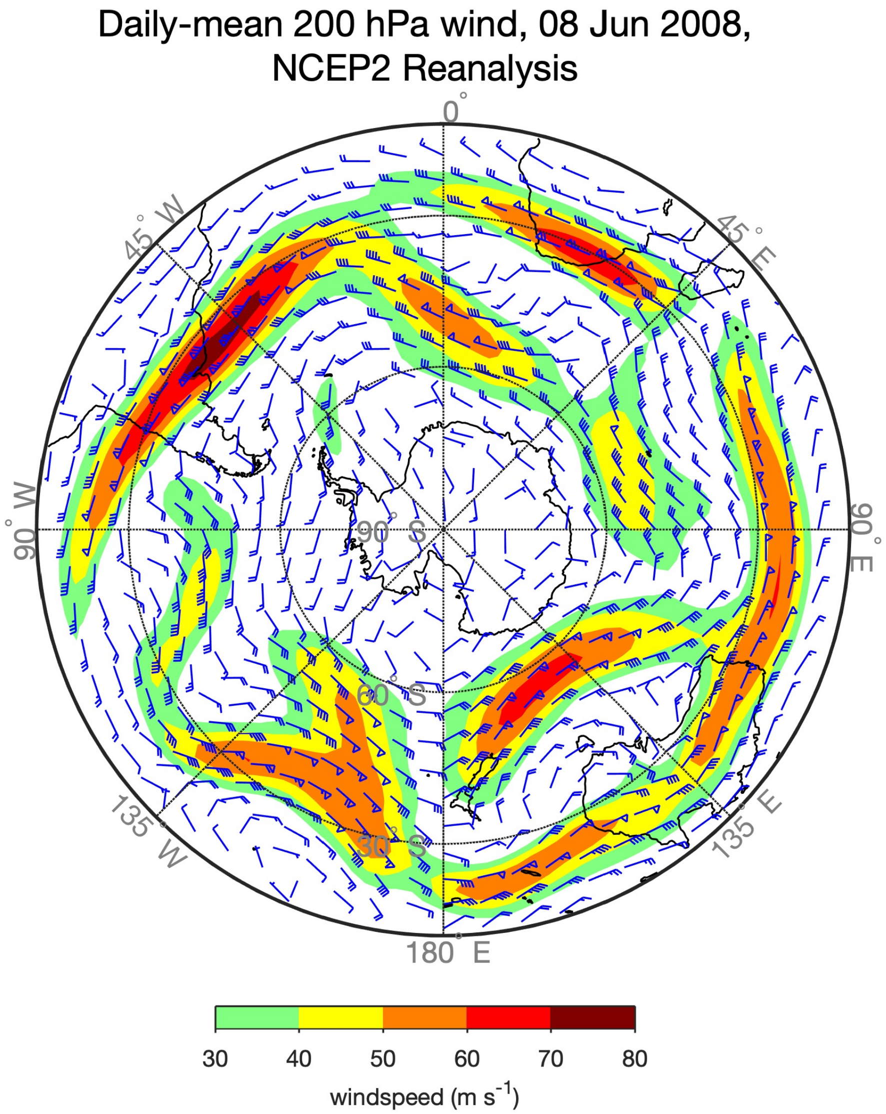
# The general circulation of the atmosphere

# Why are there jets in the atmosphere?



# Why are planetary fluid envelopes dominated by jets?

1. Turbulence in strongly stratified, rotating fluids is quasi-two-dimensional

2. Two-dimensional turbulence has an inverse energy cascade

# General information

- Lecturer
  - Martin Singh [Rm 213, 9 Rainforest Walk]

- Class times [G60, Ground floor, 9 Rainforest Walk]
  - **Fri 10am-12pm**
  - **Fri 2pm-4pm**

- 3 hours of "lectures" plus 1 hour problem solving

- Course website
  - singh.sci.monash.edu/GenCirc

# Course aims

- Characterise the large-scale circulations within Earth's atmosphere and their associated transports of momentum, energy and water

- Develop a theoretical framework and a set of mathematical tools to analyse and understand the physical and dynamical processes that maintain the large-scale circulation

- Engage with the scientific literature underpinning our understanding of the general circulation and how it may change in response to changes in climate

# Structure of the course

1. **Overview and tools (ch 1 & section 2.1)**
   1. Overview & historical account of the general circulation
   2. Governing equations
2. **Radiative-convective equilibrium & Hide's theorem (ch 3)**
   1. Radiative-convective equilibrium
   2. Hide's theorem
3. **Axisymmetric and non-axisymmetric circulations (ch 4 & section 2.2-2.3)**
   1. Axisymmetric theories of the Hadley circulation
   2. Reynolds decomposition into mean and eddy
4. **The angular momentum budget of the atmosphere (ch 5)**
   1. Angular momentum budget of the atmosphere
   2. Surface winds and the angular momentum budget
5. **Jet formation & maintenance: the barotropic case (ch 6)**
   1. Maintenance of a barotropic jet
   2. Rossby waves and momentum transports
6. **Forcing of the zonal-mean circulation (ch 7)**
   1. The transformed Eulerian mean
   2. Eliassen-Palm fluxes
7. **Non axisymmetric tropical circulations (ch 8)**
   1. Eddies and the Hadley Cell
   2. The seasonal cycle and monsoons

# References

- Course notes available at: http://singh.sci.monash.edu/GenCirc/notes/GenCirc_notes.pdf
- I borrow heavily form the following sources


  - Held, I. M., The general circulation of the atmosphere, *Proc. Geophysical Fluid Dynamics Program,* **2000**, 1-54. Available: https://www.whoi.edu/fileserver.do?id=21464&pt=10&p=17332

  - Vallis, G. K., Atmospheric and oceanic fluid dynamics: fundamentals and large-scale circulation, *Cambridge University Press,* **2006**, 745p.

  - Peixoto, J. P. & Oort, A. H., Physics of Climate, *J. Climate, AIP Press,* **1992**, 520p.

  - Stone, P., General circulation of the atmosphere lectures, course 12.812, Mass. Inst. Tech., **2005**. Available: https://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-812-general-circulation-of-the-earths-atmosphere-fall-2005/


- I will provide additional references throughout the course

# Assessment

- Honours/masters/VIEPS students:
    - 2 Assignments (15% each)
    - Report & oral presentation on a peer-reviewed paper (20%)
    - Written exam (50%)
- PhD students (Monash Doctoral Program)
    - 2 Assignments
    - Report & oral presentation on a peer-reviewed paper
- For those auditing the class
    - Present a paper to the class in the final week

# Paper report

- Pick a paper from the list on the web (or of your own choosing) and write a summary
- 1500 word report
- 10-minute oral presentation to the class

# The general circulation of the atmosphere

Section I: Overview & tools

History and overview of the general circulation

# Learning objectives

After this class you will be able to:

1. Define what is meant by the term "general circulation"

2. Recall historical models of the general circulation including those by Hadley and Ferrel/Thompson

3. Describe the basic thermal structure of the atmosphere and its seasonal variations

4. Describe the basic dynamic structure of the atmosphere and its seasonal variations

# What is the general circulation?

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*"In its broadest sense, the complete statistical description of large scale atmospheric motions"*

-- AMS Glossary

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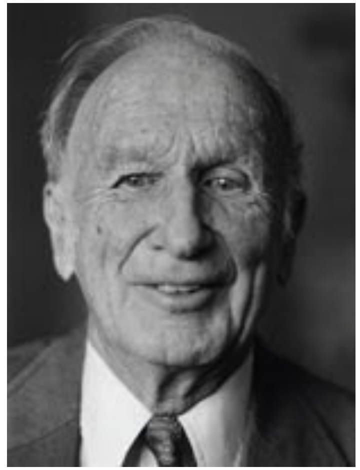
# Introduction to the general circulation

- A historical perspective

- The observed general circulation
  - Thermal structure of the atmosphere
  - Mean circulation
  - Eddies
  - Precipitation and the hydrological cycle

# The general circulation:
# a historical perspective

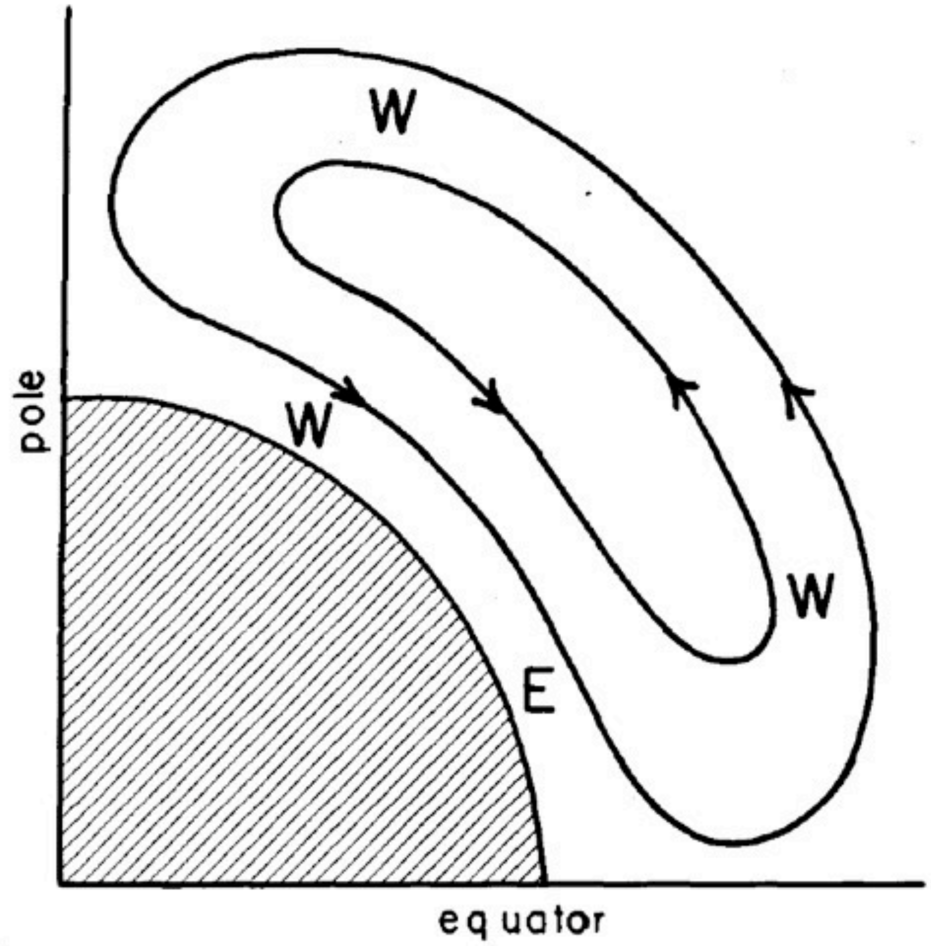
“During the past three centuries, the prevailing ideas about the general circulation of the earth's atmosphere have evolved in a stepwise manner. Early in each step, a new theoretical idea is formulated. Late in each step, the idea gains general acceptance, but, more or less concurrently, new observations show that the idea is wrong.”



- Lorenz (1983), *Bull. Amer. Met. Soc.,* **64**, 730-734.

# Hadley (1735): Single cell

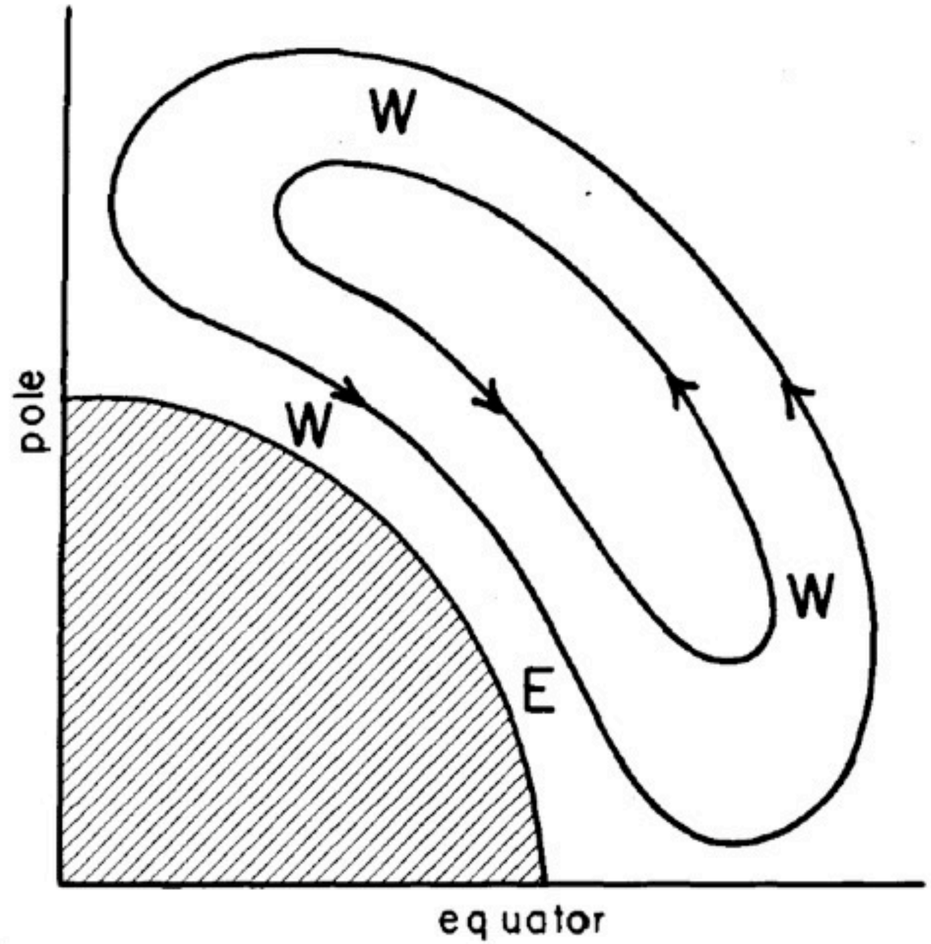
- Coriolis force on meridional motions induces surface easterlies and westerlies
- Angular-momentum balance between the surface and atmosphere




Lorenz (1983), *Bull. Amer. Met. Soc.*, **64**, 730-734.

# Hadley (1735): Single cell

- Coriolis force on meridional motions induces surface easterlies and westerlies
- Angular-momentum balance between the surface and atmosphere
- But at midlatitudes mean surface winds have poleward component!

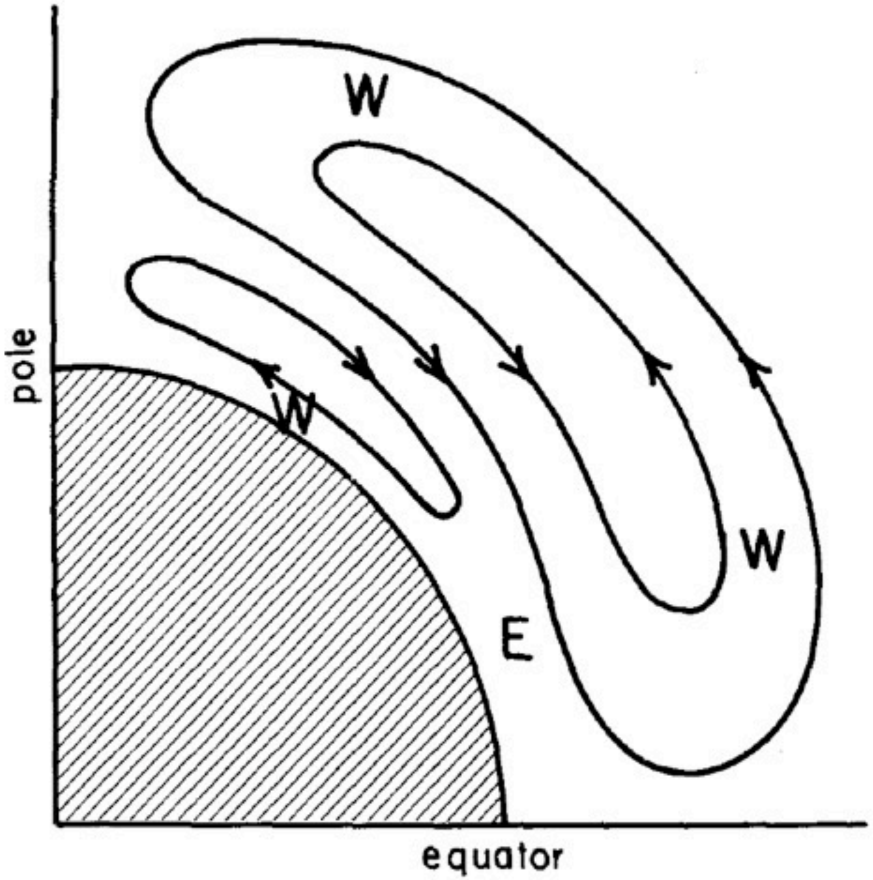



Lorenz (1983), *Bull. Amer. Met. Soc.*, **64**, 730-734.

# Thompson (1857) & Ferrel (1859): A second cell

- Coriolis force on zonal motions
- Maximum in pressure at boundary between surface easterlies & westerlies
- Shallow, thermally indirect cell at midlatitudes

- But upper level winds at midlatitudes drift equatorwards!




Lorenz (1983), *Bull. Amer. Met. Soc.,* **64**, 730-734.

# Bigelow (1902), Defant (1921) & Jefferys (1926): The importance of eddies

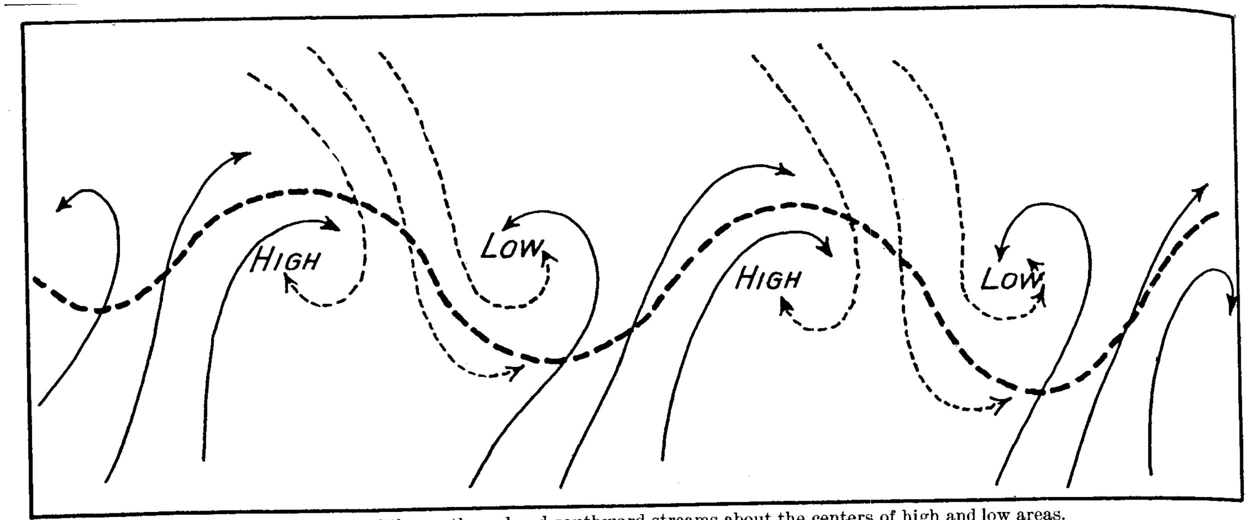


Fig. 9.—Curling of the northward and southward streams about the centers of high and low areas.

- Bigelow (1902) pointed out that heat transport could be effected by zonally asymmetric motions
- Jefferys (1926) applied these ideas to angular-momentum transports

- Key conceptual advance:

*The zonal-mean circulation may not be a solution to the zonally-symmetric equations of motion.*

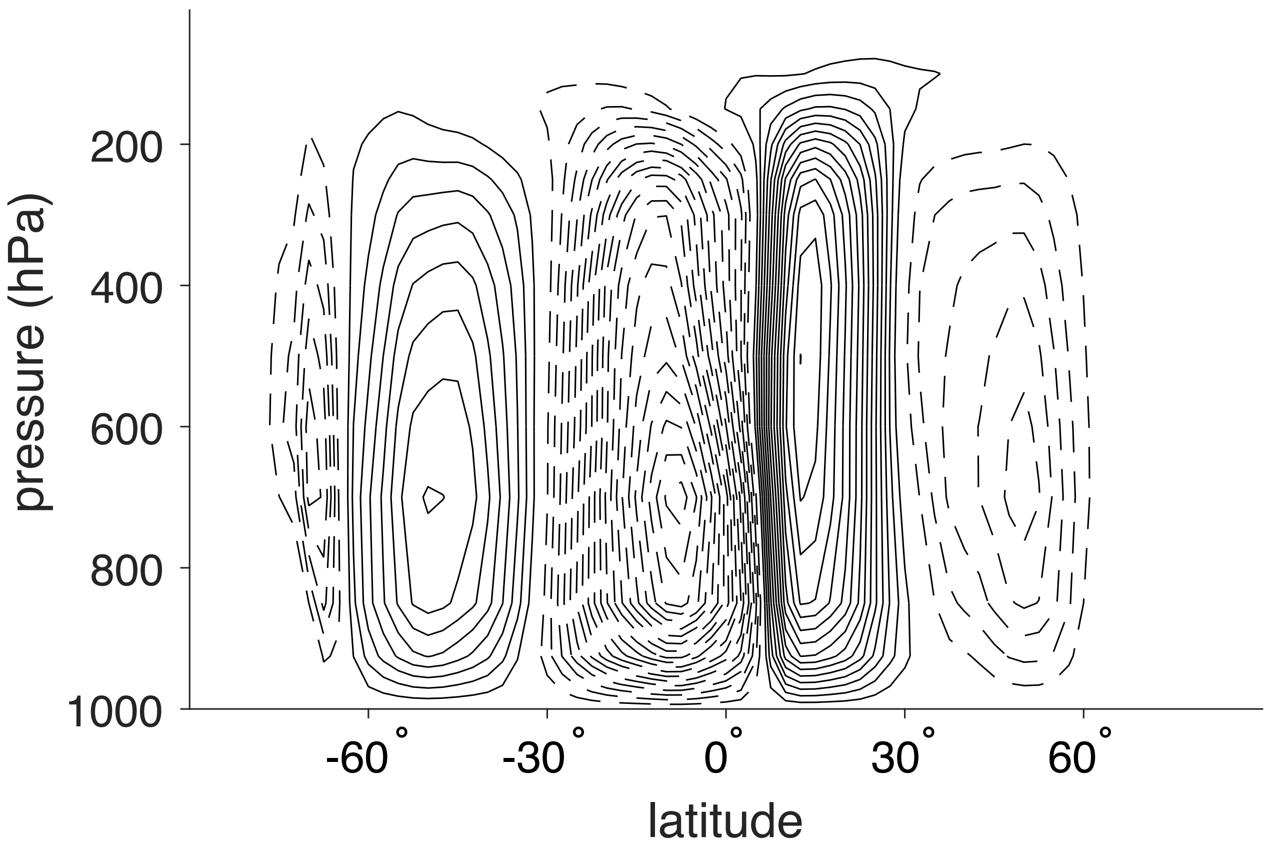
# Source of the eddies: Baroclinic instability

- Bjerknes (1919): “the kinetic energy [of the cyclones, is] furnished by the potential energy of the system of warm and cold air lying beside each other.”

- Charney (1947) & Eady (1949): Theory of baroclinic instability

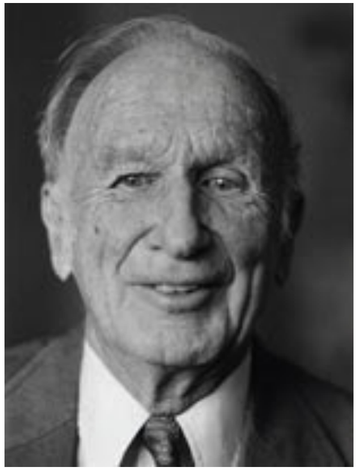
- Theory of available potential energy (Lorenz, 1955)

# The annual-mean meridional overturning circulation




(Countour interval 0.5 x $10^9$ kg $s^{-1}$, based on NCEP-DOE for 1981-2010)

“Perhaps near the end of the 20th century we shall suddenly discover that we are beginning the fifth step.”



- Lorenz (1983), *Bull. Amer. Met. Soc.,* **64**, 730-734.

# The observed general circulation

# Solar insolation forcing

# Question

- At what time of year is the maximum globally-averaged solar insolation?

# Question

- At what time of year is the maximum globally-averaged solar insolation?

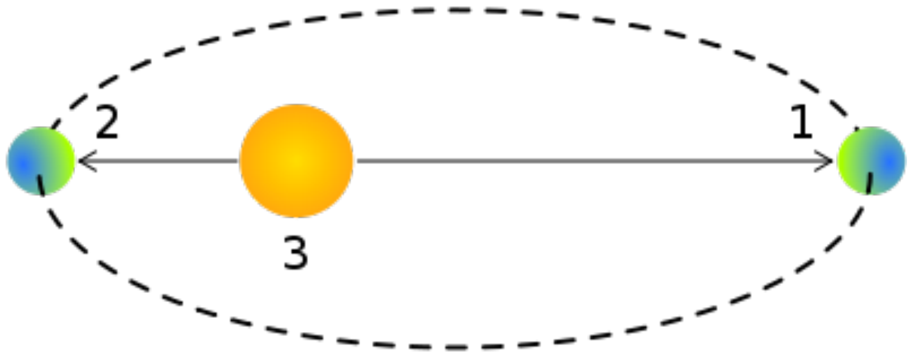
4th of Jan

# Perihelion occurs in Austral summer

- At the current time in Earth's history, Earth's closest approach occurs in our summer.

- In the mid-Holocene (6ka) Perihelion occurred in the Boreal summer

- This is thought to account for the "Green Sahara"



# Question

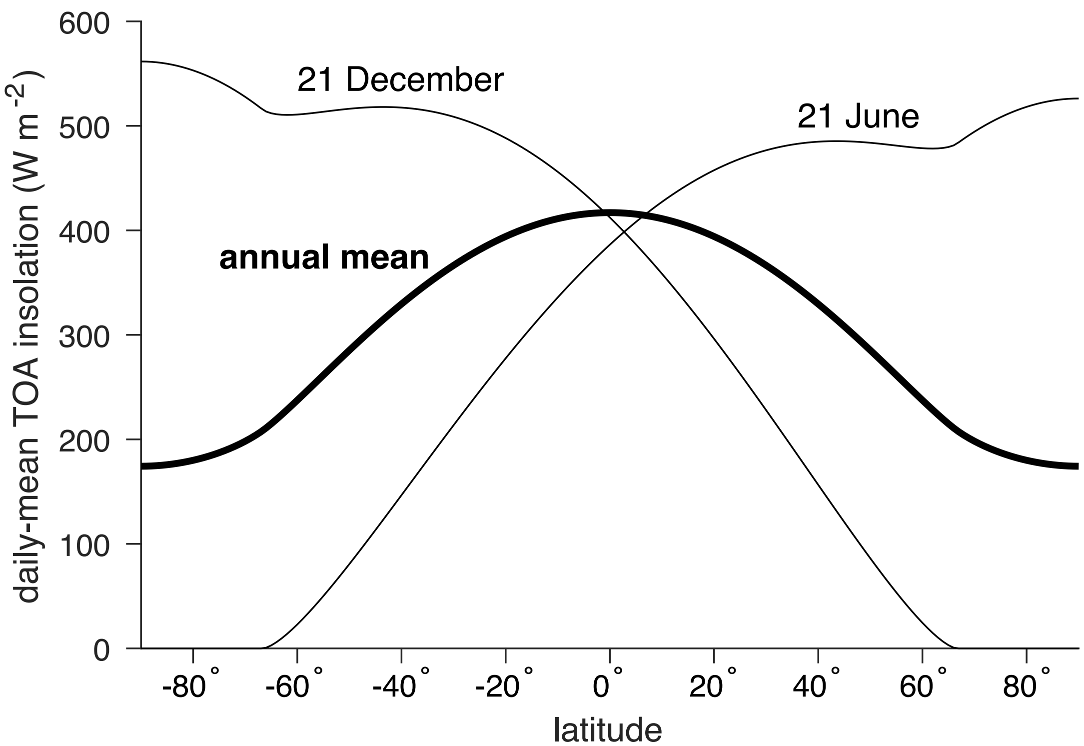
- Where is the maximum daily-mean solar insolation at the solstice?

# Question

- Where is the maximum daily-mean solar insolation at the solstice?

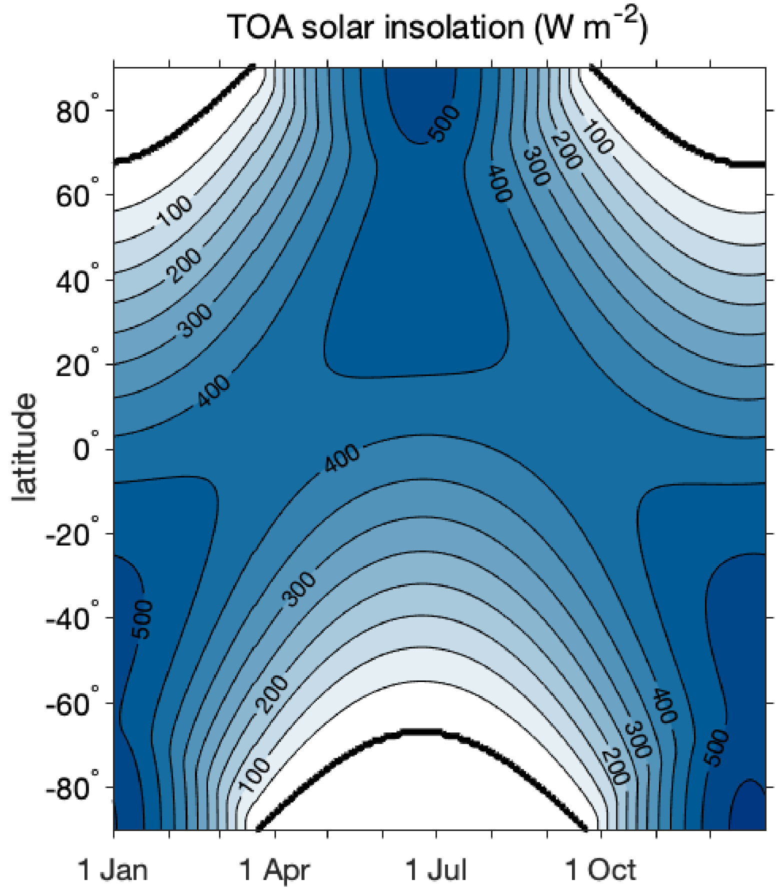
The pole!

# Daily-mean Solar insolation maximises at the poles!



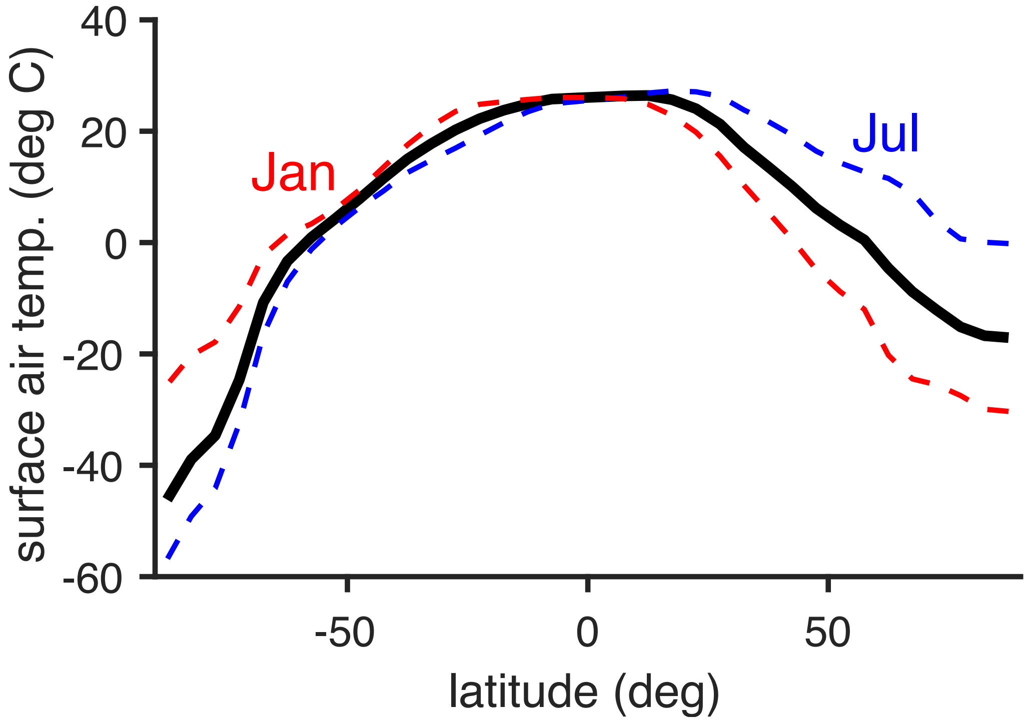
# Atmospheric circulation is driven by uneven distribution of solar radiation incident on the Earth's surface

"Top of atmosphere" insolation



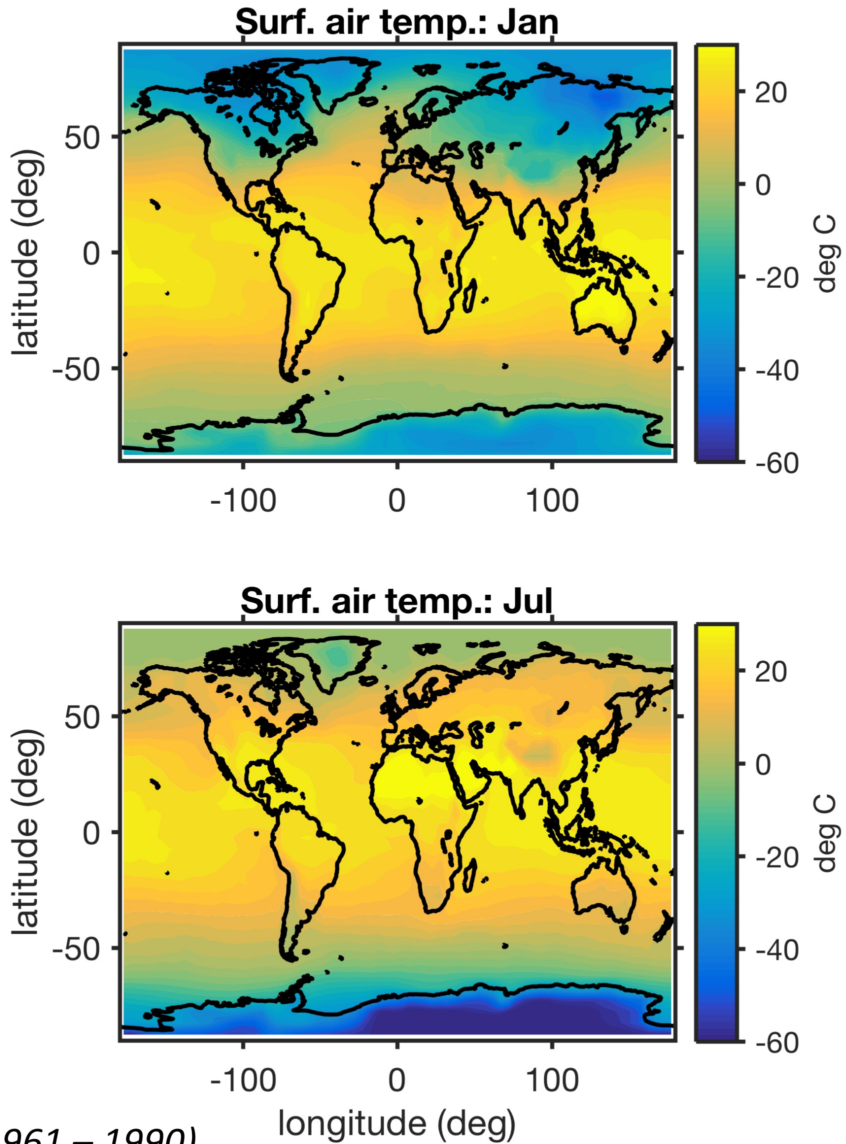
# Thermal structure of the atmosphere

# Maximum zonal-mean temperature stays near the equator




*(CRUTEM4 1961 – 1990)*

# Mean surface air temperature

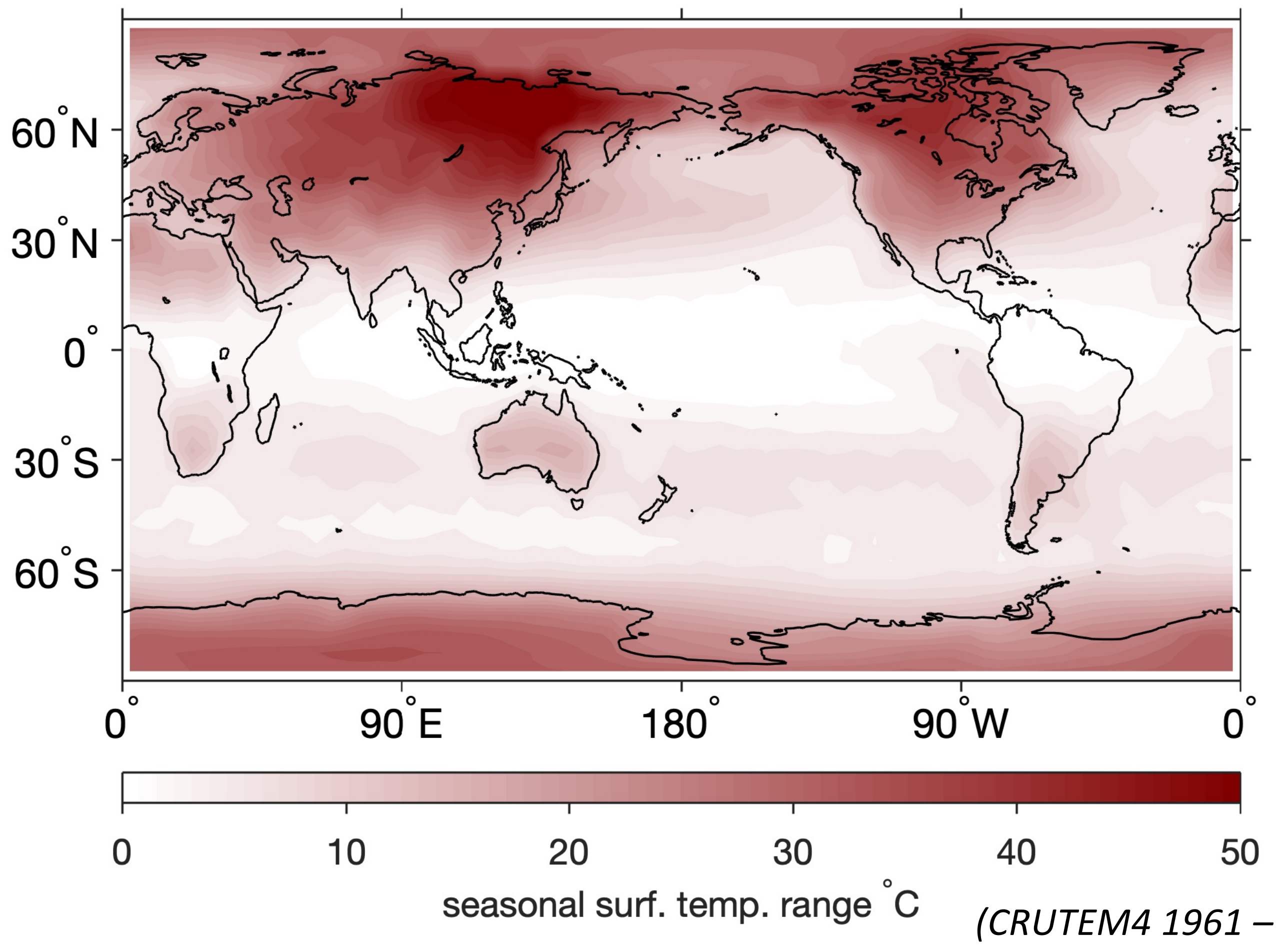



*(CRUTEM4 1961 – 1990)*

# Seasonal range of surface air temperature

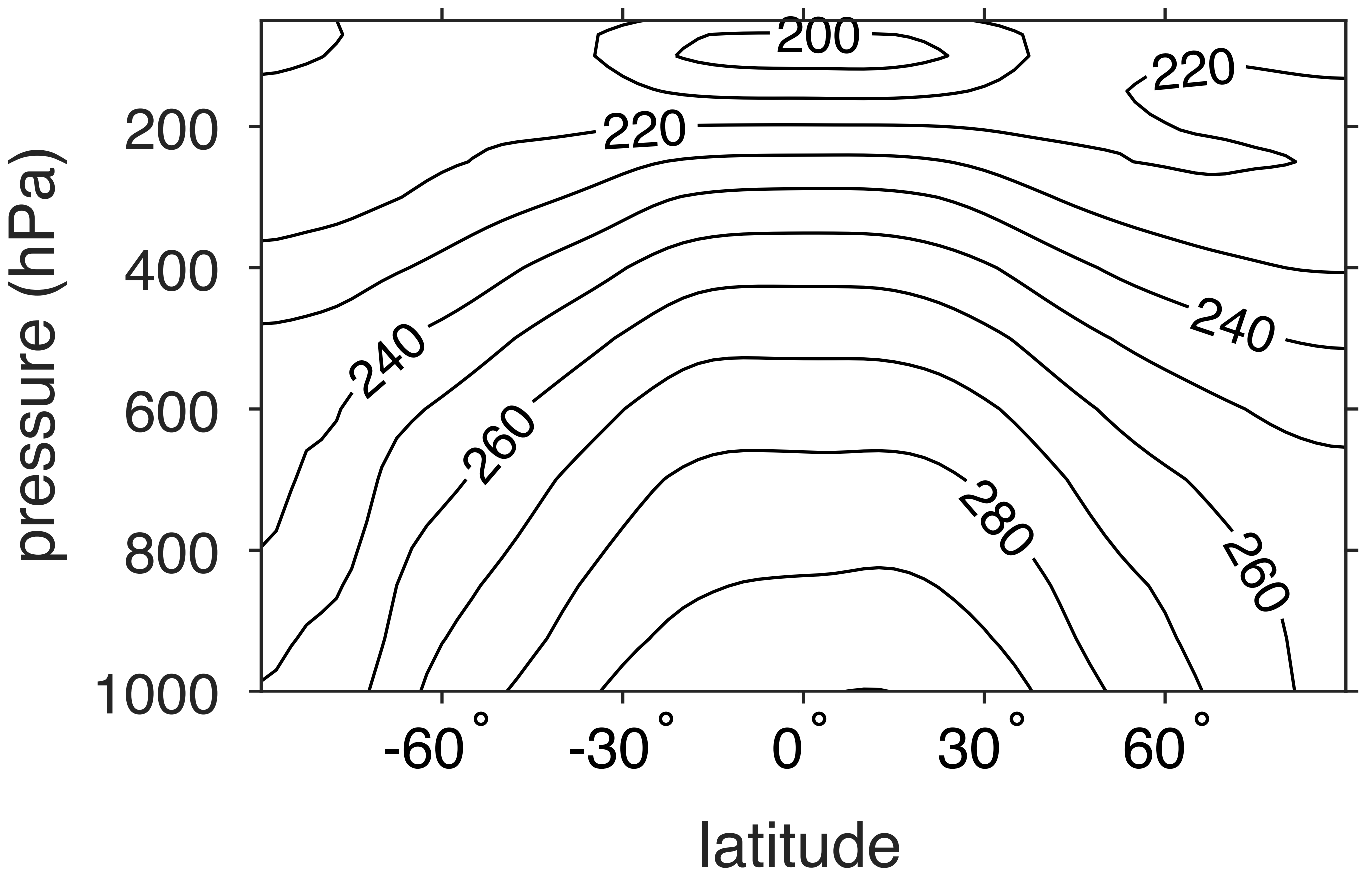
What determines the strength of the seasonal cycle of temperature?

Range in monthly-mean surface air temperature



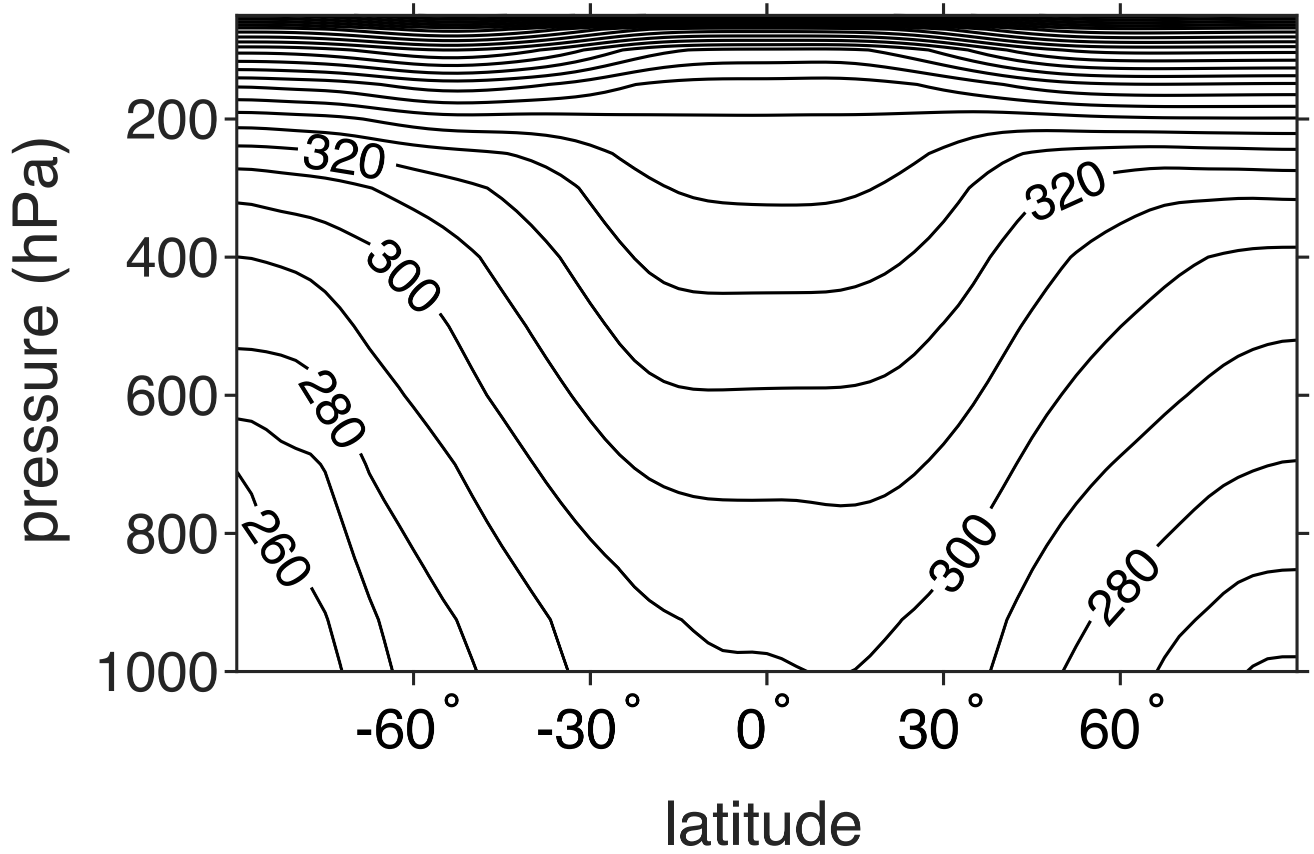

*(CRUTEM4 1961 – 1990)*

# Zonal-mean temperature (K)



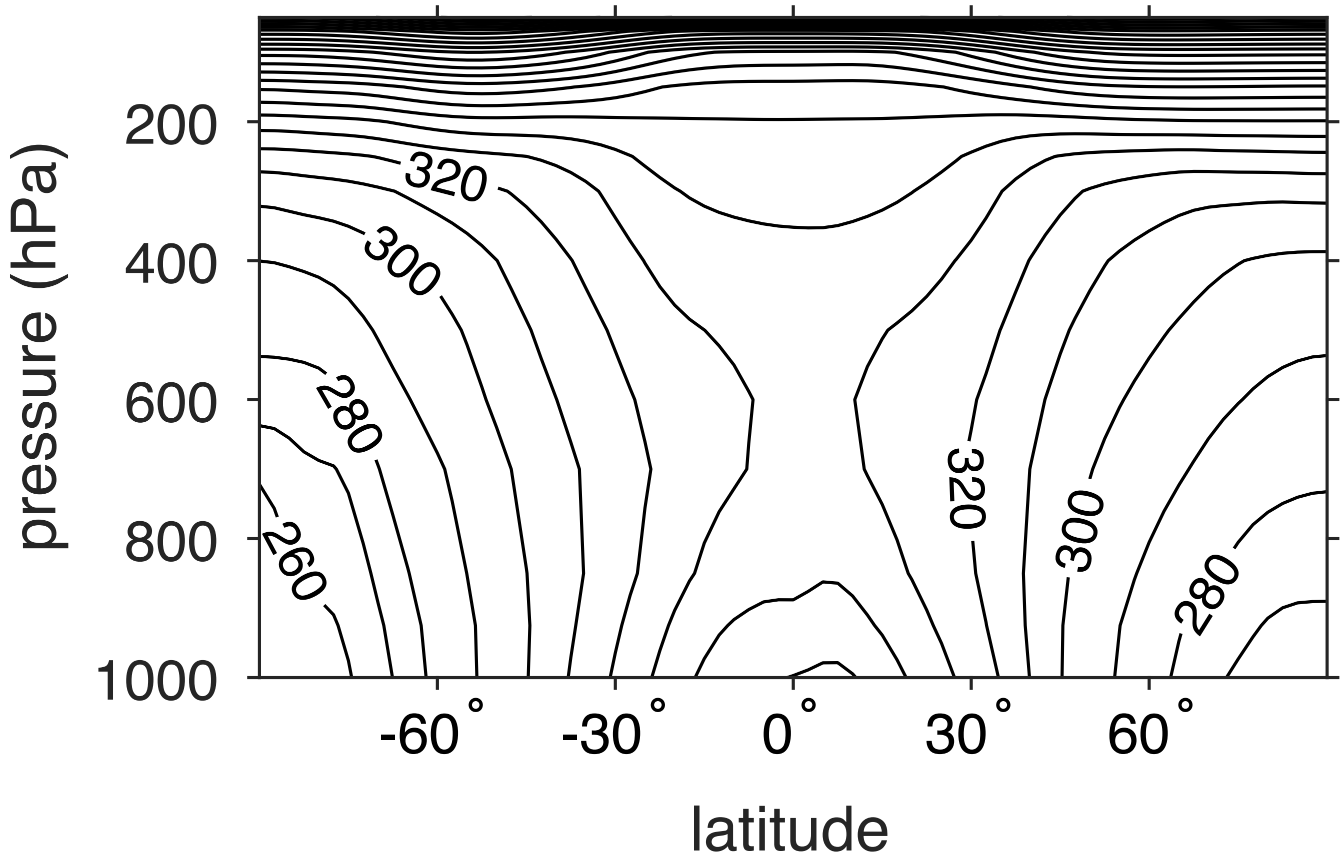

NCEP-DOE reanalysis 1981-2010

# Zonal-mean potential temperature (K)



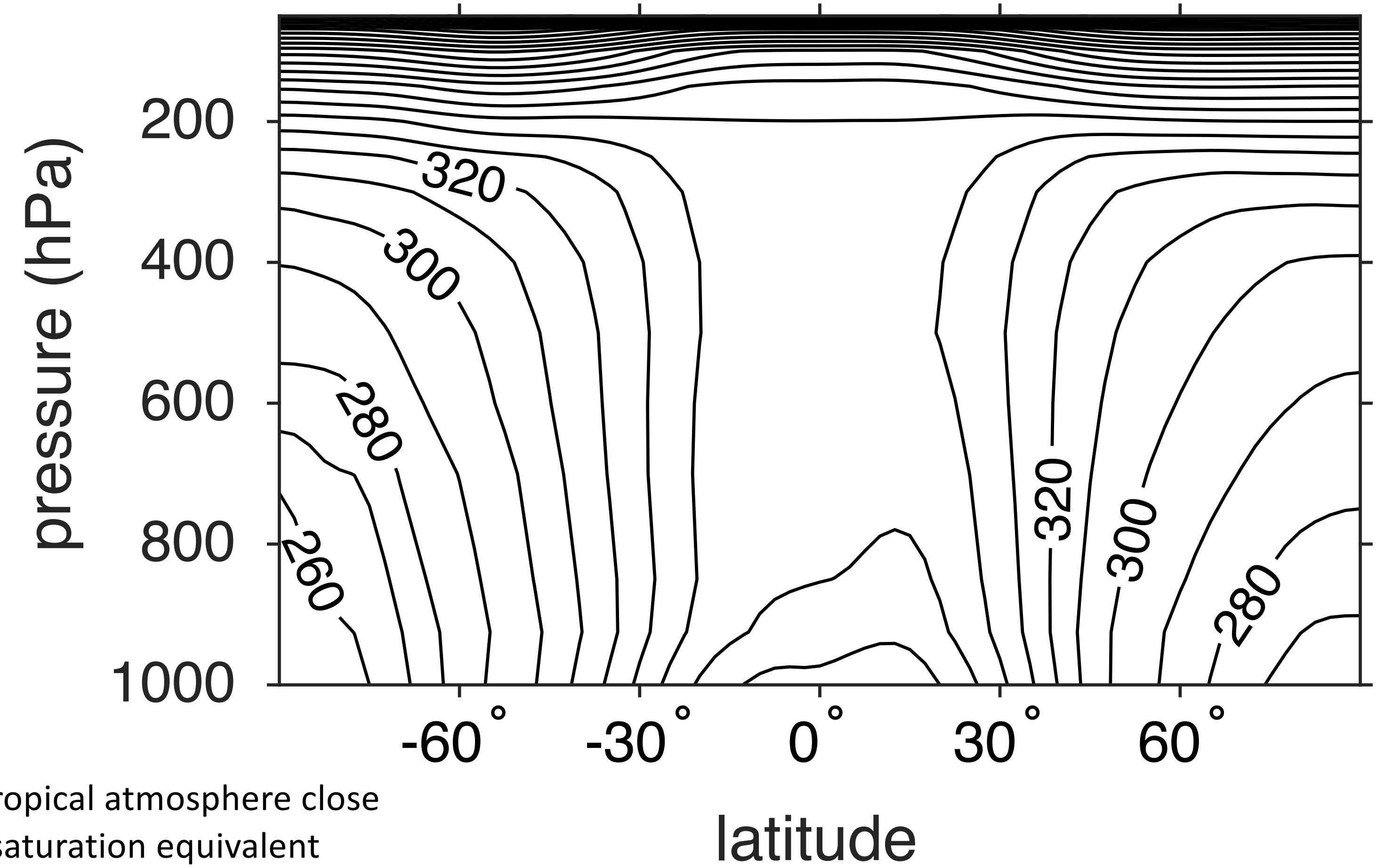

NCEP-DOE reanalysis 1981-2010

# Zonal-mean equivalent potential temperature (K)



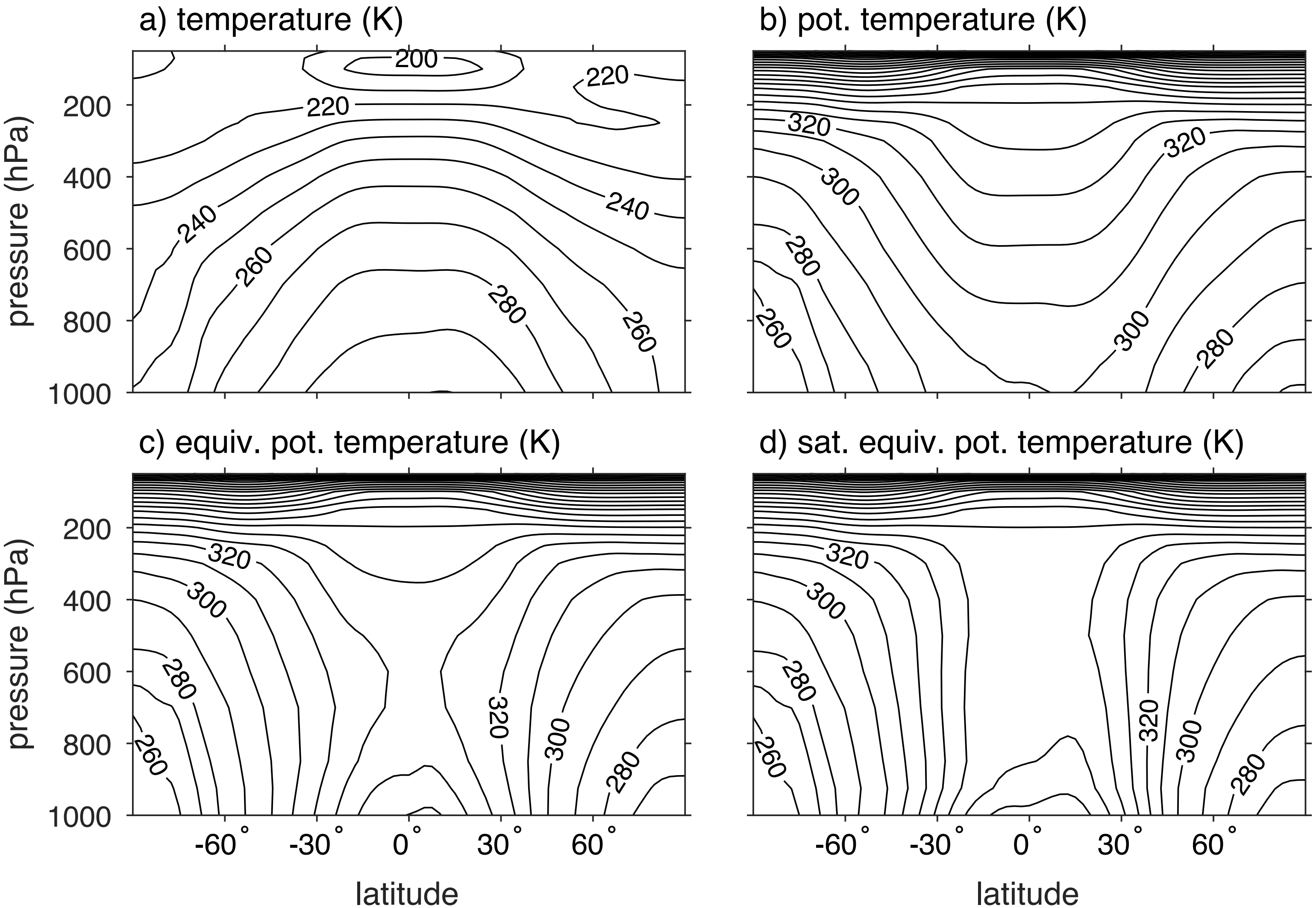

NCEP-DOE reanalysis 1981-2010

# Zonal-mean saturation equivalent potential temperature (K)



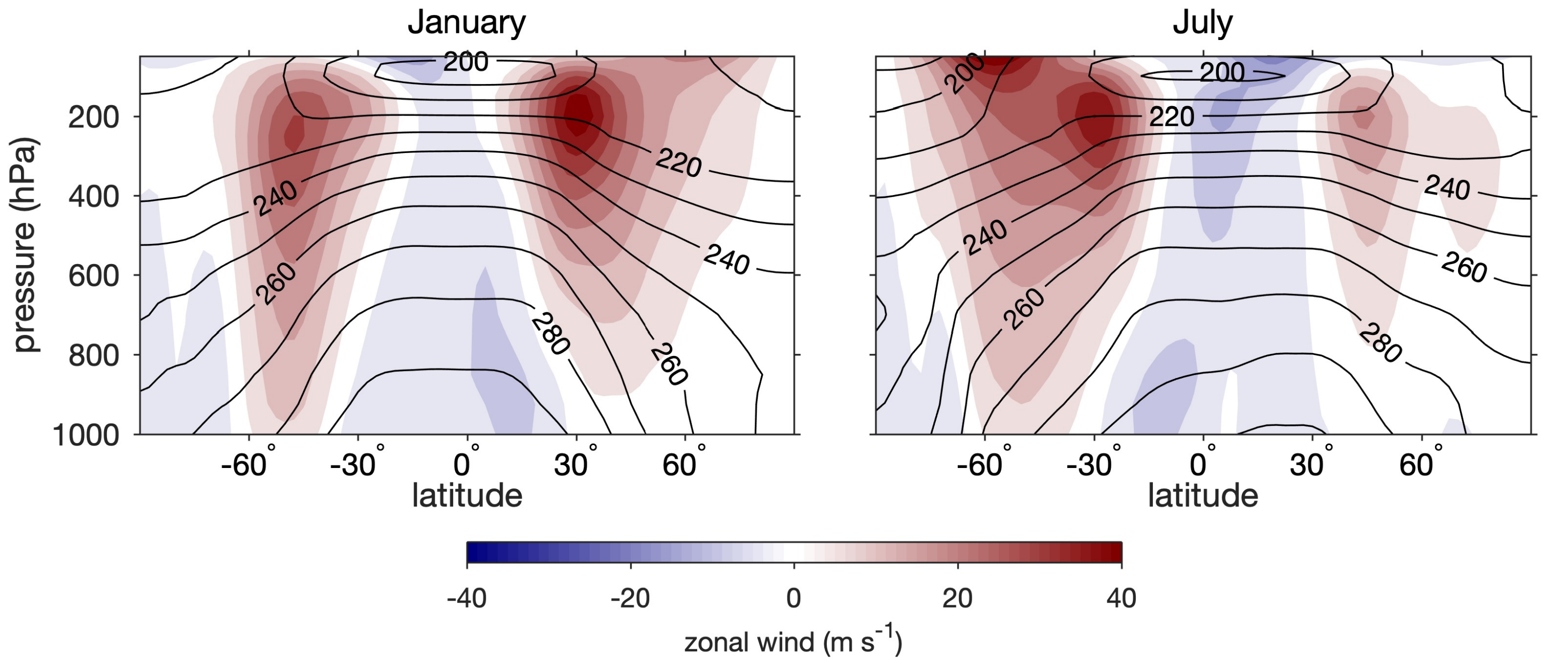

Why is the tropical atmosphere close to constant saturation equivalent potential temperature?

NCEP-DOE reanalysis 1981-2010


a) temperature (K)
b) pot. temperature (K)
c) equiv. pot. temperature (K)
d) sat. equiv. pot. temperature (K)
pressure (hPa)
200
400
600
800
1000
-60°
-30°
0°
30°
60°
latitude
200
220
240
260
280
300
320

# The mean circulation

# Zonal-mean zonal wind (colours) and zonal-mean temperature ( contours)

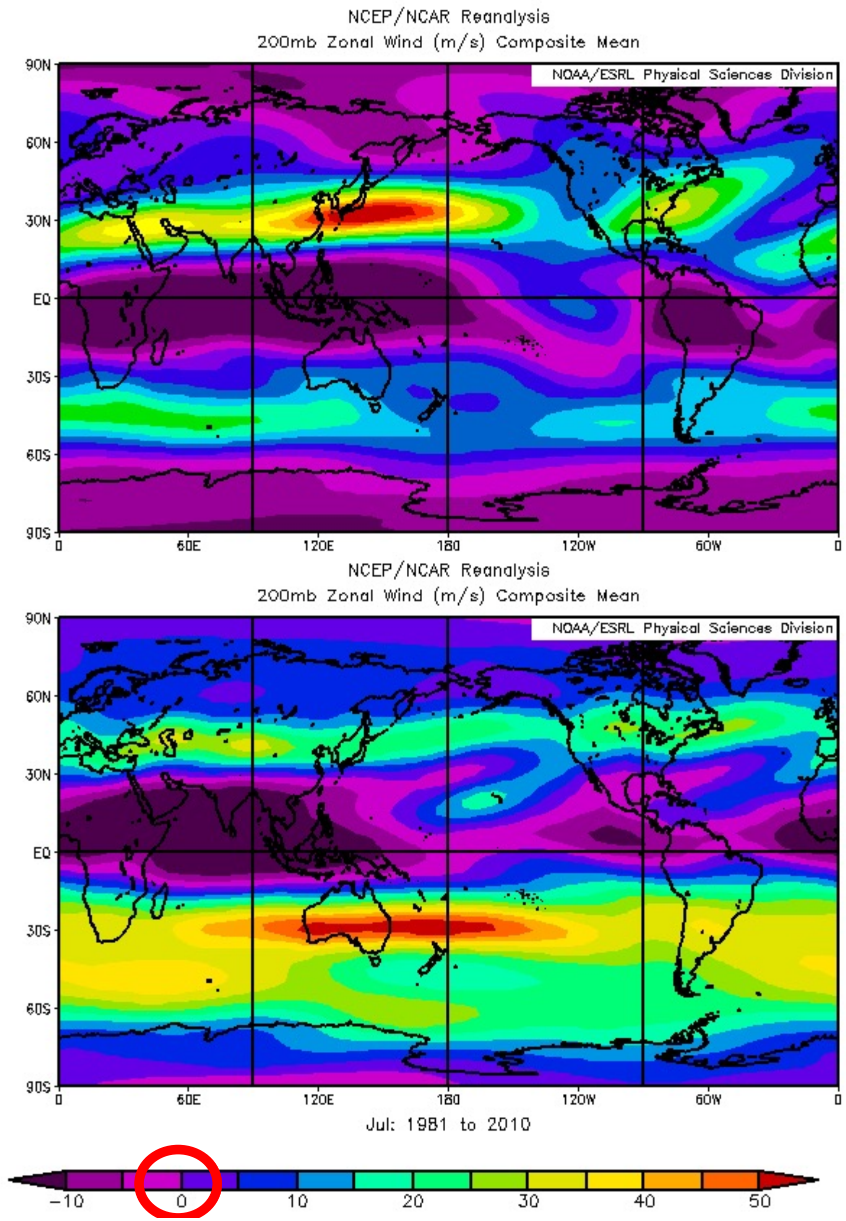



NCEP-DOE reanalysis 1981-2010

# Upper-level winds

Jul

Jan




*(NCEP Renalysis 1981 – 2010)*

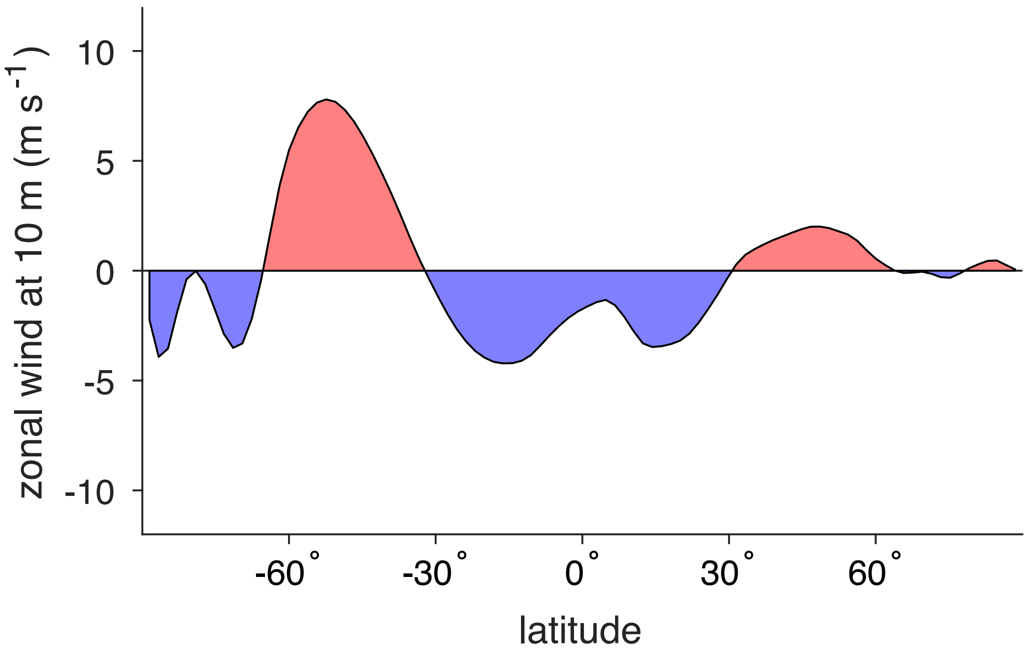
# Zonal-mean surface winds

- Upper-level winds consistent with thermal wind balance

$$f\frac{\partial u}{\partial p} = -\frac{R}{p}\frac{\partial T}{\partial y}$$

- But this does not determine surface winds

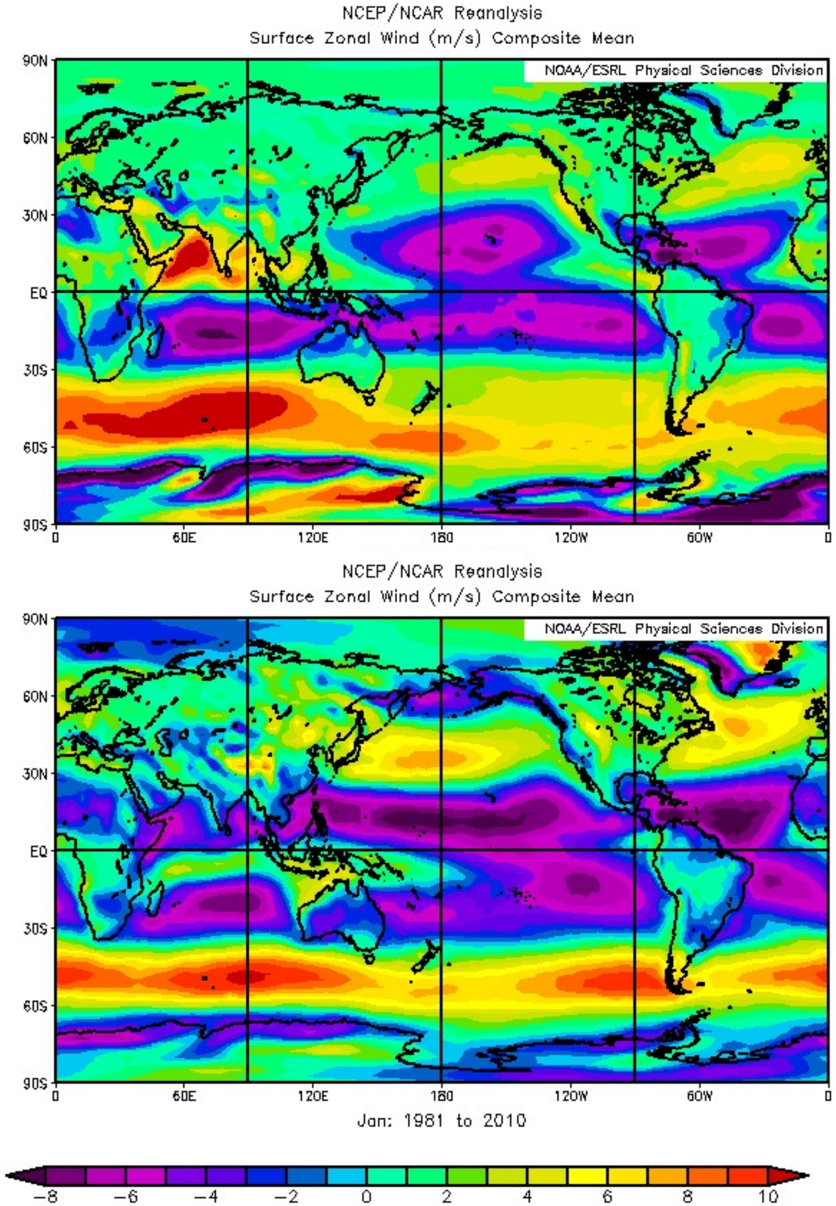
- What drives the surface wind pattern?



# Mean surface winds

Jul

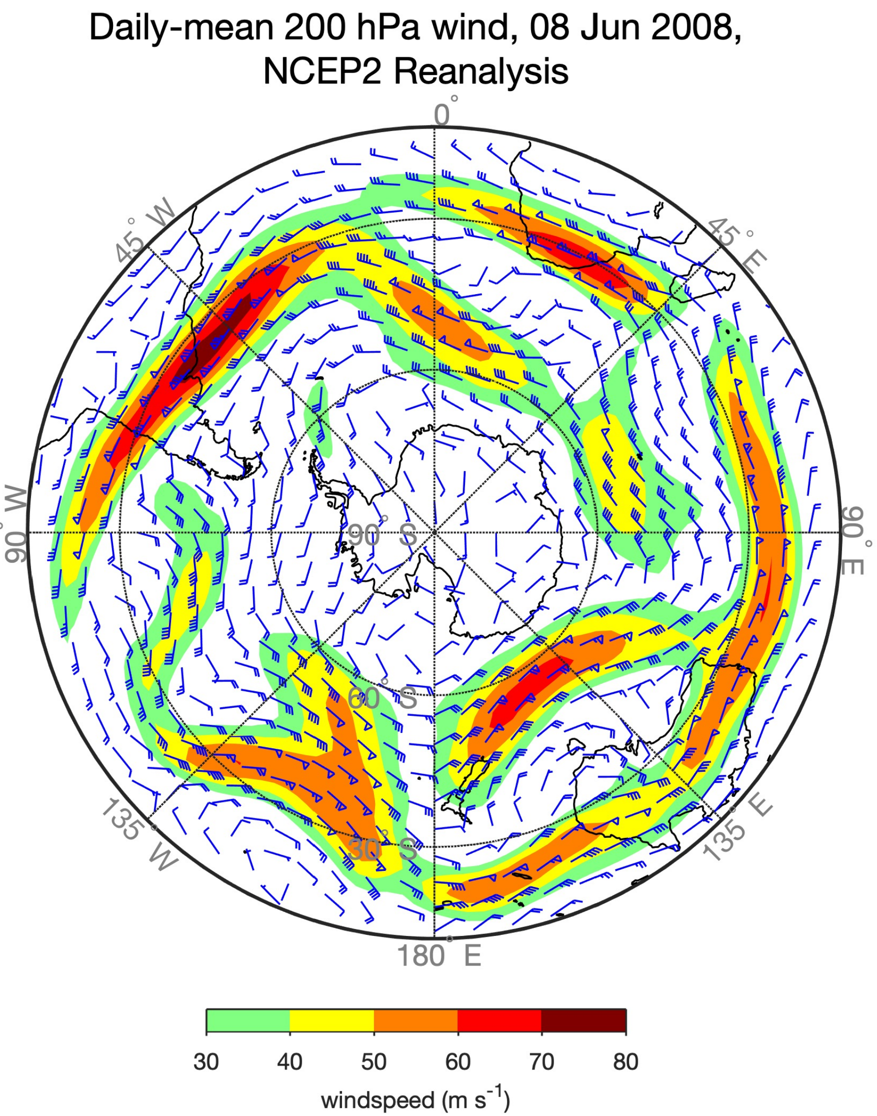
Jan



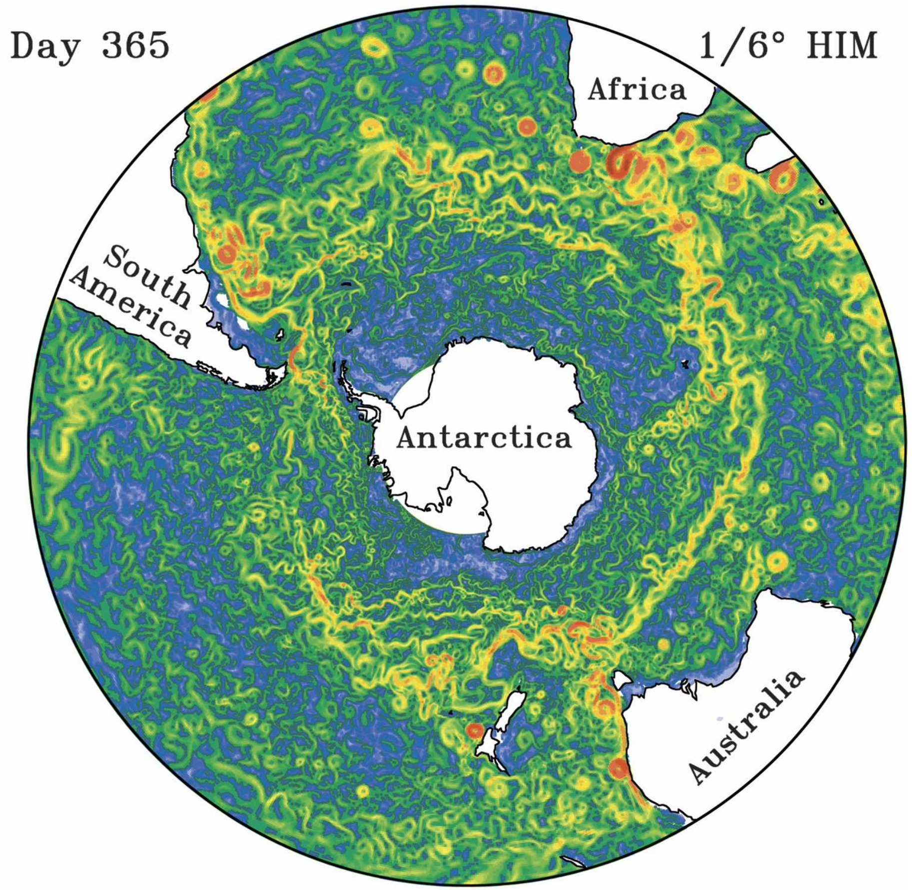

*(NCEP Renalysis 1981 – 2010)*

# Instantaneous upper-tropospheric winds

Why are the jets so sharp?



# Jets in the ocean

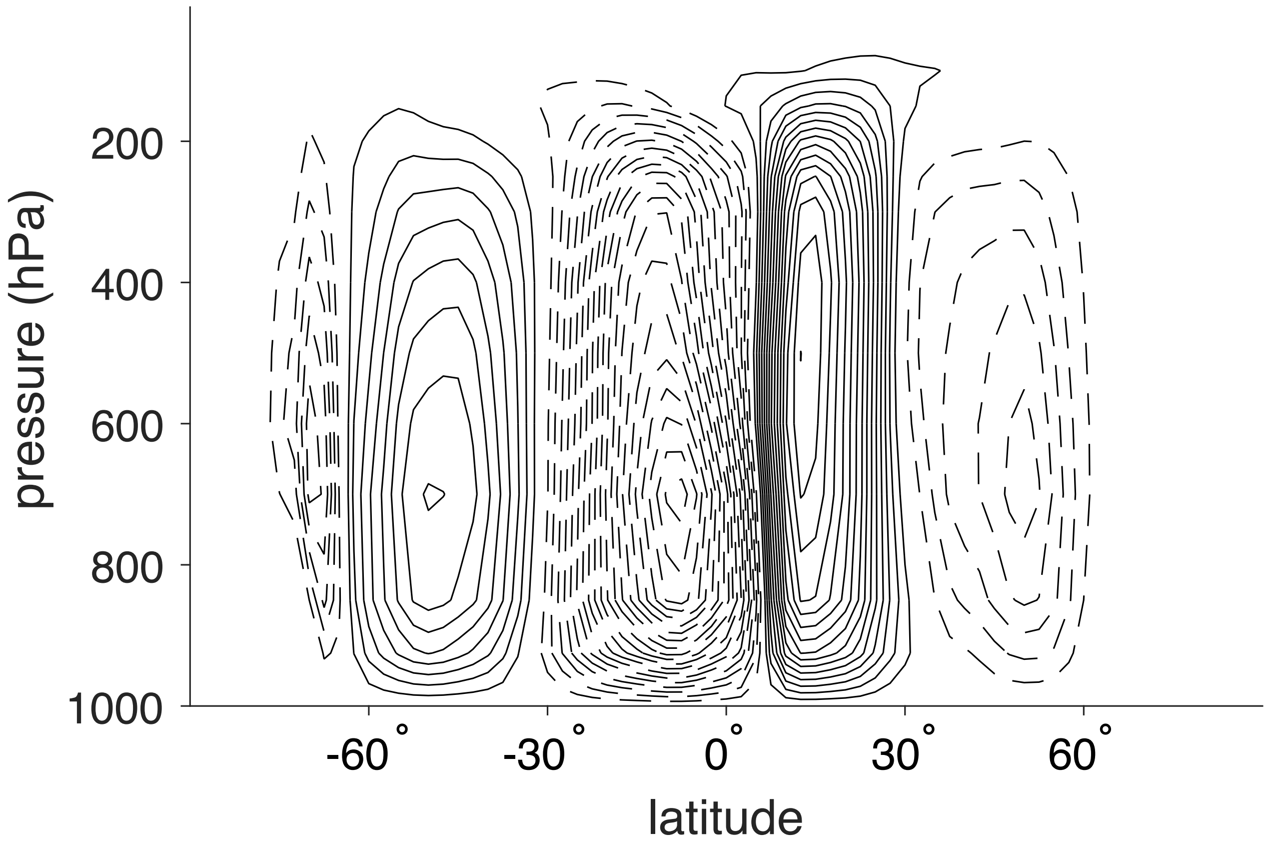


# Jets on other planets

# The meridional overturning circulation

What sets the strength of the Hadley cell?

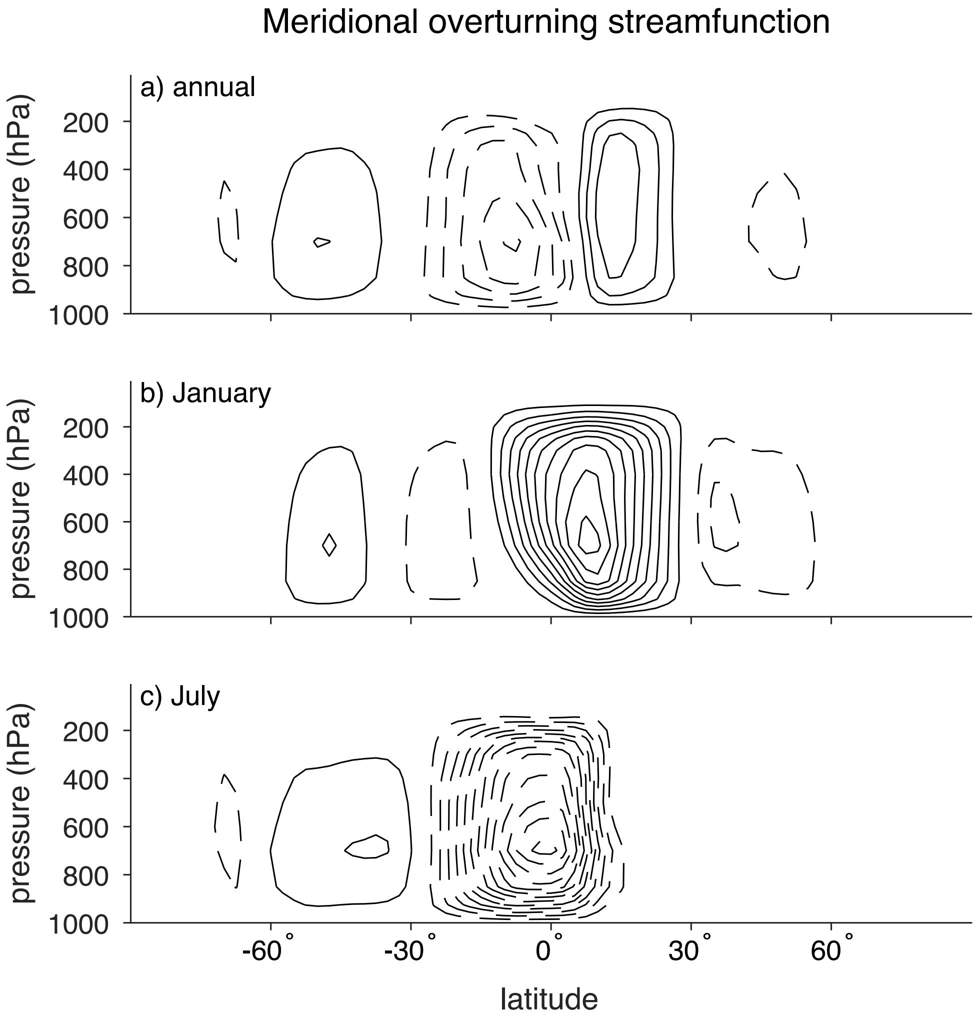
What sets the width of the Hadley cell?




(Countour interval 0.5 x $10^9$ kg $s^{-1}$, based on NCEP-DOE for 1981-2010)

# Seasonal overturning circulation

Seasonal overturning dominated by the winter Hadley Cell




(Countour interval 2 x $10^9$ kg $s^{-1}$, based on NCEP-DOE for 1981-2010)

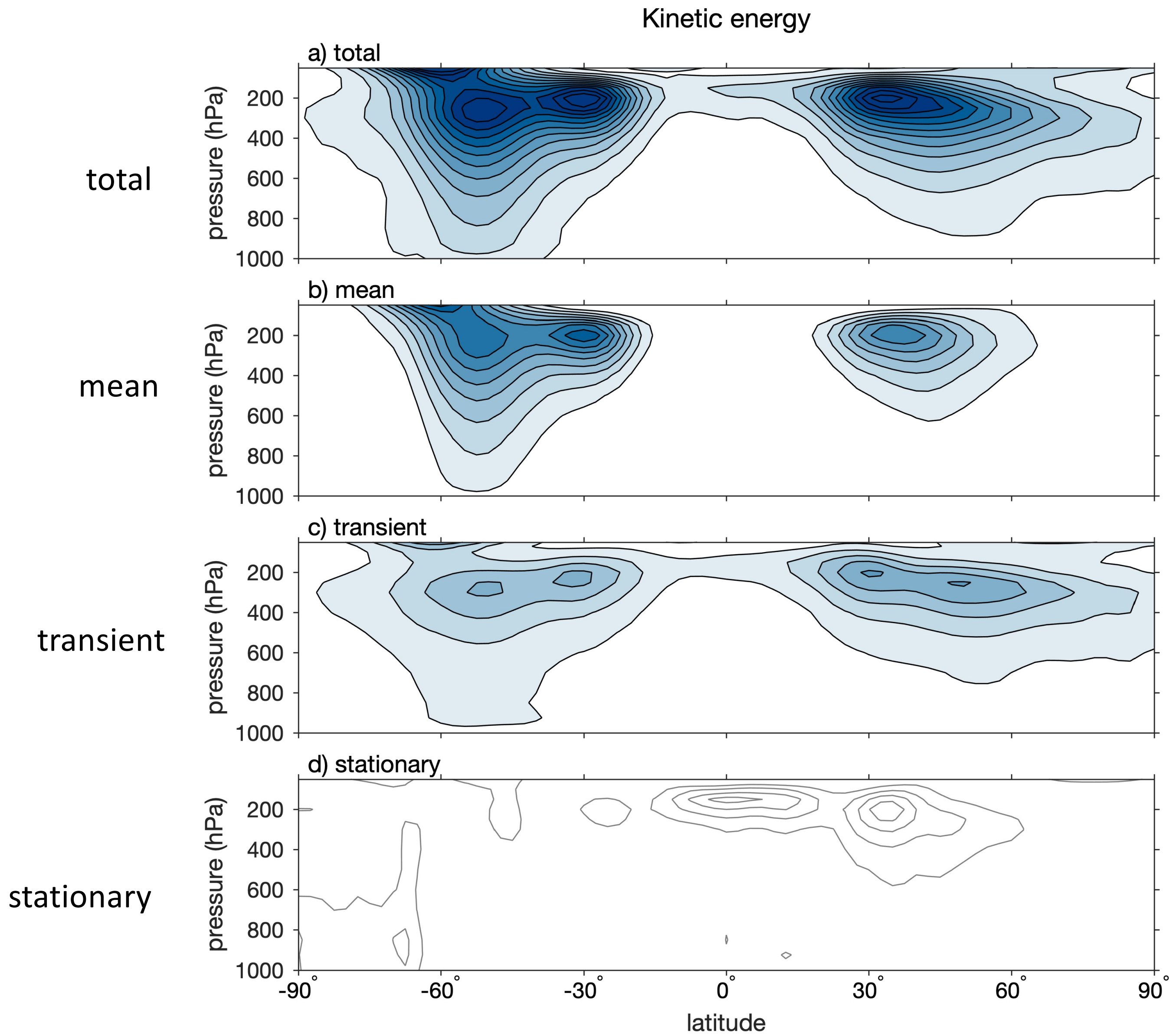
# Why do the Ferrel cells exist?

- What drives a thermally indirect circulation?
- Why are there three cells in each hemisphere and not 1? or 5? or 23? What does this depend on?

# Eddies

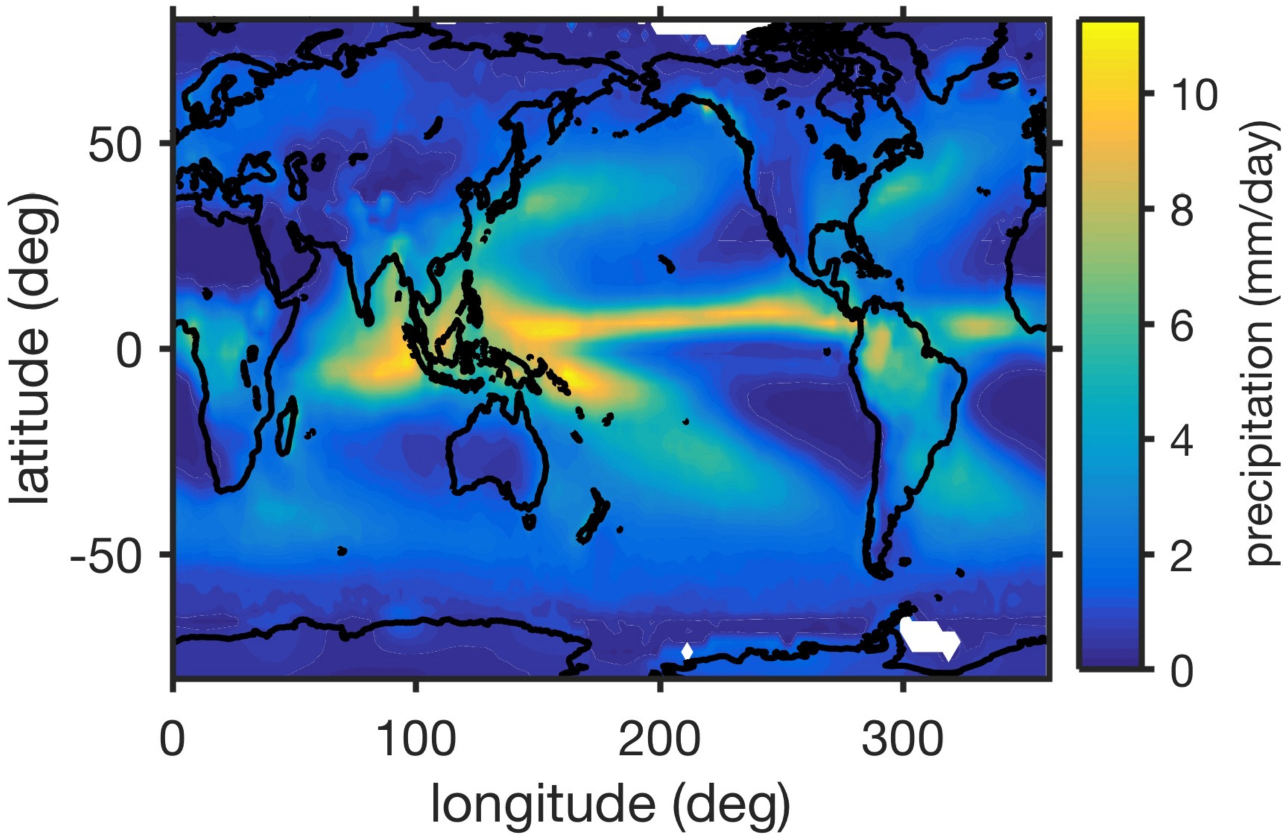
- Eddies are defined as deviations from the time and zonal mean
- We will categorise them into transient and stationary eddies

# Kinetic energy per unit mass ($m^2\ s^{-2}$)



# The hydrological cycle

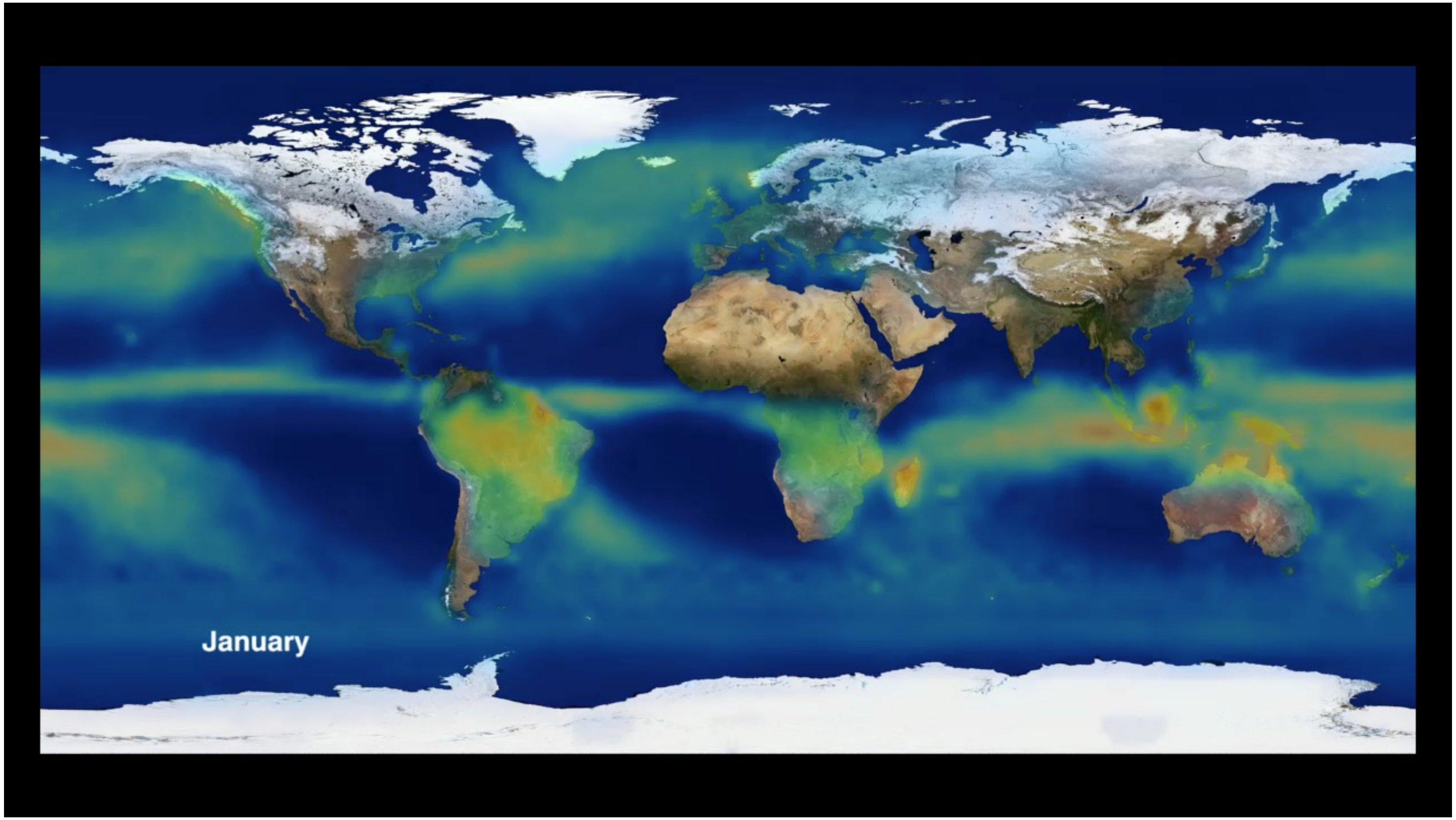
# Annual-mean precipitation




*(CMAP merged precipitation 1981-2010)*

# Seasonal cycle of precipitation

*Source: NASA*



# Questions

- Why is the tropical atmosphere close to constant saturation equivalent potential temperature?
- What drives the pattern of mean surface winds?
- Why are atmospheric jets so sharp?
- What sets the strength and width of the Hadley cell?
- What determines the strength and position of the monsoon?
- Why do the Ferrel cell exist? Why does Earth have three cells?
- What sets the relative humidity of the atmosphere?

# How will the atmospheric general circulation change under global warming?