A Study of stable Atmospheric Boundary Layer over highveld South Africa

2010 IOP Conf. Ser.: Earth Environ. Sci. 13 012012

(http://iopscience.iop.org/1755-1315/13/1/012012)

A Study of Stable Atmospheric Boundary Layer over Highveld South Africa

P. Luhunga[1], I. Esau[2,3], G. Djolov[1]

[1] University of Pretoria, Republic of South Africa

[2] G.C. Rieber Climate Institute of Nansen Environmental and Remote Sensing Center, Thormohlensgate 47, 5006, Bergen, Norway

[3] Bjerknes Centre for Climate Research, Bergen, Norway

Email: george.djolov@up.ac.za

Abstract

The study is part of the South African – Norwegian Programme for Research and Co-operation Phase II "Analysis and Possibility for Control of Atmospheric Boundary Layer Processes to Facilitate Adaptation to Environmental Changes". The research strategy of the project is based on 4 legged approach. 1) Application and further development of contemporary atmospheric boundary layer theory. 2) Use of modeling based on large eddy simulation techniques. 3) Experimental investigation of turbulent fluxes. 4) Training and developing academics capable of dealing with the present and new challenges. The paper presents some preliminary results on the micrometeorological variability of the basic meteorological parameters and turbulent fluxes.

1.Introduction

Atmospheric boundary layer (ABL) is the part of troposphere that is directly influenced by the presence of the earth's surface and responds to surface forcing with a time scale of about one hour or less. It plays an important role in the dynamic state of the whole atmosphere by controlling the exchange of heat, moisture, momentum, aerosols, gasses, pollutants and trace gases relevant to the climate change phenomenon. The success of daily weather prediction, climate simulations, air pollution and urban meteorology studies, aviation and agriculture industry are crucially dependent on the proper parameterization of the ABL dynamics.

The stable boundary layer (SBL) study over the Highveld South Africa has a special relevance since the majority of the electric power generating plants is located in this region. SBL is characterized by light (calm) wind near the surface, virtual potential temperature increase with height, humidity decrease with height, strong wind shears (directional & speed), turbulence generated mechanically by shear is destroyed by negative buoyancy and viscosity. The non-turbulent periods are frequent and SBL becomes decoupled from the surface. The oscillatory type of behavior of the near-surface atmospheric variables is a manifestation of the non-linear character of the turbulent exchange.

The aim of the paper is to study the SBL characteristics over the Highveld region of South Africa using automatic observational network data and theoretical models. In particular some preliminary results of the time variation of meteorological parameters and turbulent fluxes of momentum and heat are presented.

2. Data and calculation of the turbulent fluxes

The experimental set up for the observation of all relevant meteorological variables and the data collection are presented in paper [1], which is part of the present international conference publication. It should be noted that in addition to the Davis station experimental set up, which was mounted at height 2 m, one more temperature sensor has been installed at 0.5 m to allow for the calculation of turbulent fluxes. The calculation of the turbulent fluxes is done using the collected experimental data during 2008 and 2009 observational campaigns. The subset of SBL condition data was organized using the temperature difference between 2m and 0.5m.

The determination of the turbulent fluxes of momentum and heat is based on the recent advancement of the similarity theory method. First, for the past already 60 years Kolmogorov's [2] approach for turbulent closure models based on the turbulent kinetic energy (TKE) balance has been a major scientific tool. His hypothesis, however, is theoretically justified for-neutrally stable turbulent flows only. Many attempts to apply Kolmogorov's method for stratified flows have Ri_{cr} encountered difficulties. The straightforward application of the TKE budget equation leads to the existence of critical Richardson number. The experimental data from laboratory and atmospheric flows have persistently shown that turbulence exists at higher than the critical Richardson number values.

Recently (see [3]) it has been shown that the use of the total turbulent energy TTE=TKE +TPE (TPE is the turbulent potential energy), instead of TKE only, is a promising way for development of consistent turbulent closure models. One main result of the new theory is that the critical Richardson number does not separate the turbulent and the laminar flow regimes. Instead turbulence exists at any Richardson number.

Secondly, the Monin –Obuhkov (MO) [6] similarity theory, which postulated that the vertical variation of mean flow and turbulence characteristics in the surface layer should depend only on the surface momentum flux as measured by friction velocity u_*, the buoyancy flux F_θ , and the height z, can not be considered as the ultimate framework for studying the surface layer turbulence. According to MO the Richardson number $Ri \equiv \beta(d\Theta/dz)/(dU/dz)^2$, monotonically increases with z/L, and at $z/L \to \infty$ has an asymptote maximum value of $Ri_{cr} = \chi^2 C_{\Theta 1} k_T^{-1} C_{U1}^{-2}$. This shows that the similarity theory universal function range can not exceed $Ri > Ri_{cr}$. This is a classical result which follows from the equation of kinetic turbulent energy balance accepted at the time when MO theory was formulated. However, as it has been shown in [3] turbulence is not fully suppressed at any Richardson number.

In a papers [4], [5] the classical MO theory has been generalized by considering the fact that the boundary layer turbulence depends on the free atmosphere parameters. In addition to the Monin-Obukhov length L, which characterize the effect of local buoyancy on turbulence, there are two additional length scales: L_f - describing the effect of the

Earth rotation and L_N - characterizing the non-local effect of the static stability of free atmosphere. The definition of these parameters is:

$$L_f = \frac{\tau^{1/2}}{|f|}$$

$$L_N = \frac{\tau^{1/2}}{N}$$

where f is the Coriolis parameter, and $N = (\beta \partial \Theta / \partial z)^{1/2}$ is the free atmosphere Brunt-Vaisala frequency. Interpolation between the squared reciprocals define a new composite turbulence length scale

$$\frac{1}{L_*} = \left[\left(\frac{1}{L} \right)^2 + \left(\frac{C_N}{L_N} \right)^2 + \left(\frac{C_f}{L_f} \right)^2 \right]^{1/2}$$

where $C_N = 0.1$ and $C_f = 1$ are empirically determined dimensionless constants.

In this paper the momentum and heat resistance laws are solved using the widely accepted functional form for the universal functions for stable stratification conditions [7].

$$\varphi_m(\frac{z}{L}) = 1 + 4.7\frac{z}{L}$$

$$\varphi_\theta(\frac{z}{L}) = 0.74 + 4.7\frac{z}{L}$$

The linear form of the above equations allows for obtaining analytical solutions for the turbulent fluxes.

3. Micrometeorological variability of basic turbulence characteristics

The data in section 2 and the generalized theory discussed in the previous section allow presentation of some preliminary results for the variation of the meteorological variables and turbulent fluxes in stable stratification conditions over the Highveld region. In Figure 1 the monthly distribution of the rainfall and rainfall intensity are presented. It should be immediately noted the substantial difference between these parameters for stations, which are not too far apart. The analysis of individual cases for rainfall together with the turbulent fluxes will allow the turbulent vortex circulation expected over heterogeneous surface as an effect of dynamics-thermodynamics interactions and latent to sensible heat flux interchange.

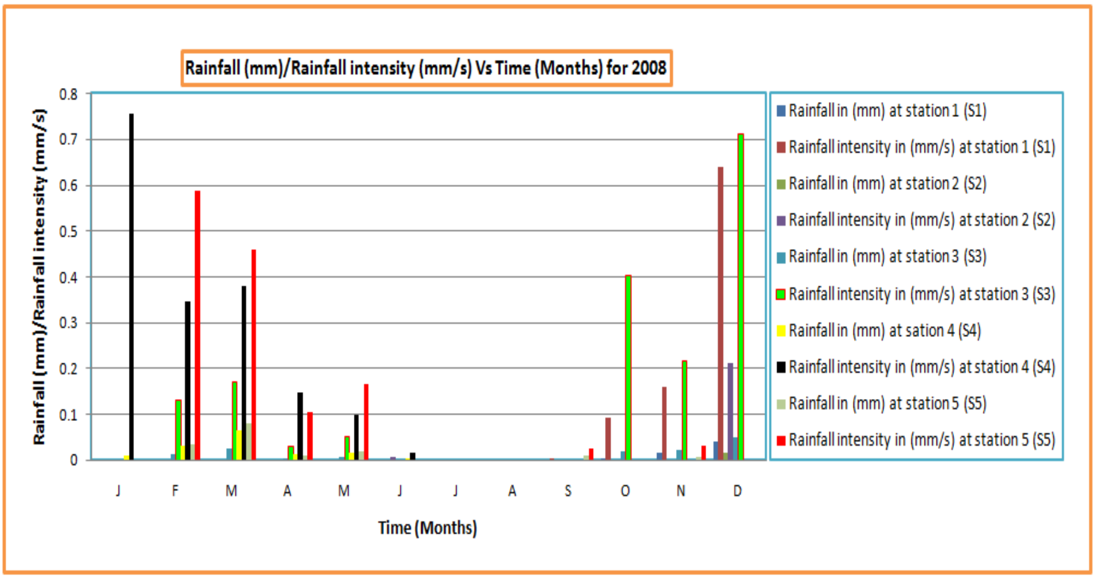

Figure 1. Rainfall and rainfall intensity distribution.

The extreme variability of the stability conditions at micrometeorological scales can be also observed in Figure 2, which presents the Monin-Obukhov length variation for a particular night.

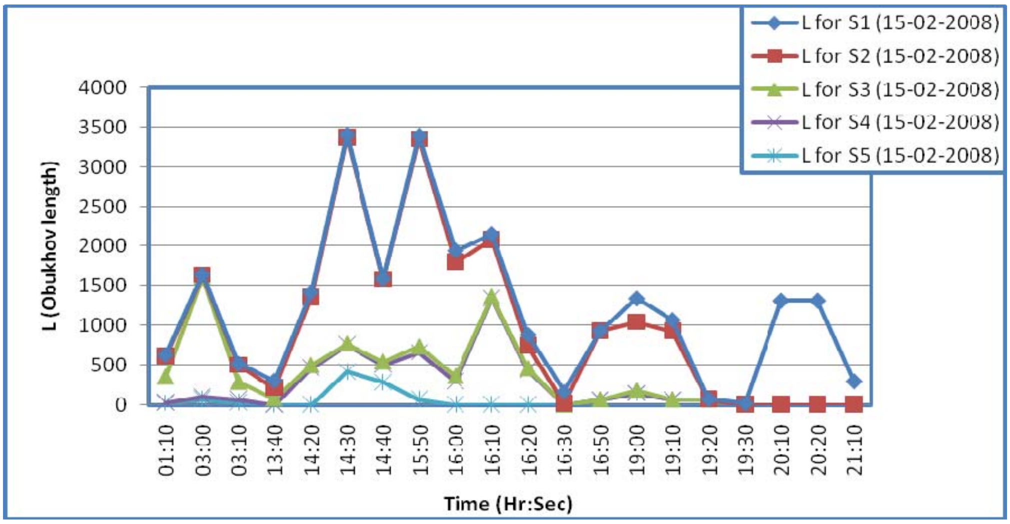

Figure 2. Monin-Obukhov length variation

Figures 4 and Figure 5 demonstrate the big difference between the turbulent fluxes at micrometeorological scale for the same particular night period as in Figure 2.

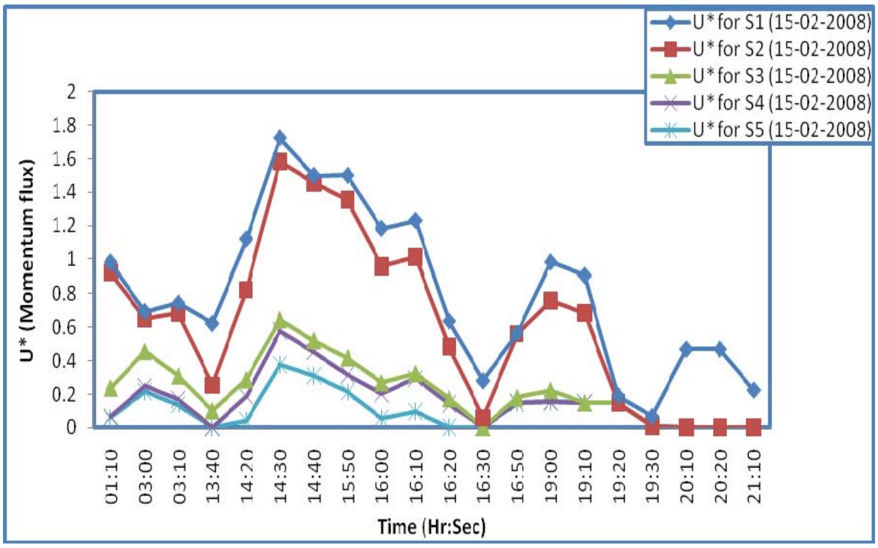

Figure 4. Variation of turbulent friction velocity.

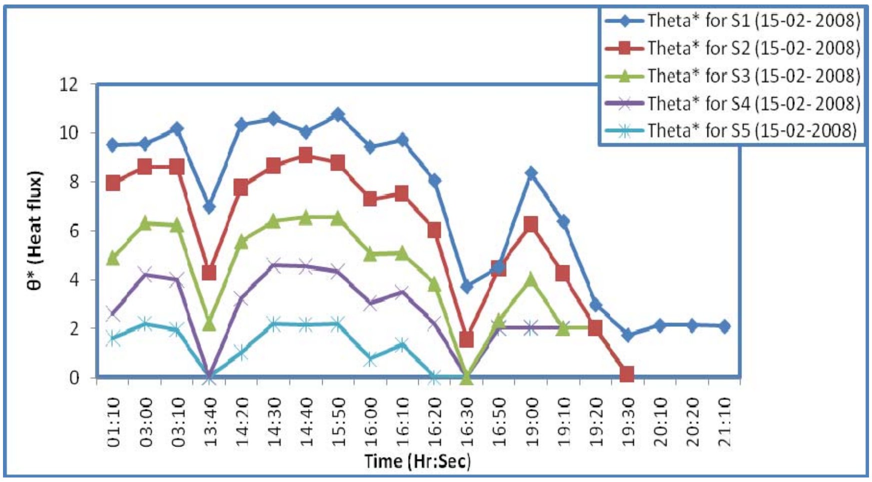

Figure 5. Variation of the heat flux.

4. Conclusions

The preliminary results presented in the paper reveal the essential variability of the SBL characteristics over Highveld region, South Africa. They are of importance for the solution of the heavy air pollution episodes in the region and long-range pollutants transports to the neighboring countries since it contains most of the coal power generating stations of South Africa. The strong variations of the micro-scale rain patterns phenomenon needs also of properly sampled spatially distributed data. Finally, the second phase of the research will concentrate on the mechanisms of convective clouds development which are controlled by the PBL turbulence and external parameters such as the atmospheric static stability, surface roughness and the mean wind as well as the moisture availability and therefore the height of the condensation level.

References

[1] Esau, I.N., Zilitinkevich, S.S., Djolov, G.D and J. deW. C. Rautenbach, 2010: A micro-meteorological experiment in the atmospheric boundary layer in Highveld region, *Paper in the present volume*.
[2] Kolmogorov AN, 1941: Energy dissipation in locally isotropic turbulence, *Doklady AN SSSR*, **32**(1):19-21.
[3] Zilitinkevich SS, Elperin T, Kleorin N and I Rogachevski, 2007, Energy and flux budge (EFB) turbulent closure model for stably flows, Part I: steady-state, homogeneous regimes., *Atmospheric Boundary Layers*, *Springler*,11-36.
[4] Zilitinkevich S and I.N. Esau, 2005, Resistance and heat transfer laws for stable and neutral planetary boundary layers: old theory, advanced and reevaluated, *Quart J Roy Meteorol Soc*. , **131**, 3339-3356.
[5] Zilitinkevich SS and I.N.Esau, 2007, Similarity theory and calculation of turbulent fluxes at the surface for the stably stratified atmospheric boundary layer, *Atmospheric Boundary Layers*, *Springer*, 37-50.
[6] Monin AS and AM Obukhov, 1954, Main characteristics of the turbulent mixing in the atmospheric surface layer, Trudy Geophys Inst AN SSSR, **24**(151), 153-187.
[7] Businger JA, Wyngaard JC, Uzumi Y and EF Bradley, 1971, Flux-profile relationship in the atmospheric surface layer, *J Atm Sci*, **28**, 181-189.