4. Atmospheric transport

Forces in the atmosphere:

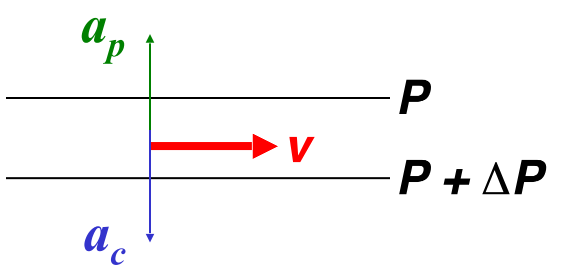
- **Gravity** g
- **Pressure-gradient** $a_p = -(1/\rho)dp/dx$ for x-direction (also *y, z* directions)
- **Coriolis** $a_c = 2\omega v \sin\lambda$ to R of direction of motion (NH) or L (SH)
- **Friction** $a_f = -kv$

Angular velocity $\omega = 2\pi/24\mathrm{h}$
Wind speed v
Latitude λ
Friction coefficient k

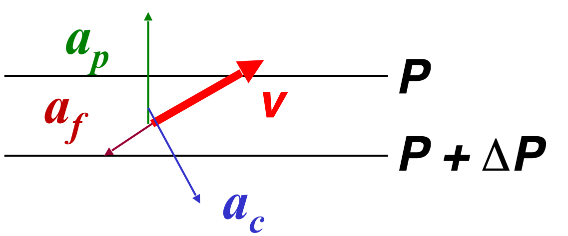
Equilibrium of forces:

In vertical: barometric law

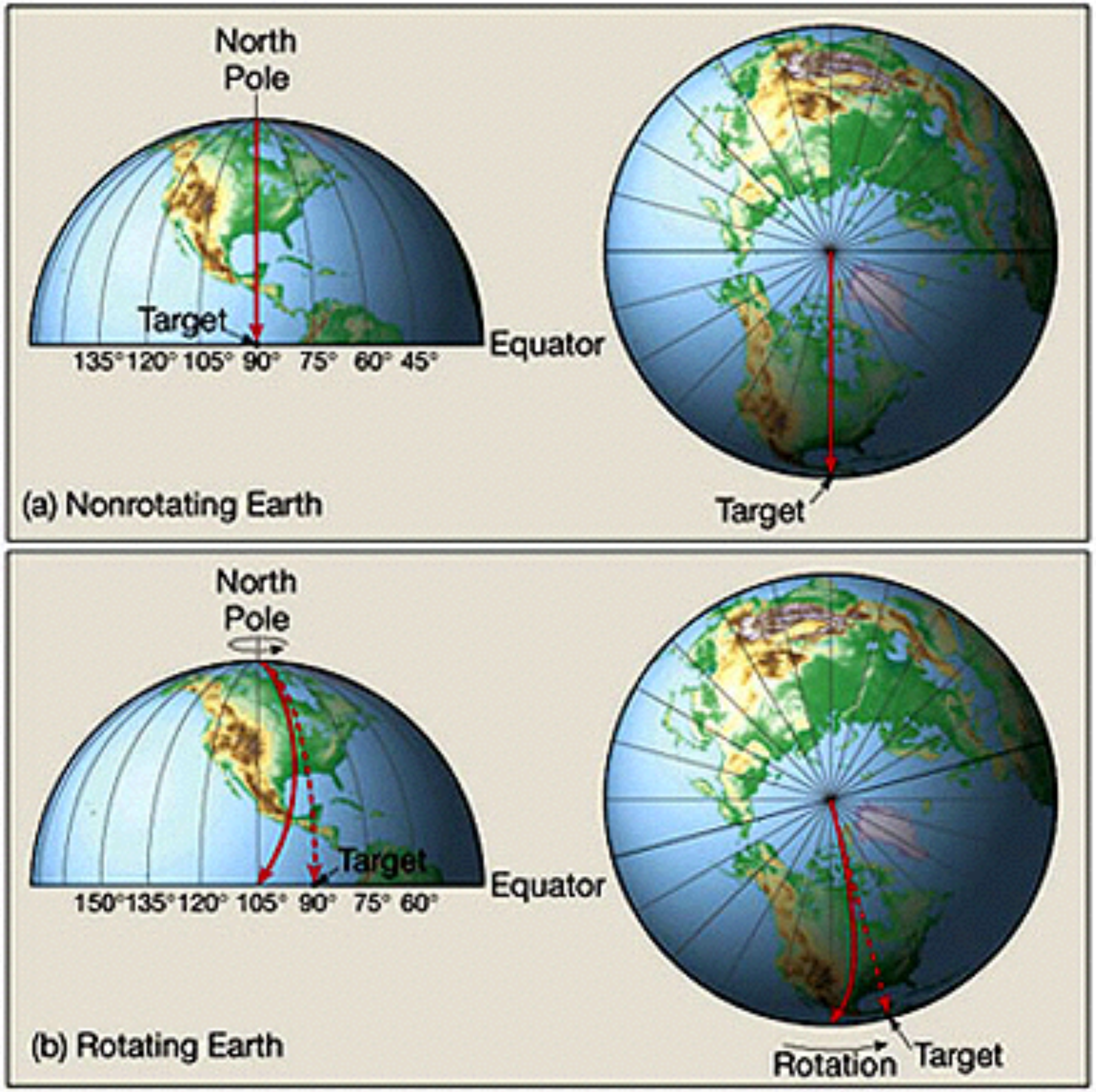
In horizontal: *geostrophic* flow parallel to isobars



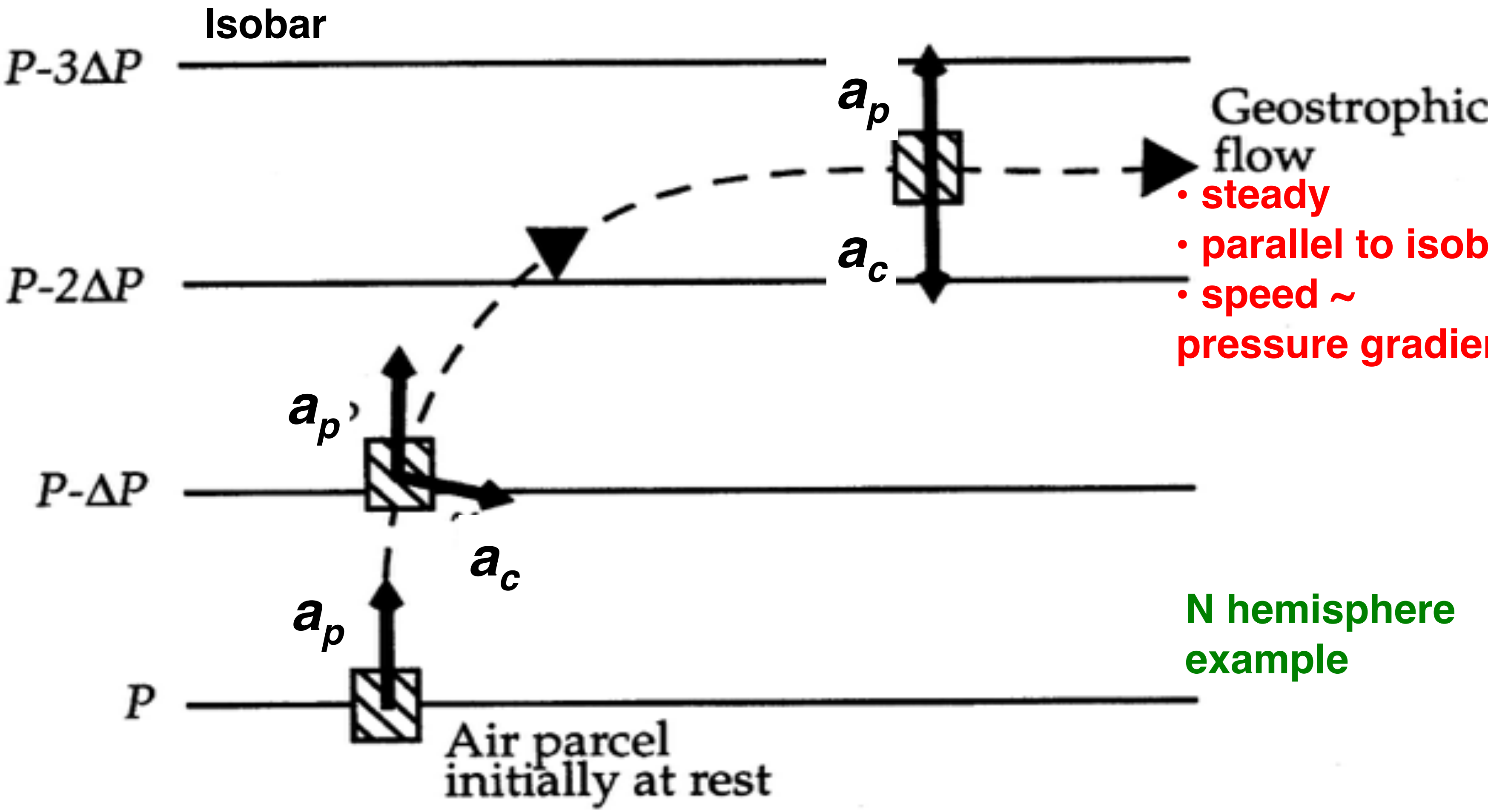
In horizontal, near surface: flow tilted to region of low pressure



The Coriolis force



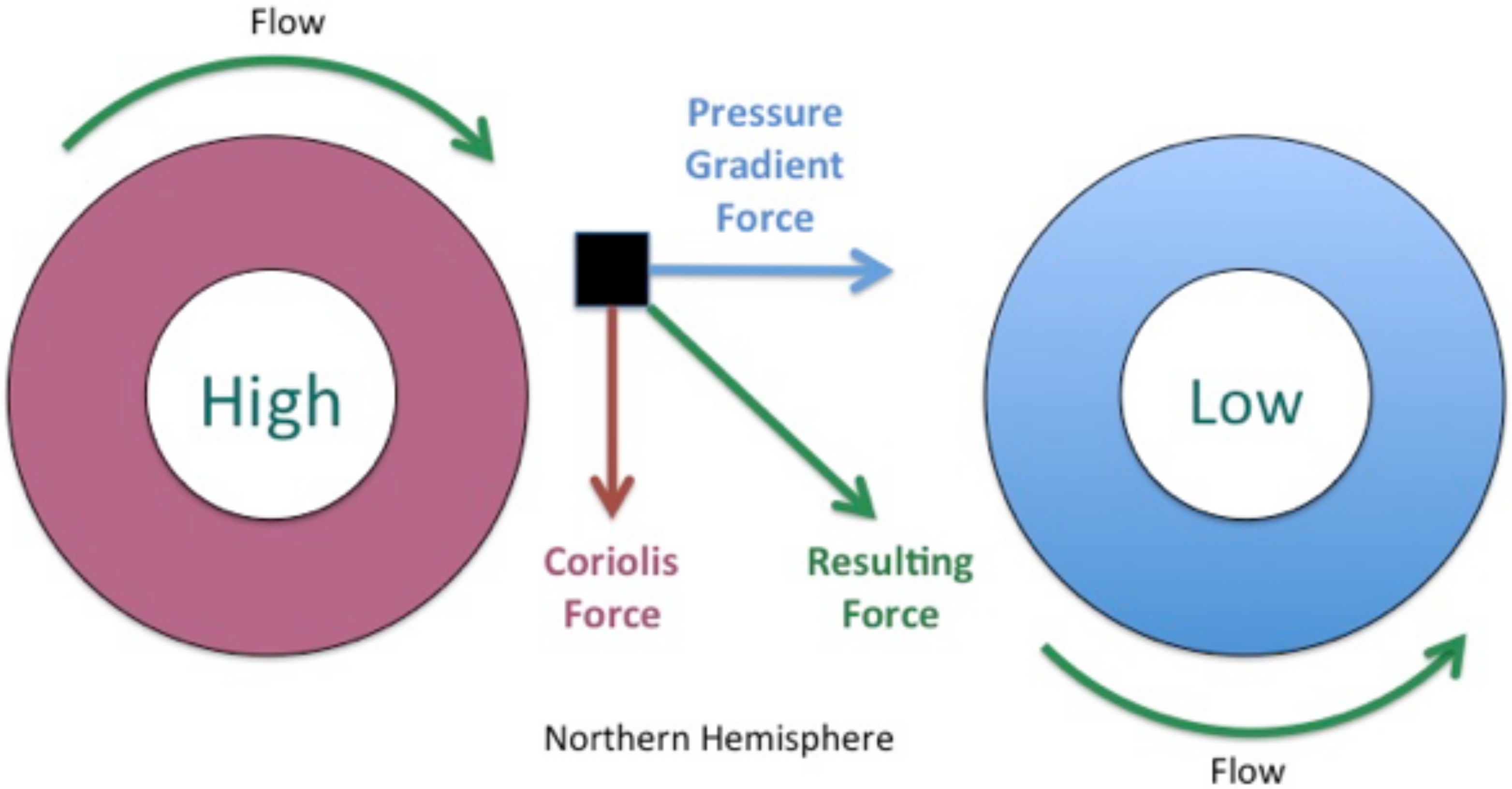
GEOSTROPHIC FLOW:
equilibrium between pressure-gradient and Coriolis forces



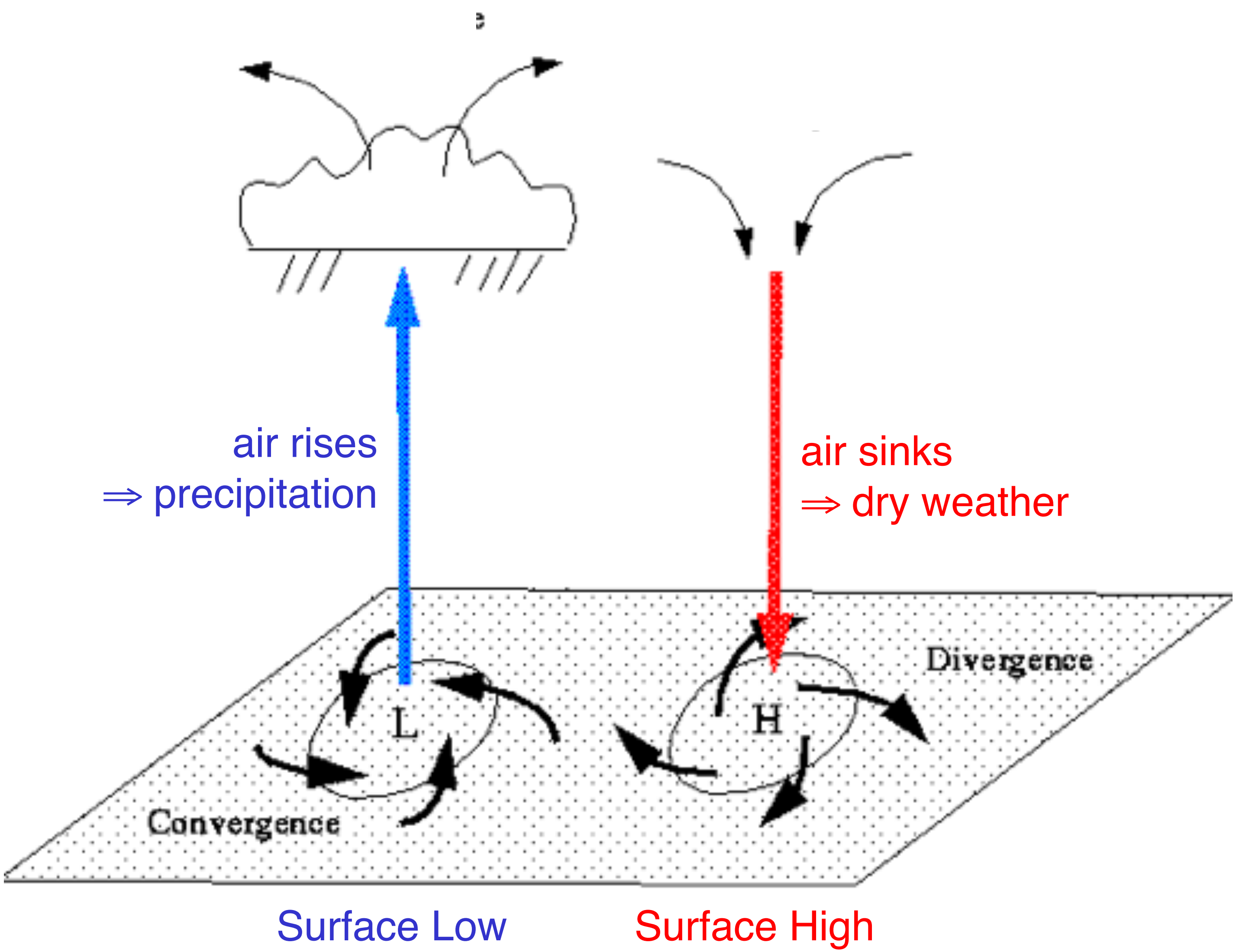
- steady
- parallel to isobars
- speed ~ pressure gradient

N hemisphere example

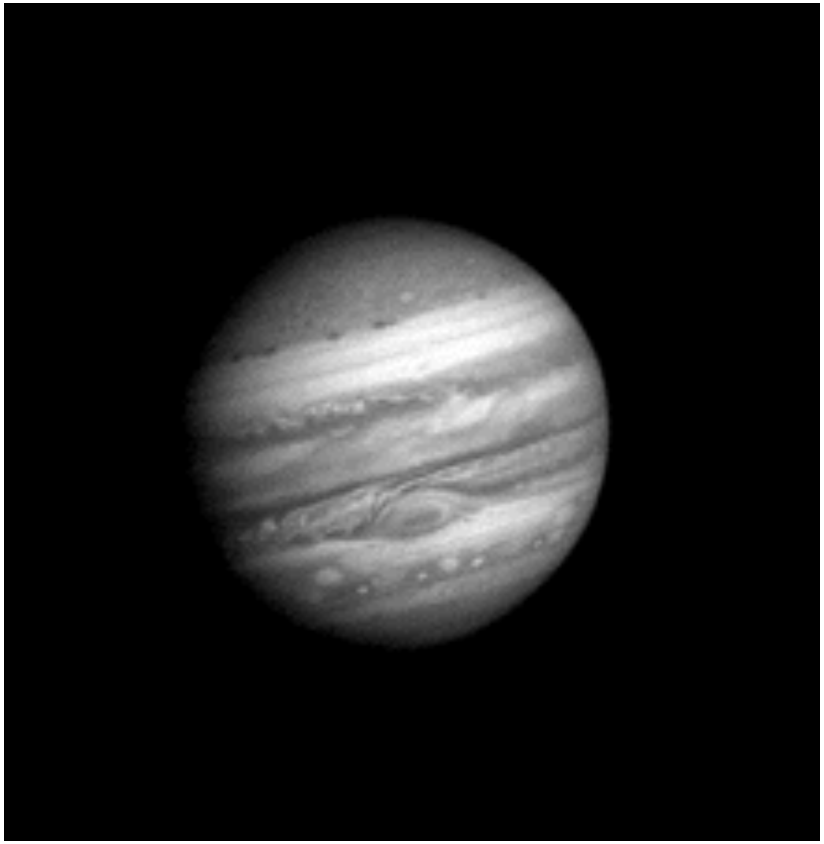
Circulation around Highs and Lows

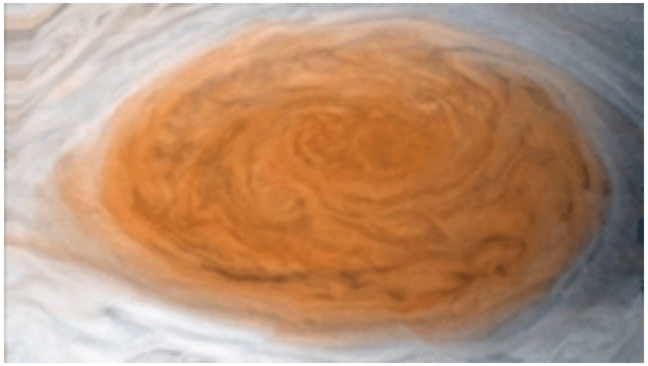


How Highs and Lows affect surface weather



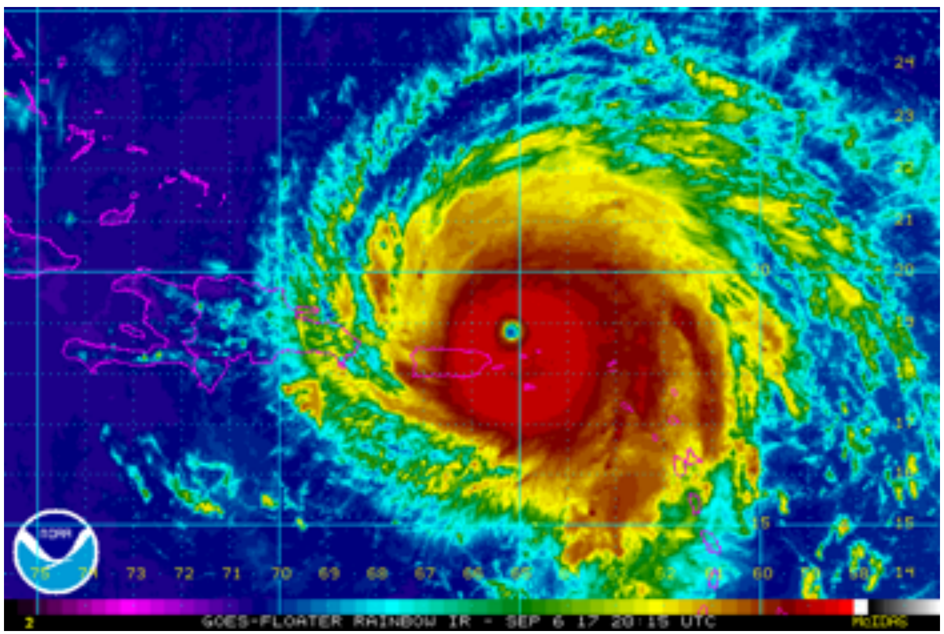
Great red spot of Jupiter:
lack of friction allows persistence of Highs and Lows



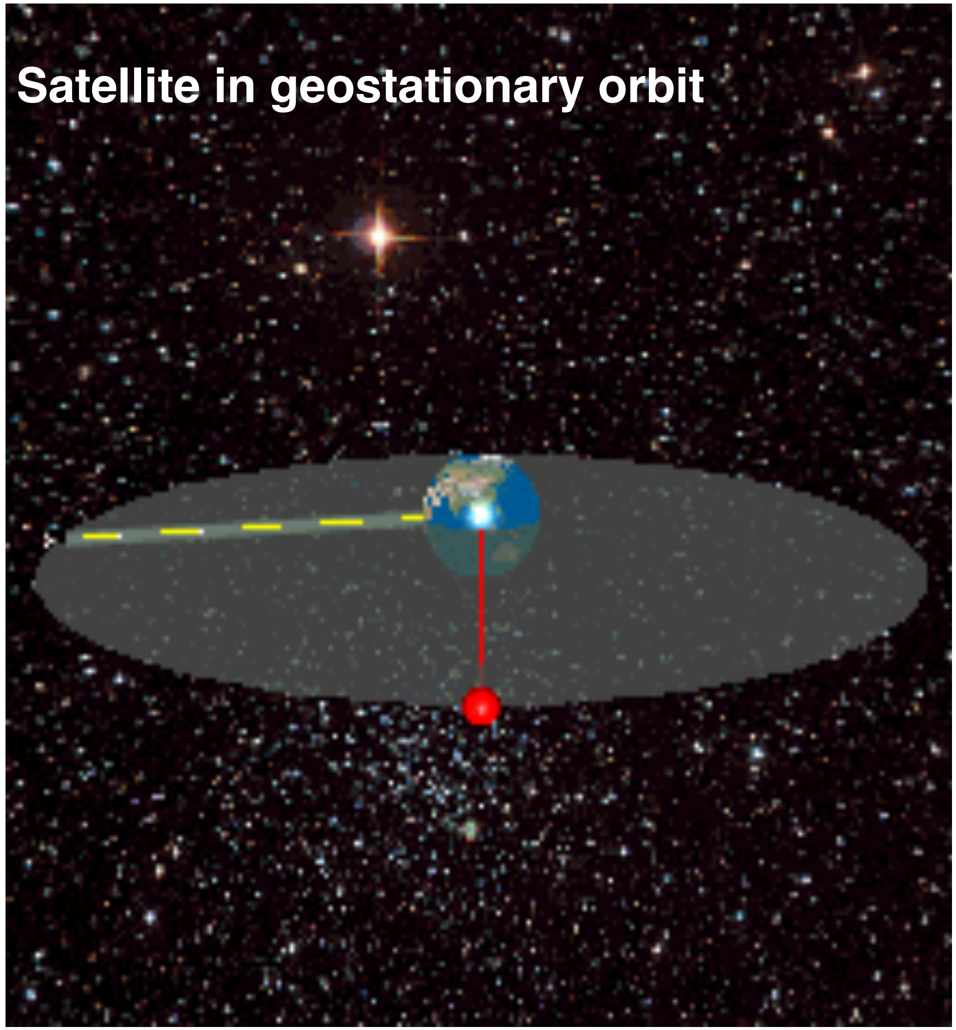


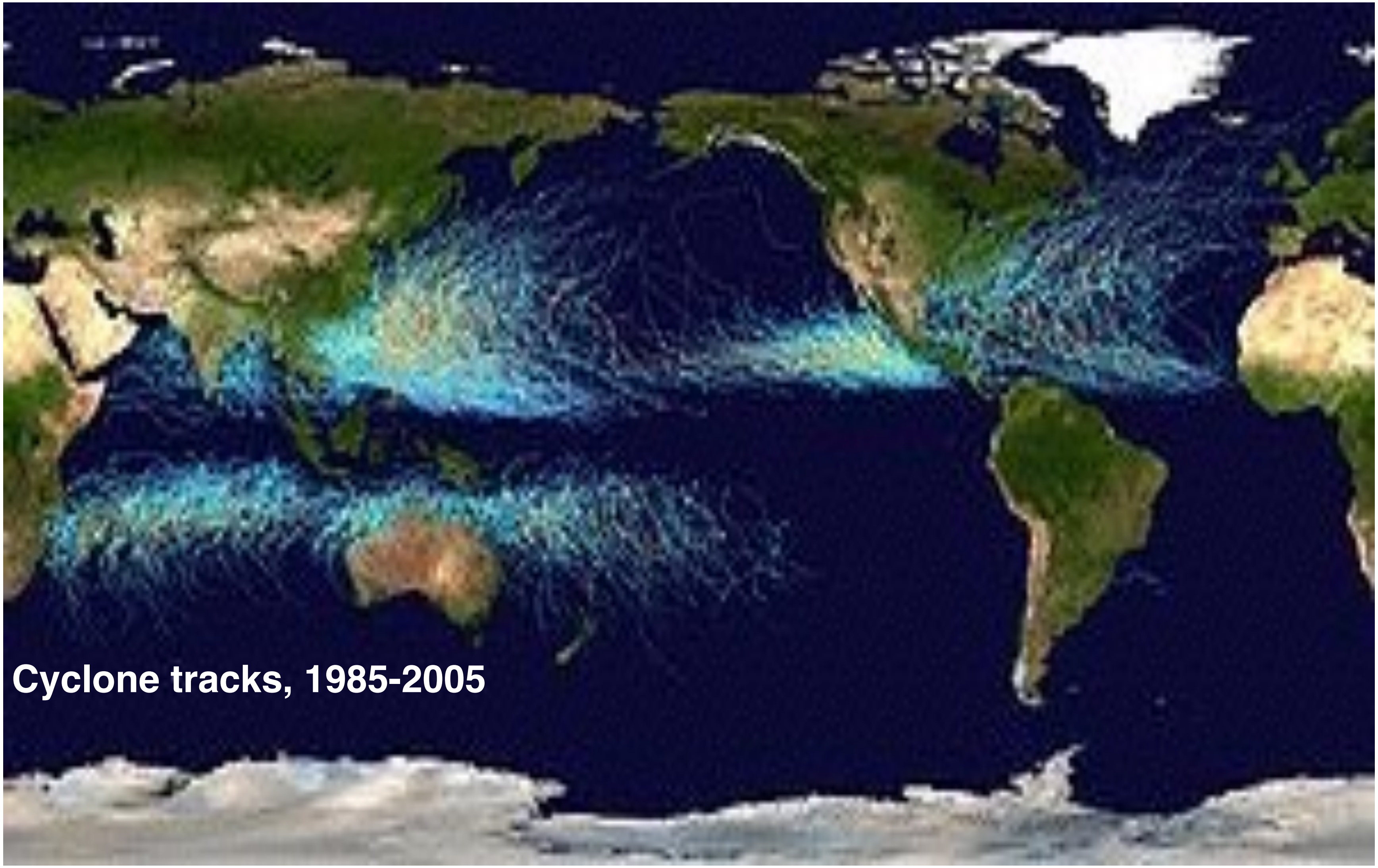
Questions

1. The Coriolis force responsible for anticyclonic and cyclonic motions (rotation around Highs and Lows) applies only when viewing motions from the perspective of the rotating Earth. Then how come we can see rotating hurricanes (strong cyclones) from weather satellites?

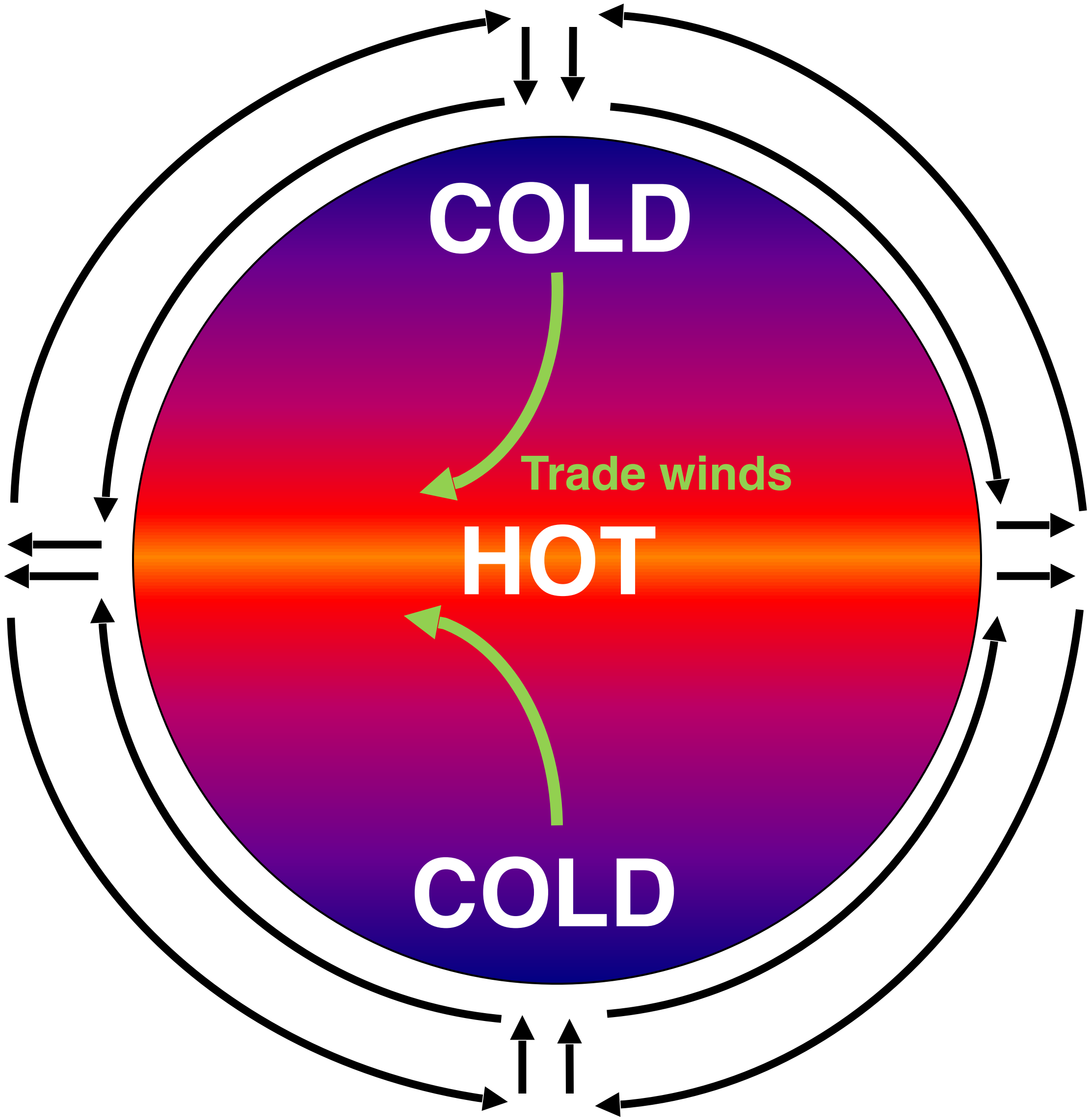


1. What happens to tropical cyclones when they cross the Equator? Do they start turning the other way?


Satellite in geostationary orbit


Cyclone tracks, 1985-2005

The Hadley circulation (1735): global sea breeze



Explains:
- Intertropical Convergence Zone (ITCZ)
- Wet tropics, dry poles
- Easterly trade winds in the tropics

But… Direct meridional transport of air between Equator and poles is not possible because of Coriolis force

Hadley circulation only extends to about 30^o latitude

- Easterly trade winds in the tropics at low altitudes
- Subtropical anticyclones at about 30^o latitude
- Westerlies at mid-latitudes

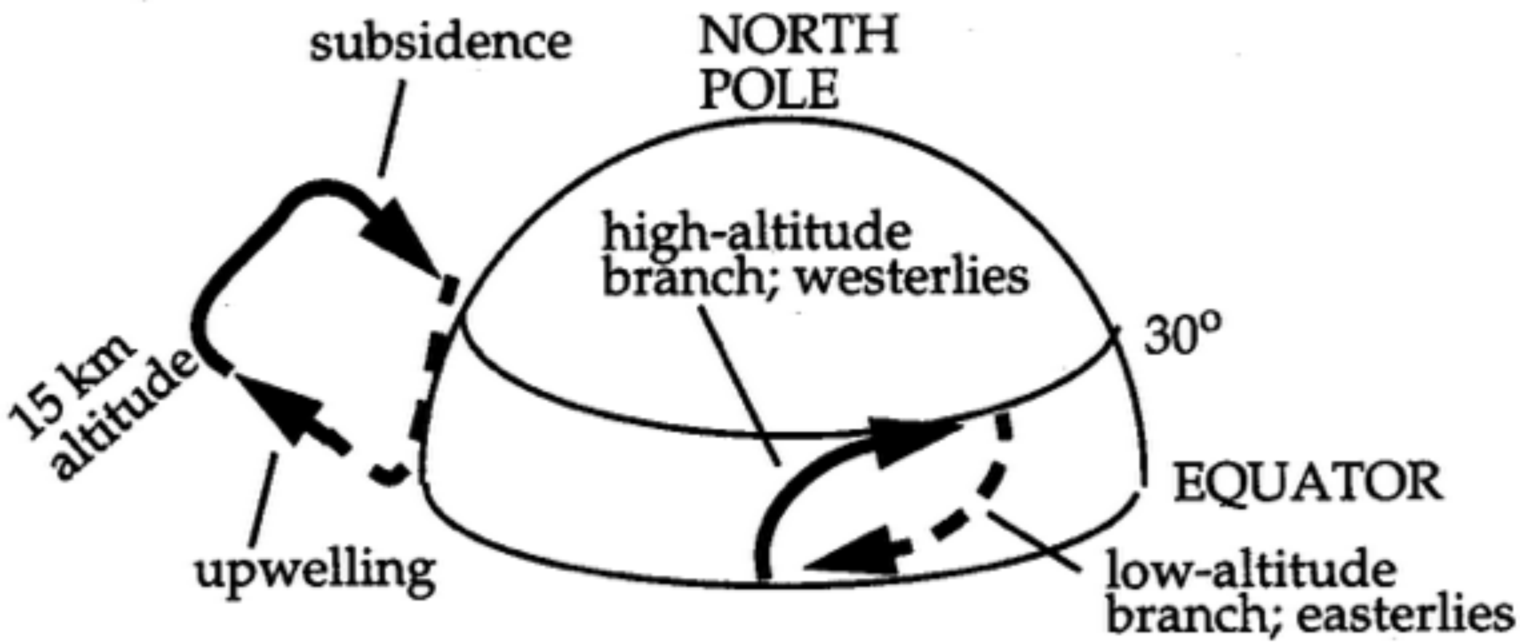
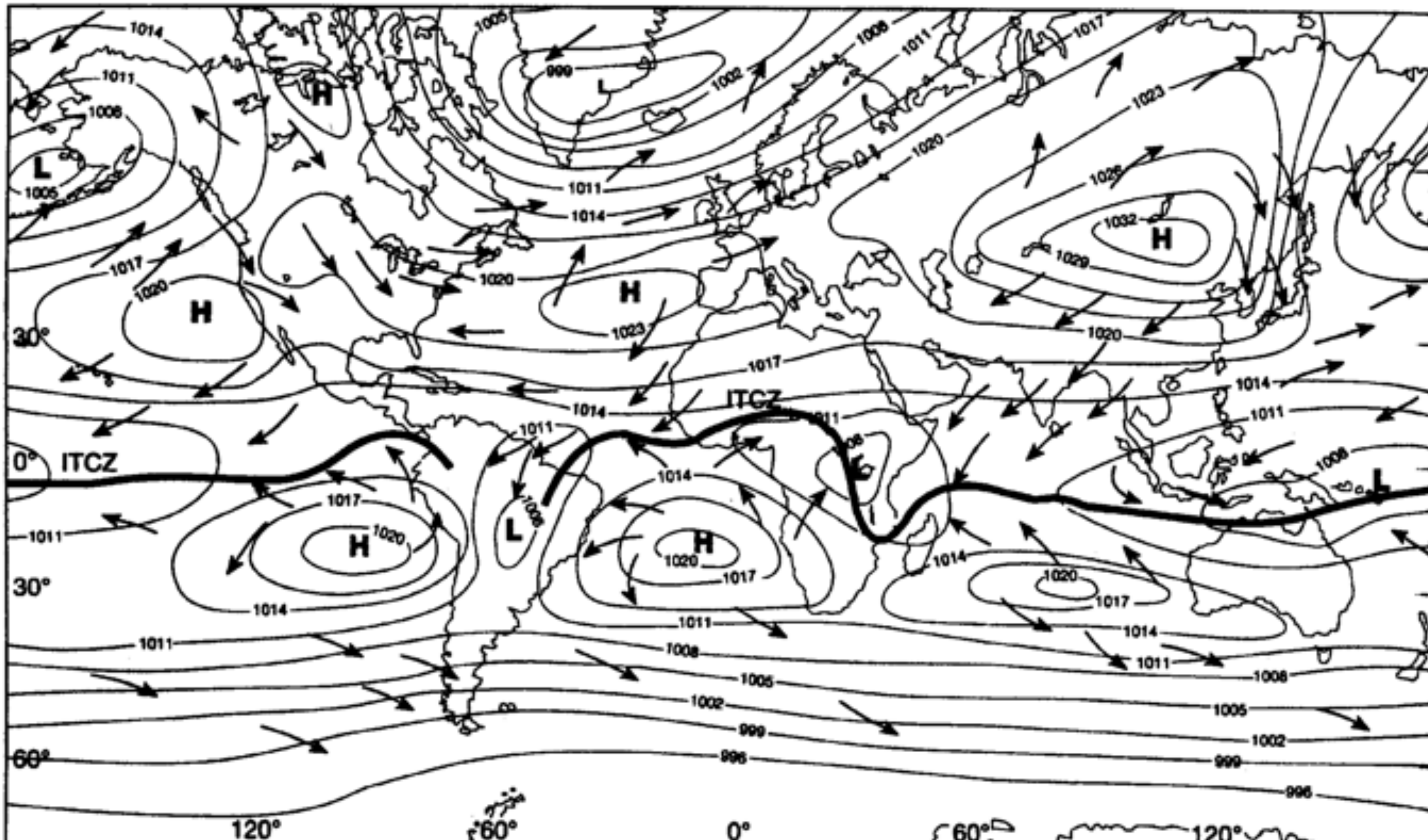


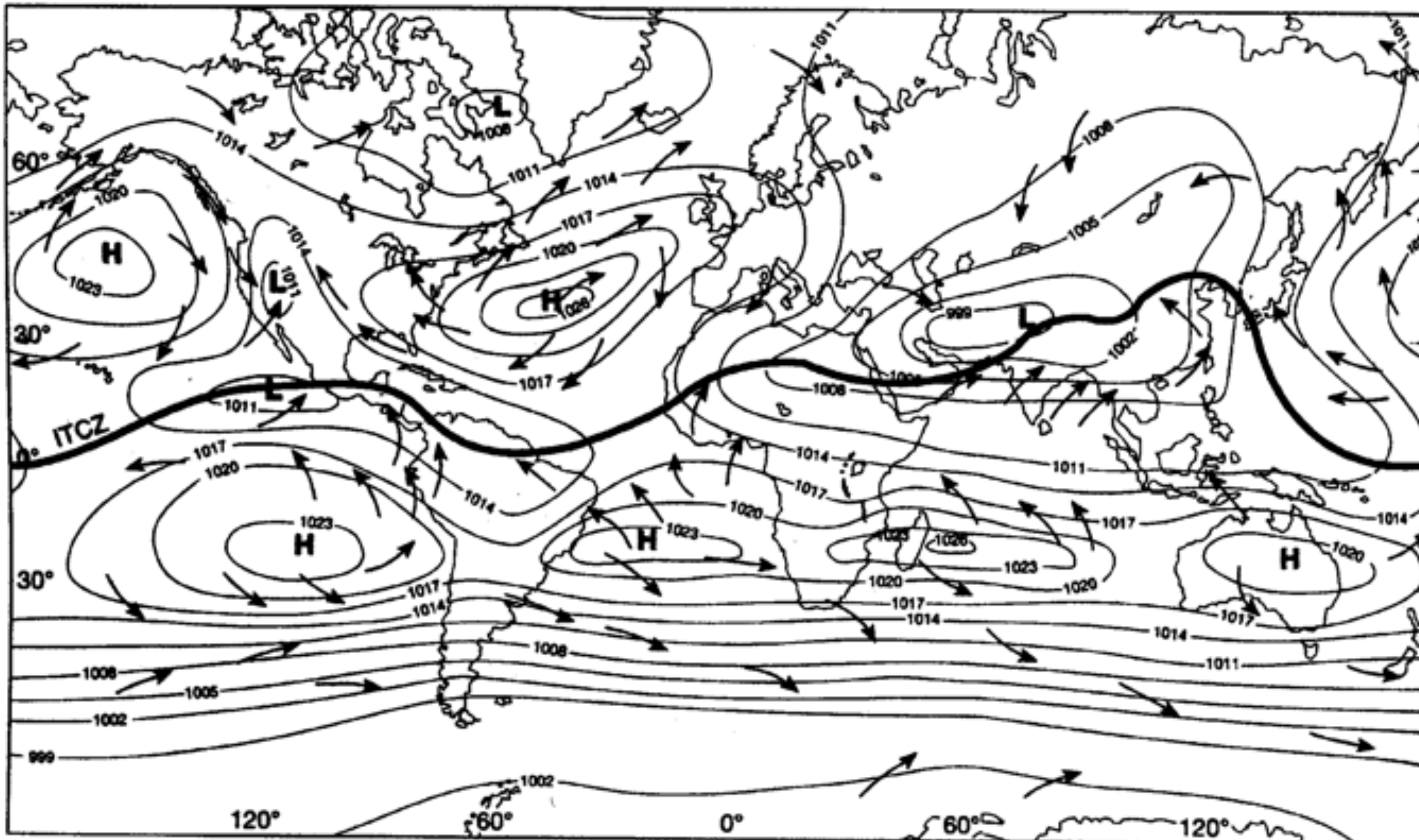
Fig. 4-11 Northern hemisphere Hadley cell.

Climatological surface winds and pressures (January)



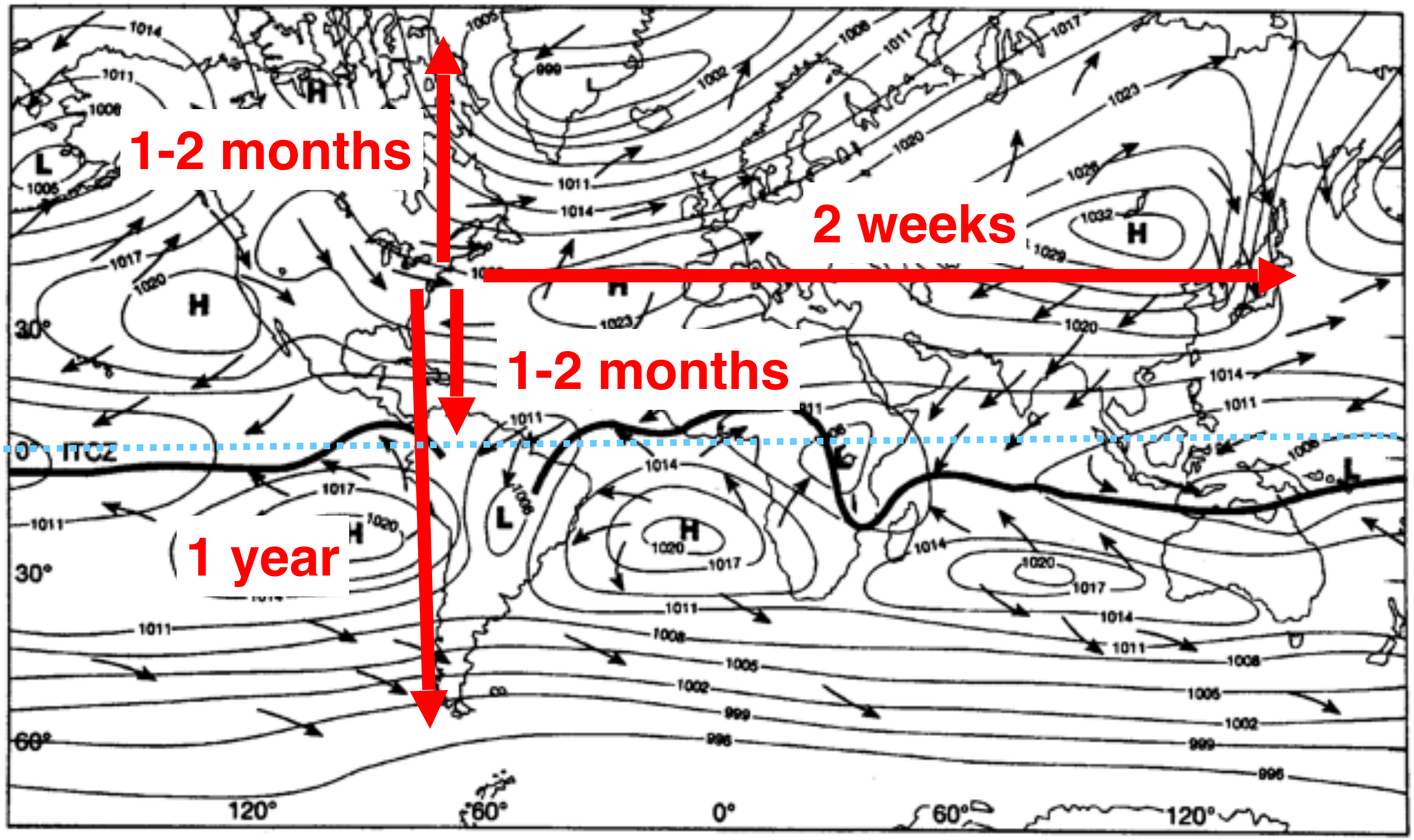
(a) January

Climatological surface winds and pressures (July)



(b) July

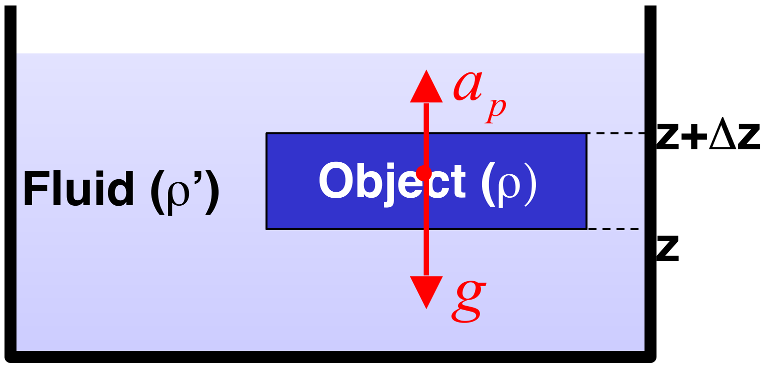
Time scales for horizontal transport (troposphere)



(a) January

VERTICAL TRANSPORT: BUOYANCY

Consider an object (density ρ) immersed in a fluid (density ρ'):



p(z) > p(z+Δz) **⇨ pressure-gradient force on object directed upward**

Buoyancy acceleration (upward) : $$a_b = a_p - g = \frac{\rho' - \rho}{\rho} g$$

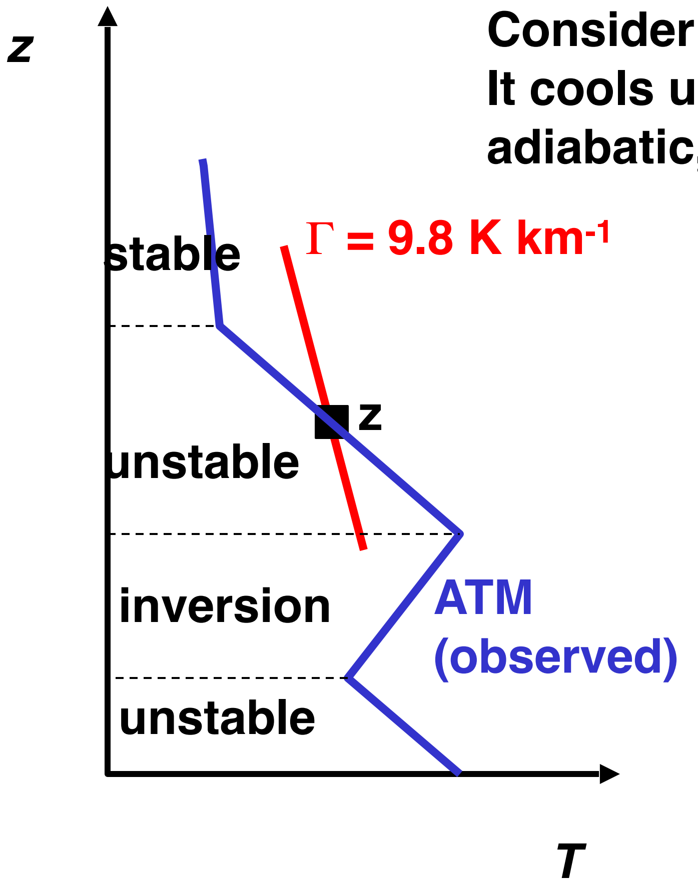
For air, $$\rho = \frac{M_a p}{RT}$$ **so ρ↑ as *T*↓**

Barometric law assumes *T = T'* **⇨** $a_b = 0$ **(zero buoyancy)**

T $\neq$ ***T'*** **produces buoyant acceleration upward or downward**

ATMOSPHERIC LAPSE RATE AND STABILITY

"Lapse rate" = $-dT/dz$



Consider an air parcel at z lifted to $z+dz$ and released. It cools upon lifting (expansion). Assuming lifting to be adiabatic, the cooling follows the adiabatic lapse rate Γ :

$$\Gamma = -\frac{dT}{dz} = \frac{g}{C_p} = 9.8 \text{ K km}^{-1}$$

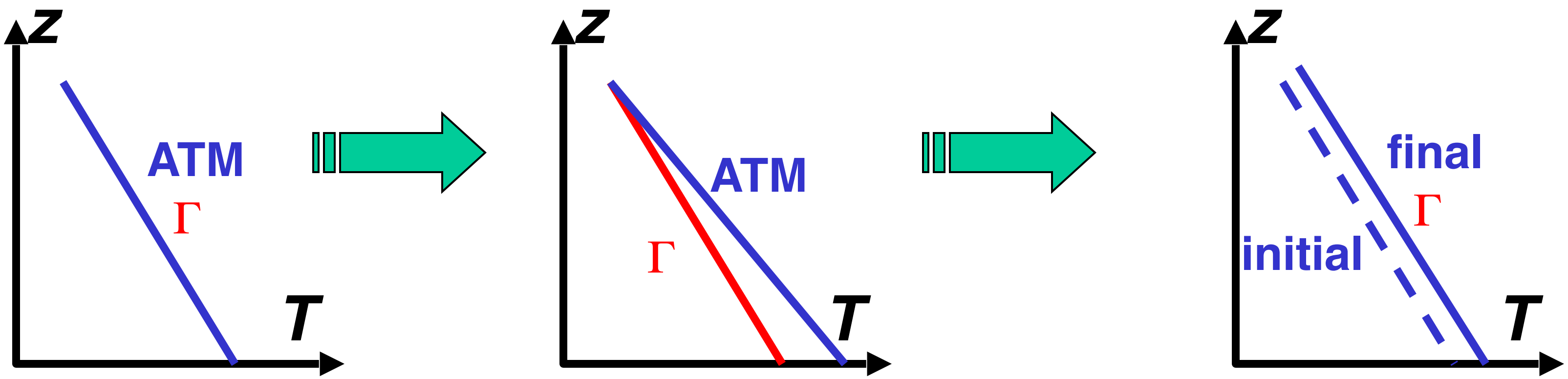
What happens following release depends on the local lapse rate $-dT_{ATM}/dz$:

- $-dT_{ATM}/dz > \Gamma$ ⇨ upward buoyancy amplifies initial perturbation: atmosphere is *unstable*
- $-dT_{ATM}/dz = \Gamma$ ⇨ zero buoyancy does not alter perturbation: atmosphere is *neutral*
- $-dT_{ATM}/dz < \Gamma$ ⇨ downward buoyancy relaxes initial perturbation: atmosphere is *stable*
- $dT_{ATM}/dz > 0$ ("inversion"): very stable

The stability of the atmosphere against vertical mixing is solely determined by its lapse rate.

WHAT DETERMINES THE LAPSE RATE OF THE ATMOSPHERE?

- An atmosphere left to evolve adiabatically from an initial state would eventually tend to *neutral* conditions ($-dT/dz = \Gamma$) at equilibrium
- Consider now solar heating of the surface. This disrupts the equilibrium and produces an unstable atmosphere:



Initial equilibrium state: $-dT/dz = \Gamma$

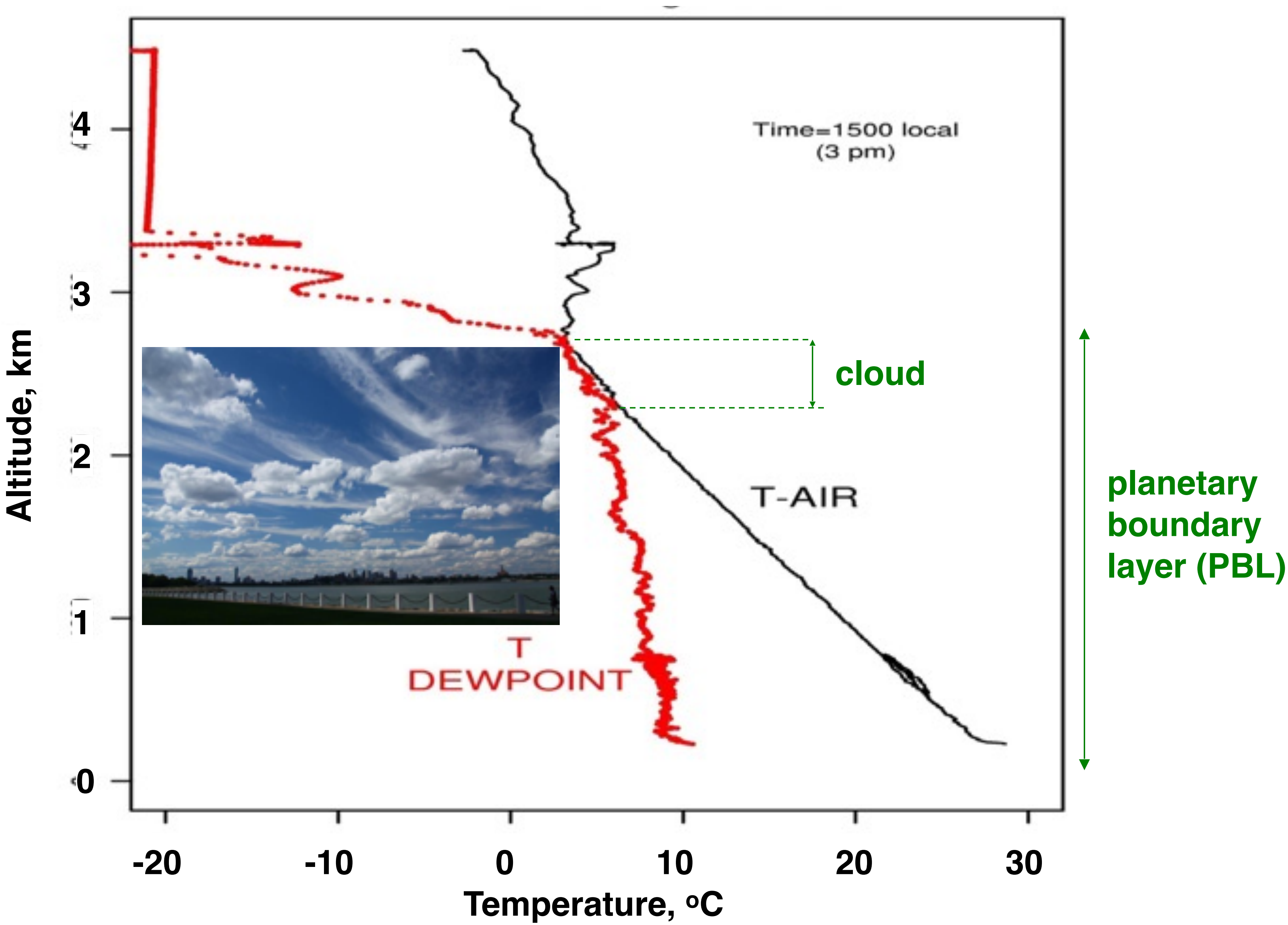
Solar heating of surface: unstable atmosphere

buoyant motions relax unstable atmosphere back towards $-dT/dz = \Gamma$

- **Fast vertical mixing in an unstable atmosphere maintains the lapse rate to Γ.**

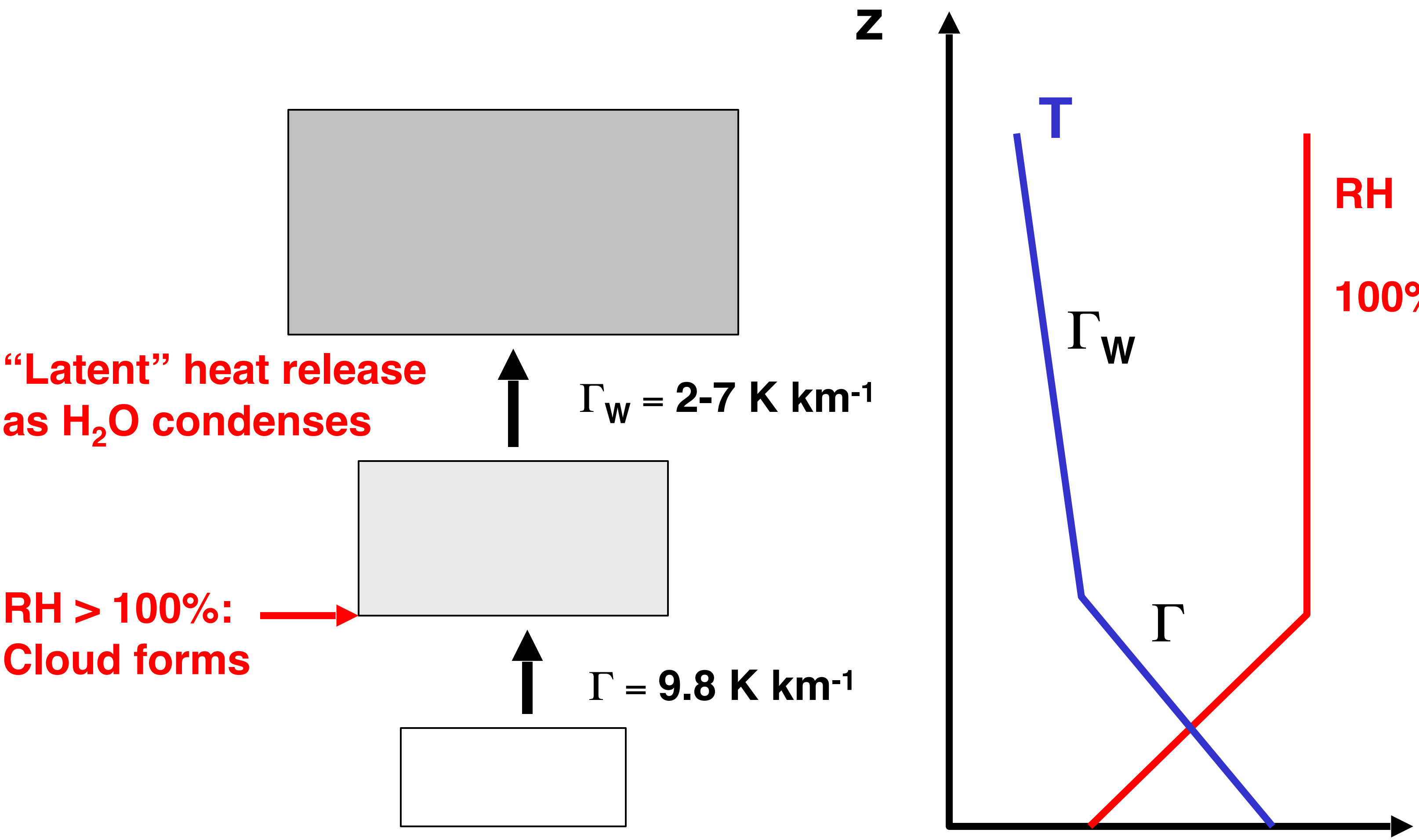
<u>Observation</u> of $-dT/dz = \Gamma$ is sure indicator of an unstable atmosphere.

Typical summer afternoon vertical profile over Boston



IN CLOUDY AIR PARCEL, HEAT RELEASE FROM H_2O CONDENSATION MODIFIES Γ

Wet adiabatic lapse rate Γ_W = 2-7 K km^{-1}



SUBSIDENCE INVERSION

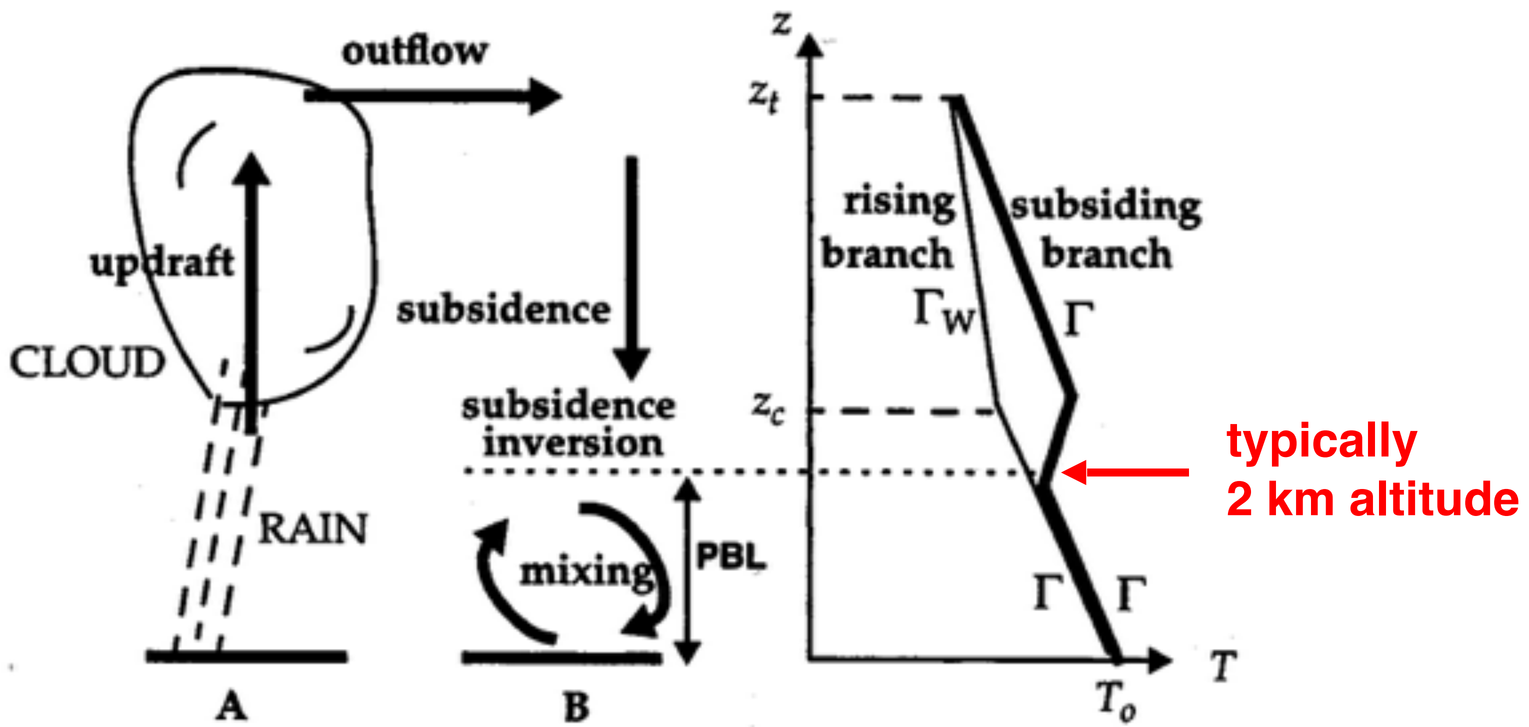
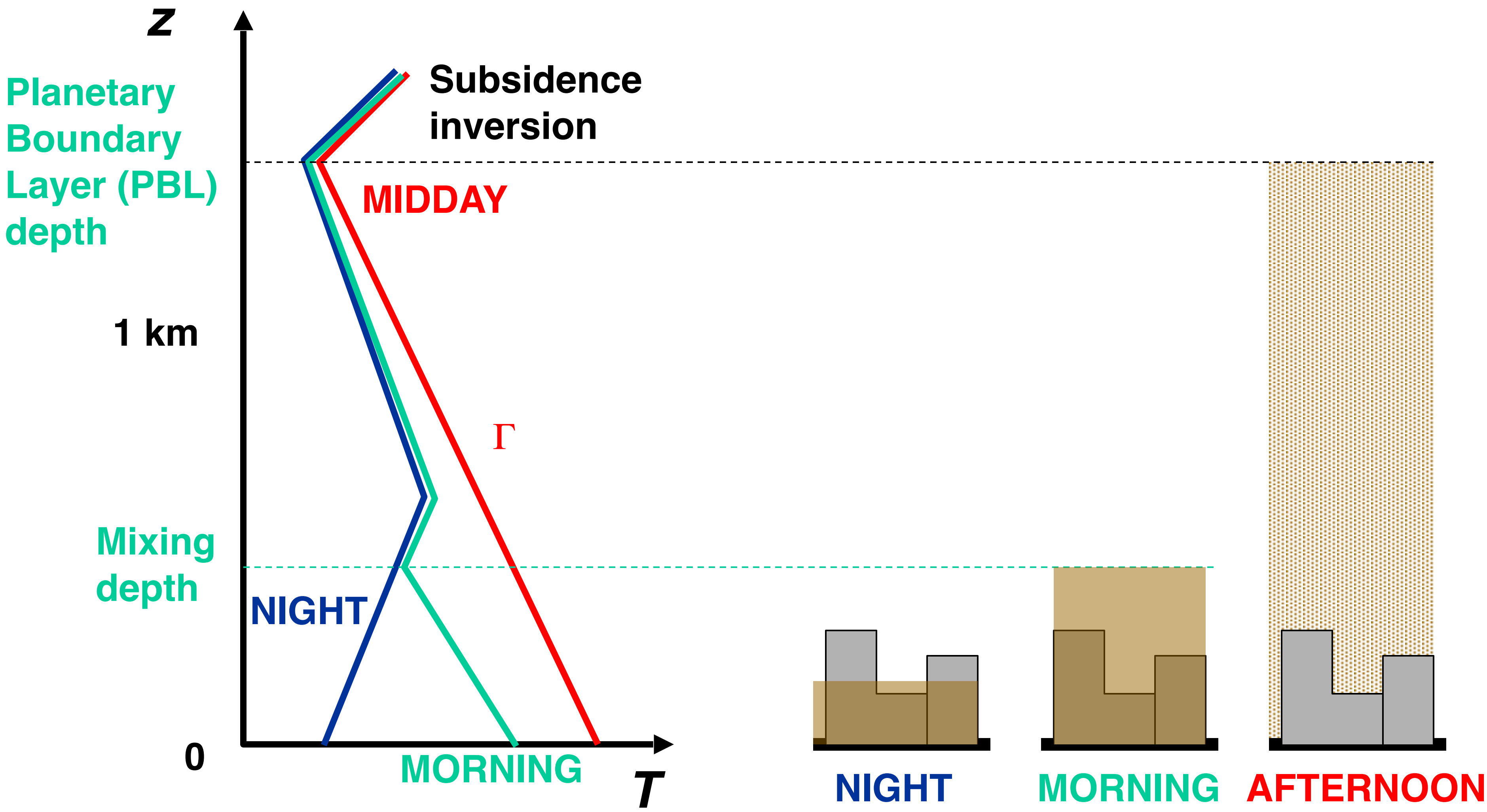
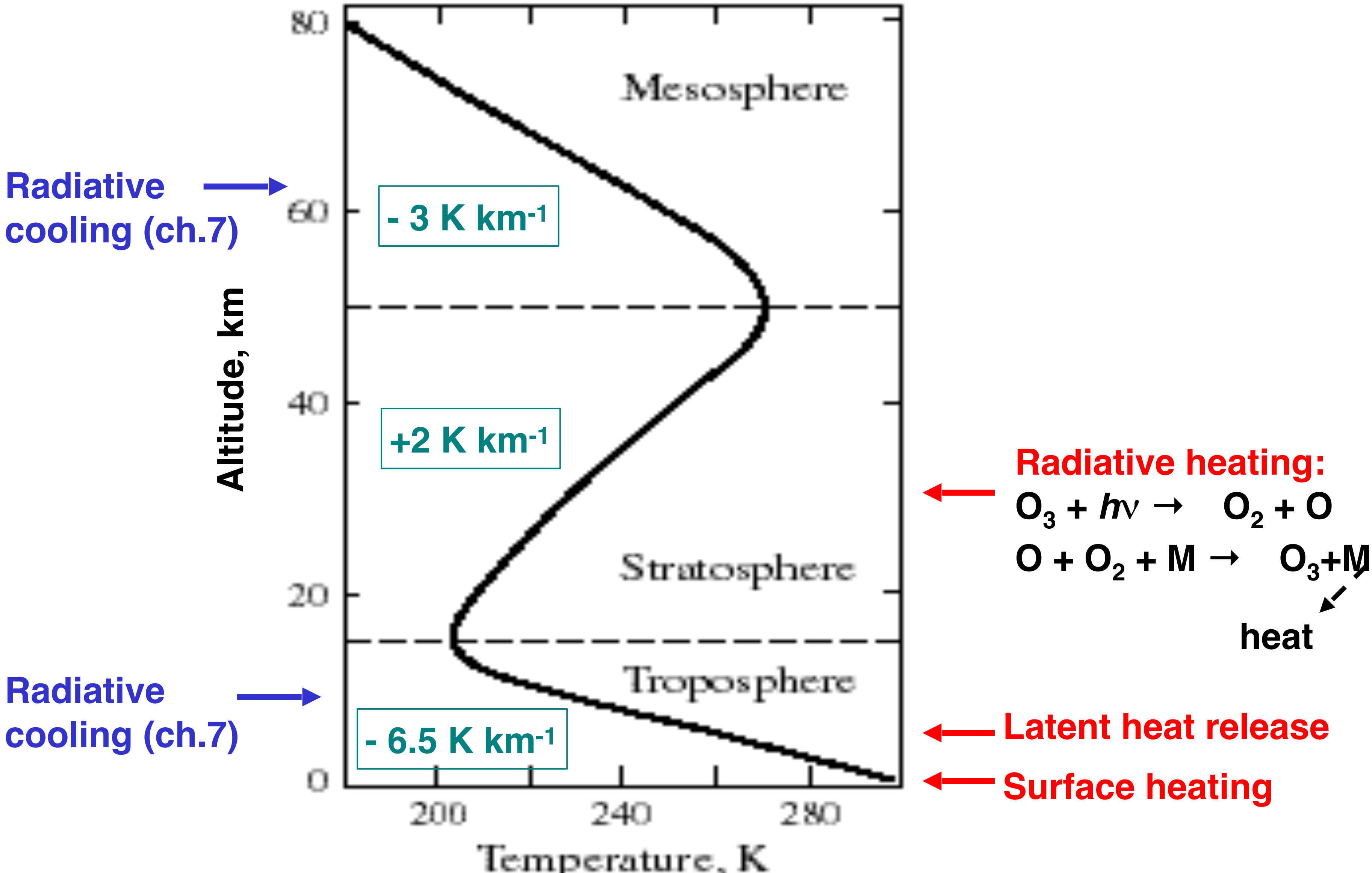


Fig. 4-17 Formation of a subsidence inversion. Temperature profiles on the right panel are shown for the upwelling region *A* (thin line) and the subsiding region *B* (bold line). It is assumed for purposes of this illustration that regions *A* and *B* have the same surface temperature T_0. The air column extending up to the subsidence inversion is commonly called the planetary boundary layer (PBL).

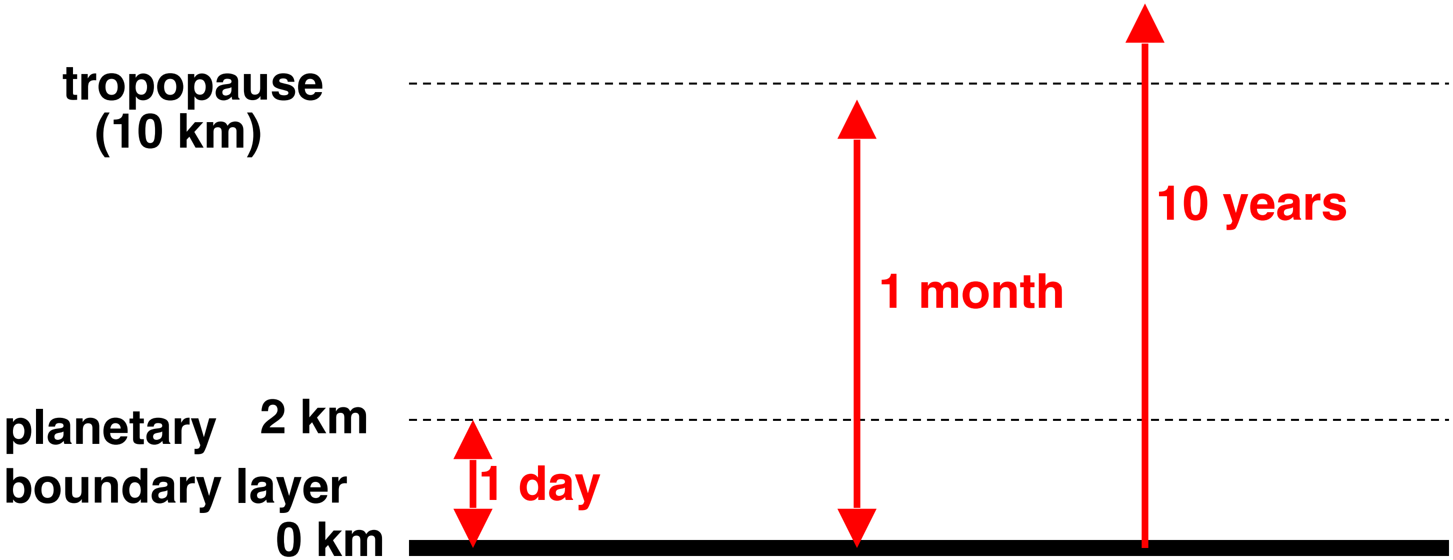
DIURNAL CYCLE OF SURFACE HEATING/COOLING: ventilation of urban pollution



VERTICAL PROFILE OF TEMPERATURE
Mean values for 30ºN, March



TYPICAL TIME SCALES FOR VERTICAL MIXING



Questions

- A sea-breeze circulation often results in an inversion. Explain why.
- A classic air pollution problem is “fumigation” where a location downwind of a tall smokestack will experience a sudden burst of high pollution from that smokestack in mid-morning. Can you explain this observation on the basis of atmospheric stability?