Atmospheric Convection

EES 2110

Introduction to Climate Change

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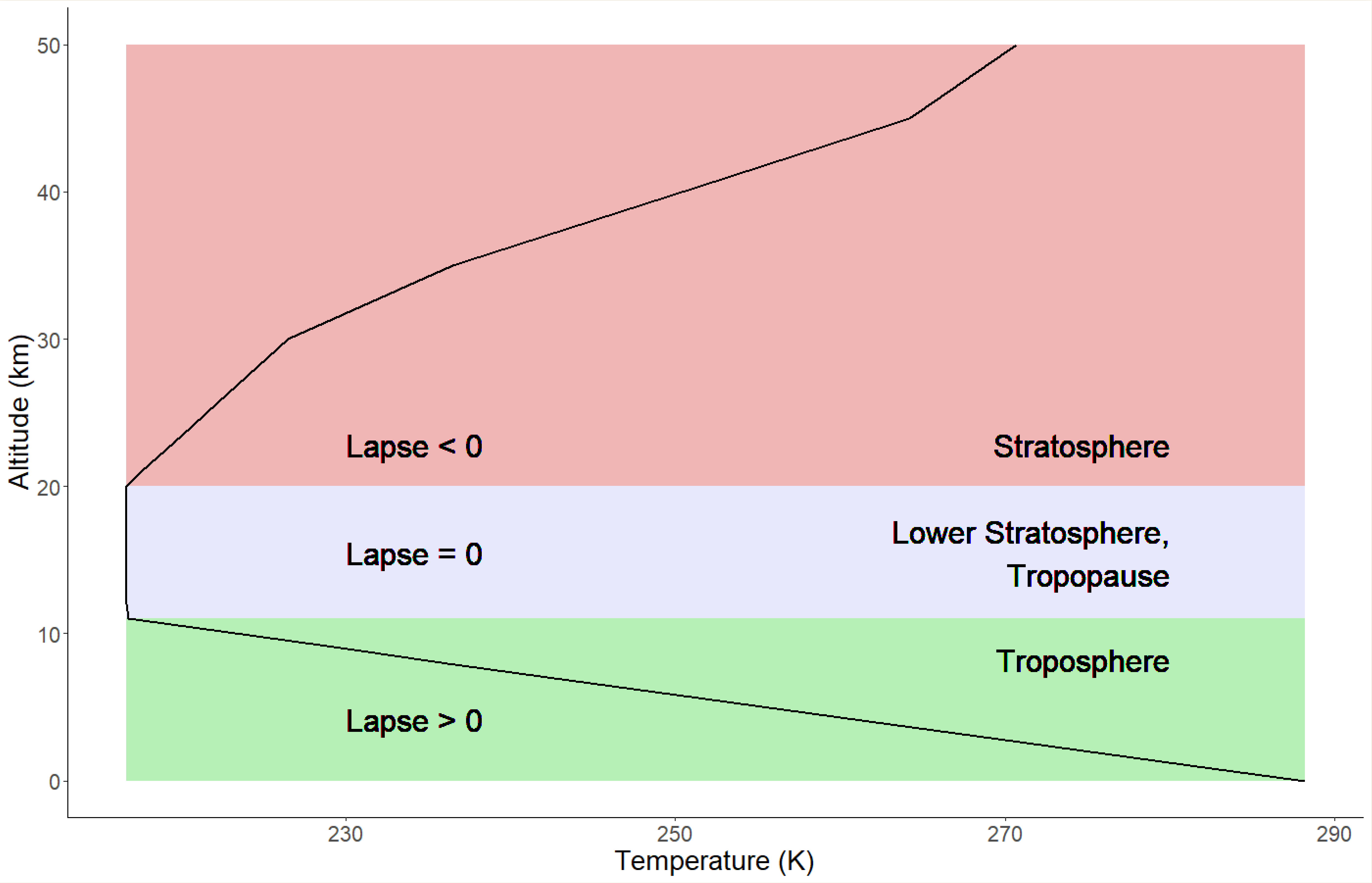
Class #8: Friday, January 27 2023

Vertical Structure of the Atmosphere

Normal Atmosphere:



Vertical Structure

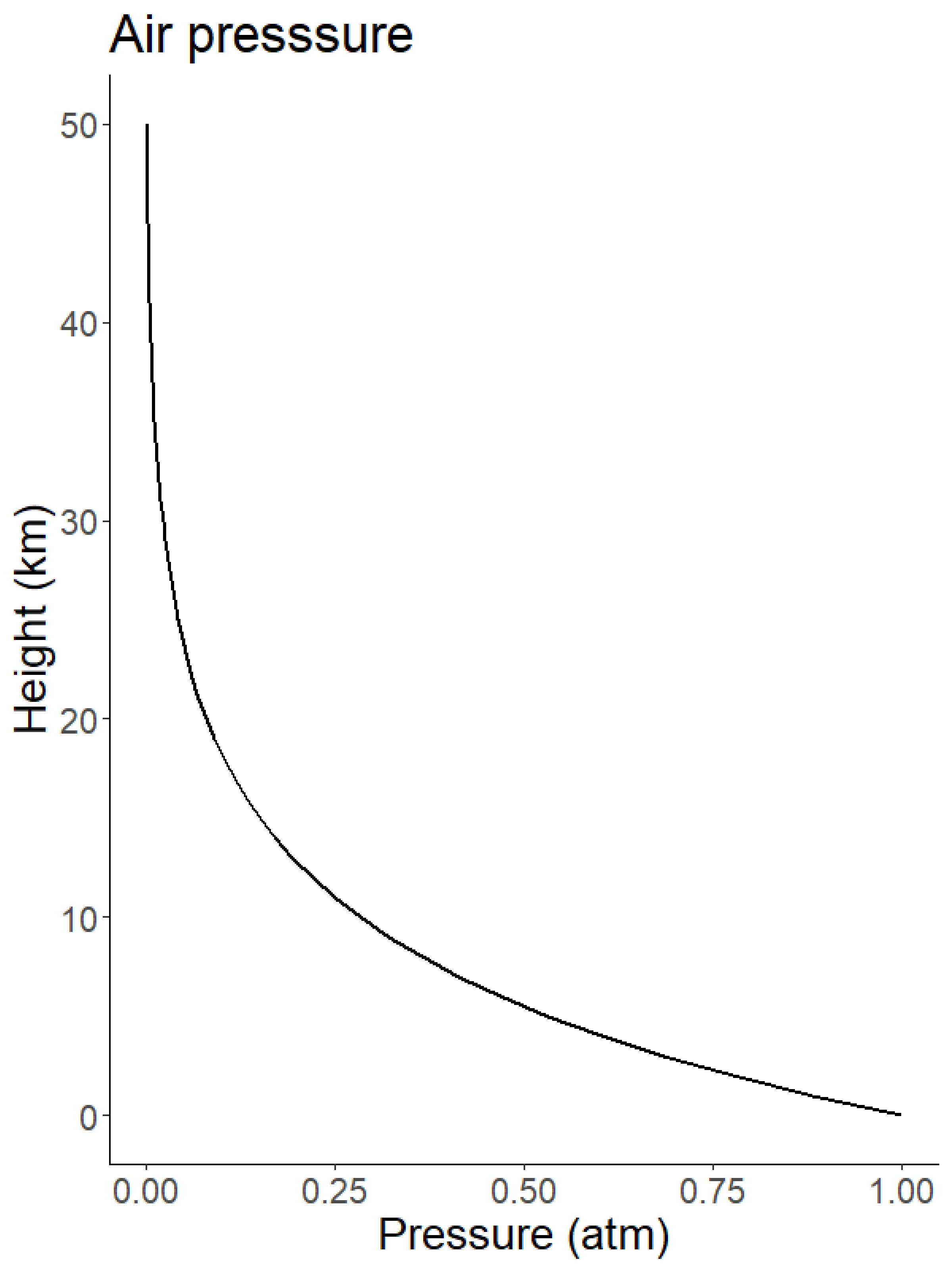
- **Lapse rate:** The change of temperature with altitude

$$\text{Lapse rate} = \frac{-\Delta T}{\Delta \text{height}}$$

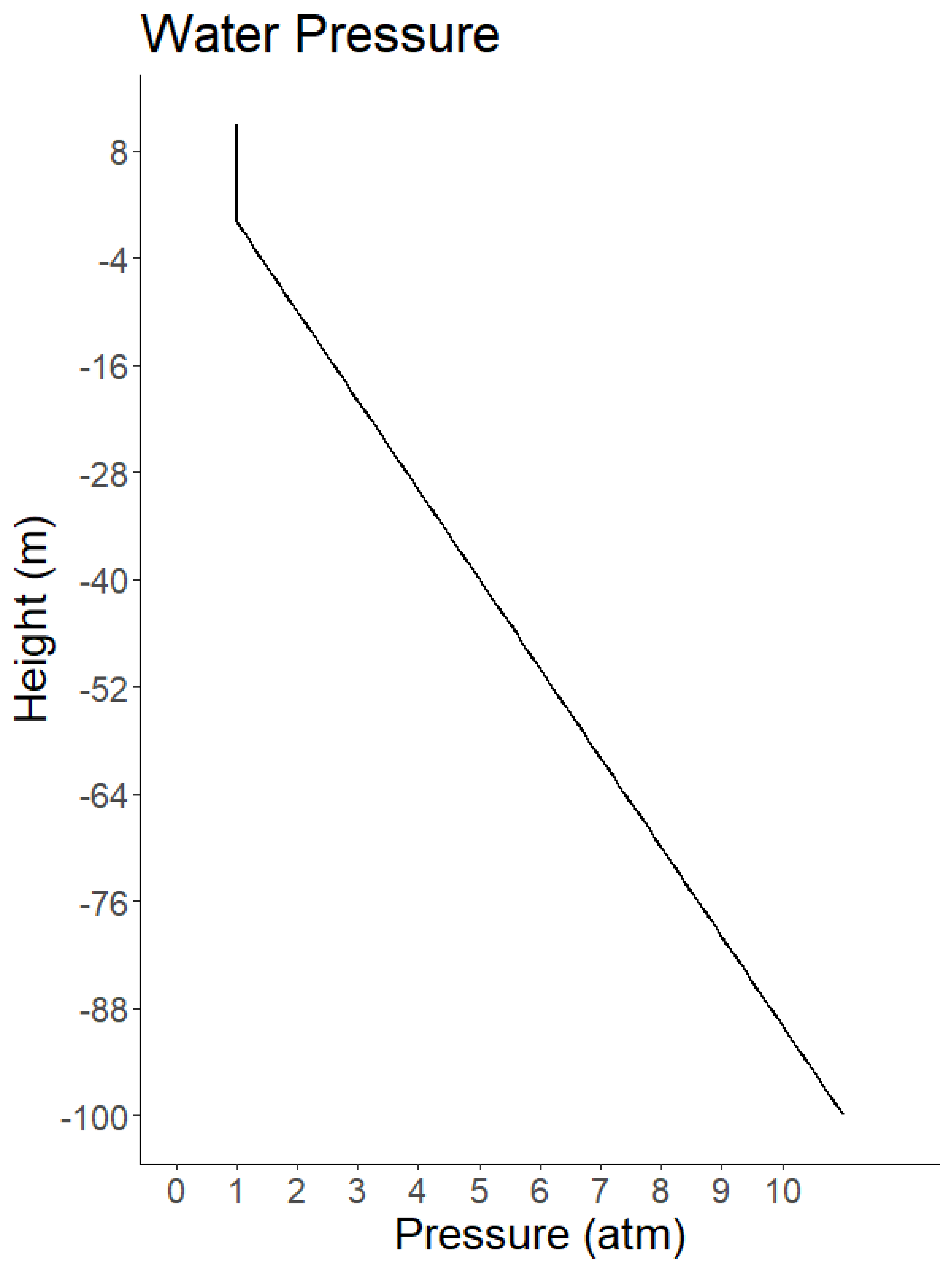
Δ means “change”

- **Positive lapse rate:** Air overhead is cooler (normal for troposphere)
- **Negative lapse rate:** Air overhead is warmer (abnormal, “inversion”)

Air vs. Water



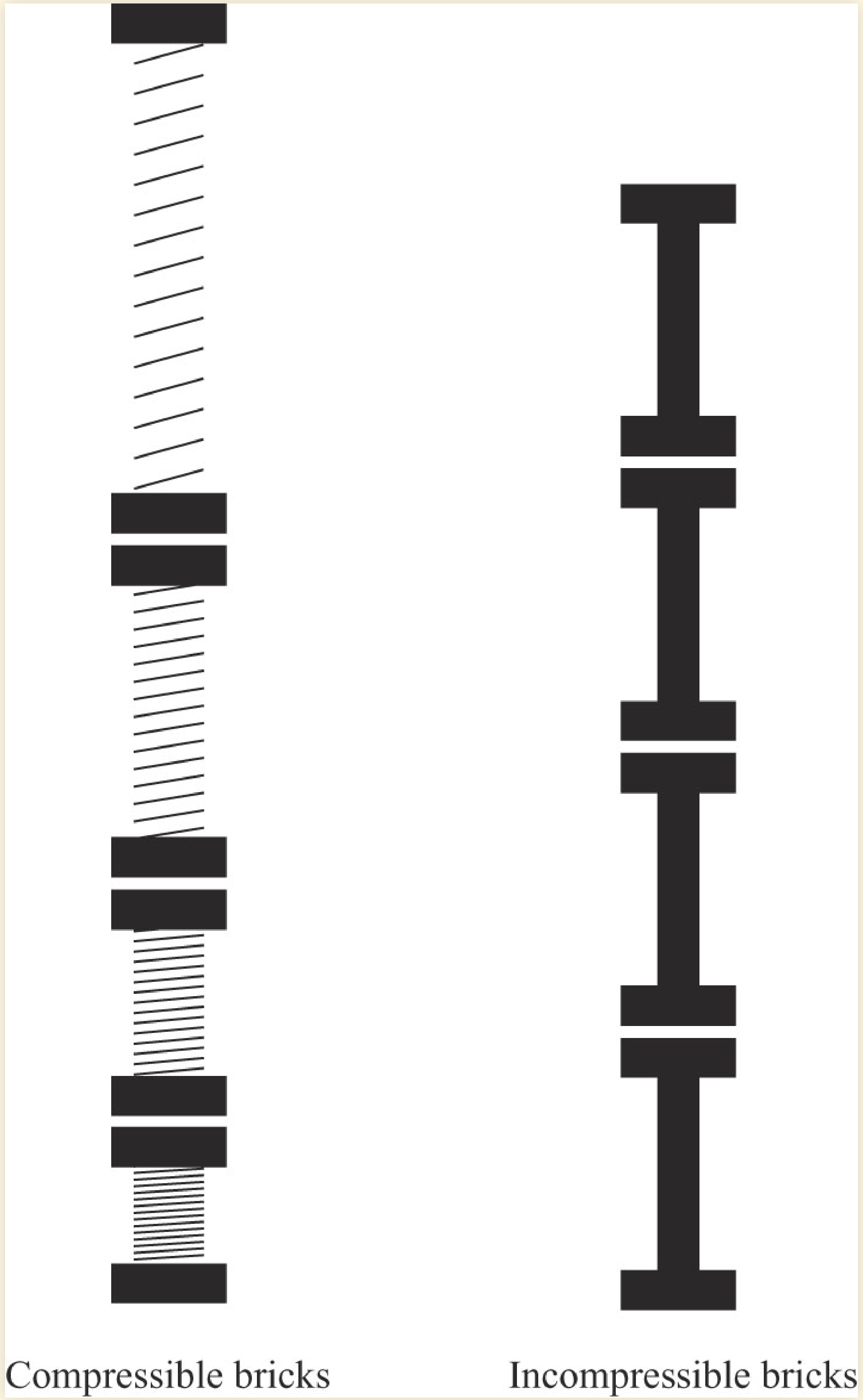
Air presssure
Height (km)
50
40
30
20
10
0
0.00
0.25
0.50
0.75
1.00
Pressure (atm)



Water Pressure
Height (m)
8
-4
-16
-28
-40
-52
-64
-76
-88
-100
0
1
2
3
4
5
6
7
8
9
10
Pressure (atm)

Air vs. Water

- Pressure = weight of everything overhead.
- Air is compressible, water isn't.
- 1 cubic meter of water weighs 1000 kg
- 1 cubic meter of dry air at sea-level density weighs 1.3 kg
- 1 cubic meter of dry air 10 km above sea level weighs 0.4 kg

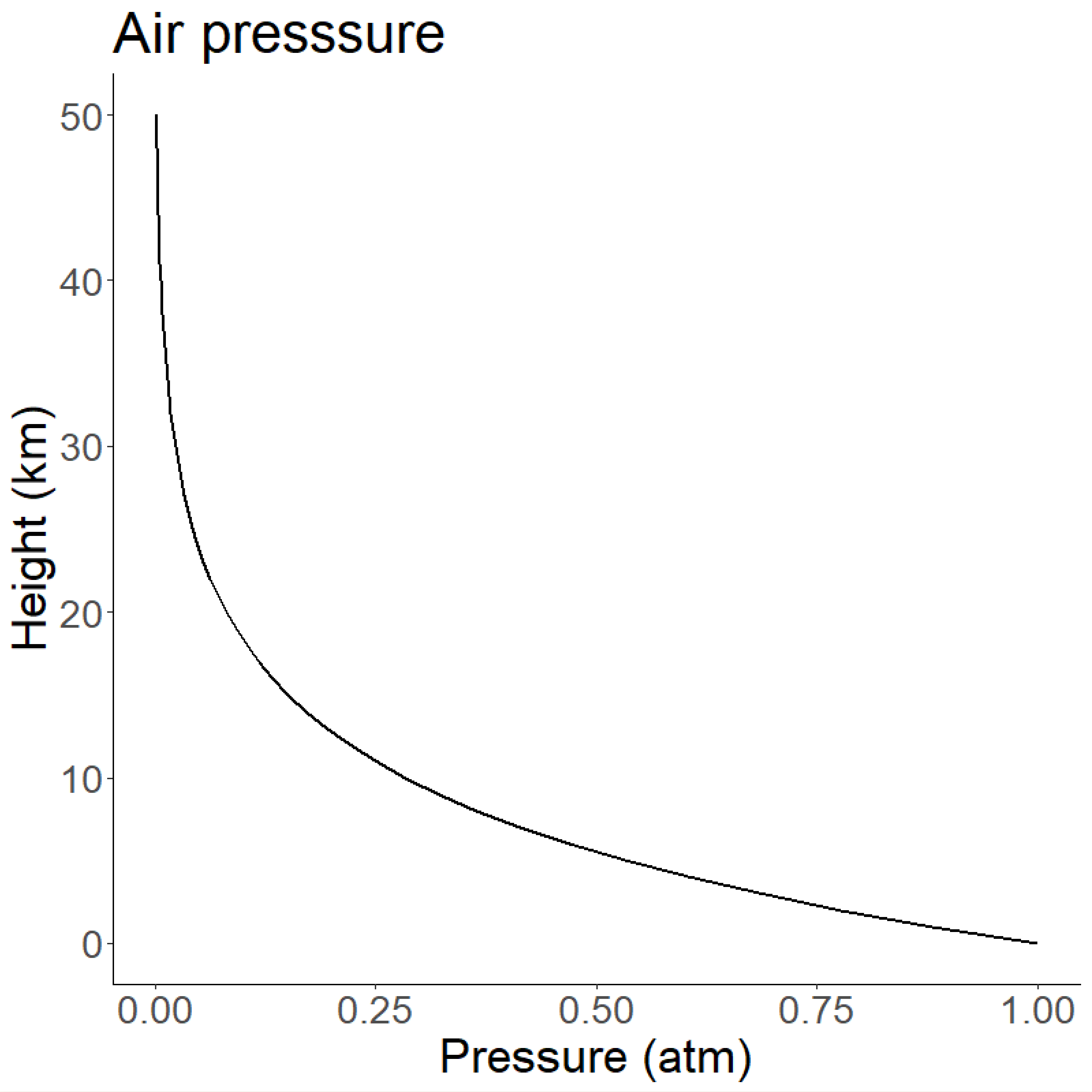


Air Pressure

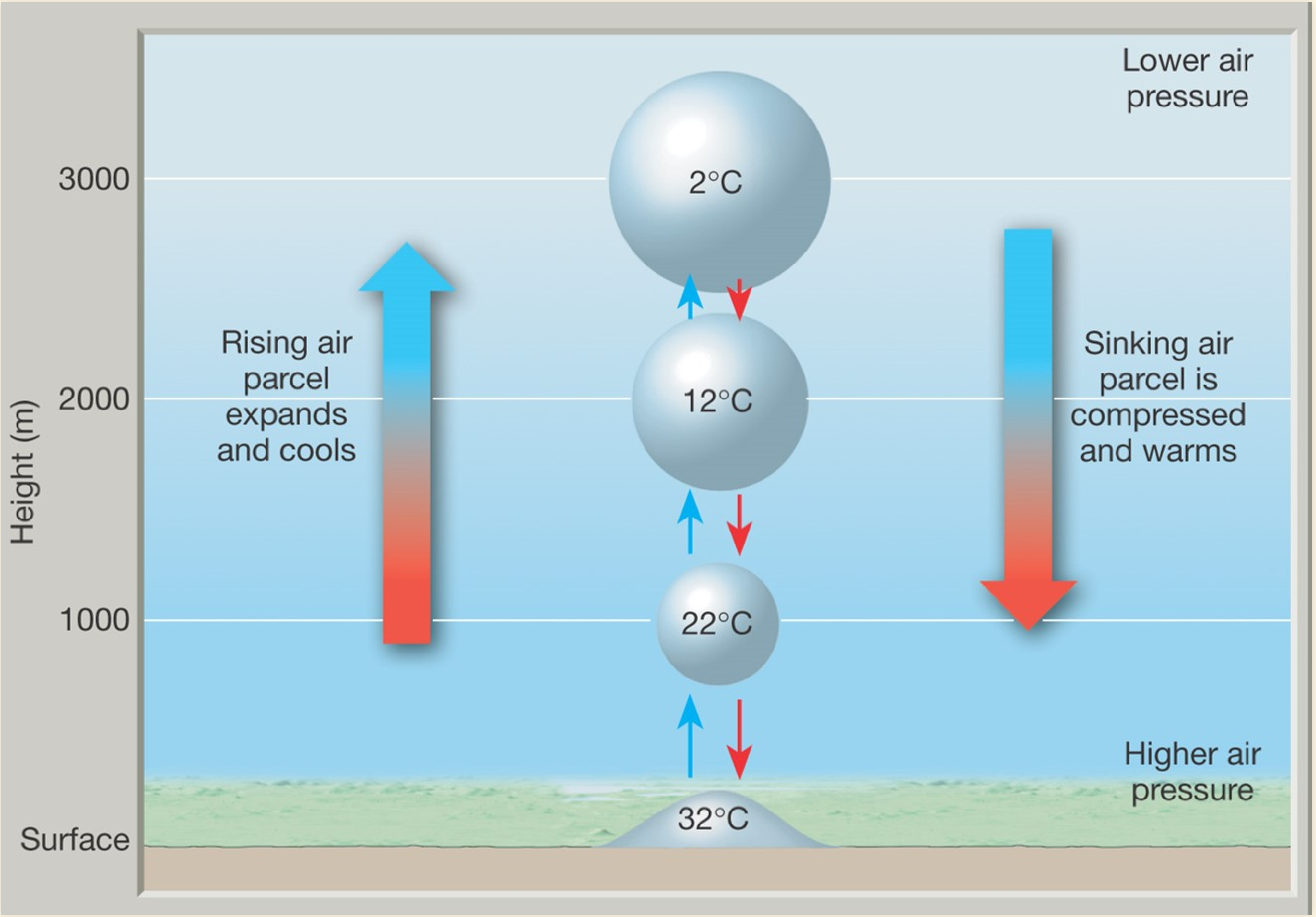
- Pressure at height h:

$$P(h) = P_0 \left(\frac{1}{2}\right)^{h/5.5\text{km}}$$

  - Every time you go up 5.5 km, the pressure drops by half
  - Half the air in the atmosphere is below 5.5 km.
  - 3/4 is below 11 km
  - 7/8 is below 16.5 km
- **NOTE:** The number 5.5 km is not exact, but it's consistent with the textbook.



Why is the air cooler higher up?

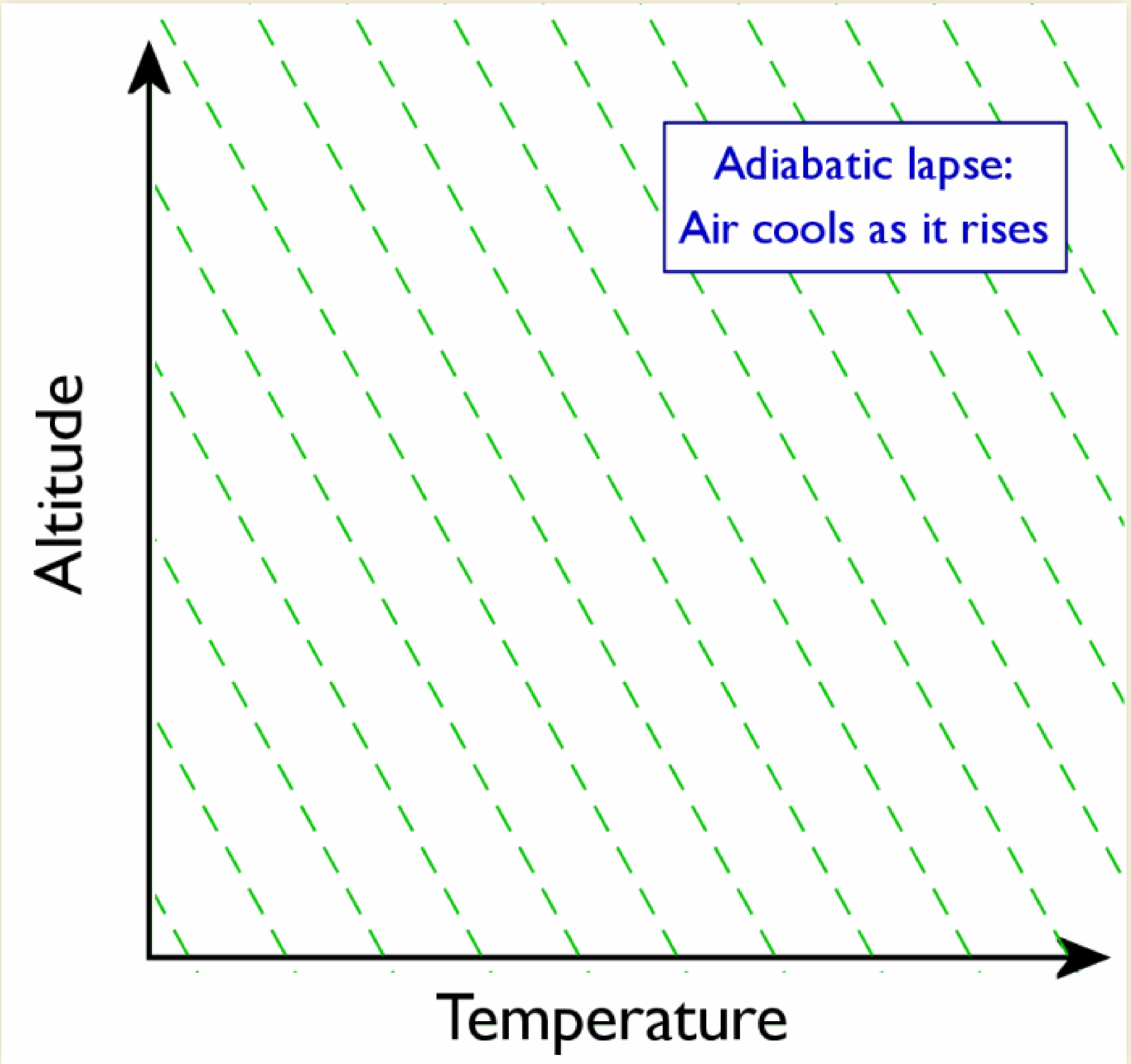


Terminology

- **Environmental Lapse**
  - Measured temperature of actual atmosphere
  - Compares one bit of air at one height with another bit at another height.
  - Changes from one time and place to another.
- **Adiabatic Lapse**
  - Change in a single parcel of air as it moves up or down
  - "**Adiabatic**" means no heat flowing in or out
    - **Adiabatic changes are reversible**
    - **Heat flow** is irreversible

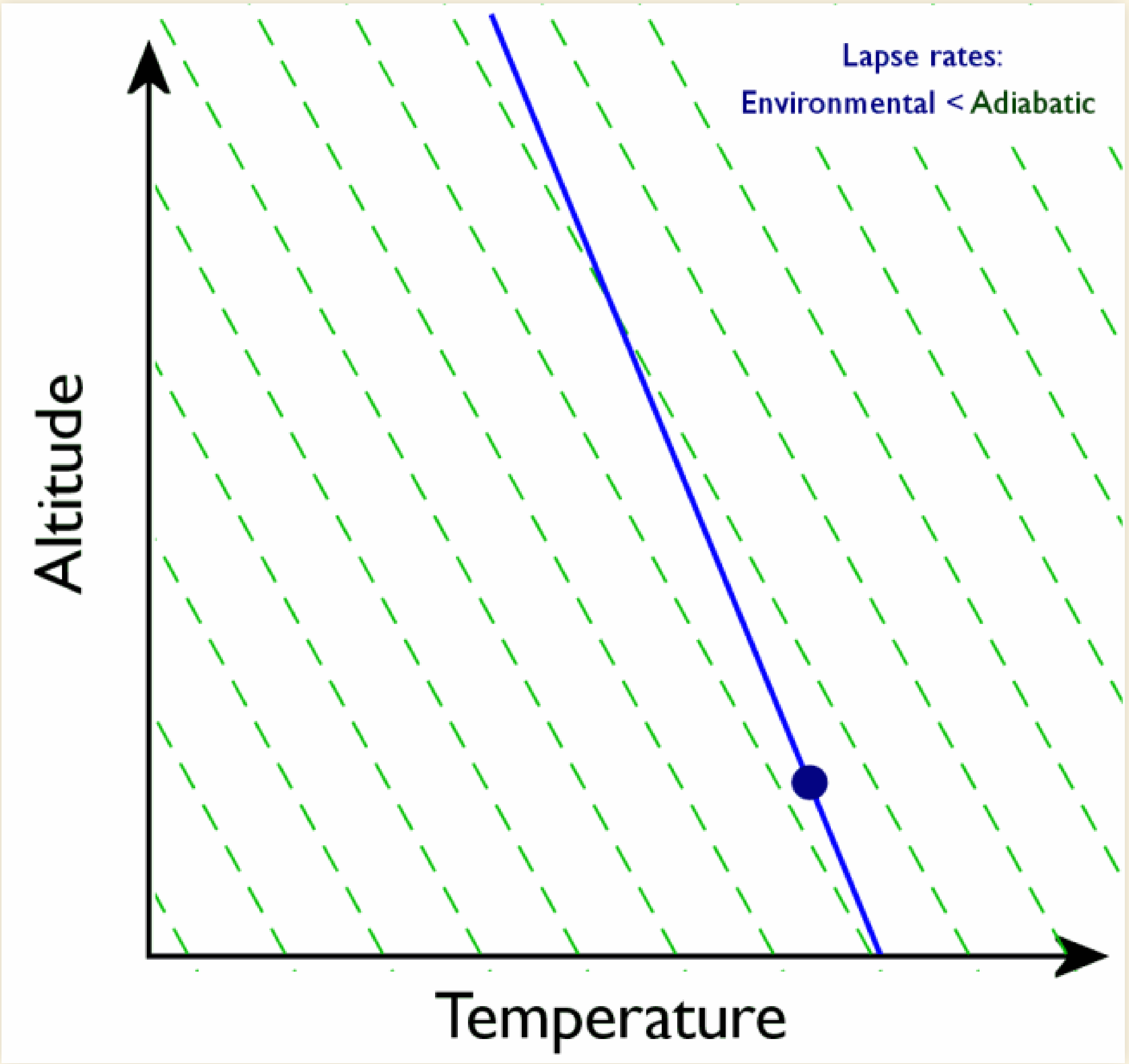
Overview of Convection

Overview of convection



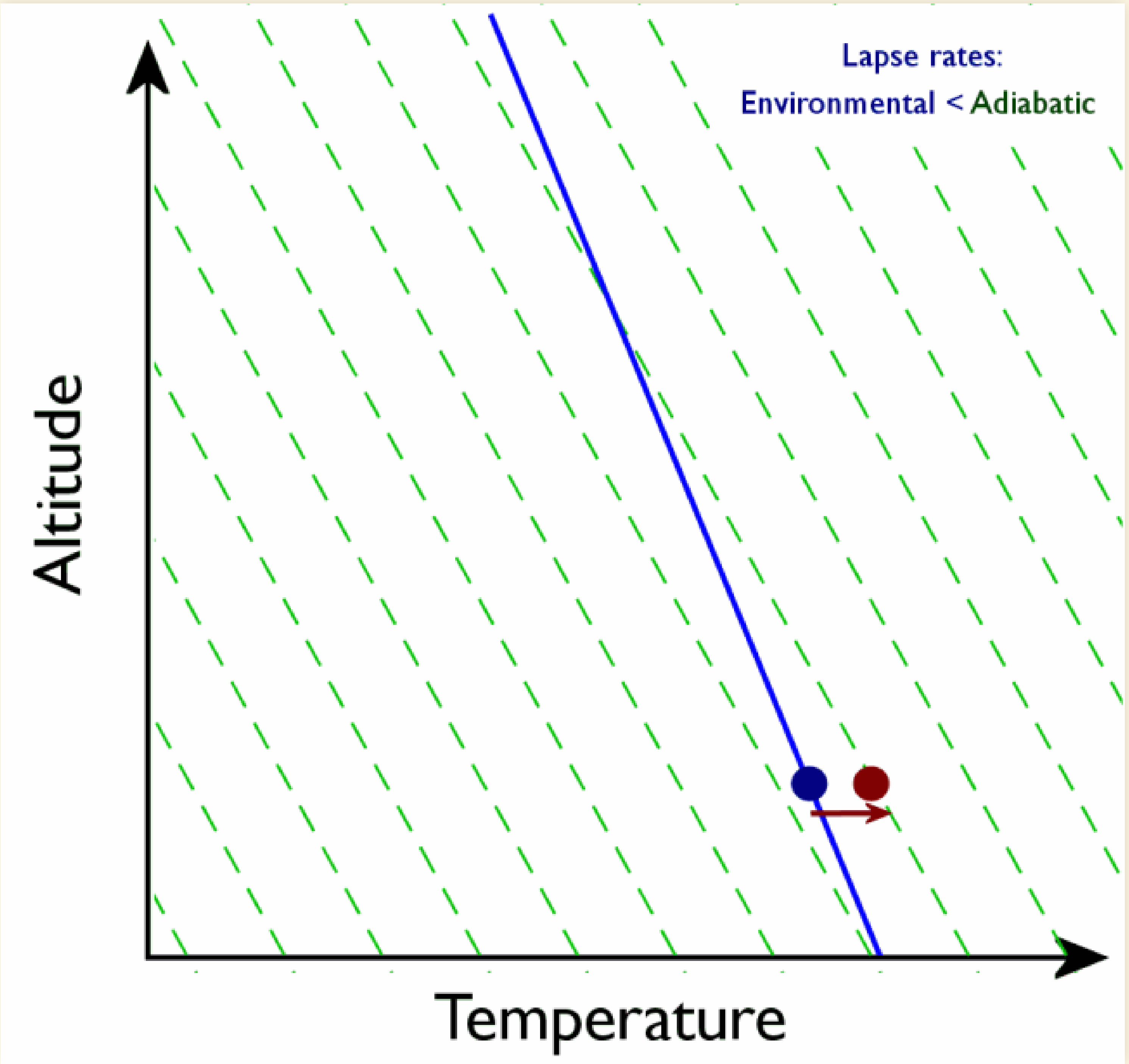
- Closer to vertical = smaller lapse rate (vertical = zero)
- Closer to horizontal = larger lapse rate

Stable Atmosphere
Initial State



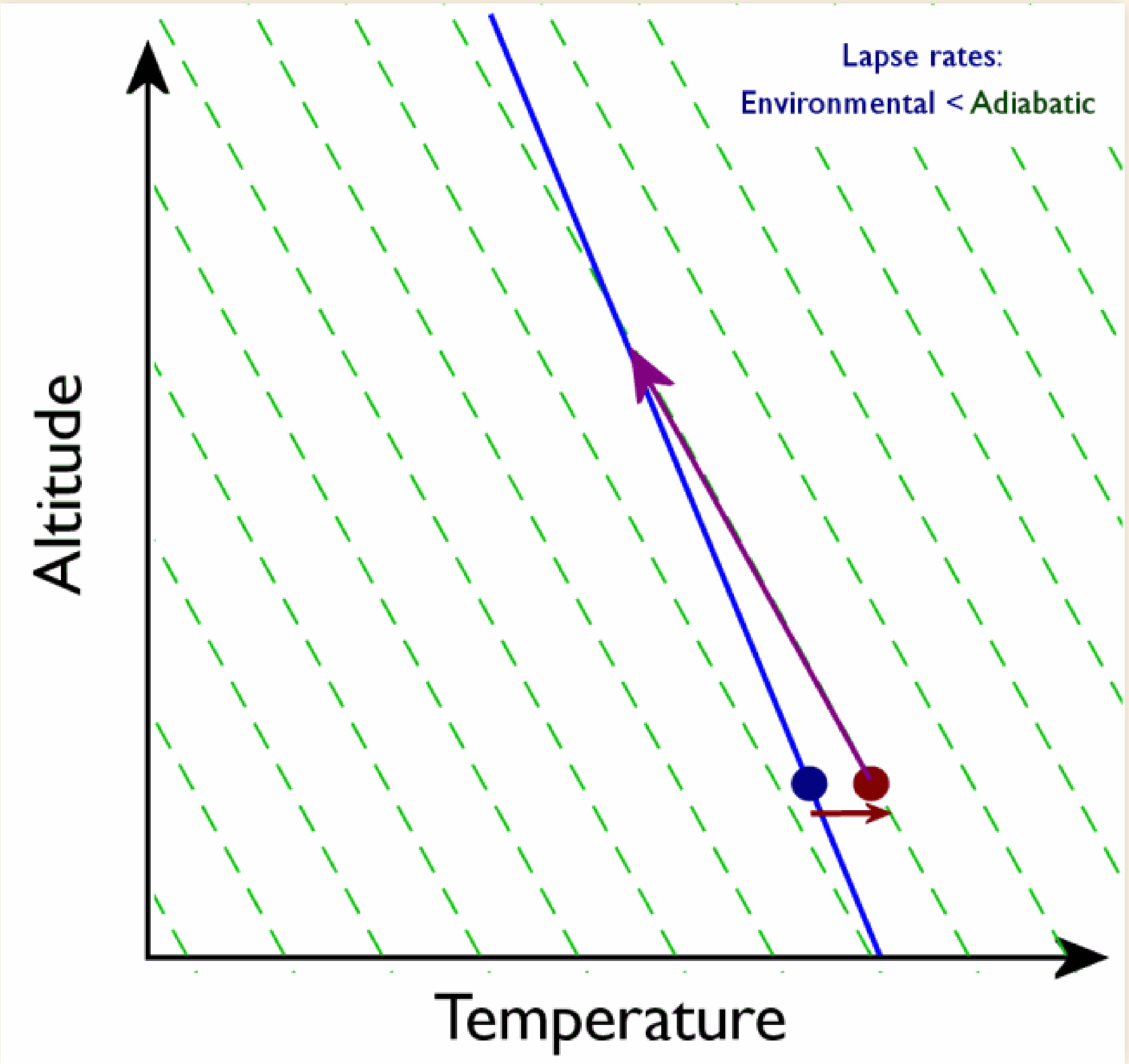
- green = adiabatic lapse
- blue = environmental lapse < adiabatic

Stable Atmosphere
Parcel is heated

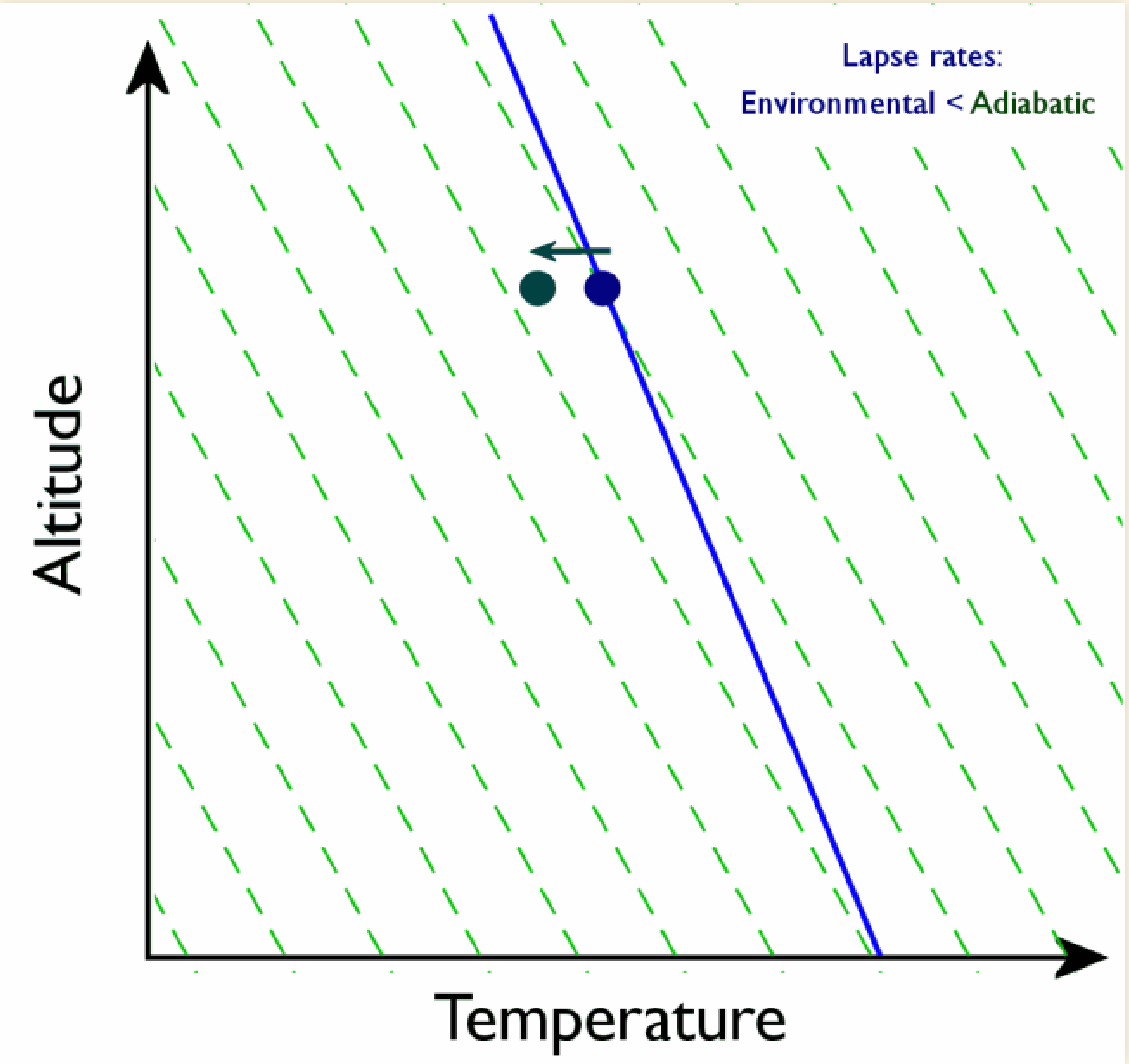


Stable Atmosphere

Rises to new equilibrium

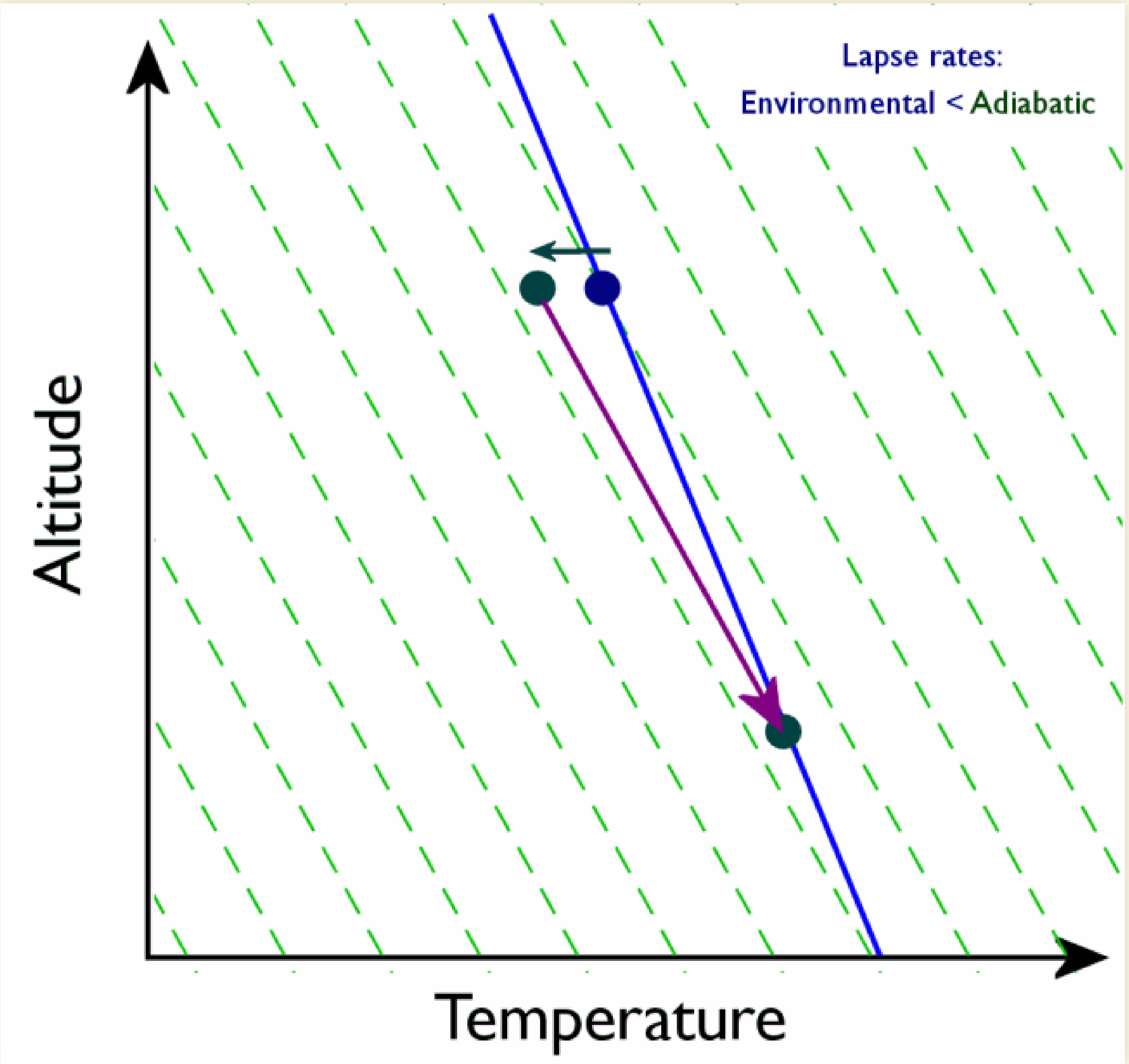


Stable Atmosphere
Parcel is cooled



Stable Atmosphere

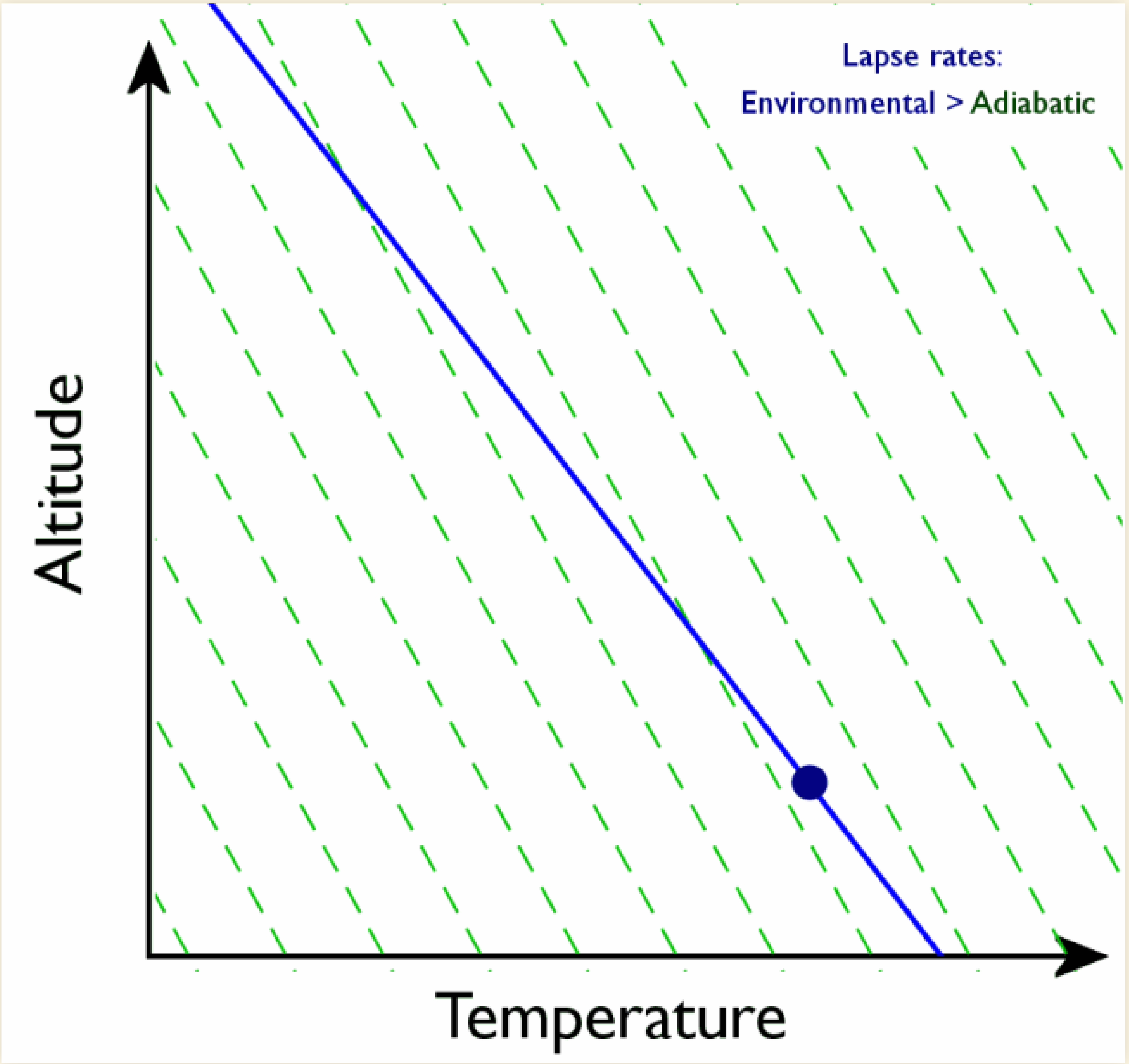
Sinks to new equilibrium



Unstable Atmosphere

Unstable Atmosphere

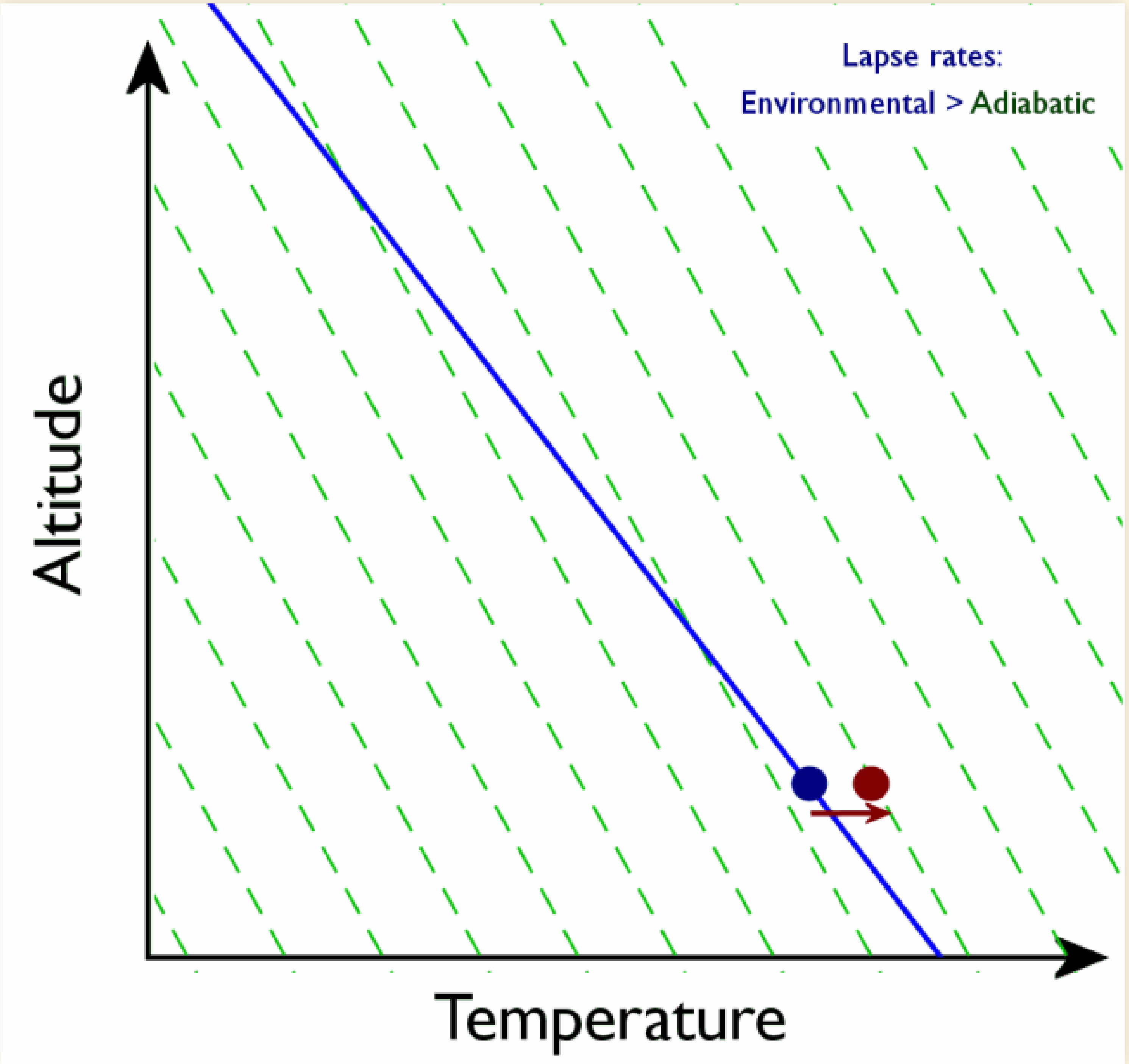
Initial State



- green = adiabatic lapse
- blue = environmental lapse > adiabatic

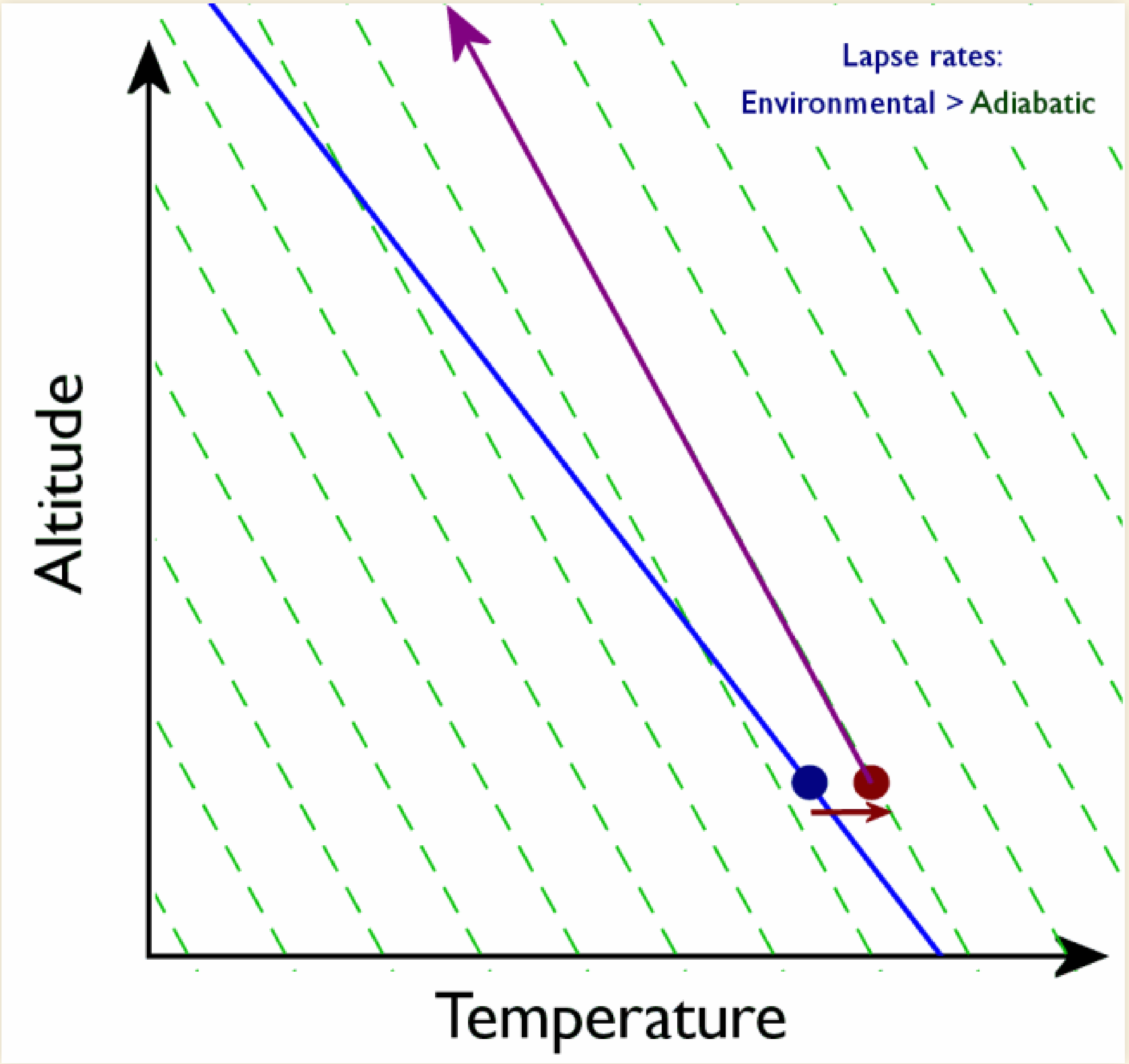
Unstable Atmosphere

Parcel is heated



Unstable Atmosphere

Rises without stopping



Summary of Stability

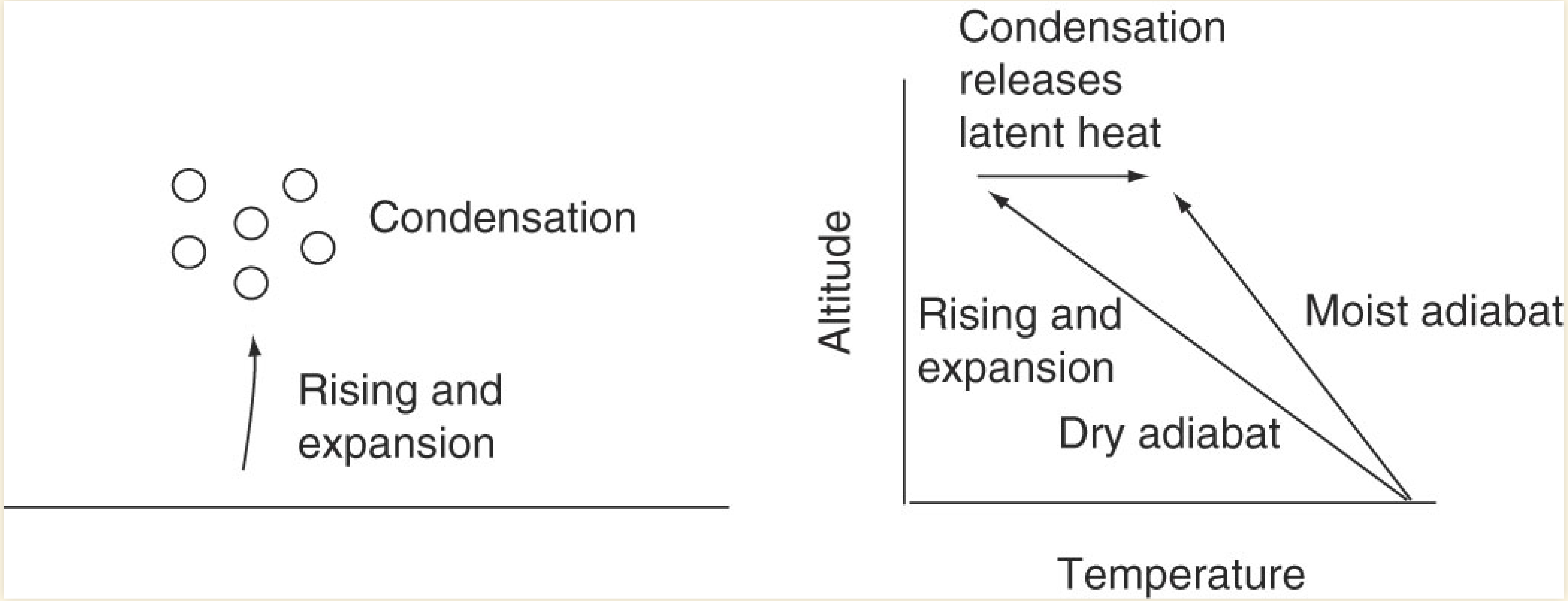
Summary of stability:

- Stable conditions:
  - Adiabatic Lapse > Environmental Lapse
- Unstable conditions:
  - Adiabatic Lapse < Environmental Lapse

- Why is stability important?
  - A stable atmosphere does not move heat around
  - An unstable atmosphere undergoes **convection**:
    - Hot air rises, cold air sinks
    - Redistributes heat

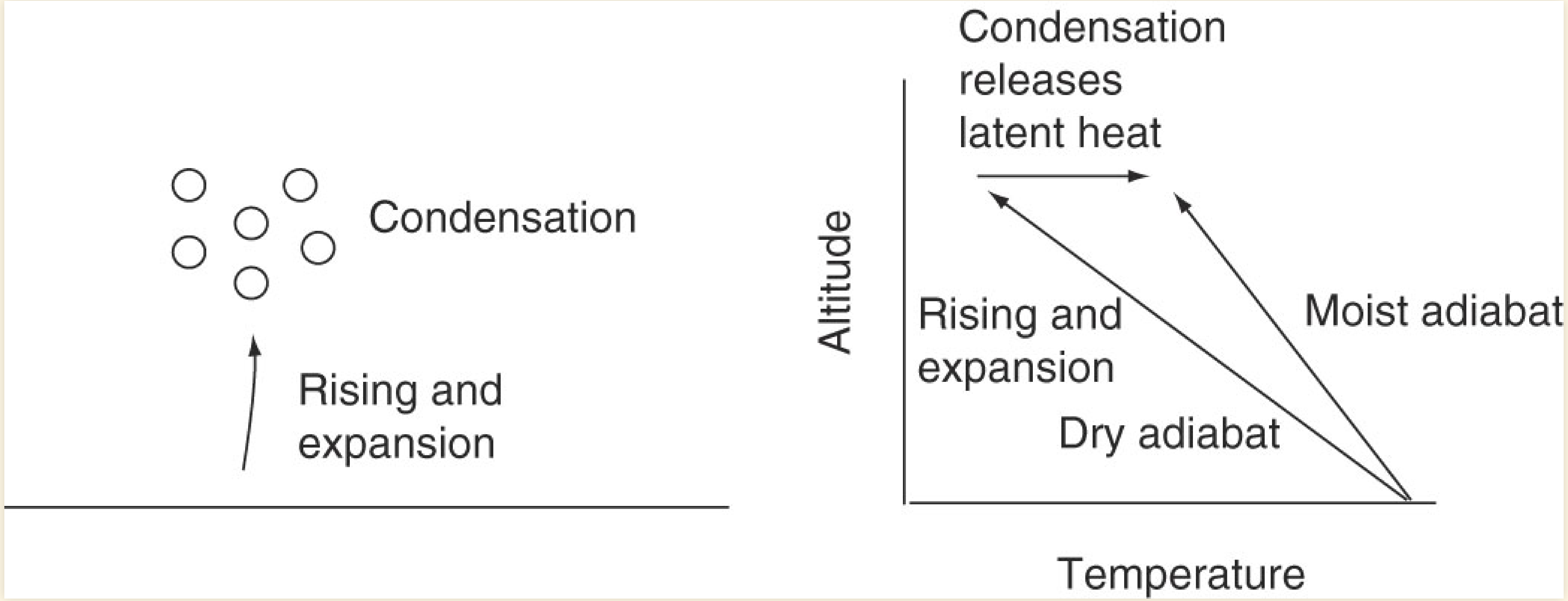
Moist Convection

Moist Convection



- Dry air rises and cools
- Cooling $\Rightarrow$ water vapor condenses to liquid
- Condensation releases latent heat
- Latent heat warms air

Moist Convection



- Latent heat warms air
- Heat reduces adiabatic cooling
- Moist adiabatic lapse < Dry adiabatic lapse
- Smaller lapse = less stable
- **Humid air is less stable than dry air**

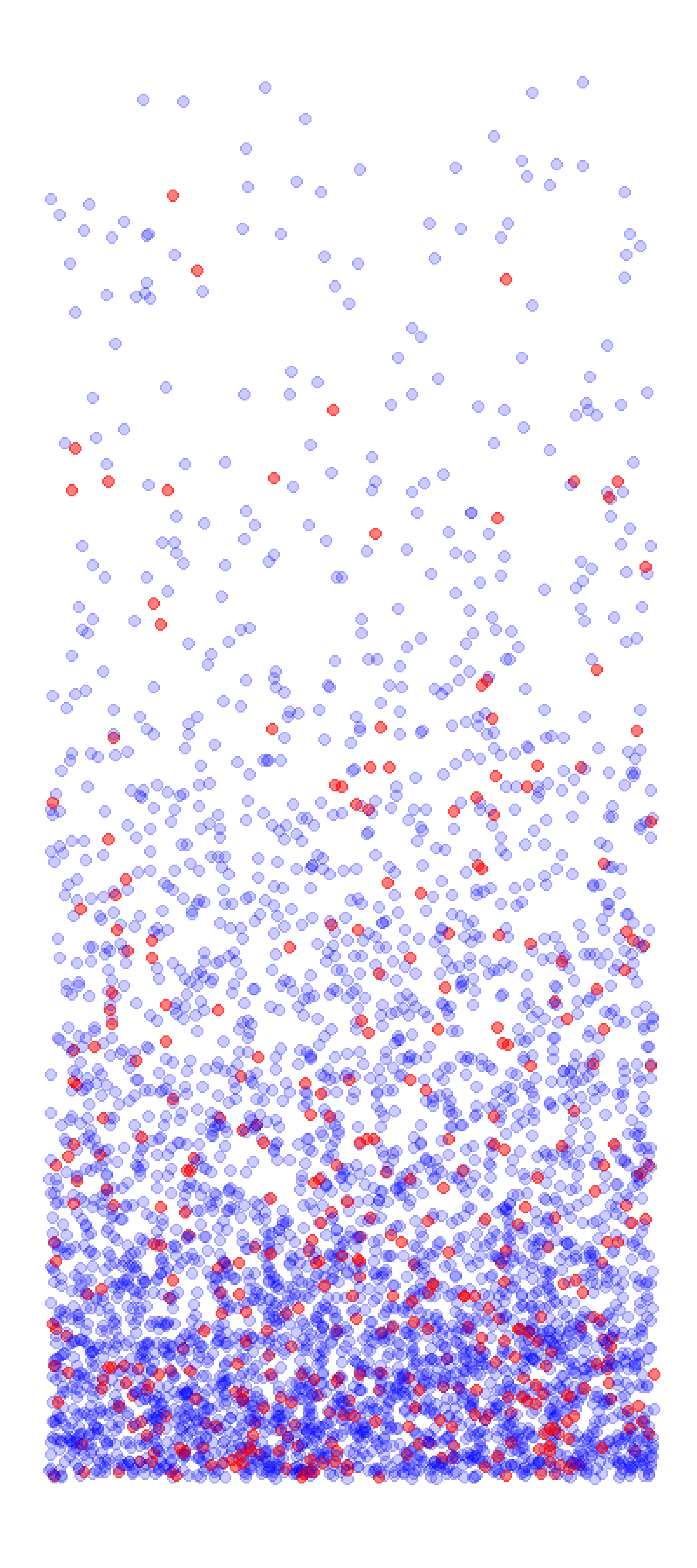
Perspective

- Stable:
  - Environmental lapse $\leq$ adiabatic lapse
- Unstable:
  - Environmental lapse > adiabatic lapse
- Adiabatic lapse:
  - Dry: 10 K/km
  - Moist: 4-8 K/km (depends on humidity)
- Pure radiative equilibrium:
  - Would produce lapse of **16 K/km**: unstable
- Radiative-Convective equilibrium:
  - Convection modifies environmental lapse
  - Normal environmental lapse is roughly **6 K/km** (typical *moist adiabatic lapse rate*)

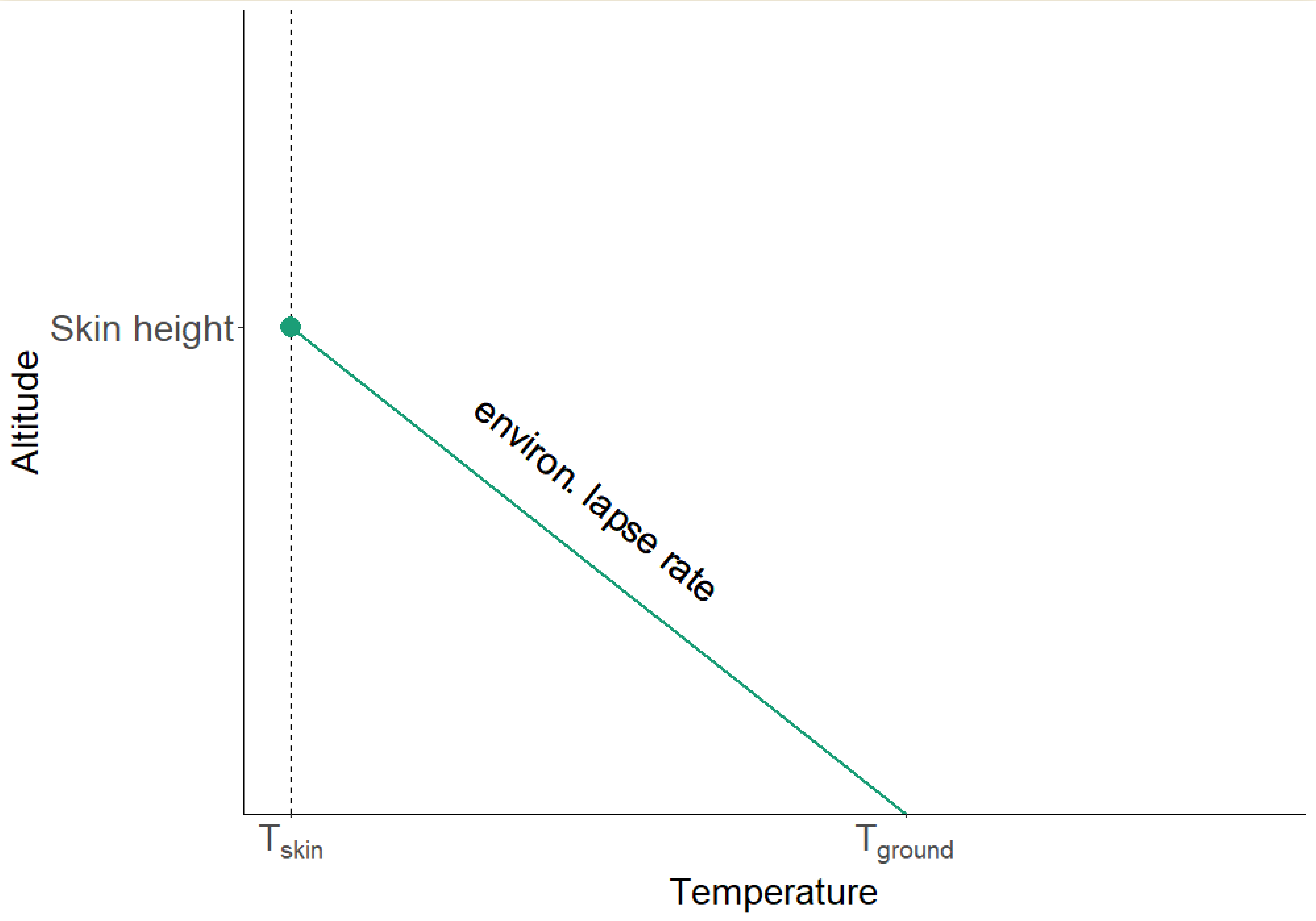
Saturation, Convection, and the Greenhouse Effect

Another Perspective on Band Saturation

- Instead of thinking of saturation as increasing absorption …
- Think of saturation as raising the skin height
  - Skin height = the height at which the atmosphere becomes transparent enough to radiate out to space
    - The height of the top of the atmospheric layer in a layer model
  - The atmosphere becomes opaque at a certain wavelength when there are more than a certain number of molecules per square meter of an absorbing gas overhead.
    - The higher you go, the fewer molecules are overhead and the more are below your feet.
    - The atmosphere gradually becomes more transparent, but we pretend that this happens suddenly at a certain height.
    - Pressure and density fall exponentially as you go higher, so this approximation is reasonable.
- After band saturation sets in, adding more greenhouse gas raises the skin height.

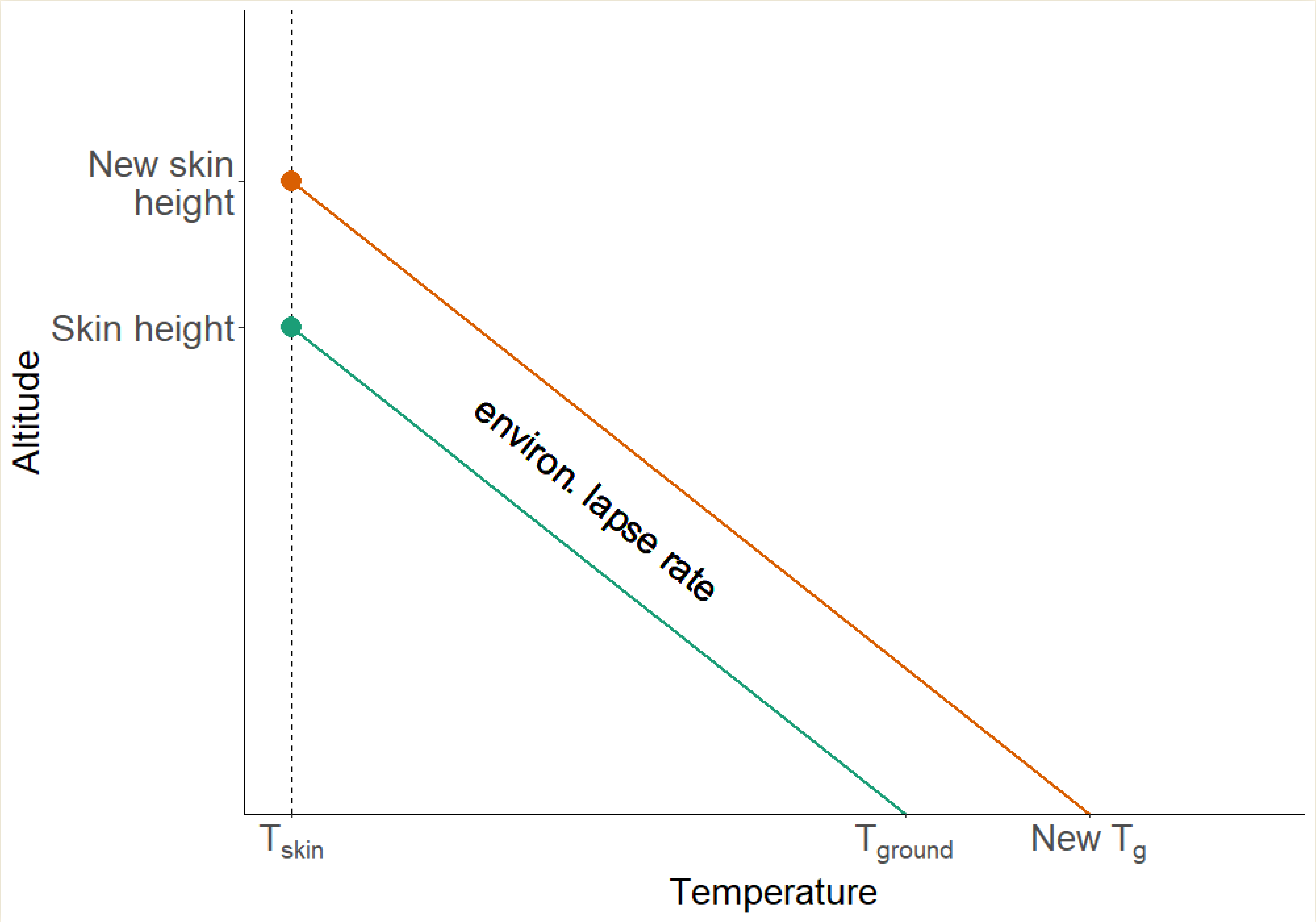


Greenhouse effect



- Skin temp: $T_{\text{skin}} = T_{\text{bare rock}} = 254$ K.
- Ground temp: $T_{\text{ground}} = T_{\text{skin}} + h_{\text{skin}} \times \text{ELR}$
  - ELR = Environmental Lapse Rate

Global warming

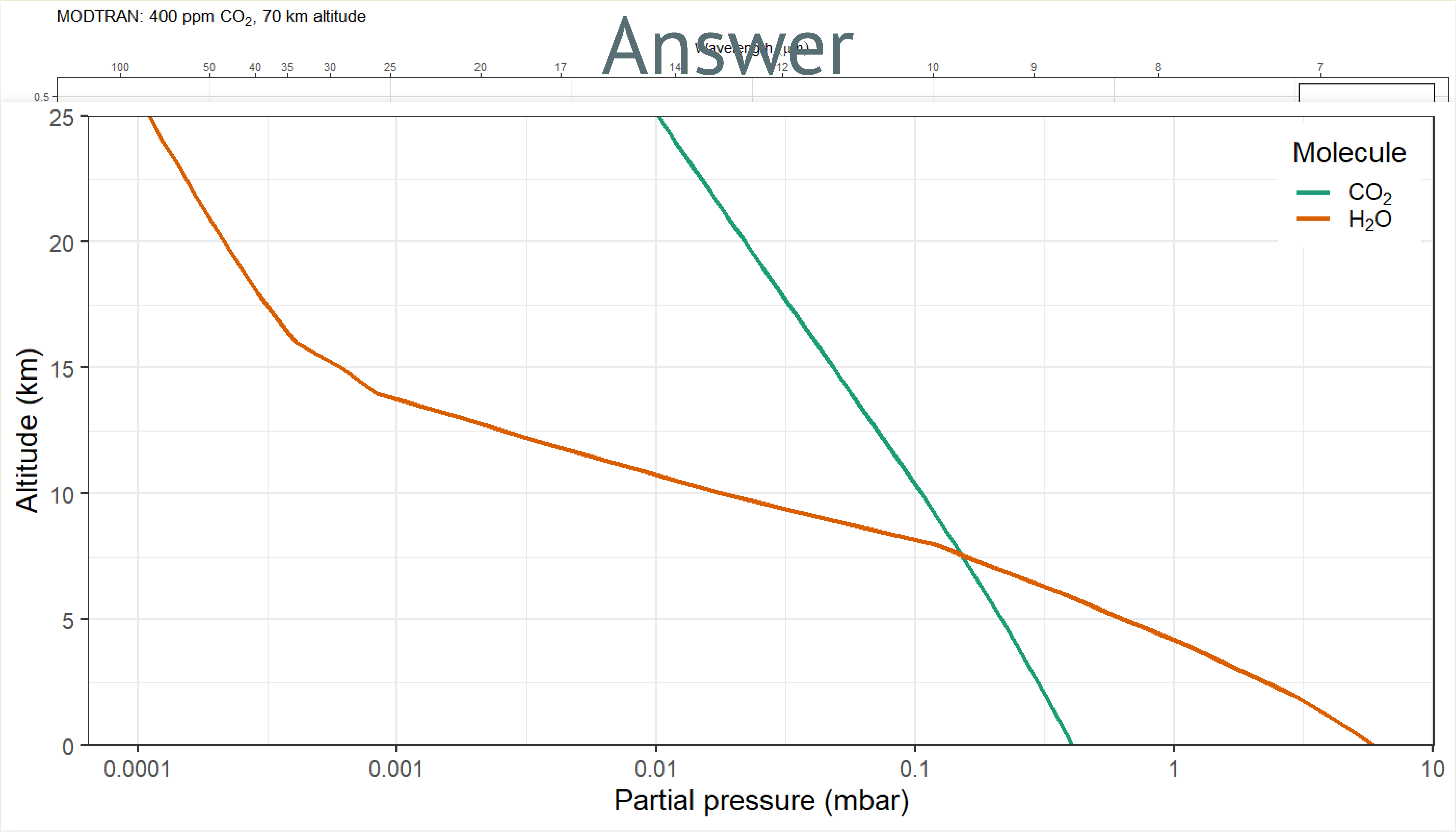


- Greater $CO_2 \longrightarrow$ greater skin height.
- Warming: $\Delta T_{\text{ground}} = \Delta h_{\text{skin}} \times$ env. lapse

Question

- Water vapor absorption is saturated, like CO_2.
  - Why does water vapor emit at warmer temperatures than CO_2?

Answer



- Near the ground, there is much more water vapor (15 times more)
- Above about 7 km, there is much more CO_2 (100 times more at 20 km)
  - Water vapor concentrations become small enough to be transparent to space at a much lower altitude than CO_2