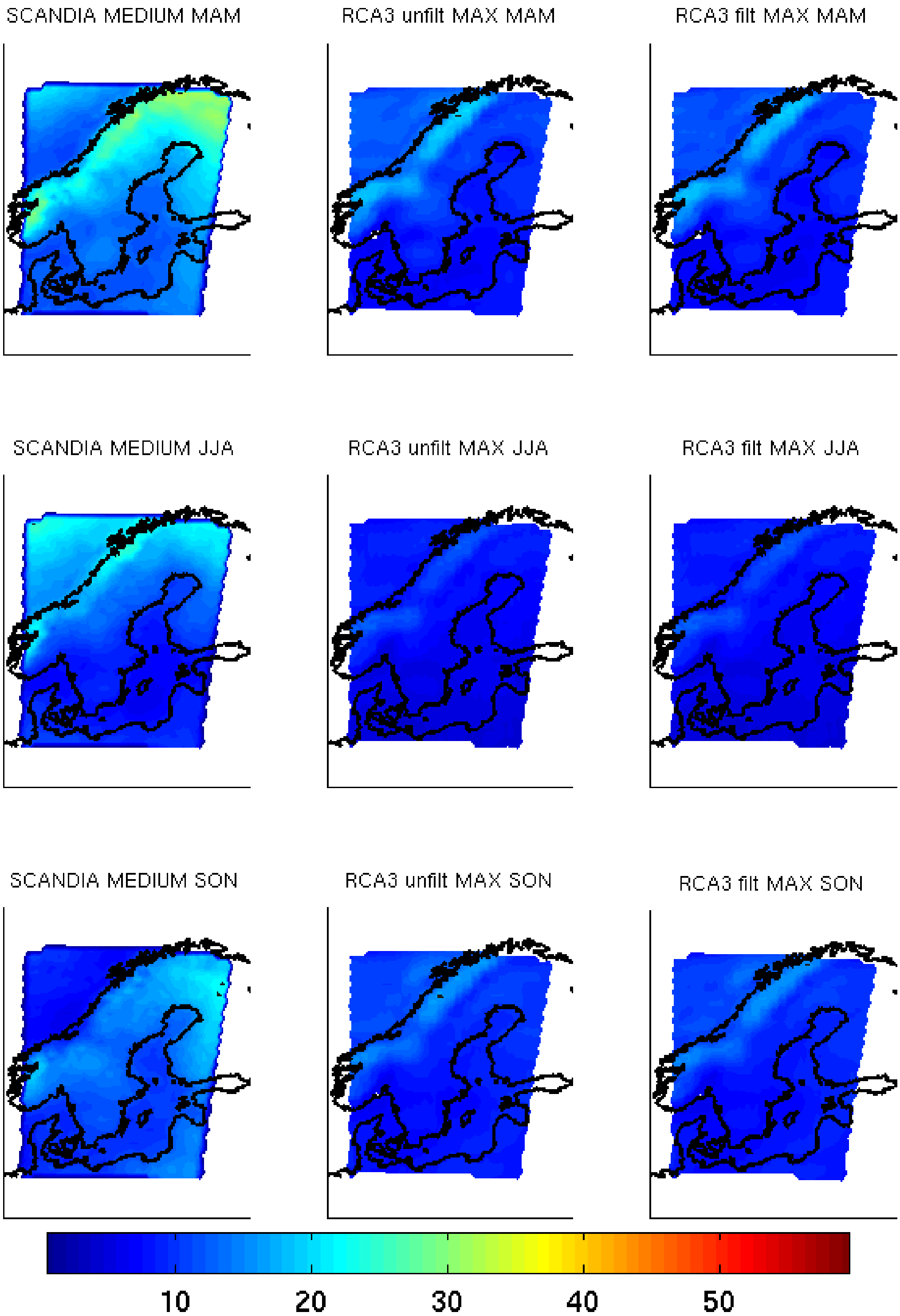

Figure 6. Seasonal means (spring, summer and autumn from top to bottom) 1991-2000 of the medium-level cloud cover contribution to the satellite-viewed total cloud cover (%) for SCANDIA (left column) compared with corresponding original (central column) and filtered (right column) RCA3 results using the **Maximum** cloud overlap assumption.

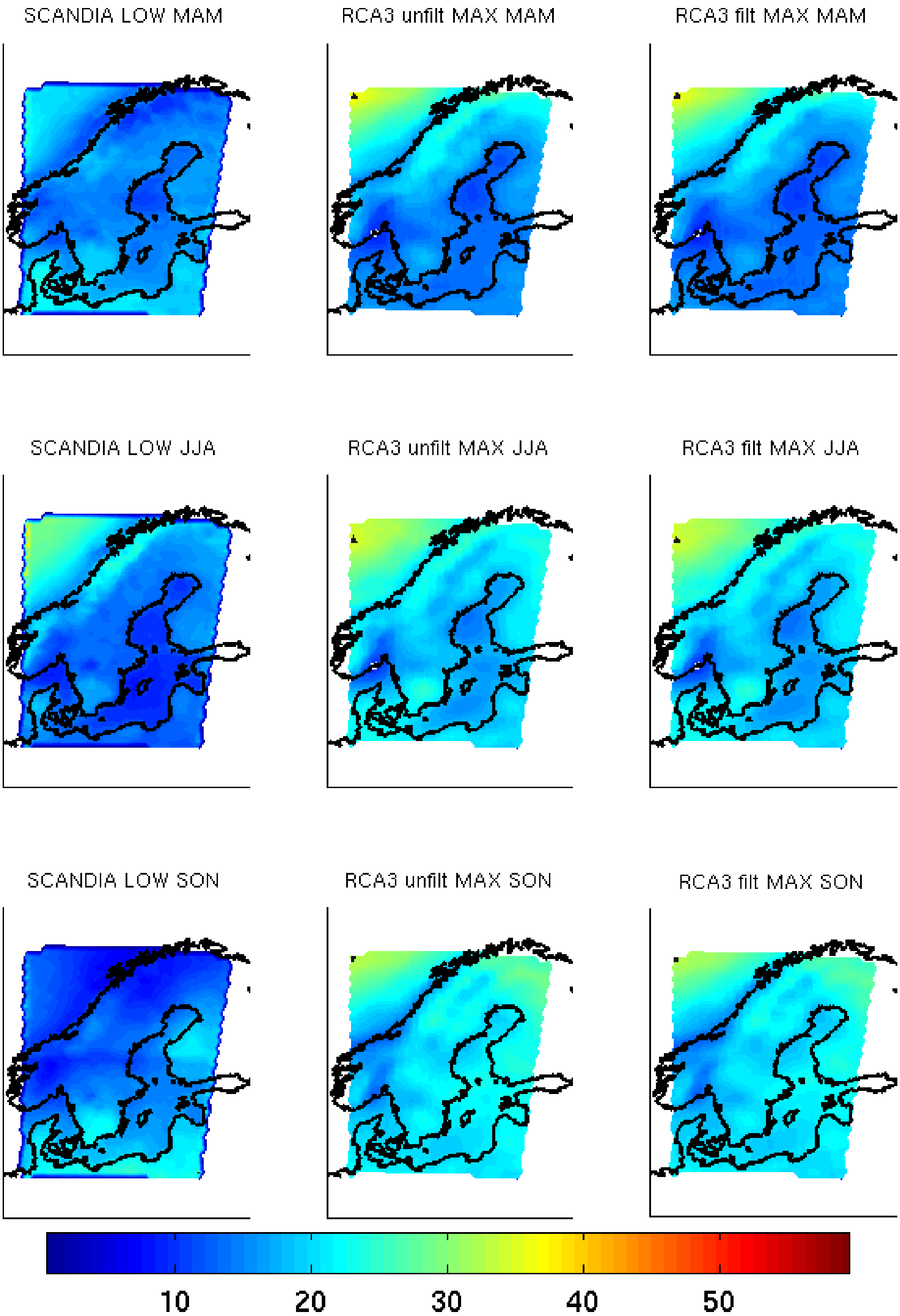

Figure 7. Seasonal means (spring, summer and autumn from top to bottom) 1991-2000 of the low-level cloud cover contribution to the satellite-viewed total cloud cover (%) for SCANDIA (left column) compared with corresponding original (central column) and filtered (right column) RCA3 results using the **Maximum** cloud overlap assumption.

5.3 *RCA3 performance of optical thickness categories linked to vertical cloud categories*

For further evaluation whether the remaining RCA3 clouds after filtering resemble the typical SCANDIA distribution of clouds we study results in Table 3. This table shows the relative frequency among all cloudy cases of vertical cloud group and optical thickness category co-occurrence, i.e., the frequency of a cloud appearing in a certain vertical cloud category and at the same time being assigned to a particular cloud optical thickness category.

The RCA3 results in Table 3 are based on effective optical thickness calculations using the Maximum cloud overlap assumption. Corresponding relative frequencies interpreted from the SCANDIA climatology are given in brackets.

The categories denoted SUB-LIMIT represent cases where the RCA3-calculated effective optical thickness for one individual cloud altitude group fell below the vertically integrated minimum value based on contributions from all cloud altitude groups (i.e., the minimum filtering value of optical thickness – in the default case set to 1.0).

For further clarification, it must be said that we want the number of SUB-LIMIT cases to be as low as possible in order to justify the comparison with SCANDIA-interpreted values (e.g., the latter being assumed to have optical thickness values always exceeding the minimum optical thickness value used when filtering model results). Full consistency here between satellite-interpreted values and model-calculated ones is impossible due to the differences in horizontal resolution and the fact that a certain cloud overlap assumption must be made when treating the modelled cloud fields while satellite-results are always considered maximally overlapped (on the individual pixel scale).

Concerning the SCANDIA relative frequencies in Table 3, we find very large differences when comparing with RCA3 frequencies. Typical for the SCANDIA dataset is a high (close to 30 %) and fairly uniform contribution by all vertical cloud groups sub-categorized as THIN whereas the THICK groups have only a few % of the total contribution and the VERY THICK groups normally have less than 1 % contribution (with the exception of high clouds that have slightly higher contribution). The RCA3 cloud distribution is very different with a smaller contribution from THIN categories and a larger contribution from THICK and VERY THICK categories. Remarkable is the high contribution to the VERY THICK category for low-level clouds for all seasons. For example, RCA3 has here a contribution of 28 % in summer whereas the corresponding contribution interpreted from SCANDIA is practically zero.

We also notice the generally lower overall RCA3 contributions to medium-level clouds and higher contributions to high and low-level clouds. This is consistent with the results presented in the previous section even if it must be remarked that we are in this case only studying cases with the sun well above the horizon. The frequency of cases characterised as being of the SUB-LIMIT categories is relatively low (about 5 %) which indicates that this overlap approach at least does not introduce large inconsistencies with how clouds are interpreted from the satellite view (i.e., basically measuring effects from vertically integrated optical thicknesses at high horizontal resolution).

Table 4 gives results for the Random case, i.e., the other extreme concerning cloud overlap. Here, RCA3 results resemble the SCANDIA-derived results to a much larger extent. Notice in particular the good agreement for the three sub-categories of low-level clouds. The total contribution from mid-level clouds is still seriously underestimated while for high-level clouds only a moderate overestimation is seen. This distribution differs to some extent from previous results shown in Table 2. However, we recall that the latter is valid for all cases and not exclusively for daytime cases with high sun elevations. Furthermore, we notice in Table 4 that the number of cases in the SUB-LIMIT category for low-level clouds has increased significantly which partly may explain the difference. At the same time, the increased number of SUB-LIMIT cases unfortunately reduces the reliability of the results slightly.

6. DISCUSSION

6.1 *General results*

Concerning the RCA3 simulation of total cloud amounts in the period 1991-2000, we have found quite good agreement for

	SPRING	SUMMER	AUTUMN
HIGH - THIN	**37.2** (28.8)	**29.6** (40.7)	**33.2** (35.5)
HIGH - THICK	**3.7** (3.5)	**2.7** (2.6)	**3.5** (3.3)
HIGH - VERY THICK	**6.1**(1.5)	**13.1** (0.5)	**10.1** (1.8)
MEDIUM - THIN	**10.2** (33.9)	**3.2** (29.4)	**7.2** (27.0)
MEDIUM - THICK	**1.8** (1.4)	**1.5** (0.1)	**1.6** (0.9)
MEDIUM – VERY THICK	**3.0** (0.2)	**6.7** (0.0)	**4.3** (0.0)
LOW - THIN	**15.8** (30.1)	**4.4** (26.2)	**10.4** (29.7)
LOW - THICK	**6.8** (0.6)	**5.5** (0.3)	**7.0** (1.3)
LOW - VERY THICK	**10.1**(0.1)	**28.0** (0.0)	**17.8** (0.4)
HIGH SUB-LIMIT	**4.9**	**5.2**	**4.6**
MEDIUM SUB-LIMIT	**0.4**	**0.0**	**0.2**
LOW SUB-LIMIT	**0.1**	**0.0**	**0.1**

Table 3. Summary of seasonal results (excluding Winter) of the relative distribution (%) of clouds among cloud altitude/cloud optical thickness categories for the **Maximum** overlap approach. Corresponding interpreted categories from SCANDIA results are given in brackets. See text for further explanation.

	SPRING	SUMMER	AUTUMN
HIGH - THIN	**38.4** (28.8)	**37.1** (40.7)	**37.4** (35.5)
HIGH - THICK	**5.7** (3.5)	**4.8** (2.6)	**6.7** (3.3)
HIGH - VERY THICK	**1.3**(1.5)	**2.2** (0.5)	**2.1** (1.8)
MEDIUM - THIN	**14.3** (33.9)	**11.4** (29.4)	**12.2** (27.0)
MEDIUM - THICK	**1.3** (1.4)	**1.6** (0.1)	**1.5** (0.9)
MEDIUM – VERY THICK	**0.2** (0.2)	**0.4** (0.0)	**0.3** (0.0)
LOW - THIN	**26.5** (30.1)	**28.9** (26.2)	**28.6** (29.7)
LOW - THICK	**0.3** (0.6)	**0.4** (0.3)	**0.4** (1.3)
LOW - VERY THICK	**0.0**(0.1)	**0.1** (0.0)	**0.0** (0.4)
HIGH SUB-LIMIT	**4.2**	**5.5**	**4.8**
MEDIUM SUB-LIMIT	**0.9**	**0.4**	**0.6**
LOW SUB-LIMIT	**7.0**	**7.1**	**5.2**

Table 4. Summary of seasonal results (excluding Winter) of the relative distribution (%) of clouds among cloud altitude/cloud optical thickness categories for the **Random** overlap approach. Corresponding interpreted categories from SCANDIA results are given in brackets. See text for further explanation.

seasonal and yearly averages (Table 1) with only a few percents difference from corresponding SCANDIA results. The only exception here is for the RCA3 Random cloud overlap approach where results indicate too high cloud amounts, especially for the summer and autumn seasons. When considering the geographical distribution of clouds, we found that RCA3 cloud amounts are always (i.e., for all seasons) in excess of SCANDIA amounts over the Scandinavian mountain range. Simultaneously, we find a pronounced deficit in cloud amounts lee-ward (i.e., closely to the east) of the Scandinavian mountain range.

For the RCA3 contributions from the three vertical cloud groups it is clear that for all cloud overlap approaches we find smaller contributions compared to SCANDIA from medium-level clouds. As a contrast, contributions from low-level clouds are generally larger and contributions from high-level clouds are close to neutral or for Random overlap larger than SCANDIA contributions. Concerning the excessive total cloud amounts over the Scandinavian mountain range, it was found that this feature could be seen for all vertical cloud groups (including high-level clouds).

In the investigation of frequencies of co-occurring vertical cloud groups and optical thickness categories, it was found that results are very sensitive to the chosen cloud overlap approach. For Maximum cloud overlap RCA3 gives much higher relative frequencies of the THICK and VERY THICK categories for all three vertical cloud groups. Remarkable is the very high frequency of 28 % for the VERY THICK category of low-level clouds in the summer season in comparison to the corresponding SCANDIA frequency which is practically zero. A much better fit to the SCANDIA-interpreted frequencies is instead found for the Random overlap approach. This results is indeed interesting since we know from observational evidence that true clouds are often seen to cluster together if being present in adjacent layers (Maximum overlap) while they only appear in a random manner if being separated by cloud-free layers (e.g. as reported by Tian and Curry, 1989, and Willén et al., 2005). We interpret this deviation as a sign of having an excess of cloud water for RCA3-simulated clouds. More clearly, we can only get a good agreement with the observed optical thickness categories if we distribute the excessive cloud water amounts using the Random overlap (spreading out or diluting cloud water amounts horizontally as much as possible).

The results from sensitivity tests testing the full range of minimum optical thickness values used for filtering (0.5-2.5) did not seriously change the general results, although it was clear that an overall RCA3 underestimation of total cloud cover followed for the extreme case when using the highest filtering value 2.5.

6.2 *The validity of the filtering concept*

When studying the effect of filtering of RCA3 results (e.g., as seen in Tables 1 and 2 and in Figures 4-7) it is seen that cloud amounts are not drastically changed. Thus, we have in this study been able to show that the suspected misrepresentation of true cloud conditions in the satellite-derived cloud climatology, due to the lack of contribution from optically very thin clouds (not detected), can be considered as relatively small. Consequently, the general results stated in the previous section are actually more or less identical to the results that were achieved also for unfiltered results. However, the filtered cloud amounts are by no means negligible and they strongly depend on the chosen cloud overlap approach. For example, cloud amounts are reduced by almost 10 % in cloud amount units for the Random overlap approach. Consequently, we claim that the filtering aspect still could be of importance and that it should be taken into account also in future similar studies.

A final remark in this respect is that this study can obviously not give any guidance in the question whether the removed contribution from optically very thin clouds is realistically modelled. To verify their existence other observation sources are needed (e.g. high-sensitivity cloud radars or lidars).

6.3 *Implications for RCA3 radiation processes and other physical and dynamic processes*

Based on the achieved results of this study, it is important to discuss the potential implications for the RCA3-simulated physical processes and to put the results in relation to the experienced RCA3 performance of other model parameters as seen in recent validation studies. This concerns in particular the radiation processes but also to some extent the links to the precipitation, evaporation and condensation processes.

Assuming that the results presented here are reliable, we would expect some effects on the radiation processes in particular at the surface, both for the shortwave and longwave components of the radiation budget. In particular, the co-existence of overestimated cloud amount contributions and overestimated optical thicknesses for low-level clouds (especially in the summer season) would potentially lead to reduction of Solar Incoming Solar (SIS) radiation at the surface as well as increased Downwelling Longwave Radiation (DLR). The latter is a consequence of the fact that an increase of low-level cloud amounts, also being optically thick, would increase the re-radiation back to the surface from clouds. We suggest that this would be manifested as a reduced diurnal cycle (i.e., reduced temperature differences between day and night) of surface temperatures compared to observations. This feature has indeed been found for all seasons in recent RCA3 validation experiments (Kjellström et al., 2006).

Concerning top-of-atmosphere radiation budget components (e.g., Outgoing Longwave Radiation – OLR – and Reflected Shortwave Radiation – RSR) it is more difficult to assess the total impact, especially when considering that the total cloud amounts appear to be reasonably well simulated. The indicated overestimation of low-level and (at least partly) high-level cloud contributions is counteracted by an underestimation of contribution from clouds at medium levels. Thus, even if simulated clouds appear to be optically too thick (especially summertime low-level clouds) this effect may be counteracted by the deficit of clouds at medium-levels. This means that we cannot be sure of the total effect on the RSR parameter. The same uncertainty holds also for the OLR parameter. High-level cloud contributions appear to be slightly overestimated and they are also over-representing optically thick clouds. Thus, the total effect of high clouds is that they will appear colder than in reality. However, this is counteracted by the lack of medium-level clouds and the overestimation of low-level clouds. The total effect is that it makes the combination of medium-level and low level clouds appearing warmer (at cloud tops) than in reality.

Thus, we conclude that the current study cannot give enough information for making firm conclusion about consequences for radiation budget components at the top of atmosphere. We can only state that there is no obvious reason to believe in the existence of a large bias in these quantities. Future studies comparing these RCA3 quantities to satellite-measured top-of-atmosphere radiation budget components (e.g., as described by Wielicki et al., 2002) are needed to make more firm conclusions.

There is a possibility that we would potentially find underestimated fractional cloud amounts accompanied with overestimated cloud optical thicknesses as a result of the relatively coarse vertical resolution (i.e., very thin clouds would potentially be described by the model as having small fractional cloud cover but with compensating larger optical thicknesses). There is indeed some indication of such a feature in the yearly averages for e.g. the case of Maximum overlap. However, since total cloud amounts appear reasonably well simulated the result rather indicate that most clouds appear to be appropriately resolved and only a small fraction could represent such geometrically very thin clouds. Nevertheless, the coarse vertical resolution is most probably still a problem but it is obvious that we are here not able to make firm conclusions due to the fact that the optically thinnest clouds are not included at all in this study (filtered out).

Concerning the link to RCA3 condensation and precipitation processes, it is currently difficult to interpret the results more than qualitatively. It seems likely that the observed over-representation of optically thick clouds at all vertical levels (but most clearly seen for low-level clouds) must be at least partly linked to deficiencies in the description/parameterisation of cloud and precipitation processes. Also, the specific geographical features of excessive cloud amounts over the Scandinavian mountain range and the associated lee-ward minima in cloudiness should have links to both precipitation/condensation processes and dynamical forcing aspects (here, forced vertical ascent/descent over topographical features). However, there could also be specific problems in achieving realistic turbulent fluxes at low levels which may limit the efficiency of the vertical mixing of moisture. This could explain the current lack of medium-level clouds while low-level clouds seem to be overestimated both regarding their total amount and their optical thickness. There is also a possibility that deviations may occur due to the occurrence of snow precipitation from high- and mid-tropospheric clouds which could be mis-interpreted as clouds in the satellite observation. However, it is not very likely that this potential mis-interpretation would give a significant influence on results. Further model experiments and validation efforts are needed for understanding all these aspects better.

7. CONCLUSIONS

In this study we have used the long-term (1991-2000) NOAA AVHRR SCANDIA cloud climatology over the Scandinavian region to evaluate the performance of the cloud fields produced by the regional RCA3 climate simulation model. We have evaluated the following three important aspects of cloud appearance:

- Fractional total cloud cover
- The vertical distribution of clouds
- The optical thickness of clouds.

In the preparation of the corresponding cloud quantities from RCA3, we have tested the three different approaches of Maximum, Maximum-Random and Random cloud overlap where the Maximum overlap approach is the one that is currently used in the RCA3 radiation scheme.

Several methods of adapting the satellite and model datasets to enable a fair comparison have been applied. The most important has been to account for the fact that the satellite sensor is not capable of detecting optically very thin clouds from the space-based platform. After removal of such contributions to the model-simulated cloud dataset from RCA3, the following interpretation of the status of RCA3-simulated cloud fields can be made:

- RCA3 appears to produce quite reasonable amounts of total cloud cover (i.e., within a few percent compared to SCANDIA) on seasonal and annual time scales during this period for all cloud overlap approaches except for the Random overlap which gives generally higher cloud amounts compared to SCANDIA.

- A substantial imbalance between the respective RCA3 contributions from low-, medium- and high-level clouds are seen for all cloud overlaps. For Maximum overlap the differences from SCANDIA contributions is +2.38 % for high-level clouds, -5.19 % for medium-level clouds and +4.0 % for low-level clouds.

- An over-representation of cloud categories with high optical thicknesses is seen for all vertical cloud groups for both the Maximum and the Maximum-Random cloud overlap. The best agreement is seen for Random overlap. Since clouds are known from observational evidence to behave more like the Maximum-Random case, this result is interpreted as a strong indication of a true overestimation of cloud water amounts and associated optical thicknesses for RCA3 clouds, particularly concerning the low-level clouds in the summer season.

The consequences for the RCA3 simulations of radiation conditions are expected to have the largest impact for surface radiation budget components (i.e., by reducing incoming solar radiation and increasing down-welling long wave radiation). Such effects have recently been confirmed in separate validation studies where an underestimated diurnal cycle of surface temperatures in RCA3 was found. Implications for top-of-atmosphere radiation budget components are more uncertain since results indicate counterbalancing effects (i.e., the increase in high cloud amounts is balanced by a decrease in medium-level cloud amounts and an increase in low-level cloud amounts).

Interesting differences in the geographical distribution of cloudiness are also revealed. In particular, excessive cloud amounts are found over the Scandinavian mountain range for all seasons and for all vertical cloud groups studied. Simultaneously, a deficit in cloud amount is found lee-ward (e.g., to the east) of the mountains which exists more or less pronounced along the whole extension of the Scandinavian mountain range.

Further modelling experiments and validation efforts must be performed to improve the understanding of these results. For example, the effect of varying the horizontal and vertical grid resolution has to be further investigated as well as the effects from further modifications of the RCA3 radiation scheme and its associated use of cloud parameters. Also, the performance of RCA3-simulated Outgoing Longwave Radiation and Reflected Shortwave Radiation top-of-atmosphere radiation budget components should be compared to available corresponding satellite measurements.

Finally, it is also necessary to consider that observed deviations from observed cloud patters might also be due to deficiencies in the simulation of the regional circulation patterns (as emphasised by Bony et al., 2004). Thus, the envisaged problems might at least partly be related to other things than deficiencies of the used cloud parameterisation scheme. However, this aspect is beyond the scope of this particular study.

For the future, we hope that the developed model validation methodology can be used in additional studies for testing future upgraded RCA model versions. However, more important is the opportunity to extend the methodology to be based on new and enhanced satellite-based climatological datasets, e.g., such as those introduced by Schulz et al. (2005) covering a much larger geographical area. This would give an opportunity to make a more comprehensive evaluation and comparison of results from both regional and global cloud climate simulations.

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