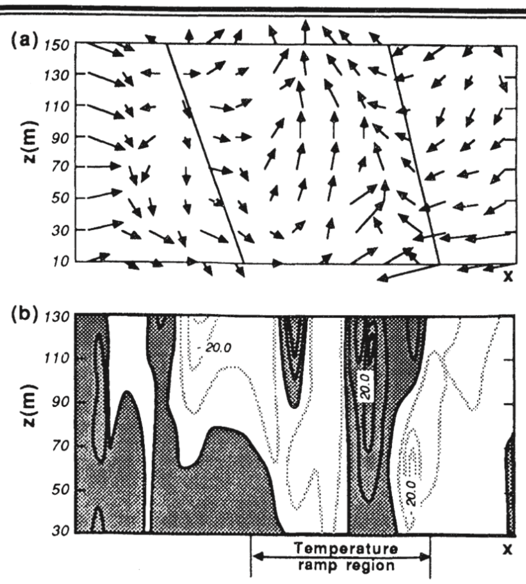
profiles show a maximum of $\overline{w'e}$ at $z/z_i = 0.3$ to 0.5. Below this maximum, there is more upward flux leaving the top of any one layer than enters from below, making a net divergence or loss of TKE. Above the maximum, there is a net convergence or production of TKE. The net effect is that some of the TKE produced near the ground is transported up to the top half of the ML before it is dissipated, as confirmed in Fig 5.4. Transport across the surface layer is illustrated in the right portion of Fig 5.9, where the Obukhov length L will be defined in section 5.7.

If one splits the vertical turbulent transport of total TKE into transport of w'^2 and $(u'^2+v'^2)$, then one finds that it is the vertical transport of w'^2 that dominates in the middle of the ML, and the transport of $(u'^2+v'^2)$ that dominates near the surface. Fig 5.10 shows these transports, as well as their ratio.

5.2.6 Term VI: Pressure Correlation

Turbulence. Static pressure fluctuations are exceedingly difficult to measure in the atmosphere. The magnitudes of these fluctuations are very small, being on the order of 0.005 kPa (0.05 mb) in the convective surface layer to 0.001 kPa (0.01 mb) or less in the ML. Pressure sensors with sufficient sensitivity to measure these static pressure fluctuations are contaminated by the large dynamic pressure fluctuations associated with turbulent and mean motions. As a result, correlations such as $\overline{w'p'}$ calculated from experimental data often contain more noise than signal.

Fig. 5.11
(a) Composite of measured circulation patterns in a vertical cross-section thru convective thermals. Velocity vectors are deviations from the mean wind. Solid lines denote the boundaries of the temperature ramp associated with a thermal updraft; they are separated by a physical distance on the order of 100 m.
(b) Contour x-z plot of $\overline{w'p'} / \rho u_*^3$, where the horizontal axis represents a composite of many thermals. Contour interval is 10.0. After Wilczak and Businger (1984).



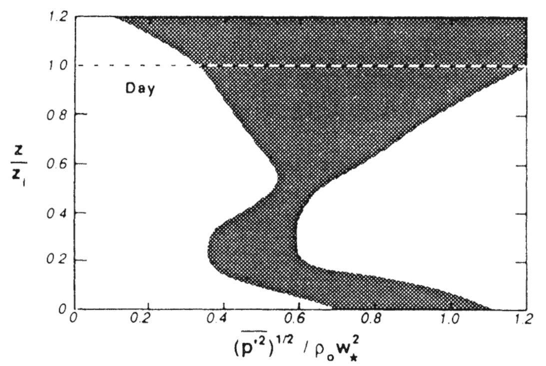


Fig. 5.12 Normalized Doppler- radar derived standard deviation of perturbation pressure. After Gal-chen and Kropfli (1984).

What little is known about the behavior of pressure correlation terms is estimated as a residual in the budget equations discussed previously. Namely, if all of the other terms in a budget equation are measured or parameterized, then the residual necessary to make the equation balance includes an estimate of the unknown term(s) together with the accumulated errors. An obvious hazard of this approach is that the accumulated errors from all of the other terms can be quite large.

Estimates of $\overline{w'p'}$ in the surface layer are shown in Fig 5.11 using this method, composited with respect to a large number of convective plume structures. We see quite a variation both in the vertical and horizontal. Here, the plume is defined by its temperature ramp signal. Fig 5.12 shows estimates of pressure variance based on Doppler radar measurements of motion within the ML.

Waves. Recall from chapters 1 and 2 that perturbations from a mean can describe waves as well as turbulence. Given measured values of $\overline{w'p'}$, it is impossible to separate the wave and turbulence contributions without additional information.

Work in linear gravity wave theory shows that $\overline{w'p'}$ is equal to the upward flux of wave energy for a vertically propagating internal gravity wave within a statically stable environment. This suggests that turbulence energy can be lost from the ML top in the form of internal gravity waves being excited by thermals penetrating the stable layer at the top of the ML. The amount of energy lost may be on the order of less than 10% of the total rate of TKE dissipation, but the resulting waves can sometimes enhance or trigger clouds.

Turbulence within stable NBLs can also be lost in the form of waves. One concludes that the pressure correlation term not only acts to redistribute TKE within the BL, but it can also drain energy out of the BL.

5.2.7 Term VII: Dissipation

As discussed in section 4.3.1, molecular destruction of turbulent motions is greatest for the smallest size eddies. The more intense this small-scale turbulence, the greater the rate of dissipation. Small-scale turbulence is, in turn, driven by the cascade of energy from the larger scales.

Daytime dissipation rates (see Fig 5.13) are often largest near the surface, and then become relatively constant with height in the ML. Above the ML top, the dissipation rate rapidly decreases to near zero. At night (see Fig 5.14), both TKE and dissipation rate decrease very rapidly with height. Because turbulence is not conserved, the greatest TKEs, and hence greatest dissipation rates, are frequently found where TKE production is the largest — near the surface. However, the dissipation rate is not expected to perfectly balance the production rate because of the various transport terms in the TKE budget.

Fig. 5.13 Range of normalized dissipation rate(ε) profiles during the daytime, where z_i is ML depth and w_* is the convective velocity scale. (After Caughey et al. (1979) and Kitchen et al. (1983)).

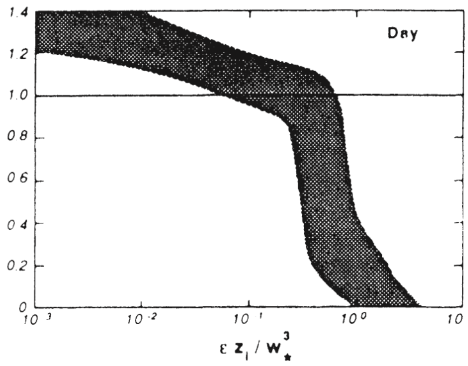
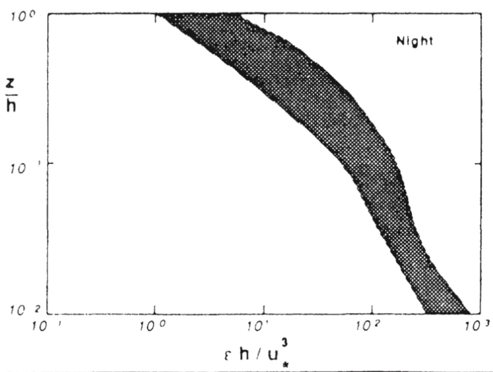


Fig. 5.14 Range of normalized dissipation rate(ε) profiles at night, where h is boundary layer depth and u_* is the friction velocity. After Caughey, et al. (1979).



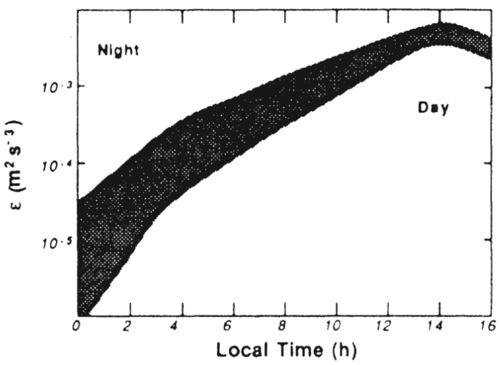


Fig. 5.15 Example of variation of dissipation rate with time from night to day. After Louis, et al. (1983).

The close relationship between TKE production rate, intensity of turbulence, and dissipation rate is shown in Fig 5.15. At night where only shear can produce turbulence, the dissipation rate is small because the associated TKE is small (refer back to Fig 5.2). After sunrise, buoyant production greatly increases the turbulence intensity, resulting in the associated increase in dissipation seen in Fig 5.15.

5.2.8 Example

Problem: At a height of z = 300 m in a 1000 m thick mixed layer the following conditions were observed: $\partial\overline{U}/\partial z = 0.01\ s^{-1}$, $\overline{\theta_v} = 25°C$, $\overline{w'\theta_v'} = 0.15$ K m/s, and $\overline{u'w'} = -0.03\ m^2s^{-2}$. Also, the surface virtual heat flux is 0.24 K m/s. If the pressure and turbulent transports are neglected, then (a) what dissipation rate is required to maintain a locally steady state at z = 300 m; and (b) what are the values of the normalized TKE terms?

Solution: (a) Since no information was given about the V-component of velocity or stress, let's assume that the x-axis has been chosen to be aligned with the mean wind. Looking at the TKE budget (5.1b), we know that term I must be zero for steady state, and terms V and VI are zero as specified in the statement of the problem. Thus, the remaining terms can be manipulated to solve for ε:

$$\varepsilon = \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \overline{u'w'}\frac{\partial\overline{U}}{\partial z}$$

Plugging in the values given above yields:

$$\varepsilon = \{(9.8 \text{ m·s}^{-2}) / [(273.15+25)\text{K}]\} \cdot (0.15 \text{ K·m·s}^{-1}) - (-0.03 \text{ m}^2\text{s}^{-2})\cdot(0.01 \text{ s}^{-1})$$

$$\varepsilon = 4.93 \times 10^{-3} + 3 \times 10^{-4} \ (\text{m}^2\text{s}^{-3})$$

$$\varepsilon = 5.23 \times 10^{-3} \ (\text{m}^2\text{s}^{-3})$$

(b) To normalize the equations as in (5.2.3), we first use (4.2a) to give $w_*^3 / z_i = (g/\overline{\theta_v})\cdot\overline{w'\theta_v'}$, which for our case equals 7.89×10^{-3} (m^2s^{-3}). Dividing our terms by this value, and rewriting in the same order as (5.2.3) yields:

	0	=	0.625	+	0.038	-	0	-	0	-	0.663
Term:	I		III		IV		V		VI		VII

Discussion: This buoyant production term is about an order of magnitude larger than the mechanical production term, meaning that the turbulence is in a state of free convection. In regions of strong turbulence production, the transport term usually removes some of the TKE and deposits it where there is a net loss of TKE, such as in the entrainment zone. Thus, we might expect that the local dissipation rate at z = 300 m is smaller than the value calculated above.

5.3 TKE Budget Contributions as a Function of Eddy Size

As will be shown in chapter 8, the TKE budget equation can be written in a spectral form where the the contributions of each term in (5.1) can be examined as a function of wavelength or eddy size. Fig 5.16b shows the following terms as a function of wavenumber: buoyant production (Term III), shear production (Term IV), and dissipation (Term VII), all measured at one height in the BL. The turbulent transport and pressure redistribution term calculations were inaccurate, and hence left out of these figures.

One additional term appears in the spectral form of the TKE equation: the transfer of energy across the spectrum. In this case, as in most atmospheric cases, the transfer is from large size eddies (low wavenumbers) to small sizes (high wavenumbers). The concept behind this cascade of energy was introduced in Chapter 2. The rate of flow of this energy, shown in Fig 5.16a, is greatest for middle size eddies. Not only is it largest there, but it is also relatively constant with wavenumber. Hence, there is no net divergence or convergence of energy in the middle of the spectral domain, but there is a large amount of energy flowing through that domain. The slope of the curve in Fig 5.16a determines the magnitude of the transport term in Fig5.16b.

Large size eddies are presented on the left side of these figures, and small on the right. We see in Fig 5.16b that there is little energy at the very largest sizes, corresponding to the spectral gap. Once we get down to a normalized wavenumber of 0.01, we see large magnitudes of the shear and buoyant production terms. The production is not dissipated