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A Micro-Meteorological Experiment in the Atmospheric Boundary Layer in Highveld Region

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Abstract. Meteorology of the planetary boundary layer (PBL) is to large extent determined by turbulent processes. Those processes and their interaction with surface properties are not well understood. The processes over heterogeneous land surfaces are understood even less. To progress in the understanding simultaneous observations with a network of meteorological stations are needed. A joint project between Norwegian and South African research foundations funded a micrometeorological experiment in the Highveld area of the South Africa (MMEH). The experiment has been organized to collect data from 5 automatic meteorological stations placed at 7 km to 23 km separation distances from each other. The data were collected continuously over 2 years. This paper presents the idea, the theoretical background and the organization of the MMEH.

1. Introduction

The planetary boundary layer (PBL) is the lowermost layer of the atmosphere where the non-linear processes of the turbulent exchange play an important role. The turbulent exchange is carried out by eddies that are conveniently described by statistical methods (see [1] for review). The statistical approach to the turbulent exchange is justifiable for well developed Kolmogorov's turbulence on scales sufficiently small as compared to the scales of the turbulence generation processes. This is not the case in the PBL. A brief look on the PBL turbulence spectra disclose that the most energetic turbulence is associated with eddies on rather large scales. For clarity and brevity, we will refer here the large eddies in the PBL as vortexes. In a narrow sense the vortexes are associated with the scales of $O(h)$, where h is the PBL depth, which is proportional to the scale of the spectral energy maxima.

The vortexes have been observed not only statistically but also as individual long-living and spatially coherent structures in the PBL. The observational studies have been focused on the marine PBL because the ocean surface maintains the large degree of homogeneity. The surface effects of the vortexes can be easily observed with the synthetic aperture radar as variations of the radar signal brightness on short-living capillary-gravity waves [2–4]. At the same time, the vortex scales are easily identified through cloud structure analysis [5, 6]. An extensive review of observations [7] disclosed that the vortex patterns such as closed or open cloud cells and cloud rolls are ubiquities at all latitudes including tropical and subtropical areas of the South Africa. The cells (see Figure 1) are observed when buoyancy dominates the turbulence production whereas the rolls are observed when the velocity shear dominates.

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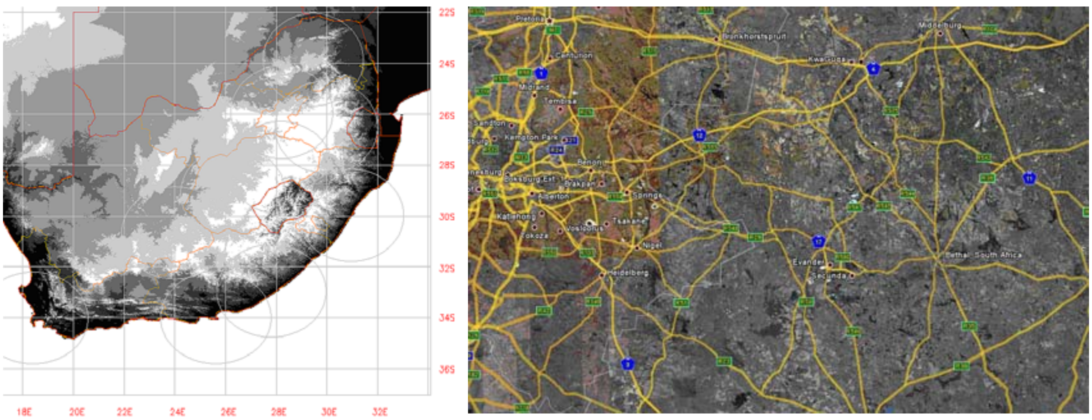
At the same time, quantitative studies of the vortexes are unusual due to lack of properly sampled spatially distributed data. Recently, several field campaigns such as HATS (The Horizontal Array Turbulence Study) provided data to study the spatial structure of small-scale turbulence. The data can be used to study the vortexes also when the Taylor's hypothesis is applied. However, the largest resolved scales in those experiments were still rather small of about 1 km. In order to collect data for studies of larger vortex scales, a micro-meteorological experiment in the Highveld area of the South Africa (MMEH) was organized in 2008-2010. The paper is aimed to describe this experiment.

Figure 1. Convective clouds over Central-North-East region of the South Africa. Clouds are organized in elongated cloud cells. Clouds prefer greener (darker and presumably wetter) areas even when it requires cell scale modification. Photo is taken by I. Esau from commercial airplane at the height of about 6000 m.



(a) (b)

Figure 2. (a) Topographic map of the South Africa. Shading shows the altitude with the brightest shades corresponding to 1500 m. (b) The map of the Central-North-Eastern region of the South African Republic (after Google Earth). The meteorological station network is placed south of Bethal.

2. Micro-meteorological experiment in the Highveld area (MMEH)

The large part of Republic of South Africa (Figure 2a) is located in dry sub-tropical and tropical areas with predominantly arid and semi-arid climate. Rainfalls are seasonal with the summertime (December through March) maximum and the wintertime (June through September) minimum. Rainfalls are largely convective by nature. The convective clouds are controlled by the PBL turbulence and external parameters such as the atmospheric static stability, surface roughness and the mean wind [8] as well as the moisture availability and therefore the height of the condensation level (LCL). The MMEH rationale suggests that the triggering of the deep convection should be controlled by the soil moisture, scales of the surface heterogeneity and types of vegetation (see Figure 3).

The Highveld region is situated in Central-North-Eastern part of the country (Figure 2b). The area is largely flat with gradual increase of elevation from west to east. At small spatial scales, depressions and hills could be found with the elevation difference of 10-20 m and the typical elevation gradients of 5-10 m km^{-1}. The main economical activities around the experimental site to the north of Bethal town are coal mining, electricity generation and agriculture (maize and wheat). The area is dotted by small water magazines, low albedo pit mines, and townships of 1-2 km in size.

The meteorology of Highveld has been intensively studied over the last 30-40 years. The studies [9] however were focussed more on stably stratified (nocturnal and wintertime) PBL than on daytime convection. It was motivated by the air quality monitoring needs [10]. Tennant and Hewitson [11] published a comprehensive analysis of the rainfall climatology at 276 stations. The climatology encompasses 1936 to 1999. It is based on a self-organized map method (a kind of hierarchical cluster analysis) to distinct homogeneous sub-regions. Highveld has been put into the North-Eastern Interior homogeneous rainfall region. The average number of days with precipitations > 1 mm is between 30 and 40. The average seasonal amount of precipitations is 350 mm to 450 mm. The 50 year climatology analysis in this region indicates increasing trends of the number of rain days while the spatial picture of trends is mosaic [12].

Thomas et al. [12] study put forward a problem, which is at the edge of physical and social climatology, that could be addressed only with research studies of the MMEH type or similar. The study showed that the perception of the climate change impact does not correlate significantly with the measured social impact. For instance in the region south of the Highveld area, 87% of the respondents identified the climate change as the observed challenge or risk while no measurable changes has been found in the region's climate by 1999. In Highveld, the observed changes are more pronounced. So, farmers have already initiated practical measures to mitigate the changes in the temporal and spatial patterns of the moisture availability. But the unguided mitigation process is chaotic, based rather on try-and-fail approach. While serving for improvement for some farmers at short time scales, it may lead to bigger challenges at long scales. In this respect, the project "Analysis and Possibility for Control of Atmospheric Boundary Layer Processes to Facilitate Adaptation to Environmental Changes" in the frameworks of the South African – Norwegian Programme for Research and Co-operation Phase II and the MMEH experiment are attempts to create some theoretical and observational background for the scientifically guided mitigation process.

Table 1. List of automatic meteorological stations, their coordinates and altitude

Station and farm name	Southern latitude	Eastern longitude	Altitude above sea level
S1. Jan de Jager, Banklaagte	26.40530	29.56912	1650
S2. Anton van Tonder, Yzervarkfontein	26.37059	29.45499	1660
S3. Bram Jordan, Rietkuil	26.28638	29.61690	1670
S4. Anton Pelse, Driefontein	26.08918	29.56606	1706
S5. Daleen von Wieligh, Bultfontein	26.12696	29.49994	1656

The area south of Bethal town was chosen as the meteorological test-bed for data collection. The area is geographically and economically homogeneous and thought to be representative for the whole Highveld region. Figure 4 shows the locations of the automatic meteorological station network in this area. In total, 5 stations were placed on farmers' land, mostly at the edge of agricultural (maize) fields. The station placing is not ideal because practical security reasons and logistics have to be taken into account. Some stations are located close to some low buildings, farmer houses and wire fences, which may contaminate the collected data. The complete list of stations with their coordinates and altitudes is in Table 1.

The experimental site is a flat, slightly inclined plain at altitudes from 1650 m to 1706 m. Thus the total elevation gradient is just 56 m with no elevations lower than 1630 m and higher than 1715 m between the stations. The area is rather densely populated but the population is living in scattered low houses often surrounded by a group of 10-15 m trees. The rest of the area is heterogeneous agricultural, mostly maize, fields. Thus the surface heterogeneity is generally small and dependent on soil moisture. In larger area there are also open coal mines that have much lower albedo. Figure 5 presents a typical view at the station site.

The stations are placed in an approximate cross pattern forming two groups. The southern group S1, S2 and S3 forms a triangle with sides 12 km (S1 to S2), 19 km (S2 to S3) and 14 km (S1 to S3). The northern group consists of two stations S4 and S5 placed 30-35 km north from the southern group and separated by 8 km. Thus the experiment site pattern allows studies of the turbulence coherency on scales from 8 km (S4 to S5) to 35 km (S1 to S4). The distances between all stations are presented in Table 2.

Table 2. Distances between meteorological stations given in km.

	S2	S3	S4	S5
S1	12.006	14.054	35.152	31.709
S2		18.656	33.195	27.459
S3			22.507	21.222
S4				7.825

The data is sampled continuously. The samples are averaged automatically by meteorological stations over intervals 10-30 min depending on the concrete station set up and the period of observations. The averaged values from temperature, humidity and wind sensors are stored into station's digital loggers. The data collection started in March 2008. Since the stations are placed in a relatively remote place, frequent regular access would have overrun the project budget. Therefore, the calibration, repair and general check of the stations' performance are carried out about once a month. It results in data collection irregularities and rather large data gaps. Table 3 gives the preliminary data recovery rate by months through September 2008 to January 2009. To study the dependence on the averaging and reduce the logger memory requirements, the data averaging interval was set to 30 min at some stations in September-October and 10 min in November-January.

The complementary data on the rainfall and cloudiness are obtained from meteorological radars in Ermelo (to the east) and Irene (to the west). The processed data [13] and combined with gauge and satellite data radar maps for daily averaged precipitations with resolution up to 1 km are available on-line from (http://metsys.weathersa.co.za/radar_image/precip.24hr/archive/). The procedure has been developed in the project SIMAR. The radars operate in a volume-scan mode with ~5 minute time resolution. The data processing system TITAN is used to manipulate and display radar data and the mdv-format is used for all data and products (all originated from NCAR, USA).

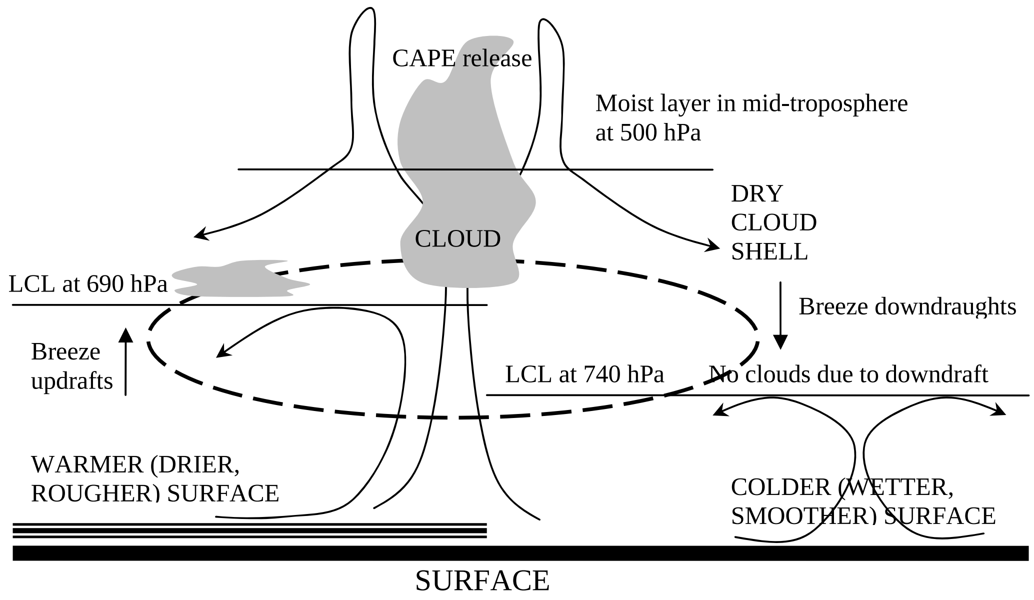


Figure 3. The scheme of the turbulent vortex circulation expected to be observed over heterogeneous surface as effect of dynamics-thermodynamics interactions and latent to sensible heat flux interchange.

Figure 4. Location of the automatic meteorological stations in the experiment. Stars denote the weather stations; gray contours are farm boundaries; blue lines are significant roads. Farm names are given in red and farm addresses are within yellow boxes.

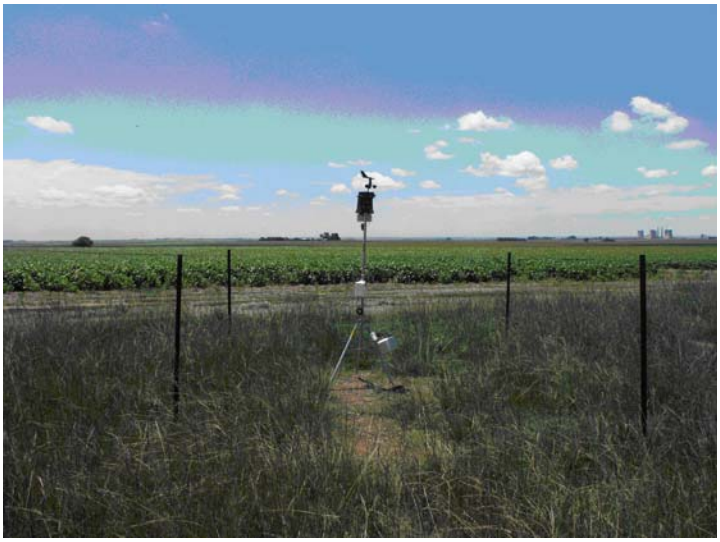


Figure 5. A typical view at the weather station site. Site S1 on Jan de Jager's farm.

Table 3. Data completeness (in % of the total possible coverage by time) at meteorological stations as achieved through September 2008 to January 2009. Observe that not all logged data are retrieved in the database yet. Such data denoted as NP – "not processed".

Station	Sep	Oct	Nov	Dec	Jan
S1.	60	100	97	54	58
S2.	60	100	58	32	58
S3.	58	NP	79	60	NP
S4.	NP	NP	NP	NP	NP
S5.	60	NP	37	NP	NP

3. Davis Vantage Pro 2 automatic meteorological station

Networks of wireless weather stations gradually become essential for investigation of the atmospheric processes over strongly heterogeneous surfaces. For example, Nadeau et al. [14] deployed 92 weather stations Sensorscope in the central part of a university campus covering an area of 300 by 400 m. The data (temperature, wind speed and direction) where sampled at the rate of 120 s with the averaging over 30-min periods. This high temporal and special resolution meteorological measurements were used to evaluate the applicability of Monin-Obukhov similarity theory for the urban surface fluxes.

Davis Vantage Pro 2 is an automatic meteorological station with independent energy supply from solar panels and wireless data transmission from a set of configurable meteorological sensors to autonomous storage and display module. This equipment has several strong advantages. It is relatively inexpensive on the price per station of about $3000. So the modest project budget could be used to purchase several or even several tens of stations. The stations are automatic. They can operate, collect, log and store data without manual maintenance, without external source of the energy supply and without frequent access to sensors and data. All these features are not only reducing the cost but also make it possible to place stations in areas with little or no infrastructure. The wireless transmission of data with the frequency hopping spread spectrum radio is able to support high transmission rate up to 1000 Hz. It does not require application for a special permit and works robustly on the range up to 100 m. More information about the station and its installation could be found in (Application Note 30).

Each of the stations are equipped with a pressure sensor, 2 temperature sensors, humidity sensors, wind anemometers, rain collection gauges and radiation measurements. This equipment allows for gradient measurements and calculation of the complete surface radiation balance and turbulent fluxes.

An important issue of the experimental meteorology is the quality characteristics of data and stability of the sensors' readings. Calibration and quality of measurements have been assessed independently [15]. He concluded that temperature sensors demonstrated good behaviour with the scaling factor ~1.0 and negligible offset. Humidity sensors demonstrated acceptable behaviour with the scaling factor above 0.9 and the offset ~6 %. However, the humidity values during wet conditions were too high. The pressure sensor has adjusted for real air pressure (not barometric pressure reduced to sea level) after several hours of working. Its behaviour was also good with the scaling factor 0.97. Wind anemometers were working acceptably good with the scaling factor 0.89 and negligible offset. Solar radiation sensors were tested against ventilated CM21 Kipp & Zonen pyranometer. Uncorrected Vantage Pro radiation data were lower by about 7% with scaling factor about 1.07 and a small offset. But the data scattering was non-negligible so longer time of averaging is required to obtain a reliable radiation flux. Applying the manufacturer's temperature coefficient of 0.12% per °C (above 25°C) improved the scaling factor to 1.04. In short, this comparison shows that the Vantage Pro Plus delivers excellent to good quality data, compared to professional-grade sensors.

The overall conclusion [15] can be formulated as follows. Certainly the Davis Automatic Weather Station accuracy is way too low to detect minor long-time trends in meteorological parameters. This conclusion opposes the statement of the producer on the station abilities. Thus, the equipment is not suitable for representative meteorological observations, at least without frequent calibration. Nevertheless, the equipment can be used for short-time micro-meteorological observations, especially those like the MMEH, which rely on statistically significant features but not on the individual readings. The data format is not carefully designed. A lot of important information is missed or stored improperly. This is especially related to the timing and sensor's location of readings. At the same time, the format reserves bytes for many derived parameters that can be computed by request. It creates significant complications for the data processing as well as reduces the amount of data to be stored in the limited logger memory.

The Davis Vantage Pro equipment has been already used in many educational and scientific projects, e.g. in the Citizen Weather Observer Program (CWOP). In Africa, the equipment has been used in BodEx-2005 (Bodele (in Chad) Experiment) meteorological experiment [16, 17] aimed to quantify the dust aerosol production. In this experiment, the focus was on measurements of the near-surface winds and their correlations to the aerosol load in the lower atmosphere. As the publications disclose the choice of the Davis Vantage Pro equipment was scientifically justified and paid of with research data of high quality.

5. Conclusions

Our experience has shown that it is feasible to organize relatively inexpensive micro-meteorological experiment based on affordable mass-production meteorological equipment, automated data collection, logging and storage, and utilization of complementary information. The experience has also highlighted several difficulties that need to be taken seriously at the stage of the experiment planning. Firstly, the experiment should be well thought of in terms of the equipment safety and accessibility. Secondly, the data should go through pre-processing as often as possible in order to find irregularities in the equipment operation and calibration. The routine has not been implemented in the MMEH, which caused somewhat lower data recovery rate. Thirdly, the accessibility of the complementary meteorological information has to be secured in advance.

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