Atmospheric Boundary Layers, Turbulence & Dispersion

(A Review for the BC Ministry of Environment)

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Topics:

1. Boundary Layer Basics
2. Static Stability
3. BL Evolution
4. Turbulence Generation
5. Turb. Kinetic Energy
6. TKE & Dispersion
7. Pile-burn Case Study
8. Clarifications of Your Issues

If requested, if time:

9. Dispersion in the Convective ML

Survey Results

1) PBL expertise: 1 high , <u>7 medium</u>, 0 low
2) Turbulence : 1 high , <u>5 medium</u> , 2 low
3) Plume dispersion: 2 high , <u>6 medium</u> , 0 low
4) Thermo diagram: 2 tephi, 3 skew-T , <u>4 not use</u>
5) Potential temperature: 2 high , <u>4 medium</u> , 2 low
6) Virtual temperature: 1 high , 2 medium , <u>5 low</u>
7) 6 AERMOD , 3 Hysplit , <u>7 CALPUFF</u> , 1 CMAQ , 1 GEM-MACH , 1 CAMx
8) Complex terrain: <u>6 high</u> , 1 medium , 1 low

Survey Results - Clarification Desired

- PBL formation and breakdown
- winter PBLs
- PBL in valleys. Also valley clouds vs. inversions
- PBL vs smoke dispersion
- dispersion prediction days in advance
- using soundings to anticipate dispersion
- how to understand Weinstein's Air Qual. Advisory fcsts.
- surface roughness
- venting: roles of shear and buoyancy
- how fine a resolution in NWP is numerically stable
- using weather forecasts to anticipate episodes of poor air quality

1. Atmospheric Boundary Layer (ABL)

Some Definitions:

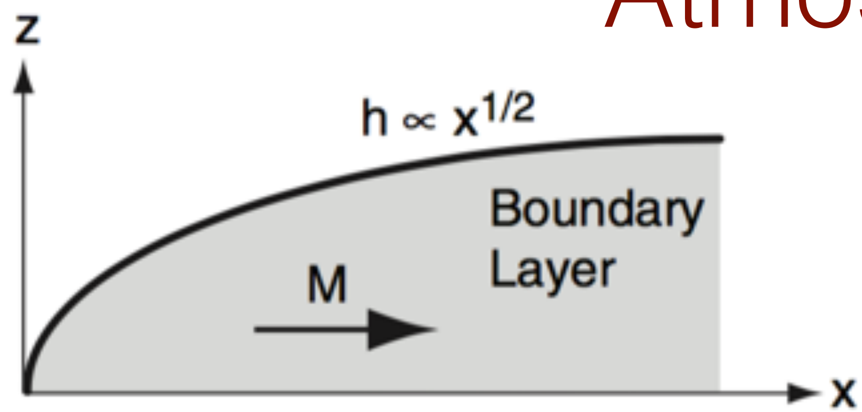
ABL = the portion of the atmosphere that feels the effects of the Earth's surface, on a timescale of roughly an hour ——————————-> {

PBL = planetary boundary layer = ABL

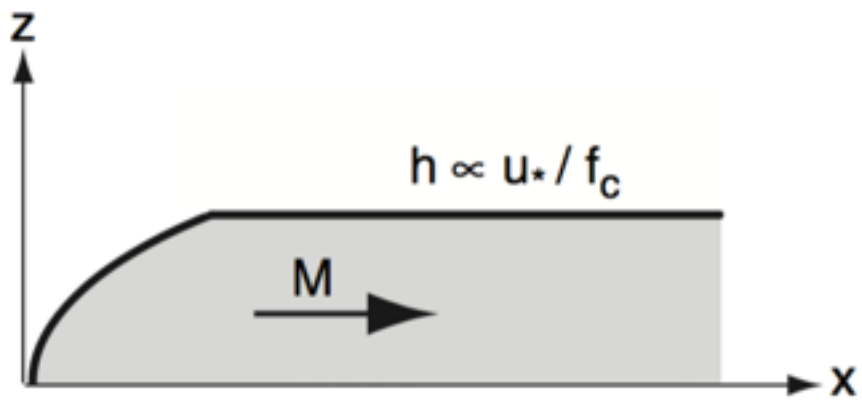
ML = mixed layer (or mixing layer), when the ABL is so strongly mixed by turbulence that conserved properties (humidity, pollutant concentration, potential temperature) are roughly uniform with height.

Evolution of Thoughts about the Atmospheric Boundary Layer (ABL)

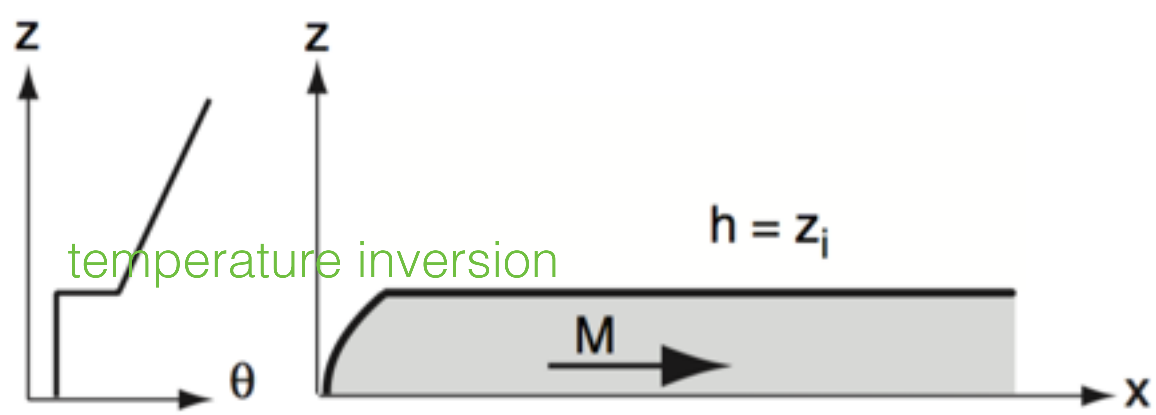
(a) Engineering Boundary Layers:



(b) Boundary Layers on a Rotating Planet:



(c) Boundary Layers in Earth's Stratified Atmosphere:



(a) No height limit. Doesn't apply in general to the whole ABL, but works for initial growth of atmos. internal boundary layer (IBLs).

(b) Based on theoretical Ekman spiral, assuming molecular diffusion on a rotating planet. Doesn't work in real atmos. (not even for neutral ABLs)

(c) Based on thermodynamics.

where:
z = height
h = ABL height
x = downwind distance
M = wind speed
u_* = friction velocity (a measure of surface stress)
f_c = Coriolis parameter (1/s) (related to Earth's rotation)
θ = potential temperature

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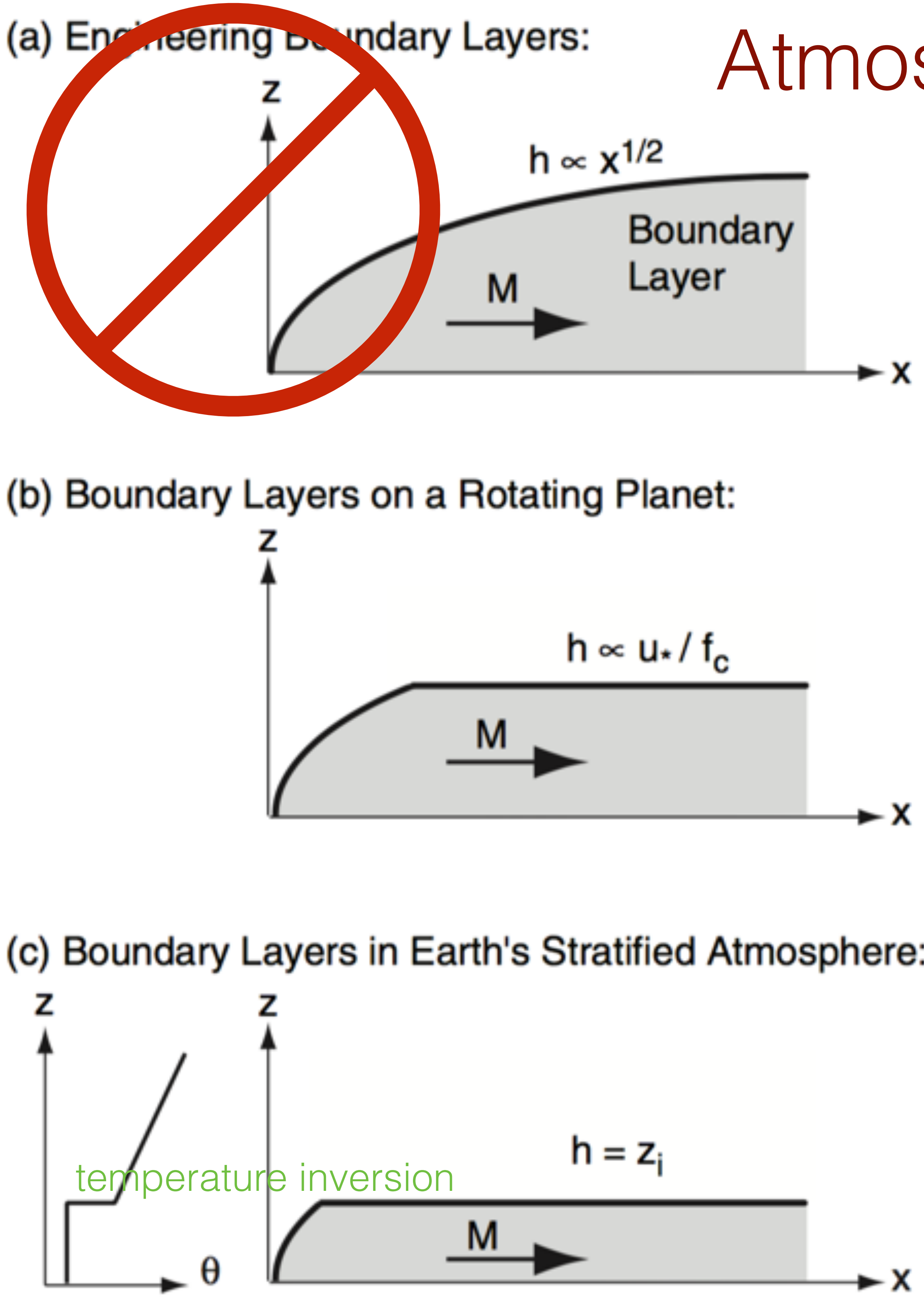

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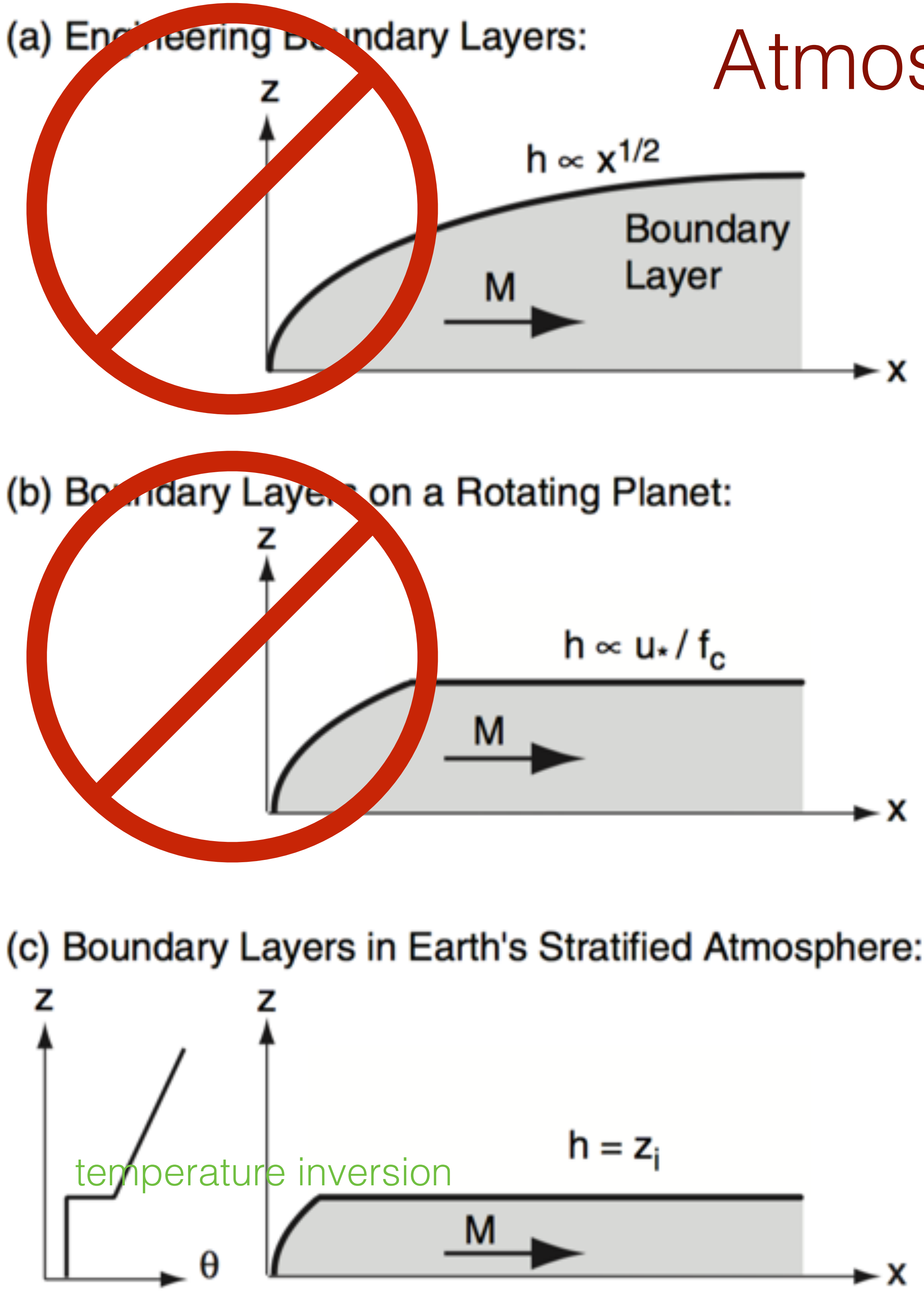

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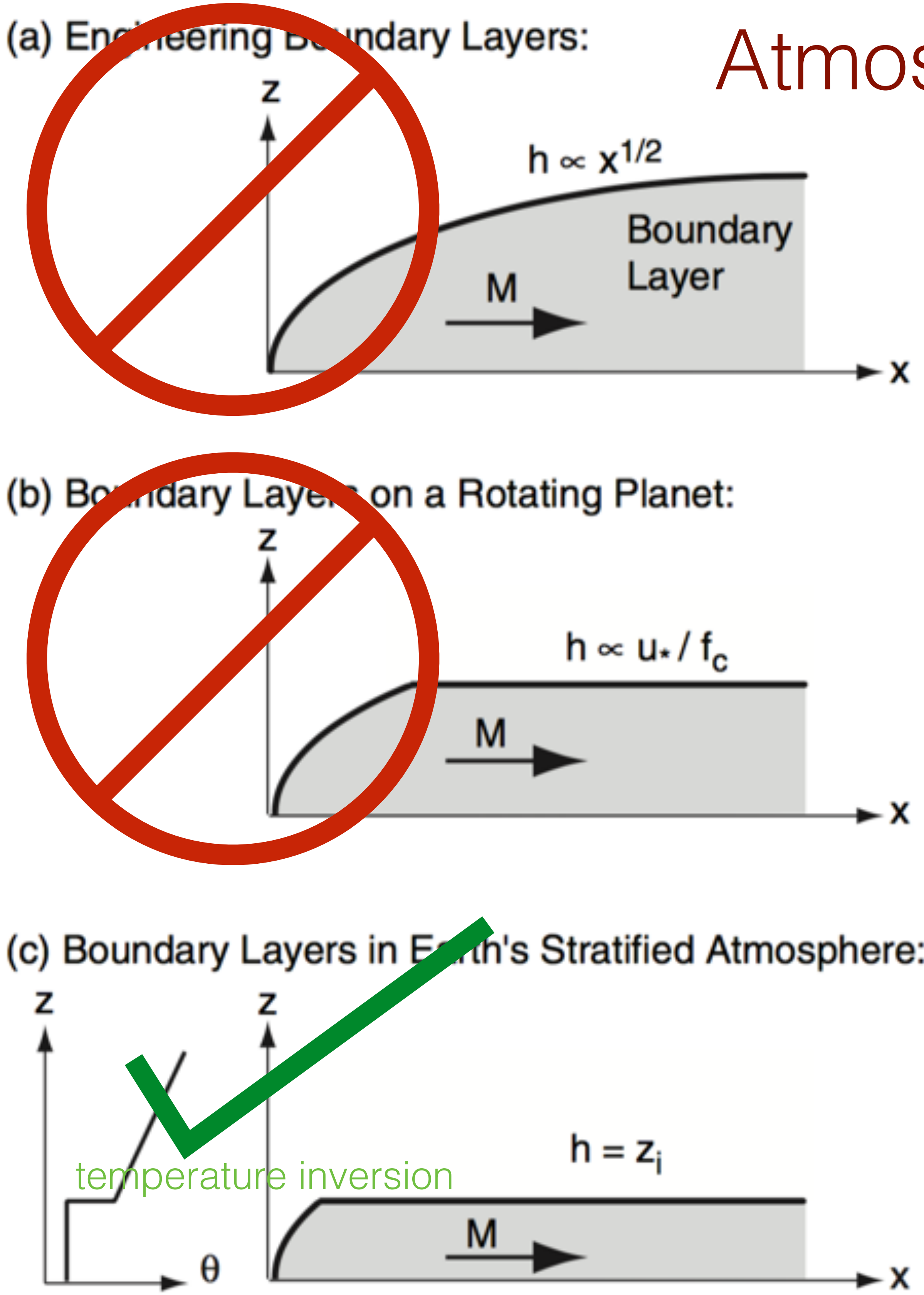

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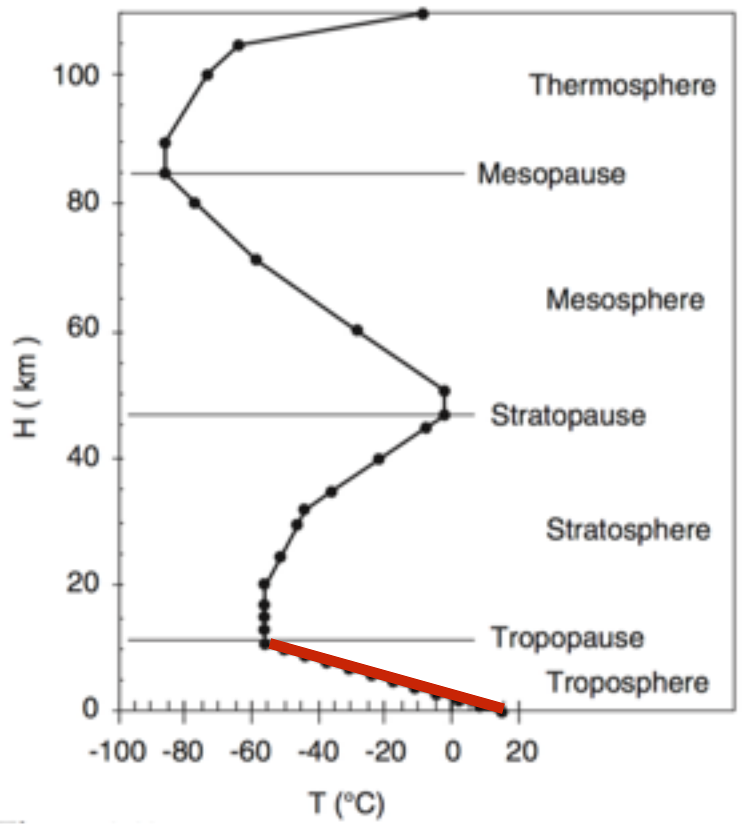
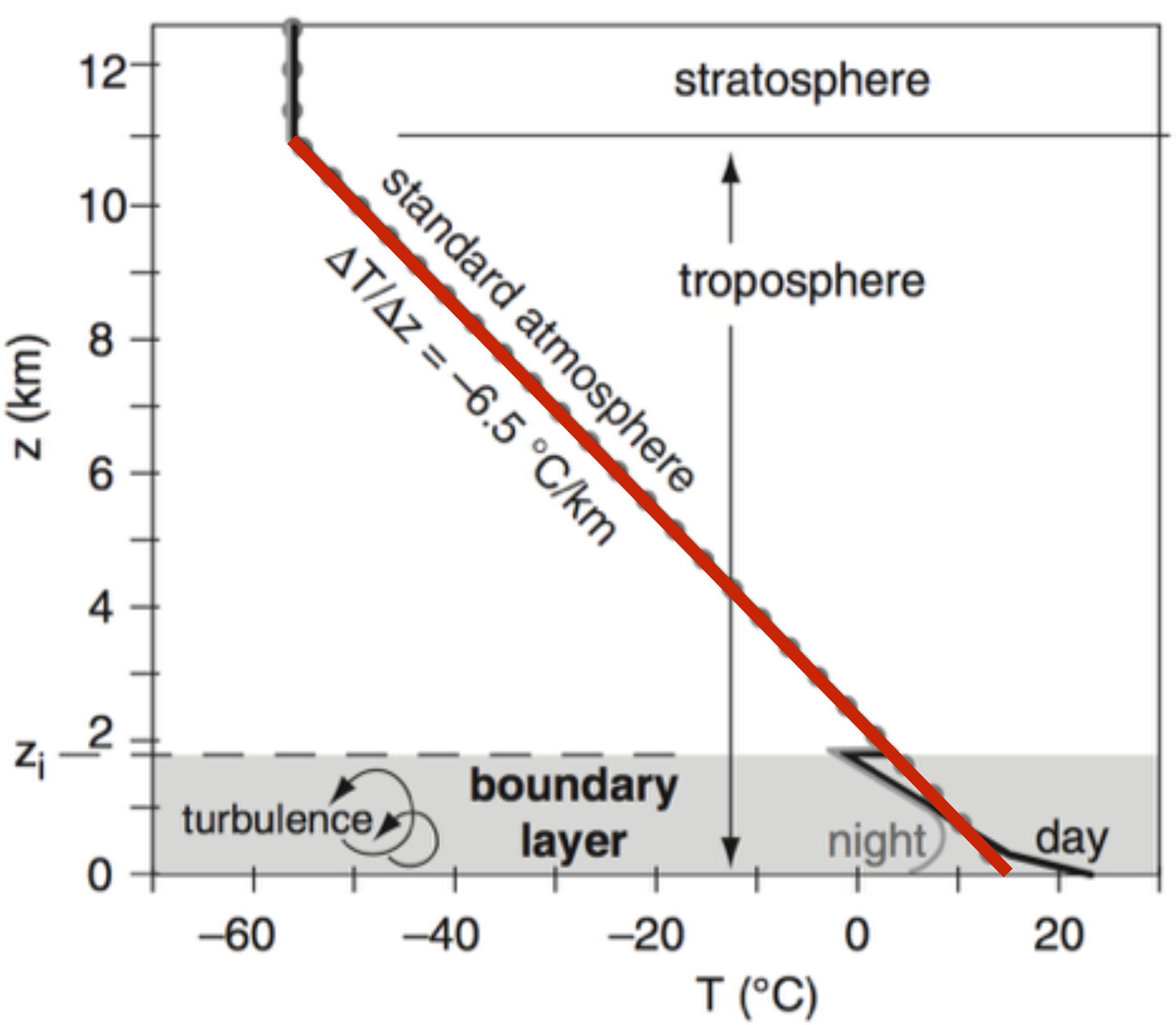
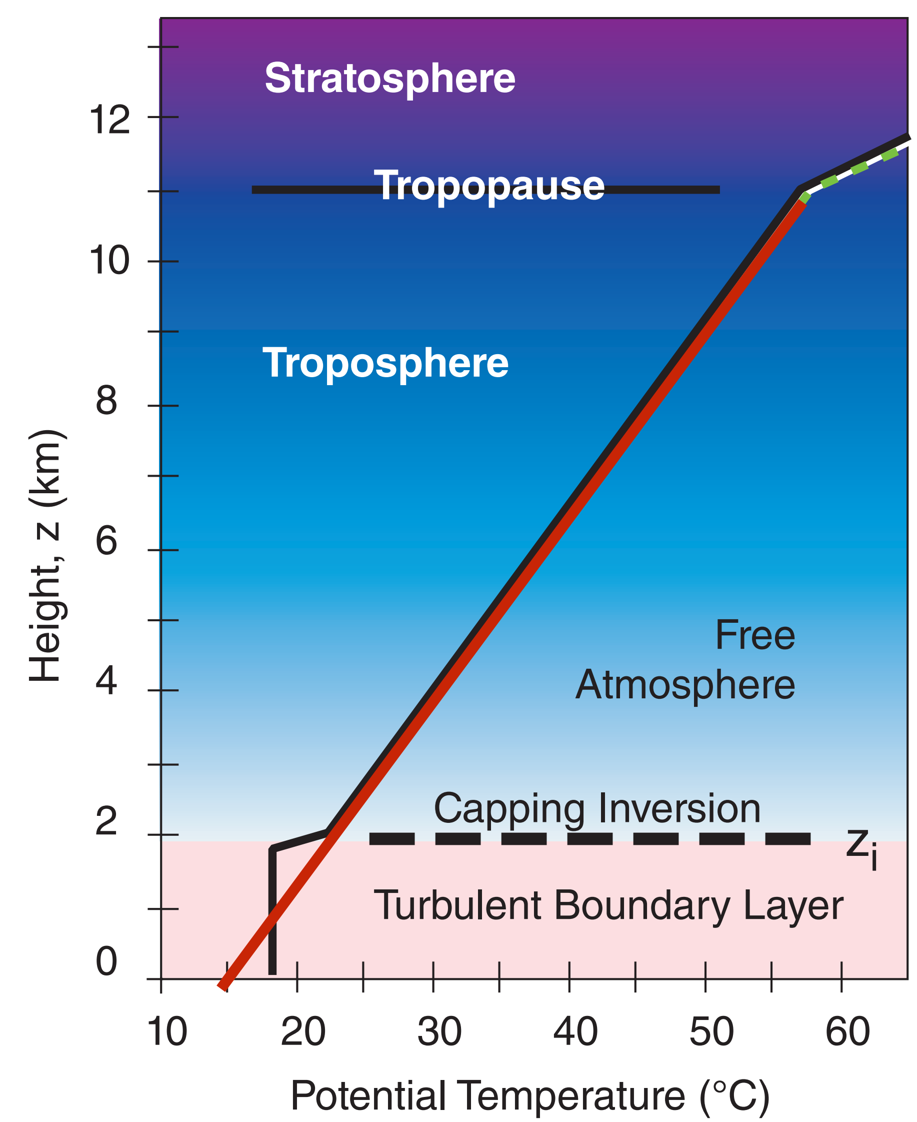
- Turbulence Creates the ABL.
- The ABL Traps Turbulence.

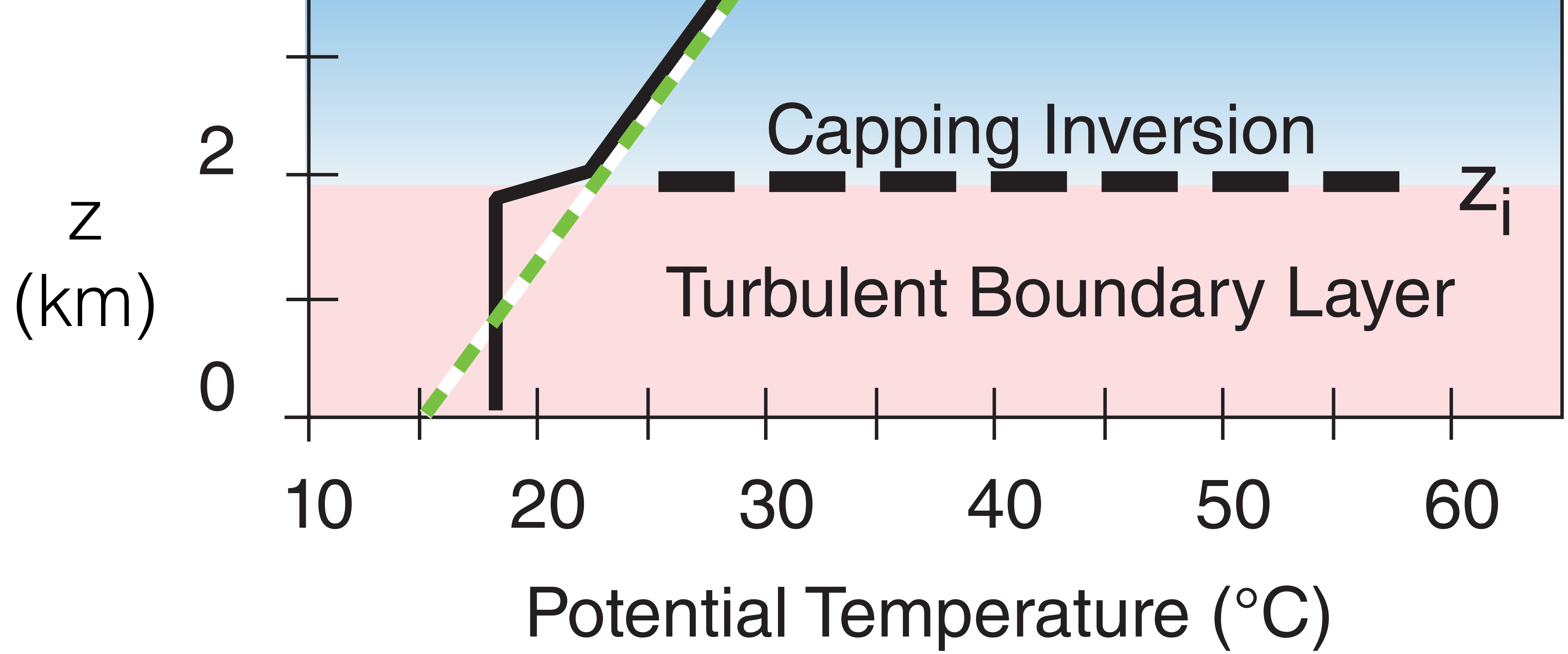
Thus: feedback.



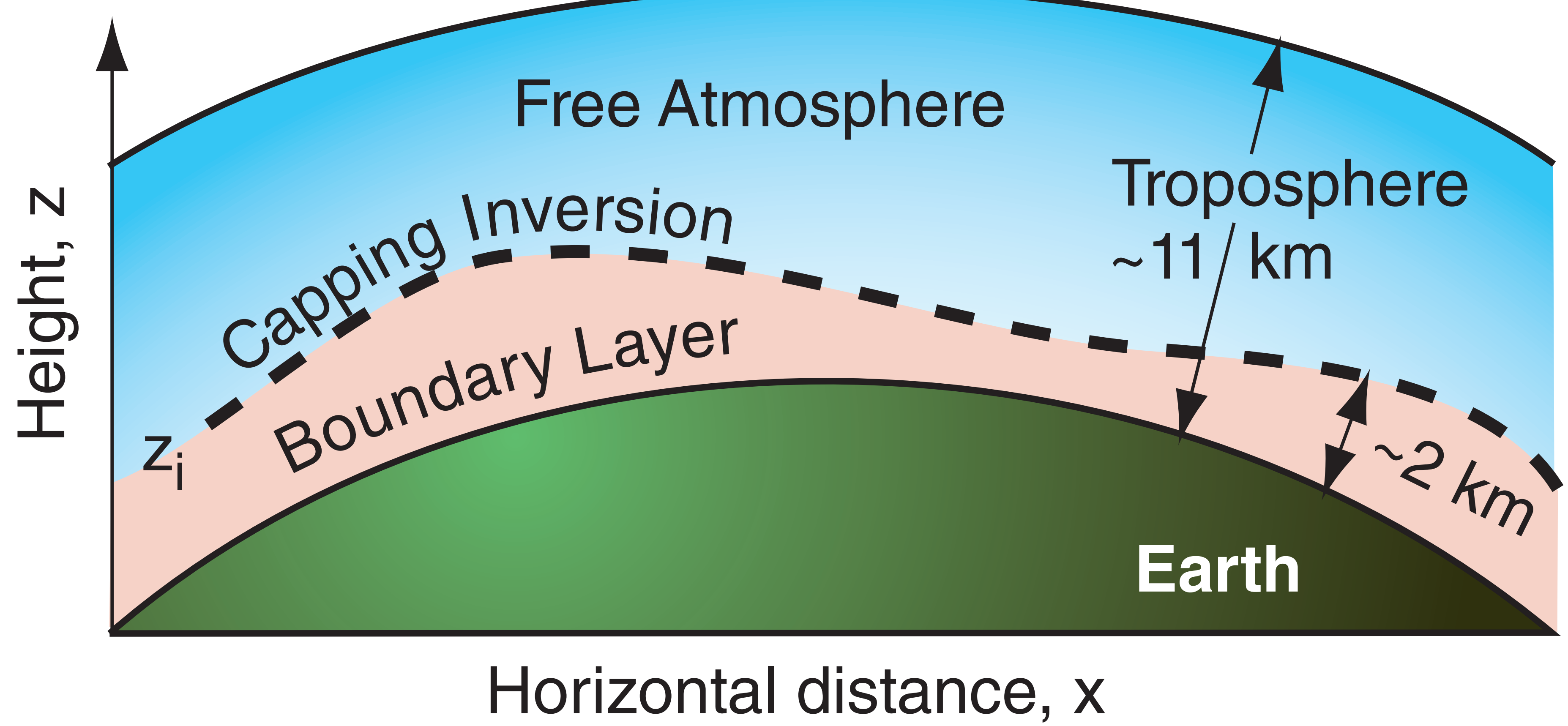
$\theta = T + \Gamma z$ = potential temperature, where Γ = 9.8 °C/km = dry adiabatic lapse rate







There is **always** a capping inversion at the top of the ABL.
Let z_i be the inversion height.



2. Static Stability

FLOW STABILITY

Stability is a characteristic of how a system reacts to small disturbances. If the disturbance is damped, the system is said to be **stable**. If the disturbance causes an amplifying response (irregular motions or regular oscillations), the system is **unstable**.

For **fluid-flow stability** we will focus on turbulent responses spanning the smallest eddies to deep thunderstorms. The stability characteristics are:

- **Unstable** air becomes, or is, **turbulent** (irregular, gusty, stormy).
- **Stable** air becomes, or is, **laminar** (non-turbulent, smooth, non-stormy).
- **Neutral** air has no tendency to change (disturbances neither amplify or dampen).

Flow stability is controlled by ALL the processes (buoyancy, inertia, wind shear, rotation, etc.) acting on the flow. However, to simplify our understanding of flow, we sometimes focus on just a subset of processes. If you ignore all processes except buoyancy, then you are studying **static stability**. If you include buoyancy and wind-shear processes, then you are studying **dynamic stability**.

Little or no pollutant dispersion if the flow is not turbulent.

<— use thermo diagram to determine static stability

2. Static Stability

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For **fluid-flow stability** we will focus on turbulent responses spanning the smallest eddies to deep thunderstorms. The stability characteristics are:

- **Unstable** air becomes, or is, **turbulent** (irregular, gusty, stormy). <- Vigorous pollutant dispersion
- **Stable** air becomes, or is, **laminar** (non-turbulent, smooth, non-stormy). <- No pollutant dispersion
- **Neutral** air has no tendency to change (disturbances neither amplify or dampen). <- Modest pollutant dispersion

---

Flow stability is controlled by ALL the processes (buoyancy, inertia, wind shear, rotation, etc.) acting on the flow. However, to simplify our understanding of flow, we sometimes focus on just a subset of processes. If you ignore all processes except buoyancy, then you are studying **static stability**. If you include buoyancy and wind-shear processes, then you are studying **dynamic stability**.

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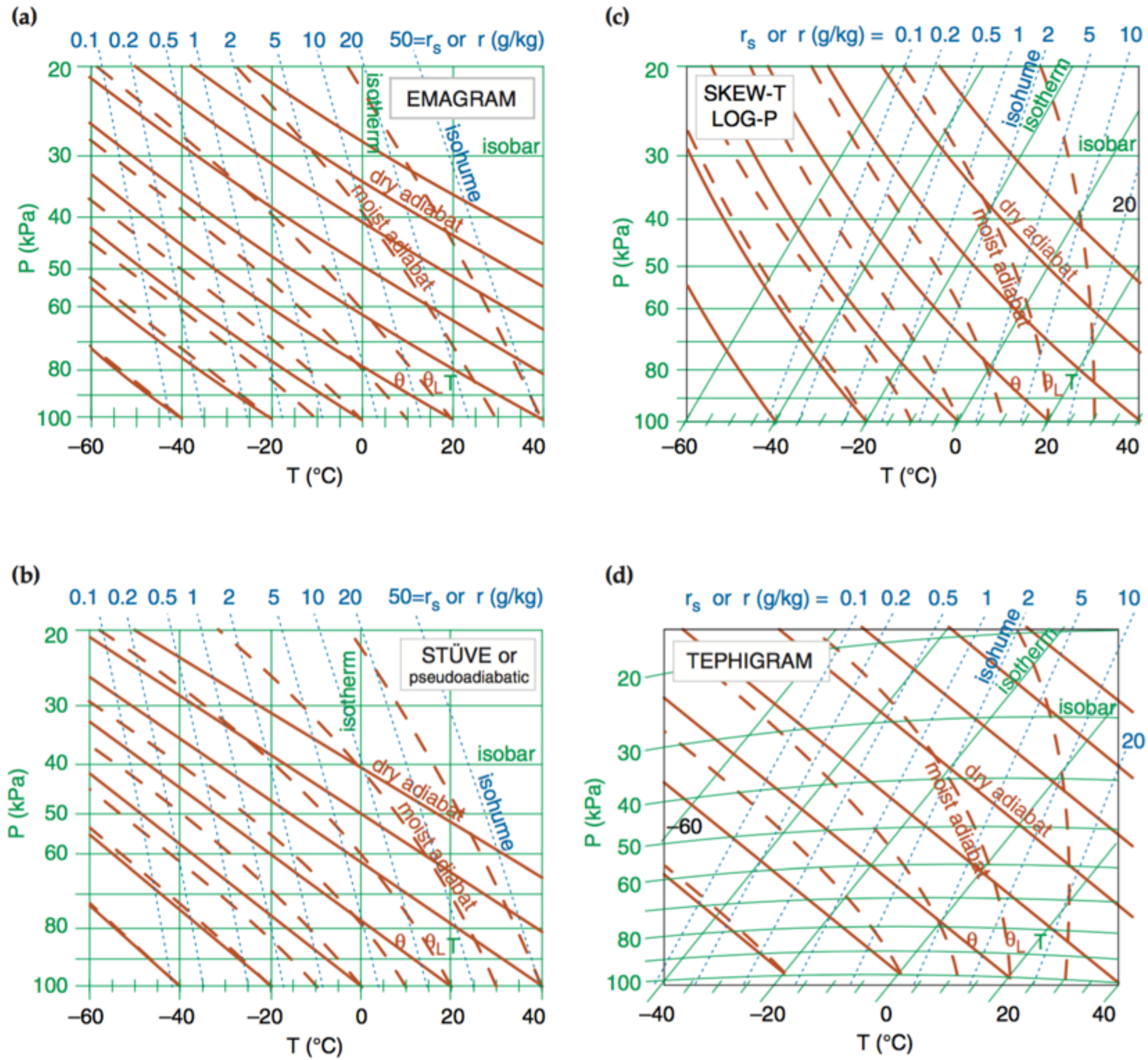
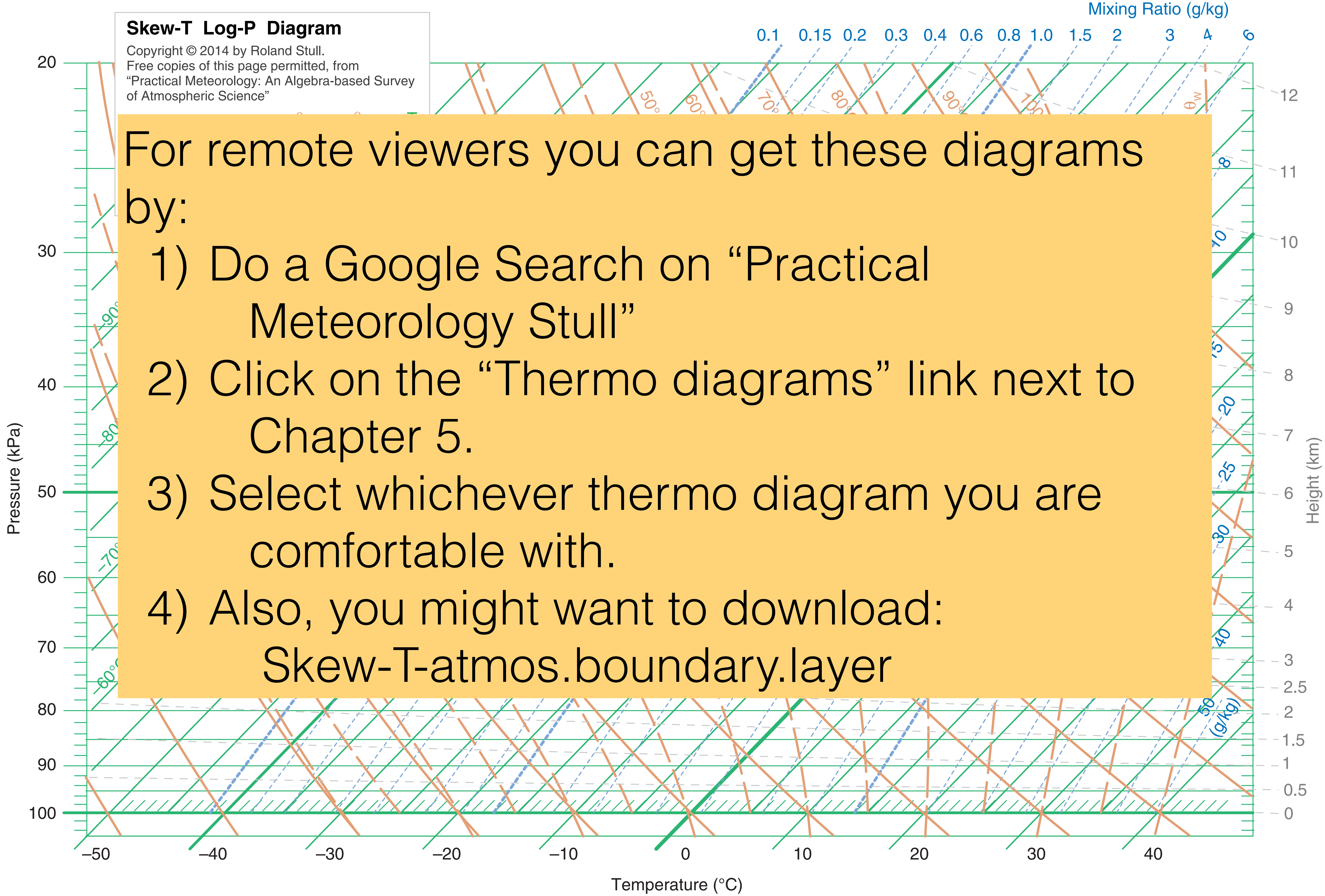
Thermo Diagrams



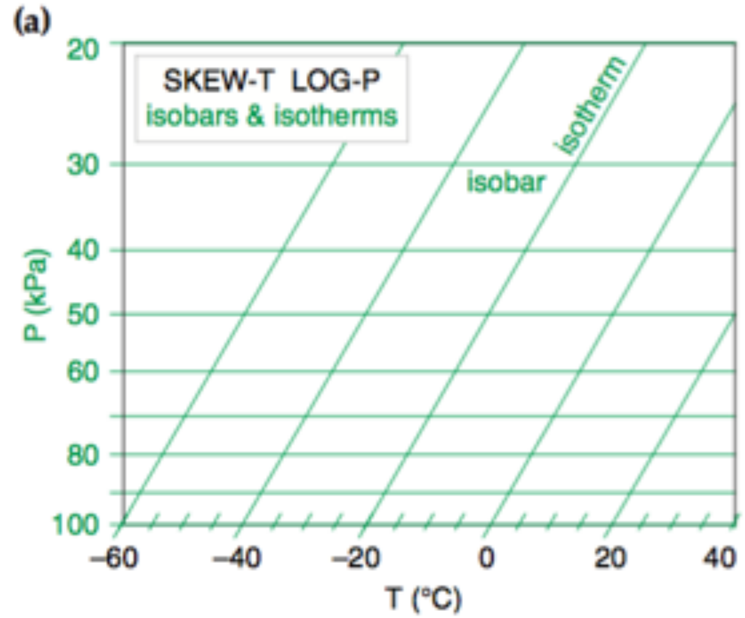
(Give handouts. Choice: skew-T or tephigram)



For remote viewers you can get these diagrams by:

1) Do a Google Search on "Practical Meteorology Stull"
2) Click on the "Thermo diagrams" link next to Chapter 5.
3) Select whichever thermo diagram you are comfortable with.
4) Also, you might want to download: Skew-T-atmos.boundary.layer

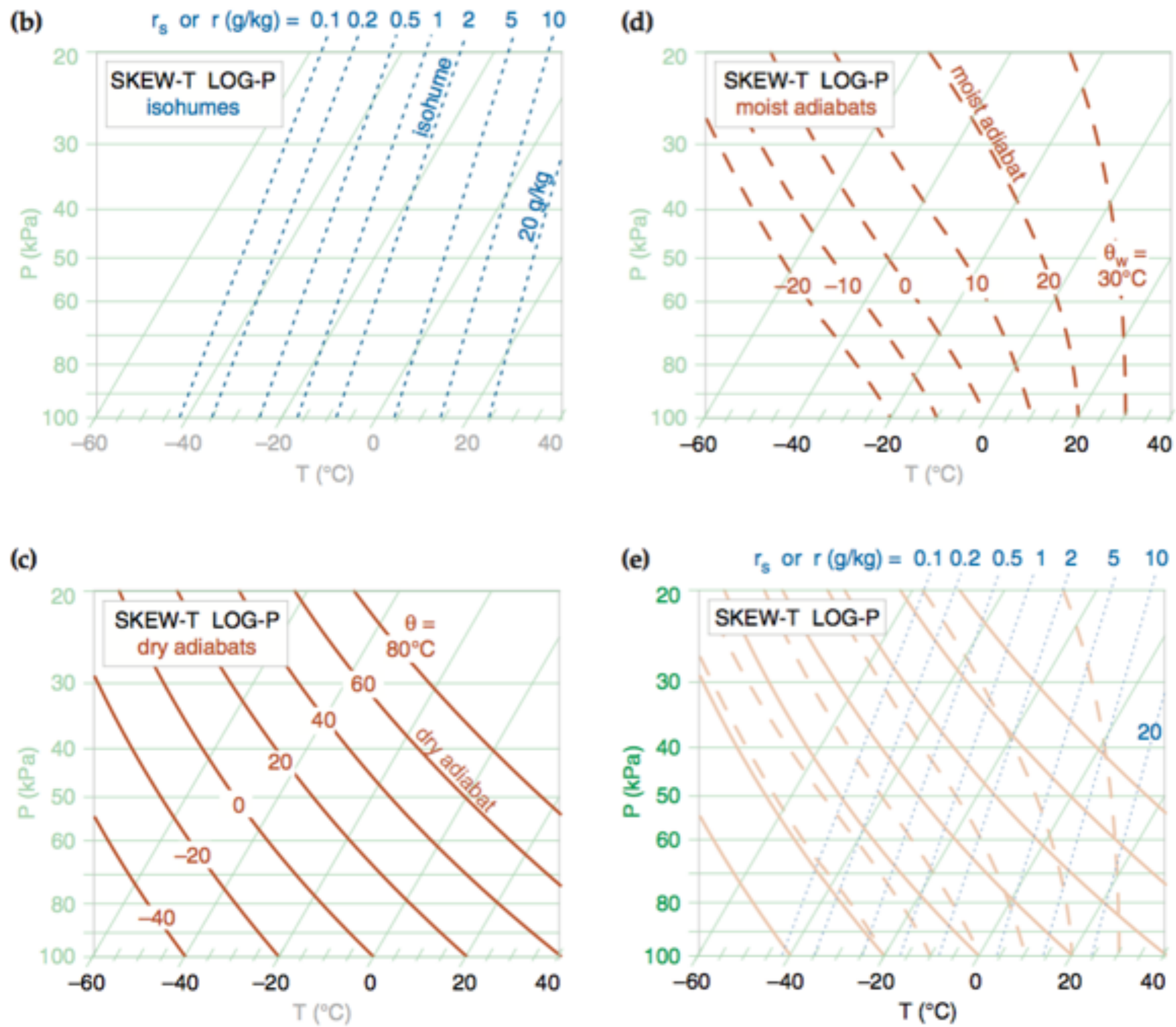
Skew-T Diagram

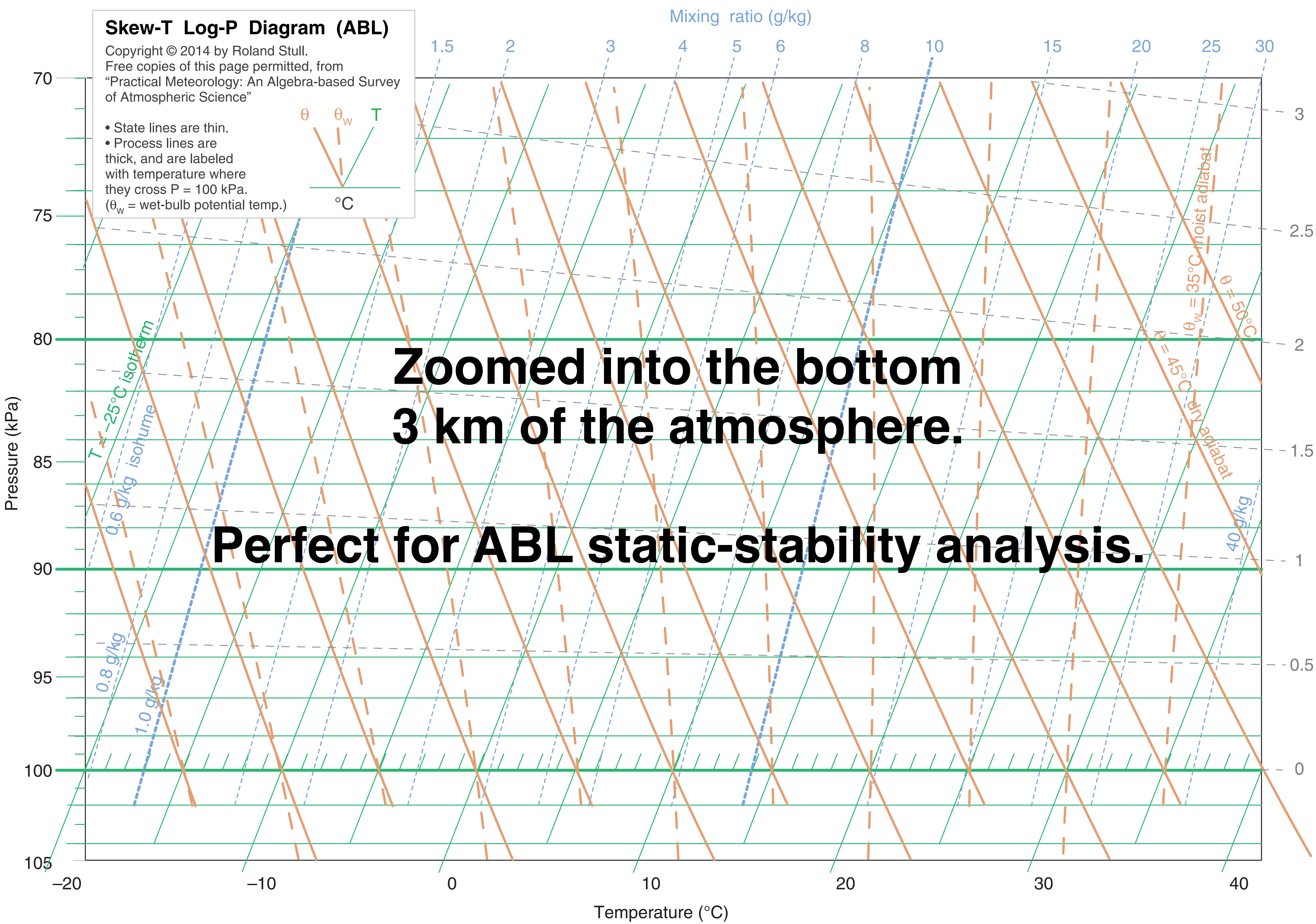


MORE ON THE SKEW-T

Because of the popularity of the Skew-T, we dissect it in Fig. 5.4, to aid in its interpretation. Tephigram users should find this equally useful, because the only noticeable difference is that the isobars are slightly curved, and increase in slope higher in the tephigram.

The Skew-T diagram is trivial to create, once you have already created an Emagram. The easiest way is to start with a graphic image of an Emagram, and skew it into a parallelogram (Fig. 5.5) using a graphics or drawing program.





Free downloads: search on "Practical Meteorology Stull". See end of Chapter 5.

Next: step by step instructions
on how to determine
static stability
from a sounding

(using a contrived example)

Step 1 find kinks in the sounding

(including top and bottom end points)

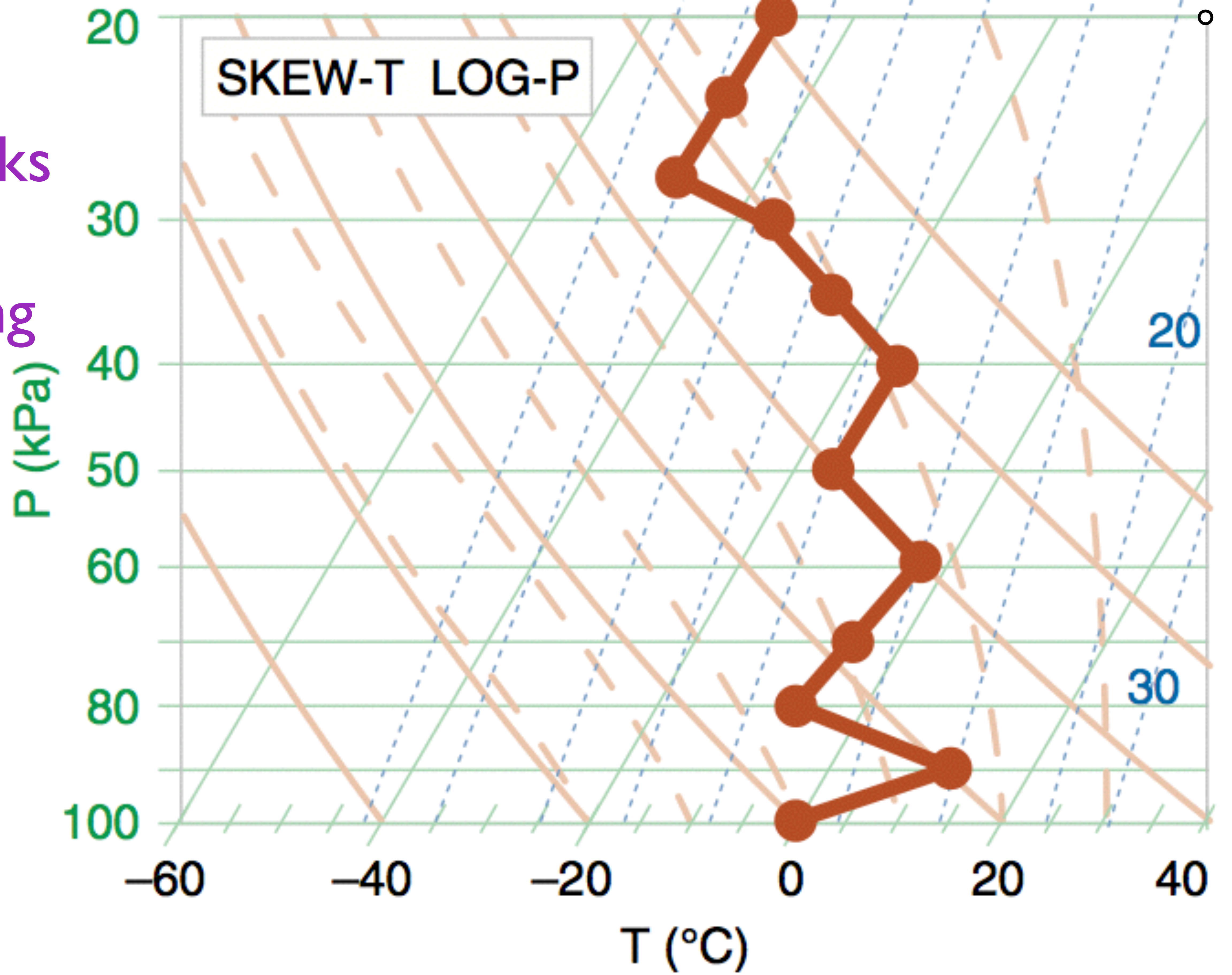


Figure 5.14a

Static stability determination. Step 1: Plot the sounding.

Step 1 find kinks in the sounding (including top and bottom end points)

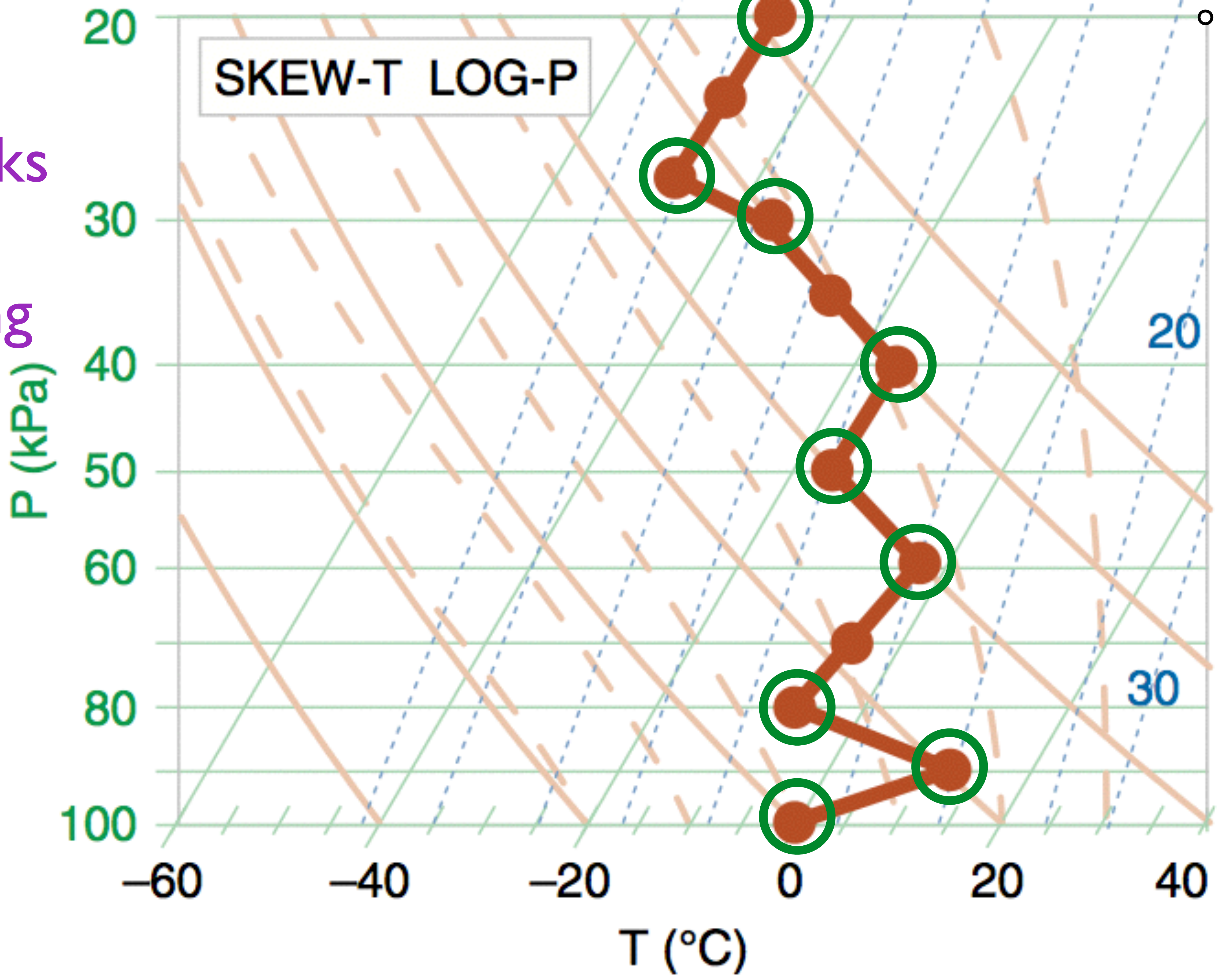


Figure 5.14a

Static stability determination. Step 1: Plot the sounding.

Step 2

from each kink, conceptually lift an air parcel following a dry adiabat.

If buoyancy force is in the same direction as your lifting, then label with “U” for unstable.

If buoyancy would return it to its starting point, then label as “S” for stable.

Otherwise, “N” for neutral.

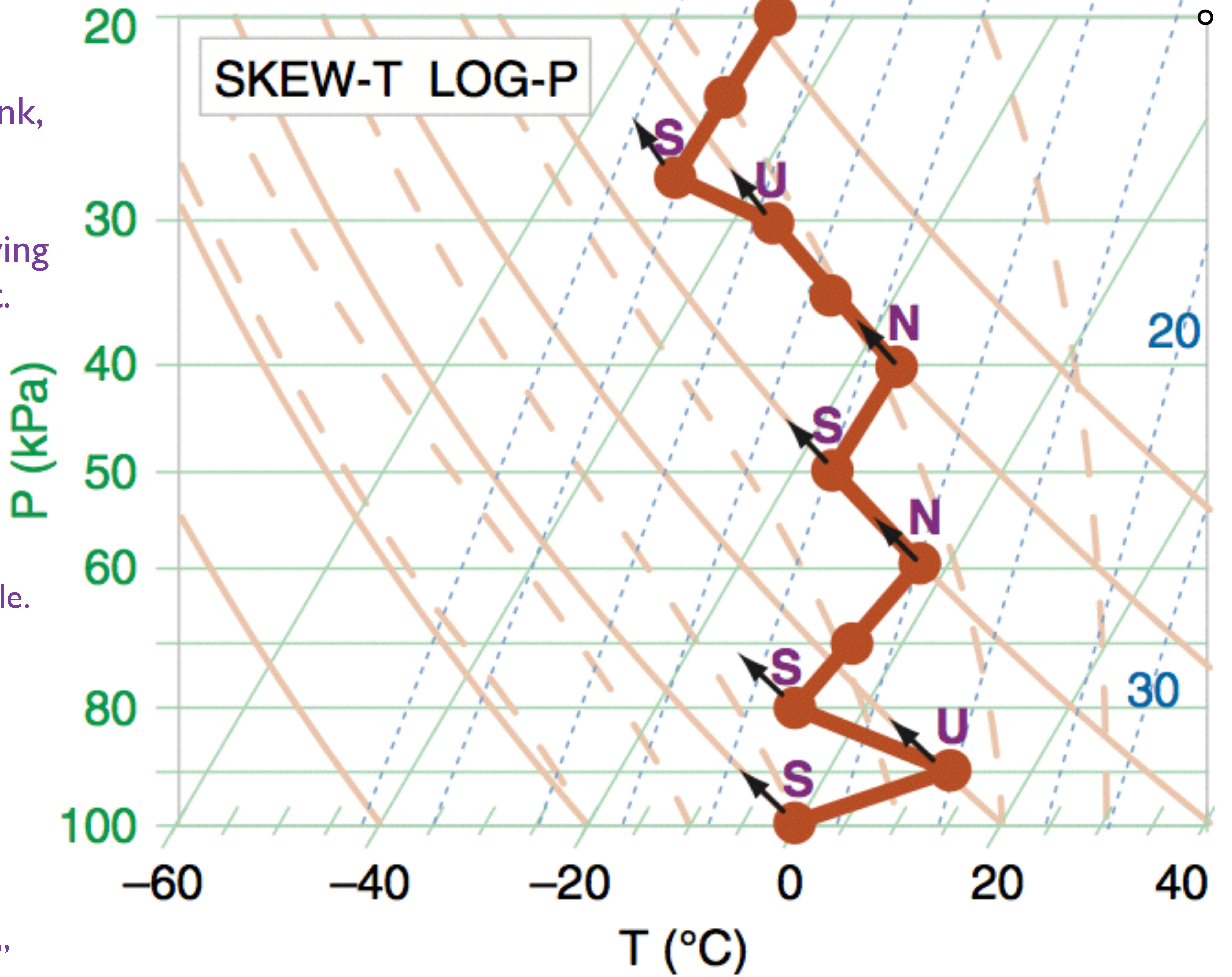


Figure 5.14b

Static stability determination. Step 2: Upward displacements.

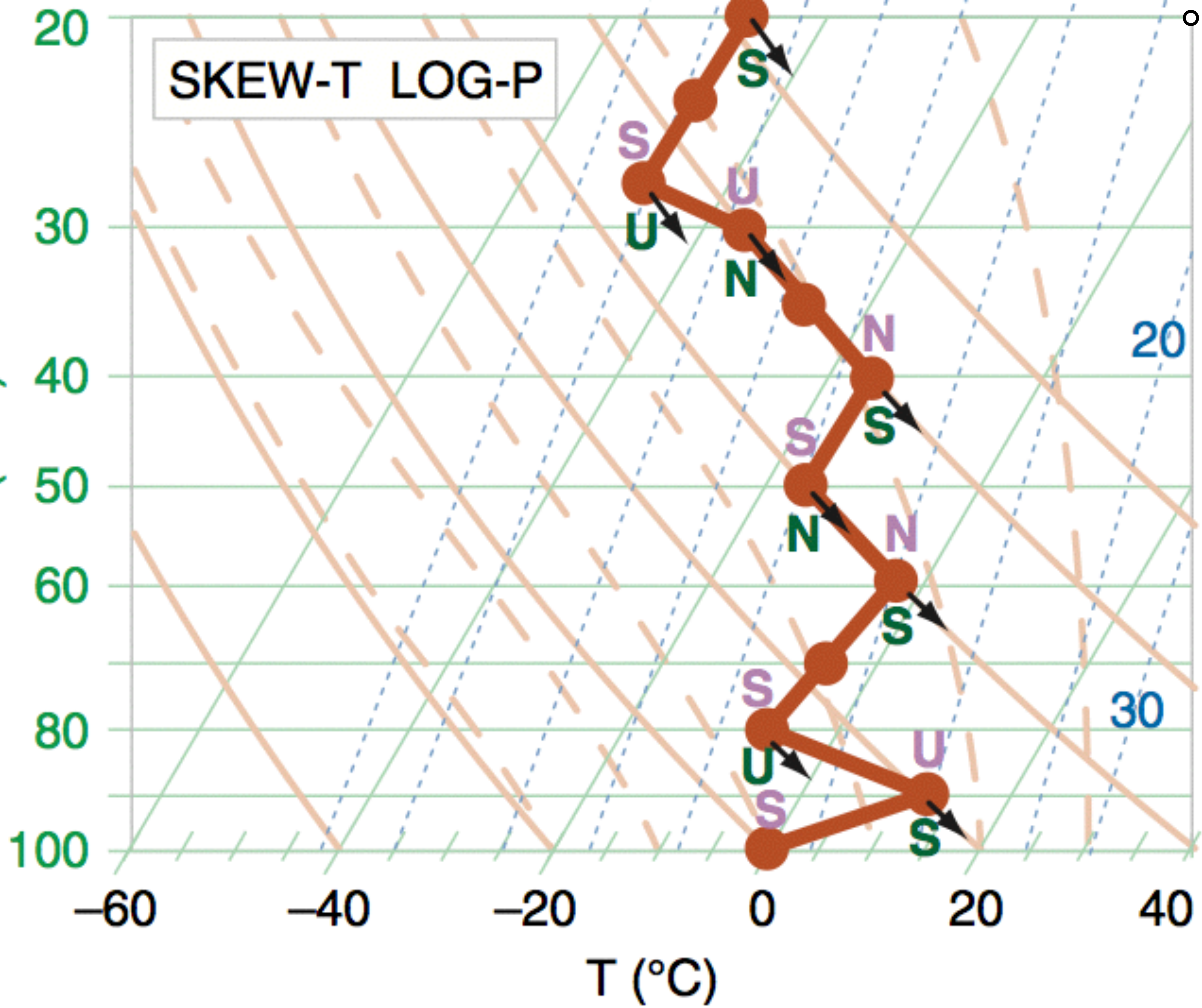
Step 3

from each kink, conceptually <u>lower</u> an air parcel following a dry adiabat.

If buoyancy force is in the same direction as your initial motion, then label with "U" for unstable.

If buoyancy would return it to its starting point, then label as "S" for stable.

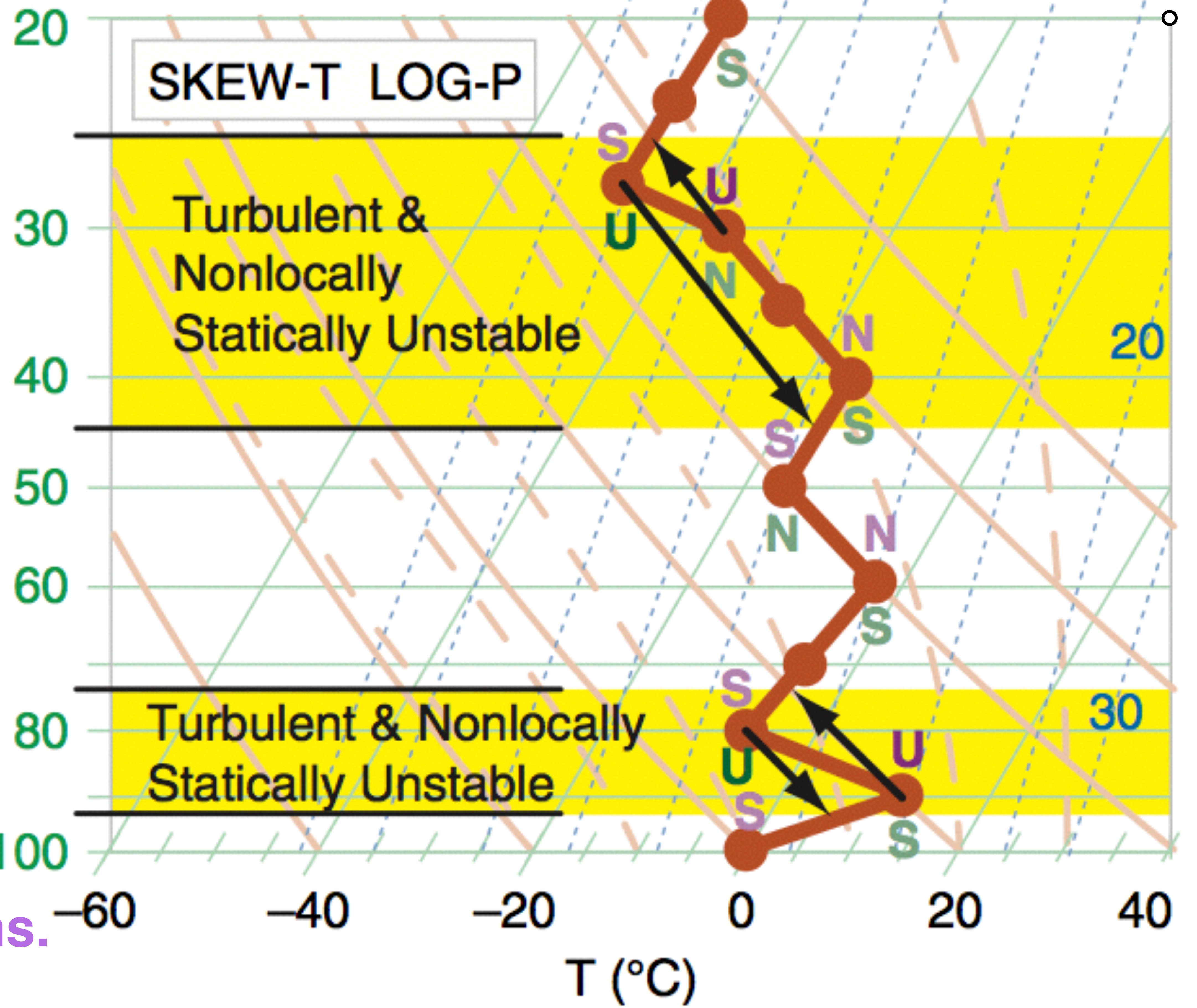
Otherwise, "N" for neutral.



Step 4

for all the motions labeled with "U", continue moving the parcial dry adiabatically until it hits the sounding or the ground.

The superposition of these "U" domains identifies all the **Unstable** layers in the atmos.



Unstable always wins.

Figure 5.14c & d

Static stability determination. (c) Step 3: Downward displace-

Step 4

the sounding
or the ground.

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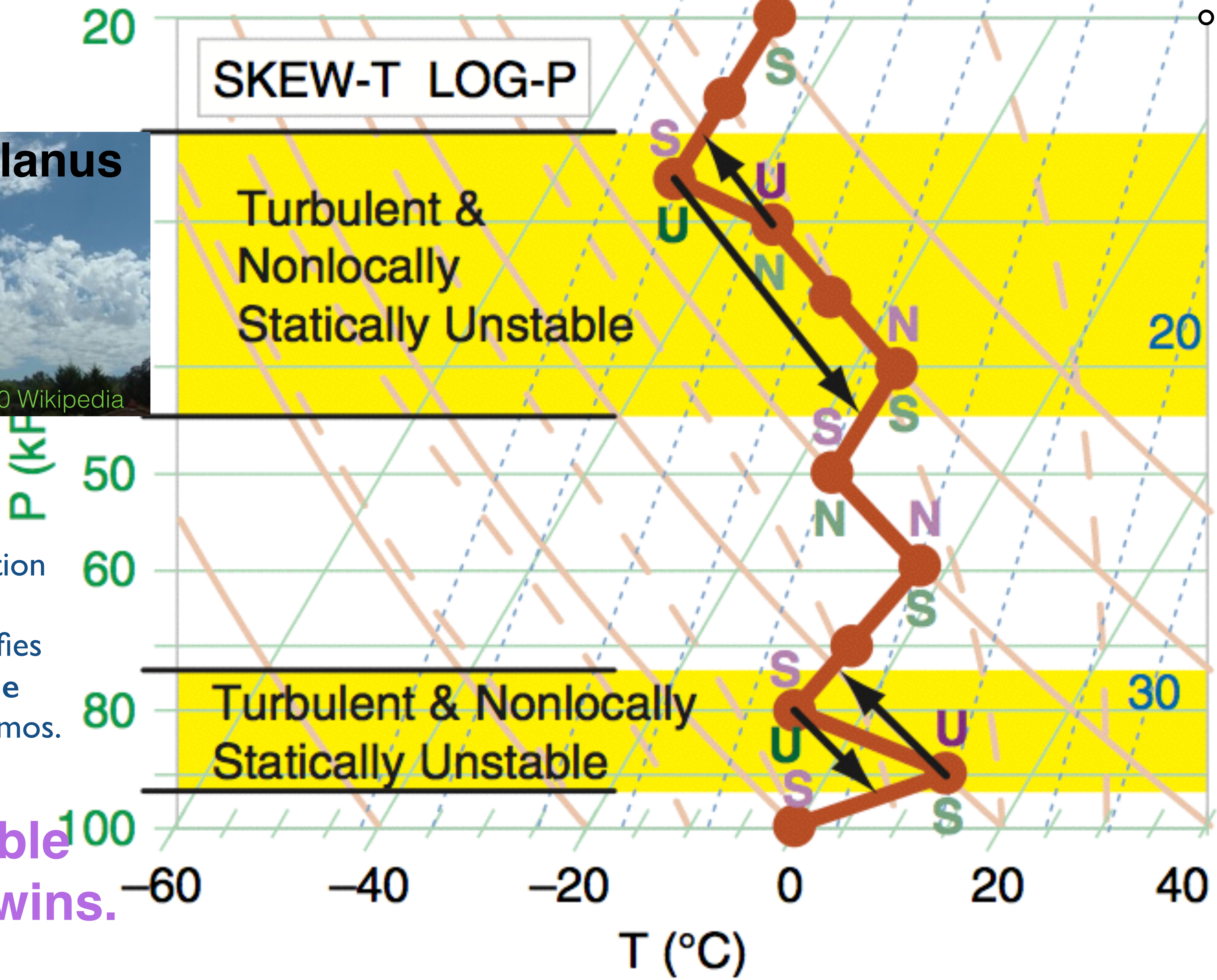

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Figure 5.14c & d

Static stability determination. (c) Step 3: Downward displace-

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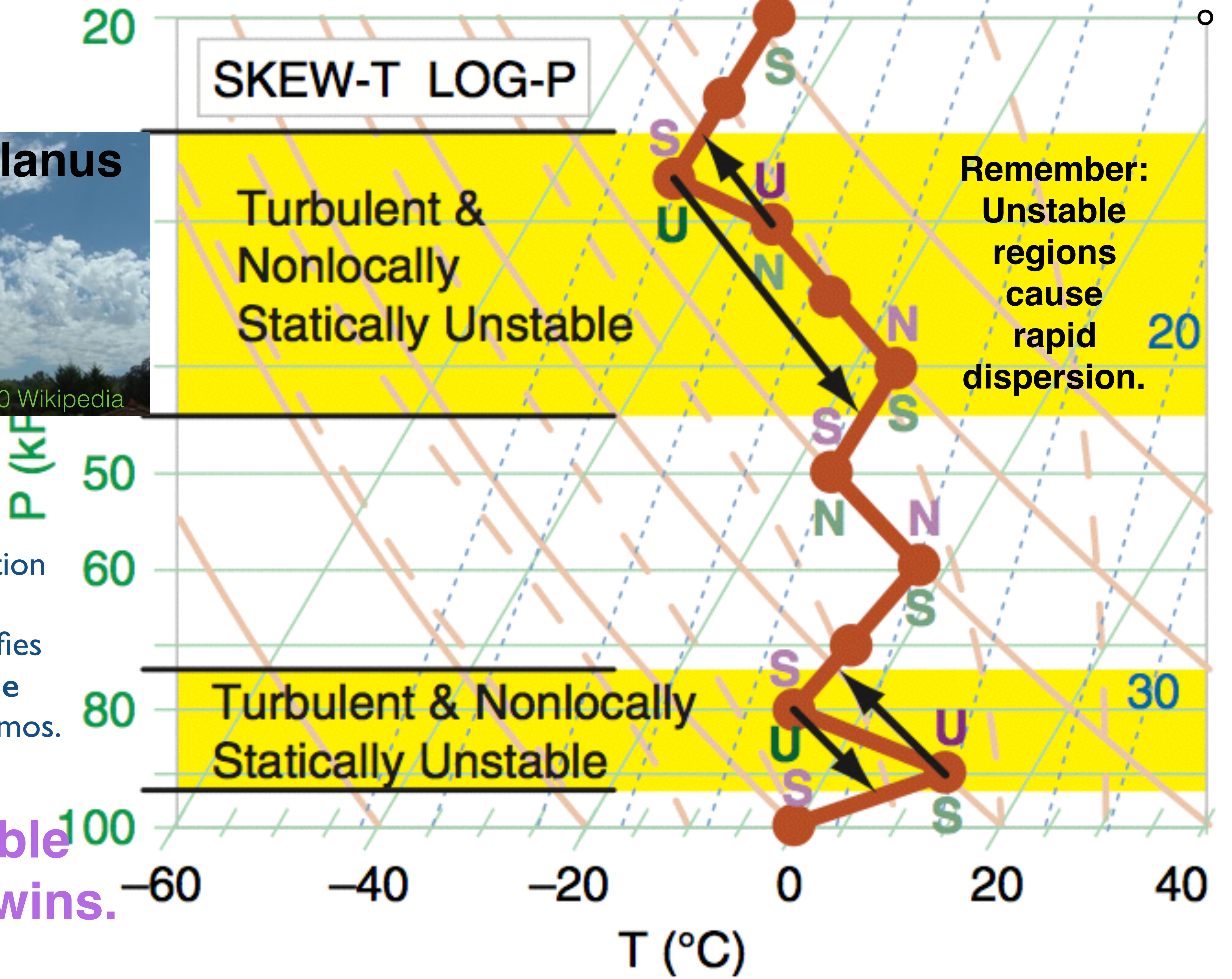


Unstable always wins.

Figure 5.14c & d

Static stability determination. (c) Step 3: Downward displace-

Step 5

all <u>remaining</u> <u>portions</u> of "S" regions that are not unstable are STABLE,

and all <u>remaining</u> <u>portions</u> of "N" regions that are not unstable are NEUTRAL.

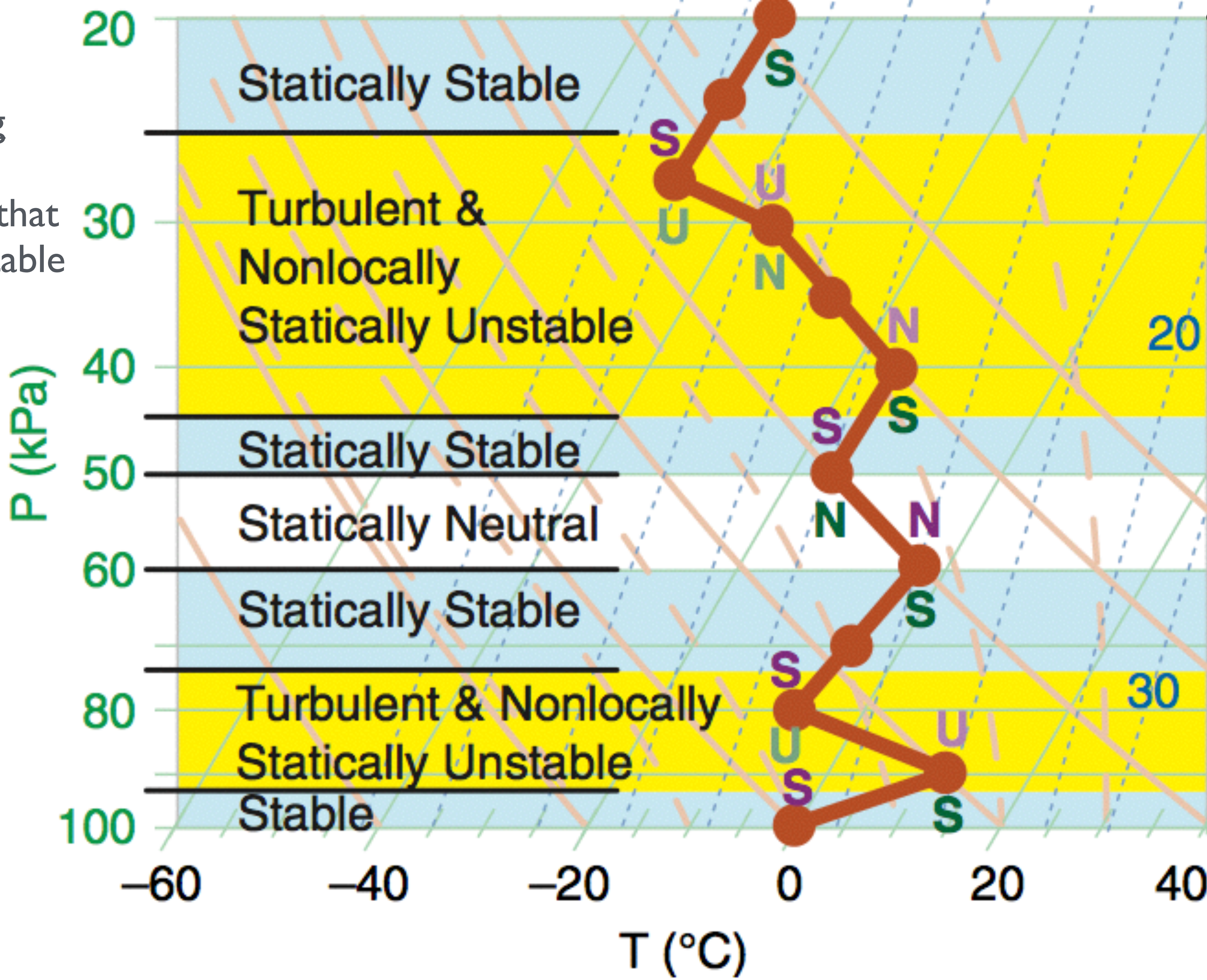
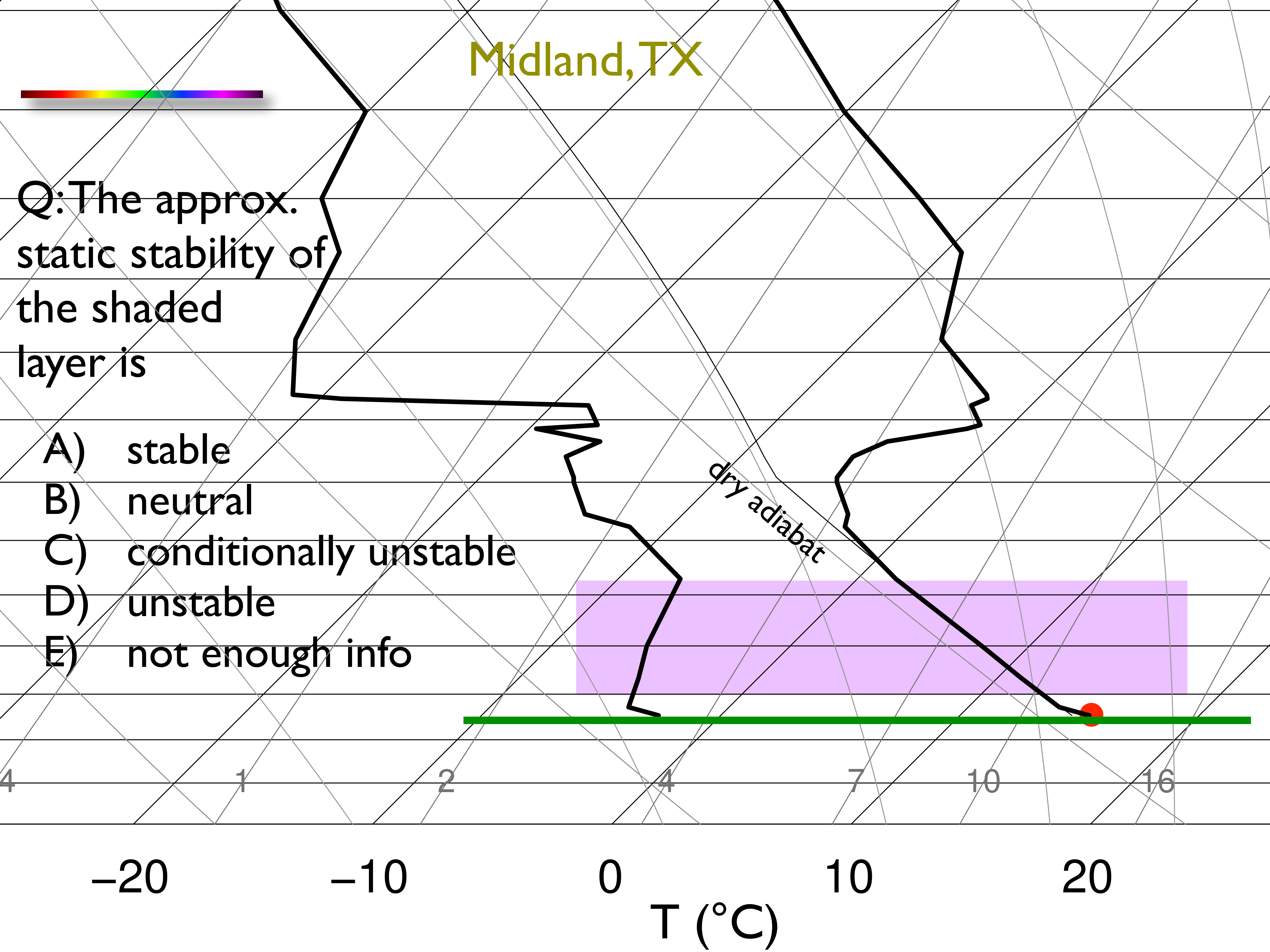


Figure 5.14e

Static stability determination. Step 5: Identify statically stable

Q: The approx. static stability of the shaded layer is

A) stable
B) neutral
C) conditionally unstable
D) unstable
E) not enough info



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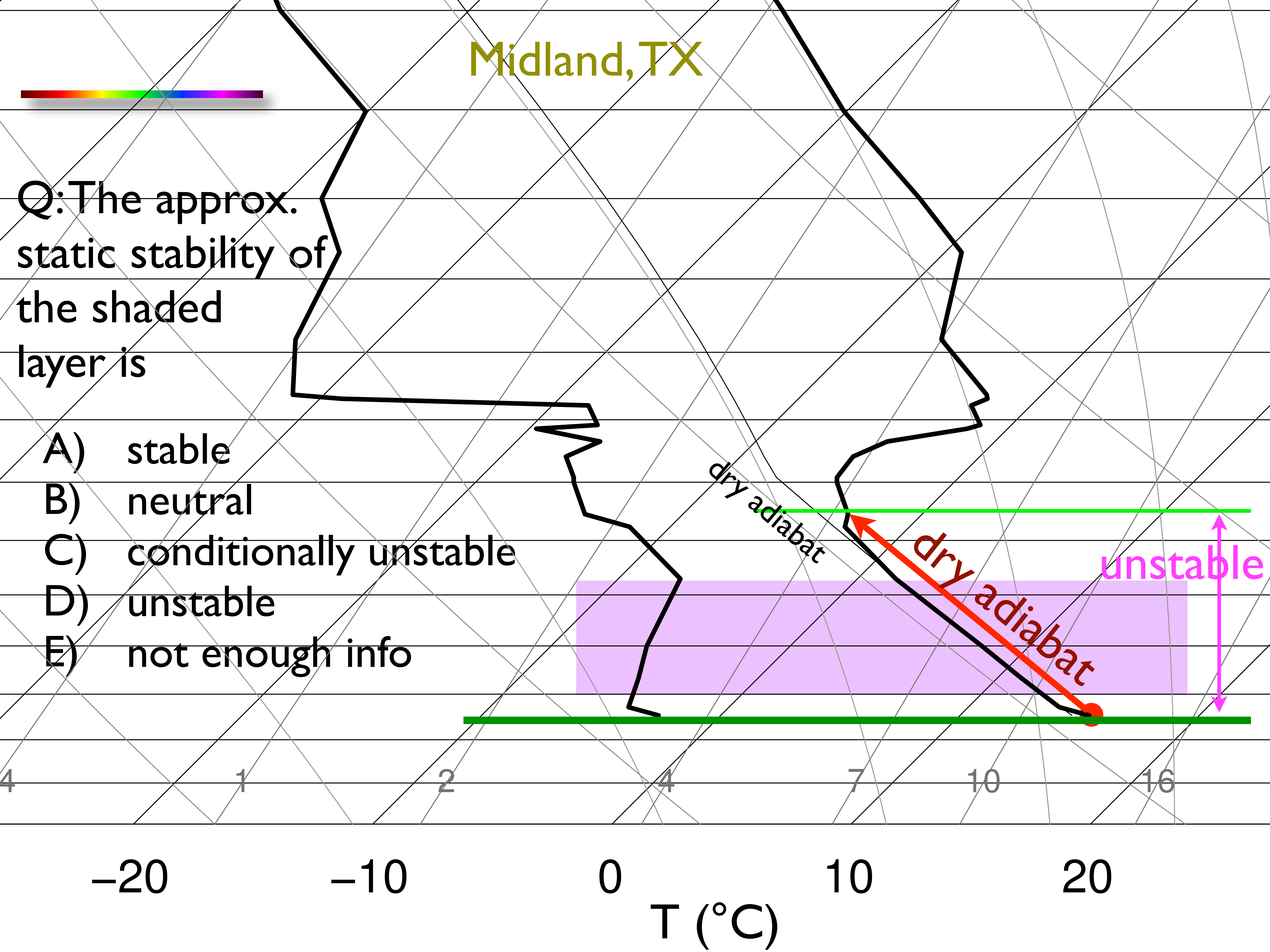

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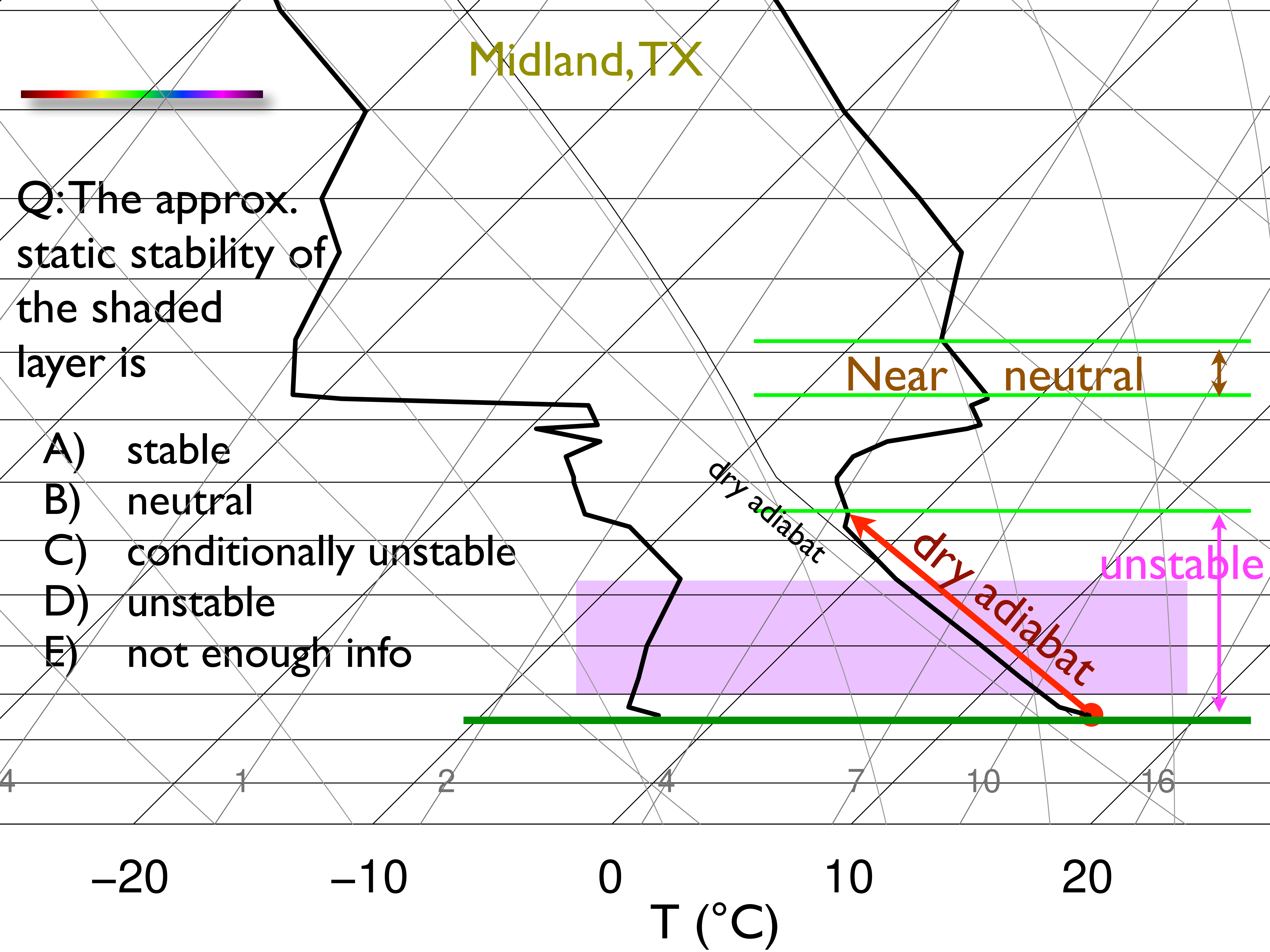

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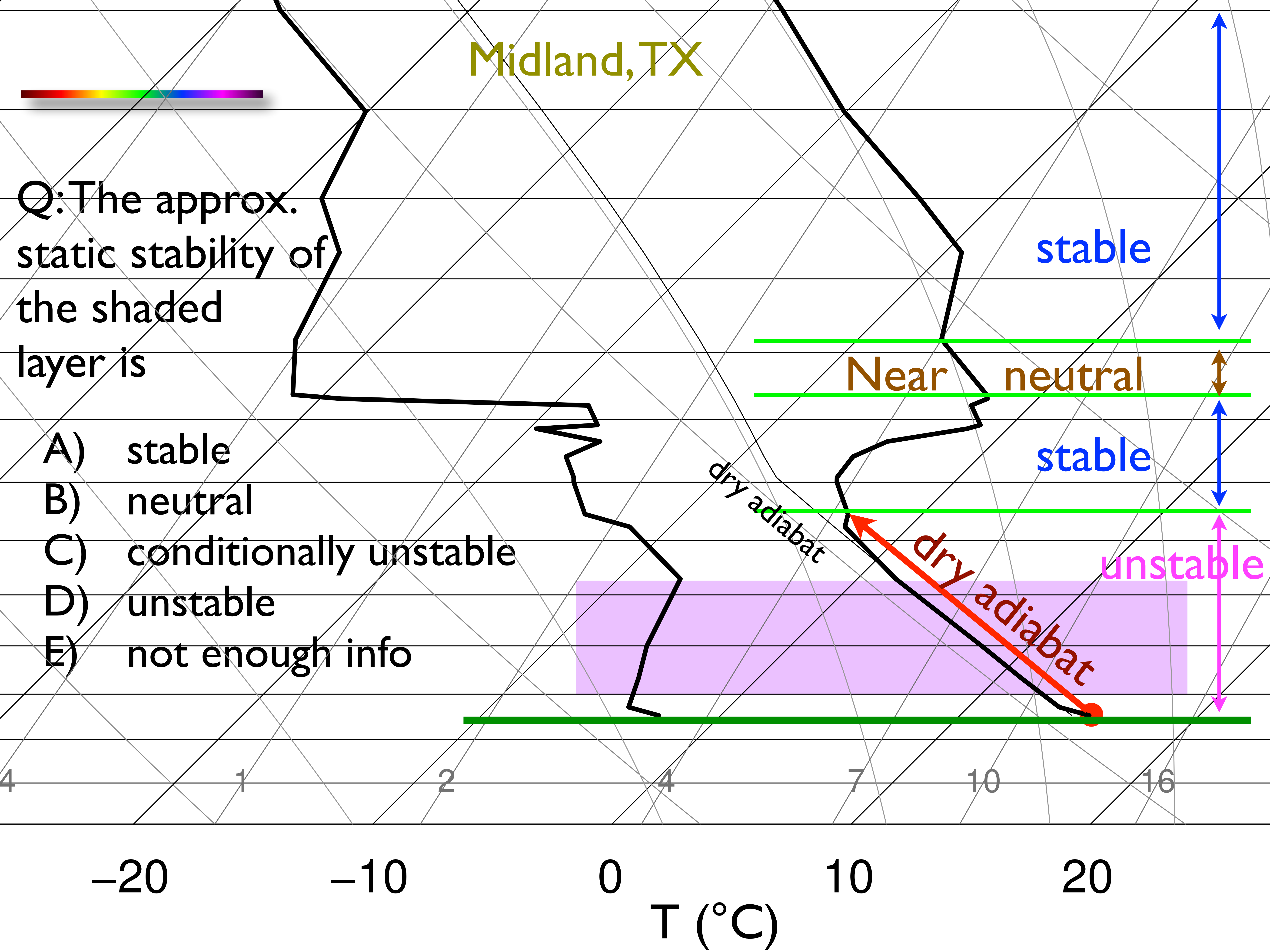
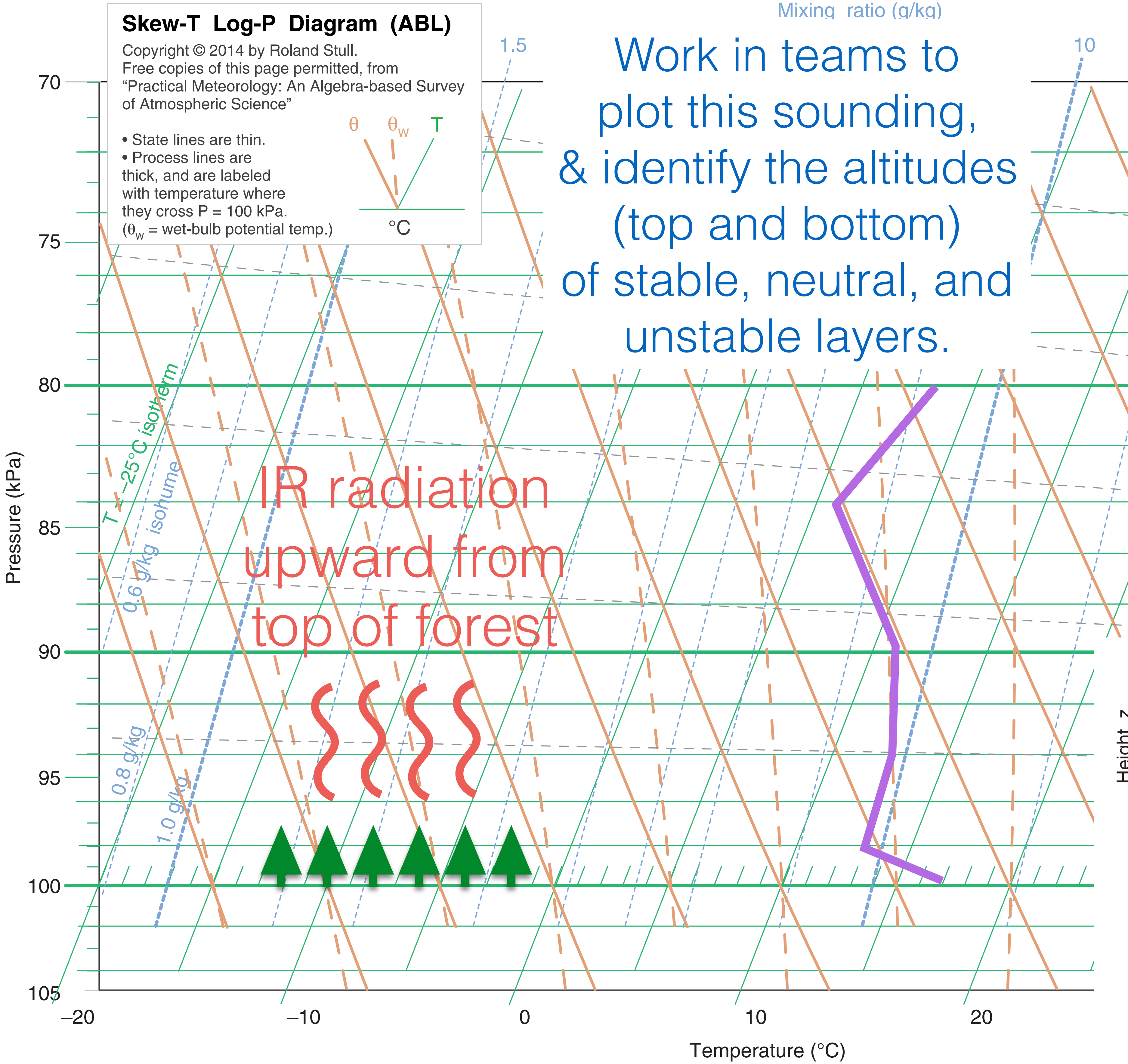


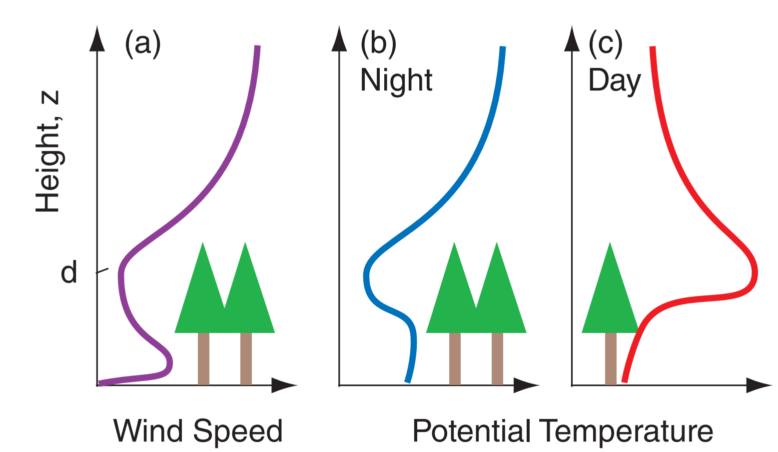
Scenario: **nighttime** over a forest. Calm winds. Clear skies.

Work in teams to plot this sounding, & identify the altitudes (top and bottom) of stable, neutral, and unstable layers.

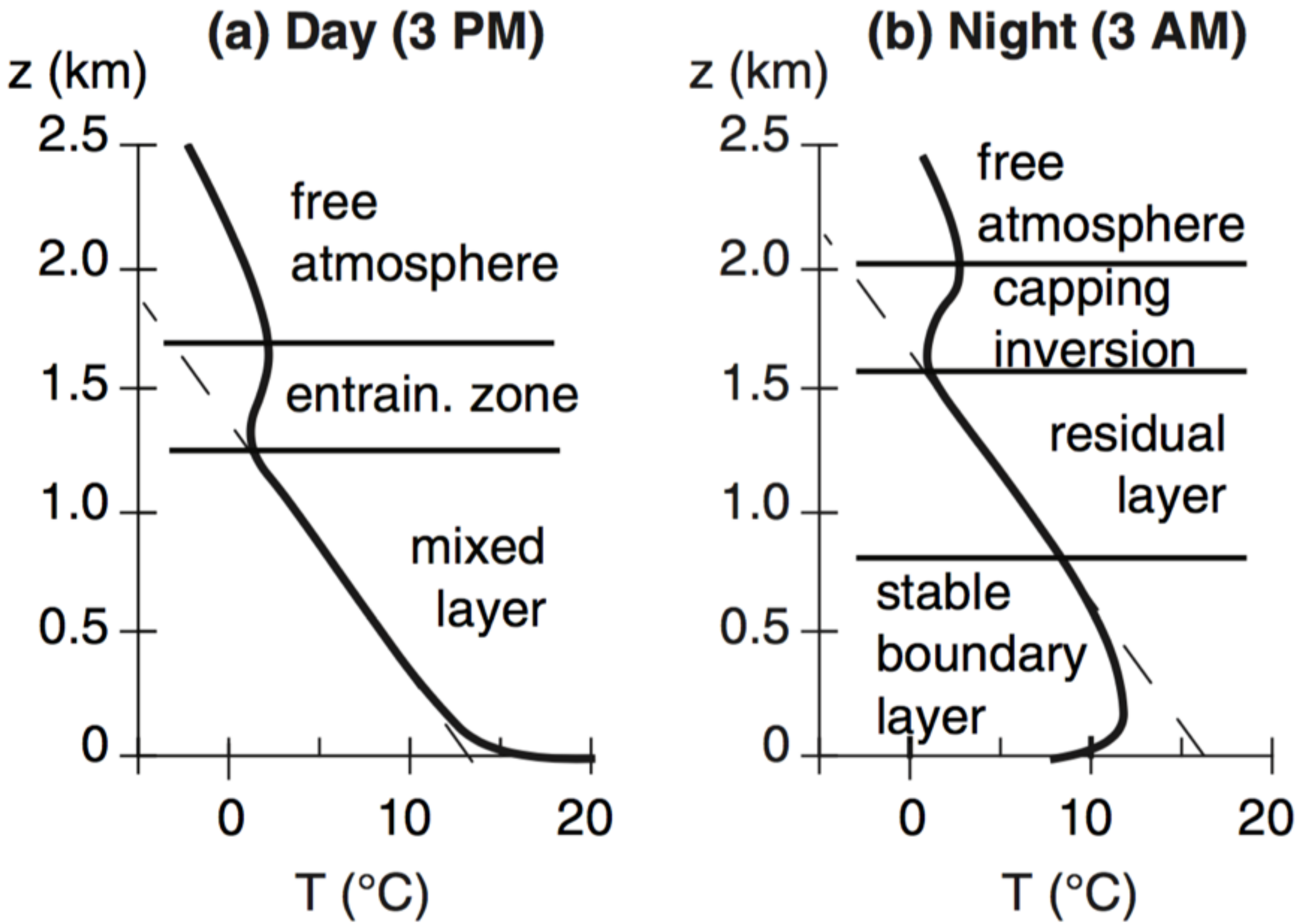


Sounding

P (kPa)	T (°C)
80	8
84	6
90	11
94	13
98	13
100	17

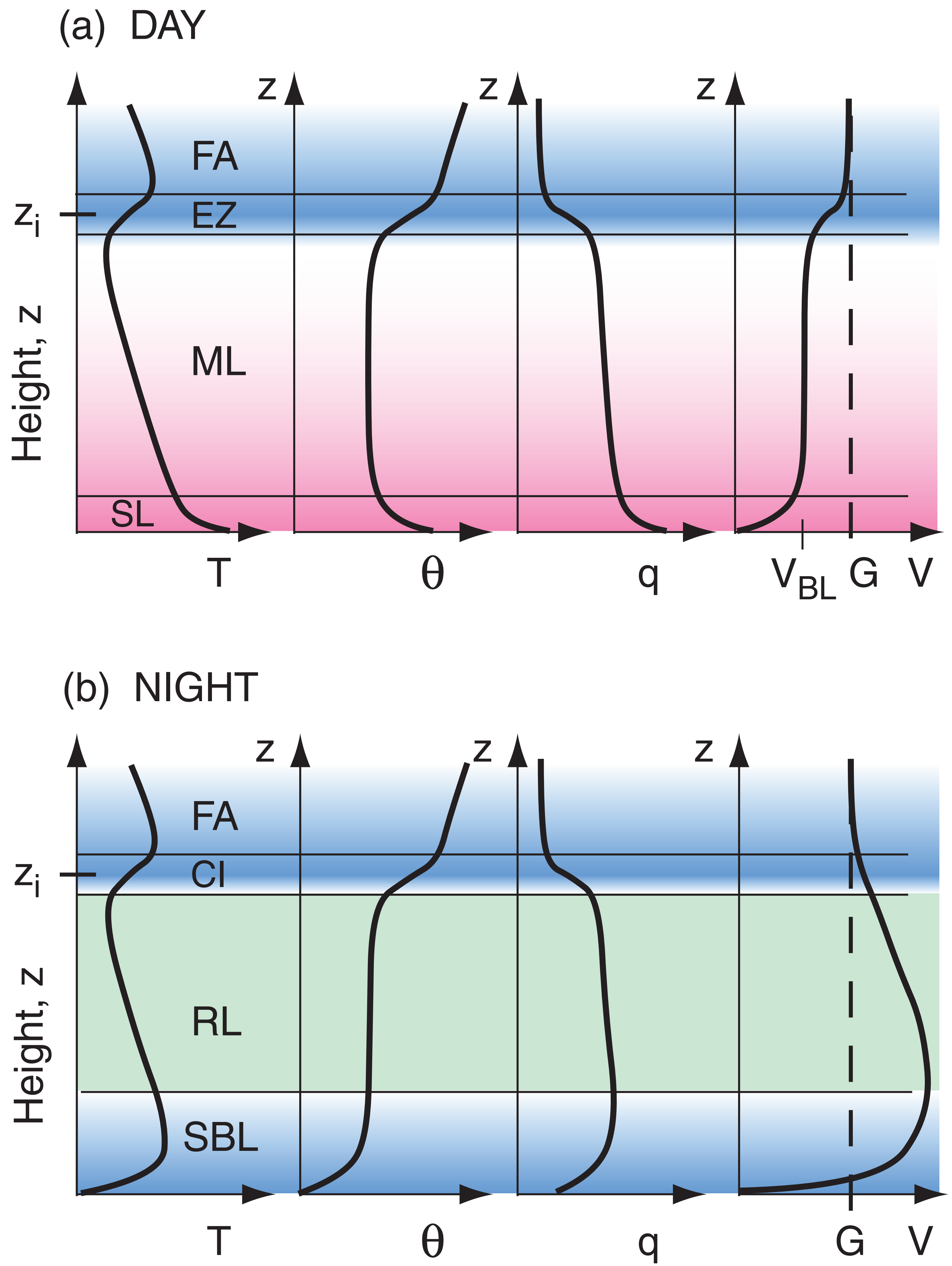


3. Boundary Layer Evolution

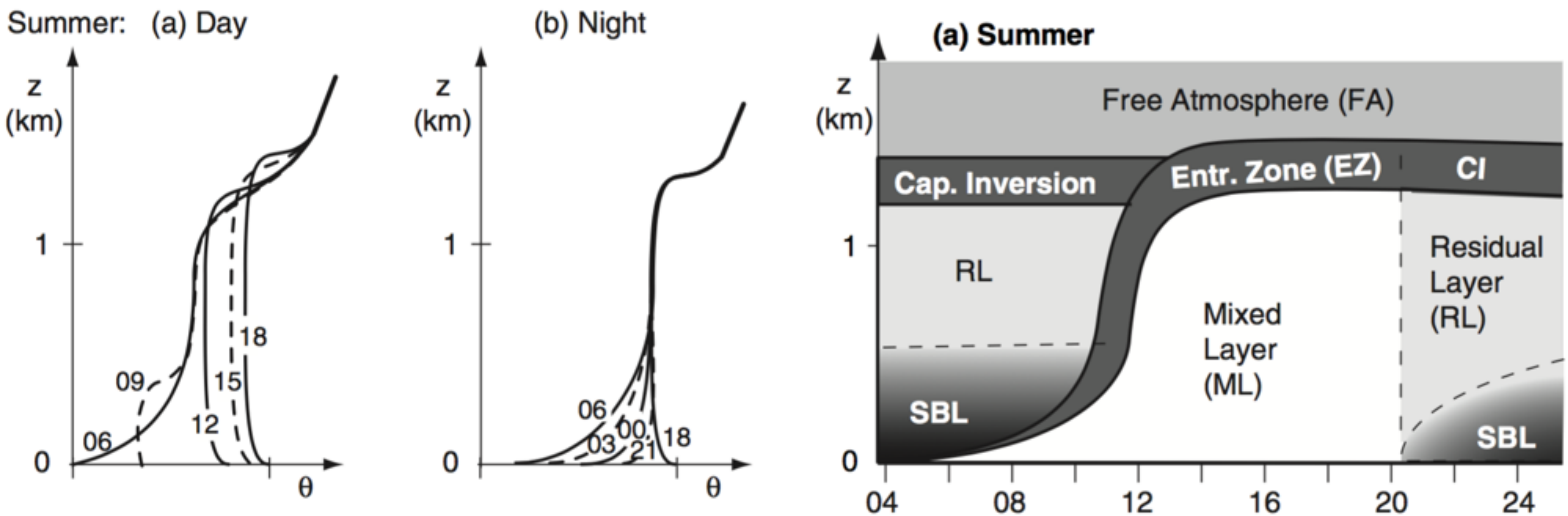


Boundary Layer Evolution

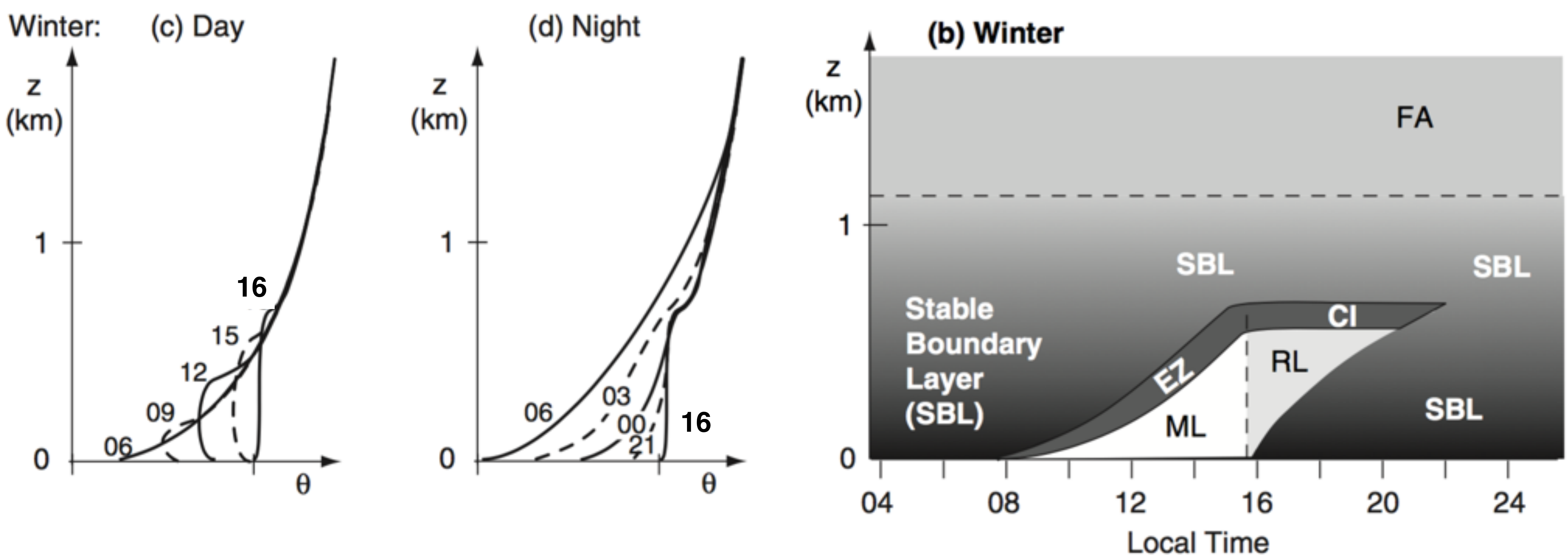
additional variables



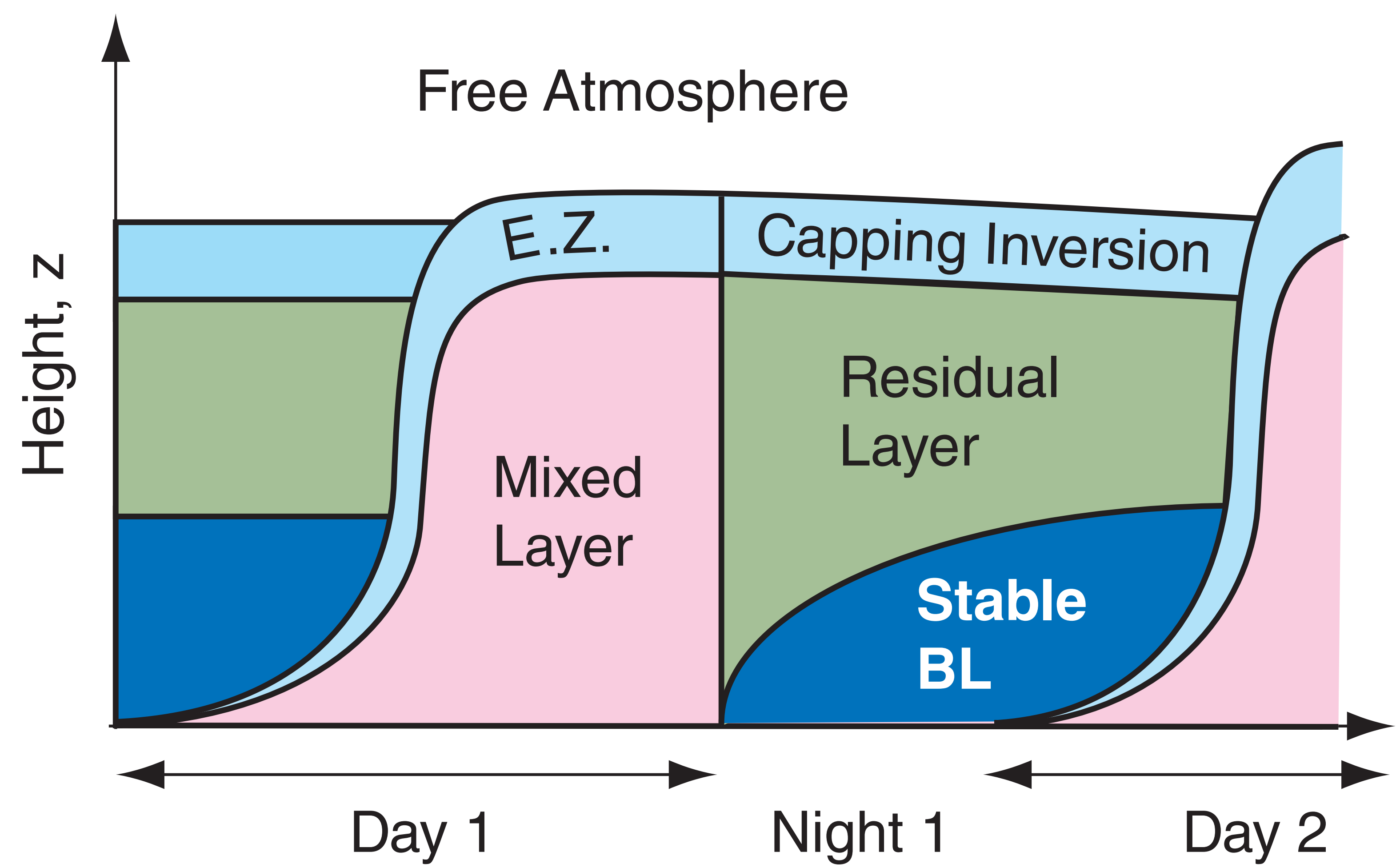
Boundary Layer Evolution - Summer, Fair Wx



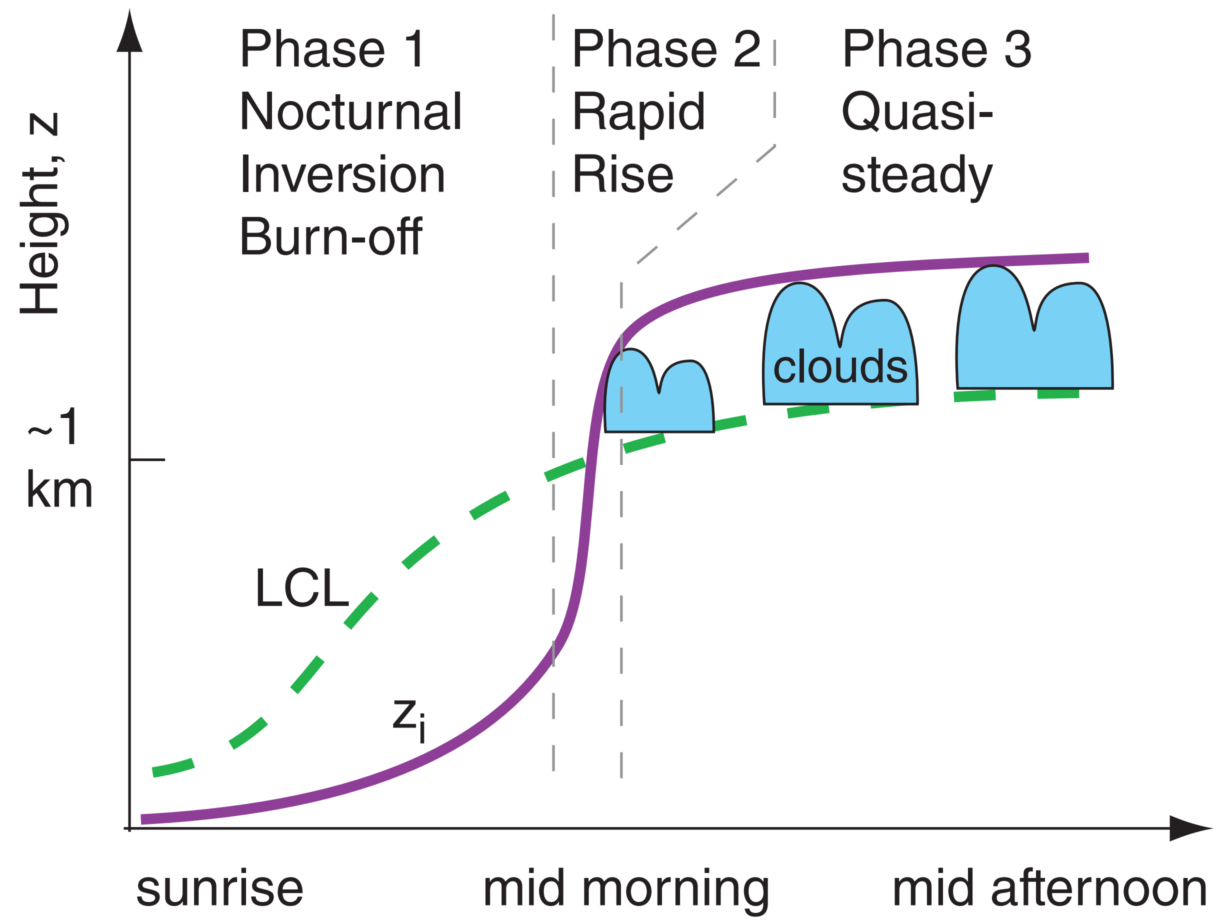
Boundary Layer Evolution - Winter, Fair Wx



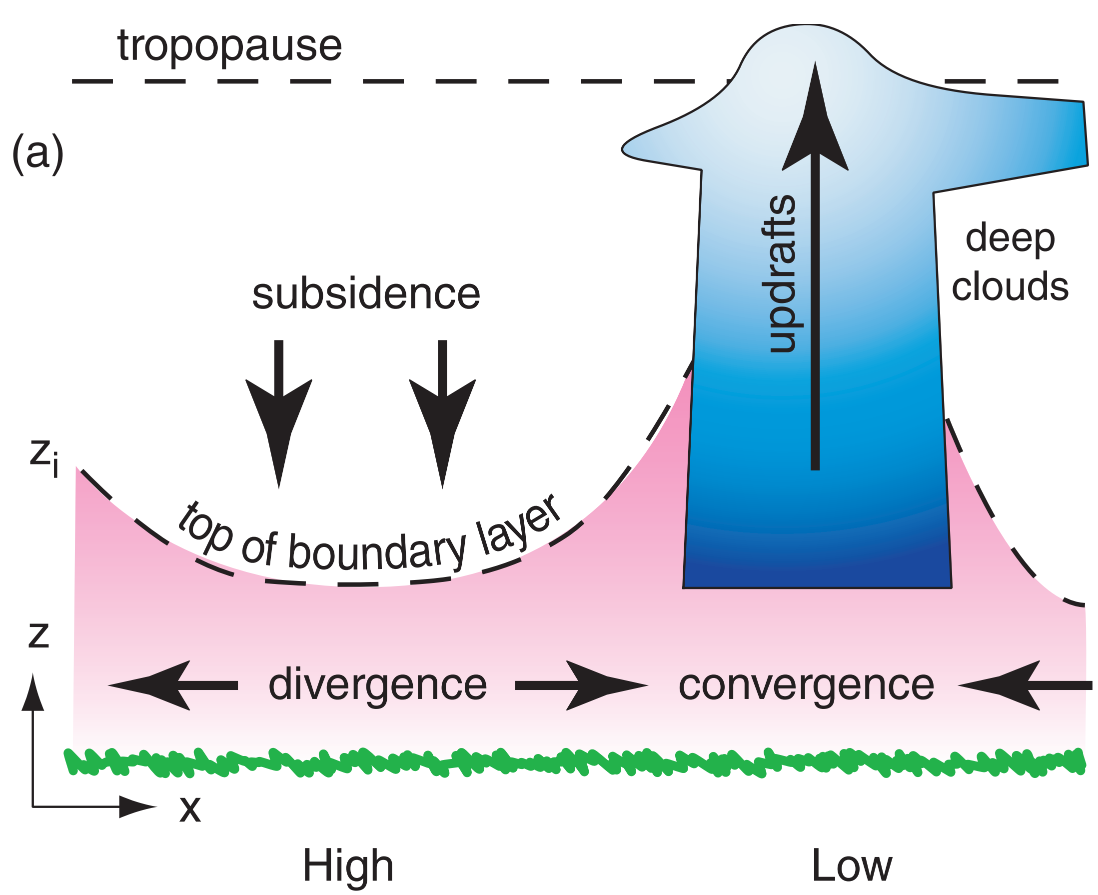
Boundary Layer Evolution - Inversions & Clouds

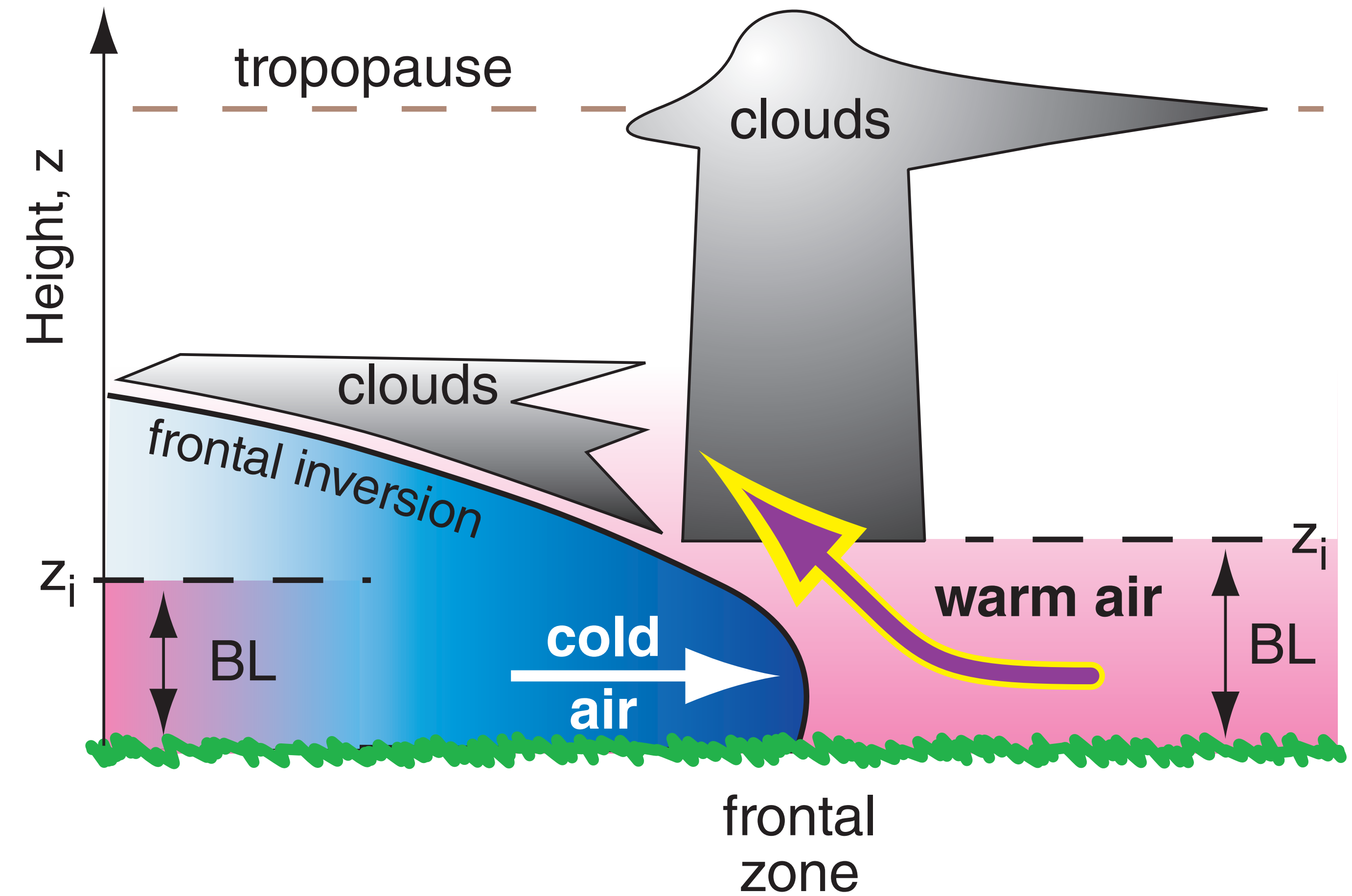


Boundary Layer Evolution - Inversions & Clouds

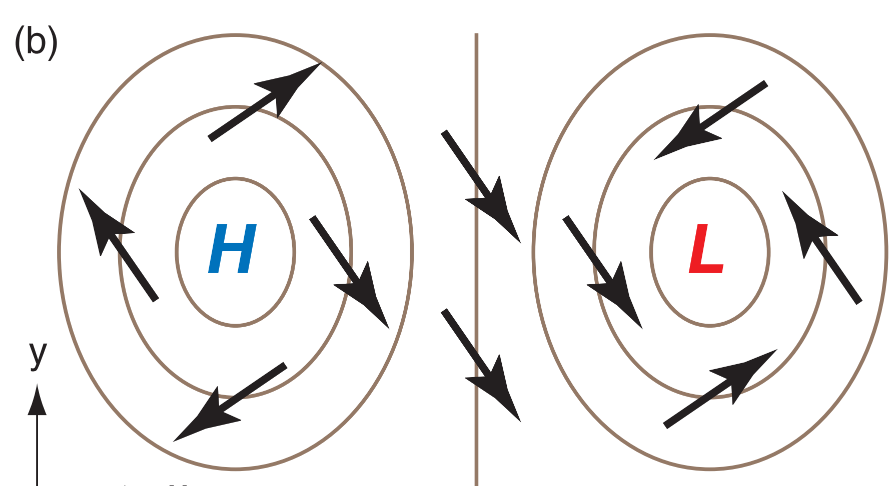


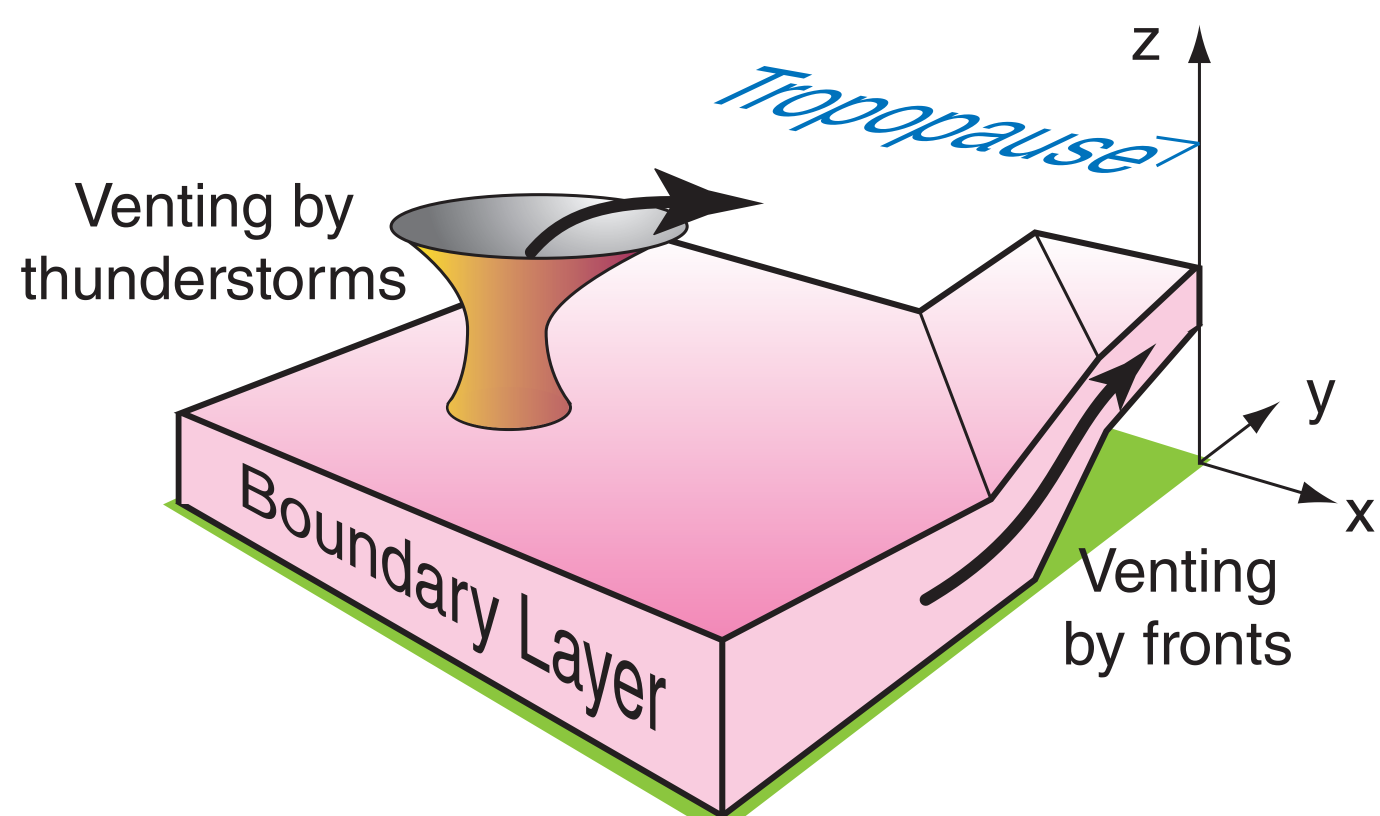
Boundary Layer Evolution - Synoptic Variations





poor air quality



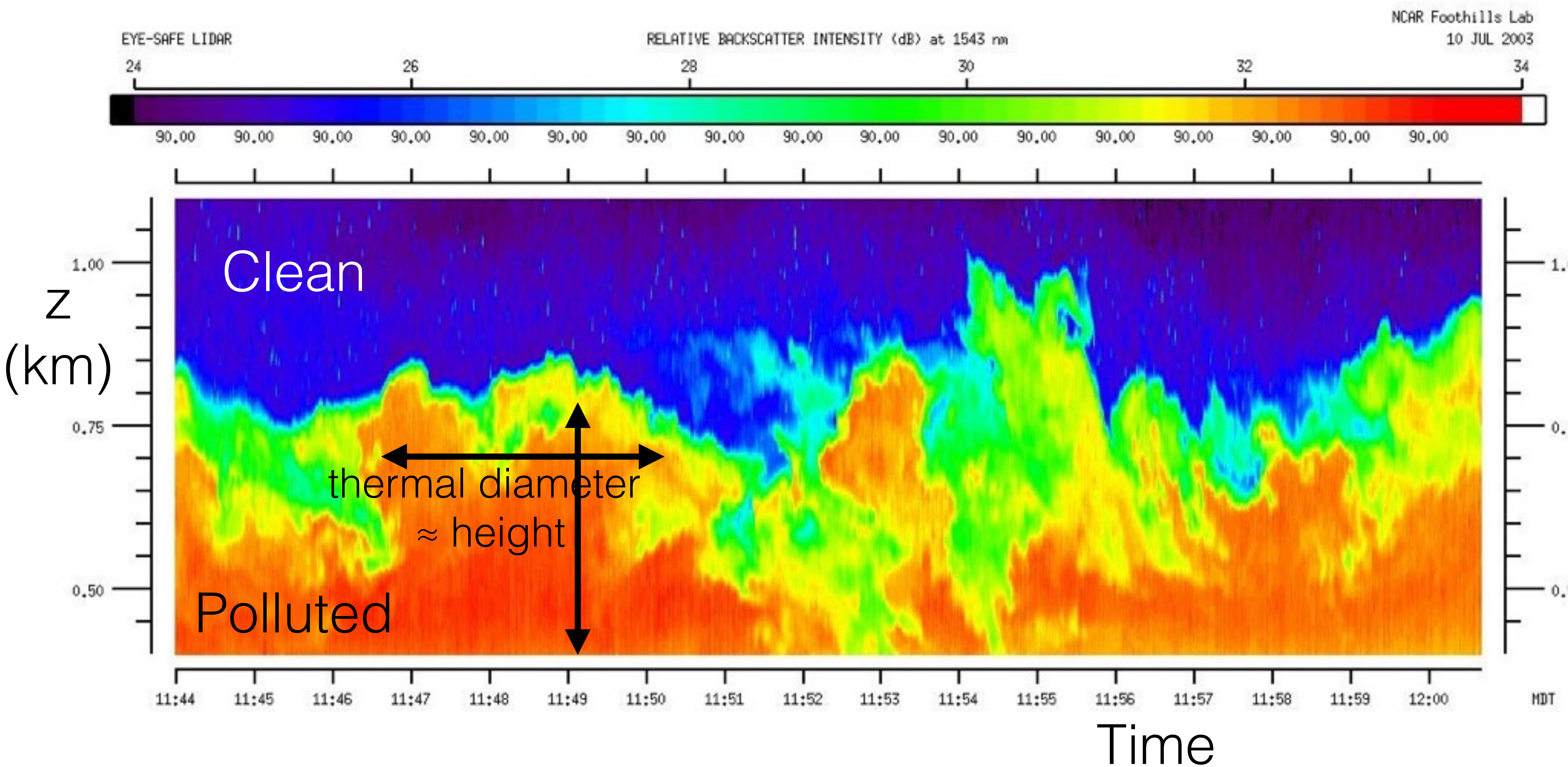


Take a 5 minute “stretch” break

4. Turbulence Generation in ABL

three mechanisms:

1) **Buoyancy** (warm air rising or cold air sinking as thermals)
=> thermal generation of turbulence in UNSTABLE ABL.

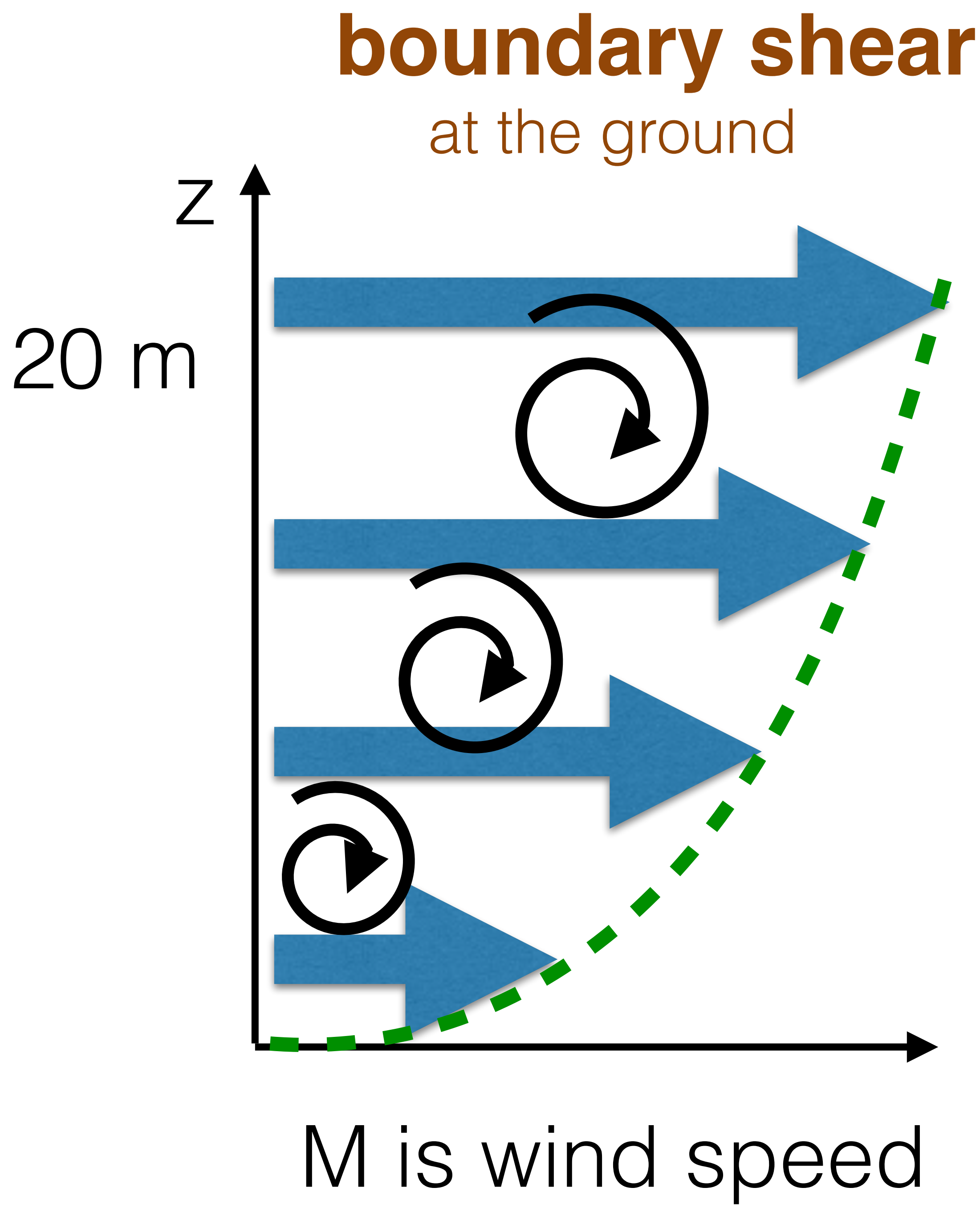


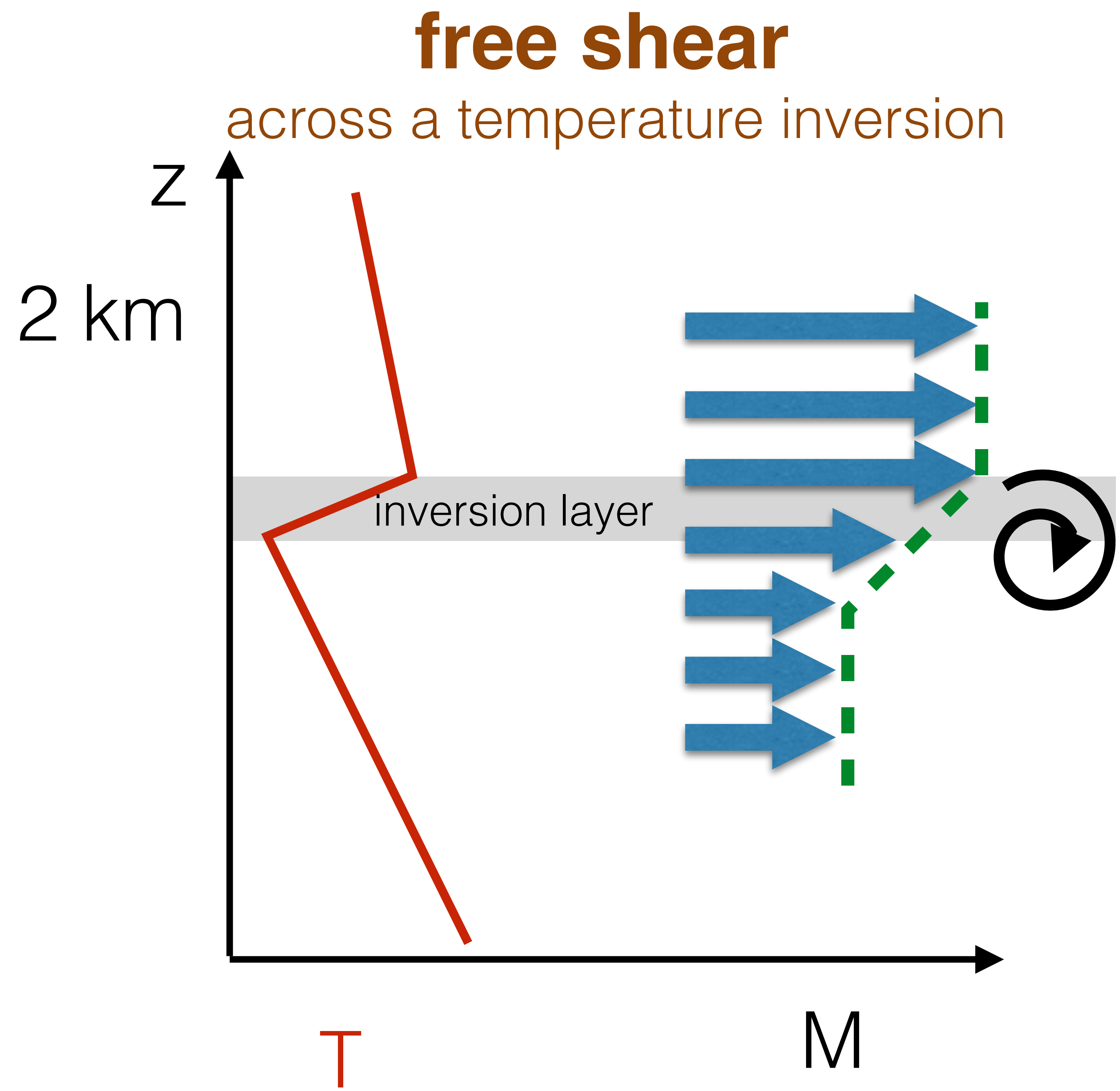
Vertical pointing lidar. Image by Shane Mayor

Turbulence Generation in ABL

three mechanisms:

2. **Wind shear** (change of wind speed or direction with z)
=> mechanical generation of turb. in neutral & stable ABL.





Turbulence Generation in ABL

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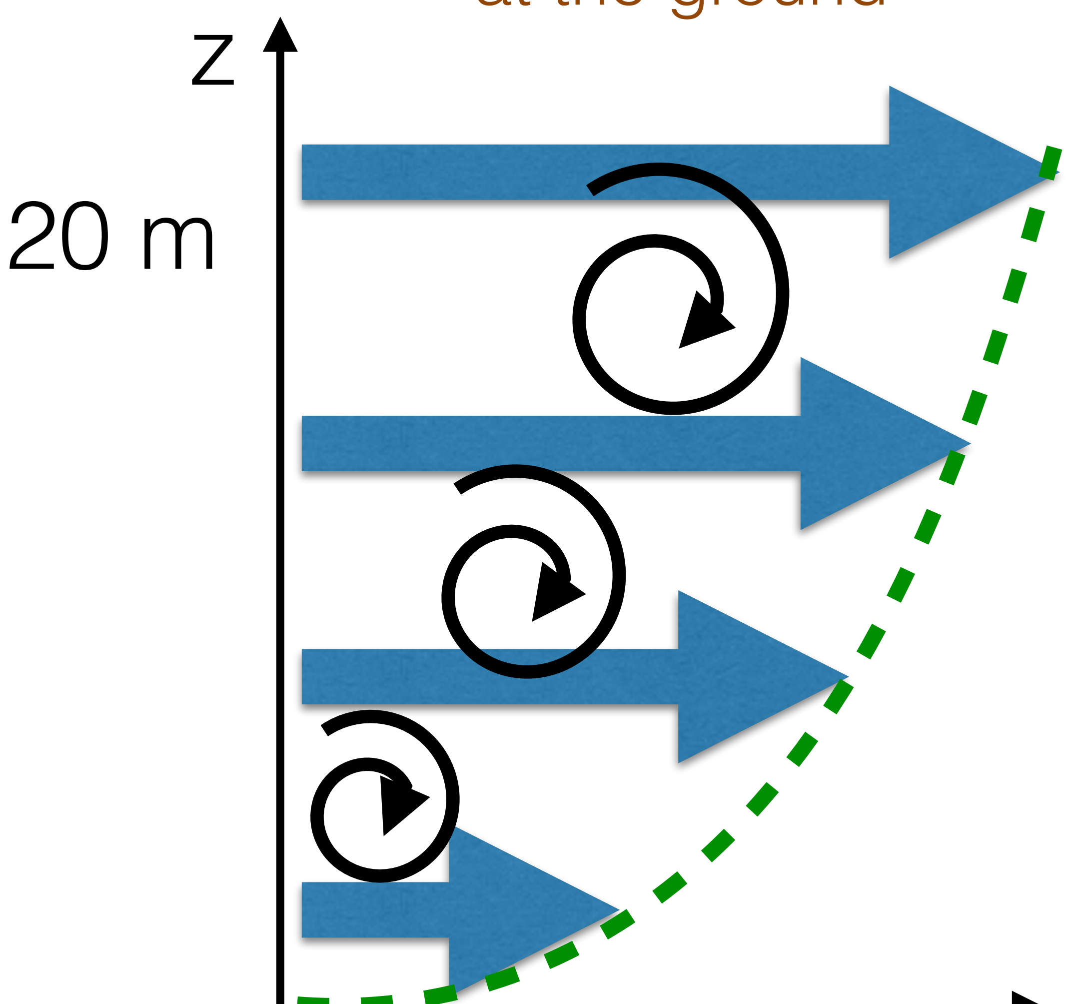
2. **Wind shear** (change of wind speed or direction with z)
=> mechanical generation of turb. in neutral & stable ABL.

boundary shear

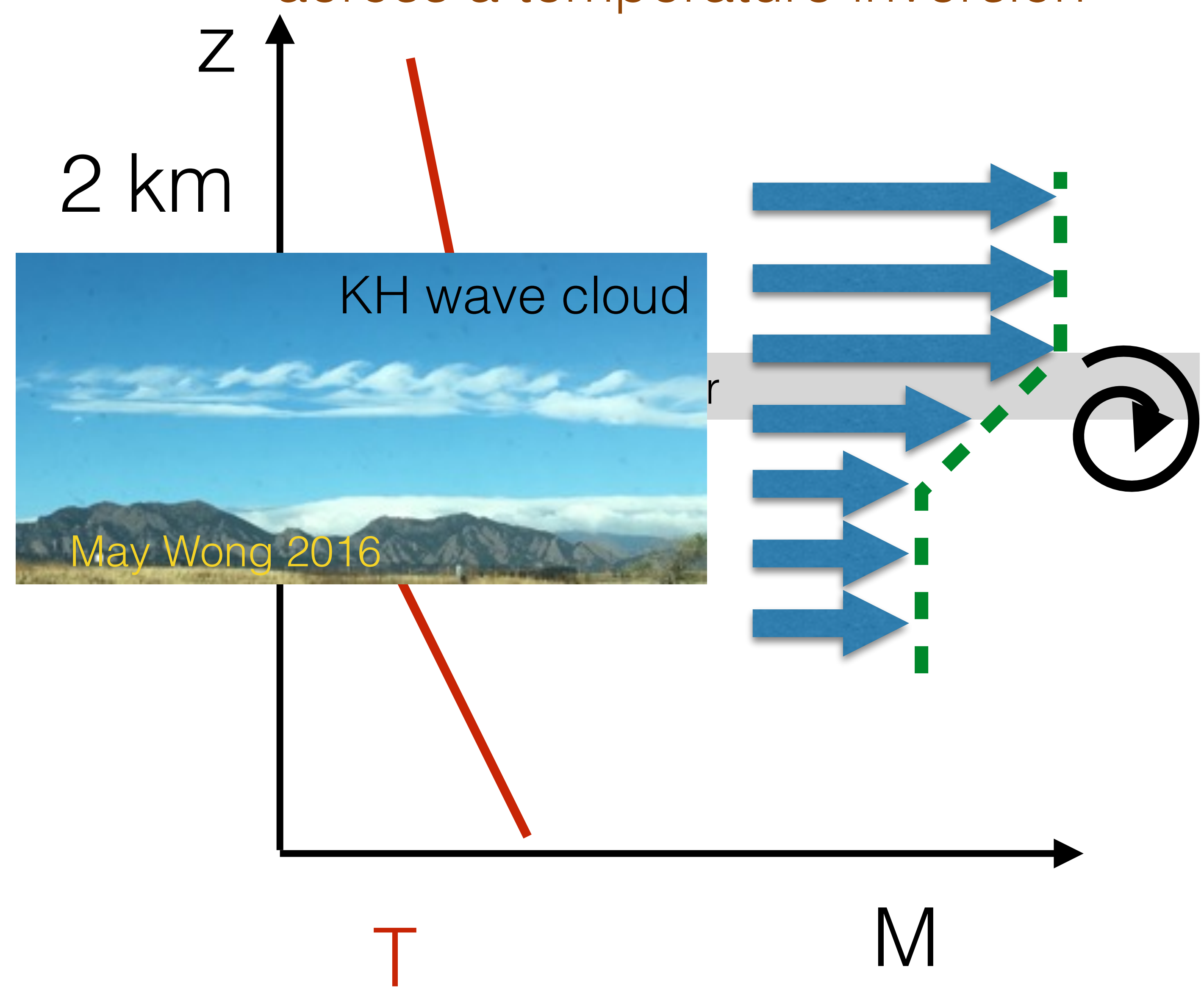
at the ground



M is wind speed

free shear

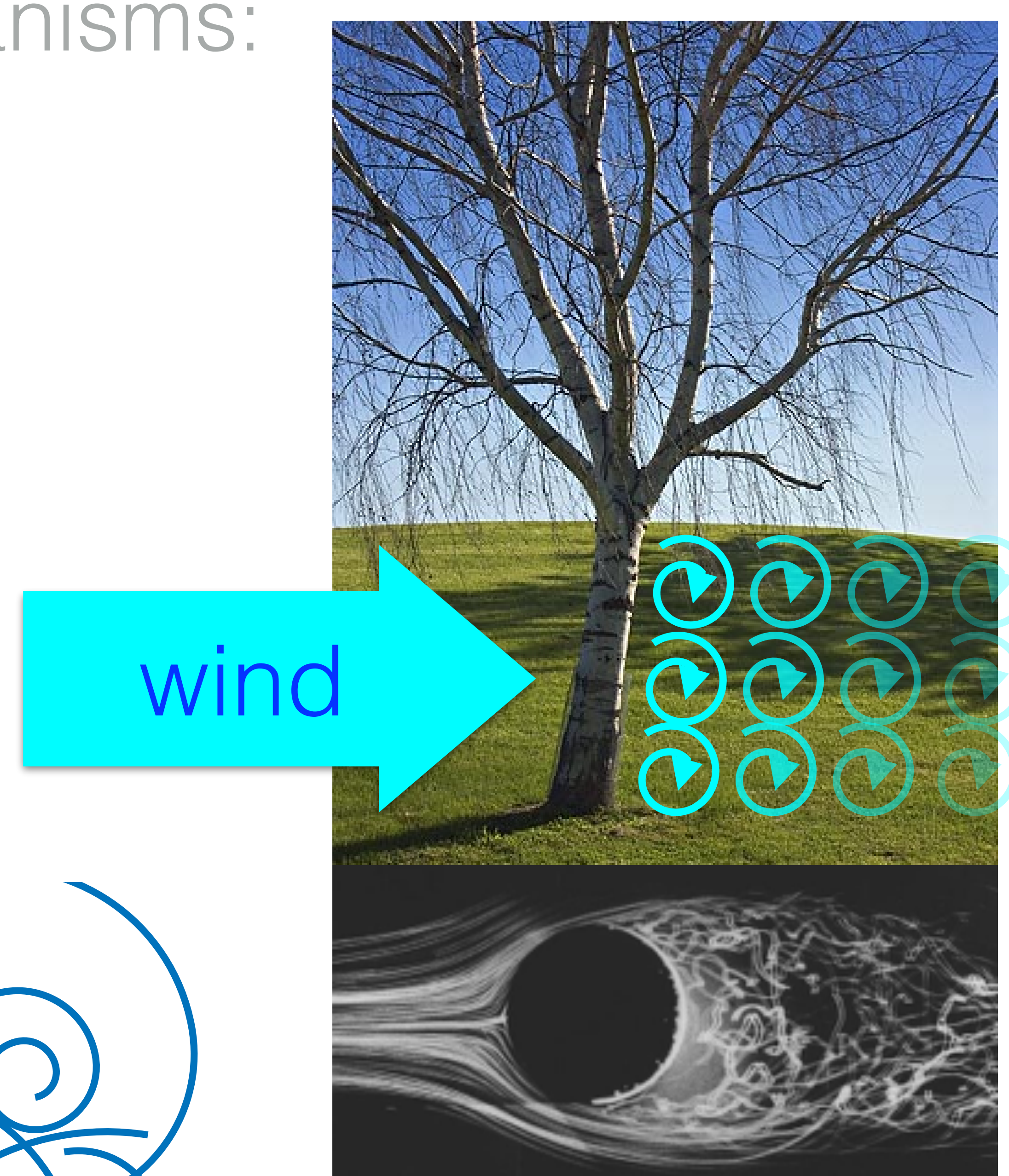
across a temperature inversion

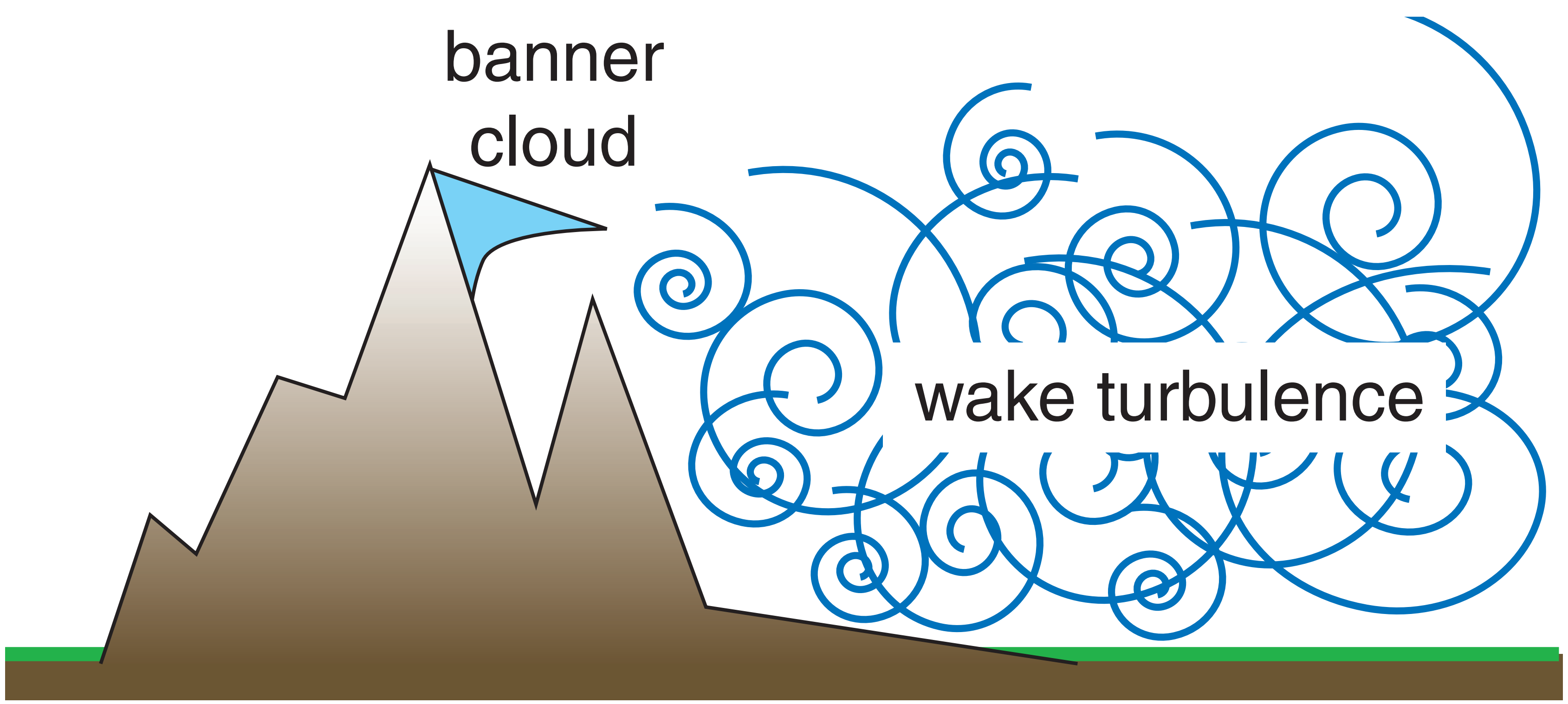


Turbulence Generation in ABL

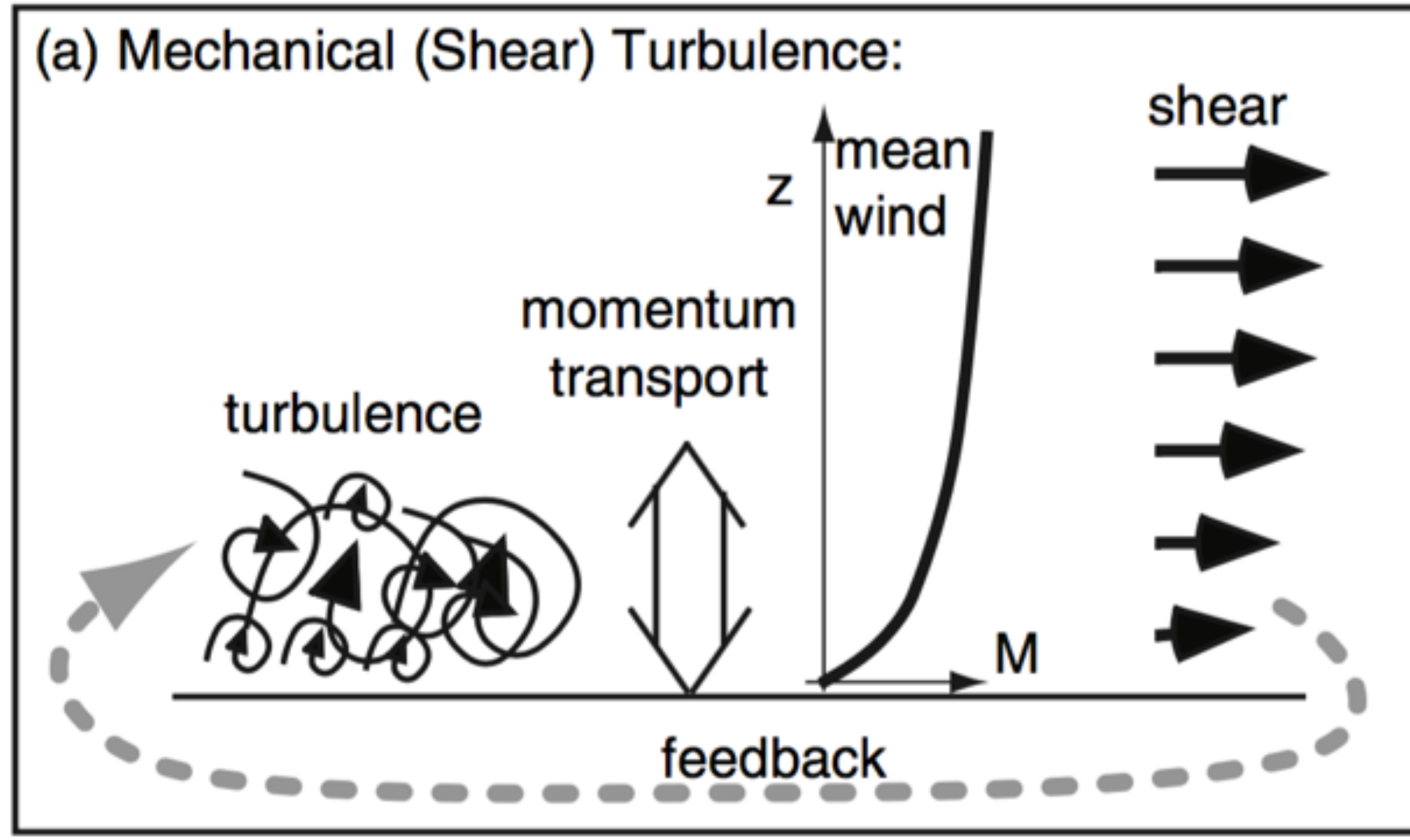
three mechanisms:

3) **Obstacle wakes** (behind trees, bldgs, mountains, cars) => mechanical generation of turbulence



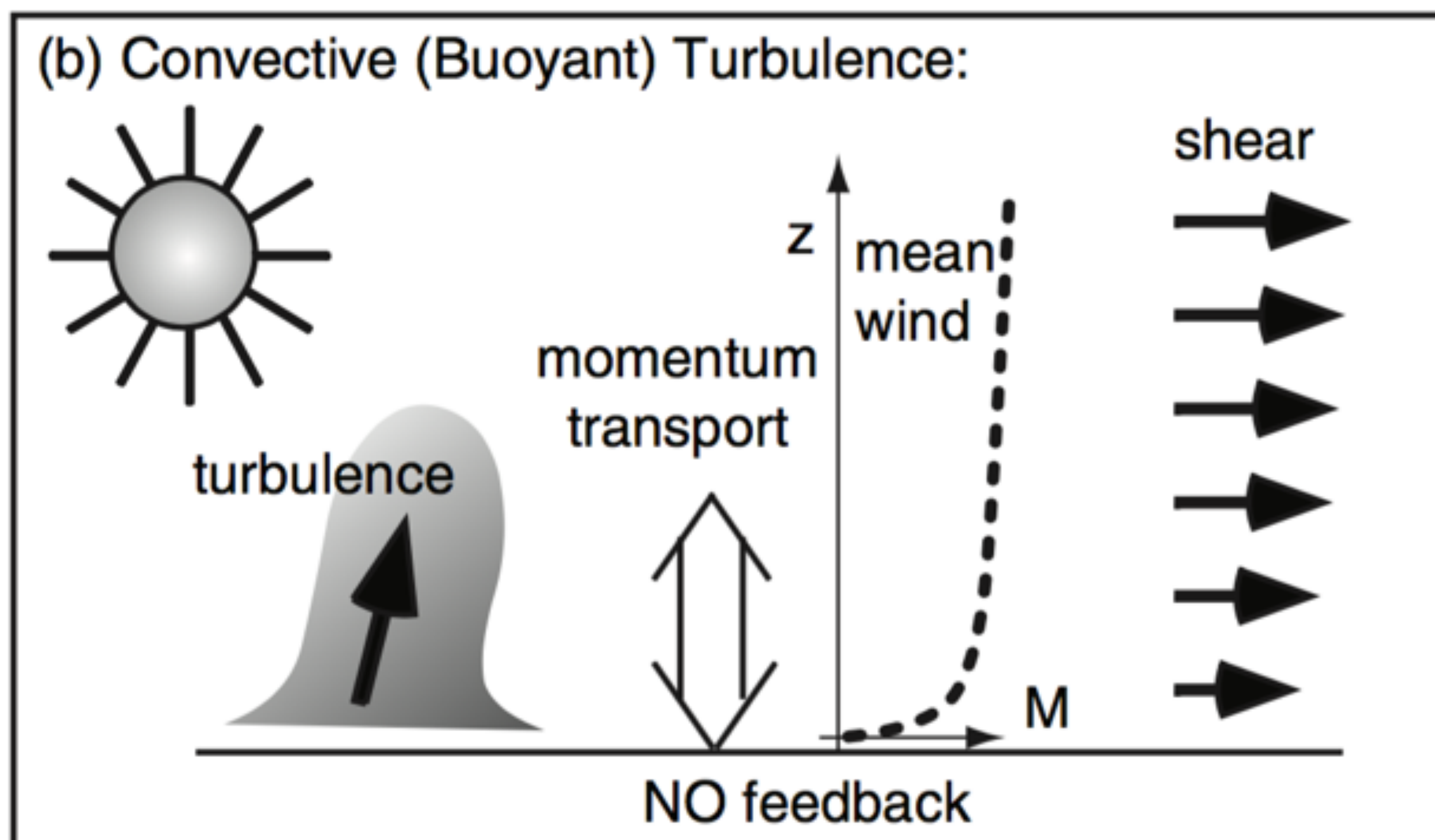


ABL Wind-Turbulence Feedbacks



Buoyantly generated turbulence behaves in a special way.

Thus, pollutant dispersion also behaves in a special way in convective mixed layers.



Turbulence = gustiness

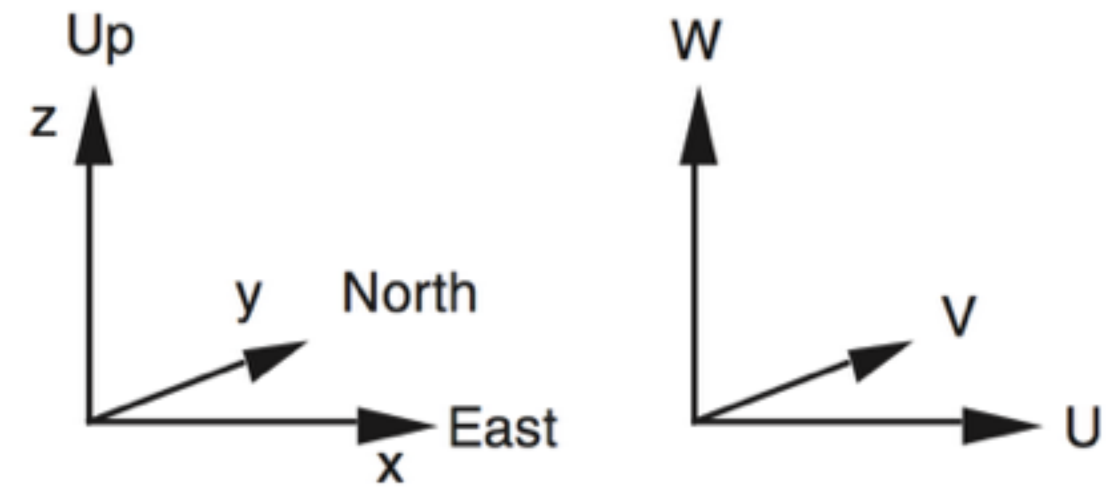
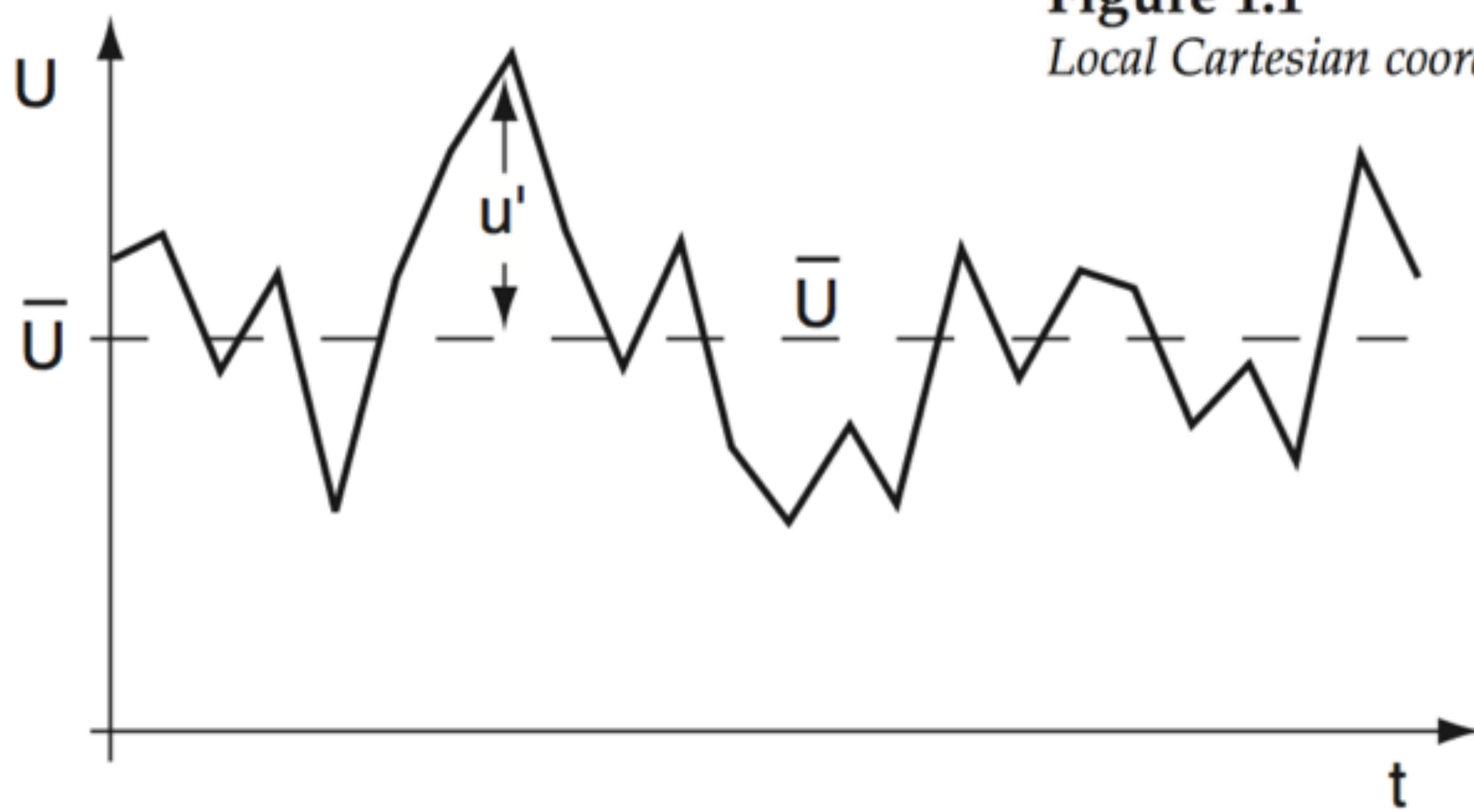


Figure 1.1
Local Cartesian coordinates and velocity components.



$$u'(t) = U(t) - \bar{U}$$

$$v'(t) = V(t) - \bar{V}$$

$$w'(t) = W(t) - \bar{W}$$

$$T'(t) = T(t) - \bar{T}$$

Figure 18.23
The instantaneous wind speed U shown by the zigzag line. The average wind speed $\bar{U}$ is shown by the thin horizontal dashed line. A gust velocity u′ is the instantaneous deviation of the instantaneous wind from the average.

Variance and Standard Deviation

The **variance** σ^2 of vertical velocity is an overall statistic of gustiness:

$$\sigma_w{}^2 = \frac{1}{N}\sum_{k=1}^{N}(W_k - \bar{W})^2$$

$$= \frac{1}{N}\sum_{k=1}^{N}(w_k{}')^2 \qquad \bullet(18.22)$$

$$= \overline{w'^{\,2}}$$

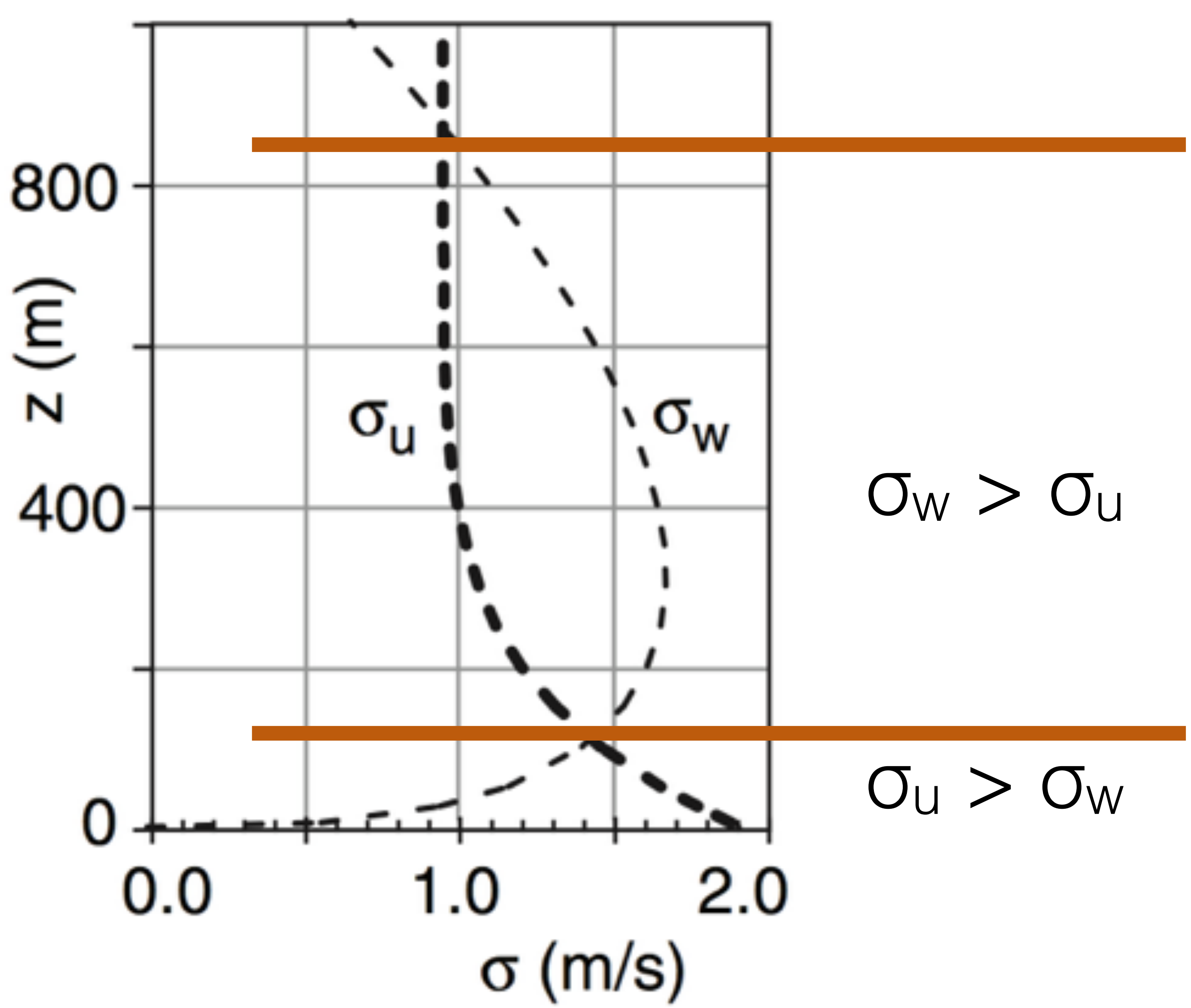
Similar definitions can be made for $\sigma_u{}^2$, $\sigma_v{}^2$, $\sigma_\theta{}^2$,

Standard Deviation: $\sigma_w = \sqrt{\sigma_w{}^2} = \overline{(w')^2}^{1/2}$

Isotropy

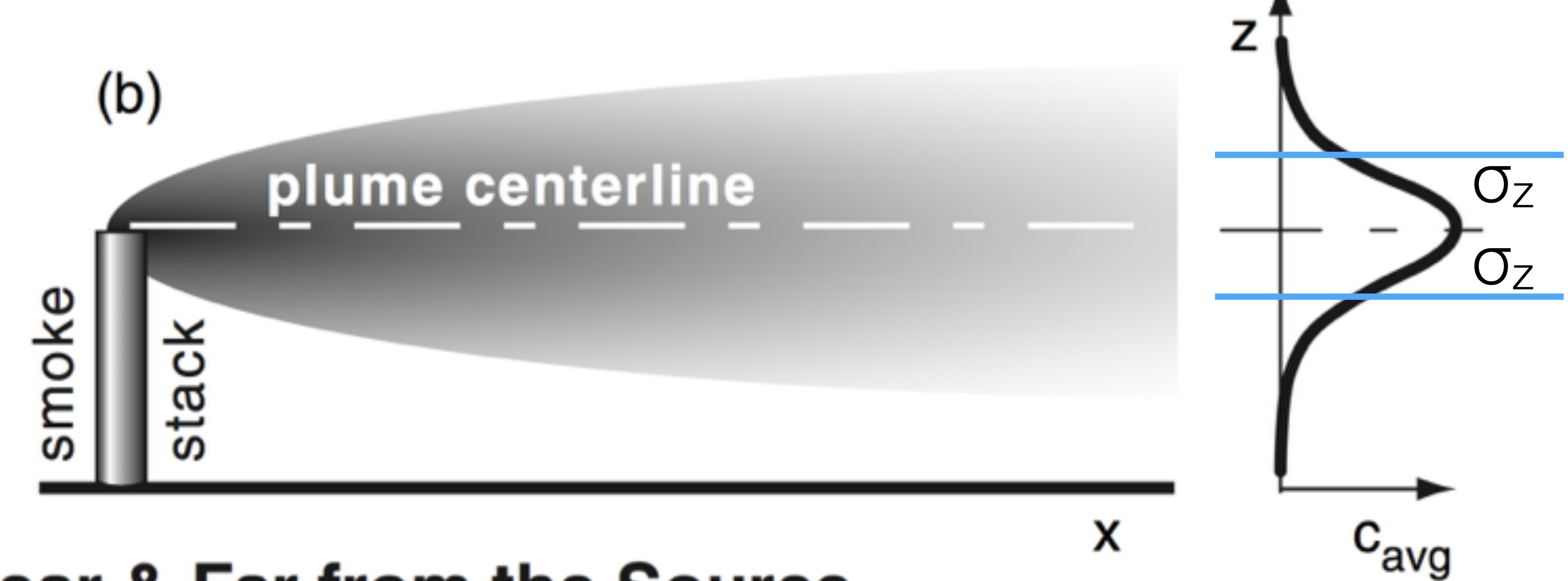
If turbulence has nearly the same variance in all three directions, then turbulence is said to be **isotropic**. Namely:

$$\sigma_u^{\ 2} = \sigma_v^{\ 2} = \sigma_w^{\ 2} \qquad \bullet(18.27)$$



Anisotropic
(not isotropic)
examples:

Why do we care about sigma-velocity?



Dispersion Near & Far from the Source

Close to the source (at small times after the start of dispersion), eq. (19.13a) reduces to

$$\sigma_y \approx \sigma_v \cdot \left(\frac{x}{M} \right) \qquad \bullet(19.14)$$

while far from the source it can be approximated by:

$$\sigma_y \approx \sigma_v \cdot \left(2 \cdot t_L \cdot \frac{x}{M} \right)^{1/2} \qquad \bullet(19.15)$$

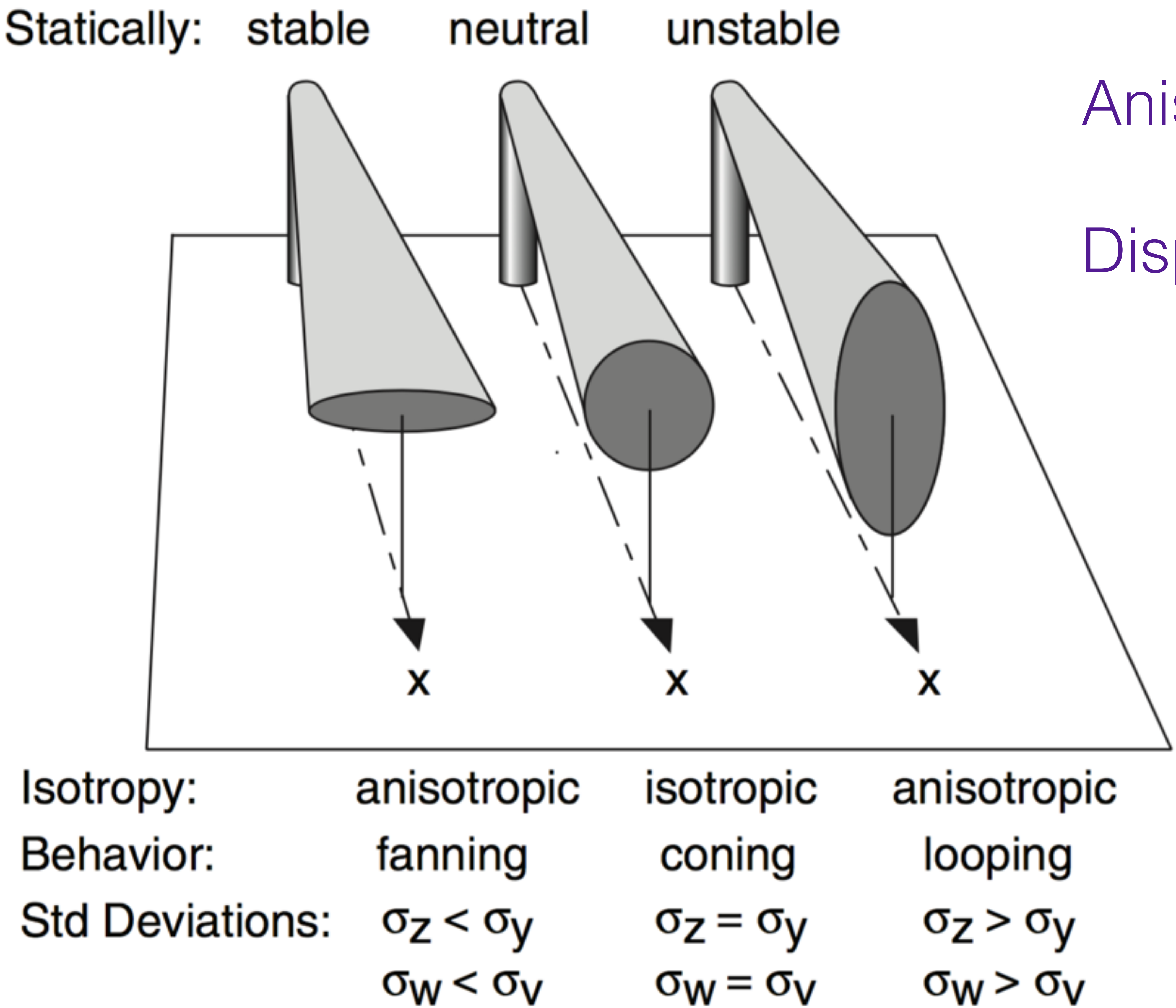
There are similar equations for σ_z as a function of σ_w.

Greater σ_w causes faster spread σ_z.

Greater σ_v causes faster spread σ_y.

Greater σ_u causes faster spread σ_x.

Anisotropy and Dispersion



5. Turbulence Kinetic Energy

An overall measure of the intensity of turbulence is the **turbulence kinetic energy** per unit mass (TKE):

$$TKE = 0.5 \cdot \left[\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2} \right] \qquad \bullet(18.28a)$$

$$TKE = 0.5 \cdot \left[\sigma_u{}^2 + \sigma_v{}^2 + \sigma_w{}^2 \right] \qquad \bullet(18.28b)$$

TKE is usually produced at the scale of the boundary-layer depth. The production is made mechanically by wind shear and buoyantly by thermals.

A statistic tells us about turbulent energy.

TKE Budget

Turbulent energy cascades through the **inertial subrange**, where the large-size eddies drive medium ones, which in turn drive smaller eddies. Molecular viscosity continuously damps the tiniest (**microscale**) eddies, dissipating *TKE* into heat. *TKE* is not conserved.

The tendency of *TKE* to increase or decrease is given by the following *TKE* budget equation:

$$\frac{\Delta TKE}{\Delta t} = A + S + B + Tr - \varepsilon \qquad \bullet(18.29)$$

where *A* is advection of *TKE* by the mean wind, *S* is shear generation, *B* is buoyant production or consumption, *Tr* is transport by turbulent motions and pressure, and ε is viscous dissipation rate. For **stationary** (steady-state) turbulence, the tendency term on the left side of eq. (18.29) is zero.

Flux **Richardson Number**:

$$R_f = \frac{-B}{S}$$

a measure of dynamic stability

TKE Budget

In a nutshell:

S Increases as wind shear increases

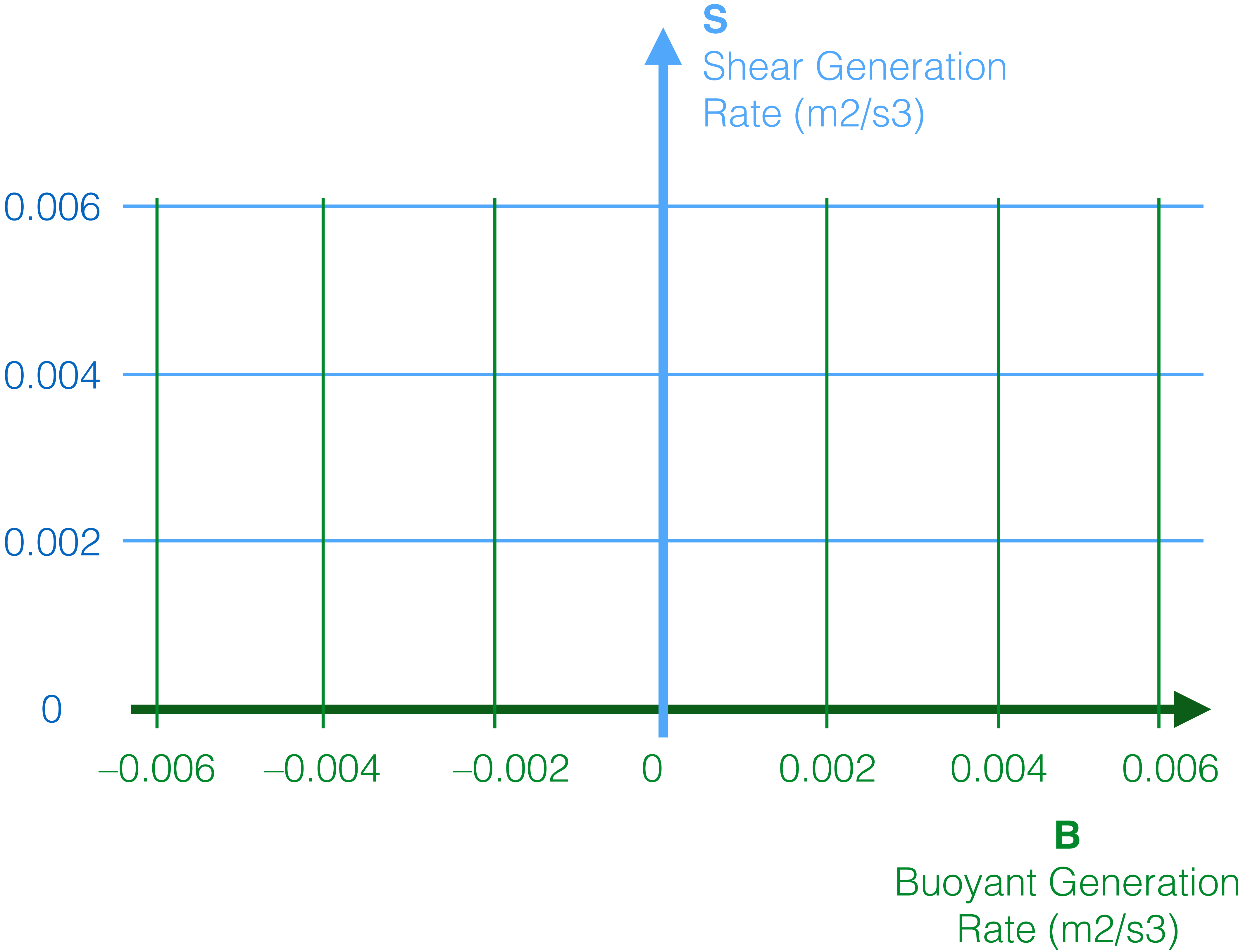
B positive when warm thermals are rising or when cold "thermals" are sinking. (this happens in statically unstable air)

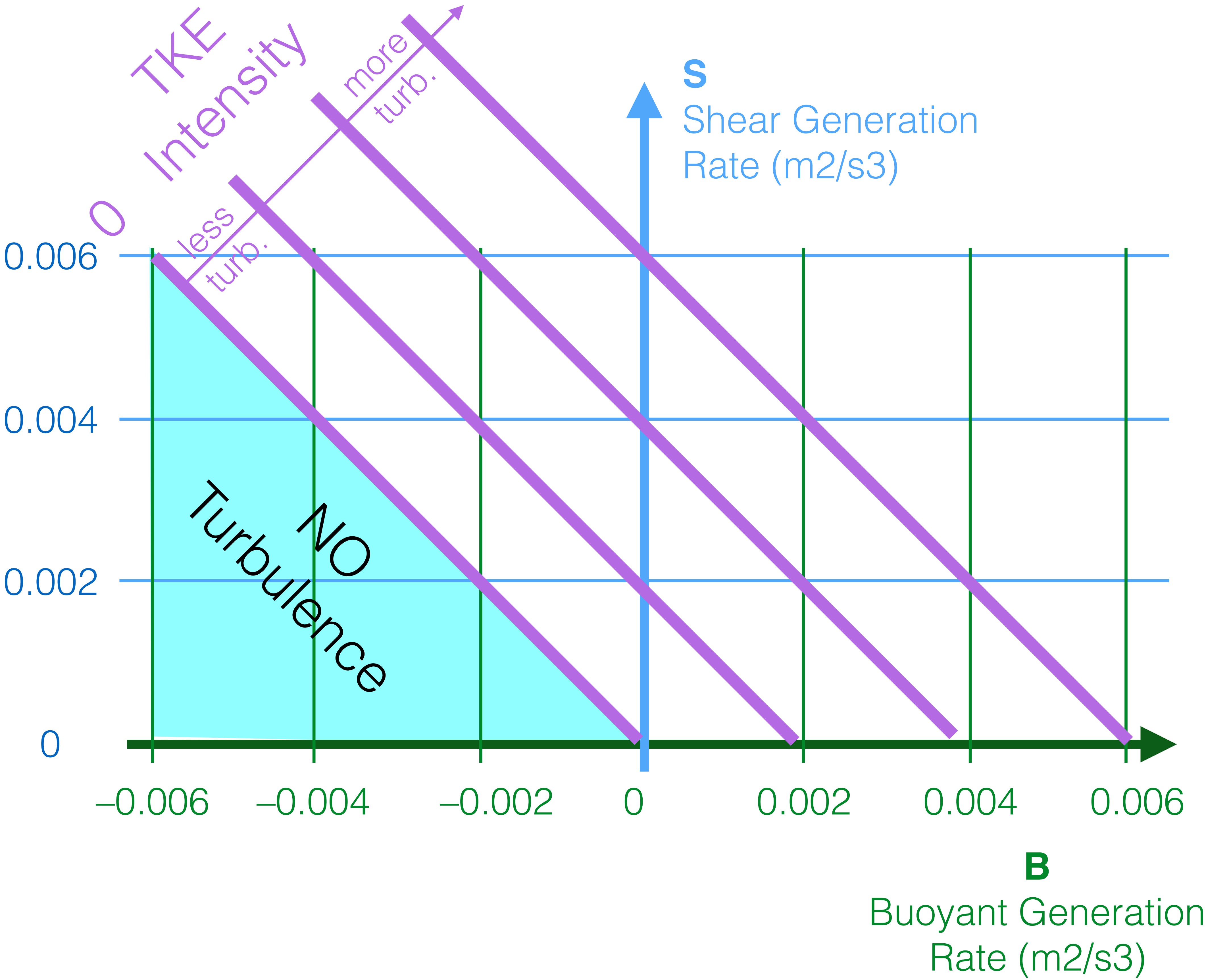
B negative when warm air tries to sink, or cold air tries to rise. (this happens in statically stable air)

ε always causes TKE to decrease.

Turbulence is NOT conserved. TKE will decay exponentially toward zero. Turbulence can be maintained ONLY if it is continually generated.

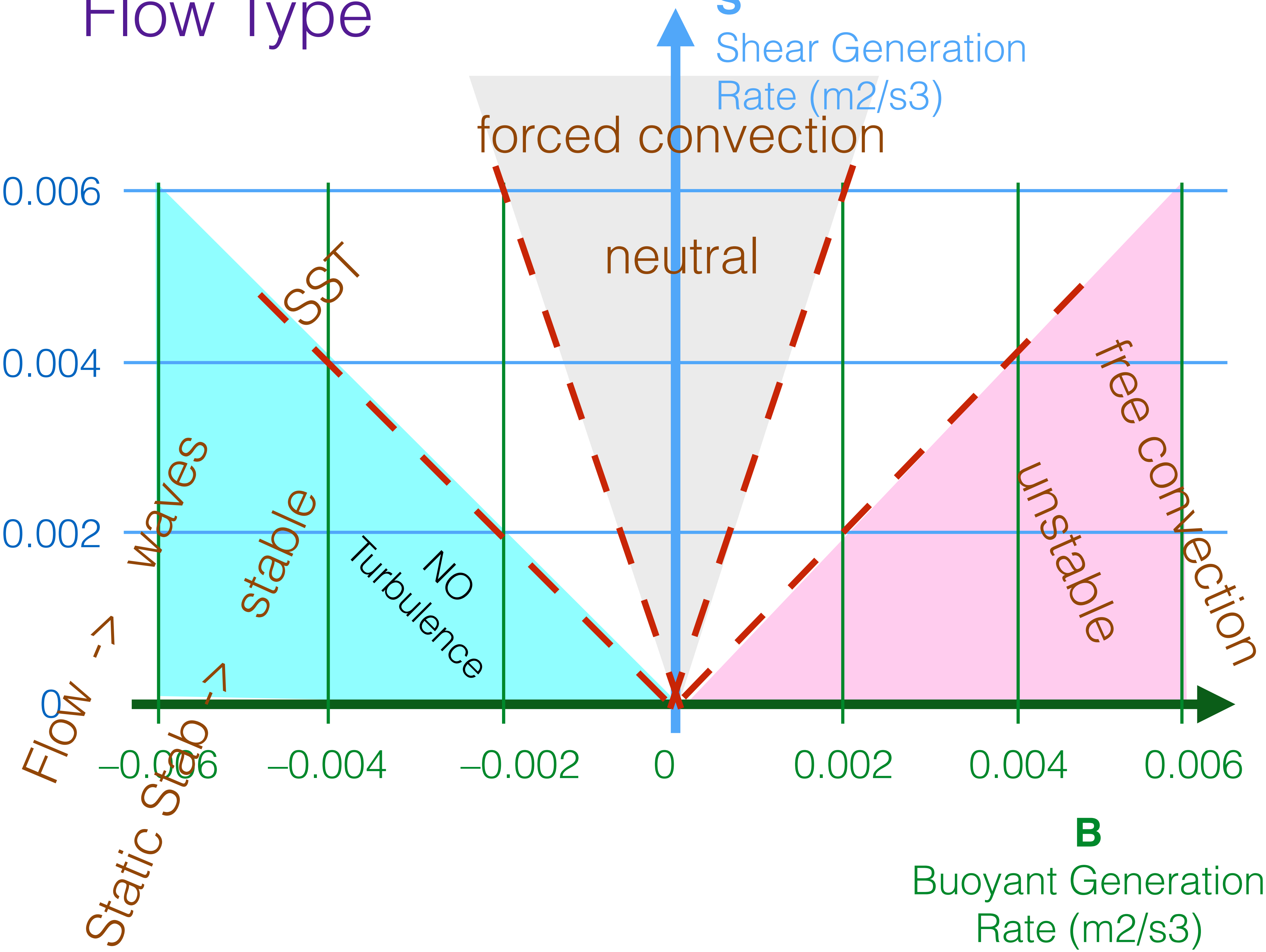
6. TKE and Dispersion





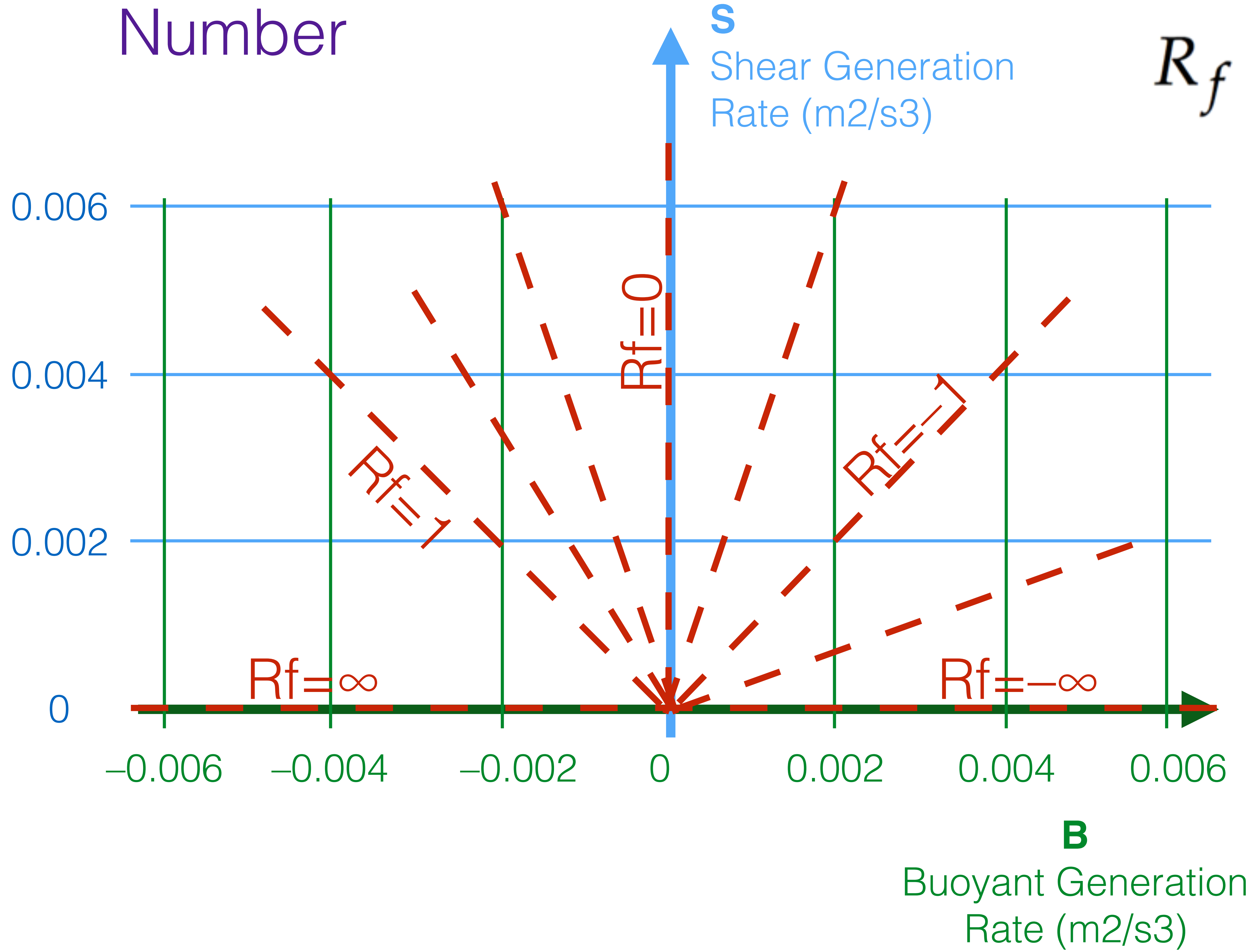
TKE Intensity
0
less turb.
more turb.
S
Shear Generation Rate (m2/s3)
0.006
0.004
0.002
0
NO Turbulence
–0.006
–0.004
–0.002
0
0.002
0.004
0.006
B
Buoyant Generation Rate (m2/s3)

Static Stability & Flow Type



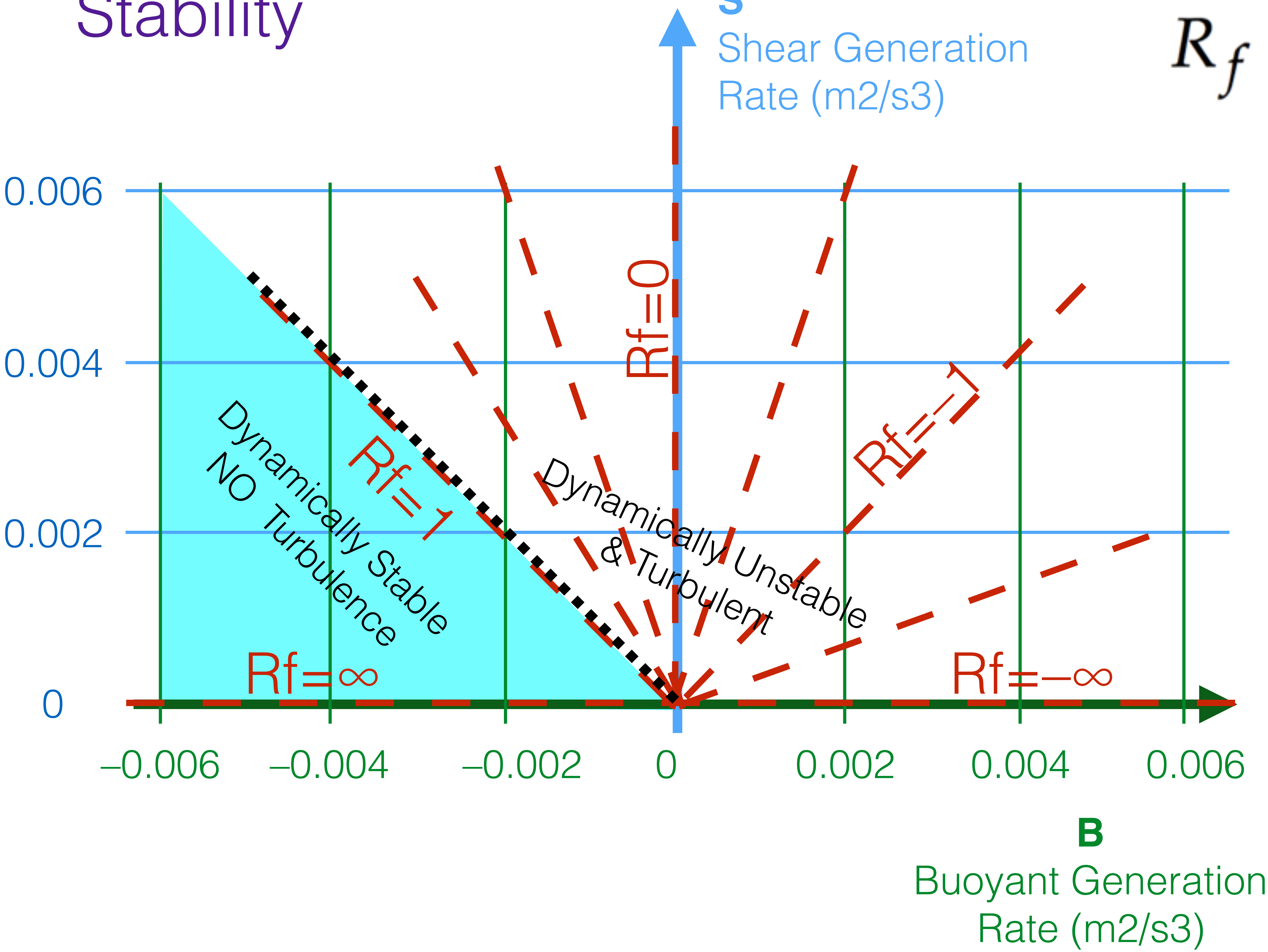
Richardson Number

$$R_f = \frac{-B}{S}$$



Dynamics Stability

$$R_f = \frac{-B}{S}$$



Pasquill-Gifford Turbulence Type

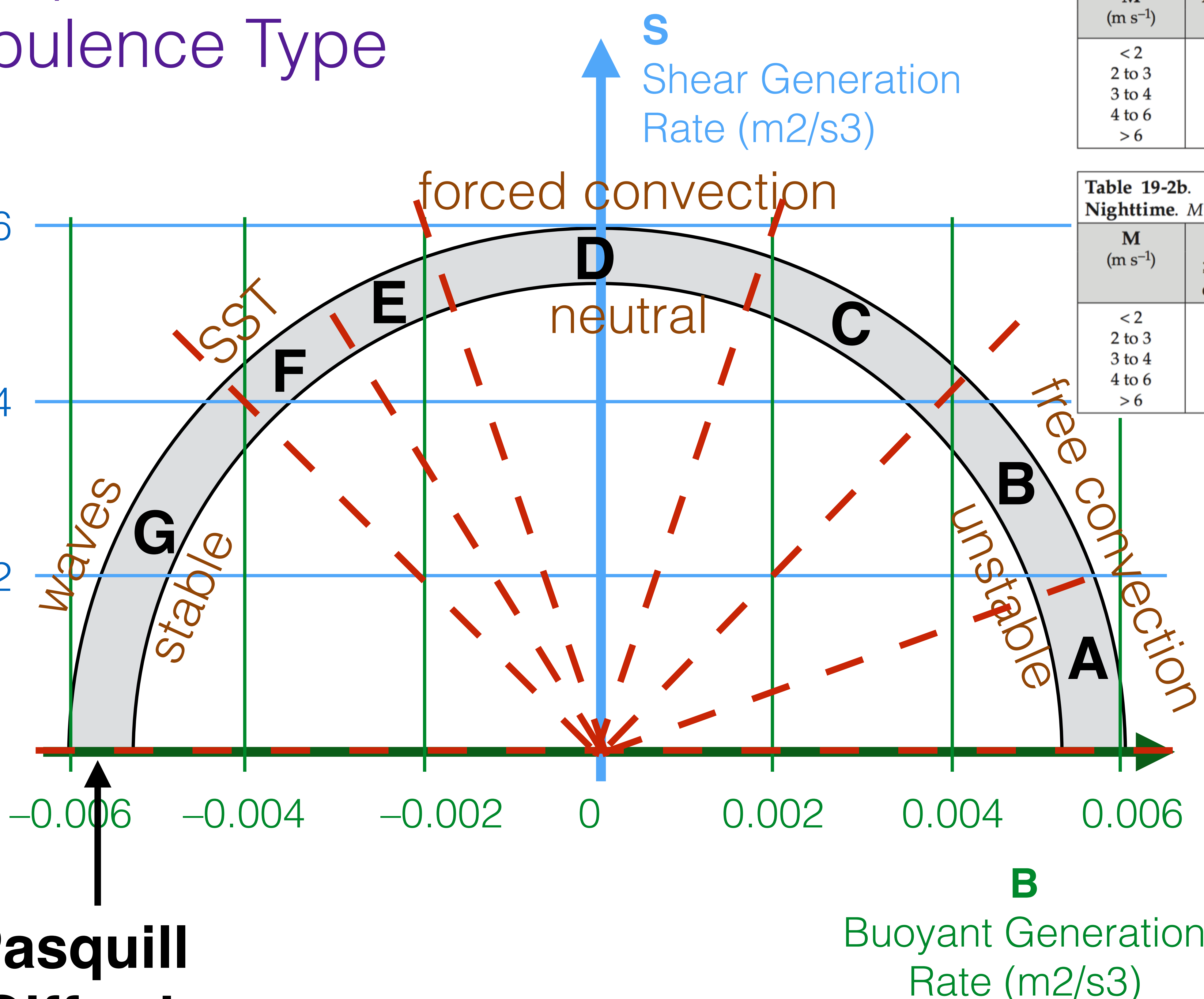
Table 19-2a. Pasquill-Gifford turbulence types for **Daytime**. M is wind speed at $z = 10$ m.

M ($\mathrm{m\ s^{-1}}$)	**Insolation** (incoming solar radiation)		
	Strong	**Moderate**	**Weak**
< 2	A	A to B	B
2 to 3	A to B	B	C
3 to 4	B	B to C	C
4 to 6	C	C to D	D
> 6	C	D	D

Table 19-2b. Pasquill-Gifford turbulence types for **Nighttime**. M is wind speed at $z = 10$ m.

M ($\mathrm{m\ s^{-1}}$)	**Cloud Coverage**	
	≥ 4/8 low cloud or thin overcast	**≤ 3/8**
< 2	G	G
2 to 3	E	F
3 to 4	D	E
4 to 6	D	D
> 6	D	D

Pasquill-Gifford Turbulence Type



Pasquill Gifford Turb. Type

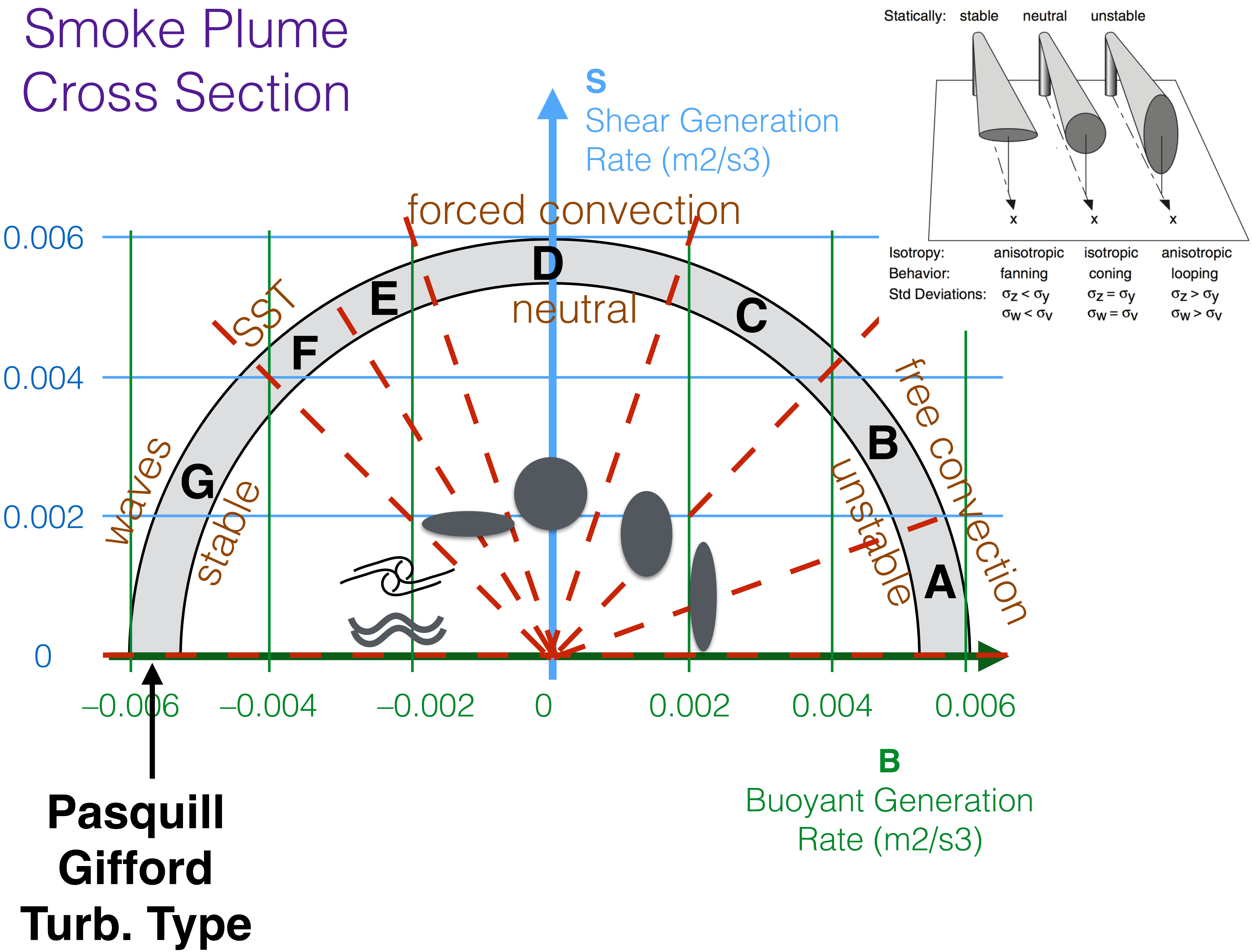
Table 19-2a. Pasquill-Gifford turbulence types for **Daytime**. M is wind speed at $z = 10$ m.

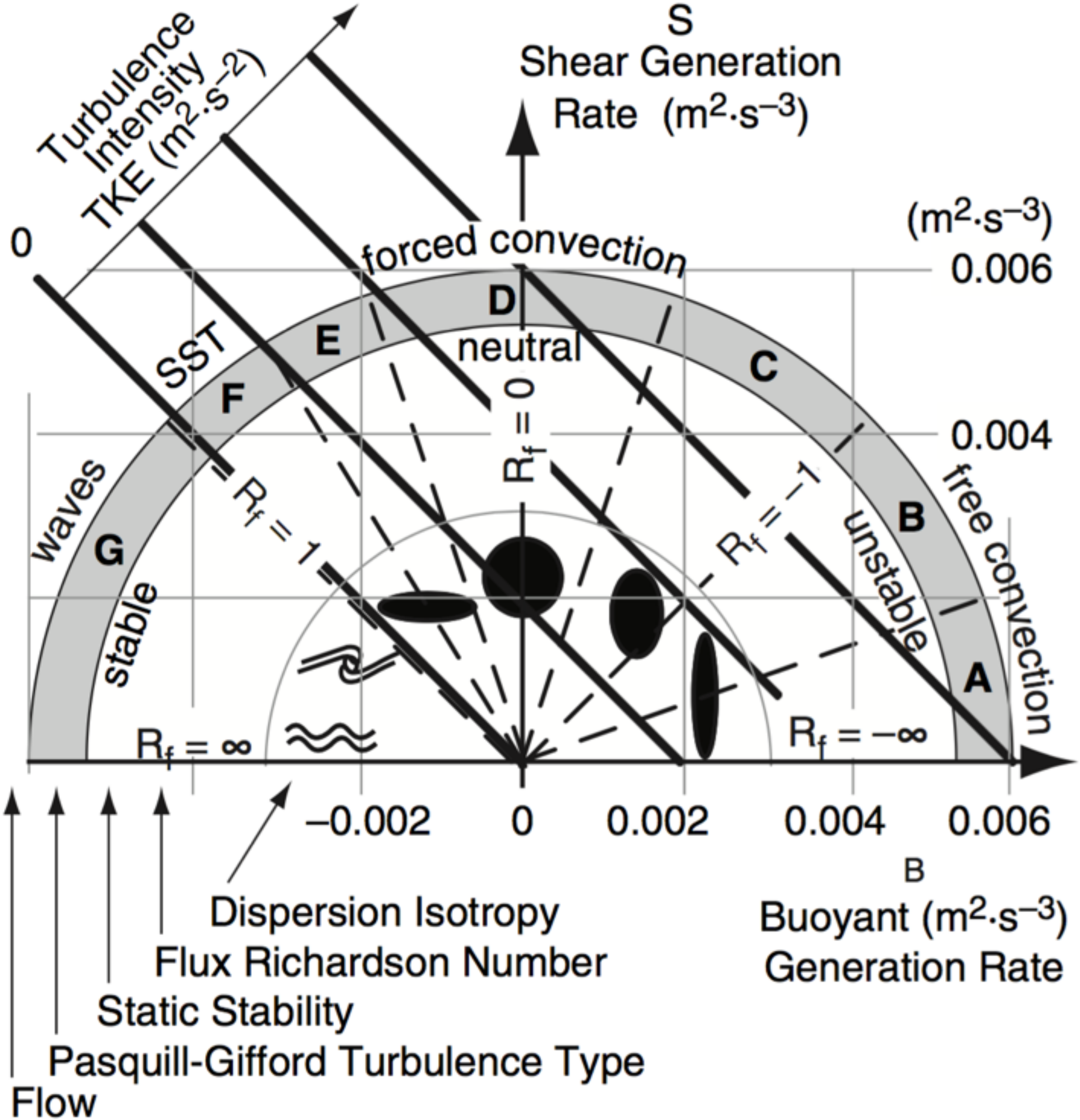
M ($\mathrm{m\ s^{-1}}$)	**Insolation** (incoming solar radiation)		
	Strong	**Moderate**	**Weak**
< 2	A	A to B	B
2 to 3	A to B	B	C
3 to 4	B	B to C	C
4 to 6	C	C to D	D
> 6	C	D	D

Table 19-2b. Pasquill-Gifford turbulence types for **Nighttime**. M is wind speed at $z = 10$ m.

M ($\mathrm{m\ s^{-1}}$)	**Cloud Coverage**	
	≥ 4/8 low cloud or thin overcast	**≤ 3/8**
< 2	G	G
2 to 3	E	F
3 to 4	D	E
4 to 6	D	D
> 6	D	D

Smoke Plume Cross Section





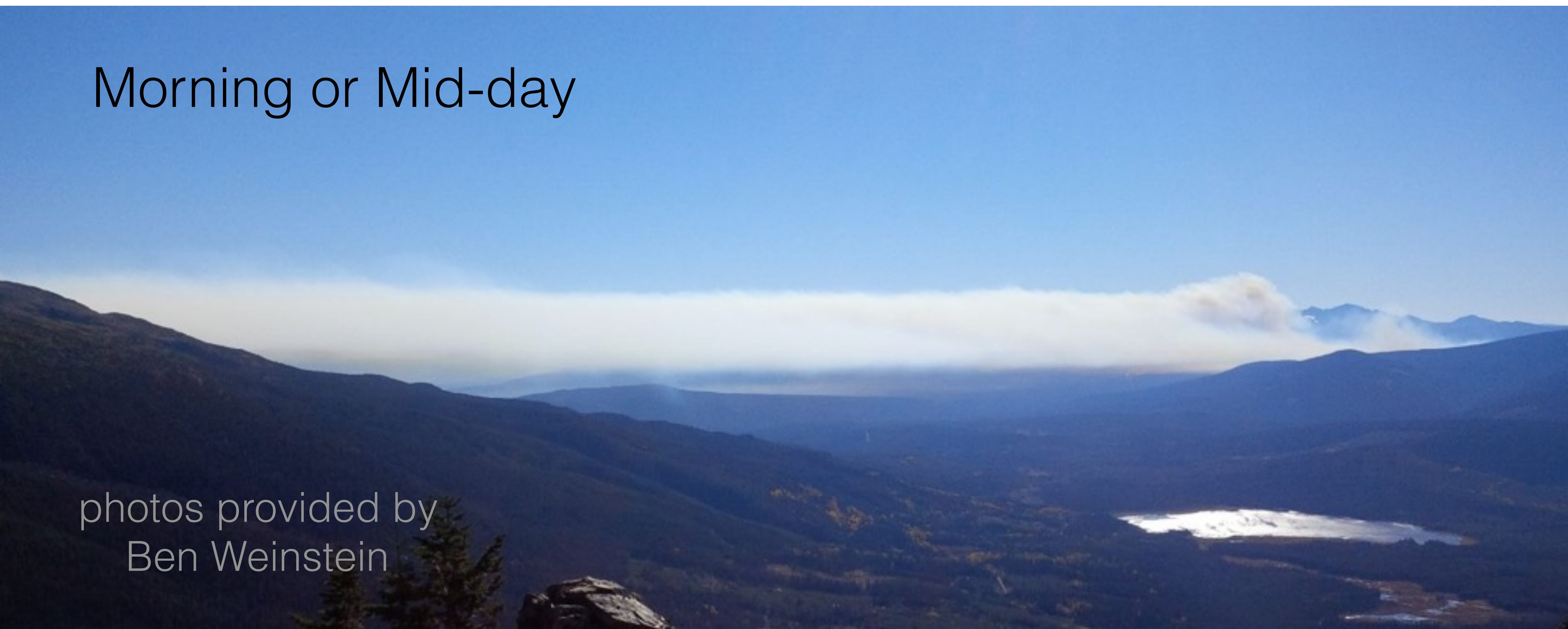
Turbulence Intensity TKE ($m^2 \cdot s^{-2}$)
S
Shear Generation Rate ($m^2 \cdot s^{-3}$)
($m^2 \cdot s^{-3}$)
0.006
0.004
0
forced convection
D
neutral
E
C
SST
F
$R_f = 0$
waves
$R_f = 1$
$R_f = -1$
B
unstable
free convection
G
stable
A
$R_f = \infty$
$R_f = -\infty$
−0.002
0
0.002
0.004
0.006
B
Buoyant ($m^2 \cdot s^{-3}$) Generation Rate
Dispersion Isotropy
Flux Richardson Number
Static Stability
Pasquill-Gifford Turbulence Type
Flow

Take a 5 minute “stretch” break

7. Pile-burn Case Study. Sep 2016 near Smithers

thanks to Ben Weinstein

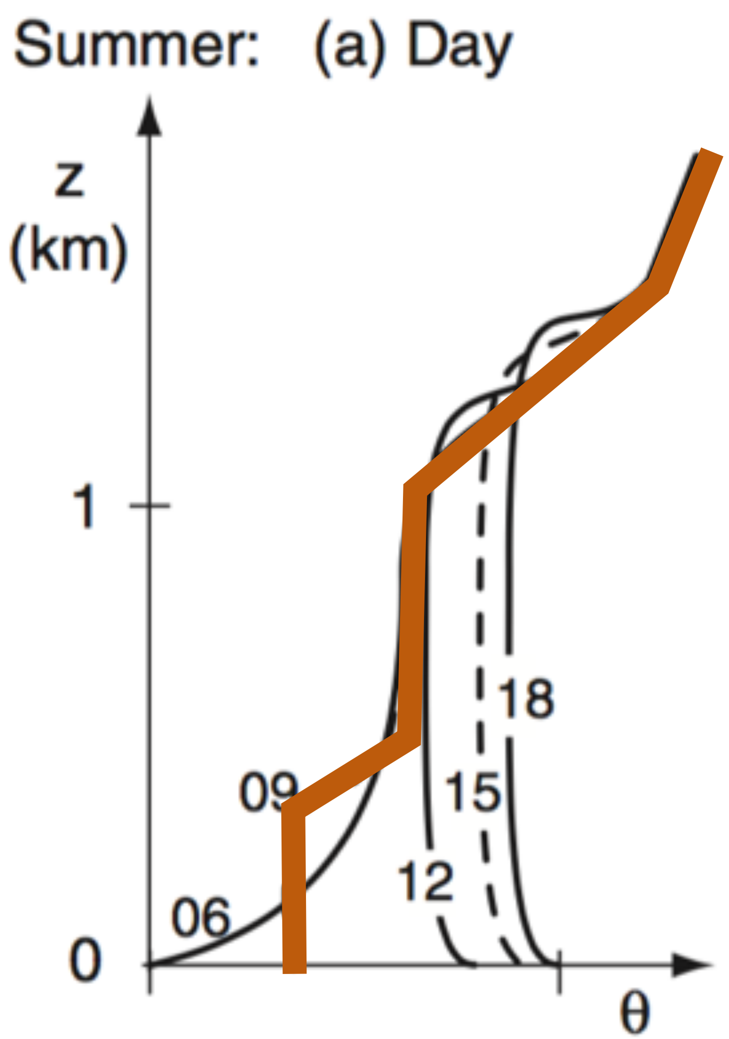
“A forest company burned 400+ industrial slash piles < 20 km from Smithers. The venting forecast was ‘good’, however the plume was trapped aloft and had a defined top and bottom (see pictures). It ended up descending into town in the evening and led to high exposure for a short time, causing me much grief and extra workload.”

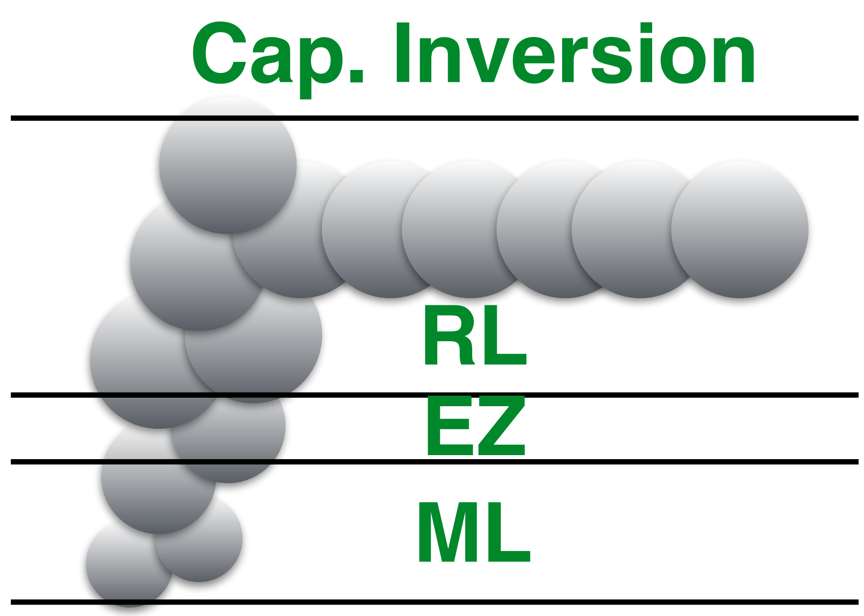


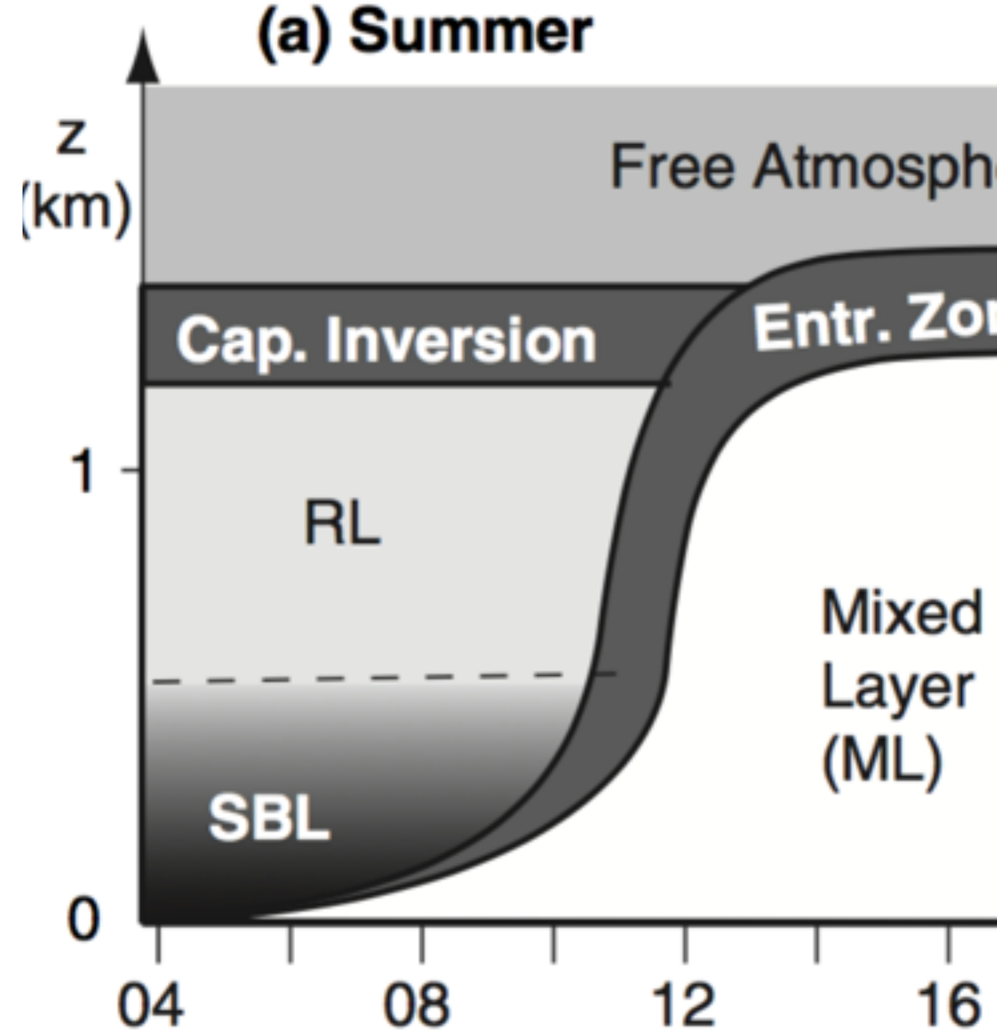

Morning or Mid-day
photos provided by
Ben Weinstein

Evening.   Photos provided by Ben Weinstein

One possible explanation.







Discussion? Thoughts?

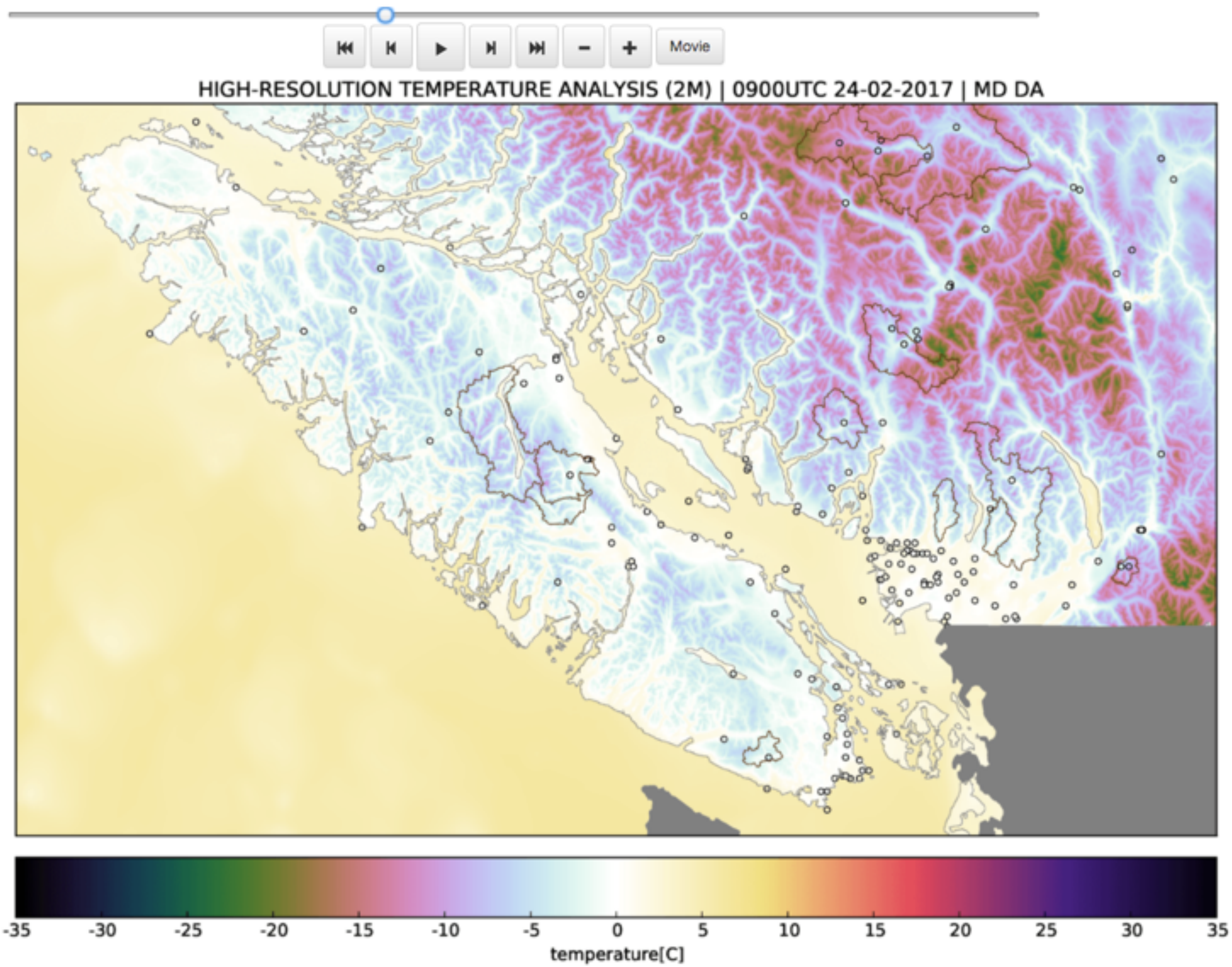
8. Clarifications of Some of Your Issues

- PBL formation and breakdown
- winter PBLs
- PBL in valleys. Also valley clouds vs. inversions
- PBL vs smoke dispersion
- dispersion prediction days in advance
- using soundings to anticipate dispersion
- how to understand Weinstein's Air Qual. Advisory fcsts.
- surface roughness
- venting: roles of shear and buoyancy
- how fine a resolution in NWP is numerically stable
- using weather forecasts to anticipate episodes of poor air quality

Clarifications

- how fine a resolution in NWP is numerically stable?

- We run NWP models at Δx = 1.3 km every day, & 0.44 km for case studies.
- "Resolution" = 7 Δx in most NWP
- Our "nowcasting" map combines NWP, station data, and very-high res. DEM.



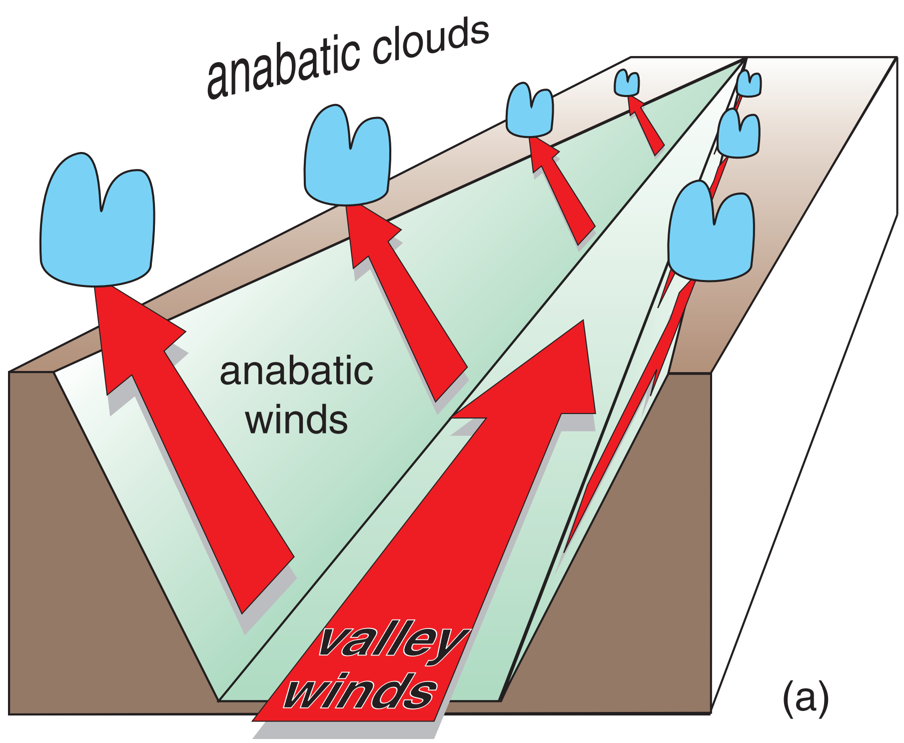
Nowcast created by Nadya Moisseeva

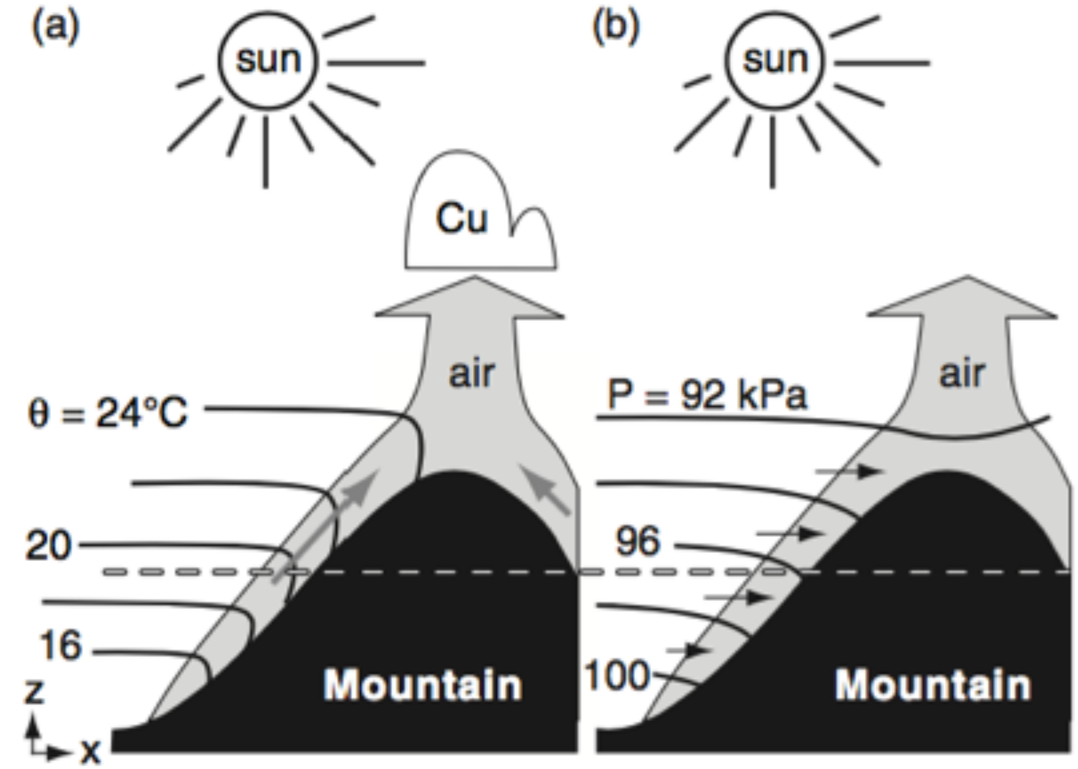
Clarifications

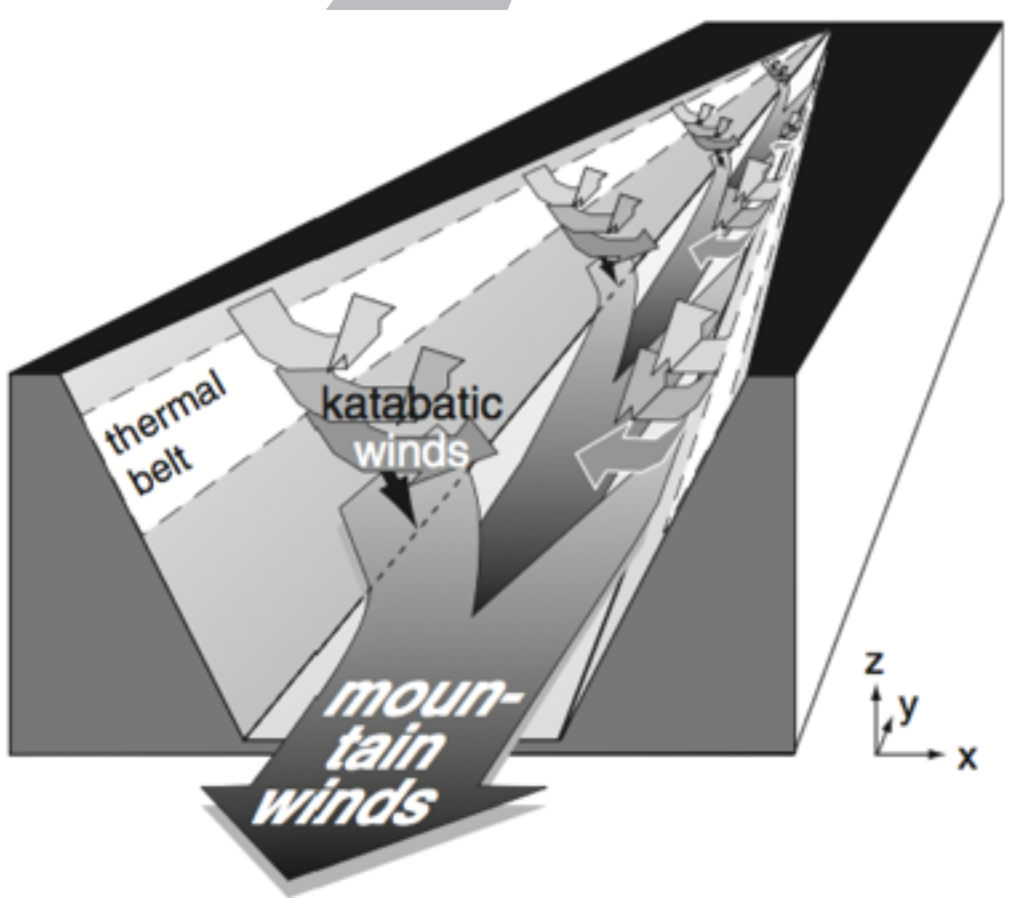
- Valley PBLs, inversions & dispersion

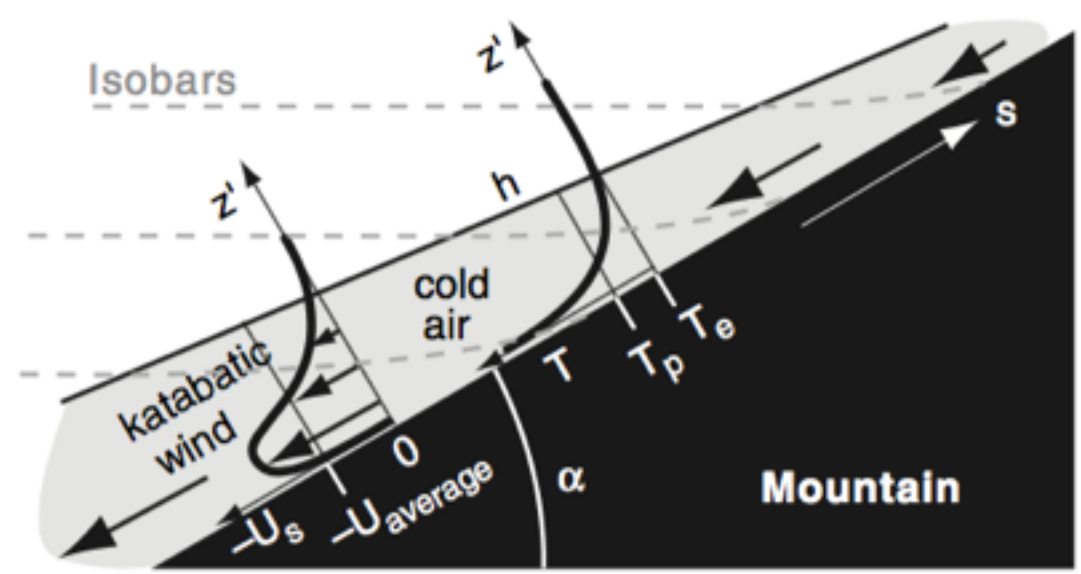
See Chapter 17 of Stull 2015: Practical Meteorology.

Anabatic & katabatic winds during <u>fair weather</u>.







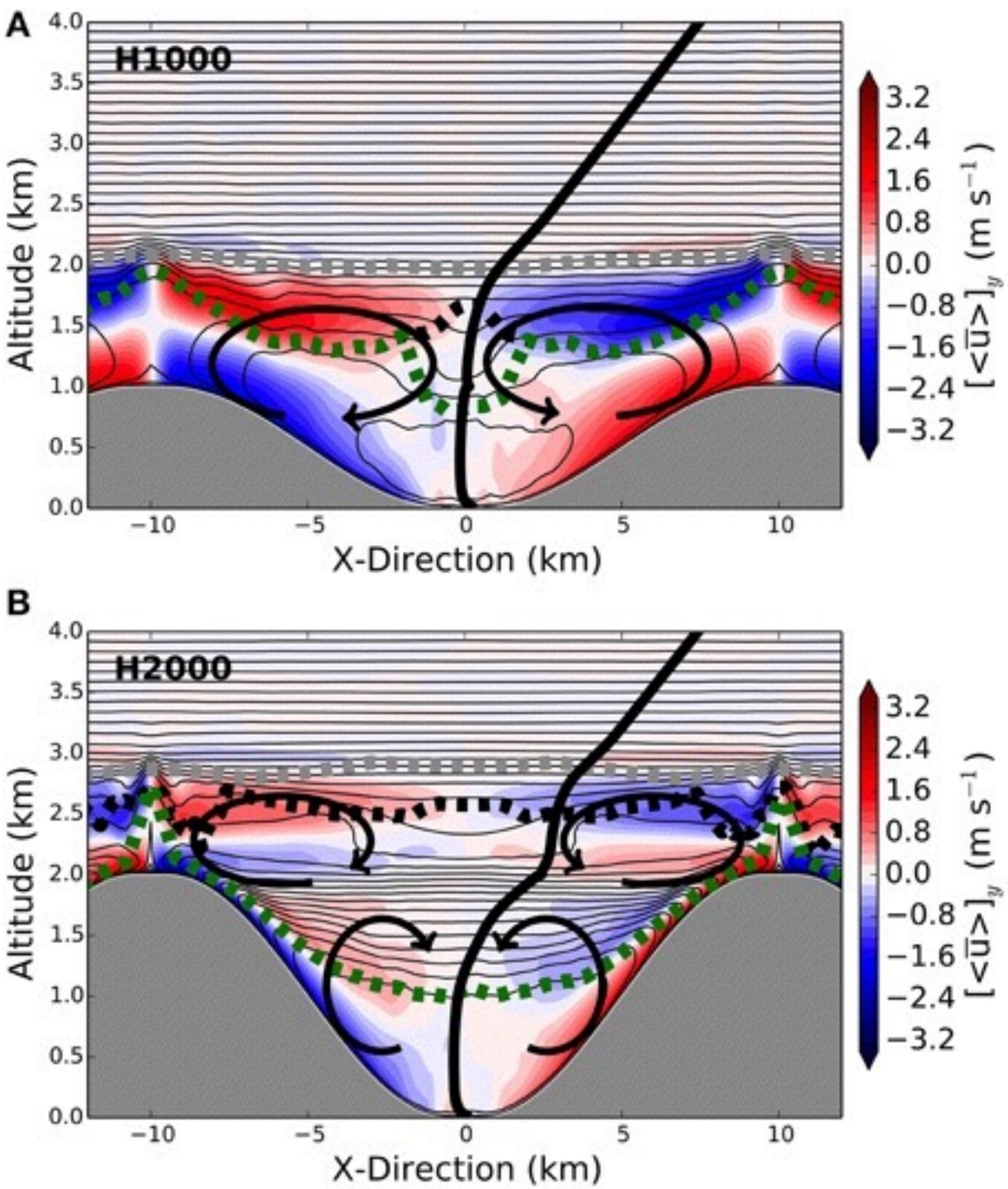


Clarifications

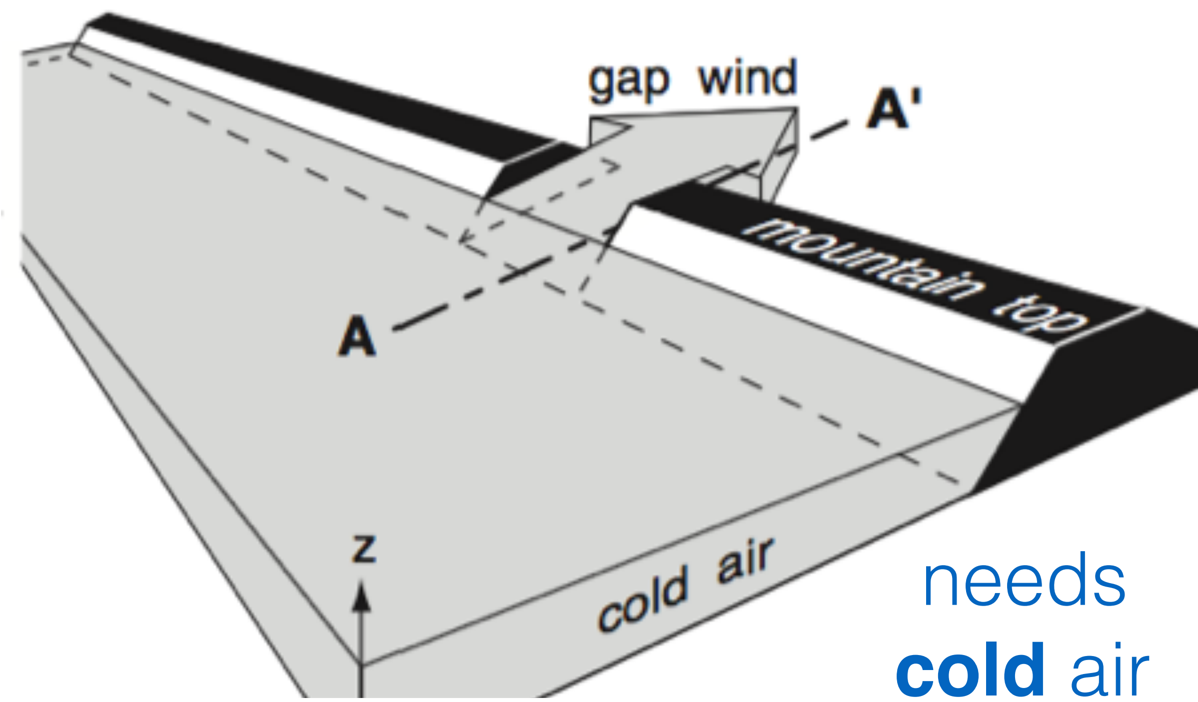
- Valley PBLs, inversions & dispersion

See Chapter 17 of Stull 2015: Practical Meteorology.

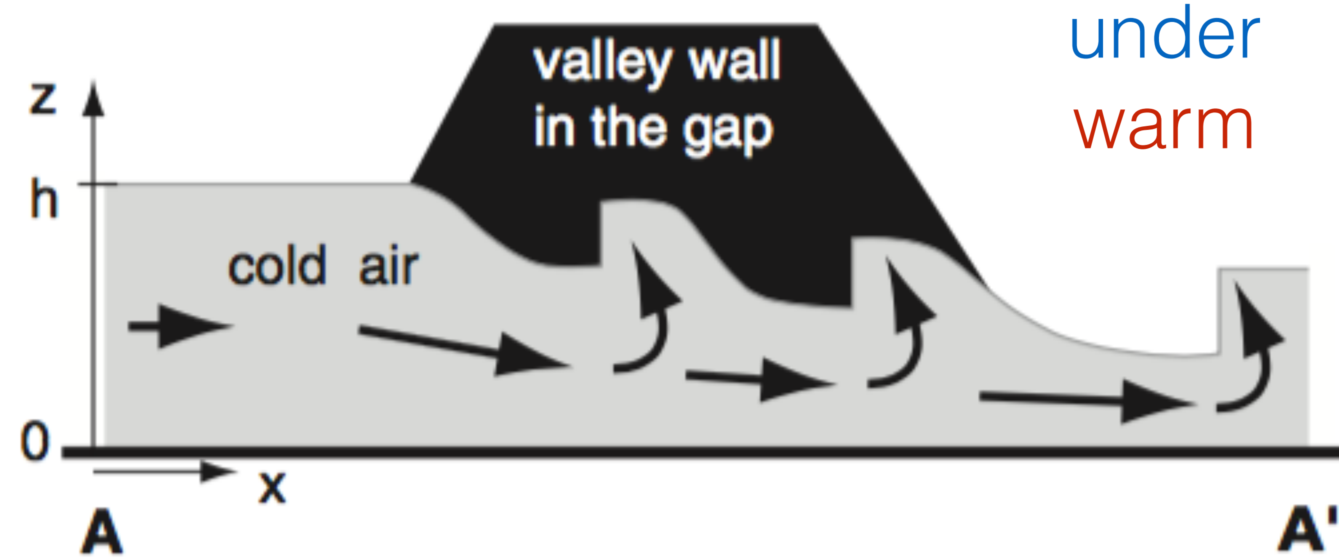
Valley inversions in fair weather.



Gap winds.



needs **cold** air under warm



$$M_{gap\ max} = \left[|g| \cdot \frac{\Delta\theta_v}{T_v} \cdot h \right]^{1/2}$$

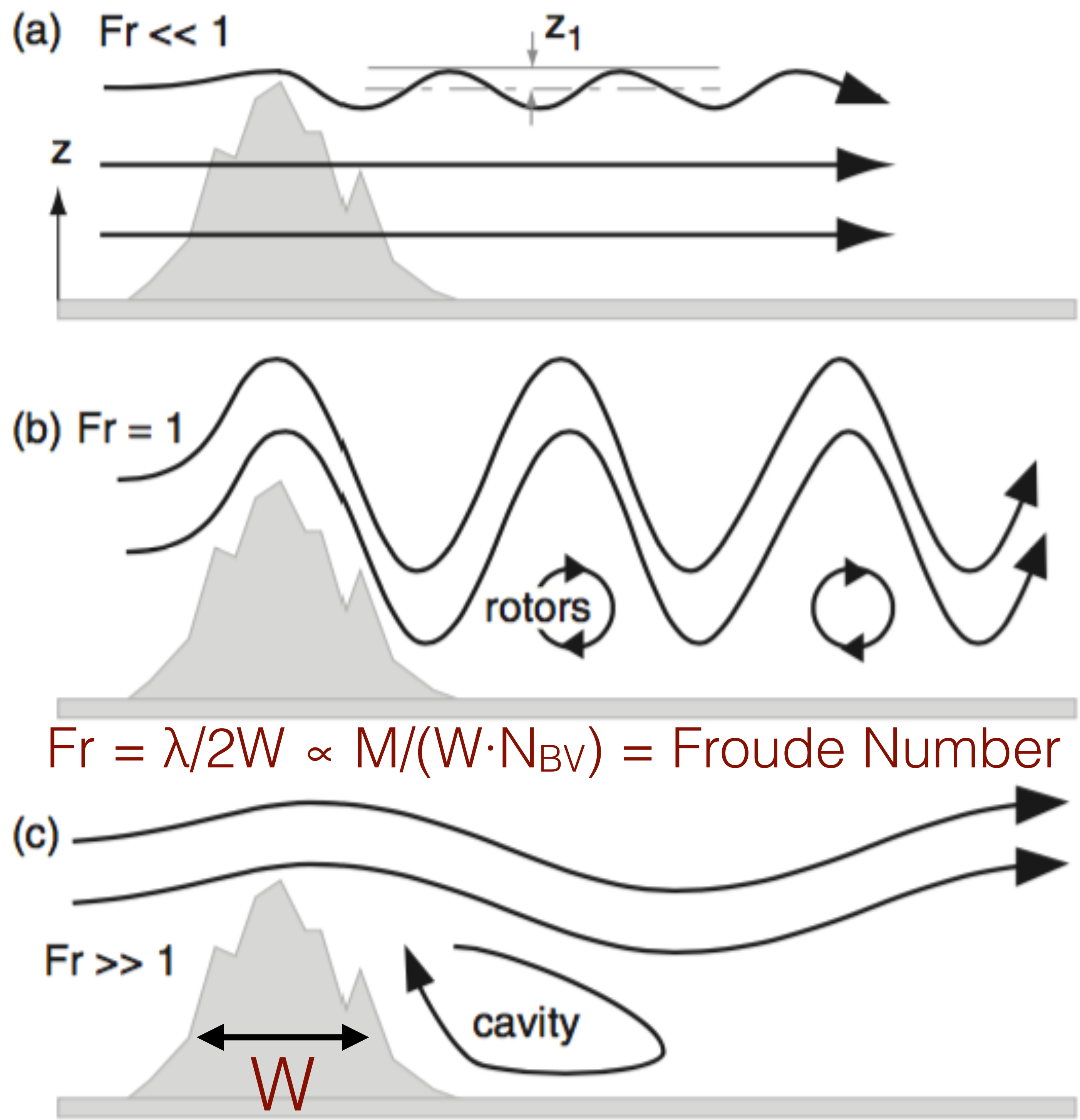
Clarifications

- Valley PBLs, inversions & dispersion

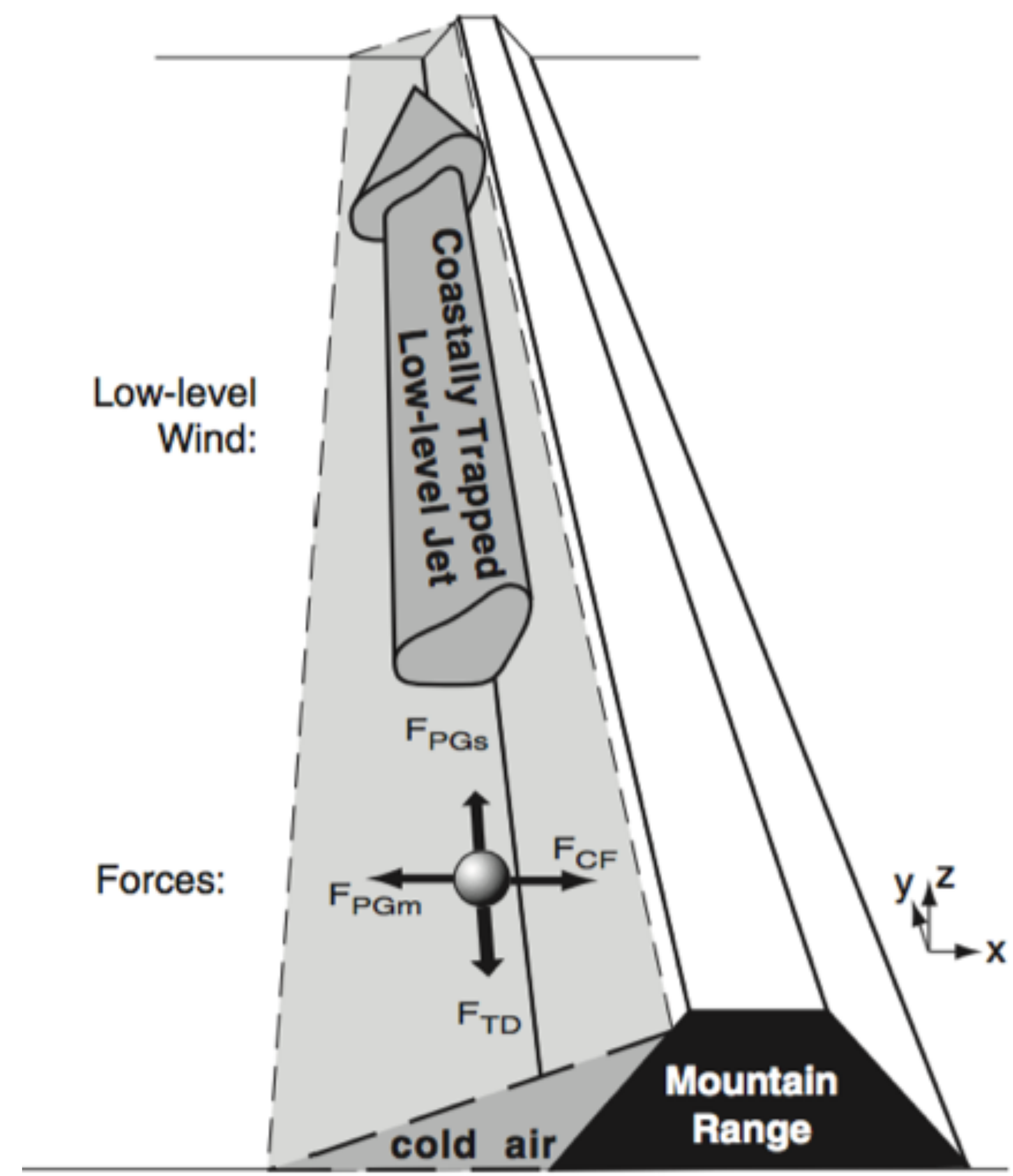
See Chapter 17 of Stull 2015: Practical Meteorology.

For synoptically windy conditions.

Mountain waves



Barrier Jet.



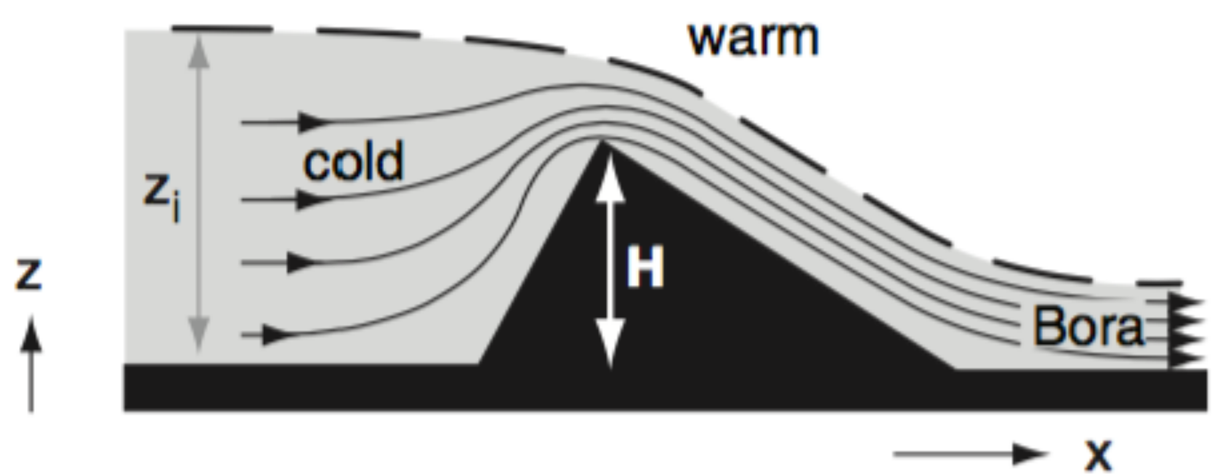
Clarifications

- Valley PBLs, inversions & dispersion

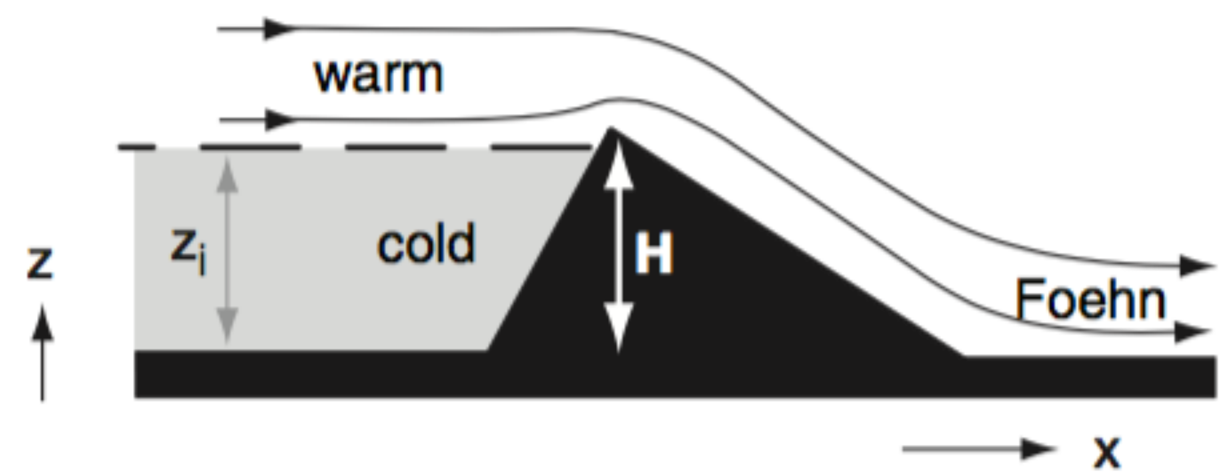
See Chapter 17 of Stull 2015: Practical Meteorology.

Downslope winds

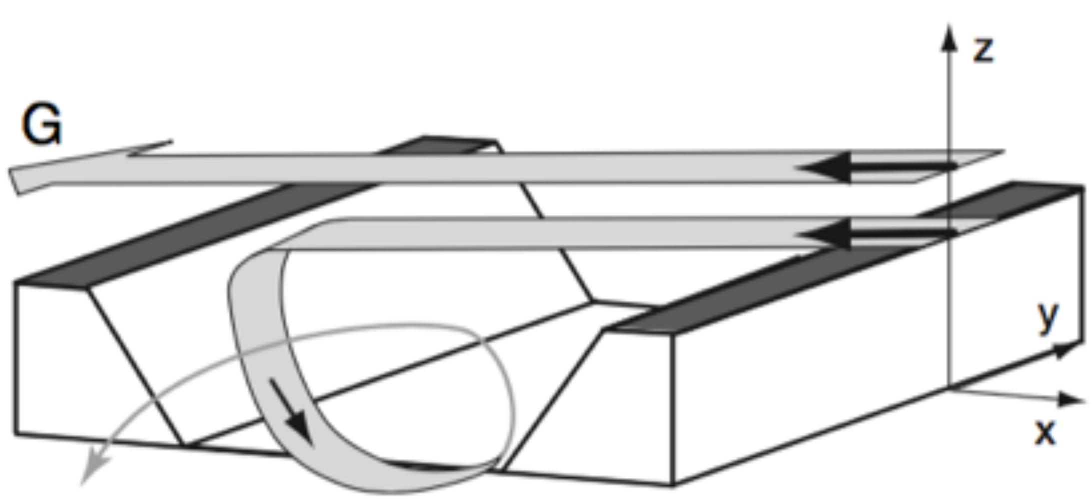
Bora

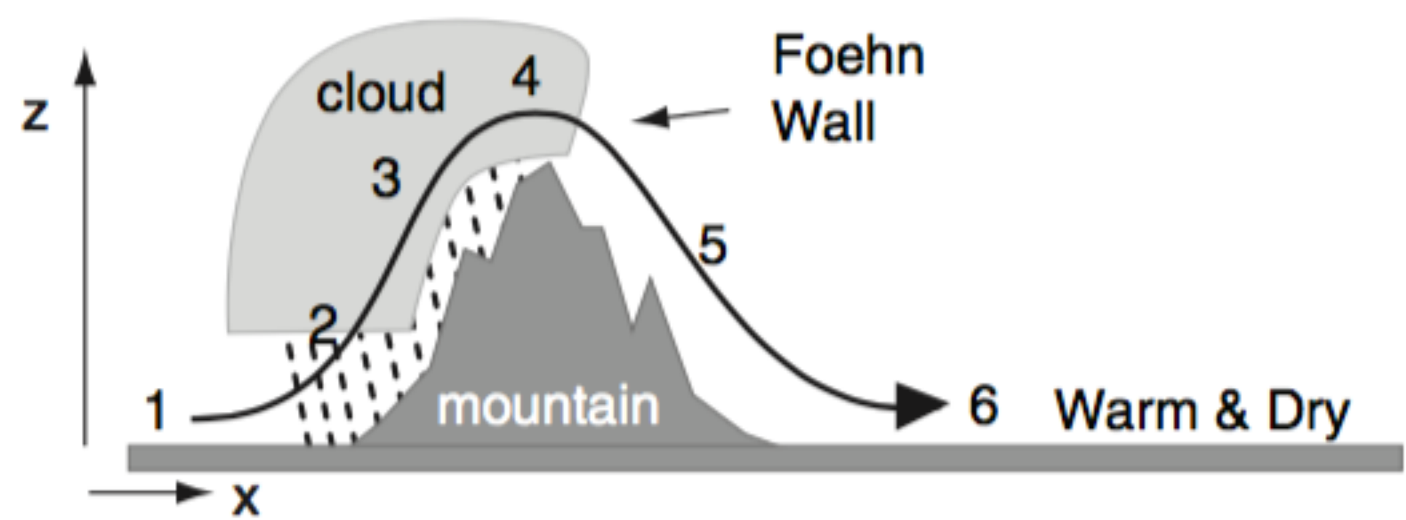


Foehn = Chinook



Channeled flow.





Survey Results - Clarification Presented

- ✓ PBL formation and breakdown
- ✓ winter PBLs
- ✓ PBL in valleys. Also valley clouds vs. inversions
- ✓ PBL vs smoke dispersion
- • dispersion prediction days in advance (use NWP)
- ✓ using soundings to anticipate dispersion
- • how to understand Weinstein's Air Qual. Advisory fcsts.
- • surface roughness (rougher terrain causes slower winds but greater turbulence intensity near the ground)
- ✓ venting: roles of shear and buoyancy (greater shear & buoyancy increase dispersion rate, but other factors for venting include inversion height and wind speed)
- ✓ how fine a resolution in NWP is numerically stable
- ✓ using weather forecasts to anticipate episodes of poor air quality

Atmospheric Boundary Layers, Turbulence & Dispersion

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+1 604 822 5901

Topics:

1. Boundary Layer Basics
2. Static Stability
3. BL Evolution
4. Turbulence Generation
5. Turb. Kinetic Energy
6. TKE & Dispersion
7. Pile-burn Case Study
8. Clarifications of Your Issues

If requested, if time:

9. Dispersion in the Convective ML

For free book online: https://www.eoas.ubc.ca/books/Practical_Meteorology/

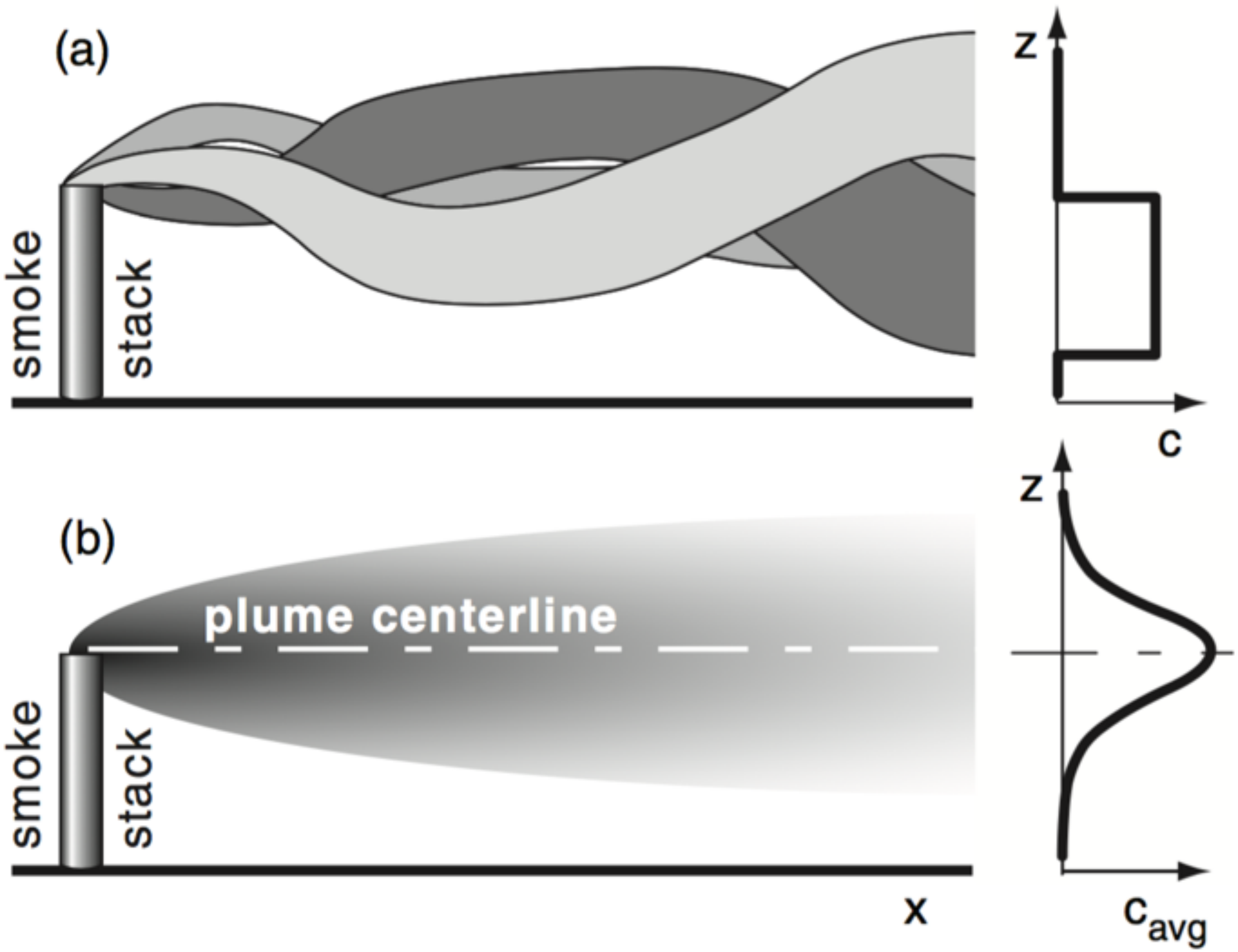
the end

9. Dispersion in a Convective Mixed Layer

Jim Deardorff

Snapshots

Time Average



Strangely, for a convective ML, the centreline can descend.

(show Deardorff tank movie if time)

Time-averaged Centreline Height (Z_{CL}) vs. Downwind Distance (x)

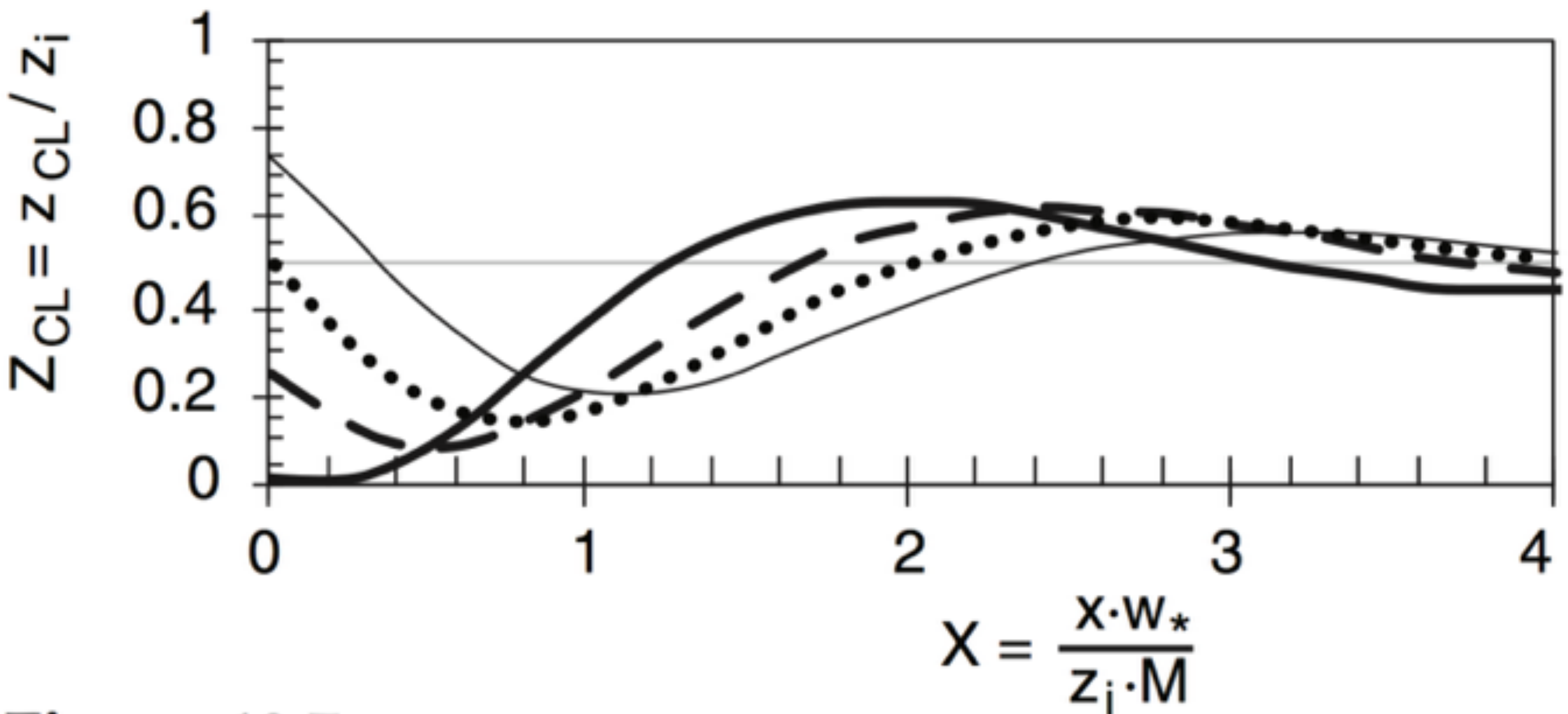
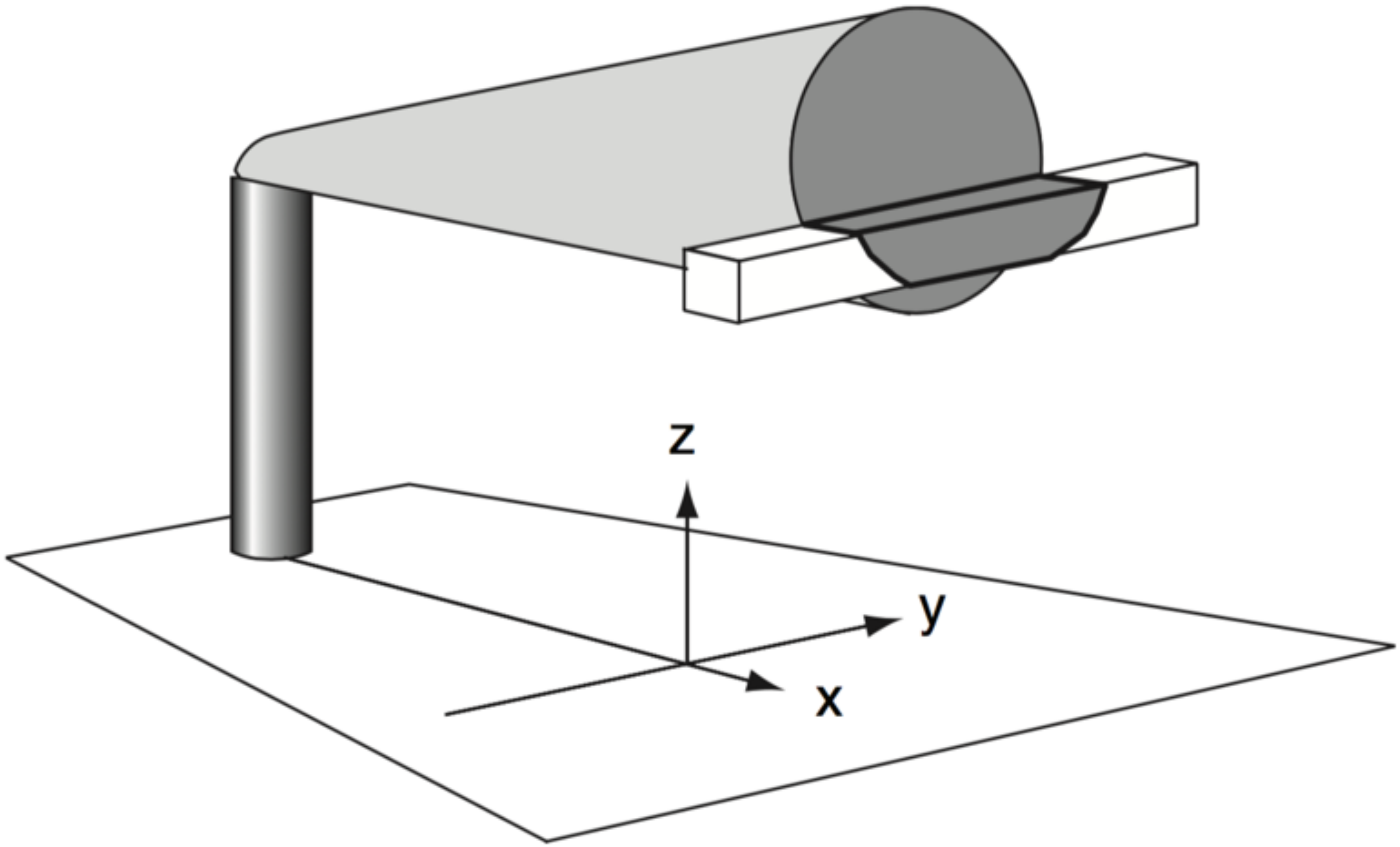


Figure 19.7
Height of the averaged pollutant centerline z_{CL} with downwind distance x, normalized by mixed-layer scales. Dimensionless source heights are $Z_s = z_s/z_i = 0.025$ (thick solid line); 0.25 (dashed); 0.5 (dotted); and 0.75 (thin solid). The plume is neutrally buoyant.

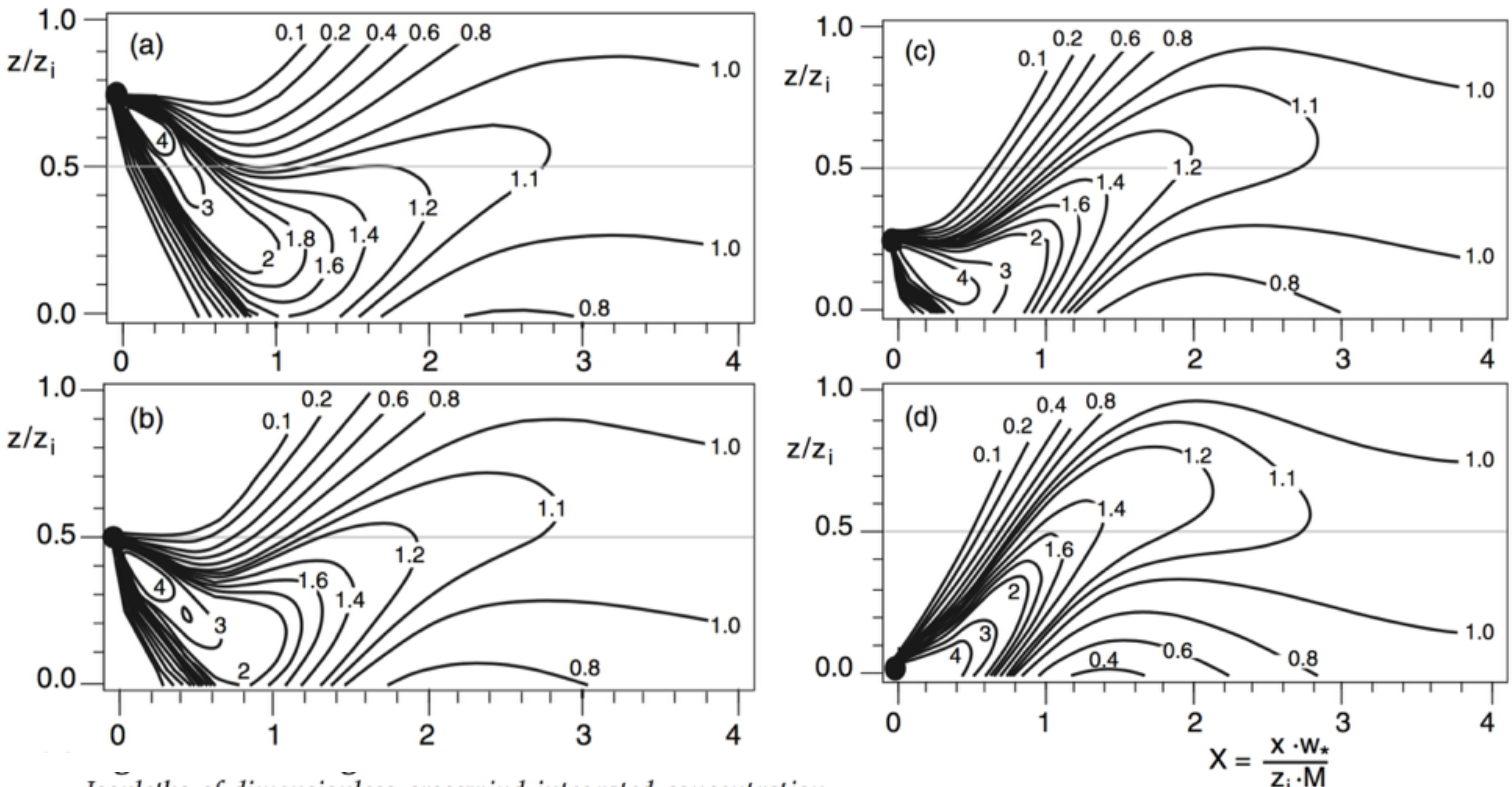
$$w_* = \left[\frac{|g| \cdot z_i \cdot F_H}{T_v} \right]^{1/3} = \textbf{Deardorff velocity}\ (\mathrm{m\ s^{-1}}) \qquad (19.22)$$

F_H = surface heat flux, z_i = mixed layer depth, M = wind speed

Cross-wind Integrated Concentration, C_y



C_y vs. z and x, for various effect stack heights



Isopleths of dimensionless crosswind-integrated concentration $C_y = c_y \cdot z_i \cdot M / Q$ in a convective mixed layer, where c_y is crosswind integrated concentration, z_i is depth of the mixed layer, M is mean wind speed, and Q is emission rate of pollutants. Source heights are $Z_s = z_s/z_i =$ (a) 0.75, (b) 0.5, (c) 0.25, (d) 0.025, and are plotted as the large black dot at left.