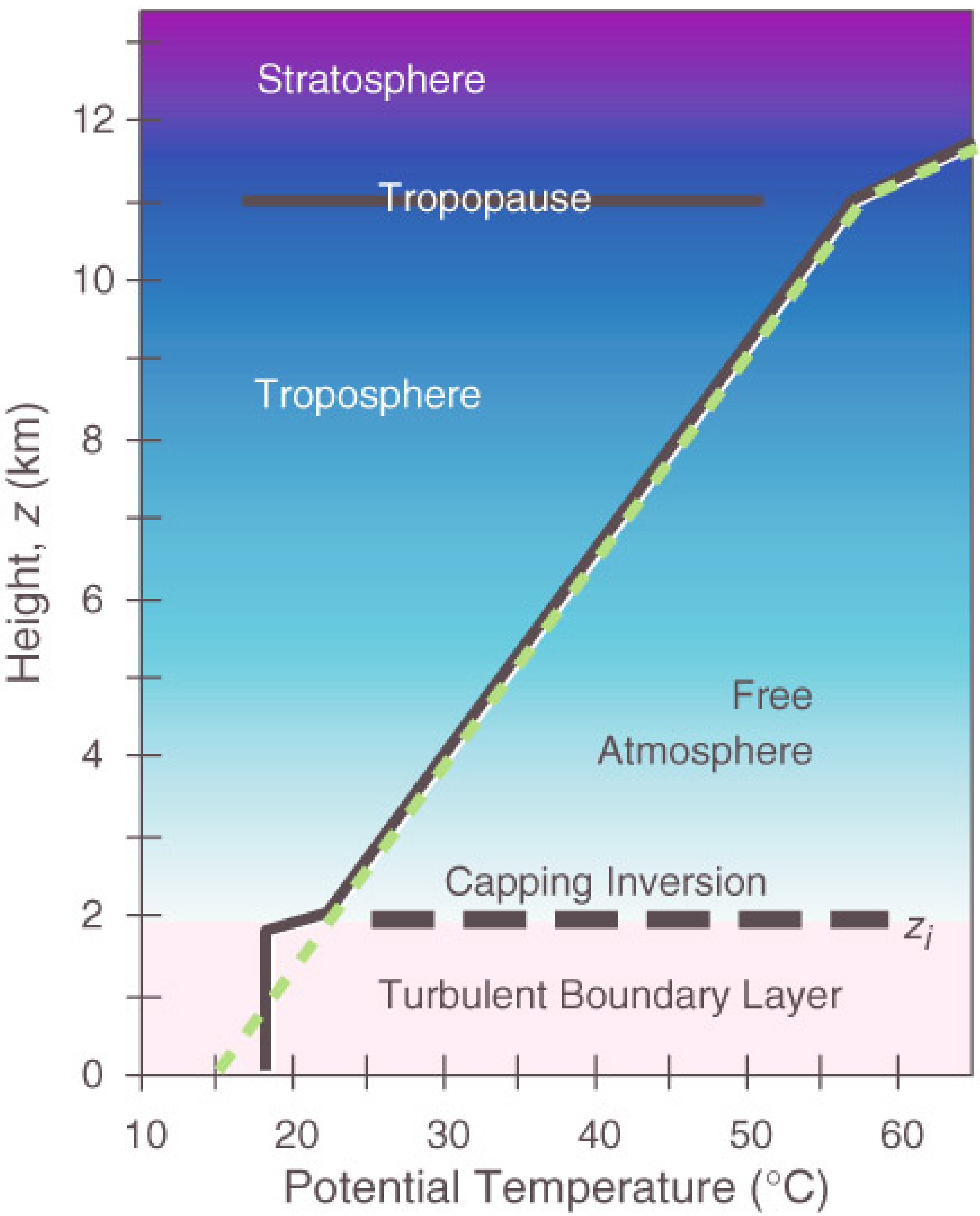
The Atmospheric Boundary Layer

- Turbulence (9.1)
- The Surface Energy Balance (9.2)
- ***Vertical Structure (9.3)***
- Evolution (9.4)
- Special Effects (9.5)
- The Boundary Layer in Context (9.6)



Stratosphere
Tropopause
Troposphere
Free
Atmosphere
Capping Inversion
z_i
Turbulent Boundary Layer
Height, z (km)
0
2
4
6
8
10
12
10
20
30
40
50
60
Potential Temperature (°C)

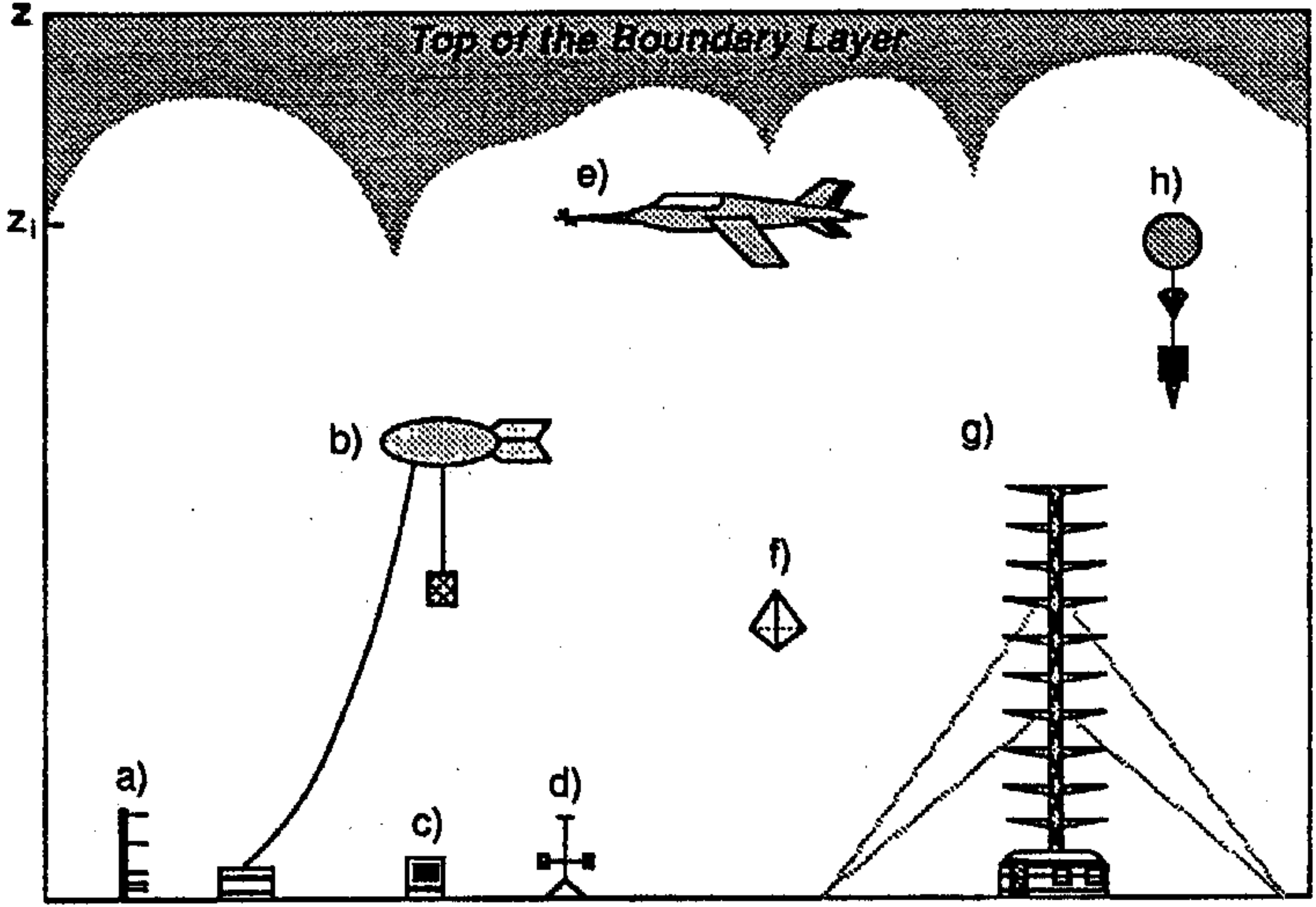
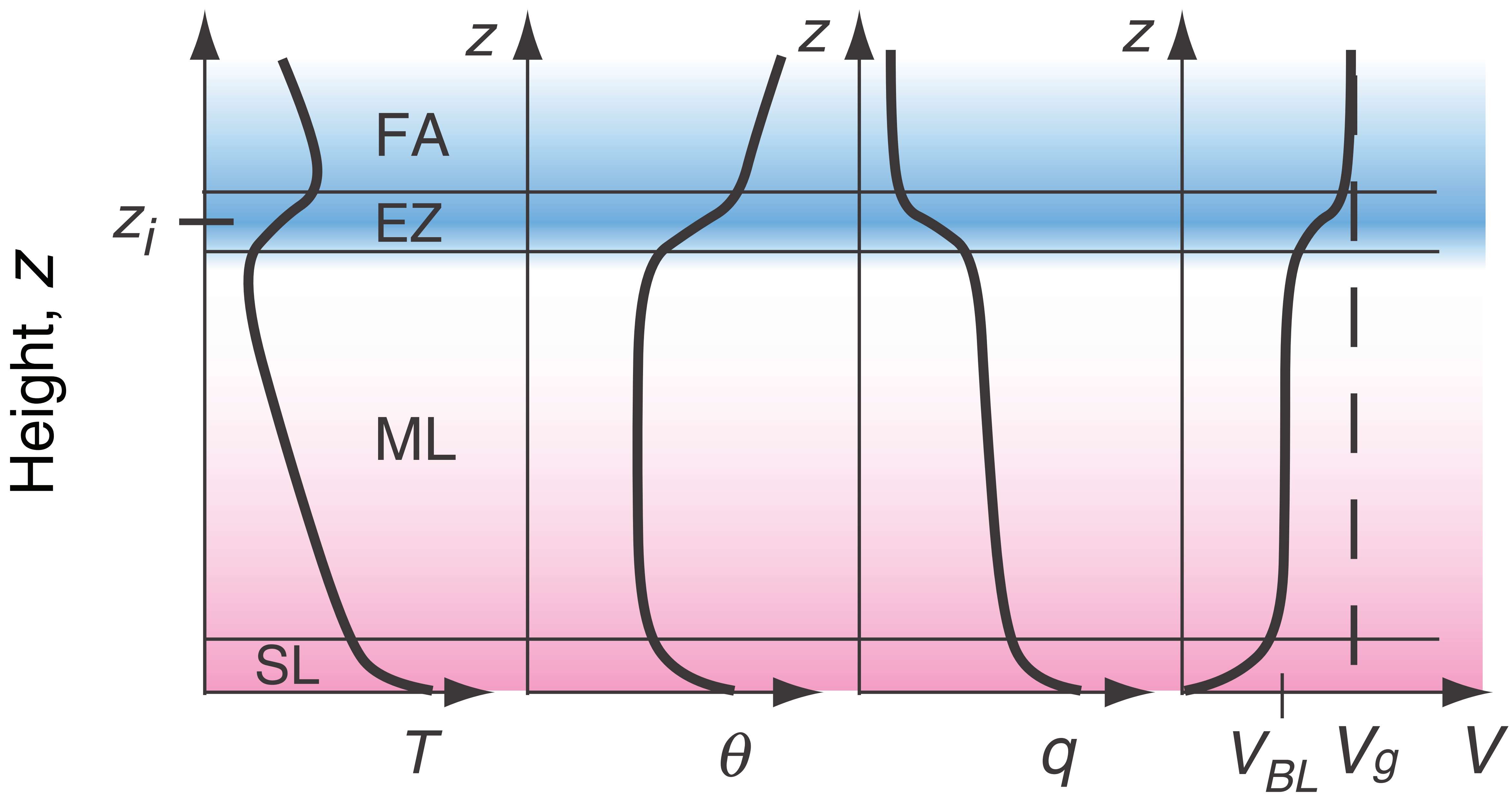
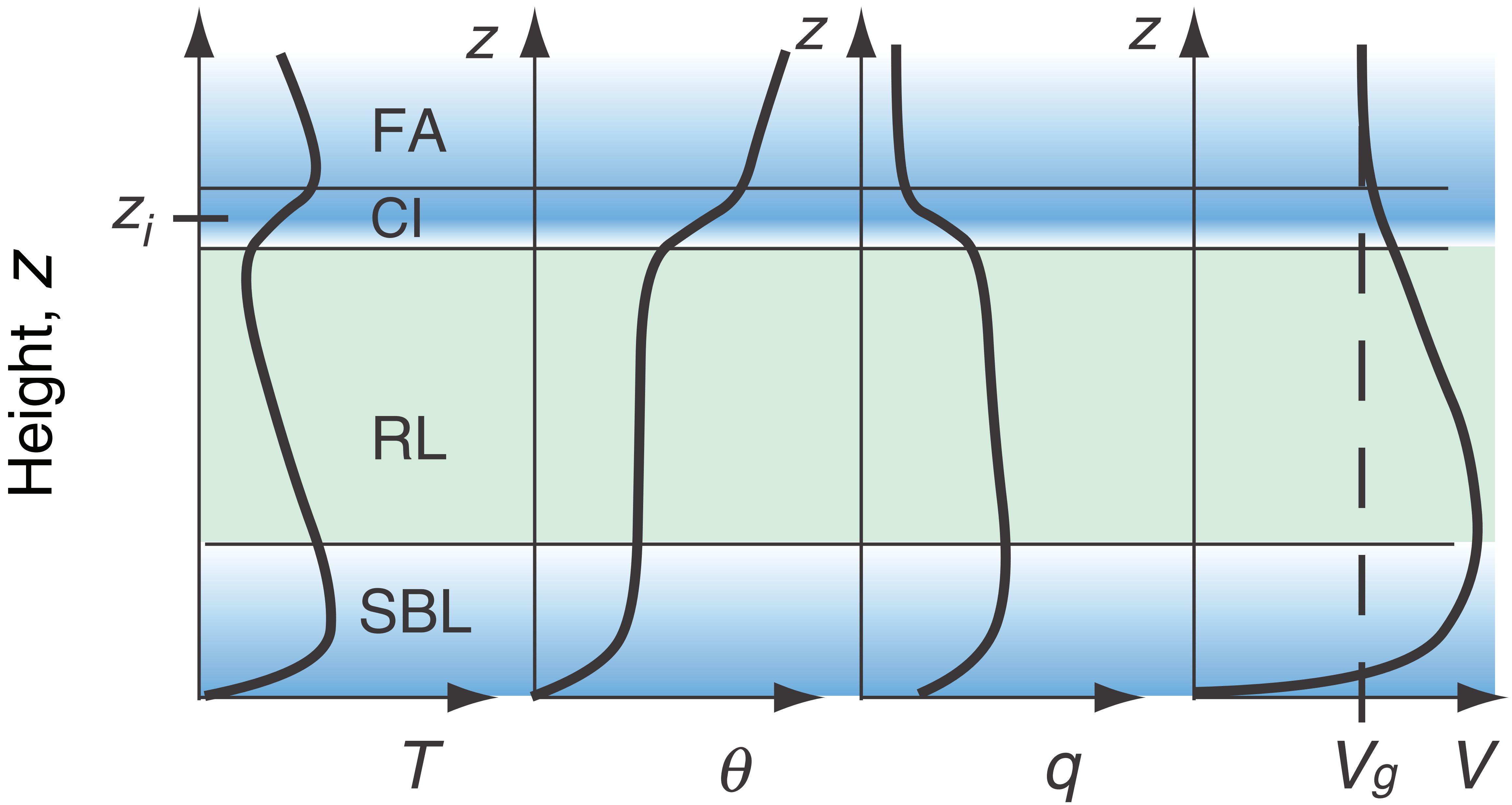


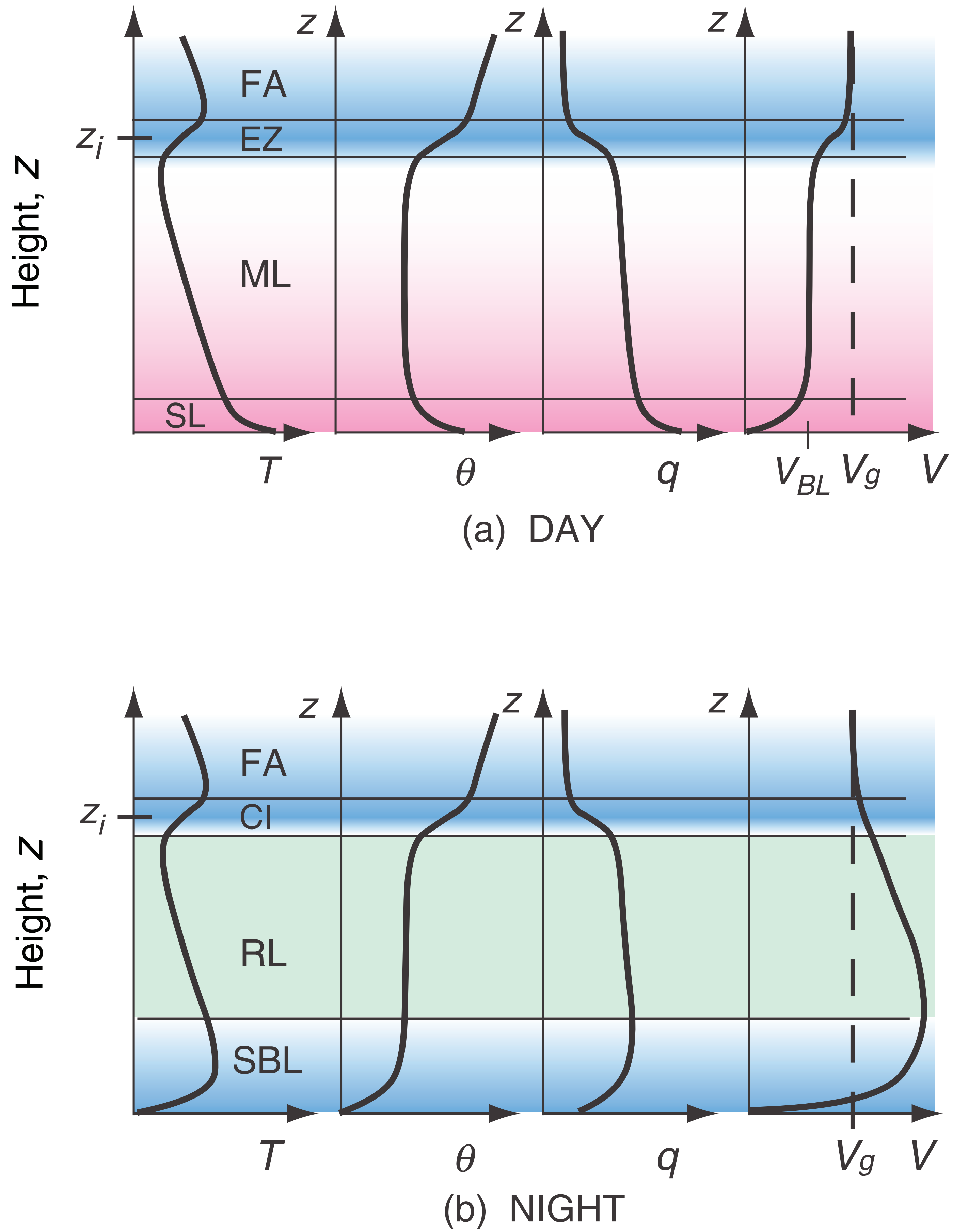
Fig. 10.2 Sketch of instrument platforms for direct sensors. (a) Mast. (b) Kytoon. (c) Instrument (screen) shelter. (d) Mesonet station. (e) Aircraft. (f) Tetroon. (g) Tower. (h) Radiosonde.



(a) DAY

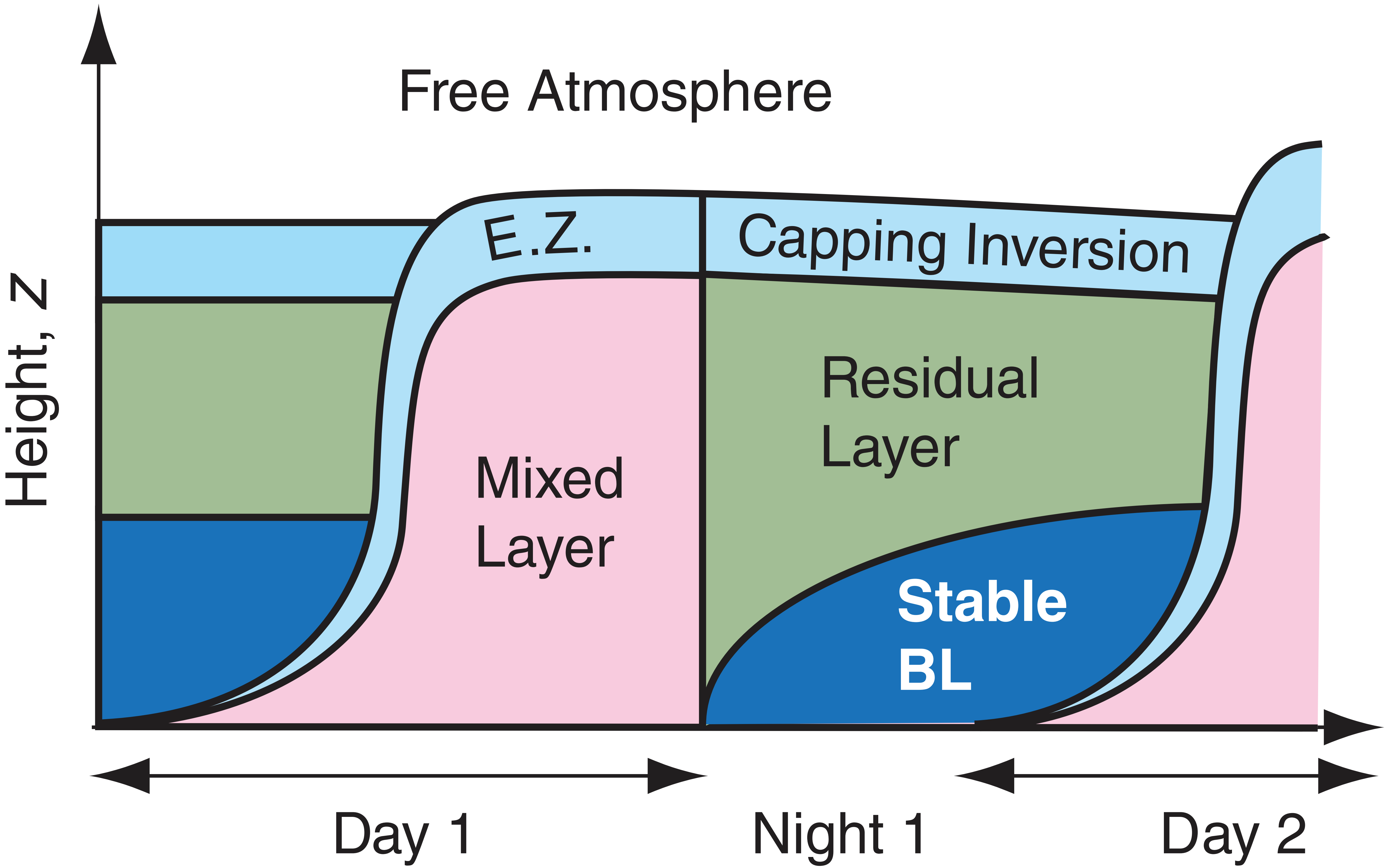


(b) NIGHT

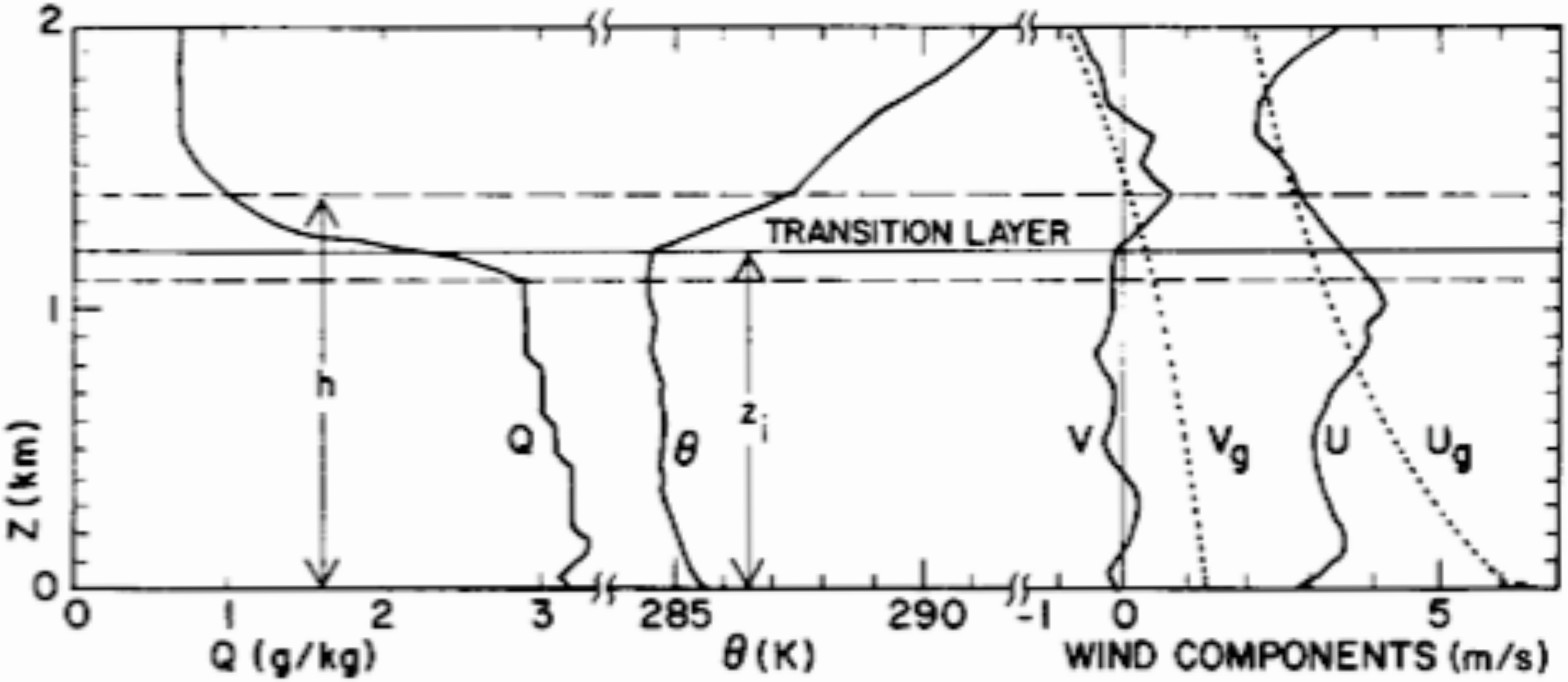


Height, z
z
z
z
FA
EZ
ML
SL
z_i
T
θ
q
V_{BL}
V_g
V
(a) DAY
Height, z
z
z
z
FA
CI
RL
SBL
z_i
T
θ
q
V_g
V
(b) NIGHT

Diurnal cycle over land of the clear convective BL



Convective BL profiles



Arya

Fig. 6.5 Measured wind, potential temperature, and specific humidity profiles in the PBL under convective conditions on day 33 of the Wangara Experiment. [From Deardorff (1978).]

Moderately stable BL profiles

Arya

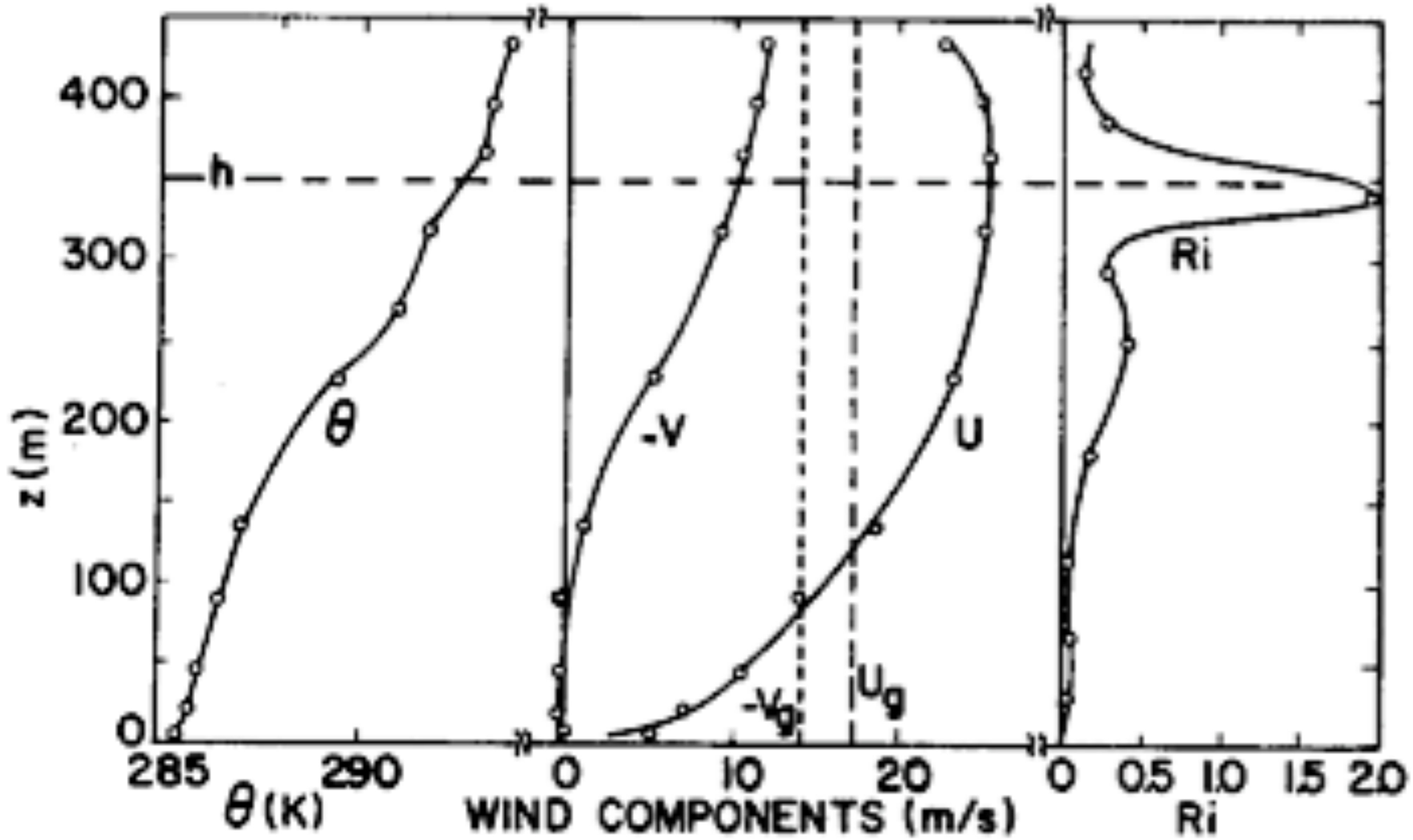


Fig. 6.7 Observed vertical profiles of mean wind components and potential temperatu and the calculated Ri profile in the nocturnal PBL under moderately stable conditio [From Deardorff (1978); after Izumi and Barad (1963).]

Highly stable BL profiles

Arya

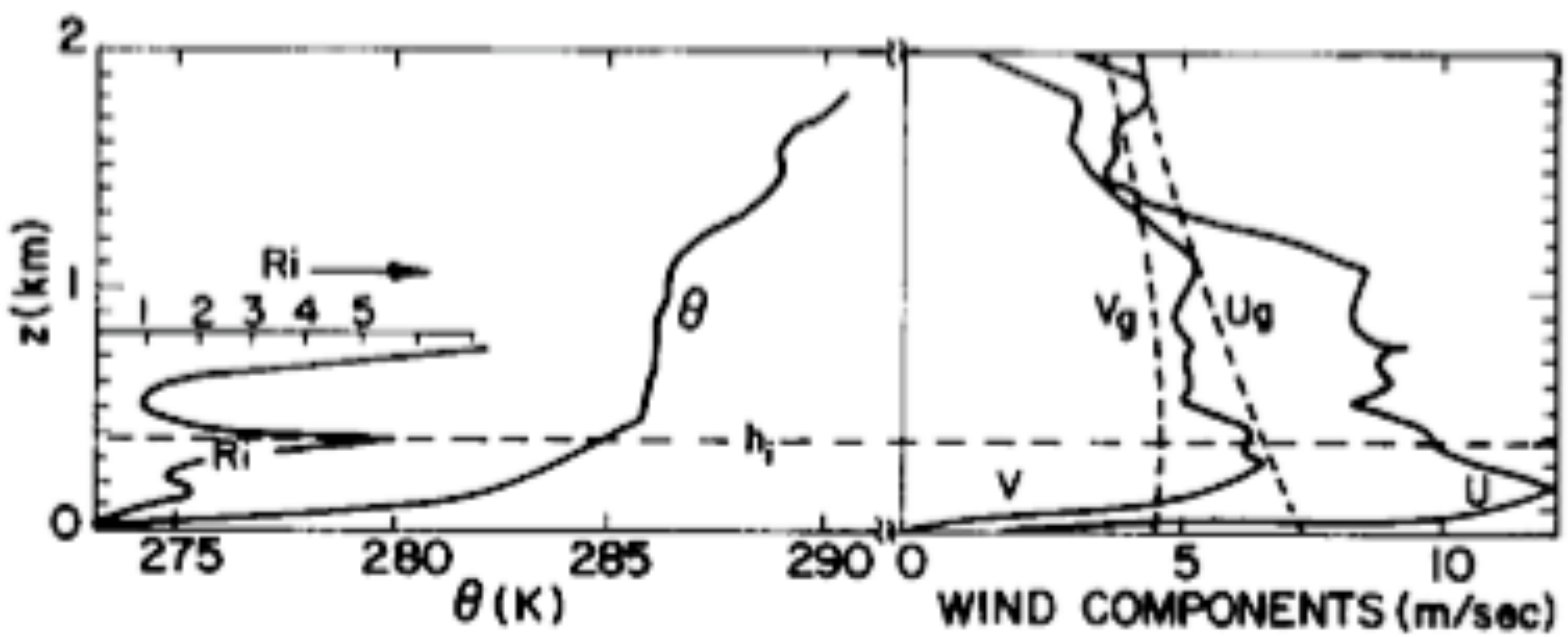


Fig. 6.8 Observed wind and potential temperature profiles under very stable (sporadic turbulence) conditions at night during the Wangara Experiment. [From Deardorff (1978).]

Surface Layer Wind Profiles

- The surface layer wind profile is determined by the surface layer turbulence.
- By dimensional analysis, $\partial V/\partial z \sim$ (turbulence velocity scale) / (turbulence length scale).
- u_* is an appropriate turbulence velocity scale, and is nearly constant within the surface layer.
- z is an appropriate turbulence length scale because eddy size $\sim z$.
- Therefore, $\partial V/\partial z \sim u_*/z$, or $\partial V/\partial z = u_*/(kz)$.

Surface Layer Wind Profiles

To obtain $V(z)$, integrate

$$\frac{\partial V}{\partial z} = \frac{u_*}{kz}$$

from $z = z_0$ where $V = 0$ to z:

$$\int_0^V dV = \frac{u_*}{k} \int_{z_0}^{z} \frac{dz}{z} = \frac{u_*}{k} \int_{z_0}^{z} d \log z$$

The result is

$$V = \frac{u_*}{k} (\log z - \log z_0) = \frac{u_*}{k} \log \left(\frac{z}{z_0} \right)$$

Surface Layer Wind Profiles

$$V = \frac{u_*}{k} \log\left(\frac{z}{z_0}\right)$$

$k \approx 0.4$ is the von Karman constant, and z_0 is the *aerodynamic roughness length*.

Table 9.2 The Davenport classification, where z_o is aerodynamic roughness length and C_{DN} is the corresponding drag coefficient for neutral static stability[a]

z_0 (m)	Classification	Landscape	C_{DN}
0.0002	Sea	Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.	0.0014
0.005	Smooth	Beaches, pack ice, morass, snow-covered fields.	0.0028
0.03	Open	Grass prairie or farm fields, tundra, airports, heather.	0.0047
0.1	Roughly open	Cultivated area with low crops and occasional obstacles (single bushes).	0.0075
0.25	Rough	High crops, crops of varied height, scattered obstacles such as trees or hedgerows, vineyards.	0.012
0.5	Very rough	Mixed farm fields and forest clumps, orchards, scattered buildings.	0.018
1.0	Closed	Regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests.	0.030
≥2	Chaotic	Centers of large towns and cities, irregular forests with scattered clearings.	0.062

[a] From Preprints *12th Amer. Meteorol. Soc. Symposium on Applied Climatology*, 2000, pp. 96–99.

$$|\mathbf{V}| = \frac{u_*}{k} \log\left(\frac{z}{z_0}\right)$$

$$u_*^2 = C_D |\mathbf{V}|^2$$

How are C_D and z_0 related?

$$|\mathbf{V}| = \frac{u_*}{k} \log\left(\frac{z}{z_0}\right)$$

$$u_*^2 = C_D |\mathbf{V}|^2$$

How are C_D and z_0 related?

$$C_D = \frac{u_*^2}{|\mathbf{V}|^2}$$

$$|\mathbf{V}| = \frac{u_*}{k} \log\left(\frac{z}{z_0}\right)$$

$$u_*^2 = C_D |\mathbf{V}|^2$$

How are C_D and z_0 related?

$$C_D = \frac{u_*^2}{|\mathbf{V}|^2}$$

$$C_D = \frac{u_*^2}{\left[\frac{u_*}{k} \log\left(\frac{z}{z_0}\right)\right]^2}$$

$$|\mathbf{V}| = \frac{u_*}{k} \log\left(\frac{z}{z_0}\right)$$

$$u_*^2 = C_D|\mathbf{V}|^2$$

How are C_D and z_0 related?

$$C_D = \frac{u_*^2}{|\mathbf{V}|^2}$$

$$C_D = \frac{u_*^2}{\left[\frac{u_*}{k}\log\left(\frac{z}{z_0}\right)\right]^2}$$

$$C_D = \left[\frac{k}{\log\left(\frac{z}{z_0}\right)}\right]^2$$

standard height is z=10 m

Drag Coefficient (C_D)

$$\tau = \rho \cdot C_D \cdot U^2$$ surface stress

$$(\overline{u'w'})_s = \frac{\tau}{\rho}$$

In practice the drag coefficient is given usually with respect to the wind speed at z=10m and for neutral conditions (C_{DN10})

Typical values of the drag coefficient over the land are significantly larger than over the water

$C_{D\ land} \approx 7\times10^{-3}$

$C_{D\ water} \approx 1\times10^{-3}$

Table 9.2 The Davenport classification, where z_o is aerodynamic roughness length and C_{DN} is the corresponding drag coefficient for neutral static stability[a]

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[a] From Preprints *12th Amer. Meteorol. Soc. Symposium on Applied Climatology*, 2000, pp. 96–99.

Surface Layer Wind Profiles

In a neutral surface layer,

$$\frac{\partial V}{\partial z} = \frac{u_*}{kz}$$

This can be generalized by defining a dimensionless wind shear:

$$\Phi_m = \frac{kz}{u_*}\frac{\partial V}{\partial z}$$

Surface Layer Wind Profiles

In a neutral surface layer,

$$\frac{\partial V}{\partial z} = \frac{u_*}{kz}$$

This can be generalized by defining a dimensionless wind shear:

$$\Phi_m = \frac{kz}{u_*}\frac{\partial V}{\partial z}$$

Then for a neutral surface layer

$$\Phi_m = 1$$

but for stable or unstable surface layers

$$\Phi_m \neq 1$$

Surface Layer Wind Profiles

For stable or unstable surface layers, there is an additional length scale, the *Obukov length*

$$L \equiv \frac{-u_*^3}{k(g/T_v)(\overline{w'\theta'})_s}$$

Surface Layer Wind Profiles

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$$L \equiv \frac{-u_*^3}{k(g/T_v)(\overline{w'\theta'})_s}$$

The magnitude of L is the height below which mechanical (shear) production of turbulence dominates over buoyancy production or loss.

Surface Layer Wind Profiles

For stable or unstable surface layers, there is an additional length scale, the *Obukov length*

$$L \equiv \frac{-u_*^3}{k(g/T_v)(\overline{w'\theta'})_s}$$

The magnitude of L is the height below which mechanical (shear) production of turbulence dominates over buoyancy production or loss.

In stable surface layers: $L > 0$.
In unstable surface layers: $L < 0$.
In neutral surface layers: $L = \pm\infty$.

Surface Layer Wind Profiles

We assume that Φ_M is a function of the non-dimensional height z/L.

For stable surface layers $(z/L > 0)$, measurements fit the empirical relationship

$$\Phi_m = 1 + 8.1\frac{z}{L}$$

Surface Layer Wind Profiles

We assume that Φ_M is a function of the non-dimensional height z/L.

For stable surface layers ($z/L > 0$), measurements fit the empirical relationship

$$\Phi_m = 1 + 8.1\frac{z}{L}$$

For unstable surface layers ($z/L < 0$), measurements fit the empirical relationship

$$\Phi_m = \left[1 - 15\left(\frac{z}{L}\right)\right]^{-1/4}$$

This is the correct version for WH Eq. (9.26).

Surface Layer Wind Profiles

Exercise 9.4 Integrate

$$\Phi_m = \frac{kz}{u_*}\frac{\partial V}{\partial z} = 1 + 8.1\frac{z}{L}$$

to obtain the wind speed profile. Assume that $V(z_0) = 0$ and that u_* and L are constants.

Surface Layer Wind Profiles

Exercise 9.4 Integrate

$$\Phi_m = \frac{kz}{u_*}\frac{\partial V}{\partial z} = 1 + 8.1\frac{z}{L}$$

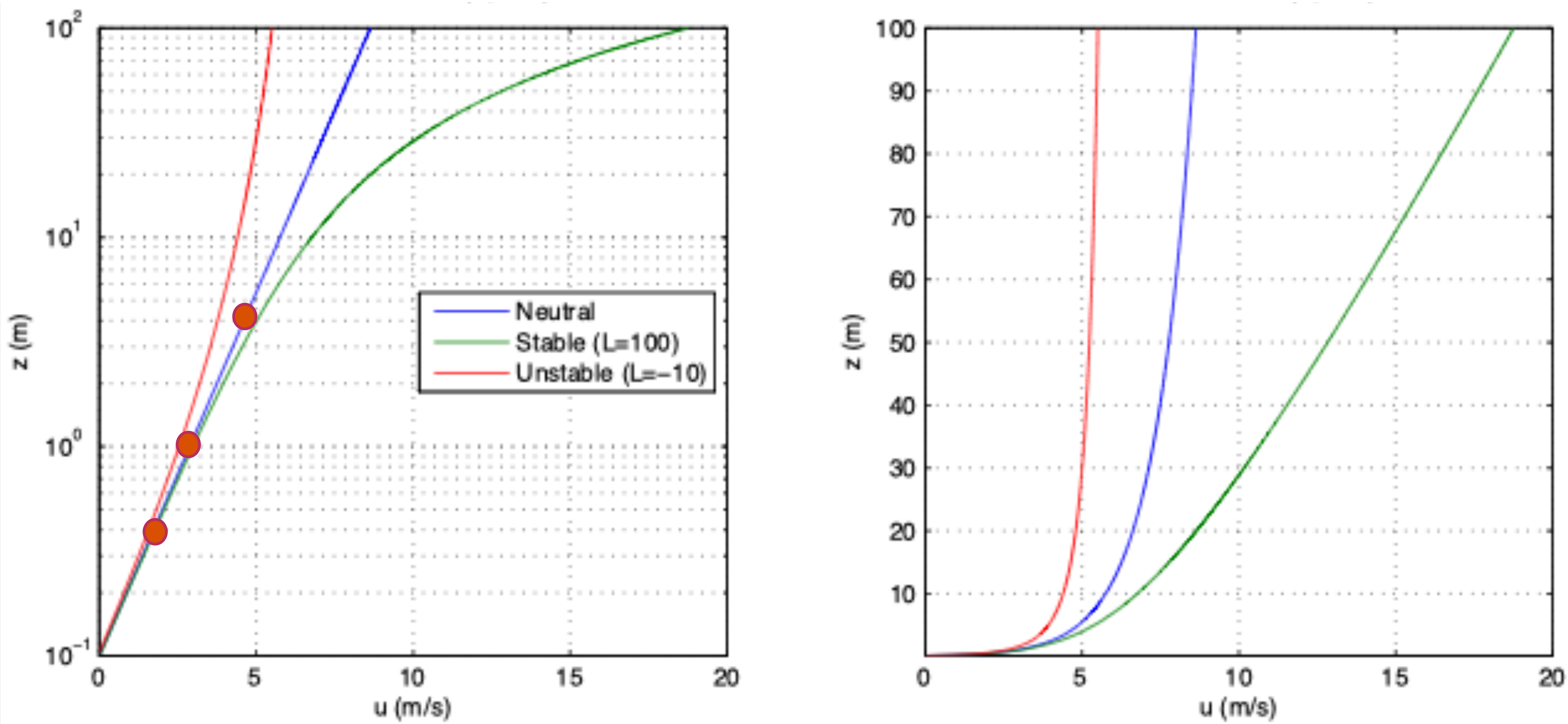
to obtain the wind speed profile. Assume that $V(z_0) = 0$ and that u_* and L are constants.

Solution: (derived in WH and in class)

$$\frac{V}{u_*} = \frac{1}{k}\left[\log\frac{z}{z_0} + \boxed{8.1\frac{z - z_0}{L}}\right]$$

This is a *log-linear* profile.

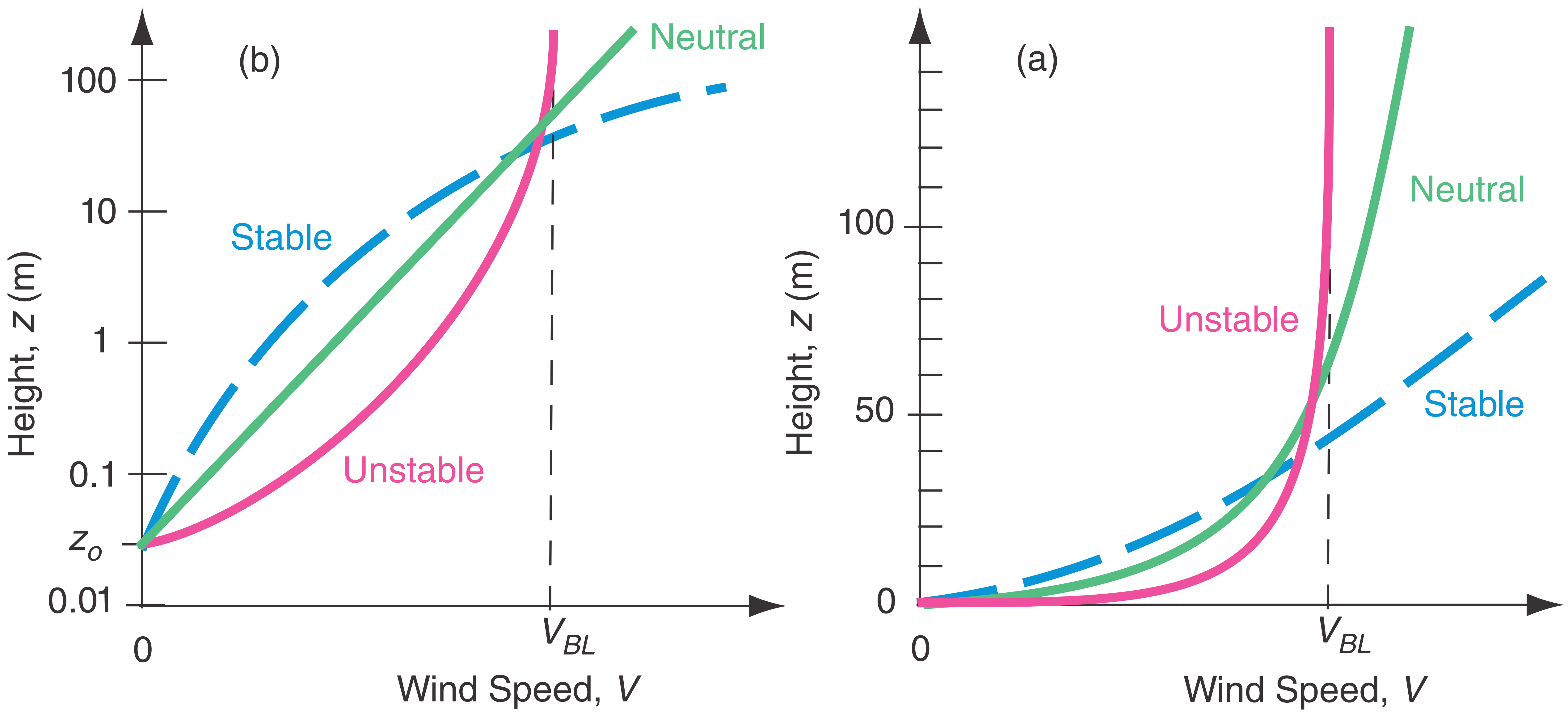
Surface Layer Wind Profiles for Different Static Stabilities



z0=0.1 m

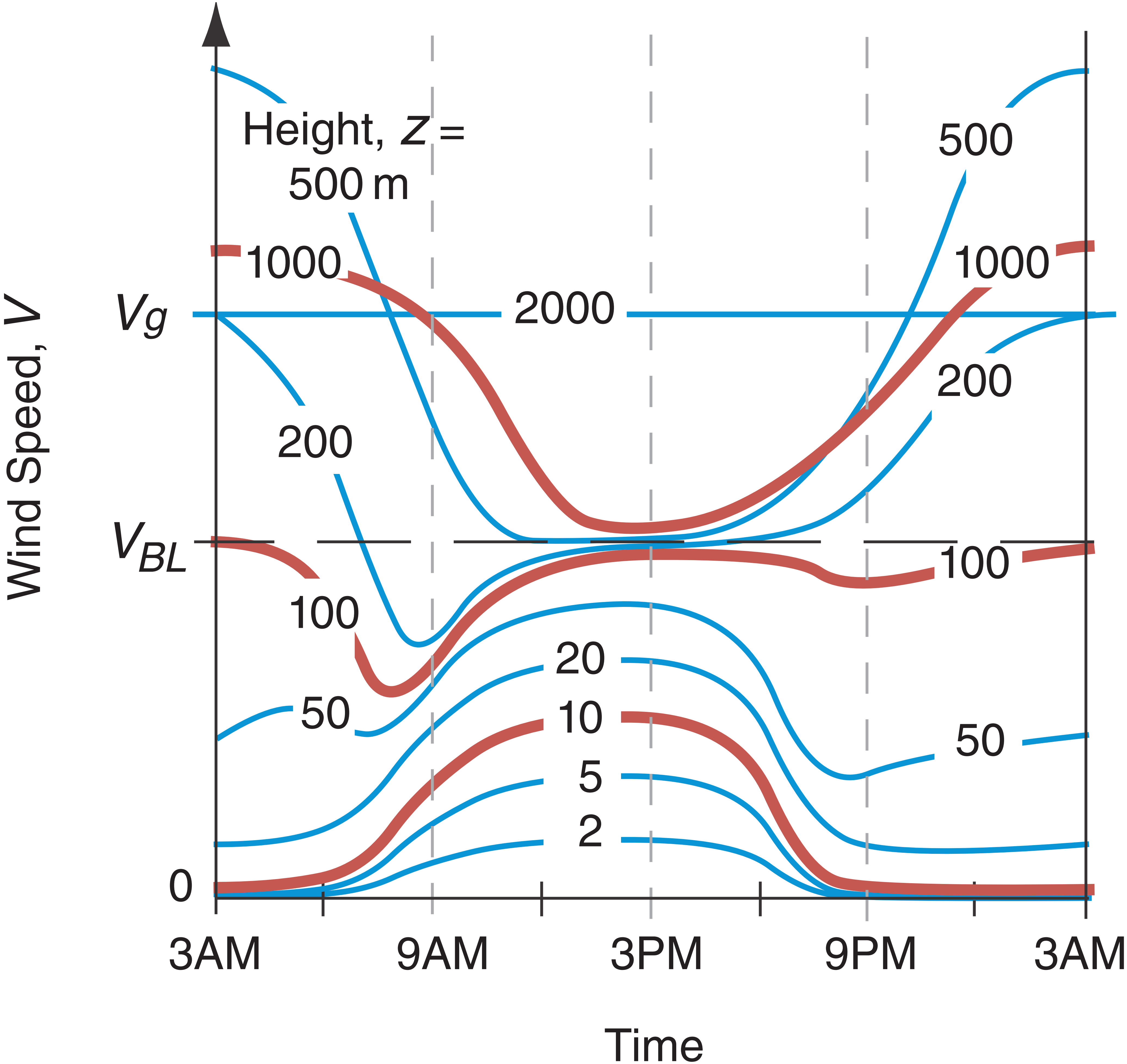
z0 is z where V=0

WH Fig 9.17
The stable and unstable profiles are wrong. These profiles do NOT cross over each other, or cross over the neutral profile.



STOP HERE

Move to EVOLUTION slides

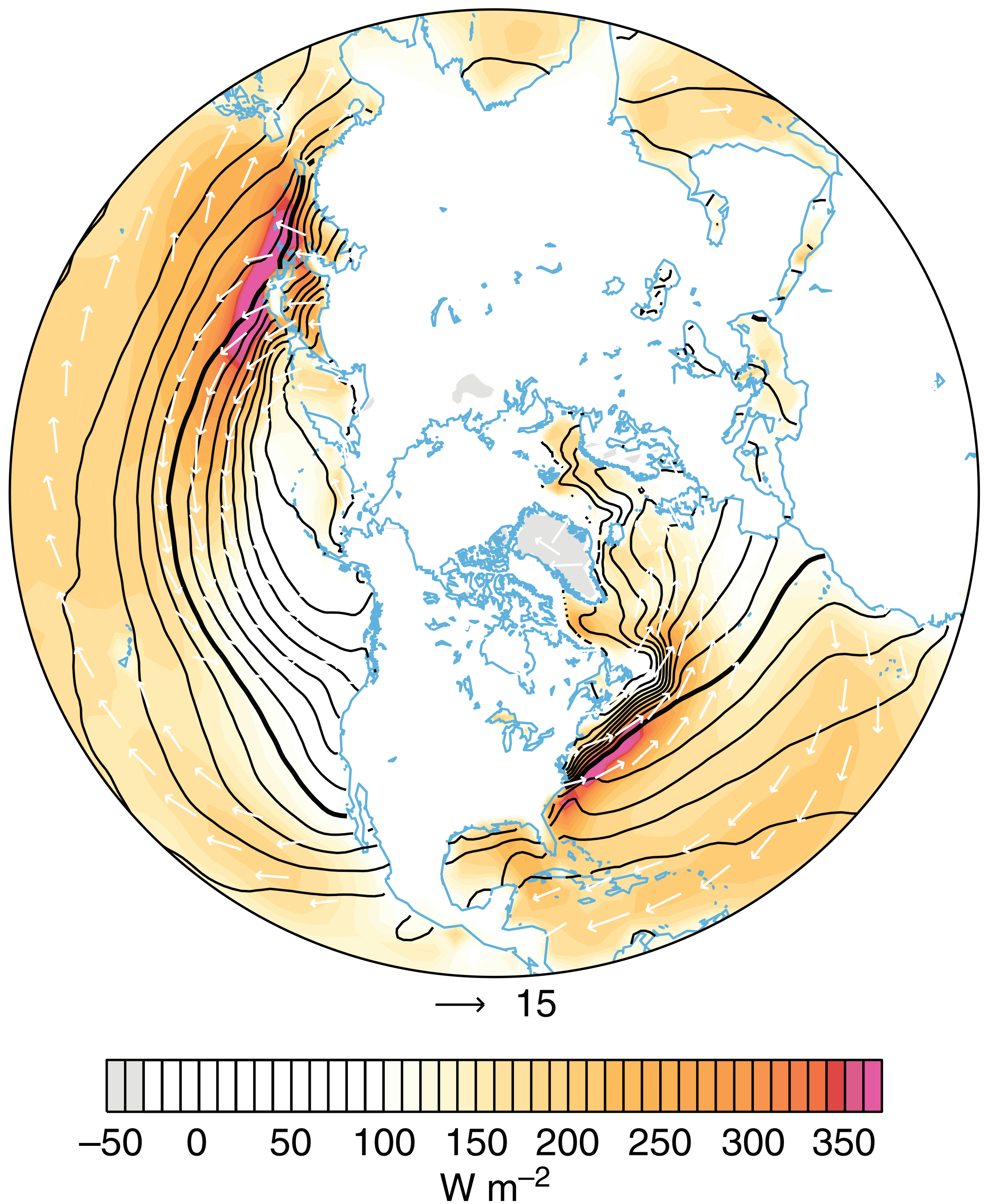


Height, Z =
500 m
1000
2000
200
100
50
20
10
5
2
500
1000
200
100
50
V_g
V_{BL}
0
Wind Speed, V
3AM
9AM
3PM
9PM
3AM
Time

Move to SEB slides

Time and Space Variations in Boundary-Layer Structure

Mean January surface sensible + latent heat fluxes



Cover these before HW problems from Stull Ch. 5

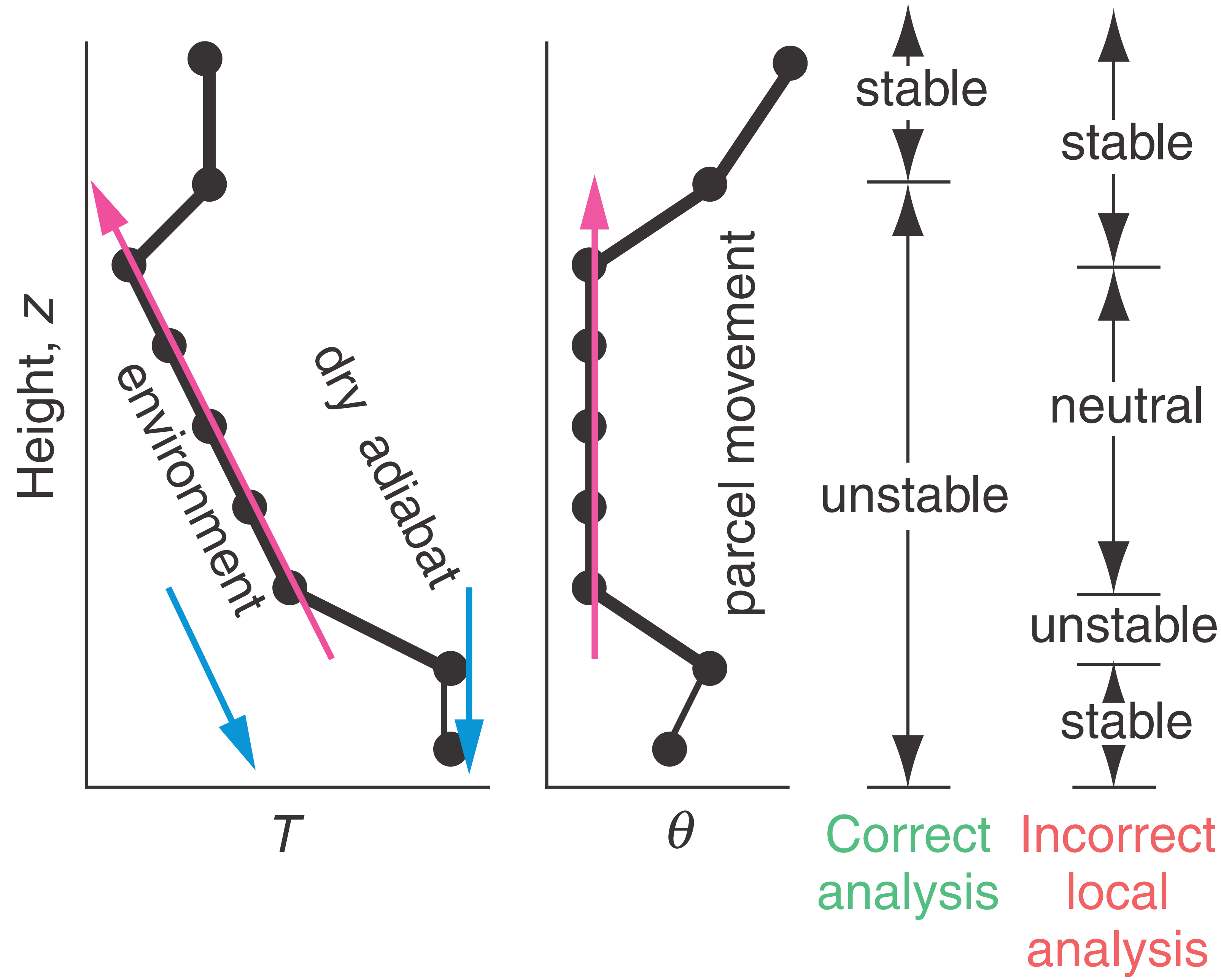
Nonlocal influence of Stratification on Turbulence and Stability

Recall HW2 problem 5.2

z (m)	$\overline{\theta_v}$ (K)	$\overline{U}$ (m/s)
80	305	18
70	305	17
60	301	15
50	300	14
40	298	10
30	294	8
20	292	7
10	292	7
0	293	2

Example Profile

- Is the middle layer neutral?
- Is the bottom layer stable?



Example Profile

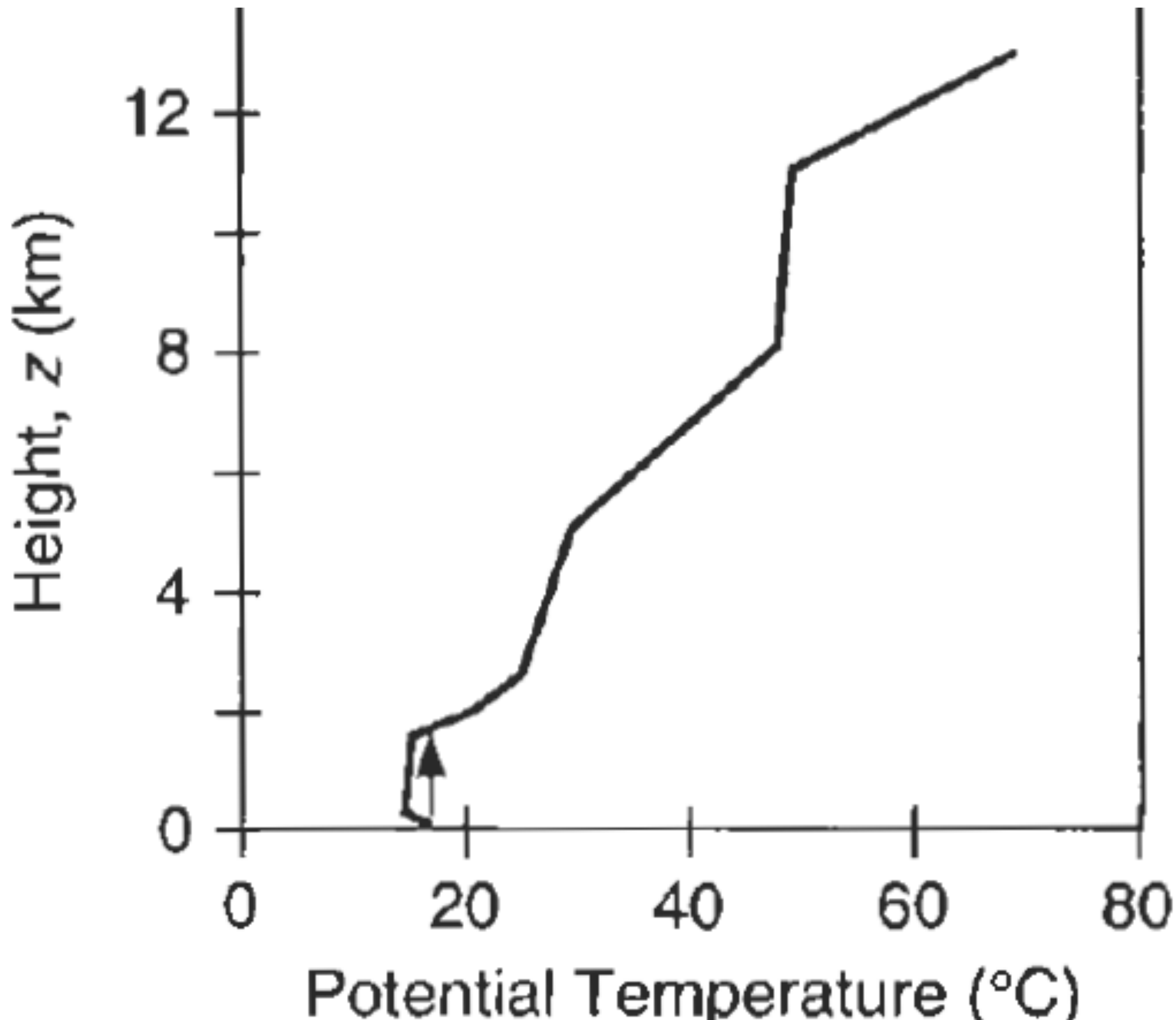
- Let's work it out for this profile!

z (km)	T (°C)	U (m s^{-1})
13	−58	30
11	−58	60
8	−30	25
5	−19	20
3	−3	18
2.5	1	9
2	2	8
1.6	0	5
0.2	13	5
0	18	0

Example Profile

z (km)	T (°C)	U (m s^{-1})	θ (°C)	T_{avg} (k)	Δz (m)	ΔU (m s^{-1})	$\Delta\theta$ (K)
13	−58	30	69.4				
11	−58	60	49.8	215.15	2000	−30	19.6
8	−30	25	48.8	229.15	3000	35	1.4
5	−19	20	30	248.65	3000	5	18.4
3	−3	18	26.4	262.15	2000	2	3.6
2.5	1	9	25.5	272.15	500	9	0.9
2	2	8	21.6	274.65	500	1	3.9
1.6	0	5	15.68	274.15	400	3	5.92
0.2	13	5	14.96	279.65	1400	0	0.72
0	18	0	18	288.65	200	5	−3.04

Example Profile



Example Profile

Layer (km)	R_B	Dynamically	Statically	Turbulent
11 to 13	1.98	Stable	Stable	no
8 to 11	0.15	Unstable	Stable	yes
5 to 8	87.02	Stable	Stable	no
3 to 5	67.29	Stable	Stable	no
2.5 to 3	0.20	Unstable	Stable	yes
2 to 2.5	69.58	Stable	Stable	no
1.6 to 2	9.41	Stable	Unstable to 1.8 km	yes to 1.8 km
0.2 to 1.6	$+\infty$	(undefined)	Unstable	yes
0 to 0.2	-0.83	Unstable	Unstable	yes