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THE UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

NUMERICAL INVESTIGATION OF A HEATED, SHEARED PLANETARY BOUNDARY LAYER

A Dissertation
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
degree of
Doctor of Philosophy

By
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Norman, Oklahoma
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NUMERICAL INVESTIGATION OF A HEATED, SHEARED PLANETARY BOUNDARY LAYER

A Dissertation APPROVED FOR THE
SCHOOL OF METEOROLOGY

BY

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ABSTRACT

A planetary boundary layer (PBL) developed on 11 July, 1987 during the First International Satellites Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) is investigated numerically by a two dimensional and a three dimensional large eddy simulation (LES) model. Most of the simulated mean and statistical properties are utilized to compare or verify against the observational results extracted from single Doppler lidar scans conducted by Gal-Chen *et. al.* (1992) on the same day. Through the methods of field measurements and numerical simulations, it is found that this PBL, in contrast to the well-known convective boundary layer (CBL), is driven by not only buoyancy but also wind shear. Large eddies produced by the surface heating, as well as internal gravity waves excited by the convection, are both present in the boundary layer. The most unique feature is that in the stable layer, the momentum flux ($\overline{u'w'}$), transported by the gravity waves, is counter-gradient. The occurrence of this phenomenon is interpreted by Gal-Chen *et. al.* (1992) using the theory of critical layer singularity, and is confirmed by the numerical simulations in this study. Furthermore, due to the existence of the critical layer, the structures of some of the statistical properties are also altered. For example, the vertical profiles of horizontal velocity ($\overline{u'^2}$), potential temperature flux ($\overline{w'\theta'}$) and its variance ($\overline{\theta'^2}$) are all found to exhibit a second local absolute value maximum in the stable layer.

Qualitative agreements are achieved between the model-generated and lidar-derived results. However, quantitative comparisons are less satisfactory. The most serious discrepancy is that in the stable layer the magnitudes of the observed momentum flux ($\overline{u'w'}$) and vertical velocity variance ($\overline{w'^2}$) are unusually larger than their simulated counterparts. Nevertheless, through the technique of numerical simulation, evidence is

collected to show inconsistencies among the observations. Thus, the lidar measurements of $\overline{u'w'}$ and $\overline{w'^2}$ seem to be doubtful.

A Four Dimensional Data Assimilation (FDDA) experiment is performed in order to connect the evolution of the model integration with the observations. The results indicate that the dynamical relaxation (nudging) scheme appears to be an appropriate method by which the observed mean quantities such as mean wind ($\bar{u}$) and potential temperature ($\bar{\theta}$) can be assimilated into the model without causing data rejection. Finally in this study, the so-called "constrained simulation" technique is introduced. This method was utilized successfully by Lilly and Mason (1990) to the PHOENIX II PBL on 22 June, 1984 to recover large- or meso-scale forcing which was not directly measured. However, due to the differences in the forcing process, the application of this technique to the FIFE PBL is not recommended.

NUMERICAL INVESTIGATION OF A HEATED, SHEARED PLANETARY BOUNDARY LAYER

CHAPTER 1

INTRODUCTION

In the summer of 1987 near Manhattan, Kansas a field project named First International Satellites Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) was conducted to study the atmospheric boundary layer processes. During the experiment, a short-pulse ($\approx 0.4\ \mu s$) CO_2 Doppler lidar ($\lambda = 10.6\ \mu m$) was operated by the National Oceanic and Atmospheric Administration (NOAA) Wave Propagation Laboratory (WPL). Later Gal-Chen *et. al.* (1992) proposed a specially designed scanning sequence to extract boundary layer parameters from the single Doppler lidar observations. Readers are encouraged to consult this paper for detailed explanations of the method. By applying this new technique to two case studies (11 July, 1987, from 11:11 to 12:10 and from 12:29 to 13:20 CDST, CDST stands for the local Central Daylight Saving Time and is 5 hours earlier than the Coordinated Universal Time, or UTC), they were able to obtain (1) mean wind ($\bar{u}, \bar{v}, \bar{w}$), where (u, v, w) are the Cartesian velocities in the (x, y, z) directions respectively; (2) the variances ($\overline{u'^2}, \overline{v'^2}, \overline{w'^2}$), where the prime indicates deviations from the mean; (3) the covariances associated with the vertical fluxes of horizontal momentum ($\overline{u'w'}, \overline{v'w'}$); (4) the third moment of the vertical velocity ($\overline{w'^3}$); (5) the kinetic energy dissipation (ε); and (6) the surface heat flux. In addition to the lidar observations, seven balloon soundings were released on the same day which gave the "snapshots" of the atmosphere in terms of vertical distributions of horizontal mean wind and potential temperature ($\bar{\theta}$).

It is known that observations always suffer from numerous difficulties and the

FIFE PBL field experiment is no exception. In the single Doppler lidar operations by Gal-Chen *et. al.* (1992), the stability of the reference frequency is a severe hardware problem. The lidar range resolution (150 m) is another serious limitation for boundary layer studies. Velocity estimations are doubtful below the range 600 m. The maximum distance beyond which the signal-to-noise ratio is too low to permit radial wind measurement is 6 km in the horizontal and 2 km in the vertical. Despite the efforts to reduce errors such as exploiting a large sample size, some results are questionable. For example, the observed vertical velocity is suspiciously large in the mixed layer. The deduced third moment of vertical velocity shows a perplexing negative value above the mixed layer. These problems led the author to consider the usage of a numerical model as a consistency check on the data. Thus, the purpose of this research is to investigate the FIFE PBL on 11 July, 1987 by numerical simulations. The model-generated results are utilized to compare or verify against the field observations. Through this procedure, the properties of the FIFE PBL can be further explored. Another advantage of using a model is that it is capable of providing information which is not measured by any field instruments. Therefore, a more complete understanding of the PBL is possible.

The previous discussions point out that use of a numerical model to conduct simulations and instruments to collect data for analyses provide complementary data for atmospheric research. The matching of models with observations is a persistent problem. Observational data should be used to initialize numerical models while the results predicted from a numerical model should be compared against subsequent observations. In reality, this is a far more involved process. Observations suffer from the limited resolution of the instruments, and the inhomogeneity and incompleteness of the measurements. Models tend to diverge from the real atmosphere because of the errors embedded in initial data and the unavoidable inaccuracy of the numerical methods, as well as inadequate modeling assumptions. On the other hand, observations can be utilized to further constrain the evolution of numerical models. A numerical model can generate physically and dynamically consistent data sets with desired spatial and time resolutions at many more points than there are observations. This leads scientists to recognize that assimilating observed data into a physically comprehensive time-dependent, dynamical model is fundamental for the synthesis of temporally and spatially diverse incomplete data into a coherent representation of a geophysical system.

Techniques for the systematic matching of dynamical models with spatial and temporal observations are commonly called "four dimensional data assimilation" (FDDA). Charney *et. al.* (1969) first showed the possibility that the present state of an atmosphere in hydrostatic balance can be inferred from incomplete historical data. Since then this technique has been extensively and fruitfully used for global and mesoscale analysis. By contrast, small scale data assimilation techniques are relatively new (Gal-Chen and Kropfli, 1984; Gal-Chen *et al.*, 1991; Liou *et al.*, 1991; Xu and Gal-Chen, 1993). In this study it is desired to find an appropriate method by which the observed mean quantities, namely $\bar{u}$ and $\bar{\theta}$, can be assimilated into the model without causing any data rejection. A successful method, if any, should be able to improve the mean value profiles and at the same time keep the vertical structure of statistical properties physically reasonable.

Large geostrophic wind shears (or vertical variation of large horizontal pressure force) are caused by large horizontal temperature gradients. Even in an idealized PBL above a flat terrain, some baroclinity is to be expected due to the climatological temperature differences. For example, a common north-south temperature gradient with magnitude 1° C/100 km gives rise to a geostrophic shear as large as 3.5 m s^{-1} km^{-1}. However, these large scale forcing terms cannot be obtained by means of direct simulation in a numerical model with periodic horizontal boundary conditions. Lilly and Mason (1990) conducted simulations with the mean field forcing included. This was accomplished by requiring the horizontally averaged velocity and/or the potential temperature profiles to remain roughly as observed. By applying this technique to the 22 June, 1984 PHOENIX II PBL they successfully estimated the mesoscale horizontal temperature gradient and temperature advection. Nevertheless, the usefulness and limitation of this approach are not well understood. Thus, another goal of this dissertation is to explore the possibility of recovering large scale forcing in the FIFE PBL by utilizing a similar method, the so-called "constrained simulations".

During FIFE 1987 observations were taken over 77 selected days from May to August. The reason for choosing 11 July for this study is that through analysis of the observed data three principal physical processes are identified. Each one of these processes has been investigated by the scientific community. But a numerical simulation of the PBL with all these processes combined together is an interesting and challenging task. In what follows these three processes, as well as the relevant literature reviews, are introduced separately.

1.1 Buoyancy Force Coexists with Wind Shear Effect

The windless convective boundary layer (CBL) has been extensively studied by scientists using laboratory experiments (e.g. Deardorff *et. al.* 1969; Willis and Deardorff 1974; Deardorff and Willis 1985) or large eddy simulation numerical models (e.g. Deardorff 1974 a,b; Moeng 1984; Nieuwstadt and Brost 1986; Mason 1989; Schmidt and Schumann 1989; Nieuwstadt *et. al.* 1993). When wind shear becomes important, the flow pattern and turbulence statistics can be quite different. Deardorff (1972) proposes the quantity $-Z_i/L$ is an appropriate stability parameter, where Z_i is the height of the mixed layer and L is the Monin-Obukhov length defined by

$$L = -\frac{u*^3\,\theta_m}{k\,g\,\langle w\theta\rangle_S} \tag{1.1}$$

Here u∗ is friction velocity, k is the von Karman's constant 0.4, θ_m is the mean value of potential temperature throughout the PBL and $\langle w\theta\rangle_S$ is the surface heat flux. When $-Z_i/L > 4.5$, the PBL is in the convective regime. In FIFE PBL the quantity $-Z_i/L$ is about 1.75. Therefore, it represents an intermediate boundary layer in which both the buoyancy and wind shear forcing are important.

Sykes and Henn (1989) conducted a series of large eddy simulations of free and sheared convective flow between two moving flat plates. They found that $u*/w* > 0.35$ is an important criterion for the formation of longitudinal rolls. Here w∗ represents the convective velocity and is defined in Deardorff (1970) as

$$w* = \left(\frac{g}{\theta} < w\theta>_S Z_i\right)^{1/3} \tag{1.2}$$

Moeng and Sullivan (1994) also utilized a LES model to investigate the discrepancies among shear-driven, buoyancy-driven, and the intermediate PBL that is driven by both forces. A new scaling for velocity is developed for the intermediate case. A common feature in these two studies is that the shear forcing considered is primarily concentrated near the surface. By contrast, the wind shear effect in the FIFE environment is found to exist throughout the PBL (Refer to Chapter 2), therefore provides a different type of problem to be studied.

1.2 Convective Gravity Waves and the Necessity of a Higher Domain for PBL Studies.

The derived momentum flux profiles as well as the spectrum analyses of the vertical velocities in the FIFE PBL by Gal-Chen *et. al.* (1992) all strongly suggest the existence of internal gravity waves in the stable layer. Widespread gravity waves have been found, probably by glider pilots first, to exist above the convectively active boundary layers in the presence of vertical wind shear over flat terrain. The mechanism that produces these gravity waves is believed to be the "obstacle effect", which occurs when large eddies or clouds at the top of the mixed layer act as small hills in a sheared environment. The requirement that some of the air must flow over these hills results in the gravity waves. Chimonas *et. al.* (1980) demonstrated the possibility that a gravity wave can reach sufficiently large amplitude to induce condensation. Under certain circumstances the heat released through this process may substantially reinforce the wave itself. Therefore a positive feedback mechanism is established through which both the waves and condensation experience a mutually accelerated growth. However, numerical experiments conducted by Mason and Sykes (1982) show that dry thermals alone are capable of launching waves. Aircraft observations taken by Kuettner *et. al.* (1987) over the western plains of Nebraska on 12 June, 1984 during the National Center for Atmospheric Research (NCAR) Convection Wave Project and a companion paper (Clark and Hauf, 1986) which simulated the tropospheric internal gravity waves detected on the same day all conclude that convection, not convective cloud formation, is the essential ingredient of convective waves. Small field of clouds are acting primarily as markers and have only slight effect on the boundary layer eddies and internal gravity waves response. In the FIFE experiment, the data sets and mission logs were reviewed by participating scientists to identify the so called "golden days" as the highest priority for data processing and submission. The day selected for this research, 11 July, 1987, is one of the golden days. An overview paper by Sellers *et. al.* (1992) indicates that only minimum cloud cover and zero precipitation were recorded on that day. Thus, as far as this research is concerned, it is appropriate to carry out our numerical studies in a dry model.

Traditional research on CBL usually concentrates only on the first 1 to 2 km of the