Atmospheric and oceanic circulations

PG Lectures, Autumn 2017

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Aim and learning outcomes

Provide new PhD students in SPAT with an overview of why and how the atmosphere and ocean circulate and the implications for Earth's climate

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Provide new PhD students in SPAT with an overview of why and how the atmosphere and ocean circulate and the implications for Earth's climate

1. Describe the **radiative drivers** of atmospheric and oceanic circulations
2. Describe the **structure of Earth's winds** (vs latitude and height)
3. Understand angular momentum conservation and implications for the **tropical Hadley cell**
4. Physical origins of **Ekman layers** and ocean gyres
5. Baroclinic instability in atmosphere and oceans, **Rossby number**, geostrophic balance
6. Atmospheric moisture transport: Influence on Earth's **water cycle** and thermohaline circulation

Structure of the week

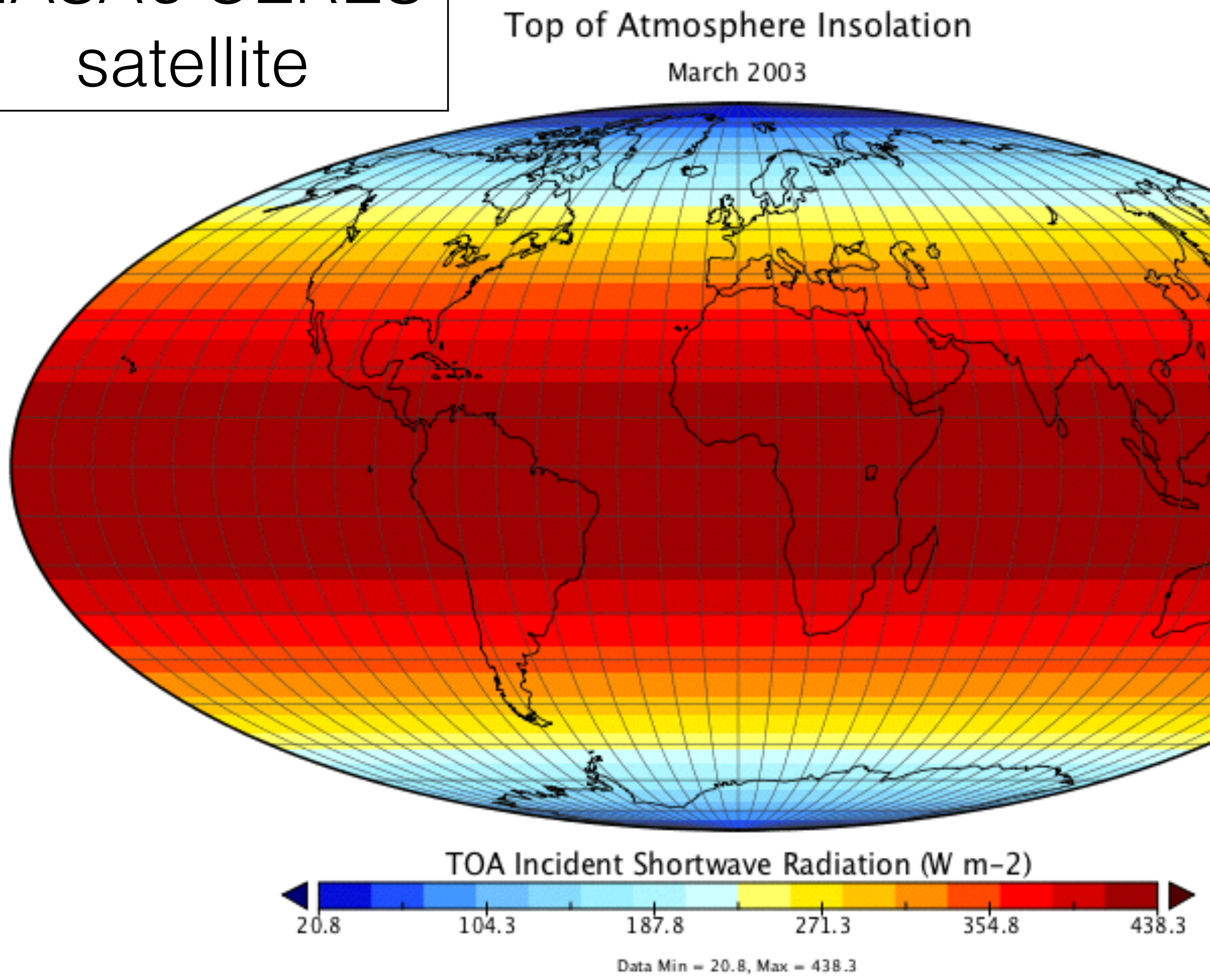
- **Monday:**
  - *attendance register*
  - Earth's radiative budget
  - Observed climate: temperature and winds
  - Atmosphere: Hadley cell and angular momentum
  - Ocean: Ekman layers, gyres

- **Tuesday:**
  - Baroclinic instability in the atmosphere, ocean, and classroom (tank experiment)
  - Rossby number, geostrophic balance
  - Impact of atmospheric circulation: Earth's water cycle

- **Friday:** 3 groups present & discuss problem-set solutions

Phenomena: Earth's radiative balance — the circulation driver

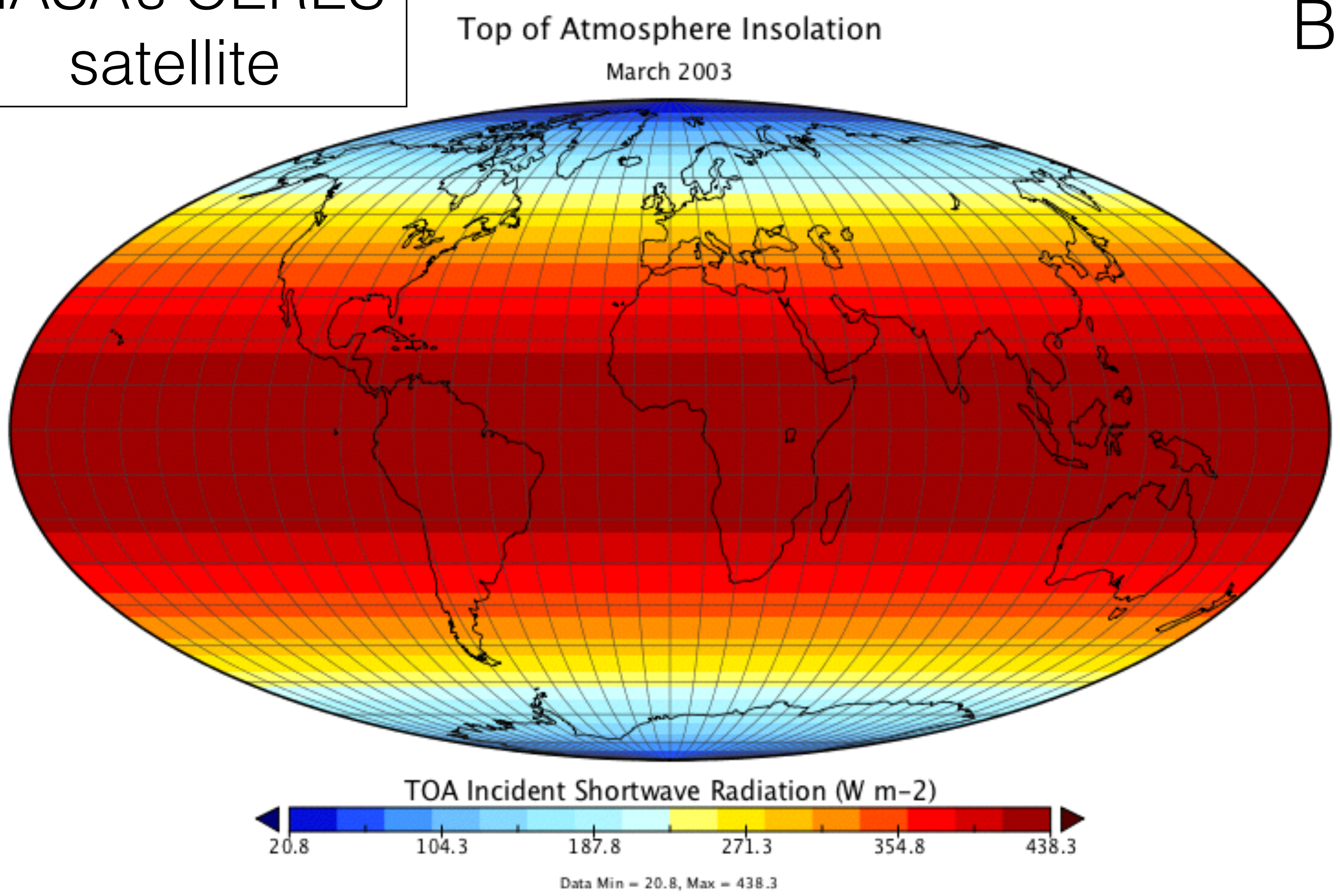
NASA's CERES satellite



solar energy received

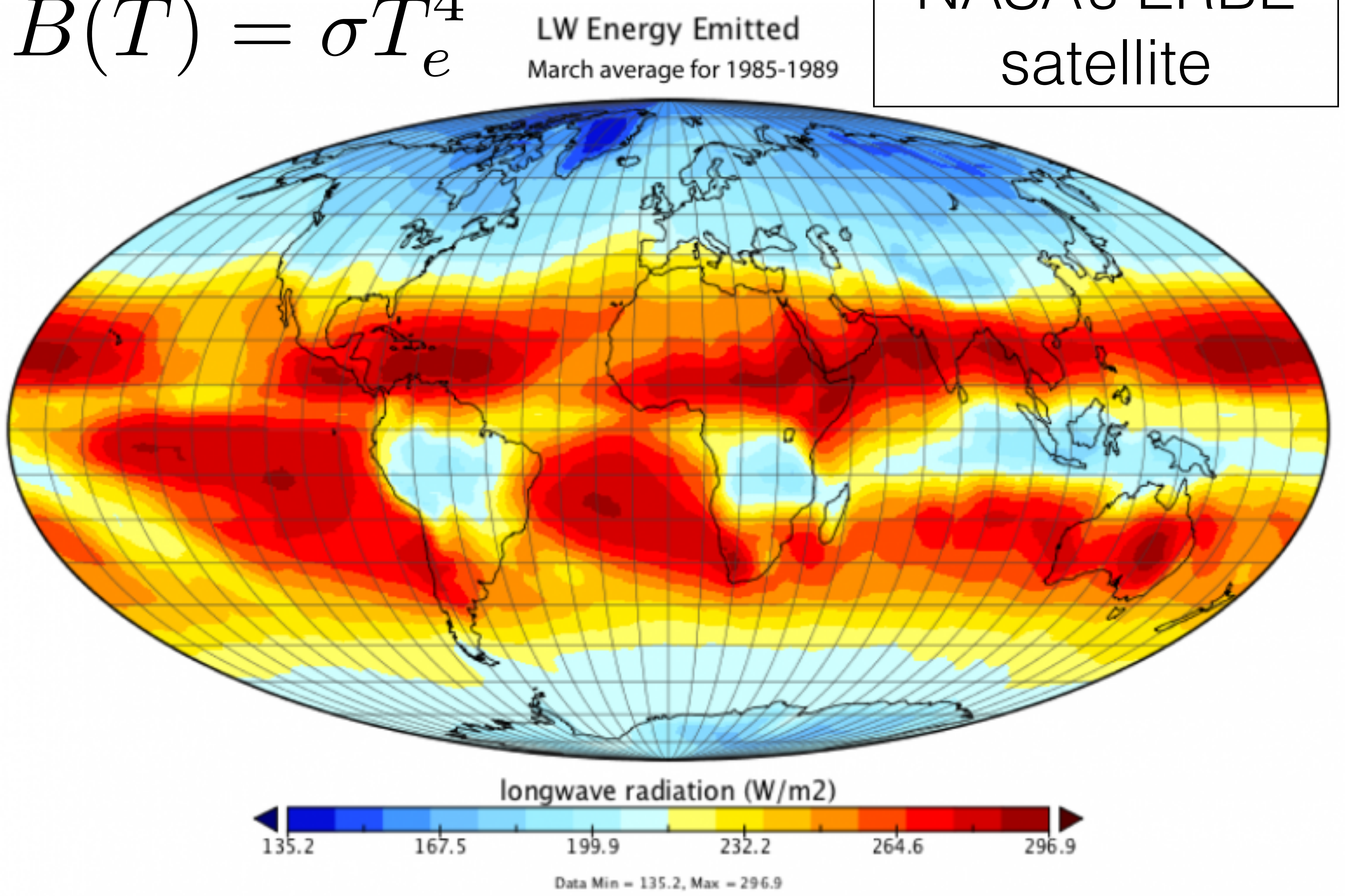
Phenomena: Earth's radiative balance — the circulation driver

NASA's CERES satellite



Stefan-Boltzmann Law: $B(T) = \sigma T_e^4$

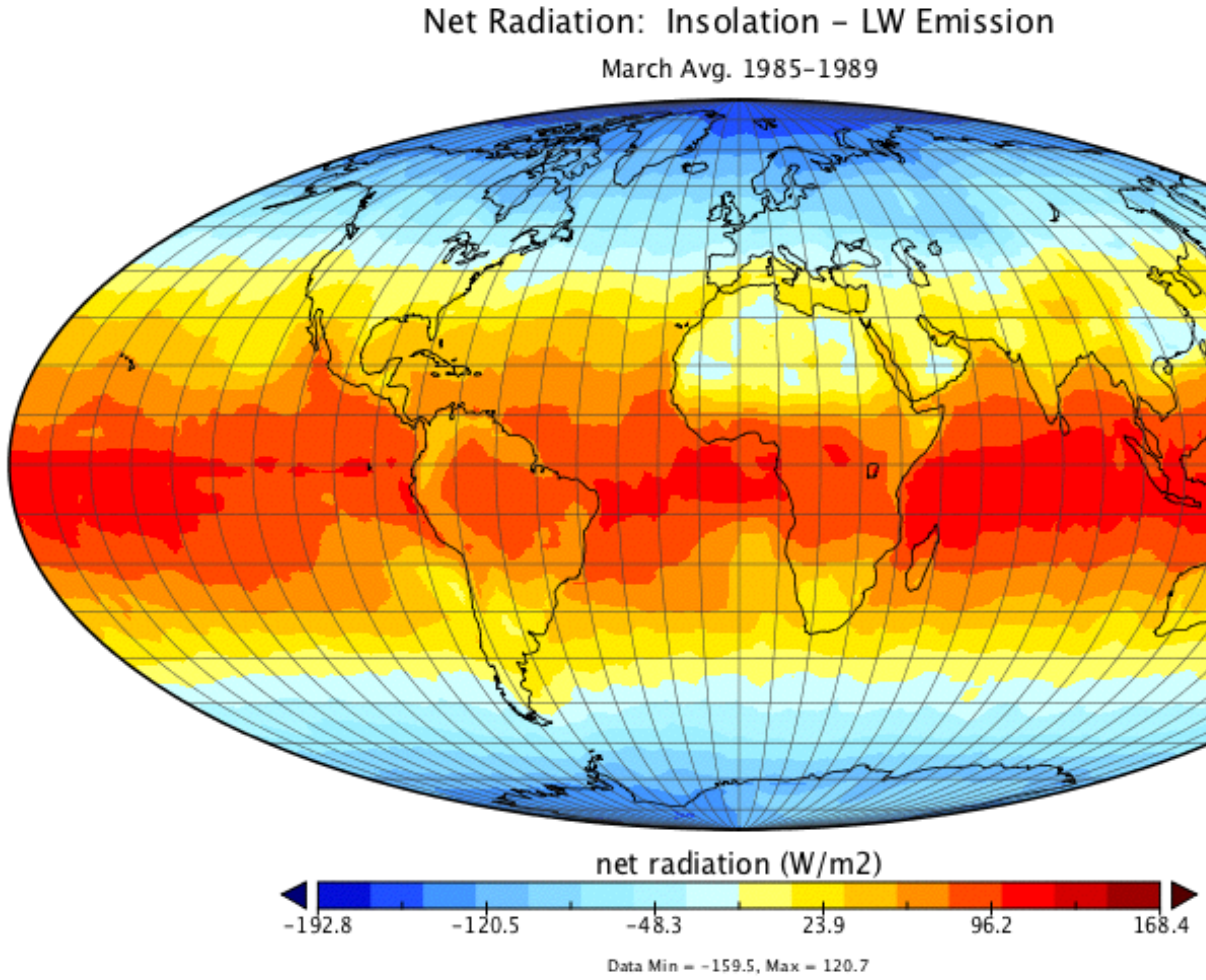
NASA's ERBE satellite

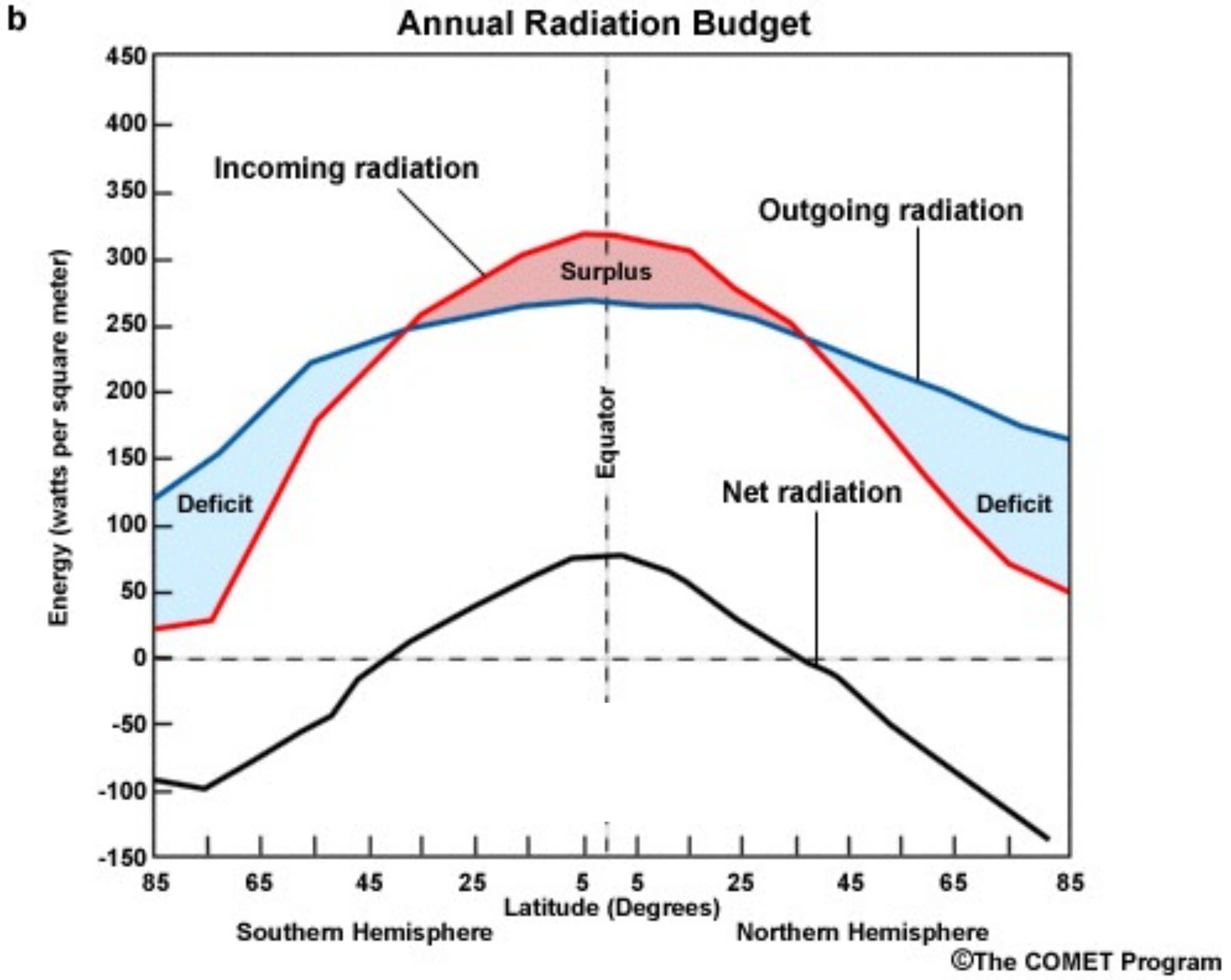


solar energy received

terrestrial energy emitted

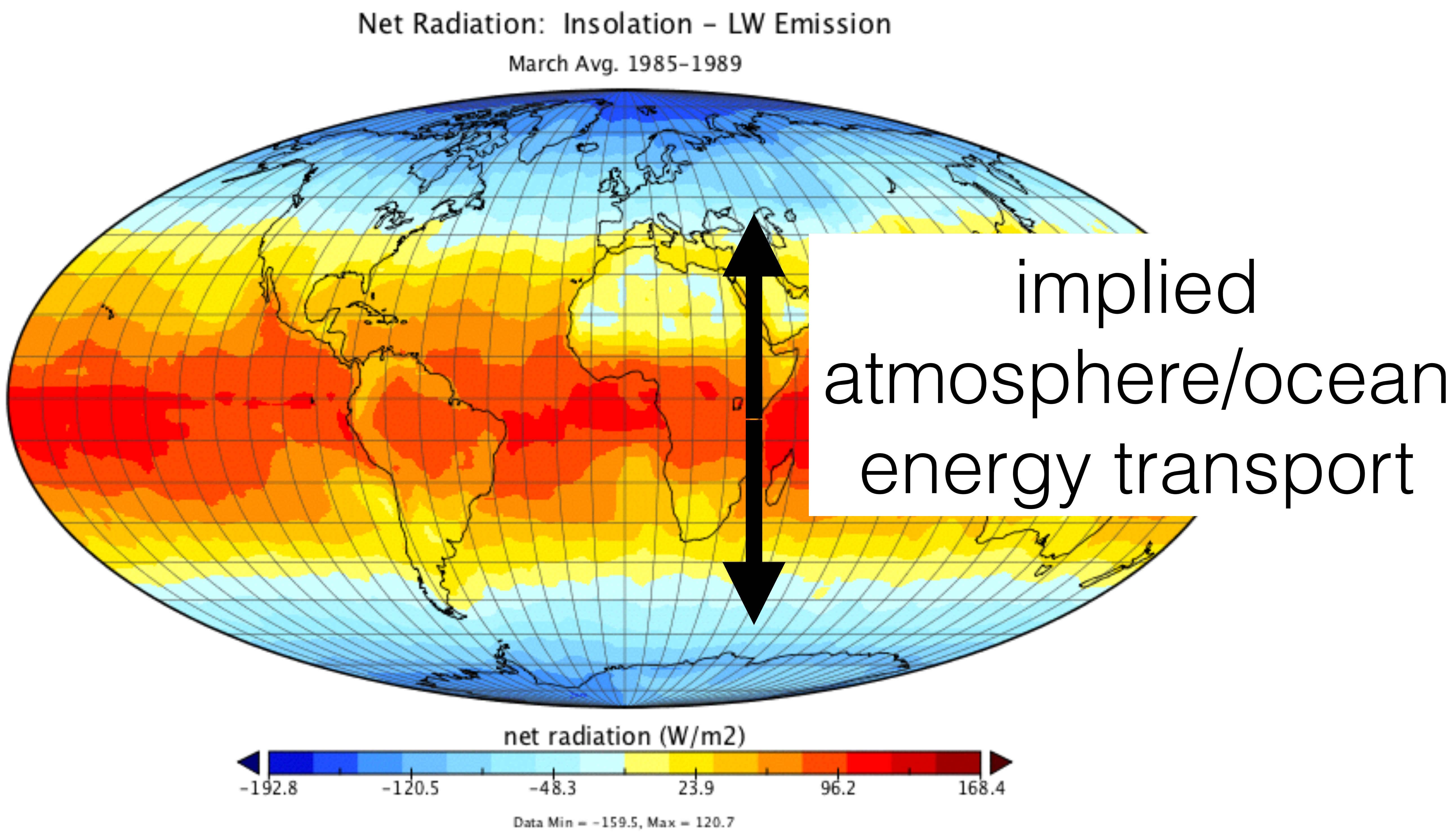
Phenomena: Earth's radiative balance — the circulation driver

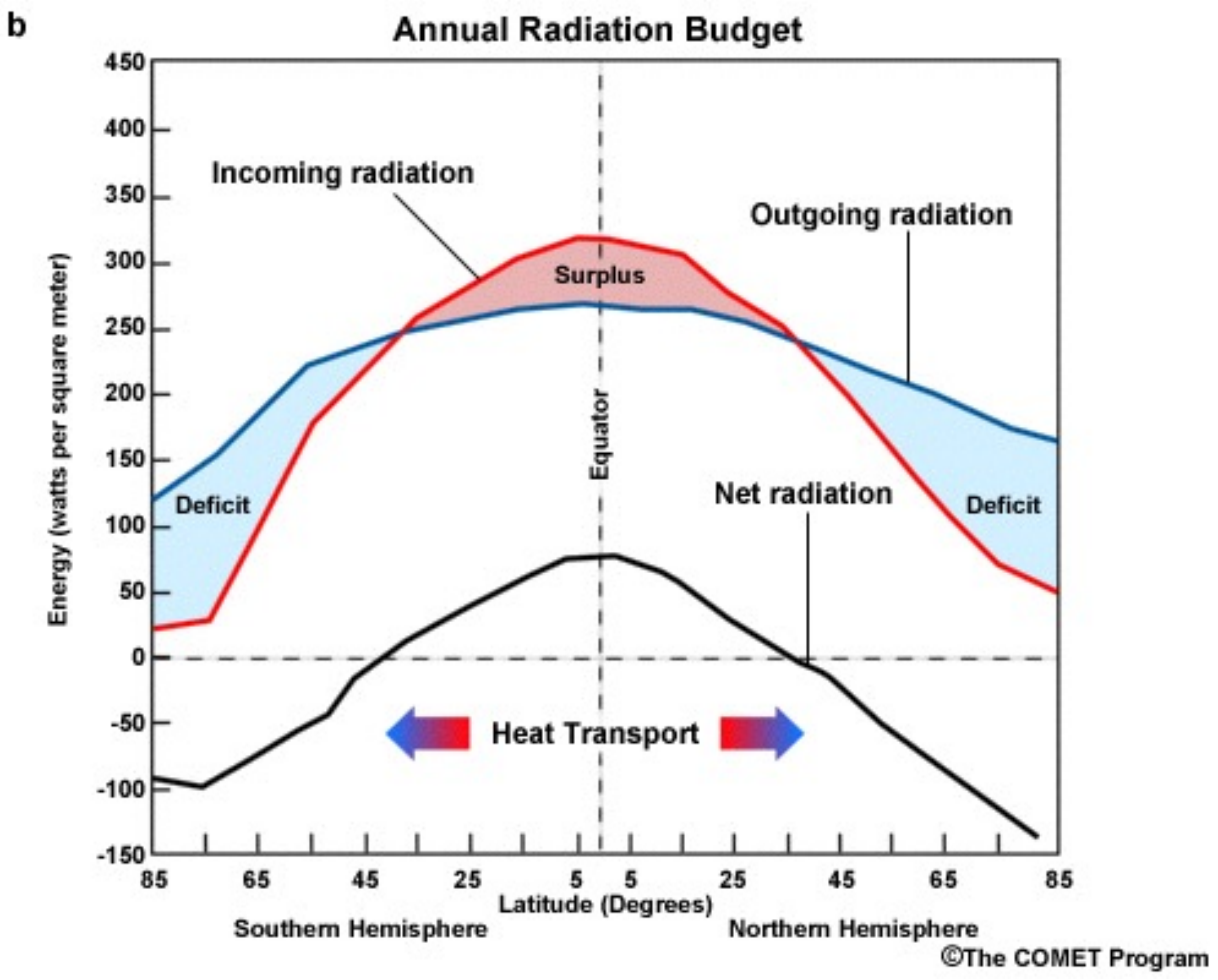




solar (SW) received minus terrestrial (LW) emitted

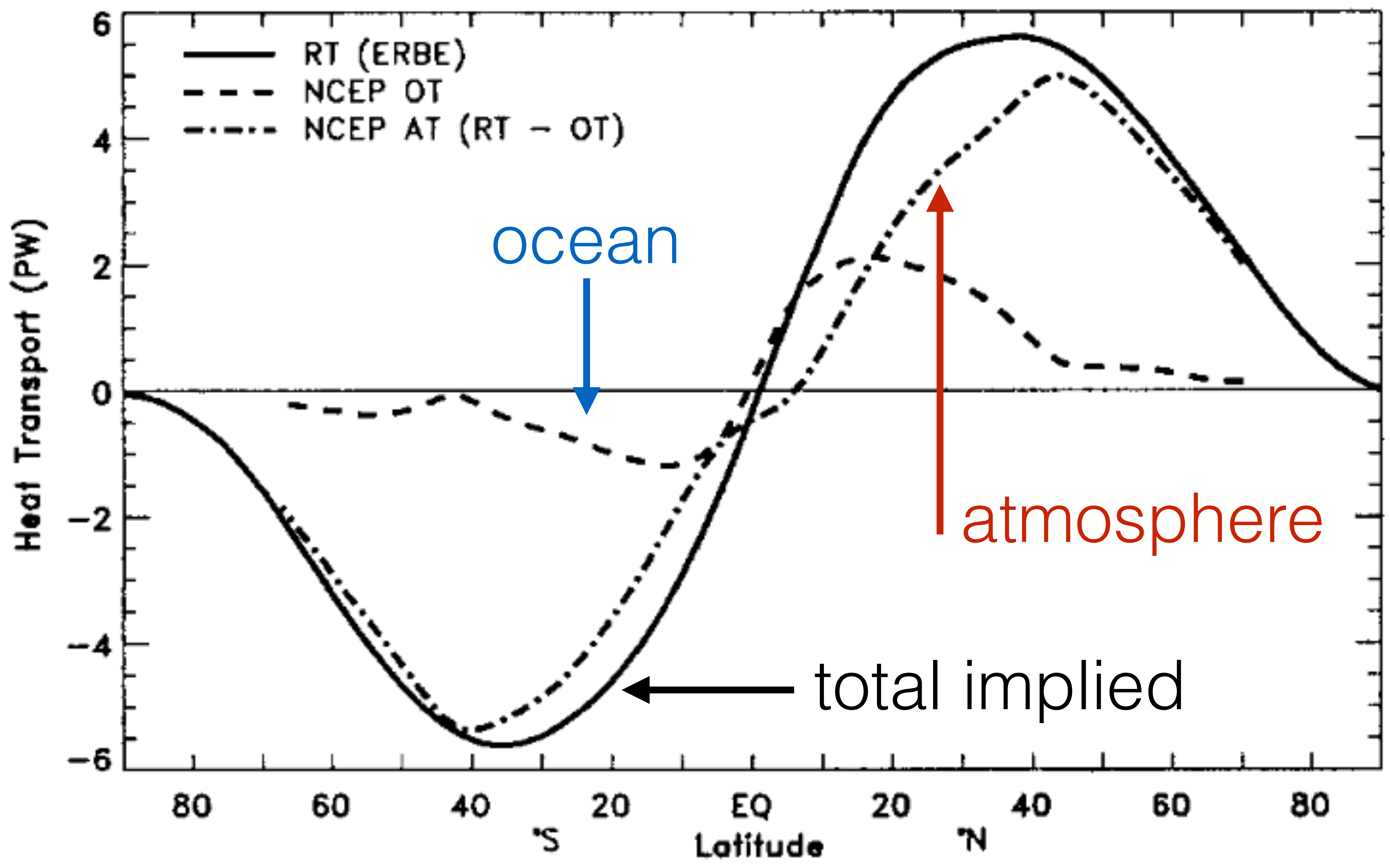
Phenomena: Earth's radiative balance — the circulation driver





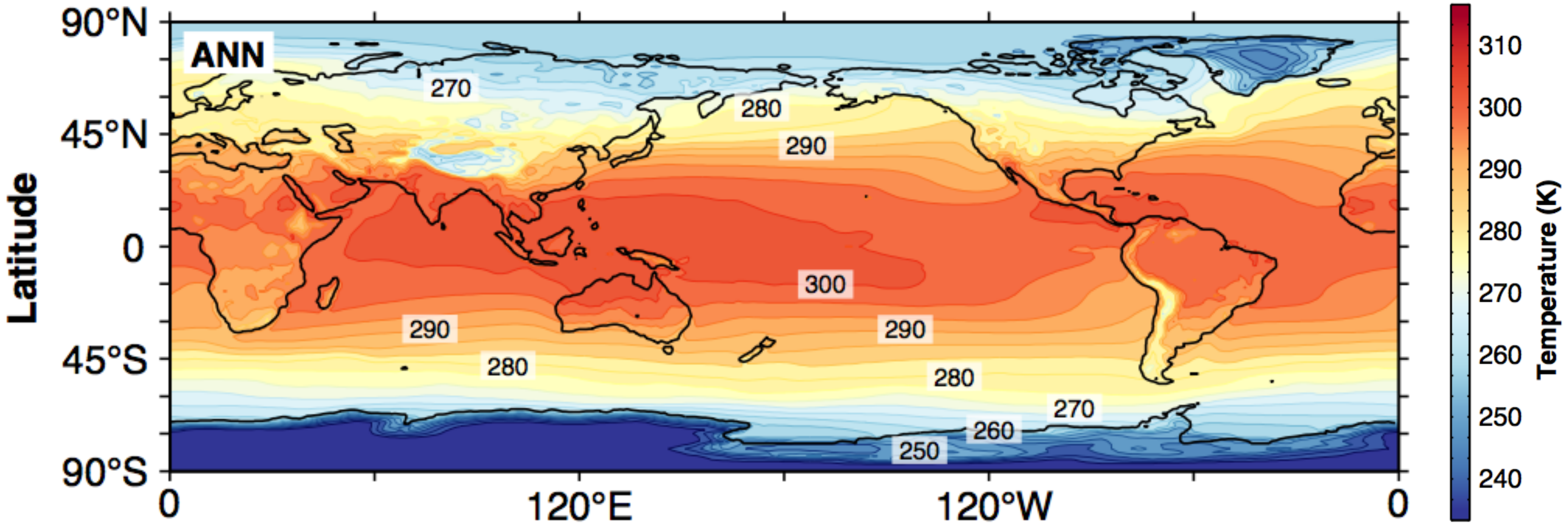
solar (SW) received minus terrestrial (LW) emitted

Phenomena: Poleward energy transport by atmosphere and oceans



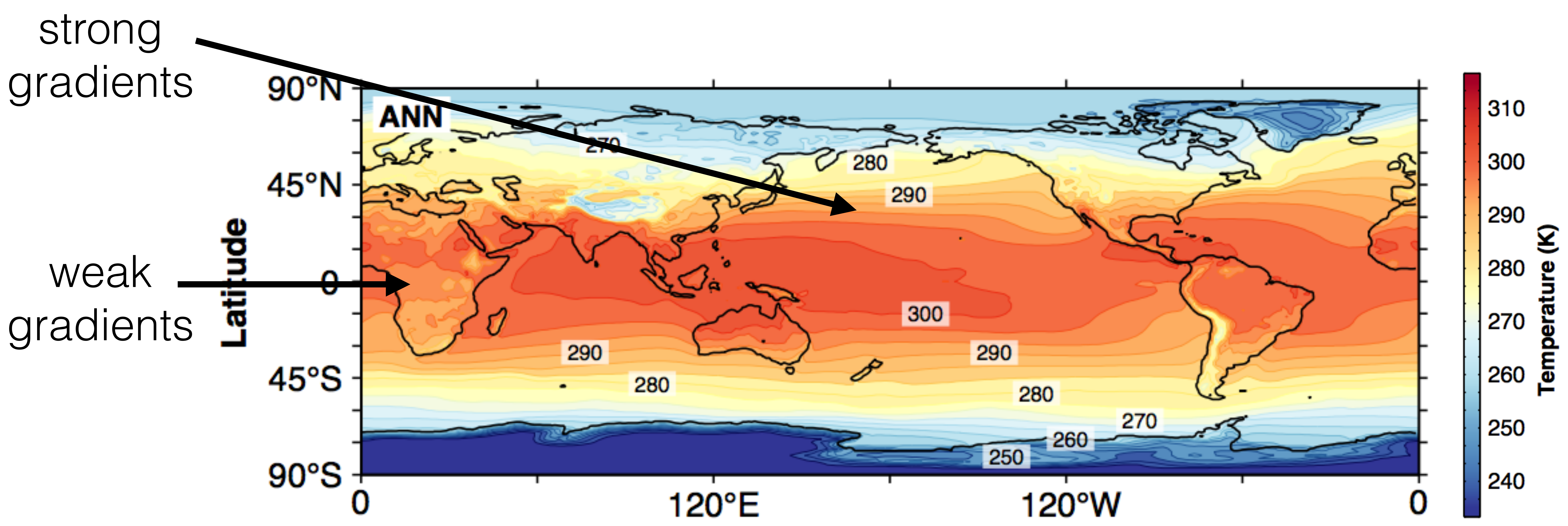
Trenberth & Caron (2001)

Phenomena: Surface temperature <-> pressure gradients -> circulations



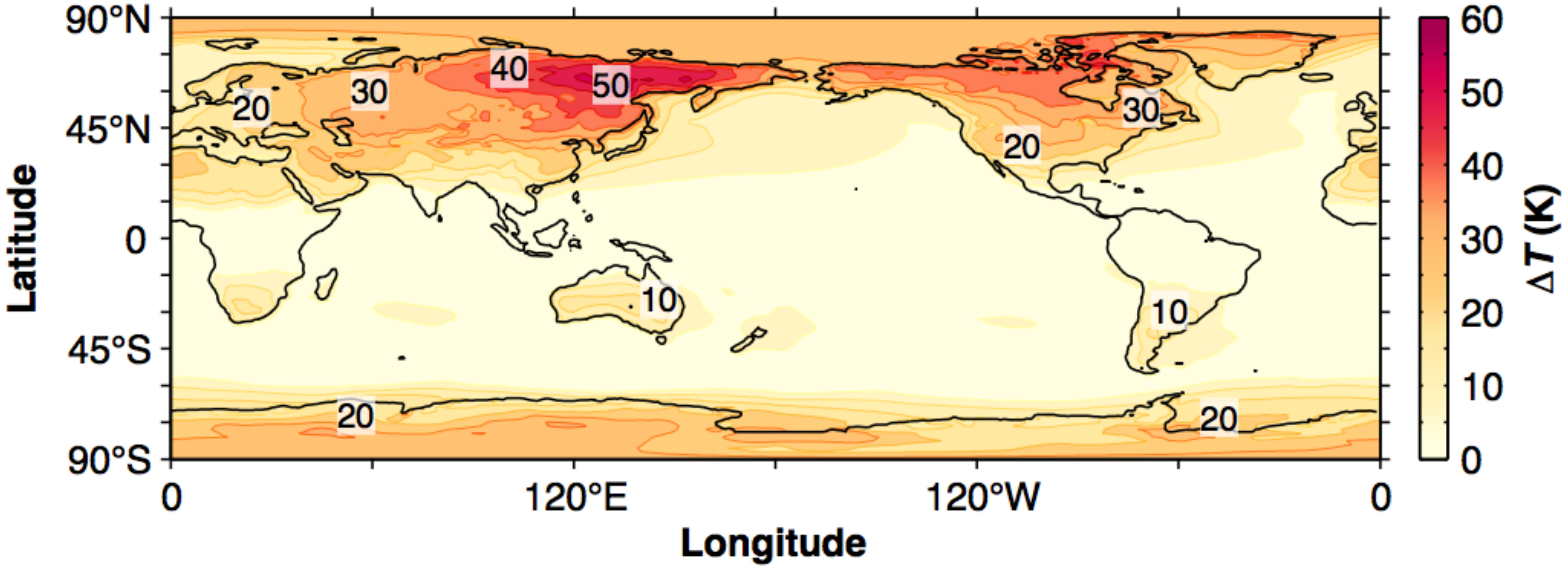
from Schneider's "Physics of Earth's Climate"

Phenomena: Surface temperature <-> pressure gradients -> circulations



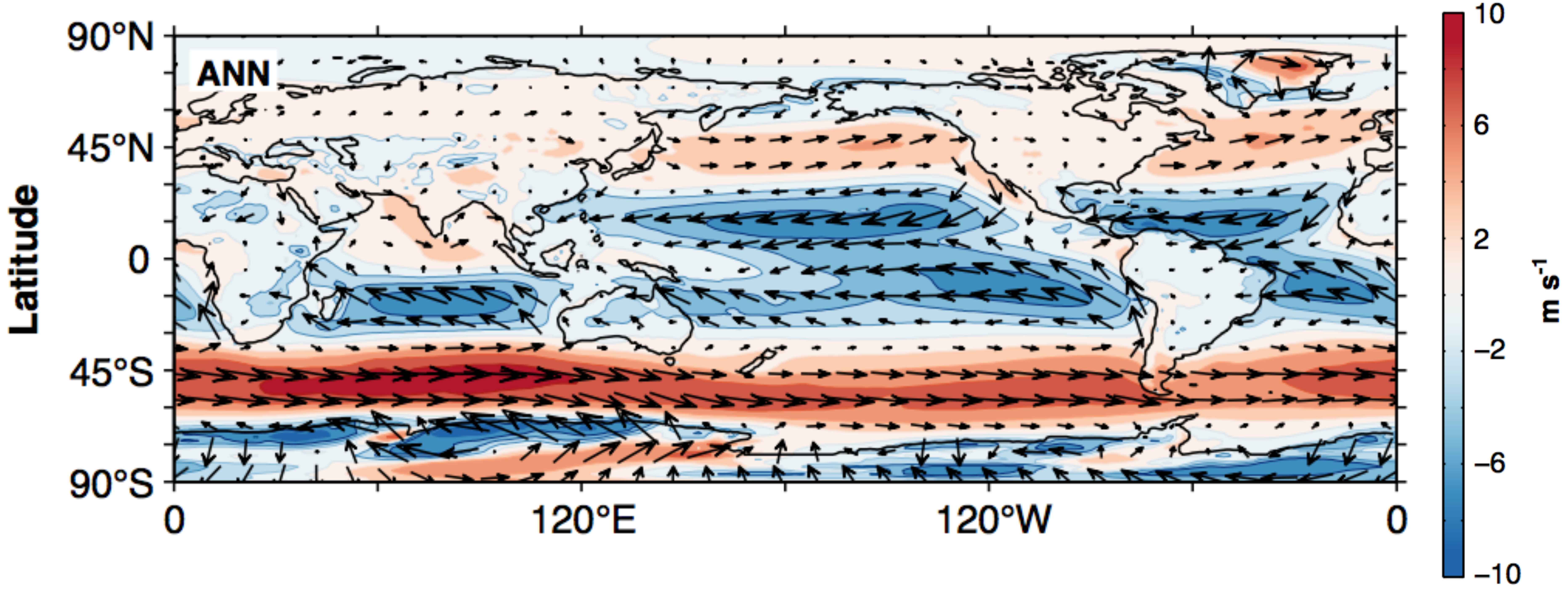
from Schneider's "Physics of Earth's Climate"

Phenomena: Surface temperature (annual range)



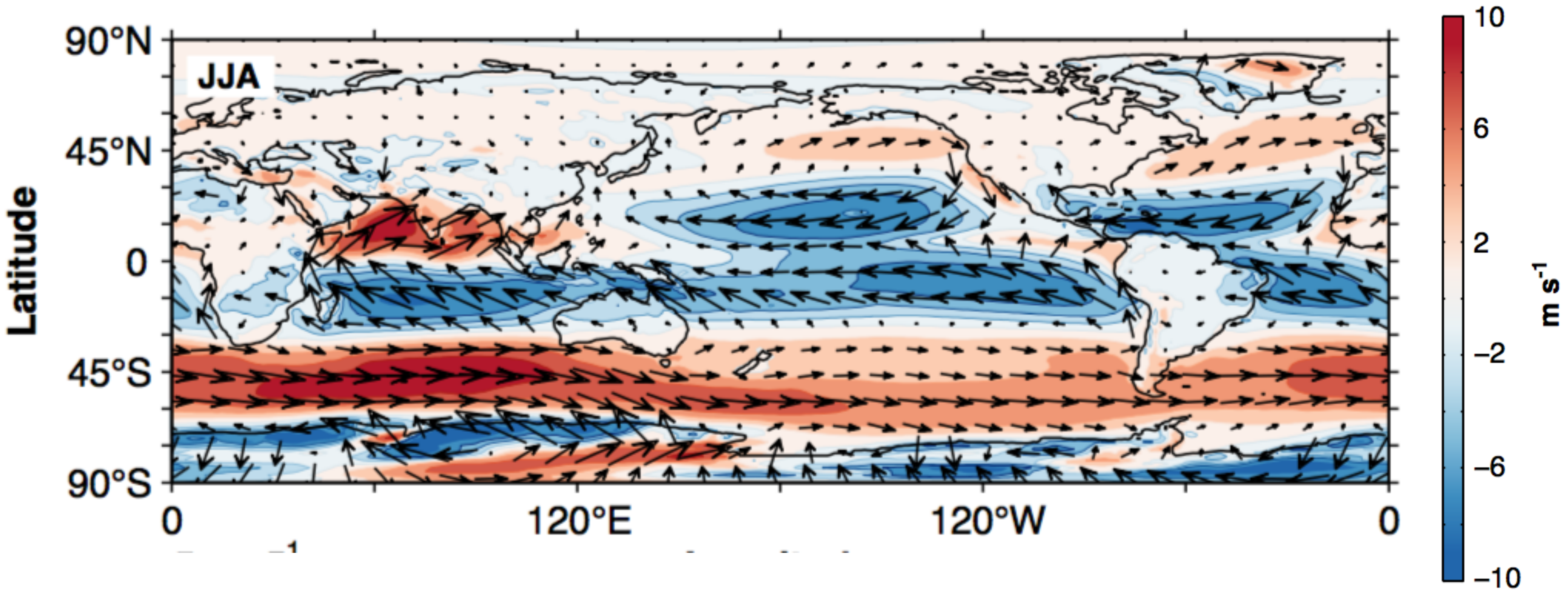
from Schneider's "Physics of Earth's Climate"

Phenomena: Annual-mean surface winds — much stronger in zonal direction because of Earth's rotation



from Schneider's "Physics of Earth's Climate"

Phenomena: NH summer (JJA) surface winds, winds vary with the seasons



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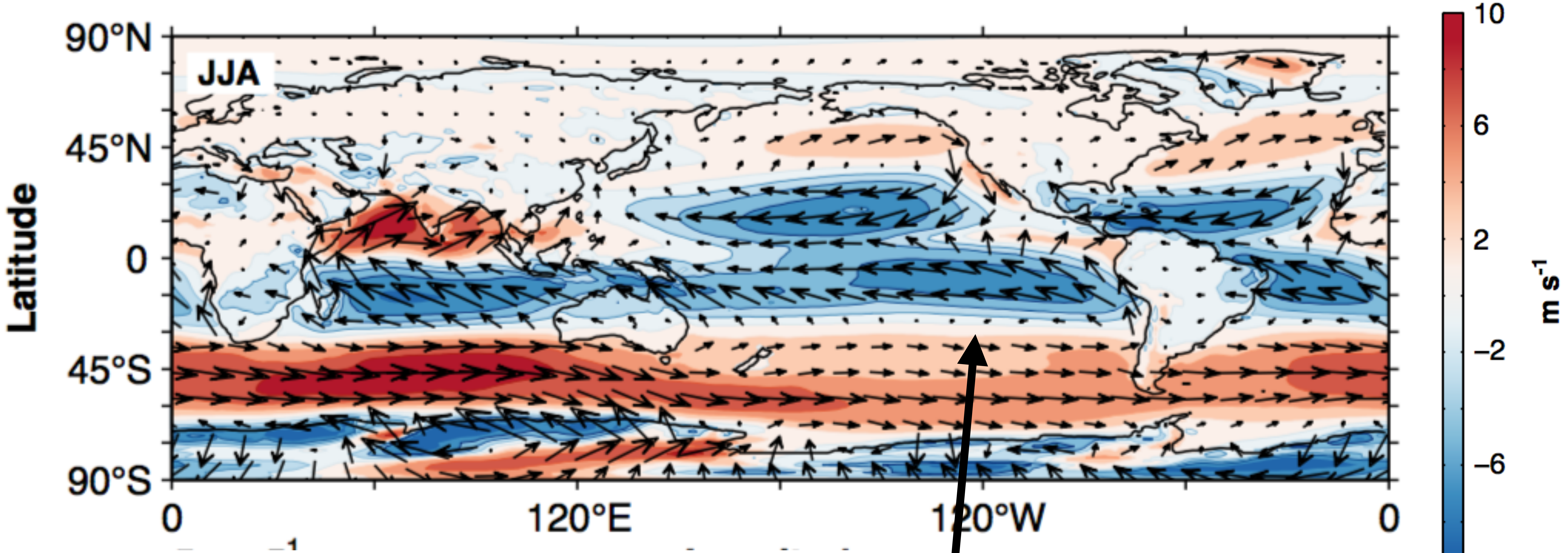
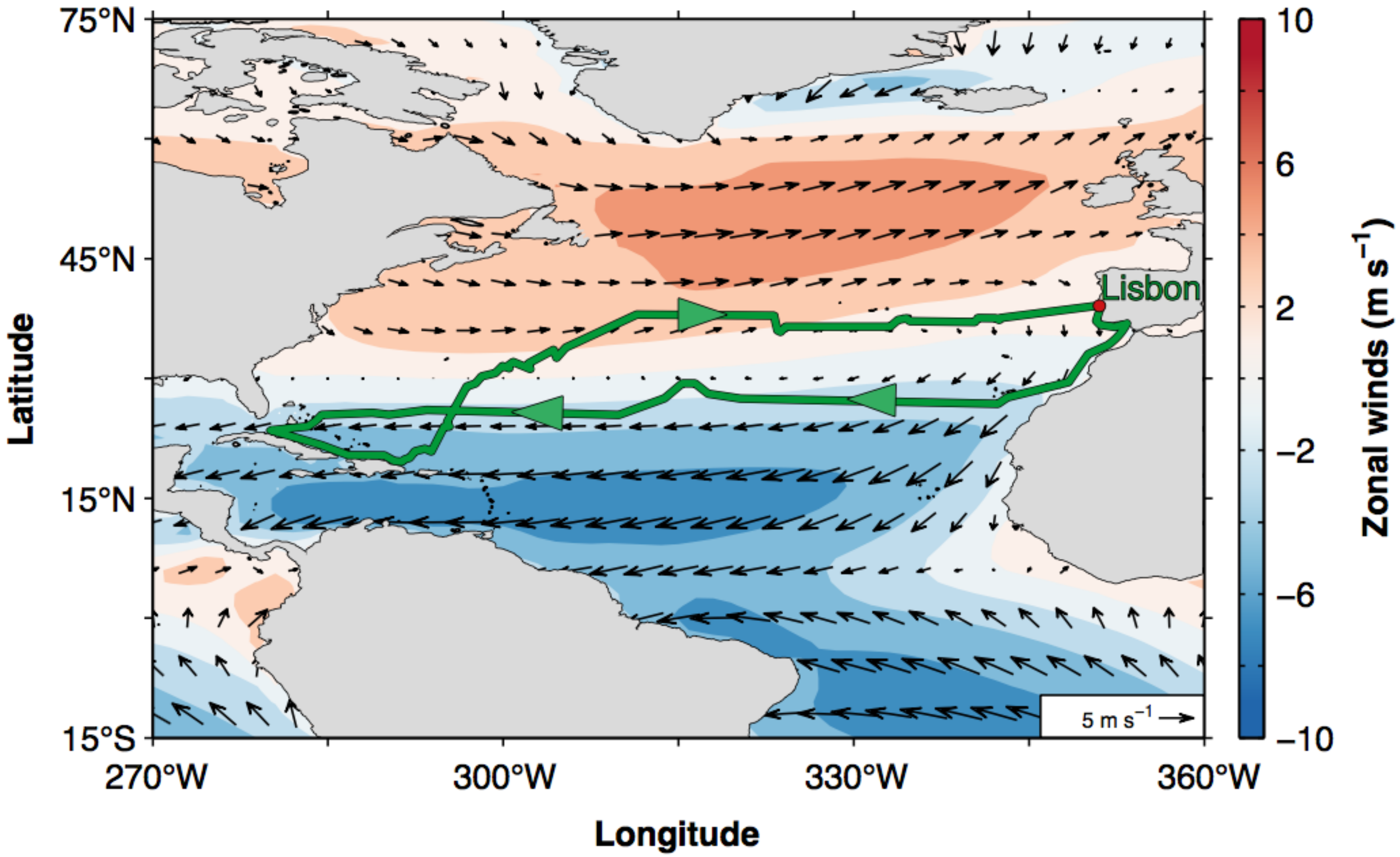


"horse latitudes"

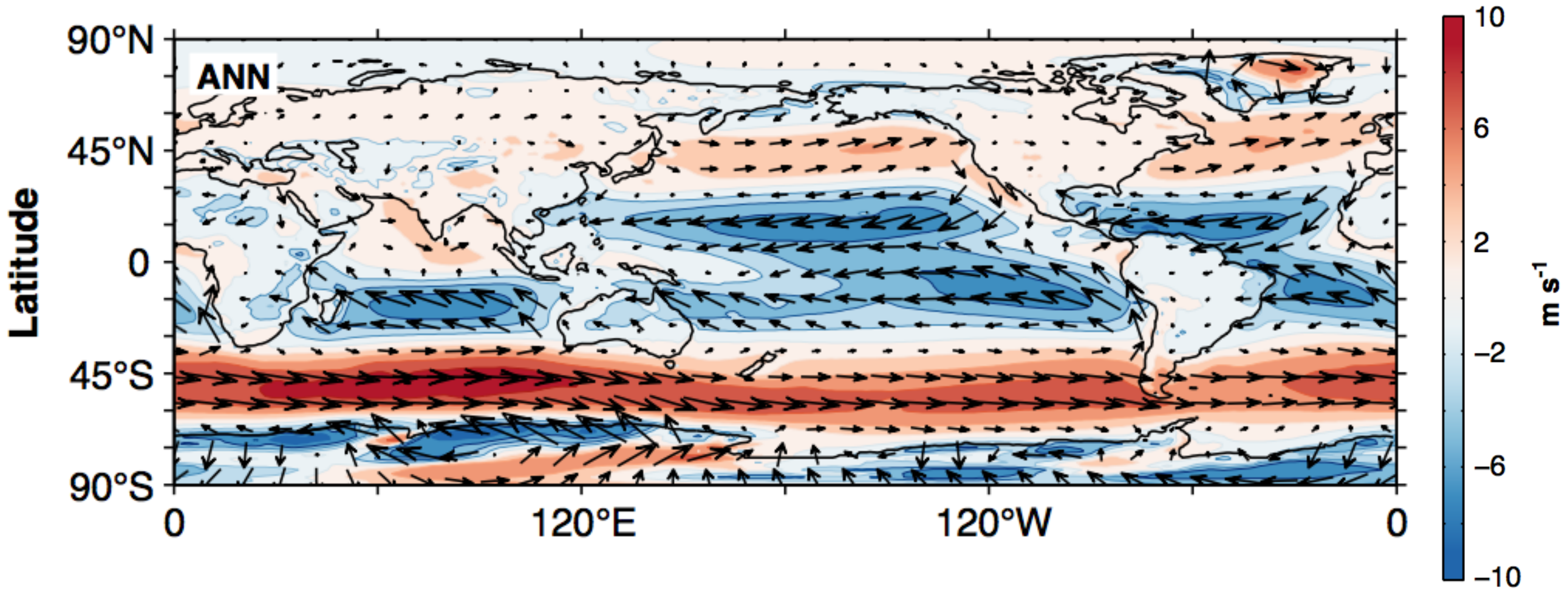
from Schneider's "Physics of Earth's Climate"

Columbus knew about the surface-wind pattern



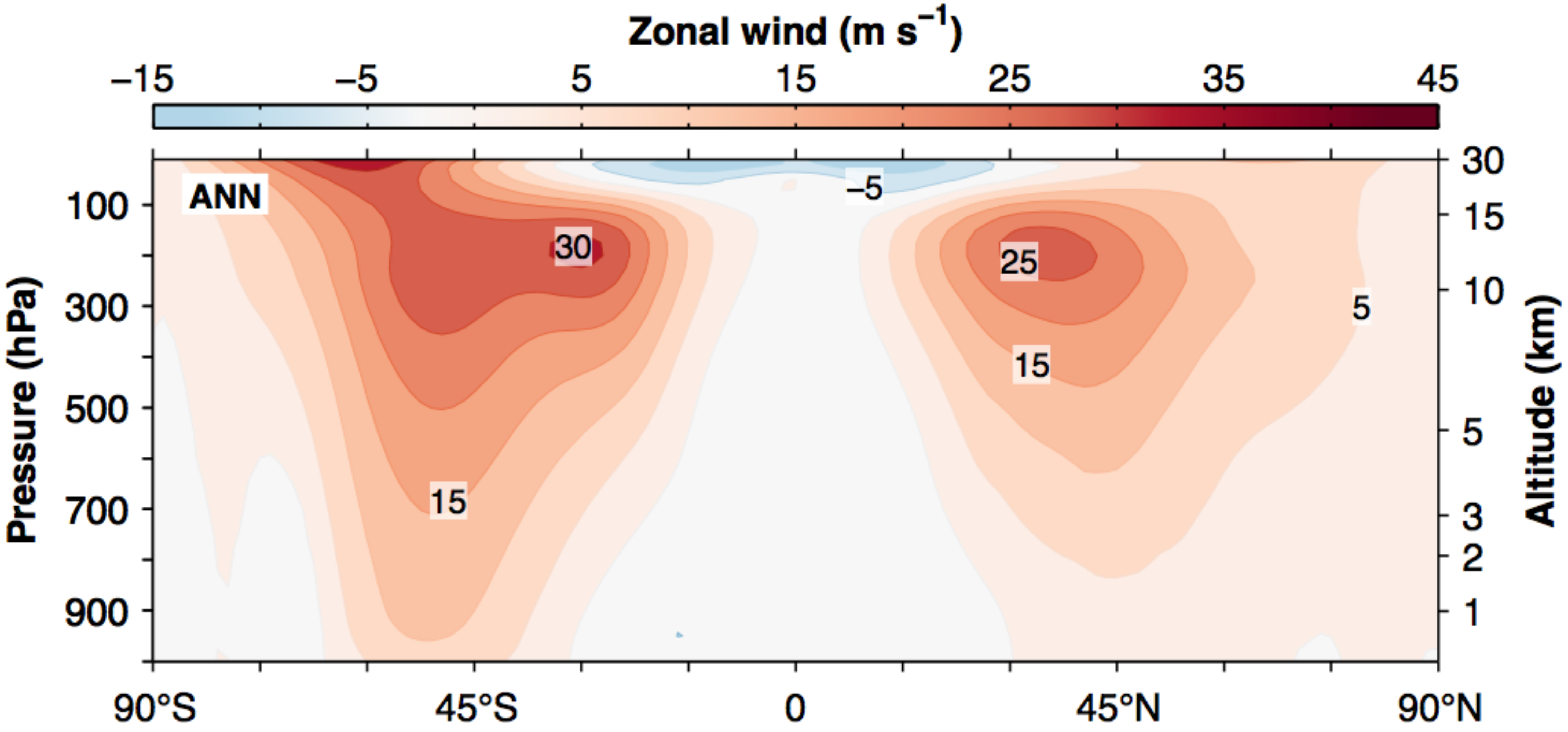
from Schneider's "Physics of Earth's Climate"

Phenomena: Meridional (north-south) winds are much weaker



from Schneider's "Physics of Earth's Climate"

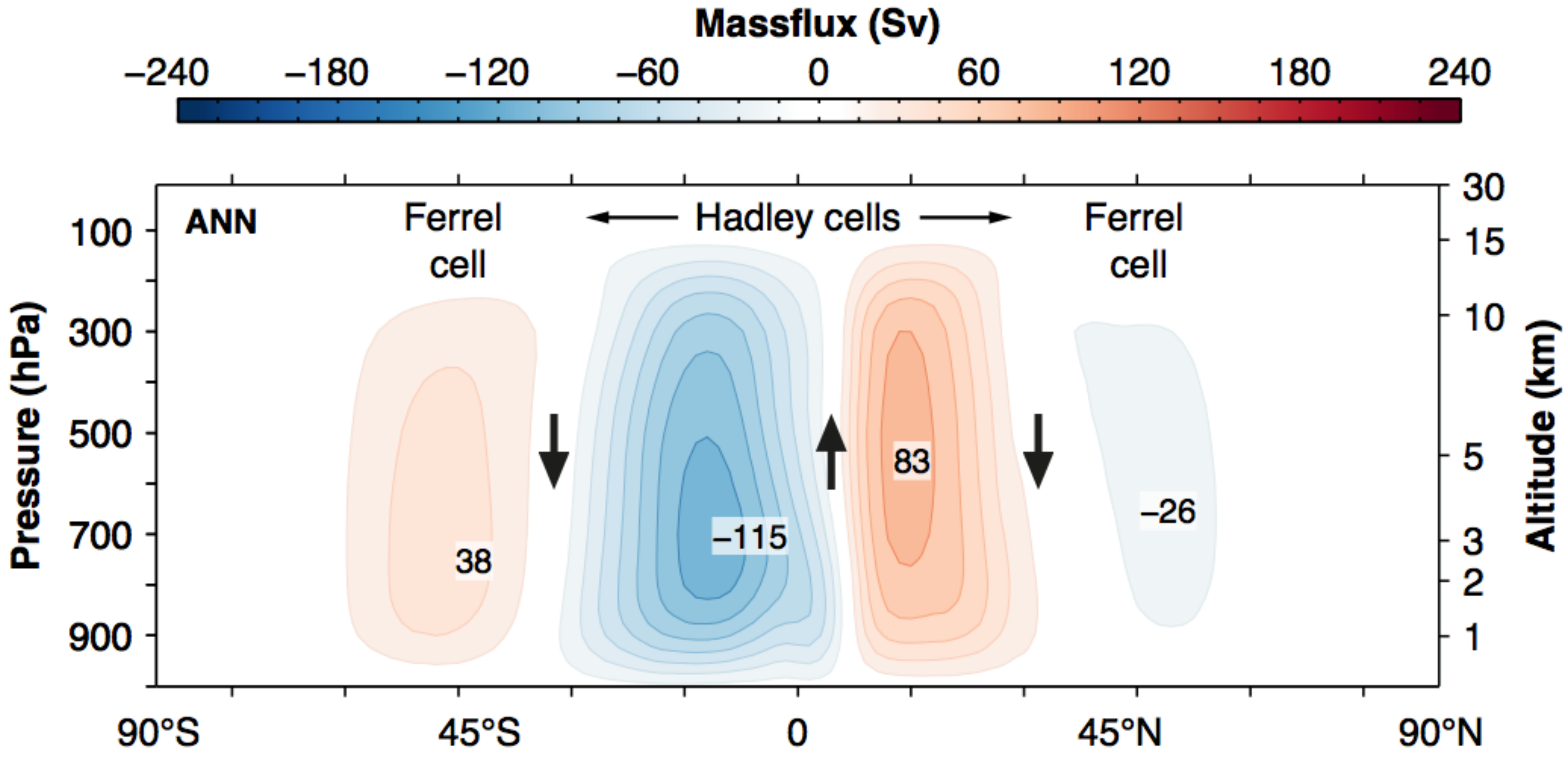
Phenomena: Vertical structure of zonal winds



from Schneider's "Physics of Earth's Climate"

Phenomena: Vertical structure of meridional mass circulation — by mass balance, Hadley and Ferrel cells must exist!

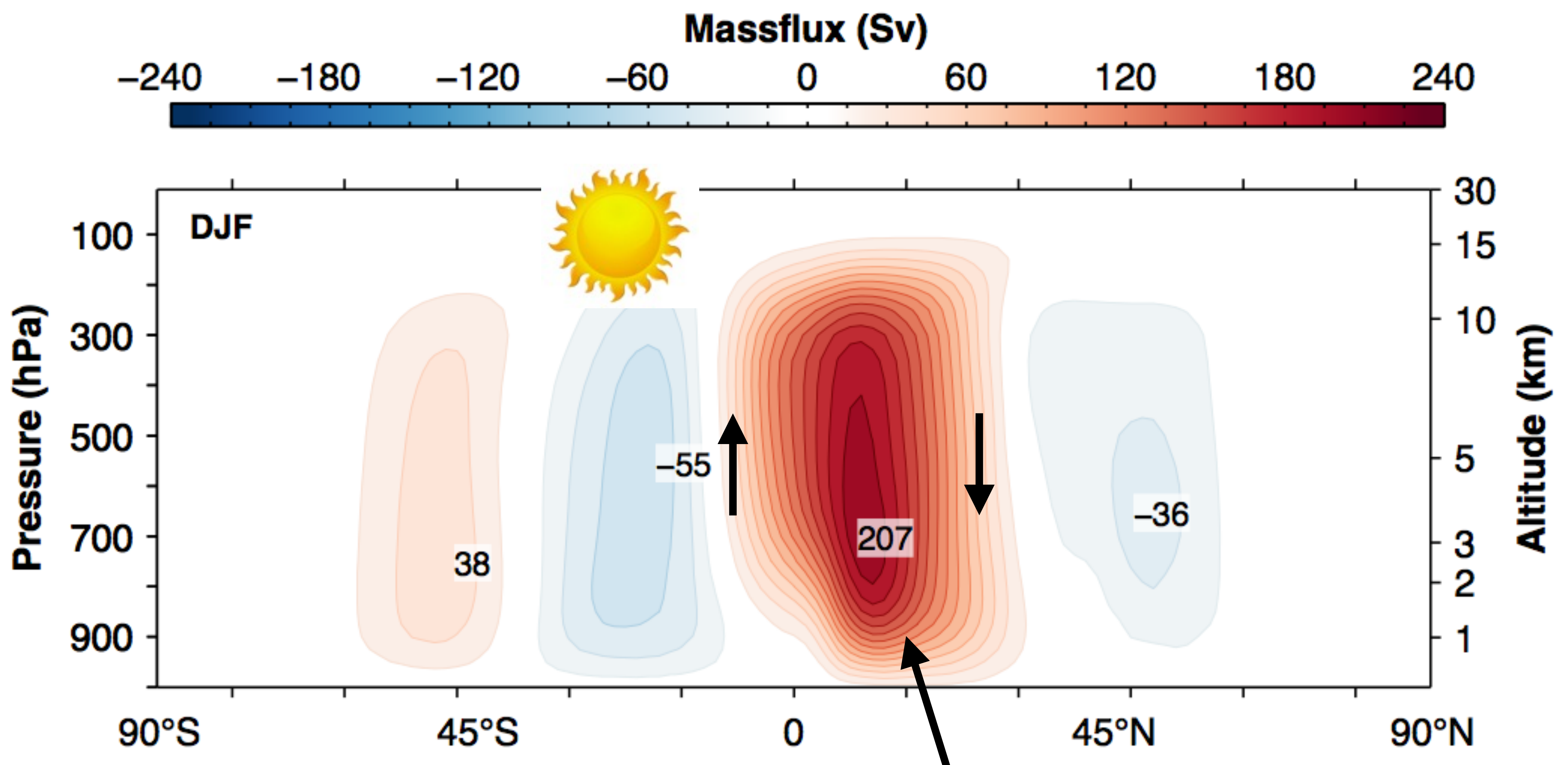
annual average



from Schneider's "Physics of Earth's Climate"

Phenomena: Atmospheric meridional mass circulation — monsoons

Dec-Jan-Feb

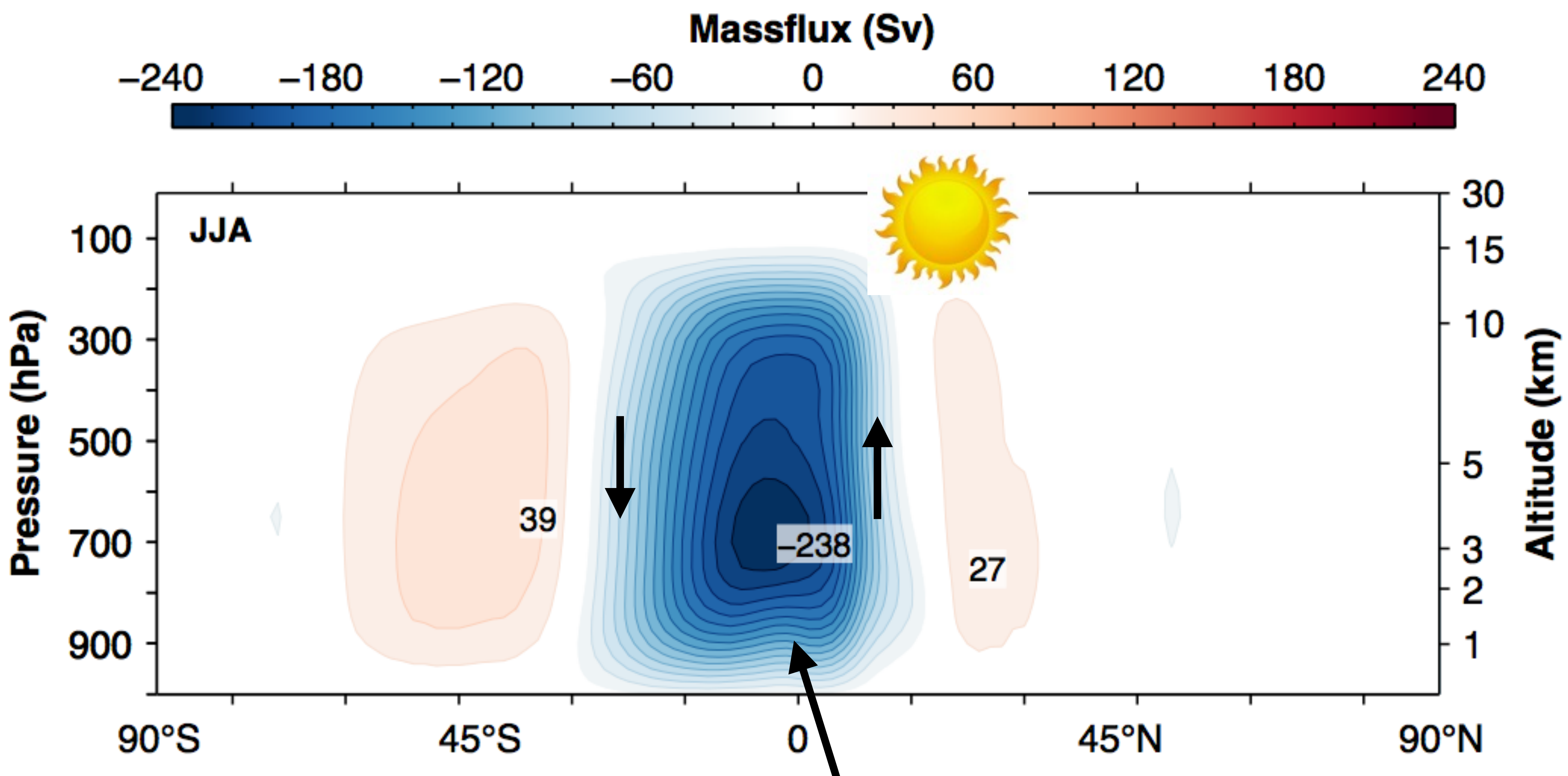


southern monsoons

from Schneider's "Physics of Earth's Climate"

Phenomena: Atmospheric meridional mass circulation — monsoons

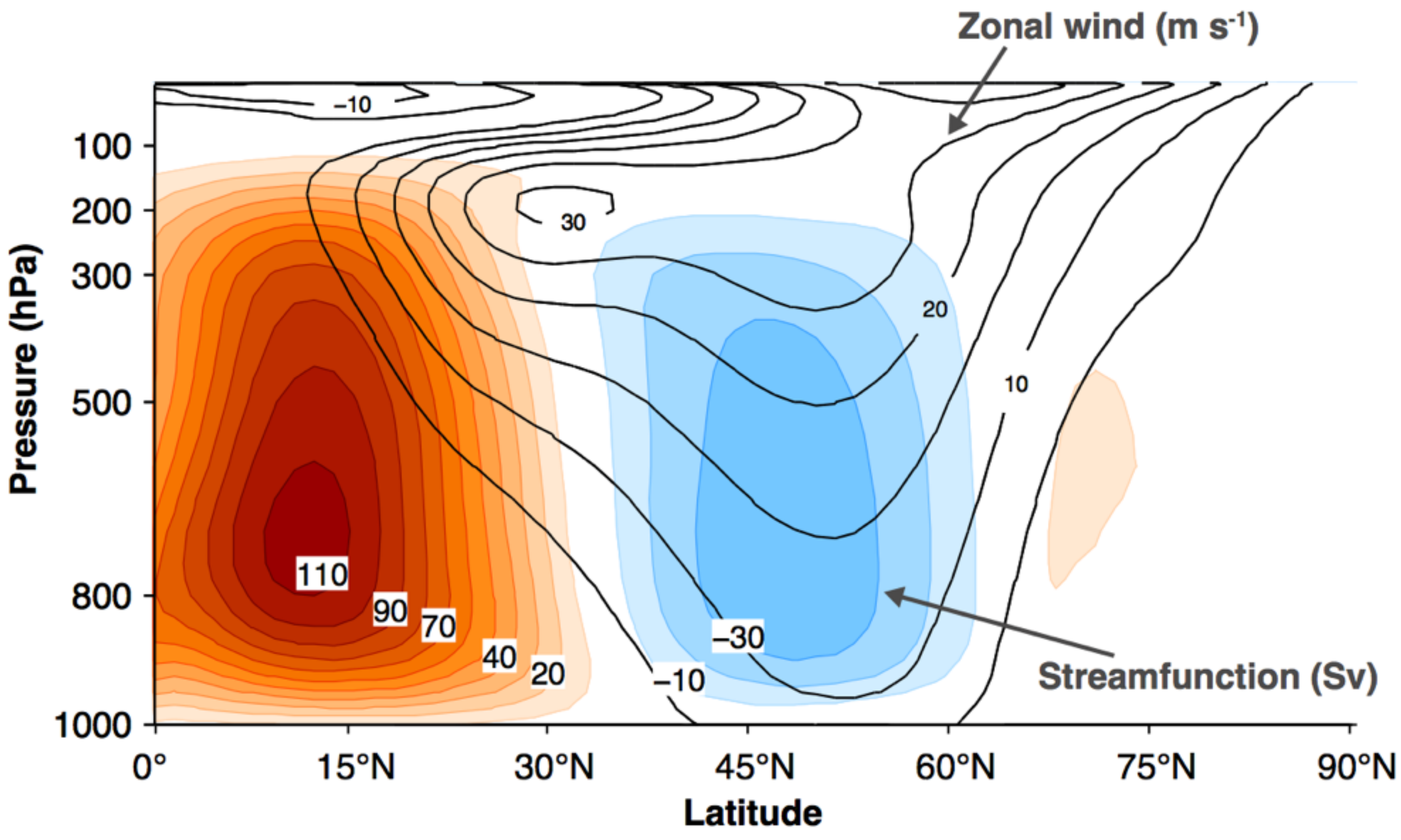
Jun-Jul-Aug



northern monsoons (e.g. in India)

from Schneider's "Physics of Earth's Climate"

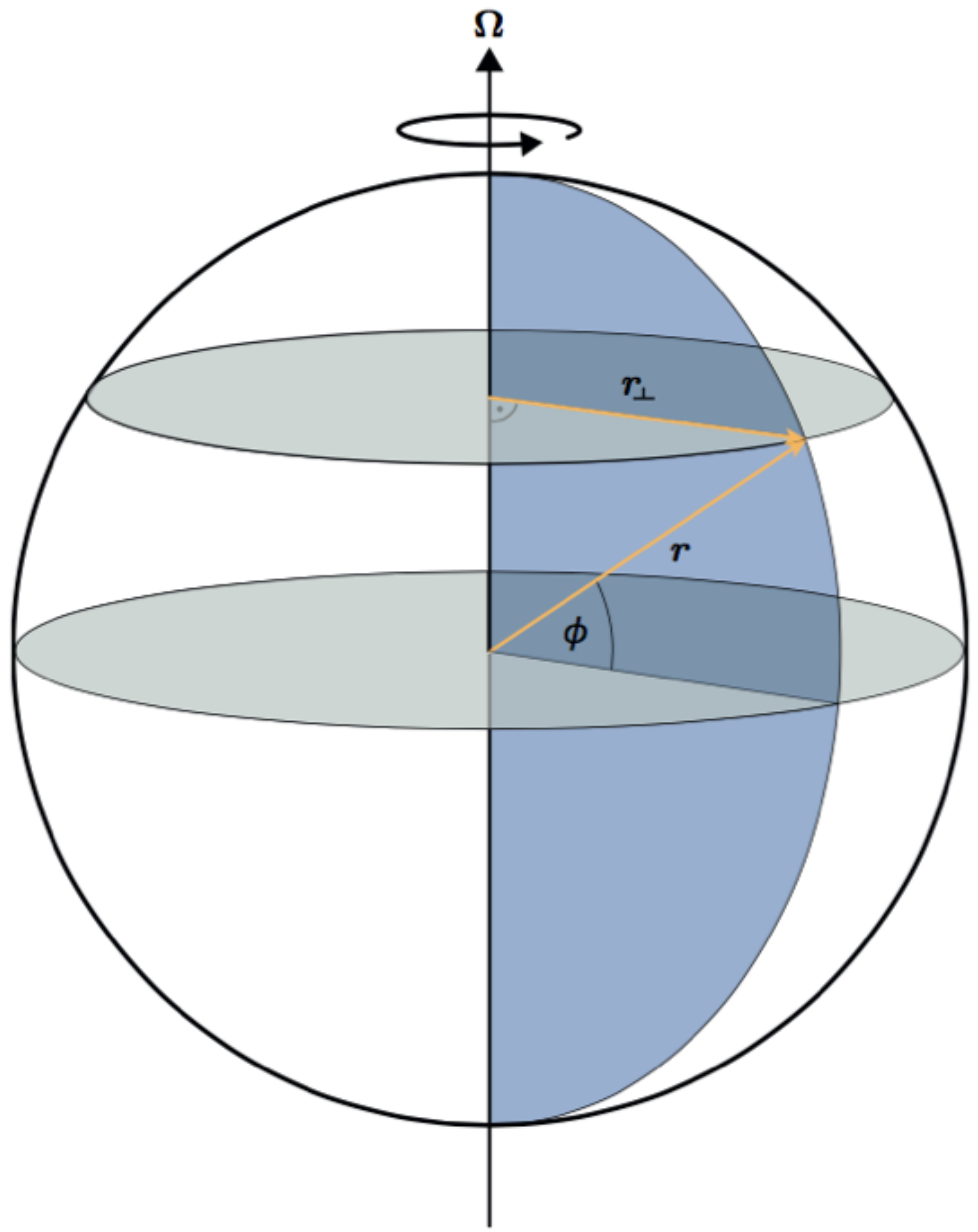
Why are there strong winds in the upper atmosphere? Why are these winds increasingly westerly as you move poleward? Angular momentum and Earth's rotation…



Understanding winds and the Hadley circulation using angular momentum conservation

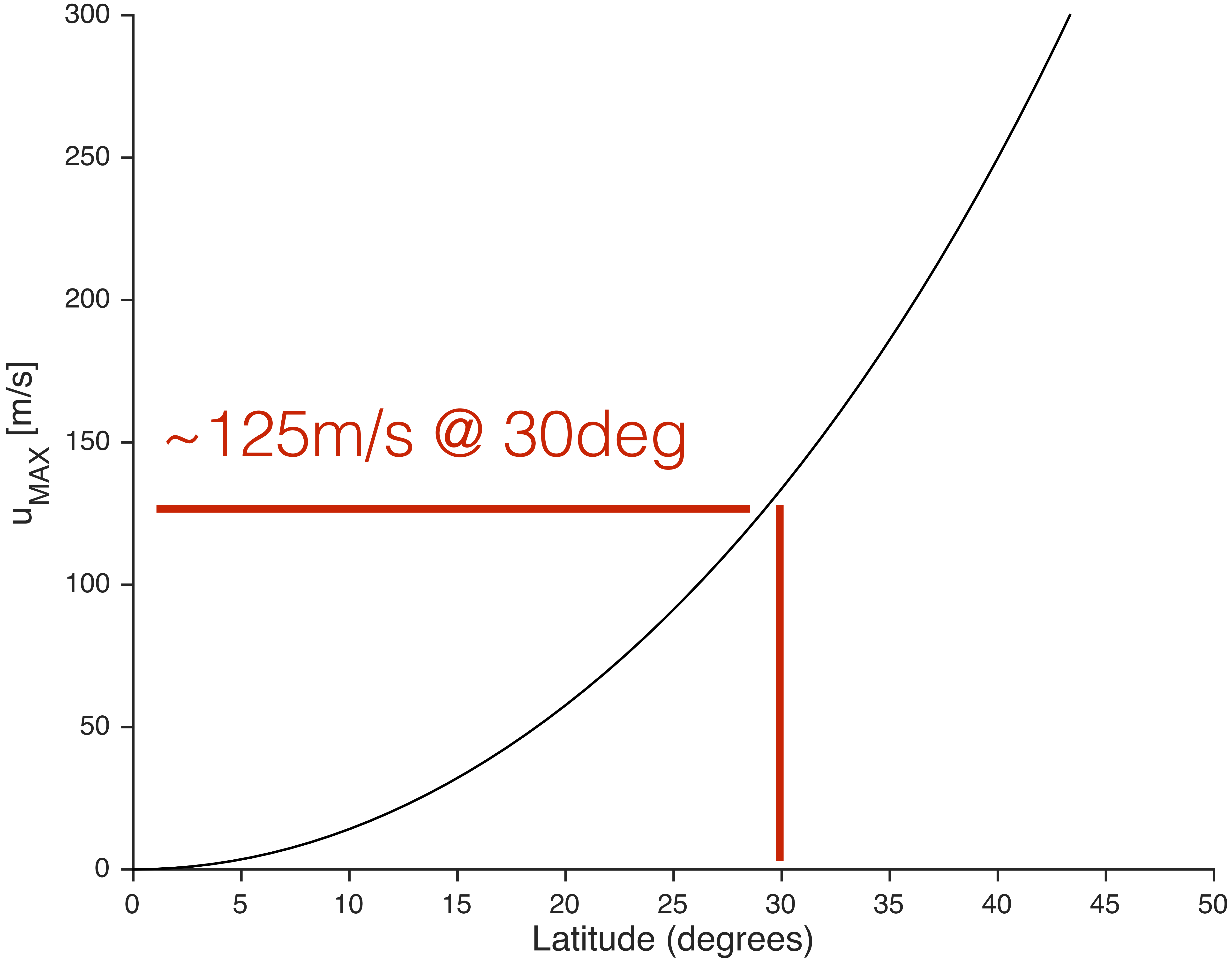
What is the angular momentum?
"velocity times distance to rotation axis"

What does it imply for upper-tropospheric winds in Hadley cell?



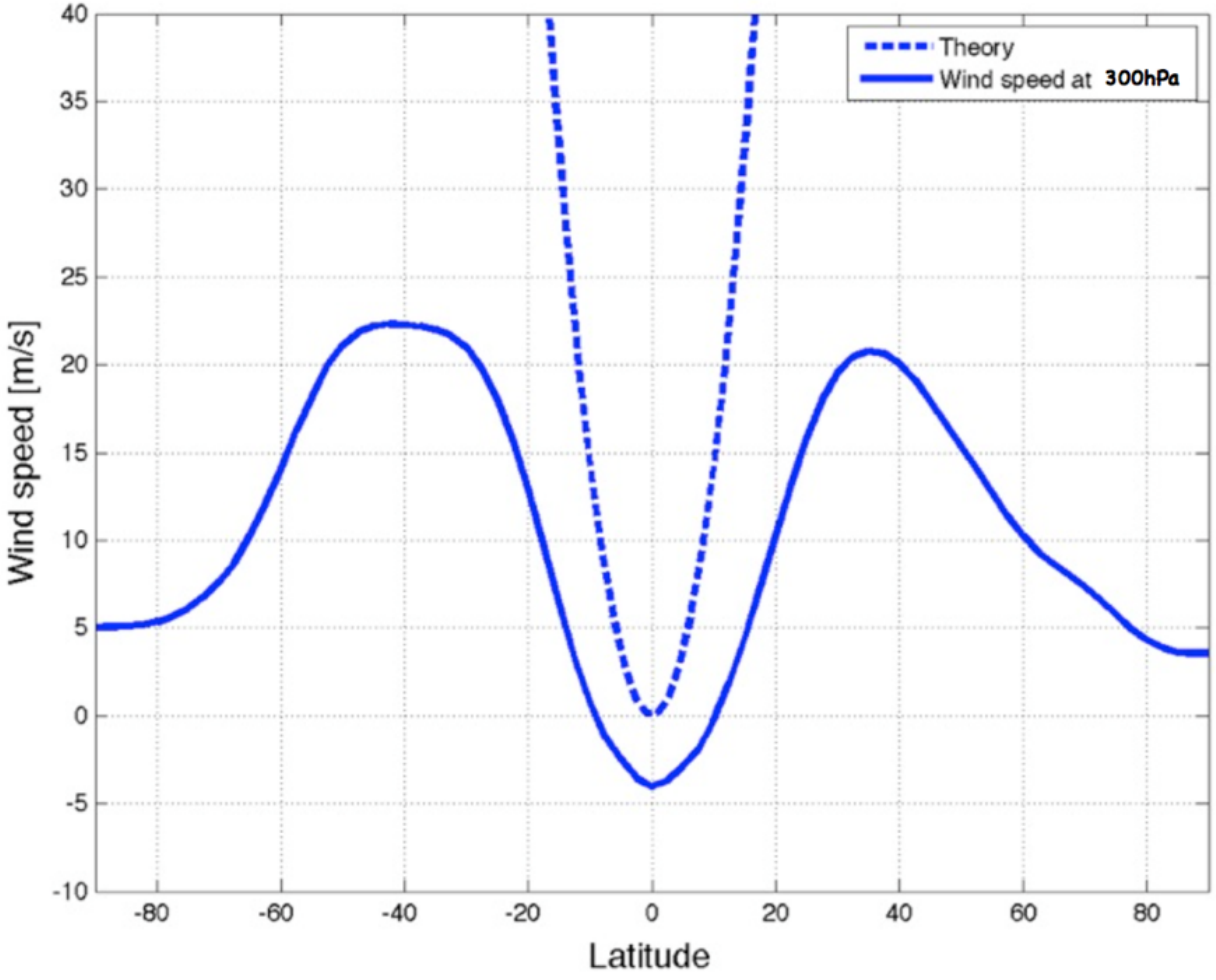
Conservation of AM implies upper-level winds become stronger (more westerly) as air moves towards pole (opposite for surface winds)

$$u_{\max} = \Omega a \frac{\sin^2 \phi}{\cos \phi}$$

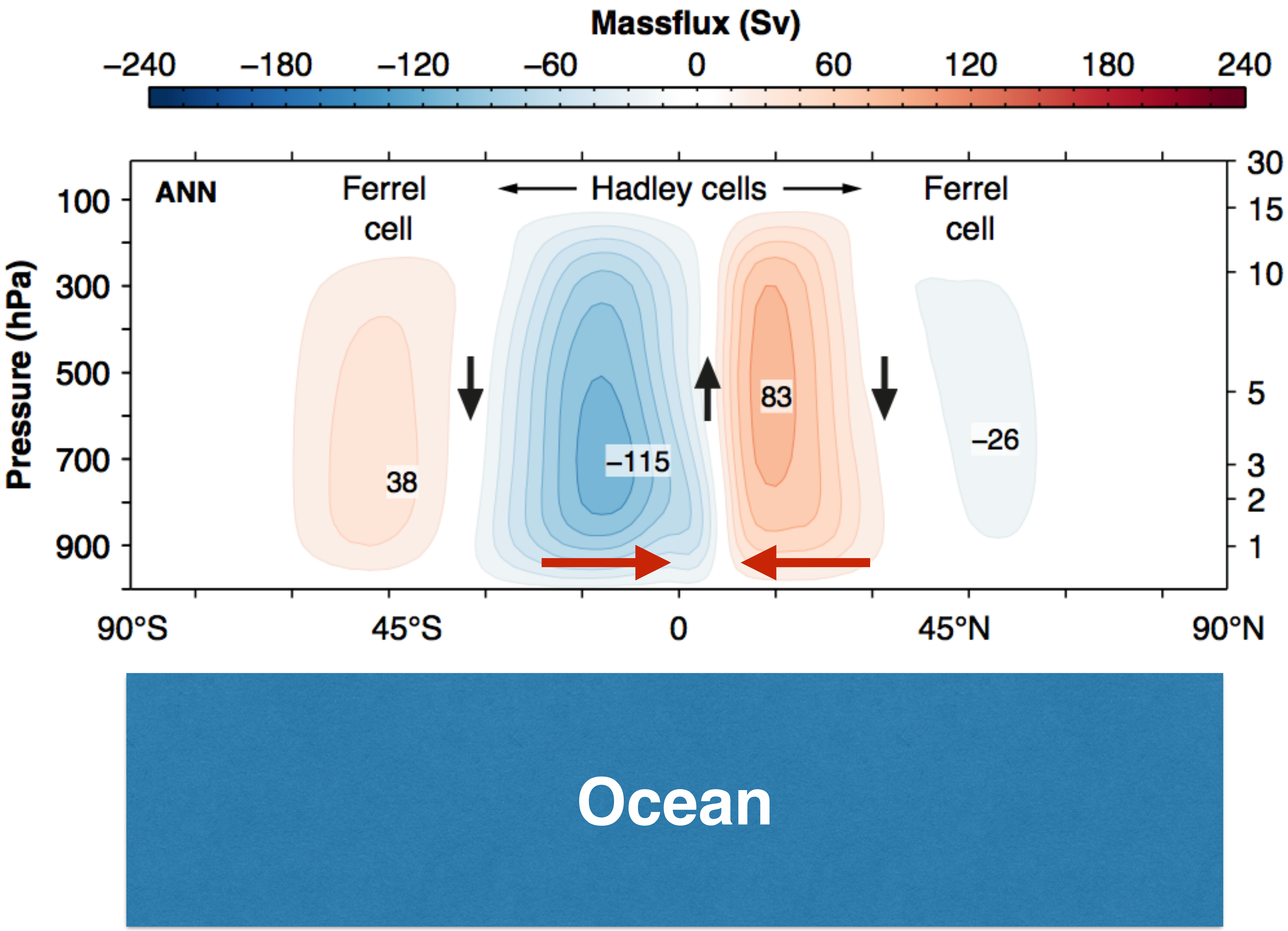


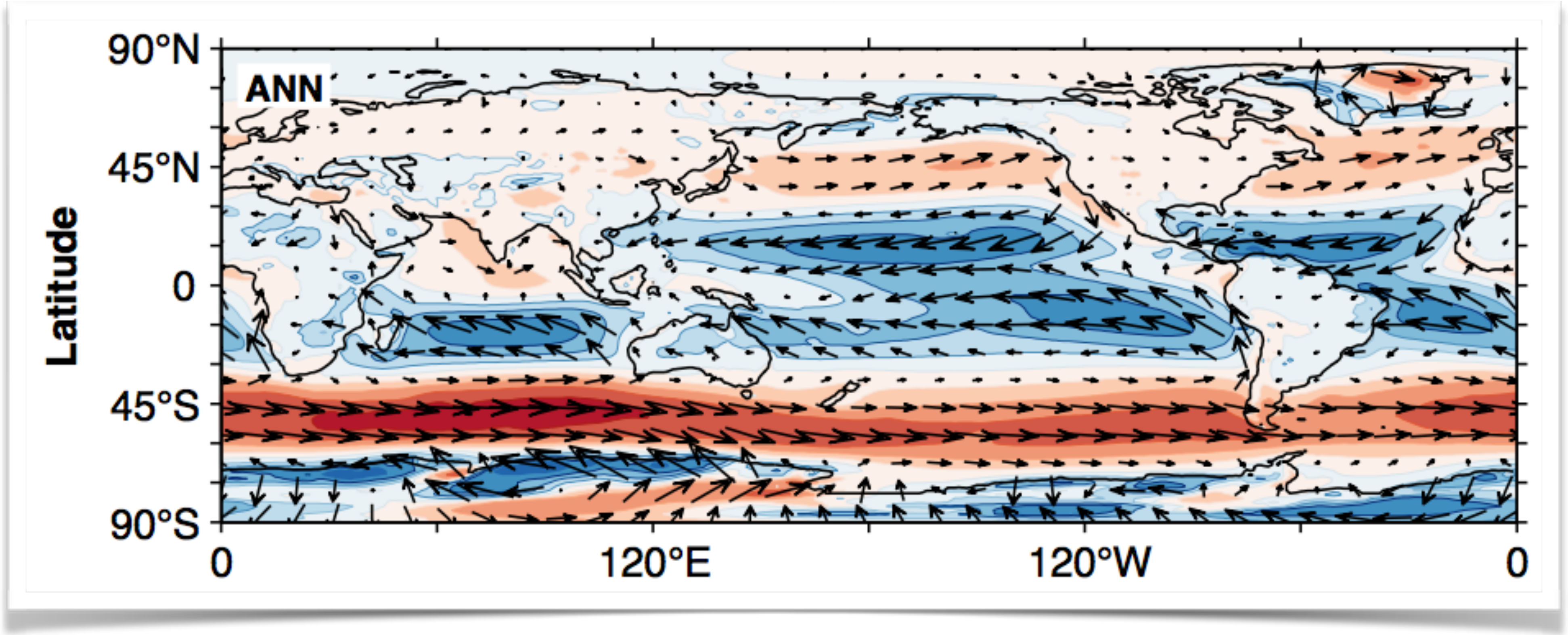
Implies infinite winds at the poles! AM conservation breaks down and Hadley circulation stops at ~30deg because of baroclinic instability and turbulence (see tomorrow's experiment)

$$u_{\max} = \Omega a \frac{\sin^2 \phi}{\cos \phi}$$



In surface branch AM is not conserved because of friction. Easterly winds transfer momentum to ocean and drive oceanic circulations -> Ekman layers



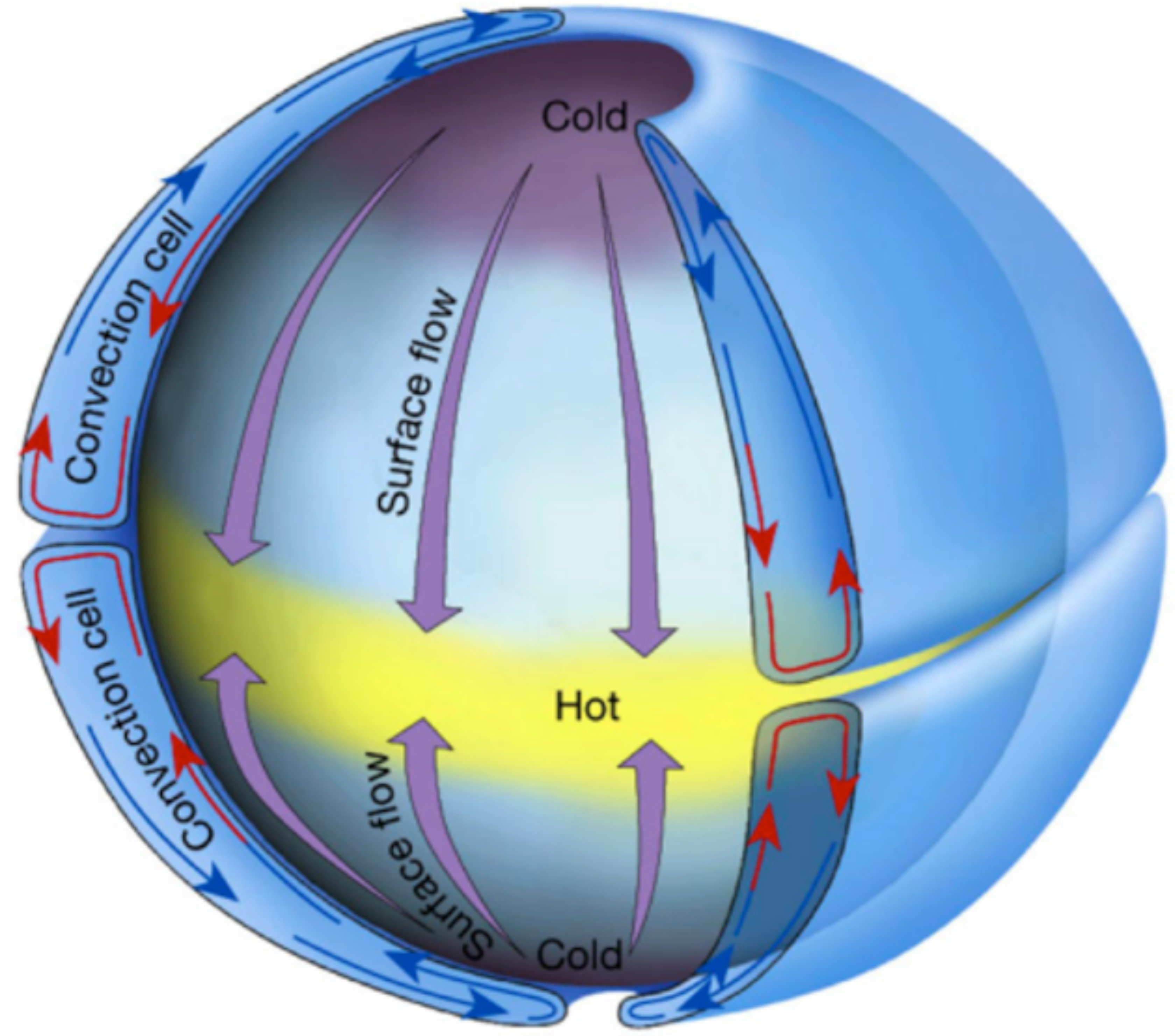


Ekman layers

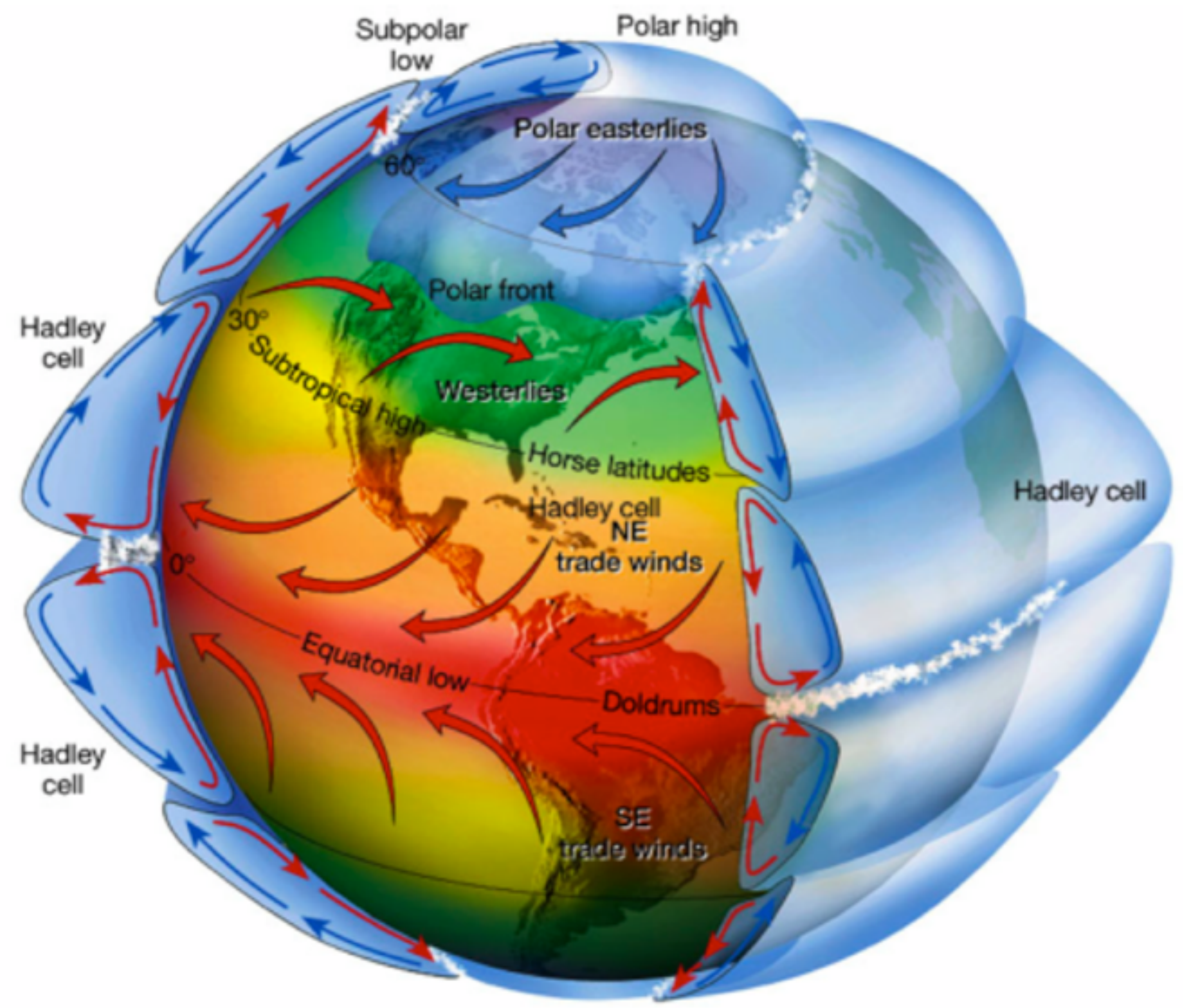
Arnaud's slides

Breakdown of Hadley cell due to Earth's rotation

non-rotating



rotating



Breakdown of Hadley cell due to Earth's rotation

<u>Macroturbulence in an Earth-like simulation</u>

<u>Macroturbulence in a more realistic more</u>

Effect of Earth's rotation on atmosphere/ocean dynamics: The Rossby number

Can begin to understand the influence of rotation on circulation by doing a scale analysis of the momentum equation…

$$\frac{Du}{Dt} + \frac{1}{\rho}\frac{\partial p}{\partial x} - fv = friction \quad \mathrm{(east - westdir.)}$$

$$\frac{Dv}{Dt} + \frac{1}{\rho}\frac{\partial p}{\partial y} + fu = friction \quad \mathrm{(north - southdir.)}$$

acceleration

pressure-gradient force

Coriolis force

Effect of Earth's rotation on atmosphere/ocean dynamics: The Rossby number

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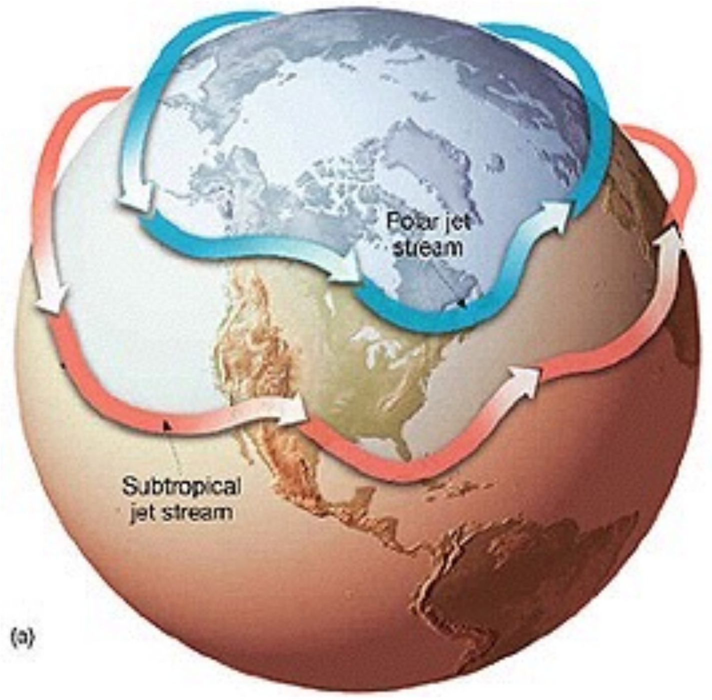
$\sim V / T = V^2/L$

$\sim fV$

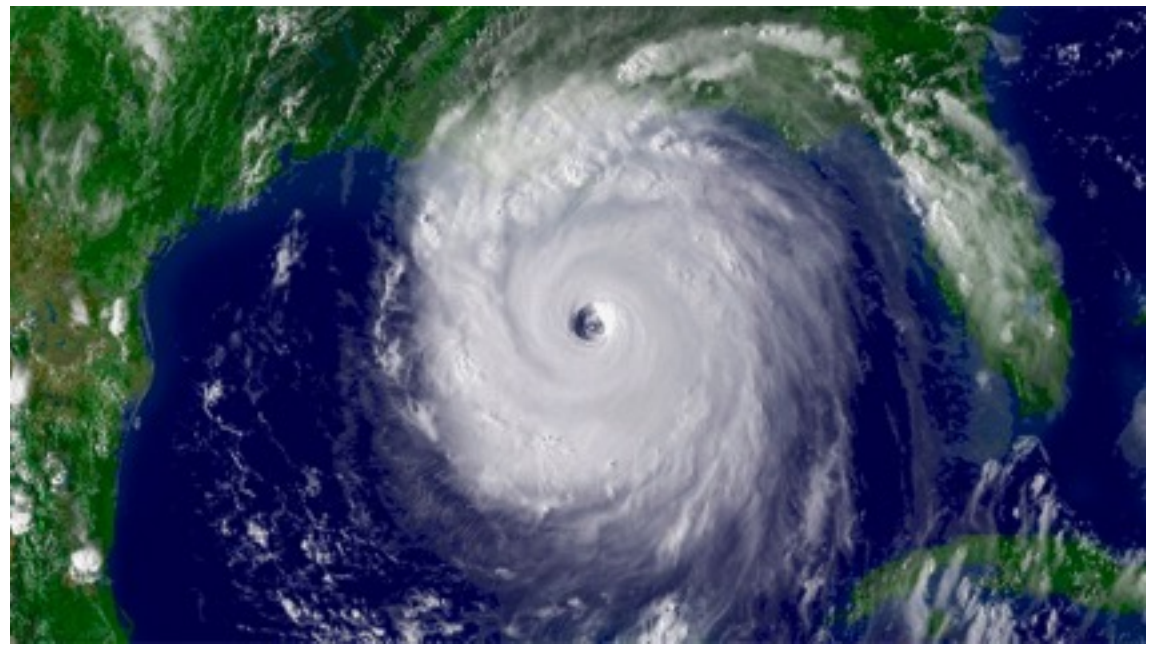
Effect of Earth's rotation on atmosphere/ocean dynamics: The Rossby number

$$\text{Ro} = \frac{\text{acceleration}}{\text{Coriolis}} \sim \frac{\text{V}}{\text{fL}}$$

geostrophic balance (jet stream)



gradient balance (hurricanes)



cyclostrophic balance (tornados)

Ro = 0.1 1 10

Geostrophic balance in Earth's atmosphere: Mid-latitude weather systems

$$\mathrm{Ro} = \frac{\text{acceleration}}{\text{Coriolis}} \sim \frac{V}{fL} \approx 0.1$$

$$\Rightarrow f\hat{\mathbf{z}} \times \mathbf{u} + \frac{1}{\rho}\nabla p = 0$$

Geostrophic balance:
"Pressure-gradient and Coriolis forces balance" -> flow along isobars

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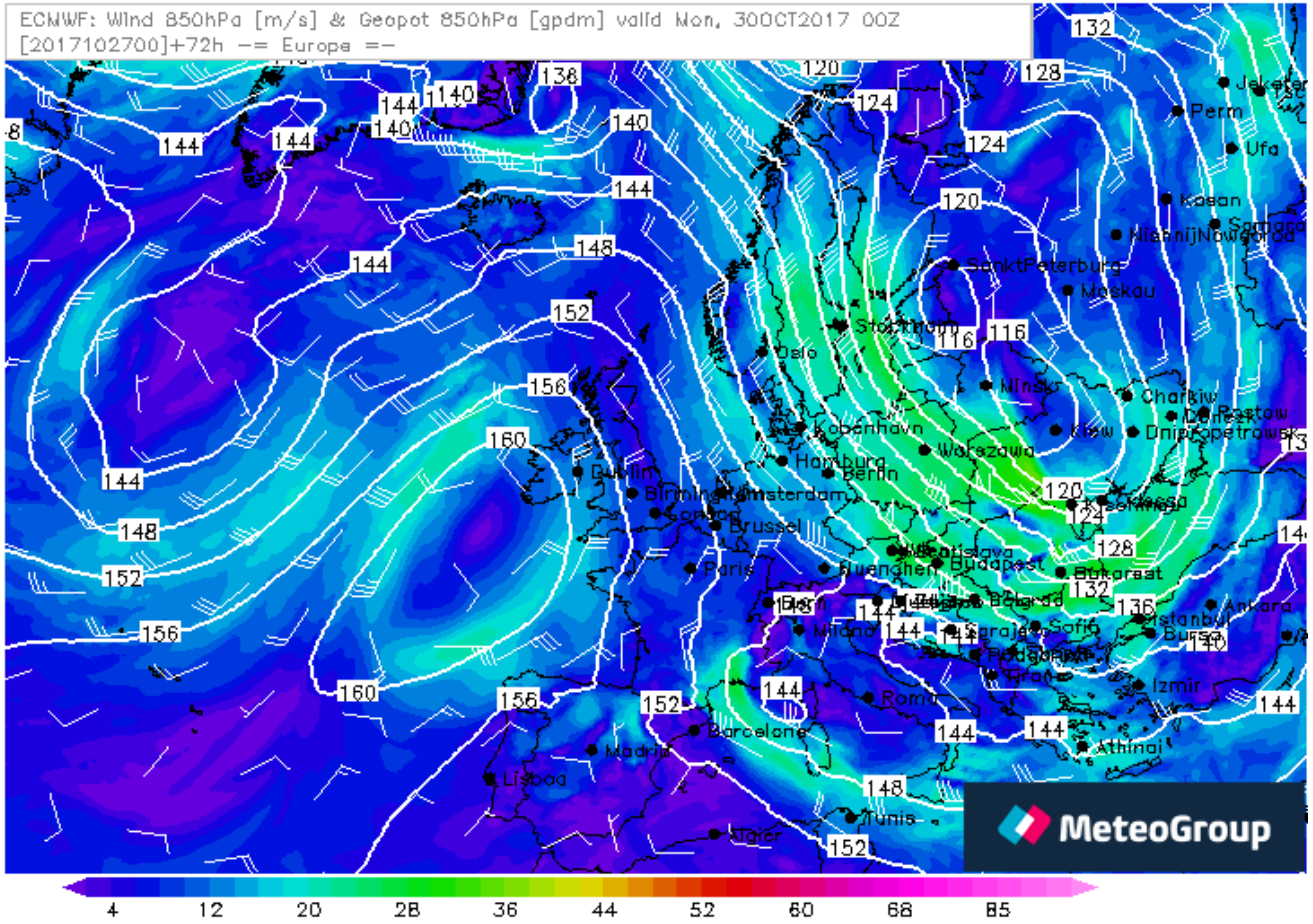

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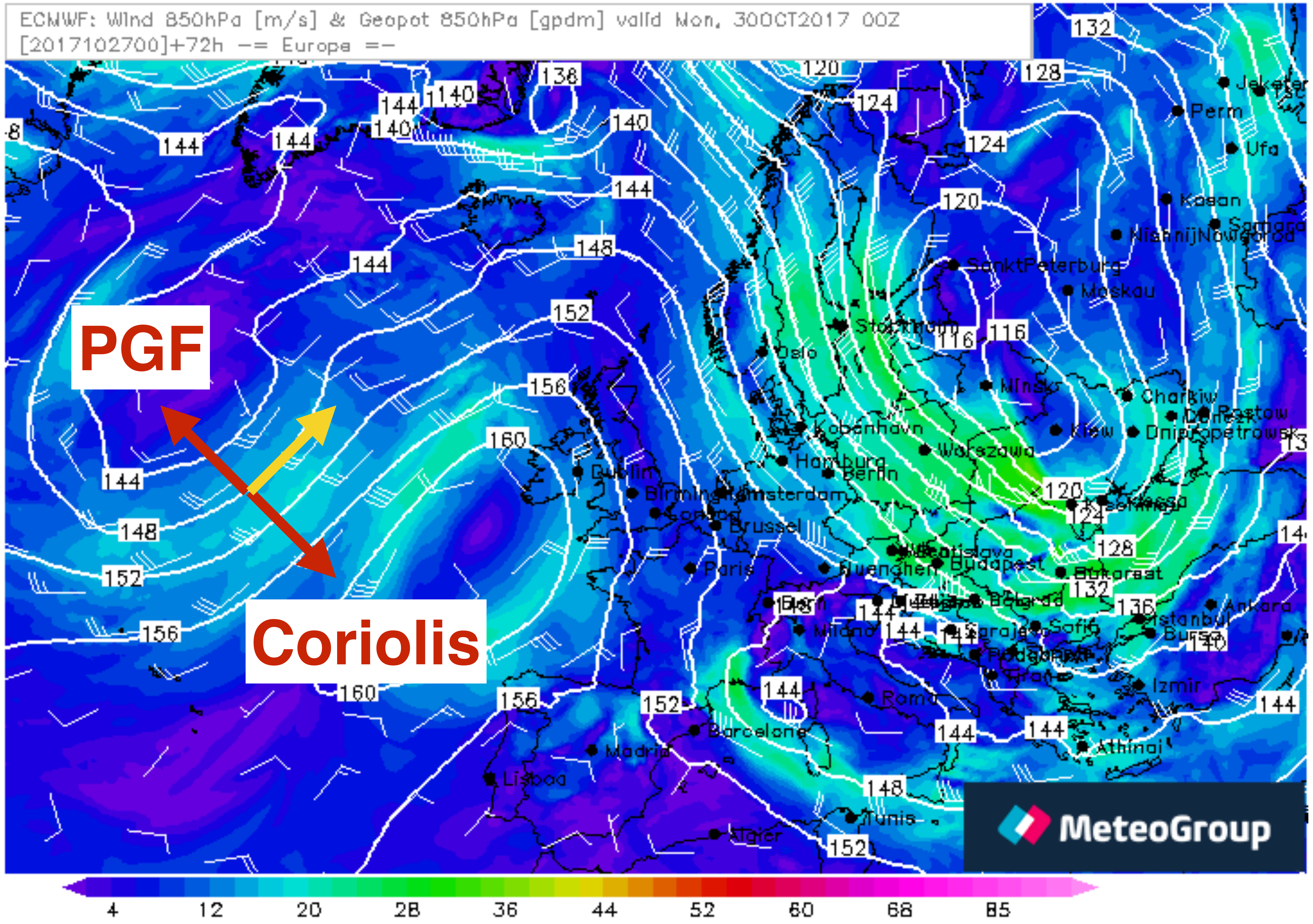
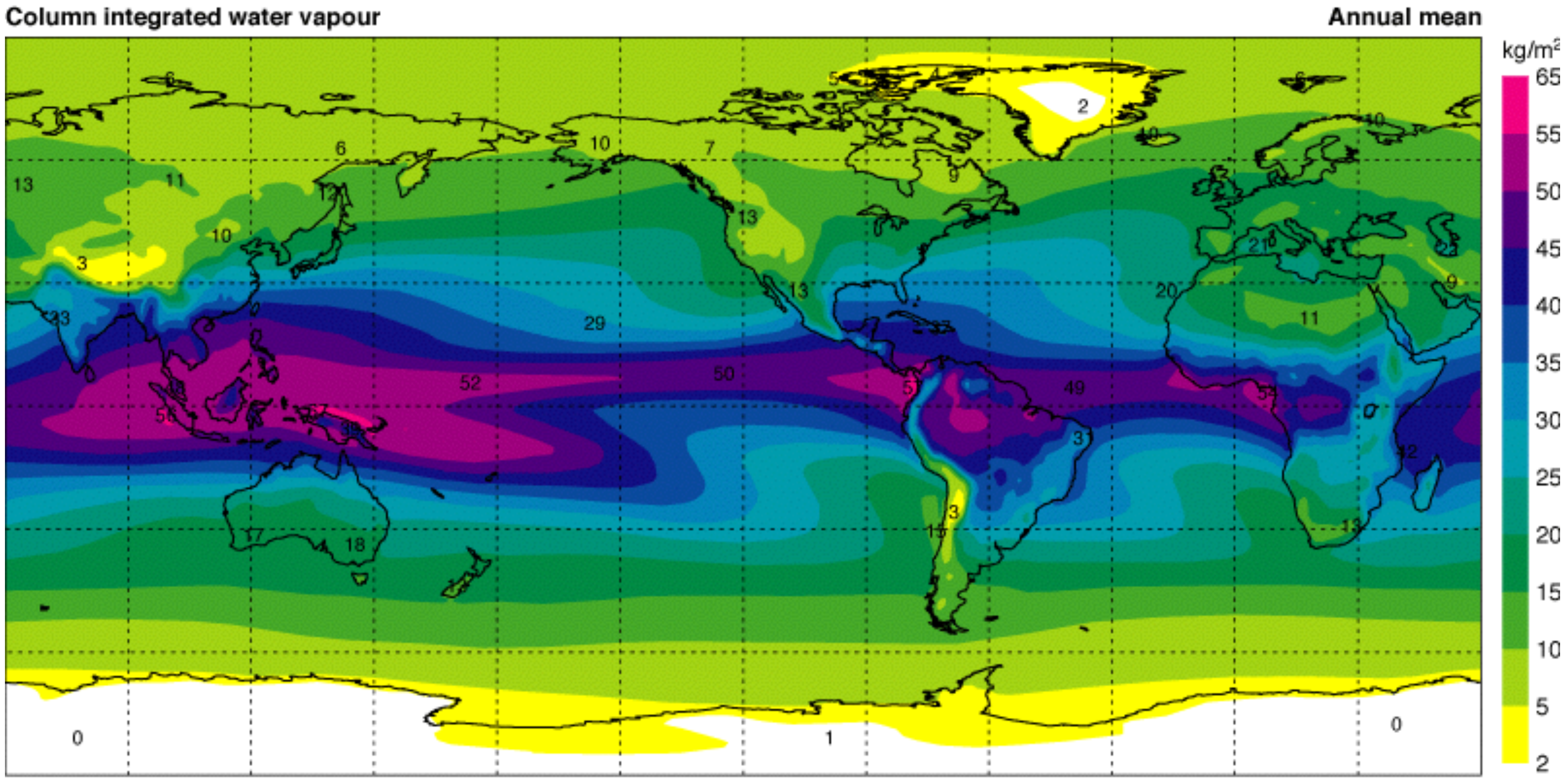
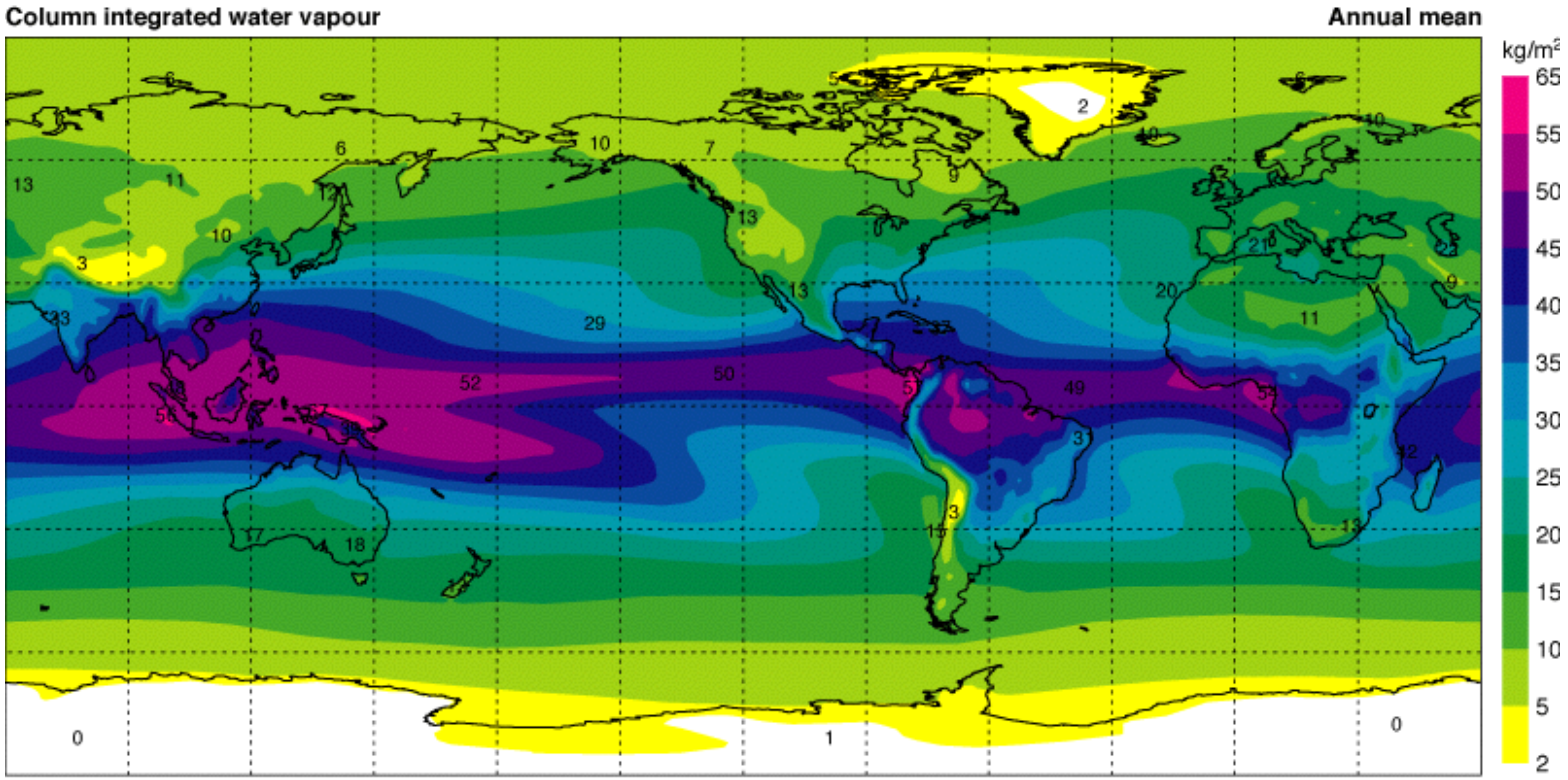


Earth's water cycle: atmospheric water vapour



ERA-40 Atlas

Earth's water cycle: atmospheric water vapour

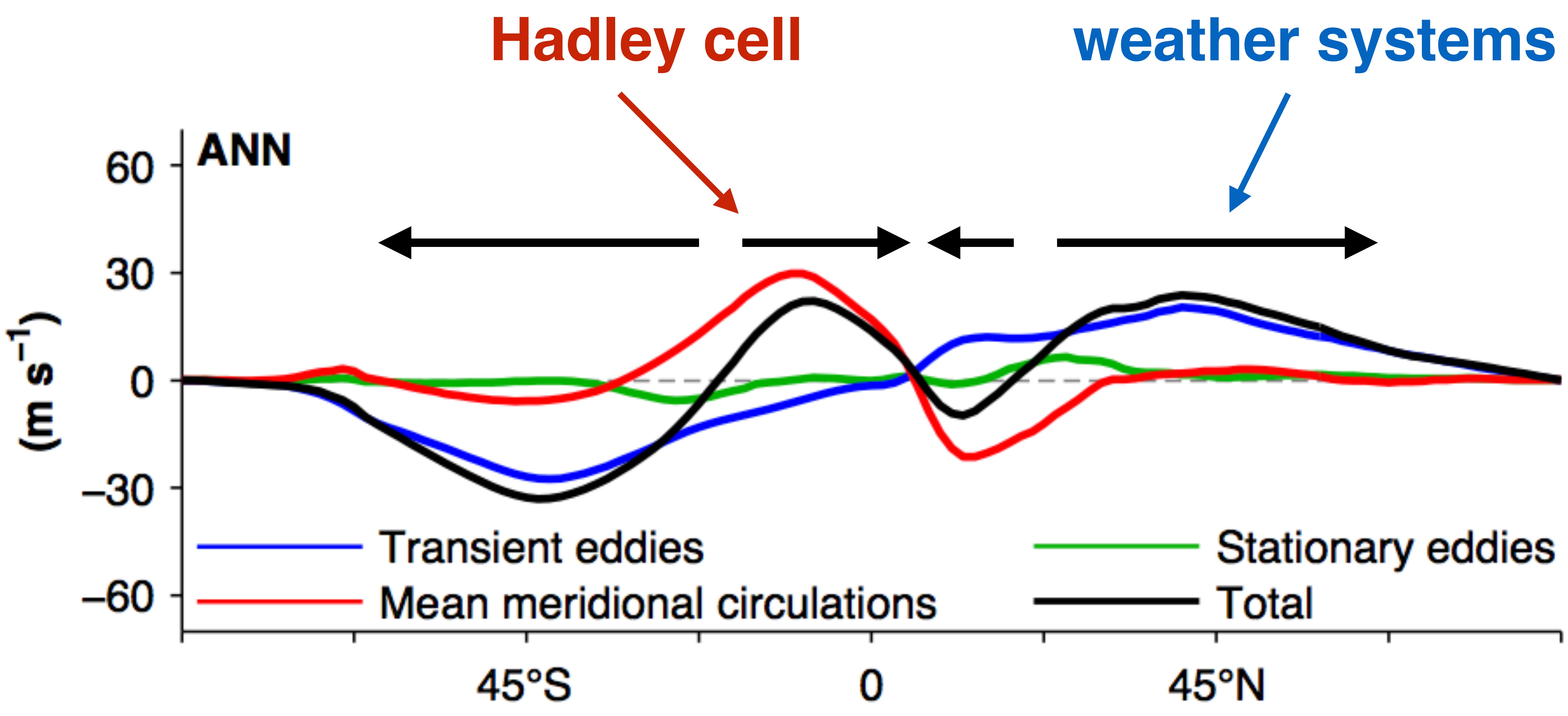


Clausius-Clapeyron: $$\frac{\delta q^*}{q^*} \approx \frac{L}{RT^2}\delta T$$

7%/K

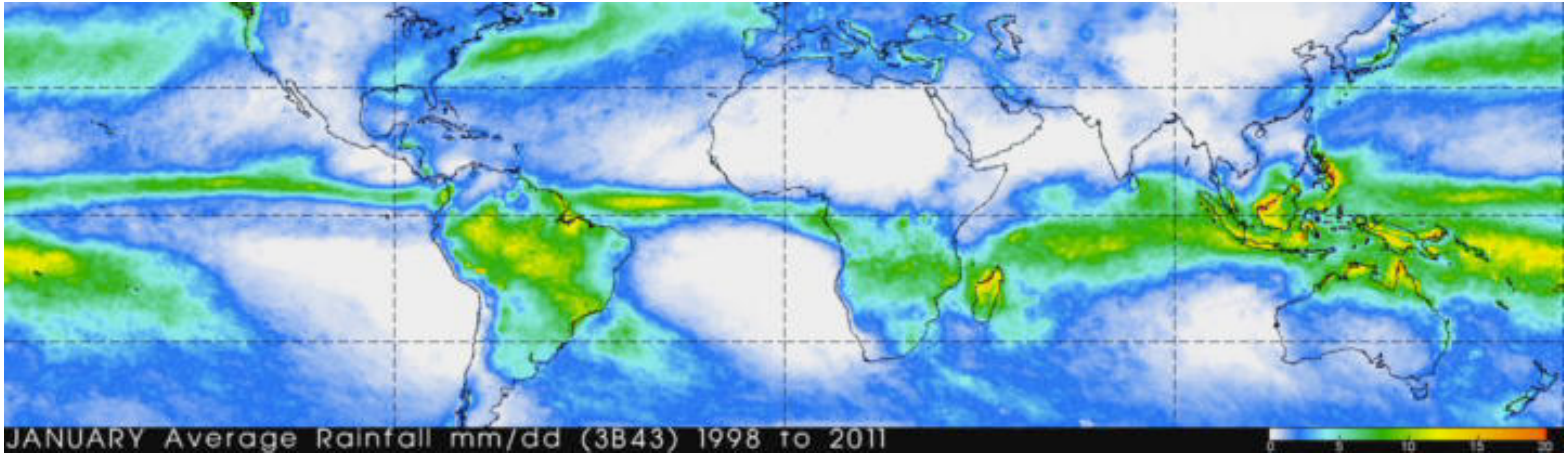
ERA-40 Atlas

Earth's water cycle: moisture transport



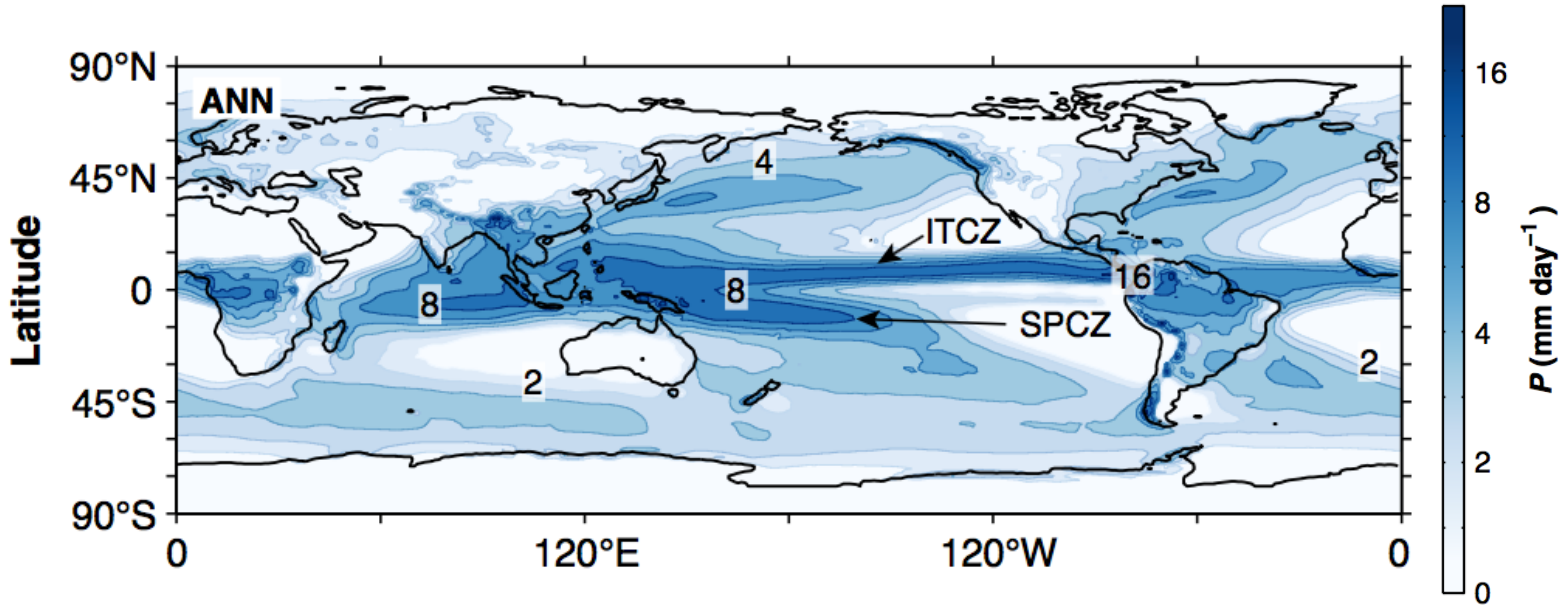
from Schneider's "Physics of Earth's Climate"

Earth's water cycle: precipitation



Tropical Rainfall Measuring Mission (TRMM)

Earth's water cycle: precipitation



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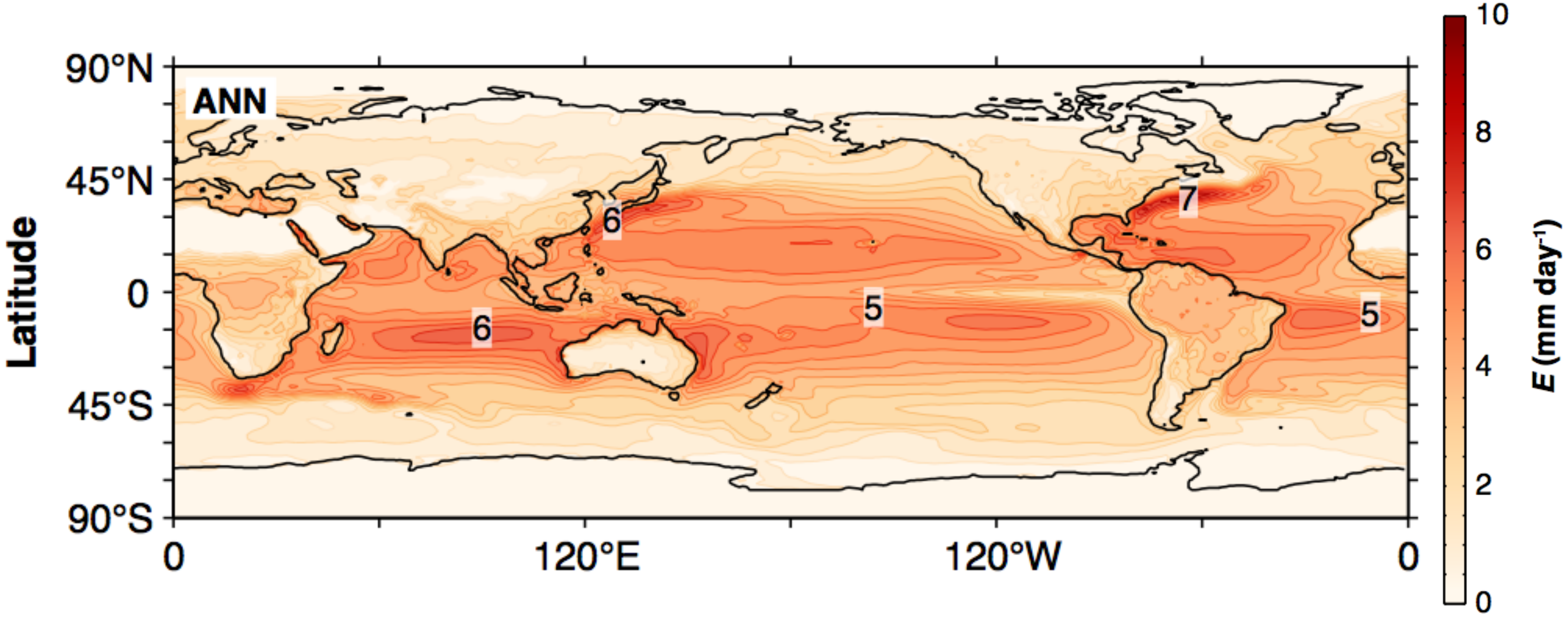
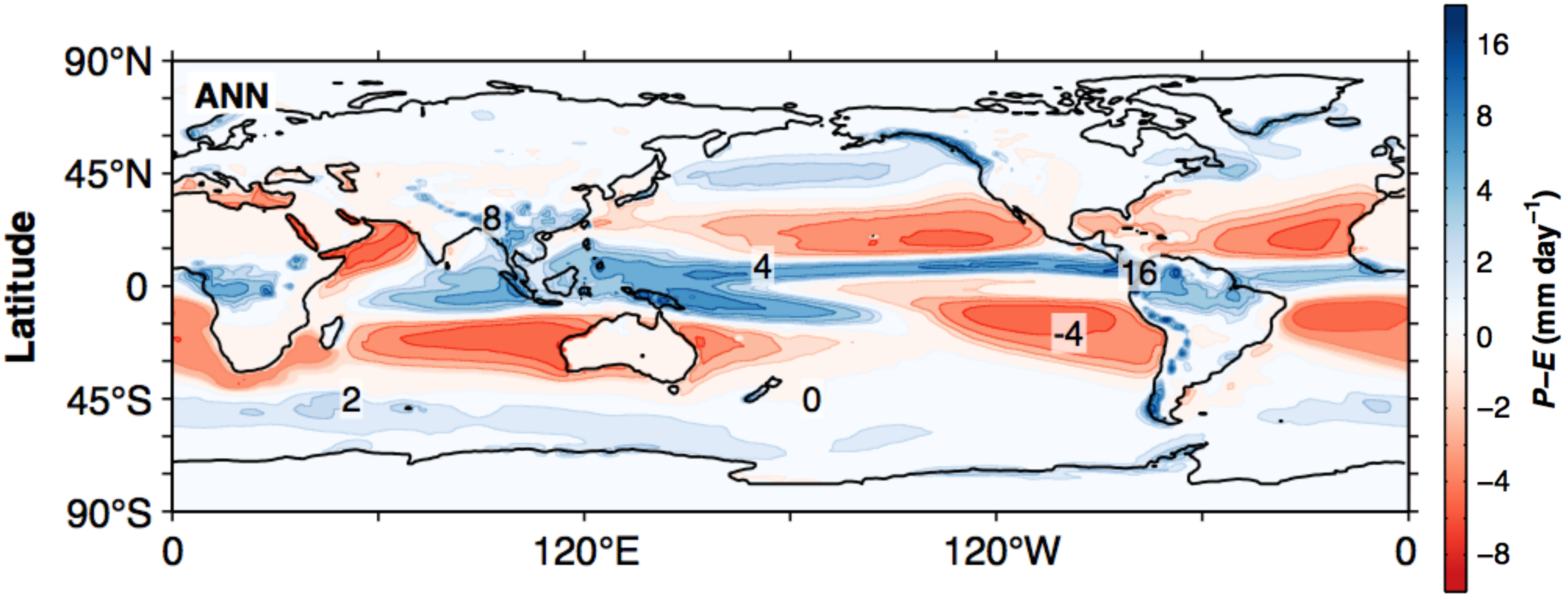
Earth's water cycle: evaporation



from Schneider's "Physics of Earth's Climate"

Earth's water cycle: *net* precipitation (P-E)



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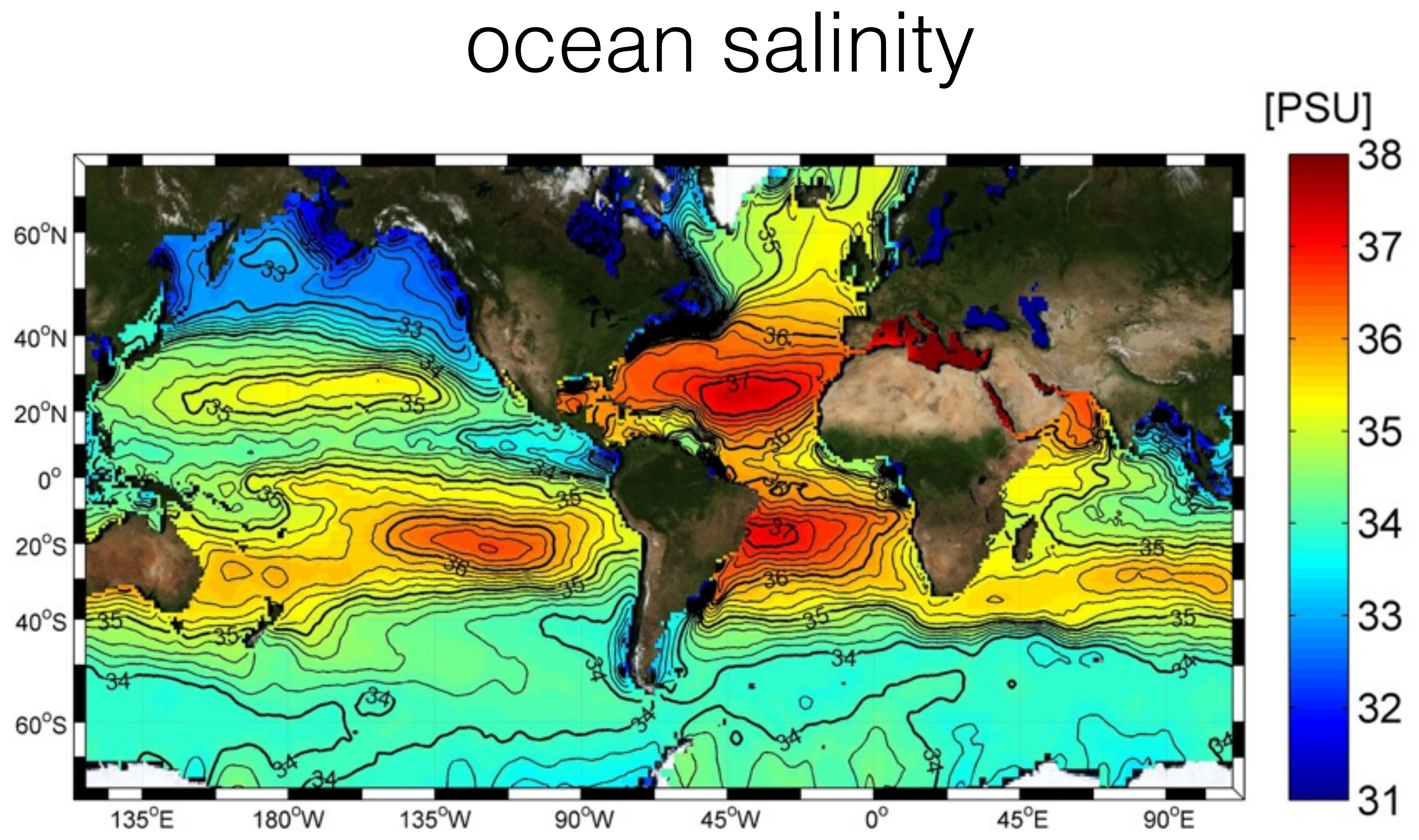
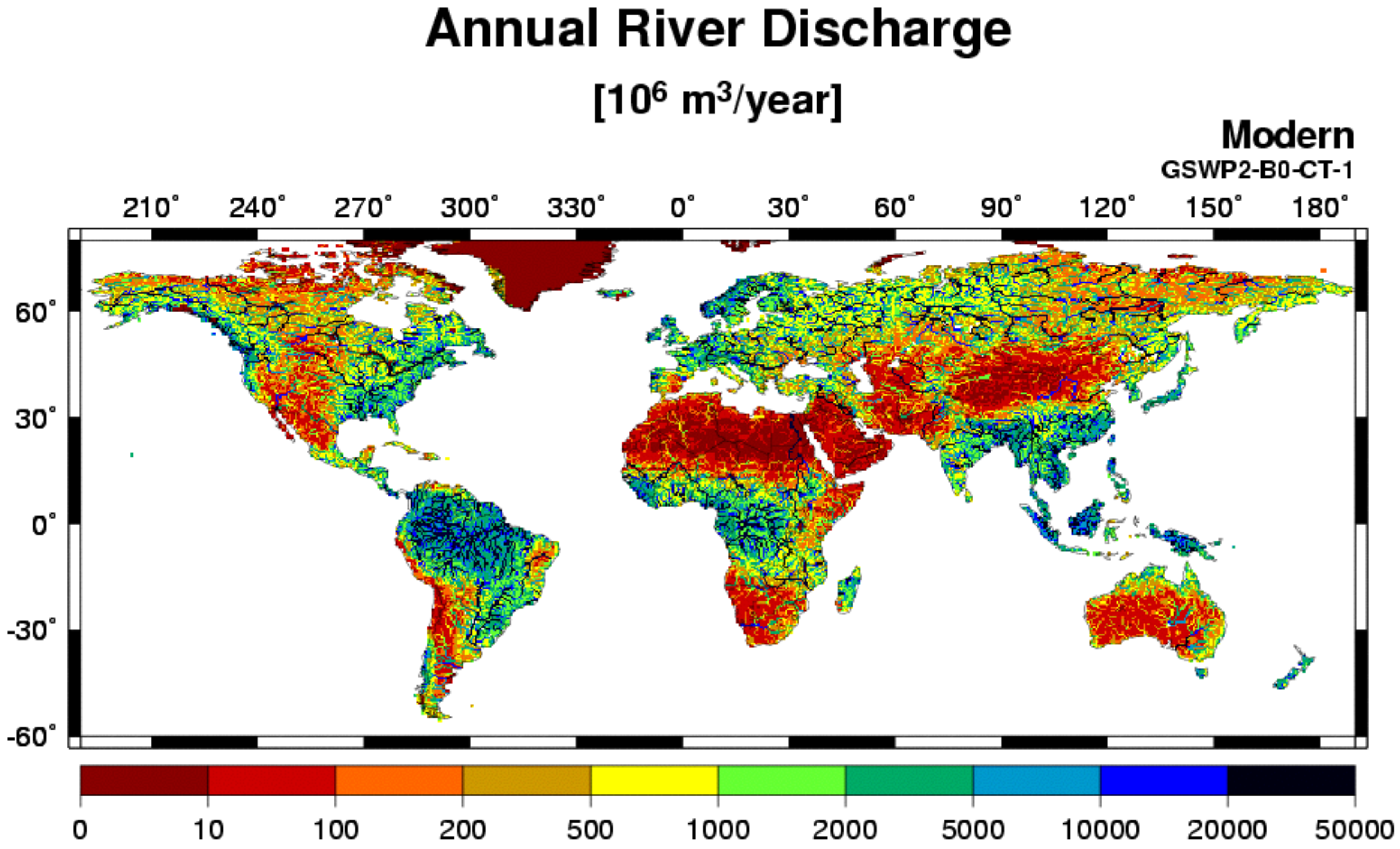
Earth's water cycle: Impact of *P-E* on oceans and continents

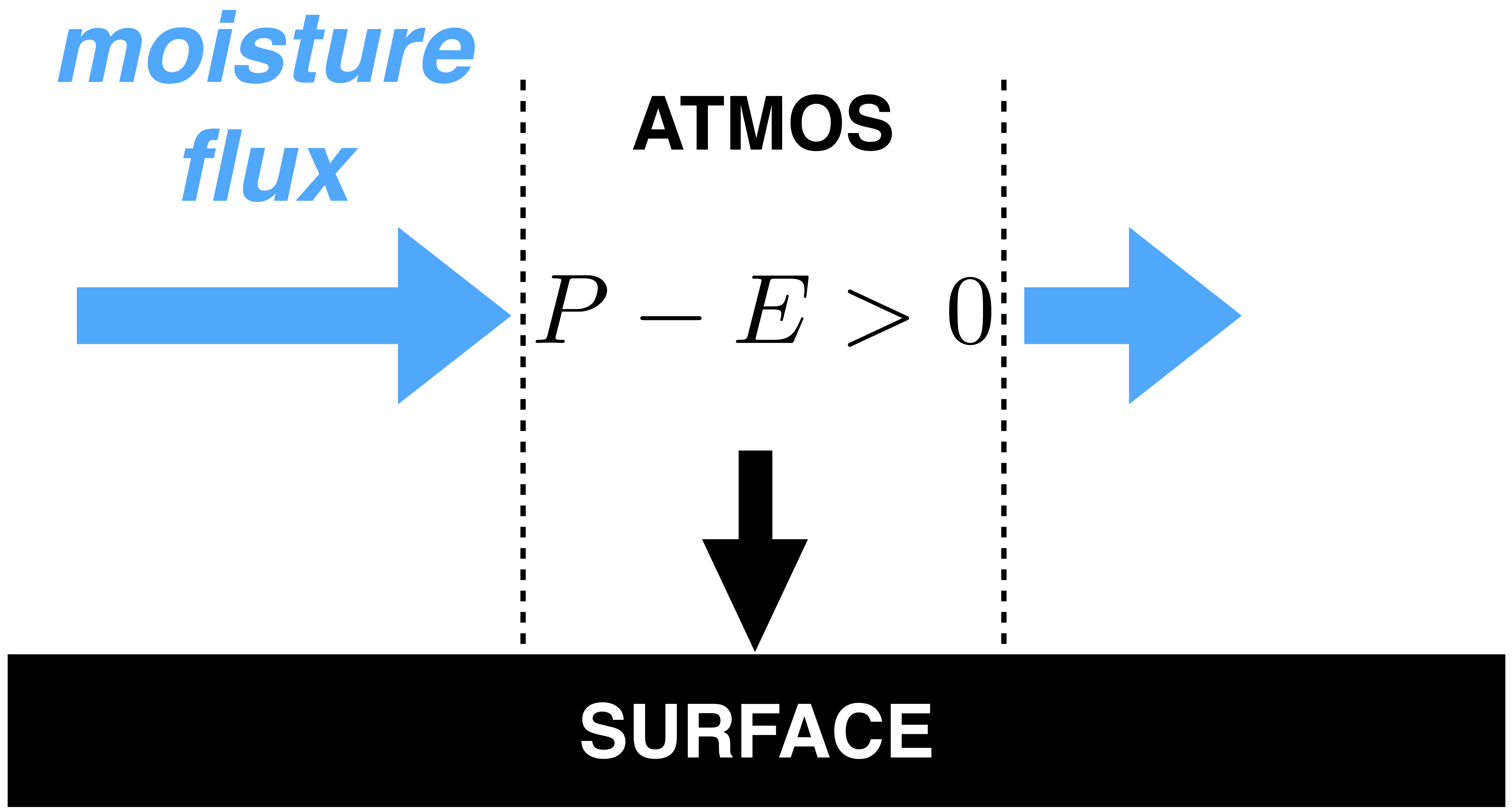




World Ocean Atlas (2005)

Global Water Resource Archive

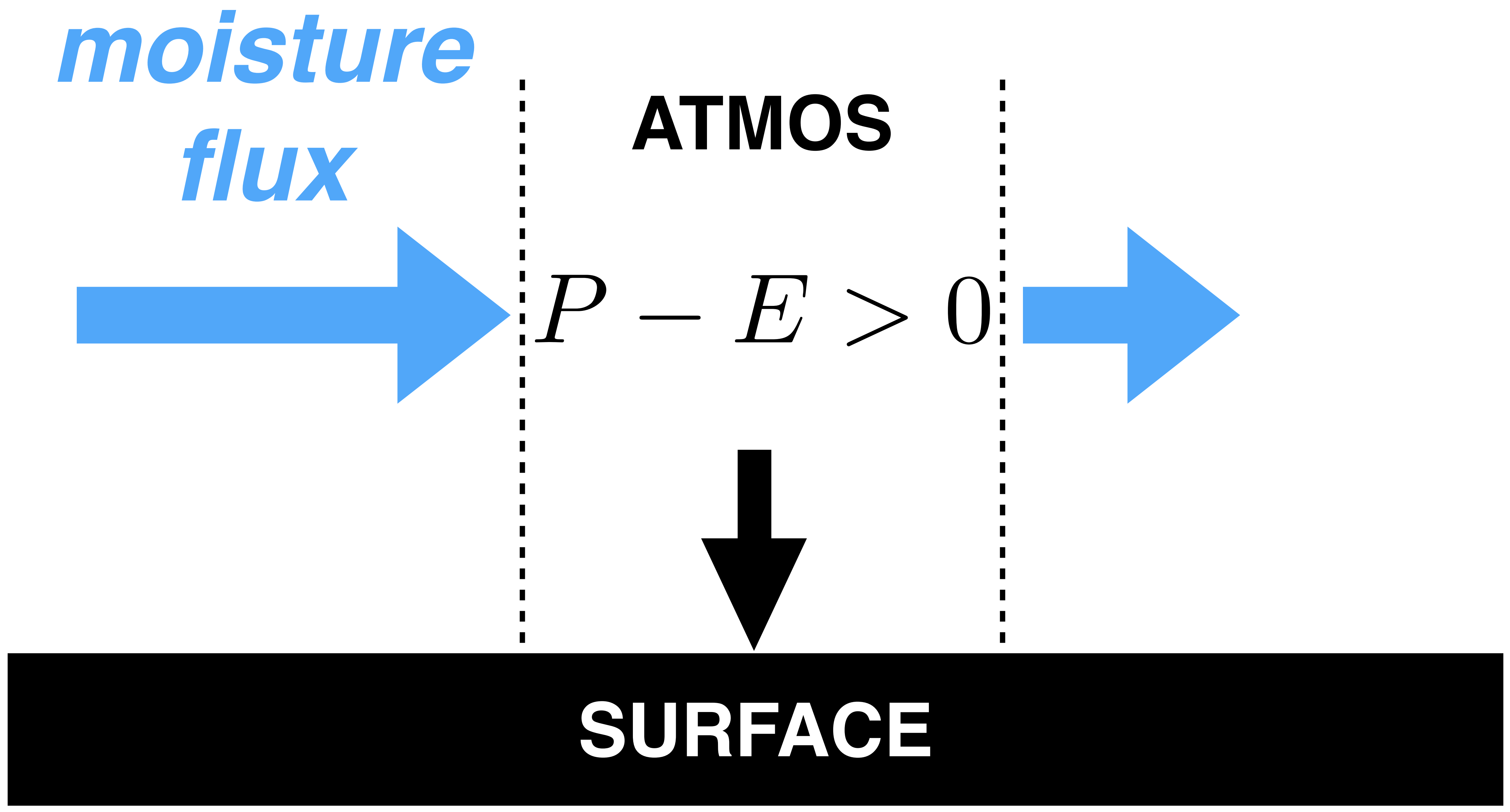
Earth's water cycle: P-E and the atmospheric circulation



$$P - E = -\nabla \cdot \mathbf{F} = -\nabla \cdot [q\mathbf{u}]$$
$$\approx -[q\nabla \cdot \mathbf{u}]$$

from Schneider's "Physics of Earth's Climate"

Earth's water cycle: P-E and the atmospheric circulation



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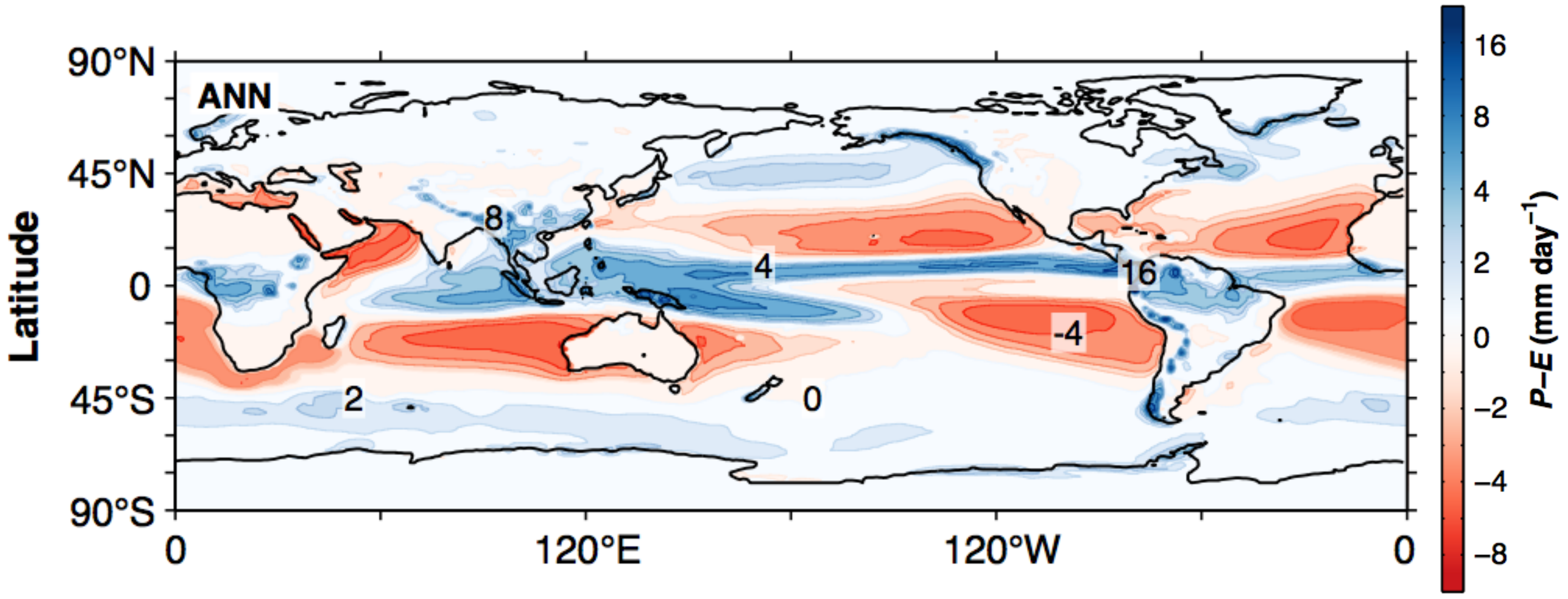
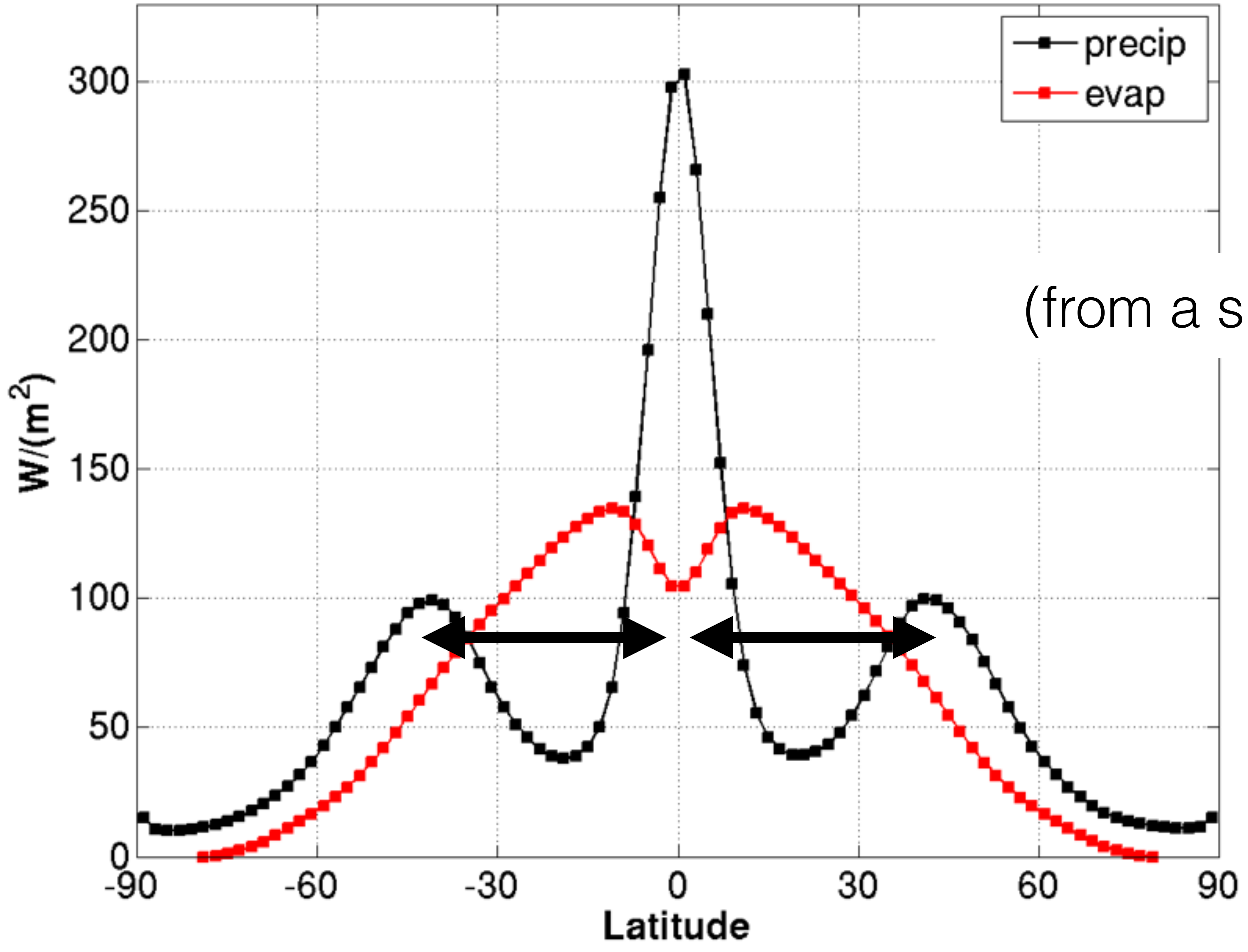


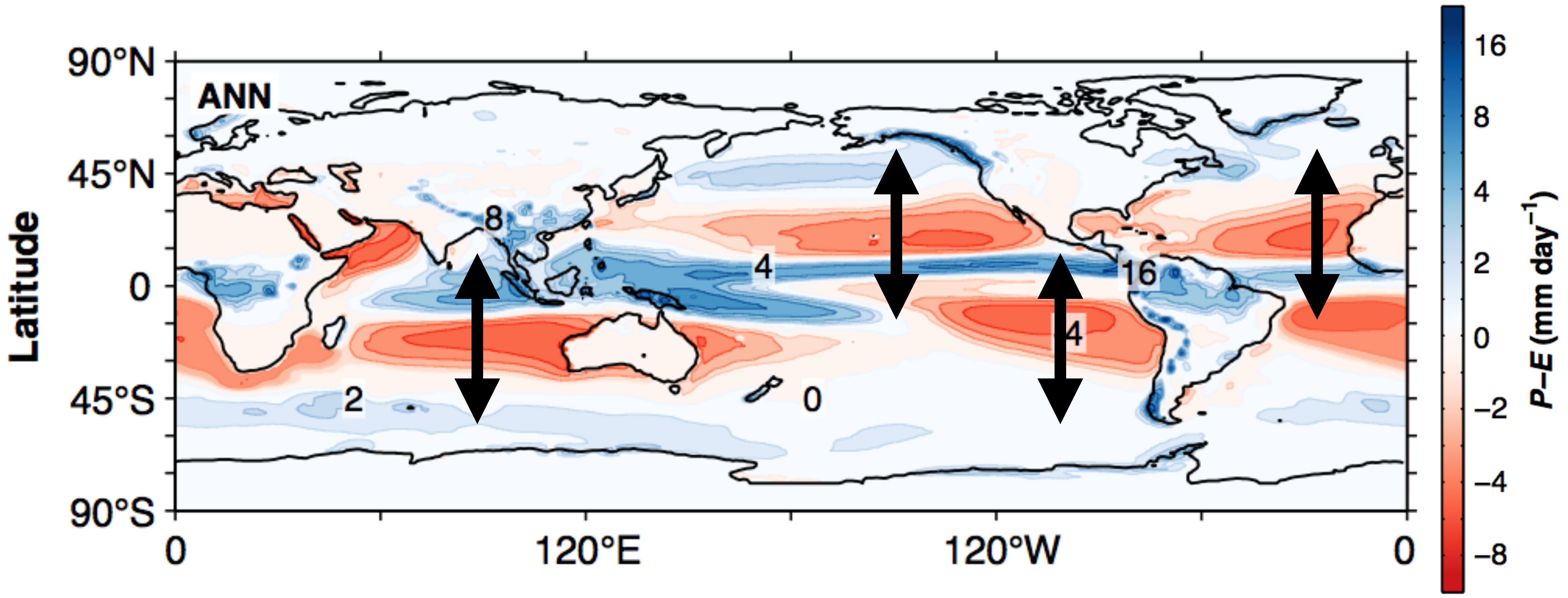
from Schneider's "Physics of Earth's Climate"

Atmosphere moves moisture from dry subtropics (P-E < 0) to moist tropics & extratropics (P-E > 0)

$$P - E = -\nabla \cdot \mathbf{F} = -\nabla \cdot [q\mathbf{u}]$$
$$\approx -[q\nabla \cdot \mathbf{u}]$$



(from a simulation)



Geophysical Fluid Dynamics Laboratory model