GEOG 321 - Reading Package Lectures 16 & 17

Arya S. P., 1998: Introduction to Micrometeorology, Second Edition.
International Geophysics Series Volume 79, Academic Press,
London, Pages 145-147, 155-157.

(terminology has been adjusted / edited for consistency with lectures)

8.1.3 *Transition to turbulence*

Experiments in controlled laboratory environments have shown that several distinctive stages are involved in the transition from laminar flow (e.g., the flat-plate boundary layer) to turbulence. The initial stage is the development of primary instability which, in simple cases, may be two-dimensional. The primary instability produces secondary motions which are generally three-dimensional and become unstable themselves. The subsequent stages are the amplification of three-dimensional waves, the development of intense shear layers, and the generation of high-frequency fluctuations. Finally, 'turbulent spots' appear more or less randomly in space and time, grow rapidly, and merge with each other to form a field of well-developed turbulence. The above stages are easy to identify in a flat-plate boundary layer and other developing flows, because changes occur as a function of increasing Reynolds number with distance from the leading edge. In fully developed two-dimensional channel and pipe flows, however, transition to turbulence occurs more suddenly and explosively over the whole length of the channel or pipe as the Reynolds number is increased beyond its critical value.

Mathematically, the details of transition from initially laminar or inviscid flow to turbulence are rather poorly understood. Much of the theory is linearized, valid for small disturbances, and cannot be used beyond the initial stages. Even the most advanced nonlinear theories dealing with finite-amplitude disturbances cannot handle the later stages of transition, such as the development of 'turbulent spots.' A rigorous mathematical treatment of transition from turbulent to laminar flow is also lacking, of course, due to the lack of a generally valid and rigorous theory or model of turbulence.

Some of the turbulent flows encountered in nature and technology may not go through a transition of the type described above and are produced as such (turbulent). Flows in ordinary pipes, channels, and rivers, as well as in atmospheric and oceanic boundary layers, are some of the commonly occurring examples of such flows. Other cases, such as clear air turbulence in the upper atmosphere and patches of turbulence in the stratified ocean, are obviously the results of instability and transition processes. Transitions from laminar flow to turbulence and vice versa continuously occur in the upper parts of the stable boundary layer, throughout the night. Micrometeorologists have a deep and abiding interest in understanding these transition processes, because turbulent exchanges of momentum, heat and mass in the SBL and other stable layers occur intermittently during episodes of turbulence generation.

It is not easy to identify the origin of turbulence. In an initially nonturbulent flow, the onset of turbulence may occur suddenly through a breakdown of streamlined flow in certain localized regions (turbulent spots). The cause of the breakdown, as pointed out in the previous section, is an instability mechanism acting upon the naturally occurring disturbances in the flow. Since turbulence is transported downstream in the manner of any other fluid property, repeated breakdowns are required to maintain a continuous supply of turbulence, and instability is an essential part of this process.

Once turbulence is generated and becomes fully developed in the sense that its statistical properties achieve a steady state, the instability mechanism is no longer required (although it may still be operating) to sustain the flow. This is particularly true in the case of shear flows, where shear provides an efficient mechanism for converting mean flow energy to turbulence kinetic energy (TKE). Similarly, in unstably stratified flows, buoyancy provides a mechanism for converting potential energy of stratification into turbulence kinetic energy (the reverse occurs in stably stratified flows). The two mechanisms for turbulence generation become more evident from the so-called mechanical production (S) and thermal production (B) terms in the TKE equation

$$d(\mathrm{TKE})/dt = S + B - \epsilon + T_r \tag{8.1}$$

which is written here in a short-form notation for the various terms; a more complete version is given later in Chapter 9. The TKE equation also shows that there is a continuous dissipation (ϵ) of energy by viscosity in any turbulent flow and there may be transport (T_r) of energy from or to other regions of flow. Thus, in order to maintain turbulence, one or more of the generating mechanisms must be active continuously. For example, in the daytime unstable or convective boundary layer, turbulence is produced both by shear and buoyancy (the relative contribution of each depends on Richardson number). Shear is the only effective mechanism for producing turbulence in the nocturnal stable boundary layer, in low-level jets, and in regions of the upper troposphere and stratosphere where negative buoyancy actually suppresses turbulence. Near the earth's surface wind shears become particularly intense and effective, because wind speed must vanish at the surface and air flow has to go around the various surface inhomogeneities. For this reason, shear-generated turbulence is always present in the atmospheric surface layer.

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shear $\longrightarrow$ mechanical (forced) production

buoyancy $\longrightarrow$ thermal (free) convection

8.6 Eddies and Scales of Motion

It is a common practice to speak in terms of eddies when turbulence is described qualitatively. An eddy is by no means a clearly defined structure or feature of the flow which can be isolated and followed through, in order to study its behavior. It is rather an abstract concept used mainly for qualitative descriptions of turbulence. An eddy may be considered akin to a vortex or a whirl in common terminology. Turbulent flows are highly rotational and have all kinds of vortexlike structures (eddies) buried in them. However, eddies are not simple two-dimensional circulatory motions of the type in an isolated vortex, but are believed to be complex, three-dimensional structures. Any analogy between turbulent eddies and vortices can only be very rough and qualitative.

On the basis of flow visualization studies, statistical analyses of turbulence data, and some of the well-accepted theoretical ideas, it is believed that a turbulent flow consists of a hierarchy of eddies of a wide range of sizes (length scales), from the smallest that can survive the dissipative action of viscosity to the largest that is allowed by the flow geometry. The range of eddy sizes increases with the Reynolds number of the overall mean flow. In particular, for the ABL, the typical range of eddy sizes is 10^{-3} to 10^3 m.

Of the wide and continuous range of scales in a turbulent flow, a few have special significance and are used to characterize the flow itself.

The first is the integral length scale of turbulence, which represents the length (l) or time scale of eddies receiving the most energy from the mean flow. Another is the characteristic small-eddy scale or microscale of turbulence, which represents the length (η) or time scale of most dissipating eddies. The ratio l/η is found to be proportional to $Re^{3/4}$ and is typically 10^5 (range: 10^4–10^6) for the atmospheric PBL.

The integral length scale - the scale of turbulence - is generally comparable (same order of magnitude) to the characteristic scale of the mean flow, such as the boundary layer thickness or channel depth, and does not depend on the molecular properties of the fluid. On the other hand, the microscale depends on the fluid viscosity ν, as well as on the rate of energy dissipation ε. Dimensional considerations further lead to the defining relationship

$$\eta \equiv \nu^{3/4}\varepsilon^{-1/4} \tag{8.7}$$

In stationary or steady-state conditions, the rate at which the energy is dissipated is exactly equal to the rate at which the energy is supplied from mean flow into turbulence.

8.7 Fundamental Concepts, Hypotheses, and Theories

Here, we briefly describe, in qualitative terms only, some of the fundamental concepts, hypotheses, and theories of turbulence, which were mostly proposed in the first-half of the twentieth century and subsequently refined and verified by experimental data on turbulence from the laboratory as well as the atmosphere. More comprehensive reviews of theories and models of turbulence are given elsewhere (Monin and Yaglom, 1971; 1975; Hinze, 1975; Panofsky and Dutton, 1984; McComb, 1990).

8.7.1 Energy cascade hypothesis

One of the fundamental concepts of turbulence is that describing the transfer of energy among different scales or eddy sizes. It has been recognized for a long time that in large Reynolds number flows almost all of the energy is supplied by mean flow to large eddies, while almost all of it is eventually dissipated by small eddies. The transfer of energy from large (energy-containing) to small (energy-dissipating) eddies occurs through a cascade-type process involving the whole range of intermediate size eddies. This energy cascade hypothesis was originally suggested by Lewis Richardson in 1922 in the form of a parody

Big whorls have little whorls,
Which feed on their velocity;
And little whorls have lesser whorls,
And so on to viscosity.

This may be considered to be the qualitative picture of turbulence structure in a nutshell and the concept of energy transfer down the scale. The actual mechanism and quantitative aspects of energy transfer are very complicated and are outside the scope of this text. Smaller eddies are assumed to be created through an instability and breakdown of larger eddies and the energy transfer from larger to smaller eddies presumably occurs during the breakdown process. The largest eddies are produced by mean flow mechanical / thermal convection. Their characteristic length scale l is of the same order as the characteristic length scale (e.g., the PBL height) of the mean flow, especially for the neutral, unstable, and convective boundary layers. In the stable boundary layer, on the other hand, large-eddy size is found to be severely restricted by negative buoyancy forces, and l is usually much smaller than the PBL height h. The stronger the stability, the smaller is the integral length scale, which becomes independent of the PBL height.

If the large-eddy Reynolds number $\mathrm{Re}_\ell = u_\ell l/\nu$ is sufficiently large, these large eddies become dynamically unstable and produce eddies of somewhat smaller size, which themselves become unstable and produce eddies of still smaller size, and so on further down the scale. This cascade process is terminated when the Reynolds number based on the smallest eddy scales becomes small enough (order of one) for the smallest eddies to become stable under the influence of viscosity. This qualitative concept of energy cascade provided an underpinning for subsequent theoretical ideas, as well as experimental studies of turbulence.

8.7.3 Kolmogorov's local similarity theory

Kolmogorov (1941) postulated that at sufficiently large Reynolds numbers, small-scale motions in all turbulent flows have similar universal characteristics. He proposed a local similarity theory to describe these characteristics. The basic foundation of his widely accepted theory lies in the energy cascade hypothesis. Kolmogorov argued that if the characteristic Reynolds number of the mean flow or that of the most energetic large eddies is sufficiently large, there will be many steps in the energy cascade process before the energy is dissipated by small-scale motions. The large-scale motions or eddies that receive energy directly from mean flow through mechanical and thermal production are expected to be inhomogeneous (directional, see lecture 18, slide 16).

But the small eddies, that are formed after many successive breakdowns of large and intermediate size eddies, are likely to become homogeneous and isotropic, because they are far enough removed from the original sources (shear and buoyancy) of inhomogeneity and have no memory of large-scale processes.

Following the above reasoning, Kolmogorov (1941) proposed his local isotropy hypothesis, which states that at sufficiently large Reynolds numbers, small-scale structure is locally isotropic whether large-scale motions are isotropic or not. Here 'local' refers to the particular range of small-scale eddy motions that may be considered isotropic.

The concept of local isotropy has proved to be very useful in that it applies to all turbulent flows with large Reynolds numbers. It also made possible for the sufficiently well-developed statistical theory of isotropic turbulence to be applied to small-scale motions in most turbulent flows encountered in practice. The condition of sufficiently large Reynolds number is particularly well satisfied in the atmosphere. Consequently, the local isotropy concept or hypothesis is found to be valid over a wide range of scales and eddies in the atmosphere.

8.8 Applications

A knowledge of the fundamentals of turbulence is essential to any qualitative or quantitative understanding of the turbulent exchange processes occurring in the PBL, as well as in the free atmosphere. The statistical description in terms of variances and covariances[1] of turbulent fluctuations, as well as in terms of eddies and scales of motion, provide the bases for further quantitative analyses of observations. At the same time the basic concepts of the generation and maintenance of turbulence, of supply, transfer, and dissipation of energy, and of local similarity are the foundation stones of turbulence theory.

[1] see upcoming Lecture 19