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Meteorological profiling of the lower troposphere using the research UAV “M^2AV Carolo”

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Abstract. Vertical profiles of temperature, humidity and wind up to a height of 1500 m a.g.l. (above ground level) were measured with the automatically operating small unmanned research aircraft M^2AV (Meteorological Mini Aerial Vehicle) during the LITFASS-2009 (LIndenberg-To-Falkenberg: Aircraft, Scintillometer and large-eddy Simulation) experiment. The campaign took place in July 2009 over the heterogeneous landscape around the Meteorological Observatory Lindenberg – Richard-Aßmann-Observatory in the eastern part of Germany. Due to a high vertical resolution of about 10 cm the M^2AV data show details of the turbulent structure of the atmospheric boundary layer (ABL). One profile took about 10–15 min allowing for a continuous monitoring of certain phases of ABL development by successive ascents and descents during one flight (50–60 min duration). Two case studies of measurements performed during the morning and evening ABL transition periods are discussed in detail. Comparison of the aircraft-based temperature, humidity and wind profiles with tower, sodar/RASS, wind profiler/RASS, radiosoundings and microwave radiometer profiler measurements show good agreement taking into account the different sampling strategies of these measurement systems.

1 Introduction

Vertical profiles of temperature, humidity and wind are important to characterise the vertical structure of the lower troposphere. For instance, the behaviour with height of the virtual potential temperature can be used to identify the thermal stratification. The vertical variation of wind speed and direction leads to wind shear which produces turbulence and thus turbulent fluxes in the atmospheric boundary layer (ABL). Investigations on the characteristics of nocturnal low-level jets, which can generate shear and turbulence below the jet and near the surface, are based on boundary layer wind profiles (Banta et al., 2002). Profile measurements of wind, temperature and humidity can also be used for scaling approaches which are needed for describing turbulence in the ABL.

Meteorological profiles can be obtained from in-situ measurements and ground-based remote sensing systems. The most common in-situ systems for measuring vertical profiles of the lower ABL are tall towers equipped with meteorological sensors. Such towers provide measurements with high temporal resolution and high accuracy. The vertical resolution is limited by the spacing between the installed instruments. Towers do not cover the total ABL in height as they are rarely higher than 200 m a.g.l.

Tethered balloon systems (TBS) and radiosondes also belong to the category of in-situ measurement systems. The vertical operation range of TBS is mostly limited to about 1 km (Storvold et al., 1998). TBS allow for high vertical resolution since it is possible to adjust the ascent speed. One main drawback of TBS is that they can only be launched in low to moderate wind conditions with up to 5 m s^{-1} surface wind and 15–20 m s^{-1} upper air wind (Storvold et al., 1998).

Radiosoundings represent a unique data base of atmospheric profile information since they are performed operationally at a few hundreds of sites all around the world. Measured profiles cover the whole lower atmosphere from ground level up to the 10 hPa level. However, typical ascent frequencies are 2–4 soundings per day giving just snapshot-like

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information about atmospheric structures. Even during field experiments sounding sequences rarely exceed 1.5–3 h which is not dense enough to study in detail certain phases of ABL evolution. The vertical resolution of radiosoundings depends mainly on the ascending speed and is usually not better than a few metres.

Towers, TBS and radiosondes do not provide information about horizontal inhomogeneities. Towers are fixed at one location, thus sample instantaneously at specific points in space and time. TBS and radiosondes sample at one point in space and time for each measured value. As radiosondes drift with the mean wind, vertical profiles are not obtained above the same location.

Remote sensing systems (RSS) are based on the propagation characteristics of electromagnetic and sound waves in the atmosphere. They can be operated continuously after installation, providing a comprehensive database for atmospheric research.

Wind profilers, sodar and Doppler lidar detect signals, that are backscattered from atmospheric structures. Depending on the wavelength of the system, these atmospheric structures are small-scale inhomogeneities of temperature or humidity or aerosol particles. These RSS provide information on the thermodynamic structure of the ABL from the profile of backscattered signals and on the mean wind profile by analysing the frequency shift of the backscattered signal (Doppler effect). A state of the art review of RSS has recently been published in the frame work of COST Action 720 (Engelbart et al., 2009).

Wind profilers are pulsed Doppler radar, which are designed to provide atmospheric measurements in almost all weather conditions. Because of the high propagation velocity of electromagnetic waves the vertical resolution of these systems is limited to about 100 m. Measurements of the three-dimensional wind vector up to 15 km a.g.l. are possible. If an acoustic source is added to a wind profiler, the virtual temperature can be estimated as well. For this radio acoustic sounding system (RASS) the maximum measurement height is limited to the lower and middle troposphere due to attenuation of the acoustic signals.

Sodars offer a vertical resolution of 5 to 20 m, a lowest range gate of 10 to 30 m, and achieve a maximum range up to several hundreds of meters. During periods of heavy precipitation and in situations with missing turbulence no reliable data are sampled by sodar systems. Sodars with RASS extensions already became standard tools in profiling of the atmospheric boundary layer.

Doppler lidar can perform wind measurements up to a maximum of several kilometres with good accuracy. Doppler lidar technique is hampered by strong rain and exceptionally clear conditions.

Snapshot-like vertical profiles of temperature, humidity and wind can be measured at very high sampling rates using research aircraft. The resulting vertical resolution can be in the range of centimetres (Muschinski and Wode, 1998) depending on the instrumentation and the rate of climb and descend. Compared to manned aircraft, unmanned and automatically operating research aircraft (see Fig. 1) present a more flexible and cheaper alternative to obtain in-situ meteorological measurements.

Fig. 1. The M^{2}AV flying near the Meteorological Observatory Lindenberg – Richard-Aßmann-Observatory during the LITFASS-2009 campaign.

In general, there are two approaches to measure vertical profiles with research aircraft. For mean profiles, several legs (horizontal straight flights) at various altitudes within the ABL have to be performed, resulting in averaged values for each altitude. The advantage of this method is the possibility of determining vertical turbulent fluxes (Bange and Roth, 1999) and it also provides a good spatial representativeness. This approach is only suitable if the ABL is quasi stationary and horizontally homogeneous.

Momentary profiles (slant flight pattern) are suitable if fast temporal changes are expected (e.g. during the morning transition of the ABL; Bange et al., 2007), if the dependence of the profile on time is requested (repeated slant flight patterns over one location) or if the dependence of the profile on the location is requested (repeated slant flight patterns over different locations). In this article the approach to measure momentary vertical profiles of temperature, humidity and wind with unmanned aerial vehicles (UAVs) using a data set obtained during LITFASS-2009 (<u>LI</u>ndenberg-<u>T</u>o-<u>F</u>alkenberg: <u>A</u>ircraft, <u>S</u>cintillometer and large-eddy <u>S</u>imulation) is demonstrated.

2 Experimental setup

2.1 Aircraft

The vertical profiles of temperature, humidity and wind presented in this article were measured during the field experiment LITFASS-2009 using an automatically operating research UAV named M^{2}AV (Meteorological Mini Aerial Vehicle; Spieß et al., 2007). It is a twin-engine member of the Carolo family of Mini-UAVs, constructed by the Institute of Aerospace Systems of the Technische Universität Braunschweig. An advantage of its electric propulsion system compared to combustion engines is that the engine power is not influenced by changes in altitude and that the total weight and the centre of mass are constant during flight. This allows for a more precise measurement and calibration of the angle of attack (van den Kroonenberg et al., 2008). Compared to combustion engines, also the vibrations during flight are much weaker, resulting in a higher precision of meteorological measurements.

The M^{2}AV has a wingspan of 2 m and a maximum take-off weight of approximately 6 kg including 1.5 kg meteorological equipment. The cruising speed of about 22 m s^{-1} and the power supply for about 50 to 60 min of flight allow flight distances of up to 70 km. The M^{2}AV is automatically operated by an electronic autopilot (see below). This allows for measurement flights in the lower ABL over larger distances outside the range of sight and in remote areas. Thereby, the M^{2}AV follows the flight pattern which was sent to the aircraft before take-off (van den Kroonenberg et al., 2008). Within the telemetry range of 5 km the ground staff is able to follow and monitor the position, attitude and speed of the aircraft. Changes of the waypoints and altitudes are possible within that range. Figure 1 shows the M^{2}AV flying near the Meteorological Observatory Lindenberg – Richard-Aßmann-Observatory (MOL-RAO) during the LITFASS-2009 campaign.

The UAV is launched and landed by a human pilot, but operates automatically when following the flight mission. The autopilot system is the MINC (miniature integrated navigation and control system; Buschmann et al., 2004). It includes all necessary components for autonomous aircraft control. The TrIMU (3-axis inertia measurement unit) sensor block contains a complete 3-axis IMU (inertia measurement unit) and two pressure sensors for barometric altitude and air speed determination. Tightly-coupled GPS/IMU data fusion is performed by the navigation filter of the MINC navigation core providing precise information about position and attitude of the aircraft. With a small size and low weight of 50 g the MINC autopilot system is very suited for the operation with small UAV. The ground station is used for mission planning and run-time control. In-flight mission supervision, including possible changes of waypoints coordinates and heights, is provided by a ground-station software running on a common laptop computer.

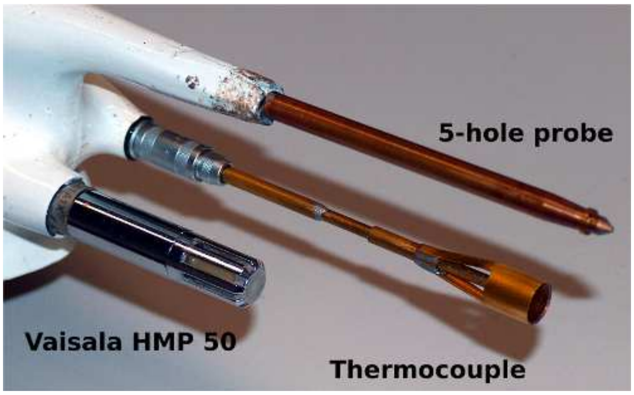

Fig. 2. The meteorological sensors of the M^{2}AV.

Operation limitations of the M^{2}AV are due to wind speeds at the flight altitude. The aircraft can not be operated if the wind speed exceeds 10 m s^{-1}. The M^{2}AV is able to operate at night with permission of the local CAA (civil aviation authorities). Such missions were already performed in the nocturnal stable boundary layer in Majorca, Spain, but not published yet. Operation in precipitation is currently not possible since the M^{2}AV is not rainproof concerning the measurement electronics. Operation in clouds is currently not allowed by the CAA in automatic flight mode.

2.2 Instrumentation

Since the main application of the M^{2}AV is the investigation of turbulent fluxes in the atmospheric boundary layer, the aircraft was equipped with fast sensors and data acquisition at 100 Hz. The meteorological sensor dome, which is shown in Fig. 2 consists of a 5-hole probe for measuring wind direction and speed, a Vaisala HMP 50 for temperature and humidity measurements, and a thermocouple for measuring fast temperature fluctuations. The sensor dome is mounted at the nose of the aircraft to minimize the aircraft's influence on the measurements and to get the sensors positioned close to each other. Also part of the meteorological payload is an IMU and a three-dimensional GPS system measuring and saving information about precise time, aircraft position, attitude and speed (van den Kroonenberg et al., 2008).

The miniature 5-hole probe which was designed by the Institute of Fluid Dynamics of the Technische Universität Braunschweig has a mass of only 22 g and a diameter of 6 mm. It provides wind data with a temporal resolution of 30 Hz for the angle of attack and sideslip in the range of −20° to +20°. The relative pressures between the five holes are measured at the tip of the probe and the static pressure is measured via four extra holes at the side of the probe. For the calculation of the meteorological wind vector, highly resolved and precise information about the attitude and ground speed of the aircraft is required (van den Kroonenberg et al., 2008). These data are obtained from the GPS and the IMU, which are integrated by a discrete error state Kálmán filter. An analysis of error propagation resulted in an accuracy of 0.8 m s^{-1} for wind speed and an accuracy of 15° for wind direction.

The Vaisala HMP 50 provides air humidity measurements (Vaisala Humicap) with an accuracy of ± 2% relative humidity in a measurement range of 0 to 98%. The sensor also measures the air temperature (resistance thermometer) with an accuracy of ± 0.6 K. During flight the sensor has a response time of about 1 s. Spectral analysis has shown that humidity and temperature fluctuations down to 1 Hz can be resolved. To reach a temperature measurement with long-term stability, high accuracy and resolution in a temperature range of −40 °C to +60 °C, this temperature signal is combined with the signal of the thermocouple by complementary filtering. The thermocouple has a short response time in the range of 10^{-1} s. It was designed and manufacture by the Institute of Aerospace Systems. The wire used for the thermocouple of type K (NiCr-Ni) has a diameter of 0.13 mm.

3 Comparison of M^{2}AV data with remotely sensing systems and tower data

During LITFASS-2009 several momentary profiles were performed by the M^{2}AV which was operated automatically or remotely controlled by the safety pilot. In Table 1 a list of all measured vertical profiles is presented.

On 21 July 2009 four automatically performed vertical profiles were measured up to about 1500 m a.g.l. and 1250 m a.g.l., respectively. The results are presented in the following sections, including a description of the LITFASS-2009 campaign, the weather conditions and the flight pattern.

The vertical profiles of 21 July 2009 were chosen for discussion here because these flights represent different atmospheric stratifications. One flight was performed during the morning transition and the other one during the transition of the mixed layer (ML) to the residual layer (RL) just before sunset. During both flights the M^{2}AV had a constant rate of climb of 3 m s^{-1} and followed the prescribed flight patterns very accurately.

3.1 LITFASS-2009 campaign

The vertical profile study discussed in this article was a part of a larger campaign called LITFASS-2009 which took place at MOL-RAO near Lindenberg about 60 km south-east of Berlin. The experiment was organised in cooperation with the German Meteorological Service (DWD), the Wageningen University, the Institute of Meteorology and Climatology of the Leibniz University Hanover, and the Centre for Ecology and Hydrology Wallingford during July 2009. The main aim of LITFASS-2009 was to provide a dataset suited to study some of the open problems in the field of scintillometry, applied to derive area-averaged structure parameters and turbulent fluxes over a heterogeneous landscape. Thus, one focus was on the turbulence over heterogeneous terrain to verify the method of calculating path-averaged structure parameters from the scintillometer signal (Martin et al., 2010). The project combined field and aircraft measurements with numerical modelling using a large-eddy simulation model. Since several remote-sensing systems and standard observations were operated during this campaign (see Table 2), it was a good opportunity for investigating the accuracy of M^{2}AV measurements and contribute a spatially flexible data set of high resolution temperature, humidity and wind measurements.

Table 1. List of vertical profiles measured with the M^{2}AV during LITFASS-2009.

Date	Time in UTC	No. of profiles	Max. height in m a.g.l.	Operation mode
6 July	08:17–08:32	2	1086	automatic
12 July	06:50–08:04	10	332	manual
13 July	11:27–11:39	6	592	manual
13 July	12:59–13:06	2	414	manual
16 July	16:32–17:20	4	720	automatic
17 July	06:07–16:19	2	527	manual
17 July	07:54–08:08	2	735	manual
21 July	07:03–07:27	2	1473	automatic
21 July	18:20–18:41	2	1252	automatic

Table 2. Operated measurement systems during LITFASS-2009.

Remote sensing systems	Standard observations
wind profiler/RASS	synoptical observations
sodar/RASS	radiosonde ascents
cloud radar	radiation measurements (BSRN)
microwave radiometer profiler	ABL field site Falkenberg
ceilometer	
Micromet. measurements	**Scintillometers**
energy balance stations	5 laser scintillometers
turbulence measurements at 99 m tower	2 microwave scintillometers
	2 large-aperture scintillometers

3.2 Measurement systems used for comparison

Data from five measurement systems that are in routine operation at MOL-RAO have been used for comparison with the M^{2}AV data (e.g., Neisser et al., 2002).

In-situ profile measurements of wind, temperature and humidity are performed at a 10 m mast and at a 99 m lattice tower at the boundary layer field site (GM) Falkenberg (Beyrich and Adam, 2007). The 10 m-mast is instrumented at several levels between 0.5 m and 10 m, the 99 m-tower carries standard meteorological sensors at 10 m, 20 m, 40 m, 60 m, 80 m and 98 m, wind direction is measured at 40 m and 98 m only. HMP 45 sensors (Vaisala) are used for the humidity and temperature measurements, the wind measurements are performed with cup anemometers and wind vanes (Thies Clima). Each of the tower levels is equipped with wind sensors at three booms roughly pointing towards North, South, and West, ensuring that at least one of the sensors is not significantly affected from tower-induced flow distortion. Details on the instrumentation and data quality control are described in Beyrich and Adam (2007).

Wind and temperature profiles from 40 m up to a few hundred meters above ground are measured with a sodar/RASS DSDPA.90-64 (METEK) operated at the GM Falkenberg. The sodar operating frequency is 1598 Hz, vertical resolution of the profiles is 20 m. 70% data availability is achieved at heights between 360 m to 480 m for wind, and 180 m to 240 m for temperature, respectively (for further details see Engelbart et al., 1999). The measurement range is often reduced during the morning and evening transition periods when thermal turbulence and stratification are weak and the sodar signal-to-noise ratio might be relatively low. The latter may also reduce the accuracy of the derived meteorological parameters. Temperature profiles derived from the RASS measurements of this system are corrected by adjustment of the constants and for the influence of the vertical wind according to Görsdorf and Lehmann (2000).

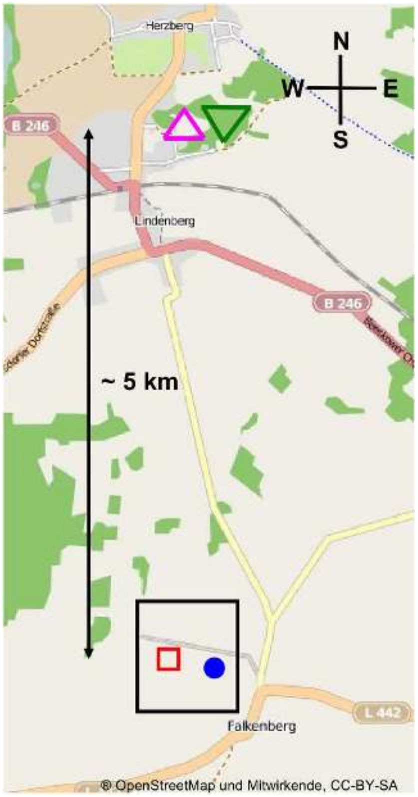

Fig. 3. Approximated location of the instruments at MOL-RAO and the location of flight path of vertical profile of the M^{2}AV. The green triangle shows the position of the wind profiler, the pink triangle the position of the MWRP, the small red square the position of the sodar, the blue circle the position of the tower, and the large black square represents one square of the flight path. The radiosonde release point is close to the position of the MWRP.

Wind profiles across the whole troposphere and temperature profiles up to about 3 km are measured with a 482 MHz wind profiler/RASS system at the MOL-RAO observatory site (e.g., Engelbart and Steinhagen, 2001). The antenna is a coaxial-colinear phased array formed by 120 elements. It is spaced above a ground plane and covers an area of approximately 12.4 × 12.4 m. Lowest measuring height is around 500 m, with a vertical spacing of about 150 m. The constants and range corrections have been applied to the RASS measurements as described in Görsdorf and Lehmann (2000). Thermodynamic profiles of the lower atmosphere can be continuously retrieved from a ground-based microwave radiometer profiler (MWRP). The TP/WVP 3000 built by Radiometrics Corp. Boulder has been in operation for more then 10 yr at the Lindenberg observatory. The 12-channel MWRP observes the atmospheric brightness temperature in 5 channels along the 22.2 GHz water vapour resonance line and in 7 channels along the oxygen absorption band from 51 to 59 GHz. Additionally, the MWRP includes a surface temperature, pressure and humidity sensor as well as an infrared pyrometer for cloud base temperature observations. A variety of retrieval techniques can be used to derive temperature and humidity profiles. In Lindenberg a measurement-based regression method is operationally applied. In order to avoid systematic errors this approach uses simultaneous radiosondes and ground-based radiometric measurements from the past to calculate the retrieval regression operator.

At the MOL-RAO radiosonde ascents are performed regularly four times each day. Ascents are attributed to the standard synoptic hours HH = 00:00, 06:00, 12:00, 18:00 UTC, the sondes are released at HH − 1 h (± 15 min). Since July 2004 the Vaisala RS92 is used for the operational measurements. Pressure, temperature, humidity and wind are measured with Barocap, Thermocap, Humicap and GPS, respectively.

Figure 3 presents the approximated location of the instruments at MOL-RAO and the location of the flight path of the vertical profiles of the M^{2}AV. The wind profiler and the MWRP are located about 5 km north of the sodar/RASS and the tower. The flights of the M^{2}AV were performed close to Falkenberg, thus close to the location of the sodar/RASS and the tower. Radiosondes are started at the MOL-RAO observatory site where also the wind profiler and MWRP are operated.

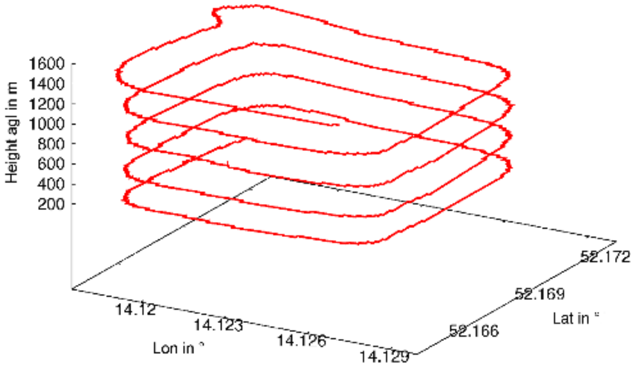

Fig. 4. Flight pattern of the ascent (first profile) performed on 21 July 2009, 07:03–07:15 UTC, near the Meteorological Observatory Lindenberg – Richard-Aßmann-Observatory.

The meteorological profiles of the M^{2}AV and the radiosonde consist of point measurements in space and time, whereas the sodar/RASS data is averaged over 15 min, the tower data and the MWRP over 10 min, and the wind profiler/RASS data over 25 min for wind data and over 5 min for virtual temperature.

3.3 Weather conditions and flight pattern

At the end of the LITFASS-2009 campaign, on 21 July 2009, four vertical profiles were performed automatically by the M^{2}AV. On that day the weather over Central Europe was influenced by a low pressure system over the eastern Atlantic. Around noon the weak warm front of the low passed the campaign site triggering some weak showers. The wind direction was west in the morning. After the front had passed the wind direction changed to south-west and sub-tropical air was transported into the study region. In the morning and evening only weak surface wind speeds of about 2 m s^{-1} were measured. During the day the wind increased to a maximum of 6 m s^{-1}. The 2 m temperature was between 11.5 °C and 24.7 °C. In the morning the sky was covered with 6/8 to 7/8 alto-cumulus clouds. From 08:00 UTC to 17:00 UTC a mixture of 4/8 to 6/8 cumulus, alto-cumulus and cirrus was observed. In the evening there was 5/8 to 7/8 alto-cumulus and cirrus clouds.

The flight pattern for measuring momentary profiles of the lower troposphere consisted of “piled” squares with straight flight sections of about 600 m length as presented in Fig. 4. This pattern was chosen to keep the M^{2}AV always within sight during the flight which was a requirement of the German aviation authorities.

For in-flight calibration of the wind vector, a square pattern at constant altitude (van den Kroonenberg et al., 2008) was performed at the end of each flight.

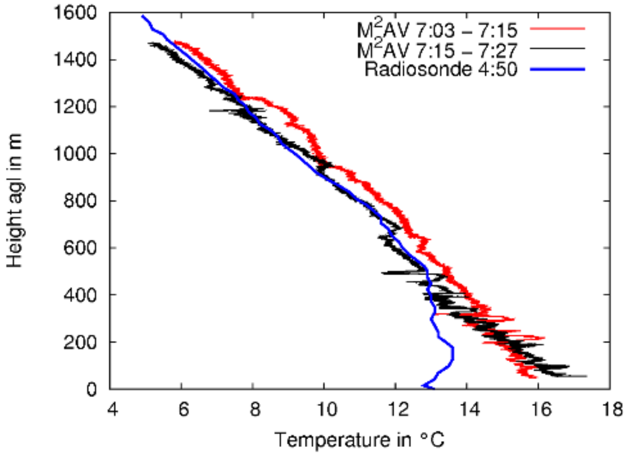

Fig. 5. Comparison of radiosonde data measured at 04:50 UTC and M^{2}AV data measured between 07:03 UTC and 07:27 UTC on 21 July 2009.

3.4 Vertical profiles during morning transition

The profiles performed during morning transition started at 07:03 UTC and ended at 07:27 UTC. During ascent and descent the development of the mixed layer was captured as a part of the evolution of the boundary layer. Figure 5 shows the measured static temperature profiles of the ascent and descent during this flight of the M^{2}AV. The flight was performed around the GM Falkenberg about 5 km away from MOL-RAO. For comparison the data of the radiosonde (blue line), which was released at the MOL-RAO at 04:50 UTC, is presented.

In Stull (1988) the evolution of the mixed layer during the diurnal cycle is classified as a 4-phase process, consisting of the formation of a shallow mixed layer, which slowly deepens, the rapid ML growth, the deep ML of nearly constant thickness and finally the decay of turbulence. On 21 July 2009 the radiosonde measurement at 04:50 UTC captured the atmospheric conditions just before the start of the evolution of the mixed layer. The ground inversion up to about 150 m a.g.l. indicates a stable stratification.

The red line shows the static temperature measured during the ascent of the M^{2}AV about two hours after the measurement of the radiosonde. During that time the temperature near the ground increased by about 3 K due to diabatic heating, dissolving the ground inversion. This profile is assigned to the first phase of the classification of Stull (1988). The boundary-layer height at about 350 m a.g.l. is captured by the M^{2}AV measurement and the development of the mixed layer is clearly noticeable because of the turbulent fluctuations measured by the UAV at altitudes below 350 m.

The black line shows the data measured during descent of the M^{2}AV. At the surface an increase of temperature, compared to the ascent, was measured. The boundary layer depth had increased up to about 500 m, which is noticeable by the increase of height up to which the M^{2}AV measured strong turbulent fluctuations. The top of the ML has moved up to the residual layer base, thus at this point the rapid growth of the ML started. Comparing the temperature measured by the M^{2}AV with the temperature measured by the radiosonde, good agreement was found for altitudes above the mixed layer (residual layer and free atmosphere).

Figure 6 shows the vertical sensible heat flux (H) measured at the tower at the measurement site on 21 July 2009. The values at 50 (red crosses) and 90 m a.g.l. (black crosses) are averaged over 30 min. The vertical lines mark the ascents and descents of the profiles performed by the M^{2}AV. For the first flight the measured sensible heat fluxes at 50 and 90 m a.g.l. are larger during descent than during ascent which is an additional argument for the increase of the turbulence in the ML and thus an indicator for the growth of the ML. In Figs. 7 and 8 the measured virtual temperature, relative humidity, wind direction, and wind speed profiles during the ascent and descent of the M^{2}AV are presented. By comparing ascent and descent it can be seen that in the ML the fast fluctuations in wind direction and speed increased as this layer evolved.

Beside M^{2}AV data, sodar/RASS, tower, radiosounding, MWRP and wind profiler/RASS data are also presented in Figs. 7 and 8. For ascent and descent, the temperature measurements of the M^{2}AV agree very well with the in-situ measurement of the tower and the remote sensing wind profiler/RASS and sodar/RASS. Sodar/RASS temperature values measured at 40 m and 60 m a.g.l. at 07:15 UTC were removed from the profile since unreliable vertical wind values lead to an inappropriate virtual temperature correction. M^{2}AV, tower and sodar/RASS data are in higher agreement for descent than for ascent. Nevertheless, the differences between the values of the systems are not larger than 1 K. During the morning transition of the ABL, fast temporal changes occur in the developing mixed layer. Therefore, differences between the M^{2}AV data, which are not averaged and the averaged data of the ground-based systems are expected. The M^{2}AV and wind profiler/RASS data measured in the free atmosphere differ only for descent above 1100 m a.g.l., which could be explained by the distance of about 5 km between the locations of operation of the systems.

The two morning profiles of relative humidity measured by the M^{2}AV show a similar structure up to 1000 m a.g.l. with maxima at approximately 300 m, 600 m and 900 m a.g.l. At 1050 m a.g.l. a local minimum is measured during the ascent, whereas a maximum is measured at the same altitude during descent just a few minutes later. This illustrates the small scale variability of moisture in the air both in space and time. Above 1200 m a.g.l. the two profiles are comparable, again. Having in mind the differences between the two aircraft profiles, the comparison between the M^{2}AV and radiosonde profiles appears quite challenging as they were measured both at different times (about 2 h) and different sites (about 5 km apart from each other). Nevertheless, the three maxima of the M^{2}AV humidity profiles are also found in the radiosonde profile. This may indicate a high degree of stationarity in the lower free atmosphere above the stable boundary layer and the early morning mixing layer. The differences of about 20% relative humidity between the M^{2}AV and the radiosonde data near the surface is attributed to the time difference between the measurements. Because of the lower temperature of 13 °C during the ascent of the radiosonde (see Fig. 5), the relative humidity is higher than during the measurement of the M^{2}AV profiles with 16 °C near the surface. Close to the surface, up to 200 m a.g.l. the M^{2}AV, MWRP and tower data agree well for ascent and descent. Being a passive remote sensing instrument, the MWRP is not able to resolve the detailed vertical structure of the humidity profile in the ABL, which explains the differences in the local values of relative humidity of up to 20% when comparing the MWRP data to the M^{2}AV and radiosonde data (mainly at altitudes above 200 m a.g.l.).

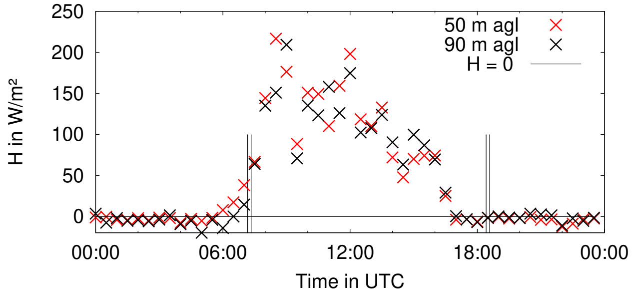

Fig. 6. Vertical sensible heat flux H measured at the tower at the measurement site on 21 July 2009. The values are averaged over 30 min. Vertical lines mark the ascends and descents of the instantaneous profiles performed by the M^{2}AV.

During ascent the measured wind direction of the sodar changes with height from west (270° on average) at 80 m a.g.l. to south-west (240° on average) at 230 m a.g.l. and to west-south-west (250° on average) at 330 m a.g.l. That trend is also measured by the M^{2}AV. However, the sodar data, which are averaged over 15 minutes, do not capture the change in wind direction to 210° at 250 m a.g.l. measured by the UAV. During descent higher fluctuations in wind direction are measured by the M^{2}AV within the ML. The sodar and the tower data for wind direction are within the range of these fluctuations. The wind speed measured by the sodar, tower and M^{2}AV agree well in the ML during the whole flight with even better results for descent.

In the free atmosphere (FA) only wind profiler/RASS data are available for comparison. This wind profiler/RASS was located in Lindenberg at the DWD site, which is about 5 km north of the measurement site of the M^{2}AV (see Fig. 3). The averaged values of the wind profiler/RASS agree very well with the in-situ measurements of the M^{2}AV. The small differences between the aircraft measurement and the remote

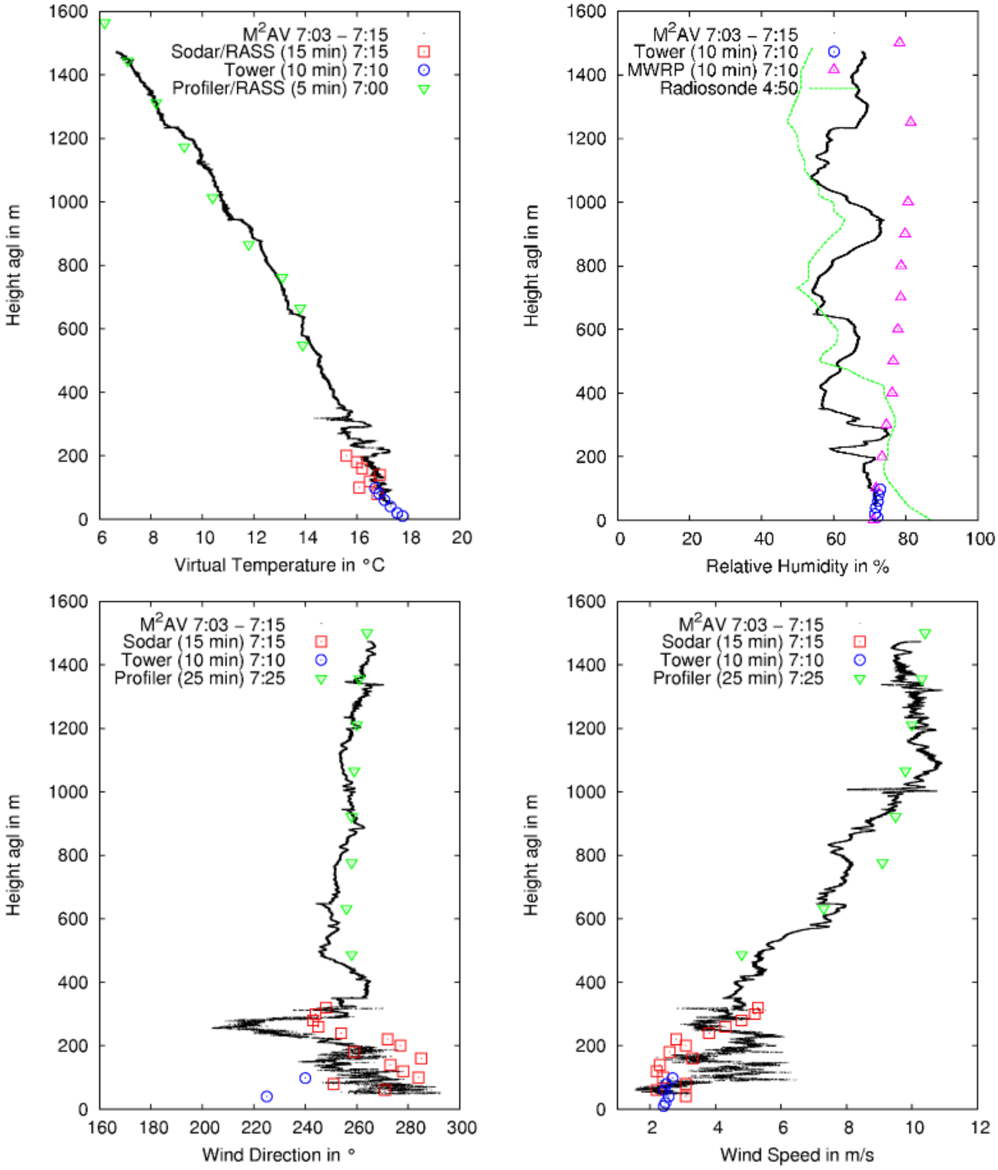

Fig. 7. Vertical profiles measured by wind profiler/RASS, sodar/RASS, tower, MWRP, radiosonde ascent and M^{2}AV. These data were collected during the ascent of the morning flight of the UAV on 21 July 2009 near MOL-RAO. Besides for the M^{2}AV, the times indicated in the captions mark the end of the averaging interval.

sensing data could be explained by horizontal separation since the two systems were not operated at the same location, but also by the different sampling and averaging strategies.

3.5 Vertical profiles during afternoon transition

The second set of profiles on 21 July 2009 was performed during transition of the mixed layer to the residual layer just before sunset, starting at 18:20 UTC and ending at 18:41 UTC. These profiles capture the fourth phase of the ML during the diurnal cycle, the decay of turbulence. The heat fluxes measured at 50 and 90 m a.g.l. during that flight are already negative (see Fig. 6), but the last few weak thermals may still be rising in the upper part of the ML (Stull and Driedonks, 1987).

The measured virtual temperature, relative humidity, wind direction and wind speed profiles of the ascent and descent of the M^{2}AV are presented in Figs. 9 and 10, including tower, MWRP, radiosounding, sodar/RASS and wind profiler/RASS data. The UAV profiles up to 1250 m a.g.l. show the structure of the ML, which is characterised by much less turbulent fluctuations compared to the ML measured in the morning.

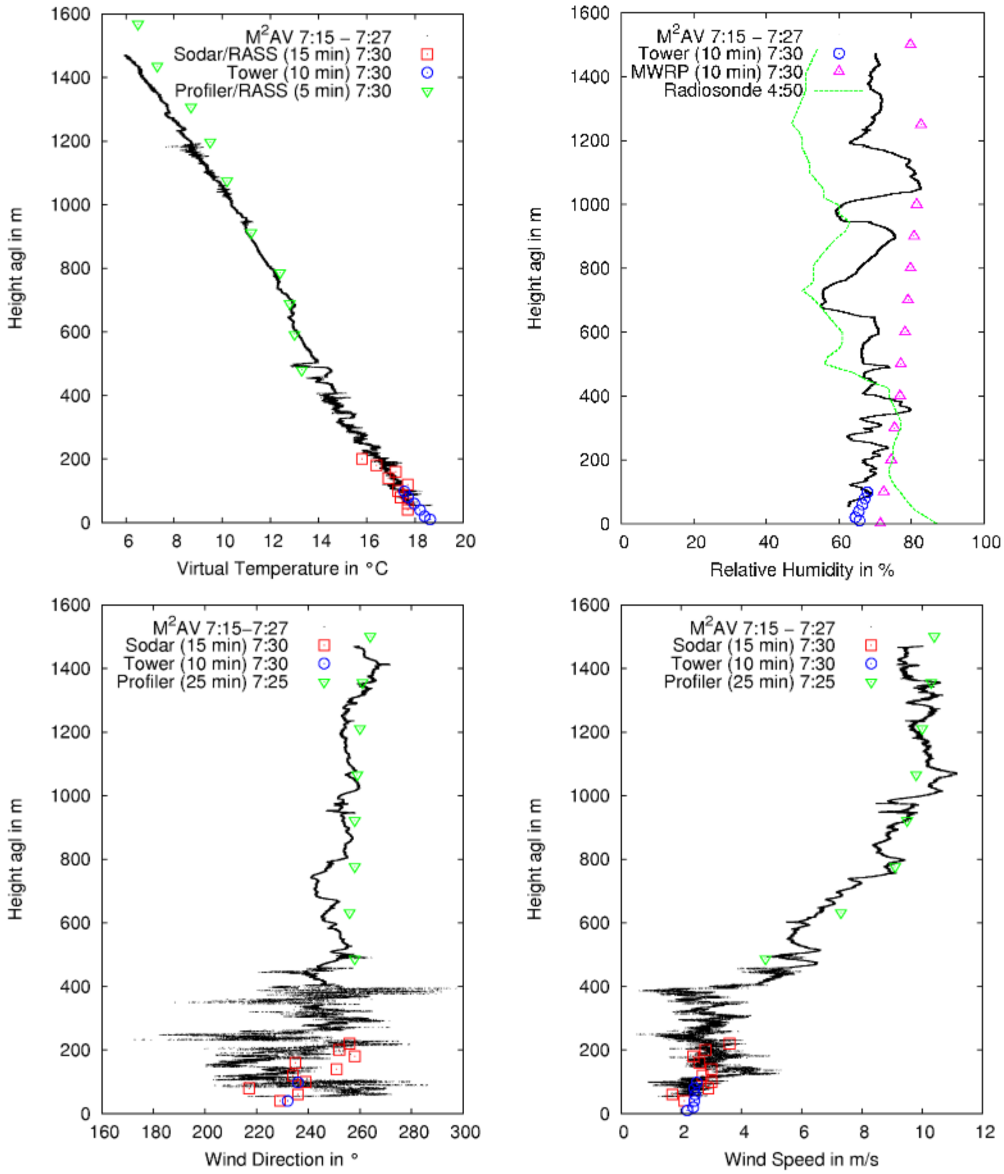

Fig. 8. Vertical profiles measured by wind profiler/RASS, sodar/RASS, tower, MWRP, radiosonde ascent and M^{2}AV. These data were collected during the descent of the morning flight of the UAV on 21 July 2009 near MOL-RAO. Besides for the M^{2}AV, the times indicated in the captions mark the end of the averaging interval.

The agreement between M^{2}AV, sodar and tower data is very good for virtual temperature, relative humidity, wind direction, and wind speed. The tower provides measurements down to 10 m a.g.l. where the stably stratified layer was observed. Above 200 m measurements are provided by the UAV and the wind profiler/RASS. For virtual temperature, wind direction and wind speed the agreement between the two systems is very good. The radiosonde and MWRP measurements of relative humidity are in high agreement to the M^{2}AV data for the second set of profiles.

4 Potential for improving the M^{2}AV flight strategies

We have characterized in Sect. 1 two main ways of performing vertical profiles with the UAV: momentary profiles, which means continuously increasing height, and mean profiles, for which several straight and level legs at different altitudes have to be performed. During LITFASS-2009 it was planned to perform only momentary profiles. But also sections of horizontal straight and level flights occurred since we underestimated the possible climbing rate of the M^{2}AV during automatic flight operation (since this was its first application for high vertical profiling). The flight pattern for the

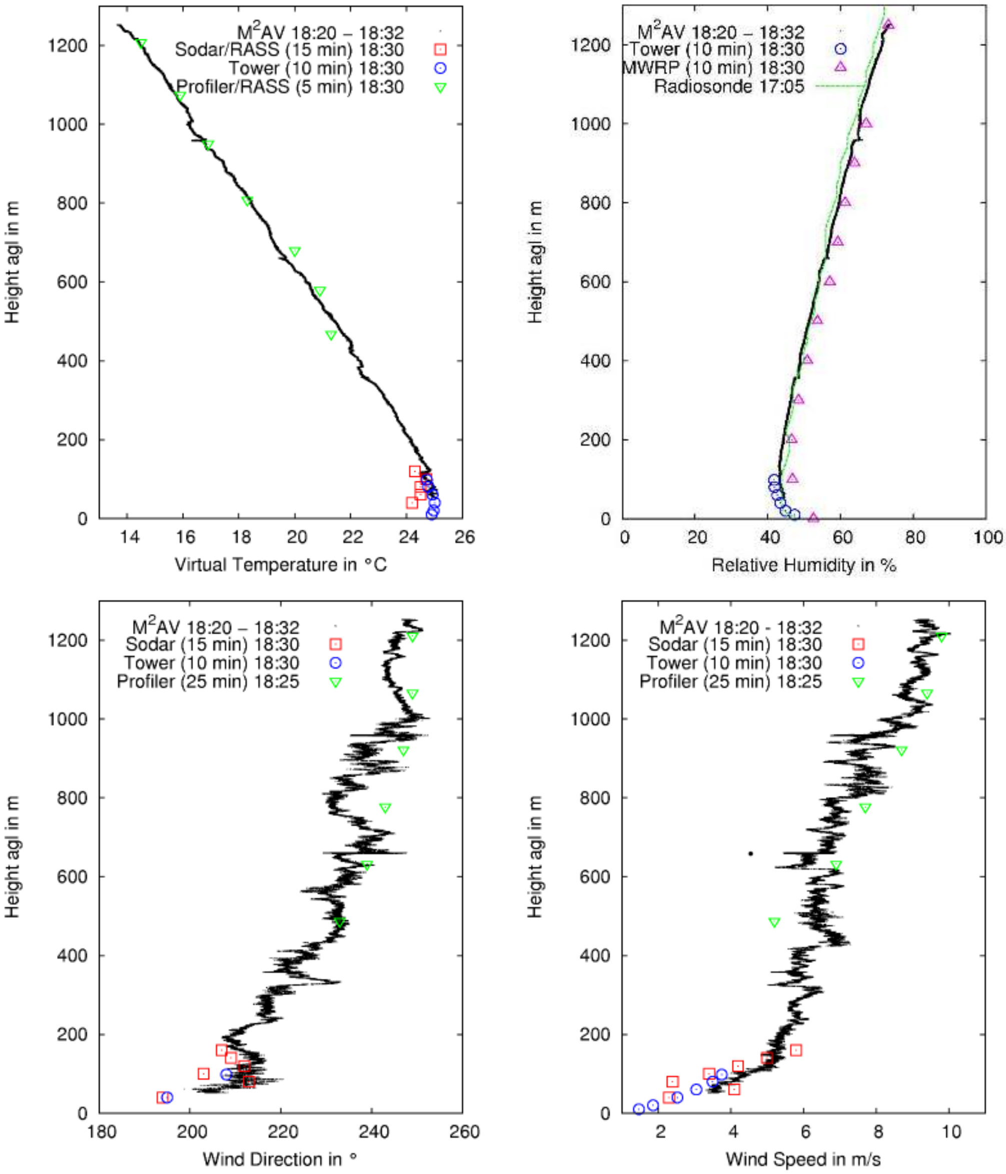

Fig. 9. Vertical profiles measured by wind profiler/RASS, sodar/RASS, tower, MWRP, radiosonde ascent and M^{2}AV. These data were collected during the ascent of the afternoon flight of the UAV on 21 July 2009 near MOL-RAO. Besides for the M^{2}AV, the times indicated in the captions mark the end of the averaging interval.

profiles consisted of ascending squares like a stair case (see Fig. 4). Since the UAV was climbing faster than expected, the requested altitude for each square was reached before arriving at the the last waypoint (corner). The UAV started climbing again only after finishing the square, so sections of horizontal flight were performed to the end of each square of the flight pattern. In Fig. 11 the measured virtual temperature and the recorded system time is plotted over height a.g.l. The data were obtained during the ascent of the first flight performed on 21 July 2009. While the UAV was not climbing, several measurements at constant height were collected. For future mission planning that outcome should be taken into consideration for the definition of the altitudes of the waypoints.

5 Summary and conclusions

The main application of the M^{2}AV is the investigation of turbulent fluxes in the atmospheric boundary layer. Therefore, the aircraft is equipped with fast sensors with response frequencies of 30 Hz. The climbing rate of 3 m s^{-1} enables vertical resolutions of 10 cm for temperature, humidity, wind direction and speed. Momentary profiles of the M^{2}AV can

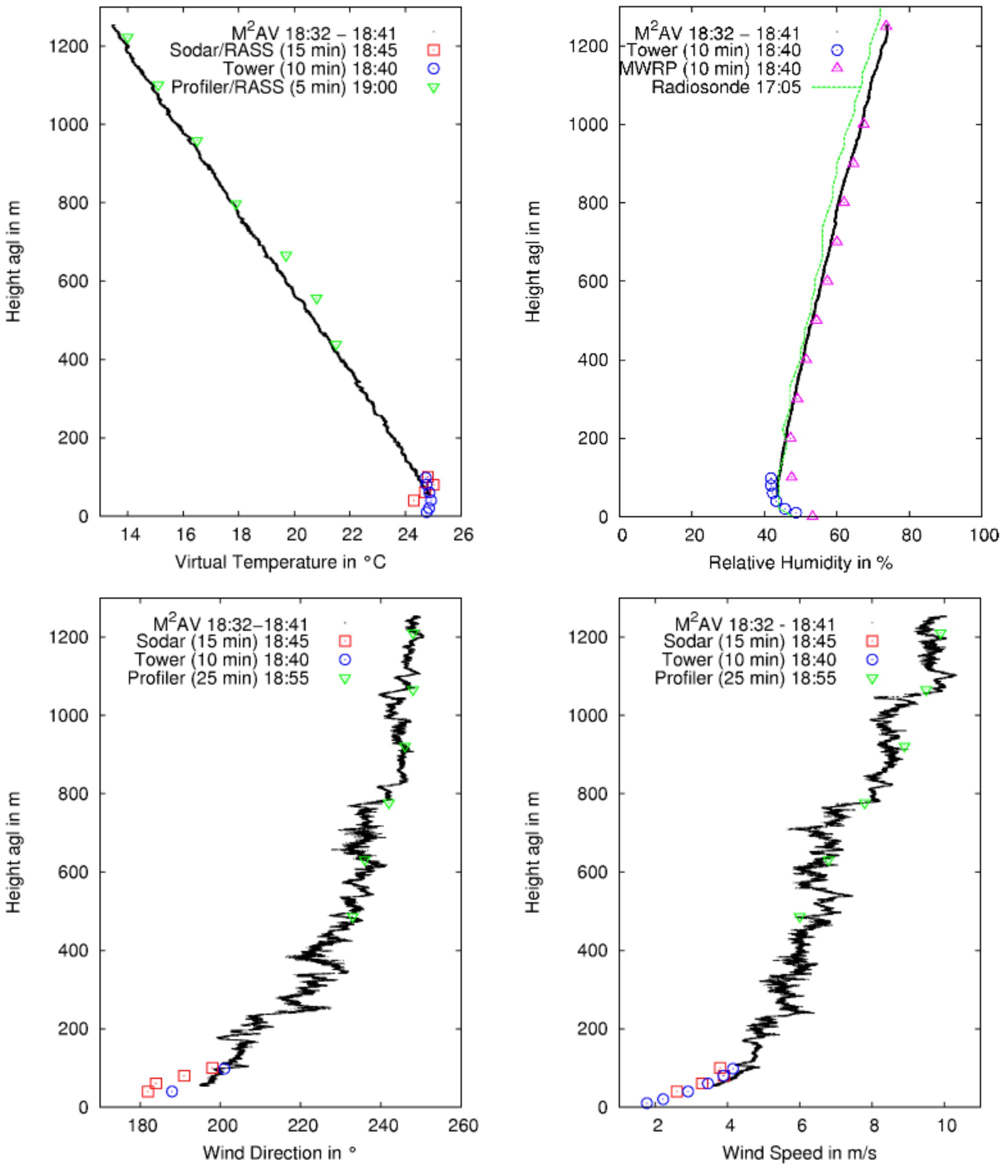

Fig. 10. Vertical profiles measured by wind profiler/RASS, sodar/RASS, tower, MWRP, radiosonde ascent and M^{2}AV. These data were collected during the descent of the afternoon flight of the UAV on 21 July 2009 near MOL-RAO. Besides for the M^{2}AV, the times indicated in the captions mark the end of the averaging interval.

provide continuous monitoring of fast temporal changes of the atmospheric conditions in the lower troposphere. Such fast temporal changes are not detected by current standard observation sensors, which makes the use of this aircraft so unique.

The analysis of the data from the two flights on 21 July 2009 shows that the M^{2}AV profiles of standard meteorological parameters in the lower troposphere are in very good agreement with a variety of in-situ and ground-based remote sensing systems. Interpretation of the data has to consider that the UAV profiles result from instantaneous local measurements at different points in space and time along the flight track, whereas the other systems provide temporally averaged data. Therefore, better agreement was observed in the late afternoon well-mixed layer than in the developing mixed layer when fast temporal changes occur. Very good agreement was also found in the free atmosphere where small-scale vertical and horizontal differences are less pronounced.

In future flights even more reliable measurements of the vertical structure of the lower troposphere will be gained by improved flight strategies.

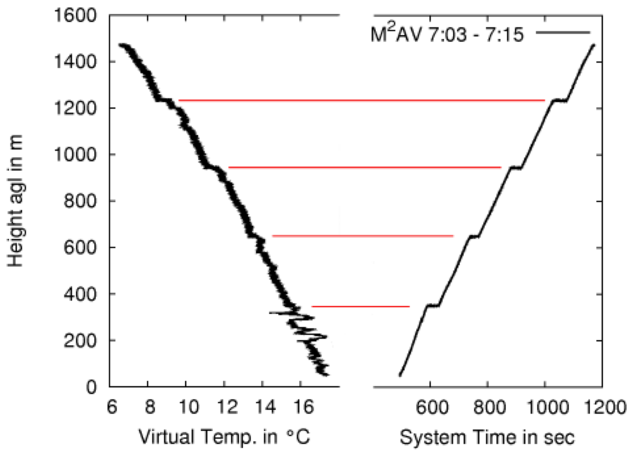

Fig. 11. Measured virtual temperature and recorded system time plotted over height a.g.l. The data was obtained during the first profile performed on 21 July 2009 near the MOL-RAO. Red horizontal lines mark sections of horizontal flight.

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