P3.5 A COMPARISON OF ATMOSPHERIC PROFILES USING A TWELVE CHANNEL MICROWAVE PROFILING RADIOMETER AND RADIOSONDES DURING LOW CEILING EVENTS

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1. INTRODUCTION

When considering ways to improve short-term forecasts of low ceiling and visibility (C&V) conditions, the availability of new technology providing frequently updated information about the thermodynamic state of the boundary layer and lower free atmosphere becomes of interest. Among the important parameters to consider when determining the likelihood of fog or a low ceiling forming are the evolving stability conditions and vertical distribution of moisture in the lower atmosphere. Once clouds have formed, the amount of cloud water and its vertical distribution are also important parameters.

Typically, the information about these parameters is obtained through rawinsondes launched twice-daily from sites across the country. However, these soundings are few and far between and are insufficient for capturing the spatial and temporal variations of the parameters thought to play a critical role in the formation and evolution of low clouds and fog.

Consequently, the use of newly developed instruments, able to provide information on the evolving thermodynamic structure of the lower atmosphere with a high temporal frequency, should be evaluated to determine if they provide added-value in the context of diagnostic studies of atmospheric C&V phenomenon or short-term forecasts of C&V conditions. One such instrument is the Radiometrics Corporation TP/WVP-3000 12-channel microwave radiometer (MWR) (Ware et al., 2003). This remote sensing instrument provides real-time vertical profiles of temperature, water vapor, and cloud liquid water from the surface up to 10 km in nearly all weather conditions (Ware et al 2004). Here, we seek to assess the accuracy of the information provided by the radiometer in situations characterized by low ceiling conditions by comparing the radiometer data against the additional rawinsonde data collected during low ceiling events.

Previous efforts in evaluating radiometric retrievals were mostly performed by examining overall error statistics obtained through comparisons with sounding data gathered over several months and/or during specific case studies. Error statistics for the retrievals from our unit obtained during 25 low C&V events (68 routine soundings) during the period from Fall 2003 to Spring 2004 (not shown) were similar to those obtained in several other studies (Güldner and Spänkuch 2001, Liljegren 2004, Hewison et al. 2004). In this work, the availability of additional soundings performed at a higher temporal frequency during low ceiling events studied by Tardif (2006) provides additional opportunity to study the evolution of a low ceiling event.

The approach here is to evaluate the ability of the MWR to represent the evolving vertical structure of the atmosphere during low ceiling events . This is done through a focused comparison of the retrievals with coincident high-resolution sounding data and derived parameters such as adiabatic cloud water content.

2. INSTRUMENTATION AND DATA

A Radiometrics TP/WVP-3000 12-channel microwave radiometer is deployed at an instrumented site located at the Brookhaven National Laboratory in eastern Long Island, NY (Tardif et al. 2005). This site is the central facility of a multi-year study of the development and dissipation of fog and low clouds in the northeastern United States. The MWR is a passive instrument that measures radiation intensities at 12 wavelengths within the microwave spectrum. Five of the wavelengths are dominated by water vapor emissions and seven are dominated by molecular oxygen emissions allowing for the retrieval of temperature, water vapor and liquid water. Measurements of brightness temperatures are made with a vertically pointing mirror. The beamwidth for the 51-59 GHz oxygen absorption band is 2-3^{o}, while the beamwidth is 5-6^{o} in the 22-30 GHz water vapor absorption band. The retrievals are performed using a neural network approach (Solheim et al., 1998) as provided by the manufacturer. Neural network profile retrievals are provided at 100 m intervals from the ground to 1 km and at 250 m intervals from 1 to 10 km. Training of the neural network is performed through forward modeling of microwave radiation using data from the available historical soundings from 1994 to 2003 from the nearby sounding site in Upton NY (KOKX) in order to incorporate information about the local climatology. Routine surface measurements as well as measurements from a vertically pointing infrared thermometer are also incorporated in the retrievals (Ware et al. 2003). The calibration of the instrument is performed using a liquid nitrogen target for the wavelengths in the oxygen absorption band, while the calibration of the water vapor channels is continuously performed using the tipping curve technique (Han and Westwater 2000). A recent software upgrade allows for retrievals to be performed with a 1-min. time interval.

The set of additional soundings was obtained during a period of enhanced activity at the field site, during which the NCAR mobile GPS LORAN Sounding System (GLASS) was deployed. The mobile GLASS consists of a vehicle fitted with equipment used to

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launch and track weather balloons as well as with surface sensors measuring ambient temperature, humidity and wind. During the experiment, balloons were configured for slow ascent in order to maximize the number of data points in the boundary layer. Biases in temperature and humidity from the Vaisala RS-80 sondes were corrected using comparisons with concurrent surface observations from the mobile GLASS and from the 90 meter instrumented tower. Most of the rawinsondes used in the evaluation presented here were co-located with the radiometer. Comparisons with the NWS routine soundings located less than 1 km away are also presented.

3. EVALUATION OF RETRIEVALS

The evaluation of the radiometric retrievals is presented in the form of comparisons between the retrieved profiles of temperature, humidity and cloud water with corresponding values measured or derived from these measurements during the ascent of the rawinsondes. These comparisons are presented in the form of profiles of temperature (T) and dew point temperature (T_d). Since T_d is not a direct retrieval from the radiometer, it is inferred from the retrieved values of temperature and water vapor density, while assuming a hydrostatic atmosphere. Cloud liquid water content (LWC) estimates are derived from temperature and humidity data from the rawinsondes by assuming an adiabatic profile from cloud base to cloud top and are estimated from the high-resolution sounding observations. A number of rawinsondes were launched at various time intervals during low ceiling events (typically every couple of hours). Comparisons between the MWR retrievals with soundings performed during two intrusions of marine boundary layer clouds over Long Island are the focus of this study.

3.1 May 11th 2005

A marine stratus layer propagated northward over Long Island NY on the night of May 11th 2005. Observations from the ceilometer indicate that the stratus reached the field site at 0330 UTC with a cloud base at about 150 m (top section of Fig. 1). An analysis of high-resolution soundings suggested that the high stability found in the inversion at cloud top and the significant amount of moisture above the cloud layer contributed to the persistence of the cloud layer as it propagated northward (Tardif 2006).

First, the MWR retrieval of the integrated liquid water (or liquid water path, LWP) indicates the instrument detected the presence of the cloud (lower panel of Fig. 1). The non-zero LWP values provided by the radiometer under clear sky conditions during the first 3 hours on the 11th suggest a "noise level" of the instrument of about 0.1 mm to 0.2 mm. The increase of radiometric LWP values above that noise level corresponds to the appearance of the cloud over the instrument as detected by the ceilometer.

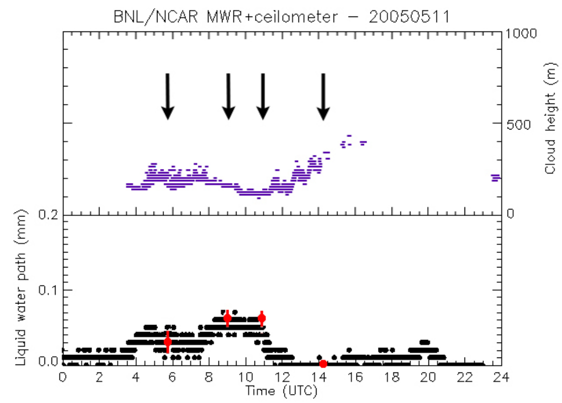

Figure 1. Temporal evolution of cloud base height from the ceilometer (top section) and of the retrievals of liquid water path by the MWR on May 11th 2005. Arrows in the top panel indicate times at which rawinsondes were launched.

An issue to consider when comparing profiles obtained from rawinsondes and MWR retrievals is the possible discrepancy between the profiles related to the difference in the "representativeness" of the measurements. Comparisons of point measurements of in-situ sounding data versus the MWR retrievals indirectly inferred from radiation emitted from atmospheric volumes are likely to yield some differences. The variability in atmospheric volumes, if present, is not properly represented by the in-situ point rawinsonde measurements, while it may be "observed" by the MWR, albeit in a volume-averaged manner. In an attempt to gleam some insight into the issue of the representativeness of rawinsonde point measurements, a GLASS high-resolution sounding was performed concurrently with the 12 UTC routine sounding at OKX on May 11th (launched at approximately 11 UTC). Both rawinsondes were launched within minutes of each other from locations about 1 km apart. The comparison between profiles over the lower troposphere shows very good agreement between the two soundings (Fig. 2). Some discrepancy can be observed in the humidity profiles. Profiles in the cloudy boundary layer are not as well resolved in the processed OKX sounding data as in the high-resolution GLASS sounding. Differences are also observed in the observations reported just after the sondes had gone through the cloud layer. Both soundings indicate an increase in dew point temperature in the stable atmosphere above the boundary layer, but disagree somewhat with the position of the layer with the maximum relative humidity. Very good agreement is observed for measurements taken above 800 m. These results therefore suggest the spatial and temporal variability of the lower troposphere was minimal and that soundings performed during this event provide adequate sampling of the actual structure of the atmosphere and thus provide a solid basis for the evaluation of radiometric retrievals. Even if the evaluation of the MWR through a comparison with balloon soundings remains imperfect, the retrievals should still be able to agree to a significant degree with these soundings.

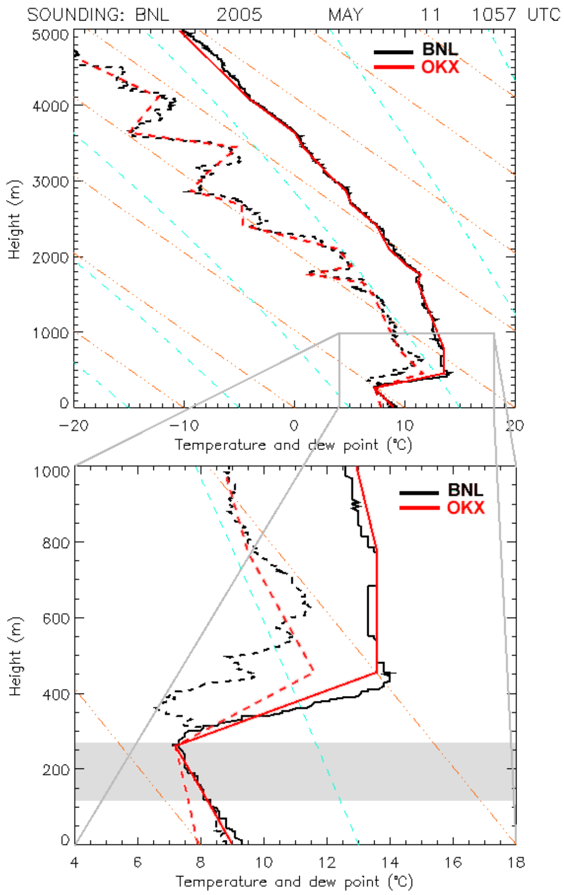

Figure 2. Comparison of temperature and humidity profiles from soundings performed concurrently at BNL and at nearby OKX. The shaded area in the bottom panel highlights the estimated location of the cloud layer. Soundings launched at approximately 11 UTC on May 11th 2005. The thin dot-dashed orange lines represent dry abiabatic lapse rates while the thin dashed blue line represent moist-adiabatic lapse rates.

As previously mentioned, four GLASS soundings were performed during the low ceiling event, complementing the data gathered from the routine soundings performed daily at 00 and 12 UTC. Starting with the 00 UTC OKX sounding on May 11th (actually launched sometime around 23 UTC on the 10th, ~4 ½ hours prior to the arrival of the stratus layer), the measurements show a colder layer near the surface corresponding to the intrusion of the marine air associated with a sea-breeze circulation (Fig. 3). A shallow inversion capped this cooler marine boundary layer, while significant levels of humidity were observed in the lower free atmosphere. Profiles from the MWR show a good agreement with the observed temperature and humidity data in the boundary layer, but show some inaccuracy in the representation of the vertical variations in temperature and humidity above. A change from neutral to stable stratification is observed in the lower levels of the retrievals, but the strong stability of the capping inversion is underestimated. An isothermal layer is found in the MWR profiles from 100 m up to 900 m, instead of the sharp and shallow inversion found in the sounding between 200 m and 400 m. A slight underestimation of humidity in the lower free atmosphere also characterizes the MWR retrievals.

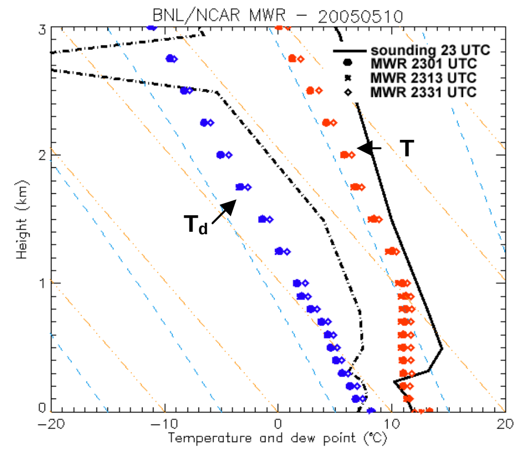

Figure 3. Comparison of temperature and humidity profiles from the 00 UTC OKX sounding (lines) on May 11th 2005 and the corresponding MWR retrievals (symbols). MWR profiles are shown at ~15 min intervals as a representation of the variability over the first ~30 minutes of the flight of the rawinsonde.

Comparisons of the MWR retrievals with measurements from the GLASS soundings are shown in figure 4. A study of these soundings by Tardif (2006) pointed out the role of the temperature and humidity vertical structure near cloud top in an explanation of the persistence of the low cloud layer as it propagated northward. For the 0547 UTC sounding (Fig. 4a), the corresponding temperature retrievals show an accurate lapse rate in the lowest 300 m compared to the rawinsonde (although retrievals performed 18 and 30 minutes later do not seem as accurate). However, the lapse rates characterizing the upper part of the cloudy boundary layer and the capping inversion found above cloud top are underestimated. Furthermore, the humidity in the cloudy boundary layer and in the lower free troposphere is underestimated. Similar comments can be made about the comparisons between the MWR profiles and the subsequent soundings launched during the presence of the low stratus (Fig. 4b and c).

The comparison of MWR retrievals and the sounding performed after the cloud had dissipated (Fig. 4d) shows the observed transition to unstable stratification in the lower boundary layer is well represented in the MWR profile of temperature. However, the lack of definition of the capping inversion at the top of the boundary layer leads to a cold bias in the retrievals of temperature in the lower troposphere, even thought the lapse rates are generally well represented above 400 m. The retrieved humidity profile suffers from a significant dry bias. Even though the surface observations are in good agreement between the MWR and the sounding, the drying observed in retrievals between the surface and 100 m is not corroborated by the in-situ rawinsonde data. Also, the apparent moistening of the troposphere that took place above 1 km between 0904 UTC and 1415 UTC is

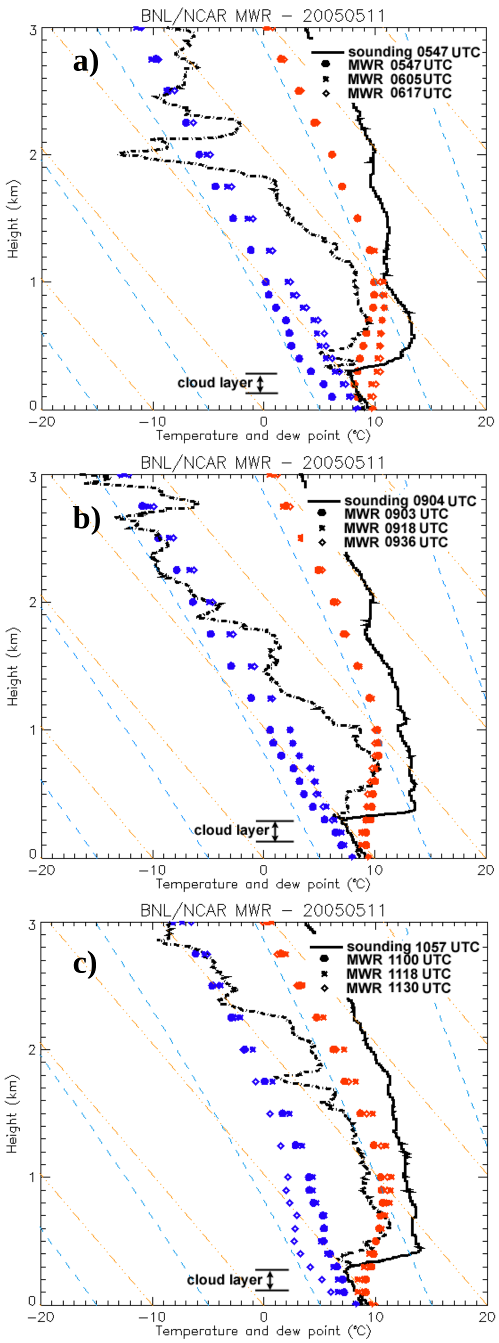

Figure 4. Same as figure 3, but for GLASS soundings (lines) launched on May 11th 2005 at a) 0547 UTC, b) 0904 UTC and c) 1057 UTC. MWR profiles are shown at ~15 min intervals as a representation of the variability over the first ~30 minutes of the flight of the rawinsondes.

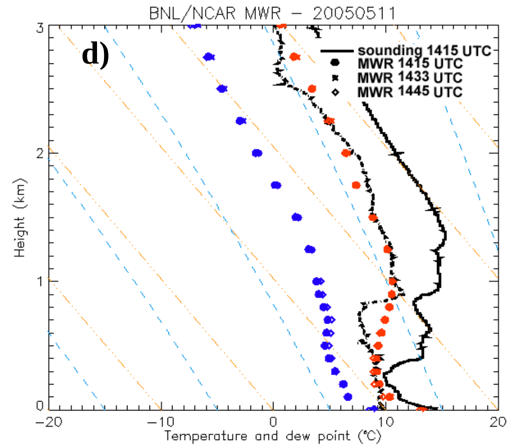

Figure 4 (continued). d) profiles at 1415 UTC.

represented but underestimated in the humidity retrievals.

The radiometric retrievals of cloud water are evaluated next. This event represents a suitable situation for this evaluation since a single cloud layer was present. This fact is indicated by the soundings and corroborated by satellite imagery (not shown). An increase in the retrieved integrated liquid water content, or liquid water path (LWP), was shown to correspond well with the time series of ceilometer cloud base returns (Fig. 1). The high resolution profiles from the GLASS soundings are used to estimate the liquid water content (LWC) of the stratus layer by assuming an adiabatic LWC. Observations reported in previous studies suggest that such an assumption provides for realistic LWC profiles for stratiform boundary layer clouds, but may lead to an overestimation of the LWC by a few percent toward cloud top (Nicholls 1984, Nicholls 1989, Albrecht et al. 1990, Pawlowska et al. 2000, Zuidema et al. 2005). The cloud layer boundaries are estimated through a close examination of the high-resolution relative humidity profile derived from the sounding temperature and humidity data. The adiabatic LWC is then determined by using the observed temperature at cloud base and assuming the conservation of total water along with a moist-adiabatic temperature lapse rate until cloud top is reached. The adiabatic LWP values obtained for each GLASS sounding are shown as red dots in Fig. 1. The results show a good agreement between the MWR retrievals and the sounding estimates. These are on the high-end of the MWR values, confirming the possible overestimation of values derived using the adiabatic assumption. The main conclusion that can be drawn from this comparison is that the high temporal resolution MWR retrievals seem to have the ability to detect observed changes in the total cloud water content.

In terms of the vertical distribution of the cloud water, the MWR profiles are compared with the adiabatic estimates derived from the high-resolution soundings (Fig. 5). As mentioned earlier, observed LWCs are usually found to be sub-adiabatic to some degree, nevertheless adiabatic profiles provide a significant degree of realism for non-precipitating stratiform clouds found atop well-mixed boundary layers (as is the case here). On a coarse scale, the MWR correctly retrieved the largest amounts of cloud water in the lowest 500 m of the atmosphere during the event. Furthermore, it correctly reproduced the ~50% increase in the maximum LWC between 0547 UTC and 0904 UTC, as well as the steady conditions suggested by the 0904 UTC and 1057 UTC soundings.

However, the MWR profiles do not match the physical realism of adiabatic profiles. For instance, the maximum LWC is underestimated and found to be too low to some degree. The underestimation of the maximum LWC is likely related to cloud water being distributed over a layer that is too deep (from the surface up to 1 km). Furthermore, cloud water contents in the 0.05 to 0.07 g kg^{-1} range are found at the surface. According to an analysis of observations of visibility and fog water content from instruments collocated with the radiometer (not shown), such values should correspond to a dense fog with visibilities below 300 m. The presence of such a fog is uncorroborated by visibility and ceilometer observations in this case. These results suggest that the introduction of additional information from other sensors and more sophisticated physical models as constraints in the retrieval process could lead to a refinement of the low resolution MWR LWC retrievals.

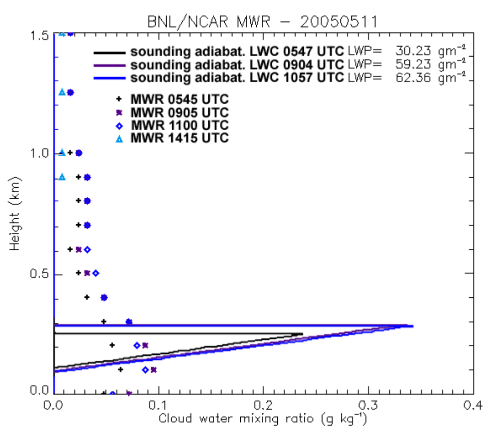

Figure 5. Profiles of liquid water content (LWC) from the MWR (symbols) at times corresponding to the available GLASS soundings, and the adiabatic LWC profiles estimated from the high-resolution sounding data, on May 11th 2005.

Tardif (2006) examined conditions of turbulence and entrainment near cloud top from the 0547 UTC high-resolution GLASS sounding data to assess the conditions related to the likelihood of cloud breakup versus its persistence as it advected inland. Here, a parameter used in this analysis, the criteria for cloud top entrainment instability (κ), is evaluated using MWR profiles as an extra step in the evaluation of the reliability of radiometric profiles for diagnostic studies. κ is a function of the vertical gradients in liquid water static energy Δs_l and total water Δq_t between the cloud layer and the atmosphere above. These parameters are evaluated using retrievals of temperature, water vapor and liquid water averaged over a 20-min window around the time of the launch of the rawinsonde to minimize sampling errors. Retrievals at 200 m and 400 m are used to represent the layers of interest, and also correspond to the part of the atmosphere in which the observed cloud top was located. Values of $\Delta s_l \approx 2566$ J kg^{-1} and $\Delta q_t \approx$ -0.6 g kg^{-1} are found, yielding a value of $\kappa \approx$ -0.7. This is in comparison with $\Delta s_l \approx 1117$ J kg^{-1}, $\Delta q_t \approx$ -0.5 g kg^{-1} and $\kappa \approx 0.1$ obtained from the sounding data. Although the conclusion about the stability of the cloud would remain the same (stable cloud layer with κ smaller than the critical value of 0.23), values obtained from the MWR are significantly different than those obtained from the in-situ sounding data.

3.2 May 17th 2005

MWR retrievals performed during a low ceiling event that occurred during the nighttime hours on May 17th 2005 are evaluated in this section. A marine fog/stratus cloud system began to move inland at sunset and reached the radiometer site at 00 UTC on the 17th (Fig. 6). The low cloud persisted until a little before 0830 UTC. As the low cloud eroded and completely dissipated, the ceilometer detected the presence of an upper cloud layer. GLASS soundings were again performed during this event.

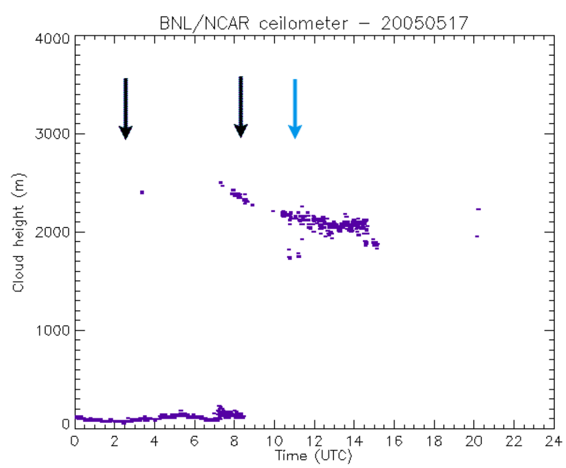

Figure 6. Temporal evolution of cloud base height from the ceilometer on May 17th 2005. Arrows indicate times at which rawinsondes were launched.

Key features in the sounding profiles are the presence of a well-mixed saturated layer in the lowest ~200 m capped by a strong inversion during the night, along with another thin saturated layer detected around 2000 m to 2500 m (Fig 7). This saturated layer is also superimposed by an inversion in which a significant decrease in moisture was observed. This confirms the appearance of a thin upper cloud layer as the low ceiling event unfolded. Even though the amount of water in the upper cloud should be fairly small, its presence creates some ambiguity in the evaluation of the MWR LWC retrievals as far as the low cloud is concerned. Other key features characterizing the series of soundings are the lowering of the upper cloud and capping dry layer over time, but more importantly the cooling and drying of the layer located just above the top of the low cloud up to about 1 km observed between 0231 UTC and 0822 UTC. Drying at lower levels is only evident when comparing profiles from the 0822 UTC and 11 UTC soundings (Figs. 7b and 7c). An analysis of sounding profiles by Tardif (2006) suggests that the rapid erosion of the low cloud layer was related to the drying of the air just above the cloud and its entrainment into the cloudy boundary layer, leading to unstable conditions according to cloud top entrainment instability (CTEI) theory. These key elements serve as the basis for the evaluation of the MWR retrievals, from the point of view of their representation of the evolving atmospheric structure during this event.

An examination of the MWR temperature and humidity profiles reveals some shortcomings, but also some positive features. On the shortcoming side, the lack of definition of changes in stability in and just above the cloudy boundary layer is noteworthy. The neutral stratification (in a moist sense) in the lowest 200 m and the strong stability characterizing the capping inversion are misrepresented (Fig 7a). The boundary layer tends to be too dry, while the thin saturated layer aloft is absent in the retrievals due to a dry bias in the humid lower free troposphere. On the positive side, the observed cooling that took place between 0231 UTC and 0822 UTC at about 400 m, leading to a weakening in the strength of the capping inversion, along with the decreasing moisture toward the top of the boundary layer, are both represented in the retrievals. This is better illustrated in figure 8, where the temporal evolution of temperature and water vapor density from the MWR is compared to the available sounding data. The cold bias in the temperature at 400 m, related to the misrepresentation of the temperature inversion during the low ceiling event and to the erroneous retrieval of a deep well-mixed boundary layer in the early morning sounding (11 UTC), is well illustrated (Fig. 8a). Nevertheless, the magnitude of the cooling compares favorably with the trends suggested by the sounding data. As far as moisture is concerned, the comparison with trends inferred from the soundings is again favorable despite the apparent dry bias during the early hours on the 17th and a possible overestimation of moisture later on. The variability present in the MWR data around the time of the low cloud dissipation, notably the increase in moisture at 0830 UTC, cannot be confirmed due to a lack of in-situ data.

As done previously, the potential for CTEI is examined with MWR data, using values at 100 m and 300 m corresponding to retrievals performed around 0822 UTC. Values of $\Delta s_l \approx 1458$ J kg^{-1} and $\Delta q_t \approx -0.9$

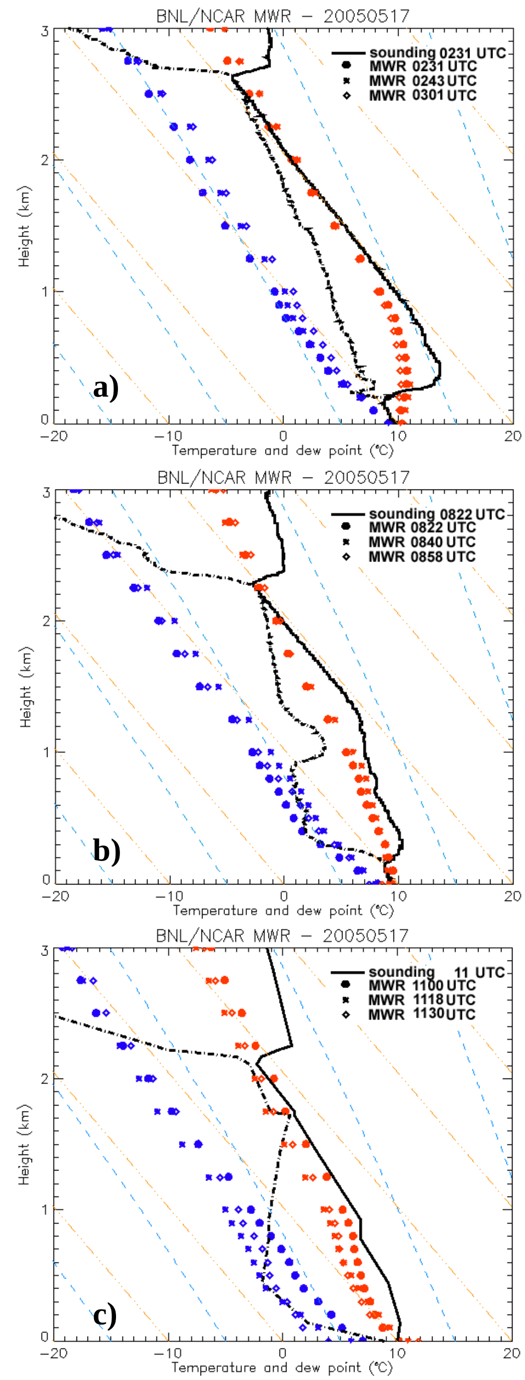

Figure 7. Profiles of temperature and dew point temperature from soundings (lines) launched on May 17th 2005 at a) 0231 UTC, b) 0822 UTC and c) 11 UTC, with corresponding MWR retrievals. MWR profiles are shown at ~15 min intervals as a representation of the variability over the first ~30 minutes of the flight of the rawinsondes.

g kg^{-1} are found, yielding a value of $\kappa \approx 0.3$. This is compared to $\Delta s_l \approx 4060$ J kg^{-1}, $\Delta q_t \approx -2.0$ g kg^{-1} and $\kappa \approx 0.19$ obtained from the sounding data. Although the conclusion about the stability of the cloud would again be the same as with the rawinsonde (unstable cloud layer with κ larger than the critical value of 0.23), values obtained from the MWR are significantly different than those obtained from the in-situ sounding data.

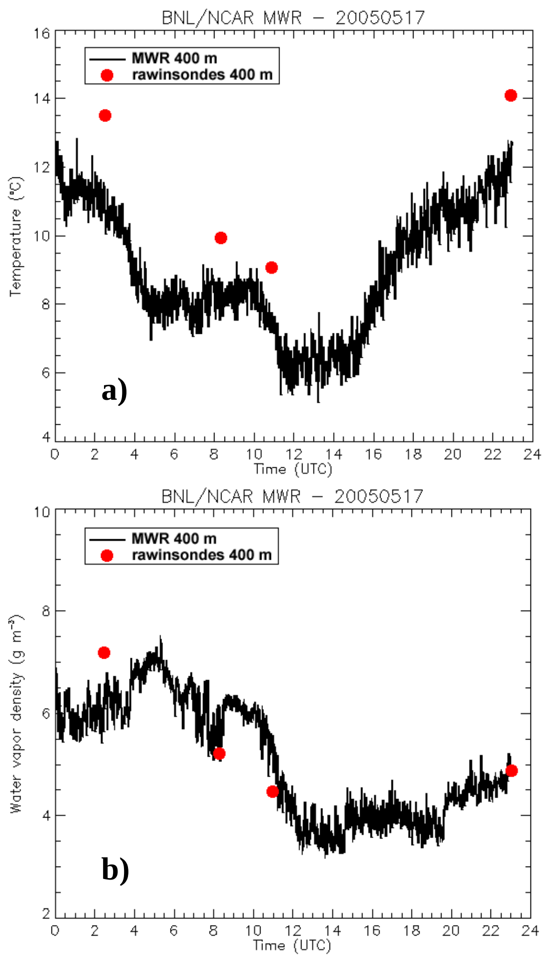

Figure 8. Temporal evolution of the MWR retrieved a) temperature and b) water vapor density at 400 m on May 17th 2005. Corresponding values extracted from the available soundings are shown as red dots.

4. SUMMARY AND DISCUSSION

The evaluation of retrievals from a profiling microwave radiometer deployed at a coastal location (Long Island) in the northeastern United States has been presented. High-resolution soundings performed during low ceiling conditions were used as a basis for the evaluation.

Our studies indicate that the MWR retrievals exhibit both strengths and weaknesses. For instance, evidence was found that radiometric retrievals are able to capture changes in stratification within the lower boundary layer. On the other hand, they were found to provide a poor representation of cloud-top inversions. An underestimation of temperature and humidity contrasts, often observed between the boundary layer and the lower free atmosphere aloft, is generally found in the retrievals. These limitations severely limit the diagnostic value of MWR profiles in situations where sharp vertical gradients define the critical characteristics of the environment. Although this study has shown that the CTEI criteria can seemingly be realistically estimated using MWR profiles (at least in a general sense), a closer examination of results point out that this is the result of compensating deficiencies in moisture and temperature retrievals. Namely, the underestimation of moisture gradients compensates for an underestimation in temperature gradients.

The difficulty of the MWR in representing elevated inversions has also been pointed out by Hewison et al. (2004). A study by Rangarajan and Vivekanandan (2002) has shown that the retrieval of such inversions should be possible in principle, although less accurate results should be expected for inversions with bases close to the surface and in cloudy conditions. Both of these factors could have played a role in the results presented in this paper.

The retrievals of cloud liquid water were shown to be excellent in terms of the liquid water path (total amount), but the representation of its vertical distribution is much less accurate. The location of the maximum amount of water was correctly retrieved in low levels (although too low by ~ 200 m), but a tendency to distribute the water over layers too thick was observed. This leads to an underestimation of the retrieved maximum cloud water content in low stratiform clouds.

In spite of these difficulties, microwave radiometry does offer some information about the state of the atmosphere in a nearly continuous manner. This represents a significant improvement over the limitations offered by the few and far apart balloon soundings. This study found that good estimates of the evolution of the liquid water path were provided by the MWR. Also, observed trends in temperature and moisture aloft that played a critical role in the nocturnal dissipation of a low cloud layer were present in the retrievals. Therefore, high-frequency radiometric retrievals appear to provide some degree of useful information about trends in temperature, moisture and cloud water.

However, current ground-based microwave radiometry does have its shortcomings as discussed earlier. These shortcomings should be addressed in order for this technology to be used with increased reliability in a wider range of applications. The vertical resolution of radiometer derived temperature, humidity and cloud water profiles needs significant improvement, particularly in inversion situations. There is potential for such an improvement through the synergistic integration of additional information provided by other sensors. For instance, the use of visibility sensors near the surface and lidar ceilometers would provide constraints on the vertical distribution of cloud water, while active remote sensing instruments such as sodars and boundary layer profilers could provide additional constraints on temperature and humidity gradients, required to increase the resolution of the retrieved profiles (Gaffard et al. 2003, Bianco et al. 2005). Furthermore, the introduction of a more sophisticated physical cloud model in the retrieval process could lead to improved representations of cloud structure. An integrated active-passive remote sensing system could potentially provide for enhanced capabilities in the context of probing and forecasting the fine structure of stratiform boundary layer clouds leading to low ceiling conditions.

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