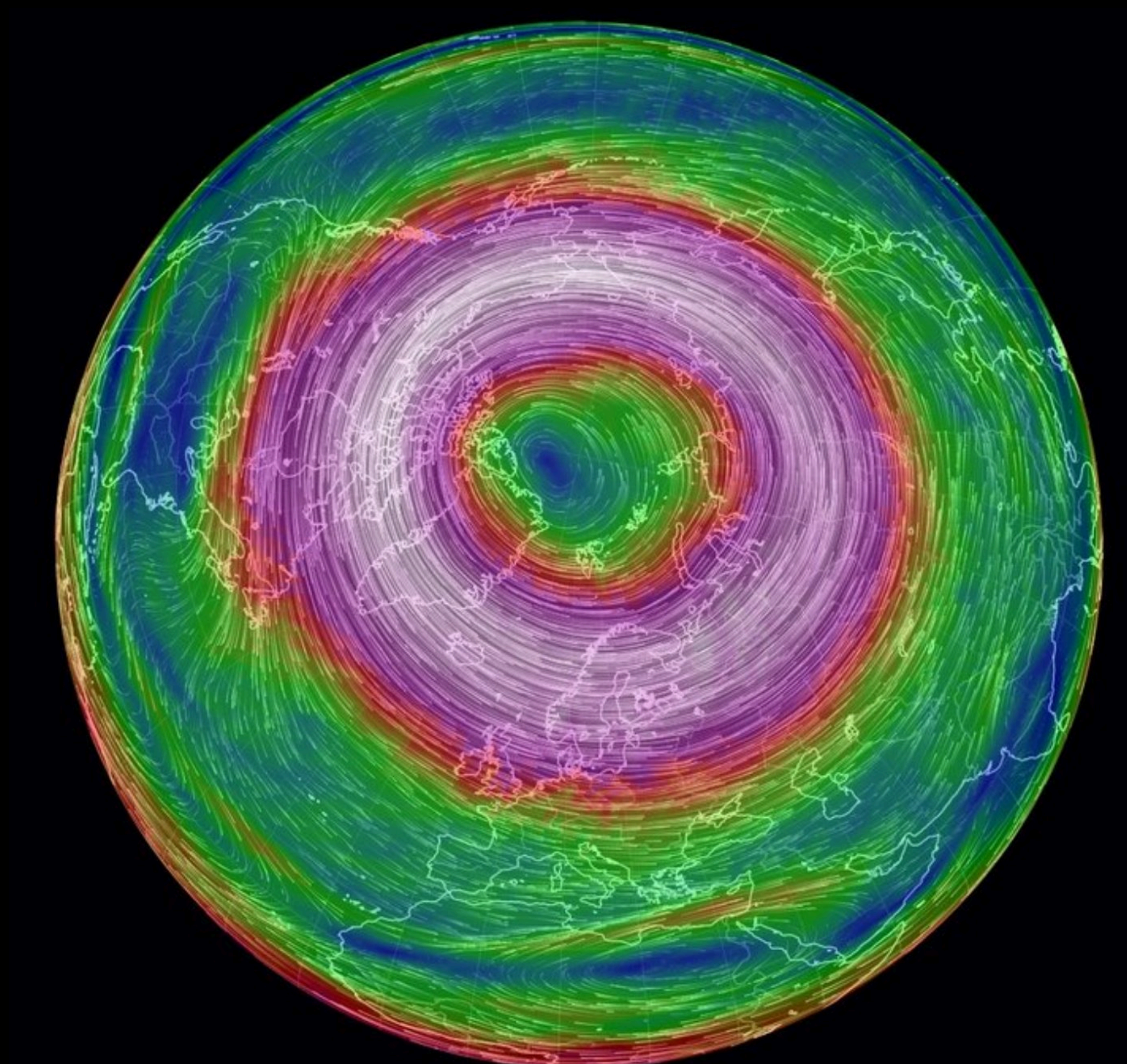
Large-scale Atmospheric Dynamics



Corentin Herbert

M2 ENS Lyon GFD Week 01/23

Outline

1. **Introduction:** a brief remainder of the observed structure of the general circulation of the atmosphere, and its role in the climate system

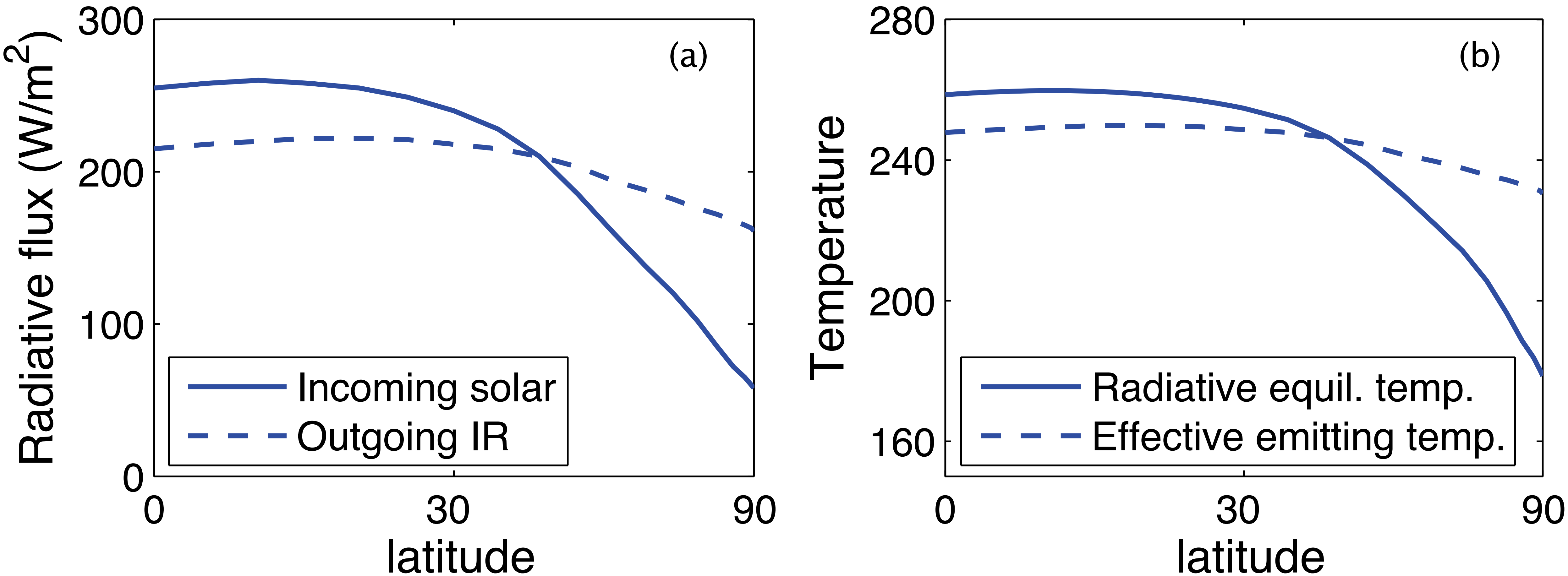
2. **Basic concepts:** equations of motion, hydrostatic balance, Rossby number, geostrophic balance, Boussinesq approximation, thermal wind

3. **Tropical circulation:** Held & Hou model of the Hadley cell

4. **Mid-latitude circulation:** quasi-geostrophic equations, baroclinic instability

Introduction

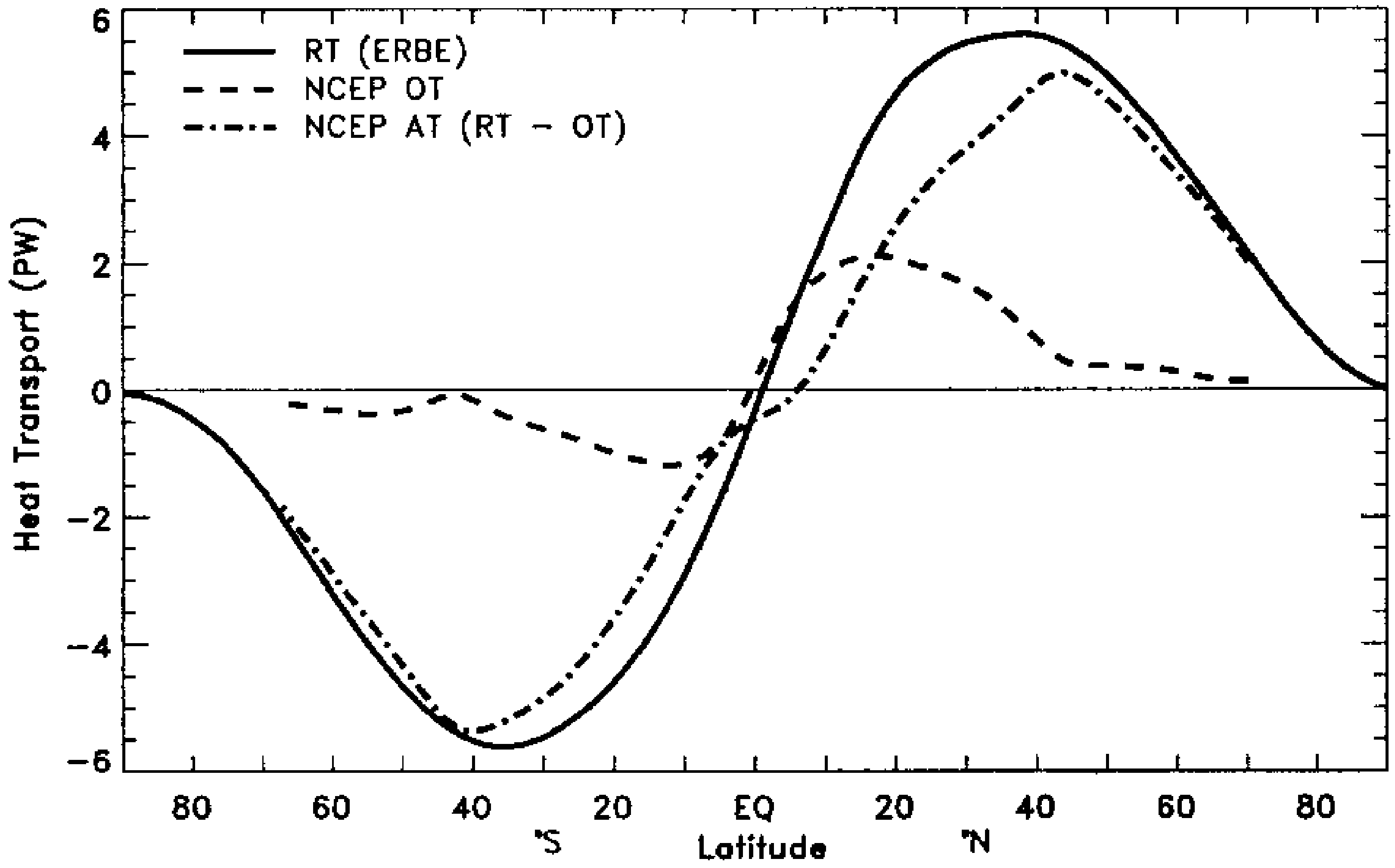
Net radiative budget at the top of the atmosphere



- **The radiative budget is not horizontally homogeneous: the tropics receive an excess of energy, the high-latitudes have a shortfall of energy**
- **The resulting energy transport reduces the meridional temperature gradient**

Vallis, AOFD, Chap. 14

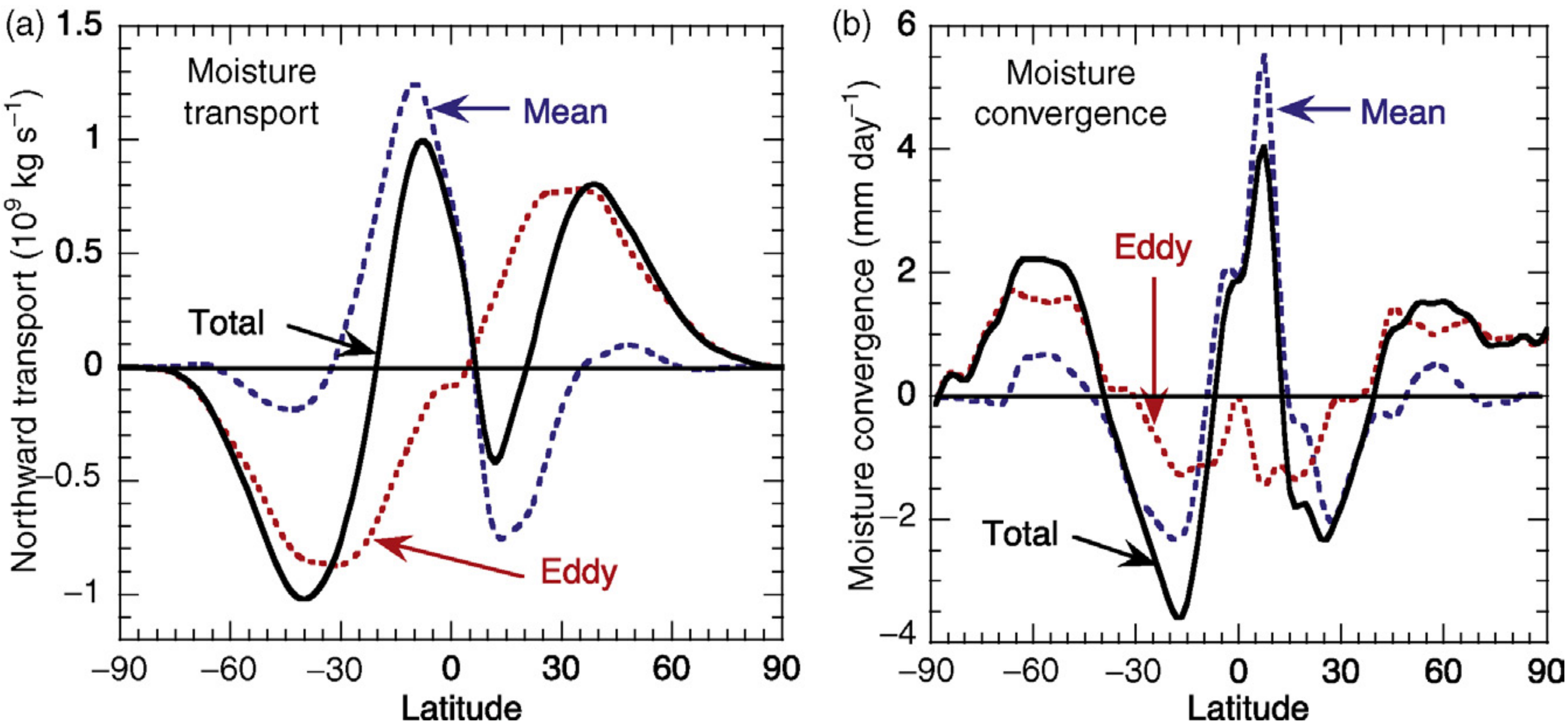
Poleward energy transport



- **The atmosphere and ocean transport energy from the equator towards the poles.**
- **The atmosphere dominates at mid- and high-latitudes. The ocean contributes mostly at low-latitudes.**

Trenberth & Caron, *J. Climate* (2001)

Water vapor transport

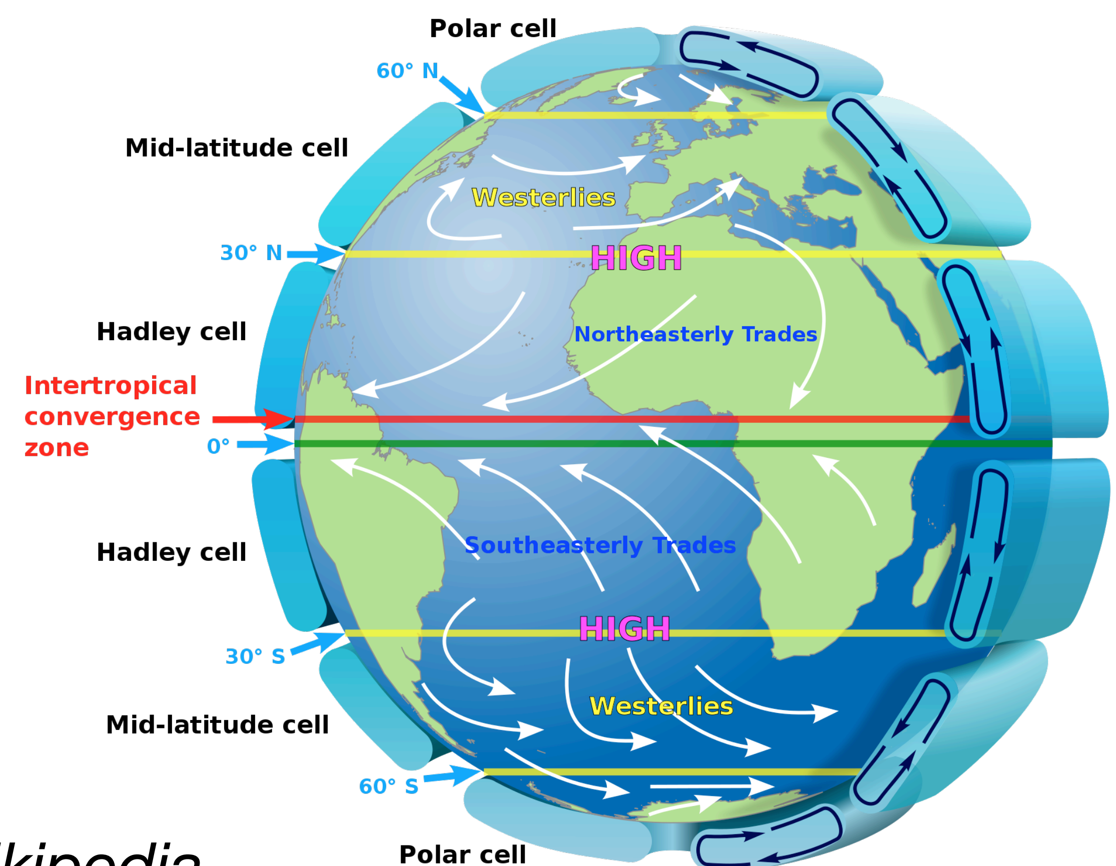


- Deserts in the subtropics
- Wet climates in equatorial zones and mid-latitudes

Hartmann, *Global Physical Climatology*

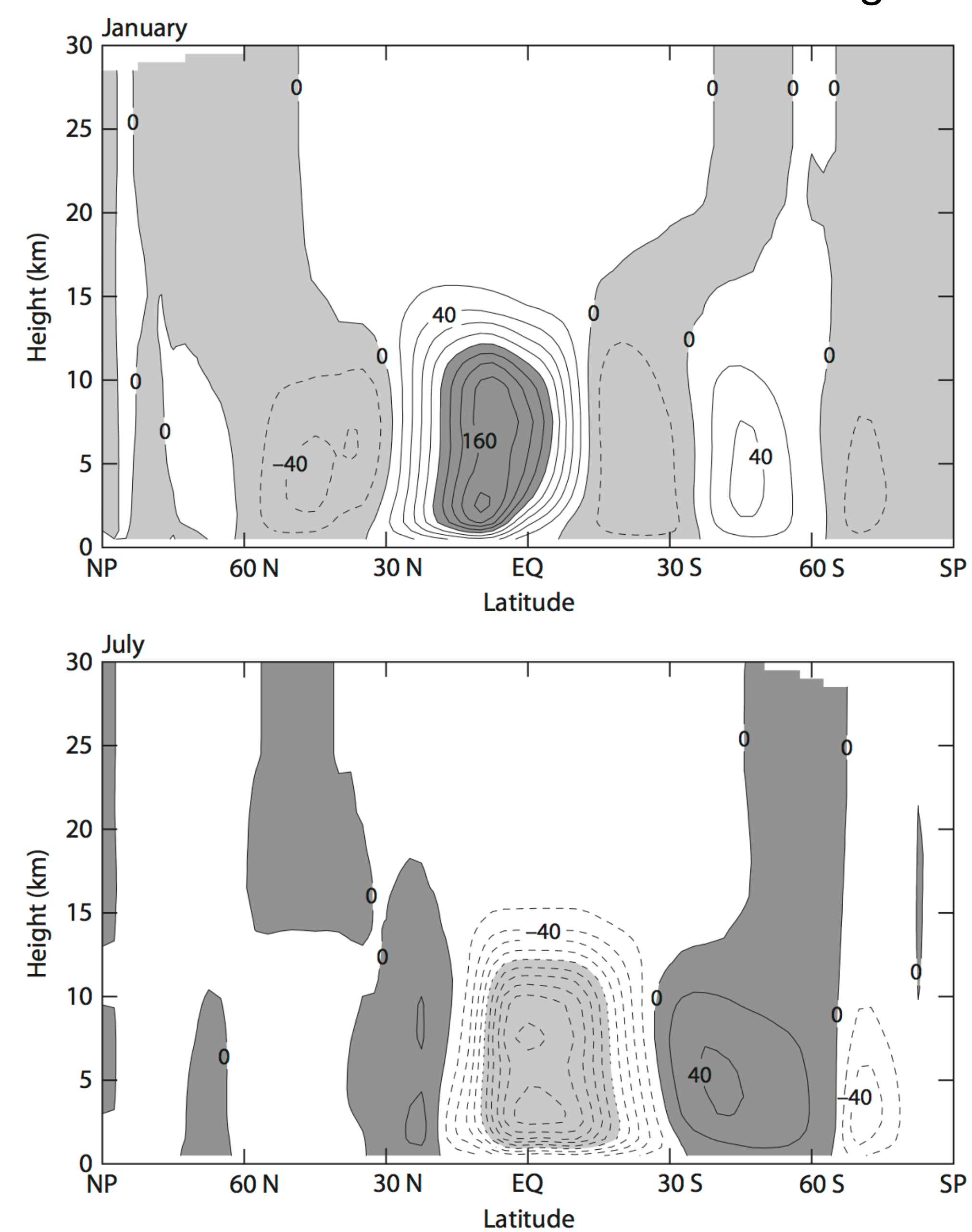
Tropical circulation

Mean Meridional Circulation



Wikipedia

Ψ in 10^9 kg.s^{-1}



mean meridional circulation is entirely described by a *stream function:*

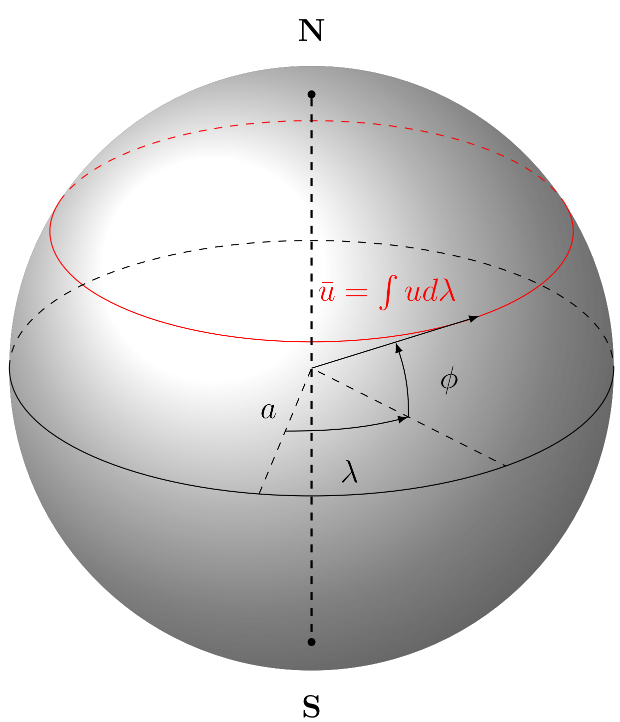
$$\bar{\omega} = \frac{-g}{2\pi a^2 \cos\phi}\frac{\partial \Psi}{\partial \phi},$$

$$\bar{v} = \frac{g}{2\pi a \cos\phi}\frac{\partial \Psi}{\partial p}.$$

Randall, *Atmosphere, Clouds and Climate*

Winds: the subtropical jet

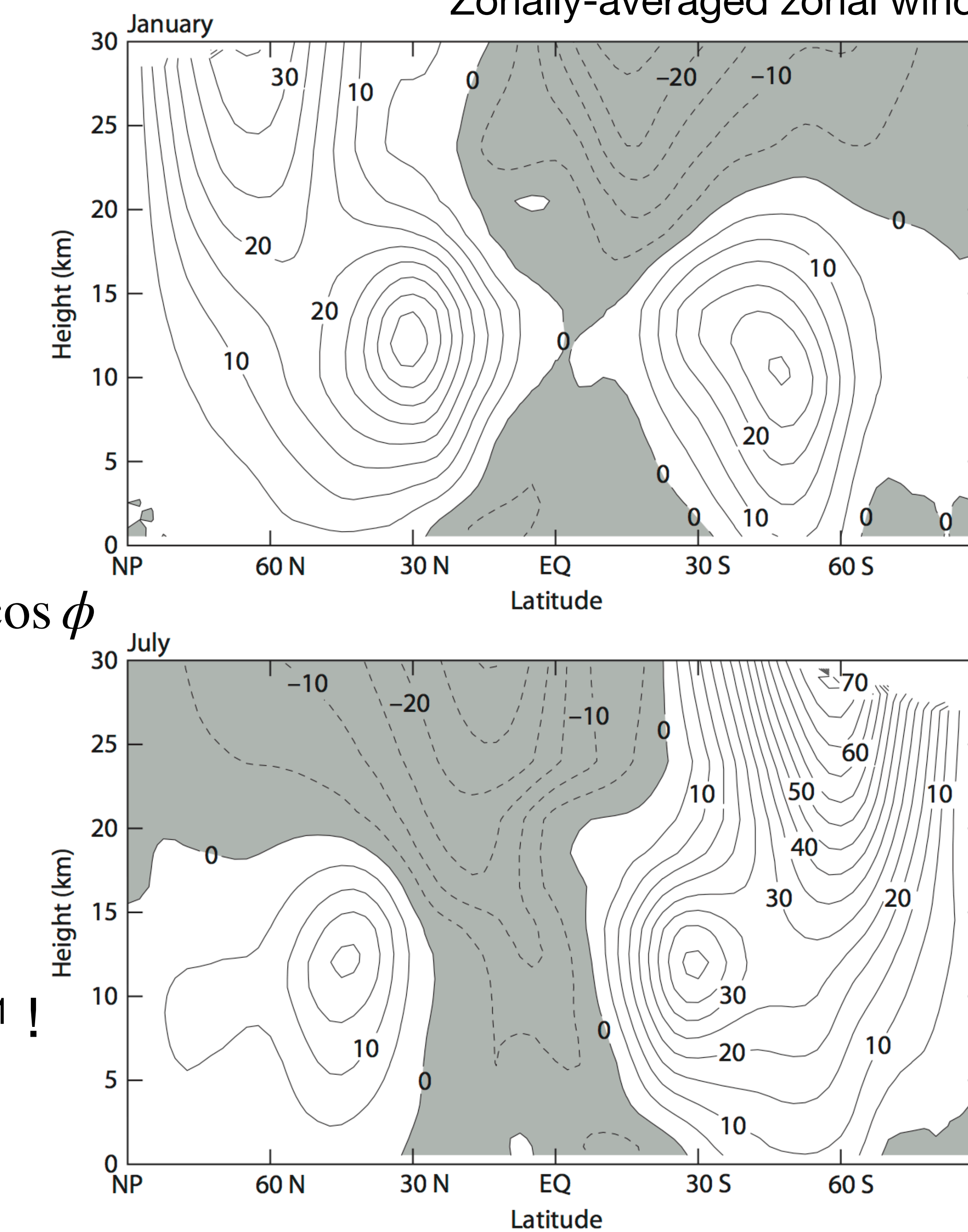
Angular momentum conservation
➔ upper-level westerlies at the poleward edge of the Hadley cell



$$\partial_t M + \bar{\mathbf{u}} \cdot \nabla M = 0$$

$$M = (\bar{u} + \Omega a \cos\phi) a \cos\phi$$

Zonally-averaged zonal wind



Angular momentum conserving wind:

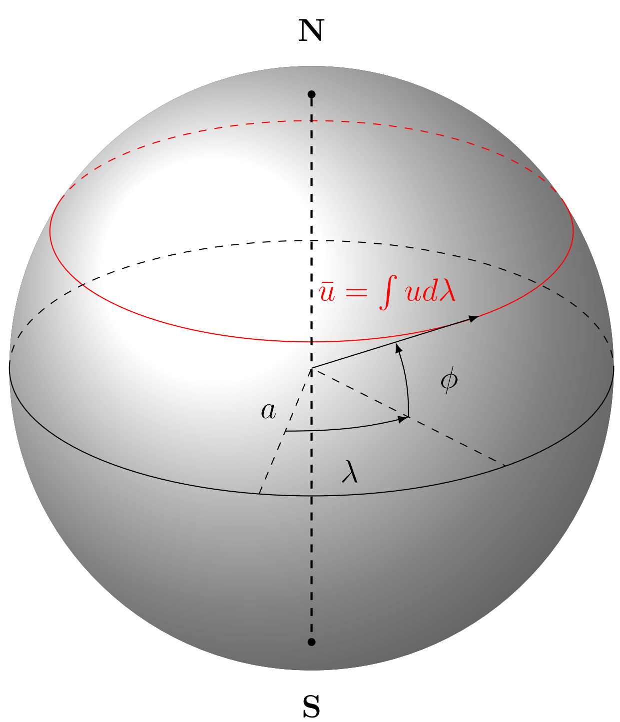
$$U_M = \Omega a \frac{\sin^2\phi}{\cos\phi} \quad \Rightarrow \quad U_M(\phi = 30N) = 134 \text{ m.s}^{-1} \text{ !}$$

Eddies decrease angular momentum

Randall, *Atmosphere, Clouds and Climate*

Angular momentum budget

Angular momentum conservation
➡ upper-level westerlies at the poleward edge of the Hadley cell



$$\partial_t M + \bar{\mathbf{u}} \cdot \nabla M = 0$$

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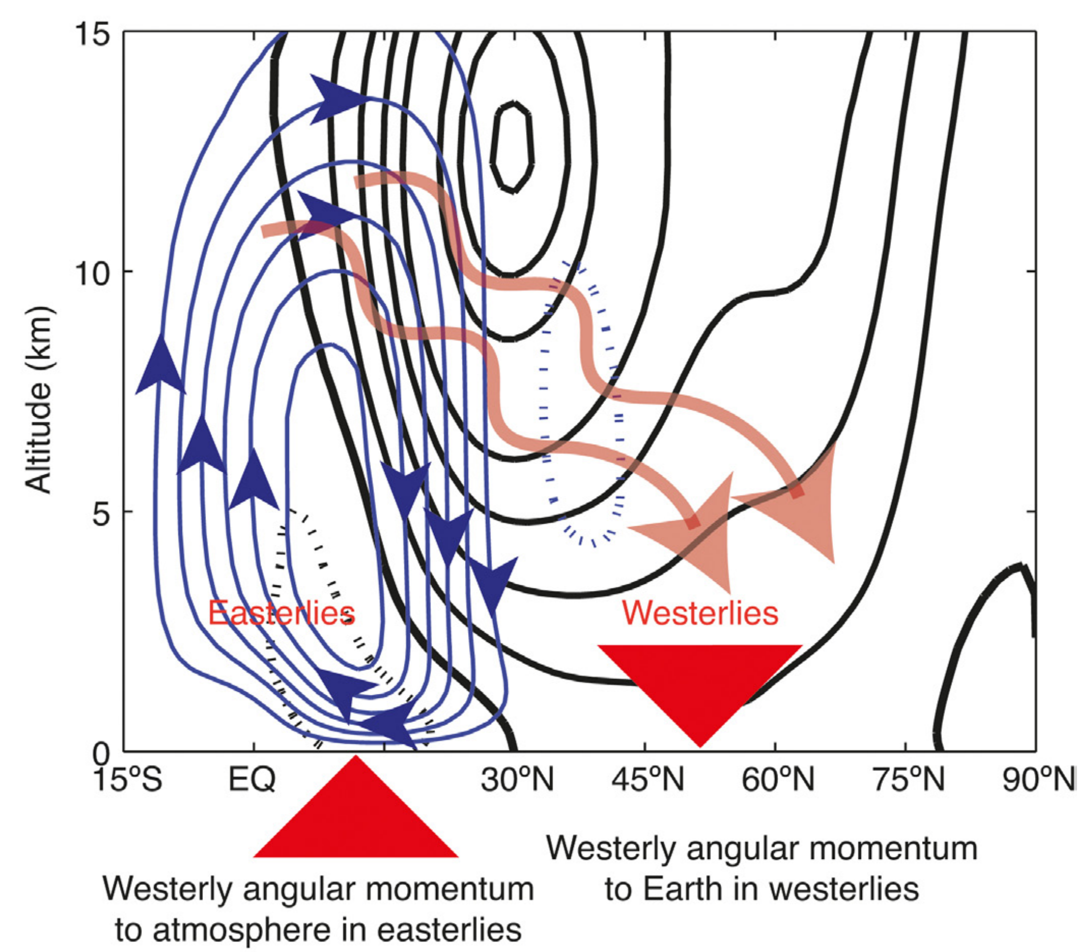
Angular momentum conserving wind:

$$U_M = \Omega a \frac{\sin^2\phi}{\cos\phi} \rightarrow U_M(\phi = 30N) = 134 \text{ m.s}^{-1} \text{ !}$$

Eddies decrease angular momentum

Surface friction exchanges angular momentum between the atmosphere and the planet



Hartmann, *Global Physical Climatology*

Model of the Hadley cell

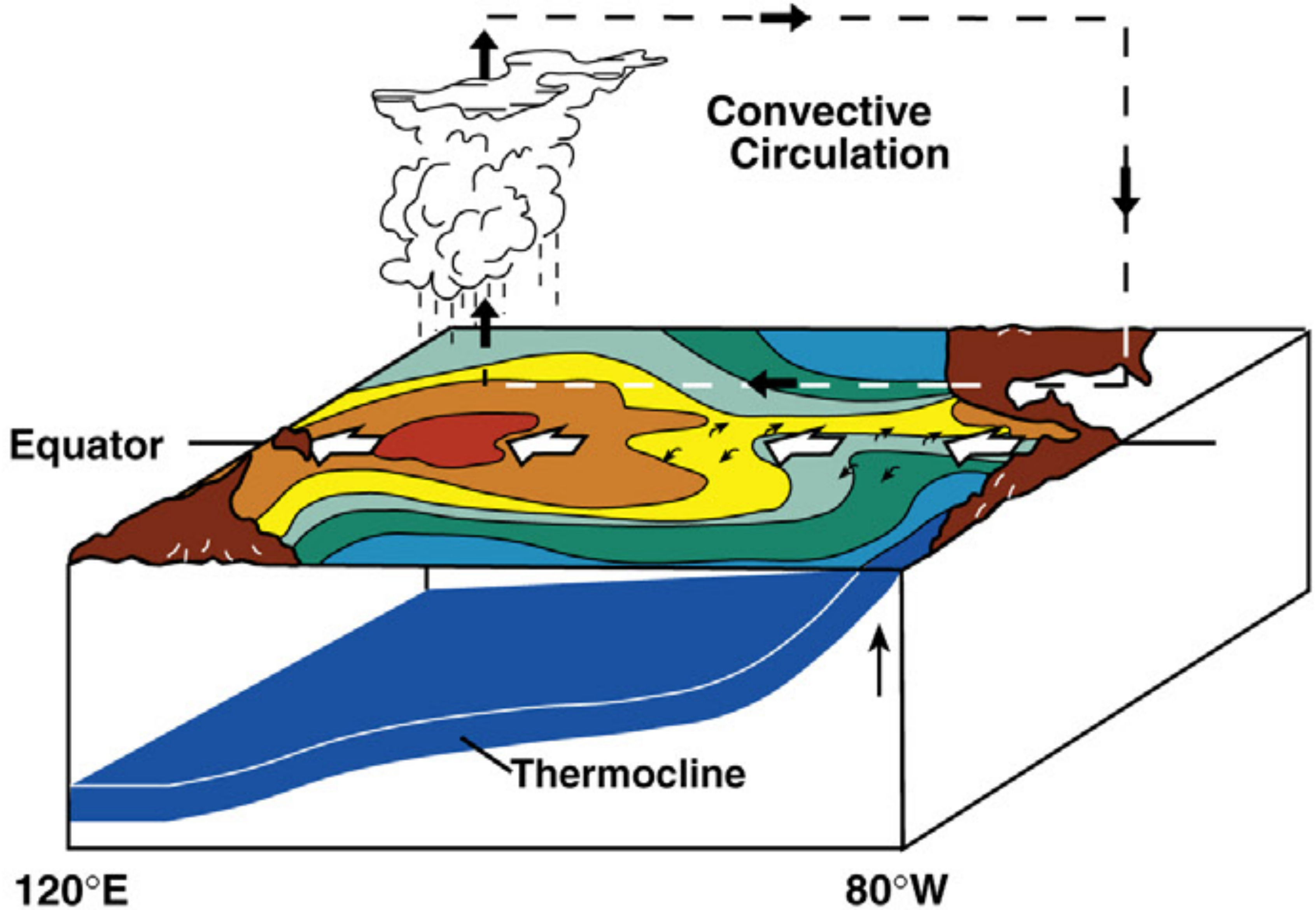
1. Fundamental concepts: equations of motion, hydrostatic balance, geostrophic balance, thermal wind
2. The Boussinesq approximation
3. The Held-Hou model of the Hadley cell

Blackboard

Atmospheric convection

The Walker circulation

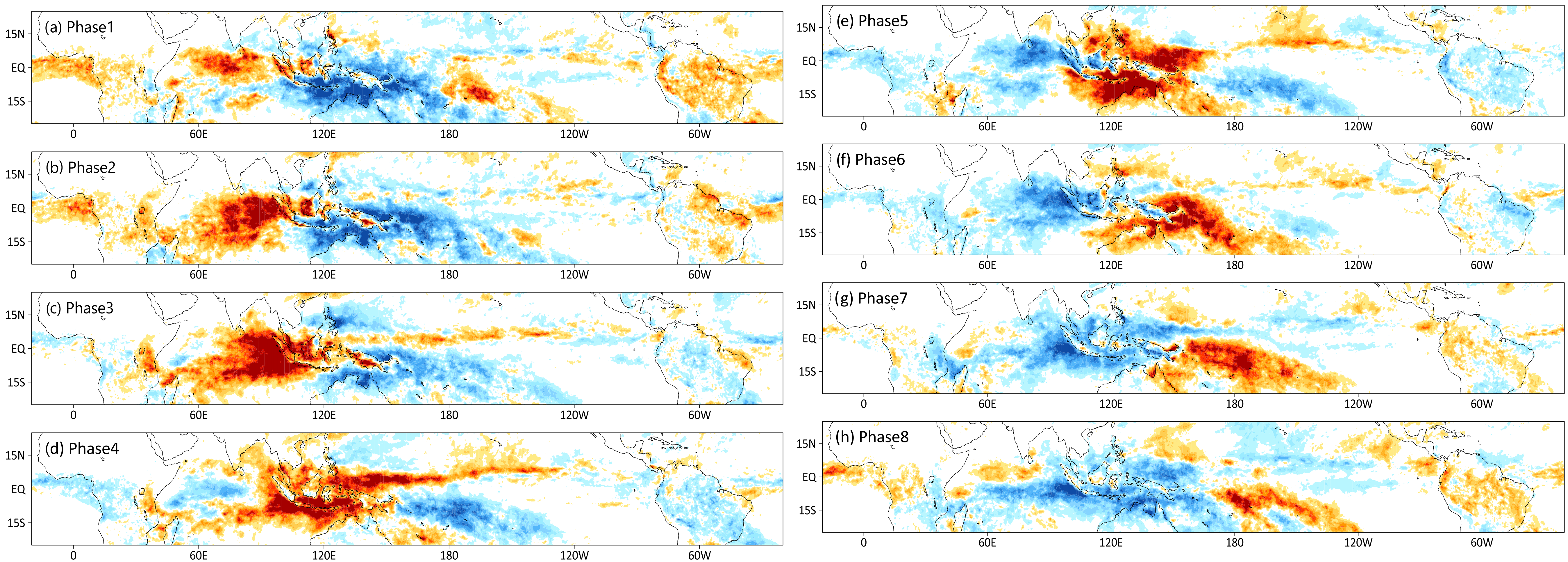
Driven by zonal temperature gradients



The circulation in the tropics is not axisymmetric!

Hartmann, *Global Physical Climatology*

The Madden-Julian circulation

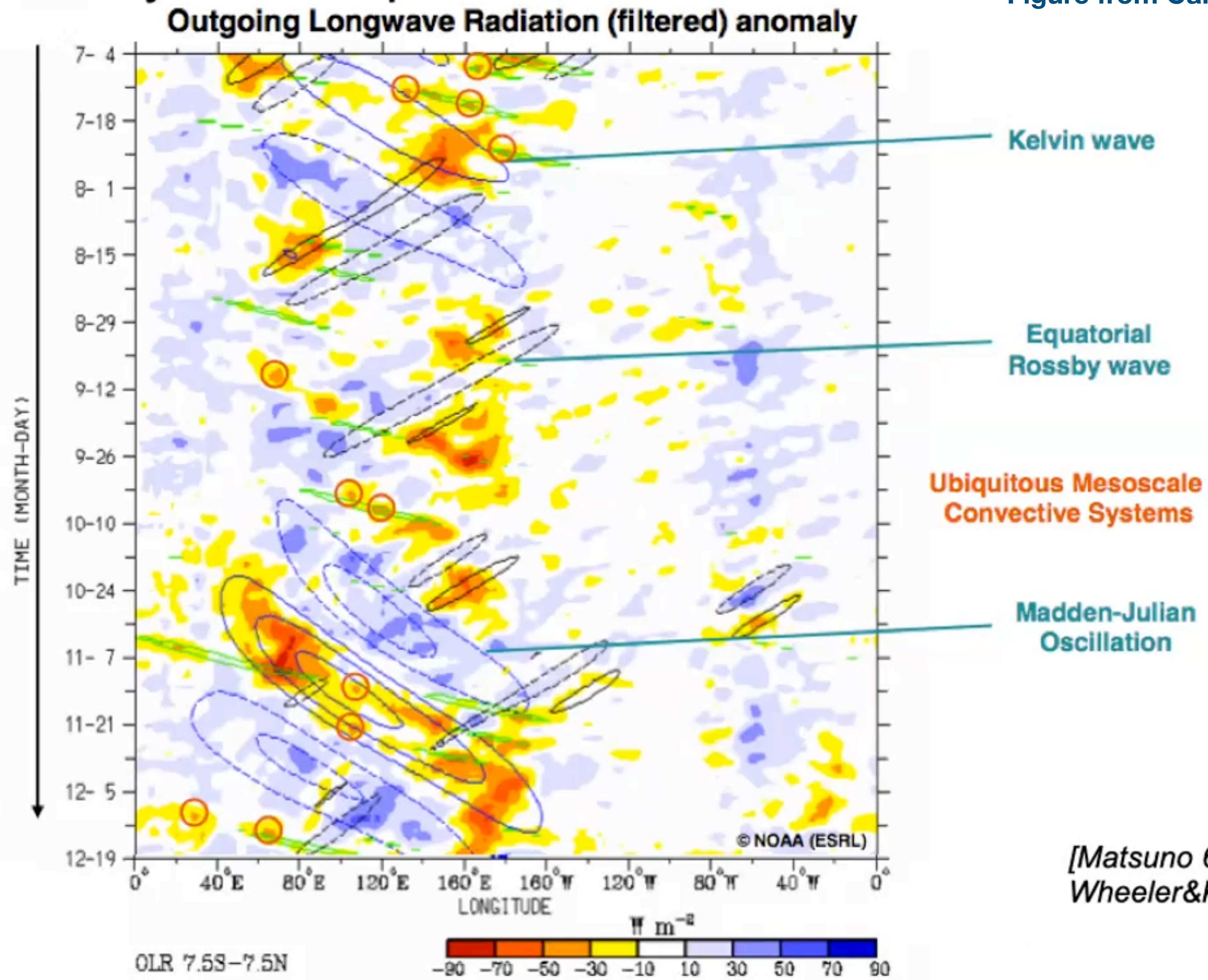


The circulation in the tropics is not axisymmetric!

Jiang et al. (2020)

OLR anomaly in the tropics :

Figure from Caroline Muller



[Matsuno 66; Wheeler&Kiladis 99]

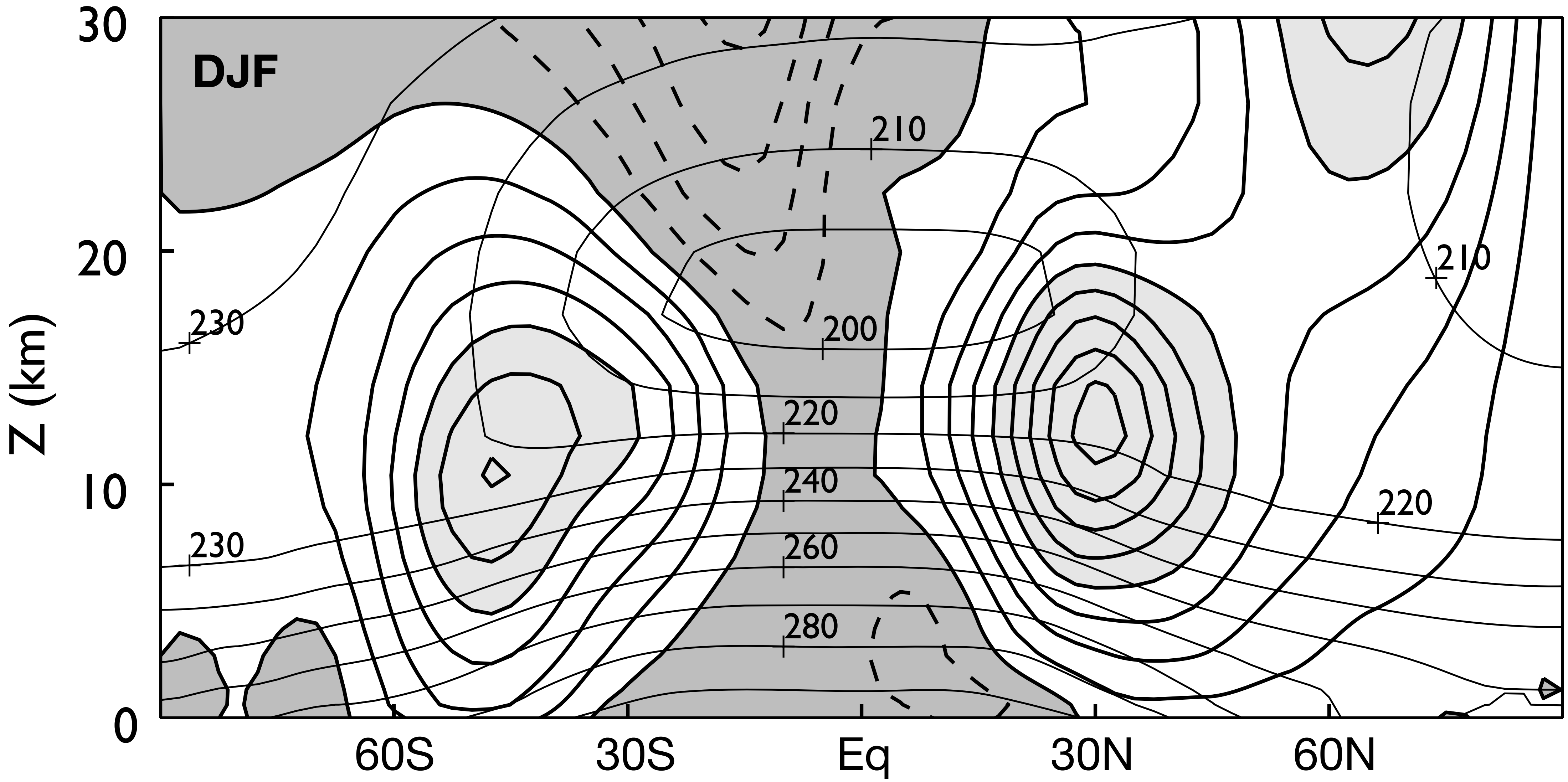
The circulation in the tropics is not axisymmetric!

Mid-latitude circulation

The Jet Stream

https://svs.gsfc.nasa.gov/10902

Baroclinic structure of the mid-latitudes



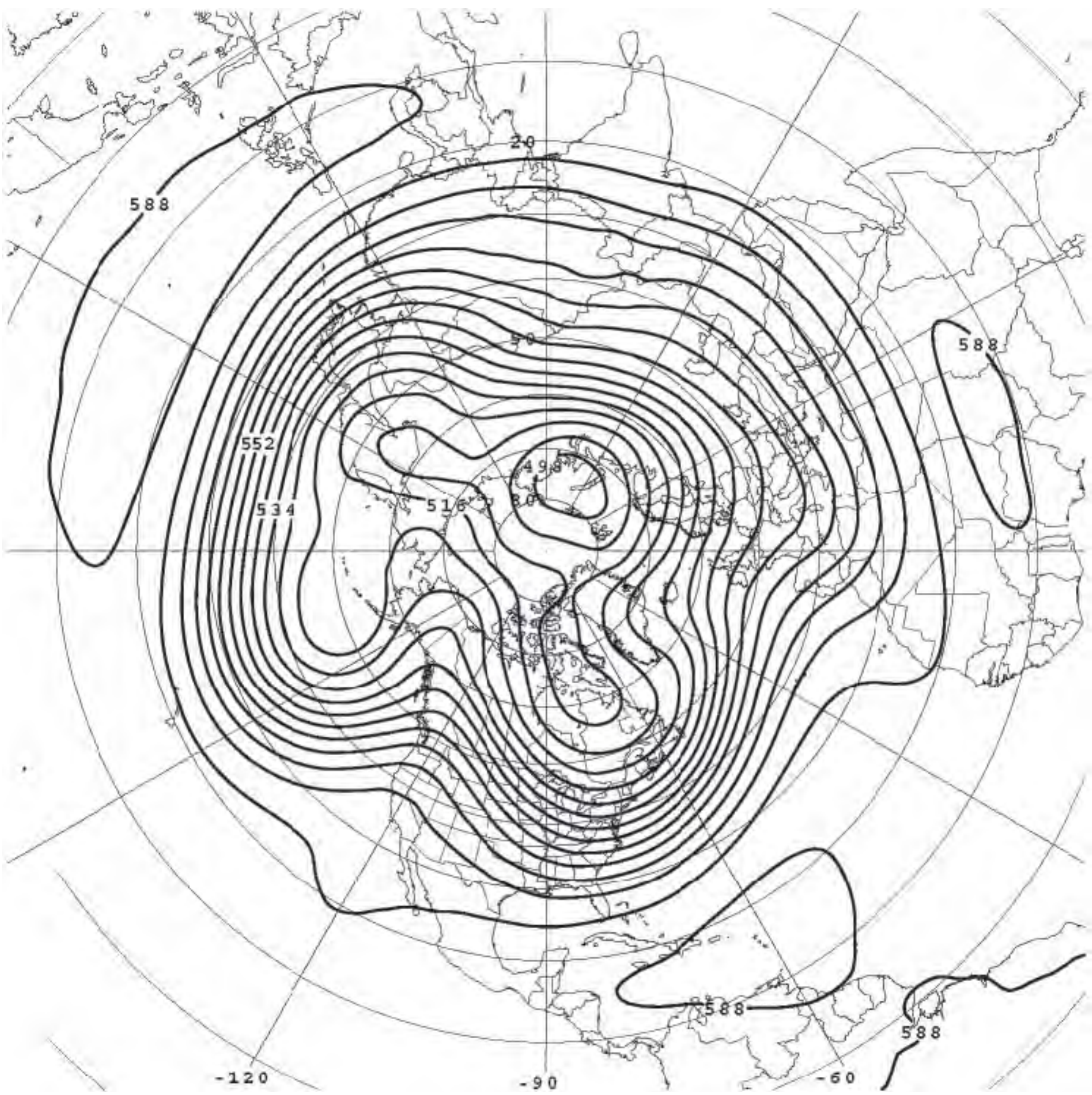
Wind contour: 5 m.s^{-1}

Barotropic fluid: $\rho(p)$
Baroclinic fluid: $\rho(p, T)$

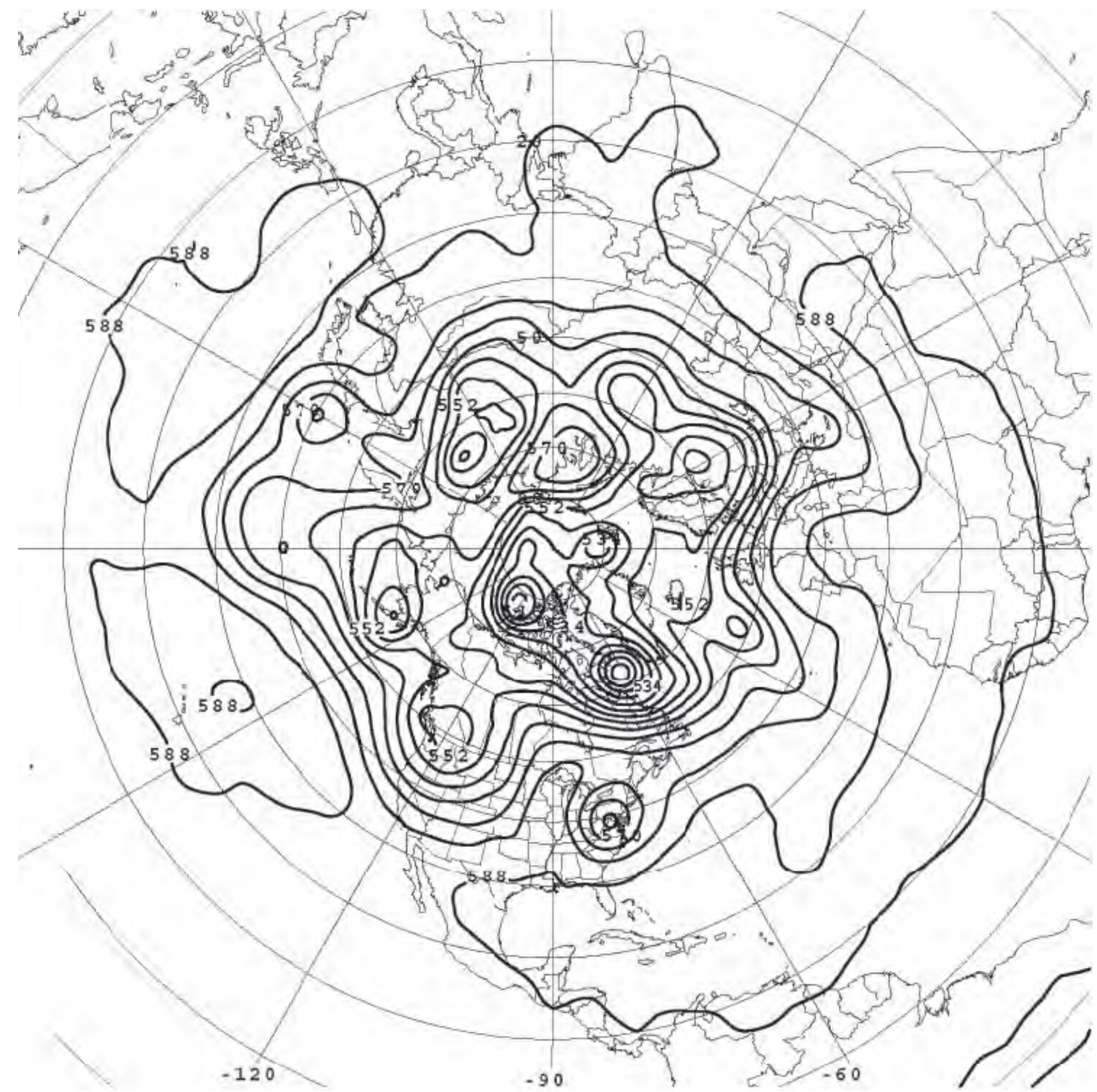
Vallis, *AOFD*, Chap. 14

Mid-latitude weather systems

500 hPa geopotential height $Z = \Phi / g$



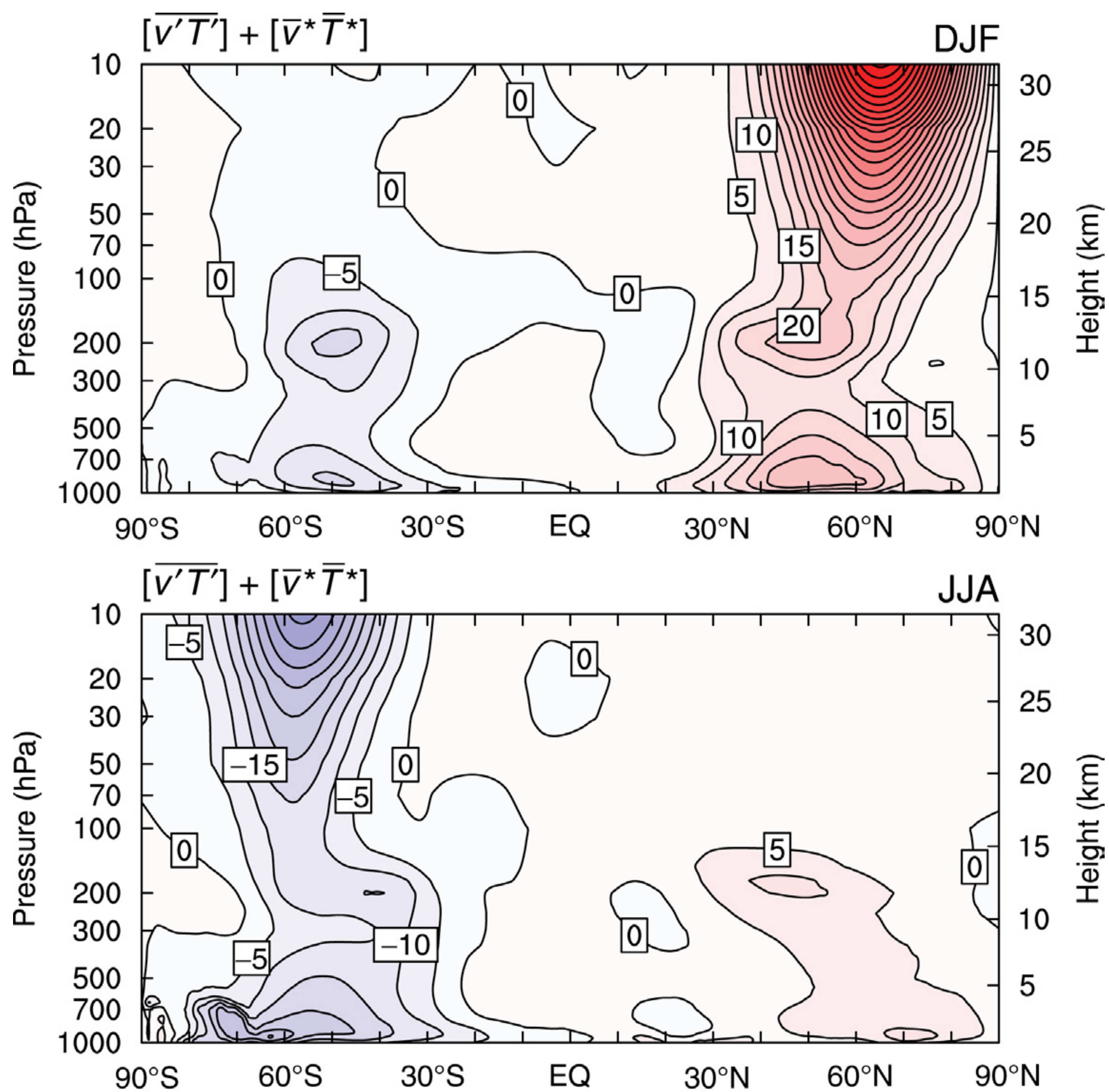
Monthly Mean, January 2003



12 GMT June 21, 2003

Marshall & Plumb, *Atmosphere, Ocean, and Climate Dynamics*

Eddy heat fluxes



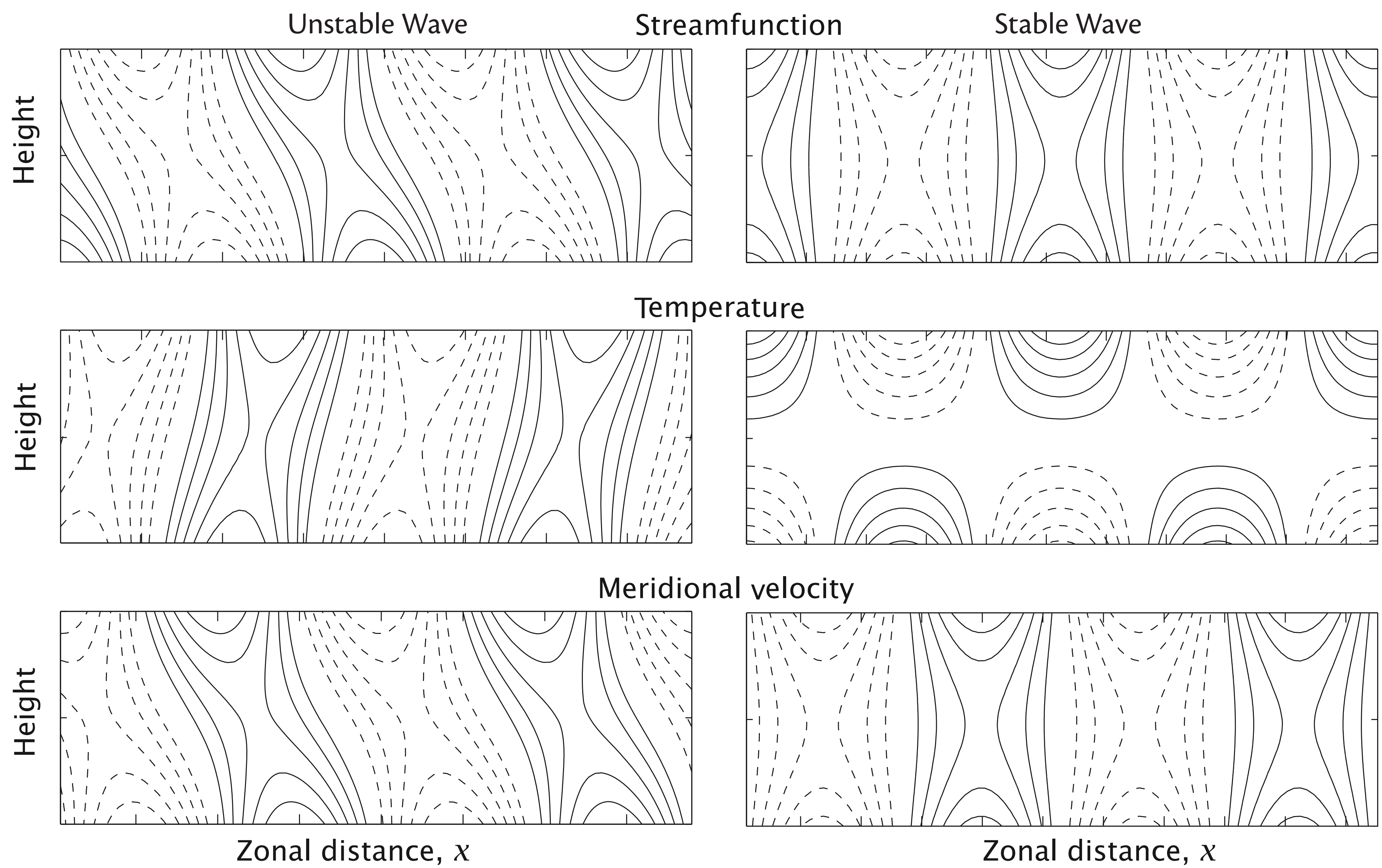
Hartmann, *Global Physical Climatology*

The Baroclinic Instability

1. Available potential energy in a stratified fluid, with or without rotation
2. The quasi-geostrophic approximation
3. Necessary conditions for the baroclinic instability
4. The Eady problem
5. Dynamical Interpretation of the baroclinic instability: edge wave interaction
6. The role of beta

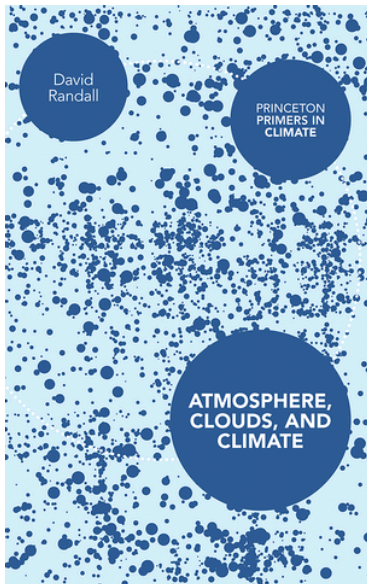
Blackboard

Vertical structure of unstable modes in the Eady problem



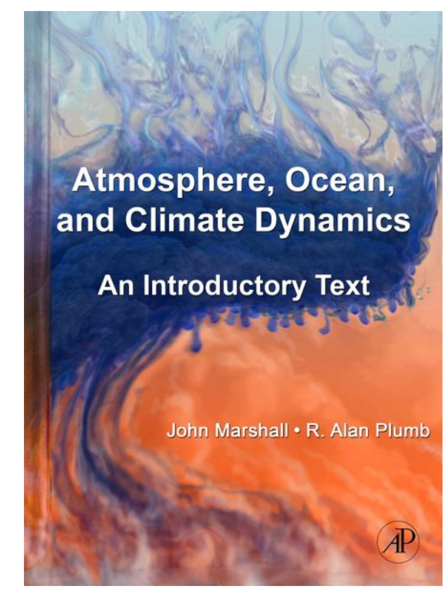
Vallis, *AOFD*, Chap. 9

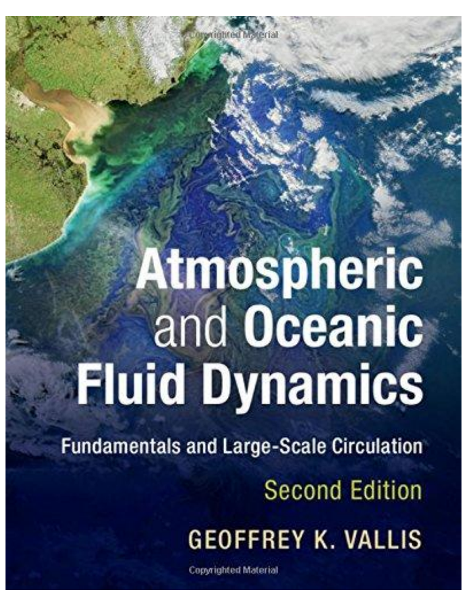
References



Atmosphere, clouds, and climate, D. Randall, Princeton Primers in Climate. Chap. 4.

Atmosphere, Ocean, and Climate Dynamics, J. Marshall and R. A. Plumb, Academic Press. Chap 5-8.
With lab experiments!





Atmospheric and Oceanic Fluid Dynamics, G. K. Vallis, Cambridge University Press. Chap 1, 2, 14, 15, 16.
The bible.

List not exhaustive…