Chapter 3 – Atmospheric Thermodynamics

Spring 2023

Avogadro's Hypothesis

- Gases containing the same number of molecules occupy the same volumes at the same temperature and pressure.

- Therefore, for any mole of gas, the gas constant is the same.

Partial Pressure and Dalton

- Dalton's law of partial pressure: total pressure exerted by a mixture of gases which do not interact chemically is equal to the sum of the partial pressures of the gases.

- Partial pressure: pressure the gas would exert at the same temperature if it alone occupied the volume the mixture occupies.
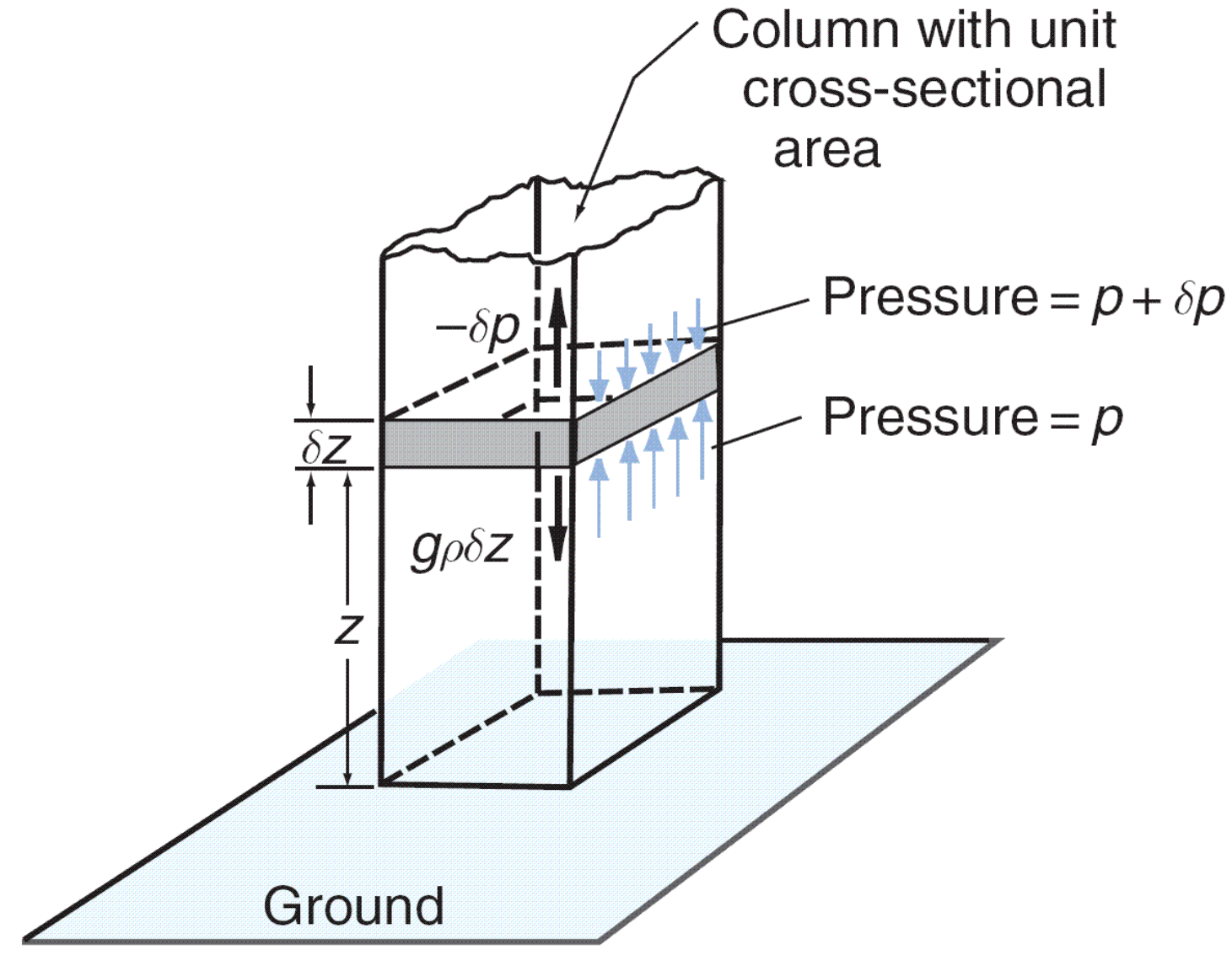
Equation of State Simplification

- To use the equation of state, we would need to consider both moist and dry air. We would also have to know the exact amount of water in the air.

- Easier to make an adjustment and consider only the amount of dry air.
  - Water vapor is only 4-5% by volume.

Virtual Temperature

- T_v = The temperature that dry air must have in order to have the same density as moist air at the same pressure.

- How does T_v relate to T?

Vertical Balance of Forces

Column with unit cross-sectional area

$-\delta p$

δz

$g\rho\delta z$

z

Pressure $= p + \delta p$

Pressure $= p$

Ground

Geopotential Height vs. Geometric Height

Table 2.1

Values of the geometric height (z),
geopotential height (Z), and acceleration
due to gravity (g) at 40° latitude

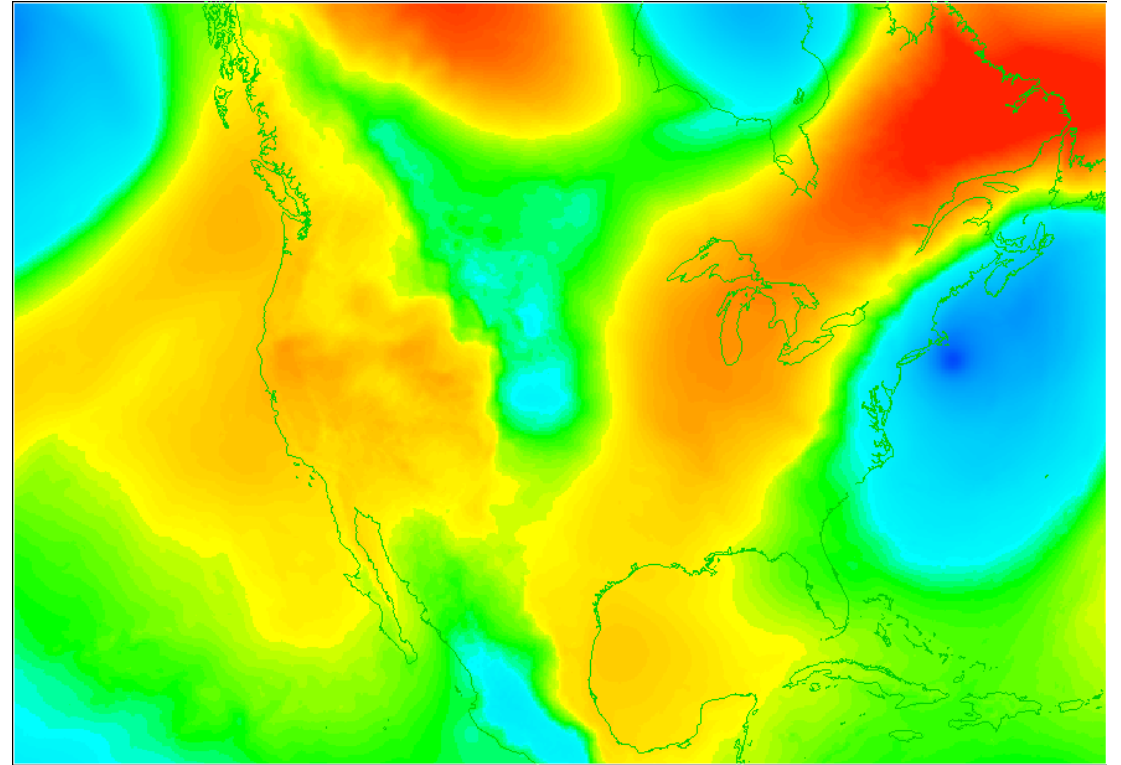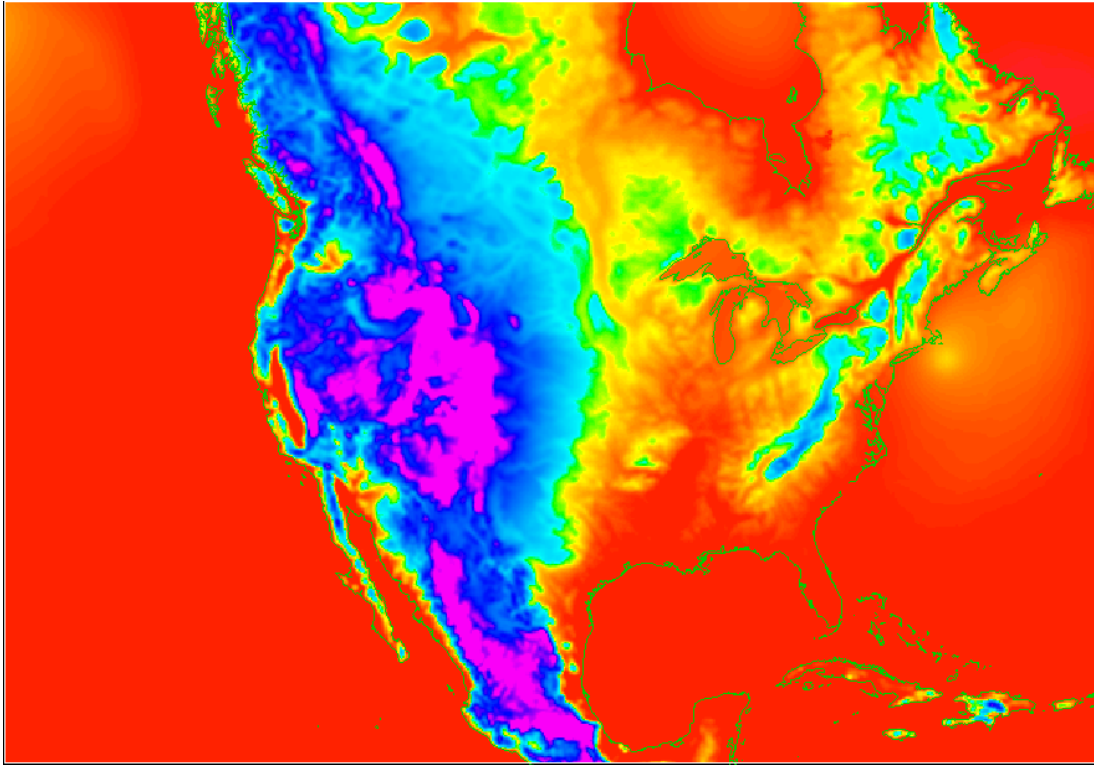| z (km)	Z (km)	g (m s^{-2})
0	0	9.802
1	1.000	9.798
10	9.986	9.771
20	19.941	9.741
30	29.864	9.710
60	59.449	9.620
90	88.758	9.531
120	117.795	9.443
160	156.096	9.327
200	193.928	9.214
300	286.520	8.940
400	376.370	8.677
500	463.597	8.427
600	548.314	8.186

Station Pressure
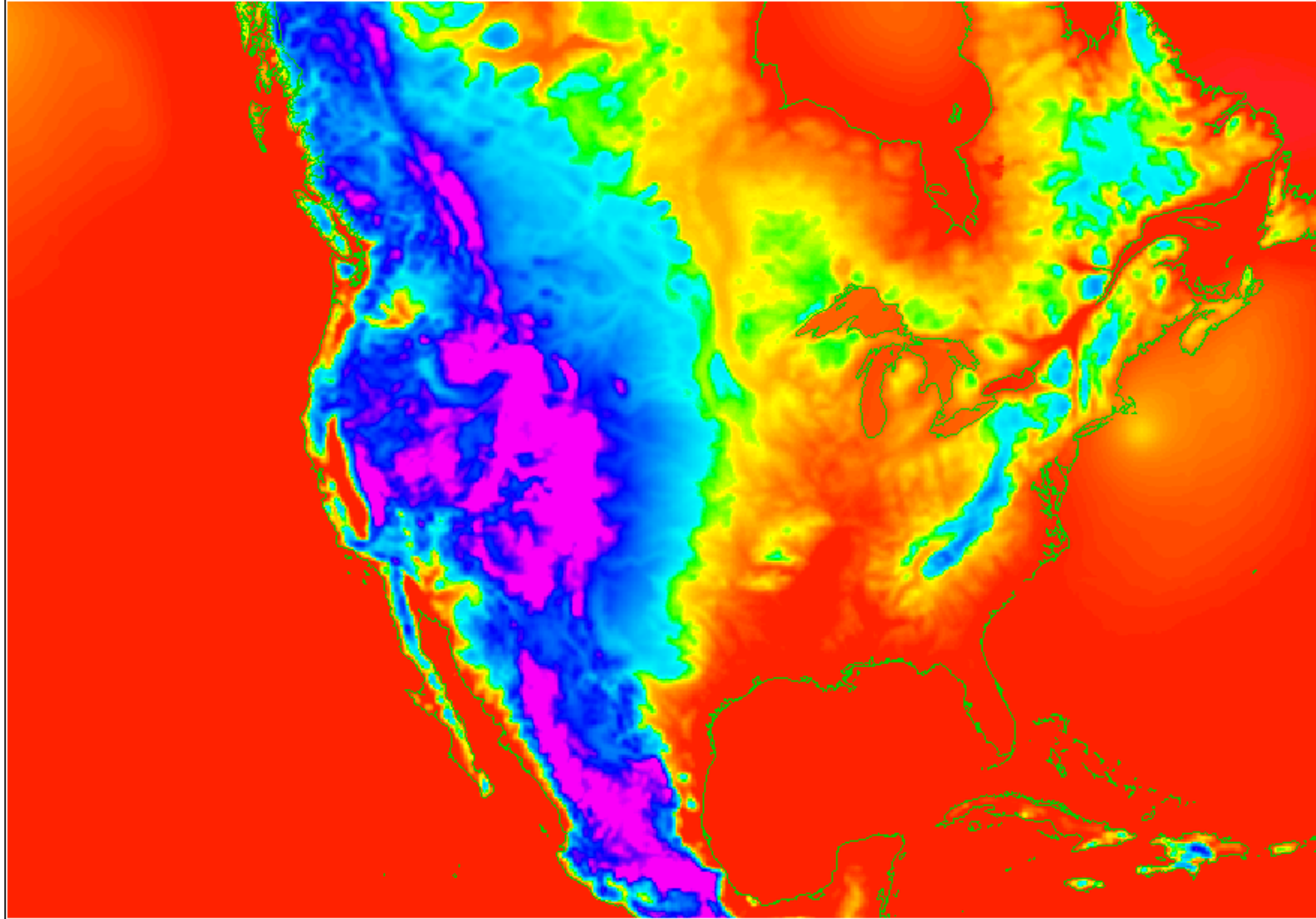
Sea-Level Pressure
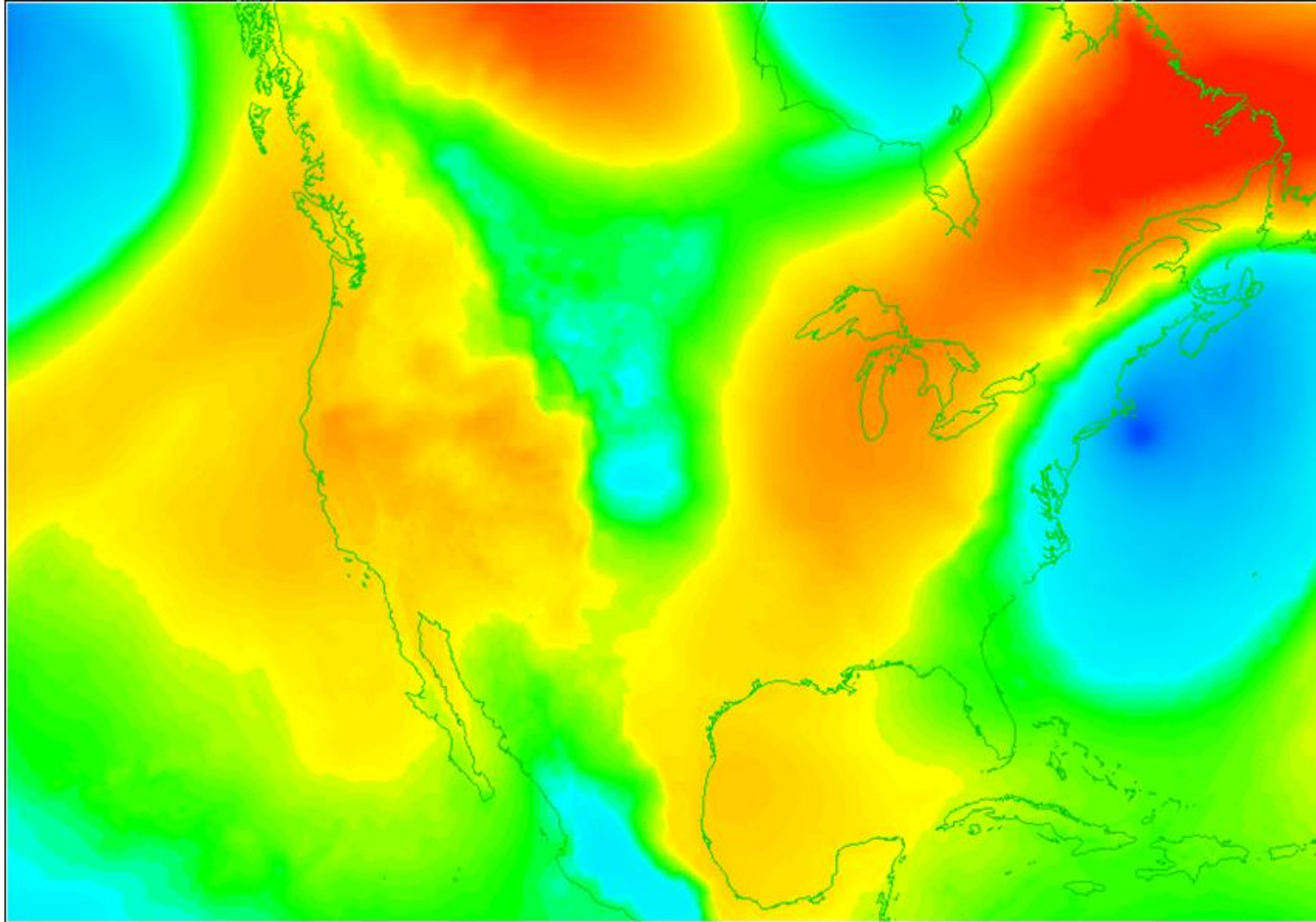
Comparison

Reduction to Sea-Level

- Mountainous regions: Pressure difference from station to station is primarily due to elevation.

- Large scale pressure fields looks a lot like topography field and isn't representative of the meteorological pressure field.

- How do we remove topography from the pressure field so we can see the meteorological pressure field?
  - Reduce all pressures to a common reference level
  - Sea level

Concept of Air Parcel

- Fluid mechanics: random motions of individual molecules.

- Atmosphere: Random motion is only important within a few centimeters from the earths surface and in the upper atmosphere (above ~150km)

- At intermediate levels, mixing is accomplished by the exchange of well defined air parcels.

Air Parcel

- Consider a parcel of infinitesimal dimensions that is:

- Thermally isolated from the environment so that its temperature changes adiabatically as it sinks or rises.

- Always at the same pressure as the environmental air at the same level, assumed to be in hydrostatic equilibrium.

- Moving slowly enough that its kinetic energy is a negligible fraction of its total energy.

Air Parcel cont.

- Note: one or more of these assumptions is nearly always violated to some extent.

- However, they assumptions are helpful in under standing the physical processes that influence vertical motions and vertical mixing in the atmosphere.

Dry Adiabatic Lapse Rate

Potential Temperature

- Temperature air parcel would have if it were raised or lowered (expanded or compressed) adiabatically from its existing temperature and pressure to 1000mb.

- Ɵ = constant for adiabatic motions.

- Ɵ is <u>conserved</u> for adiabatic motions.

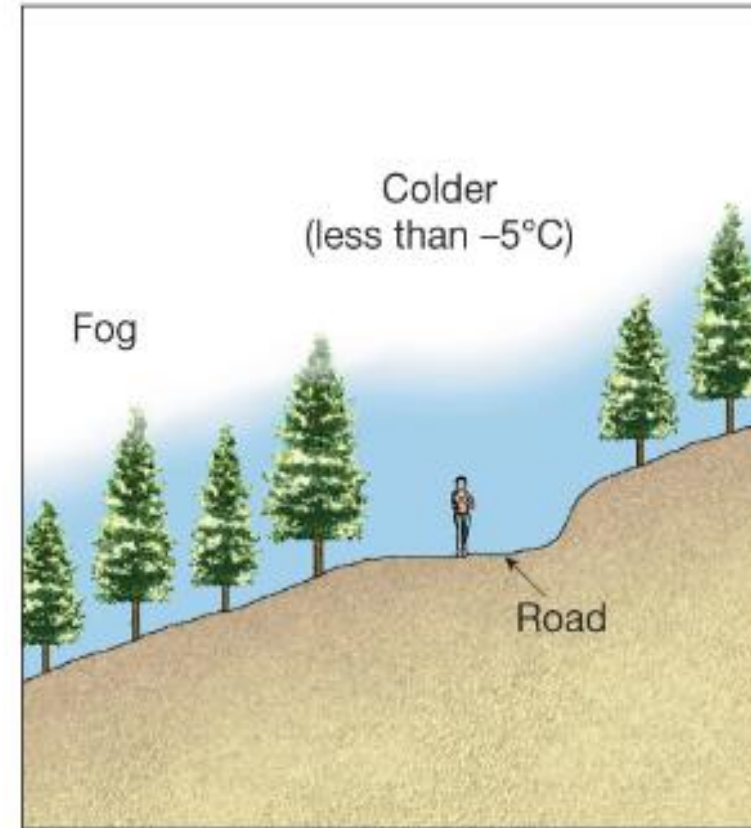- Motions in the atmosphere are nearly adiabatic which makes Ɵ a very important parameter.

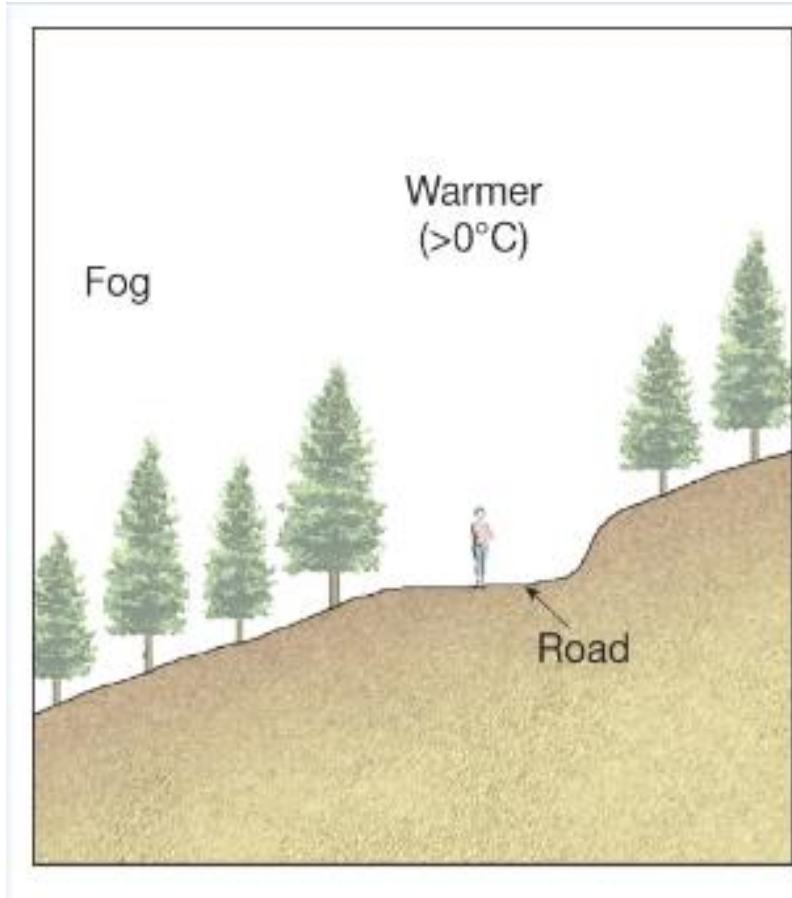# Saturation Vapor Pressure
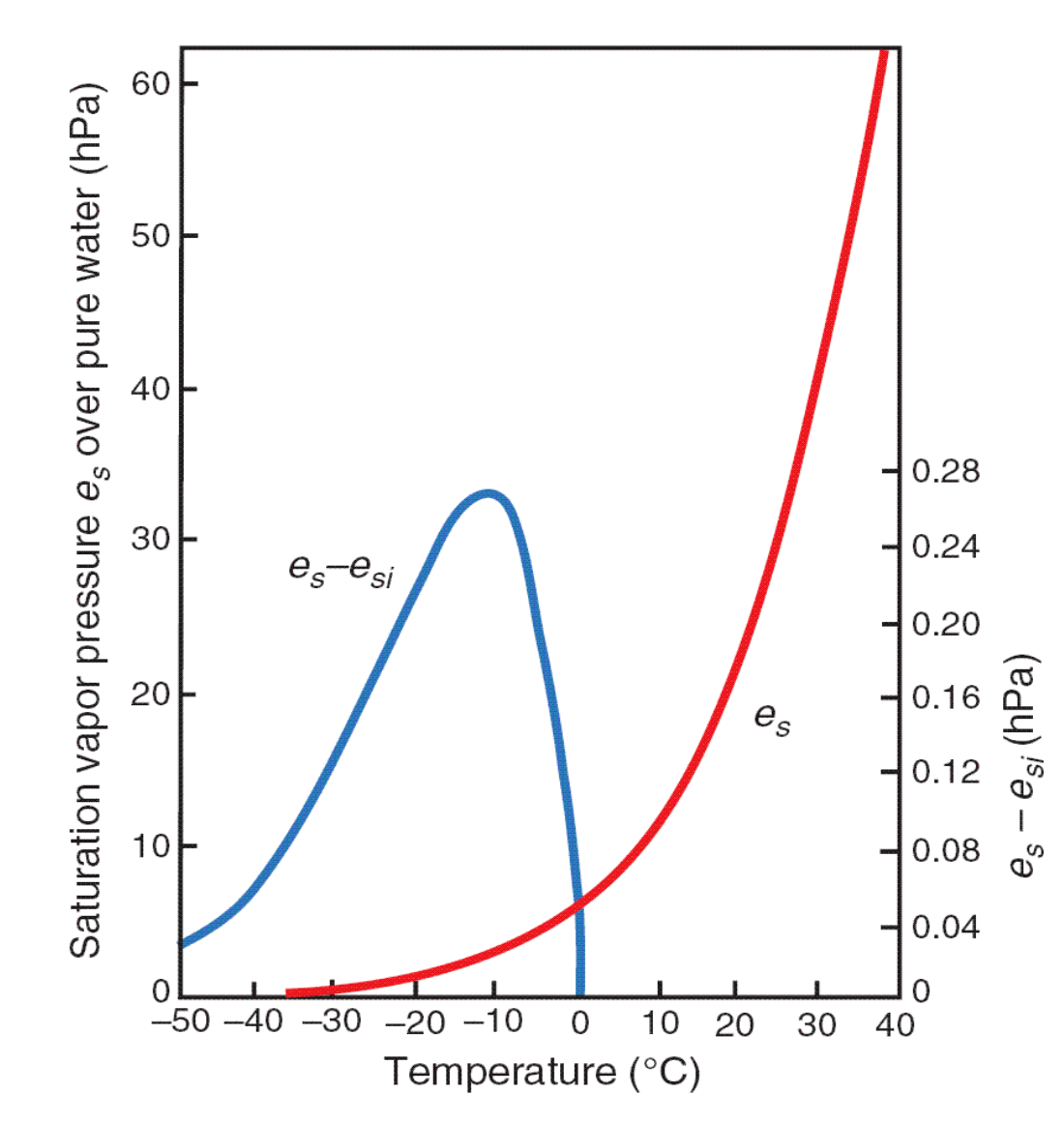
# e$_s$ over water vs. e$_s$ over ice
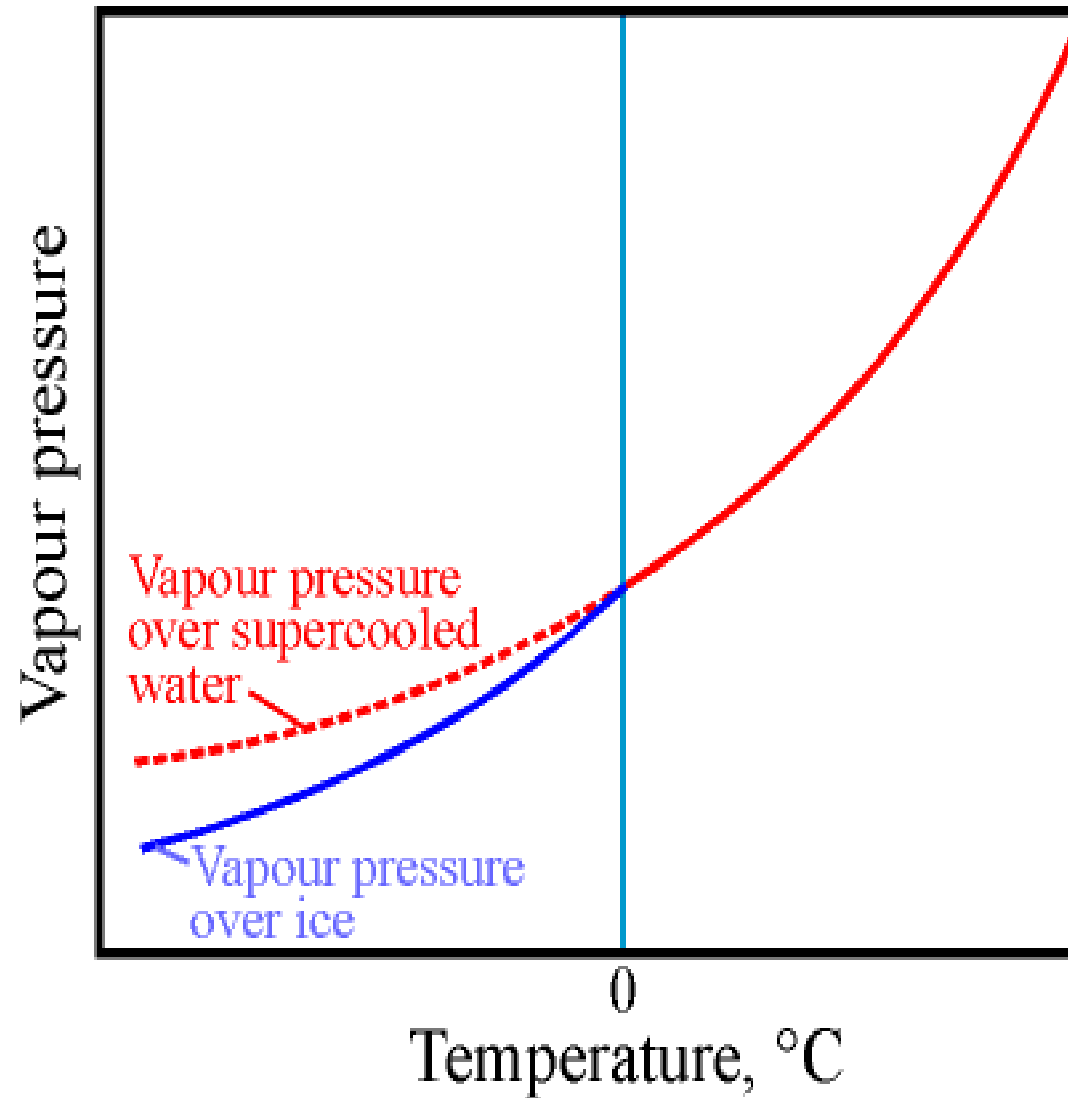
Saturation Vapor Pressure Puzzle

Moisture Variables

- Relative Humidity = 100 * W / W_s
  - Is RH conserved?

- Dew Point = T_d = temperature air must be cooled at constant pressure to become saturated with respect to a plane surface of water.
  - Temperature at which W = W_s

- Frost point = temperature at which air must be cooled at constant pressure to become saturated with respect to a plane surface of ice.
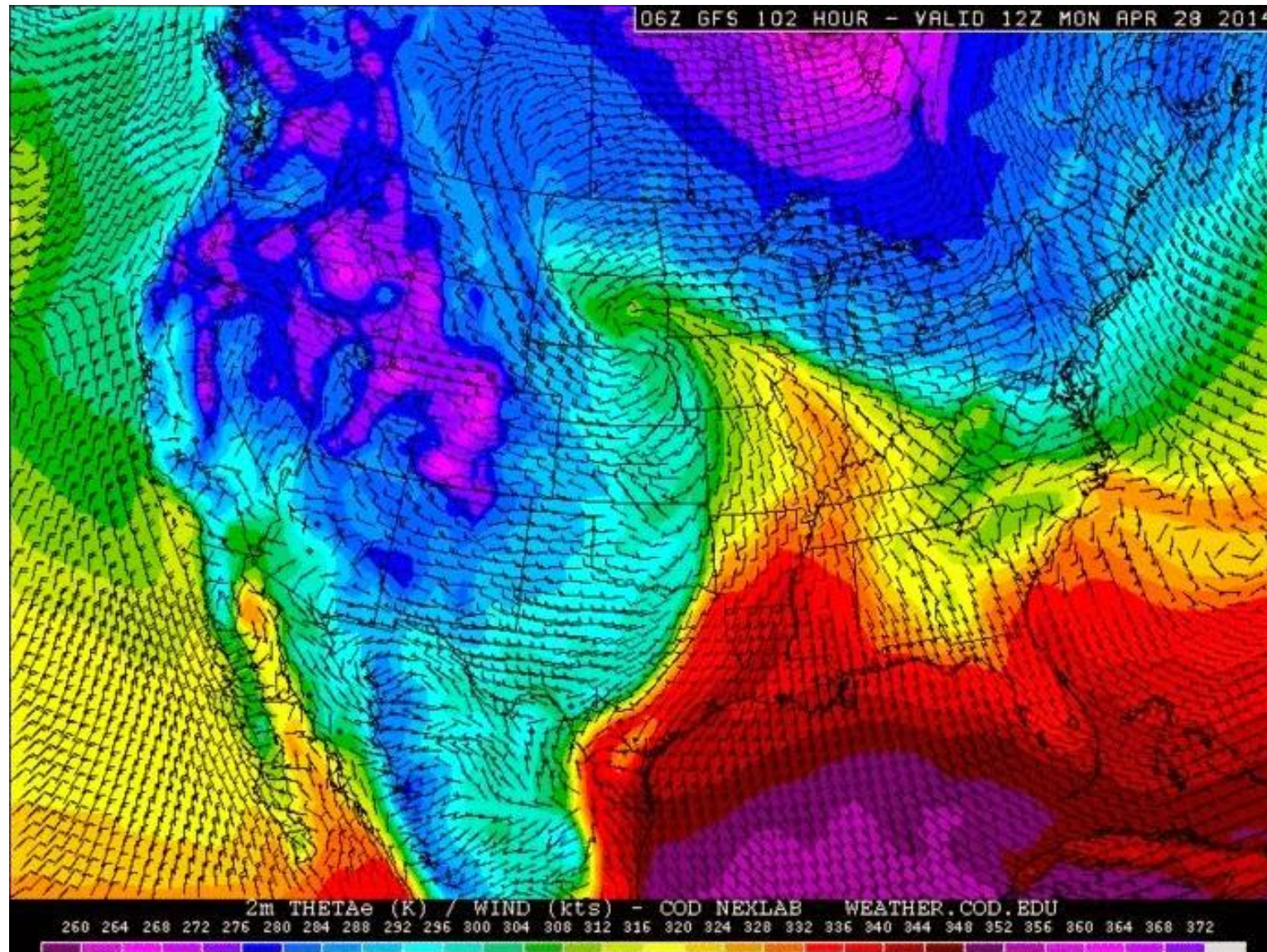
Relative Humidity and Temperature
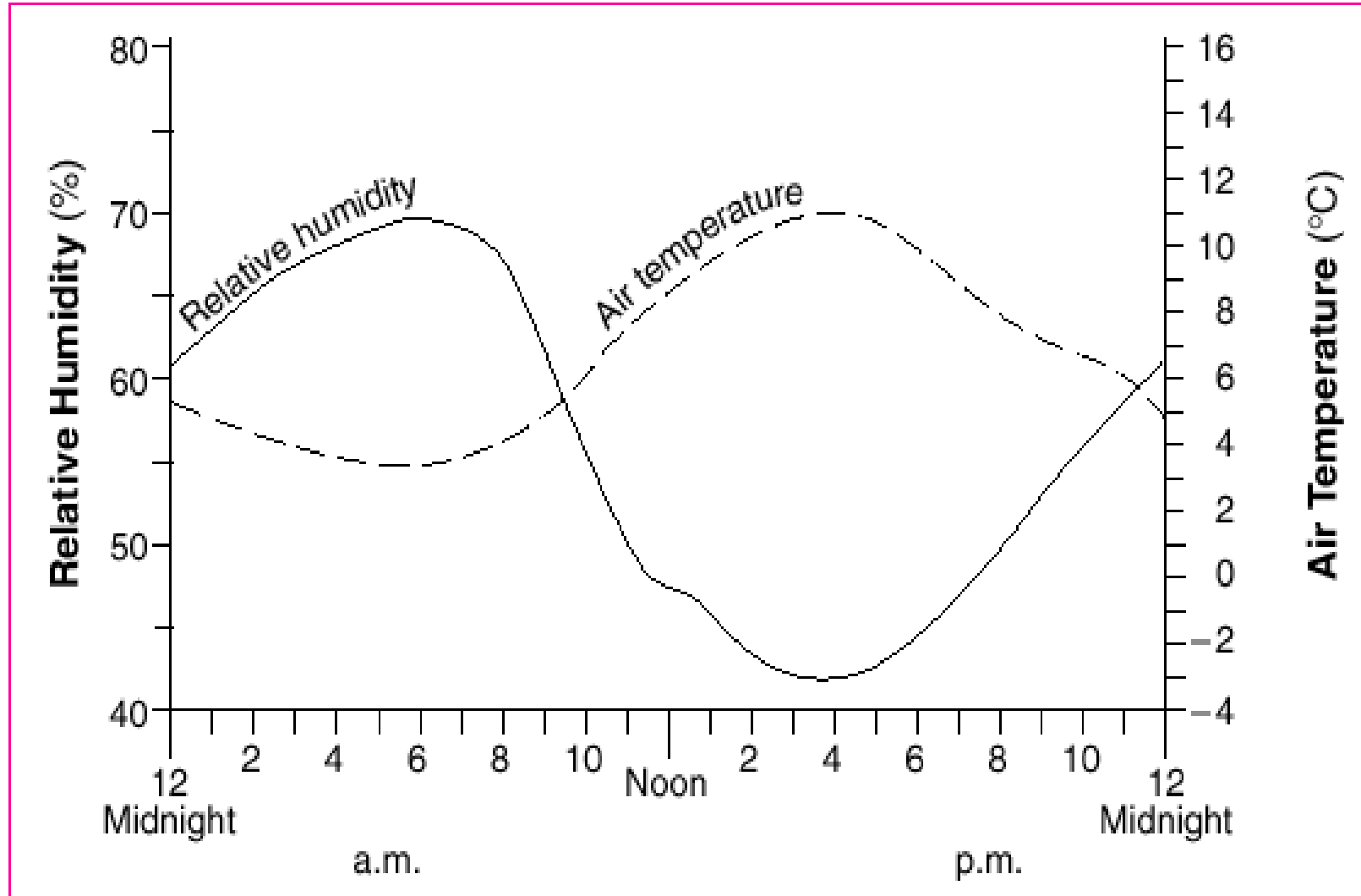
Moisture Variables cont.

- Specific humidity

- Lifting condensation level: level to which a moist parcel can be lifted adiabatically before it becomes saturated with respect to a plane surface of water.

- Think about what happens as you lift a parcel of air……

Moisture Variables cont.

- Wet-bulb temperature, T_w = temperature to which an air parcel must be cooled by evaporating water into it at constant pressure until the air is saturated with respect to a plane surface of liquid water.

- What is the relationship between T, T_d, and T_w?

- Saturated adiabatic lapse rate

- Equivalent potential temperature

Equivalent Potential Temperature

06Z GFS 102 HOUR – VALID 12Z MON APR 28 2014

2m THETAe (K) / WIND (kts) – COD NEXLAB   WEATHER.COD.EDU
260 264 268 272 276 280 284 288 292 296 300 304 308 312 316 320 324 328 332 336 340 344 348 352 356 360 364 368 372

Stability

- Stability describes how air parcels react to an initial vertical push by some external force.

- Forced to return to its original position: stable.

- Continues to accelerate away from its original position without outside help: unstable.

- Continues to move away from its original position without accelerating: neutral.

Stability cont.

- Consider a small disturbance from equilibrium....
  - Note: Primed values refer to the PARCEL.

- P = P'

- Adiabatic, displacements on small time scales.

$\Gamma < \Gamma'$

- Buoyant acceleration < 0.

- Buoyant force is opposite the displacement (negatively buoyant).

- Positive restoring force.
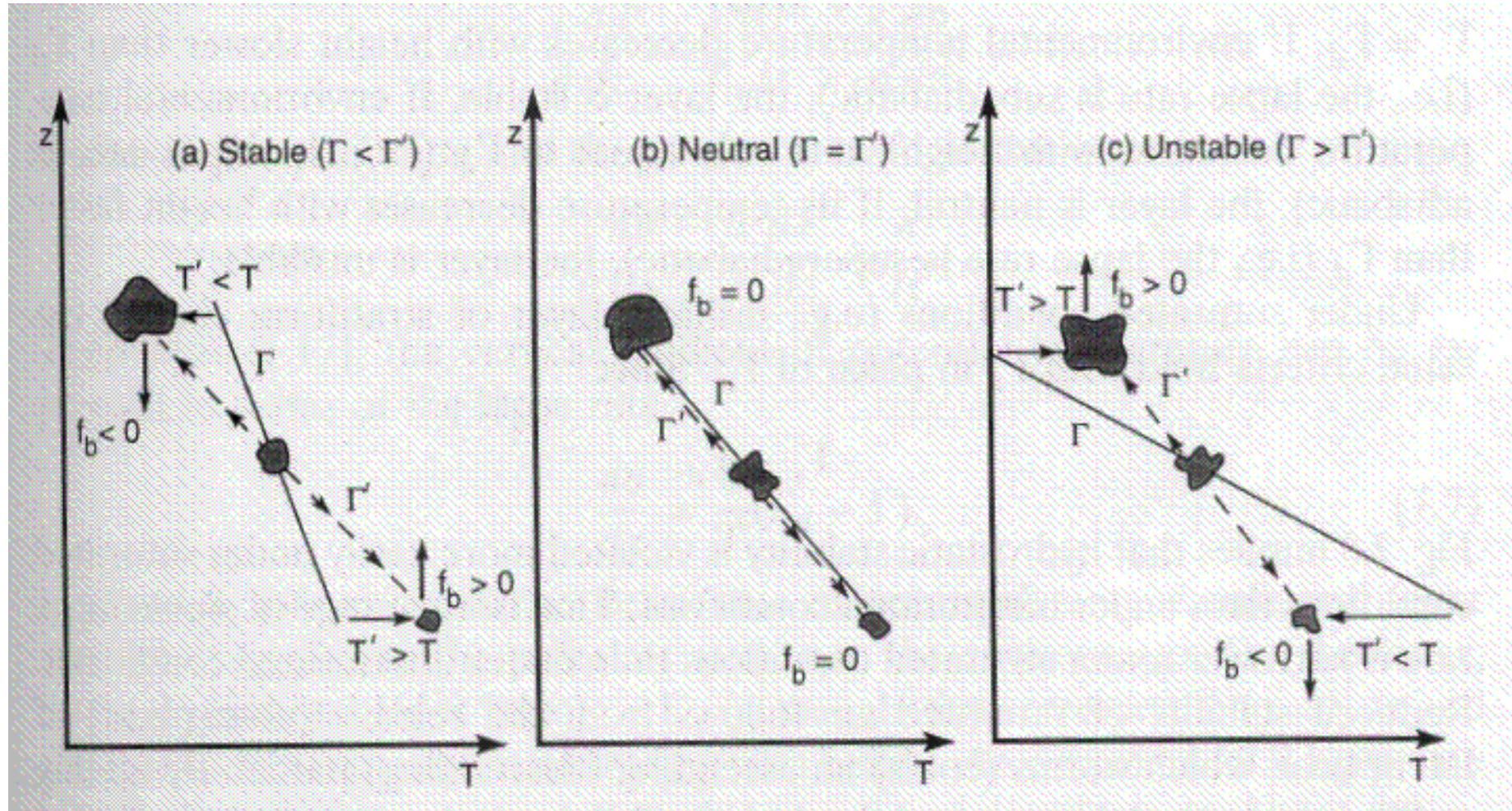
- Hydrostatically stable or positive stability.

$\Gamma = \Gamma'$

- Buoyant acceleration = 0.

- No restoring force.

- Displacements are met without opposition.

- Hydrostatically neutral or neutral stability.

$\Gamma > \Gamma\,'$

- Buoyant acceleration > 0

- Buoyant force in direction of displacement.

- Negative restoring force.
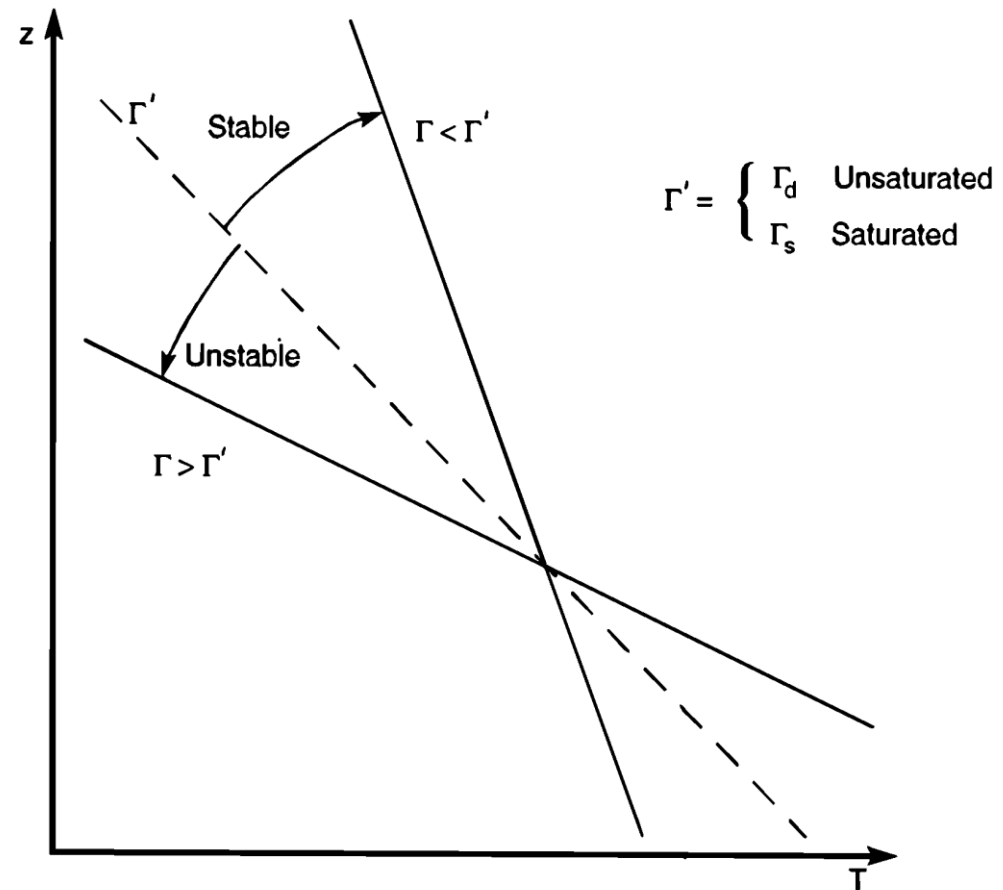
- Hydrostatically unstable or negative stability.

Stability - Visually

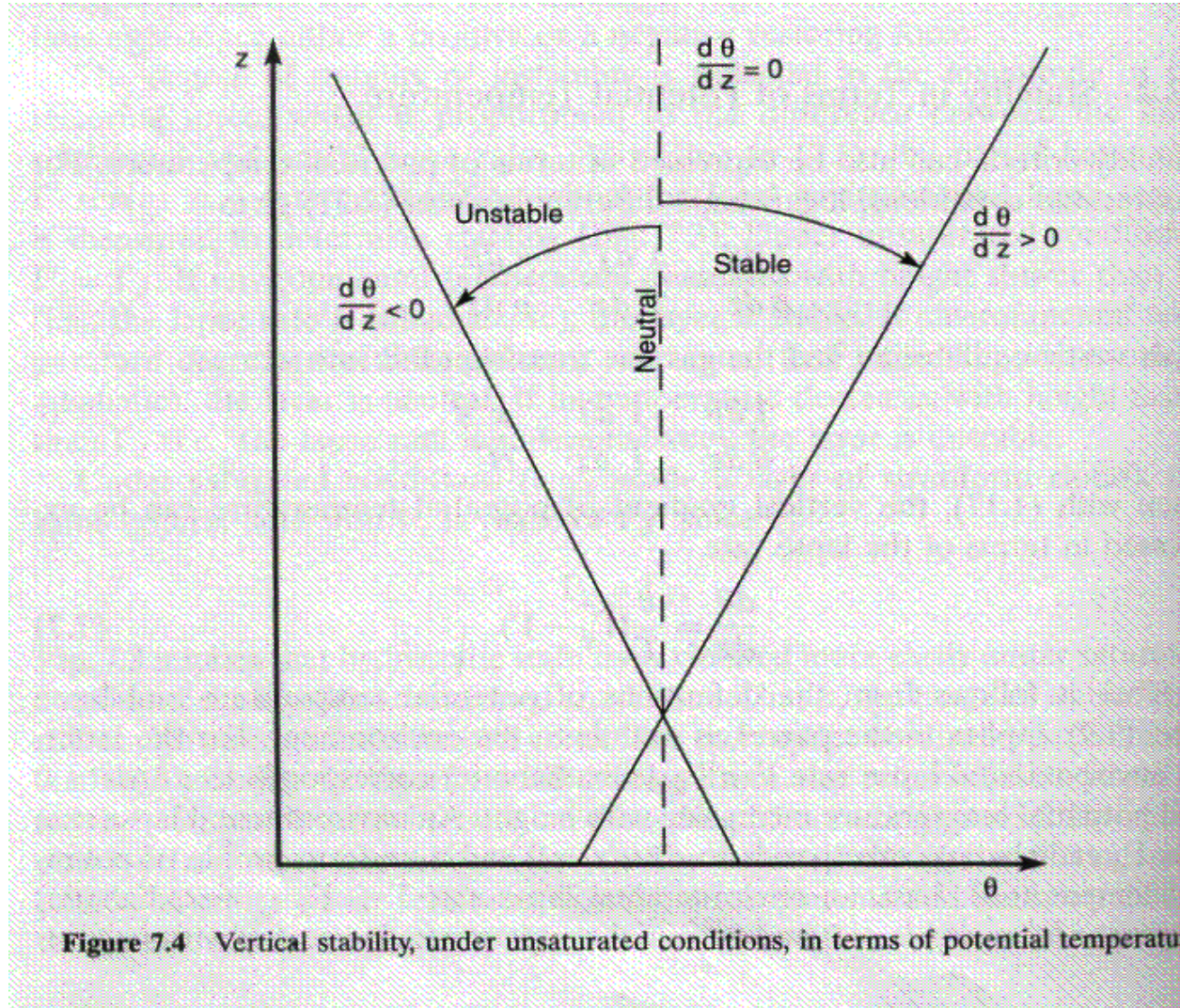# Stability – Visually - Continued

Figure 7.3 Vertical stability in terms of temperature and the environmental lapse rate Γ.

Stability – Theta

Figure 7.4 Vertical stability, under unsaturated conditions, in terms of potential temperature
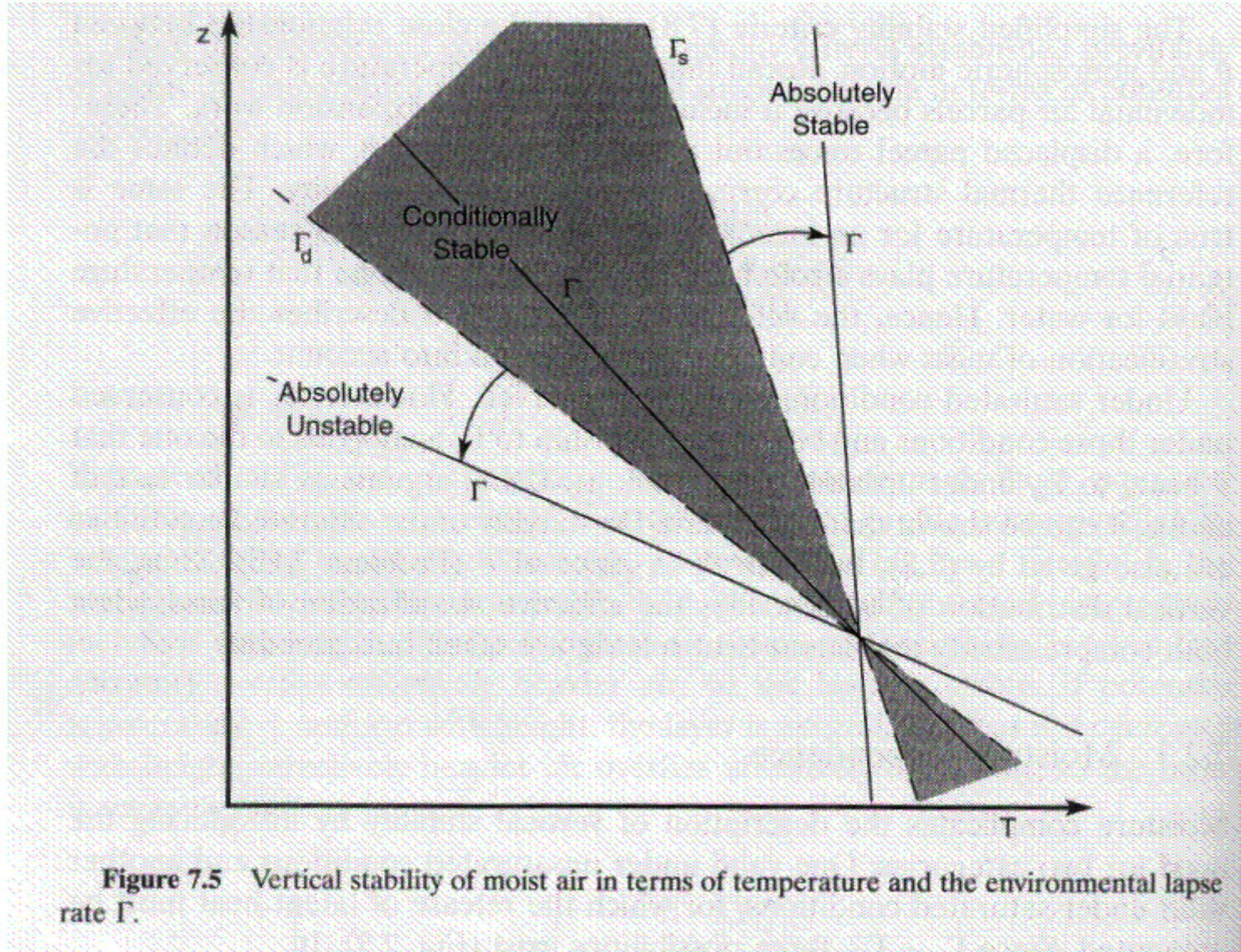
Stability and Moisture

- $\Gamma < \Gamma_s < \Gamma_d$
  - Absolutely stable.

- $\Gamma > \Gamma_d > \Gamma_s$
  - Absolutely unstable.

- $\Gamma_s < \Gamma < \Gamma_d$
  - Conditionally unstable.
  - Stable for unsaturated conditions.
  - Unstable for saturated conditions

Conditional Stability

Figure 7.5 Vertical stability of moist air in terms of temperature and the environmental lapse rate Γ.

Skew-T Diagrams

- Y-Axis is logarithmic in pressure.

- Isotherms are "skewed" 45° from lower left to upper right.

- Dry adiabats slope from lower right to upper left. Label in degrees centigrade.

- Saturated or moist adiabats are curved.

- Saturated mixing ratio lines: dashed and slope a little from lower left to upper right (g/kg)

Movement

- If air is dry (not saturated):
  - Parcels move along a dry adiabat or line of constant θ.
  - θ is conserved.
  - Mixing ratio does not change. Saturation mixing ratio changes with temperature.

- If air is saturated:
  - Moisture condenses or evaporates and impacts the temperature
  - θ changes, θ_w and θ_e are conserved.
  - Mixing ratio and saturation mixing ratio change.

Variables

- Mixing ratio, w : read w_s from T_d.

- Saturated mixing ratio, w_s : read w_s from T.

- Relative humidity: w / w_s

- Potential temperature (θ) : raise or lower parcel along a dry adiabat to 1000mb.

- LCL: The point where dry adiabatic parcel path meets the saturated mixing ratio associated with T_d.

- Wet-bulb temperature (T_w) : follow saturated adiabat from LCL to level of interest.

More Variables

- Equivalent potential temperature (θ_e)
  - Represents total energy of parcel (heat and moisture).
  - Used to compare parcels with different heat and moisture contents.
  - Raise parcel until all the moisture has been condensed out (dry adiabats begin to parallel saturated adiabats).
  - Move parcel dry adiabatically to 1000mb.