ATS 421/521

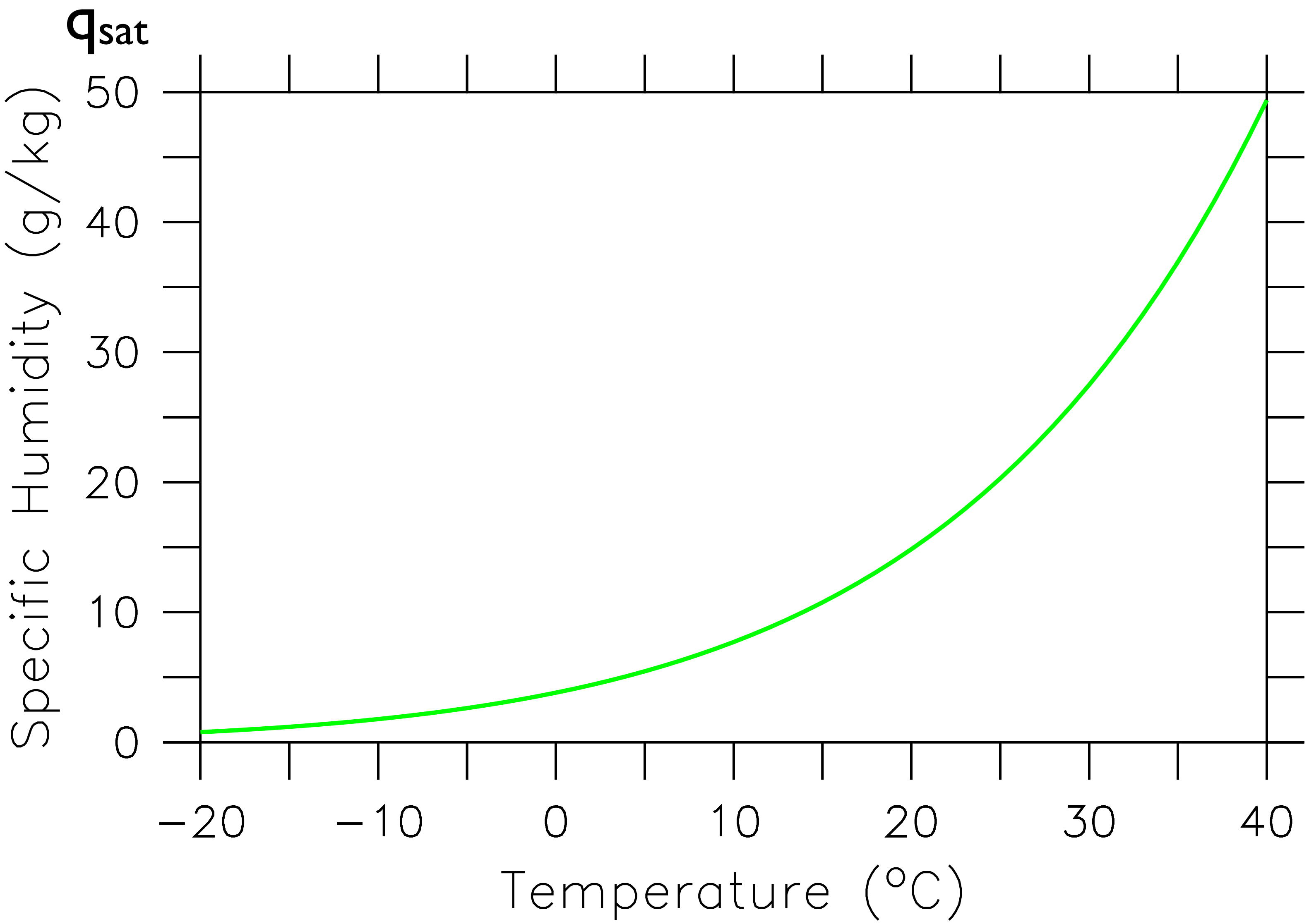
Climate Modeling

Spring 2013

Lecture 10

- The Hydrological Cycle
- The Hadley Circulation

Specific Humidity & Clausius-Clapeyron Equation



- specific humidity q is the ratio of the mass of water vapor over the mass of moist air
- the saturation specific humidity is the specific humidity at which the air parcel is saturated in moisture
- the relative humidity RH = q/ q_{sat}

Evaporation and Condensation

- Evaporation is the transition from the liquid to the vapor phase
- It occurs when the relative humidity of the air is < 100% (the lower the RH the more evaporation; $E \sim q_{sat} - q$)
- Evaporation leads to cooling of the surface because energy is put into latent heat (this is why we sweat)
- Condensation is the transition from the vapor to the liquid phase
- It occurs when the air is at 100% RH and when *cloud condensation nuclei* are available

(see experiment)

- Condensation leads to warming due to the release of latent heat
- Water vapor transport = latent heat transport

Remember:
Latent heat of vaporization/ condensation = 2300 J/g

(blowing over your coffee leads to faster cooling: wind increases evaporation)

Experiment

- Pump air into the bottle until the lid pops. What happens ?
- Now light a match and blow a little smoke into the bottle. Repeat the experiment. What happens ?

The Global Water Cycle

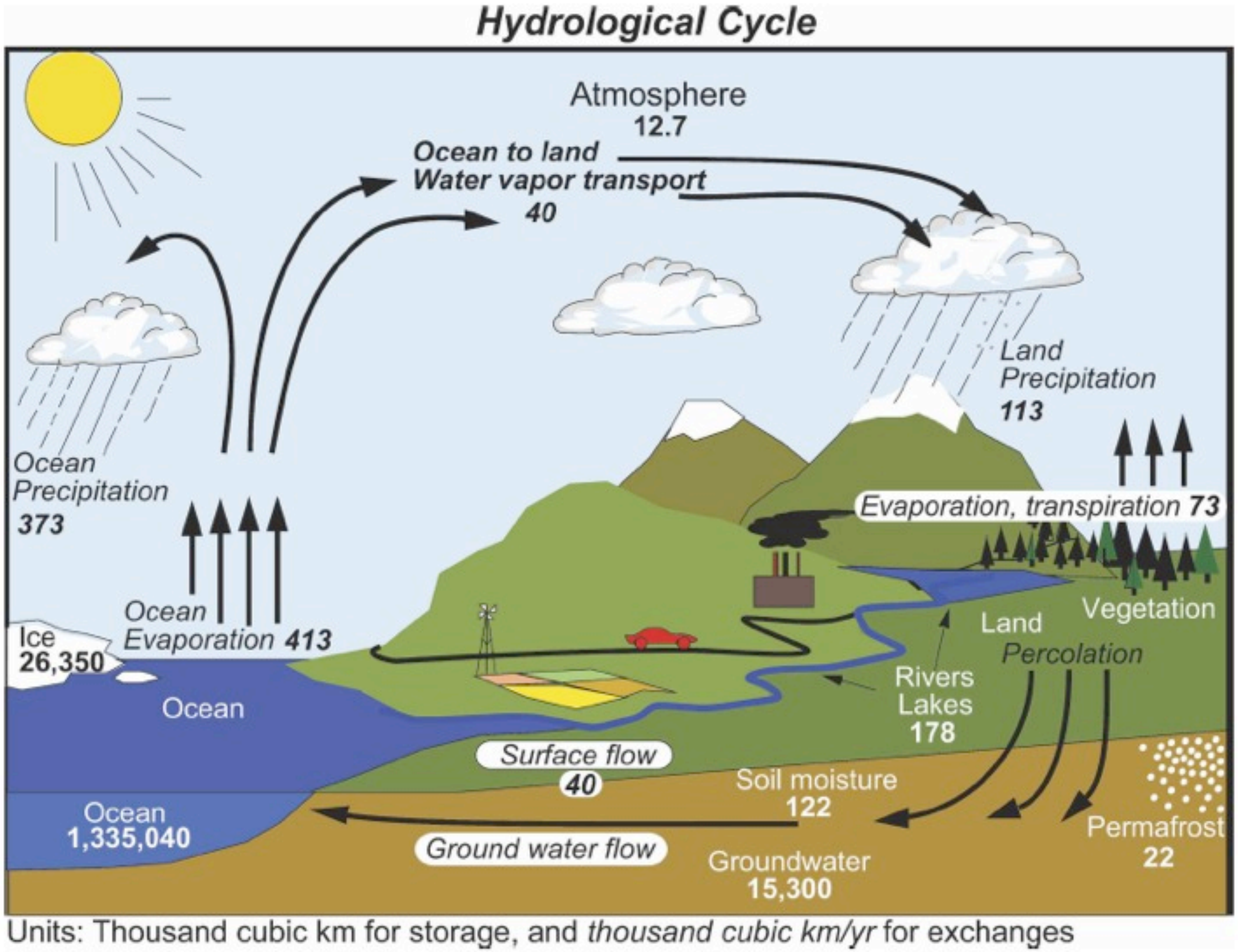
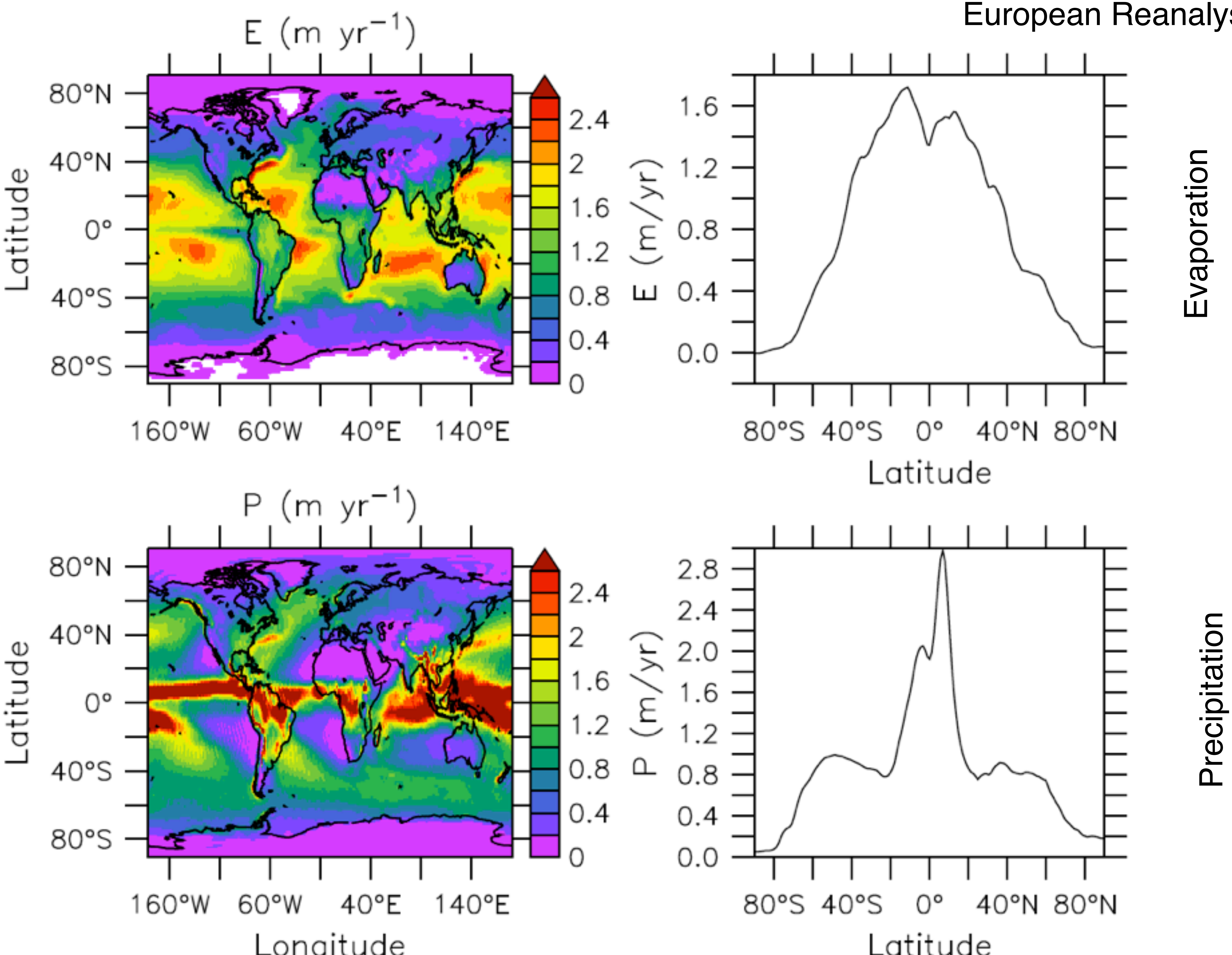


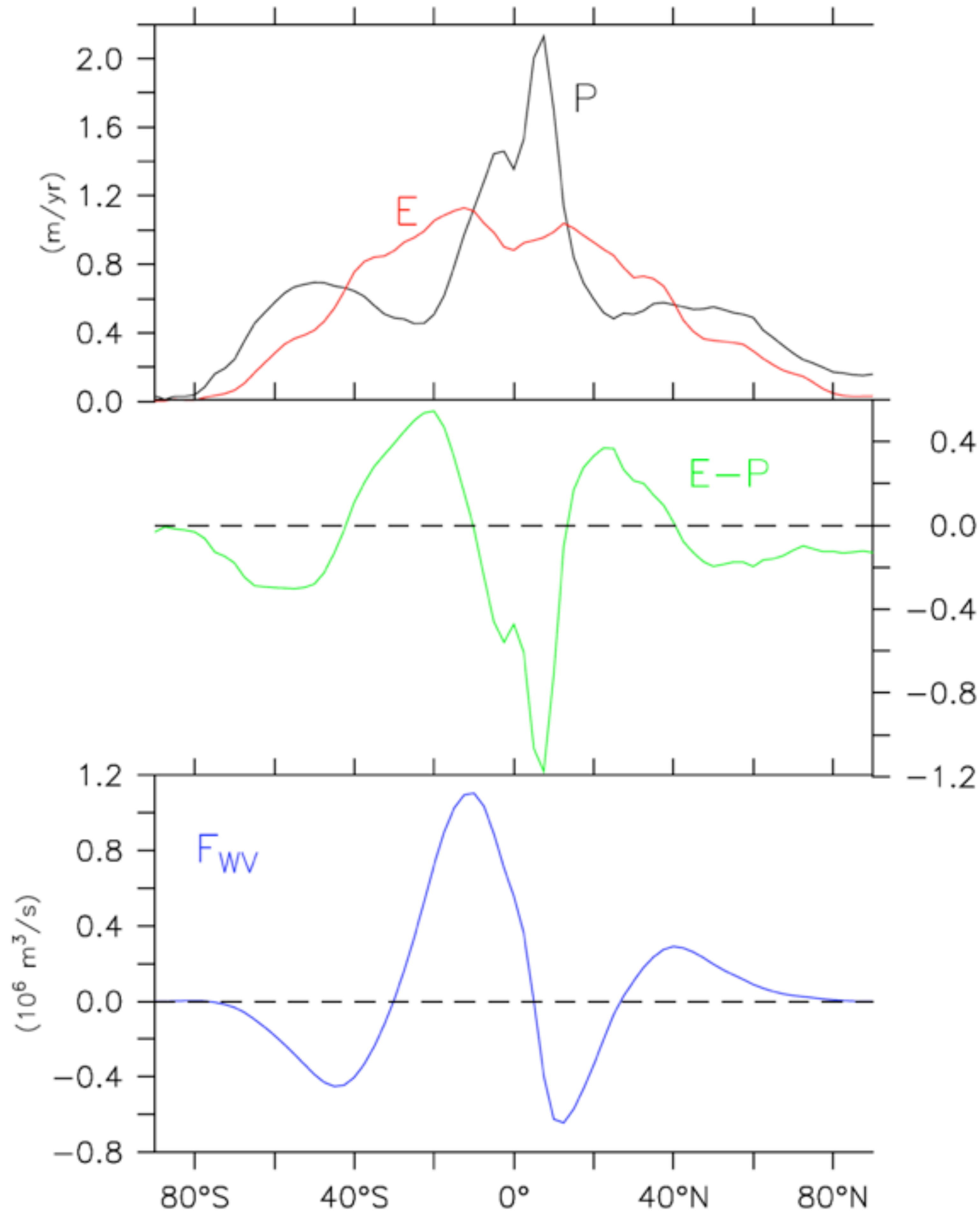
FIG. 1. The hydrological cycle. Estimates of the main water reservoirs, given in plain font in 10^3 km^3, and the flow of moisture through the system, given in slant font (10^3 km^3 yr^{-1}), equivalent to Eg (10^{18} g) yr^{-1}.

Trenberth et al. (2007) J. Hydrometeor.

ERA15 1979-1993
European Reanalysis

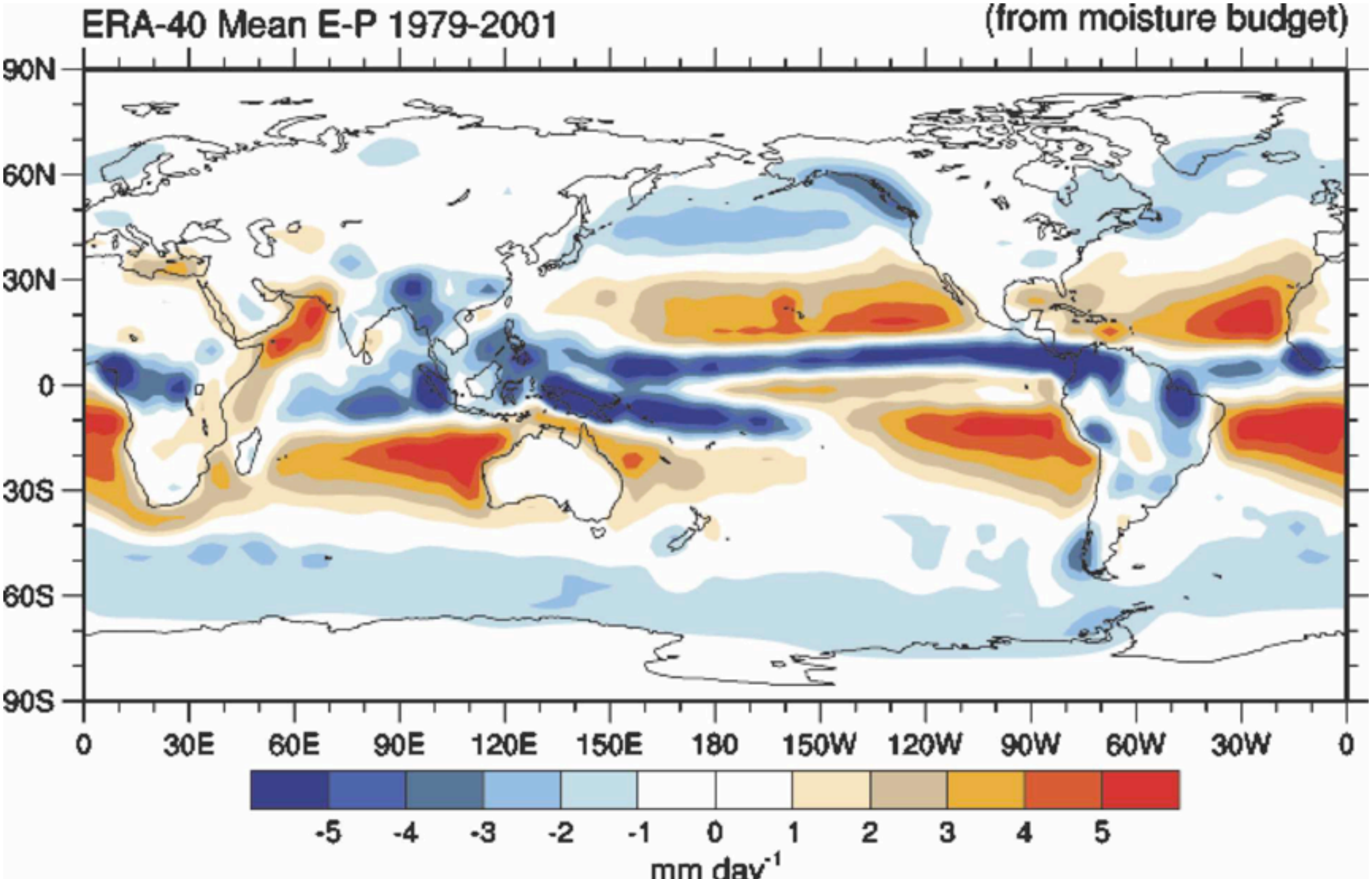


ERA40
1959-2002



Meridional Water Vapor Flux

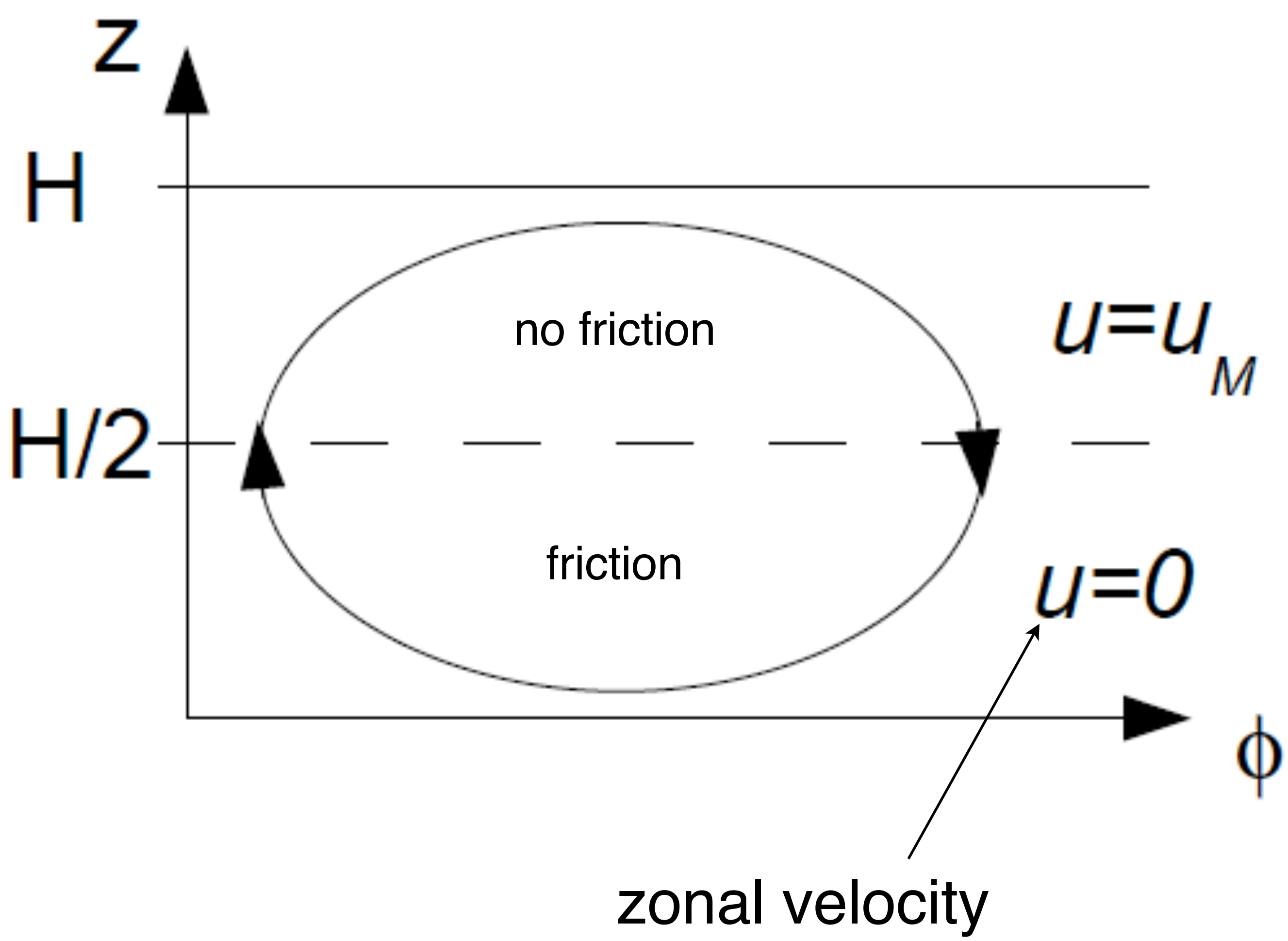
$$F_{WV} = \int_{x=0}^{360} \int_{y'=90S}^{y} E - P \, dx \, dy'$$



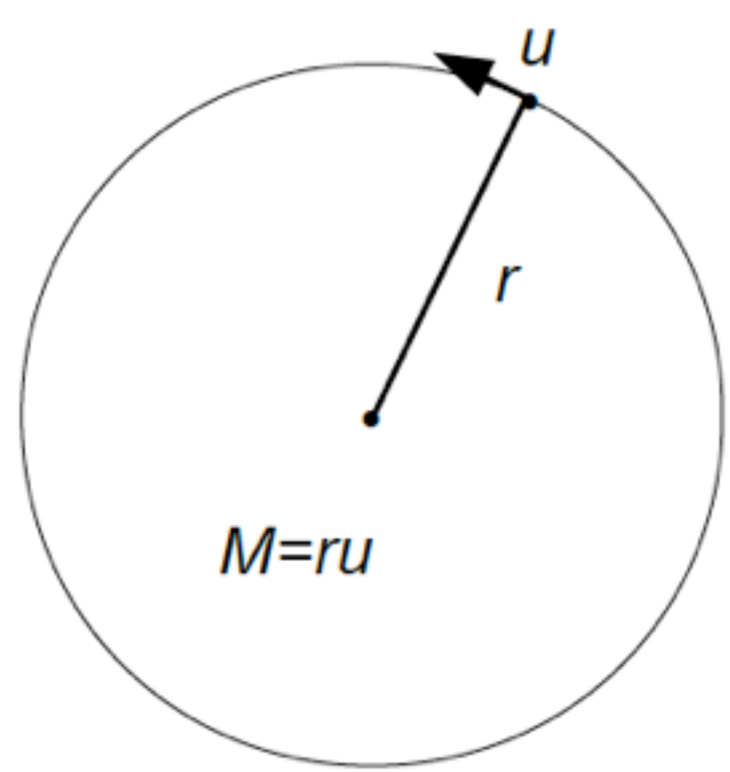
Trenberth et al. (2007)

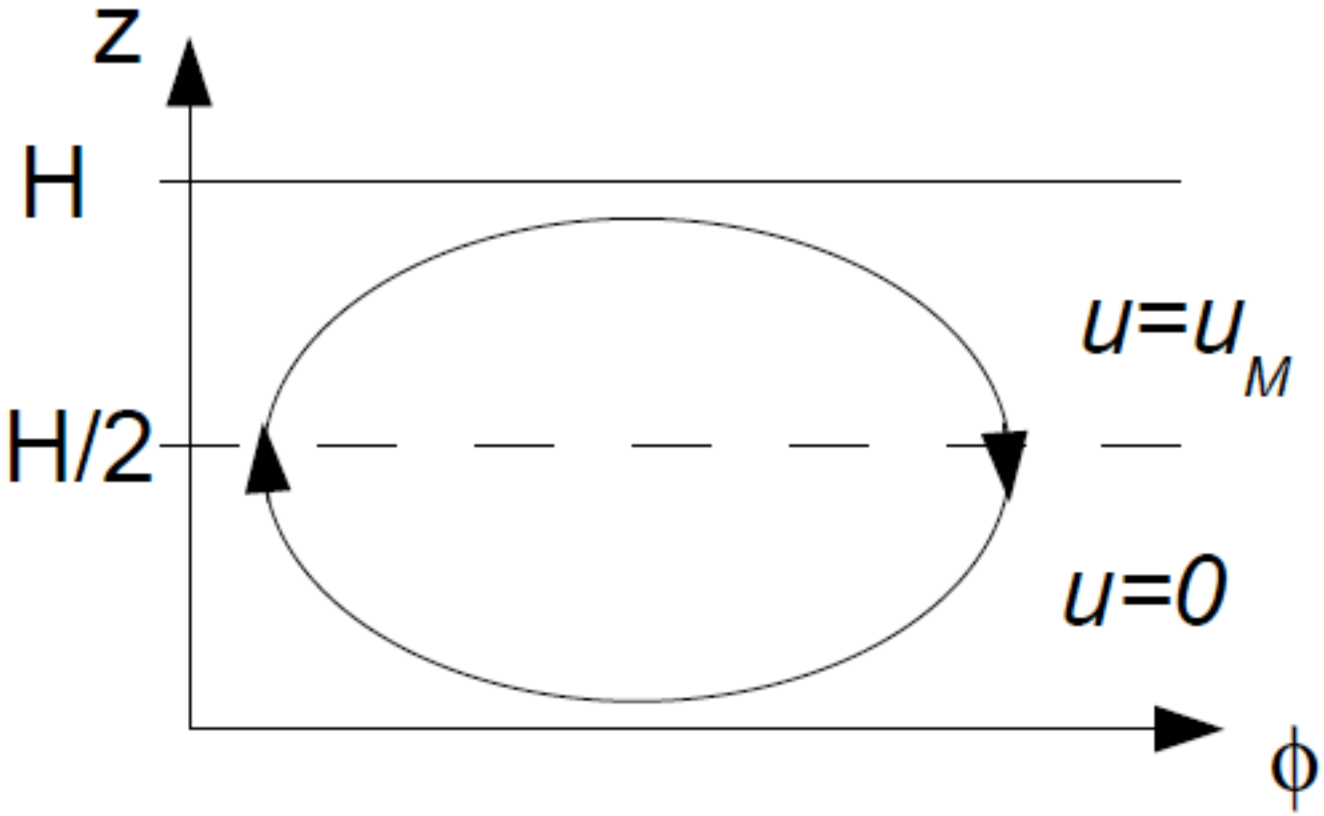
Hadley Circulation

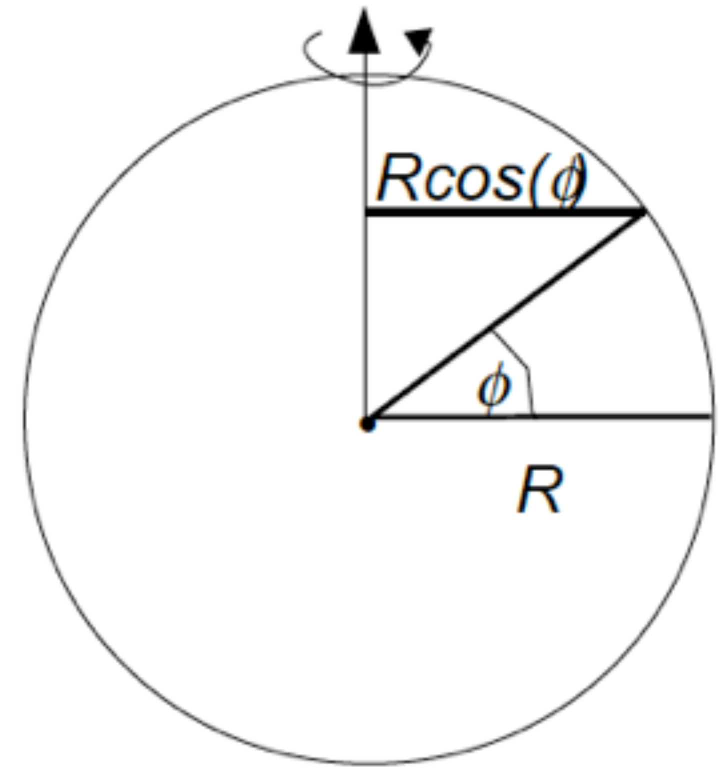
- Simple Model by Held and Hou (1980)
  - based on conservation of angular momentum in a two layer model



Angular Momentum M=ru







Assume heating: $\frac{\partial \Theta}{\partial t} = \frac{\Theta - \Theta_E}{\tau_E}$ $\Theta_E = \Theta_{E0} - \Delta\Theta\, y^2 / R^2$

At equator:
(assume no zonal flow) $u(\phi=0)=0$ $\Omega R = 462$ m/s $M = \Omega R^2$

At latitude Φ: $M = (\Omega R \cos\phi + u) R \cos\phi$

$$u_M = \Omega R \frac{\sin^2\phi}{\cos\phi} \simeq \frac{\Omega}{R} y^2$$

Φ=30°N: u_M = 110 m/s

Calculate width of Hadley Cell:

Vertical shear: $$\frac{\partial u}{\partial z} = \frac{u_M - 0}{H} = \frac{\Omega}{RH} y^2$$

Thermal wind balance: $$2\Omega \sin\phi \frac{\partial u}{\partial z} = -\frac{g}{\Theta_0} \frac{\partial \Theta}{\partial y}$$

$$\frac{\partial \Theta}{\partial y} = \frac{-2\Omega^2 \Theta_0}{R^2 g H} y^3 \qquad \Theta_M = \Theta_{M0} - \frac{\Omega^2 \Theta_0}{2 R^2 g H} y^4$$

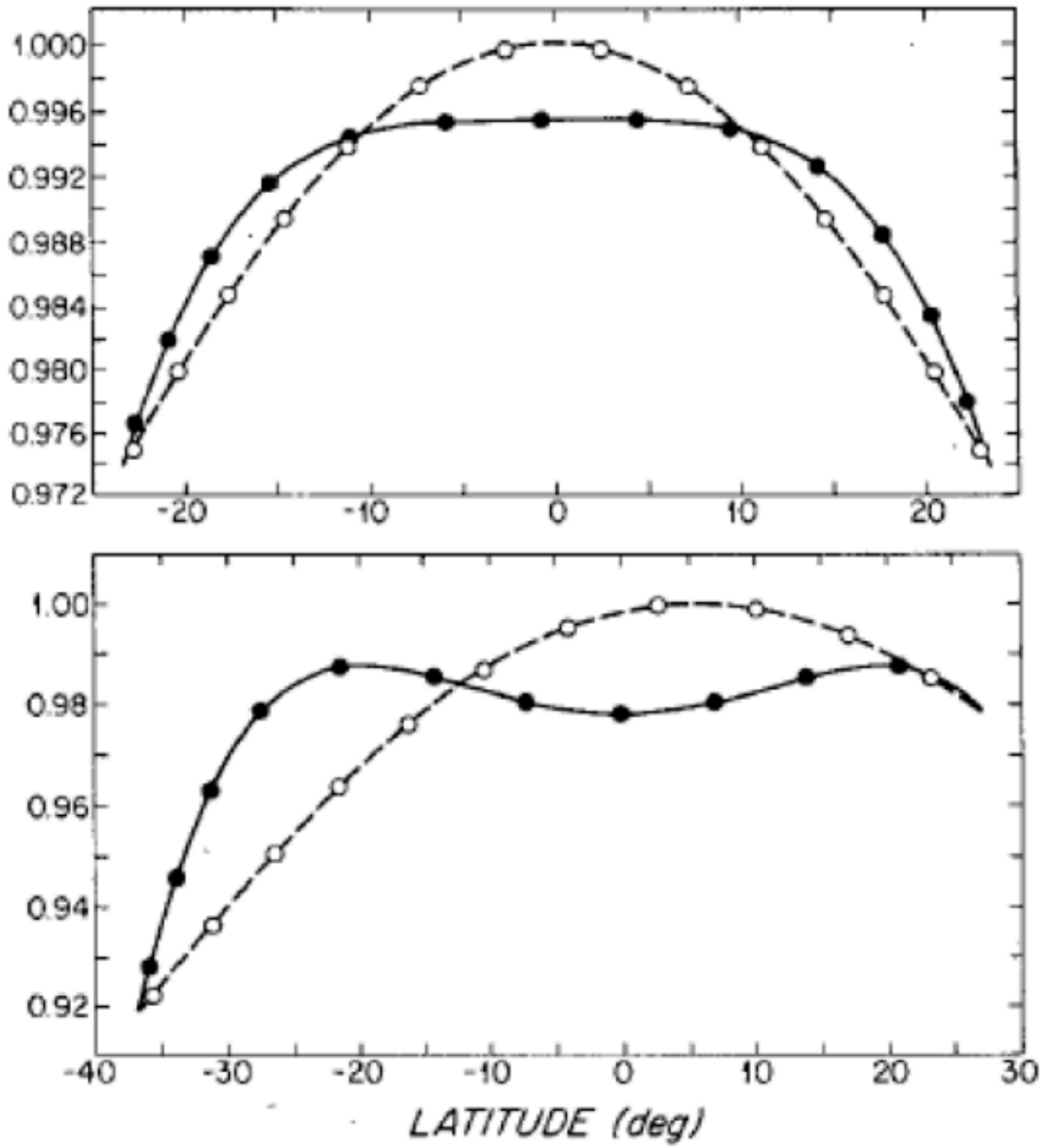
$$\int_0^{y_p} \Theta \, dy = \int_0^{y_p} \Theta_E \, dy \qquad \Theta_M(y_p) = \Theta_E(y_p) \qquad y_p = \left(\frac{\Delta \Theta \, g H 5}{\Omega^2 \Theta_0 3} \right)^{1/2}$$

$$\Theta_{E0} - \Theta_{M0} = \frac{\Delta \Theta^2 g H 5}{R^2 \Omega^2 \Theta_0 18}$$

$y_p =$ 3000 km or 30°

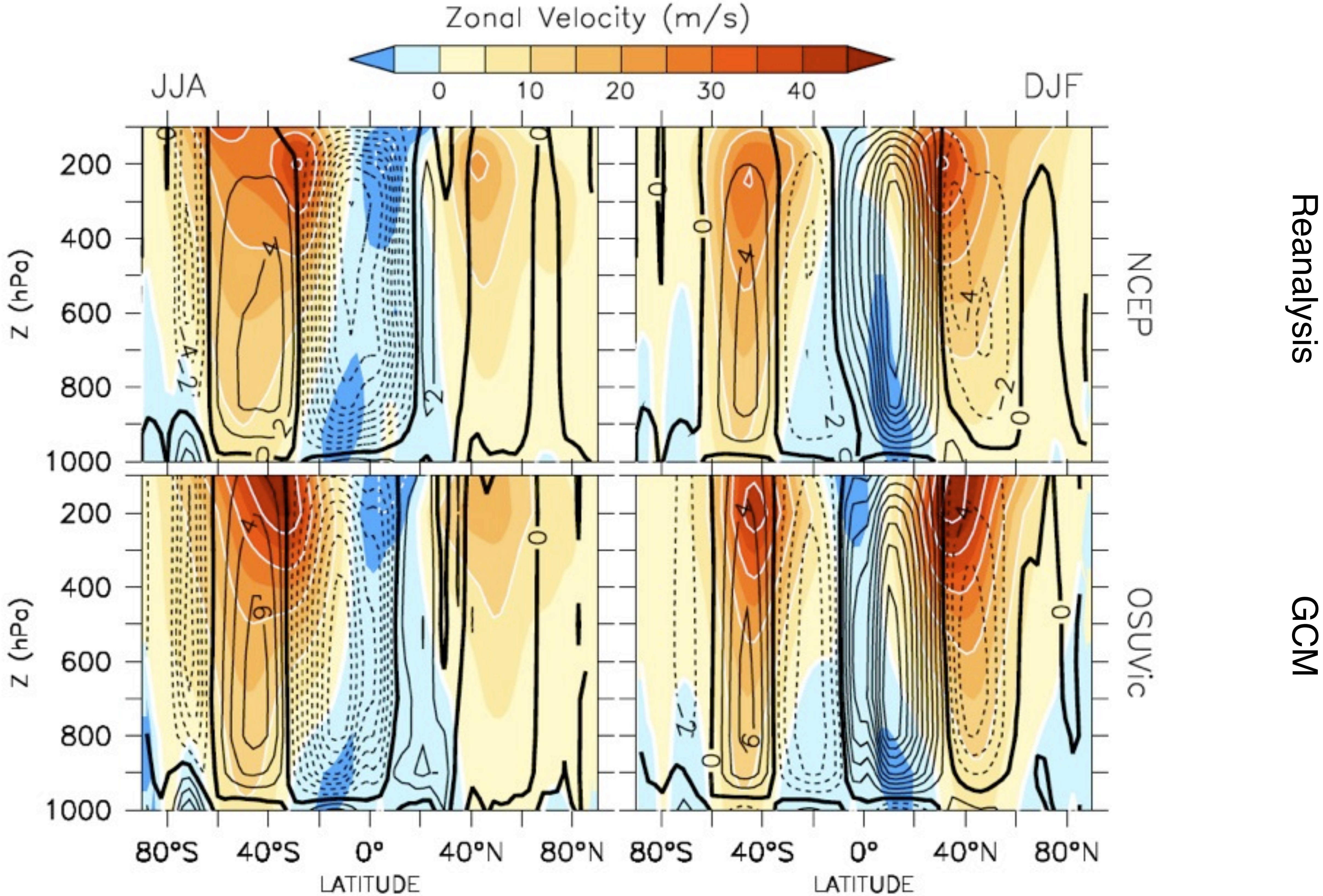
Width is in good agreement with observations but circulation is much too slow.

- Lindzen and Hou (1988) showed that the circulation is improved by considering the seasonal cycle



- annual mean conditions lead to weak heating
- seasonal heating is much stronger if maximum heating is shifted slightly away from equator

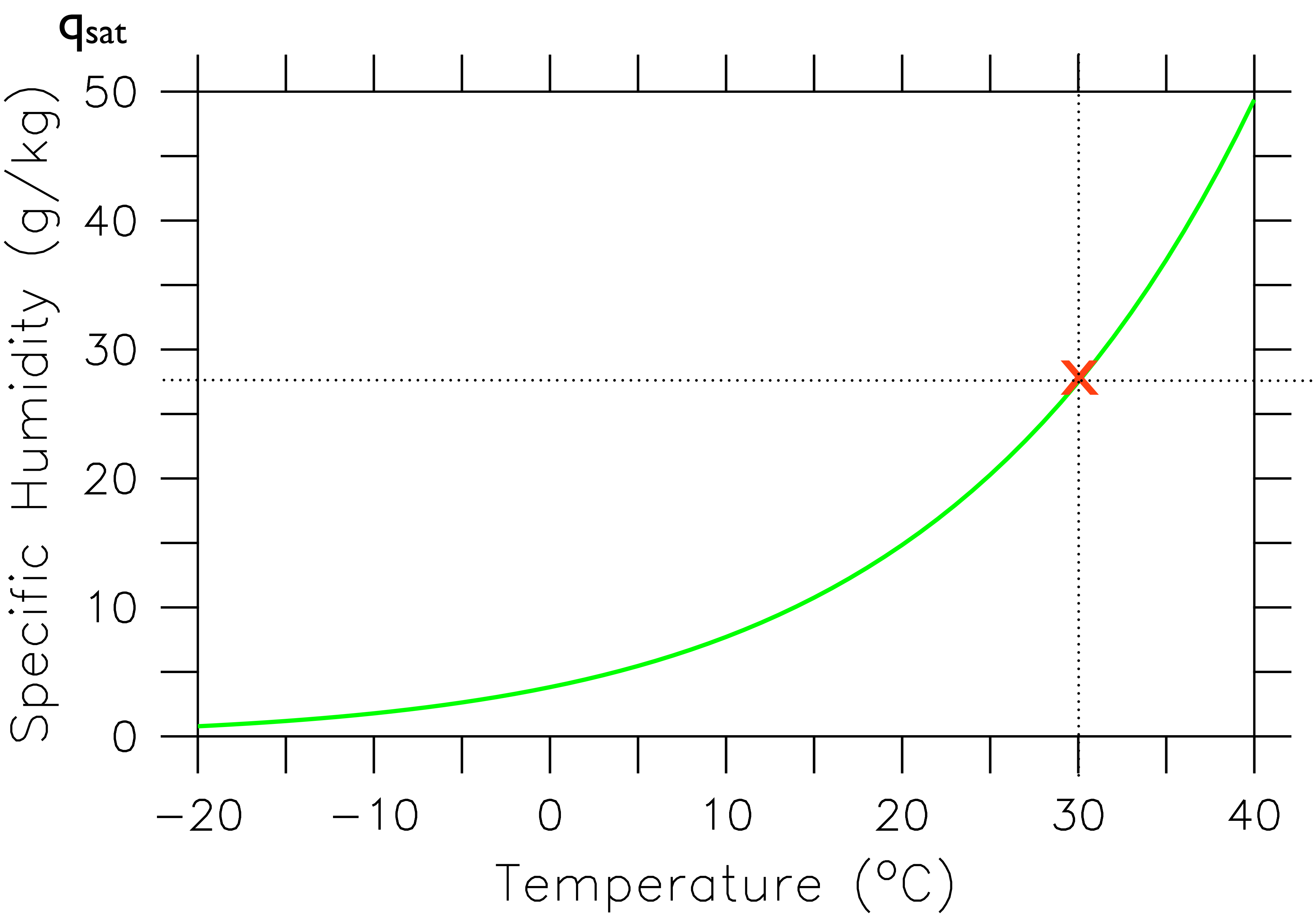
Hadley Circulation and Zonal Wind

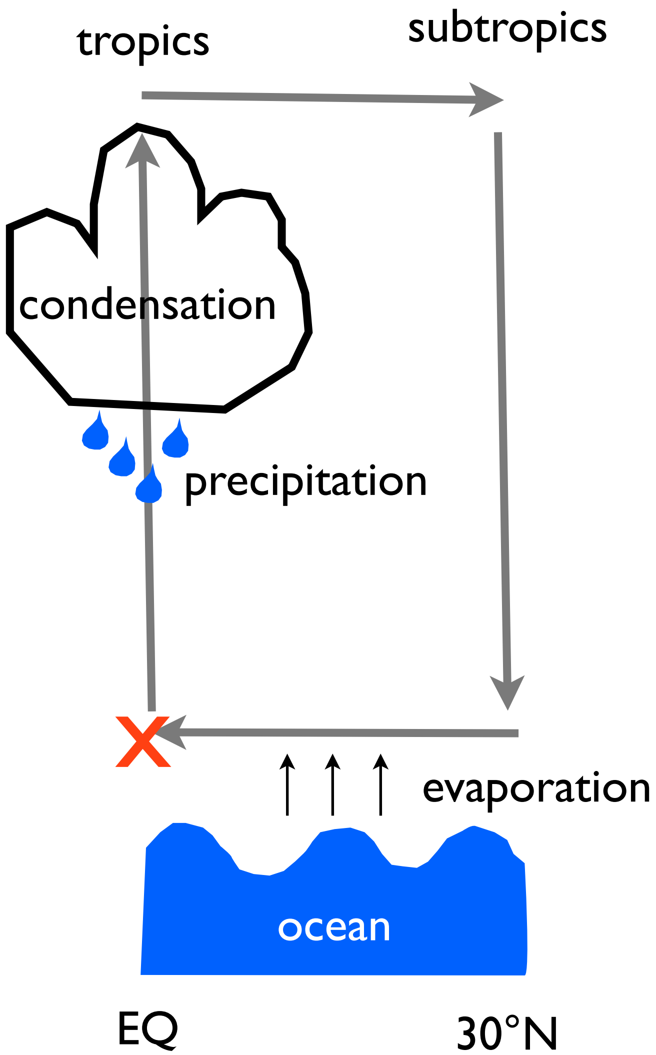


Schmittner et al. (2011)

Let's follow an air parcel along the Hadley cell.

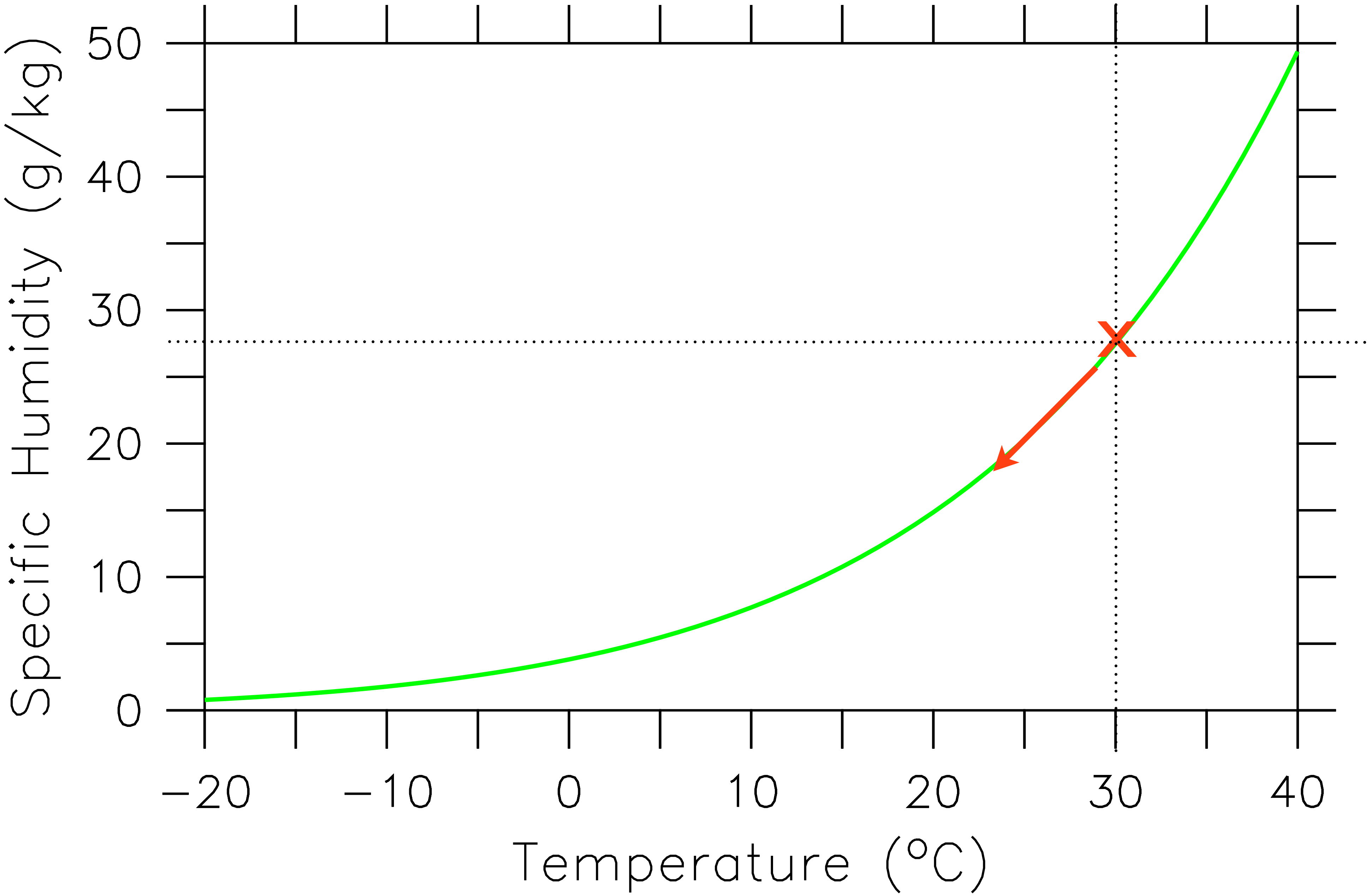
1) We start at the surface in the ITCZ. Over the ocean the air is saturated (RH = 100%)

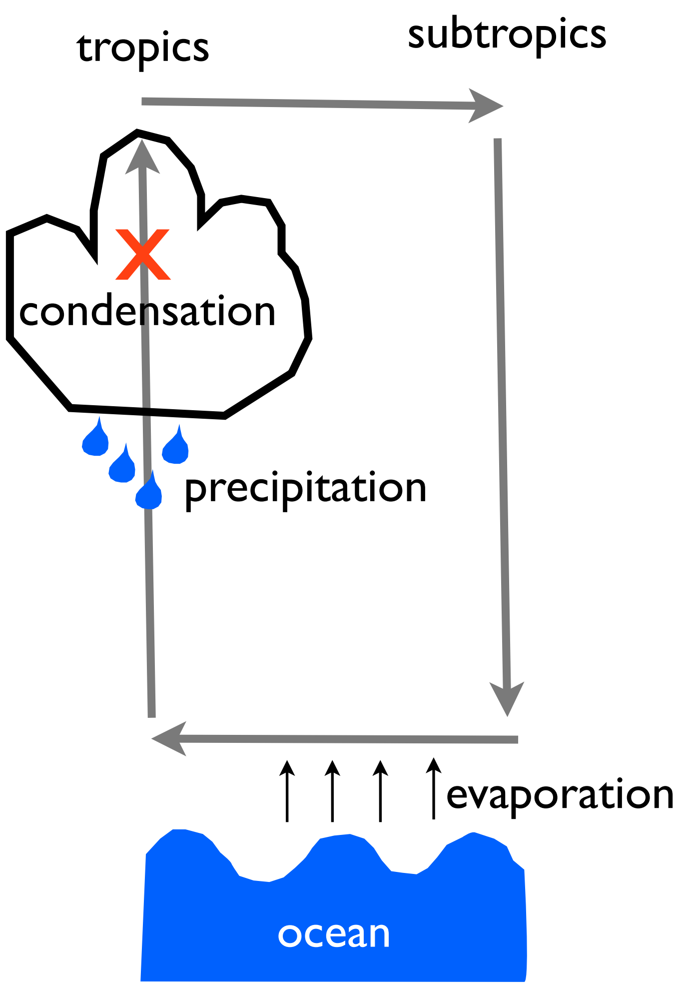




Let’s follow an air parcel along the Hadley cell.

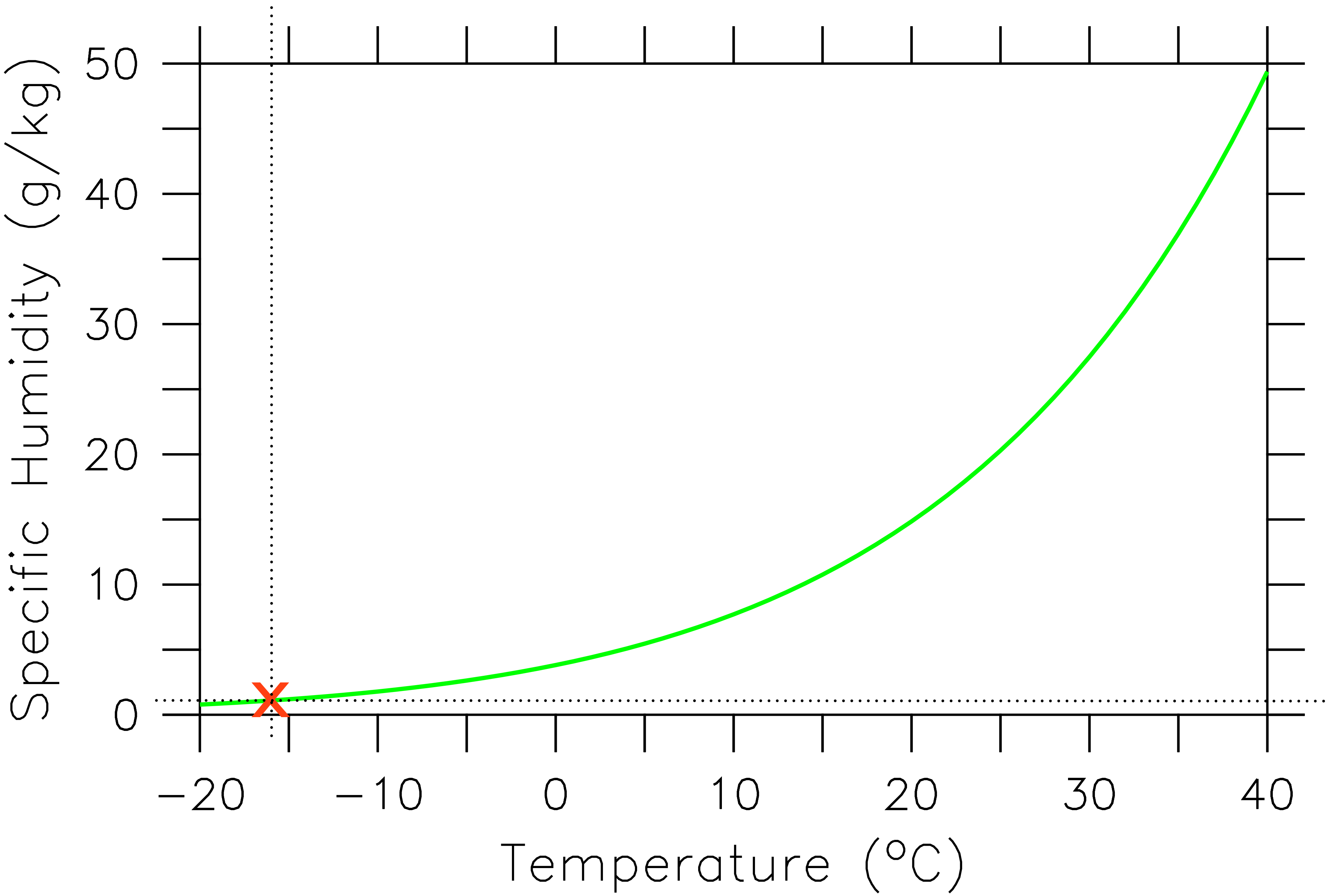
2) It raises to higher altitudes, loosing water through condensation (RH = 100%)
clouds form, precipitation (rainfall) occurs

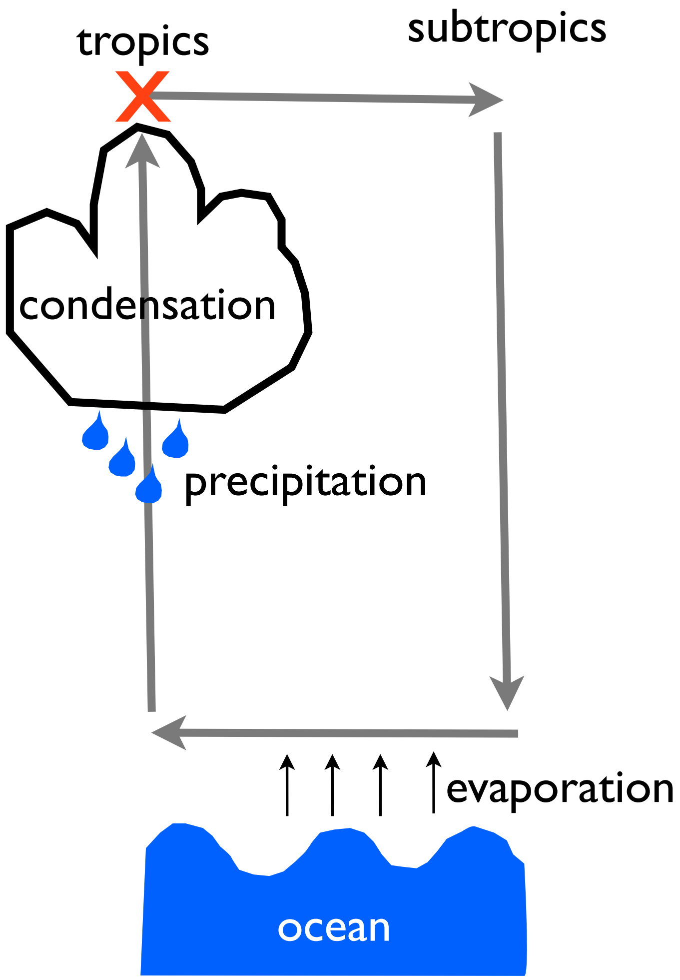




Let’s follow an air parcel along the Hadley cell.

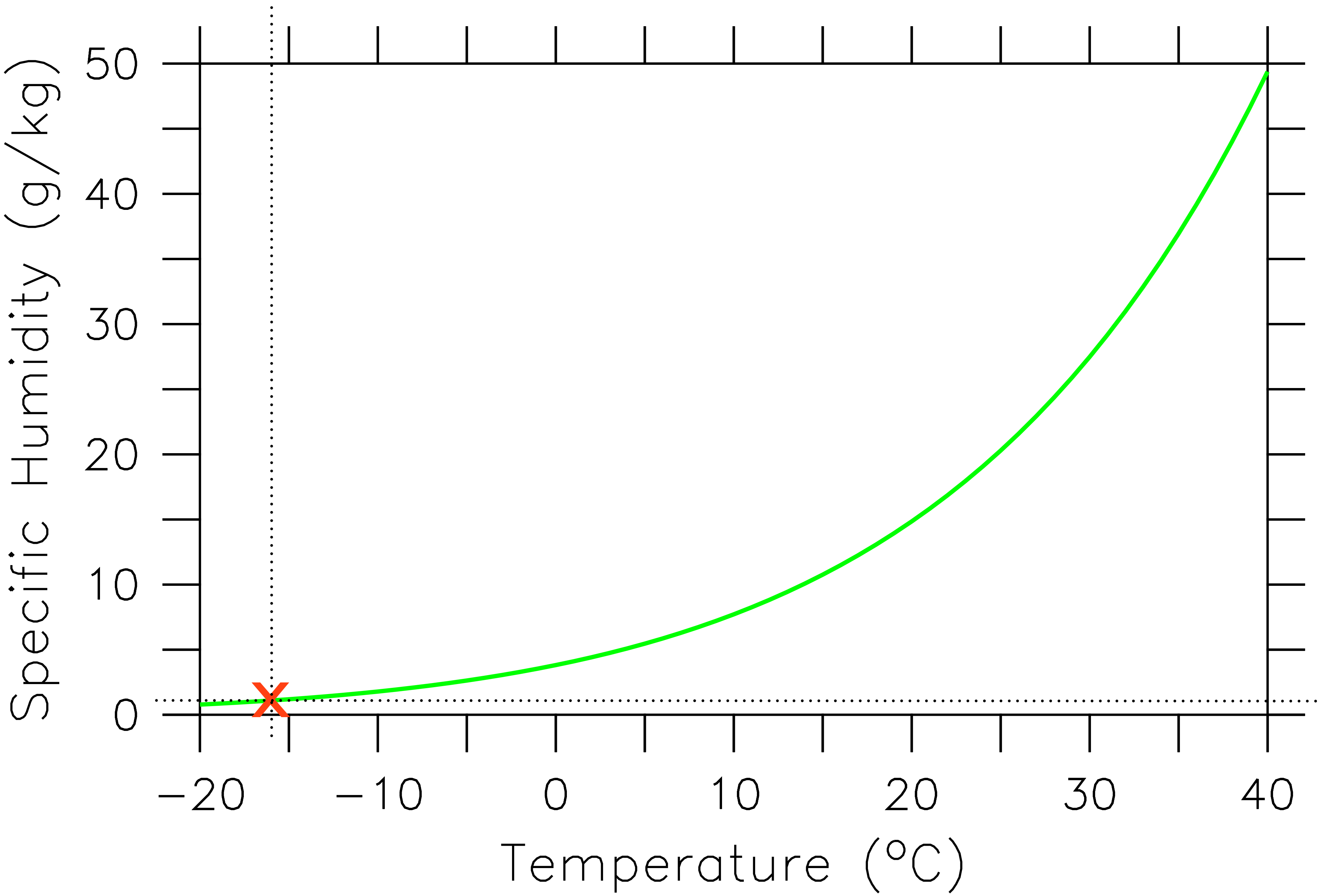
3) At high elevation it is cold and the air is dry (low specific humidity, but still high relative humidity)

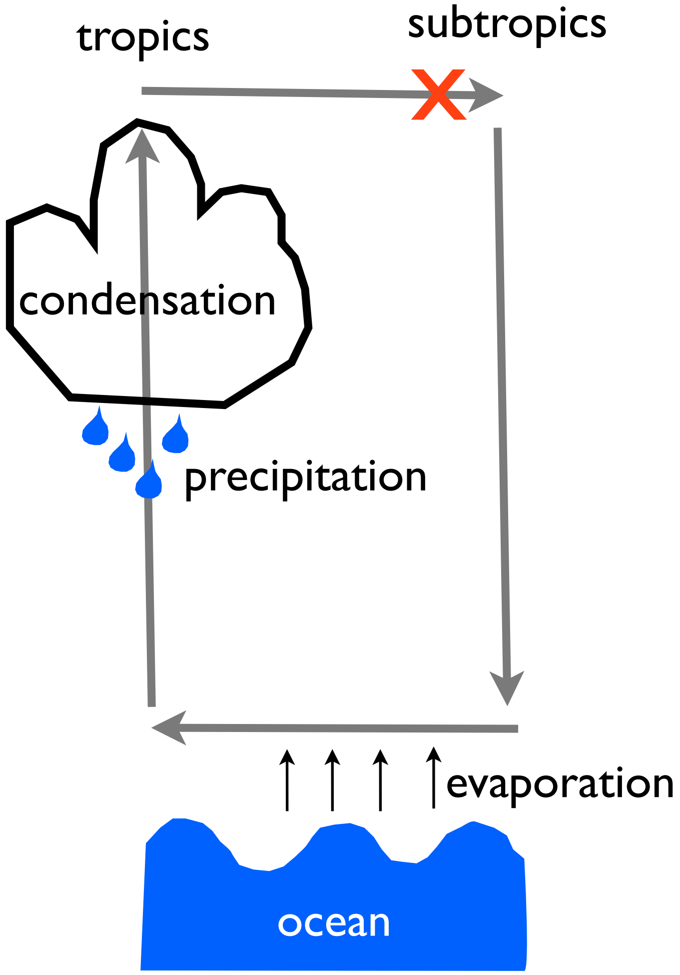




Let's follow an air parcel along the Hadley cell.

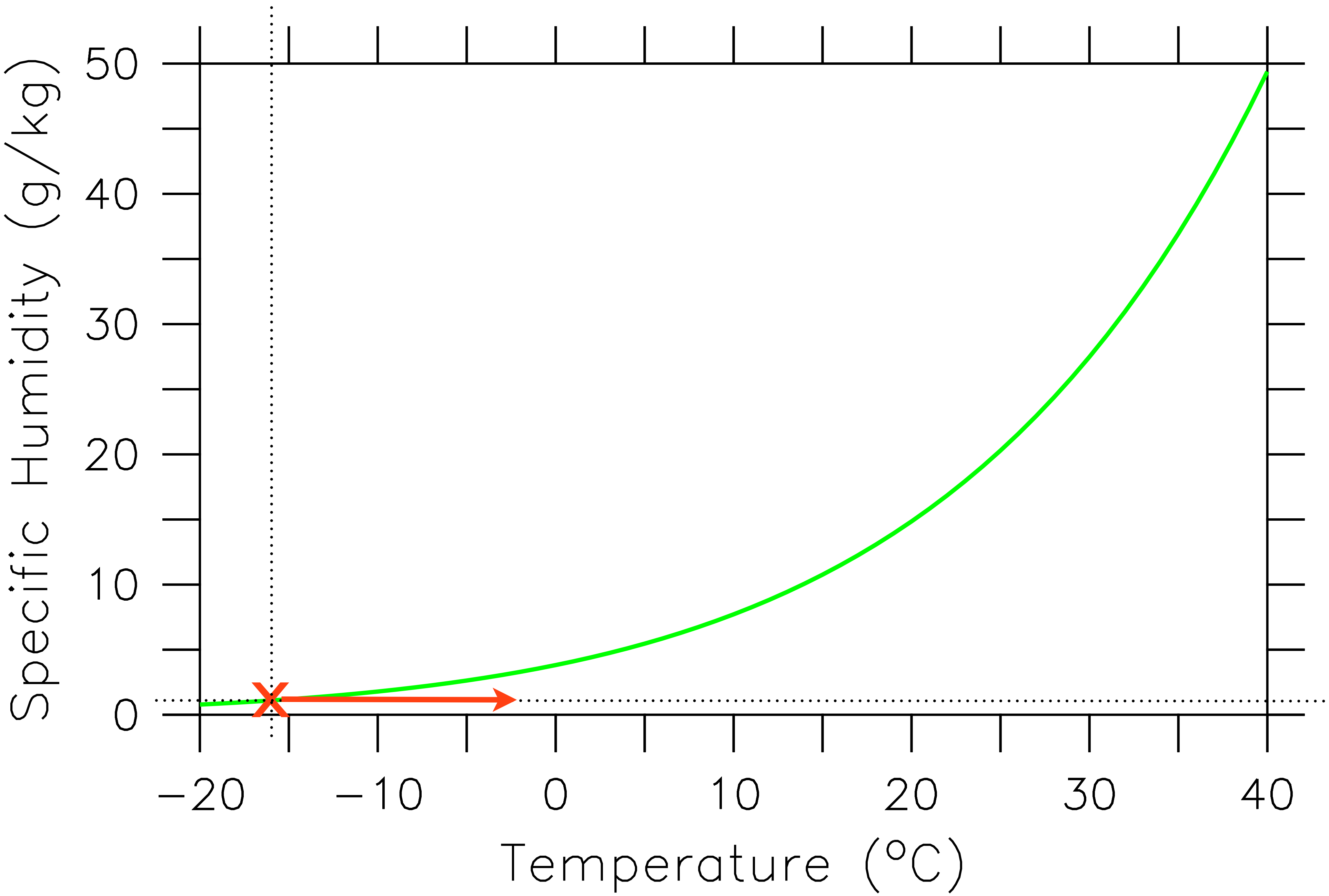
4) As the air moves toward the subtropics it stays cold and dry

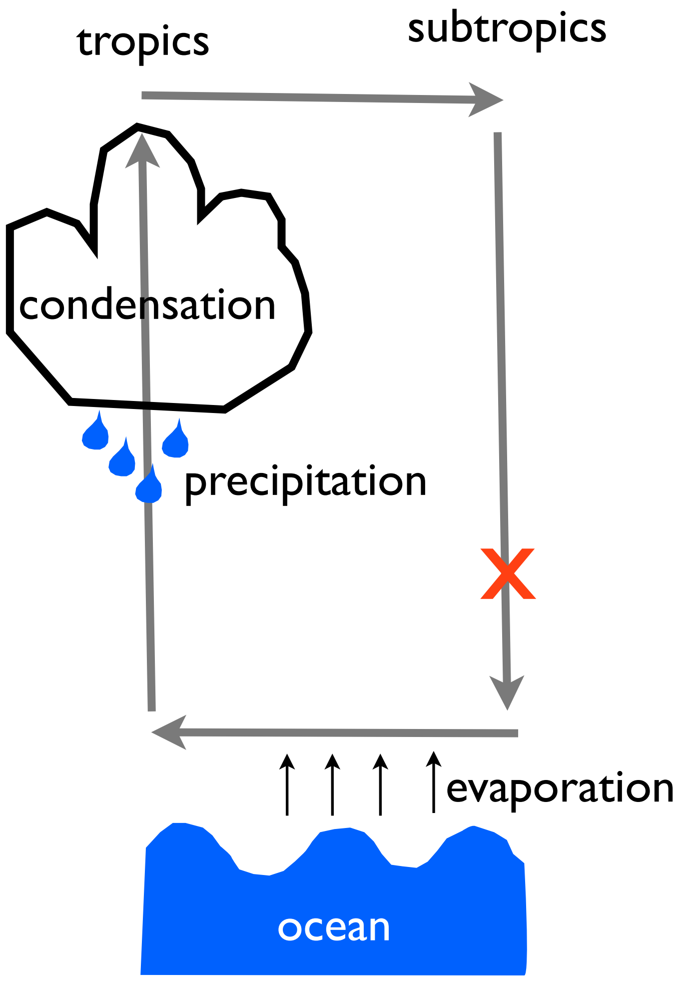




Let's follow an air parcel along the Hadley cell.

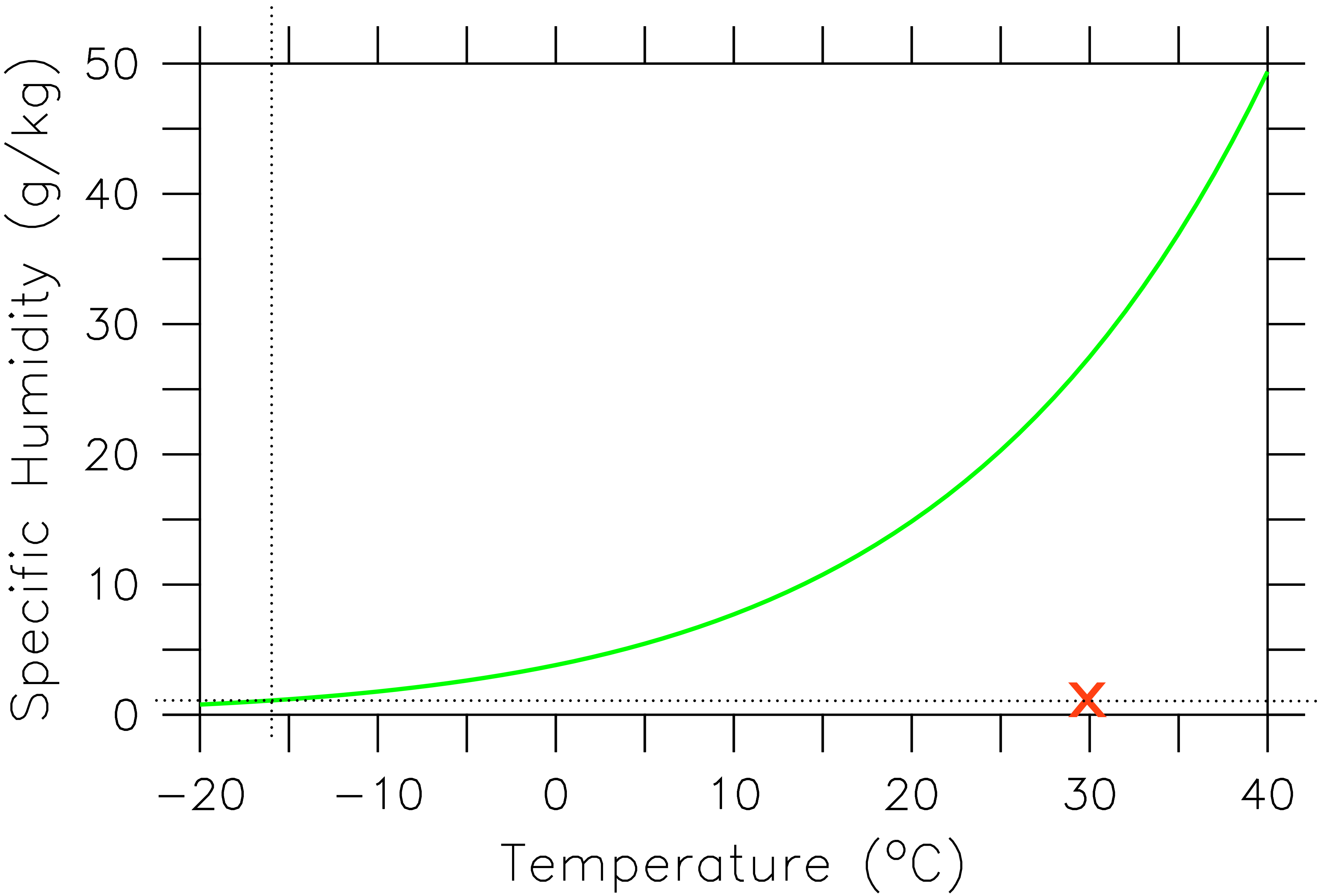
5) As the air sinks in the subtropics its temperature increases but the amount of water vapor does not increase. Thus, the relative humidity decreases.

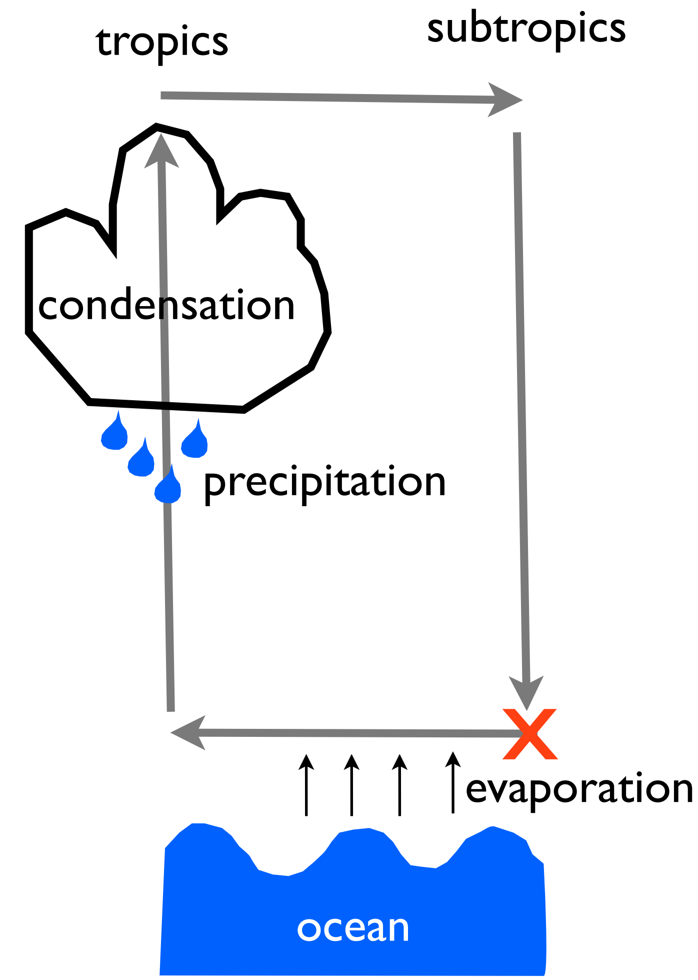




Let's follow an air parcel along the Hadley cell.

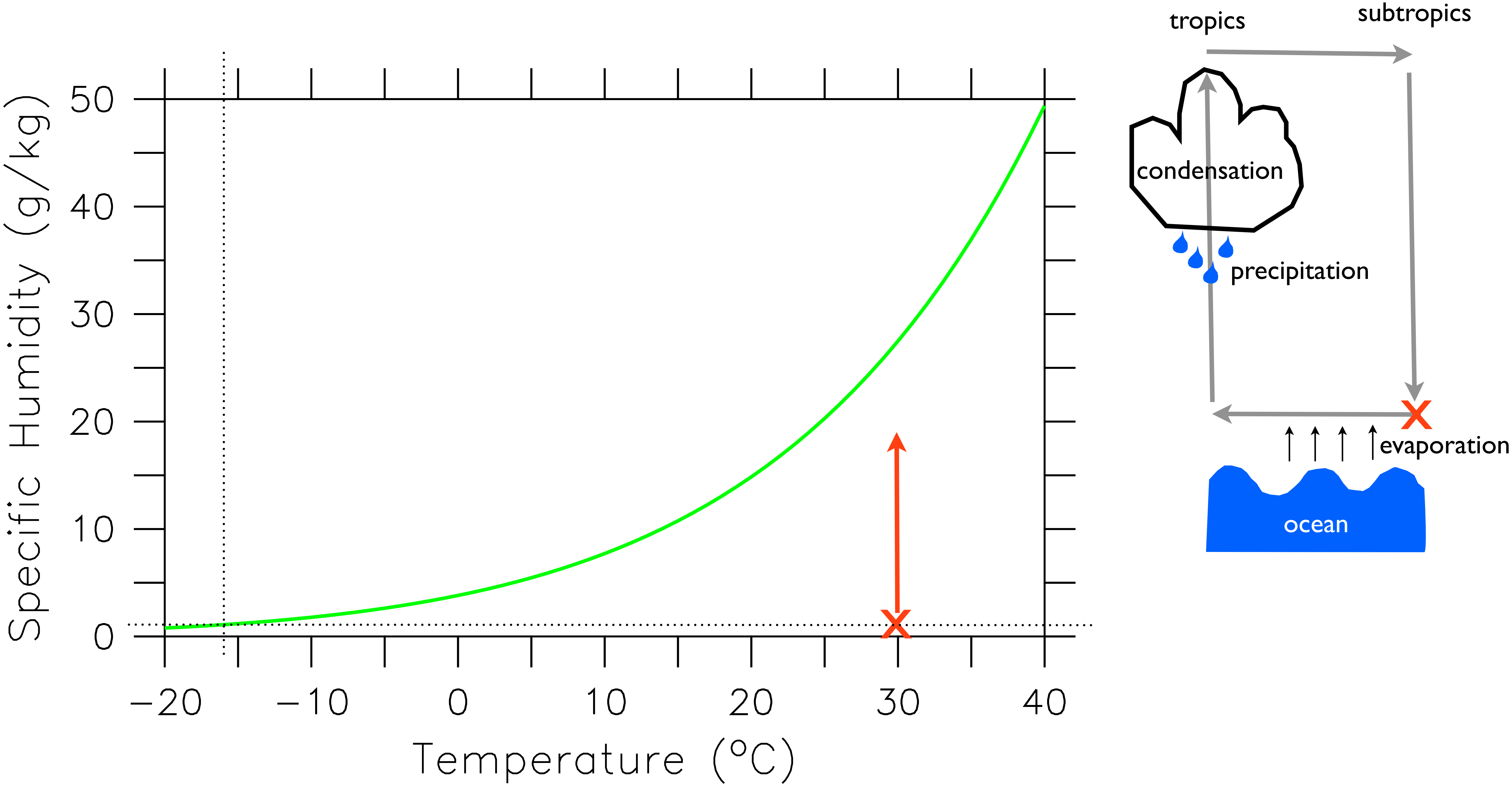
6) When the air arrives at the surface it has warmed but now it has a very low relative humidity.





Let's follow an air parcel along the Hadley cell.

7) On its way back towards the equator evaporation leads to an increase its water vapor content and relative humidity.



Let's follow an air parcel along the Hadley cell.

8) Back at the ITCZ the air is is saturated again.