Photo: A. Christen

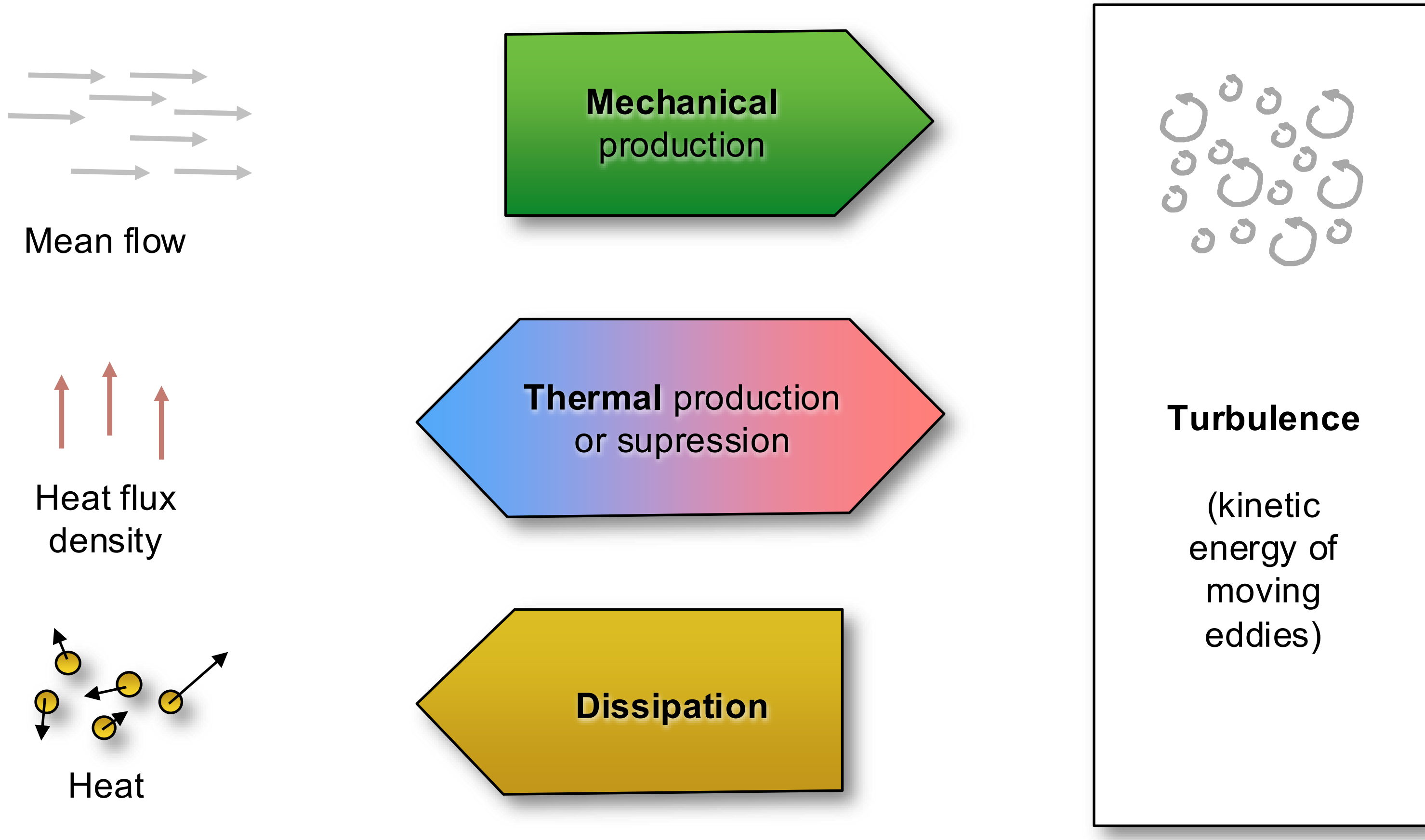
17 Dissipation of turbulence.

Today's lecture

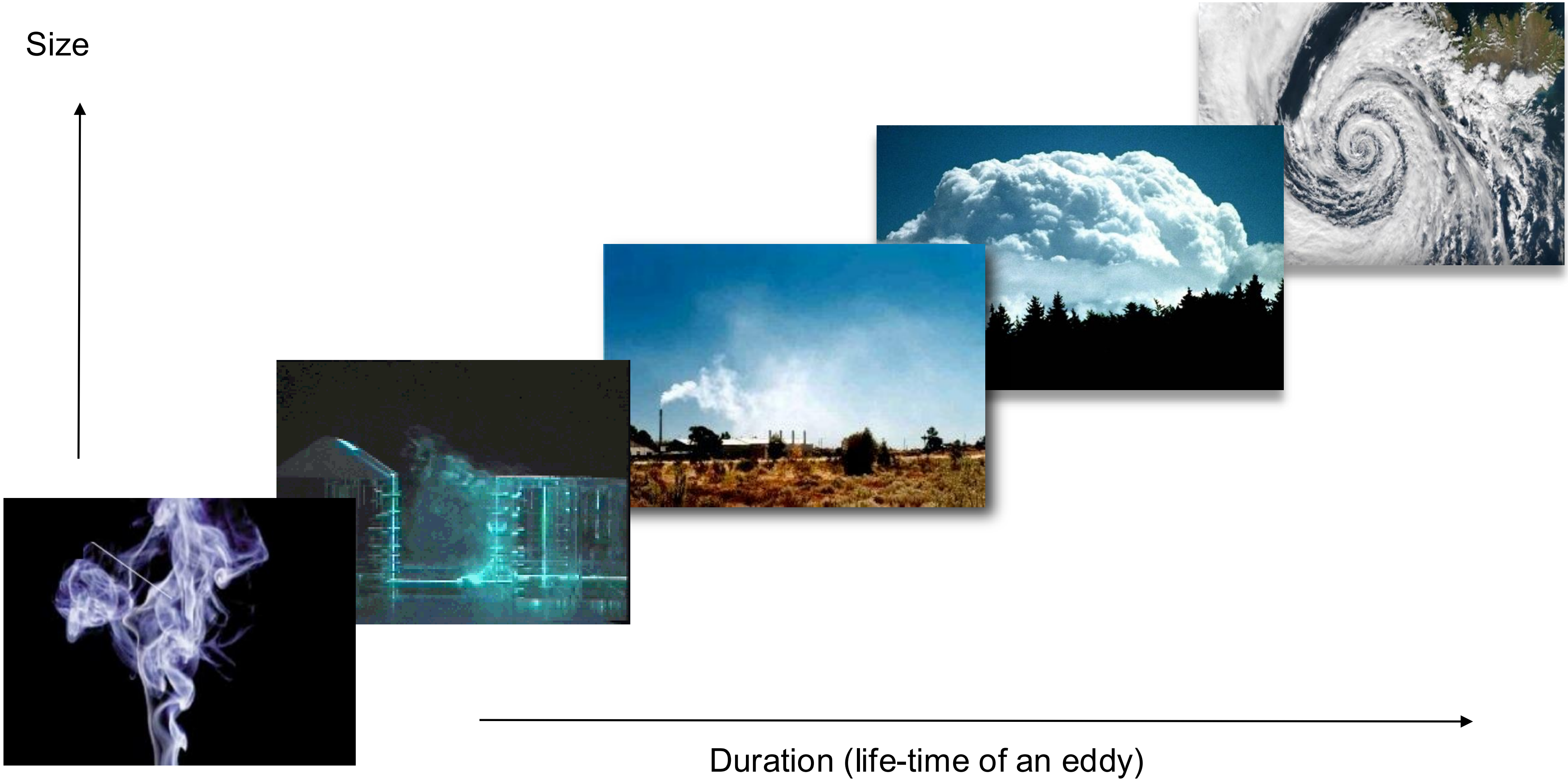
- Explain why there isn't more and more turbulence in the atmosphere if there's a continual supply of kinetic / thermal energy.
- Describe if there are limits to the scales of turbulent eddies in a system.
- Understand how we graph the size and duration of eddies.

Turbulent eddies in Jupiter are as large as the entire planet Earth (NASA)

Conservation of energy - The Turbulent Kinetic Energy (TKE) budget



Turbulence - production on different scales



The energy cascade

Breakdown continues all the way down the inertial subrange to the molecular scale where eddies dissipate into heat. This is called the **energy cascade**

"Big whorls have little whorls,

which feed on their velocity;

and little whorls have lesser whorls,

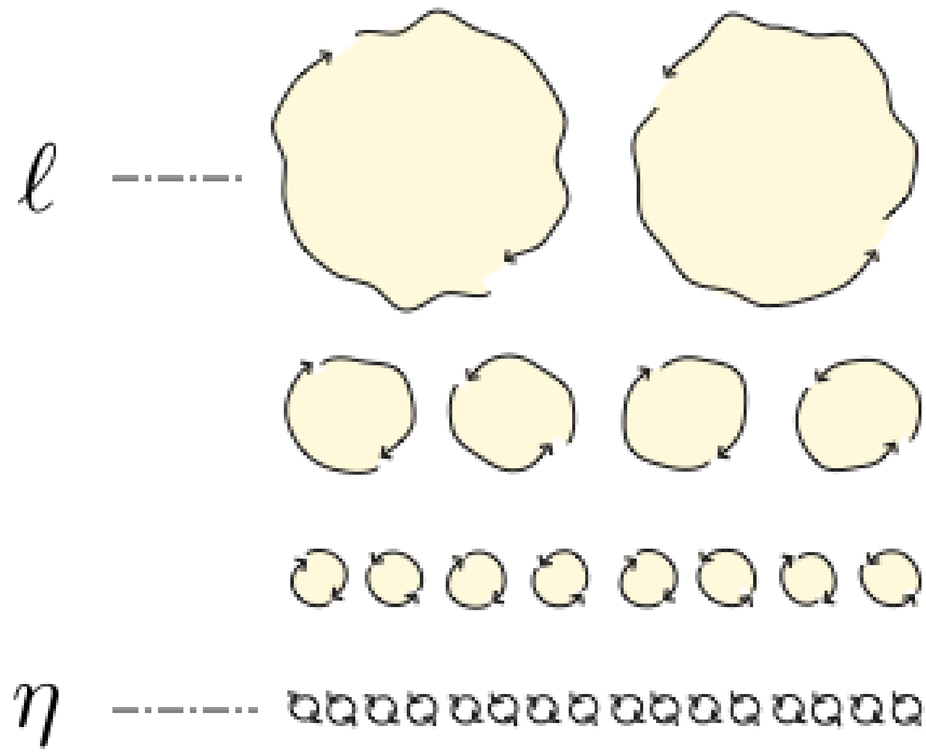
and so on to viscosity."

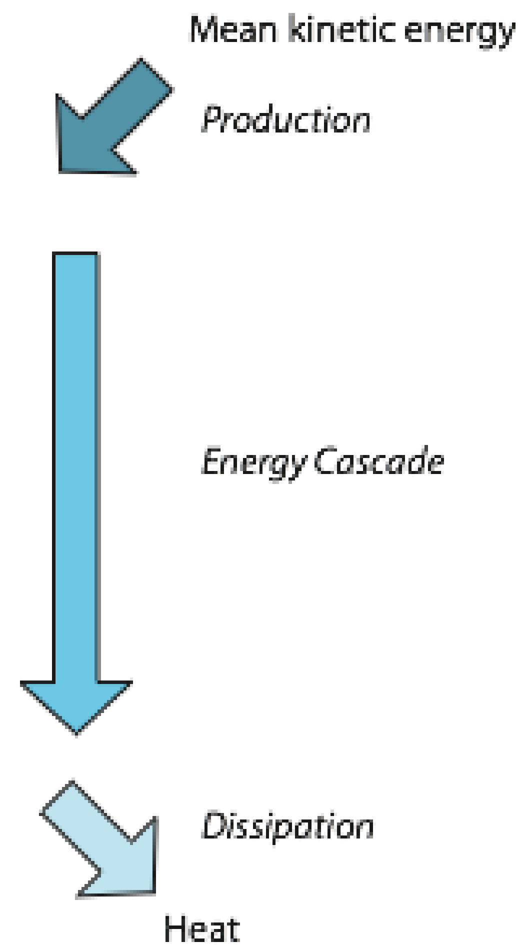
Lewis Richardson (1922)

Kolmogorov’s energy cascade theory

Largest eddies arise from dynamic instability (e.g. shear)

Integral length scale
(size of the largest eddies in the flow)





Kolmogorov microscale

smallest eddies become stable again under the influence of viscosity

Integral length scales

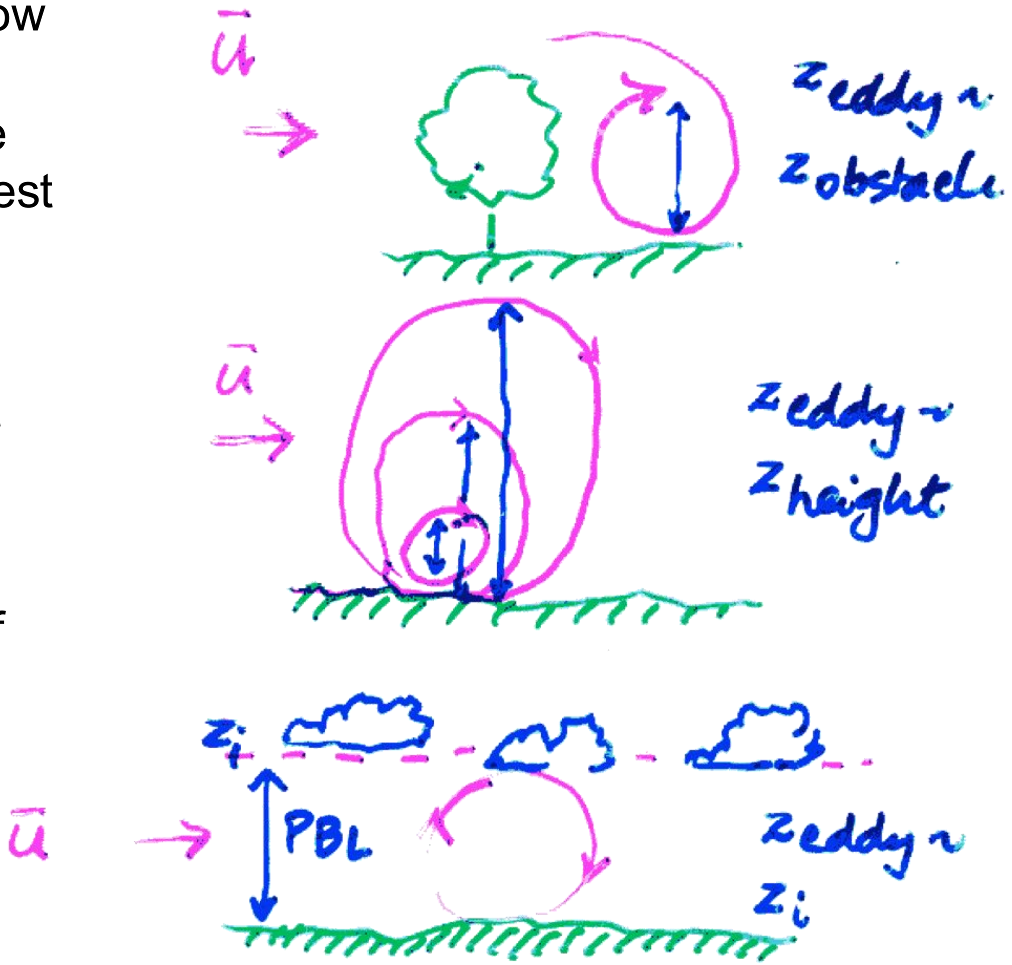
The **integral length scale** ℓ of a turbulent flow depends on the processes that create turbulence and is therefore a property of the flow not the fluid. It is a measure of the largest eddy size in turbulent flow.

The integral length scale is the size of the *energy-containing eddies* — the eddies that are created directly by the mechanism producing turbulence.

For mechanical turbulence this is the size of the obstacle, but

Limit 1: height above ground

Limit 2: depth of the PBL

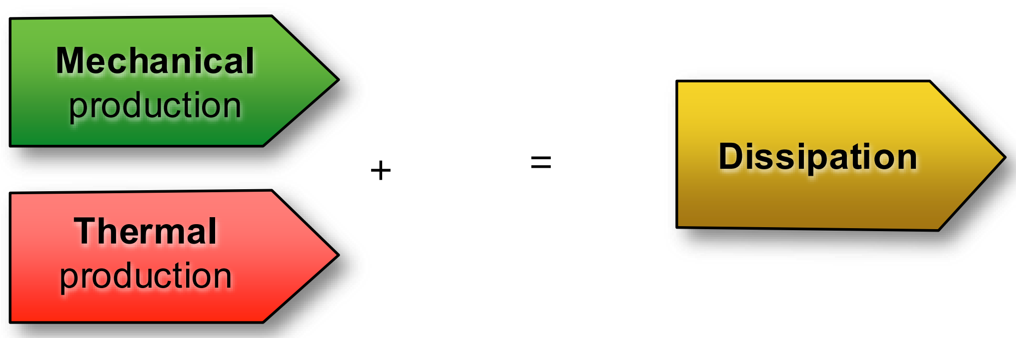


Kolmogorov microscale

The Kolmogorov microscale η depends on the fluid's viscosity ν and the rate of energy dissipation to heat ϵ.

$$\eta = \nu^{3/4}\,\epsilon^{-1/4}$$

In steady-state turbulence as often encountered in the ABL, the rate at which the energy is dissipated is exactly equal to the rate at which energy is supplied (by thermal and mechanical convection):



Ursus Wehrli 'Die Kunst, Aufzuräumen' 2011

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Separating scales - Fourier transform

Fuller description of all scales of a turbulent flow is given by calculating a velocity spectrum - i.e. decompose frequencies contributing to a time series (e.g. by **Fourier transform**):

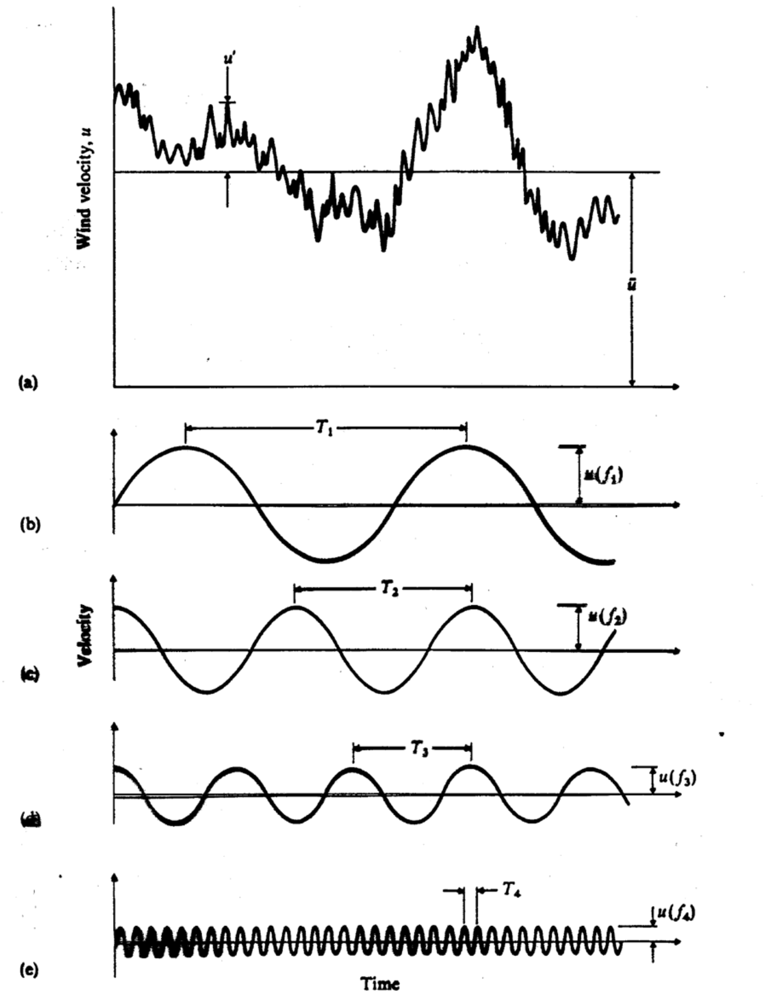


Fig. 7.8 (a) Fluctuations in the wind velocity; (b) (c) (d) (e), the turbulent eddies that cause them.

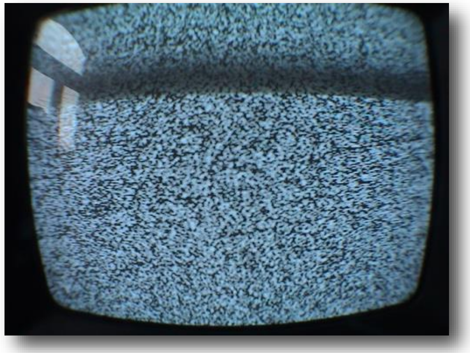
Can be applied to space and time series

https://geog321.github.io/applets/fouriertransform/

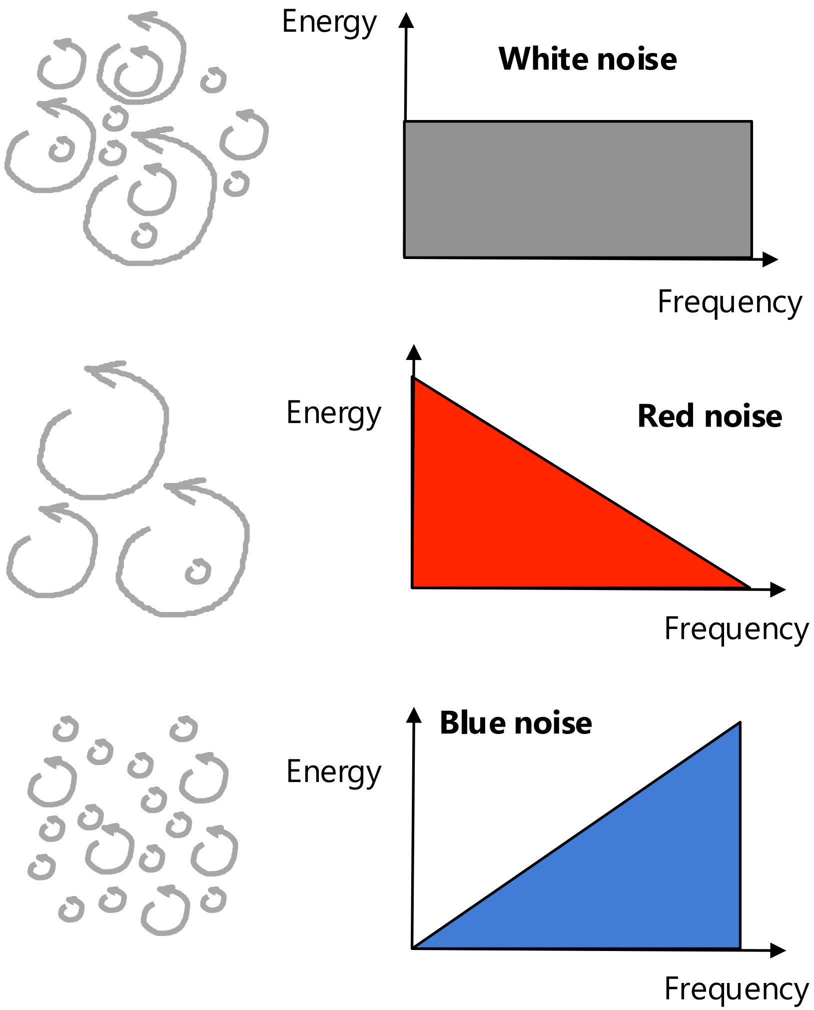
Spectra

Size of eddies can be viewed as wavelength (λ) or as frequency (v).

A turbulence spectrum shows the **energy** as function of λ or v, i.e. it **sorts a time series** by eddy duration.



In white noise all waves in all frequencies show the same energy content



A spectrum revisited

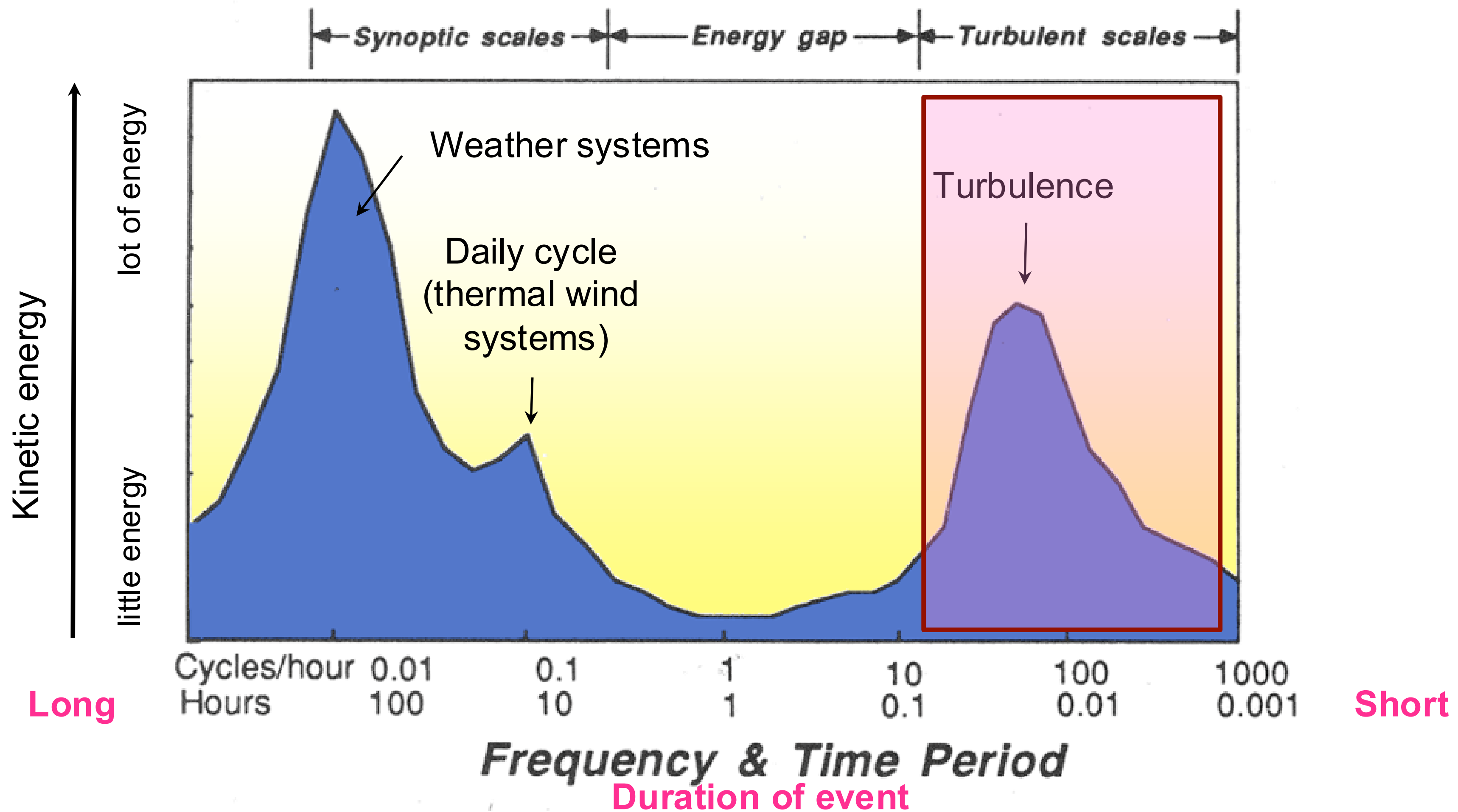
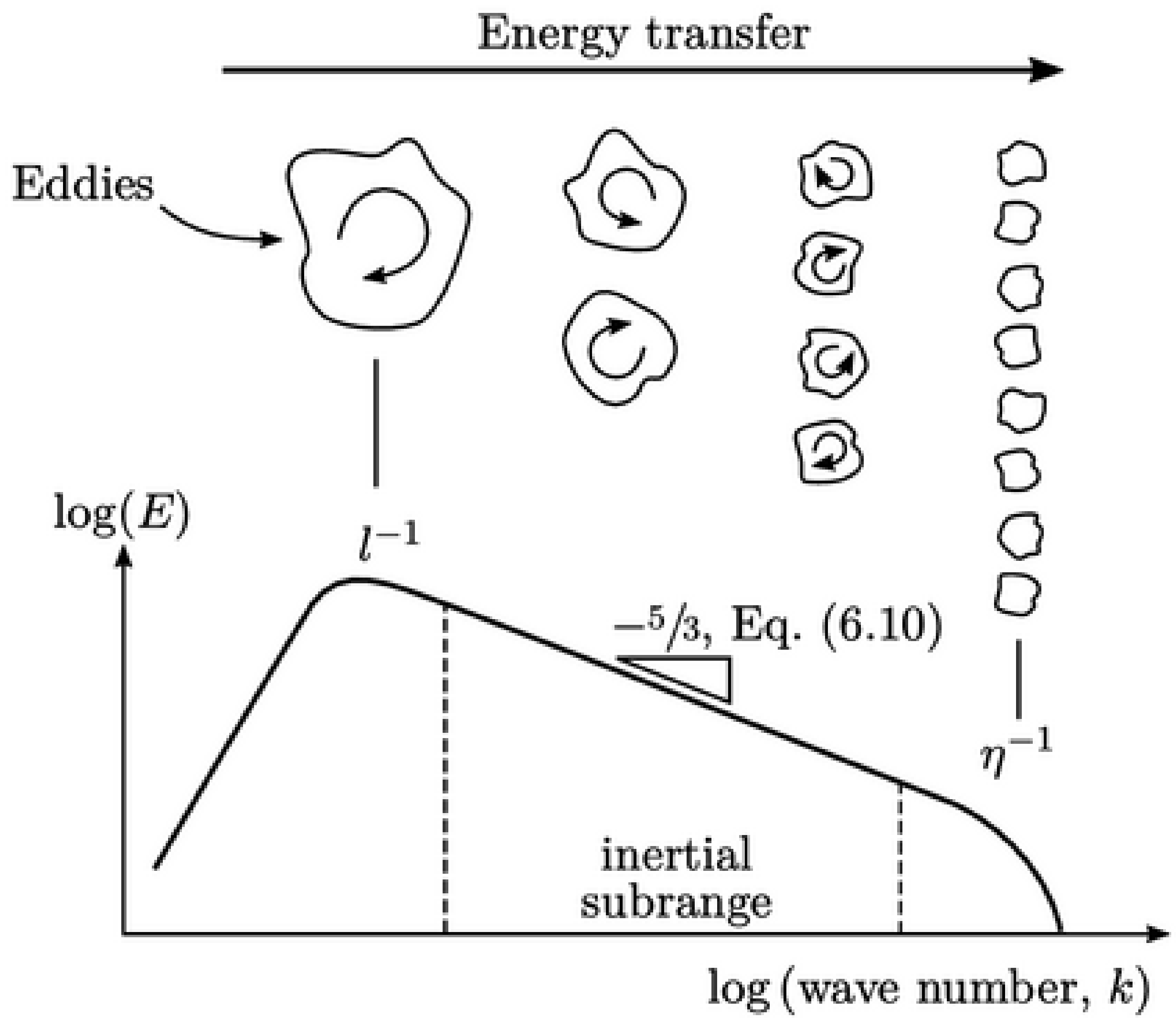


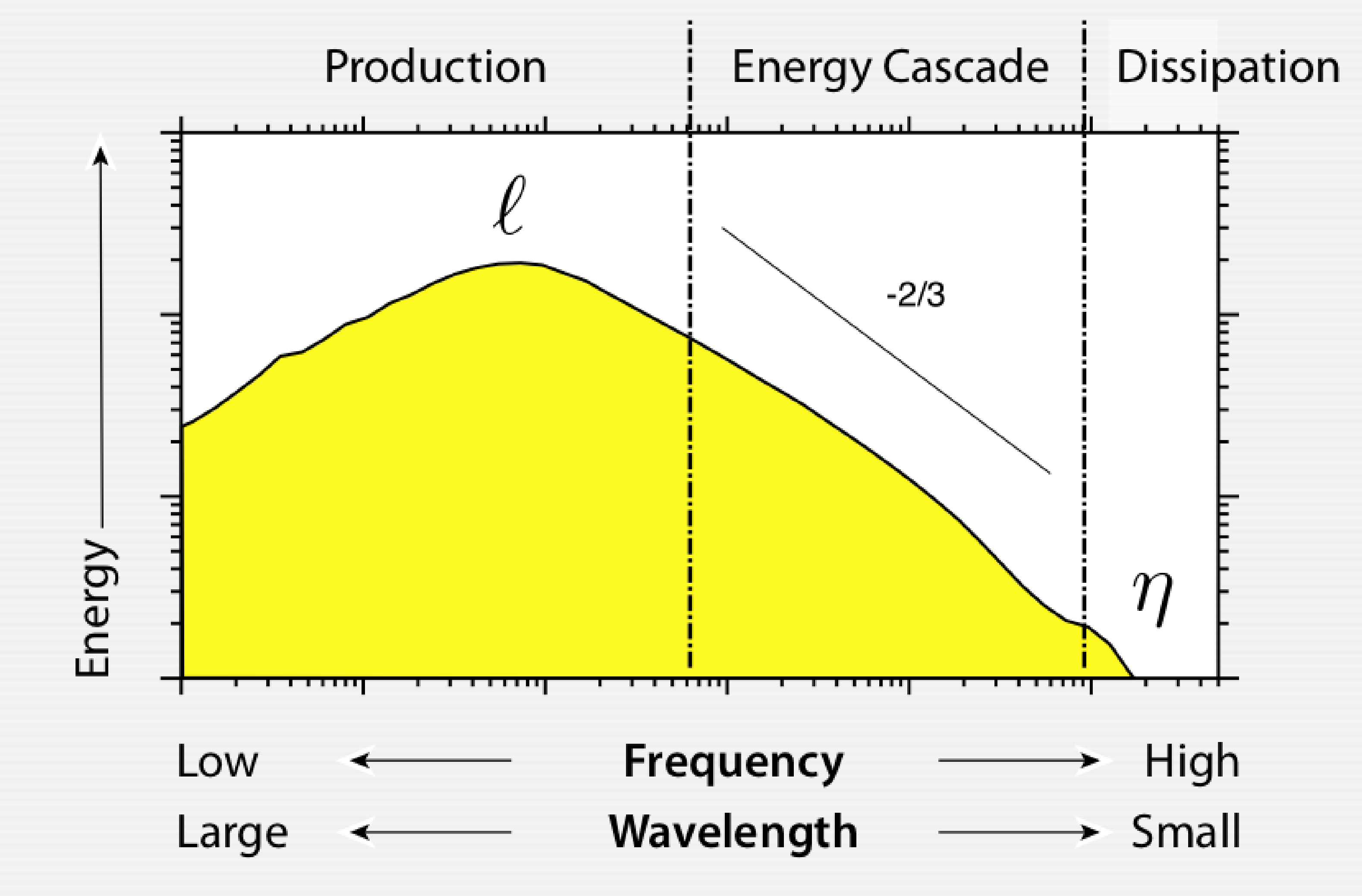
Fig. 2.2 Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).

Peaks in the spectrum show which size eddies contribute the most to the TKE.

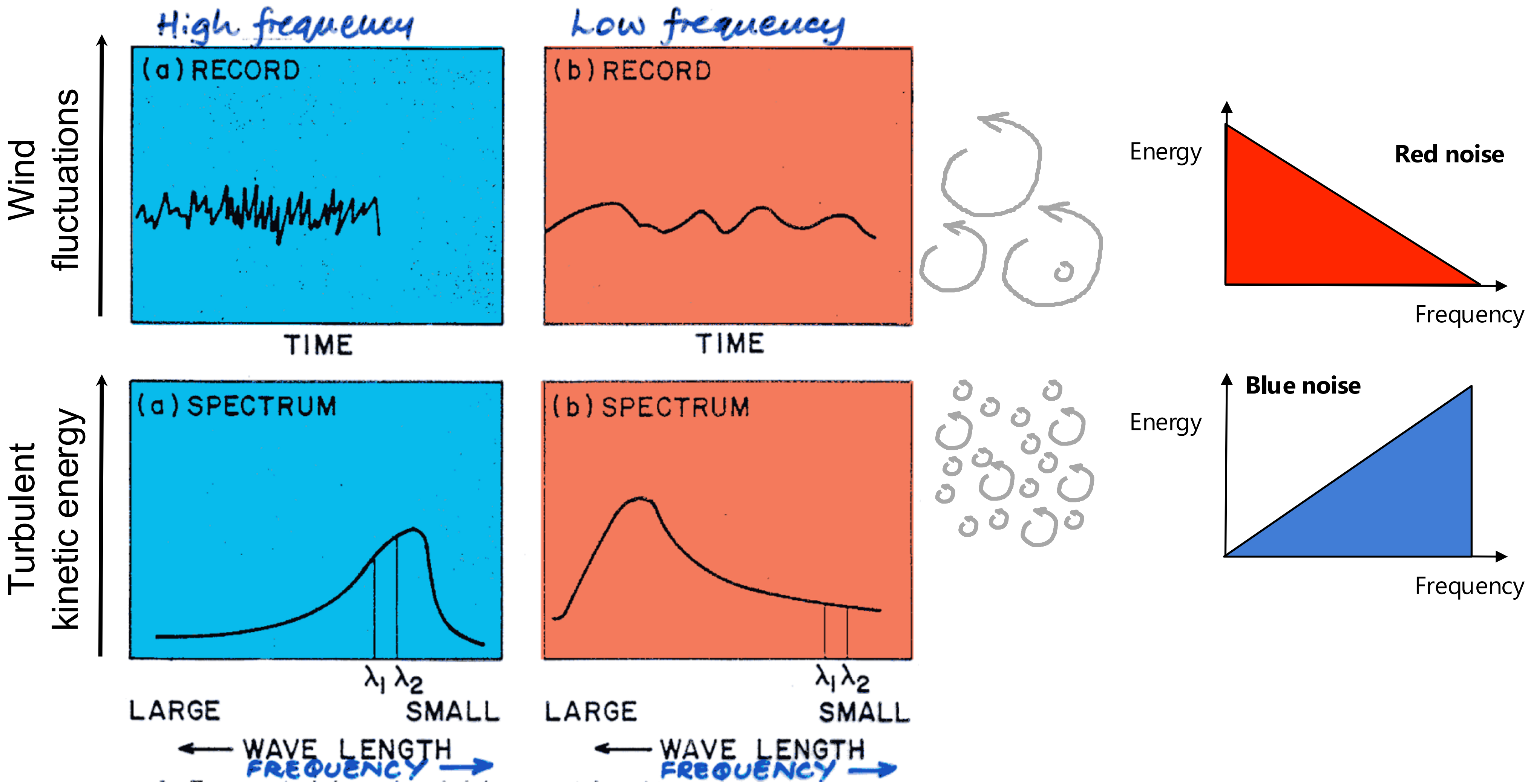
A spectrum of atmospheric turbulence



A spectrum of atmospheric turbulence

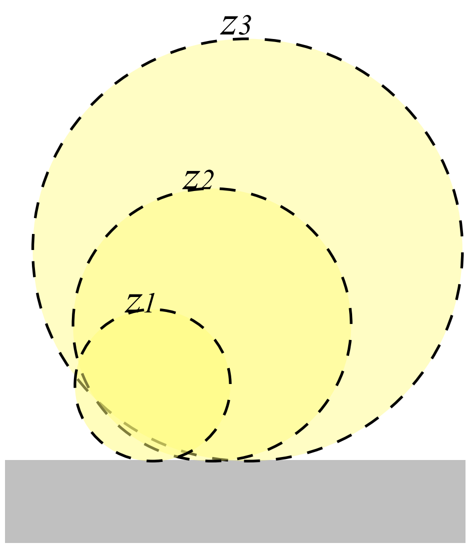


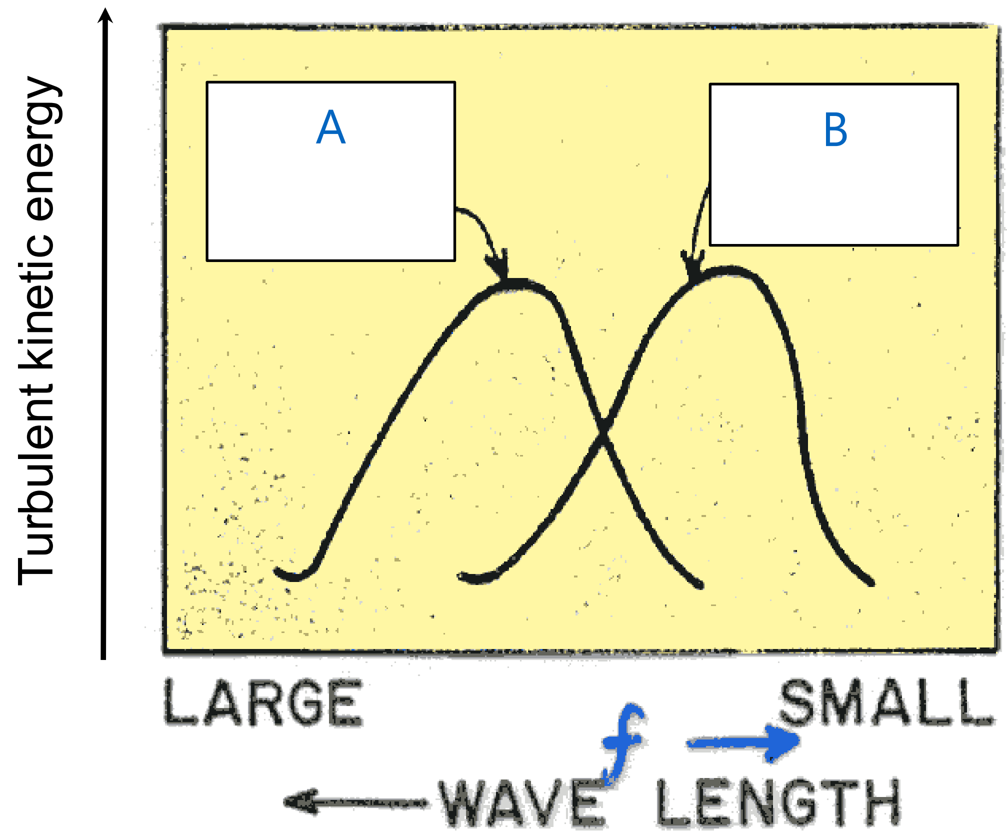
Schematic set of spectra



Turbulence spectra - influence of height above ground

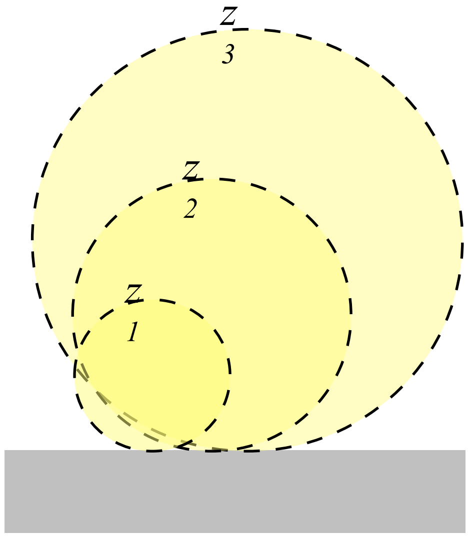
As the integral length scale increases with height above ground due to less damping by the surface boundary.

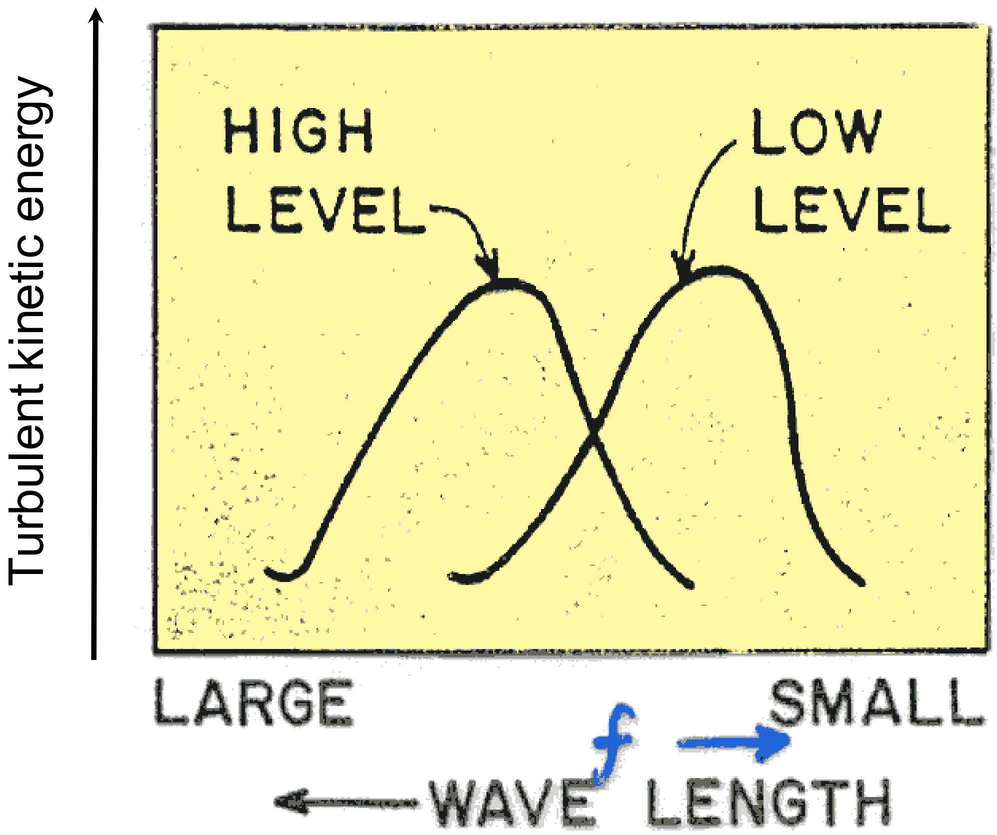




Turbulence spectra - influence of height above ground

As the integral length scale increases with height above ground due to less damping by the surface boundary, so do spectra move to the left.



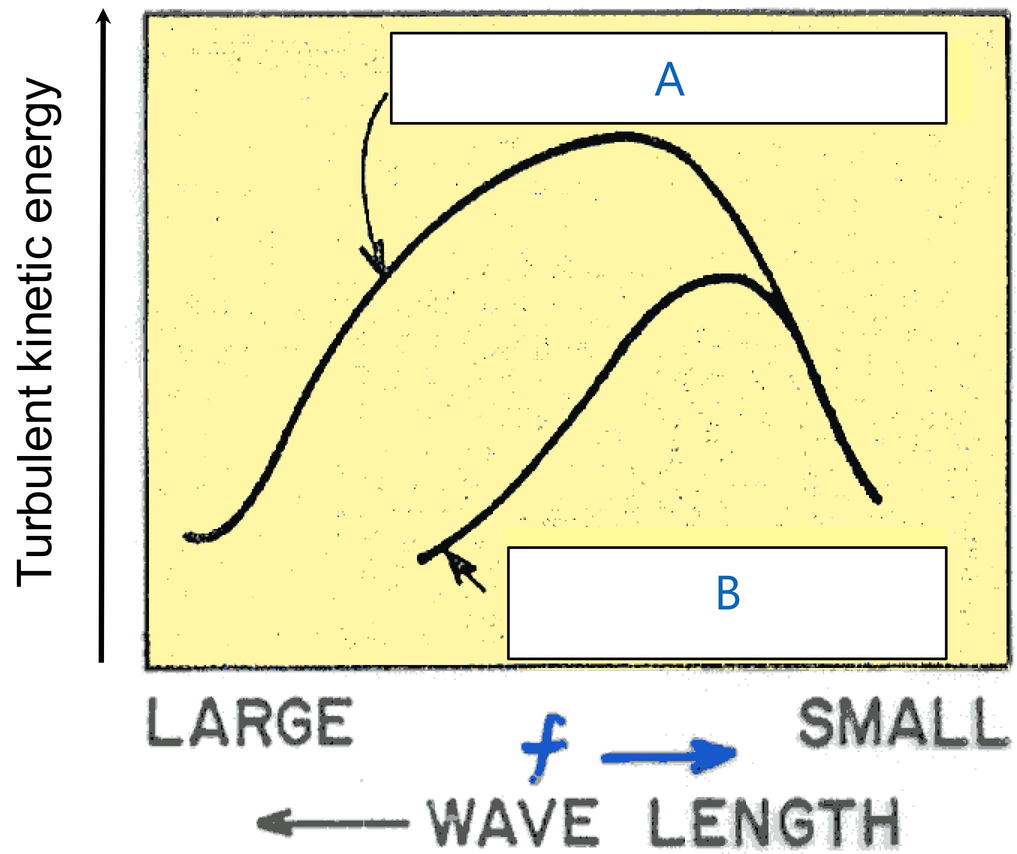


Turbulence spectra - influence of stability

Turbulent fluctuations are:

High frequency (seconds) in **stable and neutral** ABL, when only mechanical convection is present

Low frequency (minutes) in **unstable air** when thermal convection is dominant



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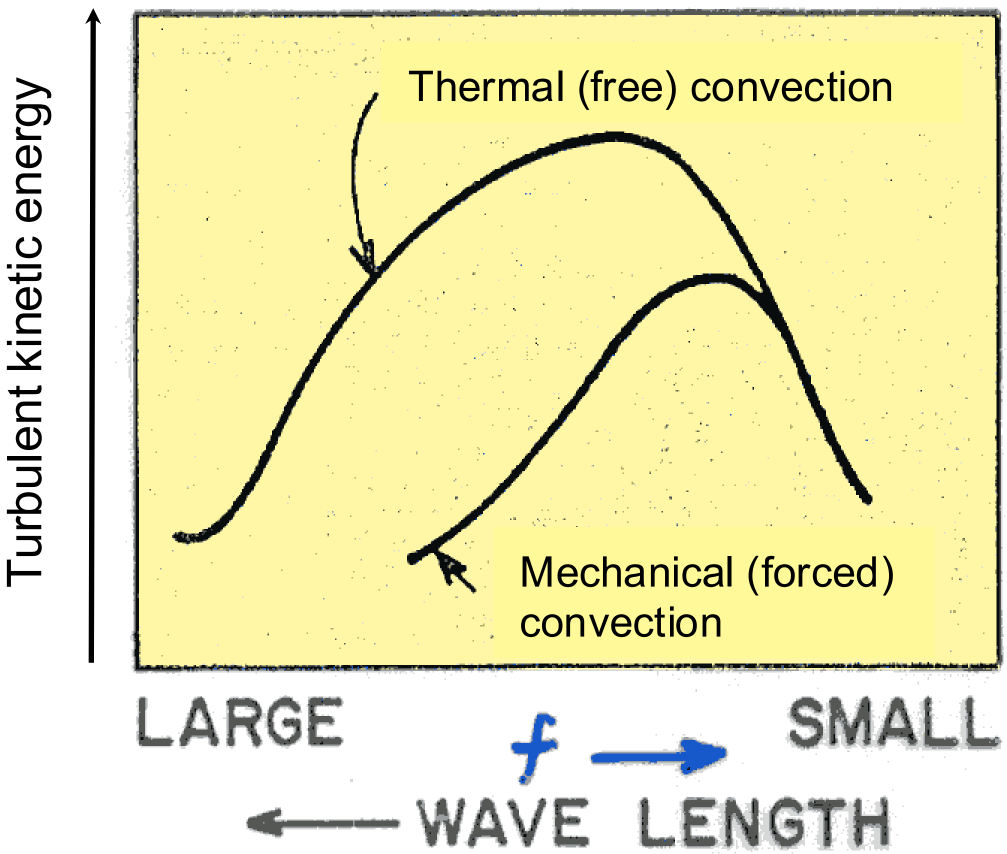
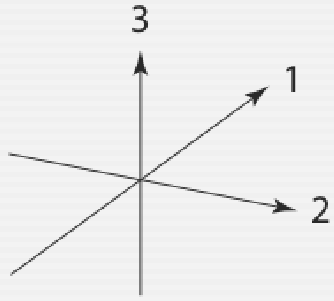
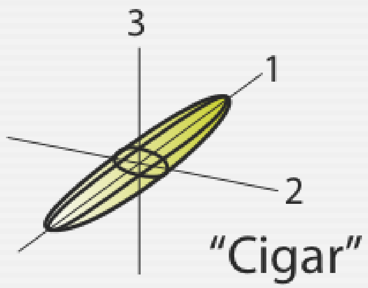


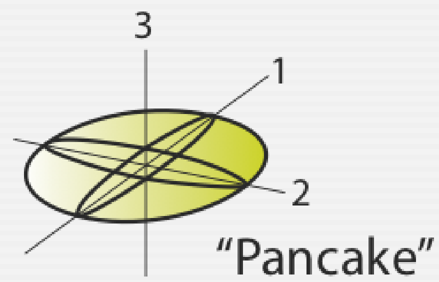
Directionality of turbulent motions



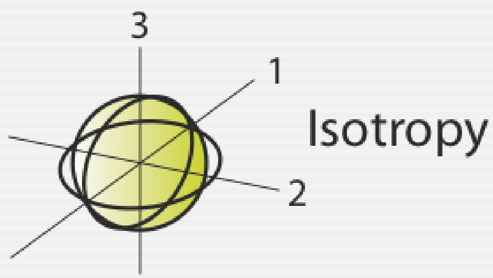
Turbulent energy in different directions



$e_1 >> e_2 = e_3$



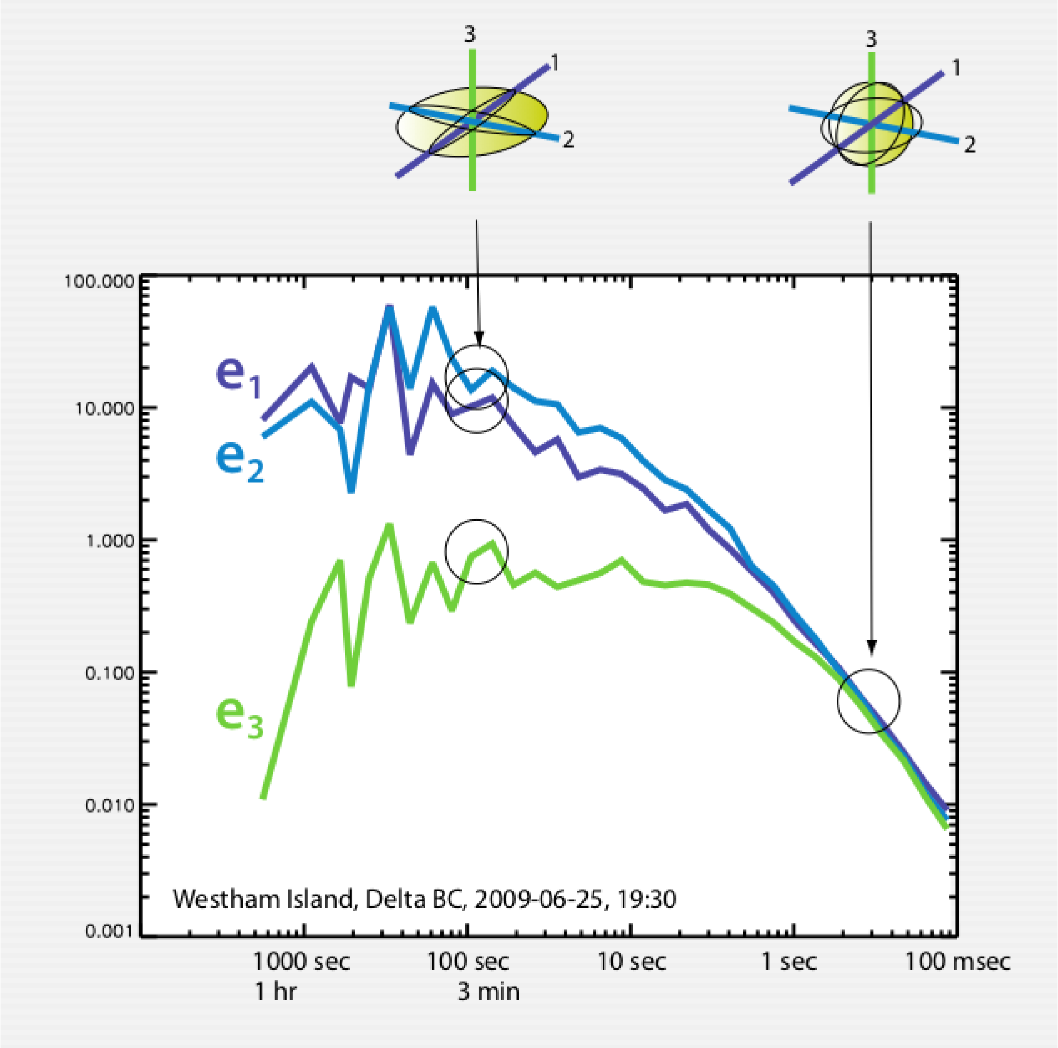
$e_1 = e_2 >> e_3$



$e_1 = e_2 = e_3$

Kolmogorov’s theory of local isotropy

The initial eddies, created at the integral length scale ℓ are likely directional, but after many break-downs into smaller ones they have the tendency **to return to isotopy**. Energy contained in one axis is transferred into other axes.



Take home points

- Eddies produced mechanically and thermally at larger scales (integral length scale ℓ) break into smaller and smaller ones creating a steady-state **energy cascade** of eddy sizes.
- The integral length scale ℓ is controlled by the **height above ground** and turbulence production mechanisms.
- At small scales - the **Kolmogorov microscale** η - eddies become stable again and energy is eventually dissipated to heat.
- The size (duration) of eddies can be graphed using an energy **spectrum.** A spectrum sorts the energy contained in turbulence according to duration (or length) of eddies.