5.2.2 Term II: Advection

Little is known about this term. When averaged over a horizontal area larger than about 10 km by 10 km, it is often assumed that there is little horizontal variation in TKE, thereby making the advection term negligible. This is probably a good assumption over most land surfaces.

On a smaller scale, however, it is clear that this term must be important. For example, picture a reservoir of water cooler than the surrounding land. The lack of heating over the reservoir would allow turbulence to decay in the overlying air, while air over the adjacent land surfaces could be in a state of active convection. A mean wind advecting air across the shores of this reservoir would thus cause significant change in the TKE budget. Over ocean surfaces, the advection term would probably be negligible even on the small scales.

5.2.3 Term III: Buoyant Production/Consumption

Production. Fig 5.4 shows the variation of a number of TKE budget terms with height within a fair-weather convective ML. The most important part of the buoyancy term is the flux of virtual potential temperature, $\overline{w'\theta_v'}$. As we have already studied in

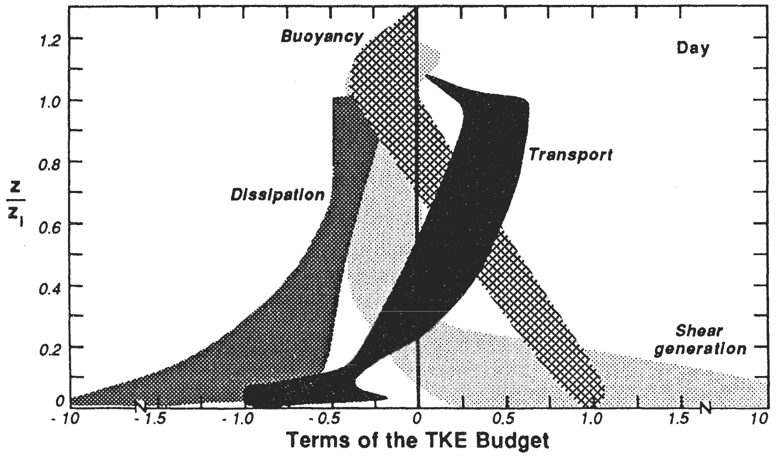

Fig. 5.4 Normalized terms in the turbulence kinetic energy equation. The shaded areas indicate ranges of values. All terms are divided by w_*^3 / z_i, which is on the order of $6x\ 10^{-3} m^2 s^{-3}$. Based on data and models from Deardorff (1974), André et al. (1978), Therry and Lacarrere (1983), Lenschow (1974), Pennell and LeMone (1974), Zhou, et al. (1985) and Chou, et al. (1986).

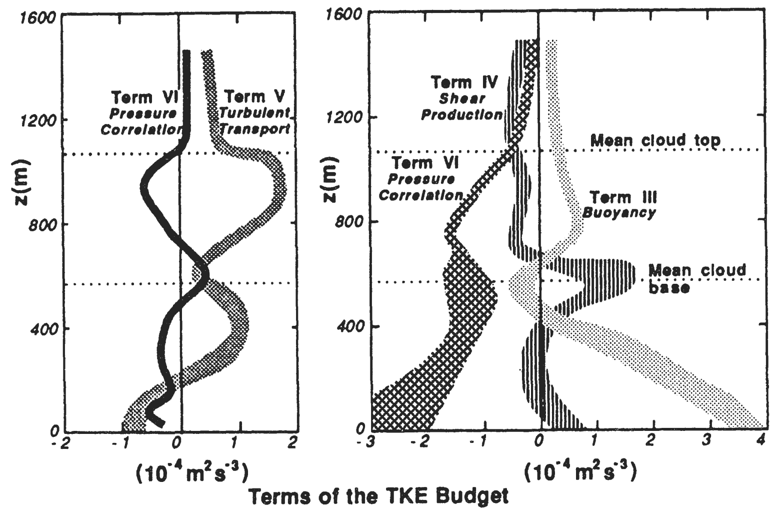

Fig. 5.5 Range of terms in the turbulent kinetic energy budget for a cloud - topped tropical boundary layer. The transport term is split into the pressure correlation (PC) and turbulent transport (T) parts. After Nicholls, et al. (1982).

the previous chapters, this flux is positive and decreases roughly linearly with height within the bottom 2/3 of the convective ML. Near the ground, term III is large and positive, corresponding to a large generation rate of turbulence whenever the underlying surface is warmer than the air.

When positive, this term represents the effects of ***thermals*** in the ML. Active thermal convection is associated with large values of this term, as large as 1×10^{-2} m^2 s^{-3} near the ground. Thus, we often associate this term with sunny days over land, or cold air advection over a warmer underlying surface. For cloudy days over land, it can be much smaller.

In convective boundary layers capped with actively growing cumulus clouds, the positive buoyancy within the cloud can contribute to the production (term III) of TKE (see Fig 5.5). Between this cloud layer contribution and the contribution near the bottom of the subcloud layer, there may be a region near cloud base where the air is statically stable and the buoyancy term is therefore negative.

Because Term III is so important on days of free convection, it is often used to normalize all the other terms. For example, using the definitions of w_* and z_i presented earlier, it is easy to show that Term III = $(w_*)^3 / z_i$ at the surface. Dividing (5.1b) by $(w_*)^3 / z_i$ gives a dimensionless form of the TKE budget equation that is useful for free convection situations:

$$\frac{z_i}{w_*^3}\frac{\partial \bar{e}}{\partial t} = \frac{g\, z_i\left(\overline{w'\theta_v'}\right)}{w_*^3\,\overline{\theta_v}} - \frac{z_i\,\overline{u'w'}}{w_*^3}\frac{\partial \overline{U}}{\partial z} - \frac{z_i}{w_*^3}\frac{\partial\left(\overline{w'e}\right)}{\partial z} - \frac{z_i}{w_*^3}\,\bar{\rho}\,\frac{\partial\left(\overline{w'p'}\right)}{\partial z} - \frac{z_i\,\varepsilon}{w_*^3} \tag{5.2.3}$$

I III IV V VI VII

By definition, the dimensionless Term III is unity at the surface. Equations that are made dimensionless by dividing by scaling parameters are said to be ***normalized***. The normalization scheme expressed by (5.2.3) is used in most of the figures in this section, and indeed has been used in the previous chapter too.

As is evident in (4.3.1j), the buoyancy term acts only on the vertical component of TKE. Hence, this production term is ***anisotropic*** (i.e., not isotropic). The return-to-isotropy terms of (4.3.1h-j) are responsible for moving some of the vertical kinetic energy into the horizontal directions. Again, the anisotropic nature of Term III confirms our picture of strong up and downdrafts within thermals.

Consumption. In statically stable conditions, an air parcel displaced vertically by turbulence would experience a buoyancy force pushing it back towards its starting height. ***Static stability thereby tends to suppress, or consume, TKE***, and is

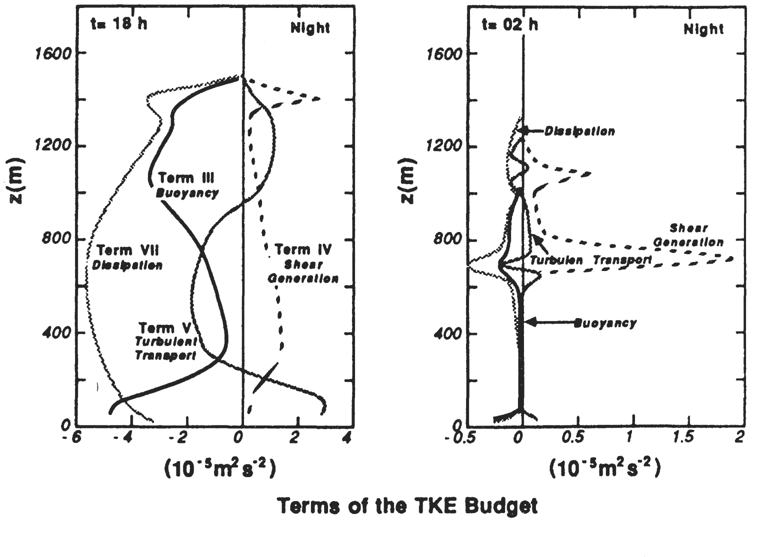

Fig. 5.6 Modeled turbulence kinetic energy budgets at t=18 h and t=02 h during Night 33-34, Wangara. After André et al. (1978).

associated with negative values of term III. Such conditions are present in the SBL at night over land, or anytime the surface is colder than the overlying air. An example of the decay of turbulence in negatively buoyant conditions just after sunset is shown in the budget profiles of Fig 5.6.

This same type of consumption can occur at the top of a ML, where warmer air entrained downward by turbulence opposes the descent because of its buoyancy (Stage and Businger, 1981). This is related to the negative values of the buoyancy term near the top of the ML in Fig 5.4.

5.2.4 Term IV: Mechanical (Shear) Production

When there is a turbulent momentum flux in the presence of a mean wind shear, the interaction between the two tends to generate more turbulence. Even though a negative sign precedes Term IV, the momentum flux is usually of opposite sign from the mean shear, resulting in production, not loss, of turbulence.

Fig. 5.4 shows case studies of the contribution of shear production to the TKE budget for convective situations. The greatest wind shear magnitude occurs at the surface. Not surprisingly, the maximum shear production rate also occurs there. As shown in Chapters 1 and 3, the wind speed frequently varies little with height in the ML above the surface layer, resulting in near zero shear and near zero shear production of turbulence. Shear production is often associated with the surface layer because of its limited vertical extent.

A smaller maximum of shear production sometimes occurs at the top of the ML because of the wind shear across the entrainment zone. In that region, the subgeostrophic winds of the ML recover to their geostrophic values above the ML.

The relative contributions of the buoyancy and shear terms can be used to classify the nature of convection (see Fig 5.7) ***Free convection*** scaling is valid when the buoyancy term is much larger than the mechanical term, ***forced convection*** scaling is valid when the opposite is true.

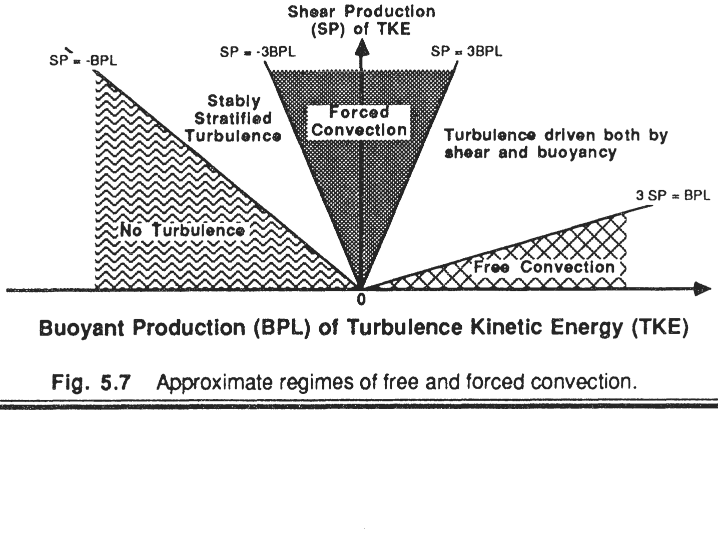

Fig. 5.7 Approximate regimes of free and forced convection.