TRANSITION TOWARDS A NEW CEILOMETER NETWORK IN THE NETHERLANDS: CHALLENGES AND EXPERIENCES

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ABSTRACT

KNMI renews all cloud ceilometers in its national meteorological observing network in 2016 and 2017. At about 40 stations, the Vaisala-Impulsphysik LD40 is gradually being replaced by the Lufft CHM15k ceilometer. By taking this step, the Netherlands will have a future-proof network in place to continue the generation of operational cloud information for synoptic and aeronautical purposes. This includes observing sites where meteorological reports are produced for the (AUTO)METAR system, such as civil airports and military airbases.

The new ceilometer network brings some great new opportunities. Benefits of the new instruments are primarily seen in the detection of high clouds and the sensitivity to aerosol layers, where the CHM15k clearly outperforms the LD40. Nevertheless, the transition to the new sensor also introduces some significant differences. This mainly concerns cloud base observations relevant for aeronautical reports, typically in the lowest 5,000 ft. Hence, the generation of fully automated, validated cloud information with an acceptable performance level poses several challenges.

1. Introduction

Cloud ceilometers using the LIDAR (LIght Detection And Ranging) principle are commonly accepted instruments for fully automated and continuous detection of cloud base height. Accurate cloud base height data is essential for aviation meteorology as it determines the ability for pilots to see the ground and is in certain weather conditions directly related to runway capacity. Moreover, information on the cloud height and cloud amount is important for general meteorology, NWP and climatology. Cloud fraction is even considered a priority II Essential Climate Variable (ECV). Traditionally, cloud observations were performed by human observers. During the past two decades there has been a tendency towards more and more unmanned observing sites, including automated equipment for cloud base recording. The LD40 ceilometer has been operated by KNMI for this purpose since the end of the nineties, but is technically end of life and not supported anymore. In 2015 the CHM15k, manufactured by Lufft GmbH, has been selected as its successor. This has opened the way for the improvement of automated cloud observations and aerosol profiling. However, the transition from the one measurement system to the other also introduces differences in the characteristics for cloud reporting.

As there is no internationally agreed quantifiable definition of a cloud and thus cloud base, the intercomparison of cloud base data measured by different ceilometers is not trivial. This was already recognized during the last WMO ceilometer intercomparison organized in 1986 (Jones et al., 1988). Systematic differences between different types of ceilometers were found. It appears that they are mainly caused by different cloud detection algorithms implemented by the manufacturers (Martucci et al., 2010). The CIMO Guide (WMO, 2014) states as definition of cloud base: *The lowest zone in which the obscuration corresponding to a change from clear air or haze to water droplets or ice crystals causes a significant change in the profile of the backscatter extinction coefficient.*

In this paper, several topics will be addressed. First of all, the layout and processing chain of the ceilometer network in the Netherlands will be briefly presented. Beside cloud data also backscatter profiles are centrally collected. The new network of CHM15k sensors will be partly included in the ALC (Automatic Lidars and Ceilometers) profiling network that is being developed within the Eumetnet E-PROFILE program (Haefele et al., 2016). Secondly, the results of the ceilometer acceptance test at the

Cabauw experimental site will be discussed. Here, a special four month campaign with collocated ceilometers, reference lidars and visibility measurements was organized in winter 2014/2015. This resulted in acceptance of the instrument and provided useful insights into the capabilities of the new cloud ceilometer. Finally, the experiences and main issues experienced during the operational implementation phase will be discussed.

2. Current status of the Dutch ceilometer network

Since the automation of the Dutch meteorological observation network in 2003, all synoptic and climatological reports are generated fully automatically (Wauben, 2006). This includes the observations of visibility, present weather and clouds. An overview of the ceilometer network is presented in Figure 1. KNMI uses around 45 Vaisala LD40 ceilometers in the Netherlands to perform observations of cloud base height and cloud cover. This includes instruments at automatic weather stations (AWS, 8x), civil airports (6x), military airbases (8x) and offshore platforms in the North Sea (11x). Furthermore, a dense network (9 ceilometers including fog stations) is part of the meteorological observing infrastructure around Amsterdam-Schiphol to provide accurate information on fog and low cloud development in close vicinity of the airport. Schiphol is also the only site in the network where a human observer is still active. A special extension of the observing network since 2015 is the site at Bonaire (Flamingo International Airport) in the Caribbean. This station is also equipped with a ceilometer providing real time cloud information. Bonaire will be upgraded to a CHM15k in profiler mode by the end of 2016.

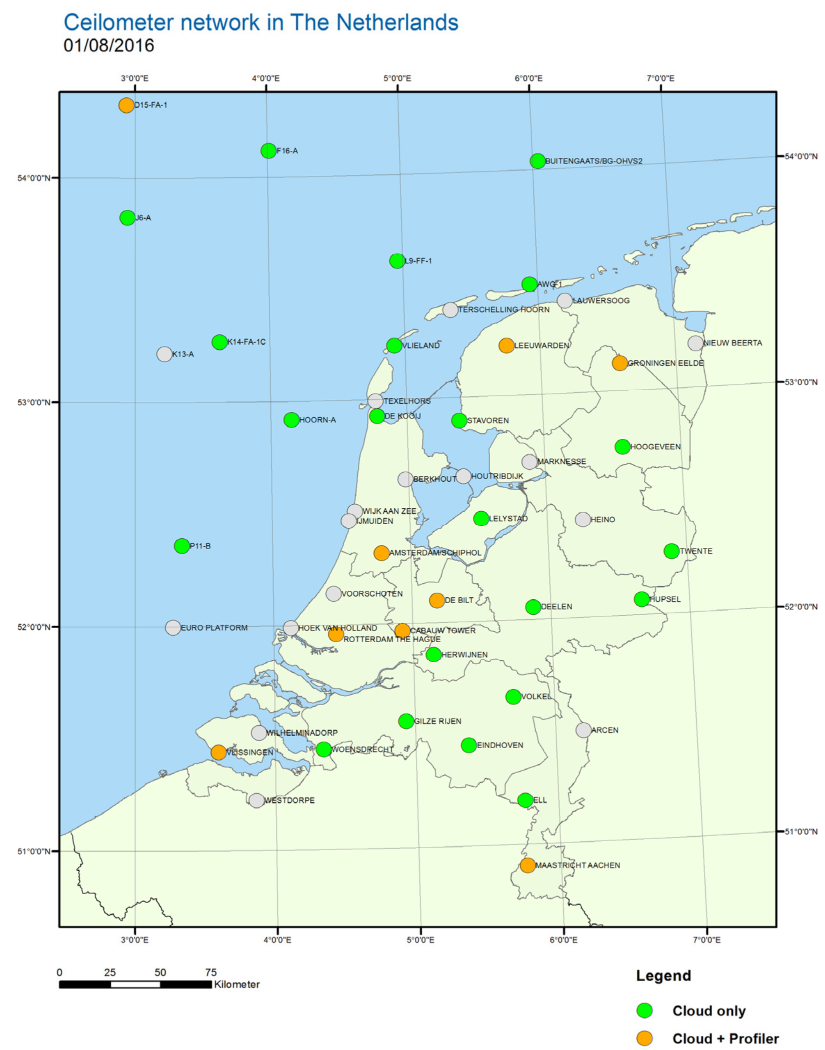

Figure 1. Layout of the ceilometer network in the Netherlands in the end situation, when all Lufft CHM15k ceilometers are implemented. Green dots denote a site for which only cloud information is provided, orange dots are ceilometers in profiler mode (Source: R. Sluiter, KNMI).

KNMI uses the so-called SIAM (Sensor Intelligent Adaptation Module) for all operational measurements in the surface observation network. It is a local interface module operated between the sensors and the data acquisition systems. The SIAM performs technical validation and computes averaged and extreme values with an update cycle of 12 seconds. For the Lufft CHM15k ceillometer, a new (cloud) SIAM was developed. It acquires the data telegram through the serial interface of the instrument and provides cloud base output for up to three layers (C1,C2,C3), together with vertical visibility (VV) and two aerosol layer heights (M1 and M2). M1 and M2 are new variables for the KNMI observing network.

Central processing

Data collected from the SIAMs in the network are processed centrally to observing products at KNMI headquarters in De Bilt, or at the airports independently. The cloud algorithm in use has been derived from the algorithm reported by Larsson and Esbjörn. The algorithm transforms sample ceilometer data (C1,C2,C3,VV) into cloud base height, total cloud cover and maximally three cloud layers with their corresponding cloud amount and height. Two different versions of the algorithm are used; one for synoptic purposes taking into account the 1-minute cloud base data from the last 30 minutes, and one for aeronautical purposes where the 12-second cloud base reports from the last 10 minutes is used. This selection has been chosen to be more sensitive to changes in the cloud amount. The lowest C1 value generally determines the cloud base height for the averaging interval. More details of the ceilometer algorithm and a comparison of automated cloud reports with observations are presented in (Wauben, 2002). In the central processing of cloud data, the automated reporting of CB (Cumulonimbus) and TCU (Towering Cumulus) is also taken into account by using information from the lightning detection network and the precipitation radars (Wauben, 2006).

Profile data

For a limited part of the network, the backscatter profile data from the LD40 and CHM15k are also collected in addition to the cloud height information. Whereas for the LD40 dedicated serial device servers had to be installed for splitting the data streams, the new CHM15k ceilometers are equipped with Ethernet extenders to connect them directly over IP to the KNMI network. This interface facilitates remote monitoring, but also real time distribution of data to KNMI end users and the E-PROFILE ALC network in the near future. E-PROFILE is interested particularly in ALC calibration, retrieval of attenuated backscatter profiles and cloud base height. The data is useful because the presence of aerosol can be detected in the backscatter profiles of more sensitive ceilometers like the CHM15k. Hence, the mixing layer height (MLH) can be derived (De Haij et al., 2007; De Bruine, 2014) providing valuable information on the evolution of the boundary layer. KNMI already has ample experience in this field with the old LD40 network and intends to extend the capabilities for boundary layer monitoring in the new network. The profile data is also of particular interest for nowcasting of fog and low clouds, and vertically resolved aerosol monitoring in the troposphere, for example during episodes with volcanic ash clouds or Saharan dust (Flentje et al. 2010).

3. Selection of a new ceilometer

In the autumn of 2014, KNMI launched a EU tender for the procurement of new cloud ceilometers. As primary point of departure, a hybrid network consisting of two lots with low range and high range cloud reporting instruments was desired. As the functional requirements in the observation network are largely determined by aviation, at roughly 75% of the observing sites a reporting range of 10,000 ft would be enough. For those sites a high performance for low cloud reporting was required. The other cloud reporting sites in the network were considered “anchor points” providing full range (0-15 km) cloud data for synoptic and climatological purposes. Given the relatively high density of cloud reporting sites in the Netherlands, the installation of 8 anchor points on land and the North Sea was chosen. The ceilometers in this second lot were required to have good performance regarding the observation of high (cirrus) clouds. Furthermore, they should have adequate aerosol layer detection capabilities. Table 1 lists a brief overview of the distinctive requirements for both lots in the tender.

The CHM15k ceilometer, manufactured by Lufft GmbH, covered the requirements of both lots and was selected as successor of the LD40. The instrument has a bi-axial design and is equipped with a Nd:Yag laser operating at 1064 nm. The vertical measurement range is 15 km and the set of parameters reported by the CHM15k contain the cloud base of (up to 9) cloud layers, vertical optical range (VOR), sky condition index and aerosol layer height. The vertical resolution is 5 m. The measured backscatter data, providing vertically resolved information on the presence of aerosols, is also reported by the instrument.

Table 1. Summary of distinctive requirements for the two lots of new ceilometers. The POD and FAR represent the Probability Of Detection and False Alarm Rate, respectively.

	Lot 1 / low-range	**Lot 2 / high-range**
Range (resolution)	0-7.5 km (10 m)	0-12 km (10 m)
Focus	Aeronautical use	Synoptic Met/Climatology
Performance POD/FAR Baseline 0-6 km Low clouds 0-500 m Cirrus >6km & τ=0.03	 98%/2% 99.5%/0.5%	 98%/2% >80%
# instruments	31	8

Ceilometer Acceptance Test

After the selection of the new ceilometer, an acceptance test was conducted to verify its real-life performance against the requirements during specific meteorological conditions. The total duration of the test was 12 weeks; the first two weeks were spent on a Site Acceptance Test (SAT) at KNMI headquarters in De Bilt followed by a field trial of ten weeks at the Cabauw Experimental Site for Atmospheric Research or CESAR [www.cesar-observatory.nl]. The CESAR Observatory is situated at the KNMI meteorological research site near Cabauw, located in the western part of the Netherlands (51.971° N, 4.927° E) in a polder 0.7 m below mean sea level. At the site a large set of instruments is operated to study the atmosphere and its interaction with the land surface. A large number of high performance remote sensing and in-situ measurements are performed, which enabled KNMI to verify whether the specifications provided by the Tenderer were being satisfied by the offered solution. The Raman lidar Caeli as well as the UV-lidar (Leosphere ALS450) and the LD40 acted as reference instruments for cloud detection in different altitude ranges.

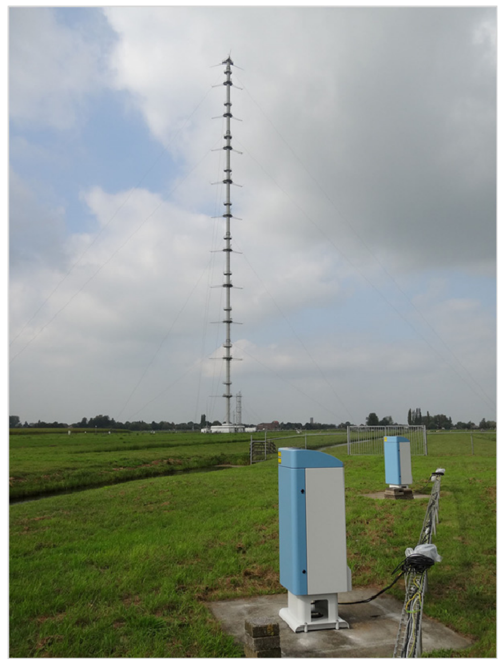

Figure 2. Two CHM15k ceilometers deployed at the CESAR site.

Two identical CHM15k instruments were rented from Lufft for the acceptance test. Both units (CHM140001 and CHM140002) were installed roughly 10 m from each other and operated with firmware v0.724 right from the start of the measurements at 28 September 2014. Beside the cloud data generated every 12 seconds by the KNMI SIAM, raw NetCDF data was acquired over the IP interface for both units and monitored during the campaign. The results from the first two months indicated that cloud base detection using firmware v0.724 could be improved in precipitation. Many examples showed reported cloud bases were too low when moderate or heavy precipitation was present. Based on this feedback, the manufacturer proposed a new cloud detection algorithm for implementation in a new firmware version. The results presented below are valid for this newer CHM15k firmware version, v0.733.

Low clouds

Special attention during the CAT was given to low cloud detection, as this range if of primary importance in the aeronautical MET reports provided by the (AUTO)METAR system. This requires good detection capabilities for clouds in the lower altitude ranges, especially below 1,500 ft. However, an assessment of the performance of the new ceilometer at low altitudes is a complex task, as no proper reference instruments measuring the cloud height are available for this height range. Unfortunately, the UV lidar cannot be used for those altitudes, because of very limited overlap in the lowest 500 m. Therefore we used an alternative method based on the seven visibility sensors (type Biral SWS-100, forward scatter sensors) in the 213 m tower. They are installed at the 2, 10, 20, 40, 80, 140 and 200 m levels. Two significant heights are derived from the time series of the 1-

minute MOR (Meteorological Optical Range) measurements and used as 'best guess' estimates for the assessment of cloud base height:

- TowerVis base is triggered at the first level at which the MOR drops below 1000 m (definition of fog). The height attributed to TowerVis base is the average of the corresponding sensor level and one sensor level below, except when it is triggered at the lowest level (i.e. 2 m).
- TowerVis top is the first level at which the MOR exceeds the 1000 m threshold again, after a valid TowerVis base has been detected.

Figure 3 presents these estimates during a situation with low clouds at Cabauw on 29 October 2014. Stratus clouds with a base around 300 m are initially present at midnight and decrease towards the surface with (C1 below 100 m) between 6 and 14 UTC. The plot shows the range corrected backscatter profile and cloud base reports from the CHM15k (CHM140001) and LD40 together with time series of the derived TowerVis base and TowerVis top. The differences between LD40 and CHM15k, generally 30-50 m in magnitude, are clearly present in the figure. The cloud base retrieved from the MOR measurements generally agree much better with the CHM15k than with the LD40 cloud base output. The temporal variability in CHM15k cloud base measurements is nicely followed by the TowerVis estimates. However, it should be noted that the 1000 m threshold is an arbitrary choice. No sensitivity analysis has been performed.

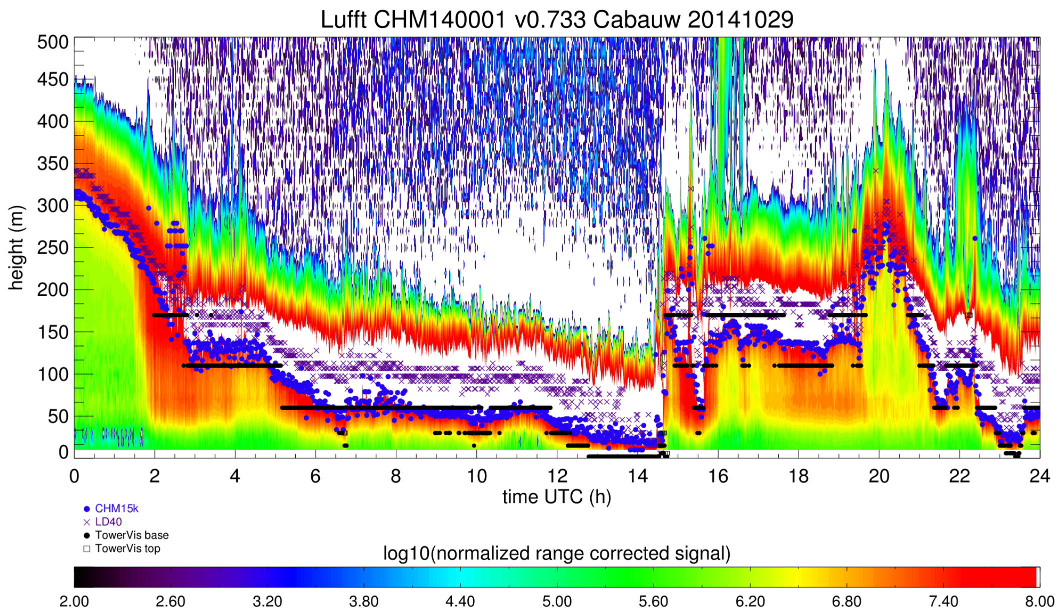

Figure 3. CHM15k backscatter data for Cabauw on 29 October 2014. Cloud base is indicated for CHM15k (●) and LD40 (x), TowerVis base (●) & top (□). Note that the maximum value possible for TowerVis base and TowerVis top is 170 m as the highest FS sensor is located at 200 m.

Three range and overlap corrected backscatter profiles measured by the CHM15k and LD40 at Cabauw on the same day, 29 October 2014, are plotted in Figure 4. It shows the individual profiles (i.e. no averaging has taken place) for 01:00, 11:00 and 21:00 UTC, together with the corresponding values of the cloud base height. Note that only the shape of the RCS is relevant here, and no attention should be paid to the absolute values of the signal.

Obviously, the cloud base reported by the CHM15k is approximately 30-40 m lower than for the LD40 in the examples shown here. As the shapes of the profiles and the location of the gradients and maxima in measured backscatter in the lowest 400 m are quite similar, it appears to be mainly the specific cloud detection algorithm implemented by the manufacturer to be the source of these differences. This is in line with earlier findings (Martucci et al., 2010; Görsdorf et al., 2016). Apparently the CHM15k cloud base is detected still in the ascending branch of the profile, whereas the LD40 algorithm triggers the cloud base at, or very close to, the maximum in the backscattered signal. The different approaches cannot be verified at this moment because the lack of an established and quantifiable definition for cloud base.

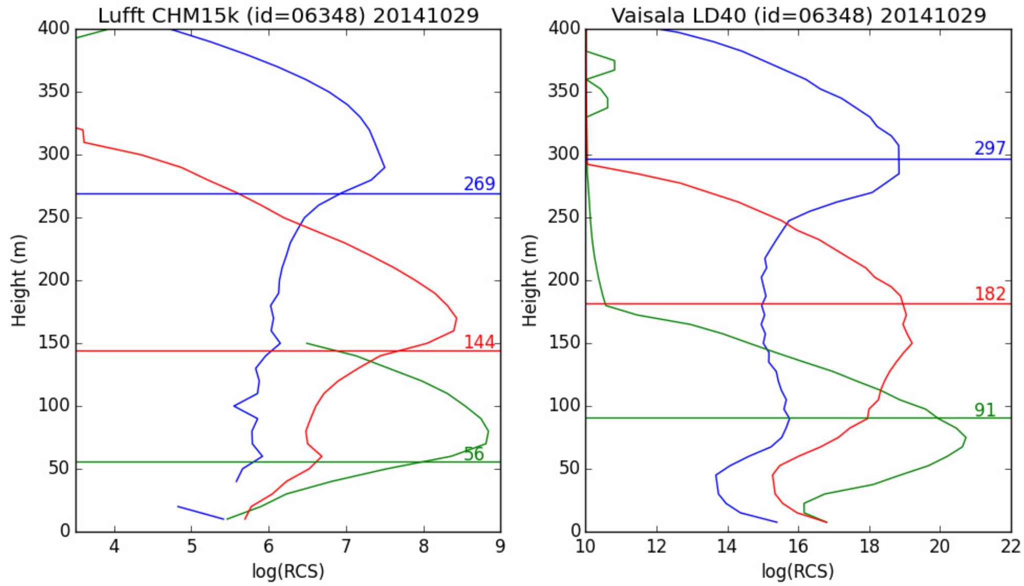

Figure 4. Profiles of the range corrected signal measured by CHM15k (left) and LD40 (right) at Cabauw on 29 October 2014 01:00 (blue), 11:00 (green) and 21:00 UTC (red). The horizontal lines represent the corresponding cloud base height (in meters) reported by the instrument.

Figure 3 suggested that the cloud base estimates from the MOR measurements in the tower agree much better with the CHM15k. Figure 5 and Table 2 summarize the results of the comparison for all levels in the Cabauw tower and the entire acceptance test period (113 days). The graphs show the cumulative probability of a cloud base when a TowerVis base is triggered between 20 and 40 m (left) and 80 and 140 m (right), respectively. The shaded areas correspond to these altitude ranges.

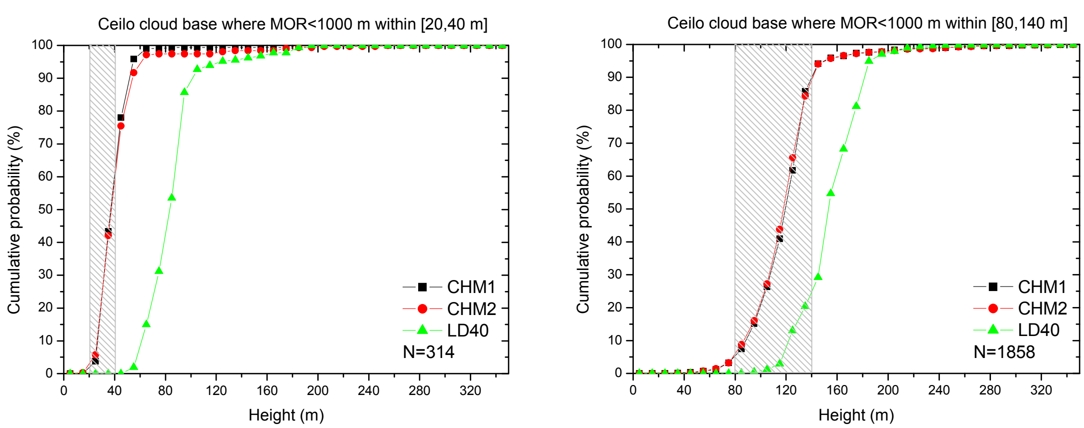

Figure 5. Cumulative probability for 1-minute cloud base height reported by the CHM15k (two instruments) and LD40 ceilometers for those cases where TowerVis base is located between 20 and 40 m (left) and between 80 and 140 m (right).

Table 2. Average cloud base height, standard deviation and Percentage Correct (PC) score for the comparison of CHM15k and LD40 1-minute cloud base data with TowerVis base estimates.

Level	**N**	**CHM1 (CHM140001)**		**CHM2 (CHM140002)**		**LD40**	
		Avg ± stdev	PC	Avg ± stdev	PC	Avg ± stdev	PC
0-20 m	1641	21 ± 35 m	72%	20 ± 34 m	76%	30 ± 43 m	58%
20-40 m	314	44 ± 15 m	46%	46 ± 24 m	45%	89 ± 23 m	<1%
40-80 m	1185	69 ± 23 m	74%	69 ± 25 m	75%	109 ± 22 m	2%
80-140 m	1858	124 ± 28 m	84%	123 ± 29 m	82%	160 ± 23 m	20%
140-200 m	1434	174 ± 42 m	64%	174 ± 44 m	66%	204 ± 30 m	45%

The difference in cloud base between CHM15k and LD40 can immediately be inferred from the two distributions, with the LD40 being a bit on the high side having only a limited number of cases within the grey shaded area. Only two levels are shown here, but identical graphs can be obtained for the other three levels as well. Note that the results for the two CHM units agree very well, which can also be observed in the nearly identical values for average cloud base, standard deviation and percentage correct scores in Table 2. This gives confidence in the instrument-to-instrument comparability for low cloud detection. Percentage Correct (PC) scores with respect to the TowerVis base estimates vary between 45 and 84% for the CHM15k with the lowest scores obtained for the 20-40 m level. For the LD40, the PC score is significantly lower for each altitude level, with a maximum PC of 58% for the lowest level (0-20 m).

High clouds

The required performance of the CHM15k for high cloud detection (POD 98%/FAR 2% for the altitude range 6,000-7,500 m) is verified with ALS450 cloud base as reference. This was achieved by a comparison of 1-minute cloud base reports during clear sky events and single layer cloud conditions in the range 6,000-7,500 m. Skill scores for cloud detection are based on a tolerance of ± 3 classes in hh code (WMO Table 1677). A selection of suitable events lead to 20.2 hours of cloudy and 43.4 hours of clear sky conditions. In all the 1-minute records where the UV lidar reports a valid cloud base in the considered height range, both CHM15k instruments report a cloud base as well, however, sometimes at a slightly different altitude. Allowing the deviation of max. 3 height classes in the WMO hh code reporting practice leads to an average POD exceeding 98% and a FAR of 0.0% for both CHM15k instruments. For the LD40 data, analysed in an identical way, POD and FAR scores of 74.5% and 0.0% are found, respectively.

Figure 6 shows one of the cases used for verification, on 31 October 2014. For this test, only the time interval 11:00-14:30 is considered. Note that even higher clouds up to 12 km, present above Cabauw in the early morning, are detected without any problem. The cloud base reported by the CHM15k (blue dots) is nearly spot on with the ALS450, whereas the LD40 ceilometer is clearly not capable of detecting these clouds.

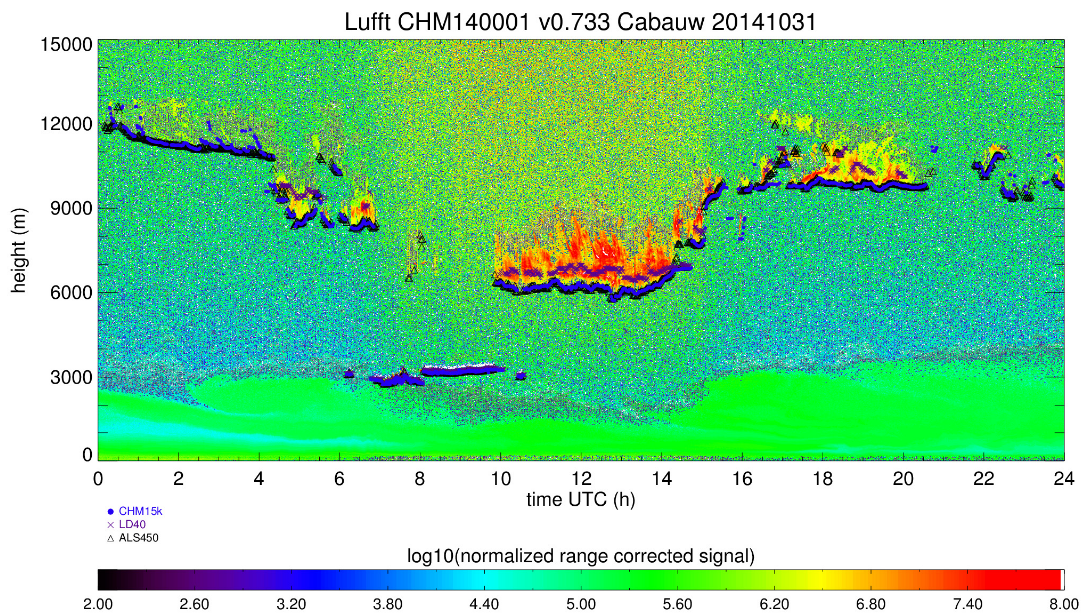

Figure 6. CHM15k backscatter data for Cabauw on 31 October 2014. Cloud base is indicated for CHM15k (●), LD40 (x) and the ALS450 UV lidar (Δ).

Precipitation

Accurate determination of the cloud base is often problematic in precipitation as the attenuation of the signal by falling droplets and snow particles are obscuring the actual cloud base. For the LD40 this was a shortcoming leading sometimes to serious 'gaps' in the cloud deck during precipitation. In current practices KNMI overcomes this issue in the cloud algorithm used on LD40 data by using vertical visibility (VV) as cloud base when no 'real' cloud base (C1) can be detected. This reduces the occurrence of potential gaps, but is in principle an undesirable correction. During the acceptance test it was verified whether a 95% detection probability is possible with the CHM15k in moderate and heavy precipitation at the surface, including snow. Figure 7 shows the fraction of cases with precipitation where no cloud base was reported by the two CHM15k's and the LD40, as function of the precipitation intensity. The grey line denotes the number of cases associated with a certain threshold in precipitation intensity; hence it represents the total number of events where the 1-minute intensity by the Vaisala FD12P weather sensor (PWS) was larger than that value. It is evident that both CHM15k instruments report a cloud base much more frequent than the LD40 in precipitation. The selection LD40 (C1) is in fact the only subset exceeding the 5% threshold indicated in magenta, and increasing with the precipitation intensity. For the CHM15k the fraction of events where no cloud is reported is far below the required threshold, with values smaller than 0.25%. This is in the same order of magnitude as the LD40 when also vertical visibility is considered as cloud base for that instrument (C1+VV).

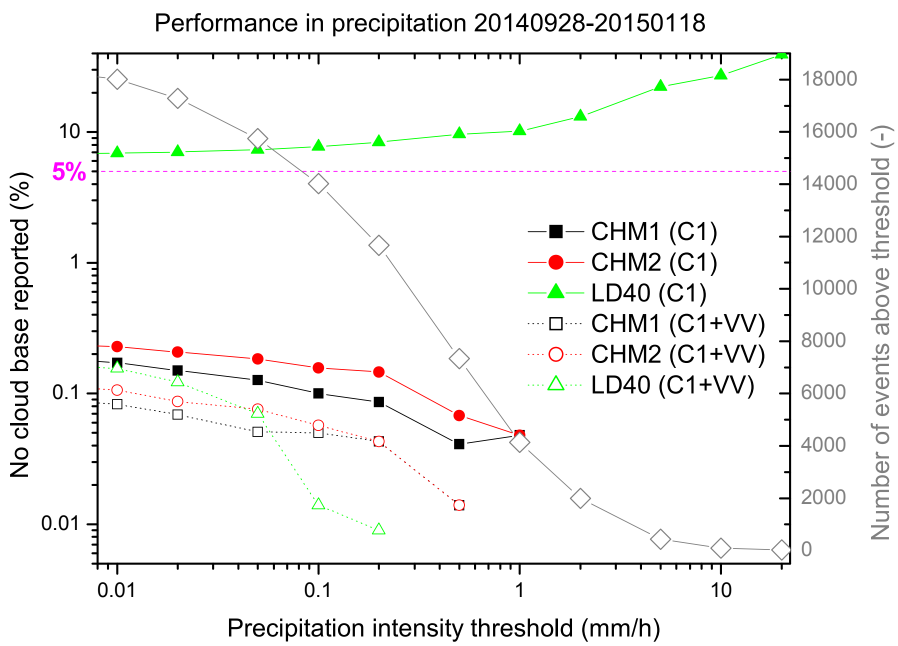

Figure 7. Probability distribution of 1-minute events where no cloud base (C1) or no cloud base/vertical visibility (C1+VV) was reported by the CHM15k and LD40 as function of the PWS precipitation intensity. The 5% threshold (~95% for "cloud base reported") is indicated in magenta.

Aerosol layers

The importance of adequate observing capabilities for aerosol layers was discussed in section 2. Hence, in addition to the verification of the new ceilometers for cloud information, this has also been part of the tests at the CESAR site. For a number of cases, the Aerosol Optical Depth (AOD) was estimated from a collocated sunphotometer. Visual detectability of the layer in graphical output from the CHM15k was investigated and compared to Raman lidar measurements. Figure 8 presents a layer with boundary layer aerosol in Cabauw on 8 November 2014. The layer between the surface and about 1.5 km is clearly visible in the CHM15k data and dynamical processes can be observed. The optical depth of the layer between 0 and 1.5 km altitude, estimated from the Raman lidar measurements at 20:19 UTC, is about 0.075. The AERONET sunphotometer data just before noon UTC when it the sky is clear is about 0.1. The CHM15k shows the aerosol layer in great detail and can be visually recognized, as is the requirement. From several cases experienced during the CAT, it can be judged that aerosol layers with AOD of about 0.1 in a vertical extent of about 1 km can be observed in great detail in the lower 2-3 km of the atmosphere. Lofted aerosol layers could also be observed and visually recognized in the colour plots.

Note that for case presented in Figure 8 the colour scales were presented on a linear scale for the data, while the colour scale itself is designed to show structure (i.e. intensity variations) at various levels of intensity. This colour scale seems appropriate for graphically representing aerosol layers and clouds at the same time. Using these graphical representations, the colours are indicative of aerosol loads. One has to bear in mind that the signal calibration of the CHM15k units as well as the settings of the plotting parameters is part of this, so long term stability and inter-comparability cannot be guaranteed. However, between periods of revision, an expert could judge that an aerosol load is ‘low’ or ‘high’.

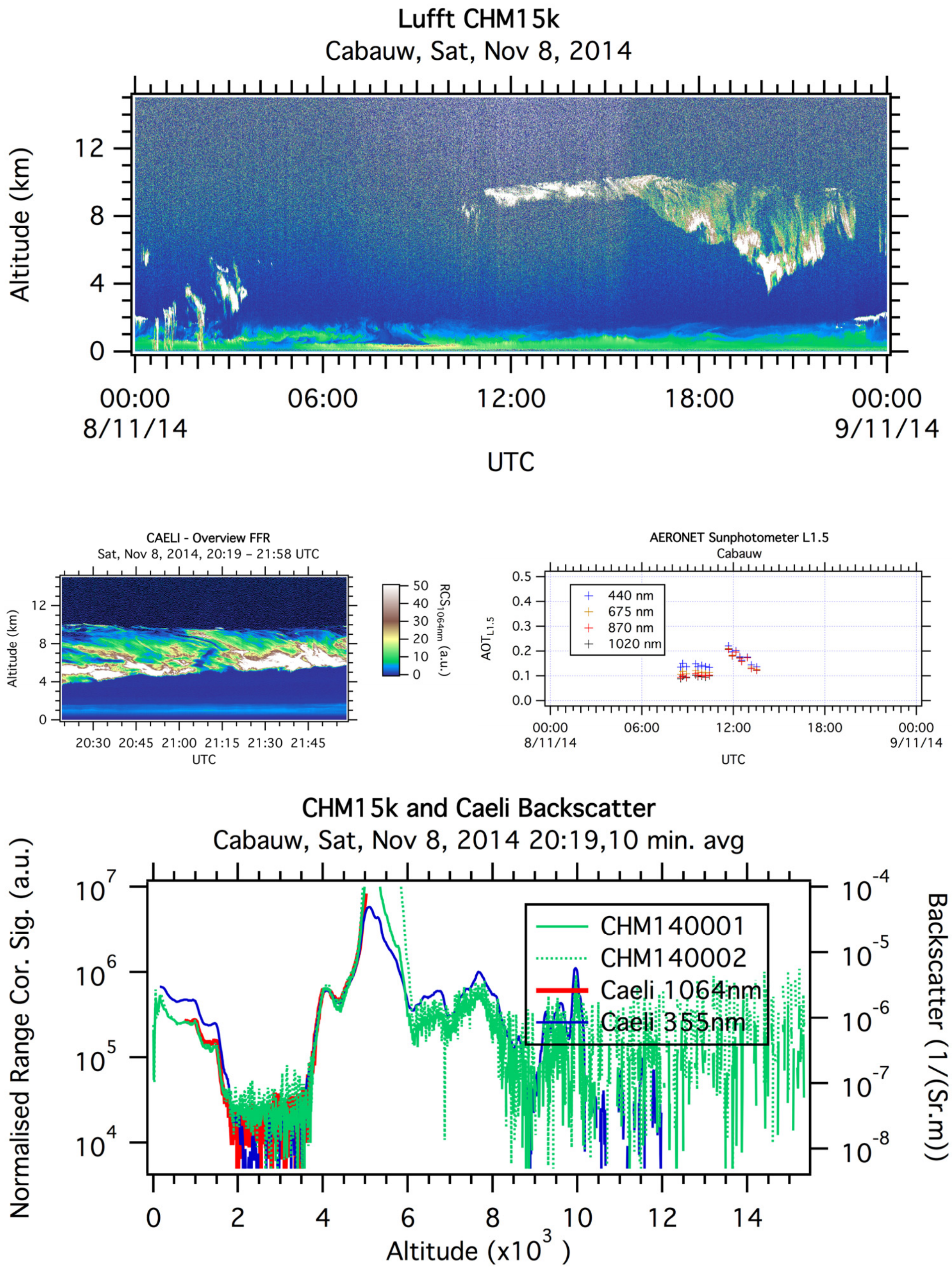

Figure 8. Overview of backscatter from CHM15k (top) for 8 November 2014 between 0 UTC and 24 UTC, Caeli for that day between 20:19 UTC and 21:58 UTC (middle left) and the AERONET aerosol optical depth (AOD) (middle right). The backscatter profiles from both instruments are shown in the bottom panel.

4. Estimated impact on KNMI observation reports

The cases presented for cloudy conditions in section 3 suggest that large impact may be expected on the operational cloud reports generated by KNMI for synoptic and aeronautical purposes, during the transition from the LD40 to CHM15k. The increased sensitivity to high cirrus clouds will significantly affect the observed cloud amount. On the other hand, the lower cloud base reported by the CHM15k will have impact on the characteristics for cloud base and ceiling height (i.e. the height of the lowest cloud layer with a cloud amount of at least 5 octa). This is the most critical cloud parameter for aviation.

A first assessment of the impact is made by processing the cloud base data from the LD40 and CHM15k sensors at Cabauw with the cloud algorithm for both synoptic and aeronautical purposes over the entire period of the acceptance test. This results in 16,272 10-minute intervals (113 days) with a collocated observation for cloud amount and cloud base height. Table 3 shows the contingency table obtained for the mutual comparison between both instruments for 10-minute total cloud cover obtained with the cloud algorithm in use for (AUTO)METAR. The green cells indicate the cases with exactly identical cloud cover, whereas the yellow and white cells indicate the cases within ±1 and ±2 reporting classes, respectively. The relative occurrences presented for Band0, Band1 and Band2 at the bottom of the table show that the reports of the CHM15k and LD40 agree within 0, ±1 and ±2 octa for respectively 73, 85 and 87% of the time. The scores for Misses (orange) and False alarms (light blue) also show that for 13% of the time differences in total cloud cover between the sensors are more than 4 octa. This is primarily caused by the increased detection capability of the CHM15k for high, relatively optically thin, clouds, as illustrated in Figure 6 for the early morning of 31 October. CHM15k's enhanced detection capabilities for these clouds results in a high relative occurrence in the light blue ('false alarm') cells in the upper right corner of the table: 11.8%. Of course, this has a significant effect on the total cloud cover observed for the entire test period. The average difference in total cloud cover <Δn> amounts to 0.72, which corresponds to roughly 10% more cloud cover reported by the CHM15k when considering the entire vertical range. Note that the results shown here are valid for the aeronautical cloud algorithm, but comparable numbers can be derived for the synoptic version of the cloud algorithm (see Table 5 for the complete overview).

Table 3. Contingency table of 10-minute total cloud cover reported by the aeronautical cloud algorithm, for the CHM15k and LD40 in Cabauw (28 September 2014-18 January 2015).

Total cloud cover (n in okta)													
	CHM15k →												
LD40 ↓	*NA*	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*Sum*	*<n>*
NA	1	32	20	9	9	7	11	8	20	99	0	216	
0	11	1388	75	35	46	64	50	46	72	520	0	2307	2.50
1	5	241	161	20	11	22	11	21	46	288	0	826	3.81
2	2	19	53	42	16	11	7	4	13	151	0	318	5.02
3	3	9	22	45	40	20	7	9	17	134	0	306	5.25
4	0	9	5	20	43	60	27	11	16	183	0	374	5.86
5	1	3	5	5	16	40	34	26	20	164	0	314	6.39
6	4	4	1	2	1	9	38	54	45	201	0	359	6.99
7	11	3	8	4	8	12	10	54	294	1041	0	1445	7.56
8	38	14	9	4	3	9	8	13	198	9511	0	9807	7.95
9	0	0	0	0	0	0	0	0	0	0	0	0	
Sum	76	1722	359	186	193	254	203	246	741	12292	0	16272	
<n>		0.30	1.51	2.35	2.72	3.05	3.57	4.35	5.82	7.15			
Band0 = 72.5%		Band1 = 84.9%		Band2 = 87.4%		<Δn> = 0.72		<|Δn|> = 0.91		Miss = 0.8%		False = 11.8%	

Table 4. Similar to Table 3, but for the mutual comparison of the ceiling height reported by the aeronautical cloud algorithm.

Ceiling (h in height class)													
	CHM15k →												
LD40 ↓	*No Ceil*	*<100ft*	*<200ft*	*<300ft*	*<500ft*	*<1000ft*	*<1500ft*					*Sum*	*<h>*
No Ceil	12354	6	5	2	2	8	140	0	0	0	0	12517	
<100ft	9	145	0	0	0	0	0	0	0	0	0	154	0.00
<200ft	0	21	6	0	0	0	0	0	0	0	0	27	0.22
<300ft	0	12	117	2	0	0	0	0	0	0	0	131	0.92
<500ft	22	4	137	144	148	31	1	0	0	0	0	487	2.15
<1000ft	94	3	6	7	303	1177	121	0	0	0	0	1711	3.86
<1500ft	152	3	0	0	5	296	789	0	0	0	0	1245	4.71
	0	0	0	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	0	0	0	0	
Sum	12631	194	271	155	458	1512	1051	0	0	0	0	16272	
<h>		0.45	2.54	3.03	3.69	4.18	4.86						
Band0 = 65.2%		Band1 = 94.9%		Band2 = 99.5%		<Δh> = -0.32		<|Δh|> = 0.41		Miss = 0.0%		False = 0.5%	

Next, Table 4 presents a very similar contingency table but now for the evaluation of 10-minute ceiling height. The ceiling classes used are those relevant for SPECIAL reports in the Netherlands, i.e. 0-100, 100-200, 200-300, 300-500, 500-1000 and 1000-1500 ft. Full agreement in ceiling height category is only found in 65% due to the large number of cases that are omitted where both agree that the ceiling is above 1500ft (N=12,354). Together with the adjacent classes (Band 1) the score is 95%. It is evident that the CHM15k often reports a ceiling height which is 1 class (~25% of cases) or 2 classes (~5% of cases) lower than the LD40. The opposite is very rare. This is not surprising given the systematic differences in cloud base height between both instruments. Further investigation on the effect of the lower cloud base on the reported ceiling and its possible impact on operations still has to be finished.

Summarized results for AUTO SYNOP and AUTO METAR

To summarize, an overview of the intercomparison for four relevant cloud parameters generated by the cloud algorithm in use at KNMI is provided in Table 5. All scores are calculated for the entire period of the Ceilometer Acceptance Test at the CESAR site, 28 September 2014-18 January 2015. Because the cloud cover of middle/low clouds is only relevant for synoptic purposes ("synop"), and the ceiling height for aeronautical purposes ("metar"), the number of entries for those variables is only limited to those selections of data. Be aware that none of the instruments can be considered as a reference; the results only provide information on the differences between both types of ceilometers.

- Large (positive) impact is expected for the detection of high clouds, such as cirrus. This was an important shortcoming of the LD40. Generally, the CHM15k reports approximately 10% (<Δn> =+0.7) more cloud cover for the 4 months of testing. T In case only the low and middle clouds, up to 15,000 ft or 4,500 m, are considered, the total cloud cover reported by the CHM15k is only 2% (<Δn> =+0.1) higher. Hence, the largest benefit for cloud detection is found above that limit.
- The systematic difference in cloud base height between CHM15k and LD40 becomes clear from the scores for ceiling height. For the considered range (0-1,500 ft) <Δh> is close to -0.3. The classes in use for cloud base height are, on average, too large to see the effect on <Δh>.
- The two collocated CHM15k test units at Cabauw show good instrument-to-instrument comparability. The Band0,1&2 scores for one of the CHMs versus the LD40 are all within 1% of the other CHM for all selections. Consequently, the scores for mutual comparisons with "chm1-chm2" are fairly high compared to those for two collocated LD40's (not shown here).

Table 5. The scores of the intercomparison between CHM15k and LD40 for (i) total cloud cover, (ii) cloud base height, (iii) cloud cover for low and middle clouds, <4,500 m and (iv) ceiling height for the CAT period at the CESAR site (113 days, 16,272 10-minute intervals). The two different versions of the cloud algorithm are indicated by metar/synop. Note that the results of two CHM15k instruments are included (chm1 and chm2).

Total cloud cover (nc)								
Selection	**N**	**Band0**	**Band1**	**Band2**	**Miss**	**False**	**<Δn>**	**<|Δn|>**
metar-ld40-chm1-v0733	16272	72.5%	84.9%	87.4%	0.8%	11.8%	0.72	0.91
metar-ld40-chm2-v0733	16272	71.5%	84.5%	87.1%	0.8%	12.1%	0.73	0.93
metar-chm1-chm2-v0733	16272	91.9%	97.0%	98.0%	0.9%	1.1%	0.01	0.16
synop-ld40-chm1-v0733	16272	67.9%	83.1%	87.2%	0.7%	12.1%	0.71	0.90
synop-ld40-chm2-v0733	16272	67.0%	82.9%	86.9%	0.7%	12.4%	0.72	0.92
synop-chm1-chm2-v0733	16272	89.3%	97.4%	98.7%	0.6%	0.7%	0.01	0.17
Cloud base height (hc)								
Selection	**N**	**Band0**	**Band1**	**Band2**	**Miss**	**False**	**<Δh>**	**<|Δh|>**
metar-ld40-chm1-v0733	16272	79.1%	94.5%	97.1%	2.3%	0.6%	-0.01	0.33
metar-ld40-chm1-v0733	16272	79.1%	94.5%	97.1%	2.3%	0.6%	-0.01	0.33
metar-ld40-chm1-v0733	16272	79.1%	94.5%	97.1%	2.3%	0.6%	-0.01	0.33
synop-ld40-chm1-v0733	16272	78.1%	94.2%	97.1%	2.3%	0.6%	-0.01	0.34
synop-ld40-chm2-v0733	16272	77.8%	94.1%	96.8%	2.5%	0.7%	0.00	0.36
synop-chm1-chm2-v0733	16272	93.0%	98.3%	98.8%	0.6%	0.5%	0.01	0.12
Cloud cover low and middle clouds (nhc)								
Selection	**N**	**Band0**	**Band1**	**Band2**	**Miss**	**False**	**<Δn>**	**<|Δn|>**
synop-ld40-chm1-v0733	16272	80.6%	94.2%	96.3%	0.9%	2.9%	0.11	0.38
synop-ld40-chm2-v0733	16272	79.2%	93.2%	95.5%	1.1%	3.4%	0.12	0.43
synop-chm1-chm2-v0733	16272	92.7%	98.8%	99.2%	0.3%	0.5%	0.01	0.12
Ceiling height								
Selection	**N**	**Band0**	**Band1**	**Band2**	**Miss**	**False**	**<Δh>**	**<|Δh|>**
metar-ld40-chm1-v0733	16272	65.2%	94.9%	99.5%	0.0%	0.5%	-0.32	0.41
metar-ld40-chm2-v0733	16272	66.1%	94.7%	99.5%	0.0%	0.5%	-0.35	0.40
metar-chm1-chm2-v0733	16272	89.0%	99.7%	100.0%	0.0%	0.0%	-0.03	0.11

5. Conclusions and Outlook

The Lufft CHM15k ceilometer has been selected by KNMI as the successor of the Vaisala LD40 in the Dutch surface observation network. In addition to the continuation of 24/7 accurate information on cloud height and cloud cover for various applications, it is intended to implement the new network of CHM15k's partly as aerosol profilers in the ALC network of E-PROFILE.

The new ceilometer network brings some great new opportunities. Benefits of the new instruments are primarily seen in the detection of high clouds and the sensitivity to aerosol layers, where the CHM15k clearly outperforms the LD40. Nevertheless, the transition to the new sensor also introduces some differences. This mainly concerns cloud base observations relevant for aeronautical reports, typically in the lowest 5,000 ft. To verify the performance of the CHM15k against the requirements for cloud observations, a four month acceptance test was organized in winter 2014/2015 at the Cabauw Experimental Site for Atmospheric Research or CESAR. This paper discusses the comparison between CHM15k and reference instruments (Caeli Raman lidar, ALS450 UV lidar, visibility sensors) for specific meteorological conditions, focusing on the performance level in low clouds and detection in precipitation and sensitivity to high clouds and aerosol layers. A first assessment of the impact on KNMI observational products containing cloud information has been made by processing the raw cloud base data by the cloud algorithm in use at KNMI for synoptic and aeronautical purposes.

The acceptance test at the CESAR site showed that the Lufft CHM15k meets the KNMI requirements for cloud observations, as far as they could be verified. The improved sensitivity of the instrument to high clouds has significant impact on the observed total cloud amount. For the 113 days in the comparison, the CHM15k observed on average 10% more clouds than the LD40. When only low and middle clouds (<4,500 m) are considered, the difference is only 2%. On the other hand, the lower cloud base reported by the CHM15k will have impact on the characteristics for cloud base and ceiling height (i.e. the height of the lowest cloud layer with a cloud amount of at least 5 octa). The difference in cloud base height between CHM15k and LD40 was on average 35-45 m (115-150 ft). This is in line with earlier ceilometer comparisons. The lack of a clear WMO definition for cloud (and thus cloud base) makes it difficult to judge the results of the comparison.

Outlook

In August 2016, 14 CHM15k ceilometers are operational at automatic weather stations in the Dutch observation network. These instruments already deliver 24/7 real time information on cloud height and cloud amount to end users. However, still some further investigation is needed to be sure that a smooth transition will occur for the sites where the ceilometer is mainly used for aeronautical purposes. Based on the findings from the Ceilometer Acceptance Test, an evaluation of the new sensor by the human observer at Schiphol airport was conducted from January-April 2016. This evaluation confirmed the earlier findings, but also showed problems regarding cloud base detection in precipitation. The difference between detected cloud bases from LD40 and CHM15k instruments are mainly caused by different algorithms and thresholds for detecting cloud bases.

Together with the manufacturer, the following steps are now taken:

- Improved overlap functions: For some instruments, effects of the from the manufacturer pre-defined overlap correction in the lowest altitude range (typically 0-200 m) have been found. It is expected that finetuning of the correction function will improve the low cloud detection and reduce the instrument-to-instrument variability.
- Tilting experiments at 5-15°: A vertically pointed ceilometer will measure the light reflected back by the flattened base of the rain drops. The sensor will detect less light coming back from precipitation when it is tilted under a small angle. This may improve the detection performance in precipitation.

Furthermore, 2 years of parallel measurements have already started at three sites covering different meteorological conditions. These measurements provide the opportunity to assess the impact of the transition for climatological time series (mainly cloud cover) and enable further investigation of the impact on cloud information generated for the (AUTO)METAR system in the Netherlands.

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