23 Dynamic stability

Learning objectives

- Explain the difference between static stability vs. dynamic stability in the ABL.
- Explain how we can we quantify dynamic stability in the ABL.
- Understand the implications on eddy size and shape.

Photo: A. Christen

Static stability

You learned about static stability in the prerequestits.

You compared the **environmental lapse rate** (ELR) to the **process lapse rate** (e.g. the dry adiabatic lapse rate Γ_d):

unstable $\Gamma_d <$ ELR

neutral $\Gamma_d =$ ELR

stable $\Gamma_d >$ ELR

Static stability allows us for example to determine the mixing of warm exhaust from a power plant
Photo: A. Christen

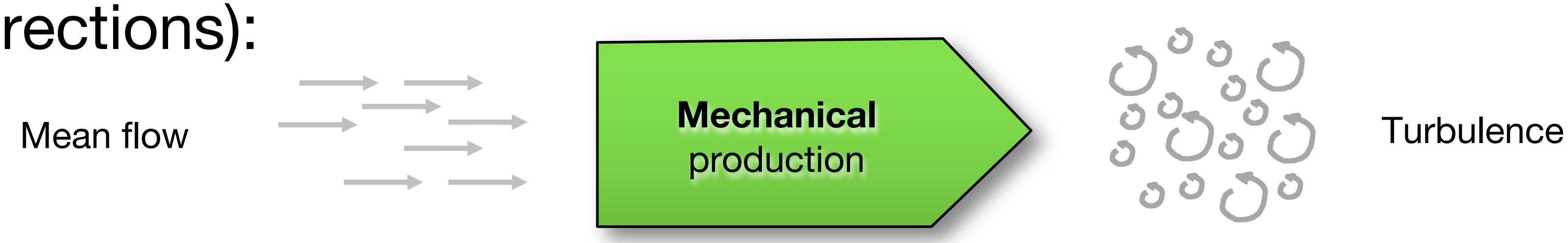
Richardson’s stability criterion

The simple classification of **static stability** using the temperature profile omits dynamic aspects (i.e. shear, buoyancy) that cause actual mixing. It only speaks to the potential ability to mix air vertically, not the actual mixing.

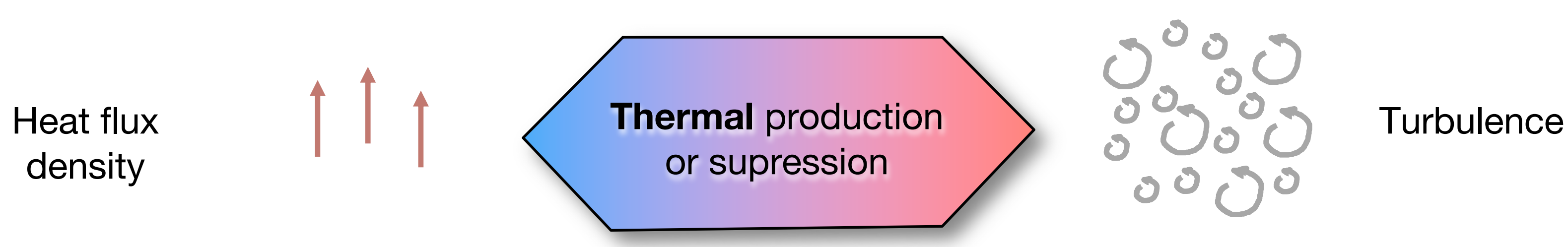
In 1920, Lewis Fry **Richardson** devised a scheme which **combined mechanical and thermal production of turbulence**, because both forms of turbulence are key for understanding the degree of mixing in a convective flow.

Review - mechanical and thermal production

Mechanical production is the process when turbulence is produced by work extracted from mean wind by shear (skin drag, form drag, drag between layers flowing in different directions):

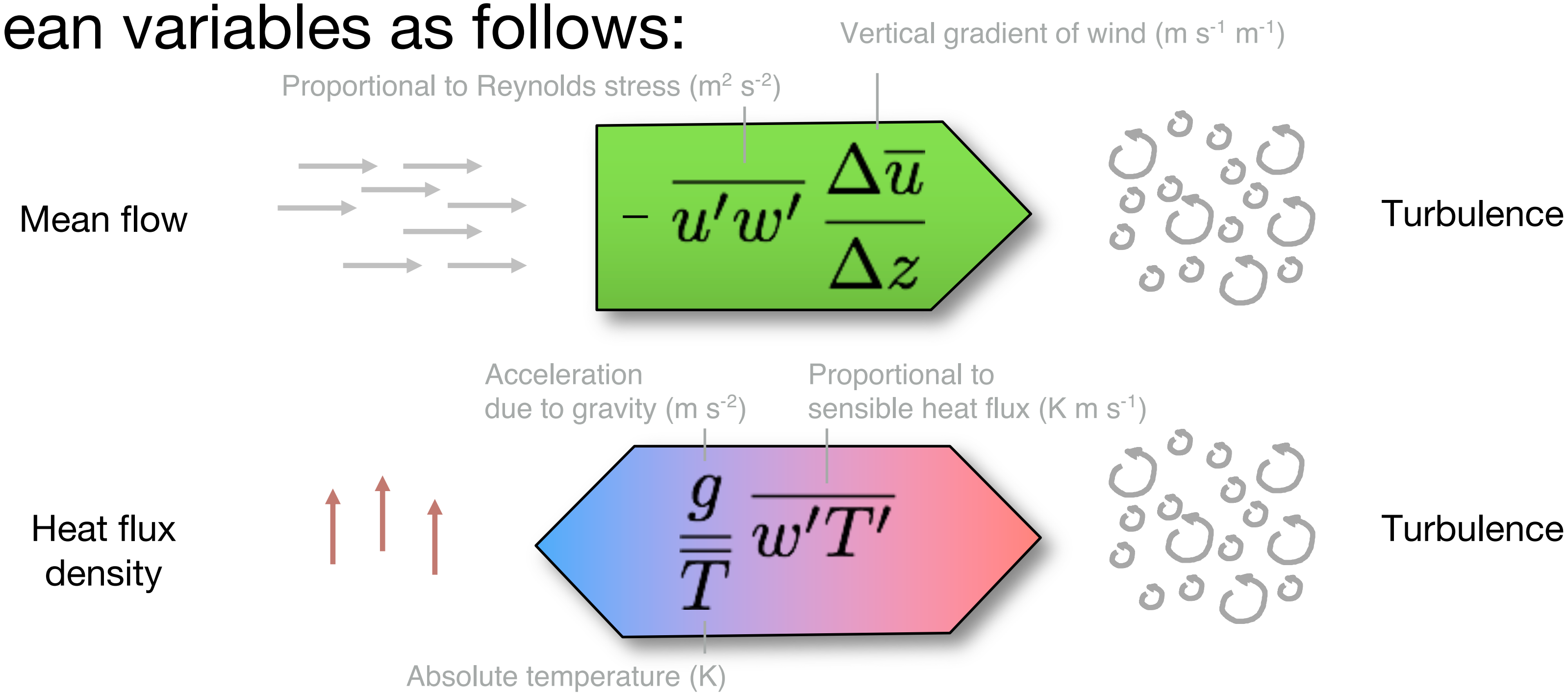


Thermal production (or **suppression**) is the process when turbulence is produced (inhibited) due to heating (cooling) by a sensible heat flux:



Mechanical and thermal production

Mechanical production and **thermal production** (**suppression**) can be expressed in discrete form of fluxes and gradients of mean variables as follows:



Extra info: Here we use the absolute temperature T (in K), assuming the air is dry, but strictly for moist air we need to use the virtual temperature T_v (see Stull, ‘Practical Meteorology’, 2015). The difference between T_v and T for the purpose of this course is small.

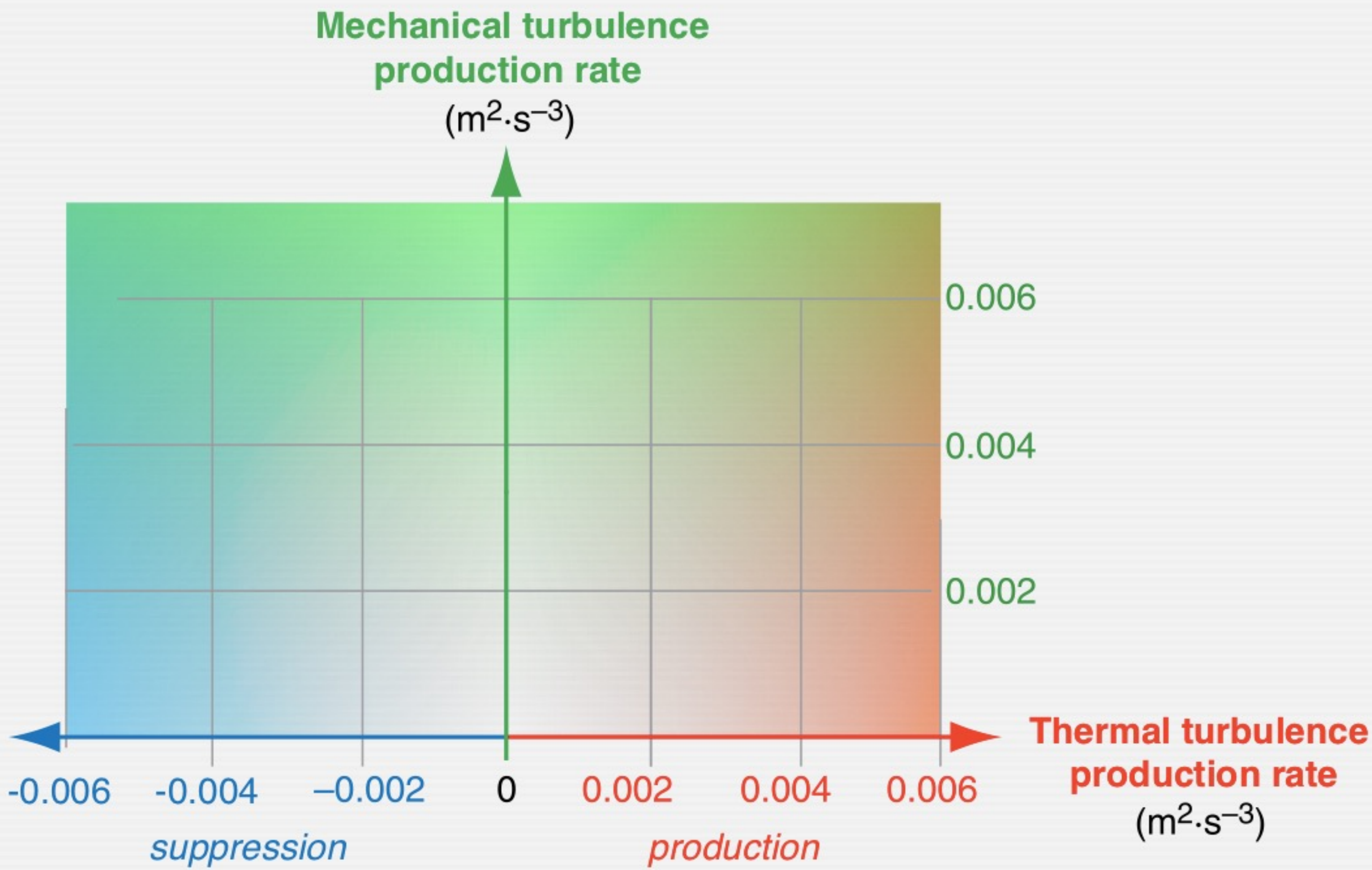
Thermal production and suppression

Mechanical production can be only zero or positive - wind increases with height is linked to momentum transfer in opposite direction.

Thermal production can be zero, positive or negative.

A negative thermal production means turbulence **suppression**, in this case the sensible heat flux cools the atmosphere, increases density, and prevents vertical mixing.

Mechanical vs. thermal turbulence production



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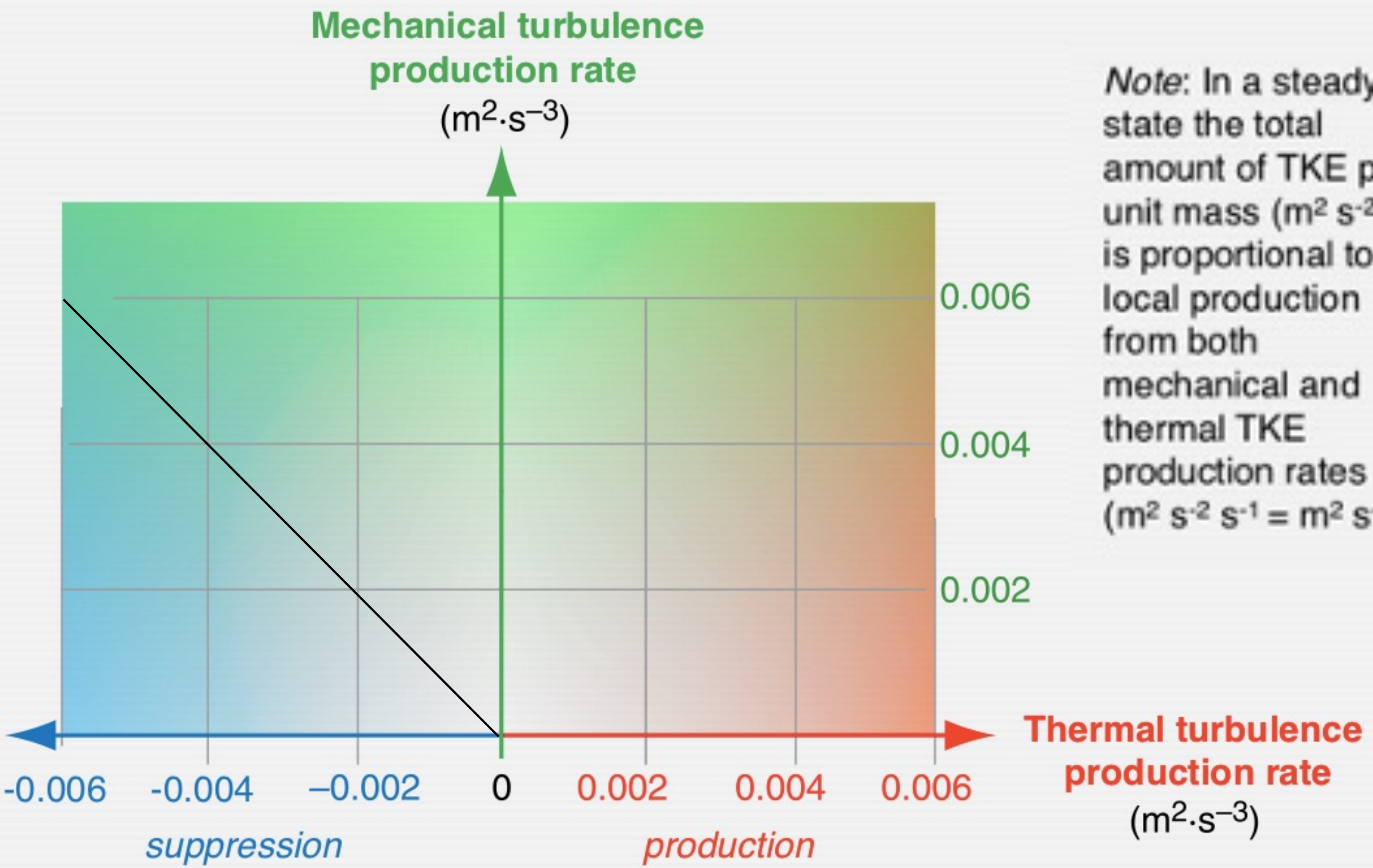
Turbulence vs. no turbulence?



Note: In a steady-state the total amount of TKE per unit mass ($m^2 s^{-2}$) is proportional to local production from both mechanical and thermal TKE production rates ($m^2 s^{-2} s^{-1} = m^2 s^{-3}$)

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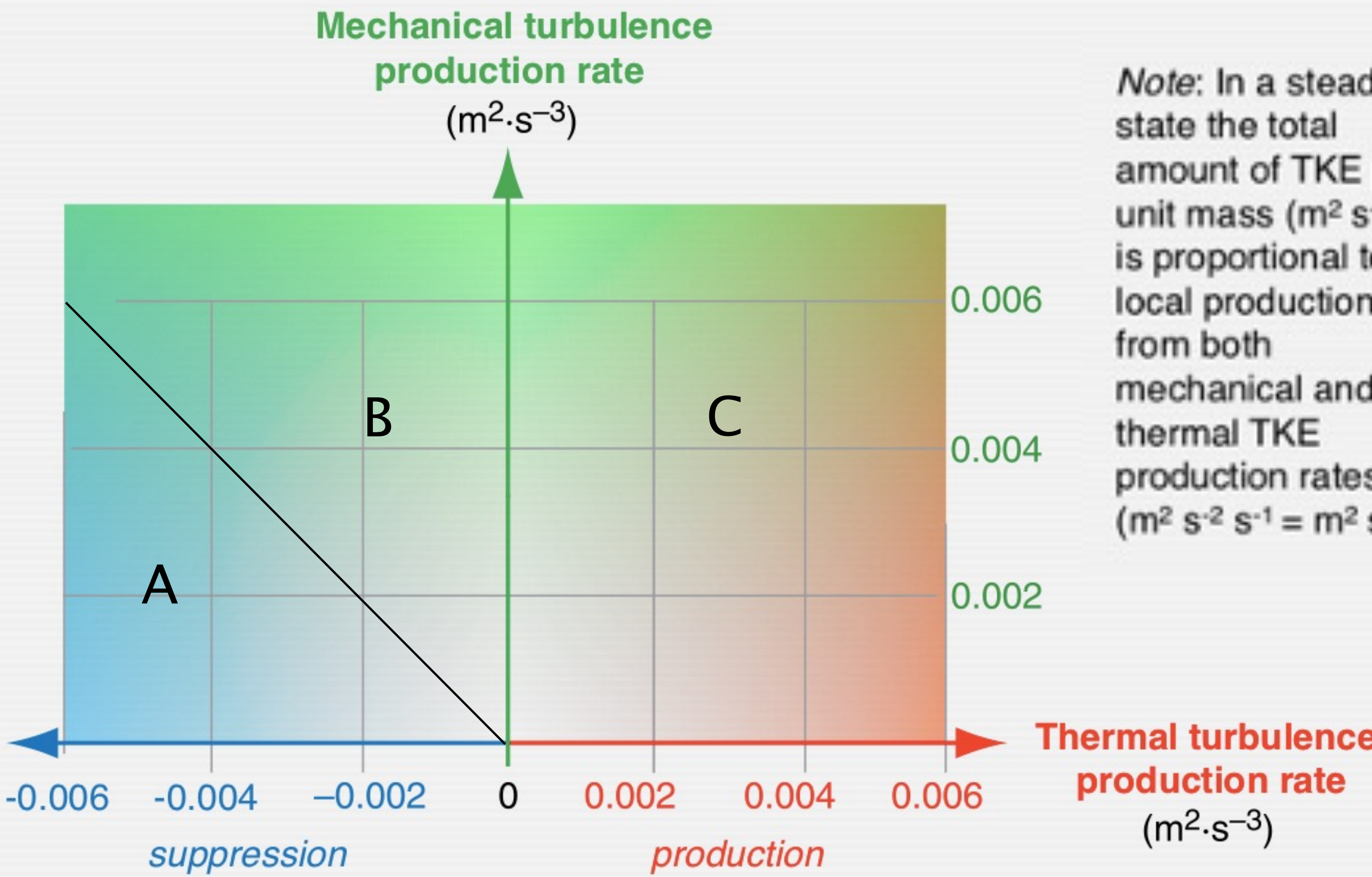
Where will we see no turbulence?



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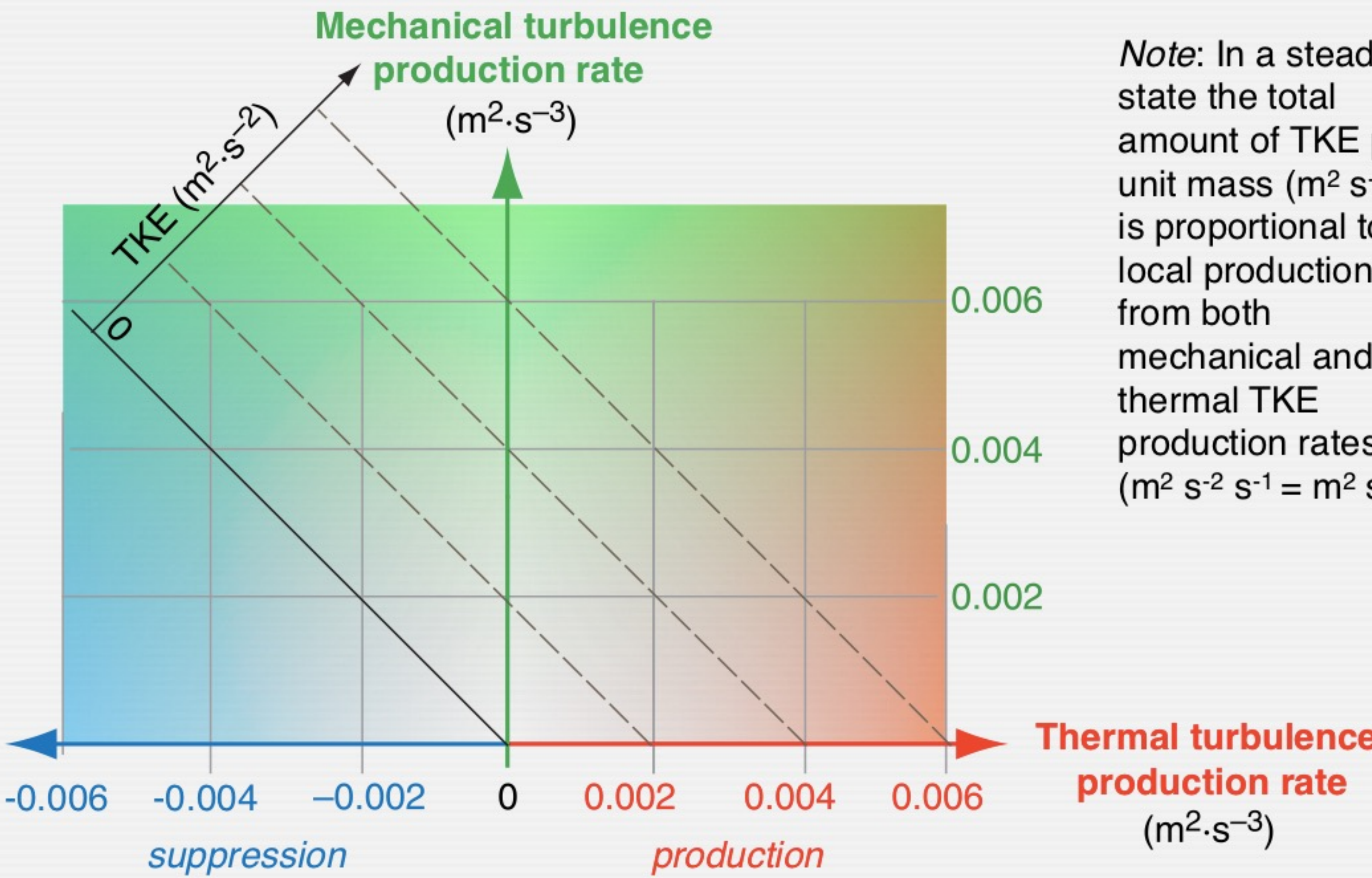
modified after Stull (2015)

Test your knowledge

What are the units of the terms for mechanical production rate and the thermal production rate of turbulence?

Mechanical vs. thermal turbulence production



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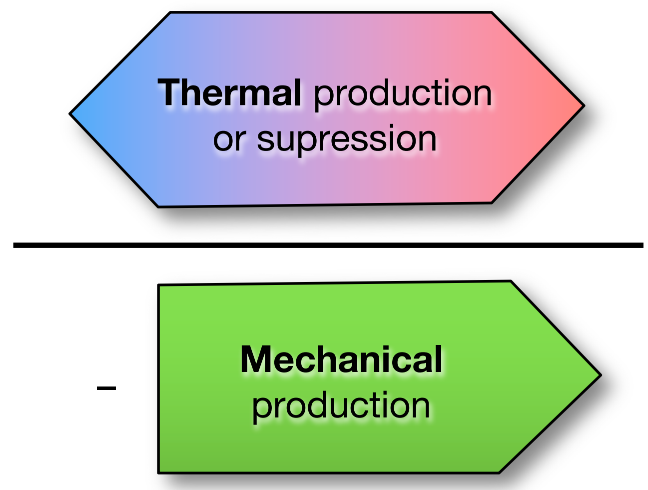
Flux Richardson Number (*Rf*)

Ratio of the two axes returns relative strength of thermal and mechanical production in a flow, expressed by the Flux Richardson number (Rf):

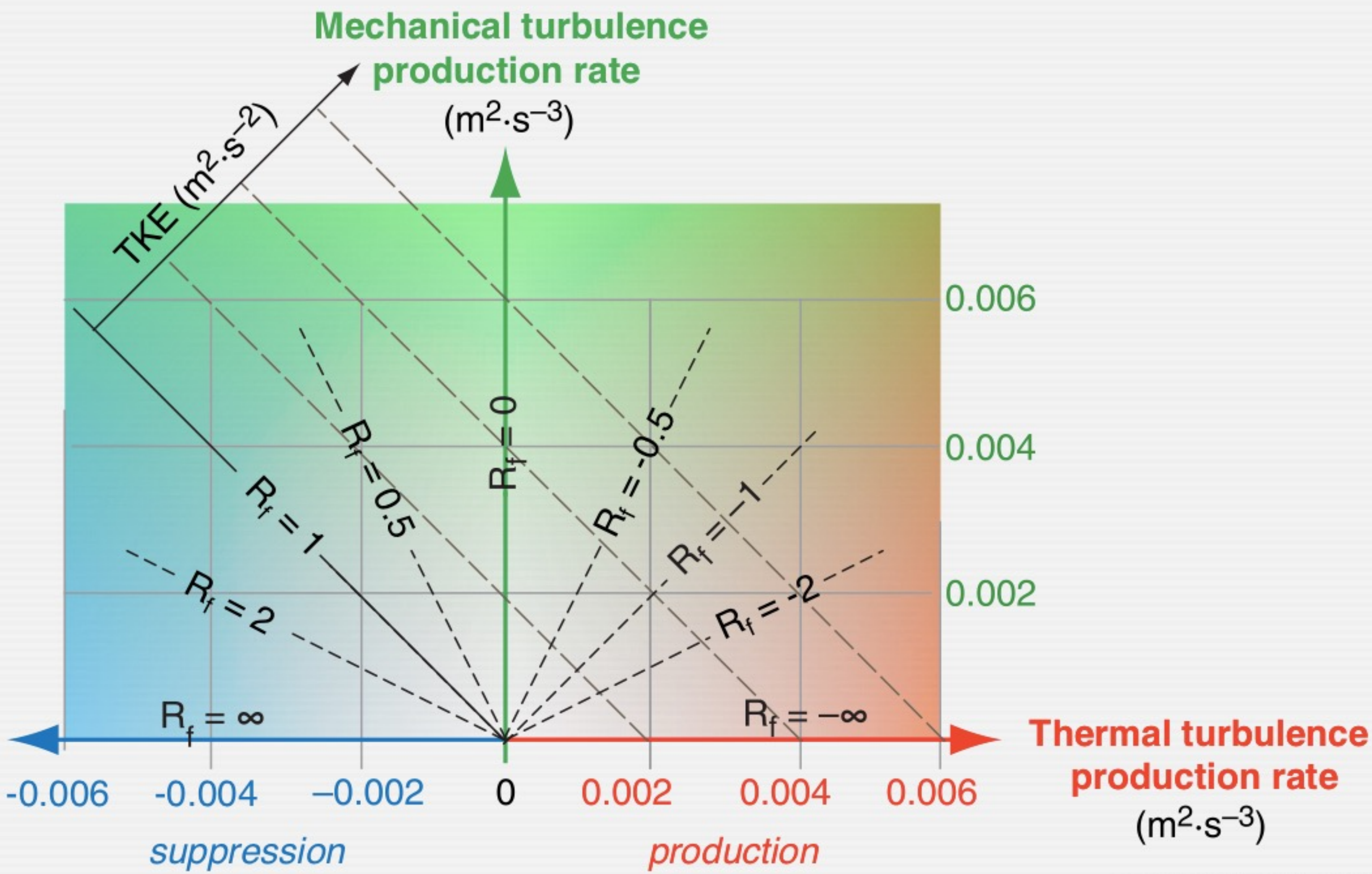
$$Rf = \frac{\frac{g}{\overline{T}}\,\overline{w'T'}}{\overline{u'w'}\,\frac{\Delta \overline{u}}{\Delta z}}$$



The Flux Richardson number (*Rf*) is a non-dimensional number saying which term (‘color') is the most dominant one

Rf > 0 : **stable** *Rf* ≈ 0 : **neutral** *Rf* < 0 : **unstable**

Flux Richardson Number (*Rf*)



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Gradient Richardson Number (*Ri*)

Second order moments (i.e. covariances) can be difficult to obtain, so assuming similarity, i.e. $K_M = K_H$, we get the Gradient Richardson number (*Ri*):

Thermal production or suppression

$$Ri = \frac{g}{\overline{T}} \frac{\Delta\overline{\theta}/\Delta z}{(\Delta\overline{u}/\Delta z)^2} \quad \star$$

Mechanical production

Note, $Rf = (K_H/K_M)\ Ri$

Dynamic stability regimes

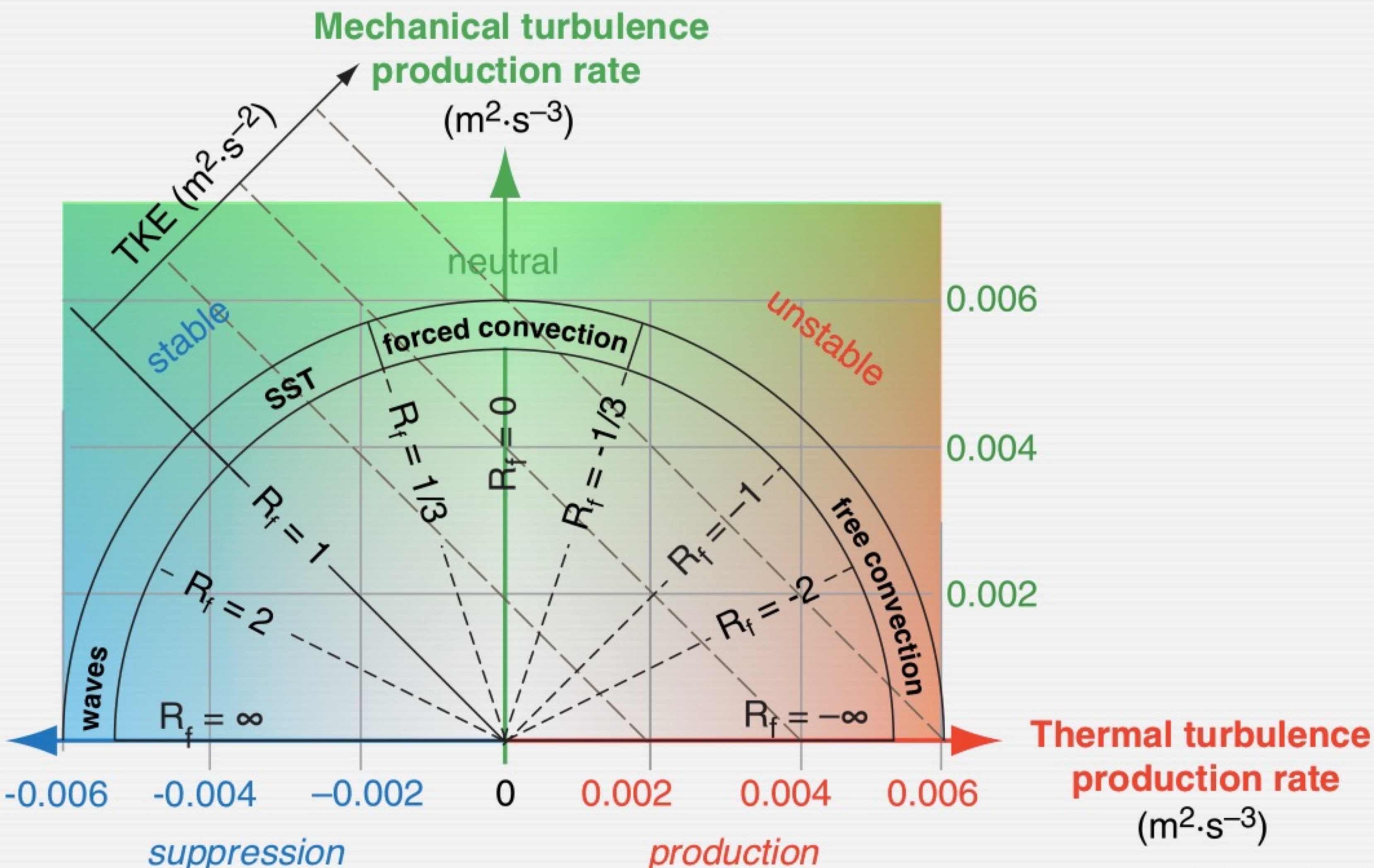
Both, the Flux Richardson number (*Rf*) and the gradient Richardson number (*Ri*) are non-dimensional number that indicate the relative ratio of processes in the production or suppression of turbulence:

$Ri, Rf > 0$: **stable** $Ri, Rf \approx 0$: **neutral** $Ri, Rf < 0$: **unstable**

Can be used to classify turbulence regimes:

Rf or Ri	Turbulence regime
Rf < -1/3	free convection
-1/3 < Rf < 1/3	forced convection
1/3 < Rf < 1	stably stratified turbulence (SST)
Rf > 1	no turbulence, only waves

Turbulence regimes in graph of production / suppression



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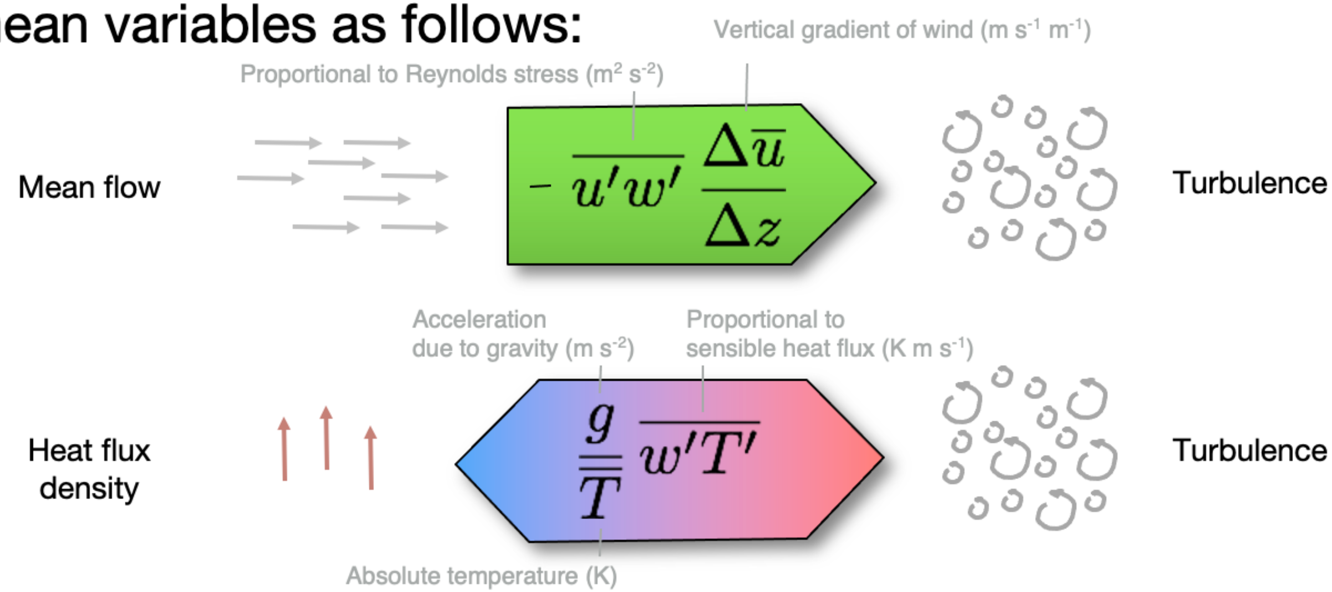
Test your knowledge

Given the following terms, calculate the mechanical, thermal, and total production rate of TKE per unit mass: $\overline{w'T'} = 0.30\,\mathrm{K\,m\,s^{-1}}$, $\overline{u'w'} = -0.52\,\mathrm{m^2\,s^{-2}}$, $\overline{T} = 304.1$ K (31°C) and a wind gradient of $\Delta\overline{u}/\Delta z = 0.07\,\mathrm{m\,s^{-1}\,m^{-1}}$.

Mechanical production and **thermal production** (**suppression**) can be expressed in discrete form of fluxes and gradients of mean variables as follows:



Test your knowledge

What is the Richardson flux number (Rf) in this situation?

$$Rf = \frac{\frac{g}{T}\overline{w'T'}}{\overline{u'w'}\frac{\Delta \overline{u}}{\Delta z}}$$

TopHat question

What is the turbulence regime in this situation?

TopHat question

What is the turbulence regime in this situation?

What is the dynamic stability (stable, neutral, unstable)?

Monin-Obukhov Similarity Theory (MOST)

Ri has the disadvantage that it is a function of *z* in the surface layer (SL). So we might be interested in another stability parameter which is not. Indeed, using dimensional analysis we can derive a global dimensionless stability parameter ζ (a greek ‘zeta’) for the SL:

$$\zeta = z/L$$

where *L* is the **Obukhov-Length**

Specific heat of air (J kg^{-1} K^{-1})

Air density (kg m^{-3})

Absolute temperature (K)

$$L = -\frac{T\,u_*^3}{k\,g\,\overline{w'T'}} = -\frac{\rho\,c_p\,T\,u_*^3}{k\,g\,Q_H}$$

Friction velocity (m s^{-1})

Sensible heat flux (W m^{-2})

$\overline{w'T'}$

von Karman constant

Accelleration due to gravity (m s^{-2})

Because both friction velocity u_* and sensible heat flux Q_H are roughly constant with height in the SL, *L* is therefore invariant with height.

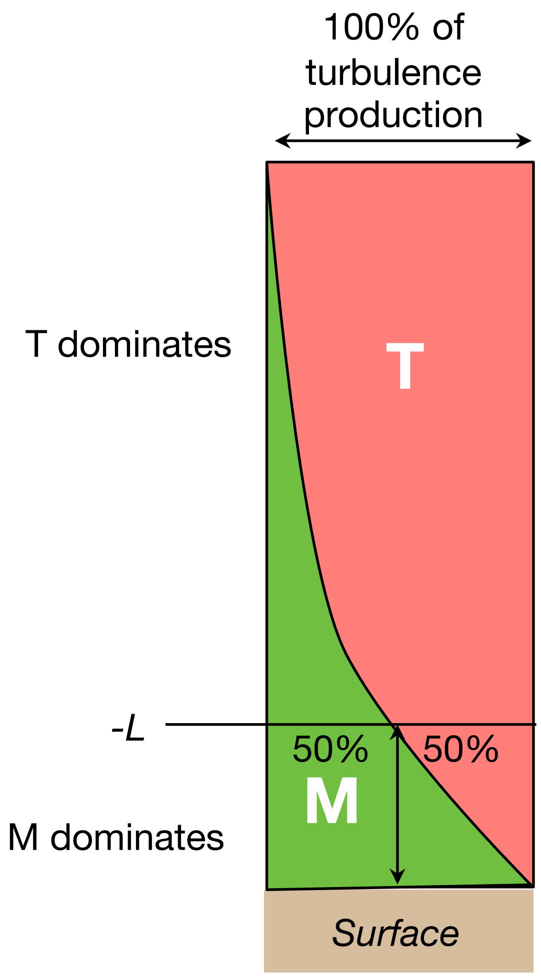
Interpretation of the Obukhov-Length

Very close to the surface, **mechanical production** (**M**) dominates. In the upper SL typically **thermal production** dominates (**T**) because wind shear ($\Delta\bar{u}/\Delta z$) decreases more rapidly with height than the sensible heat flux ($\overline{w'T'}$).

So there must be a **height where M = T**.

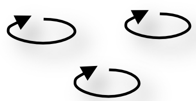
L can be physically interpreted as the (minus) height above ground where the mechanical and thermal production are equal, in non-neutral conditions.

The sign of *L* is given by that of Q_H and it is related to *Ri*



Summary of stability parameters used in the ABL.

weak or no mean wind



strong cooling

surface cooler than air

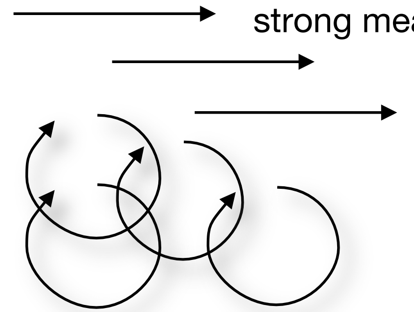
R_f, $R_i > 0$

$L > 0$

$z/L > 0$

stable

strong mean wind



surface indifferent

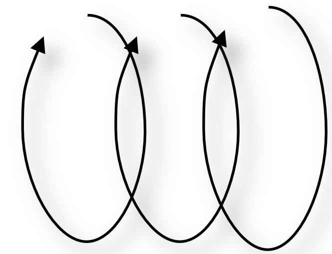
R_f, $R_i = 0$

$L = \infty$

$z/L = 0$

neutral

weak or no mean wind



strong heating

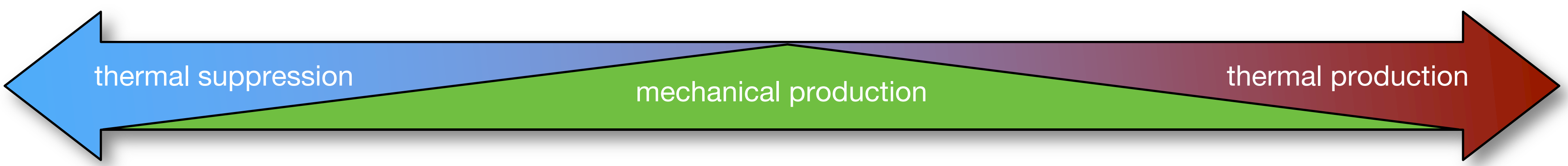
surface warmer than air

R_f, $R_i < 0$

$L < 0$

$z/L < 0$

unstable



Effect on eddy size

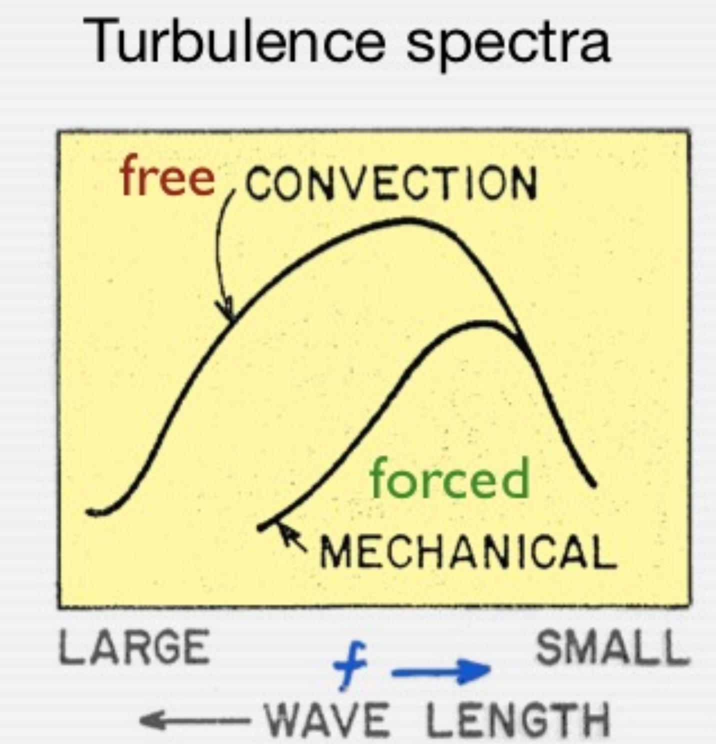
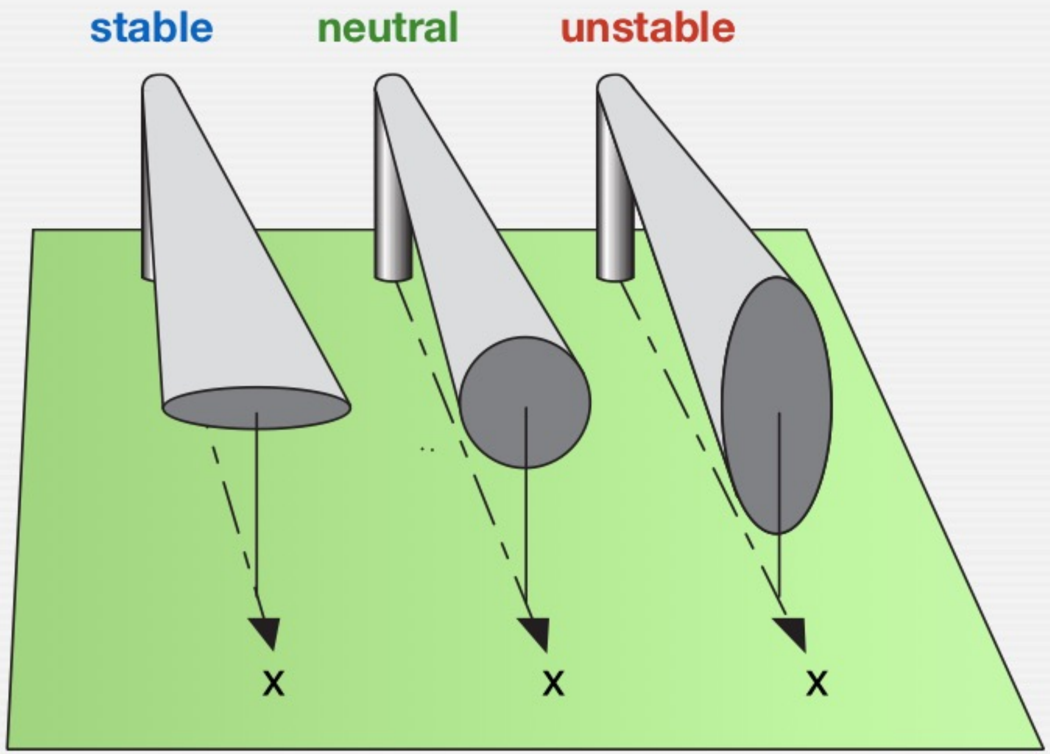


Figure 4. Effect of adding heat convection on spectrum of wind direction.

Effects on eddy-shape



Isotropy:	anisotropic	isotropic	anisotropic
Behavior:	fanning	coning	looping
Std Deviations:	$\sigma_z < \sigma_y$	$\sigma_z = \sigma_y$	$\sigma_z > \sigma_y$
	$\sigma_w < \sigma_v$	$\sigma_w = \sigma_v$	$\sigma_w > \sigma_v$

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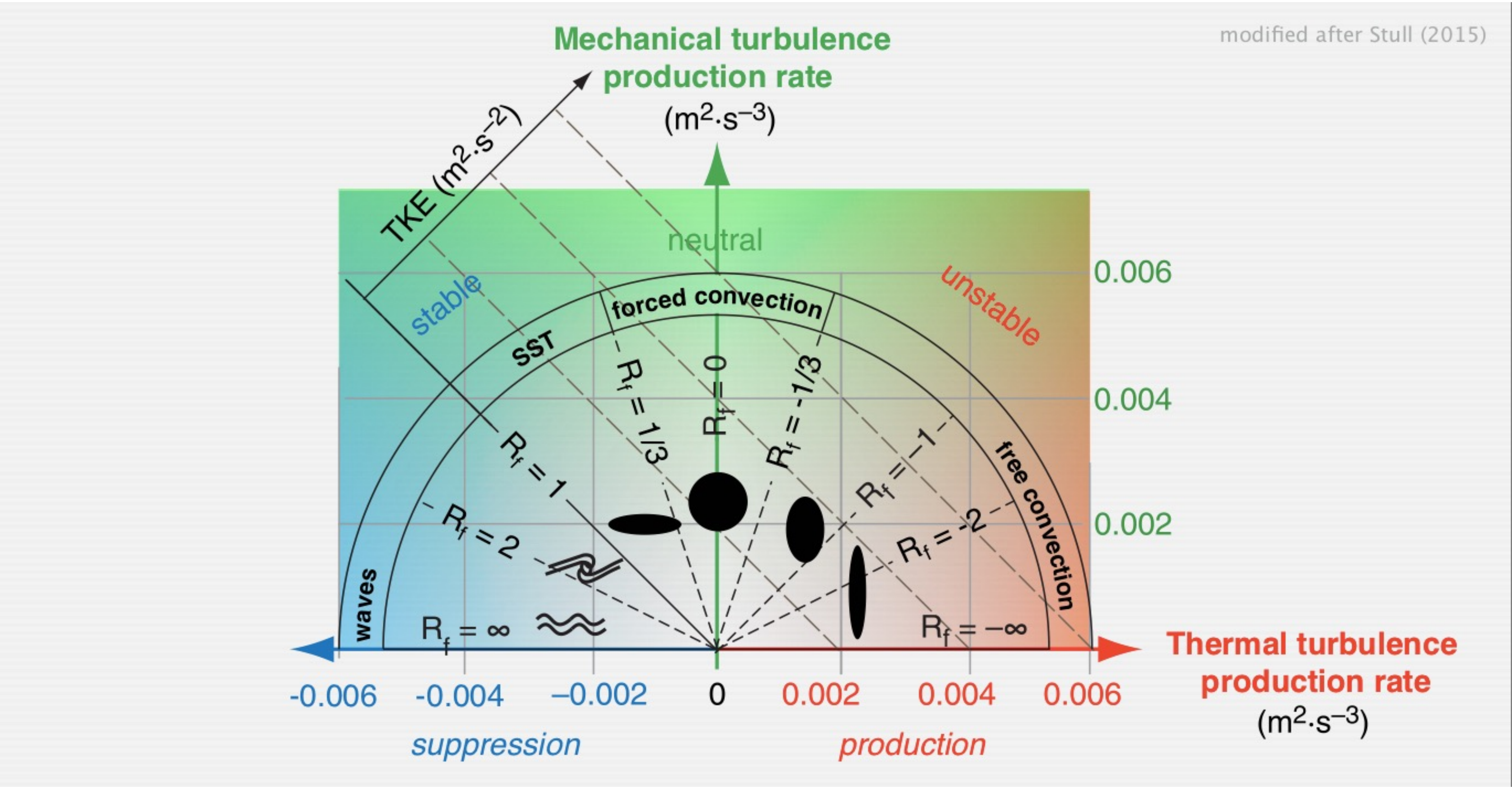
Eddy-shape under non-neutral situations



Take home points

- Dynamic stability parameters describe **ratio of thermal turbulence** production to (minus) **mechanical turbulence** production.
- Dimensionless flux and gradient **Richardson numbers** are commonly used to describe the atmosphere's dynamic stability and the turbulence regime.
- Monin-Okukhov similarity theory (**MOST**) is using four variables controlling turbulence, u_*, $\overline{w'T'}$, g and T and derives a stability length L (called the **Obukhov length**)
- Dynamic stability controls the **eddy spectrum** and **eddy shape**.