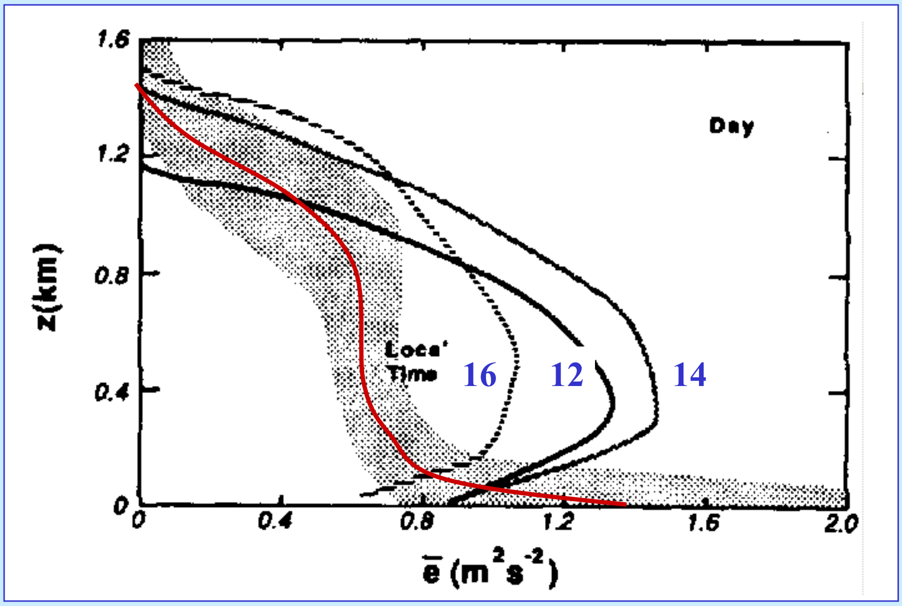


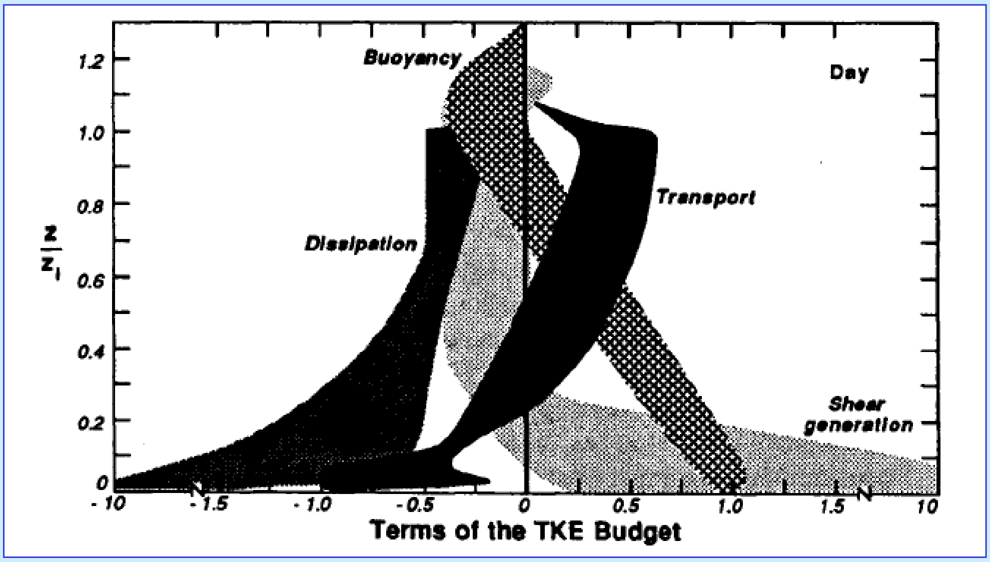
Lines show modelled vertical profiles of TKE during Day 33, Wangara. The shaded profile applies when both shear and buoyancy are active.

N

•The vertical profile of TKE can sometimes increase to a maximum at a height of about $z/z_i = 0.3$ when free convection dominates, as modelled for the Wangara experiment.

•When strong winds are present, the TKE might be nearly constant with height within the BL, or might decrease slightly with height as shown for BLX83 data. At night, the TKE often decreases very rapidly with height, from a maximum value just above the surface.

•Over surfaces such as oceans that do not experience a large diurnal cycle, the rate-of-change term is often so small that it can be neglected (i.e. a steady state can be assumed). This is not to say that there is no turbulence, just that the intensity of turbulence is not changing significantly with time.



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 10^{-3} m^2s^{-3}.

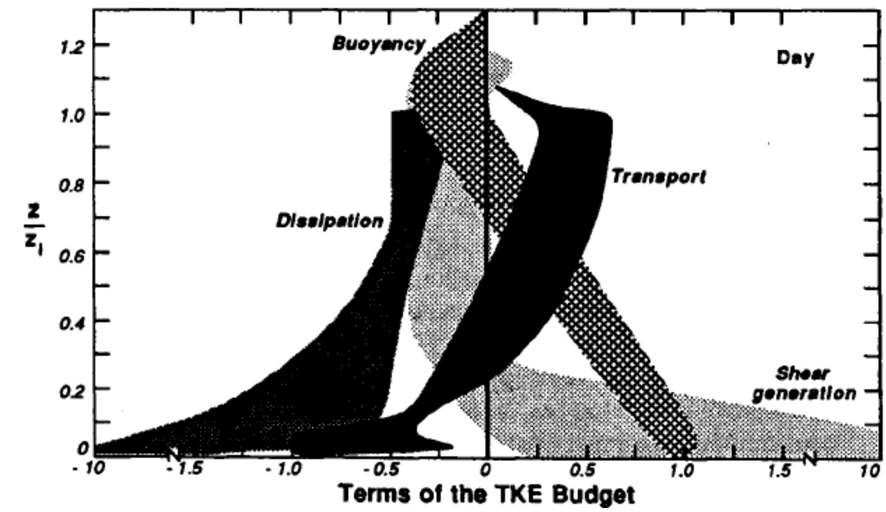
N

•The variation of a number of TKE budget terms with height within a fair-weather convective mixed layer. The most important part of the buoyancy term is the flux of virtual potential temperature $\langle w'\theta'_v \rangle$.

•As seen earlier, this flux is positive and decreases roughly linearly with height in the bottom 2/3 of the mixed layer.

•Near the ground, term III is large and positive, corresponding to a large rate of generation of turbulence whenever the underlying surface is warmer than the air.

Buoyant production/ consumption



Normalized terms in the turbulence kinetic energy equation. The shaded areas indicate ranges of values. Based on data and models.

N

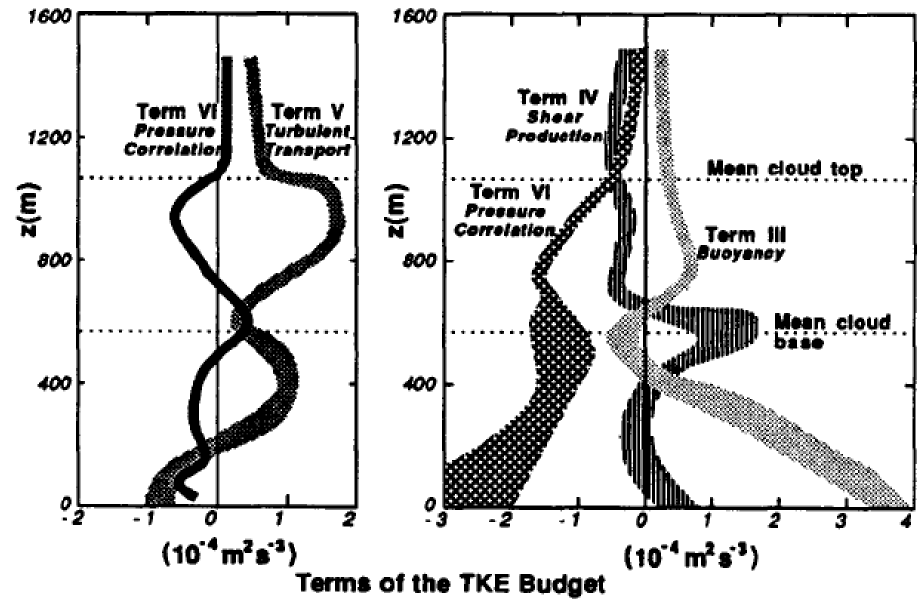
•This figure shows the variation of a number of TKE budget terms with height within a fair-weather convective mixed layer. All terms are divided by $(w^*)^3/z_i$, which is on the order of 6×10^{-3} m^2 s^{-1}.

•The most important part of the buoyancy term is the flux of virtual potential temperature $<w'\theta_v'>$.

•We have seen that this flux is positive and decreases roughly linearly with height in the bottom 3/3 of the convective mixed layer.

•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 mixed layer. Active thermal convection is associated with large values of this term, as large as 1 $\times 10^{-2}$ 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.

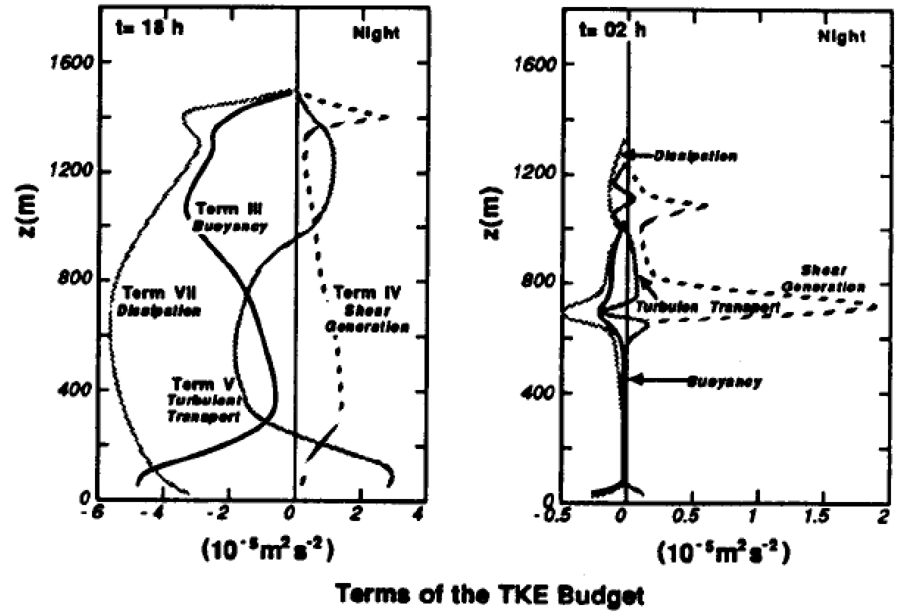


Range of terms in the turbulence kinetic energy budget for a cloud-topped tropical boundary layer. The The transport term is split into the pressure correlation (PC) and turbulent transport (T) parts.

N

•In convective BLs capped with actively growing cumulus clouds, the positive buoyancy within the cloud can contribute to the TKE production term (Term III).

•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.



Modelled turbulence kinetic energy budgets at t = 18 **h and** t = 02 **h during the night 33-34, Wangara.**

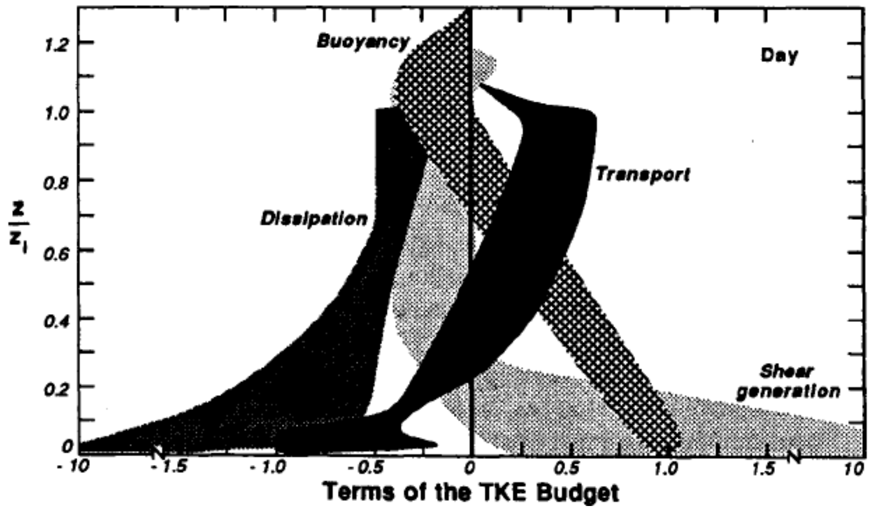
N

•Shows an example of the decay of turbulence in negatively buoyant conditions just after sunset.

•This same type of consumption can occur at the top of the mixed layer, where warmer air entrained downwards by the turbulence opposes the descent because of its buoyancy.

•This process is related to the negative values of the buoyancy term near the top of the mixed layer in the above figure.

Buoyant production/ consumption

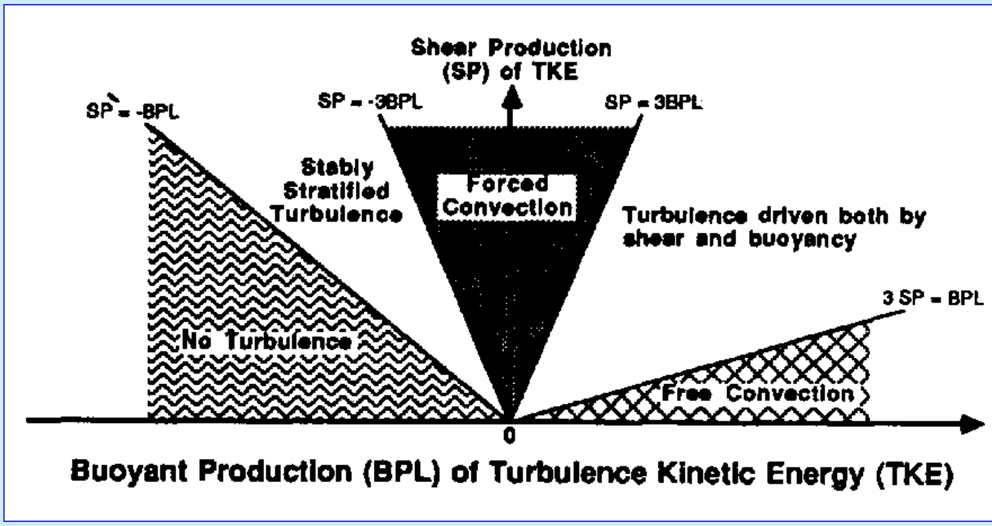


Normalized terms in the turbulence kinetic energy equation. The shaded areas indicate ranges of values. Based on data and models.

N

- This figure 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 occurs there also.
- As shown earlier, the wind speed frequently varies little with height in the mixed layer above the surface layer, resulting in 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 mixed layer because of the wind shear across the entrainment zone. In that region, the subgeostrophic winds of the mixed layer recover to geostrophic values above the mixed layer.

Shear versus buoyant production



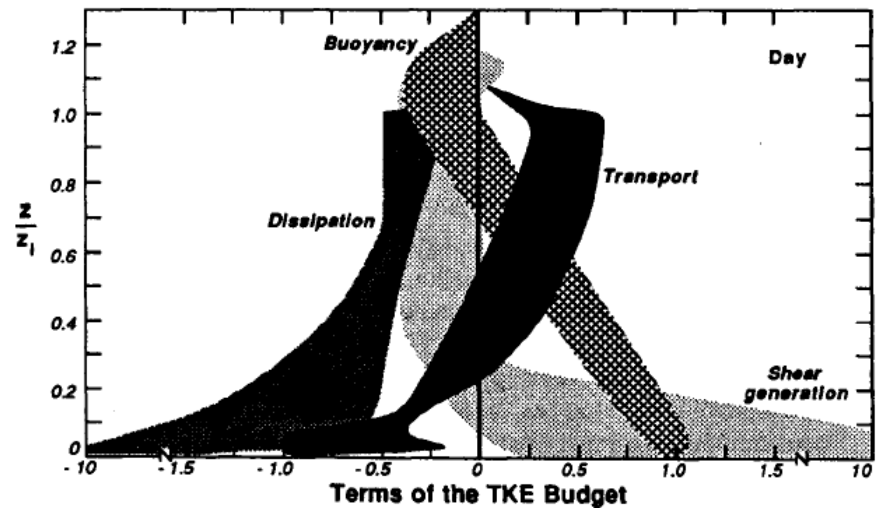
Approximate regimes of free and forced convection.

N

•The relative contributions of the buoyancy and shear terms can be used to classify the nature of convection.

•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.

Buoyant production/ consumption



Normalized terms in the turbulence kinetic energy equation. The shaded areas indicate ranges of values. Based on data and models.

N

•We can see from this figure that the shear term is active over just a relatively small depth of air, so it is not surprising that, over land, the nocturnal BL is usually thinner than the mixed layer.

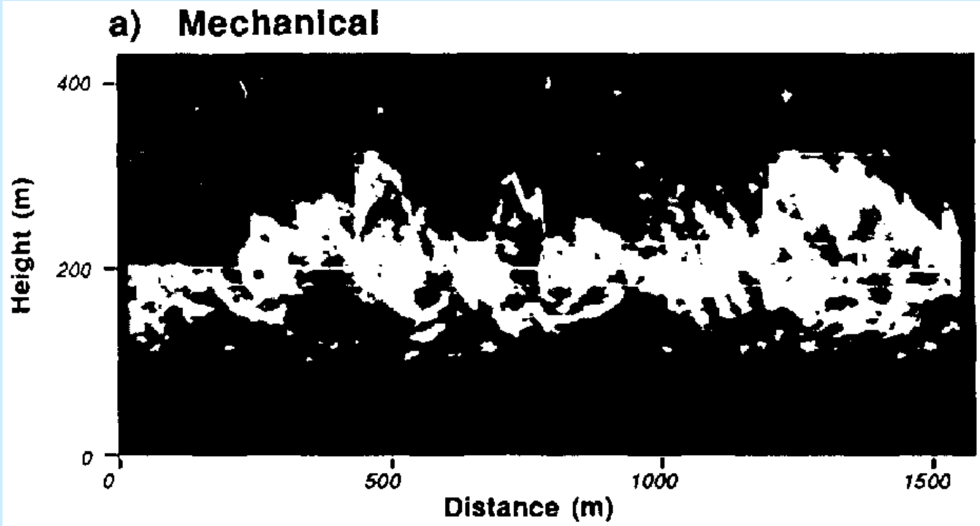


Fig. 5.8 Radar images of turbulence near the boundary layer top, showing (a) forced convection, and (b) free convection. After Noonkester (1974).

N

•A high powered vertically pointing continuous-wave radar was used to observed the time evolution of eddy structure within the BL.

•This instrument senses moisture contrasts between dry and moist air.

•The boundary between regions of different moisture appear white in the photographs, while regions of more uniform high or low humidity appear black.

•Taylor's hypothesis has been used to convert from time-height graphs to vertical cross sections.

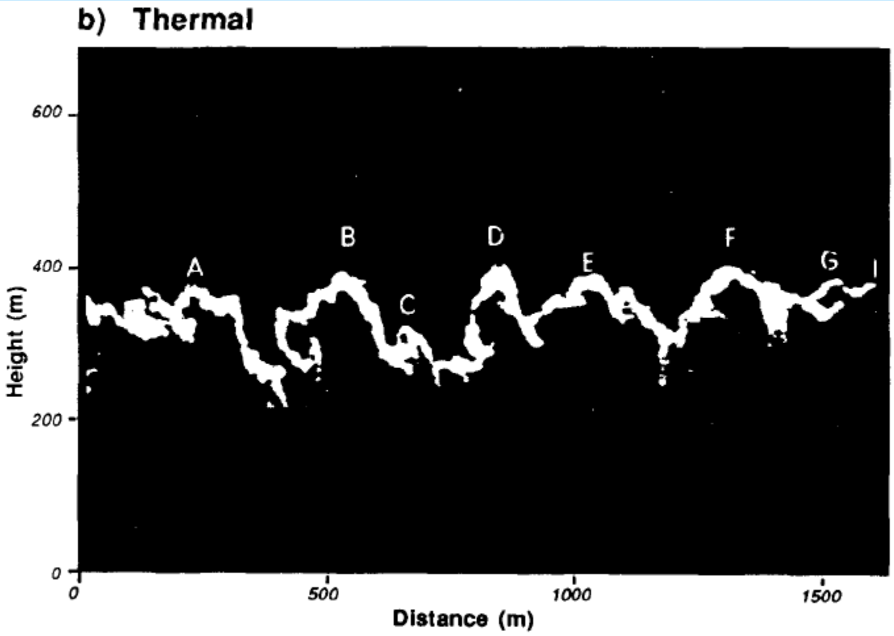


Fig. 5.8 Radar images of turbulence near the boundary layer top, showing (a) forced convection, and (b) free convection. After Noonkester (1974).

•For free convection, the “inverted U-shaped” tops of thermals shows up as white because they separate the dry FA air from the moister ML air.
•These structures are predominantly vertical.
•In the previous figure for forced convection, the eddies are sheared into a much more horizontal or slanting orientation, with a much more chaotic appearance.
•Similar structures are apparent in the lidar-generated images shown in the frontispiece figure of Stull on page xiii, for (a) free and (b) forced convection.

Turbulent transport

- **Term V**

$$\frac{\partial \overline{e}}{\partial t} = \frac{g}{\overline{\theta}_v}\overline{w'\theta'_v} - \overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \underbrace{\frac{\partial(\overline{w'e})}{\partial z}}_{V} - \frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \varepsilon$$

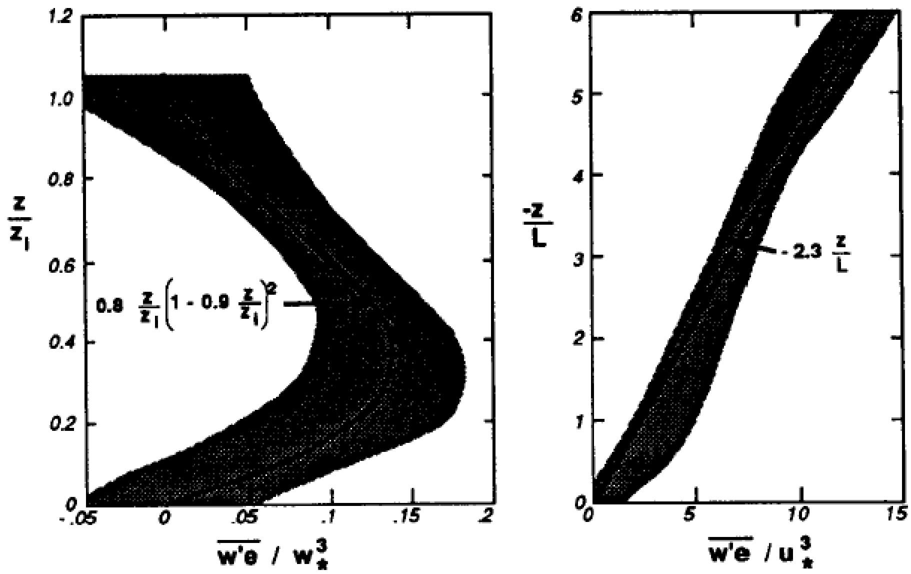
- $\overline{w'e}$ **represents the vertical turbulent flux of TKE.**
- **As for other vertical fluxes, the change in flux with heights is more important than magnitude of flux.**
- **Term V is a flux divergence term; if there is more flux into a layer than leaves, then the magnitude of TKE increases.**
- **This term simply redistributes TKE: when integrated over the depth of the mixed layer, it gives zero contribution.**

N

•On a local scale (i.e., at any one height within the mixed layer), Term V acts as either production or loss, depending on whether there is flux convergence or divergence.

•When integrated over the depth of mixed layer, however, Term V becomes identically zero, assuming as bottom and top boundary conditions that the earth is not turbulent, and that there is negligible turbulence above the top of ML.

•Overall, Term V neither creates nor destroys TKE, it just moves or redistributes TKE from one location in the BL to another.



Range of vertical profiles of the normalized vertical flux of turbulence kinetic energy using mixed layer scaling (left) and surface-layer scaling (right) where L **is the Obukhov length.**

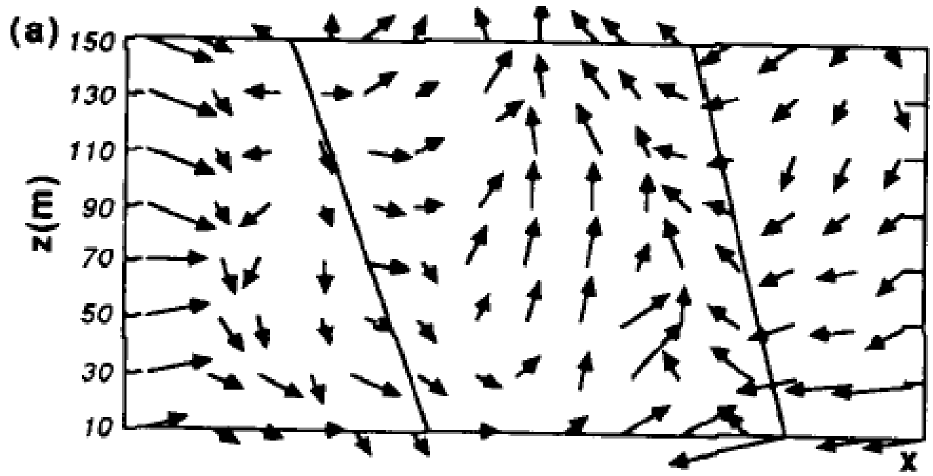
N

•This figure shows vertical profiles of <w'e> for daytime, convective cases. Most of these profiles show a maximum of <w'e> at z/z_i = 0.3 to 3.5.

•Below this maximum, there is more upward flux leaving the top of any 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 mixed layer before it is dissipated, as confirmed in Stull Fig 5.4. Transport across surface layer is later.

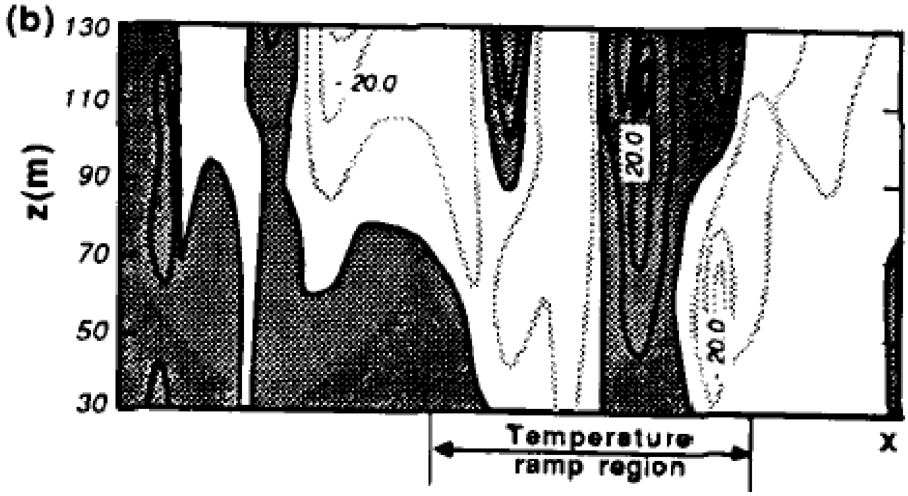
•If one splits the vertical turbulent transport of total TKE into transport of w'^2 and ($u'^2 + v'^2$), then one finds that it is the vertical transport of w'^2 that dominates in the middle of the mixed layer, and the transport of ($u'^2 + v'^2$) that dominates near the surface. The next figure shows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



(a) Composite of measured circulation patterns in a vertical cross-section through convective thermals. Velocity vectors: deviations from the mean wind. Solid lines: the boundaries of the temperature ramp associated with a thermal updraft; they are separated by a physical distance on the order of 100 m.

N

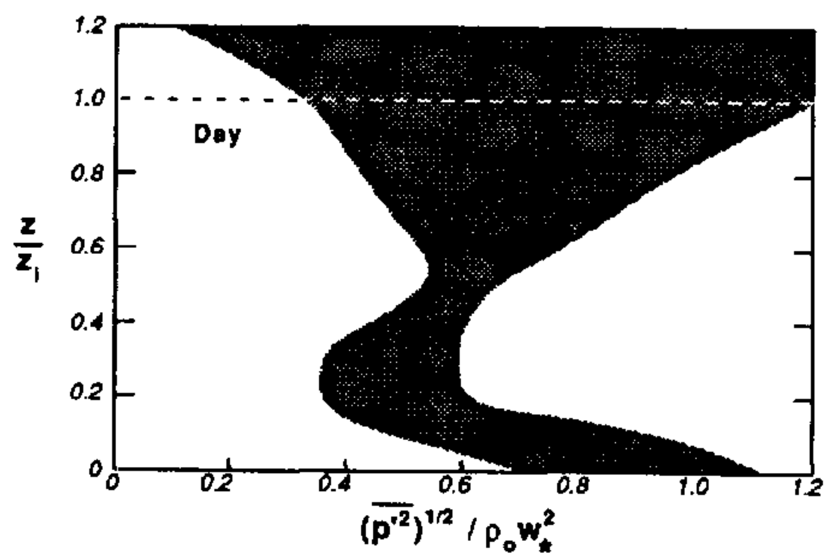
•This figure shows vertical profiles of <w'e> for daytime, convective cases. Most of these profiles show a maximum of <w'e> at z/z_i = 0.3 to 3.5.
•Below this maximum, there is more upward flux leaving the top of any layer than enters from below, making a net divergence or loss of TKE.
•Above the maximum, 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 mixed layer before it is dissipated, as confirmed in Stull Fig 5.4. Transport across surface layer is later.
•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 mixed layer, and the transport of ($u'^2 + v'^2$) that dominates near the surface. The next figure shows these transports, as well as their ratio.



(b) Contour z-z plot of $\overline{w'p'}/\rho u_*^3$, where the horizontal axis represents a composite of many thermals. Contour interval is 10.0.

N

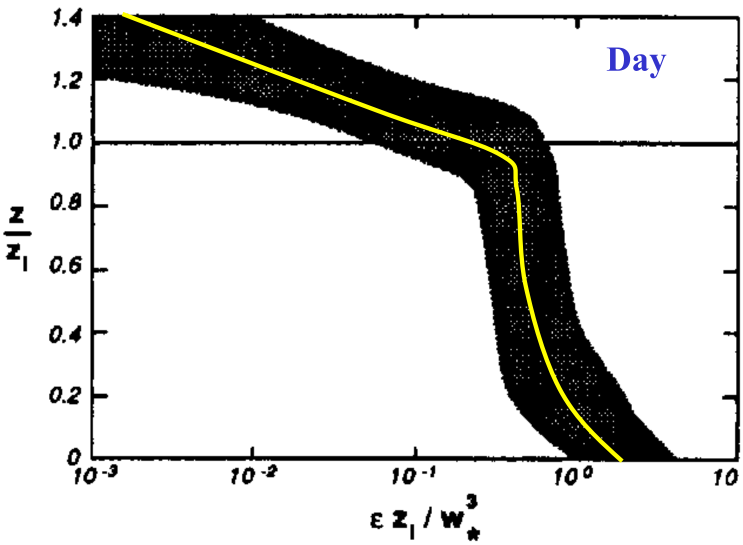
- We see quite a variation both in the vertical and horizontal.
- Here, the plume is defined by its temperature ramp signal.



Normalized Doppler-radar derived standard deviation of perturbation pressure.

N

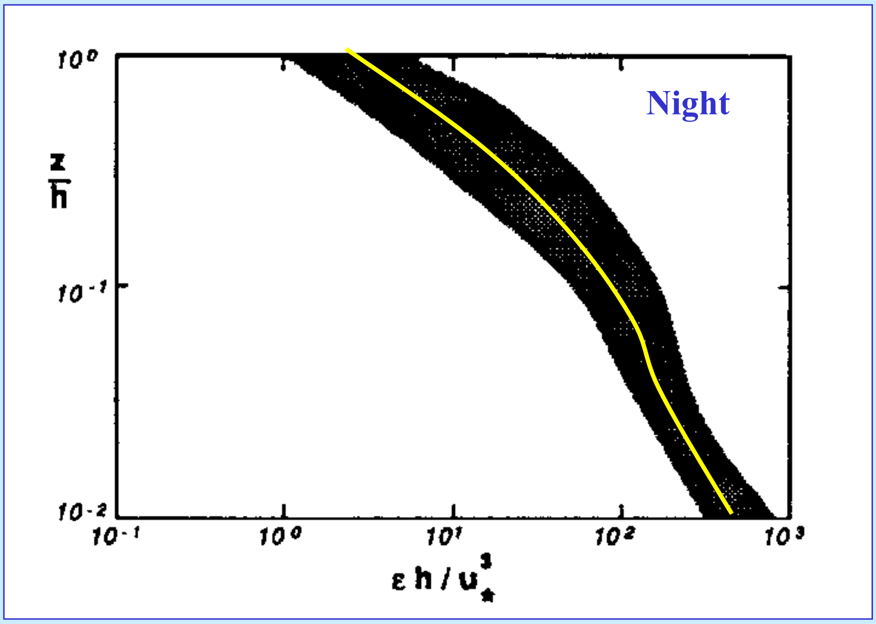
•This figure shows estimates of pressure variance based on Doppler radar measurements of motion within mixed layer.



Range of normalized dissipation rate (ε) profiles during the day-time, where z_i is the mixed layer depth and w_* is the convective velocity scale.

N

- Daytime dissipation rates (see above figure) are often largest near the surface, and then become relatively constant with height in the mixed layer.
- Above the mixed layer top, the dissipation rate rapidly decreases to near zero.



Range of normalized dissipation rate (ε) profiles at night, where h is boundary layer depth and u_* is the friction velocity.

N

- At night, both TKE and dissipation rate decreases very rapidly with height.

- **Mean KE equation**

III IV zero

$$\frac{\partial}{\partial t}\left(\tfrac{1}{2}\overline{u}_i^2\right)+\overline{u}_j\frac{\partial}{\partial x_j}\left(\tfrac{1}{2}\overline{u}_i^2\right)=-g\delta_{i3}\overline{u}_i+f\varepsilon_{ij3}\overline{u}_i\overline{u}_j$$

$$-\frac{\overline{u}_i}{\overline{\rho}}\frac{\partial\overline{p}}{\partial x_i}+\nu\overline{u}_i\frac{\partial\overline{u}_i}{\partial x_j^2}-\overline{u}_i\frac{\partial\overline{u_i'u_j'}}{\partial x_j}$$

V VI VII

Term VII ⇒

$$-\overline{u}_i\frac{\partial\overline{u_i'u_j'}}{\partial x_j}=\overline{u_i'u_j'}\frac{\partial\overline{u}_i}{\partial x_j}-\frac{\partial\left(\overline{u_i'u_j'}\,\overline{u}_i\right)}{\partial x_j}$$

N

III Is the rate of working against gravity

IV is the Coriolis term (is zero when summed)