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Detection of Fog and Low Cloud Boundaries with Ground-Based Remote Sensing Systems

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ABSTRACT

The performance of the boundary determination of fog and low stratiform cloud layers with data from a frequency-modulated continuous-wave (FMCW) cloud radar and a Vaisala ceilometer is assessed. During wintertime stable episodes, fog and low stratiform cloud layers often occur in the Swiss Plateau, where the aerological station of Payerne, Switzerland, is located. During the international COST 720 Temperature, Humidity, and Cloud (TUC) profiling experiment in winter 2003/04, both a cloud radar and a ceilometer were operated in parallel, among other profiling instruments. Human eye observations ("synops") and temperature and humidity profiles from radiosoundings were used as reference for the validation. In addition, two case studies were chosen to demonstrate the possibilities and limitations of such ground-based remote sensing systems in determining low clouds. In these case studies the cloud boundaries determined by ceilometer and cloud radar were furthermore compared with wind profiler signal-to-noise ratio time series. Under dry conditions, cloud-base and -top detection was possible in 59% and 69% of the cases for low stratus clouds and fog situations, respectively. When cases with any form of precipitation were included, performances were reduced with detection rates of 41% and 63%, respectively. The combination of ceilometer and cloud radar has the potential for providing the base and top of a cloud layer with optimal efficiency in the continuous operational mode. The cloud-top height determination by the cloud radar was compared with cloud-top heights detected using radiosounding humidity profiles. The average height difference between the radiosounding and cloud radar determination of the cloud upper boundary is 53 ± 32 m.

1. Introduction

Precise forecasting of the formation, evolution, and erosion of fog and low stratus is a major challenge for meteorology, especially in complex topography. One of the goals of the COST 720 Temperature, Humidity, and Cloud (TUC) winter experiment undertaken in Switzerland in 2003/04 (Ruffieux et al. 2006) was to provide a dataset for determining the base and top of low clouds using a simple combination of ground-based remote sensing instruments.

Frequent and detailed information about the meteorological conditions are important for weather forecasters, climate studies, and aviation control. One of the high priority duties of observers is the description of the evolution of clouds, especially within the planetary boundary layer. However, automatic weather reports are becoming important because human observations are becoming more difficult to organize, especially dur-

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ing nighttime (Aviolat et al. 1998). The cloud amount (sky coverage in octas) can be automatically estimated using for example incoming longwave radiation and surface parameters (Dürr and Philipona 2004). However, this method does not include information on cloud-base and -top height, and such measurements are crucial for a variety of applications. Cloud-base and -top heights are important in order to describe the impact of clouds in a changing climate (Ramanathan et al. 1989), and there is a general need for improvement of automatic cloud observation at weather stations and continuous cloud description for climatological issues. For aviation and traffic, such systems improve the detection of fog and low stratus, but the prediction of their appearance and dispersion is still an ongoing challenge. High-resolution observations of the cloud and fog boundaries can help modelers verify and improve local fog prediction models or numerical weather prediction/climate models (e.g., the Baltex Bridge Campaign; Crewell et al. 2004). In response to such demands, long-term and high-resolution cloud-base and -top height measurements are performed at some meteorological stations [e.g., at Chilbolton Observatory (United Kingdom), at the Site Instrumental de Recherche par Télédétection Atmosphérique (SIRTA) in Palaiseau (France), and in Cabauw (Netherlands), where long-term cloud measurement schemes were developed as part of the Cloudnet project (Illingworth et al. 2007)].

During wintertime stable episodes, fog and low stratiform cloud layers often occur over the Swiss Plateau, a relatively flat region between the Jura Mountains to the north-northwest (1000–1500 MSL) and the Alps to the south-southeast (2000–2400 MSL). The aerological station of Payerne, Switzerland, is located in this area, and was the site of the international COST 720 TUC profiling experiment (Ruffieux et al. 2006). This experiment, which took place during three months in winter 2003–04, was mainly designed to test ground-based temperature and humidity profiling systems and cloud detection instruments. Among other instruments, a Vaisala CT25K ceilometer and a 78-GHz frequency-modulated continuous-wave (FMCW) cloud radar were installed and operated at the measurement site from mid-November 2003 to mid-February 2004.

In this paper a method to determine fog and low stratiform cloud layers from cloud radar and ceilometer data is described. The efficacy of the combination of the two systems during the winter 3-month period is assessed. In section 2, the instruments and the method of the determination of cloud or fog base and top are described as well as the data used for validation of the results (human eye observations, radiosoundings, and, as an additional confirmation, wind profiler data). In section 3, the performance of the method is assessed first with the help of two selected cases and then over the entire campaign. Section 4 presents a discussion of the performance of the studied remote sensing instruments for low cloud and fog detection and compares our results with previous studies. Our concluding remarks are given in section 5.

2. Instrumentation and method

The aerological station of Payerne is an official World Meteorological Organization (WMO) site for synoptic weather observations, including cloud information, which are performed every 3 h, starting at 0000 UTC. It is also a site for balloon-borne meteorological radiosoundings including pressure, temperature, and humidity profiling twice a day at 1200 and 0000 UTC (launched at 1100 and 2300 UTC respectively). (Radiosondes are launched an hour before the officially reported time, in order to account for the balloon ascent. In the rest of the paper the official time will be reported, but comparison will be made with the data measured at launching time.) In addition, a wind profiler is operated continuously. During the TUC campaign, several additional radiosoundings were performed with different types of radiosonde. A large set of additional remote sensing instruments were operated, including a ceilometer, a cloud radar, as well as microwave radiometers profiling temperature and humidity, and other instruments. The ceilometer and cloud radar were used in combination for the detection of fog and stratiform low clouds, and for determining their lower and upper boundaries. To estimate the detection efficiency, human eye observations were used as a reference. The determination of the upper boundary by the cloud radar was compared with a determination using radiosounding humidity profiles according to Wang et al. (1999). Technical details of the observation techniques used for this study are listed in Table 1 and described more precisely below.

Cloud-base height was determined with a commercially available Vaisala ceilometer CT25K, using the measured vertical visibility. This light detection and ranging (lidar) system sends out short, powerful laser pulses (905 nm) in the vertical direction. The reflection of light (backscatter) caused by aerosol, fog, mist, clouds, or precipitation is measured as the laser pulses traverse the atmosphere. The resulting backscatter profile (signal strength versus height) is processed to detect cloud-base height. The ceilometer can detect up to three cloud layers simultaneously and retrieve cloud heights every 30 s with a vertical resolution of 15 m up to 7.5 km above the ground. The minimum vertical vis-

TABLE 1. Observation techniques and instruments used for the study, operational at the meteorological station in Payerne, Switzerland (i.e., synop, radiosondes, wind profiler) and experimental for the TUC campaign (i.e., ceilometer and cloud radar).

Observation technique	Parameter	Time resolution	Height resolution	Lower limit	Upper limit	Field of view (vertical)	Manufacturer	References
Synop*	Cloud amount, type, height; visibility	3 h	30 m for low-level clouds	Ground	21 km	180°		Müller (1982)
FMCW cloud radar	Cloud-top height	30 s	15 m	50 m	8 km	0.8°	Rutherford Appleton Laboratory; UK	Nash et al. (2005)
CT25K ceilometer	Cloud-base height	30 s	15 m	15 m	7.57 km	~0.6 mrad	Vaisala, Finland	Kollias et al. (2004)
Radiosondes SRS 400, Snow White, RS80 A	Temperature, humidity, pressure	12 h	~15 m	20–30 m	34–35 km	Vertical profile	Meteolabor AG, Switzerland Vaisala, Finland	Richner (1999) Ruffieux et al. (2006)
LAP3000 1290-MHz wind profiler	Signal-to-noise ratio	30 s	42 m	158 m	1489 m	6°	Vaisala, Finland	Neff (1990)

* Human eye observations.

ibility that can be measured is 15 m (e.g., in case of fog). A disadvantage of this system is that high cirrus clouds can hardly be detected because they often occur above 7.5 km. This kind of system is widely used to detect cloud-base heights and cloud cover (e.g., at airports or within climate studies such as stratocumulus research in the southeast Pacific; Kollias et al. 2004).

The 78-GHz FMCW cloud radar, designed at the Rutherford Appleton Laboratory, retrieves backscatter information at a time interval of 30 s. It is sensitive to clouds and precipitation and was set up to measure up to 8 km above the ground with a vertical resolution of about 15 m. The FMCW radar has a transmitter power of approximately 120 mW. It transmits at a frequency of 78.2 GHz with a frequency modulation of approximately 10 MHz over a period of approximately 770 μs. In general cloud radars use two basic types of transmission: pulsed or FMCW. The most important benefit of the FMCW system in this application is that it can make measurements at a shorter range than pulsed systems, which are typically only measuring above 150 m. For the system operated in Payerne during TUC campaign, the lowest detected cloud-top height is 65 m and the minimum range for the detection of mist or fog is about 50 m above the radar. The radar was calibrated at the Chilbolton Observatory, United Kingdom, alongside the pulsed 35-GHz Copernicus cloud radar. The results from this calibration indicate that the sensitivity of the 78-GHz FMCW cloud radar is comparable to that of a modern pulsed cloud radar (Nash et al. 2005). It is still better to use a ceilometer to detect the cloud base of fog and low clouds, because such instruments are more efficient and precise for this task (Clothiaux et al. 2000). With a FMCW system, the vertical resolution is controlled by the quality of the system phase noise, the continuous-wave slew rate, and the sampling speed of the detected signal, while fast Fourier transform effects tend to place a limit on the minimum detection height. For a pulsed system the minimum height is predominantly determined by the length of the transmitted pulse, with no measurements possible below a height equivalent to the pulse duration. FMCW radars are also simpler and cheaper than pulsed cloud radars, the cost of a pulsed system being partly driven by the magnetron, which needs replacement after few thousand hours of operation.

A simple empirical method was applied to retrieve cloud-top height from the cloud radar (Ruffieux et al. 2006). An automatic search for the cloud-top signal level within a specified range was performed on each vertical profile recorded by the FMCW cloud radar. Provided the maximum signal in a profile was higher than a threshold value (indicating the presence of cloud), the height of the maximum radar reflectivity was registered. A second threshold value was specified for determining the cloud top. The height at which the reflectivity decreased below this second threshold value was taken as the cloud top. The current configuration allowed the detection of the upper boundary for one cloud layer only.

Human eye observations ("synop") were used to estimate the efficiency of cloud detection by the ceilometer and cloud radar combination. Cloud cover, type, and base height are reported for the three main cloud levels (low, middle, and high clouds) as well as the ground visibility (Müller 1982). These human eye observations are generally of excellent quality and give regular and important information to meteorologists about the state of the sky, the meteorological conditions (fog, snow, rain, etc.), and the visibility. A known limitation is the restriction to the lowest cloud layer in the case of multilayer clouds with full sky coverage of the lowest layer. In addition, observations are difficult to perform during nighttime; they remain subjective and may vary from one observer to another. However, such observations are extremely reliable for verifying the presence or absence of low clouds or fog.

For our study, fog situations were defined as either fog being reported or mist with a code 9 for the parameter "total cloud cover" (sky not visible because of fog, snow, or other meteorological phenomenon). Situations with fog or stratus clouds in combination with other clouds or more than one cloud layer were discarded and just low-level stratus and fog situations with total sky coverage (8 octas) were selected. This allowed testing of the automatic detection of fog or stratus boundaries with the ceilometer and cloud radar in simple and clearly identified cases.

Three different radiosondes were used for humidity and temperature profiling during the TUC campaign. Operational radiosoundings were performed with the SRS 400 (Richner 1999; Ruffieux et al. 2006). In addition, radiosoundings with the Snow White hygrometer (Miloshevic et al. 2006) were available for some of the studied cloudy situations, and one case was detected concurrently with a sounding using the Vaisala RS80A (Verver et al. 2006). The radiosoundings include measurements of the temperature and relative humidity from the ground to about 35 km (relative humidity profiles up to 12 km). The vertical resolution in the lower atmosphere is about 15 m (Table 1). Cloud layers were identified as regions with a relative humidity above a given threshold. Cloud upper boundaries were determined by finding sudden negative relative humidity jumps (hydrolapse; Wang et al. 1999). The thresholds chosen for this study depend on the radiosondes used for the profile, the minimum being 93% for the SRS 400.

Studies on specific cases also used information from wind profiler signal-to-noise ratio (Gossard et al. 1982) time series measured concurrently. The wind profiler is used to observe the vertical profile of wind direction and velocity. It sends a signal at 1290 MHz when operated at low mode, the vertical resolution is 42 m, the first layer of detection is at 158 m, and the maximum height range is 1489 m AGL. Information on the cloud upper boundaries can be derived from the wind profiler signal because of the strong gradients at the cloud top: the backscattered signal from the wind profilers is directly proportional to the refractive-index structure function parameter C_n^2, and there is a close relationship between refractive-index gradient with height and the distribution of Bragg backscatter power (Gossard et al. 1999). The refractive-index structure function parameter C_n^2 profile depends mainly on temperature and humidity gradients in the atmosphere as well as turbulence. At the top of a well-defined stratus layer, the strong change in humidity and temperature with height as well as a possible increase of turbulence initiated by wind shear between the two distinct layers can be used as information to detect it. In the presence of precipitation, however, this layer is often masked by the strong return from large falling particles.

3. Automatic detection of cloud base and top

a. Case studies

Two single-day case studies are chosen to demonstrate the possibilities and limitations of such ground-based remote sensing systems in determining low clouds. The first case is typical of a day with low stratus changing with time but remaining present the entire day. The second case represents a more complex situation with a thick fog layer developing during the afternoon.

The first example illustrates a day with an excellent determination of the stratus (Fig. 1). On 9 December 2003, a low-level stratus cloud layer was reported in the synops at 0000, 0900, 1200, 1500, 1800, and 2100 UTC and at 0000 UTC the following day. At 0300 and 0600 UTC, fog with visibility below 1 km was observed. In this situation a good determination of the fog and low stratiform cloud situation was possible over 24 h. A few measurement points of the cloud radar (cloud top) retrieval are detected crossing or going below the ceilometer (cloud base) signal (after 0900 UTC and between 1200 and 1800 UTC). This may be explained either by the instruments pointing in slightly different directions,

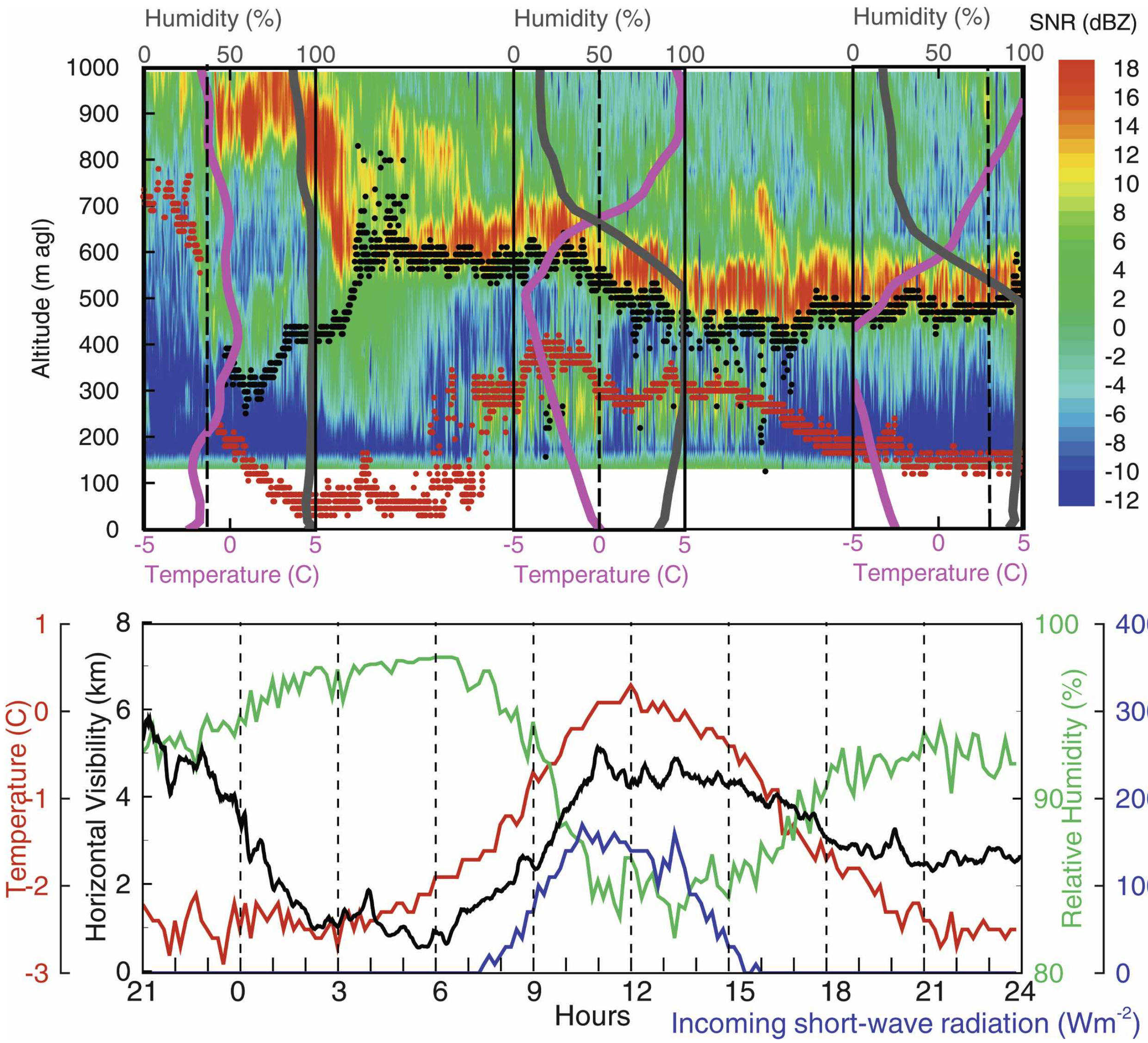

FIG. 1. (top) Time series of cloud base (ceilometer, red dots), cloud top (cloud radar, black dots), and 2D color time series of wind profiler signal-to-noise ratio on 9 December 2003 starting at 2100 UTC 8 Dec 2003. The three rectangles with gray and purple lines correspond to the profiles measured with the radiosounding at 1100 and 2300 UTC (dashed line = time of sounding, purple line = temperature with a horizontal scale of 10 K, and green line = humidity with a horizontal scale of 100%). (bottom) Time series of surface relative humidity (green), temperature (red), incoming shortwave radiation (blue), and horizontal visibility (black).

or by a height measurement error in one or both instruments.

The determination of cloud base and top was compared with the temperature and humidity profiles measured with radiosoundings from Payerne at 0000 UTC, at 1200 UTC with a Snow White sensor, and at 0000 UTC 8 December 2003 (see the three boxes in Fig. 1, top panel). At 1200 and 0000 UTC 9 December there is an excellent agreement between the top of the cloud as detected with the cloud radar and the bottom of the thermal inversion, indicated by a sharp decrease of the humidity (gray line), and temperature (magenta line) starting to increase with altitude. Confirmation of the cloud-top determination is also obtained by overlaying the data with the Payerne wind profiler signal-to-noise ratio profiles (colored background in Fig. 1): the intensity of the returned signal depends mainly on humidity gradients and turbulence, producing an intensity maximum just above the cloud layer (Dibbern et al. 2003). On the other hand, when comparing with the first radiosonde profile (0000 UTC 8 December 2003), or with the wind profiler SNR between 2100 and 0300 UTC, the cloud radar seems to give an erroneous cloud top height. Close inspection of the information provided in the top panel of Fig. 1 reveals the reason for this discrepancy. First, between 0000 and 0300 UTC, the wind profiler shows higher SNR at two altitudes separated by one region of lower SNR. This may indicate multiple layers in the first 1000 m, of which the cloud radar would have picked the lowest one. Second, the temperature inversion was at 1500 m AGL (not shown), which is out of the limit chosen for the cloud radar top height detection algorithm (1200 m, the study focuses on fog and low clouds). Finally, the ceilometer shows a transition period from a higher cloud layer to well detected low stratus cloud between 2100 and 0000 UTC. Thus, it can be assumed that there was a transition period until 0400 UTC from a multilayer cloud situation in the lower troposphere to a well-defined low stratus cloud situation for the rest of the day.

Surface information (Fig. 1 bottom) is consistent with a day constantly overcast with a low cloud layer or fog. The relative humidity (green) was high all day long (>80%), the temperature (red) shows only a modest increase during daytime, and the incoming shortwave radiation (global radiation, blue) is very low even at noon. Similarly, the horizontal visibility was low all day corresponding well with the low visibilities reported in the synops, even though the correspondence is not perfect (synops indicate >10 km of visibility at 0 UTC, then visibility <2 km until 1500 UTC, then again >10 km).

The case of 19 November 2003 is an example where the determination of the fog base and top was not possible for the whole day with the two systems running in parallel. During this day, fog and cloudy conditions alternated. Fog was reported in the synops at 0600, 1500, 1800, and 2100 UTC, as well as 0000 UTC. Figure 2 displays the data retrieved from ceilometer and cloud radar for that day. The cloud radar was unable to detect the fog top corresponding to observations at 1800, 2100, and 0000 UTC, but the fog base was well detected with the ceilometer. At 0600 UTC the cloud top was not detected, but the cloud base and top of a layer of fog was detected during the previous hour, while at noon, the base and top of a cloud layer was detected by the ceilometer and cloud radar, even though the observation at that time did not report fog. In the period between 1000 and 1500 UTC conditions were unstable with fog setting and clearing, which explains the apparently contradictory results. Radiosounding temperature and humidity profiles recorded at 0000, 1200, and 0000 UTC the next day are consistent with the reported intermittent fog situations. The two radiosoundings at 0000 UTC show a high relative humidity (gray line) with a sudden decrease between 200 and 400 m AGL. At 1200 UTC, the humidity is high but not as much as expected in a foggy situation, and the drop at around 300 m is less marked. The humidity at this time may have been too low for a dense fog to set up, and fog and mist episodes alternated. This explains the fog detection by the ceilometer and cloud radar while the observation at noon did not report fog, and the relative humidity from the profile being below the selected threshold. Wind profiler signal-to-noise ratio profiles also show patchy layers that indicate variable hydrolapse and temperature inversion height and strength. This is likely to be associated with alternate presence and absence of fog or cloud. The surface information (Fig. 2 bottom) is consistent with such a situation, as well. The relative humidity (green) was above 80% all day and 100% when fog was reported. The horizontal visibility varied between 0 and 8 km. The very low visibility observed at 1800, 2100, and 0000 UTC also confirms the presence of fog. Temperature (red) and shortwave radiation (global radiation, blue) are as expected for such conditions.

The alternated fog and cloud conditions are confirmed by multiple observations and can explain the relatively poor performance of the cloud radar particularly when fog was present. Possible explanations are the droplets being too small to be detected by the radar or the presence of water on the reception dish of the system (the dish which was not heated, and the relative humidity being 100% during that period, it is highly probable that water condensed on the instrument). Finally, it is possible that in some cases, the top of the fog layer was below the lower detection height of the cloud radar.

b. *Automatic detection of cloud-base and -top performances during the TUC experiment*

During the TUC campaign, human eye reports stated 200 stratus cloud or fog situations, divided into 110 stratus cloud and 90 fog observations (Table 2). The efficiency of the automatic cloud detection with the ceilometer and cloud radar was evaluated using only the measurements performed concurrently with the operational synops. Since synop are performed every 3 h and cloud situations can evolve significantly in a much shorter duration, the cases can be considered independent of each other. The ceilometer was operational for all cases and the FMCW radar for 143 of them. For the rest of this section only cases where both remote sensing systems were in operation (143 cases) are analyzed. This consists of 83 cases of low stratus clouds, including 25 cases with precipitation, and 60 fog cases including 9 cases with precipitation.

For the stratus situations, the ceilometer retrieved cloud bases in 89% of the situations (74 of 83 cases, see

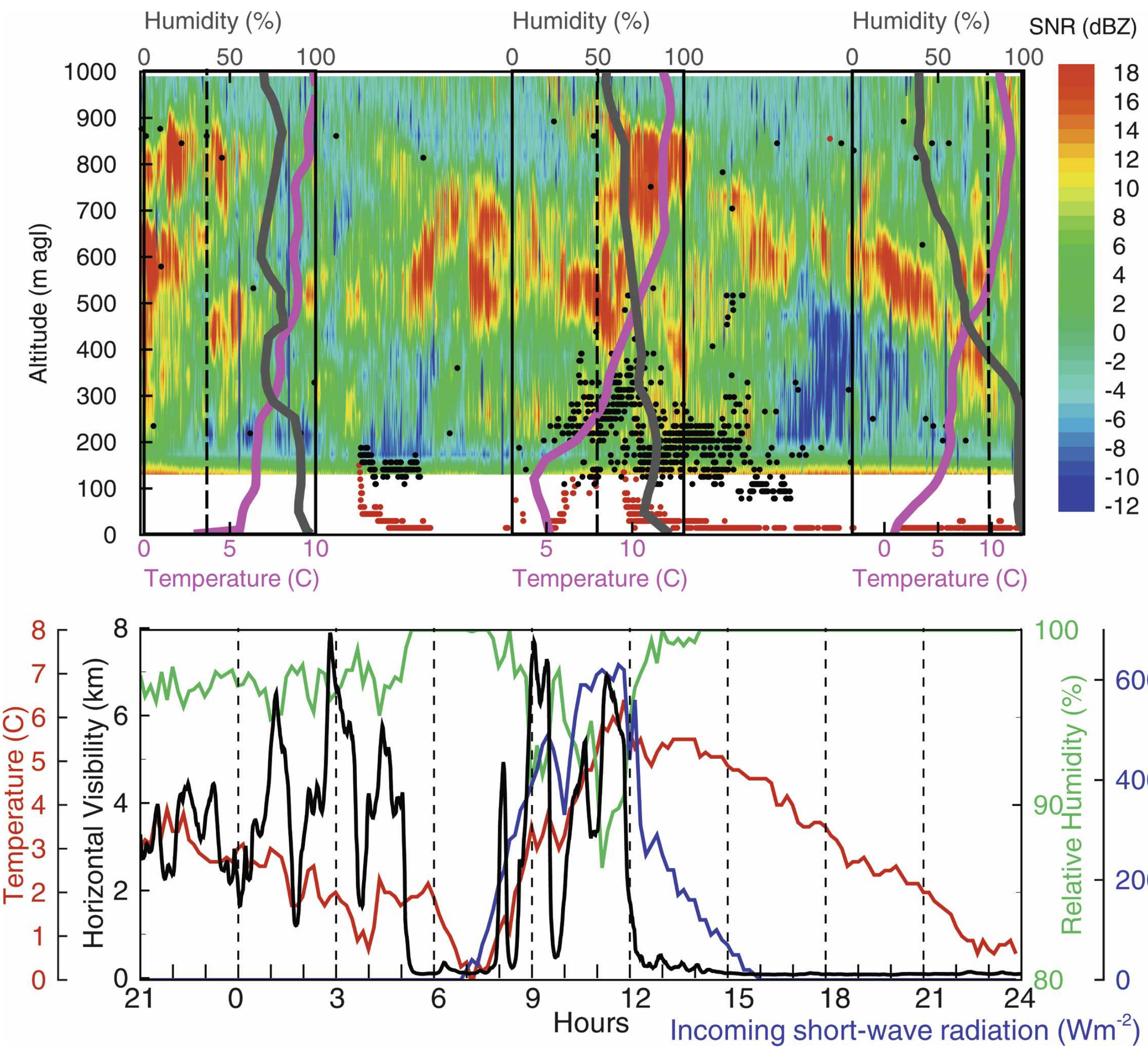

FIG. 2. As in Fig. 1, but for 19 Nov 2003.

Table 2 and Fig. 3), while the cloud radar retrieved the cloud top in 41% of the cases (34 out of 83). All the 34 latter cases were also in the 74 cases when cloud base was retrieved by the ceilometer. Furthermore, it was not possible to retrieve cloud top with the FMCW radar in the low stratus cloud situations with precipitation, and consequently all 34 cases were dry low stratus situations. Considering only dry situations, the ceilometer

TABLE 2. Rate of cloud-base and cloud-top detection, relative to the total observed situations for both systems operative during TUC in Payerne, Switzerland. The total observations correspond to the number of stratus or fog situations reported during the TUC campaign.

	Total observations	Cloud radar and ceilometer operative	Cloud radar (cloud top)	Ceilometer (cloud base)	Cloud radar and ceilometer simultaneous detection
Stratus all	110	83	34 (41%)	74 (89%)	34 (41%)
Stratus dry	79	58	34 (59%)	56 (97%)	34 (59%)
Fog all	90	60	38 (63%)	59 (98%)	38 (63%)
Fog dry	80	51	35 (69%)	50 (98%)	35 (69%)

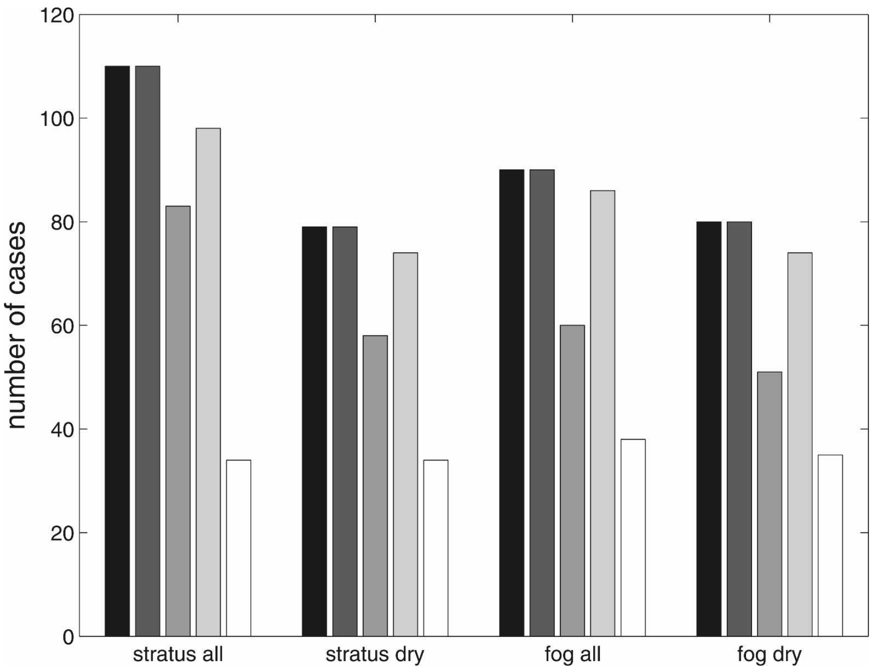

FIG. 3. Number of stratus cloud and fog cases detected at time of synop observations during the TUC campaign. Four groups describe all stratus cases, stratus cases without precipitation, all fog cases, and fog cases without precipitation. All cases detected by synop observation (black), ceilometer operative (dark gray), cloud radar operative (gray), ceilometer retrieval successful (light gray), and cloud radar retrieval successful (white).

retrieved the cloud base in 97% of the cases (56 out of 58), and the cloud radar also detected the cloud top in 59% of the cases.

In 59 of the 60 fog situations, the vertical visibility could be retrieved by the ceilometer (98%), leading to the detection of a lower boundary, while the cloud radar detected the cloud top in 63% of the situations (38 of 60 cases). In fog situations also, precipitation again made cloud-top detection with the cloud radar more difficult. Three situations with drizzle were detected by the cloud radar out of nine fog situations with precipitation. When cases with any form of precipitation are disregarded, the fog detection with both systems worked for 69% of the observed fog situations (35 of 51 cases).

In addition to assessing the detection efficiency, the height of the upper boundary determined by the cloud radar was also compared with the height of this boundary determined using humidity radiosounding profiles. During the TUC campaign humidity and temperature profiling radiosoundings were performed in some cases at 0300, 0600, 0900, 1500, 1800, and 2100 UTC in addition to the regular 0000 and 1200 UTC radiosoundings. Among the cases analyzed earlier for cloud detection efficiency, 25 radiosounding humidity profiles were measured concurrently with cases when the fog or low cloud upper boundary was detected by the cloud radar. For these cases, we compared the determination of the cloud radar at the time of sonde launching with the height determined using the humidity profile. Figure 4 shows the extent of the cloud as determined by the ceilometer and cloud radar for the 25 selected cases. It also shows the cloud-top determination using the information from the sounding humidity profile. The average difference between the radiosounding and cloud radar determination of the cloud upper boundary is 53 m (radiosounding–cloud radar). The standard deviation of the sample is 77 m, which leads to an estimate of a 95% confidence interval on the average of 32 m, using a Student's t test with 24 degrees of freedom (small sample test). Consequently, a positive bias of 53 ± 32 m exists between the radiosounding and cloud radar determination of the upper cloud boundary. Among the 25 selected cases, the cloud extent (cloud top from cloud radar and cloud bottom from ceilometer) varied from 50 to 585 m, while the cloud top as determined by the cloud radar varied from 110 to 1020 m (see Fig. 4).

4. Discussion

We first discuss the reasons limiting the efficiency of fog and low cloud detection by the ceilometer and

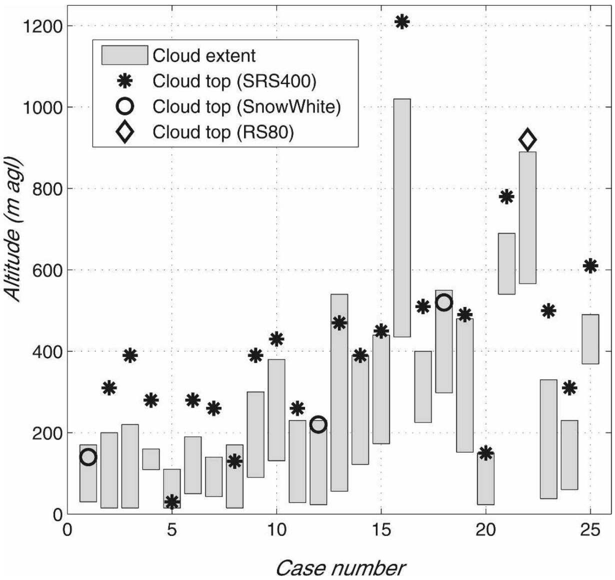

FIG. 4. Comparison of cloud extent (cloud base from ceilometer to cloud top from cloud radar) with determination of cloud top from radiosounding humidity profile (radiosoundings include three types of sondes: SRS400, SnowWhite, and RS80).

cloud radar, and then the quality of the cloud upper boundary determination by the cloud radar. Finally, the case studies are looked into, and our results are compared to other studies. Concerning the detection efficiency, the main limiting factor of the experiment was the availability of cloud radar data. The cloud radar used during the campaign was not an operational system, but a prototype, and was affected by problems typical of prototypes, limiting the data availability. Therefore some loss of data due to communication failure, changes of settings according to local conditions and other problems was inevitable. Considerable availability and performance improvements are expected with a new system currently under construction. These include improvement in sensitivity, a reduction in the occurrence of data artifacts, particularly when there are strong returns (e.g., in presence of precipitation), and a general improvement in the stability and reliability of operation. In other systems of comparable complexity (e.g., wind profilers or stratospheric ozone monitoring radiometer) operational mode data availability better then 95% is achieved (Engelbart et al. 2007). In the following discussion, the 143 situations with both remote sensing system operatives are considered.

The ceilometer showed excellent efficiency as 98% of the fog situations and 89% of the low stratus situations could be determined. Restricting the stratus cases to situations without precipitation allows an overall detection efficiency >95%. The lower efficiency in case of precipitation is explained by the laser light of the instrument being scattered back by the hydrometeors.

In the case of the FMCW radar, precipitation (snow and rain) produces artifacts in the reflectivity signal. It was thus not possible to determine the cloud top when precipitations occurred, using the algorithm for cloud-top detection. However, under fog conditions with drizzle, the determination of the top of the cloud was still possible. Boers et al. (2000) mention similar limitations with precipitation for the Delft Atmospheric Research Radar (DARR), which is an FMCW radar operating at 3.315 GHz with a range of 15 m. In the current study, about 60% of the stratus cloud tops and 70% of the fog tops could be determined under dry (without precipitation) conditions. In the remaining cases, the cloud top may sometimes have been outside the detection range of our algorithm, which was set to 1200 m AGL. Another possibility for cases when the FMCW cloud radar did not detect the cloud top in dry situations may be its lack of sensitivity to small droplets, or to saturation in the first range gates in the presence of very thin fog layers. Finally, further improvement of the cloud-top retrieval algorithm would probably result in better scores (e.g., in the case of multilayer clouds).

Comparison of the stratus cloud or fog upper-boundary determination by the cloud radar with that using the radiosonde profile revealed a statistically significant bias of about 50 m. Ruffieux et al. (2006) mentioned that the SRS400 (used in 21 of the 25 studied cases) is affected by a bias of about 100 m in the determination of the hydrolapse above fog or low stratus cloud layers, compared to other radiosondes. Our comparison shows a similar but smaller bias. In addition, it should be noted that for the three cases using a SnowWhite sensor and the case using an RS80 sensor all differences are within ±30 m. Ruffieux et al. attributed the bias of the SRS400 to a combination of droplets contaminating the protective duct of the carbon hygristor and lower ventilation early in flight, while the balloon is still accelerating. Taking into consideration that the determination of the fog or stratus cloud upper-boundary determination by the SRS400 is affected by a positive bias, the 95% confidence interval of about ±30 m shows a good agreement, given that both the radiosonde and the cloud radar height resolution is about 15 m. Finally, comparison with the wind profiler SNR confirmed that the highest SNR is normally found just above the cloud radar–determined upper boundary, as expected.

The case study of 9 December (Fig. 1) further demonstrates that the capabilities of the ceilometer and cloud radar combination to determine cloud boundaries are good for well delimited clouds. In this case, the location of the cloud top as determined by the cloud radar is confirmed during the day by the high signal-to-noise ratio of the wind profiler and the inversions detected by the radiosoundings (section 3a). This excellent result was helped by good conditions such as the absence of precipitation, well-defined low stratus cloud, and a marked inversion at the top of the cloud. The cloud top detected with the radiosoundings at 0000 and 1200 UTC 9 December and 000 UTC 10 December 2003 (2 SRS 400 and 1 Snow White sounding) also agrees within 10–110 m with the cloud-top observation of the cloud radar.

The case of 19 November 2003 shows that such detection is more complex when the boundaries themselves are not well defined as inferred from the sounding profiles and the wind profiler signal-to-noise ratio time series. Note that the stratus cloud situations are reported by ground-based observations. The clouds may be multilayered and/or nonhomogenous, which is difficult to assess since the first cloud layer hides potential higher cloud layers. This hypothesis is given weight by the wind profiler SNR that at some times shows multiple maxima at different altitudes, and also exhibits a large and rapid variability with respect to time. In such cases, the retrieval of the cloud top seems to be hampered by the nature of the cloud itself (inhomogeneous, rapidly changing, etc.). In addition, the ceilometer detected a very low base after 1200 UTC and the visibility was below 1 km indicating the presence of ground fog. Therefore, it is also possible that the fog top was below the lower detection limit of the cloud radar.

For situations without precipitation the combination of cloud radar and ceilometer is promising for the detection of fog and low stratus clouds. Despite its prototype nature, the cloud radar already displayed satisfactory performances, and its cloud-top height detection efficiency will be further enhanced by improvements in its algorithm and design. The two systems running in parallel deliver information at a very high temporal resolution with a reasonable cost, which would allow deployment at additional meteorological stations in Europe or over the world. They can give valuable information for the understanding of the development of clouds, help establishing cloud climatology, and improve the analysis of cloud–radiation interaction. Protat et al. (2006) showed that in order to evaluate the representation of clouds in operational models, the use of both a cloud radar and a lidar is imperative. The sampling should be regular but not necessarily continuous, and should not be driven by meteorological conditions. In comparison, the setup of the systems used for the TUC campaign was limited in altitude. For high cloud detection, the cloud radar should be used with a different setup and a ceilometer with a longer range should be used.

As mentioned in section 2, it is better to use a ceilometer for detecting the base of clouds, rather than using the cloud radar for determining both boundaries. The cloud radar is more sensitive to precipitation and the detection of the cloud base is attenuated (O'Connor et al. 2005). The radar reflectivity is dependent on the drop concentration and on the sixth power of the droplet diameter so the larger precipitation droplets in and below a cloud dominate the radar return. Therefore, the radar is able to detect the large droplets but clear distinction between precipitation and cloud is not possible. The ceilometer is efficient for measuring the cloud base; its dependency to the concentration of the droplets is only affected by the square of the drop size. However it cannot normally detect the cloud top due to attenuation of the beam in the cloud. The cloud radar can penetrate the cloud and detect the cloud top. Further advantages of this FMCW radar system are the low costs compared to other cloud radars and the simplicity to operate them in a continuous way. The estimated cost of the prototype was at least a factor of 2 below that of a commercially available pulsed system, and even a combination of a Vaisala ceilometer and FMCW cloud radar would remain significantly less expensive than a pulsed system.

Other studies attempted to assess the potential for detecting the cloud boundaries by different means. Wang et al. (1999) analyzed cloud radar and ceilometer data to determine cloud vertical structure during the Atlantic Stratocumulus Transition Experiment (ASTEX) in June 1992 and compared the results with satellite and radiosonde data. They also used radiosoundings for determining low cloud base and top for a 20-yr dataset in the ASTEX region. They conclude that a combination of cloud radar, ceilometers, and lidar is needed to provide the most accurate and complete information on cloud vertical structure. Using radiosoundings severely limits the number of locations and the time resolution.

The temporal resolution (30 s) of the wind profiler is well suited for this task, but its cost is the main limiting factor for an operational network. Further studies are under way to combine wind profiler information with other systems to improve unambiguous determination of cloud levels (Engelbart et al. 2007).

The collocation of cloud radar and ceilometer was also tested also during the Cloud and Radiation experiment (CLARA) in 1996. Hollars et al. (2004) presented comparisons of data from a vertically pointing 35-GHz Millimeter Wave Cloud Radar (MMCR) and the *Geo-*

stationary Meteorological Satellite-5 (*GMS-5*). Retrievals of both single-layer and multilayer clouds as seen by radar were compared, but only for satellite-detected clouds with 100% coverage of one cloud type within a 0.3° × 0.3° domain centered at the Atmospheric Radiation Measurement (ARM) site on Manus Island in the tropical West Pacific. Good agreement of the cloud-top heights was found between MMCR and *GMS-5* retrievals. For convective clouds with heavy precipitation, MMCR retrievals underestimated the cloud-top heights significantly.

Ground fog detection has been shown to be possible from space using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) during daytime (Bendix et al. 2005) and from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) aboard Meteorological Satellite (Meteosat) Second Generation (Cermak et al. 2006). Encouraging performance was found for the discrimination between low stratus and ground fog, but the method of Bendix et al. does not yet allow indisputable distinction.

5. Summary

A combination of both ceilometer and cloud radar has the potential for providing the height of a cloud layer with optimal efficiency in continuous operational mode (by optimal we mean satisfactory capabilities at a reasonable cost). These instruments complement each other: the ceilometer is very efficient at detecting clouds and can locate the bottom of a cloud layer precisely, but cannot usually detect the cloud top due to attenuation of the beam in the cloud. On the other hand, the cloud radar is able to detect the cloud top, although signal artifacts can cause difficulties during precipitation. It could eventually detect higher layers in case of multilayered clouds. Furthermore, the cloud radar used in this study was a prototype system and considerable performance improvements are expected with a new system. Once set up and adjusted to the local conditions, the systems operate autonomously and require little maintenance. The costs of both systems are low compared to other types of radar. This makes these systems in combination with another system to estimate the cloud cover amount a good alternative when human observations are not available for monitoring low cloud evolution.

Comparison of the cloud-top height determination by the cloud radar and using radiosounding humidity profile showed a bias of about 50 m. A previous study mentioned that the determination using radiosounding humidity profile with the type of sonde operated during the campaign suffered from a bias of even larger magnitude (about 100 m). Once a 50-m bias is taken into account, the agreement between both determinations is good. Comparison with wind profiler data confirmed the quality of the cloud-top height determination by the cloud radar. To improve information on the accuracy of the cloud boundary retrievals with the ceilometer and cloud radar, systematic comparisons should be made in future studies with 94-GHz cloud radar, which have a higher sensitivity to small droplets compared to the FMCW radar. Additionally, cloud-top height could also be compared with satellite data.

In this study, the information from two systems was combined in order to provide a better description of a cloud layer. It was possible to achieve this in a simple and straightforward manner because both systems deliver the same type of information (elevation of a layer). When information from more systems is integrated, this task becomes more difficult, especially when the information provided cannot be easily combined. In this study, it would have been relatively difficult to also integrate the information from the wind profiler and the radiosounding; while the information from these systems is clearly related to the information from the ceilometer and the cloud radar, their relationship is not straightforward. A promising direction to explore for more ambitious multisystem integration is the Bayesian model-based inversion technique such as explored by Löhnert et al. (2004).

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