Proceedings of ERAD (2002): 167–172 © Copernicus GmbH 2002

ERAD 2002

Statistics of non-precipitating daytime clouds, based on 95 GHz cloud radar measurements during the BBC campaign

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Abstract. As a coordinated field phase within the projects CLIWA-NET, BALTEX-BRIDGE and 4D-Clouds, the BBC campaign took place in Cabauw/The Netherlands during August and September 2001. About 400 hours of atmospheric profiles taken with the 95 GHz cloud radar MIRACLE are available from this eight week period, from which more than 350 hours are used to derive statistics of cloud height distribution, number of cloud layers and cloud overlap. A comparison of the radar data with ceilometer data shows that even if both instruments identify the profile as cloudy the derivated cloud base agree in only 17%, mainly due to drizzle events that occur in nearly 70% of the profiles that are definitely cloudy. Ignoring these discrepancies and assuming that the radar data give accurate cloud boundaries, the applied cloudmask identifies about 70% of all clouds as being single layered. Mean cloud overlap changes from maximum overlap for near range gates to nearly minimum overlap for very distant range gates.

1 Introduction

It is well known, that the dynamic of the atmosphere is driven mainly by variations of the radiation field in space and time (Budyko, 1969), which are caused primarily by clouds (Raschke and Kondratyev, 1983). Nevertheless, cloud processes are still not well known, and their representation in current weather and climate models are one of the largest sources of uncertainty. Better knowledge of (among others) internal structure, the vertical and horizontal distribution of cloud liquid water and cloud layer arrangements is highly desireable. To accomplish this for liquid water clouds, the data of several instruments like microwave radiometers, cloud radars and ceilometers are combined during the CLIWA-NET project. The ground-based GKSS cloud radar MIRACLE was used to profile the vertical structure of the clouds. For the third period of enhanced observations during CLIWA-NET, BBC, we present statistics of all measured clouds. In Sect. 2 a brief introduction into the CLIWA-NET campaign is given, followed by a description of the cloud radar data that entered the calculations. All statistics are highly influenced by the cloudmask which is visualized in Sect. 4, statistics of cloud occurence and some quality estimate by comparison with ceilometer data follow in Sect. 5, and the cloud overlap behaviour is examined in Sect. 6. We will finish with some concluding remarks.

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2 CLIWA-Net and BBC

Within the 5th Framework of the EU, the project BALTEX Cloud Liquid Water Network (CLIWA-NET) started in March of 2000. The aim is to establish a prototype of a Europe-wide cloud observation network with several related topics, including evaluation of atmospheric models and improvement of the parametrization of cloud processes (Crewell et al., 2001, 2002). Three Enhanced Observation Periods (EOPs, Van Lammeren, 2001) took place to combine synergetic sensor data (Crewell et al., 2000) at several stations all over Europe during CLIWA-NET Network I and II (CNN I and II) and to compare the instruments used during CNN I and II at the same location during the third EOP, the BALTEX BRIDGE cloud campaign (BBC). BBC took place in Cabauw/The Netherlands in August and September of 2001 in co-ordination with the BALTEX-BRIDGE campaign and the German project 4D-Clouds.

3 Availability of MIRACLE during BBC

The 95 GHz Cloud Radar MIRACLE (for technical details see Quante et al., 2000) arrived at Cabauw on 31/07/01 and left on late 28/09/01. Due to several limitations a continuous measurement was not possible. The receiver and other electronic parts are not completly protected against severe rainfall and corresponding penetrating water. To avoid damage to the system it was switched off during precipitation events except very weak showers. For the same reason no measurements were taken during night time.

Table 1. Total times of MIRACLE data available. For the statistics, all data taken in regular mode are used reduced by four profiles each started hour (due to the cloudmask)

(all values: hours: minutes)	August	September	Total
Total	198:50	198:09	396:59
Aircraft	–	15:02	15:02
Scan/not vertical	0:32	7:59	8:31
Rejected data	10:11	–	10:11
Regular BBC	188:07	175:08	363:15
Data used for statistics	187:48	174:50	362:38

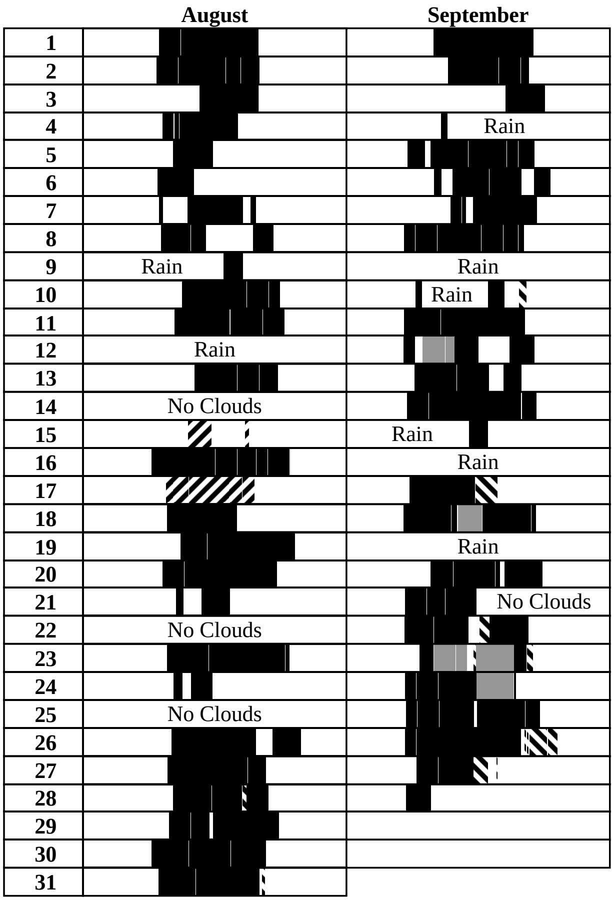

Fig. 1. Schematic of the MIRACLE data coverage during BBC. Black: data with regular settings used for this statistics; Slashes (/): data refused due to technical problems; Grey: aircraft settings; Back-slashes (\): measurements not pointing vertically.

During the 59 day period MIRACLE was available at Cabauw, a total of seven days failed completedly due to steady precipitation or the absence of clouds. The data coverage is shown schematically in Fig. 1. All periods marked in black are data taken in so-called "regular BBC mode" what means a pulse-to-pulse frequency of 5040 Hz, a vertical range gate spacing of 82.5 m in an altitude range between

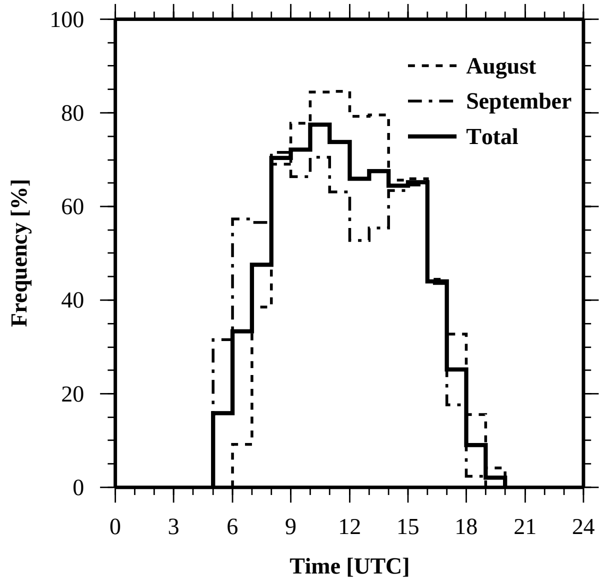

Fig. 2. Diurnal cycle of data coverage during BBC.

500 m and 12 000 m and a vertical beam orientation. On two days in August (marked by increasing lines in Fig. 1) the data were disturbed by a not identified signal and were therefore rejected from this analysis.

In September several aircraft observations took place in the vicinity of Cabauw. To improve the possibilities of combining ground-based remote sensing data with the aircraft observations, the vertical resolution of the radar has been increased during the flight times to 37.5 m which results in an altitude range of 150 m to 6000 m. These data are marked grey in Fig. 1. Furthermore, joining the 4D-Clouds project which shared the experimental effort with the BBC campaign several data were taken in scanning mode (marked by decreasing lines). The total amount of data is given in Table 1. To calculate this cloud layer statistics, all data in "regular mode" are taken into account. Because of the cloudmask which is discussed in the next chapter, the useable data is reduced by 20 seconds each started hour of measurements. The diurnal coverage of data entering this analysis is shown in Fig. 2. Values are relative to active days only, i.e. 25 days in August and September, respectively.

4 Cloudmask

The statistics of radar derived cloud layers depend strongly on the choice of the cloudmask. For this work we use a five-step cloudmask that is optimized for application on average values of five seconds. Each of these steps except the third, consider a five-by-five grid surrounding the pixel actually looked at, leading to a loss of four profiles for each examined data file. The steps are: (1) Check for saturation effects, (2) Removal of noise, (3) Static threshold on reflectivity, (4) Removal of isolated cloudy pixels and (5) Removal of isolated cloud-free pixels. The first two steps are based on the cloud-

Table 2. Comparison of cloud detection with radar and Ceilometer CT75 (KNMI), relative to a total of 134 340 (August) and 125 030 (September) Radar profiles

			Ceilometer	
			Cloud-Free	Cloudy
Radar	Cloud-Free	August	23.2%	8.2%
		September	22.7%	6.3%
		Total	23.0%	7.3%
Radar	Cloudy	August	28.1%	40.5%
		September	17.6%	53.3%
		Total	23.0%	46.7%

mask of Clothiaux et al. (1995) but with adjusted thresholds. They depend on the preliminary derived vertical velocities and the received power in the surrounding 5-by-5-pixel-box. Any pixel with a reflectivity of less than −54 dBZ is defined as cloud-free by the static threshold. Step four assumes that no cloudy pixels could be isolated but have a certain number of likewise cloudy pixels around, otherwise it is declared as noise. The main goal of this step is to remove small clusters of noisy pixels that passed the physical significance test in steps one and two, and furthermore, together with the last step, to identify scattered and broken cloud layers and define them as either cloud-free or cloudy, respectively.

The influence of the different steps is shown in Fig. 3, which is an example measured between 10:27 UTC and about 10:47 on 2 September 2001. The time axis is given in decimal hours, representing UTC. Panel (a) presents the cloud as it would be without a cloudmask, with black pixels representing a reflectivity of at least −54 dBZ. At either 10.675 and 10.70 hours there is some saturation found by the first step, removed pixels are marked in red in Fig. 3b. The second check for physical significance removes all the noisy pixels above the lowest layer (red pixels in Fig. 3c), but also adds some cloudy pixels (marked in green). Note that there are still clusters of cloudy pixels found which are obviously noise, because of their vertical orientation, in the altitude range between one and two kilometers. These pixels are removed by step four (see Fig. 3d), as well as the scattered layer between five and six kilometers height. The broken layer in this altitude range around the time 10.65 to 10.675 hours is filled as (nearly) totally cloudy by the final step, as well as several other small cloud gaps (green pixels in Fig. 3e). The result after applying all steps is summarized in Fig. 3f.

5 Cloud layer occurence

It is well known that radar measurements tend to underestimate the cloud base in case of drizzle events (Quante et al., 2000). The uncertainty associated with this can be reduced by using a simultaneously operated ceilometer that would not see any light precipitation. During the BBC campaign the KNMI operated a CT75, these data were combined with the MIRACLE data for several occasions (Meywerk et al., 2002). In this presentation we do not make any correction to the cloud base statistics but use the ceilometer data as a rough quality estimate.

In the BBC data set the CT75 data are given as cloud base height, averaged over 30 seconds. The distance between MIRACLE and the ceilometer was less than 50 meters. Comparing each 5-second-averaged profile of MIRACLE with the corresponding ceilometer 30-second value, we found that both instruments give the same indication, whether there is a cloud or not in only 69.7% of the radar profiles (23.0% cloud free, 46.7% cloudy; see Table 2). In 23.0% of all radar profiles the radar shows at least one cloud layer but the ceilometer does not. In 7.3% of the radar profiles the radar algorithm fails to see any cloud that was detected by the ceilometer.

To give a quality estimate of the cloud base detection by radar, we limit the further analysis to those profiles for which both, the radar and the ceilometer found clouds. This was the case in 54 377 (August) and 66 699 (September) radar profiles used for this statistics. In 16.6% of these profiles the ceilometer and the radar agree in the lowest cloud base with an accepted difference of not more than one radar range gate (see Table 3). In another 15.7% the lowest ceilometer cloud base (CCB) is detected below the lowest radar cloud base (RCB). This is mainly the case for either very low or geometrically thin clouds. Drizzle events are indicated by a CCB above the RCB, when the CCB falls inside the lowest radar cloud layer. This was the case in 58.0% of the treated radar profiles. Moreover, if the lowest radar cloud is missed by the ceilometer, the CCB hits any other radar cloud layer in 4.9% or identifies a cloud layer that is not seen by the radar (5.0%).

Assuming the radar data give a correct identification of cloud bases, i.e. declaring any drizzle underneath the cloud as part of it, the vertical distribution of cloud coverage, cloud bottom and cloud top occurence is calculated. Figure 4 shows the mean cloud occurence in altitude bins of one kilometer thickness. In August of 2001 the vertical distribution of clouds was quite regular with a small peak at low level clouds below three kilometers. That behaviour changes in September when both low level clouds and high clouds increased in presence, meanwhile medium level and highest level clouds above 9 kilometers kept steady or were reduced significantly.

The increase of cloud cover in the two levels during the second half of the BBC period is accompanied with an increase of multi-layer clouds (Fig. 5). In August about 75% of all profiles that are identified as cloudy (52% of all profiles) are single-layered, 20% are two-layered, and the remaining 5% are nearly completely three-layered clouds. Four and five layers were detected but in negligible number of occurence. This distribution changes in September to 65% single-layered, 27% two-layered, 7% three-layered clouds and 1% with a higher number of layers.

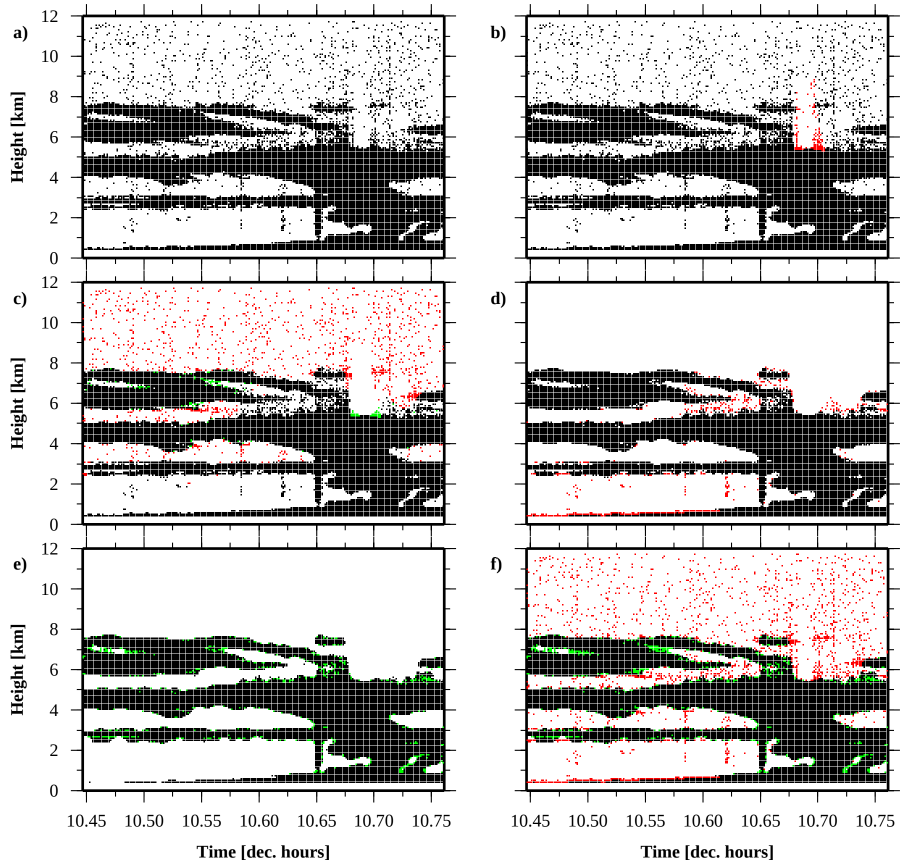

Fig. 3. Influence of different cloudmask steps. Black pixels are cloudy, red (green) pixels represent removed (added) cloudy pixels after last step. (a) Original data without cloudmask but reflectivity threshold of −54 dBZ. (b) After saturation check. (c) After removal of physical noise. (d) After removal of isolated cloudy pixels. (e) After filling isolated cloud free pixels. (f) Influence of total cloudmask on original data.

6 Cloud overlap

Atmospheric models usually assume that the cloud cover overlap of two different layers is either maximal or random (Hogan and Illingworth, 2000; from now on HI). Following this publication, the MIRACLE data were examined for the true cloud overlap between any pairs of two range gates. Mean cloud cover for each range gate was calculated for averages of 30 minutes, with the cloud cover defined as the fraction of profiles that were analysed as cloudy. Levels that show a cloud cover of either zero or unity during this period are rejected from further consideration. Any combination of pairs of the remaining levels are used to calculate the true overlap which is averaged for each vertical level separation. This true overlap cloud cover is compared with three overlap models, which are the maximum, the minimum and the random overlap (HI, 2000). The mean combined cloud cover C of two levels a and b can be calculated as

$$C_{rand} = c_a + c_b - c_a c_b \tag{1}$$

$$C_{max} = \max(c_a, c_b) \tag{2}$$

$$C_{min} = \min(1, c_a + c_b) \tag{3}$$

The results of these calculations can be seen in Fig. 6a and b, with data for August and September, respectively. On the right hand side the cloud cover for single layer clouds is shown, left hand side the combined cloud cover values for seperated clouds (i.e. at least one range-gate between the cloudy levels is cloud-free for the 30-minute-period). The graphs for the single-layer clouds show that for small vertical level differences the true overlap (thick line) is (nearly) equal to the maximum overlap but approach random overlap with increasing level separation. To elucidate the ratio between true, maximum and random overlap the overlap parameter α is introduced by HI:

$$\boldsymbol{C}_{true} = \alpha \boldsymbol{C}_{max} + (1-\alpha)\boldsymbol{C}_{rand} \tag{4}$$

A value of $\alpha = 1$ means maximum overlap and $\alpha = 0$ random overlap. As is shown in Fig. 6c (August) and Fig. 6d (September), for single-layer clouds the overlap parameter starts with a value of 1 for low values of level separation and decreases with increasing level difference. In contrast to HI who used data of an 11-week near-continuous observation period, α does not converge at a value of 0 for high level separations. For vertical separated clouds the amplitude of the

Table 3. Position of ceilometer CT75 detected lowest cloud base (CCB) relative to lowest radar cloud base (RCB), relative to a total of 54 377 (August) and 66 699 (September) Radar profiles which were detected as cloudy both by Radar and CT75

	CCB below RCB	CCB equal RCB	CCB above RCB (CCB inside lowest Radar layer)	CCB above RCB (CCB inside any but the lowest Radar layer)	CCB above RCB (CCB outside any Radar layer)
August	11.1%	17.5%	58.0%	6.2%	7.3%
September	19.4%	15.8%	58.0%	3.8%	3.8%
Total	15.7%	16.6%	58.0%	4.9%	5.0%

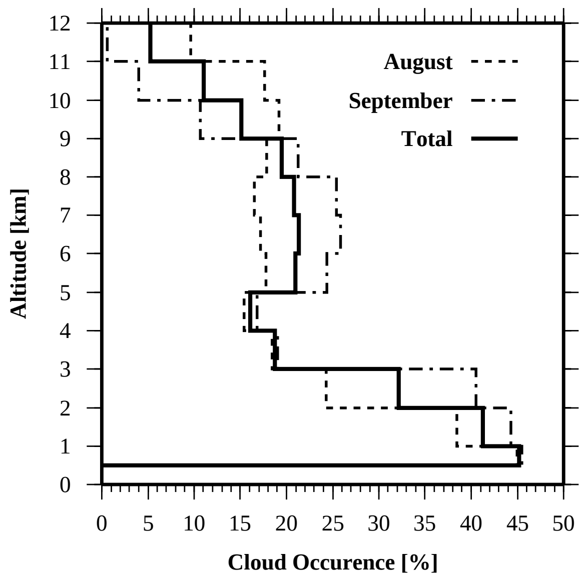

Fig. 4. Vertical distribution of cloud occurence during BBC, relative to total time of measurement.

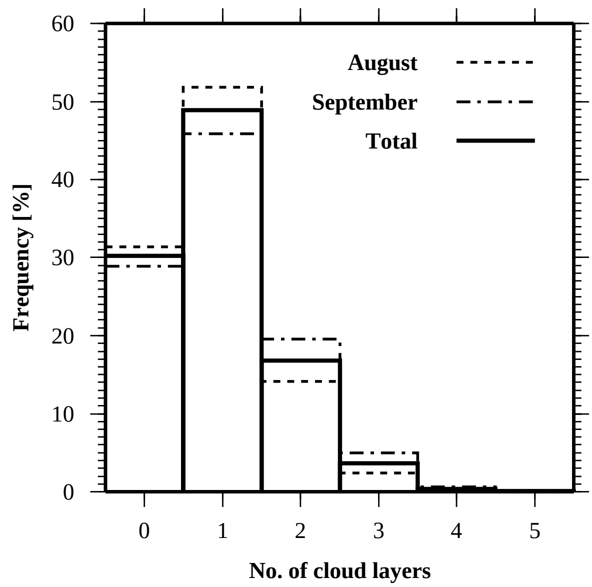

Fig. 5. Frequency distribution of number of cloud layers during BBC.

overlap parameter changes much more than at HI, but on the other hand the absolute differences between minimum and maximum overlap are much smaller during BBC, as well as the true overlap of separated cloud layers found to be larger by HI. This leads to the higher amplitudes of α in this presentation.

Two main discrepancies can be identified between this work and HI. The BBC data set is not only smaller than the HI-dataset due to the missing night measurements but also biased due to avoiding most precipitating events. Second, HI did not use the high resolution as we do here. To simulate the resolution of current General Circulation Models, they averaged their data about, at least, 360 m in vertical and two minutes time periods. If only one pixel of their original data (60 m vertical, 10 seconds horizontal) was cloudy, the whole grid box was marked cloudy which leads to a non-classified overestimation of cloud cover. First tests showed that the general behaviour of α is not sensitive to varying this smoothing mask. For high level separations, a converging of α at a value of zero could not be observed, even with simulating the grid resolution shown in HI (not shown). Further examinations have to be done to explain these differences.

7 Summary

For an eight week period cloud layer and cloud overlap statistics were derived from 95 GHz cloud radar data. About 360 hours of data are processed by a cloudmask that investigate cloudy pixels for their pysical significance and has a smoothing effect as well. We showed that the assumption of a single layer cloud which is often made in radiative transfer calculations is realized in about 70% of all cloudy radar profiles. Indeed there are uncertainties as can be shown by a comparison of the radar data with ceilometer data. The processing algorithms of radar and ceilometer disagree in the decision whether a profile is cloudy or not in about 30% of all radar profiles. If both the radar and the ceilometer detect a cloud, there are hints for drizzle events in nearly 60% of the cloudy profiles. In about 10% the lowest radar cloud layer is missed by the ceilometer. The cloud overlap differs much more from the random overlap assumption than in earlier publications.

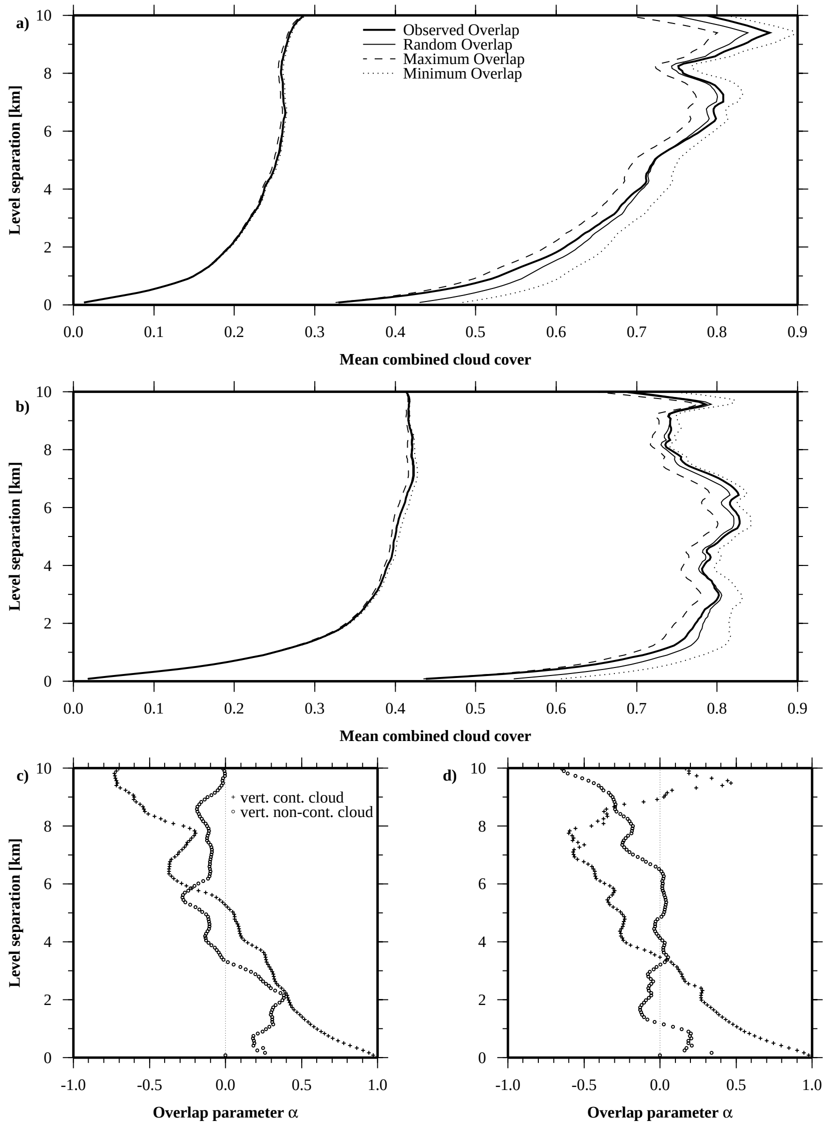

Fig. 6. Cloud overlap statistics.(a) Mean combined cloud cover versus level separation for different overlap models and observed overlap (August 2001); parted into vertical continuous clouds (right hand side) and vertical non-continuous clouds (left hand side). (b) As (a), but for September 2001. (c) Overlap parameter α versus level separation for August 2001. (d) As (c), but for September 2001.

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