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Evaluating cloud fraction and ice water content in the ECMWF Integrated Forecast System and three other operational models using long-term ground-based radar and lidar measurements

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Abstract

Following Part I of this study which focussed on the evaluation of cloud occurrence in four operational weather forecast models (ECMWF, ARPEGE, RACMO and UKMO) as part of the Cloudnet project using Vertically pointing ground-based radar and lidar observations, the present paper goes one step further by evaluating the parameters involved in the prognostic cloud schemes of some of these models: the cloud fraction and the ice water content.

To avoid mixing of different effects these parameters are evaluated only when model and observations agree on a cloud occurrence. Several comparisons and diagnostics are proposed. As a first step the complete two years of observations are considered in order to evaluate the "climatological" representation of these variables in each model. Overall, models do not generate the same cloud fractions, and they all under-represent the width of the ice water content statistical distribution. For the high-level clouds all models fail to produce the observed low cloud fraction values at these levels. Ice water content is also generally overestimated, except for RACMO. These clouds are considered as radiatively important because of their feedback on weather and climate and therefore their relatively inaccurate representation in models may be significant when computing fluxes with the radiation scheme. Mid-level clouds seem to have too many occurrences of low cloud fraction, while the ice water contents are generally well reproduced. Finally the accuracy of low-level clouds occurrence is very different from one model to another. Only the arpege2 scheme is able to reproduce the observed strongly bimodal distribution of cloud fraction. All the other models tend to generate only broken clouds.

The data set is then split on a seasonal basis, showing for a given model the same biases as those observed using the whole data set. However, the seasonal variations in cloud fraction are generally well captured by the models for low and mid-level clouds.

Finally a general conclusion is that the use of continuous ground-based radar and lidar observations is a powerful tool for evaluating model cloud schemes and for monitoring in a responsive manner the impact of changing and tuning a model cloud parametrisation.

1 Introduction

Most operational models now predict cloud amount and cloud water content and how they vary with height, but there have been few studies to evaluate their performance. In this paper we compare cloud properties observed with radar and lidar and their representation in such models via parameters such as the amount of water stored in liquid or ice phase as well as how the cloud is distributed within the grid-box. In most of the operational weather forecast models these parameters are included in the cloud schemes and interact with other schemes like the radiation scheme.

The first part of this paper (Bouniol *et al.* 2007) evaluated the ability of the four operational models (ECMWF, ARPEGE with two different cloud schemes, RACMO and Met Office) involved in the Cloudnet project in predicting a cloud at the right place and at the right time by comparing the observed and modelled frequency of cloud occurrence using continuous ground-based active measurement which monitored the cloud vertical profiles above three sites in Western Europe in the framework of the Cloudnet project (from October 2002 to September 2004, Illingworth *et al.* 2007). It was shown from the two-year data set that all the models significantly overestimated the occurrence of high-level clouds and that different behaviours occurred depending of the model for the other types of clouds at lower levels. At a seasonal scale the models were found to capture well the variabilities observed from one year to another for the same season as well as the large variability in a given year.

This second paper is dedicated to the evaluation of cloud parameters when a cloud is present. To do so we consider only the situations where model and observations agree on a cloud occurrence, thus avoiding mixing the effect of occurrence when evaluating the cloud fraction and the ice water content (the liquid water content is not investigated here). The two following sections are dedicated to the evaluation using the same strategy as for cloud occurrence in Part I (Bouniol *et al.* 2007): considering first the two year data set as a whole, then splitting it by season in order to determine if the models are able to reproduce the typical weather situations associated with the different seasons in western Europe (*i.e.* mainly convective systems during summer and frontal systems and associated stratiform precipitation during winter, Hogan *et al.* 2001). Finally some concluding remarks are given in section 4.

2 Comparison of model cloud fraction with observations

Cloud fraction is an important parameter since it is a crucial input to the radiation schemes. It is now a prognostic variable of the cloud schemes held in the ECMWF and RACMO models. The model data consist of hourly snapshots over the Cloudnet sites. To derive the "observed" cloud fraction we follow the approach of previous workers (e.g. Mace *et al.* 1998, Hogan *et al.* 2001) and assume that temporal sampling yields the equivalent of a two-dimensional slice through the three-dimensional model grid-box. Using the model wind speed as a function of height and the horizontal model grid-box size, the appropriate sampling time is calculated. It is assumed that in this time the cloud structure observed is predominantly due to the advection of structure within the grid-box across the site, rather than evolution of the cloud during the period. Nonetheless, the averaging time is constrained to lie between 10 and 60 minutes. However these time series are bi-dimensional while a model grid-box represents a three-dimensional volume. It is then assumed that the fraction of the grid filled by cloud in the two-dimensional grid-box represents the amount of cloud in the three dimensional volume. This assumption is identical to that used in previous studies comparing observed and model cloud fractions (Brooks *et al.* (2005) or Hogan *et al.* (2001)). Two ways for computing cloud fraction are typically used, depending on the application: the first way is to compute the fraction of observed pixels in a model grid-box that is categorized as cloud according to the radar-lidar observations. The other way is for radiative transfer calculations and for estimating the radiative effect of clouds (e.g., Stephens (1984); Edwards and Slingo (1996)), and corresponds to the fraction of the grid-box that is shadowed by cloudy pixels when looking at the cloud scene from above. In the following, the first approach has been used since it corresponds to the way cloud fraction is defined in the models involved in this study. Cloud fractions have been computed from the individual observed pixels (60m/30s) deemed to be cloudy or not-cloudy which are grouped together with the temporal and vertical resolution appropriate to each model. When the instruments operated less than 20% of the averaging time required to compute cloud fraction in a model grid-box, the obtained value was not included in the statistics.

Once data are remapped to each model grid scale and the cloud fraction and mean liquid and ice water contents computed, the mean cloud fraction profiles and the probability distribution functions (pdfs) of cloud fraction as a function of height can be found; these pdfs are equivalent to the Contoured Frequency by Altitude Diagrams (CFAD, Yuter and Houze (1995)). The rationale for using pdfs in addition to the mean profiles considered in earlier studies (Mace *et al.* 1998, Hogan *et al.* 2001) is to investigate how the model is distributing the cloud fraction between 0 and 1, since a mean value of 0.5 can be the result of very different cloud fraction distributions. As in part I of this paper, we document the statistics of cloud fraction using the two years of Cloudnet observations and compare with the four models. We then split the dataset into seasons in order to further evaluate the models' performance.

2.1 Comparison for the whole Cloudnet period

The mean profiles and pdfs of cloud fraction for all models using the whole Cloudnet period are displayed in Figure 1 for the Cabauw site. Each row in the Figure corresponds to a different model, with the first column showing the distributions obtained using the full two-year model data set of cloudy grid-boxes, where a grid-box is defined as cloudy if cloud fraction is larger than 0.03, the same threshold as used for cloud occurrence in Bouniol *et al.* (2007). The third column corresponds to the distribution obtained from the whole observation sample, whereas the second and fourth columns show the distributions for models and observations respectively but for the sub-sample where models and observations agree on a cloud occurrence; the black number in the top left corner of each panel is the total number of cloudy grid-boxes used fo building the statistics. The reduction in grid-boxes number when moving from the first column to the second or from the third to the fourth results from the intermittent sampling of the instruments and the removal of the clouds undetected by the instruments in the model sample.

The solid black lines in Figure 1 superimposed on each panel are the mean profiles of cloud fraction, or 'the mean amount when present'. This should be distinguished from the mean cloud fraction including occasions when no clouds were present shown in Figure 6(a) of Illingworth *et al.* (2007) which, since it includes many cloud-free occasions, results in much lower values than those displayed in Figure 1. Also superimposed on each panel is the dashed black line, which shows the fraction of the total number of cloudy grid-boxes (the black number in the figure) which is found for each grid-box height. This fraction, read out on the upper axis, provides a kind of "confidence level", since, especially for the higher levels, the distributions can result from a small number of grid-boxes. It should be noted that the equivalent distributions obtained for the two other sites are not shown here as they do not exhibit significant differences with the Cabauw data and model skills are found to be similar over the three sites. This consistency of the three sites is supported by the correlation coefficients between the cloud fractions distributions of Cabauw in Figure 1 and the equivalent distributions for the other sites which are displayed in Figure 2.

The first important point to notice in Figure 1 is that this mean profile (solid line) does not correspond at all to the maximum of the pdf. The mean value can, therefore, be quite misleading as it is the average of a pdf which has usually has two maxima at the highest and lowest cloud fractions. It is quite possible to have the correct mean value, but a pdf which is quite wrong. Therefore, in what follows we concentrate mostly on the evaluation of the cloud fraction pdfs rather than on the mean profiles.

The end objective of this section is to compare the common sub-set of observation and model data in the second and fourth columns in Figure 1. But first we need to investigate if the model and observational subsets are representative of the complete model and observational statistics (that is, to compare the first and second columns for the model and the third and fourth columns for the observations). Such a comparison indicates that the conclusions to be drawn in this section are indeed representative of all clouds, and is confirmed by the correlations of Figure 2. The first row of Figure 2 shows the correlation between the model pdfs for the whole sample and the pdfs from the model sub-sample for which model and observations agree on a cloud occurrence; the high correlation coefficients for all models confirms that the model sub-sample is indeed representative of the complete model data. The slightly reduced correlation for the Palaiseau site (though still larger than 0.9) may be attributed to the intermittent sampling at this site. The second row in Figure 2 shows the equivalent correlation coefficient but for the sub-sample and the complete sample of the observed pdfs. The anomalously low correlations at the Palaiseau site above 10 km is probably due to the very sensitive lidar at that site, which can detect very thin clouds which would not be observed at Cabauw or Chilbolton and are probably not produced by the models. Otherwise, the high correlation level between model/model sub-sample and observation/observation sub-sample over the three sites demonstrates that the common model/observation sub-sample is representative of the whole data set.

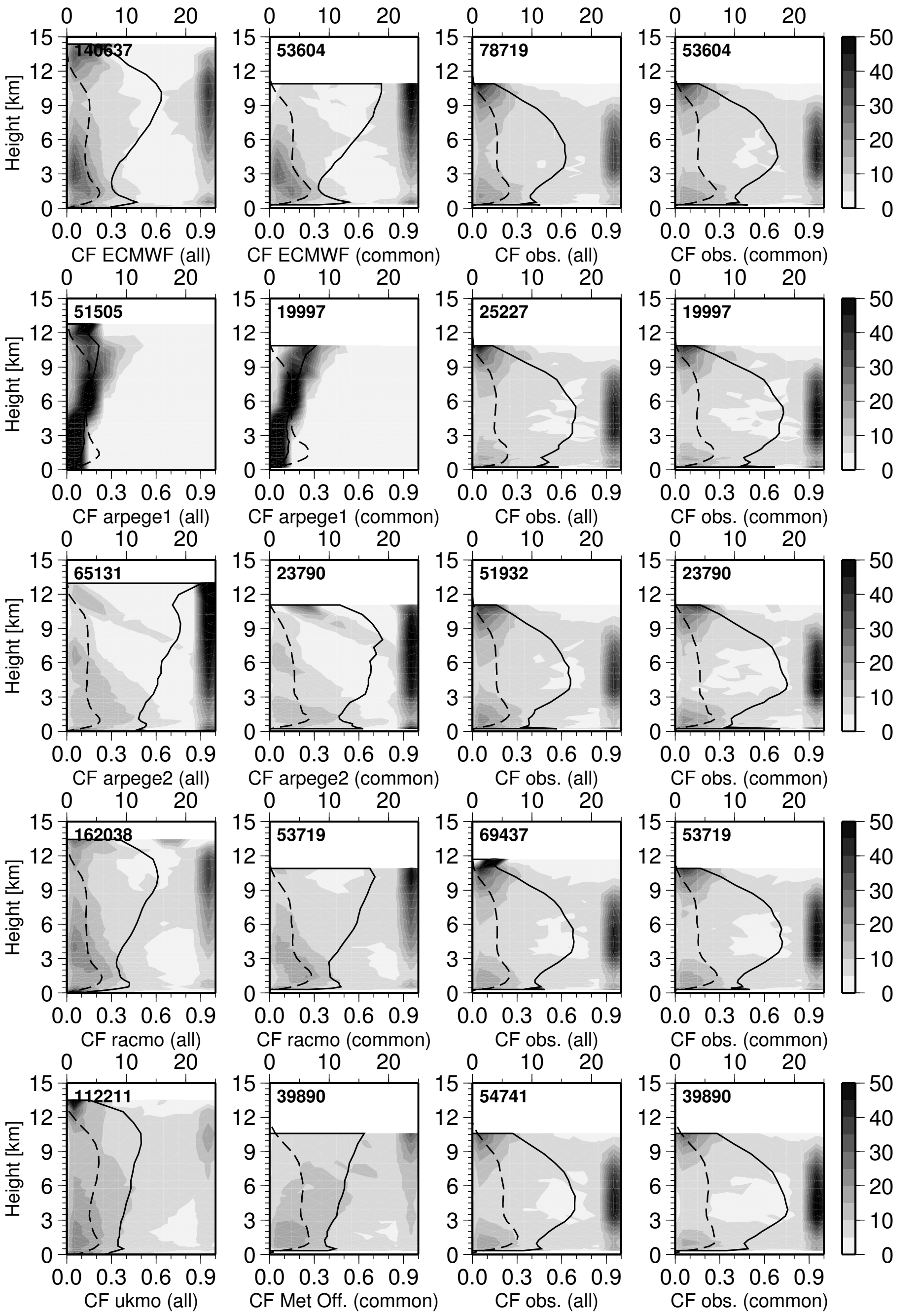

Figure 1: Probability distribution functions (pdfs) of the occurrence of different cloud fractions as a function of altitude at the Cabauw site for the two year period with the contour shading changing for every 5%. The black solid line (lower axis) shows the mean value of cloud amount when present. The black number in the upper left corner of each panel corresponds to the total number of cloudy grid-boxes used in the sample. The dashed black line (upper axis) shows how the this total number of cloudy grid-boxes is distributed, as a percentage, over the different heights of the grid-boxes. Each row of panel is dedicated to a model (or model version), from top to bottom : ECMWF, arpege1, arpege2, RACMO and Met Office. The first column shows the distributions obtained from the model over the two year period, whereas the second column is a sub-set of the model to include only those occasions when a cloud was observed. The third column is the distribution obtained from all observations and the fourth is a sub-sample to include only those observations when the model agreed that a cloud was present.

The third column of Figure 1 which compares the distributions obtained from the whole observational data set with cloud fractions calculated at the different model resolutions indicates that the effect of model resolution is fairly small. The observed cloud fraction is characterized by a bimodal distribution for low-level clouds (clouds below 3 km), with about the same amount of clouds with low cloud fraction (less than 0.3) and high cloud fraction (larger than 0.85). At mid-levels (clouds between 3 and 7 km altitude) clouds are essentially characterized by large cloud fraction values (larger than 0.8). In contrast the high-altitude clouds (from 7 to 12 km) are characterized from 7 km up to 9-10 km by a bimodal distribution (very small and very large cloud fraction values), and above 10 km by very small cloud fractions (less than 0.2).

We are now in a position to compare these observed cloud fraction pdfs with those in the four models. It is immediately obvious that the four models are producing different pdfs of cloud fraction (Figure 1, first and third columns). The ECMWF and RACMO (which use the same cloud scheme) have strong similarities with the same skills and discrepancies with respect to the observations. The core of small cloud fractions observed for low-level clouds extends too much upward (up to 8 km instead of 3 km in the observations) indicating that the ECMWF and RACMO models produce too many broken clouds at mid-levels. This signature is also reflected by the smaller amount of clouds with high cloud fractions between 3 and 7 km (30% compared to the 50% observed, roughly) in these models. In terms of correlation, (Figure 2 row 2) these differences translate into a smaller correlation between model and observed cloud fraction at mid-levels (around 0.75 at 4 km) for all sites. This smaller correlation at mid-levels is slightly more significant at the Cabauw site. The ECMWF and RACMO models also clearly have difficulties in producing high-level clouds with small cloud fractions (high-level clouds are essentially characterized by very high cloud fractions in Figure 1), which is not in agreement with the observations. This corresponds in Figure 2 row 3 to a drop in correlation for clouds higher than 8 km, which is common to all models.

The Met Office model is characterized by a very different cloud fraction distribution, with many more small cloud fractions overall (between 0 and 0.4), and a much more homogeneous distribution of cloud fractions between 0 and 1 than in the observations. The most striking feature is the lack of mid-level clouds with a high cloud fraction, and high-level clouds with a small cloud fraction. This corresponds to a significant drop in correlation at mid-levels in Figure 2 (fourth column of the third row) which is more apparent than for the other models, and a low correlation for high-level clouds as found in all models. There is no large difference in correlation from one site to another for the Met Office model.

The impact of the change in cloud scheme in the ARPEGE model is obvious, as it was in Bouniol *et al.* (2007). It is clear from Figure 1 that the cloud scheme in the first version of ARPEGE was unable to generate high cloud fractions at any height leading to extremely low correlations throughout the troposphere in Figure 2 (dashed line in the second panel of the third row). The second scheme is clearly much better, with a good representation of the bimodal distribution of low-level clouds, and of the high cloud fractions in mid-level clouds. This arpege2 scheme produces the highest correlations with the observed cloud fractions from 1.5 to 8 km height and no difference in skills from one site to another, in contrast to the behaviour of the ECMWF and RACMO models in Figure 2 row 3. However, as was the case for the other models it is less accurate in describing the distribution of cloud fraction in high-level clouds, with too many high-level clouds characterized by a high cloud fraction, although there is some indication of bimodality in this model for the high-level clouds, suggesting possible further improvements / tuning of this scheme.

The impact in the change in the ARPEGE cloud scheme on cloud fraction was also investigated by Illingworth *et al.* (2007) who noted that errors in cloud occurrence and cloud fraction compensated to give a reasonably unbiased mean cloud cover. The same results can be obtained here if one goes back to Figure 1 of Bouniol *et al.* (2007) observing that arpege1 produces far too many clouds but with too low a cloud fraction (especially at mid-levels, as shown in Figure 1). This combined effect of two inaccurate representations of cloud fraction and cloud occurrence can result in an unbiased total cloud coverage. On the other hand the

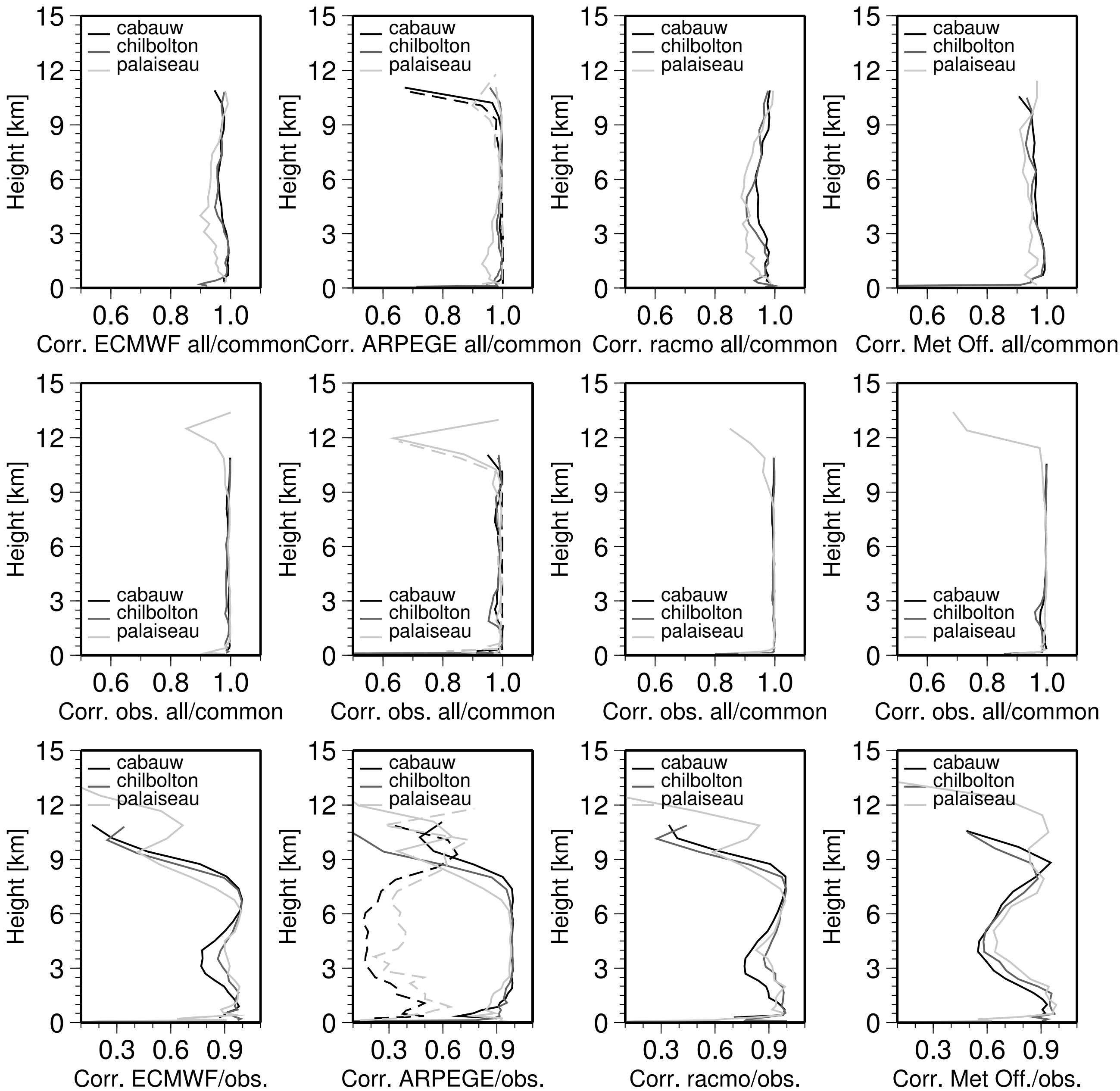

Figure 2: Correlation coefficient profiles between the cloud fraction pdfs shown in Figure 1 in black, with the Chilbolton and Palaiseau profiles superimposed in grey. Each column, from left to right, corresponds to a model: ECMWF, ARPEGE, RACMO and Met Office. The ARPEGE data set is split in two according to the two cloud schemes. The arpege1 period profiles appear in dashed, the arpege2 period in solid line. The first row corresponds to the correlation between the pdfs for the complete model sample and the model sub-sample where a cloud occurred simultaneously in model and observations (correlation between first and second column in Figure 1). The second row is the equivalent correlation for the observations (correlation between third and fourth column in Figure 1). The third row is the correlation between the model and the observation pdfs for the common sub-sample (correlation between second and fourth column in Figure 1).

arpege2 scheme underestimates the frequency of cloud occurrence and shows an increase in the cloud fraction especially at mid-levels. Both effects do not seem to be enough to compensate, since it yields a biased total cloud cover (about 20% too small) which Illingworth *et al.* (2007) explained by an additional change in the cloud overlap hypothesis.

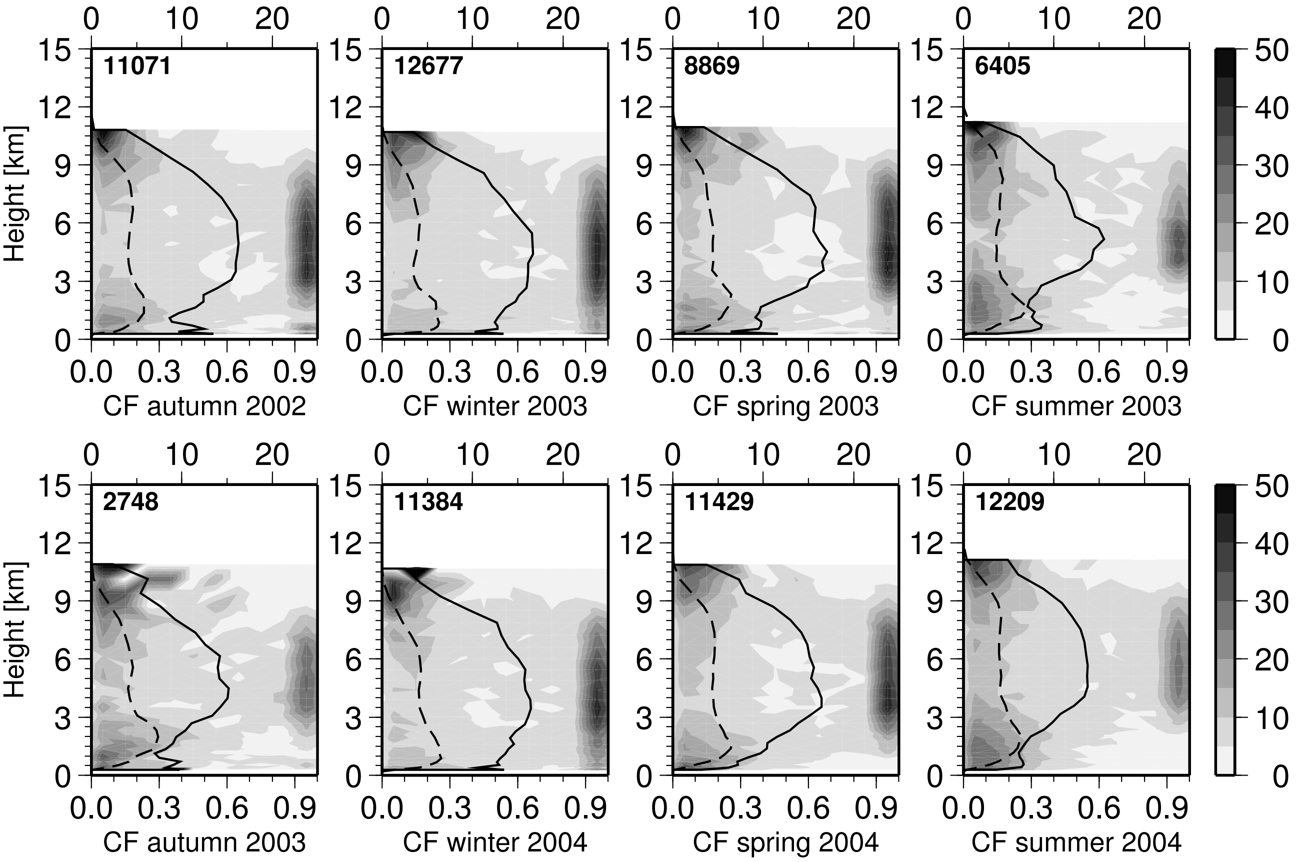

Figure 3: Observed pdfs of cloud fraction for each season of the Cloudnet Project using the ECMWF model grid at the Cabauw site. The black solid line (lower axis) shows the mean value of the distribution, the black dashed line (upper axis) shows the amount (in percentage) of cloudy grid-boxes at each level. The black number in the upper left corner of each panel corresponds to the total number of cloudy grid-boxes used for statistics computations.

As an intermediate conclusion, this comparison of the two year Cloudnet data set has demonstrated how instantaneous profiles, as long as they are part of a long time series, may be used to evaluate the climatological behaviour of cloud amount in models.

2.2 Comparison at seasonal scale

As detailed in Bouniol *et al.* (2007) the Cabauw site had the most continuous sampling, so in the following we use only the observations from this site to document the seasonal (from one season to another during a year) and "season-to-season" (from one season in one year to the same season another year) variabilities of cloud fraction in Western Europe and if such changes are captured by the models.

2.2.1 Season-to-season variability

Figure 3 shows the evolution of the distribution of cloud fraction as a function of the season and demonstrates that the season-to-season variability is fairly weak for all seasons, but the seasonal variability is significant. The models also produce roughly the same correlation profiles (not shown) for a given season when comparing the two years, in good agreement with Figure 3. The seasonal variability appears to be much larger, and is discussed in the next subsection.

2.2.2 *Seasonal variability*

The seasonal evolution of the observed cloud fraction distribution can be followed using Figure 3 for the two years of Cloudnet. For all seasons the general structure of the pdfs is similar to that already discussed for the two year data set (Figure 1): a bimodal distribution for low-level clouds (clouds below 3 km) (low and high cloud fractions, essentially), large cloud fraction values in the mid-level clouds (clouds between 3 and 7 km altitude), and the high-level clouds (from 7 to 12 km) are characterized from 7 km up to 10 km by a bimodal distribution (very small and very large cloud fraction values), and above 10 km by very small cloud fractions (less than 0.2). However, although there is, as noted in the previous section, a very small variability for a given season between the two years, the seasonal variability of these structures is, in contrast, larger and warrants further analysis.

At low levels the clouds with high cloud fraction values are more numerous during winter (Figure 3, second column), while the clouds with small cloud fraction values are slightly more numerous during summer (Figure 3, fourth column). Fewer mid-level clouds with high cloud fraction are observed in summer as well. Finally, the seasonal variability of high-level cloud fraction is fairly small.

The same seasonal distributions as Figure 3 for all models but only for 2004 only are shown in Figure 4; similar results were found for 2003 (not shown), confirming the observed small season-to-season variability discussed previously. The variability is, as expected, larger for the ARPEGE model but is fully explained by the change in parametrisation. At low-levels, the ECMWF, RACMO, and Met Office models tend to fairly well reproduce the observed increase in amount of low-level clouds characterized by high (small) cloud fraction in winter (summer). This is much less obvious in arpege2, but the specific case of the ARPEGE model and associated changes in cloud scheme will be discussed separately below in further detail. Mid-level clouds with high cloud fraction are observed less frequently in the ECMWF, RACMO and Met Office models. For the high clouds, the ECMWF, RACMO, and (to some extent) the Met Office models tend to produce more high-level clouds with high cloud fraction in winter, which does not correspond to observations. The reason for this behaviour is unclear. In general it appears clearly that the small structures of seasonal variability are well captured in the ECMWF, RACMO, and Met Office models, although obviously the defaults of the models obtained previously when considering the whole Cloudnet period are still present in the seasonal scale comparison.

For the ARPEGE model, the impact of the change in the cloud scheme is again obvious, with almost no clouds generated with a high cloud fraction values at any height with the first scheme for the 2003 seasons (not shown). When the second year was analyzed (fourth row of Figure 1 and solid line in the second column of Figure 2), the second scheme (arpege2) had a much improved cloud fraction, with a good representation of the bimodal distribution of low-level clouds, and of the high cloud fractions of mid-level clouds. However, when split into seasons in the second year, an additional feature appeared (Figure 3 second row): the skill of the second scheme remains poor for the two first seasons, while it is much improved for the two last seasons. After checking the successive upgrades of the model, this mysterious feature has been explained. On 24 May 2004, the coefficients of the Xu and Randall (1996) scheme used in arpege2 was tuned to produce more cirrus clouds, and especially tropical cirrus clouds. At the same time, the radiation scheme was modified to be more similar to the ECMWF scheme. It appears that this tuning has also benefited to the representation of cloud fraction in mid-latitude ice clouds. We believe that this result is a particularly good advertisement of the potential for model evaluation of the continuous Doppler cloud radar observations and methodology developed in the present paper, since it offers to a modeller the possibility to rapidly evaluate the effect of a change in a parameterisation.

Figure 5 shows the correlation coefficient profiles for the seasons of the second year of the project (results simi-

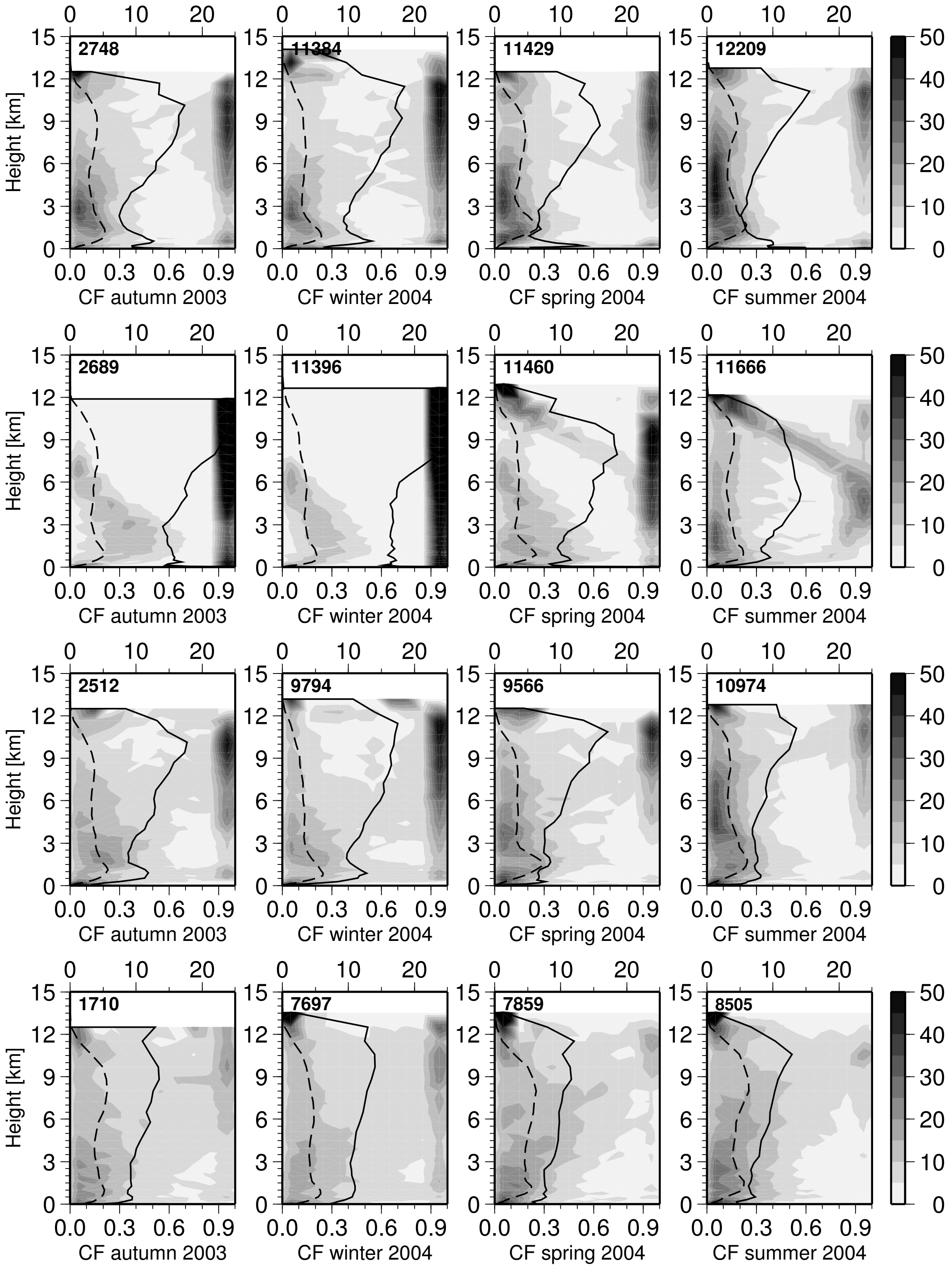

Figure 4: Seasonal evolution of cloud fraction pdfs for the second year of the project derived from the model time series: ECMWF, arpege2, RACMO and Met Office from top to bottom. The black solid line (lower axis) shows the mean value of the pdf, the black dashed line (upper axis) shows the amount (in percentage) of cloudy grid-box at each level. The black number in the upper left corner of each panel corresponds to the total number of grid-boxes used for statistics computations.

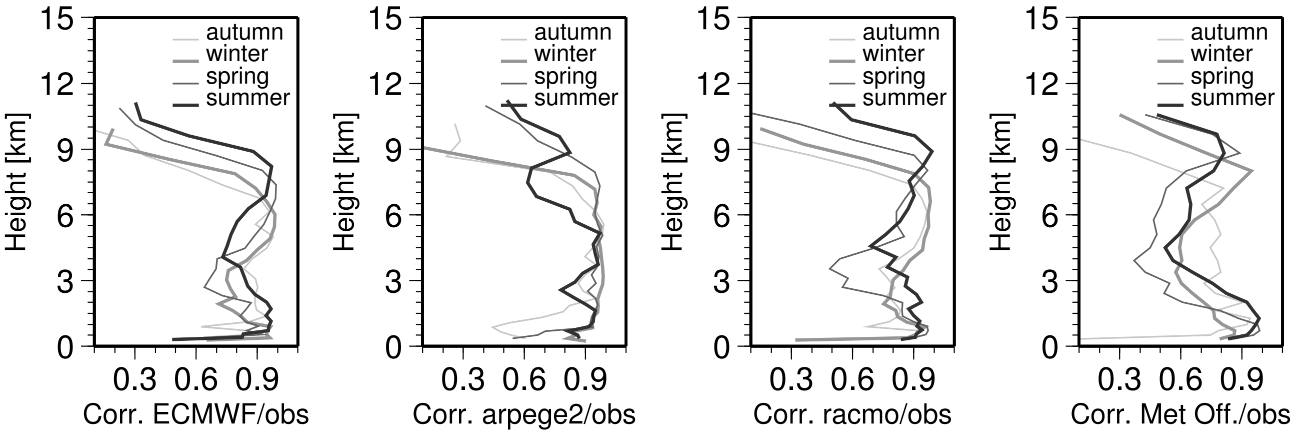

Figure 5: Seasonal evolution of the correlation coefficient between the cloud fraction pdfs derived from the models (ECMWF, arpege2, RACMO and Met Office from left to right) and observations at the Cabauw site for the second year of the project.

lar when using the first year, except for the particular case of the ARPEGE model that has already been detailed) in order to evaluate more quantitatively the seasonal variability of the model representation of clouds. From this Figure, interesting features are observed, which may give some clues to modellers for parameterization tuning or improvement. First it appears that the models have different characteristics. The ECMWF and RACMO models tend to better reproduce the observed cloud fractions in high-level clouds in spring and summer than in autumn and winter, and they also both tend to be less successful with the lowest mid-level clouds in spring and mid-level clouds in summer. The Met Office model is characterized overall by the same skills over the different seasons, similar to the profiles shown in Figure 2. As discussed the case of ARPEGE is special, but it seems from Figure 5 that the "May 2004 tuning" of the scheme produced very good correlations in spring from 1 to 9 km altitude, and a lower correlation for high-level clouds and for low-level clouds below 1 km height. The situation is different in summer, with an improved correlation for high-level clouds, but a lower correlation for mid-level clouds. Going back to Figure 4, this lower correlation can be attributed to the generation by the new tuned scheme of mid-level clouds with intermediate cloud fraction values (0.3 to 0.7), which are not present in the observations.

3 Comparison of ice water content between models and observations

The ability of the models to reproduce the cloud fraction distributions was evaluated in the previous section. We now consider in this section the second variable generally held in NWP model prognostic ice cloud schemes: the ice water content (IWC). The same methodology: distributions and mean profiles are computed. For this variable there is less risk of bimodal distributions which would be smeared out by a mean profile, but instead, at a given level, the IWC values range over several orders of magnitude. If we imagine for instance a Gaussian distribution a linear mean would be biased towards high values. In the present paper, the distributions are built using fixed classes in each decade on a logarithmic scale (1, 2 and 5). There is no remote sensing instrumentation able to provide a direct measurement of the IWC profiles. The profiling instruments (radar and lidar) measure radar reflectivity, Doppler velocity and lidar backscatter coefficient. A significant part of the job achieved in Cloudnet was to develop sophisticated methods to go from these measurements to the cloud parameters of interest, including the IWC. Numerous methods with different degrees of complexity exist and have been developed in the Cloudnet project to derive IWC either from radar reflectivity only (Liu and Illingworth ,2000 ; Protat *et al.*, 2007) or using an additional constraint (air temperature in Liu and Illingworth *et*

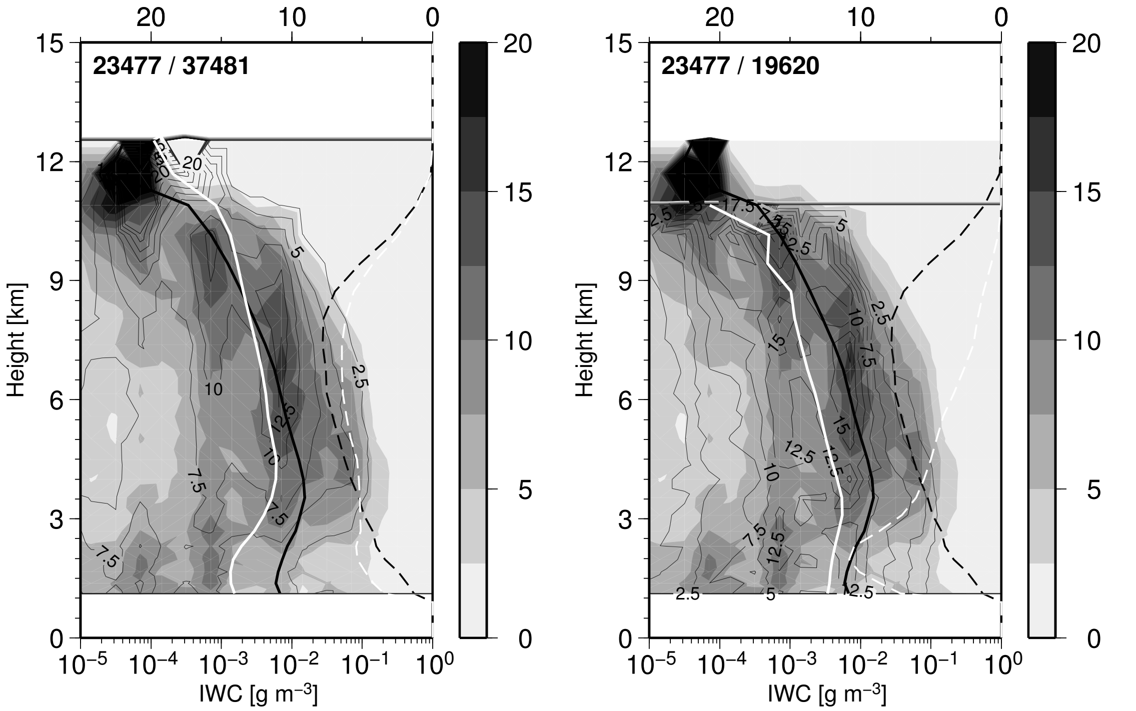

Figure 6: pdfs of IWC in g m^{-3} derived from the observations collected at the Cabauw site for the whole Cloudnet period. The filled contours, the black lines (lower axis) and the dashed black lines (upper axis) in both figures correspond respectively to the pdf, the mean and the number of cloudy grid-boxes at each level for the IWC retrieved with the RadOn method (Delanoë et al. 2006). The numbered contour lines, the white line (lower axis) and the white dashed lines (upper axis) corresponds respectively to the pdf, the mean and the number of cloudy grid-boxes for the IWC retrieved using the statistical relationship of Hogan et al. (2006) in the left-hand side panel and the radar-lidar method of Tinel et al. (2005) in the right-hand side panel. The black numbers at the top left corner give the total amount of cloudy grid-boxes used in the statistics (RadOn first and compared method the second).

al. 2000, Hogan *et al.* 2006 and Protat *et al.* 2007; Doppler radar velocity in Matrosov *et al.*, 1995 or Delanoë *et al.*, 2007) ; lidar backscatter in (Donovan and Van Lameren, 2001 and Tinel *et al.*, 2005). Among these methods, the radar-lidar is expected to be the most accurate, because reflectivity and backscatter are directly linked to two moments of the particle size distributions (*e.g.*, Tinel *et al.*, 2005). However its applicability is limited to clouds with an optical depth smaller than 3, roughly, which may result in a model evaluation biased towards thin clouds.

The retrieval of IWC from radar reflectivity using an additional constraint other than lidar offers the possibility to extend this statistics to the thick ice clouds as long as the reflectivity has not been attenuated or is at least corrected for attenuation by water or rain below. In the framework of Cloudnet, when possible this correction has been calculated by estimating the profile of liquid water content using a combination of radiometer-derived liquid water path and the cloud base and top heights from lidar and radar (Illingworth *et al.* 2007). This correction is deemed unreliable when rainfall is observed at the ground and above melting ice (because of uncertainties in the retrieval liquid water path), additional attenuation due to water on the radar instrument (Hogan *et al.* 2003) and unknown attenuation by melting particles. In these cases the ice part of the clouds has not been processed.

Morcrette (2002) computed radar reflectivity from the IWC of the ECMWF model using the procedure of Beesley *et al.* (2000) and the relationship of Atlas *et al.* (1995), but as in the case of retrieving IWC from measurements, some hypotheses on the particle distribution for instance are needed and therefore the error on the retrieved reflectivities is in the same range as the error on the retrieved IWC. The main advantage of the Cloudnet project is that several methods have been applied to the same data set by several teams. The differences in CFADs of IWC obtained from the different retrieval algorithms are illustrated in Figure 6. In this figure the filled contours show the results obtained using the RadOn algorithm of Delanoë *et al.* (2007), which makes use of radar reflectivity and Doppler velocity to retrieve the cloud properties. The results obtained from the IWC-Z-T statistical relationship of Hogan *et al.* (2006) are superimposed on the left panel of Figure 6, and the results of the radar-lidar algorithm of Tinel *et al.* (2005) are superimposed on the right panel of Figure 6. As expected the number of cloudy grid-boxes included in the distribution strongly varies from one method to another (see the numbers in Figure 6). Indeed less constraints exist for the application of a statistical IWC-Z-T relationship. The only requirement is to ensure that reflectivity is not attenuated by cloud water and precipitation below the ice cloud. The temperature profiles can be provided by a model output since it has been shown that these profiles were fairly accurate (Mittermaier and Illingworth 2004). For the application of the RadOn method a substantial amount of points is needed in order to determine the most representative particle area-diameter and density-diameter relationships inside the cloud (Delanoë *et al.* 2007). That is why the number of cloudy grid-boxes is reduced by about a half as compared to the IWC-Z-T statistical relationship. However if one looks at the vertical distribution of the number of points (black and white dashed lines in Figure 6), they look very similar. Finally the radar-lidar method is clearly the most restrictive. Only one third of the points are used compared to the statistical relationship so that the most common region of observation with both radar and lidar is located at about 2.5 km, so it is expected that the retrieval will not be representative of all clouds encountered within the troposphere.

An interesting pattern observed from the comparison of these different retrieval methods is that they produce very similar pdfs, namely, a skewed distribution with a narrow distribution of the high values and a wider distribution of the small values. The differences observed in the pdfs of the small IWCs produced by the various methods seem to be responsible for the small differences in the mean profiles. But the overall shape is the same for the three methods, with a peak IWC of about 10^{-2} gm^{-3} at 3.5-4 km height and a decrease above and below. Accordingly, the consistency of the retrieved IWCs derived from the independent methods increases our confidence in the derived pdfs. The comparison between IWC-Z-T and RadOn (Figure 6, left panel) shows that RadOn produces larger mean IWCs than IWC-Z-T below 8 km altitude, smaller mean IWCs above. These differences are probably due to the fact that in RadOn the density-diameter relationship is adapted for each cloud, while in IWC-Z-T it is assumed to be the same for all clouds (the Brown and Francis 1995 relationship for aggregates). In addition, Delanoë *et al.* (2007) have shown that RadOn was expected to be more accurate than IWC-Z-T over the whole IWC range. The comparison between RadOn and the radar-lidar method (Figure 6, right panel) shows that the mean IWC profiles are very similar in shape, with however smaller values produced below 8 km altitude by the radar-lidar method. This is certainly due to the fact that the radar-lidar method can only be applied to clouds of relatively small optical depth which can be penetrated by the lidar, thus tending to produce statistical biases towards smaller mean IWCs in the mean radar-lidar IWC profile. As a result, in the following the RadOn method is retained as the reference for the observed IWCs to be compared with the models.

3.1 Comparison for the whole Cloudnet period

Figure 7 displays the pdfs of IWC obtained from the model time series and from the observations at the Cabauw site. For each distribution the mean IWC profiles have also been computed (solid lines); the model profile of the second column is plotted as a dashed line in the fourth column for direct comparison with the observations. Once again the mean profiles of Figure 7 are “IWC when present” rather than the mean profiles shown in Figure 12(a) in Illingwoth *et al.* (2007) which include the null values in their computation leading to mean values about one order of magnitude smaller. As discussed previously the observed IWC distribution is fairly

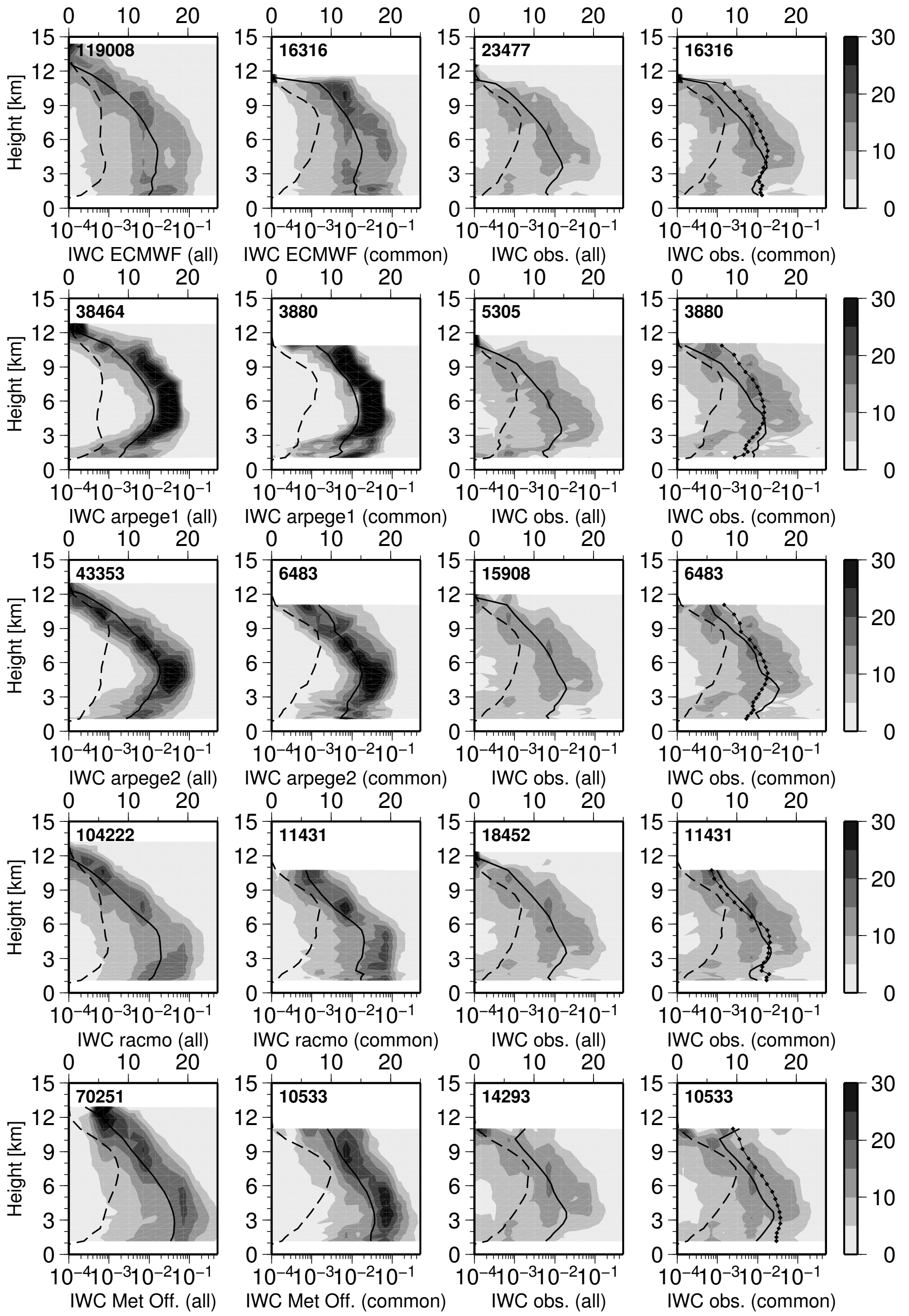

Figure 7: pdfs of IWC in g m^{-3} for the two year Cloudnet period at the Cabauw site. The black line (lower axis) shows the mean value, the black dashed line (upper axis) show the amount (in percentage) of cloudy grid-boxes at each level. The black number in the upper left corner of each panel corresponds to the total number of grid-boxes used for the statistical computations. Each row is dedicated to a model (or model version): ECMWF, arpege1, arpege2, RACMO and Met Office from top to bottom. The first column shows the distributions obtained from the models. The second column is the same but for the grid-boxes for which model and observations agree on a cloud occurrence. The third column is the distribution obtained from the data and the fourth shows the same distribution but when there is an agreement on occurrence between models and observations. Superimposed in the fourth column (diamond lines) is the mean profile obtained from the model sub-sample in the second column.

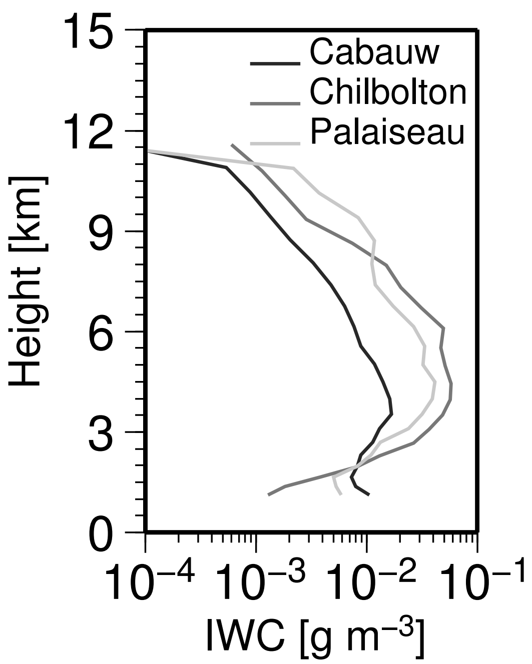

Figure 8: Comparison of mean IWC profiles in g m^{-3} (ECMWF model resolution) obtained at the three sites for the whole Cloudnet period.

skewed, with a narrow distribution of the high values and a wider distribution of the small values. This effect is somewhat smeared out in Figure 7 due to the change in scale, but still can be seen. The comparison of the observed and model IWC distributions on the second and fourth columns of Figure 7 clearly shows that the models reproduce this skewed distribution rather well. The IWC distribution of the models is nevertheless generally narrower than the distribution obtained from the observations. The ECMWF and RACMO models seem to best reproduce the observed width of the IWC distributions at all heights, but above 7 km altitude the RACMO IWC distribution is skewed toward small IWC. This result explains the difference between the dotted and solid line in Figure 1 of Bouniol *et al.* (2007) for this model. Indeed the dotted line does not includes the cloud occurrence where the reflectivity values computed from the IWC were below the detection threshold of the radar as often occurs for the small IWC observed at these levels in this model. The Met Office model produces a much too narrow distribution, with a significant skewed towards the largest IWCs at all heights. Again, the ARPEGE model outputs have been split into two datasets according to the two parameterisations. The comparison of the IWC distributions produced by the first and second parameterisations show that IWCs are significantly smaller (about one order of magnitude) for clouds higher than 6 km when the second parameterisation is used. This effect is not obvious from the mean values but can be observed on the contours where the distribution is centred on larger IWC. This feature is not in agreement with the observations, so it is solely due to the change in parametrisation.

An aspect that must be addressed is the impact of radar sensitivity on the results, because all the retrieval algorithms use the radar reflectivity as an input, but the radars involved in the project at the different sites are not the same. The 35 GHz radar at the Cabauw site is more sensitive (-55 dBZ at 1 km) than the other two 94 GHz radars at Palaiseau and Chilbolton whith in average -45 dBZ at 1 km, but experienced a stead loss in sensitivity during the observation period (Hogan *et al.*, 2003). Therefore, some lower reflectivity values will be included at the Cabauw site corresponding to very small IWC which would not be detected at the two sites. This is confirmed in Figure 8 where the mean profiles derived from the observations at the three sites are compared: the Chilbolton and Palaiseau IWC profiles are similar whereas the Cabauw IWC profile has smaller IWCs. This demonstrates that the IWCs missed by cloud radars of -45 dBZ sensitivity at 1 km do play a significant role in the mean IWC profile. Therefore in order to include the largest range of IWCs in the comparisons, we have chosen to use only the Cabauw observations to evaluate the model IWCs.

The comparisons between the model and observation are plotted in the fourth column of Figure 7. Overall, as was the case for cloud fraction, the sub-sample for which model and observations agreed on a cloud occurrence is reasonably representative of the whole sample at all heights. Some differences are observed at the top and bottom of the profiles, but in this region the number of points included in the analysis is much reduced. The comparison of the solid and dashed profiles in the fourth columns of Figure 7 clearly shows that the shape of the mean IWC profiles is rather well reproduced by all models. The ECMWF and arpege1 cloud schemes both tend to overestimate IWC above 4 km height, and slightly underestimate below. In the case of ECMWF, this overestimation is the result of a too strong production of large IWCs, while in the case of arpege1 it is merely the result of a pdf which is much too narrow. The second ARPEGE cloud scheme reproduces the observed IWC profile more faithfully than the first cloud scheme above 4 km height, but strongly underestimate the observed profile below 4 km height. The Met Office cloud scheme produces a systematic overestimation of IWC at all heights, but captures the shape of the profile very well. This result suggests that the Met Office cloud scheme is good but probably needs some general tuning in order to produce smaller IWCs. Finally, the RACMO model reproduces almost perfectly the observed IWC profile, as a result of a relatively good representation of the observed IWC distribution.

A complementary analysis can be performed using a point-by-point comparison of model and observed IWCs at the three sites and for all the models. The results of this comparison are shown in Figure 9 where we wish to investigate the effect of including more low IWCs in the Cabauw statistics due to the higher sensitivity of the radar (Figure 8). Globally, we find that the models all tend to overestimate the small IWCs and to underestimate the high IWCs, which in other words means that the model schemes tend to generate a range of IWC values smaller than observed. This result is consistent with the model distributions in Figure 7 which are narrower than those observed. This trend is particularly obvious for the two versions of the ARPEGE model and the Met Office model but remains true for the other models.

This result, as a side effect, shows that attention must be paid to carefully account for the instrument sensitivity in such an evaluation of models with observations. As an illustration if one looks at the second and third panels (Chilbolton and Palaiseau) of Figure 9, the agreement seems to be better between models and observations than in the first panel (Cabauw) (higher density of points along the 1-1 line). However these improved results do not result from a better behaviour of the model over these two sites, but rather from the suppression of low IWCs in the statistics of observations, thereby giving more weight to the region where the observed IWCs are in the same range as the simulated one.

3.2 Comparison at seasonal scale

The seasonal (from one season to another during a year) and "season-to-season" (from one season a given year to the same season another year) variabilities of ice water content were investigated using the Cabauw observations, in order to evaluate if the models are able to reproduce them. A clear result is that the seasonal variability of the IWC distribution in both the observations and the model remain fairly similar (not shown). The absence of a seasonal variability in the IWC pdf means that any changes in the model leading to more realistic pdfs should lead to an improvement for all seasons. Below, we will concentrate on the comparison of mean IWC profiles, which do exhibit some seasonal variability that can be compared to that produced in models.

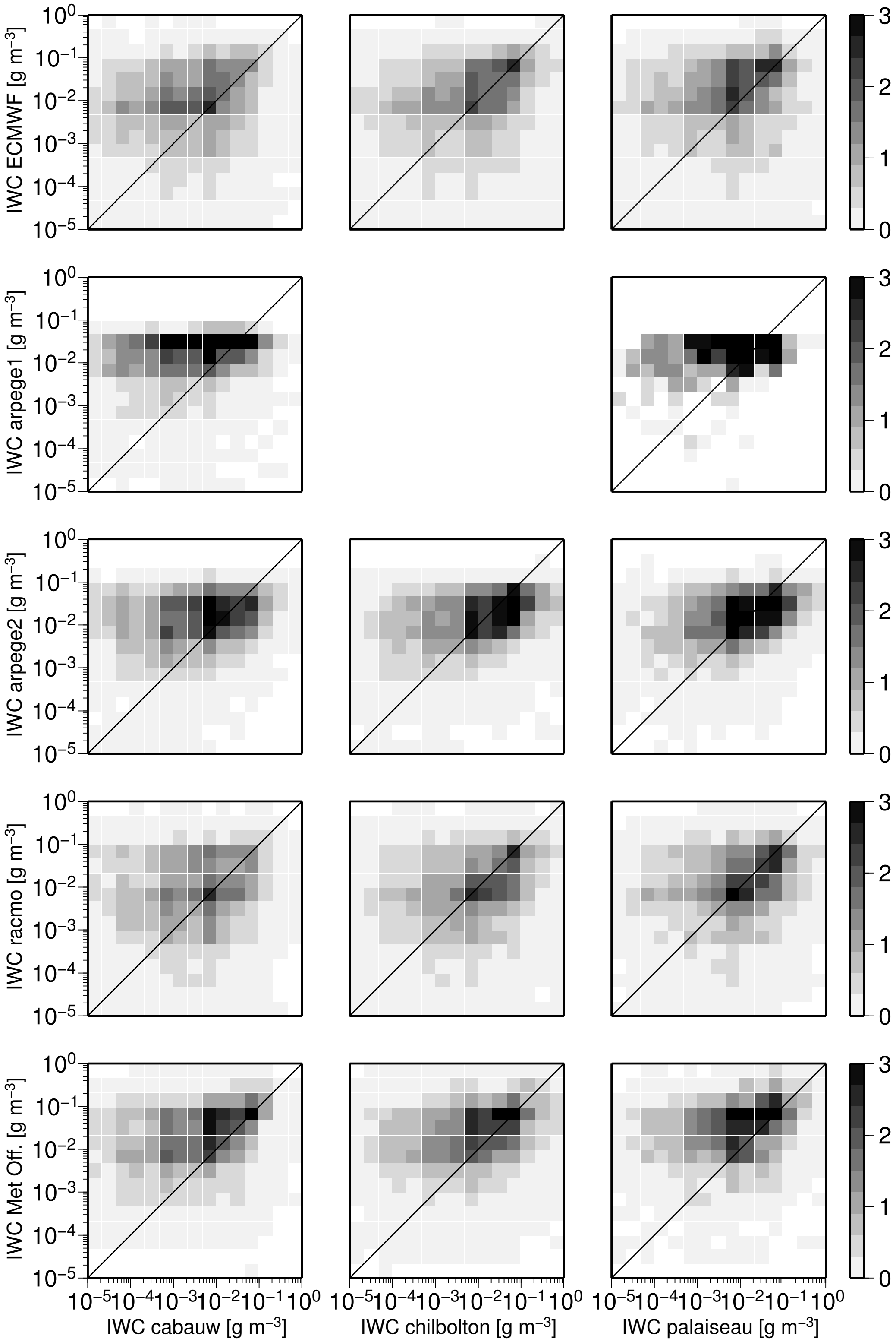

Figure 9: Density plots in grey levels of number of points (in percentage, normalised by the total number of points). Each line corresponds to a model (ECMWF, arpege1, arpege2, RACMO and Met Office from top to bottom) and each panel is dedicated to a site (Cabauw, Chilbolton and Palaiseau from left to right).

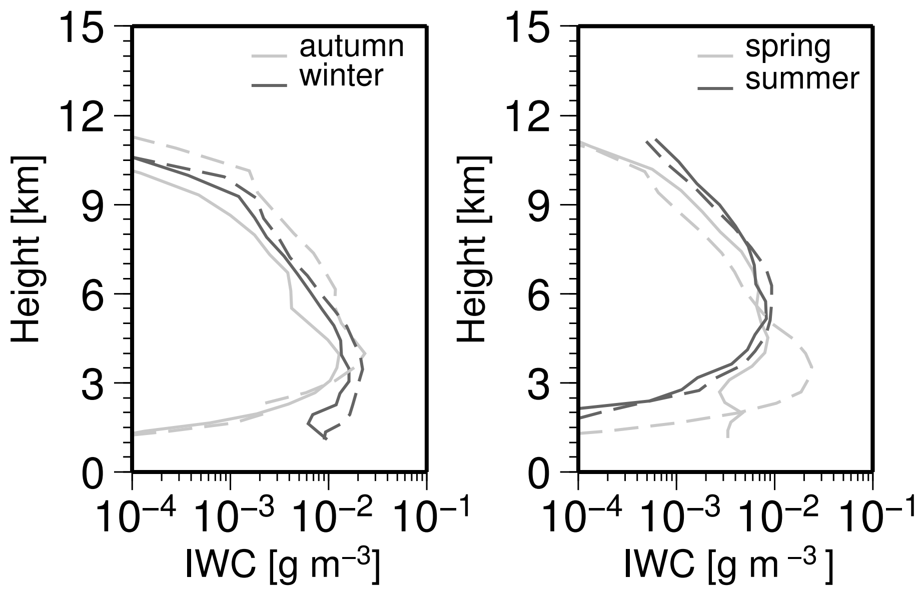

Figure 10: Seasonal evolution of IWC at the Cabauw site. Solid lines correspond to the first year of the project (autumn 2002 up to summer 2003), dashed line are for the second year (autumn 2003 up to summer 2004)

3.2.1 Season-to-season variability

Figure 10 shows the mean profiles of observed IWC for autumn and winter on the left panel and spring and summer on the right panel. There is some variability between the two years of the project (comparison of dashed and solid lines for a given season) in autumn and spring, while there is almost none in winter and summer.

The equivalent plots to those in Figure 10 but for the different models are shown in Figure 11. The overall conclusion is that the variability found in the models does not agree with that observed. In addition, the models tend to generate the same profile for a given season for the two years. This latter conclusion is particularly obvious for the Met Office model. The ECMWF model tends to best produce the observed season-to-season variability.

3.2.2 Seasonal variability

The observed seasonal variability is displayed in Figure 12 for the two years of the Cloudnet project. As expected there is a significant seasonal variability, simply owing to the fact that ice is present in the troposphere at higher levels during the hottest seasons and extends to lower altitudes during the coldest season. It is however surprising to see that above 3 km height, there is a large contrast between summer and the three other seasons which all have very similar profile. Below 3 km height, the most prominent feature is a clear IWC maximum in winter, as expected, and a gradually-decreasing mean IWC from the warmest to the coldest season.

The same seasonal variability is given in Figure 13 for the models. It appears clearly from this figure that the ECMWF, RACMO and ARPEGE models reproduce accurately the large variability between summer and winter, while the Met Office model tends to produce the same profile whatever the season, which is particularly clear for the first year of the project.

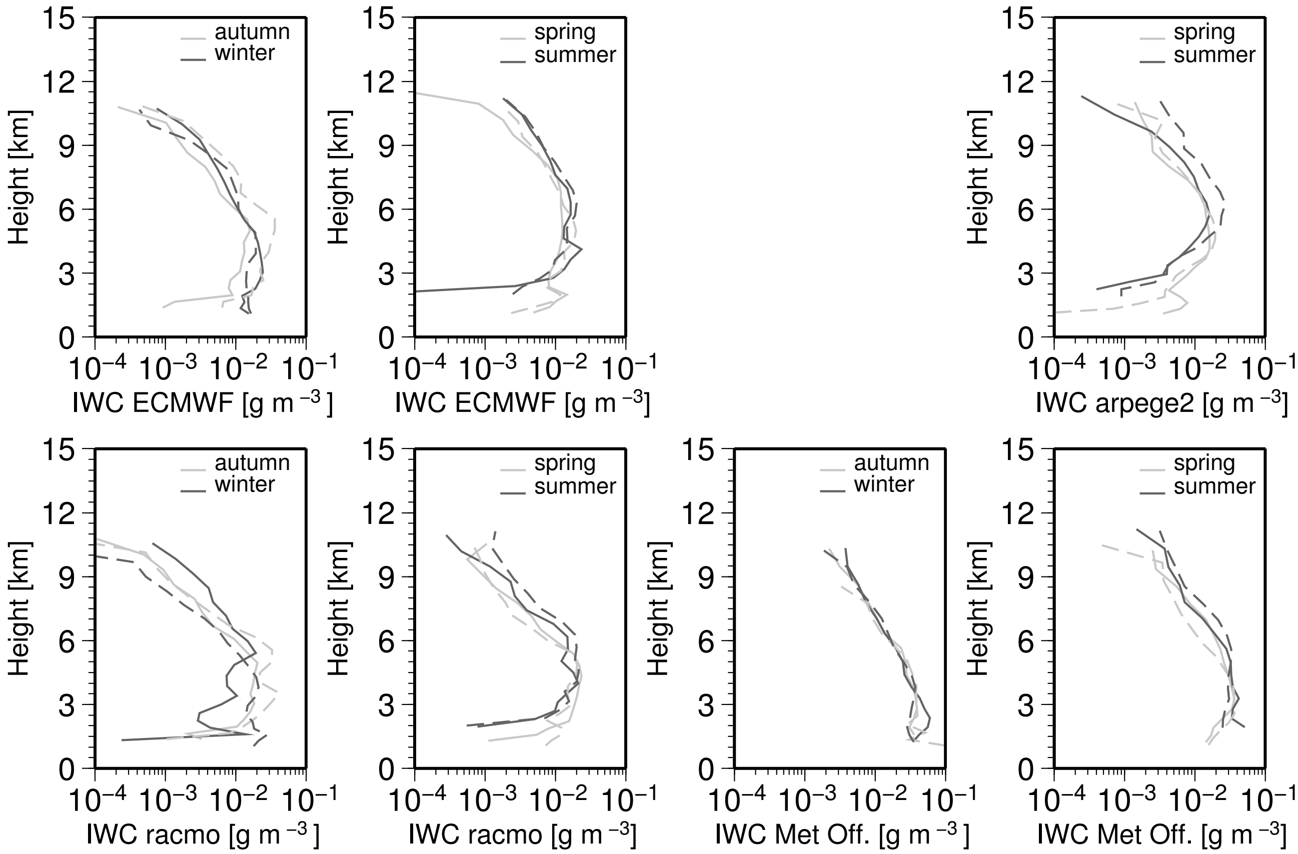

Figure 11: Seasonal evolution of IWC obtained from the models : ECMWF and arpege2 for the first row, RACMO and Met Office for the second. Solid lines correspond to the first year of the project (autumn 2002 up to summer 2003), dashed line are for the second year (autumn 2003 up to summer 2004)

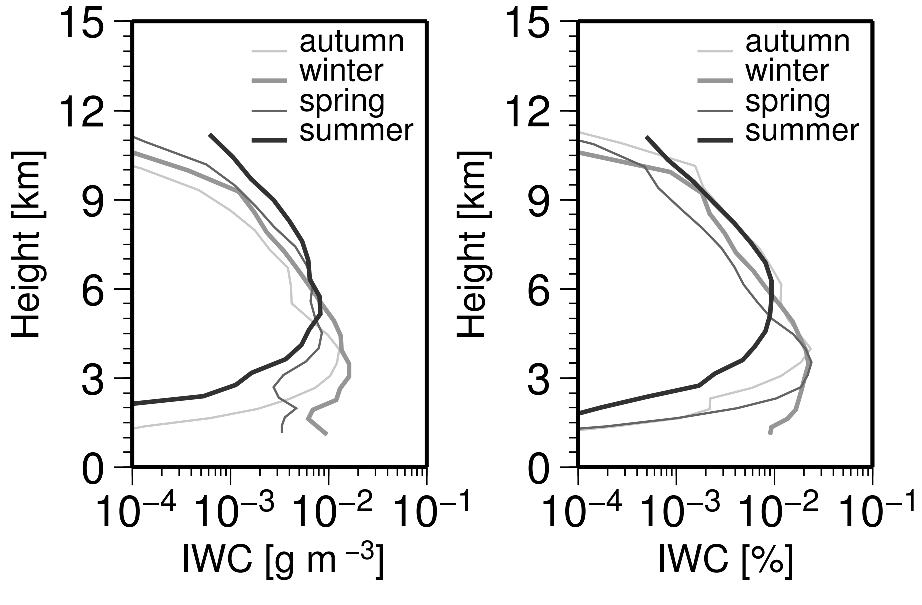

Figure 12: Seasonal variability of IWC derived from observations at the Cabauw site. The first year of the project is shown on the left-hand side panel, the second being on the right-hand side.

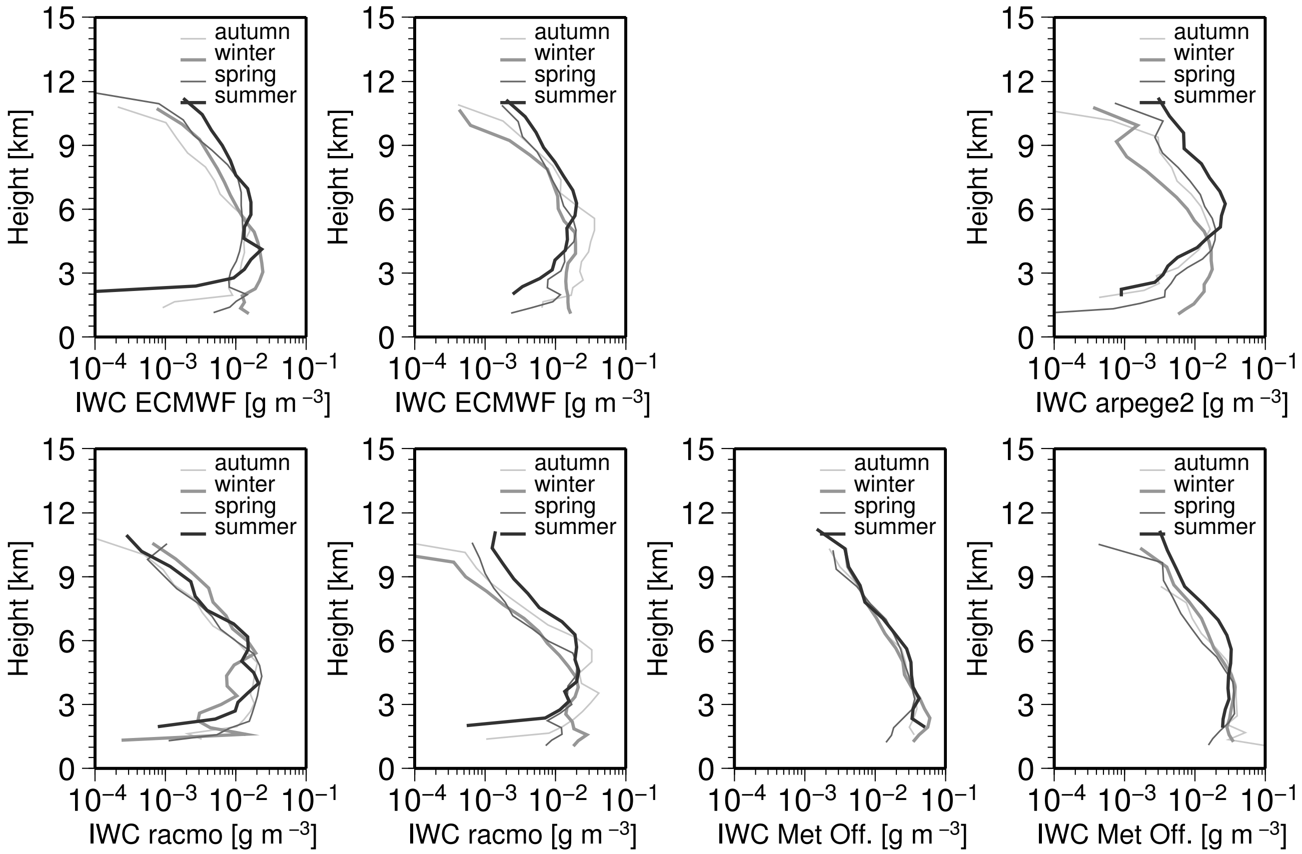

Figure 13: Seasonal variability of IWC from the models (ECMWF, arpege2 on the first row, RACMO and Met Office on the second row) at the Cabauw site. For a given model, the left hand side panel displayed the seasons of the first year of project, the right hand side panel the seasons for the second year.

4 Conclusions

This paper presents an evaluation of the parameters involved in the state-of-the-art cloud schemes (IWC and cloud fraction) in four operational weather forecast models (ECMWF, ARPEGE, RACMO and UKMO) when model and observations agree on a cloud occurrence. The evaluation of this latter parameter has been fully performed in Bouniol *et al.* (2007). For each variable the dataset has also been investigated on a seasonal basis to see if the model can generate the full ensemble of different weather situations.

One aim of the Cloudnet project (Illingworth *et al.* 2007) was to build climatologies of cloud properties at regional scale by continuous operation of three cloud observing stations in western Europe. This paper has demonstrated the importance of having the same set of instrumentation, otherwise apparent differences observed at the three sites cannot be unambiguously attributed to regional properties rather than being due to differences in the instrumentations. The CloudSat/CALIPSO tandem will overcome this problem by providing a view of the three sites with the same instruments and it would be interesting as soon as long time series from these instruments are available to build up the same statistics as in the present paper.

To summarise the main results of this paper, completed by the results of Bouniol *et al.* (2007) on cloud occurrence, a two year data set of operations and models has been analysed to produce profiles of the pdfs of cloud fraction and IWC which have then been subdivided into high, mid and low-level clouds. For the high-level clouds all the models tend to overestimate the frequency of cloud occurrence (even when the instrumental sensitivity is taken into account) and all schemes except the first version of the ARPEGE model fail to produce the low cloud fraction values observed at this height. The IWC is generally overestimated, except for RACMO. So the picture is as follows: there are too many high-level clouds in the models, not broken enough, and with too large IWCs. These clouds are considered as radiatively important because of their feedback on weather and climate and therefore their relatively inaccurate representation in models may not be negligible when computing fluxes with the radiation scheme.

For mid-level clouds their frequency of occurrence is generally overestimated, except for the second version of the ARPEGE model scheme. The models produce broken cloud too frequently. In contrast, the IWCs in mid-level clouds are generally well reproduced.

Finally the accuracy of low-level clouds occurrence is very different from one model to another: RACMO, ECMWF and arpege1 tend to overestimate the occurrence of such clouds, while the Met Office is fairly accurate and arpege2 underestimates their occurrence. On the other hand, only the arpege2 model is able to generate the observed strongly bimodal distribution of cloud fraction of the low-levels. All the other models tend to generate too many broken clouds. Another characteristics common to all models is their tendency to underestimate the width of the IWC distribution as compared to the observed one.

From this overall comparison it is interesting to see that the arpege2 model, although it is still using a diagnostic cloud scheme and a coarser resolution than RACMO and Met Office, produces overall the ”best” representation of clouds .

As a second step the season-to-season and seasonal variabilities of the cloud properties and their representation in models have been investigated. The objective of a season to season comparison is to determine if some seasons can be used as references for general tuning of a cloud scheme and the seasonal study aims at investigating if the models are able to reproduce the differences in the observations, *i.e* how well do the parametrisations reproduce different weather situations. In such comparisons the model biases evidenced in the overall comparison are generally observed as well at seasonal scale. However, variations can still be looked at. Regarding the frequency of cloud occurrence the main seasonal signatures are generally well captured by the models (less accurate results in autumn, though) and the corresponding results for the cloud fraction show that the variations are generally well reproduced by the models for low and mid-level clouds. For IWC the variability found in the models do not agree with that observed whereas ECMWF, ARPEGE and RACMO models reproduce rather well the large variability between summer and winter.

As a second step, the season-to-season and seasonal variabilities of the cloud properties have been investigated, to determine if the model parameterisation schemes are able to generate the full range of different clouds expected for different weather situations, or if different tuning is needed at different times of the year expected. The models were generally able to capture the cloud occurrence and the cloud fractions for most seasons for low and mid-level clouds, although they were less accurate in the autumn. For IWC the seasonal variability found in the models did not agree with observations, although ECMWF, ARPEGE and RACMO models reproduce rather well the large variability between summer and winter.

A further evaluation of the parametrisation could involve a comparison of observed and model shortwave and long wave fluxes, as done by Morcrette (2002) or Guichard *et al.* (2003). However in the framework of the Cloudnet project not all the same fluxes have been stored for the different models, which does not allow such a comparison to be performed in the present case. It should be noted that these fluxes computations in the models depend strongly (but not only) on both cloud fraction, IWC and cloud occurrence. As a result compensating effects may well produce a good agreement between model and observations but for wrong reasons.

Finally, it has been shown that continuously operating cloud profiling stations provide an efficient way of rapidly evaluating the impact of any changes in the parameterisation schemes within operation models. For example, it was possible to demonstrate that the new cloud scheme in the ARPEGE model and its subsequent tuning was having a positive impact in the representation of clouds. The A-Train satellites providing now cloud profiles on a global scale, will be also very valuable in the future to investigate the cloud properties in regions where ground based observations are generally sparse but where clouds have a large influence on the climate system such as in the tropical belt (including Africa and South-America). Therefore, it is proposed that in a near future, using the same methodology as that developed in the present paper, cloud parametrisations of global models (such as ECMWF or ARPEGE model) be evaluated using the A-Train data set in very different meteorological conditions.

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