Measurements of Cloud Water Content and Droplet Density; and Calculation of Cloud Water Gradients at Kuopio, Finland

Dr. K. Harstveit[1] and J. Hirvonen[2]
[1]Kjeller Vindteknikk [2]Finnish Meteorological Institute
[1]Po 122, 2027 Kjeller, Norway, *knut.harstveit@vindteknikk.no*

Abstract— **At Puijo tower, situated at a top of a hill in Kuopio, Finland, spectral measurements of cloud water content is carried out. From those measurements, cloud droplet density is easy calculated. Wind, temperature, cloud height and cloud amount measurements close to the foot of the hill are compared to temperature, visibility, wind speed, wind direction, and cloud water content at a tower on the top of the hill. Together with the droplet density number, we find a sub-adiabatic cloud water gradient. In addition, for typical in-cloud icing situations, we find a near adiabatic temperature gradient.**

I. Introduction

At the Puijo hill, Kuopio, Finland, a meteorological station is established at the top floor of the telecommunication tower. At the Campus area at the foot of the hill an automatic station also collects data. Temperature and wind data from both sites, cloud data from the Campus site, and visibility at the tower are collected parameters relevant for this study. In addition, cloud water data from the tower exist for a number of situations above freezing point. These data make it possible to do icing relevant analysis and draw some interesting conclusions.

Using meteorological data from a winter season, we can study the conditions in the atmospheric boundary layer, and characterize the conditions when in-cloud icing should be expected. Portin et.al., 2009 [1] present average water content of 0.06 g/m3, average diameter of d=7 µm, and droplet density of N=220 cm-3 in typical situations during cloudy conditions at the site (T>0°C), defined by visibility below 200m (200 hours). Given T<0°C, those situations will indicate icing situations. A situation of higher water content will be analyzed here to look at the cloud water characteristics during a potential stronger icing situation.

In Harstveit, 2002 [2], and Tallhaug et.al, 2005 [3] it is clearly shown that for exposed hill sites above cloud base in maritime climate; the lower the cloud base, the lower the visibility, and a mathematical expression for the connection is given, presumed adiabatic cloud water gradient. In Harstveit, 2009 [4] this is shown to be a good approximation. Since measurements of droplet distributions and LWC exist at the Puijo tower, we can look for the validity of the adiabatic cloud water gradient at this site, and correct for deviations.

This study may increase our knowledge of cloud water gradients and droplet distributions at hill sites in wooded inland areas. It should be mentioned, however, that the data material contains information from many episodes not used here. A more comprehensive analyzed should be done before drawing final conclusions.

II. Site and Data Descriptions

The Puijo station was established in 2005 by the Finnish Meteorological Institute, FMI and the University of Kuopio, UKU [1]. The station is situated 306 masl, at the top floor of the Puijo telecommunication tower, 74 m above local ground. The tower is sited at the Puijo hill, a rather steep 3 D hill, 1x3km, orientated S – N. The hill top at 232 masl is situated 150 m above the lake, Kallavesi. The town Kuopio is built on the shores of Kallavesi, and is partly surrounding the Puijo hill. The UKU-campus station is situated at the University area, about 2 km southwest of the tower.

The Kuopio area is found in Central Finland, 330 km to the north – northeast of Helsinki. The landscape is characterized by wooded lowland and lakes, 50 – 150 m asl.

At the tower top floor, the visibility (MOR - meteorological optical range) measurements are carried out using a forward scattering instrument. Light pulses are sent and scattered light from droplets is received, using a laser technique. A corresponding technique is used at the campus station to measure cloud height, and for the occurrence of grouped signals within each time step, the cloud cover content is measured. The data are transformed to metar data with three possible cloud heights with respective cloud cover. To transform this information to a significant cloud height, we use the method described in [2] The cloud height thus transformed is given in intervals of 100 feet, that is some 30 m, and relevant cloud heights are 0, 30, 60, 120, 150, 180, 210 and 240 m, where 30 m means 15 – 45 m and so on. Each height is related to the UCU-campus level (87 masl)

III. Data Analysis

A. Data Grouping

We now classify the data in 4 groups, according to limits of Hc =195 m at the UKU-campus and MOR = 500m in the tower. For each group, median values of MOR and Hc are given. Also shown is the temperature difference between the two stations, given as median and mean difference.

Table 1 shows that for the period January to March 2007, 19.1 % was in the group of thick, low clouds (group 1). The temperature difference is not far from adiabatic, indicating well mixed layer between the two stations.

In the group 2, 4.3% of the observations were characterized by low clouds with *Hc*<195m, and with MOR > 500 m at the top station. The median MOR of 9.4 km in this group indicates that the typical situation is characterized by cloud layers or fog below the tower station. This is further illustrated by the typical temperature inversion in those situations, the temperature then is 3.7°C higher at the tower station.

In the group 3, another 4.3% is connected to low visibility, but high clouds. The median values of MOR=298 m and *Hc*=230 m, indicating that this group mainly consists of situations of cloud base very close to the top level station. The temperature difference is close to the adiabatic, indicating well-mixed air.

The most frequent group 4 with 72.4% of the situations are characterized by higher clouds and better visibility, characterized by a typical isotherm situation, but the high average temperature difference indicate many situations of strong inversion.

TABLE I

FREQUENCY OF MOR/HC – GROUPS FOR ALL DATA, 1.1 – 31.03.07 WITH VALID MOR AND HC DATA. ALSO SHOWN IS THE MEDIAN AND MEAN TEMPERATURE DIFFERENCE BETWEEN THE TWO SITES

Mor [m]	*Hc [m]*	*Freq*	*MOR, median [m]*	*Hc, median [m]*	*Tdiff [°C] median*	*Tdiff [°C] mean*	*Gr No*
<500	<195	19.1%	134	120	-1.59	-1.37	1
>500	<195	4.3%	9379	90	3.72	3.58	2
<500	>195	4.3%	298	230	-1.88	-1.32	3
>500	>195	72.4%	28485	>2000	-0.33	1.65	4
All	All		14611	600	-1.18	1.03	

To conclude, the cloud cover was below 195 m in 23 % of the time (groups 1 + 2), of which 19 % (group 1) is well mixed thick clouds, while 4% (group 2) was connected to stable layers and thin, low cloud cover.

Only the group 1 of low visibility and low cloud cover may produce significant in-cloud icing at the tower site, and we will analyze this group further.

Figure 3 illustrates that typical values during low cloud base at UKU-campus and low visibility at the Puijo tower is MOR(Puijo) = 90 to 150 m, and *Hc*(UKU)=60 to120 m. The figure also illustrates a gradually lower cloud visibility when the cloud base is getting lower. The typical temperature at UKU-campus was -1°C. When MOR(Puijo) increases from 150 to 200 m, the temperature is gradually falling to several degrees minus.

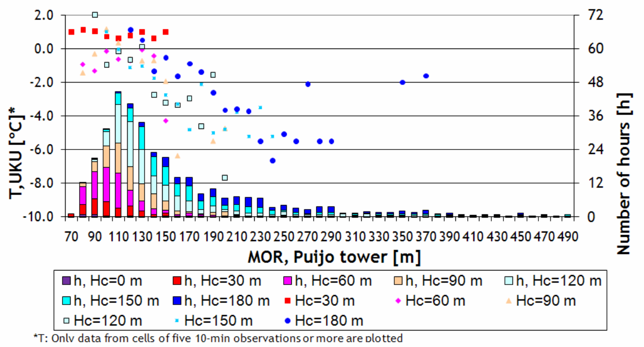

Fig. 1. Relation between visibility, MOR at the Puijo tower and cloud base, Hc at the UKU-campus station, Jan - Mar 2007. Also plotted is the corresponding air temperature, T at UKU.

Table 3 illustrates that the typical wind direction during low visibility and low cloud base during the observational period is 210°, measured in the Puijo tower, which means transport of humid air from the Baltic Sea. The distance over Southern Finland is about 330 km, dominated by wooded plains and low hills and frozen lakes.

TABLE II

AVERAGE WIND DIRECTION AT THE TOWER STATION FOR GROUPS OF MOR (≤500M) AND HC (<195M), GIVEN FOR GROUP NO≥5, AND SHADED FOR GROUP NO≥20. THE GROUPS ARE DEFINED FOR EACH 10 M MOR BUT A COMBINED GROUP IS USED FOR 210 – 500 M (LABELLED350M)

MOR [m]	*Hc= 0 m*	*Hc= 30 m*	*Hc= 60 m*	*Hc= 90 m*	*Hc= 120 m*	*Hc=1 50 m*	*Hc= 180 m*	*Total*
70		205						205
80		255	162	148				189
90		173	182	181	223			182
100		203	206	203	189	226		203
110		188	208	218	196	193		203
120		181	200	228	223	188	176	211
130		170	222	208	222	208	180	210
140		165	211	213	228	212	188	213
150		182	232	217	252	215	192	221
160				215	211	217	191	208
170			218		207	234	207	217
180					211	257	180	221
190				192	197	219	213	209
200				219	190	225	195	206
350			258	223	205	223	206	211
Total	226	193	201	211	214	217	201	208

B. Cloud Water Content and Droplet Size from a Theoretical Point of View

We can express the cloud water content, *w* in a cloud at height *z* in some distance from the surface by the equation

$$LWC = \alpha \cdot \delta \cdot (z - H_C) \approx \alpha \cdot 1.56 \cdot (1 + 0.034\theta_w) \cdot (z - H_C) \qquad (1)$$

where *Hc* is the cloud base and δ the adiabatic cloud water gradient, given as a function of the potential wet-bulp temperature θ_w, here approximated for the lower 500 m of the atmosphere. If all the humid air is lifted adiabatically and all condensed water stay in the lifted cloud mass as liquid water, the cloud water increases with height according to the adiabatic cloud water gradient. The factor α ($0 \le \alpha \le 1$) expresses the deviation from the adiabatic cloud water gradient, and may be lowered from 1.0 due to loss of cloud water in old clouds or by partly or slowly lifting of the air allowing droplet loss due to mixing, freezing or precipitation washout to occur.

The visibility, MOR, measured by automatic instruments, is defined as the distance where the original light is reduced to 5%. According to Behrs law, the extinction coefficient, k then is given as the relation between MOR and ln(0.05). Using Mies "large – drop approximation", $k = 2A$, where A is total droplet cross section per volume unity clouded air. Then, using (1) and simple geometry,

$$MOR(z) = \frac{-\ln(0.05)}{k} = \frac{-\ln(0.05)}{2A} = 1.24\rho_w \omega^{-2}\beta^{-1}\alpha^{-2/3}Nc^{-2/3}\delta^{-2/3}(z - H_C)^{-2/3} \quad (2)$$

where ρ_w is the water density, and we also have introduced the two constants β ($0 \le \beta \le 1$) and ω ($0 < \omega \le 1$), to allow for reduction of droplets near a surface due to wet deposition ($N_C = \beta N_0$; N_0 is the droplet density), and deviation coefficient from a narrow droplet spectrum, ω. ω is the relation between radius weighted and the volume weighted average droplet radius.

C. Comparing Theory and Observations

We have chosen an episode characterized by low visibility in the tower. Figure 2 illustrates the meteorological conditions; MOR=64m, Hc=60 m, and temperature decrease from UKU campus to the tower position of 1 °C (-0.005°C/m), close to wet – adiabatic conditions. The wind direction is 200° at the tower, which is typical for situations with low visibility and low clouds (Table II). The visibility is somewhat lower than typical conditions during Jan – Mar, 2007, which may be explained by the higher temperature (+8°C in the tower) which enlarges LWC (1) and thereby reduces MOR (2). At UKU - campus the wind direction is 160 – 180°, indicating a channeling effect along the hill and not complete lifting up to the tower floor.

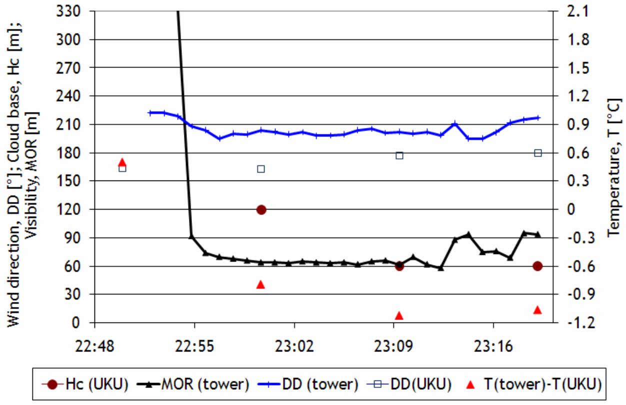

Fig. 2. Meteorological conditions at the Kuopio area during the low – visibility episode in the evening Oct 2, 2007.

In Fig. 3 we have plotted the spectral distribution of the cloud water during this episode, illustrating some deviation from a narrow droplet spectrum.

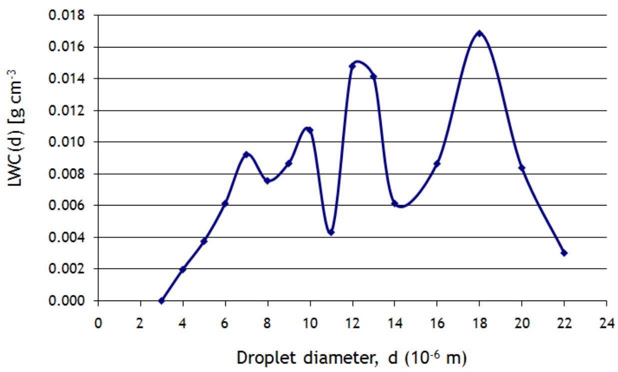

Fig. 3. Average spectral distribution of cloud water content, LWC, integrated to 0.17 g cm^{-3}, during the low – cloud episode Oct 2, 2007, 22:52 – 23:17.

In Fig. 4 we have plotted the liquid water content, LWC, the total number of droplets, Nc, and the deviation coefficient from a narrow droplet spectrum, ω during the episode. Typical values of Nc is 350 cm^{-3}, LWC=0.15 g m^{-3}, and ω=0.82.

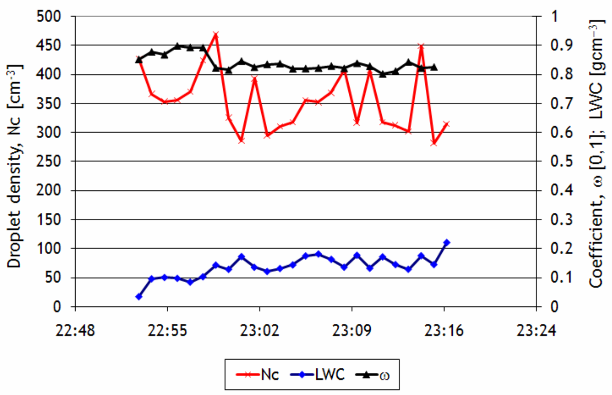

Fig. 4. Cloud water characteristic at the Puijo tower during the low – cloud episode in the evening Oct 2, 2007.

Using (T(306msl)=+8°C, Hc=60m (147 masl), Nc=340cm^{-3}, ω=0.82, MOR=64m, and assuming β=1, that is no or very little deposition from the height of 74m within the short distance of 2 km compared to the height above ground, we calculate α=0.6 from (2). This means that the calculated cloud water gradient from the Puijo observations is 60% of the adiabatic gradient.

Using the measurements from [1], Nc=220cm^{-3} together with the typical winter conditions of cloud base and visibility (Hc=120 m and MOR=134m, Gr 1, Table I), and θ_W=0°C, ω=0.82 we find α=0.52. Using this value, LWC=0.08 gm^{-3}, while the measured value is 0.06. Since Hc might deviate between the winter groups and the group used by Portin et. al, we find this result satisfactory. The median values of T, Hc and MOR during the Portin group selection can easily be calculated from the data and taken into account before the final conclusion is done.

IV. Conclusion

Meteorological measurements, including visibility from Puijo tower in Kuopio, Central Finland, were analyzed for the period Jan – Mar 2007, together with measurements including cloud data at the UKU campus station at the foot of the hill. When the winter time visibility in the tower is low, it is a rather sharp distribution around visibilities of 90 – 150 m. When there is low visibility in the tower there are typically low clouds at UKU-campus, indicating in-cloud conditions. When there are in-cloud conditions at the tower, the typical temperature gradient is -0.7°C/100 m in the area. During in-cloud situations, the typical wind direction comes from the south – southwest.

When there is fog or low clouds below the tower station there is several degrees warmer in the tower than in town, but this situation is far more infrequent than the in-cloud situation.

There also exist cloud water data and cloud droplet data from the tower for a number of situations above freezing point. There was significant deviation from a narrow droplet spectrum in the analyzed in-cloud situation 2.10.2007, the relation between radius weighted and volume weighted average droplet radius was found to 0.82 from measurements.

The cloud water gradient was calculated to 60 % of the adiabatic gradient in the episode of very low visibility 2.10.2007. There is indication of 50 % from data for a longer period. There is reasonable connection between theory and observations.

There is possibility to do more analysis from the data material to verify and find variability in those numbers.

V. References

[1] H. J. Portin, M. Komppula, A. Leskinen, S. Romakkaniemi, A. Laaksonen and K. E. J. Lehtinen, "Aerosol-cloud interactions at Puijo semi-urban measurement station." In: Kulmala M, Bäck J, Nieminen T, Lauri A, eds. *Proceedings of the Finnish Center of Excellence and Graduate School in Physics, Chemistry, Biology and Meteorology of Atmospheric Composition and Climate Change Annual Workshop*, 27-29.04.2009, p. 352-355. Helsinki: 2009. Report Series in Aerosol Science 102.

[2] K. Harstveit, 2002, "In-cloud rime calculations from routine meteorological observations at airfields," in *Proc. 10th Int. Workshop on Atmos. Icing of Structures*, Brno, Czech Republic.

[3] L. Tallhaug, K. Harstveit, and A. Fidje, "Atmospheric Icing on Wind Turbines". Kjeller Vindteknikk, KVT/LT/2005/011. Kjeller 2005 pp. 1-50

[4] K. Harstveit, 2009, "Validation of an in-cloud icing model based on cloud water gradient calculated from metar airport data," to be presented at the *13th Int. Workshop on Atmos. Icing of Structures*, Andermatt, Switzerland.