The Turbulent Structure of the Atmospheric Boundary Layer

AERSP/ME 525: Turbulence and Applications to CFD: RANS
Term Paper Summary

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Introduction

The structure of the atmospheric boundary layer (ABL) is studied by fluid dynamicists who specialize in the field as well as meteorologists and climate scientists. The structure of the atmospheric boundary layer has been described in detail in several books previously [1, 2, 3]. Like a flat plate boundary layer, a topic familiar to those who have studied fluid mechanics, the term ”atmospheric boundary layer” describes the layers of the atmosphere near the earth’s surface in which the presence of a surface below plays a significant role [1]. Unlike a classical flat plate boundary layer, the ABL is greatly affected by buoyancy, humidity, and the Earth’s rotation. Turbulence in the boundary layer serves to transport heat, momentum, moisture, and particulates at large scales. An understanding of this turbulent structure is crucial in applications including weather prediction, aeronautics, and urban air quality.

Basic Structure

The ABL is driven by many forces and energy transport mechanisms. Solar radiation causes the lowest layers of the atmosphere to heat up, but the presence of clouds and humidity affects the tranmissivity of the atmosphere and in turn the heat transfer. At night, the heat loss from the earth to space again affects the temperatures of the atmosphere. When there is a difference in temperature in the boundary layer, buoyancy causes warm pockets of air to rise. Additionally, the presence of humidity and pollutants affect the thermodynamic state at a given location. These are only some of the many interactions affecting the ABL, illustrating that the ABL is a highly complex system. It has been established that the ABL exhibits diurnal behavior, as illustrated in Figure 1.

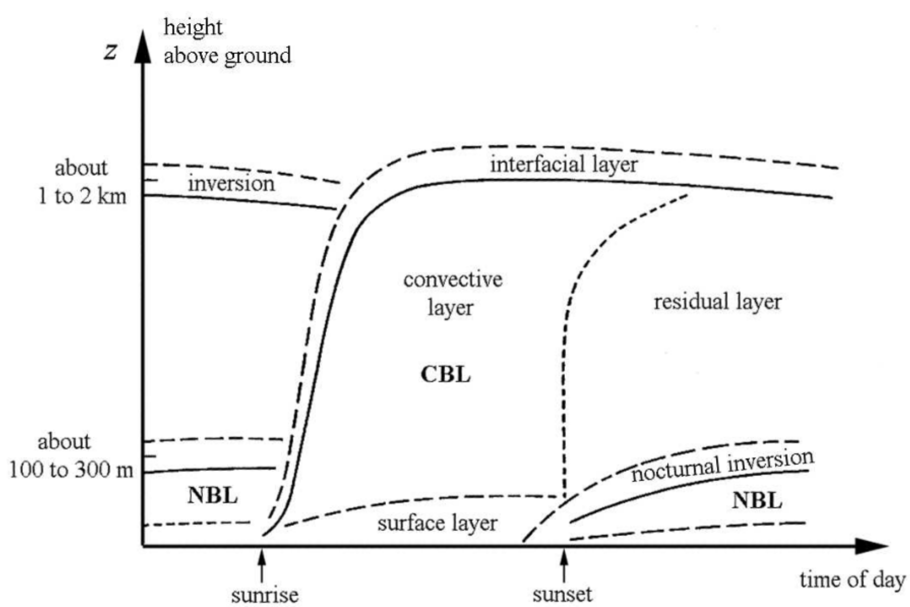

Figure 1: The diurnal structure of the atmospheric boundary layer, from [4]

The ABL is usually about 1 km to 2 km in thickness, and is within the region of the atmosphere known as the troposphere. At sunrise, solar radiation heats the surface of the earth and causes air at the surface to increase in temperature and rise due to buoyancy, forming what is called the convective layer. These thermals are driven by turbulence, and are themselves turbulent eddies. The upper limit of the ABL is the interfacial layer. The upper limit of the ABL is difficult to define, but the cloud base is typically (arbitrarily) used as the cut-off for boundary layer studies [1]. At sunset, the surface is no longer heated, stopping the thermals from rising, and a stable, nocturnal boundary layer is formed. At night, the absence of vertical motion causes the layers to be stably-stratified in the residual layer, until sunrise when it is disrupted by convective thermals once again.

Theoretical Background

The fundamental laws of physics - conservation of mass, conservation of momentum, and conservation of energy - must be upheld when describing motion in the ABL. For brevity, the full equations will not be written here; the referenced textbooks include equations in detail. The simplest 3-dimensional fluid mechanics problems with laminar, constant-property flow and no heat transfer consist of four equations: the continuity equation (mass) and the three Navier-Stokes equations (momentum). When turbulence is considered, additional equations must be added to model the effects of turbulent eddies. Using the eddy viscosity approach, so-called "two-equation models" are often used, in which two transport equations are added for the turbulent kinetic energy (TKE or K) and rate of viscous dissipation (ϵ).

For the atmospheric boundary layer, the averaged continuity and Navier-Stokes equations are utilized plus further equations to adequately describe the ABL. To account for the Earth's rotation, terms describing the Coriolis forces must be added to the momentum equations. The energy equation must be added to the system, as the thermal effects in the ABL cannot be neglected. The energy equation is strongly coupled to the flowfield, and the flowfield is coupled to thermal affects in the way of buoyancy. An equation of state such as the ideal gas law is needed to account for changes in thermodynamic properties as functions of pressure and temperature. To account for the presence of liquid water, a conservation equation for the mean liquid water content must be added to the system. An equation of radiative equilibrium must be added if clouds are to be accounted for, when the atmosphere can no longer be assumed to be fully transmissive. The energy equation and water content equations must have terms to account for the possibility of phase change. Because the atmosphere consists of many gases, the mass conservation equation must be modified into a species balance equation to ensure that not only is the total mass conserved, but the mass of each species is also conserved. With direct numerical simulation (DNS) at a high computational cost, eddy-viscosity-based Reynolds-Averaged Navier Stokes (RANS) turbulence models are typically used to provide closure [5].

Turbulence Models for the Atmospheric Boundary Layer

In providing closure for RANS turbulence models of the ABL, not only does the Reynolds stress tensor need to be modeled, an additional term which contains the product of velocity fluctuations and temperature fluctuations must be modeled. Explicit algebraic Reynolds stress models (EARSM) can be formed which account for buoyancy and turbulence effects and allow the problem to be closed. Modified algebraic models have shown good agreement with measurements for stably-stratified ABLs, but have difficulty with flows that feature anisotropy in the Reynolds stress tensor. One-equation models involving TKE or turbulent potential energy (TPE) have been used with reasonable success. Finally, robust three-equation models using K, ϵ, and a quantity related to TPE have been developed which do not rely on the mixing length hypothesis.

Conclusion

The atmospheric boundary layer is a complex system governed by turbulent flows. The understanding of this turbulence is crucial in climate and weather modeling as well as aviation. The ABL is heavily affected by buoyancy, solar radiation, and moisture and follows a diurnal cycle. Turbulence models, including algebraic Reynolds stress models and higher-order 1, 2, and 3-equation models have been developed to account for the buoyancy effects.

References

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