9.3 DIRECT NUMERICAL SIMULATIONS OF INTERMITTENT TURBULENCE IN THE VERY STABLE EKMAN LAYER

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1. INTRODUCTION

Turbulence in very stable boundary layers may exhibit singular behavior which is not found in less stable environments. Perhaps the most striking of component of this unusual behavior is intermittency (Mahrt, 1985; Mahrt, 1998), defined as the tendency of turbulence to occur in short bursts in an otherwise quiescent fluid. Over the years, a number of theories have been promulgated to explain intermittency. These theories include:

- the mechanism of Blackadar (1979)
- various gravity wave phenomena including critical layer absorption (see for example, Nappo [1991], Winters and D'Asaro [1994], Lombard and Riley [1996], Dörnbrack [1998])
- Kelvin-Helmholtz instabilities
- the so-called "upside down boundary layer" (Mahrt, 1999)
- the formation of roll vortices (Thorpe and Guymer, 1977).

Which of the above theories, if any, might be applicable to a particular observation of turbulence intermittency is difficult to determine. This is particularly true when one attempts to infer the physics of the intermittency phenomenon from observations, because the observations usually cover only a limited volume of the fluid being examined, and therefore one cannot "see" the entire picture.

To get around the temporal and spatial limitations inherent in any observational campaign, one can supplement the observations with numerical modeling. The goal here is to use the model to gain physical insight, which in turn may help interpret the observations. For reasons discussed below, we choose to model intermittent turbulence using a direct numerical simulation (DNS) of turbulence.

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2. DIRECT NUMERICAL SIMULATIONS OF TURBULENCE

The DNS method can often provide physical insight into the nature of turbulent flows that can be obtained in no other way. This method simulates all scales of turbulence, from the smallest, dissipation scales up to the largest, energy containing scales. The entire range of scales is modeled exactly, without the use of approximations. Of course, one must pay a price for such fidelity, and the price demanded is the restriction of DNS to low Reynolds number, *Re* (For the simulations described here, the *Re* is defined as GD/ν, where G is the geostrophic wind, D is the laminar Ekman layer depth, and ν is the kinematic viscosity of air).

Despite the restriction to low *Re*, the DNS method has been applied both to laboratory and atmospheric flows. Recently, it has been possible to match the Reynolds number of a laboratory flow with that of a DNS (de Bruyn Kops and Riley, 1998), and the correspondence between the DNS and these measurements was quite good. Such good agreement suggests that DNS is indeed capable of simulating real, turbulent flows when the *Re* of the flow and the simulation are about the same.

However, the *Re* of a DNS of a boundary layer (400) and the *Re* of a real atmospheric boundary layer (10^7 or greater) are dramatically different from one another. Thus, at first glance it would seem that a DNS of a turbulent boundary layer could not provide useful information about real atmospheric flows. This conclusion does not appear to hold, however, for several reasons.

First, the principle of Reynolds number similarity (Townsend, 1980) may permit some aspects of low *Re* DNS to be applicable to atmospheric flows of much larger *Re*. This principle states that as *Re* increases, the flow properties become *independent* of Reynolds number (i.e., the magnitude of *Re* doesn't matter as long as *Re* is "large enough"). So the real question is: at what Reynolds number does Reynolds number similarity begin to take effect? To answer this question, we appeal to a recent DNS of a boundary layer (Coleman et al., 1999) that compared turbulence statistics obtained from three DNS simulations at

Reynolds numbers of 400, 500 and 1000. This study suggests that Reynolds number similarity begins to take effect at *Re* as low as 400.

Second, in a DNS (*Re* = 400) of stably stratified, but continuously turbulent Ekman layer, Coleman et al. (1992) compared predictions of from Nieuwstadt's (1984) "local scaling" theory with the results of DNS. The local scaling theory predicts that appropriately scaled turbulent statistics (e.g., velocity variances) are functions of the z/L only, where z is the distance above the surface and L is the local Obukhov length. Scaled turbulent statistics obtained from the DNS were plotted versus z/L, and compared with Nieuwstadt's measurements, also subject to the same local scaling. The comparison was very favorable for some, but not all of the scaled variables.

Taken together, the above results suggest that DNS can represent some of the physics of the real atmospheric flows under conditions ranging from unstable to stable stratification. With this conclusion in mind, we developed a DNS model designed to model the very stable Ekman layer, where the stability of the flow is so great that continuous turbulence cannot be supported.

3. RESULTS

This DNS model used here is described in Barnard (2000). This model simulates an Ekman layer over flat terrain with a horizontal resolution of 48 x 48 grid points. Fifty-five grid points are used in the vertical direction. A key aspect of this model is the lower boundary condition applied to the sensible heat flux, *H*. This flux can be varied to specify, indirectly, the stratification of the model run. For example, a small negative heat flux cools the atmosphere and produces mild stratification, while a much stronger cooling heat flux results in much more stable conditions. It is possible to cool the flow at such a large rate that the flow becomes very stable and the turbulence becomes intermittent.

This process used to induce intermittent turbulence works as follows. Starting from a fully developed neutrally stratified flow, a cooling heat flux is abruptly applied at a time, t_0. The magnitude of this cooling is described by a bulk Richardson number, Ri_b, defined as:

$$Ri_b = \frac{\dfrac{g}{\Theta_o}\left.\dfrac{\partial\Theta}{\partial z}\right|_{z=0}}{\left(\dfrac{G}{D}\right)^2} \qquad (1)$$

where Θ_0 is the reference temperature, g is the acceleration of gravity and Θ is the temperature of the fluid. Once the heat flux is applied the output of the DNS is examined for evidence of intermittency. If none is observed, the simulation is repeated using a slightly higher Ri_b. This process is repeated until the signs of intermittency are found.

The presence of intermittency in the fluid may be inferred by examining the friction velocity, u_*/G; this velocity is an indication of the surface stress. Values of the friction velocity close to the laminar value indicate laminar flow while higher values suggest the presence of turbulence. For the simulation reported on here, the Reynolds number is equal to 400, and the laminar value of the friction velocity is $\left(\sqrt{2/\mathrm{Re}}\right)^{\frac{1}{2}}$ (= 0.059 at *Re* =400).

Figure 1 illustrates this procedure. In this figure the friction velocity is shown as a function of time. (In this figure, the time has been non-dimensionalized by the Coriolis parameter, *f*). At time $t = 0$, the simulation is started from a quiescent state and allowed to develop in a neutrally stratified environment. At a time, $(tf)_0 = 15.0$, a negative surface heat flux is suddenly applied and the fluid begins to cool and becomes stably stratified. The stratification changes the characteristics of the turbulence, so that at a time of about $tf = 24$, the stress has dropped to value close to the laminar value (indicated in this figure by the dashed line).

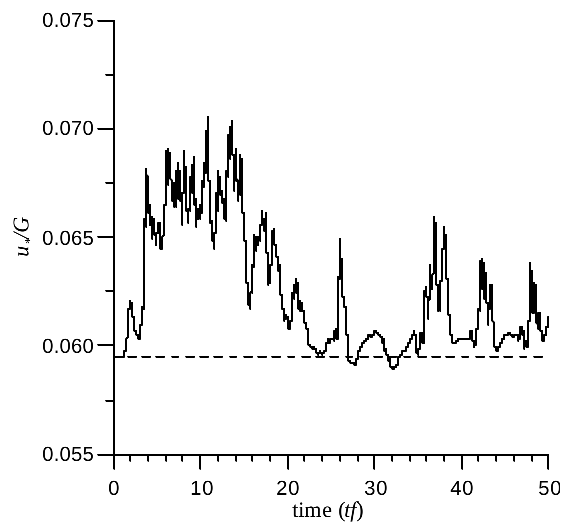

Figure 1: Friction velocity plotted versus time. The time is non-dimensionalized by the Coriolis parameter, *f*, so that *tf* is equal to the non-dimensional time. The dashed line indicates the laminar value of the friction velocity.

An examination of the flow at this time shows that it is indeed laminar. However, as time progresses, the friction velocity dramatically increases – an indication of turbulence -- only to decrease again to its laminar value. This alternation between the laminar state and an apparently turbulent state persists through the duration of the simulation. Apparently, the turbulence is not continuous but occurs in short bursts.

The supposition that the turbulence occurs in bursts can be verified by examining a time series of the vertical velocity recorded by a "probe" at a fixed point in the fluid. Such a time series is shown in the top panel of Figure 2 over a time interval extending from *tf* = 40 to *tf* = 45. Here we see that the vertical velocity is essentially zero for most of this interval indicating a lack of turbulent activity. However, large and sudden fluctuations in the vertical velocity, characteristic of turbulence, occur between times of 42 and 43.5, and then the flow becomes quiet again. This intermittent behavior is defining characteristic of a boundary layer that is termed "very stable" (Mahrt et al., 1998).

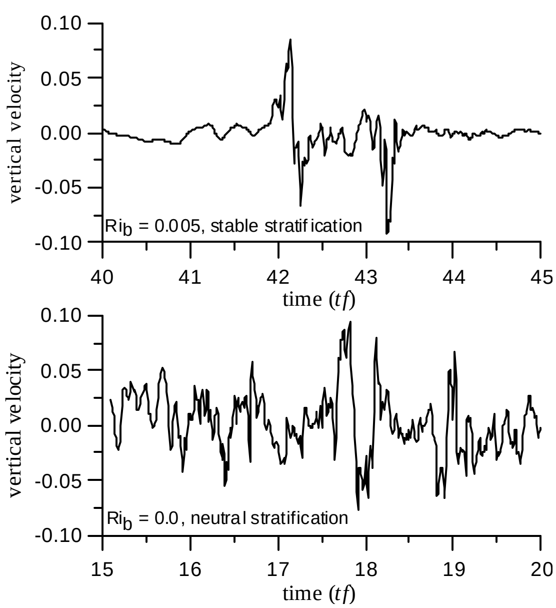

Figure 2: Time series of the non-dimensional vertical velocity, *w/G*, as measured by a probe placed in the fluid. The top panel shows *w/G* for a stably stratified flow where the turbulence is intermittent, while the bottom panel shows *w/G* for a neutrally stratified flow.

The bottom panel of Figure 2 shows the vertical velocity as measured by a probe (positioned identically as the probe in the stratified flow). A comparison between the two panels shows that the turbulence found in the very stable boundary layer, when it occurs, is as strong as the turbulence found in the neutrally stratified simulation.

Given that the simulation can produce intermittent turbulence, we now can examine what physical mechanisms are responsible for the turbulence. The simulations indicate that the development of intermittency follows these steps.

- When the fluid is in a laminar state, a shear instability develops. This shear instability is of the inflectional type (Brown, 1972), leading to a roll vortex.
- The roll structure of the instability lifts small pockets of cold air from near the surface to elevated position in the fluid.
- The cold air overrides warmer air resulting in a cataclysmic convective instability. This instability creates a short burst of intense turbulence.
- In the process of creating turbulence, the roll cell is destroyed, thus choking off the source of the turbulence.
- The turbulence that was produced by the convective instability is damped by the stratification and ceases to exist, and the flow returns to a laminar state.
- Once the flow re-laminarizes, the above process starts anew.

An important feature of this mechanism is the role of the inertial oscillation. As shown in Figure 1, the turbulent events occur more-or-less regularly with a period of about $tf = 2\pi$, the inertial period for the simulations.

We conjecture that the inertial oscillation contributes to the intermittency mechanism during the time that the roll vortex is lifting cold air over warmer air. In the initial stages of the vortex development, and intense nocturnal jet is evident in the mean flow. The height and intensity of the jet enhances the rotation of the vortex which, in effect, supplies kinetic energy to the vortex. This additional kinetic energy helps overcome the gravitational force when the vortex is transporting cold air upward, and without this injection of energy, this cold air transport is significantly weakened. In fact, if the inertial oscillation is artificially removed from the simulations, intermittency does not develop.

4. CONCLUSIONS

This study has used a Direct Numerical Simulation of Turbulence, applied to boundary layer flow, to study the development of intermittent turbulence in the very stable boundary layer. Starting from a fully developed, neutrally stratified flow, a cooling heat flux is applied to the flow. This flux changes the stratification of the flow from neutral to stable, and if the stratification becomes sufficiently strong, the turbulence ceases to be continuous and becomes intermittent. Further increases in stratification extinguish the turbulence entirely.

The turbulence in the "intermittent range" of stability occurs in short, but intense bursts. The strength of the turbulence, as gauged by the magnitude of the vertical velocity fluctuations, is as strong as that occurring in neutrally stratified flow.

The intermittency develops from two fluid instabilities. Firsts, an inflectional instability spawns a roll vortex that carries colder air over warmer air. This condition sets up a violent convective instability, thus generating an intense burst of turbulence. In this process, the inertial oscillation plays in important role in providing energy to the roll vortex so that the cold air can be lifted over the warmer air below.

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