PARCWAPT – Passive Radiometry Cloud Water Profiling Technique

By:

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A new cloud liquid water profiling technique by Radiometer Physics GmbH (patent pending)

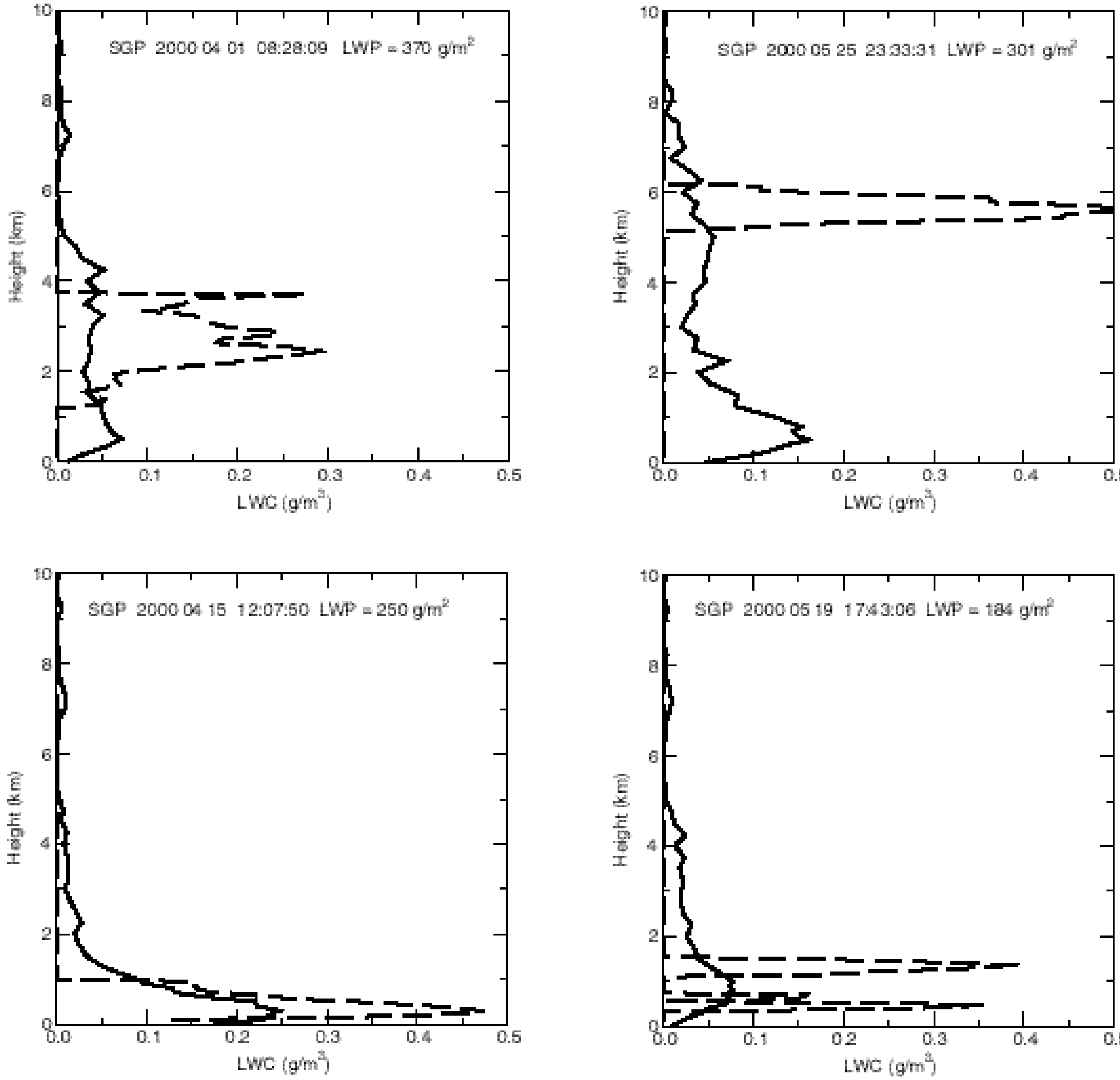
Introduction

At Radiometer Physics GmbH (RPG), we are convinced that vertical profiles of liquid water content cannot be derived from passive microwave radiometers with significant retrieval skill, even when the microwave radiometer is combined with an infra red (IR) radiometer.
The reason is the limited height information of the emitted radiation. For water vapour and oxygen gases, their spectral lines offer the great advantage of strongly varying optical depth within a small frequency band. For this reason, we can receive radiation from different depths of the atmosphere in different frequency channels.
While Oxygen has the strongest variation of optical depth up to totally opaque atmosphere, therefore allowing a good retrieval of the vertical structure of atmospheric temperature, the change of water vapour absorption characteristics with frequency is much weaker, leading to reduced quality of vertical humidity retrievals.
Liquid water is not showing spectral emission lines, but a broad absorption continuum with only moderate frequency dependence. It must be stressed that 1 kg of liquid water will emit the same amount of microwave radiation whether it is at 1 km height or at 2 km height.

Existing LWC profiling techniques (and their problems)

When using regression schemes to retrieve LWC in each level of a model atmosphere, the LWC profiles tend to produce non-zero LWC at all vertical levels. An example for this behaviour can be found in the ARM programs "**Microwave Radiometer Profiler Handbook"** by James C. Liljegren (http://www.radiometrics.com/mwrp_handbook.pdf), where one can find (p.60) a comparison of radar LWC profiles (dashed) and Radiometrics microwave radiometer LWC profiles (solid lines).

Although this Radiometrics approach is using an IR radiometer, the cloud height is totally inconsistent. The LWC profile is non-zero at all heights, sometimes with significant LWC below the (highly elevated!) cloud. The maximum LWC is not correlated with the real cloud, neither in vertical position (several km away), nor in LWC amplitude. The non-zero LWP at all levels necessarily leads to underestimated LWC amplitudes, because the total area of the curve has to match the LWP (a variable which can be retrieved by microwave radiometers to much better accuracy).



Therefore, the retrieved profiles are showing a LWP-scaled variation of ever the same profile: Maximum LWC close to the surface, non-zero everywhere else, fading out above the cloud to top-of-the-atmosphere.
Additionally, this approach can generate artificial clouds under high water vapour concentrations when the IR signal is significantly attenuated. Therefore the IR temperature increases (private communication, UK-MetOffice) and ‘suggests’ a cloud base. An independent check of a low or zero LWP value would easily resolve the error but a single NN retrieval is obviously not capable of handling this.

This very limited retrievals skill has to be expected when using regression schemes to retrieve LWC in each level of a model atmosphere: When correlation is bad (e.g., information content in the measurements is small), then a regression will produce results close to the expectation value, which is the mean value of all profiles in the training set.

Since clouds usually occur in all levels, with a maximum likelihood of thick rain clouds in lower altitudes, the retrieved profiles are basically showing the mean values, with little variations.

PARCWAPT – The RPG Method

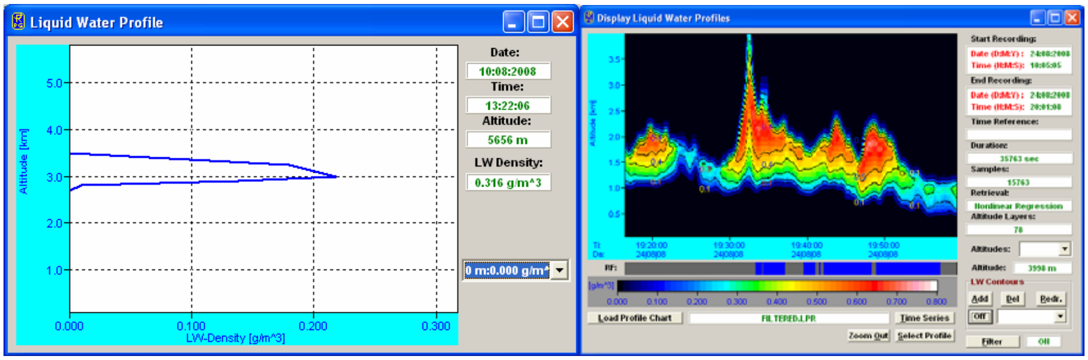
The available data (14 channels microwave brightness temperatures, one IR radiometer temperature, ground sensors of RH, T, p) has limited information content of the clouds vertical structure. Therefore, we are not using the usual regression schemes, but more an "expert system" approach. This way, we make optimal use of the information content in our variables.
The detailed steps of the **PARCWAPT** LWC profile retrieval (patent pending):

1. Retrieve temperature profile of the atmosphere. The temperature profile is needed to determine the cloud base height from the IR temperature reading. One of the strongest points of the RPG-HATPRO instruments is the high-precision boundary layer scan obtained with narrow-beam elevation scanning techniques. Regardless of using explicit look-up tables or implicit retrievals using the oxygen line channels, the high quality in the temperature profile will be beneficial for precise cloud base height estimation.
2. Retrieve liquid water path (LWP, total of vertically integrated LWC profile)
3. Retrieve cloud base height by combining IR temperature reading and the T-profile
4. Retrieve the maximum LWC of the cloud (using all 14 microwave channels and the surface sensor readings)
5. Modify a normalised LWC profile shape to model the actual LWC profile:
    a. The profile amplitude is scaled to match the retrieved maximum LWC value
    b. The profile height is then scaled to match the retrieved LWP
    c. The scaled profile is shifted in vertical position to match the cloud base retrieved from IR sensor
6. Certain thresholds are applied to ensure rejection of inconsistent cases:
7. very small LWP values indicate thin clouds, which might be transparent to the IR radiometer, in which case the cloud base would be miscalculated
8. very small values of retrieved maximum LWC are set to a minimum LWC of at least 0.1 gm^-3

Obviously, such an algorithm can only retrieve one-layer clouds. The shape of the normalized curve which we use for the LWC profile inside the cloud has a physical meaning (modified adiabatic liquid water content):
http://www.springerlink.com/content/k506hwh681823720/ paper by Karstens et al 1993), but the LWC curve inside the actual cloud may differ from this idealistic assumption due to the variety of cloud formation processes.

Advantages

- The RPG algorithm produces LWC profiles with sharp boundaries. Below the cloud base height and above cloud top height, the LWC is strictly zero:



- The vertical position of maximum LWC is highly correlated with cloud height
- The maximum LWC is constrained to reasonable values by the regression retrieval which is producing this value from all 14 microwave channels.
- Cloud base height is precisely following the (high-quality) information from the IR sensor.
- The vertically integrated LWC is consistent with the LWP retrieval.
- Typical high-temporal resolution data of the RPG radiometers reveal rapid changes within the cloud properties and evolution.

In contrast to regression schemes (like quadratic regressions and artificial Neural Networks), the RPG mixture of retrieved quantities and "expert system" analytical equations produces physically reasonable cloud profiles in the case of single layer clouds.

Limitations / Discussion

Beyond the usual random errors ("noise") in the retrieved quantities, the RPG LWC algorithm is producing misleading (meaning: incorrect) results whenever the real cloud structure deviates from the underlying assumptions.

- Multilayer-clouds:
  The LWP of all cloud layers will be produced by simply extending the single layer cloud to larger vertical cloud top height. Largest deviations are expected in cases where a small but IR-detectable cloud is at lower levels, and all further cloud levels are at much higher elevations.
- Clouds with LWC curves that deviate from the modified adiabatic liquid water content are retrieved with a wrong LWC curve inside the cloud. Possible examples are deep convection, thunderstorms, decaying cloud fields, etc…
- Errors in the retrieved maximum LWC directly relate to errors in cloud thickness. We have three free parameters (cloud base height, total water amount LWP (= the integrated LWC), and the maximum LWC inside the cloud. These parameters are used to modify the constant normalised standard profile. A better way would use variable LWC profile shapes, but if LWP and maximum LWC are kept as

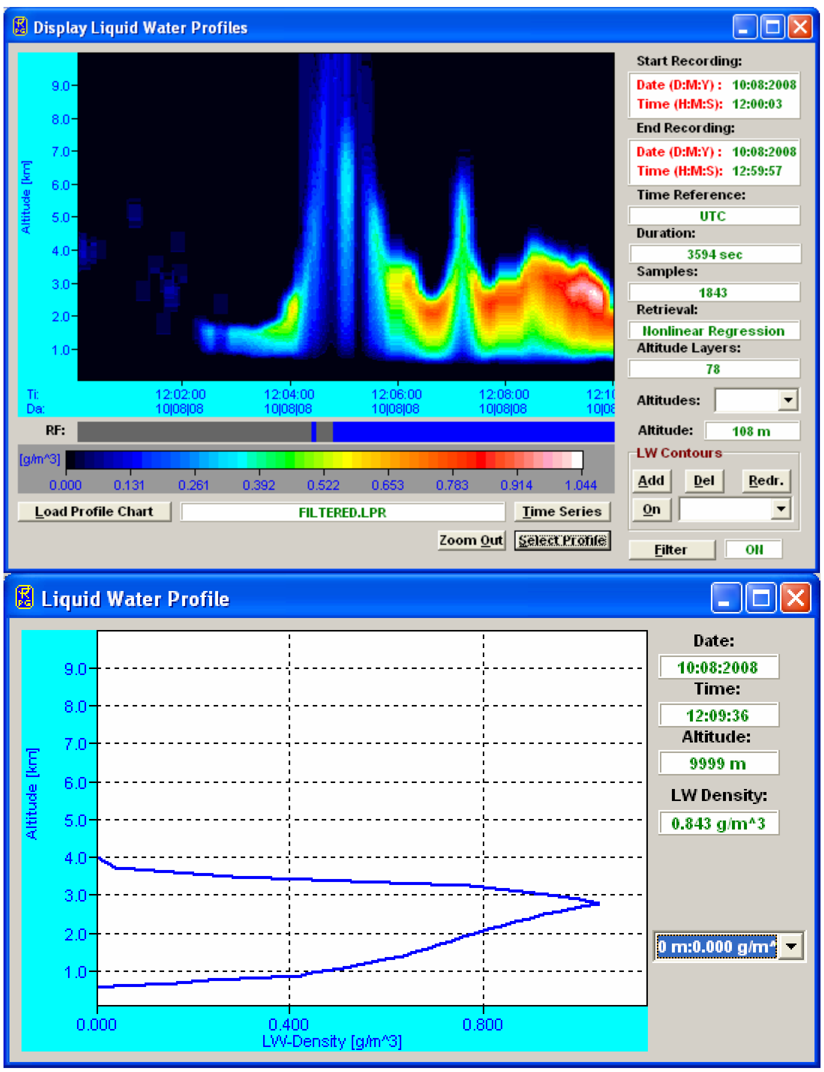
independent variables, then the degrees of freedom would be higher than 3. With passive microwave radiometers, we just do not have this information. Using variable profile shapes and adjust maximum LWC or LWP accordingly would result in possibly incorrect and un-physical numbers for these parameters.

In summary, RPG is providing this LWC retrieval as a visualization of parameters that are basically already visible in their raw representation: cloud base height from IR and LWP as the total water amount. Beyond this information, the only new insight into LWC profiles is the retrieved maximum LWC, which acts (when combined with a standard profile shape) as an estimator for cloud thickness.

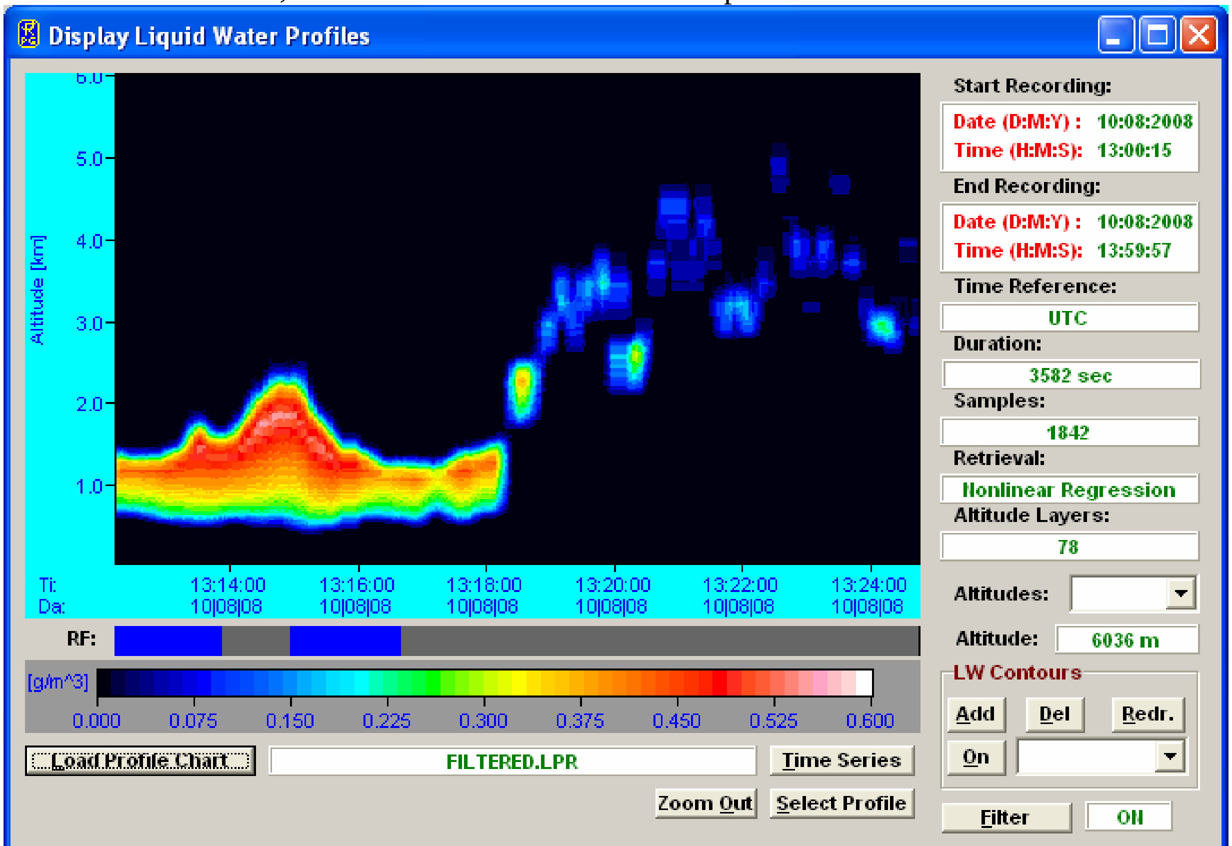
Measurement Examples

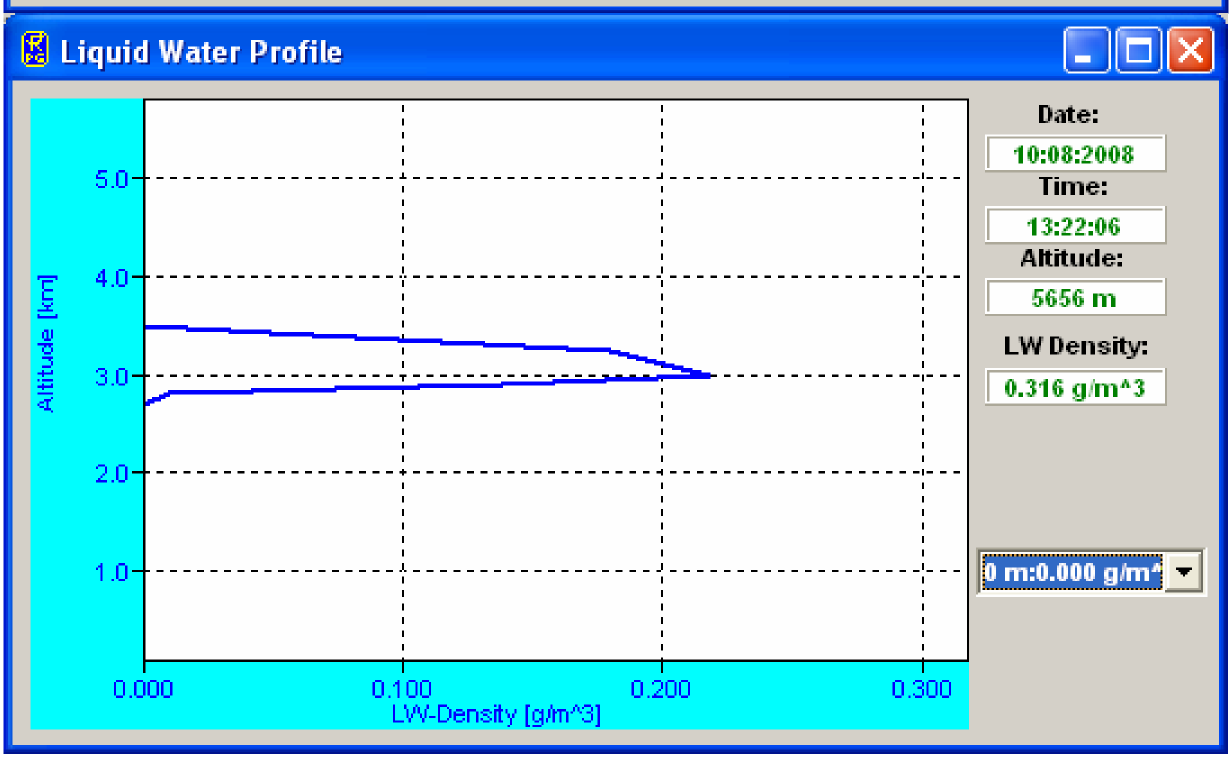
All cases were processed with the current version of the HATPRO operating software.

Thickening cloud, start of rain. Single LWC from inside the rain period (12:09 UTC).

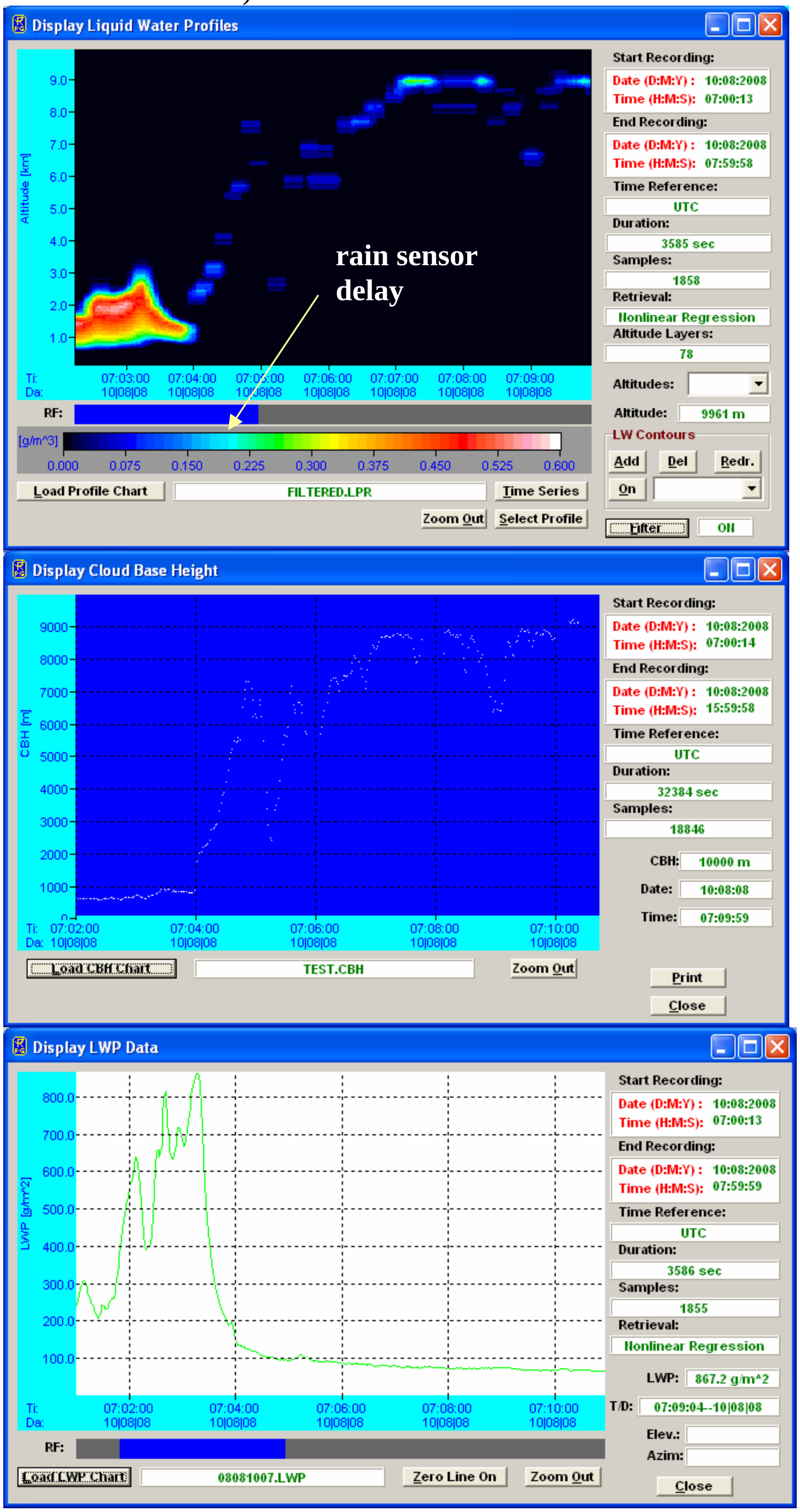


End of one rain event, cloud cover becomes thin. Lifts up to 3 km.

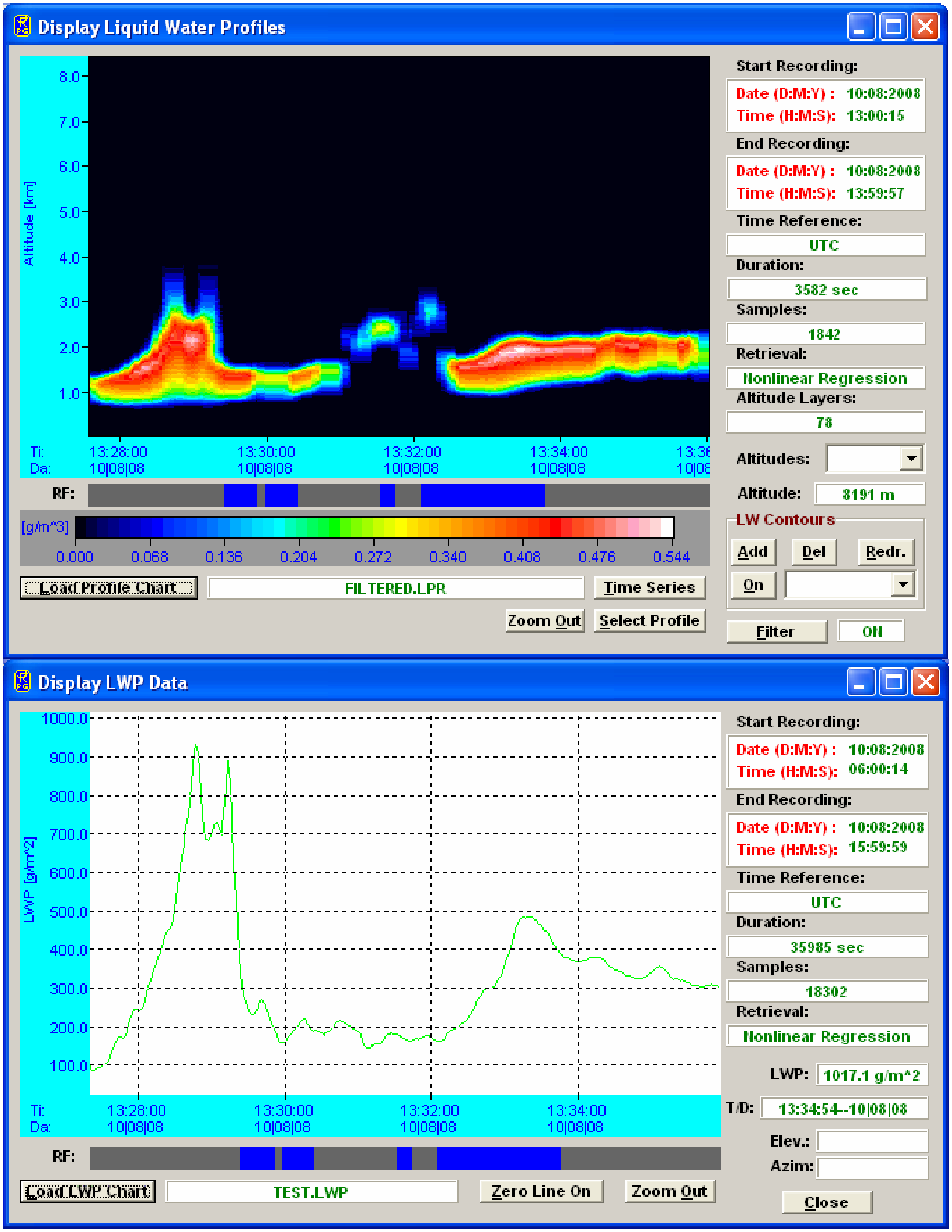




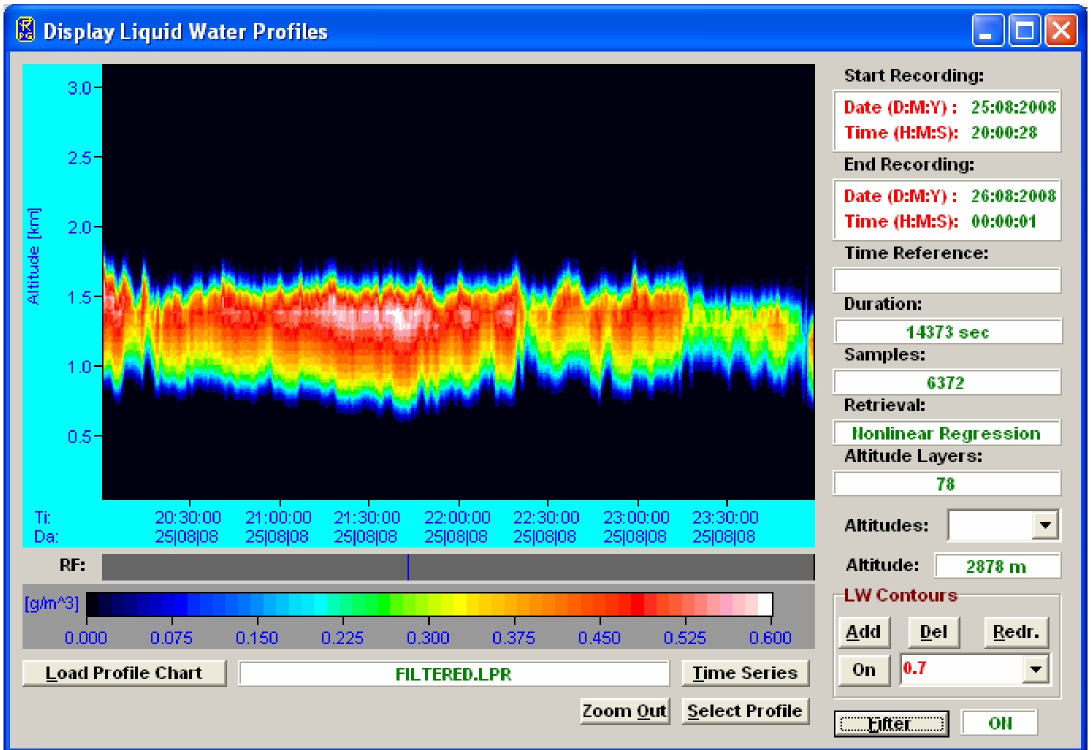
End of one rain event, lifting of cloud base, decay of LWP in high cloud cover (above low level rain cloud).

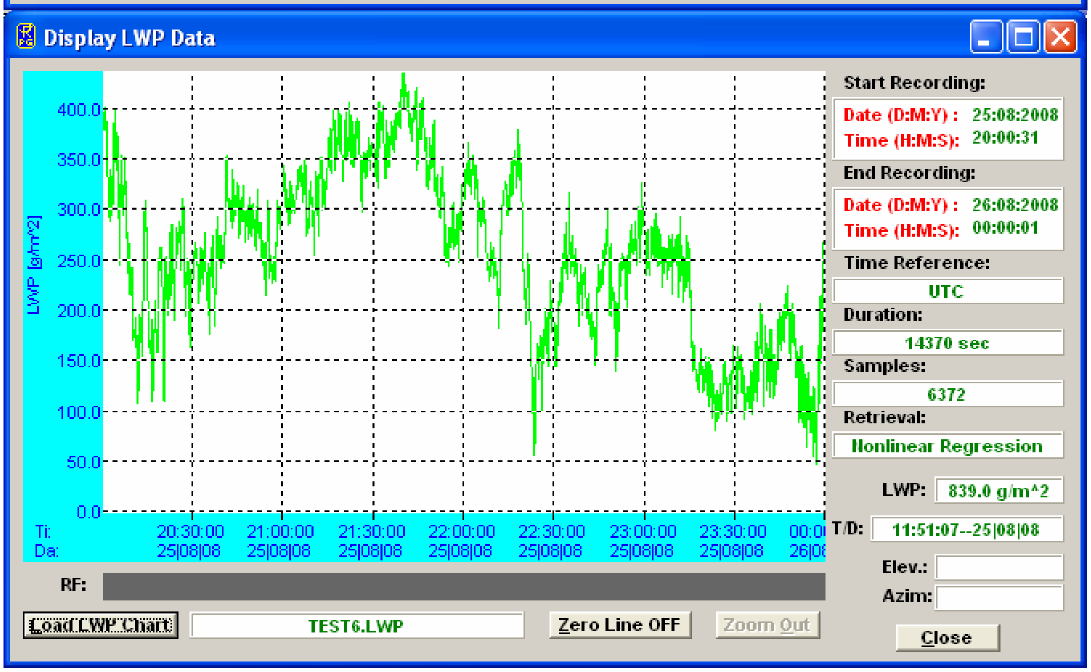


Rain event with rain-free period (and lifted cloud cover) in the middle.

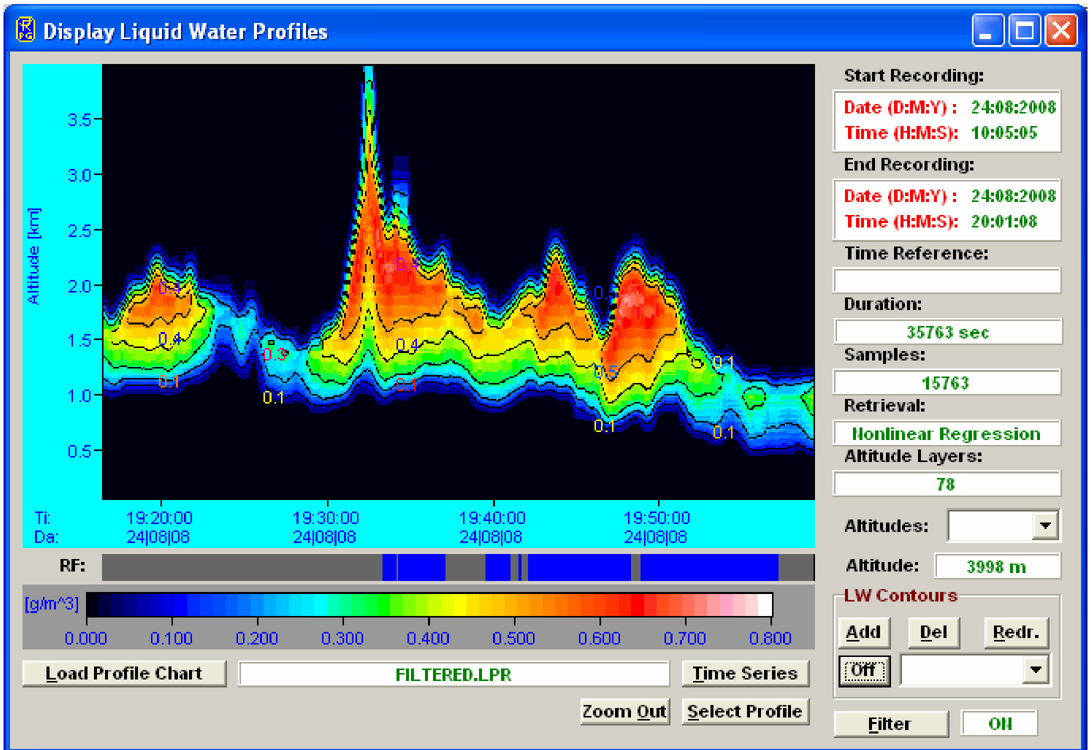


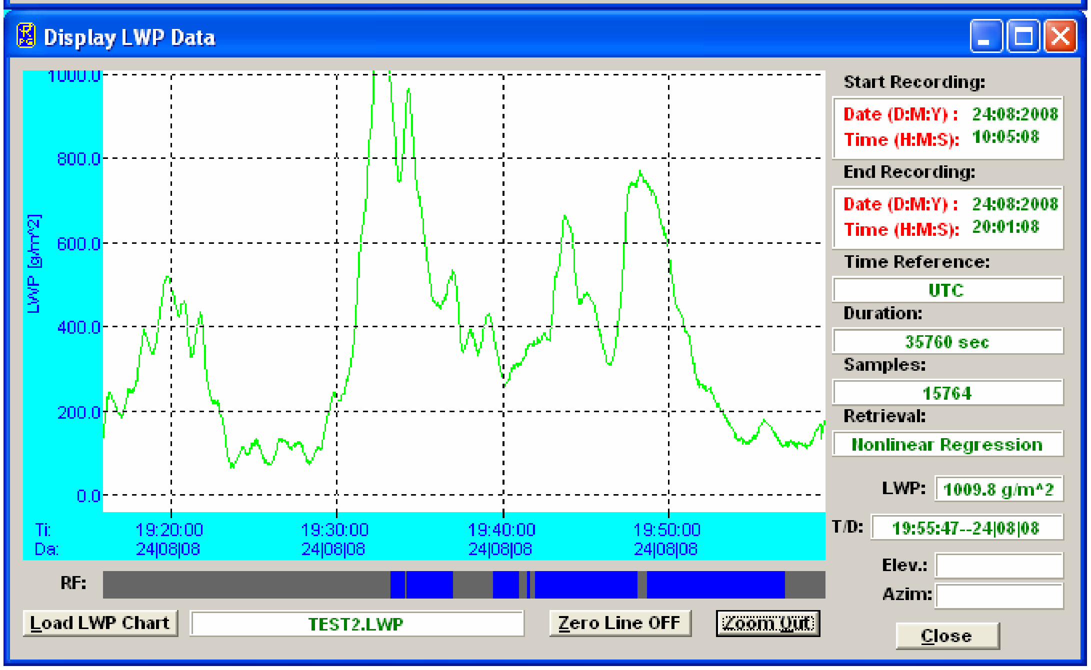
Moderate cloud thickness, variable cloud base, height of maximum LWC quite uniform.



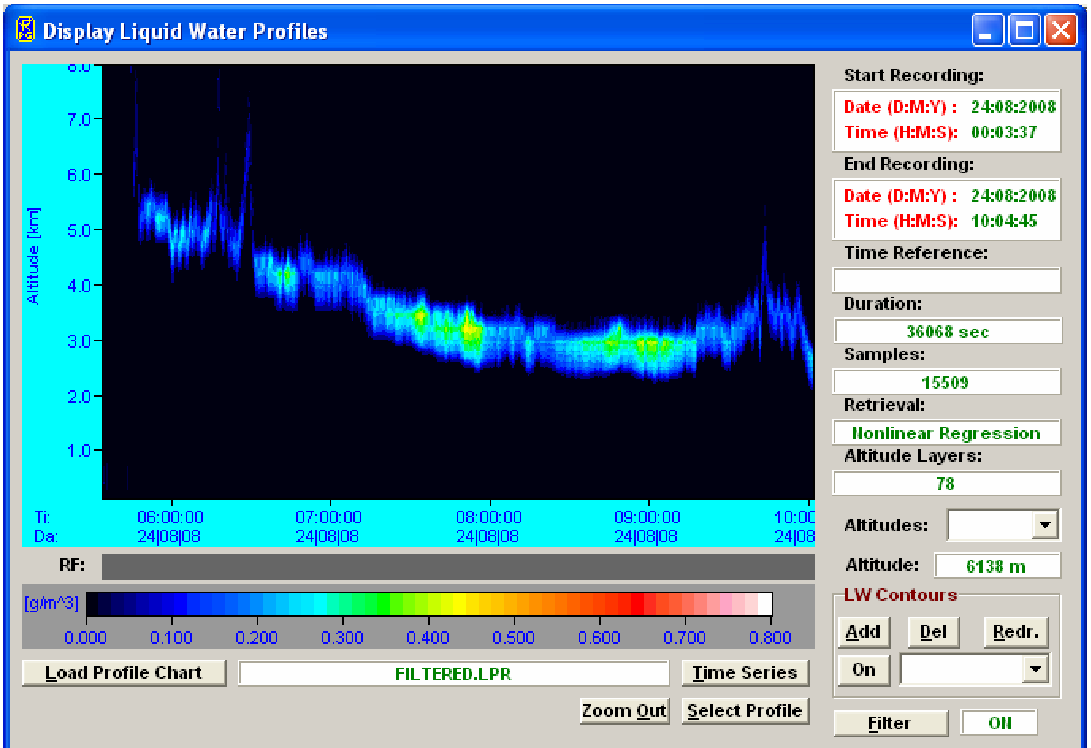


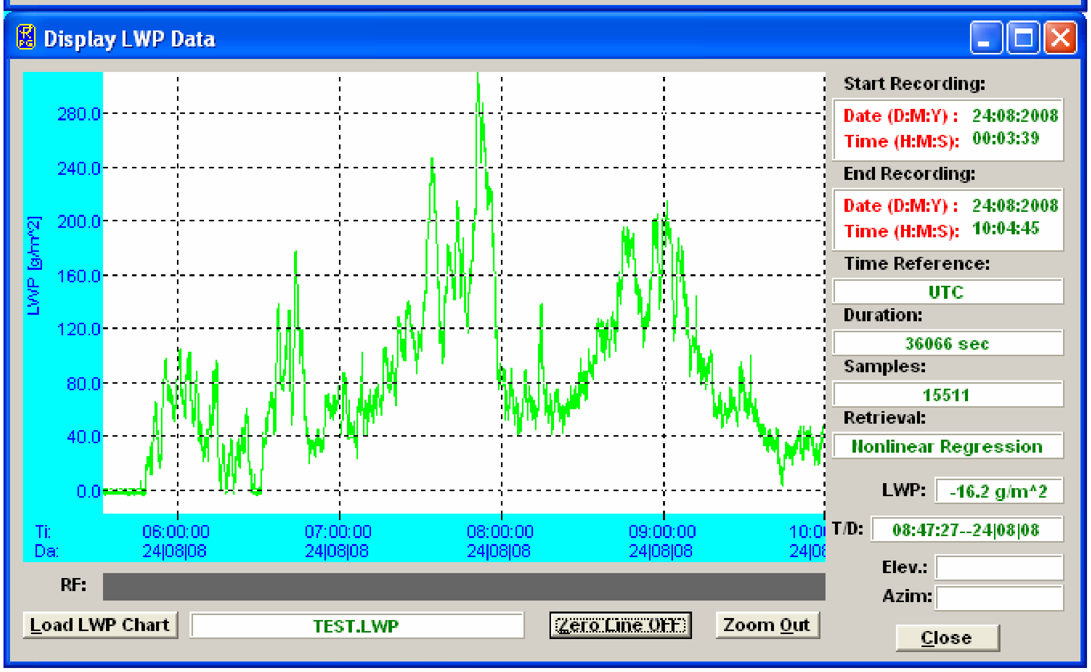
Very variable LWP, varying cloud thickness, most likely convective precipitation (LWP > 1000 g/m^2).



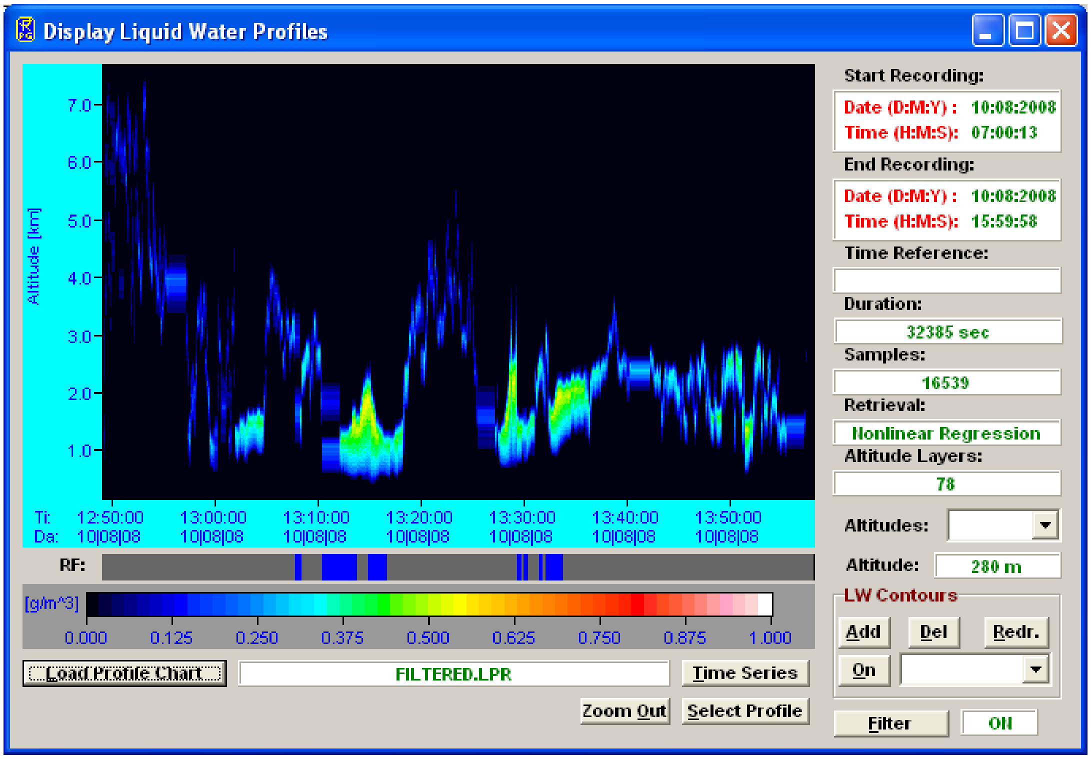


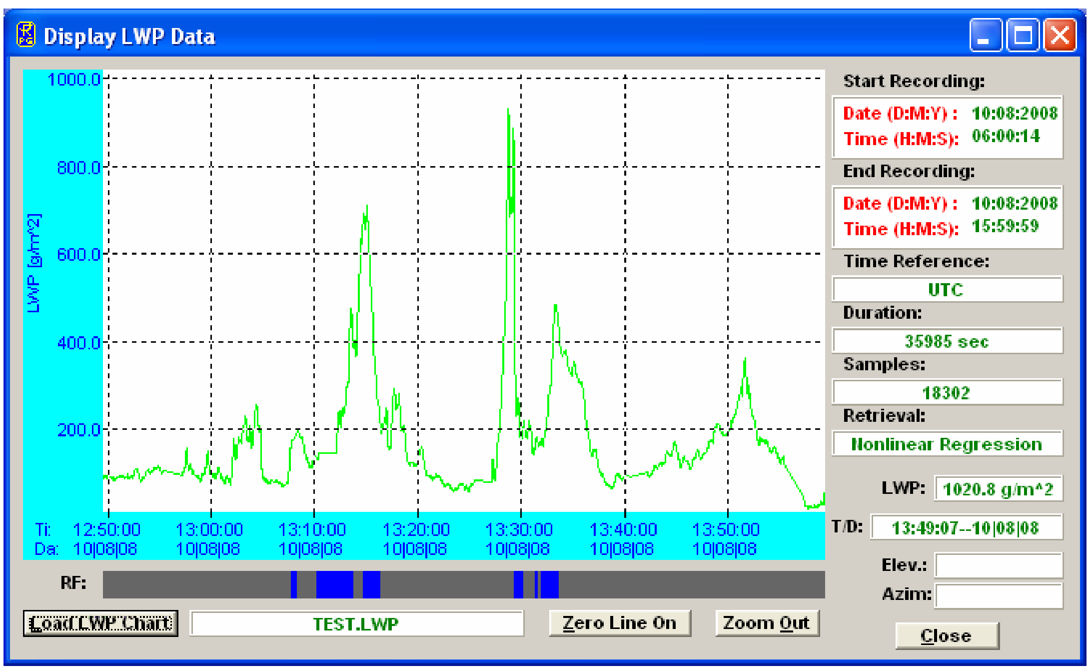
Thin cloud layer without rain.



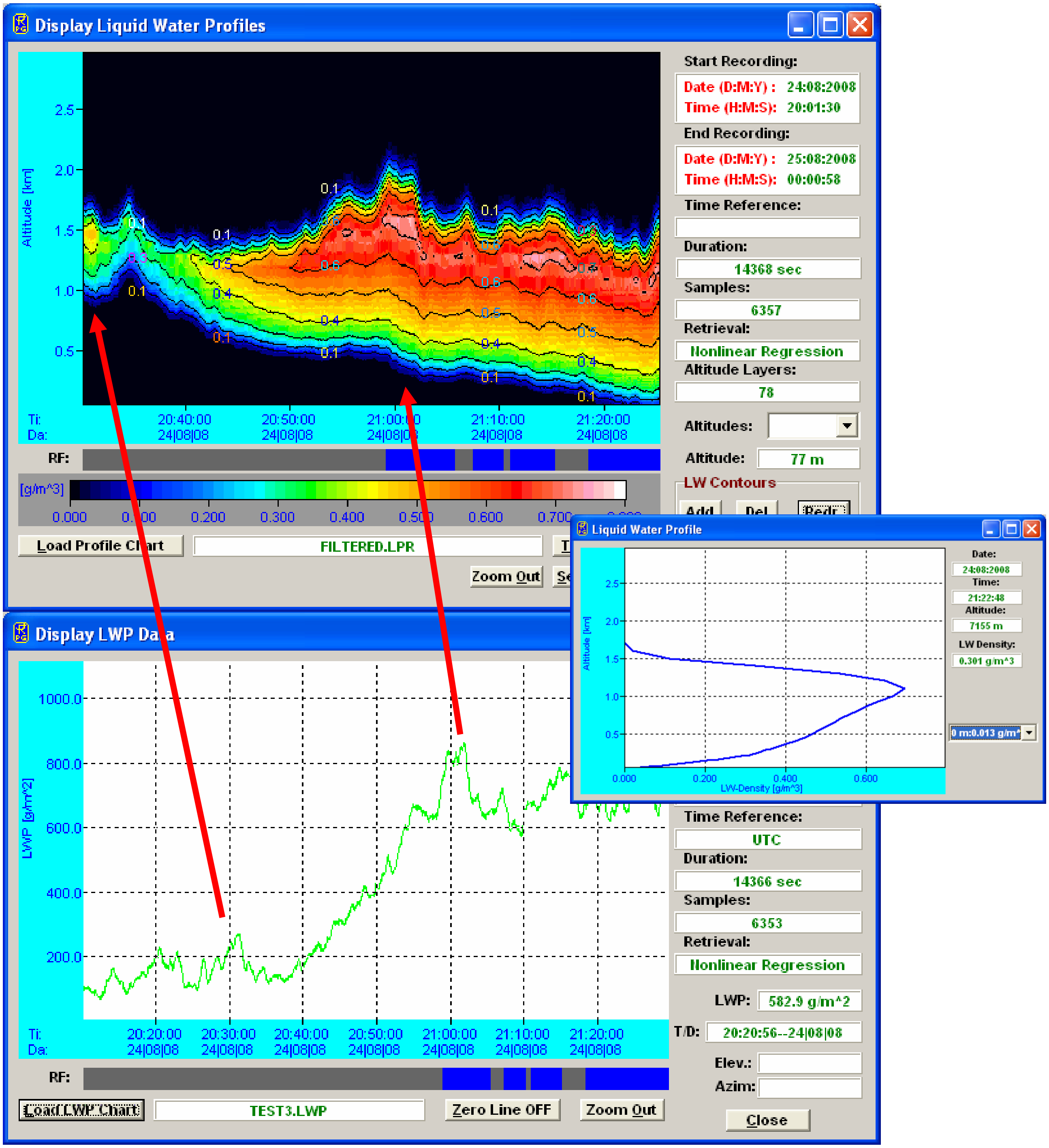


Broken cloud layer.

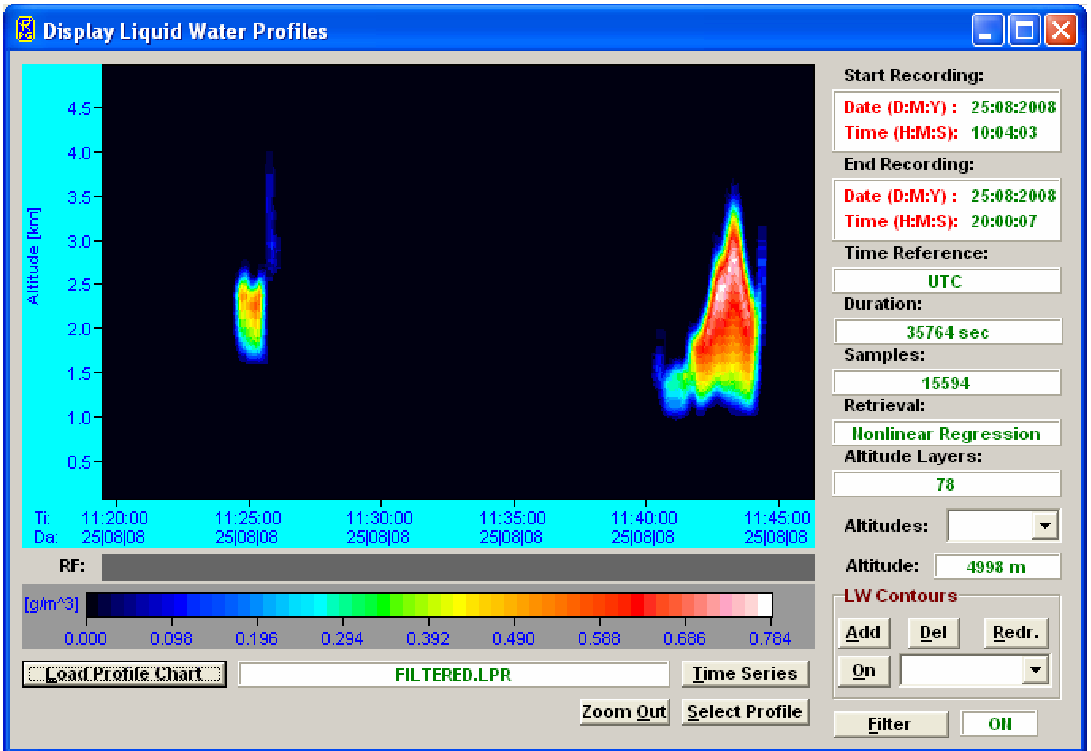


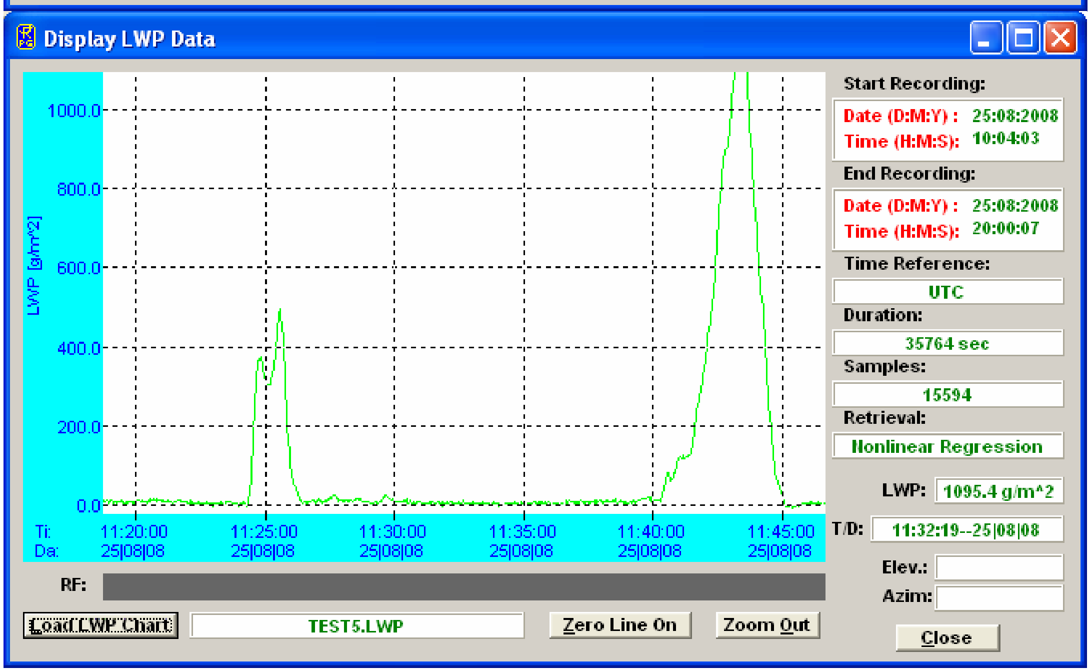


Decreasing cloud base height, increase of LWP and LWC, start of rain.

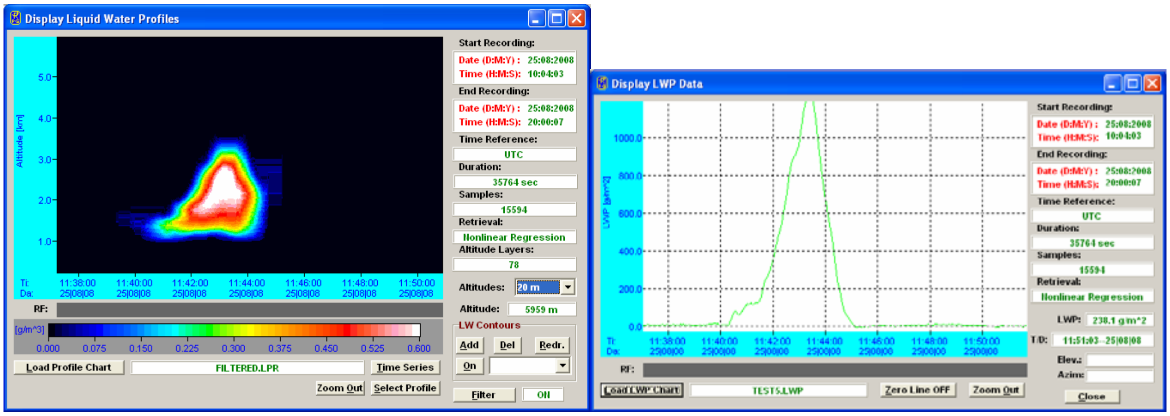


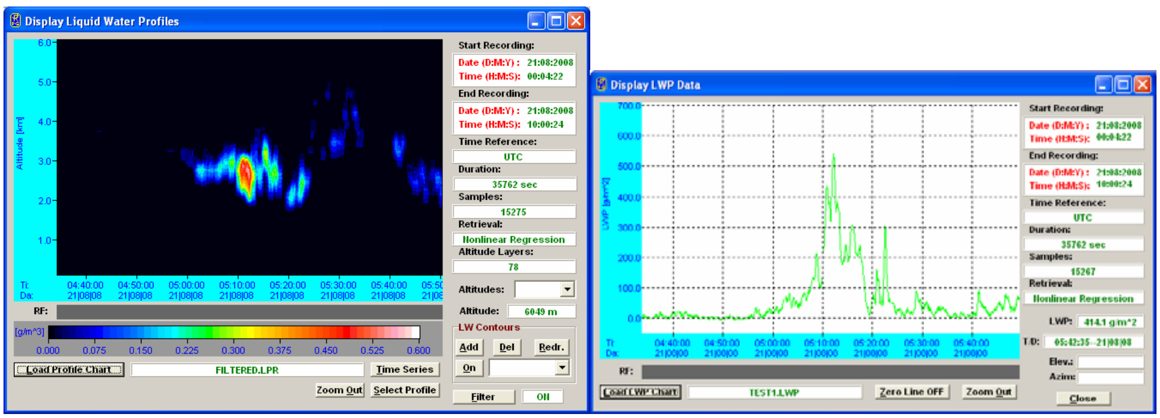
Two isolated clouds with rather high LWP.

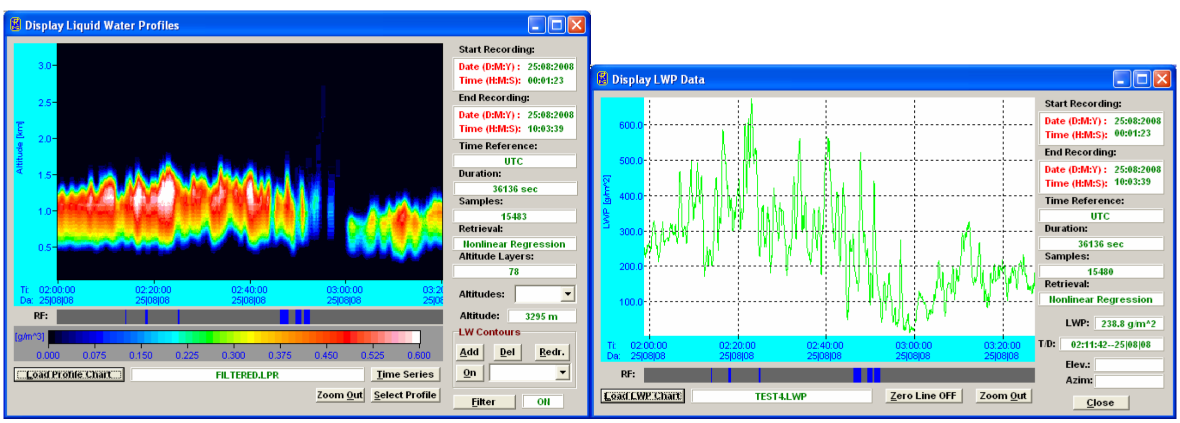




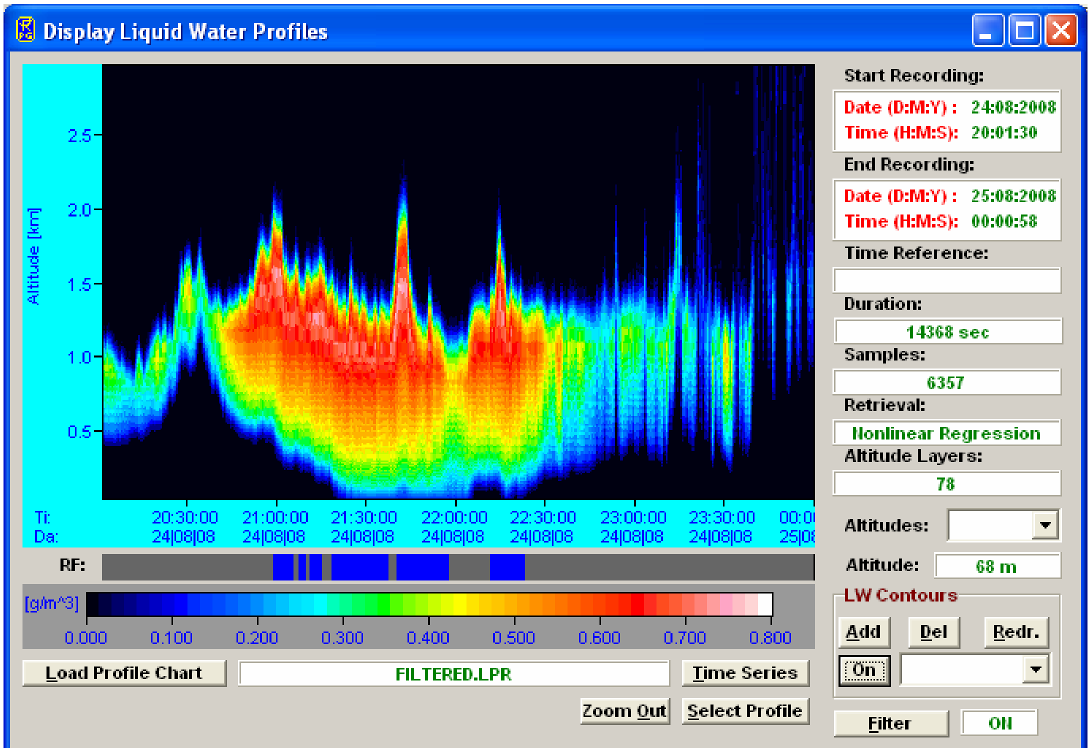
More isolated or broken cloud cover examples.

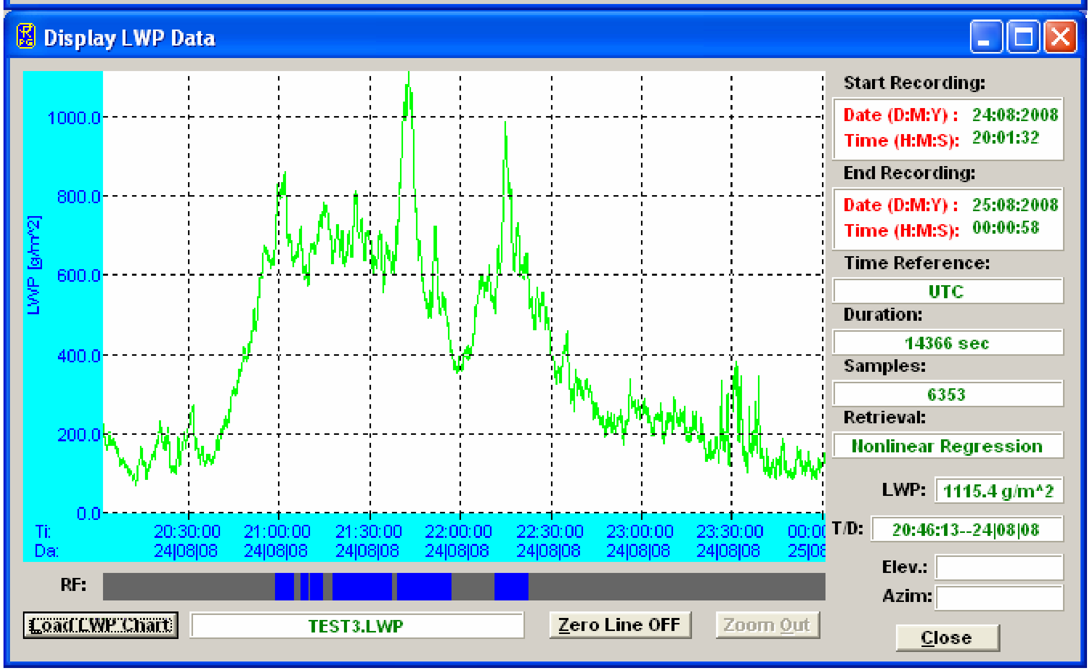




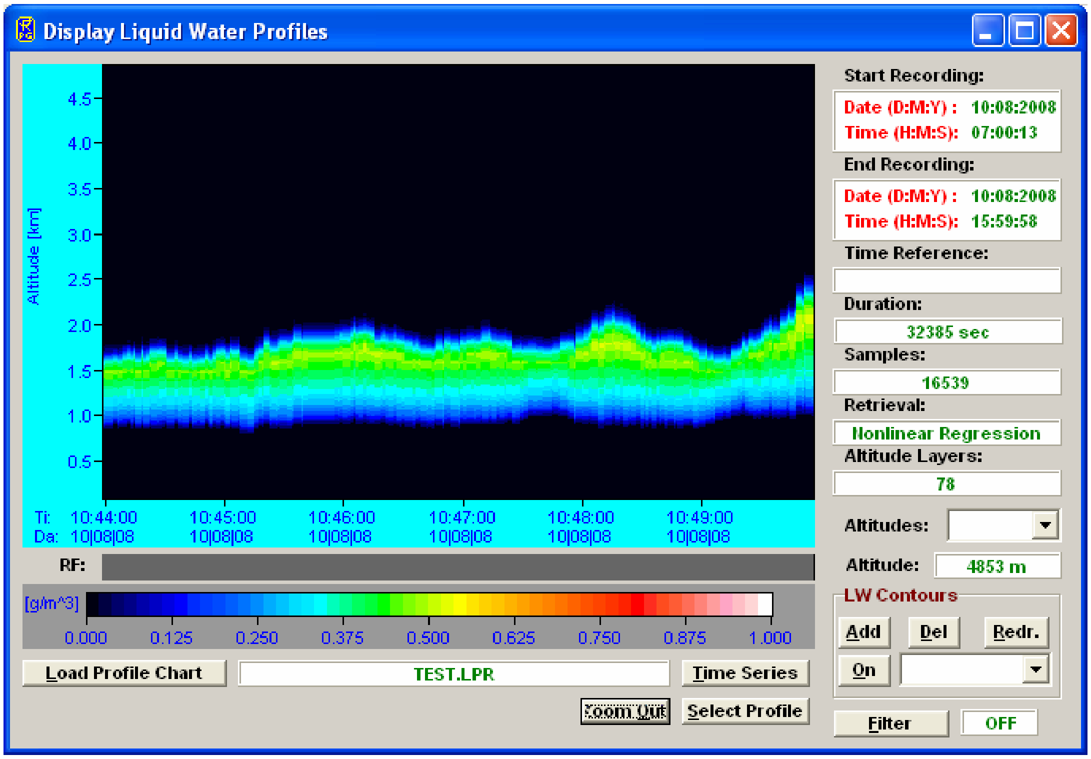


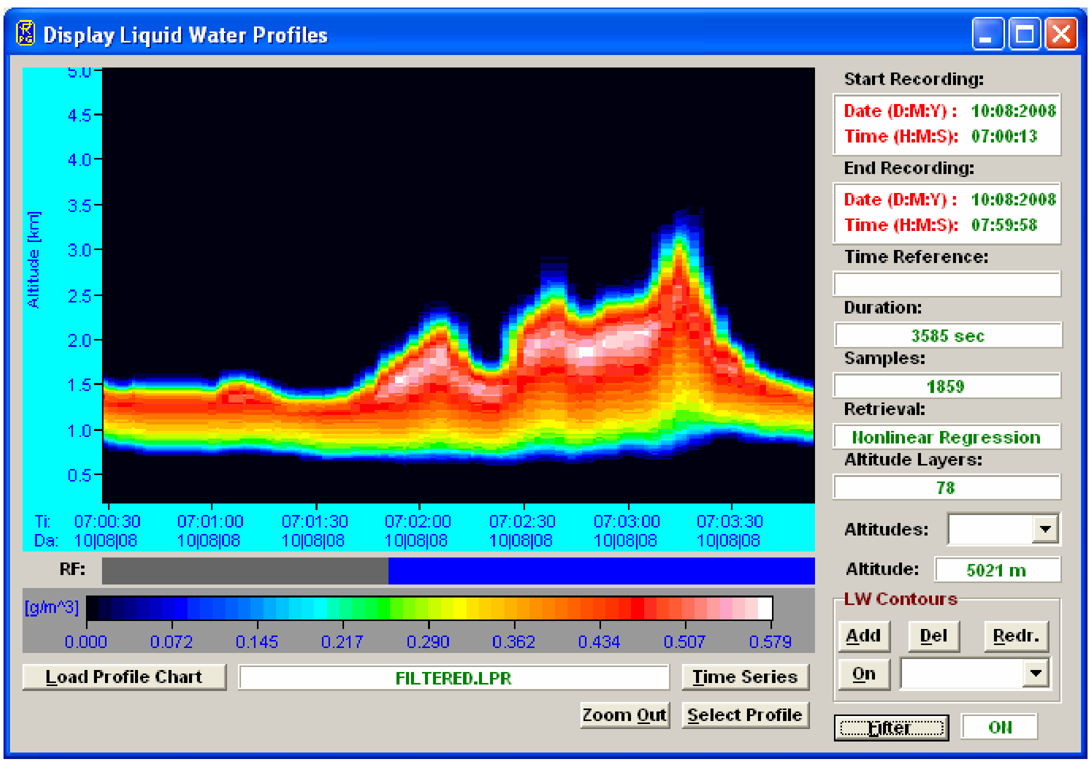
Heavily precipitating cloud layer, extending down to surface.

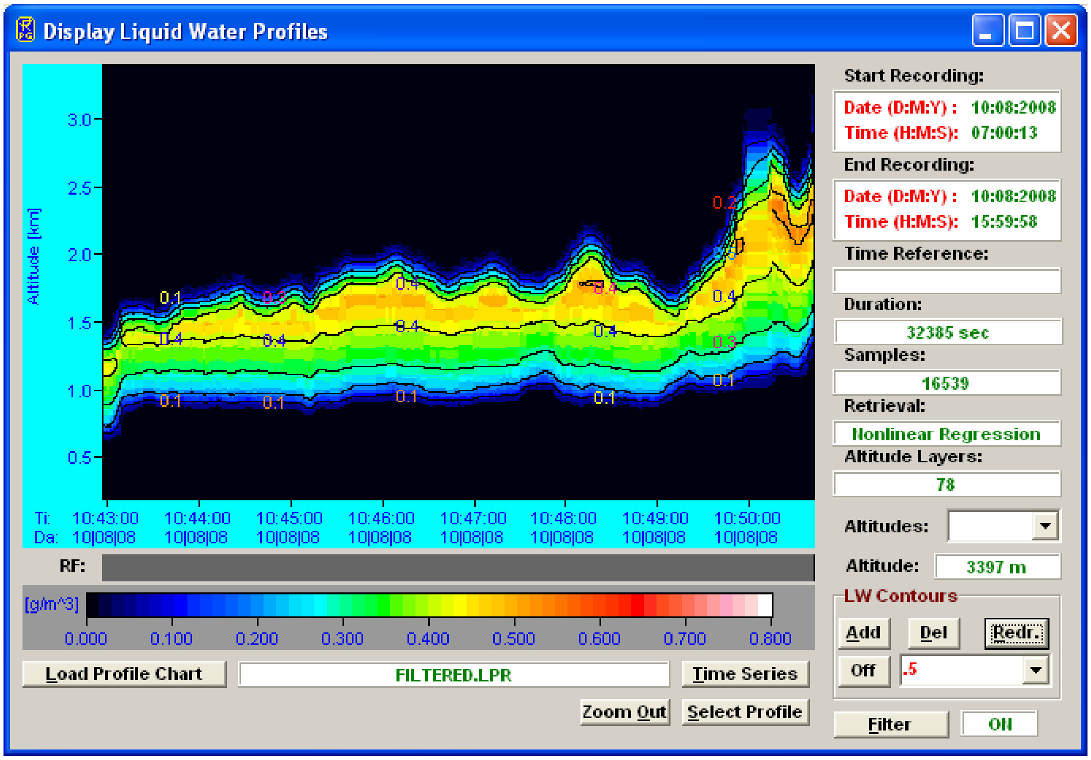




Examples of flat cloud base height.



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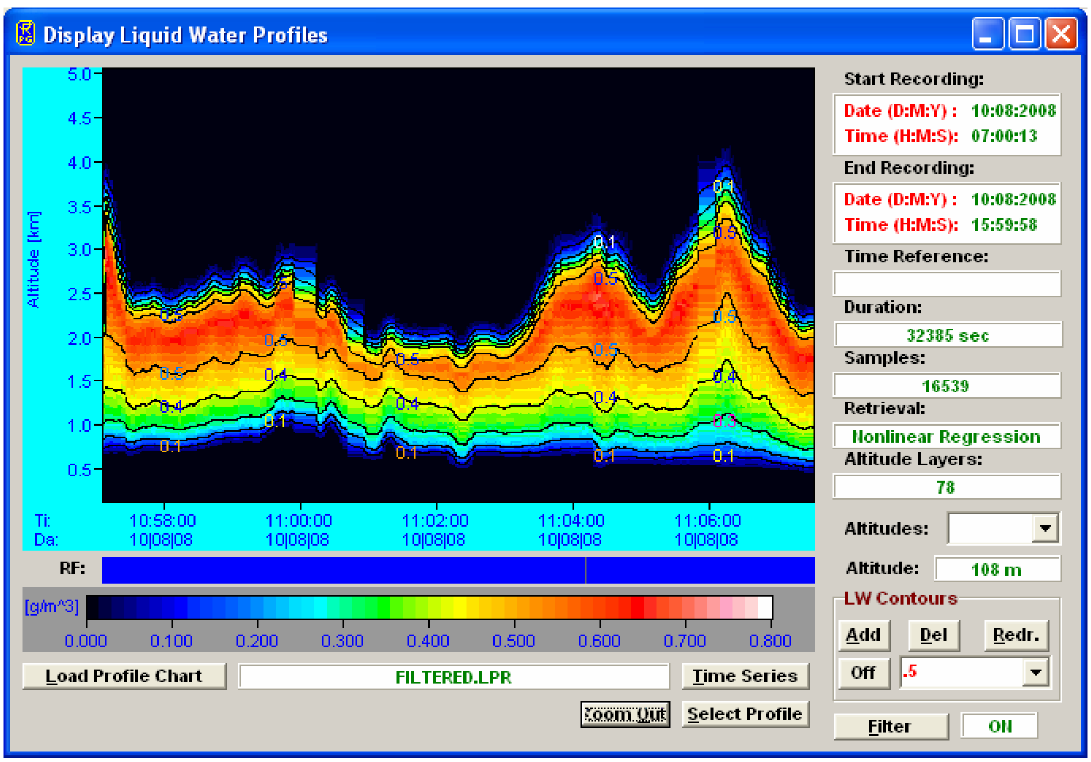
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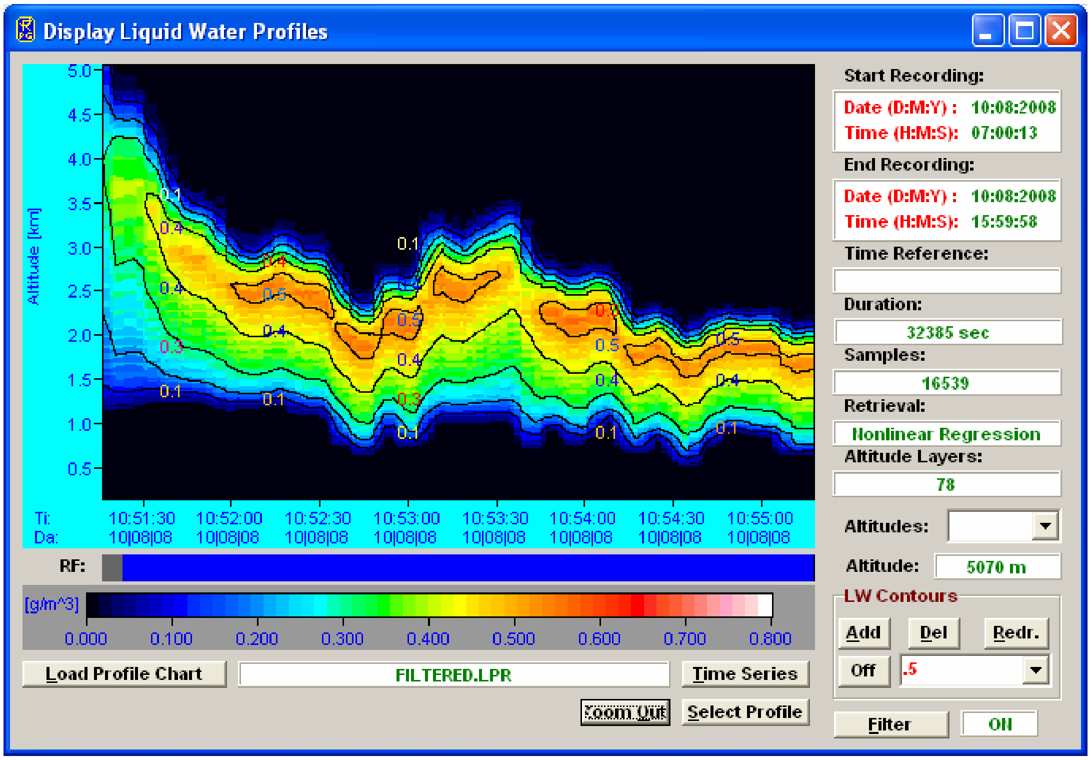
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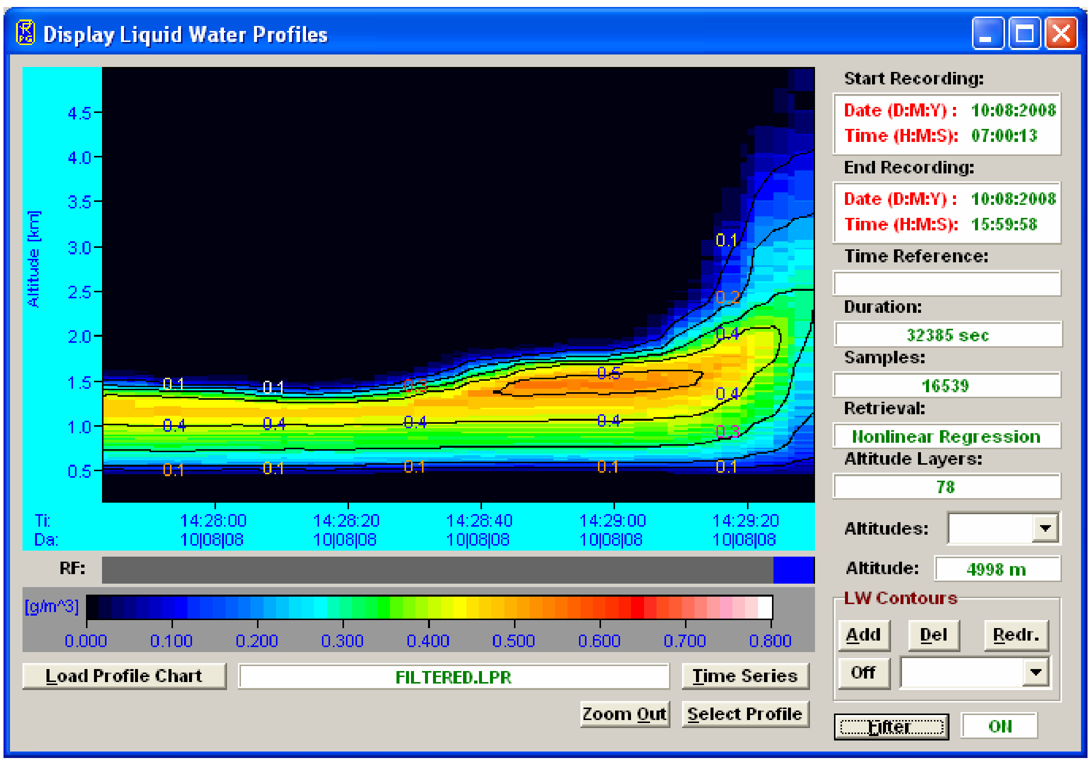
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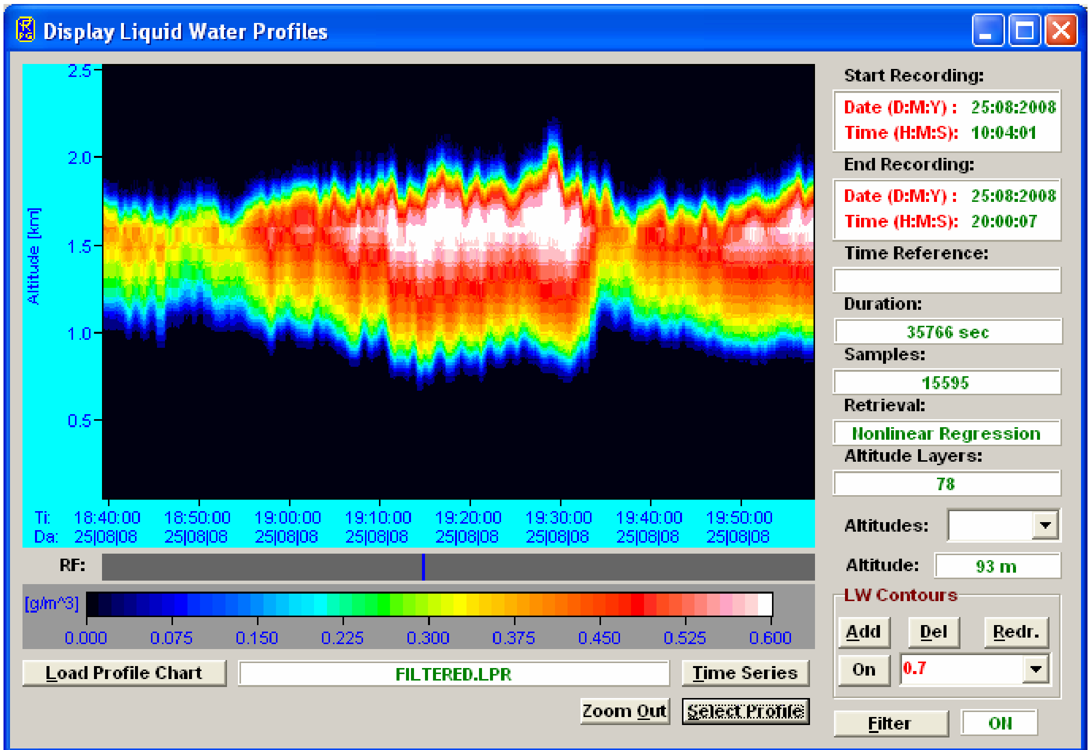
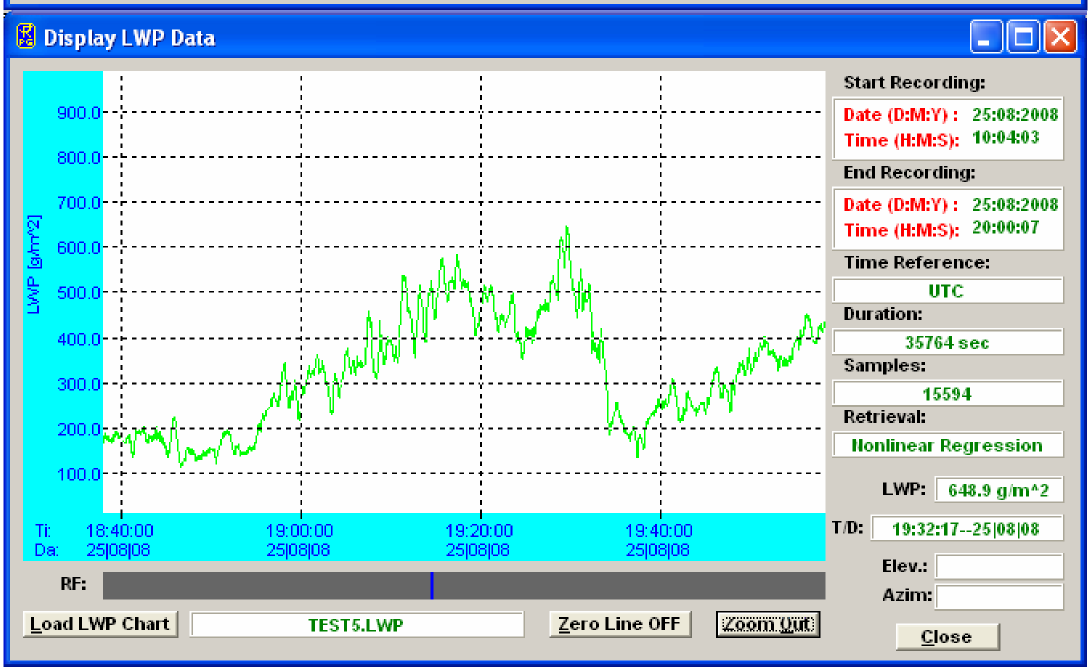
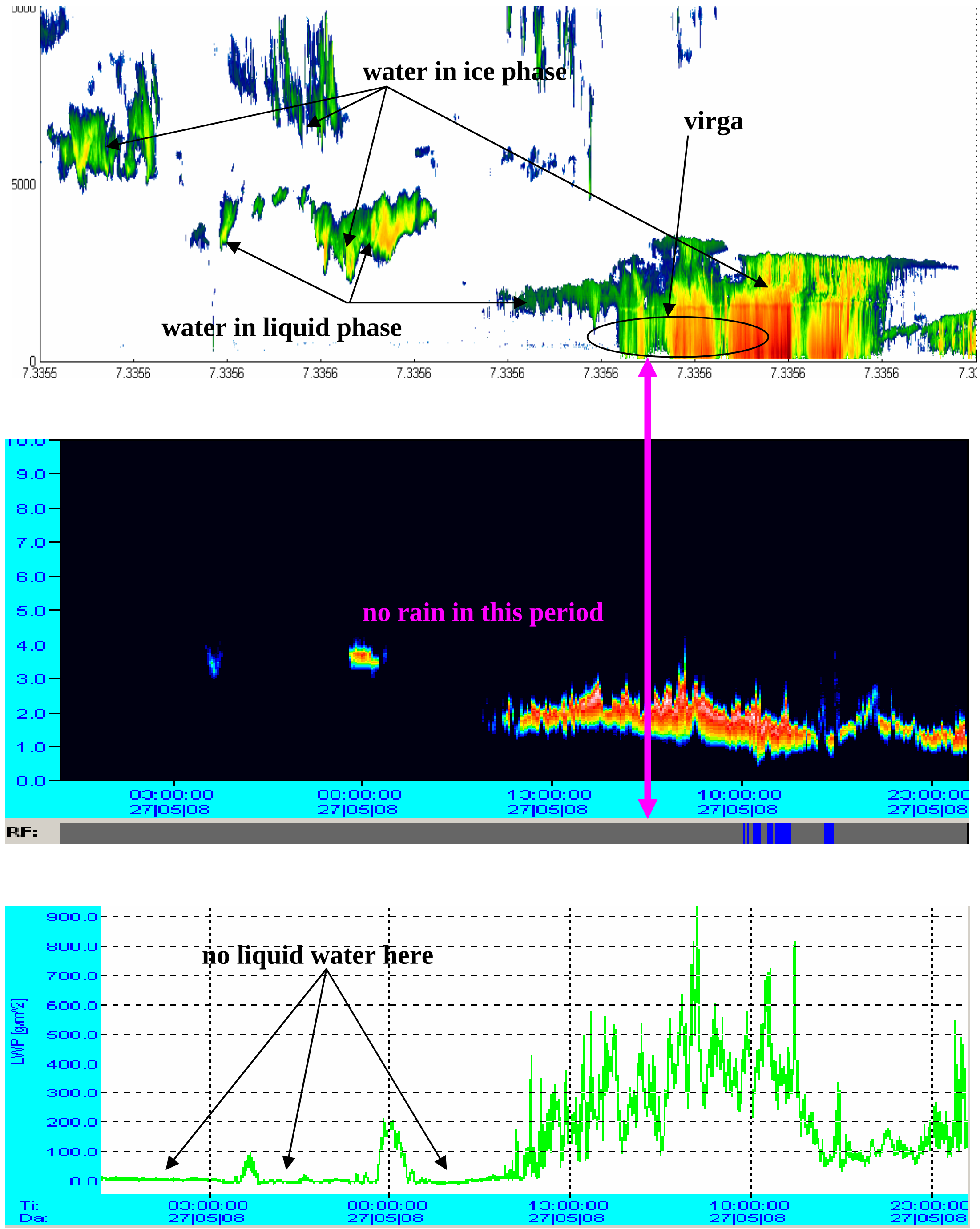




Comparison with Cloud Radar Data

A comparison of the Microwave / IR derived LW profiles with active cloud radar data is useful and interesting. The microwave receivers operating in the 22-32 GHz band are not sensitive to ice clouds which show a strong response in the cloud radar data. Therefore a comparison of both data sources allows for the discrimination of ice and liquid water phases.
Clouds of high integrated water content often develop a fine curtain of rain with small droplets which never reach the ground (virga). Virga is not detected in the IR but generates a strong signal in the cloud radar. The IR temperature detects the real cloud base.



water in ice phase
virga
water in liquid phase
5000
0
7.3355
7.3356
no rain in this period
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
03:00:00 27|05|08
08:00:00 27|05|08
13:00:00 27|05|08
18:00:00 27|05|08
RF:
no liquid water here
LWP [g/m^2]
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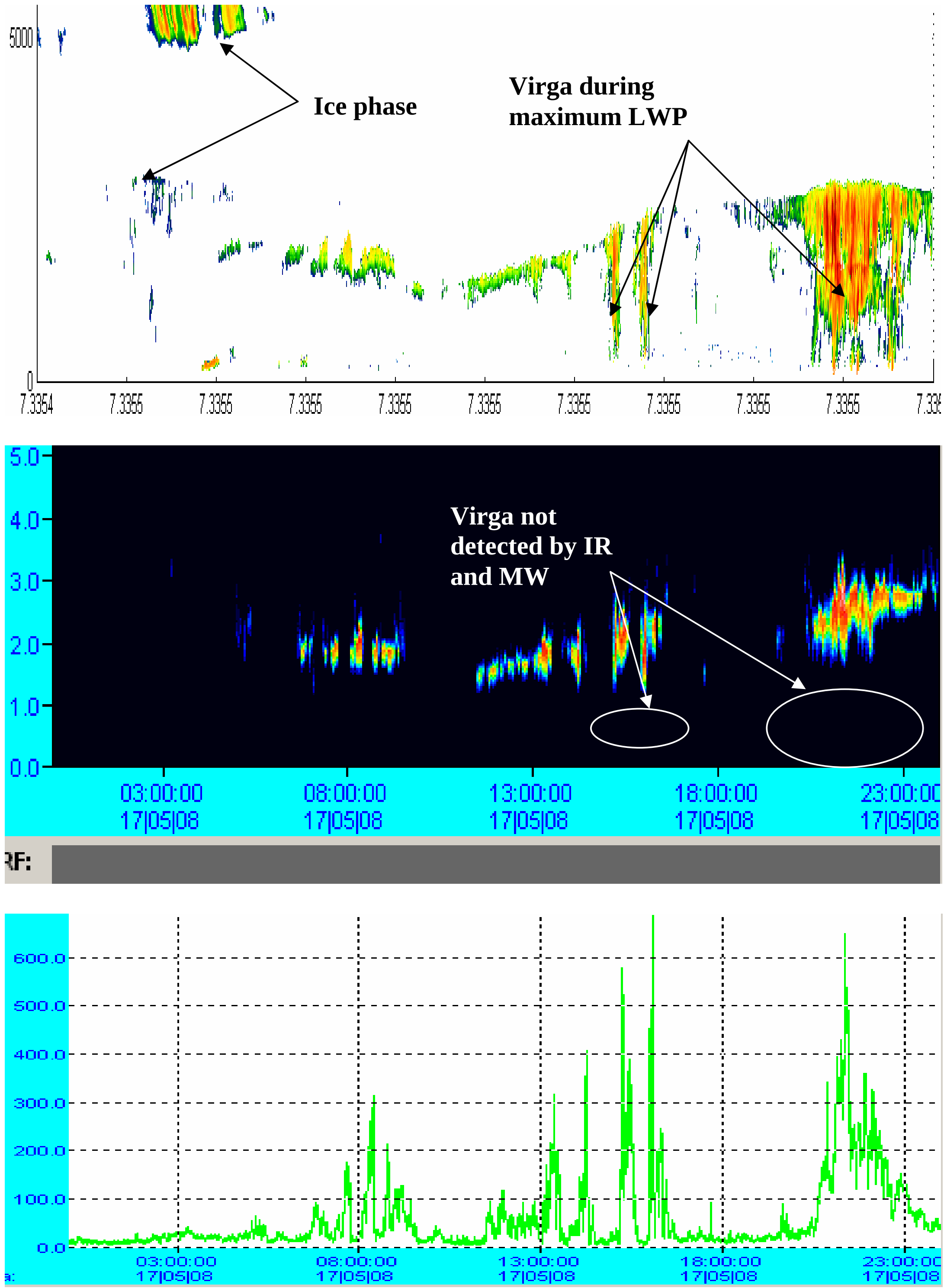

Ice phase
Virga during maximum LWP
5000
0
7.3354
7.3355
Virga not detected by IR and MW
5.0
4.0
3.0
2.0
1.0
0.0
03:00:00 17|05|08
08:00:00 17|05|08
13:00:00 17|05|08
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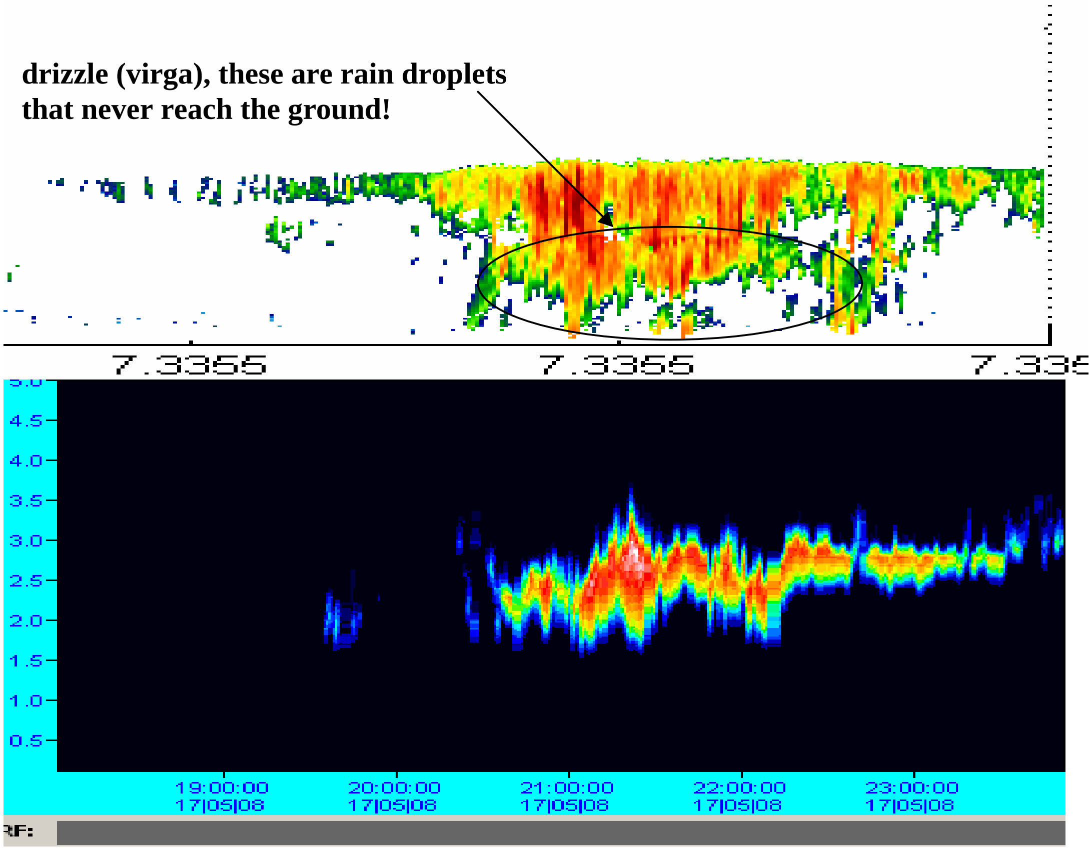
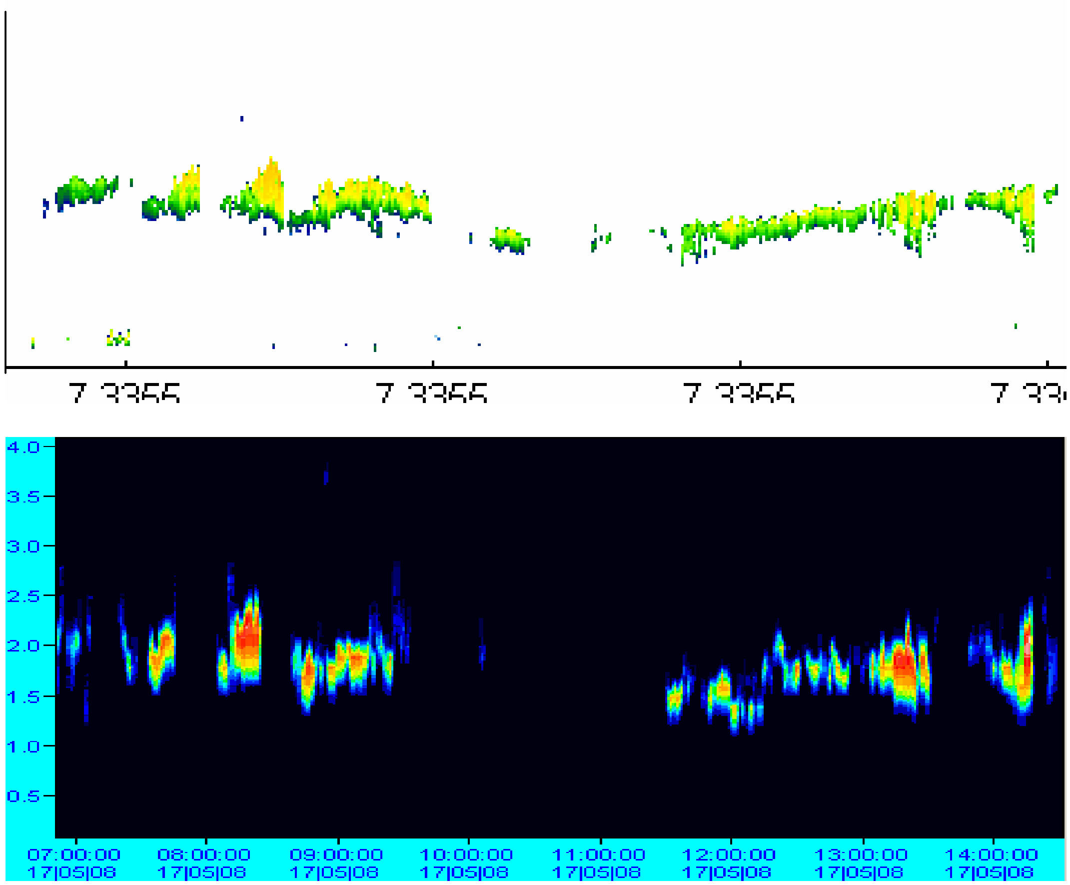


Thin and broken cloud layer, no precipitation:



Heavy clouds and development of temperature inversion, causing a trapped cloud layer with flat cloud top: