Turbulence kinetic energy & stability

Modelling wind and dispersion in urban environments

Q4 2023-2024

Text book references: And Introduction to Boundary Meteorology, R.B. Stull, chapter 5

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Learning Objectives:

After this class, you will be able to:

- Recognise the terms within the turbulent kinetic energy equations

Activities during the class:

During this class, you will perform the following activities:

1. Refreshing question
2. Find the equations terms
3. One-minute notes (the muddiest point)

NO summative assignments

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Outline of the class:

1. Definition
2. TKE budget
3. Mean kinetic energy
4. Introduction to stability
5. Static and Dynamic stability
6. Richardson Number
7. Wrap-up

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Refreshing question

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What type of stability?

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Definition

In the previous class we summarised the equations needed to forecast wind right, especially continuity and momentum:

$$\frac{\partial \overline{U_j}}{\partial x_j} = 0$$

$$\frac{\partial \overline{U_i}}{\partial t} + \overline{U_j}\frac{\partial \overline{U_i}}{\partial x_j} = -\delta_{i3}g + f_c\varepsilon_{ij3}\overline{U_j} - \frac{1}{\overline{\rho}}\frac{\partial \overline{P}}{\partial x_i} + \nu\frac{\partial^2 \overline{U_i}}{\partial x_j^2} - \boxed{\frac{\partial\left(\overline{u_i' u_j'}\right)}{\partial x_j}}$$

These last term is a covariance, for which additional prognostic equations are required.

Turbulence departure of variables refers to the variables deviations from the means: u',v',w',… in theory equations for these terms can be derived, with a bit of work

In this class, this is out of the scope, but these equations are directly linked to the turbulence kinetic energy concept, as you can see in the following turbulence kinetic energy budget equations

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Refreshing question

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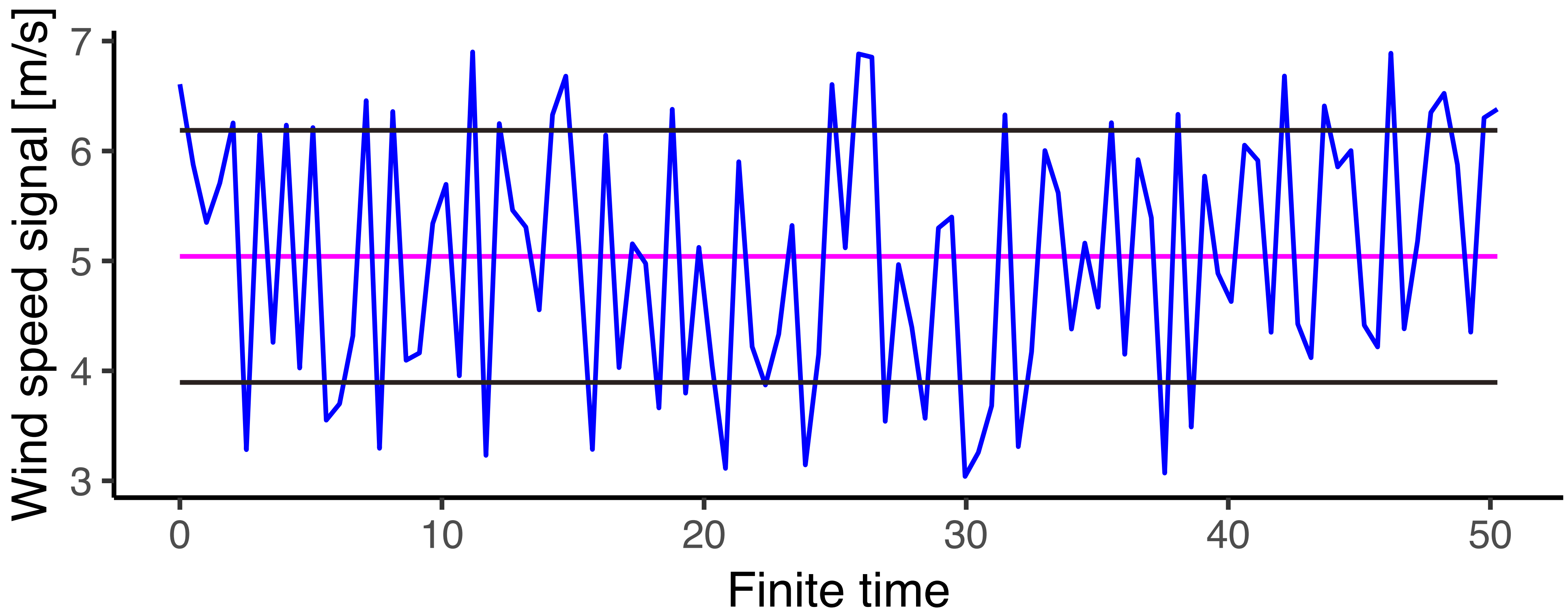
Refreshing question

Refreshing question



Definition

Turbulence kinetic energy (TKE) is one of the most important variables in micrometeorology, and therefore the flow around building environments.

- It measures the intensity of turbulence
- It is directly linked to the momentum, heat and moisture transport through the boundary layer
- Its individual equation terms describe physical processes that generate turbulence —> the balance of those terms, will define if the flow is turbulent, or not

Its definition was already presented before: $\overline{e} = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) = \frac{1}{2}\overline{u_i'}$

So if we have an equation for the velocity variances, we can get the TKE budget equation as we did for momentum and continuity

$$\frac{\partial \overline{e}}{\partial t} + \overline{U_j}\frac{\partial \overline{e}}{\partial x_j} = \delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right) - \overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j} - \frac{\partial\left(\overline{u_j'e}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{u_i'p'}\right)}{\partial x_i} - \varepsilon$$

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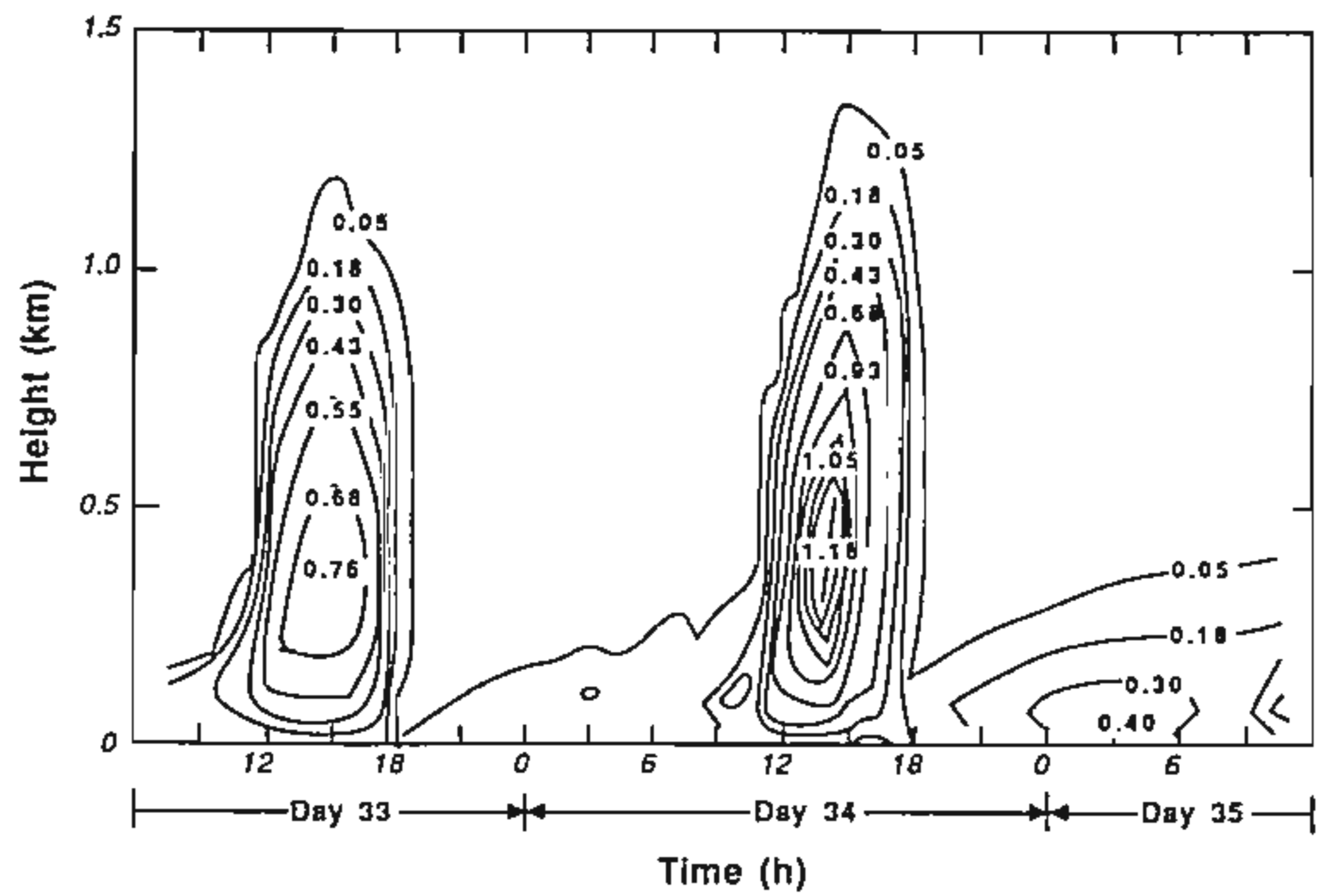
TKE budget

Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

$$\boxed{\frac{\partial \overline{e}}{\partial t}} + \overline{U_j}\frac{\partial \overline{e}}{\partial x_j} = \delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right) - \overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j} - \frac{\partial\left(\overline{u_j'e}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{u_i'p'}\right)}{\partial x_i} - \varepsilon$$

1.Storage or tendency

- Over the day, TKE can vary drastically with time and space
- Increase in TKE from a small early morning value to a larger early afternoon value represents a net storage of TKE in the air
- Non-turbulent FA air must be spun-up as entrainment incorporates into the mixed layer
- During late afternoon we have a negative storage term



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2.Advection by mean wind

- There is few known about this term
- When averaged over a horizontal area larger than 10km, there is little variation of TKE
- This doesn't hold for urban environments
- This term is probably negligible over ocean surfaces
- Not negligible over water reservoirs or coastal areas: you can imagine a water reservoir colder than the surrounding land, where turbulence would decay in the overlaying ai, while the air over the land is actively convective —> a mean wind advecting air across the shores of the reservoir may cause significant change in this TKE budget

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TKE budget

Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

$$\frac{\partial \overline{e}}{\partial t} + \overline{U_j}\frac{\partial \overline{e}}{\partial x_j} = \boxed{\delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right)} - \overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j} - \frac{\partial\left(\overline{u_j'e}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{u_i'p'}\right)}{\partial x_i} - \varepsilon$$

3.Buoyant production/ consumption

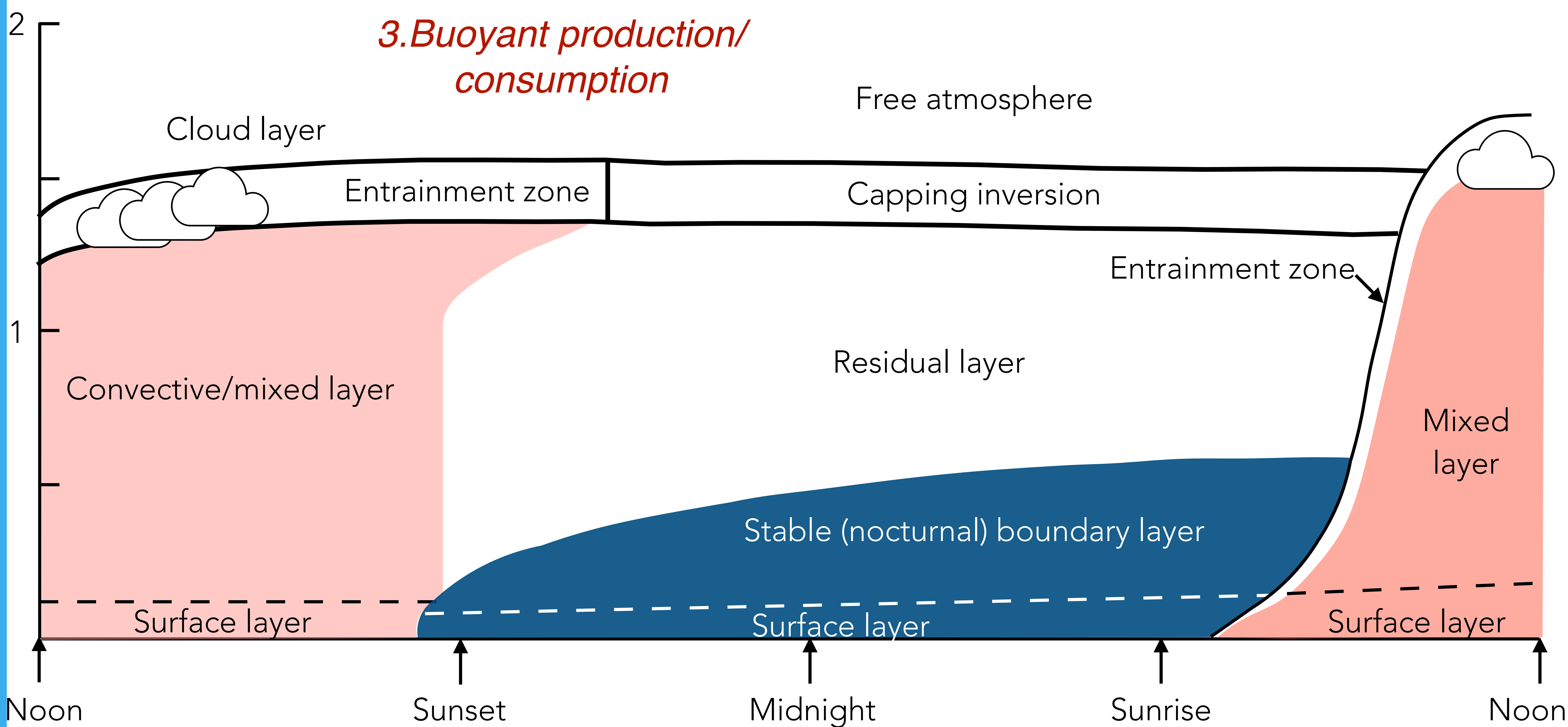
- The most important term is the flux of virtual potential temperature, which is positive and decreases roughly linearly with height within the bottom 2/3th of the convective ML $\left(\overline{u_i'\theta_v'}\right)$
- Acts only in the vertical component —> anisotropic.
- When positive: represents the effects of thermals in the ML, values can go up to $1\times10^{-2} m^2/s^3$ near the ground on sunny days over land, it would be much smaller during cloudy days
- When negative: during stable conditions, which surpasses or consumes TKE. During t night over land, or anytime the surface is colder than the overlaying air. Also at the top of the mixed layer

TKE budget

Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

$$\frac{\partial \overline{e}}{\partial t} + \overline{U_j}\frac{\partial \overline{e}}{\partial x_j} = \boxed{\delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right)} - \overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j} - \frac{\partial\left(\overline{u_j'e}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{u_i'p'}\right)}{\partial x_i} - \varepsilon$$

3.Buoyant production/ consumption



Questions so far?

TKE budget

Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

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4.Mechanical (shear) production

- This term is typically positive, since mean gradient and momentum flux are opposite sign
- It is often associated with surface layer: maximum production occurs close to the surface, where the wind shear is maximum
- Near 0 production in the ML above the surface layer, because changes in wind speed are small
- Anytime the ground is colder than the air, the shear term is the only term generating turbulence
- Greatest shears associated with the change of U and V components of mean wind with height —> anisotropic, and strongest in the horizontal

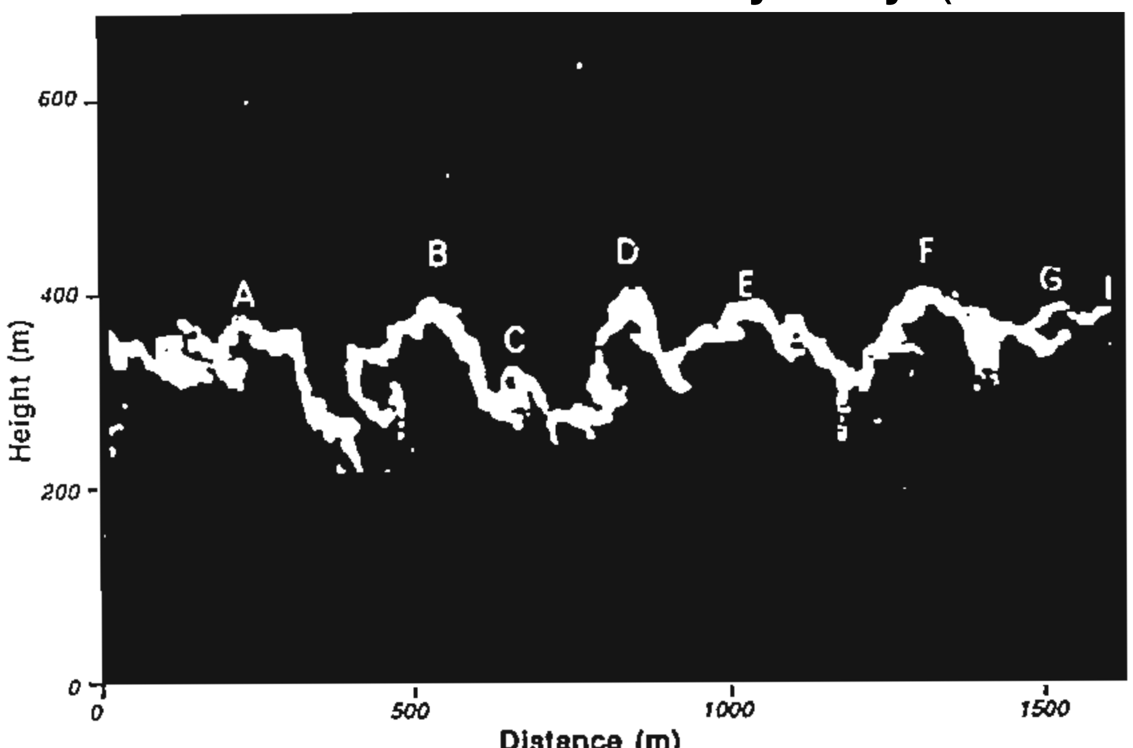
TKE budget

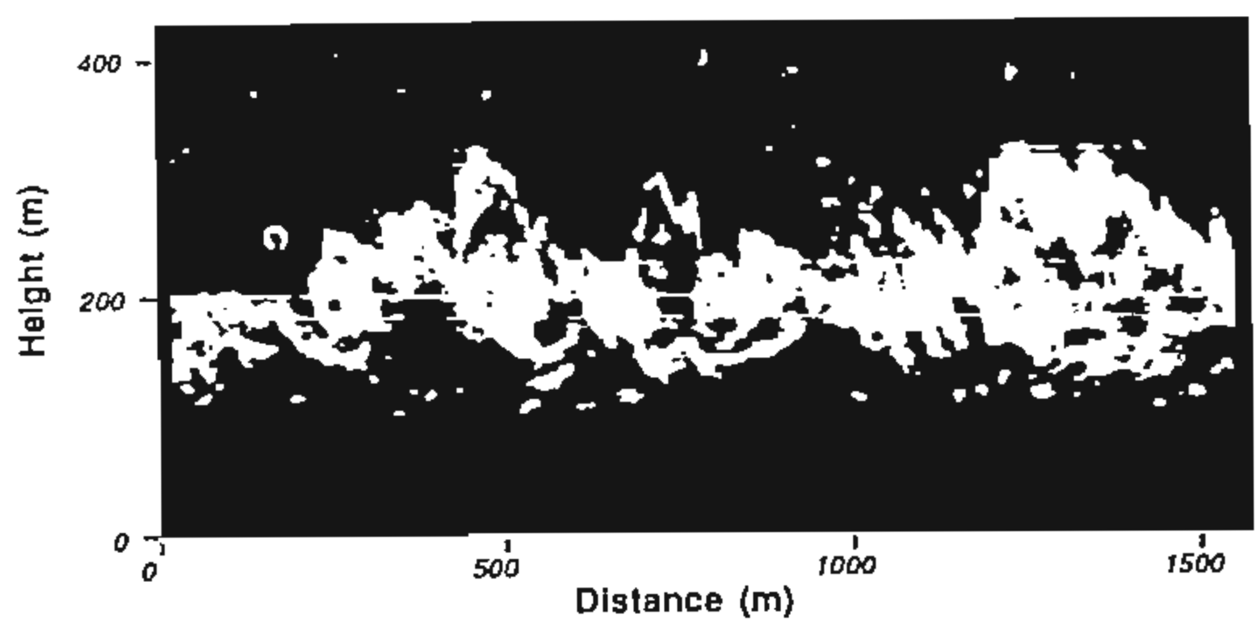
Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

$$\frac{\partial \overline{e}}{\partial t} + \overline{U_j}\frac{\partial \overline{e}}{\partial x_j} = \delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right) \boxed{-\overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j}} - \frac{\partial\left(\overline{u_j'e}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{u_i'p'}\right)}{\partial x_i} - \varepsilon$$

4.Mechanical (shear) production

- Differences between buoyancy (free convection) and shear (forced convection)





TKE budget

Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

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5.Turbulent transport

- Neither creates, nor destroys TKE, but moves or redistributes from one location to another
- Integrated over the ML depth is identically to 0
- If there is more flux into a layer than leaves, TKE increases. On a local scale at any height of the ML, it can lead to production or loss of TKE
- w'^2 dominates in the middle of the ML and $(u'^2+v'^2)$ dominates near the surface

Questions so far?

TKE budget

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6.Pressure correlation

- We know also few about this term, because measuring pressure fluctuations is very complicated, very small pressure fluctuations ~0.005-0.001kPa or less in the ML
- Normally this term is estimated as a residual from the budget, which means that accumulated errors int he other terms are an issue.
- Not only turbulence, but waves can also contribute to this term, and it is impossible to separate waves and turbulence within measurements.
- It does not only redistribute TKE, but it can draw energy out of the BL, ~<10% of total dissipation

TKE budget

Each term describe physical processes that generate turbulence and the balance of those terms, will define if the flow is turbulence:

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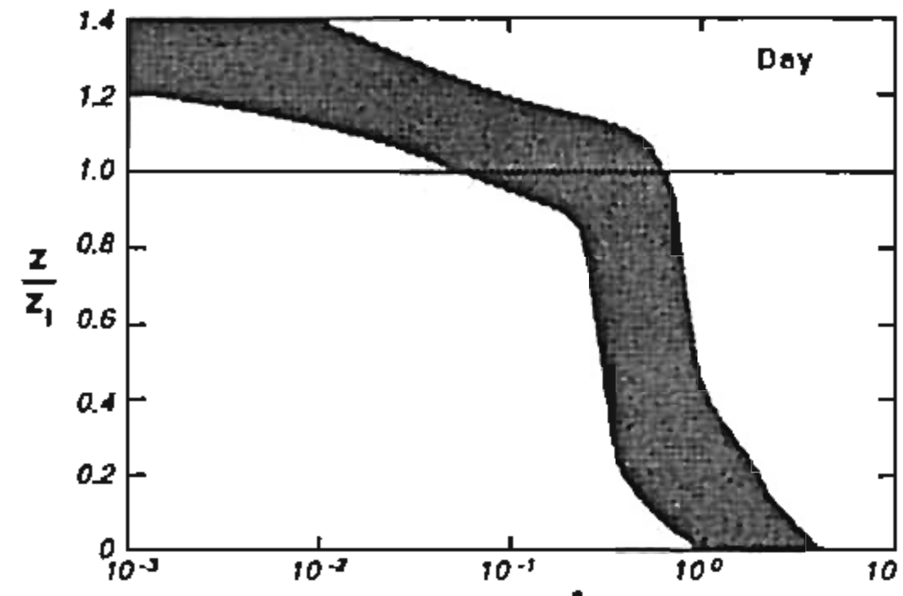
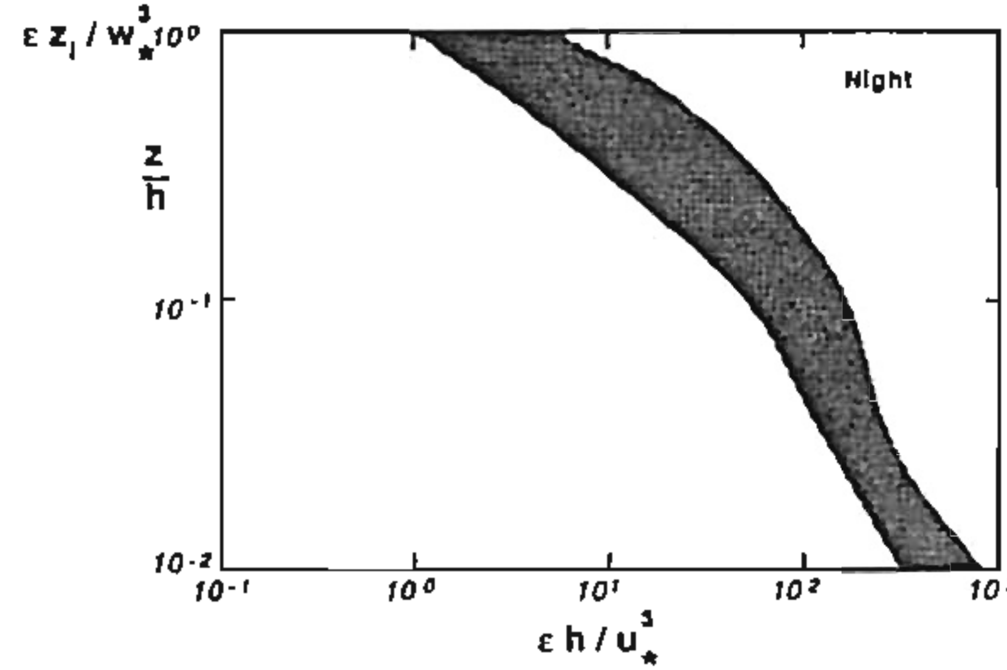
7.Dissipation

- 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 driven by the cascade of energy from larger scales
- Turbulence is not conserved, so the largest TKE and dissipation rates are found where production is largest (near the surface)
- Not expected to perfectly balance production because of transport terms





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Find equations terms

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Refreshing question

Find equations terms

What type of stability?

Finding the terms

Turbulent transport

Storage or tendency

Dissipation

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Mean Kinetic Energy

In the TKE equation, 4th term involves the production of TKE by interaction of turbulence with the mean wind:

$$\frac{\partial \overline{e}}{\partial t} + \overline{U_j}\frac{\partial \overline{e}}{\partial x_j} = \delta_{i3}\frac{g}{\overline{\theta_v}}\left(\overline{u_i'\theta_v'}\right) - \boxed{\overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j}} - \frac{\partial\left(\overline{u_j'e}\right)}{\partial x_j} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{u_i'p'}\right)}{\partial x_i} - \varepsilon$$

Does this mean, that the production of TKE is accompanied by a corresponding loss of KE from the mean flow?

Obtaining the equation for the mean kinetic energy (MKE)

$$\frac{\partial\left(0.5\overline{U_i^2}\right)}{\partial t} + \overline{U_j}\frac{\partial\left(0.5\overline{U_i^2}\right)}{\partial x_j} = -g\delta_{i3}\overline{U_i} + f_c\varepsilon ij3\overline{U_i}\,\overline{U_j} - \frac{\overline{U_i}}{\overline{\rho}}\frac{\partial \overline{P}}{\partial x_i} + \nu\overline{U_i}\frac{\partial^2 \overline{U_i}}{\partial x_j^2} + \boxed{\overline{u_i'u_j'}\frac{\partial \overline{U_i}}{\partial x_j}} - \frac{\left(\overline{u_i'u_j'}\,\overline{U_i}\right)}{\partial x_j}$$

YES, the energy that is mechanically produced from turbulence is lost from the mean flow

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Introduction to stability

Unstable flows, become or remain turbulent

Stable flows, become or remain laminar (no turbulence)

Destabilizing factors

Stabilizing factors

These factors can be interpreted as terms within the TKE budget equation

Researchers normally pair stabilising and destabilising factors in non-dimensional numbers

Reynolds number: inertia/viscous

Richardson number: buoyancy/inertia

Introduction to stability

Unstable flows, become or remain turbulent

Stable flows, become or remain laminar (no turbulence)

<u>Destabilizing factors</u> >> <u>Stabilizing factors</u>

Turbulence occurs

These factors can be interpreted as terms within the TKE budget equation

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Static and Dynamic Statibility

Static stability

- It is a measure of the capability for buoyant convection
- This type of stability does not depend on wind (“static”)
- Air is *statically unstable* when:
  - Less dense air (warmer) underlies more dense air
  - This leads to convective circulation, thermals
  - Buoyant air rises to the top, stabilising the fluid
  - In the real BL thermals need a trigger: trees, hills, buildings…

Local definition

- Static stability determined by the local lapse rate
- Fails to detect convective MLs, because the rise of the thermals from the surface or their descent from cloud top depends on their excess buoyancy, and not on the ambient lapse rate

Non-local definition

- Examines the stability of the whole layer
- Knowledge of the whole profile virtual temperature / knowledge of the turbulent buoyancy flux at the surface

Stable	Unstable	Neutral
$\overline{w'\theta'_v} < 0$	$\overline{w'\theta'_v} > 0$	$\overline{w'\theta'_v} \approx 0$

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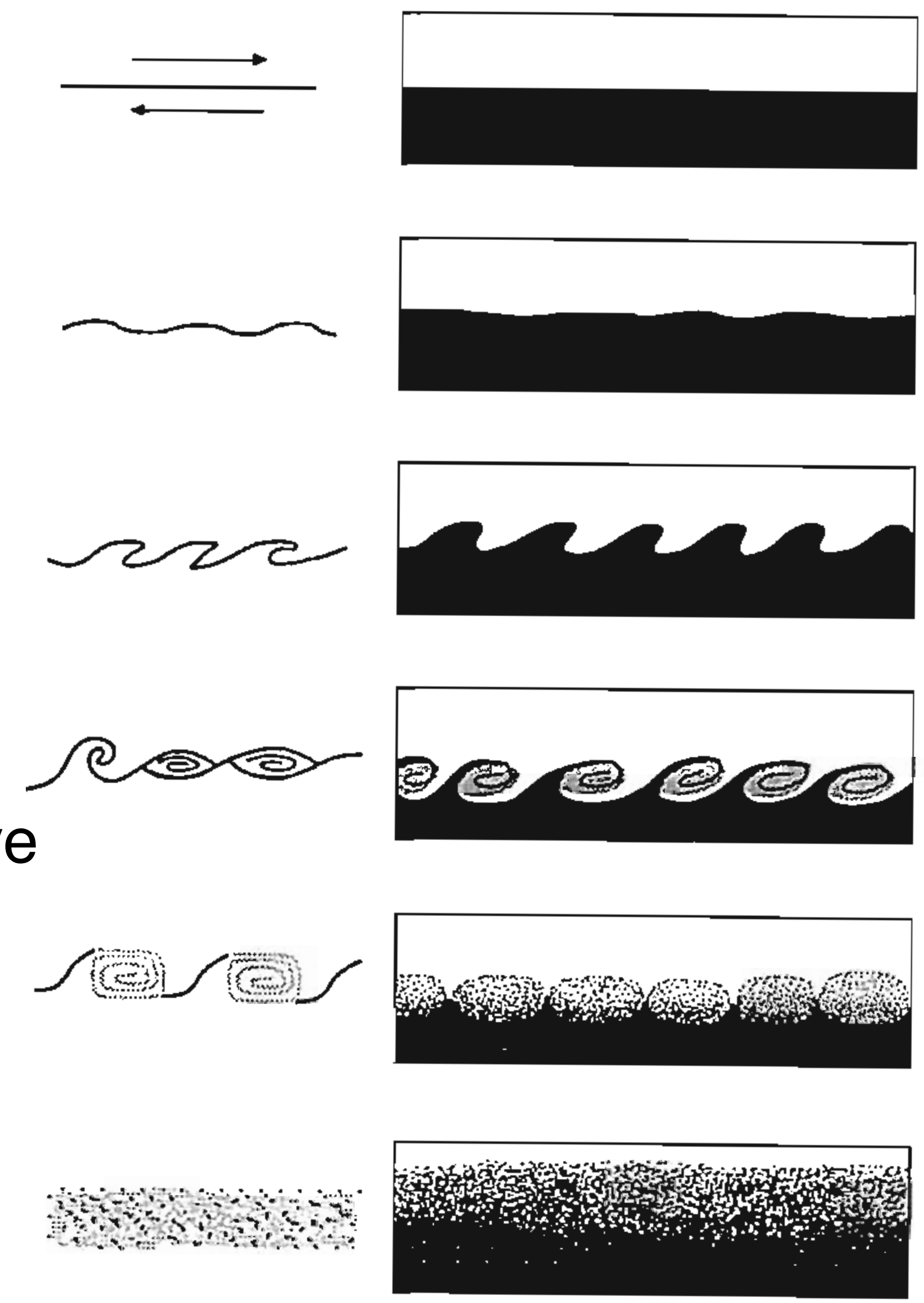
Static and Dynamic Statibility

Dynamic stability

- Depends in part on the winds, and part on the buoyancy
- Even if the air is statically stable, wind shears may generate turbulence dynamically

1. Shear exists across density interface, initially laminar
2. After critical value of shear —> gentle waves
3. Waves roll up and brake (Kelvin-Helmholtz wave)
4. Lighter fluid rolled under denser fluid, giving patches of static instability
5. Combined static/dynamic instability causes each wave to become turbulent
6. Turbulence spreads throughout the layer, causing mixing, diffusion and transfer of momentum



Static and Dynamic Statibility

Dynamic stability

- Occurs during Clear Air Turbulence
- Continued dynamic forcing can allow turbulence to continue for hours to days
- These regions can have large horizontal extent (~O(100km)) but limited in vertical extent (~O(10-100km))
- Probably occur frequently, but are only visible when there is sufficient moisture in the air

Amusing planet

youtube.com

Static and Dynamic Statibility

Fluid Reaction

Fluid reacts in a manner to undo the cause of the instability: Le Chatelier's principle of chemistry: 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.

Turbulence is mechanism whereby fluid flows tends to undo the effect of the instability

Static stability

Convection occurs to move more buoyant fluid upward, stabilising the system

Dynamic stability

Turbulence tends to reduce the wind shears, towards stabilising the system

Turbulence acts to eliminate itself, after the unstable system is stabilised turbulence tends to decay

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Richardson Number

Flux Richardson Number

Determines whether the flow might become dynamically stable

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$$R_f = \frac{\boxed{\left(\frac{g}{\overline{\theta_v}}\right)\left(\overline{w'\theta_v'}\right)}}{\boxed{\left(\overline{u_i'u_j'}\right)\frac{\partial \overline{U_i}}{\partial x_j}}} \begin{array}{l} \longrightarrow \textbf{Buoyancy} \\ \longrightarrow \textbf{Shear} \end{array}$$

$R_f>1$ ⟶ Flow becomes laminar (dynamically stable)

$R_f=1$ ⟶ Flow neutral (dynamically stable)

$R_f<1$ ⟶ Flow becomes turbulent (dynamically unstable)

Drawback: since it includes turbulent terms ($w'\theta_v'$), we can use it to determine if turbulent flow will become laminar, but not when laminar flow becomes turbulent!!!

Richardson Number

Gradient Richardson Number

Using the approximations hereafter:

$$-\overline{w'\theta_v'} \propto \frac{\partial\overline{\theta_v}}{\partial z} \qquad -\overline{u'w'} \propto \frac{\partial\overline{U}}{\partial z} \qquad -\overline{v'w'} \propto \frac{\partial\overline{V}}{\partial z}$$

$$Ri = \frac{\underbrace{\boxed{\left(\frac{g}{\overline{\theta_v}}\right)\left(\frac{\partial\overline{\theta_v}}{\partial z}\right)}}_{\text{Buoyancy}}}{\underbrace{\boxed{\left[\left(\frac{\partial\overline{U}}{\partial z}\right)^2 + \left(\frac{\partial\overline{V}}{\partial z}\right)^2\right]}}_{\text{Shear}}}$$

This is the usually referred to by researchers.

$Ri < R_c \longrightarrow$ Laminar flow becomes turbulent $\quad R_c = 0.21\text{-}0.25$

$Ri > R_T \longrightarrow$ Turbulent flow becomes laminar $\quad R_T = 1$

Drawback: we will rarely know the actual local gradients!!

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Richardson Number

Bulk Richardson Number

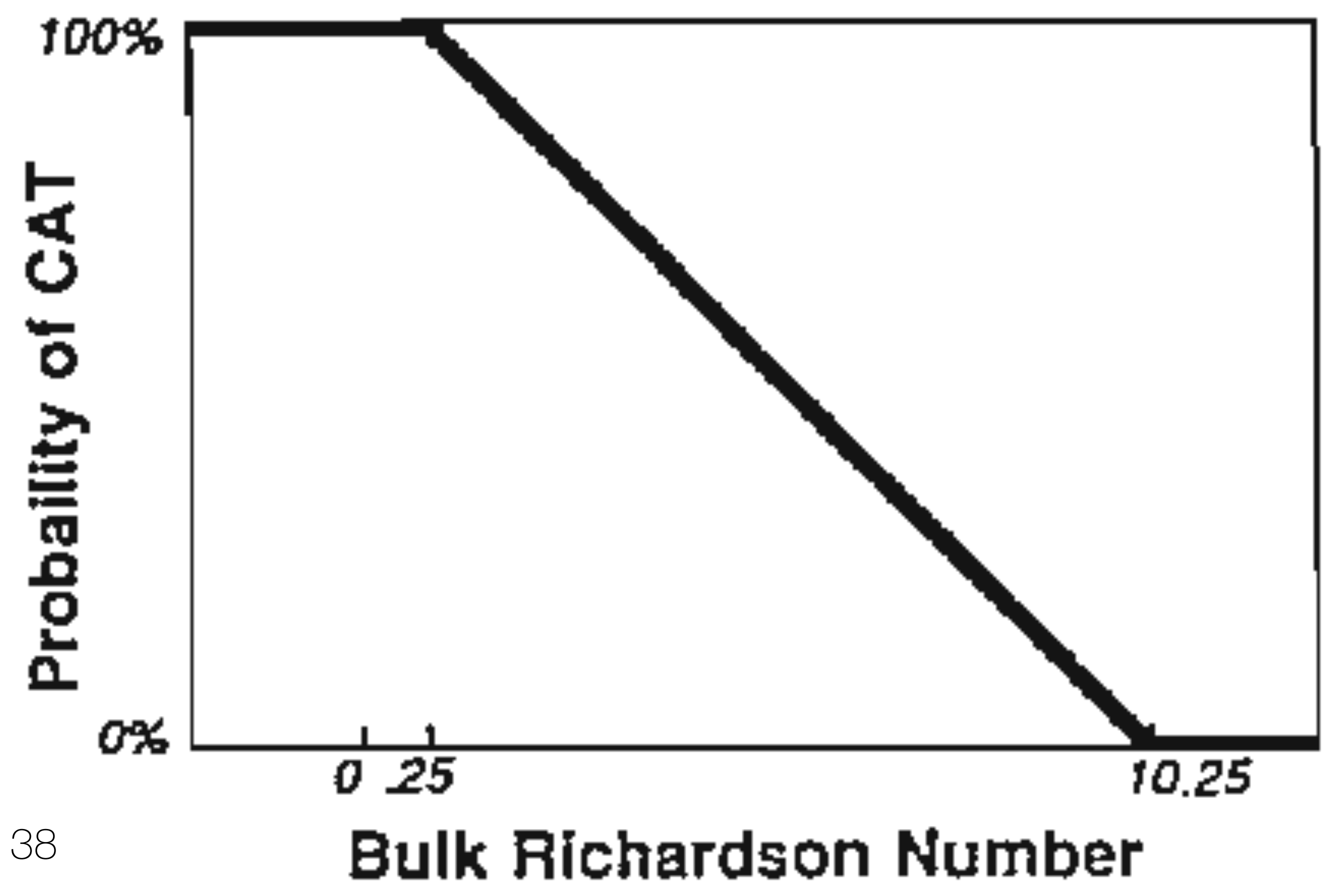
Using approximations:

$$\frac{\partial\overline{\theta_v}}{\partial z} \approx \frac{\Delta\overline{\theta_v}}{\Delta z} \qquad \frac{\partial\overline{U}}{\partial z} \approx \frac{\Delta\overline{U}}{\Delta z} \qquad \frac{\partial\overline{V}}{\partial z} \approx \frac{\Delta\overline{V}}{\Delta z}$$

$$R_B = \frac{g\Delta\overline{\theta_v}\Delta z}{\overline{\theta_v}\left[\left(\Delta\overline{U}\right)^2 + \left(\Delta\overline{V}\right)^2\right]}$$

This is the usually used by meteorologists. R_c=0.25

Relationship between the bulk Richardson number, Ri, over a layer and the probability of turbulence within that layer.



Questions so far?

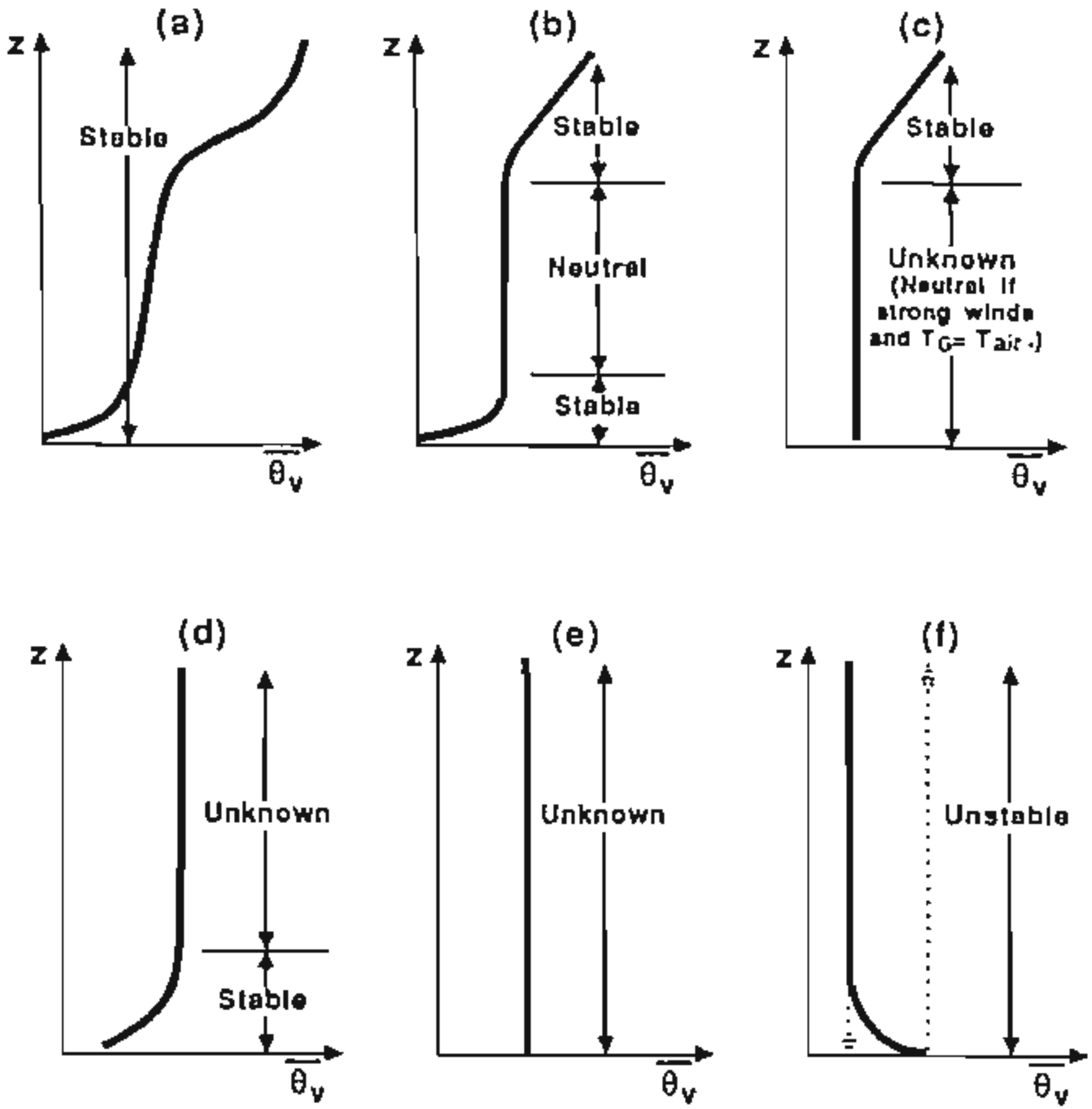
Wrap up:

1. Recognise the terms in the turbulent kinetic energy equations

Next class:

The turbulent closure problem

What type of profiles are this?



What type of profiles are this?