5.5.3 Dynamic Stability and Kelvin-Helmholtz Waves

The word "dynamic" refers to motion; hence, dynamic stability depends in part on the winds. Even if the air is statically stable, wind shears may be able to generate turbulence dynamically.

Some laboratory experiments have been performed (Thorpe, 1969, 1973; Woods 1969) using denser fluids underlying less-dense fluids with a velocity shear between the layers to simulate the stable stratification and shears of the atmosphere. Fig 5.18 is a sketch of the resulting flow behavior. The typical sequence of events is:

(1) A shear exists across a density interface. Initially, the flow is laminar.

(2) If a critical value of shear is reached (see section 5.6), then the flow becomes dynamically unstable, and gentle waves begin to form on the interface. The crests of these waves are normal to the shear direction

(3) These waves continue to grow in amplitude, eventually reaching a point where each wave begins to "roll up" or "break". This "breaking" wave is called a ***Kelvin-Helmholtz (KH) wave***, and is based on different physics than surface waves that "break" on an ocean beach.

(4) Within each wave, there exists some lighter fluid that has been rolled under denser fluid, resulting in patches of static instability. On radar, these features appear as braided ropelike patterns, "cat's eye" patterns or breaking wave patterns.

(5) The static instability, combined with the continued dynamic instability, causes each wave to become turbulent.

(6) The turbulence then spreads throughout the layer, causing a diffusion or mixing of the different fluids. During this diffusion process, some momentum is transferred between the fluids, reducing the shear between the layers. What was formerly a sharp, well-defined, interface becomes a broader, more diffuse shear layer with weaker shear and static stability.

(7) This mixing can reduce the shear below a critical value and eliminate the dynamic instability.

(8) In the absence of continued forcing to restore the shears, turbulence decays in the interface region, and the flow becomes laminar again.

This sequence of events is suspected to occur during the onset of ***clear air turbulence (CAT)***. These often occur above and below strong wind jets, such as the nocturnal jet and the planetary-scale jet stream. In these situations, however, continued dynamic forcings can allow turbulence to continue for hours to days. These regions of CAT have large horizontal extent (hundreds of kilometers in some cases), but usually limited vertical extent (tens to hundred of meters). They can be visualized as large pancake-shaped regions of turbulence. Aircraft encountering CAT can often climb or descend into smoother air.

Although KH waves are probably a frequent occurrence within statically stable shear layers, they are only rarely observed with the naked eye. Occasionally, there is sufficient moisture in the atmosphere to allow cloud droplets to act as visible tracers. Clouds that form in the rising portions of the waves often form parallel bands called ***billow clouds***. The orientation of these bands is perpendicular to the shear vector. One must remember that the wind SHEAR vector need not necessarily point in the same direction as the mean wind vector.

For both static and dynamic instabilities, and many other instabilities for that matter, it is interesting to note that the fluid reacts in a manner to undo the cause of the instability. This process is strikingly similar to ***LeChatelier's principle*** of chemistry, which states that "if some stress is brought to bear upon a system in equilibrium, a change occurs such that the equilibrium is displaced in a direction which tends to undo the effect of the stress". Thus, turbulence is a mechanism whereby fluid flows tend to undo the cause of the instability. In the case of static instabilities, convection occurs that tends to move more buoyant fluid upward, thereby stabilizing the system. For dynamic instability, turbulence tends to reduce the wind shears, also stabilizing the system.

With this in mind, it is apparent that turbulence acts to eliminate itself. After the unstable system has been stabilized, turbulence tends to decay. Given observations of turbulence occurring for long periods of time within the boundary layer, it is logical to surmise that there must be external forcings tending to destabilize the BL over long time periods. In the case of static instability, the solar heating of the ground by the sun is that external forcing. In the case of dynamic instabilities, pressure gradients imposed by synoptic-scale features drive the winds against the dissipative effects of turbulence.

By comparing the relative magnitudes of the shear production and buoyant consumption terms of the TKE equation, we can hope to estimate when the flow might become dynamically unstable. The Richardson number, Ri, described in the next subsection, can be used as just such an indicator.

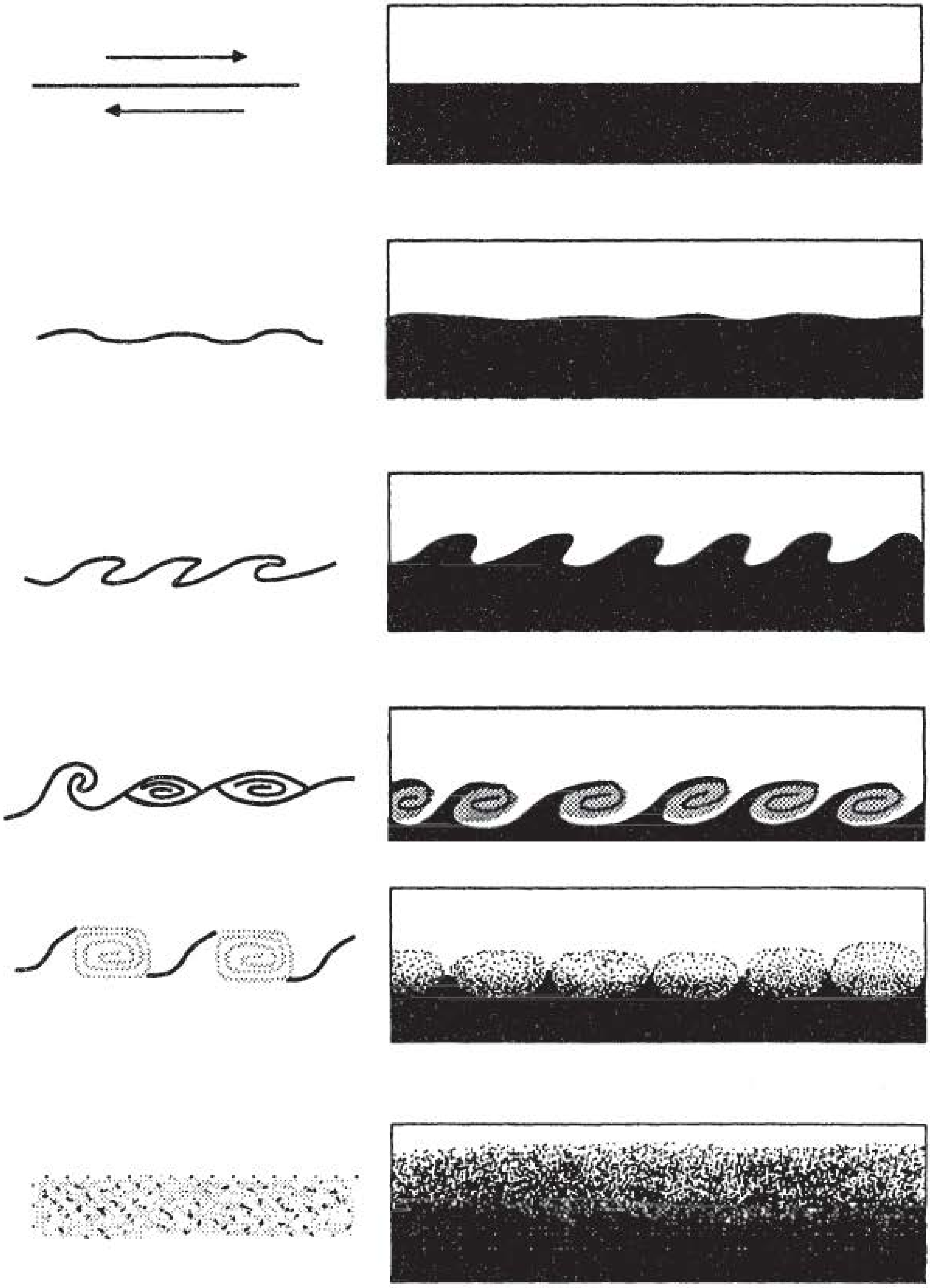

Fig. 5.18 Schematic diagram of Kelvin-Helmholtz instability in a laboratory experiment where shear flow has been generated. The upper layer, water, flows to the right, and the lower more dense fluid, dyed brine, flows to the left. The figures are about half a second apart. After Thorpe (1969,1973) and Woods (1969).