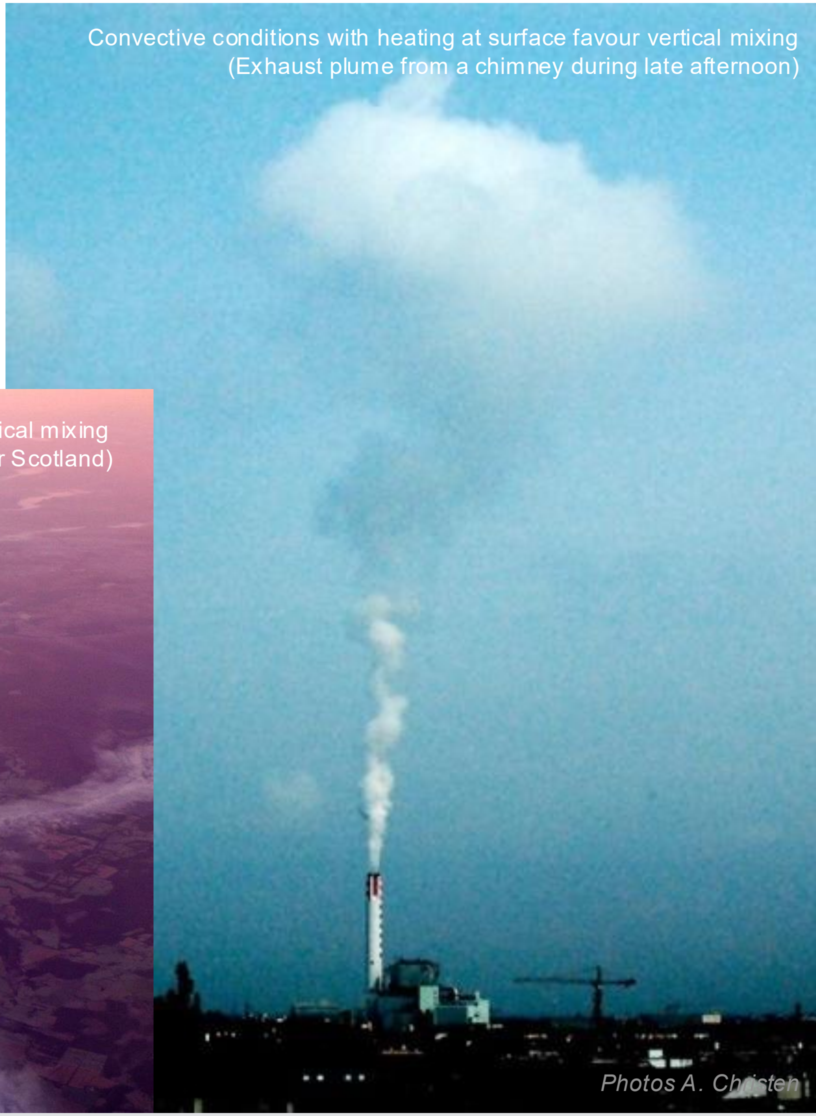
Air pollution over Los Angeles (Photo: A. Christen)

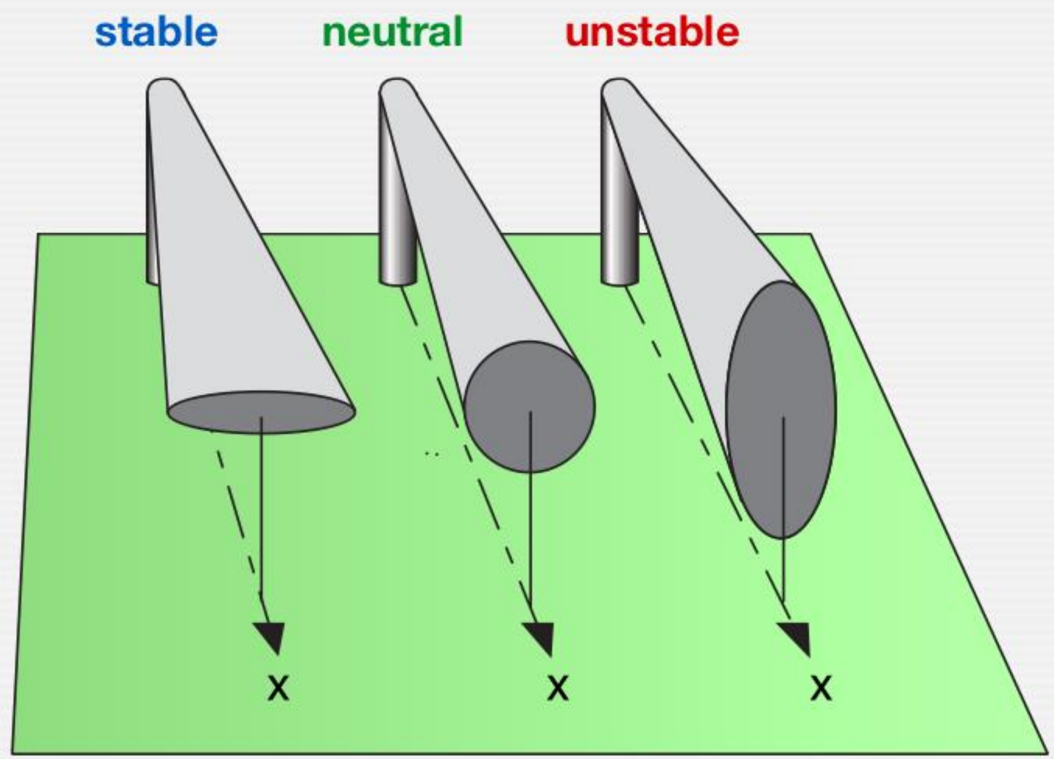
24 Turbulent exchange in non-neutral conditions

Today's learning objectives

- Describe how are eddies modified by stability.
- Understand how we expand the wind profile beyond just neutral conditions.



Effects on eddy-shape

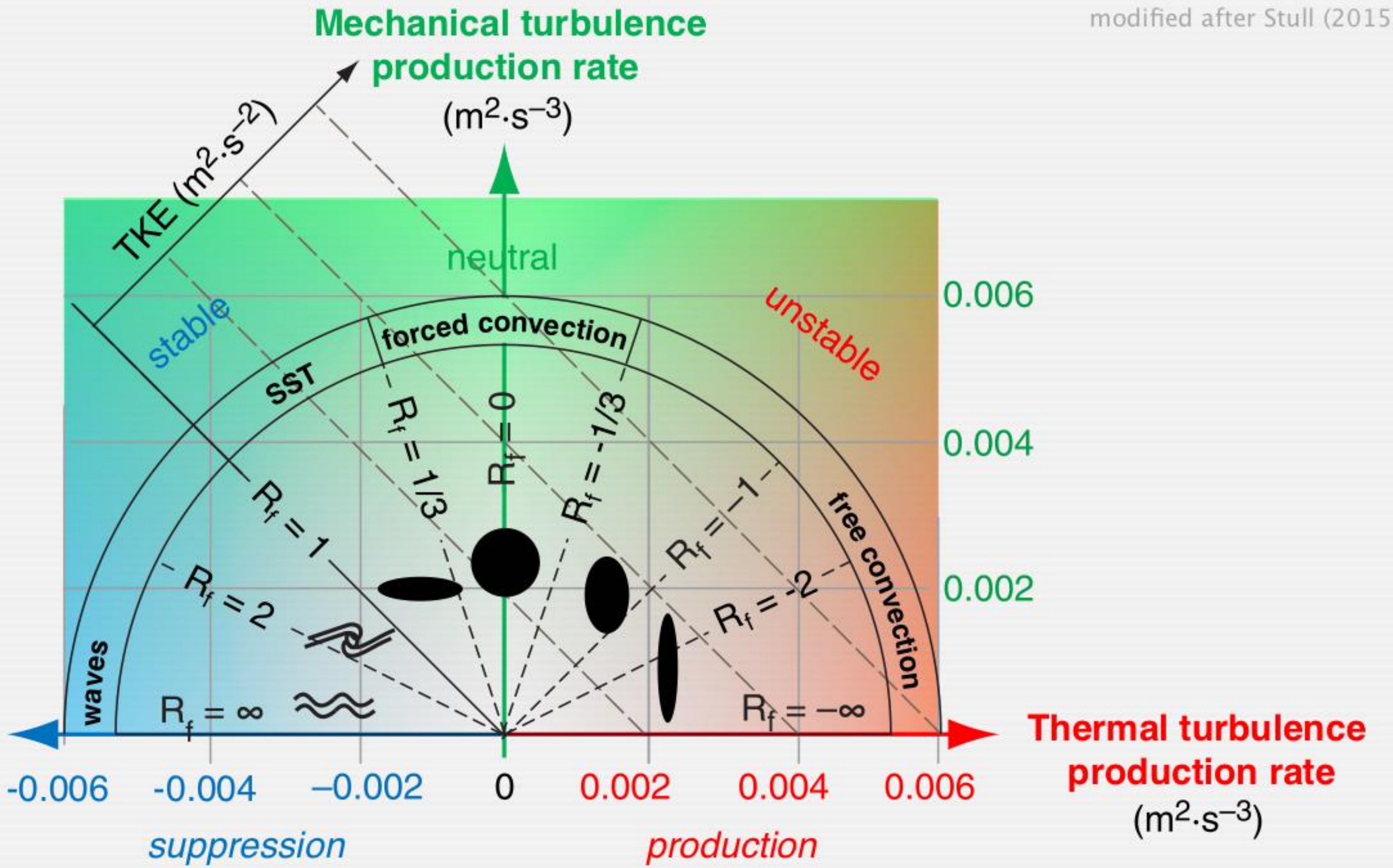


Isotropy:	anisotropic	isotropic	anisotropic
Behavior:	fanning	coning	looping
Std Deviations:	$\sigma_z < \sigma_y$	$\sigma_z = \sigma_y$	$\sigma_z > \sigma_y$
	$\sigma_w < \sigma_v$	$\sigma_w = \sigma_v$	$\sigma_w > \sigma_v$

modified after Stull (2015)

Eddy-shape under non-neutral situations

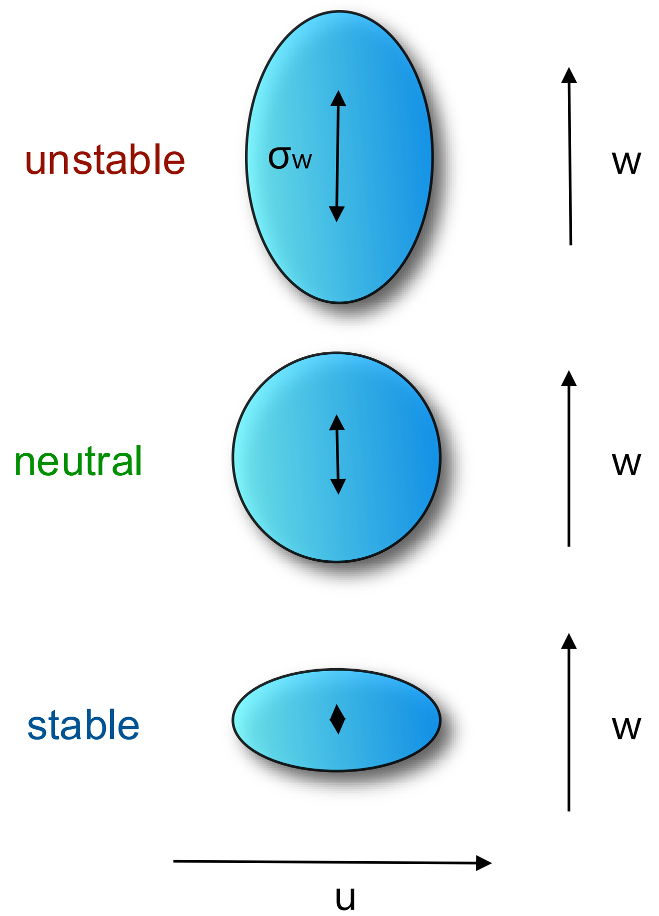
modified after Stull (2015)



Stability effects on profiles and fluxes.

In the neutral case we envisaged eddies as spherical (diameter given by mixing length, $\ell = k\,z$) and rotating and tangential velocity:

$$w' = u' = u_* = \ell \frac{\Delta \overline{u}}{\Delta z}$$ (from Topic 20)



Buoyancy can enhance or diminish vertical motion, so

$$w' = u' \pm \text{effects of buoyancy}$$

Where still $u' = \ell(\Delta\overline{u}/\Delta z)$ but now

$$\ell > \text{ or } < k\,z$$

Making use of the similarity theory - example of σ_w

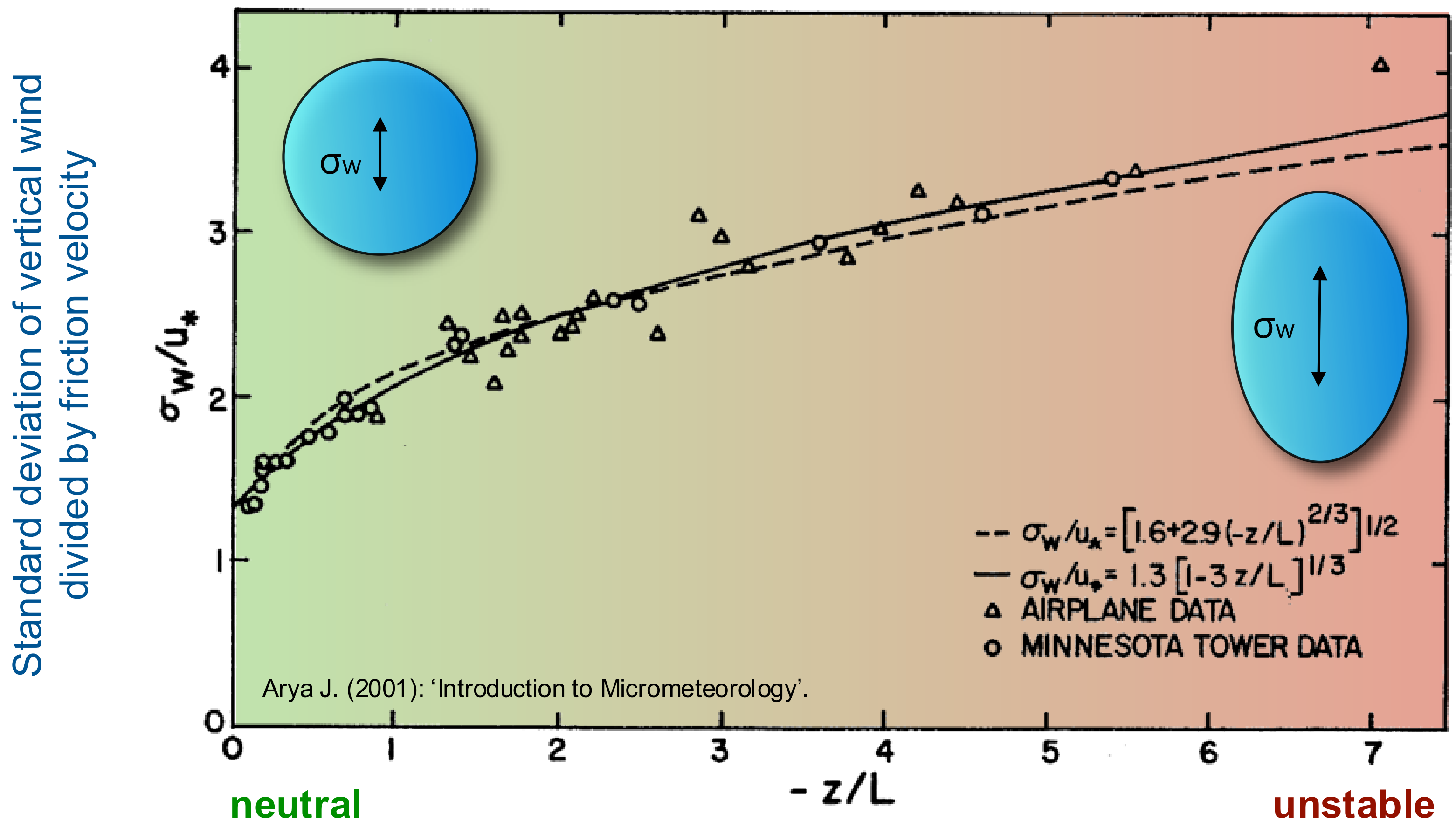
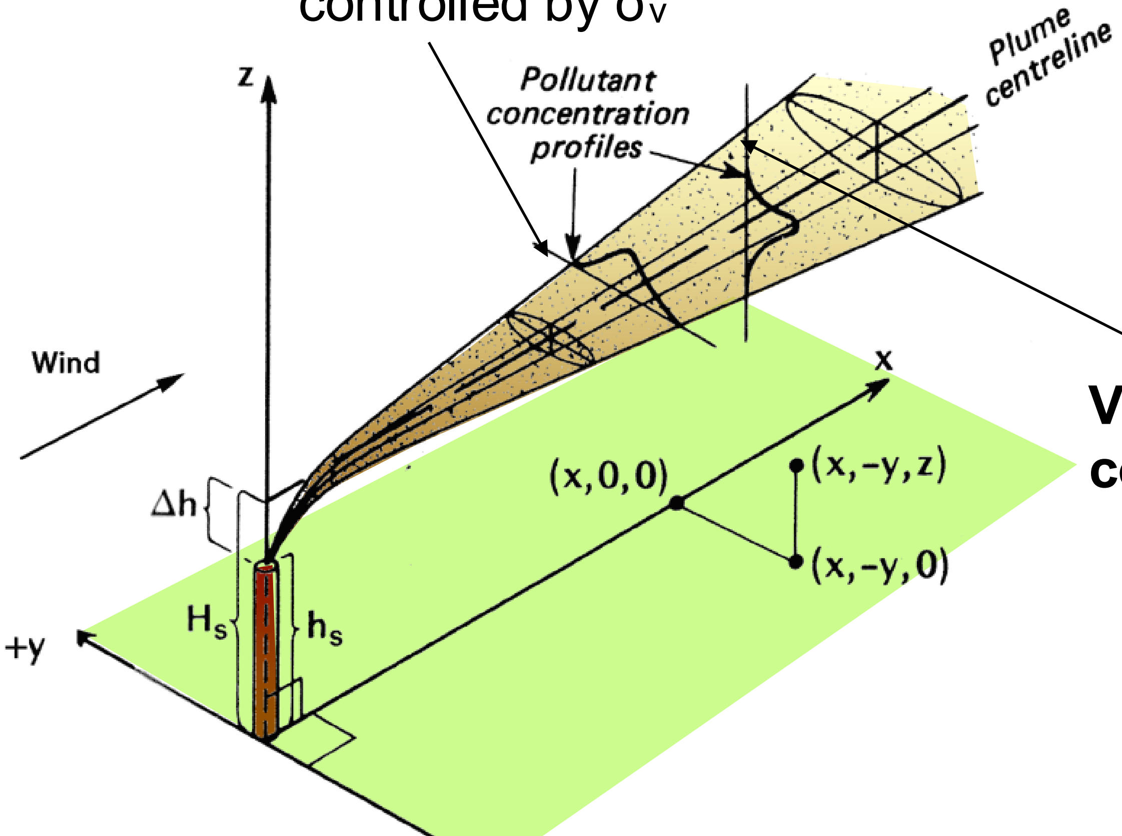


Figure 11.10 Normalized standard deviation of vertical velocity fluctuations in the surface layer as a function of z/L. [After Panofsky *et al.* (1977).]

Why is σ_w/u_* of importance?

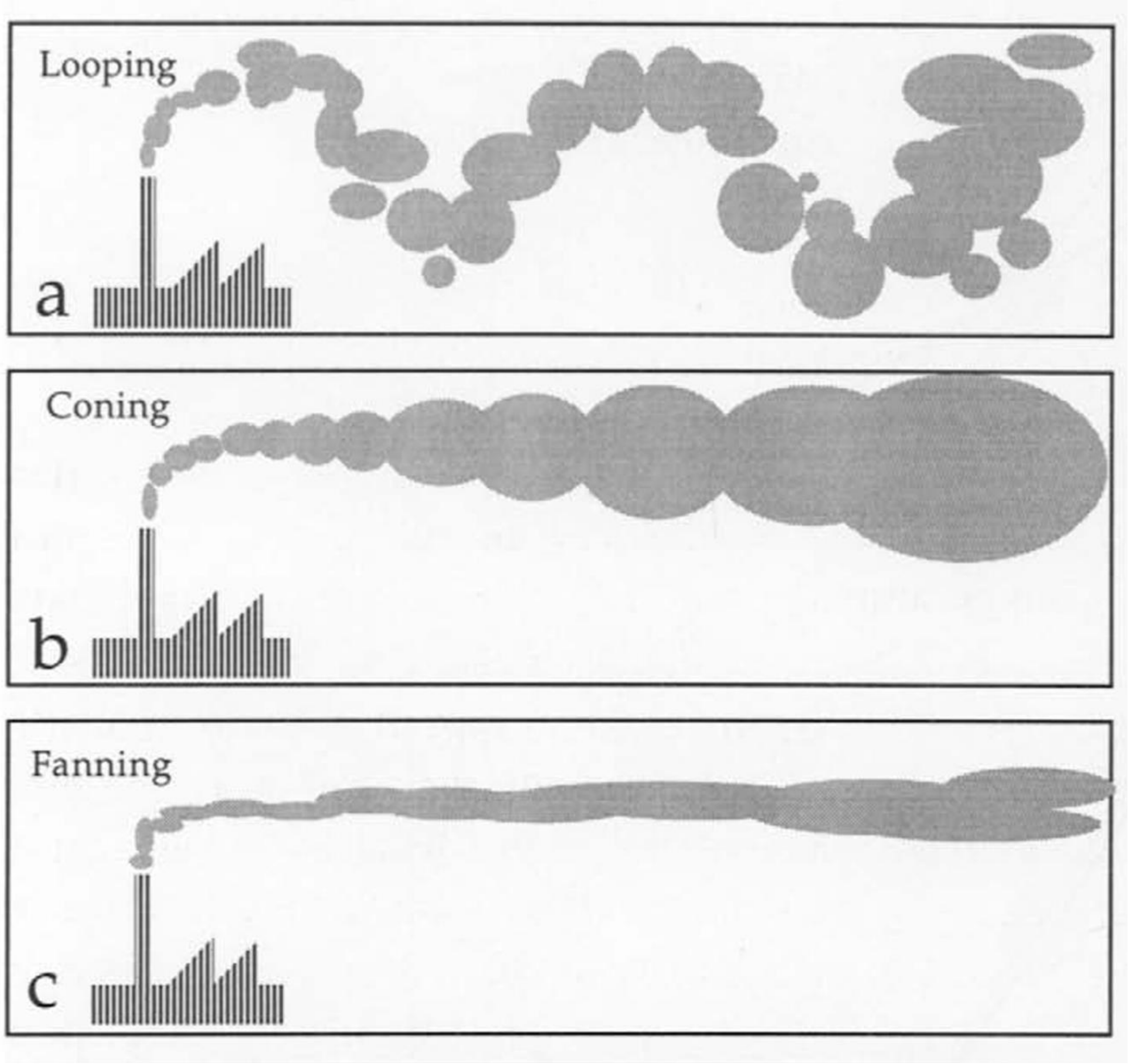
lateral mixing controlled by σ_v



(after Turner, 1969).

Vertical mixing controlled by σ_w

Impacts on air quality



unstable

neutral

stable

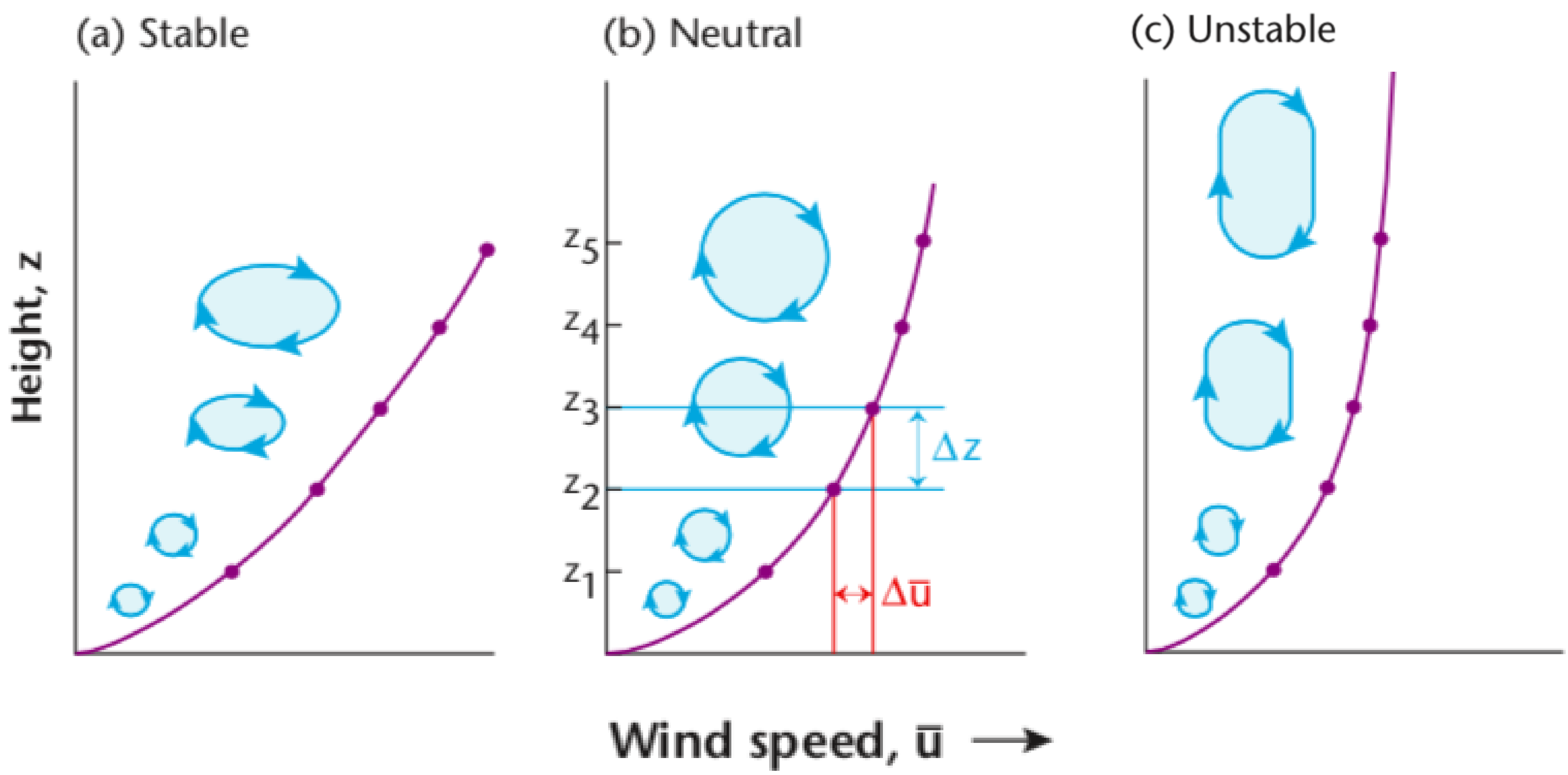
Monin-Obukhov Similarity Theory (MOST)

For many situations in the atmospheric boundary layer (ABL), our understanding of the governing physics is insufficient to predict statistics from first principles.

However, field studies show repeating ‘patterns’ that suggest that we might find **empirical relationships** between various variables in the ABL.

The dimensionless stability parameters (*Ri, Rf, z/L*) derived in topic 23 have been shown to be useful to predict a number of statistics.

Modification of the wind profile with changing stability

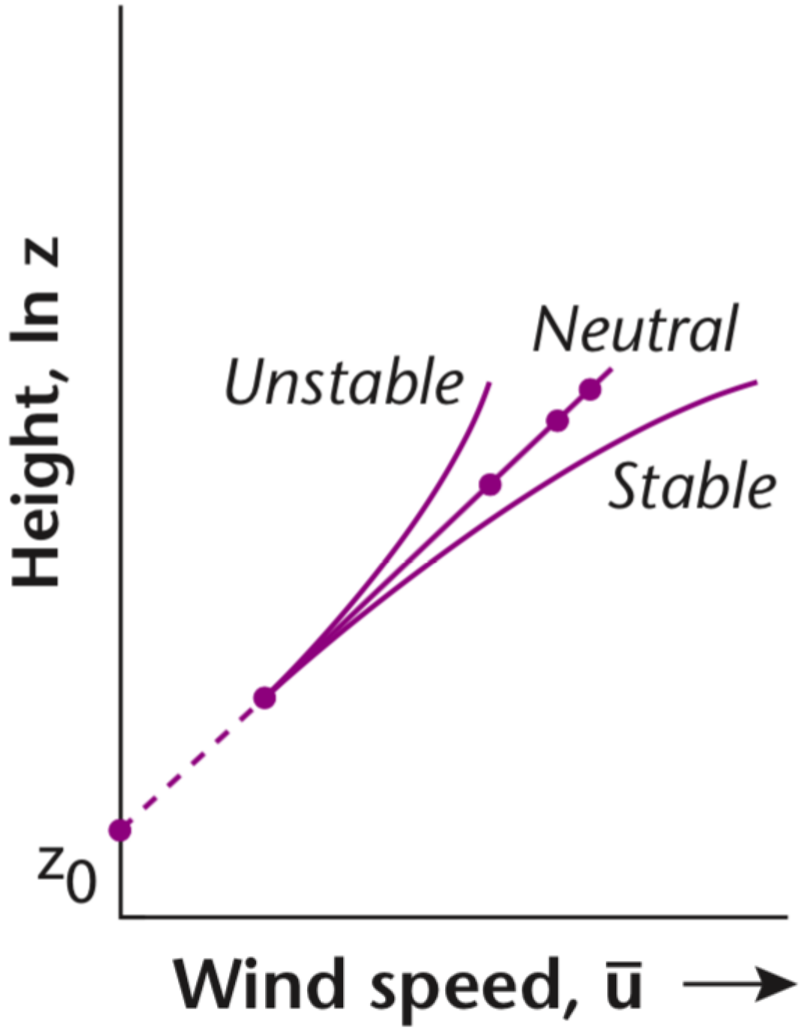


Stability effects on wind profile

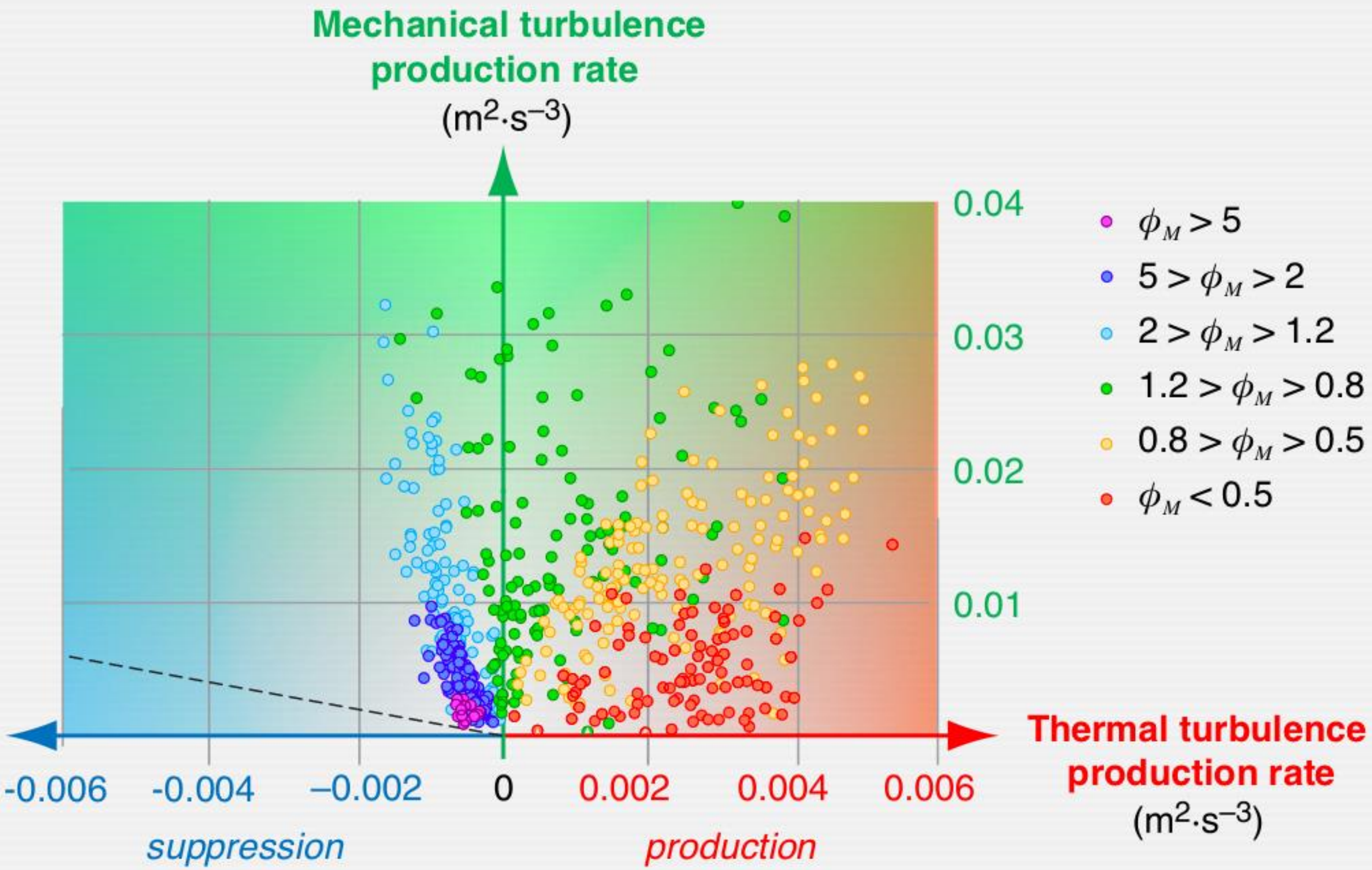
We seek a way of 'correcting' the neutral form of the wind profile to include non-neutral (**diabatic**) situations:

$$\frac{\Delta \overline{u}}{\Delta z} = \frac{u_*}{k\, z} \phi_M$$

The stability function ϕ_M is
$\phi_M = 1$ in the **neutral** case
$\phi_M > 1$ in **stable** case
$\phi_M < 1$ in the **unstable** case



Correction factors depend on turbulence regime



Correction function - Φ_M

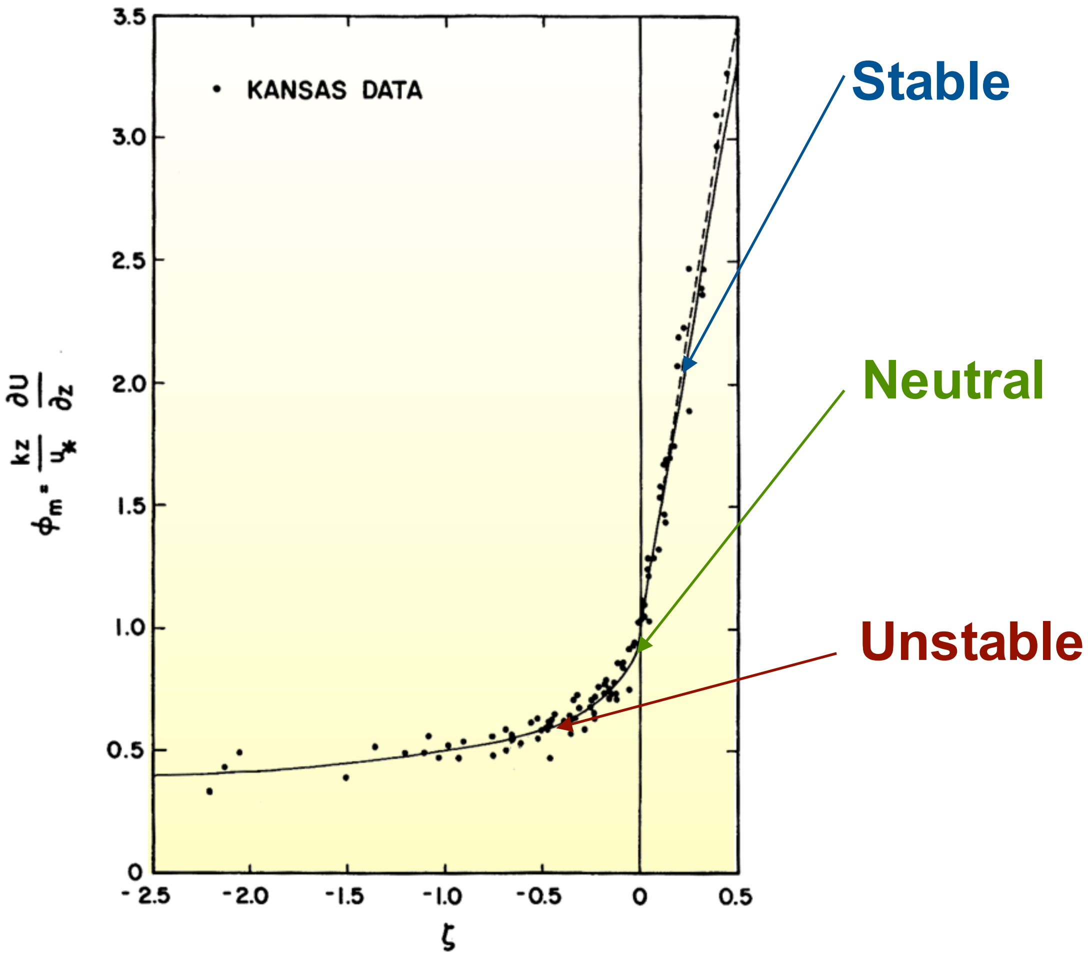


Figure 11.2 Dimensionless wind shear as a function of the M–O stability parameters. [Kansas data from Izumi (1971).]

Businger-Dyer flux-gradient relationship for momentum

$$\phi_M = \frac{k\,z}{u_*}\frac{\Delta\overline{u}}{\Delta z}$$

Stable ($\zeta > 0$, $Ri > 0$)

$$\phi_M = 1 + 4.7\zeta$$

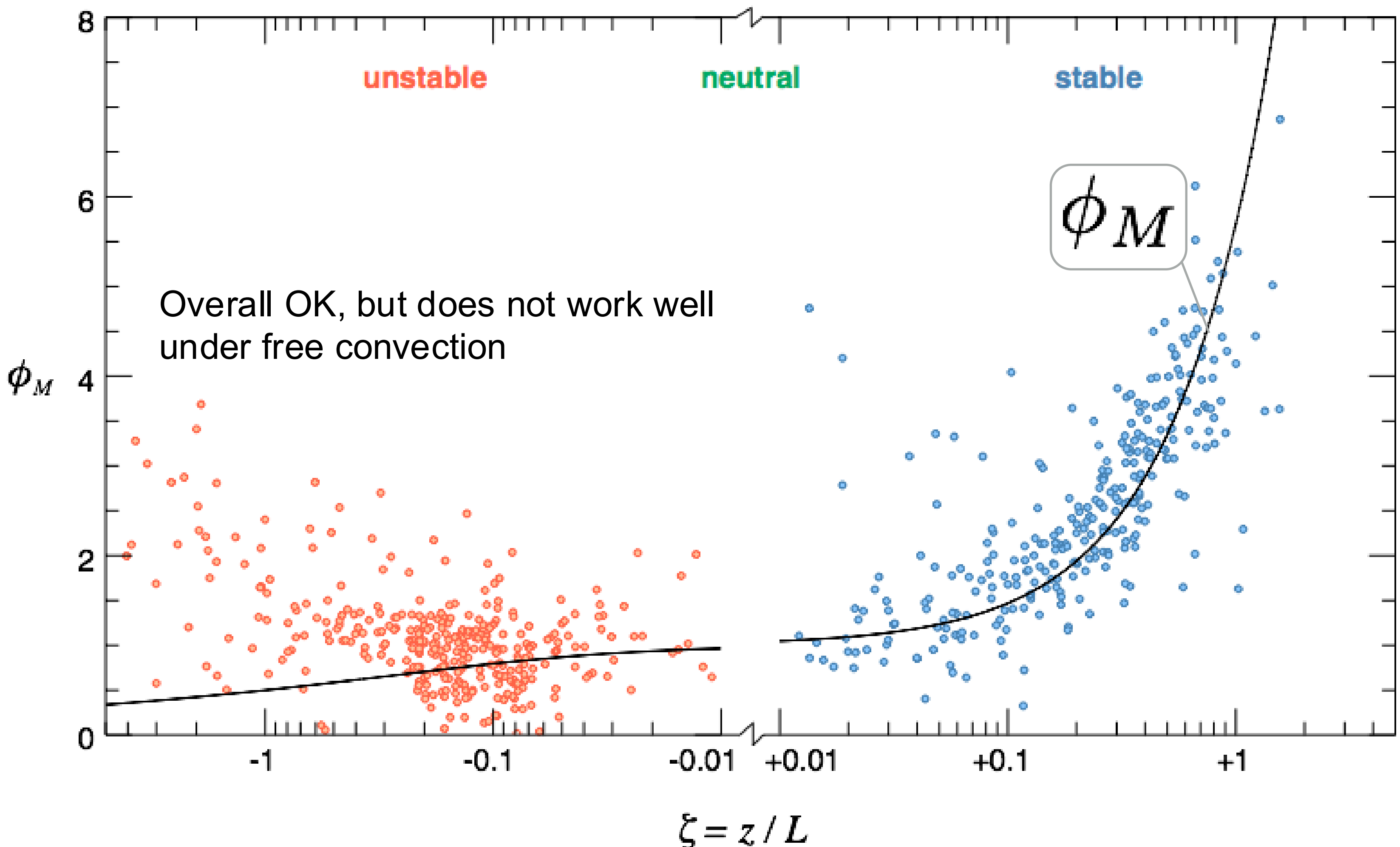
Neutral ($\zeta = 0$, $Ri = 0$)

$$\phi_M = 1$$

Unstable ($\zeta < 0$, $Ri < 0$)

$$\phi_M = (1 - 15\zeta)^{-1/4}$$

Data from the same tower you used in assignment #3



Data: EBEX-2000 (Oncley et al., 2007)

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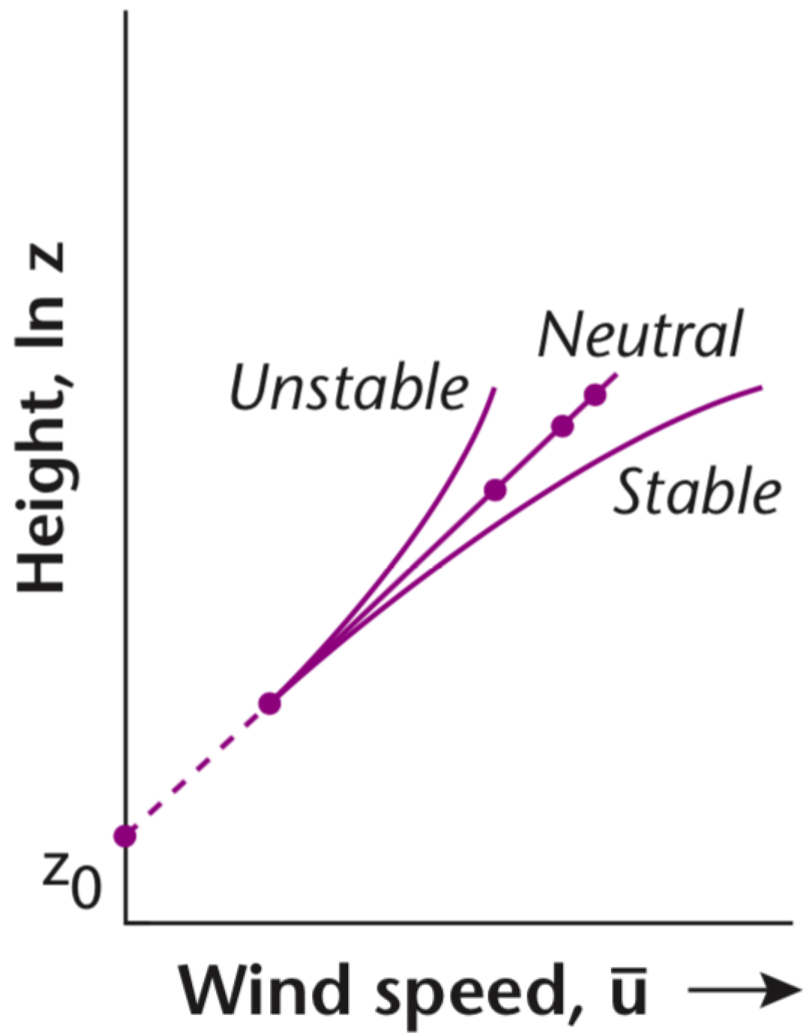


Numerical integration of wind profile

To calculate wind at any height z under diabatic conditions, you must **numerically integrate** over finite layers, adjusting $\zeta = z/L$ as you move up (or down).

Download the example Excel-Sheet on the course website

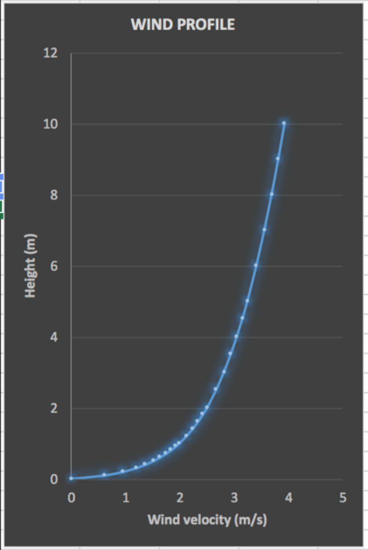
Non-Neutral-Wind.xlsx

=F15+E16*B15

Roughness length z_0	0.02	m
Sensible heat flux Q_H	-30	W m^{-2}
Friction Velocity u_*	0.3	m s^{-1}

Absolute Temperature	293.15	K
Acceleration due to gravity	9.81	m s^{-2}
Air density	1.2	kg m^{-3}
Obukhov Length	79.50275229	m

Height a.g.l. (m)	Height increment (m)	z/L	Phi_M	Δu/Δz (m s-1 m-1)	u (integrated) (m s-1)
0.02	0.10	0.000	1.001	36.63	0
0.12	0.10	0.002	1.007	6.14	0.6
0.22	0.10	0.003	1.013	3.37	1.0
0.32	0.10	0.004	1.019	2.33	1.2
0.42	0.10	0.005	1.025	1.79	1.4
0.52	0.10	0.007	1.031	1.45	1.5
0.62	0.10	0.008	1.037	1.22	1.6
0.72	0.10	0.009	1.043	1.06	1.7
0.82	0.10	0.010	1.048	0.94	1.8
0.92	0.10	0.012	1.054	0.84	=F15+E16*B15
1.02	0.20	0.013	1.060	0.76	2.0
1.22	0.20	0.015	1.072	0.64	2.1
1.42	0.20	0.018	1.084	0.56	2.2
1.62	0.20	0.020	1.096	0.49	2.3
1.82	0.20	0.023	1.108	0.45	2.4
2.02	0.50	0.025	1.119	0.41	2.5
2.52	0.50	0.032	1.149	0.33	2.7
3.02	0.50	0.038	1.179	0.29	2.8
3.52	0.50	0.044	1.208	0.25	2.9
4.02	0.50	0.051	1.238	0.23	3.0
4.52	0.50	0.057	1.267	0.21	3.1
5.02	1.00	0.063	1.297	0.19	3.2
6.02	1.00	0.076	1.356	0.16	3.4
7.02	1.00	0.088	1.415	0.15	3.6
8.02	1.00	0.101	1.474	0.13	3.7
9.02	1.00	0.113	1.533	0.12	3.8
10.02	1.00	0.126	1.592	0.12	3.9



Estimating wind under all conditions is relevant in the wind energy industry (Photo: A. Christen)

Wind power generation

We can estimate the **power generation** U (in W) by a wind turbine using the following equation:

$$U = \frac{\pi}{2} \rho_a E R^2 \overline{u}^3$$

Where R is the radius of the turbine (in m), E is the **turbine efficiency** (usually about 30 - 45%), and ū is the approaching mean wind speed at the height of the turbine.

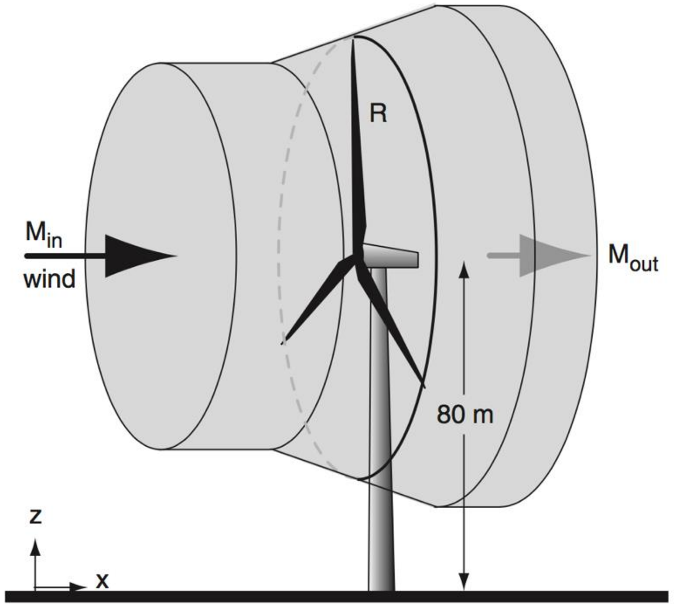


Figure 17.4
Wind turbine for electrical-power generation. Grey region shows the air that transfers some of its energy to the wind turbine.

Stull R. B. (2015): Practical Meteorology

Example 1

Estimate the power generation of a turbine with R = 30m, z = 80m and E = 40% under the following conditions:

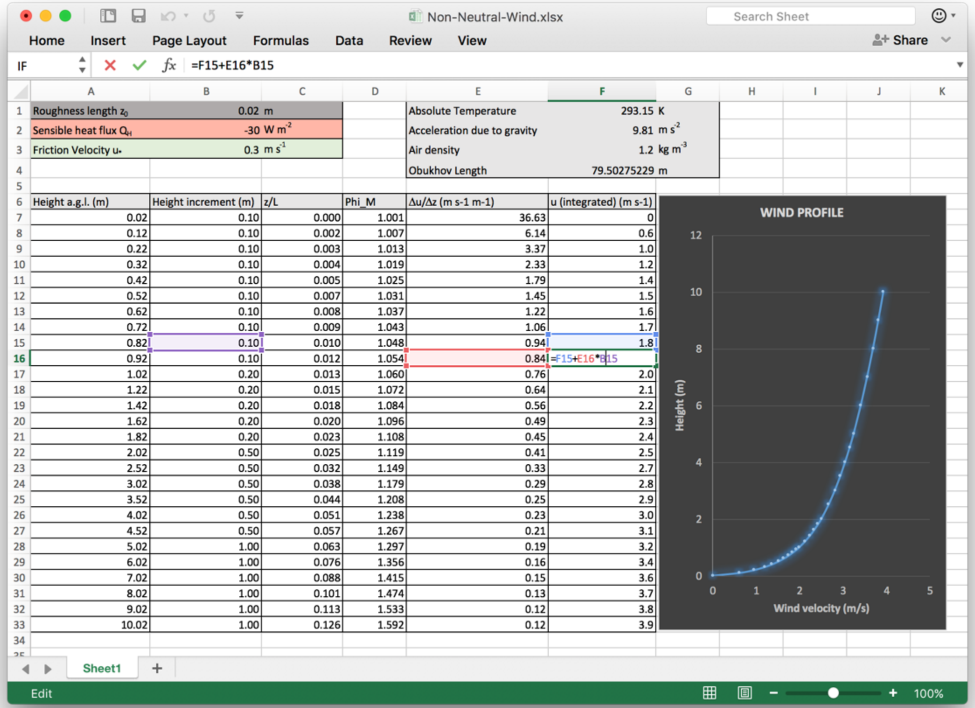
Neutral, u_* = 0.5 m/s, z_0 = 0.02 m, ρ_a = 1.22 kg m^{-3}:

$$\overline{u} = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right)$$

Example 2

Estimate the power generation of the same turbine with under the following conditions:

Unstable, $u_* = 0.2$ m/s, $z_0 = 0.02$ m, $Q_H = 400$ W m^{-2}



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How did power generation compare between the two conditions?

Power generation for the same turbine was higher for unstable conditions.

A) True
B) False

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Wind energy

Estimate the power generation (kW) of the same turbine:

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

Friction velocity u_* (m s^{-1})

	0	20	40	100	200	300
0.475	562	485	445	379	325	292
0.450	478	405	369	312	265	237
0.425	403	334	302	253	213	190
0.400	336	272	244	202	169	150
0.375	277	218	194	159	132	116
0.350	225	172	152	123	100	88
0.325	180	133	116	92	75	65
0.300	142	100	86	68	54	47
0.275	109	73	63	48	38	33
0.250	82	52	44	33	26	22
0.225	60	35	29	22	17	14
0.200	42	22	18	13	10	8
0.175	28	13	11	8	6	5
0.150	18	7	6	4	3	2
0.125	10	4	3	2	1	1
0.100	5	1	1	1	0	0
0.075	2	0	0	0	0	0
0.050	1	0	0	0	0	0
0.025	0	0	0	0	0	0
0.000	0	0	0	0	0	0

Take home points

- Under non-neutral (**diabatic**) conditions, the mixing length changes, and so does the vertical extent of eddies.
- As a consequence the **wind gradient** becomes weaker under unstable and stronger under stable conditions.
- A a set of **semi-empirical correction functions** can be used to predict wind profiles under such conditions.
- Such relations are for example relevant to estimate spread of pollutants or wind energy potential.