# 12.810 Dynamics of the Atmosphere

**Course description:** Discusses the dynamics of the atmosphere, with emphasis on the large scale.

**Instructor:**
Paul O'Gorman

# Introductions

Name (and how you would like to be addressed)

Year and course (grad/ugrad)

Current research focus

Reason taking 12.810

Optional: interesting fact about yourself

# Logistics

**Course webpage**
https://canvas.mit.edu/courses/12778

**Class times**
Tuesday and Thursday 10:30-12

**Prerequisite**
Fluid dynamics of the atmosphere & ocean (12.800)
or instructors permission

**Missing class due to Covid**
Some students may have to miss classes. In addition to the class slides, references to textbooks and some introductory notes, I will also post the "blackboard" notes from a previous remote version of the class on the Canvas website.

Talk to me after class if:

1. you do not have the pre-requisite (12.800)

*or*

2. you are not yet preregistered or registered (otherwise you won't get class emails)

# Assessment: Problem sets and Project

**Grading:**

1. Problem sets (5 in total, 60%)
2. Project:
   - writeup (≤12 pages+references, 20%)
   - class presentations (~12 mins + 3 mins for questions, 20%)

**Problem Sets Policy:**

Collaboration is allowed, but students must write up the problem set on their own.

**Project topics:**

Project topics should be decided at midterm. I will give out topics, or you can come up with a topic yourself in consultation with me.

# Problem set partners website (psetparters.mit.edu)

The purpose of this site is to make it easier for MIT students to find classmates to work with on problem sets. Collaboration is an integral part of the MIT experience, but finding people to work with can be a challenge, especially when so many of us cannot meet in person.

To find partners, students start by indicating the times there are available for collaboration, the classes they are taking, and any preferences they have, such as their preferred group size or when they like to start working on problem sets.

A student may then:

- join an existing group that is open to new members and compatible with their schedule and preferences
- create a new group and list it publicly or send invitations to other students
- enter the pool of students to be matched by the system on the next match date

# Schedule

**Projects:**
Project presentations will be in the last two classes (May 11th and 16th)

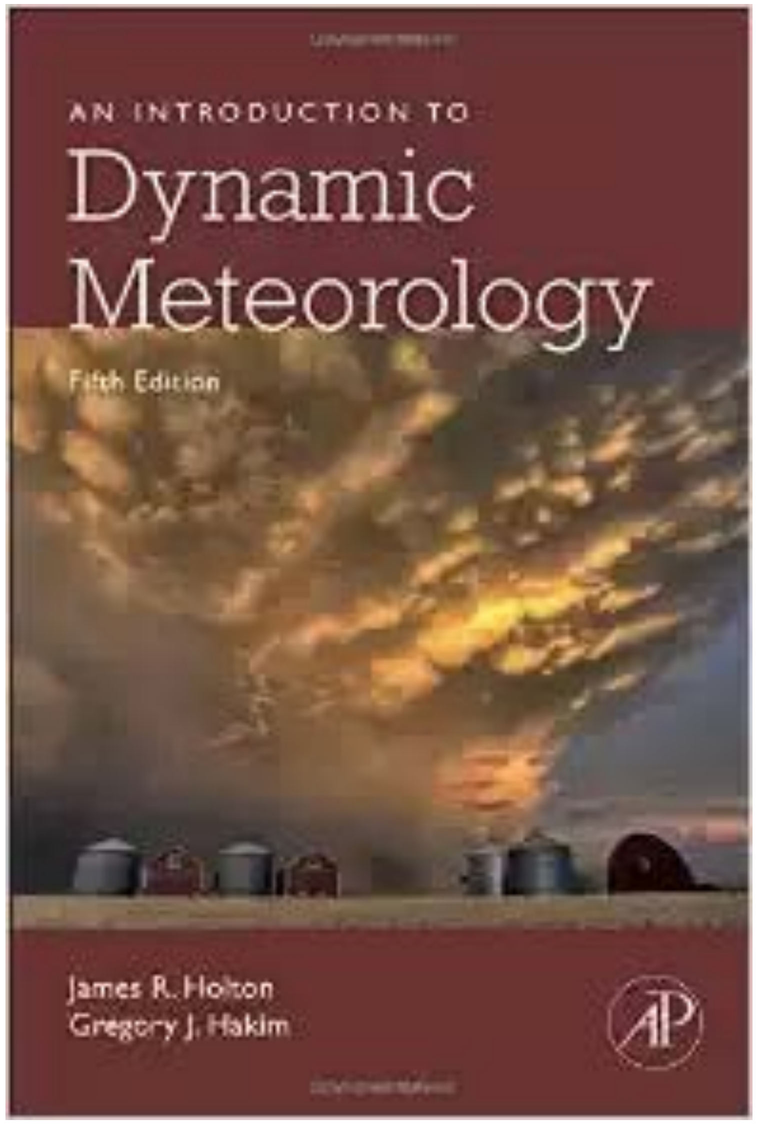
Project reports are due on the last day of class (May 16th)

**Problem sets**
See Canvas website for exact dates for each problem set (given out roughly every two weeks)

# Textbooks and other resources

**Primary Textbook**

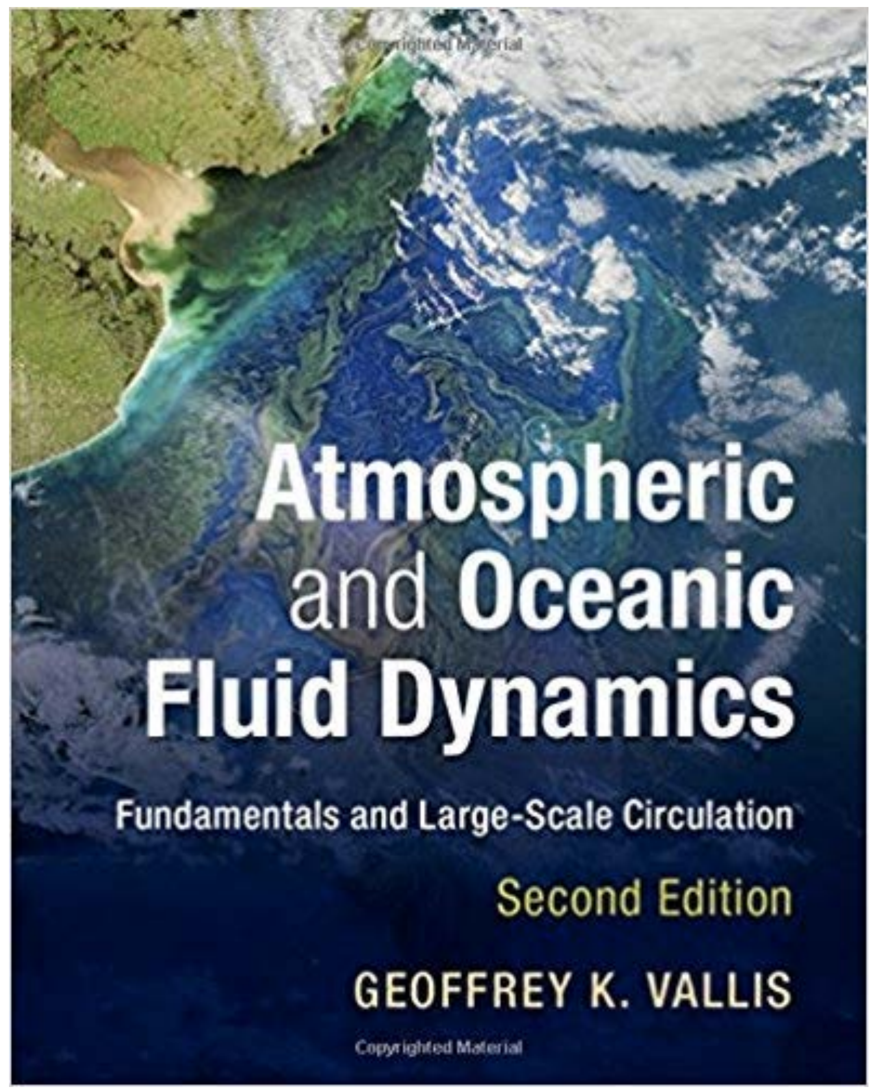
An Introduction to Dynamic Meteorology, Holton and Hakim (5th edition)



# Textbooks and other resources

**Secondary Textbook**

Atmospheric and Oceanic Fluid Dynamics, Vallis (2nd edition)



# Textbooks and other resources

**Other references:**

Physics of Climate, Peixoto and Oort

Interactive plotting website:
http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl

Gridded datasets:
http://www.cdc.noaa.gov/data/gridded/

# Course topics

1. **Hadley-cell dynamics** for a zonally symmetric atmosphere and links to monsoons (the role of eddies is discussed later in the course)
2. **Internal gravity waves:** propagation, effect on mean flow, forcing by mountains
3. **Potential vorticity, quasigeostrophic dynamics, and Rossby waves:** balanced dynamics and omega equation for vertical motion
4. **Growth of disturbances**: wave activity and E-P fluxes, Charney-Stern condition, Eady model, non-modal growth, observed cyclogenesis
5. **Energetics:** available potential energy of the atmosphere
6. **The general circulation**: the role of eddies, the circulation in isentropic coordinates and transport of tracers

# Plan for the remainder of this introduction

- Sources of observations
- Basic aspects of observed circulations and thermal structure
- Some motivating questions

# Sources of observations

# Observational data for studies of large-scale atmospheric dynamics

- Data sparseness in space and time is a major issue
- Often combine the data with an atmospheric general circulation model (GCM) using data assimilation (includes analysis and initialization)
- Goal is minimization of discrepancy between observations and model variables (e.g., 4D var)

# We will often use reanalysis products

- Reanalysis means that model (general circulation model; GCM) is held fixed over long time period, but observational inputs vary

- Reanalysis was pioneered by Eugenia Kalnay (first woman to get a PhD in meteorology at MIT) and are now very popular

The **NCEP**/NCAR 40-year **reanalysis** project
E Kalnay, M Kanamitsu, R Kistler… - Bulletin of the …, 1996 - journals.ametsoc.org
The **NCEP** and NCAR are cooperating in a project (denoted "**reanalysis**") to produce a 40-year record of global analyses of atmospheric fields in support of the needs of the research and climate monitoring communities. This effort involves the recovery of land surface, ship …
Cited by 24845 Related articles All 24 versions Web of Science: 18405 Import into BibTeX

- Commonly used modern reanalyses:
  - National Centers for Environmental Prediction (NCEP): NCEP2, CSFR
  - European Centre for Medium-Range Weather Forecasts (ECMWF): ERA40, ERA interim, ERA5
  - NASA: MERRA, MERRA2
  - Only using surface data so can go back to 1836: 20CR, ERA-20C

# Timeline of observations assimilated in ERA40

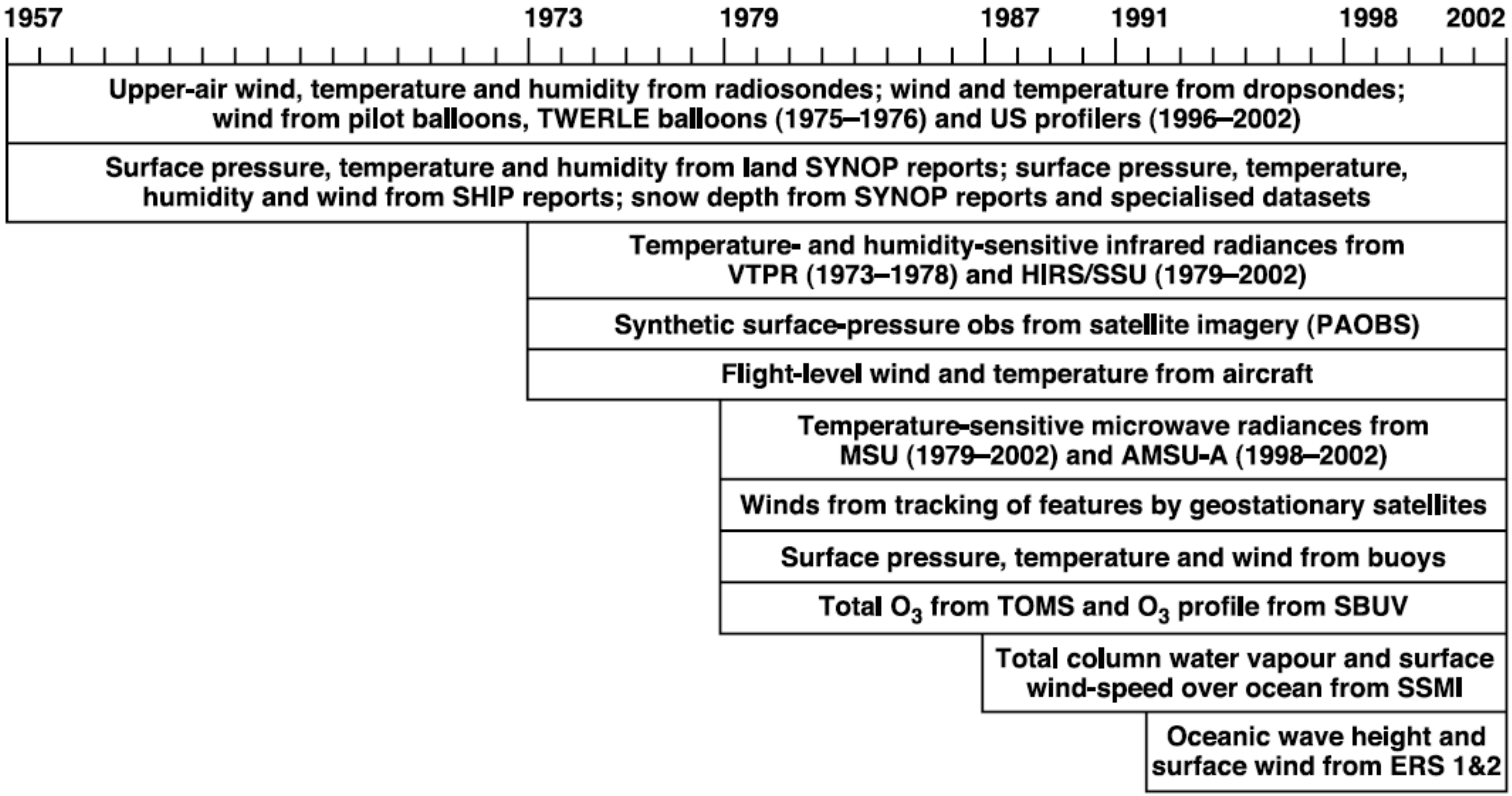
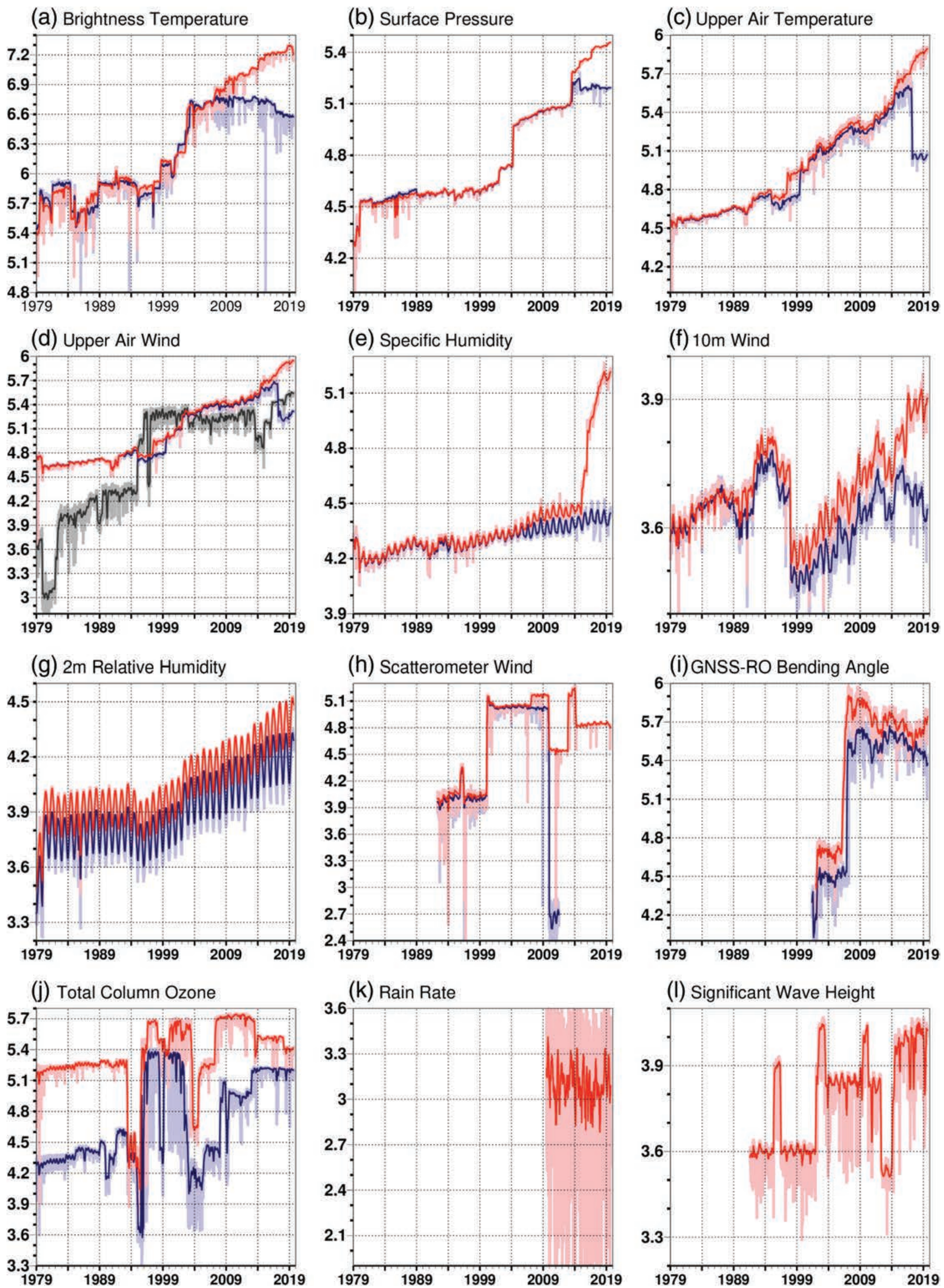



Figure 1. Chronology of types of observations assimilated in ERA-40 from 1957 to 2002. (See appendix A for acronyms.)




## Number of observations (log10 scale) assimilated in ERA5 (red) and ERA interim (blue)



*Hersbach et al, QJRMS, 2020*

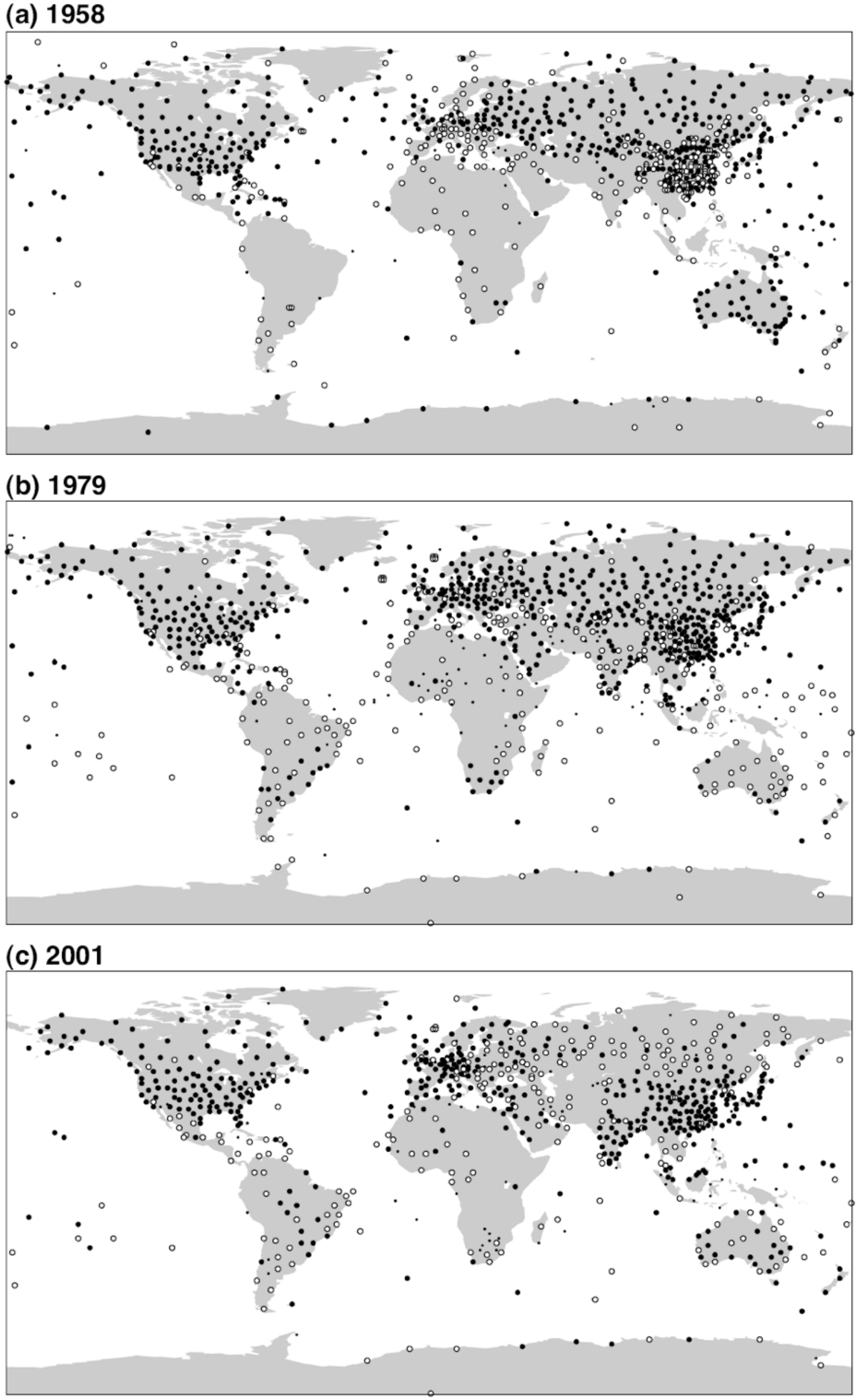



Figure 2. Frequency of radiosonde reports for: (a) 1958, (b) 1979 and (c) 2001. Solid circles denote stations from which at least three reports are available every 2 days on average, open circles denote other stations reporting at least once every 2 days, and small dots represent stations reporting at least once per week.

# Frequency of radiosonde reports



*Uppala et al, QJRM 2005*

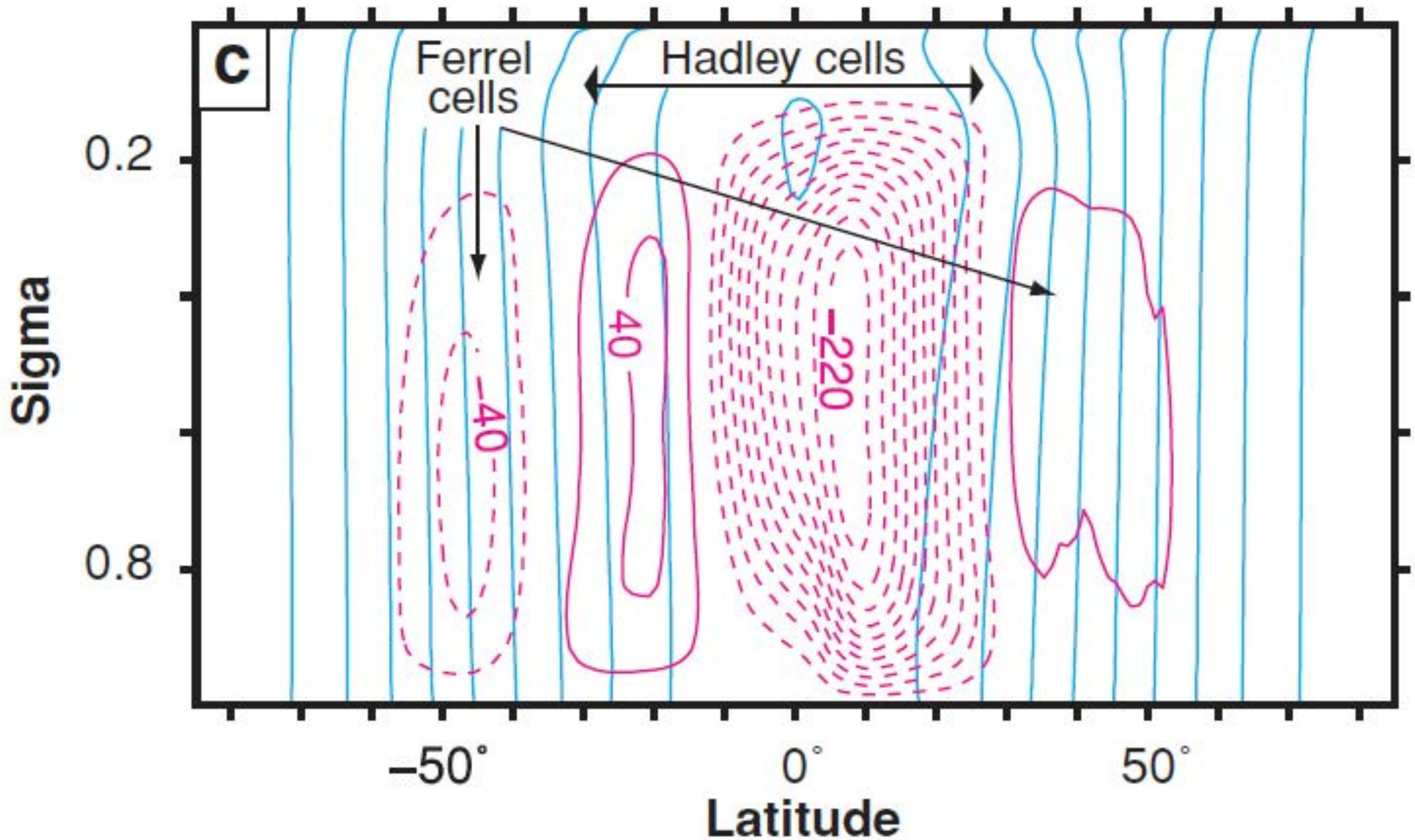
# “20th century” reanalyses

- Use only surface data which has the advantage that it goes back further in time and is more homogeneous in time (20CR, ERA-20C)
- 20th century reanalysis project (20CR, Compo, 2010):
  - only assimilates SST, sea ice, and surface pressure
  - V3 is from 1836-2015!

# Basic aspects of observed circulations and thermal structure with some motivating questions

# Hadley cells, and subtropical and eddy-driven jets

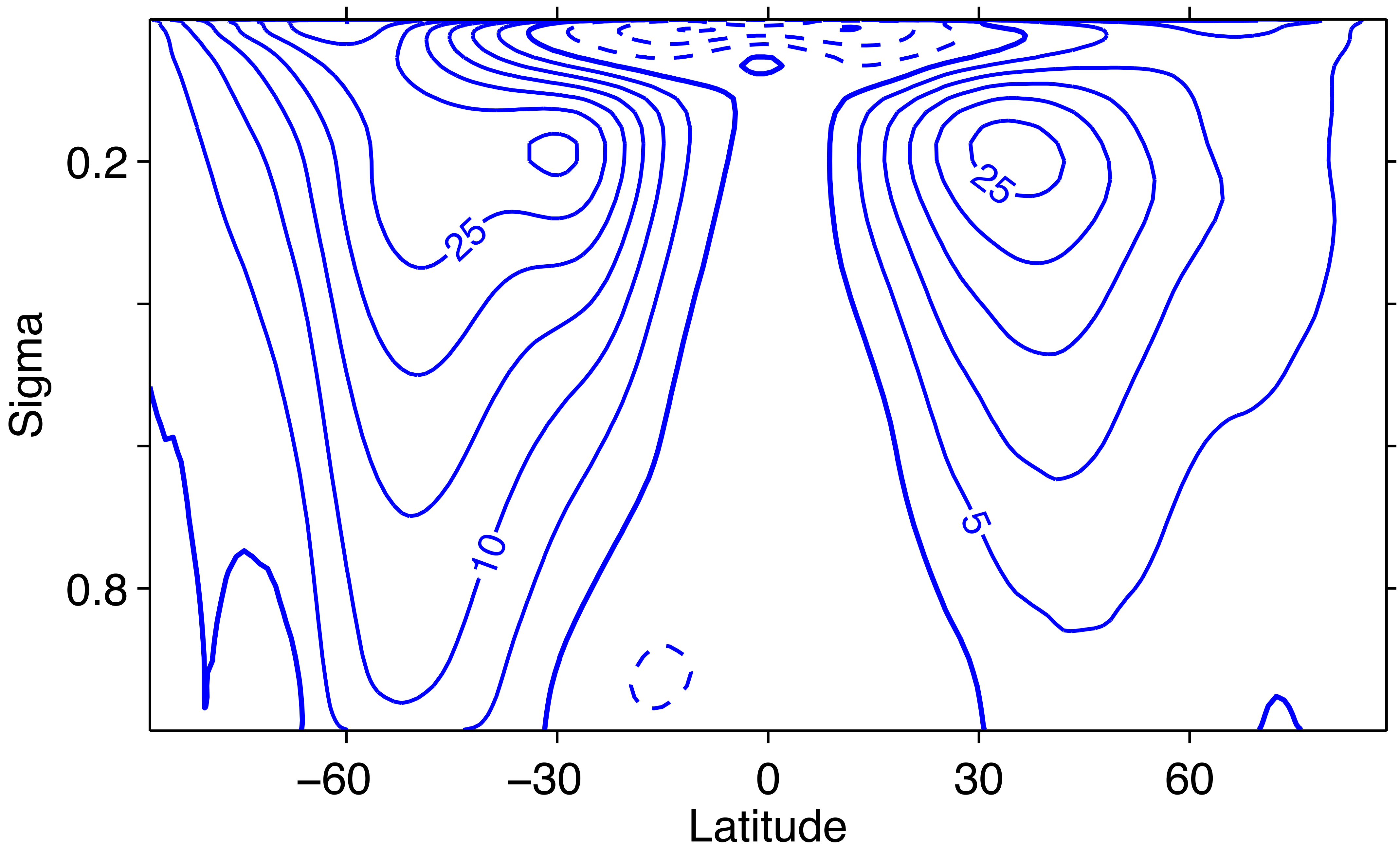
# Mean meridional circulation and contours of angular momentum per unit mass (January; ERA40)




(*c*) Eulerian mass flux streamfunction (*magenta*) and angular momentum (*light blue*). Contour intervals are $20 \times 10^9$ kg s$^{-1}$ for streamfunction and $0.1\Omega a^2$ for angular momentum, with angular momentum decreasing monotonically from the equator to the poles.

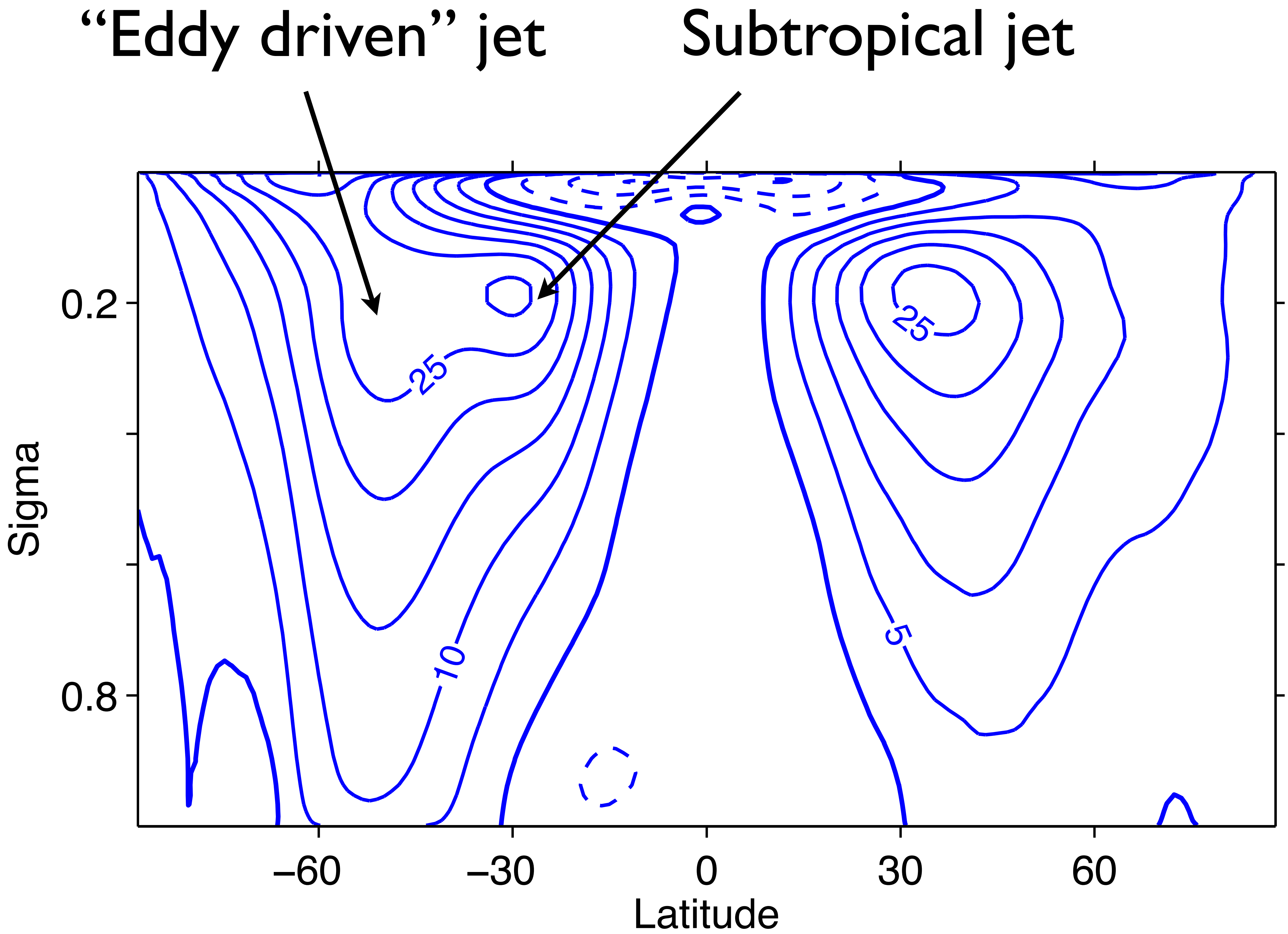
*(T. Schneider, Fig. 1, Ann. Rev. Earth Planet. Sci. 2006)*

# Zonal- and time-mean zonal wind (m/s)





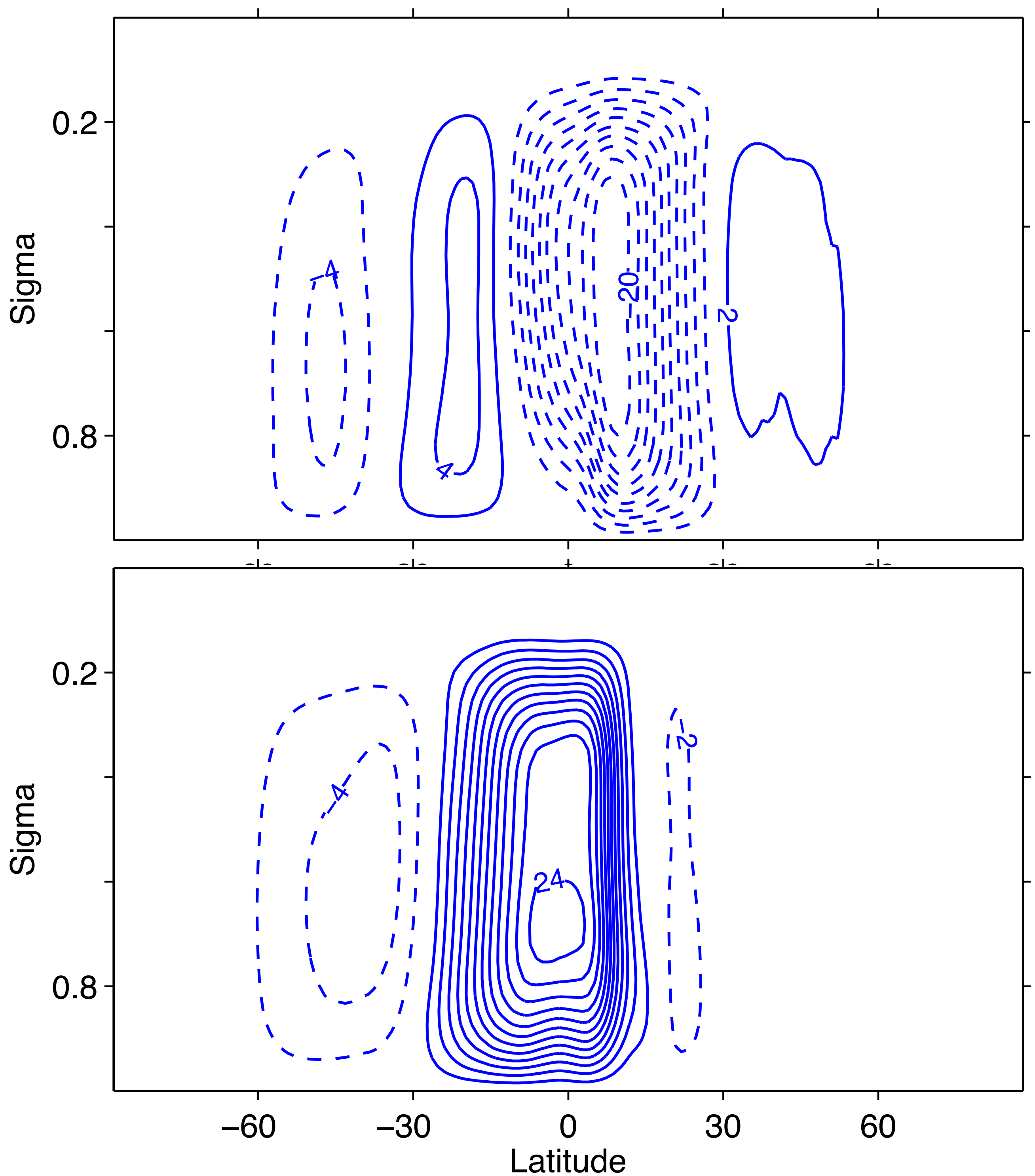

*(ERA40 reanalysis 1980-2001)*






*(ERA40 reanalysis 1980-2001)*

# Mean meridional streamfunction ($10^{10}$ kg s$^{-1}$): different seasons




December-January-February (DJF)

June-July-August (JJA)

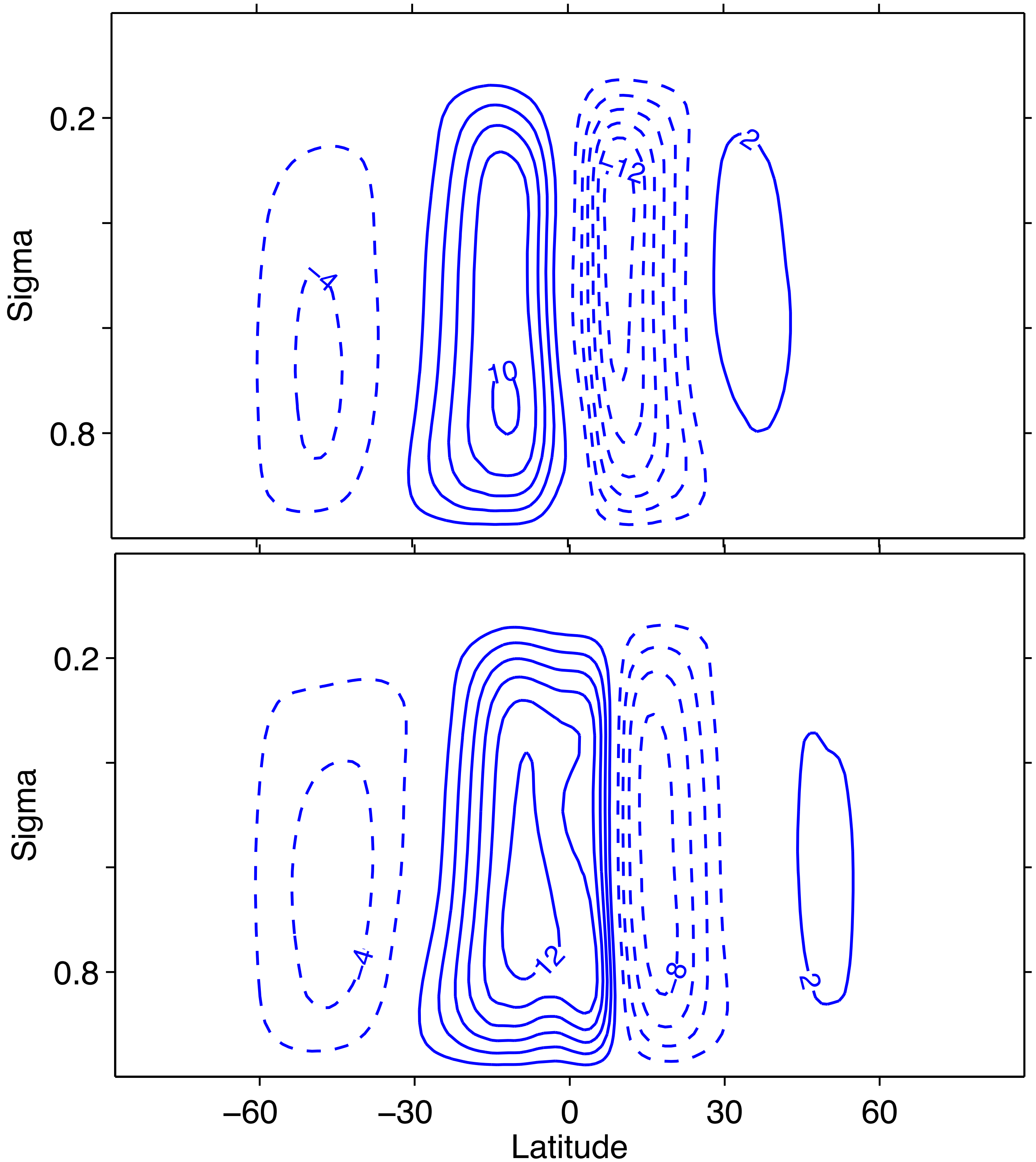


*(ERA40 reanalysis 1980-2001)*

# Mean meridional streamfunction ($10^{10}$ kg s$^{-1}$): different seasons

MAM

SON






*(ERA40 reanalysis 1980-2001)*

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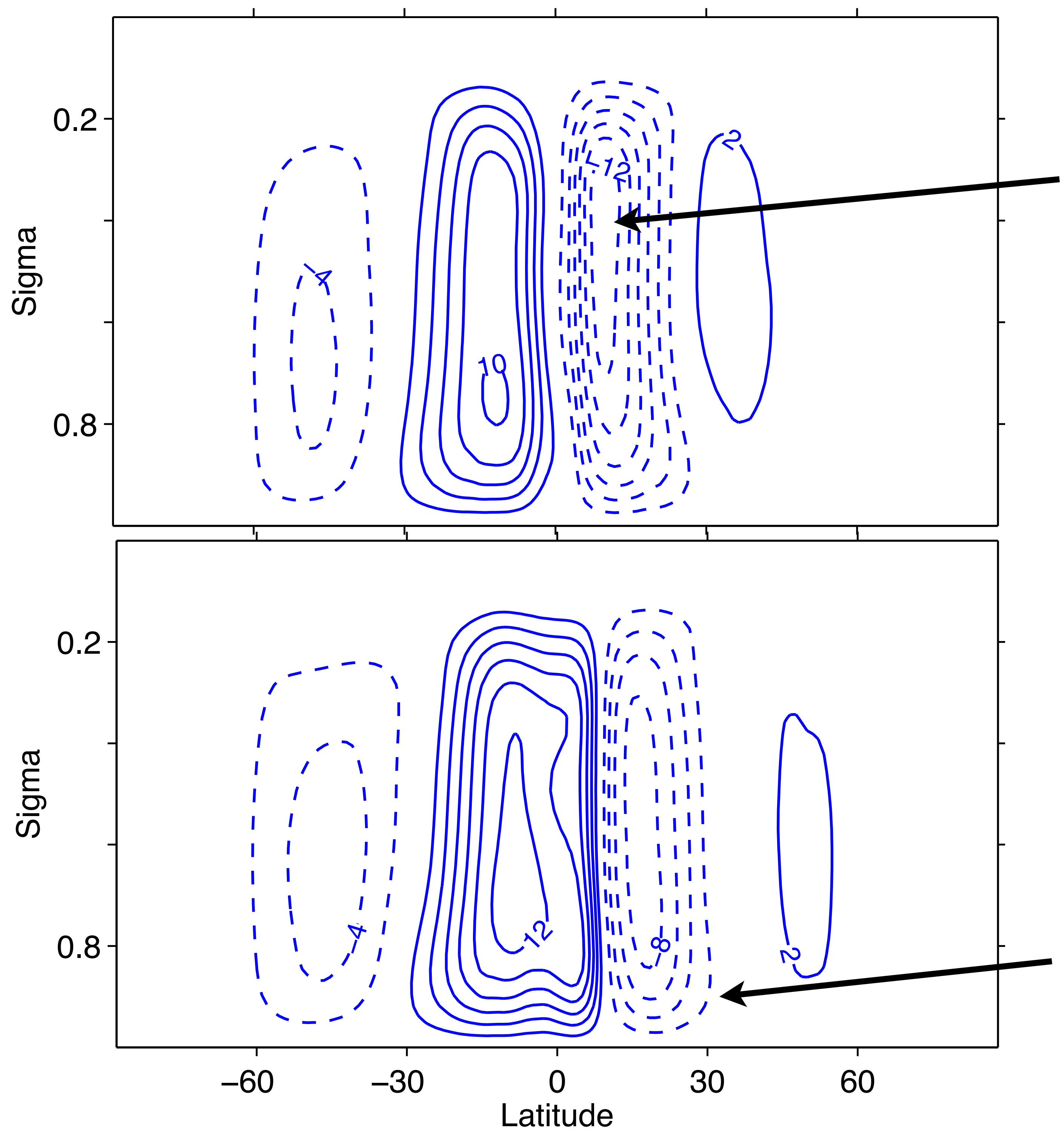



1. What determines strength of Hadley cells?

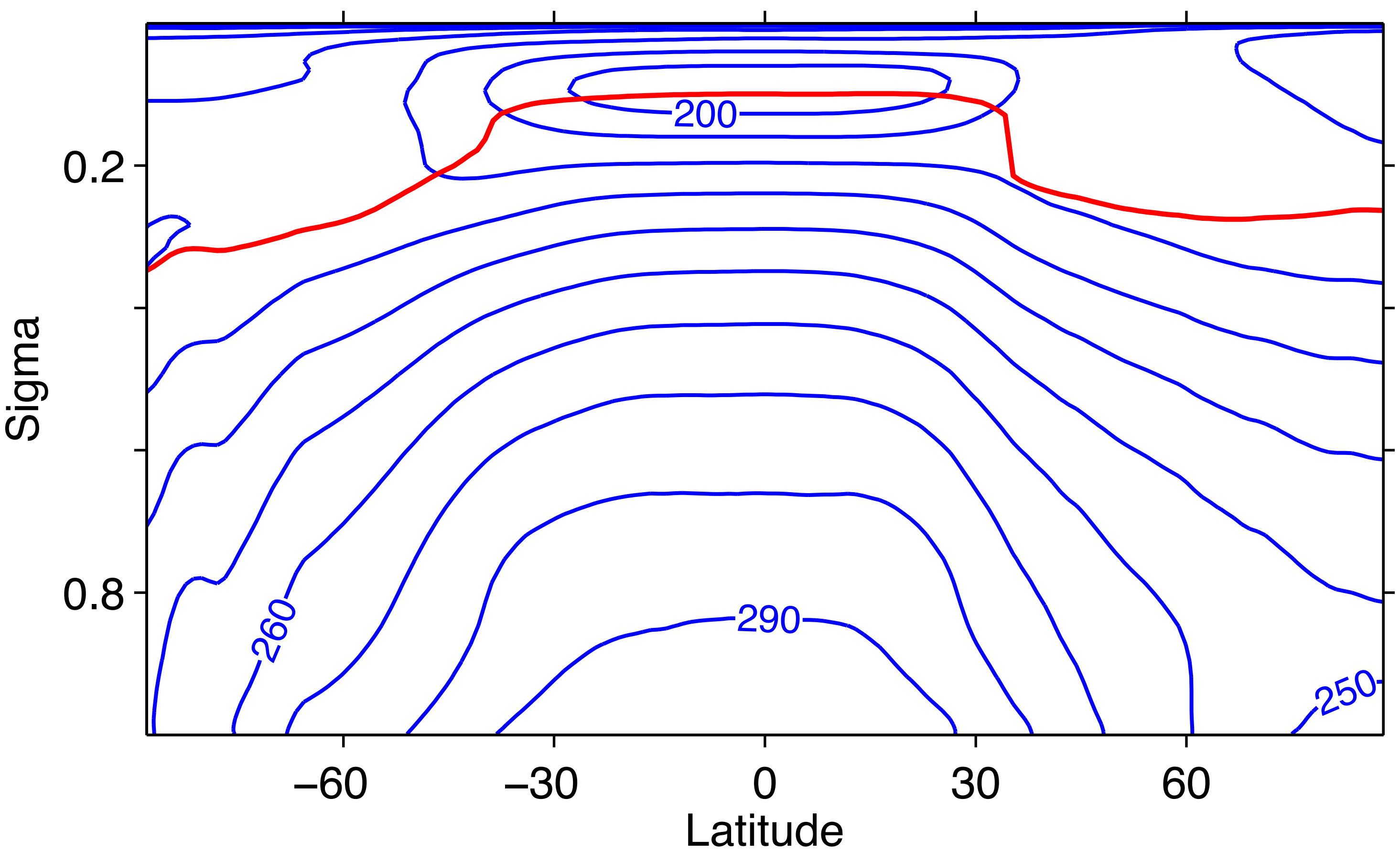
2. What determines extent of Hadley cells?



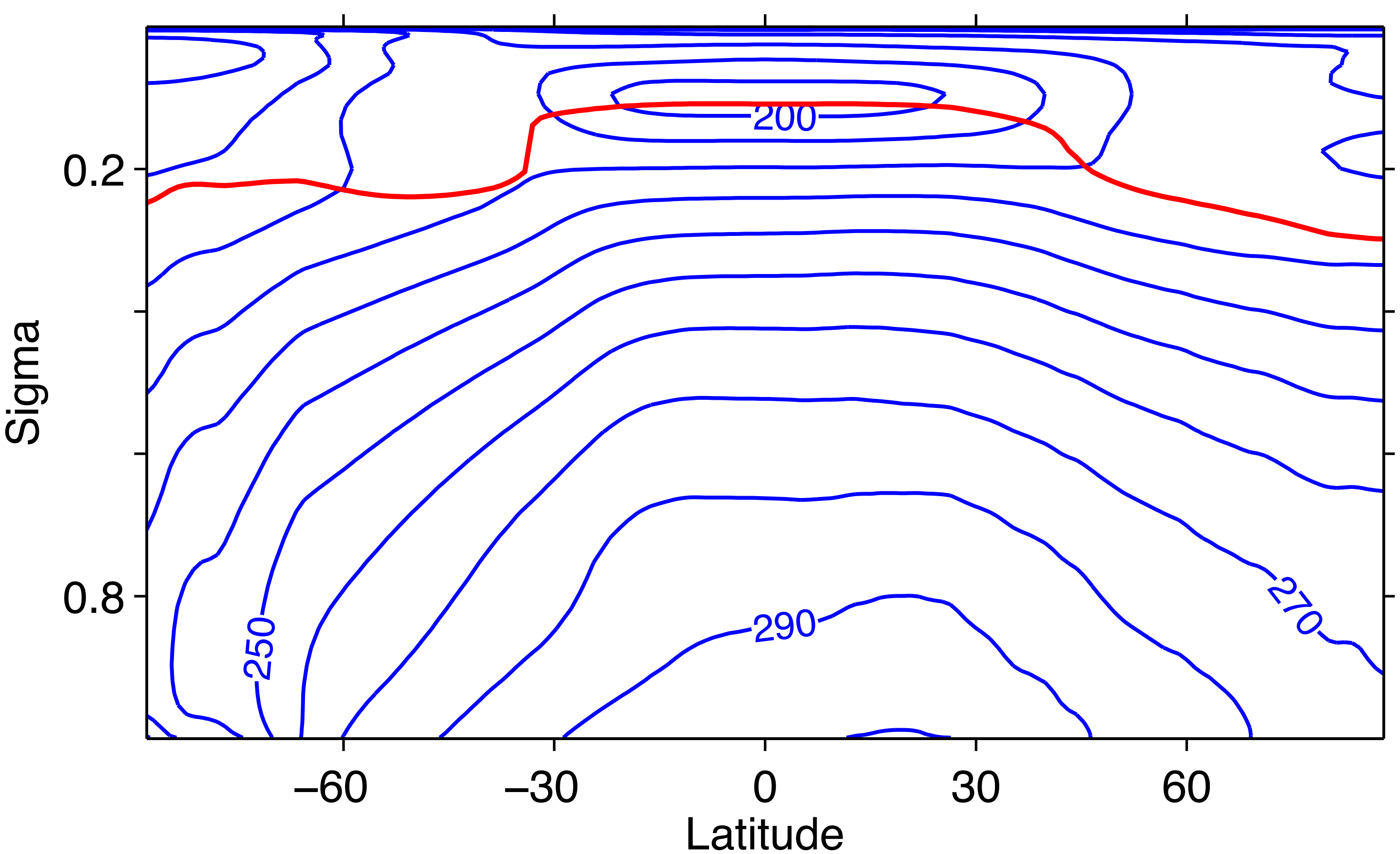
*(ERA40 reanalysis 1980-2001)*

# Observed thermal structure and gravity wave dynamics

# Zonal and time mean temperature (K)




December-January-February (DJF)




June-July-August (JJA)

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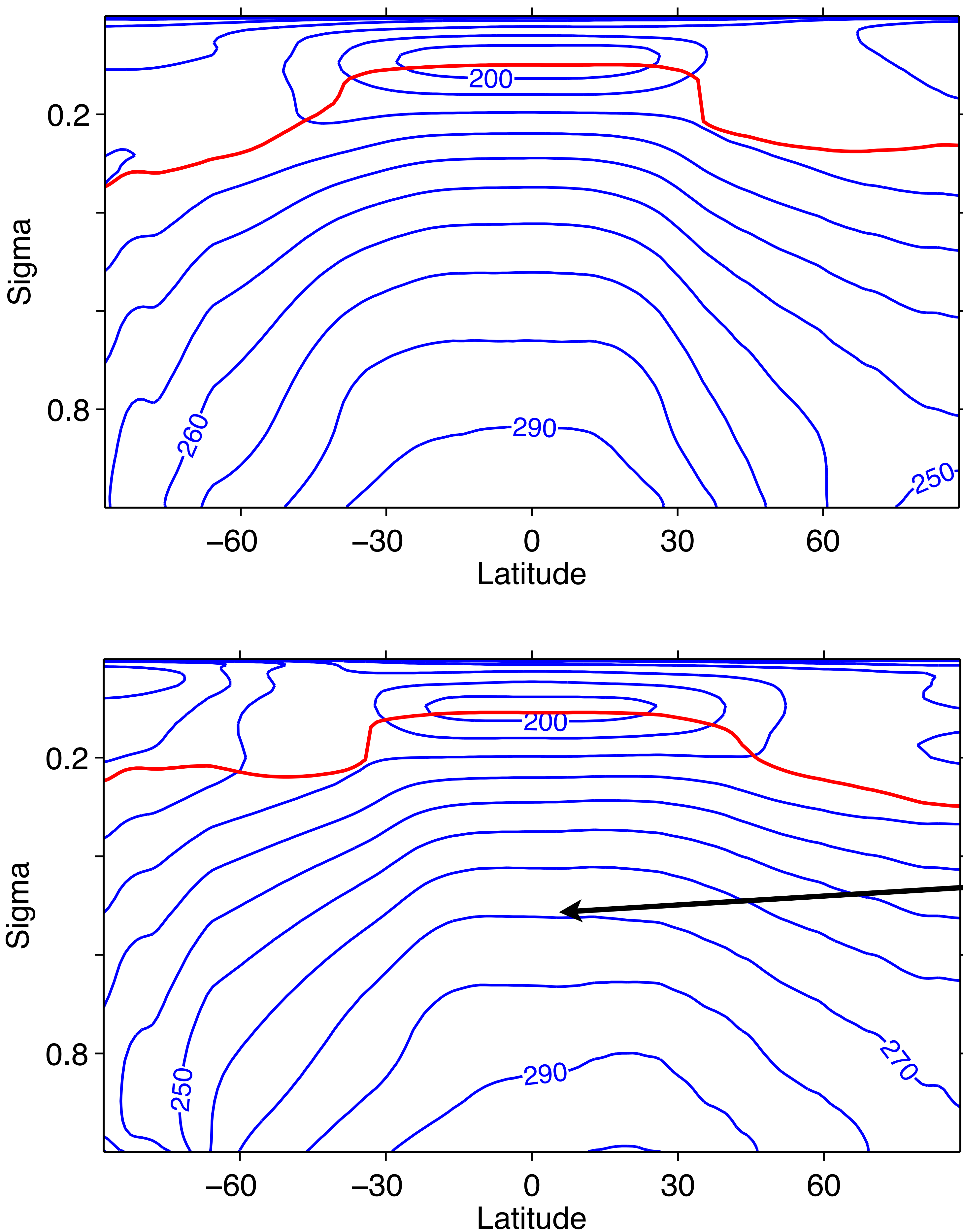
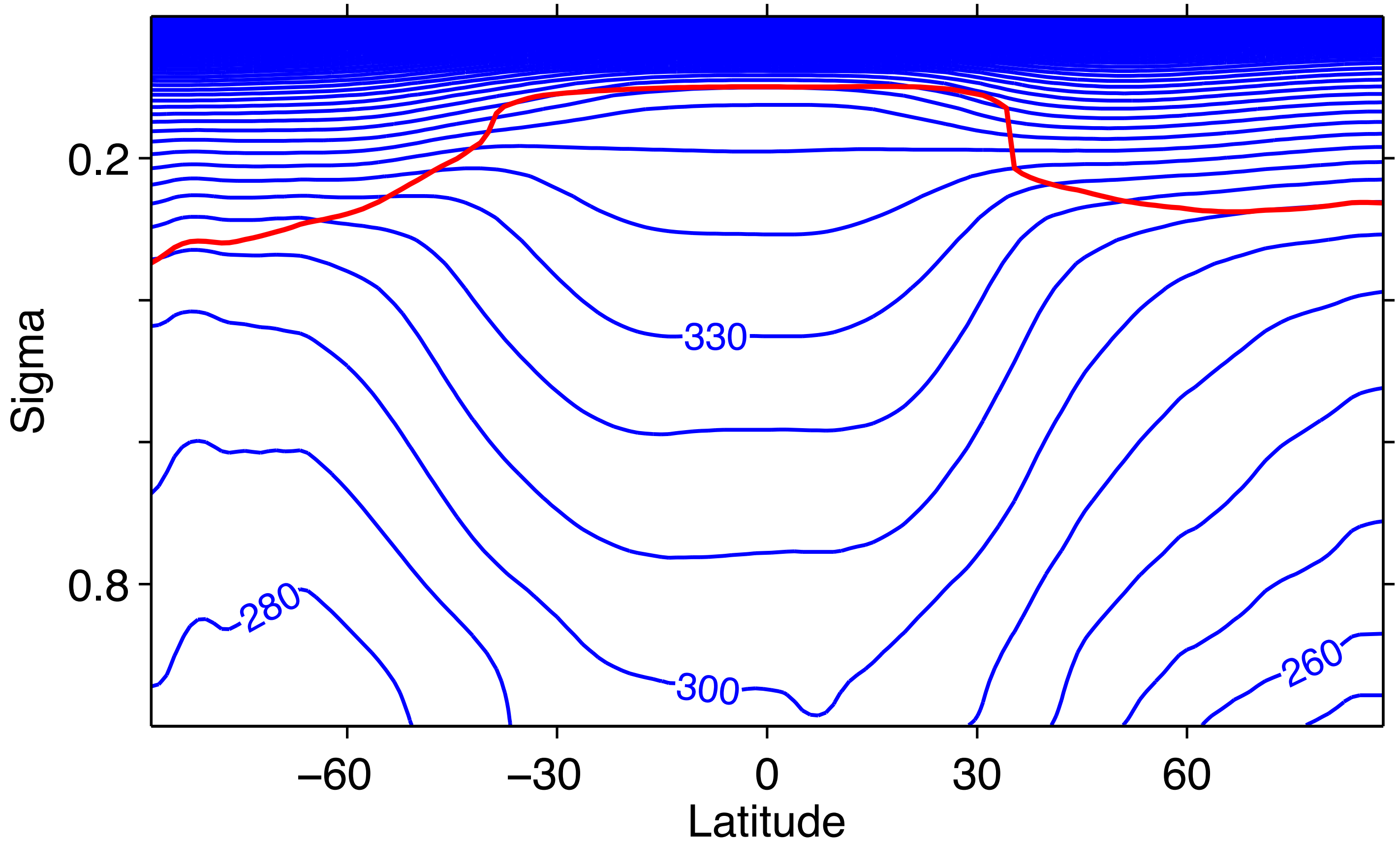


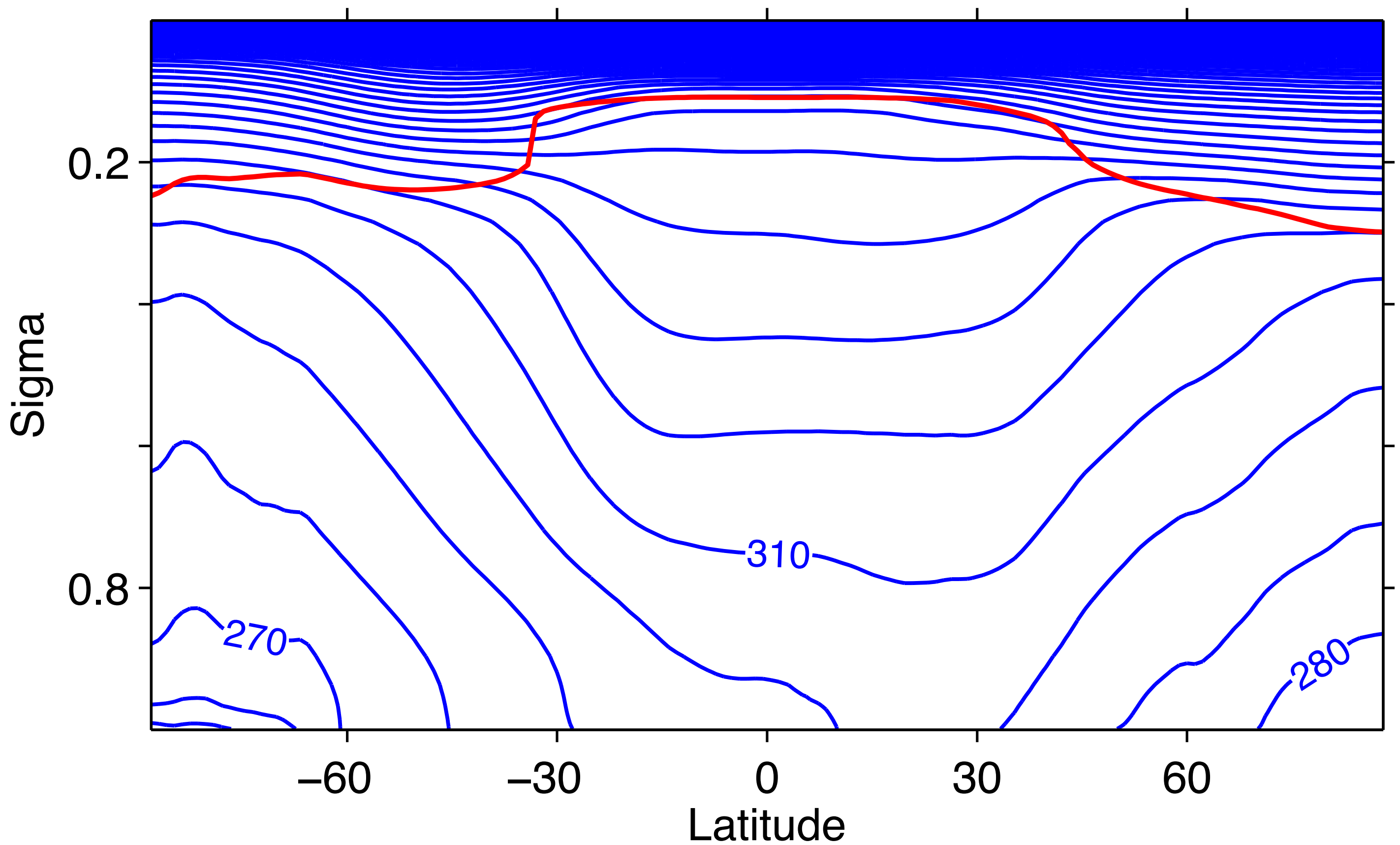

December-January-February (DJF)

Why are isotherms so flat in tropics?



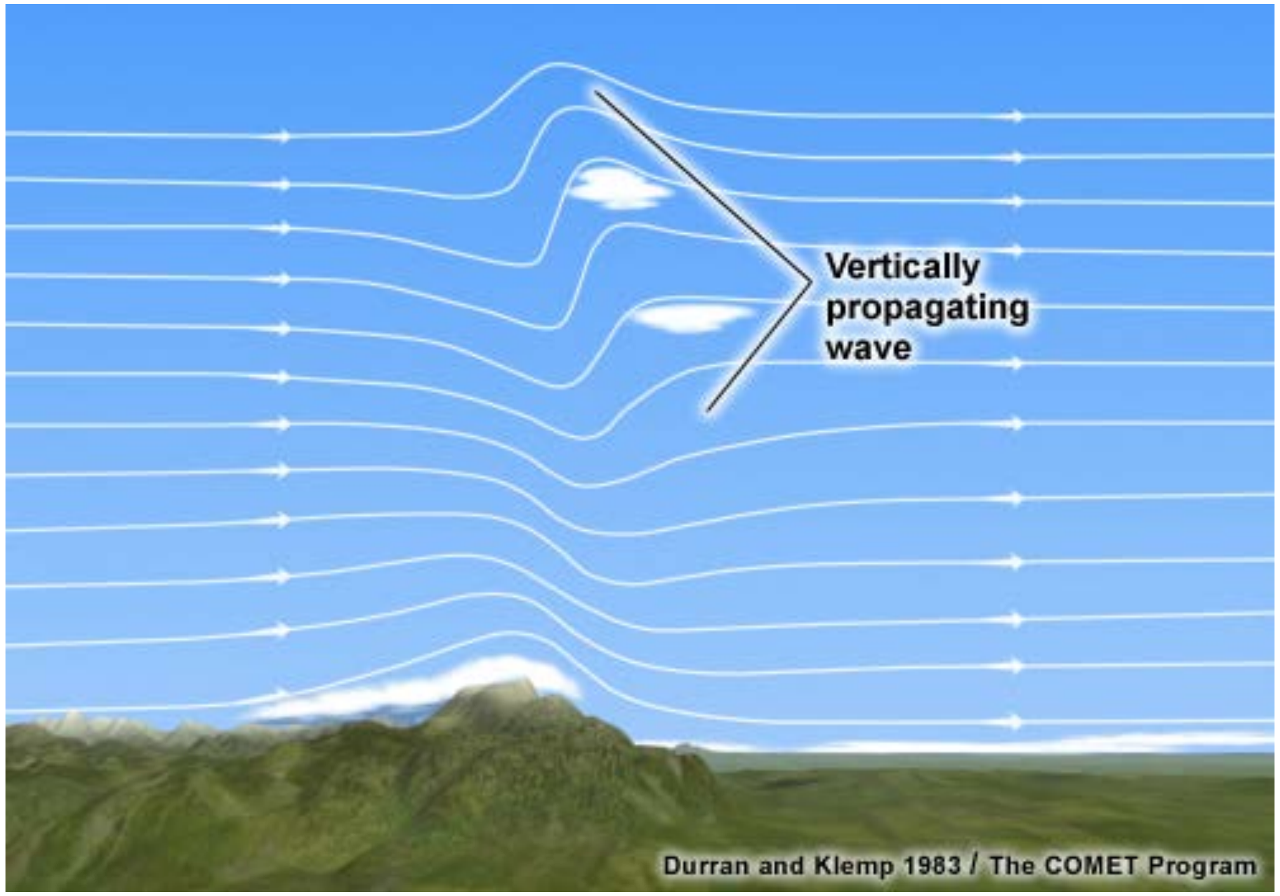

DJF

# Potential temperature (K)

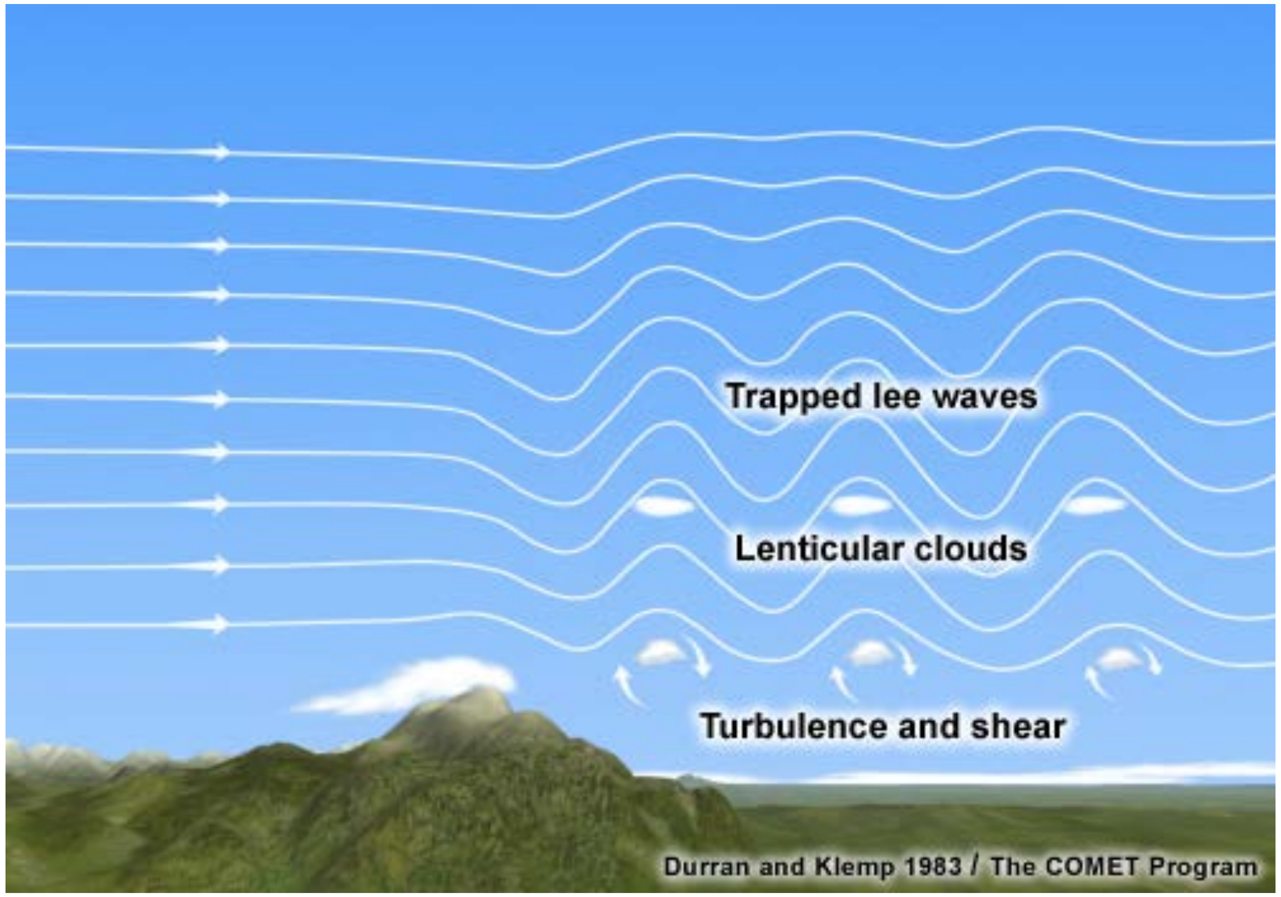



JJA

Increase with height (implies dry static stability)




# Static stability allows for internal gravity waves: here forced by mountain



# Trapped lee waves downwind from Hawaiian Islands

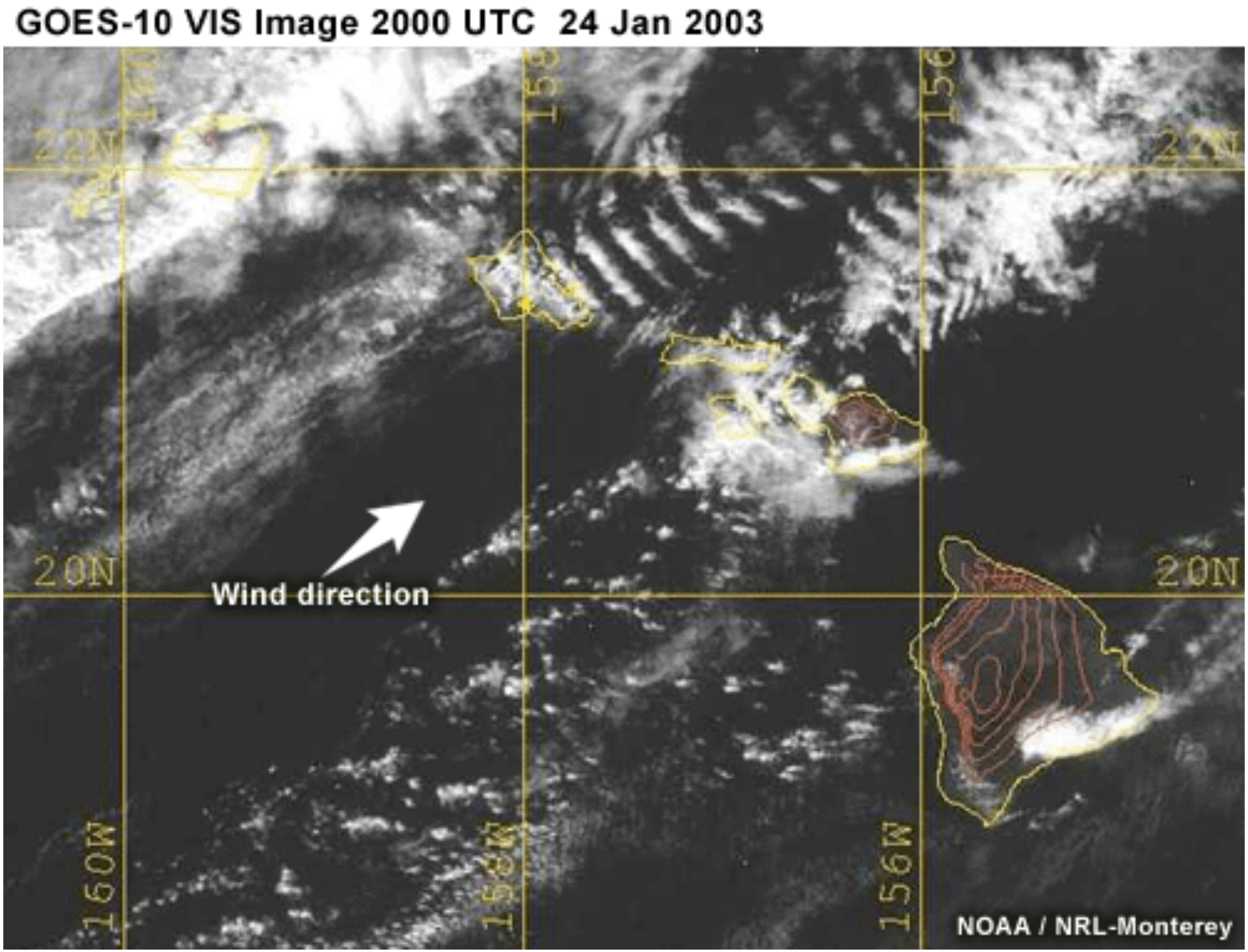
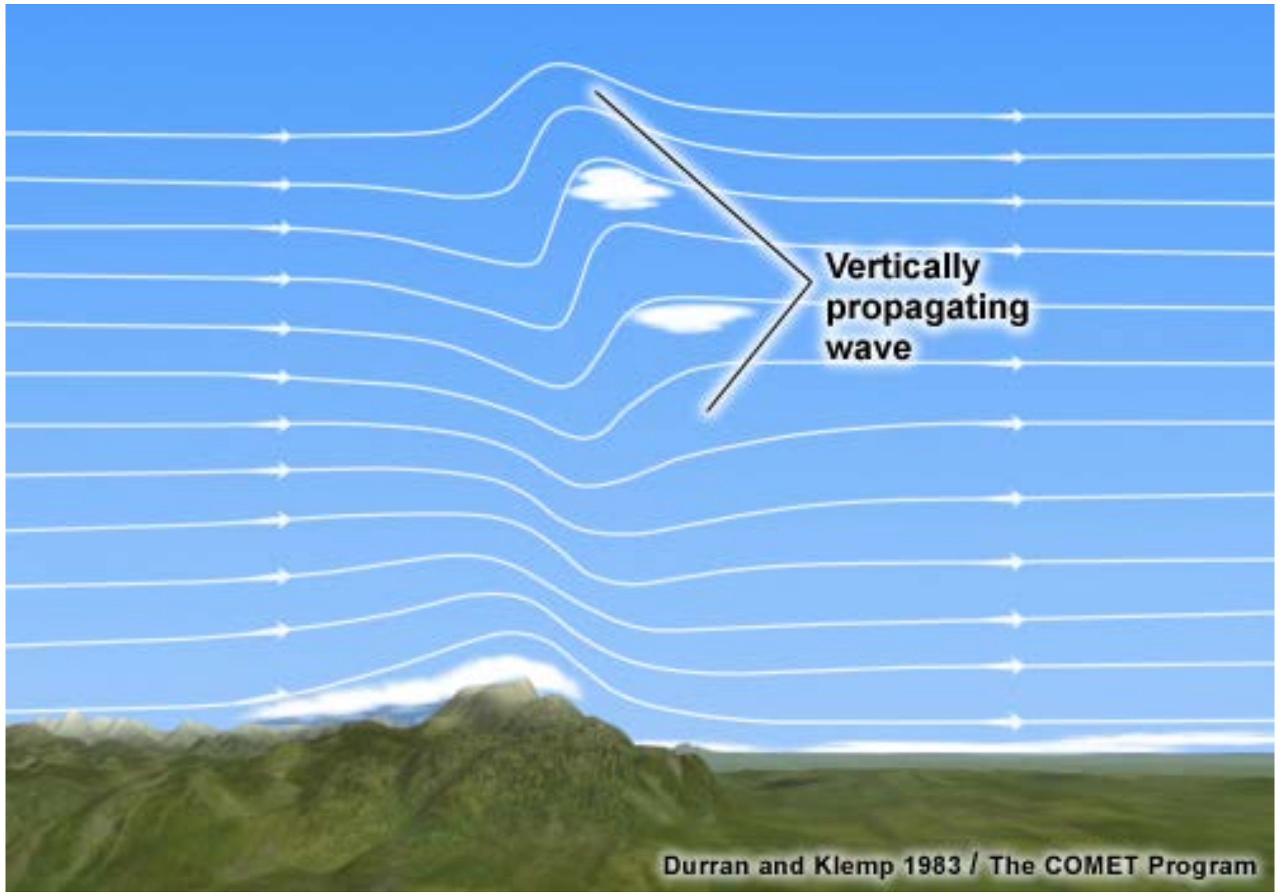
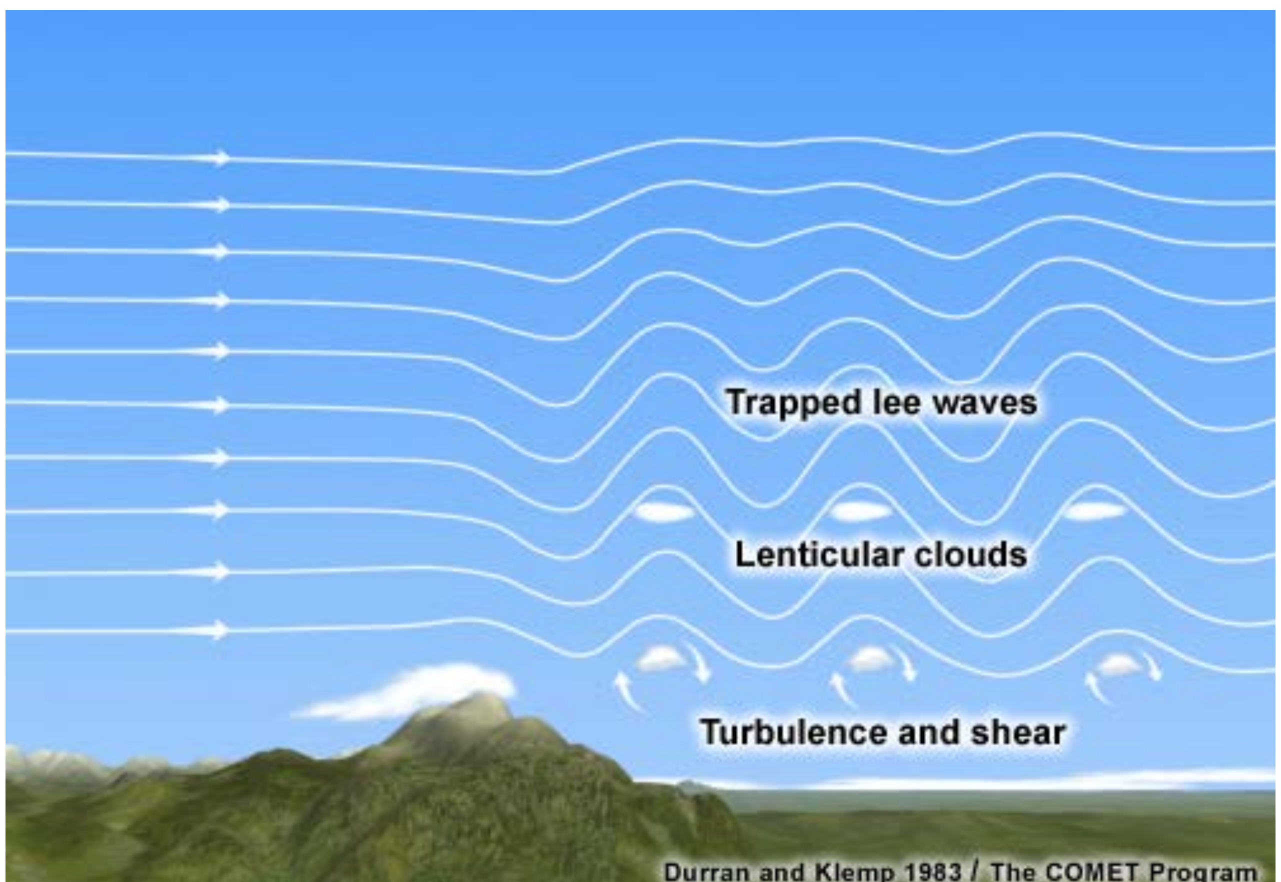



Image courtesy of NOAA/NRL-Monterey.



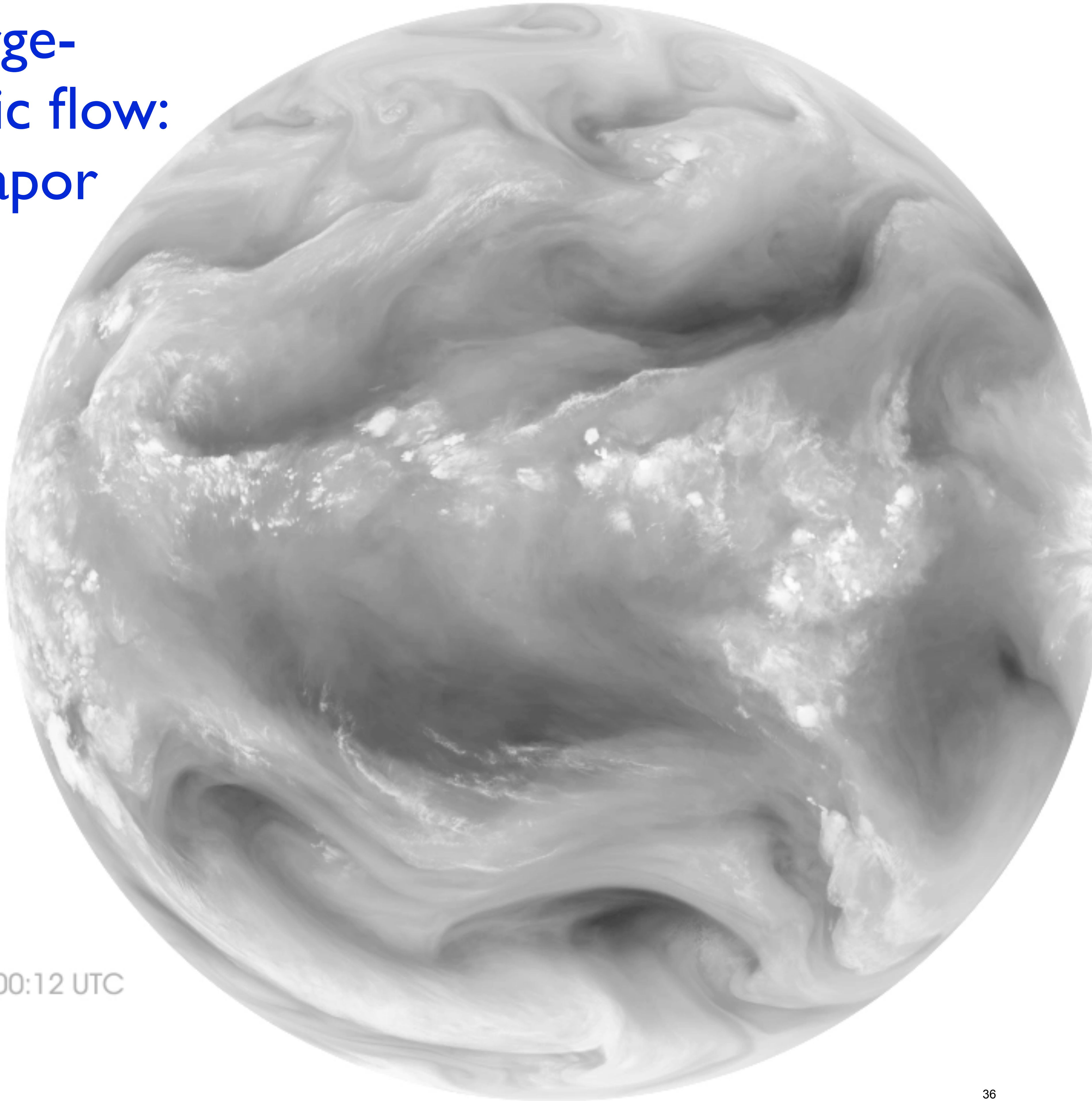

Questions:

1. What determines whether internal gravity waves are vertically propagating or trapped?

2. How do the waves affect the mean flow?

# Large-scale eddies:
# Growth of baroclinic eddies, propagation of planetary waves, forcing of vertical motions

# Illustration of large-scale atmospheric flow: satellite water vapor imagery



October 7, 2007 00:12 UTC

Animation: Robert Simmon,NASA
Data: Seviri water vapor (IR)

Image courtesy of NASA.

# Transient (<1 week) eddies in midlatitudes in observations

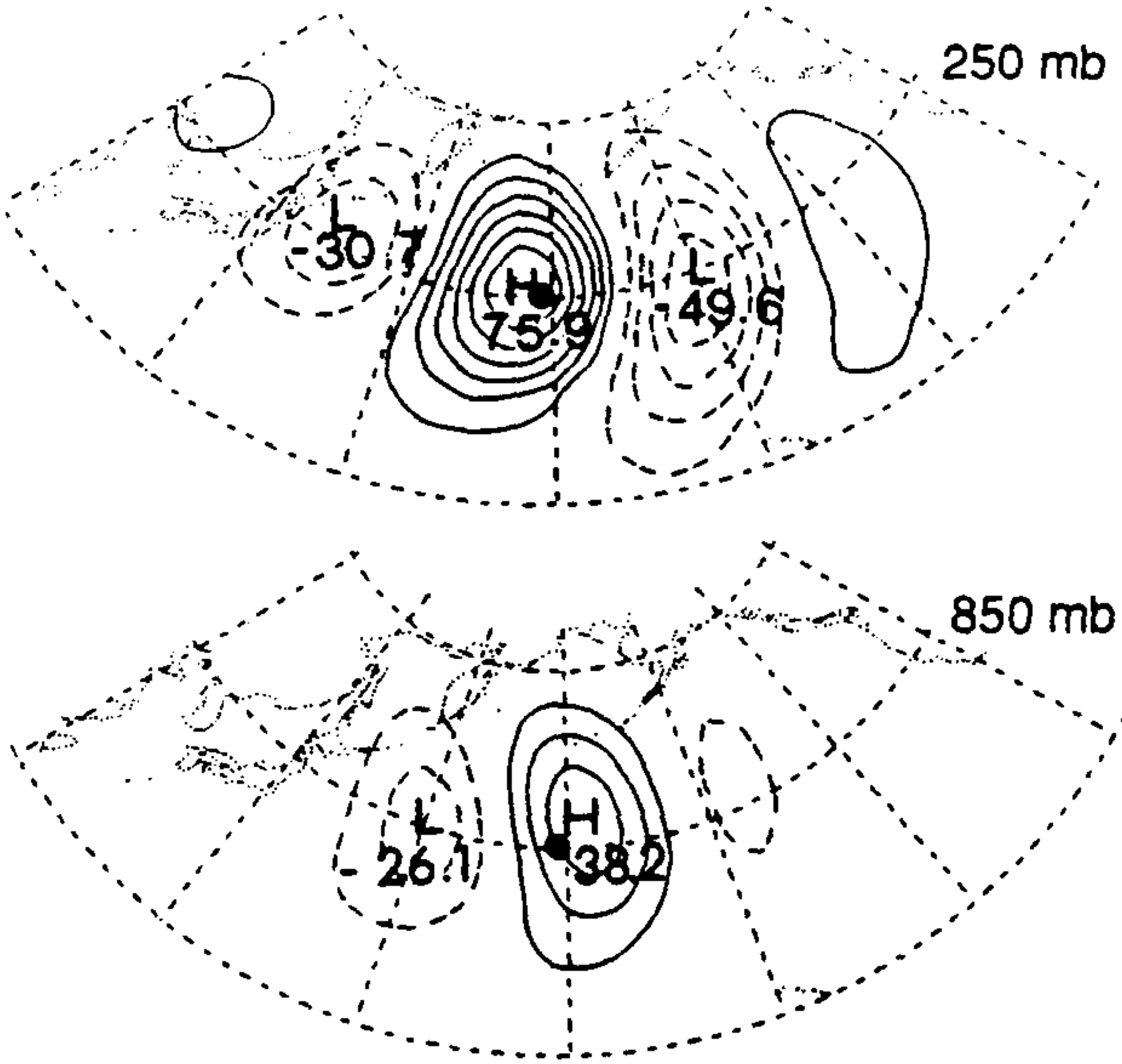



FIG. 1. The 250-mb (upper) and 850-mb (lower) geopotential height regression maps based on highpass filtered, normalized 500-mb height at the reference grid point marked with a solid circle. Each map covers from 140°E through the date line to 140°W in longitude and 20°N to 60°N. The interval between latitude and longitude lines is 20°. Negative contours are dashed and the zero contour is omitted. Contour interval: 10 m.

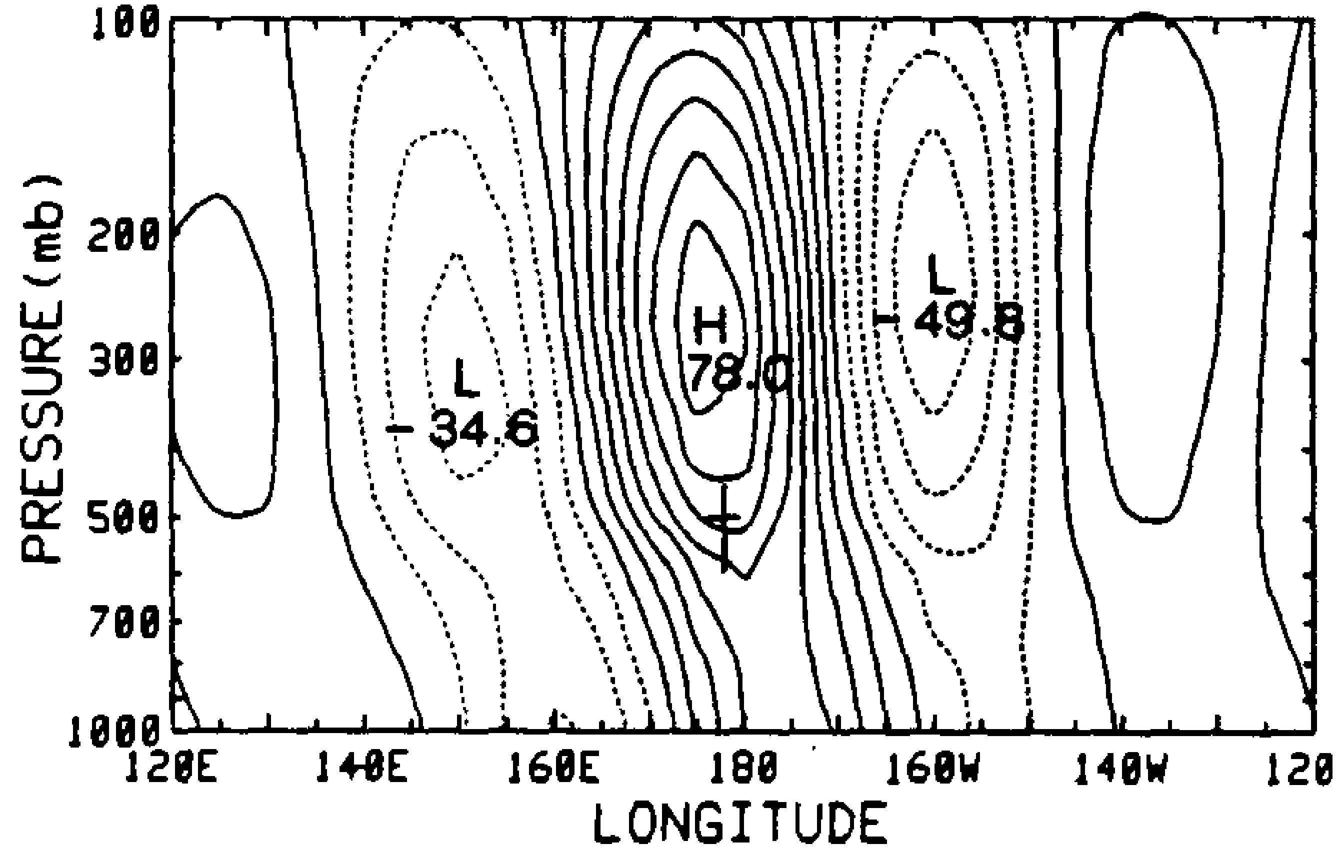
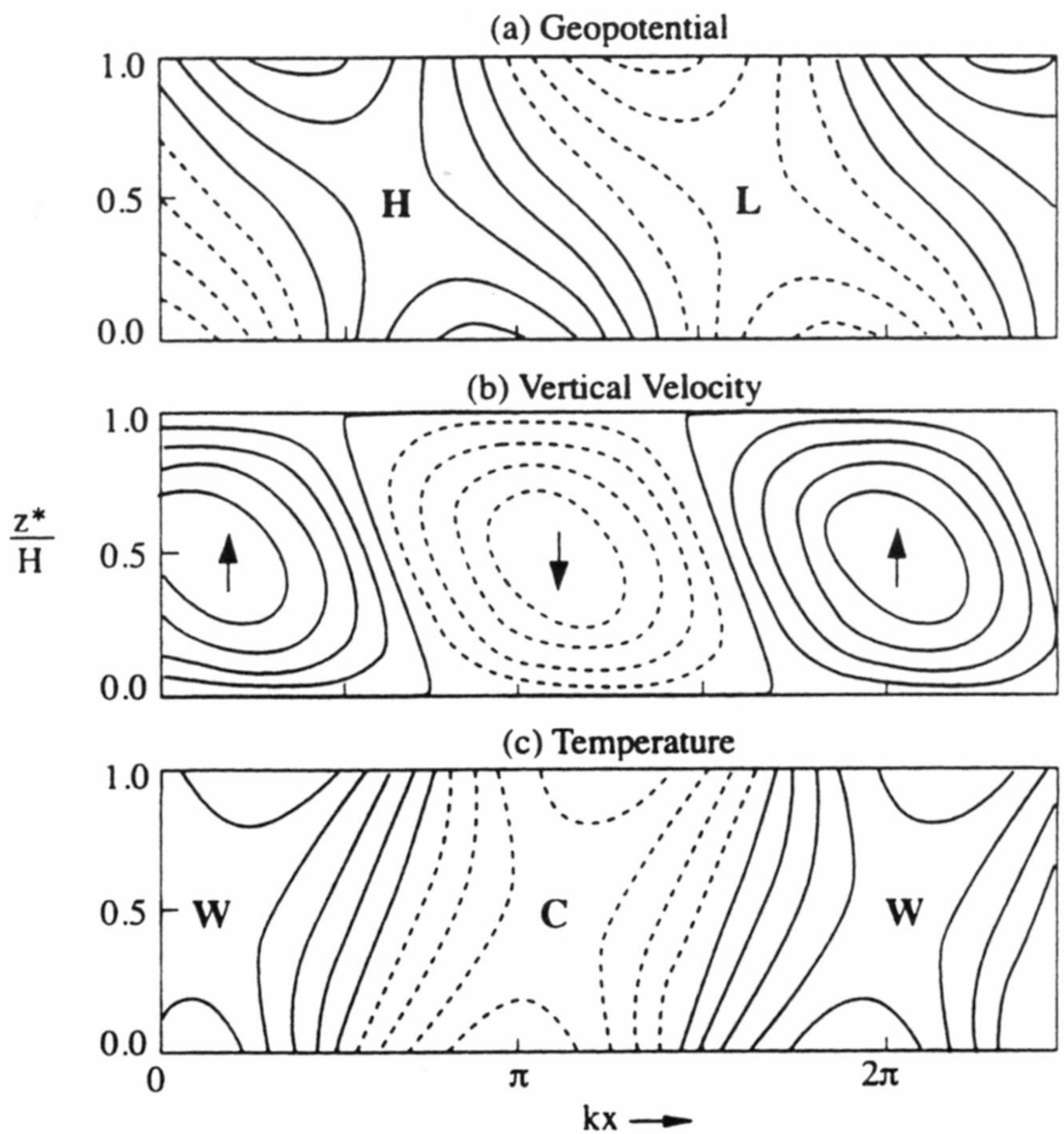



FIG. 3. Geopotential height regression cross section along 40°N for the same reference time series as in Fig. 1, assembled from one-point regression maps of geopotential height at ten standard pressure levels. Negative contours are dashed. Contour interval: 10 m.

*Lim and Wallace 1991*

# Why do eddies grow in midlatitudes?

Most unstable wave in the Eady model



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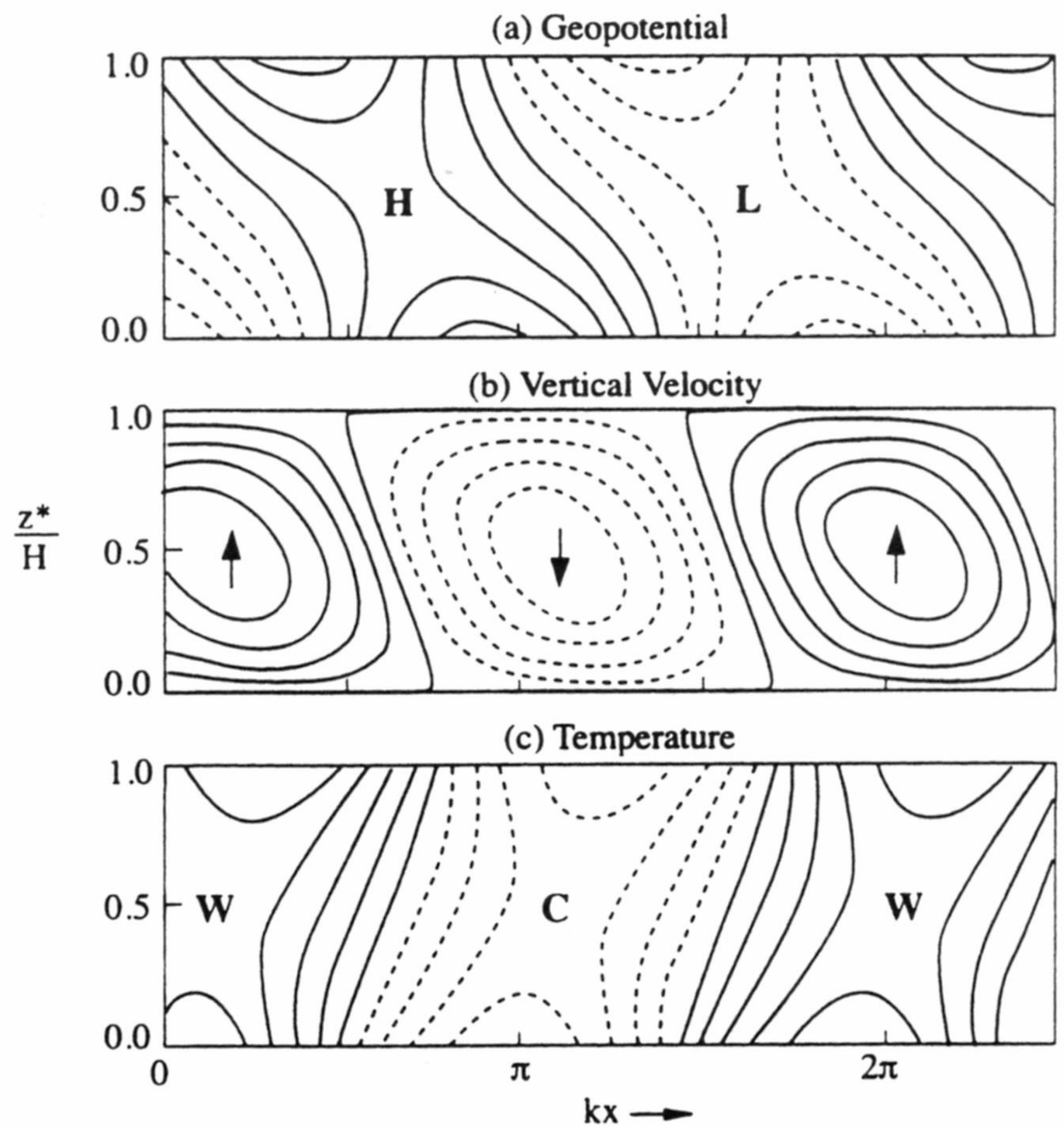



And what controls the magnitude of the vertical velocity?

# How can we understand individual cyclogenesis events? (using potential vorticity!)

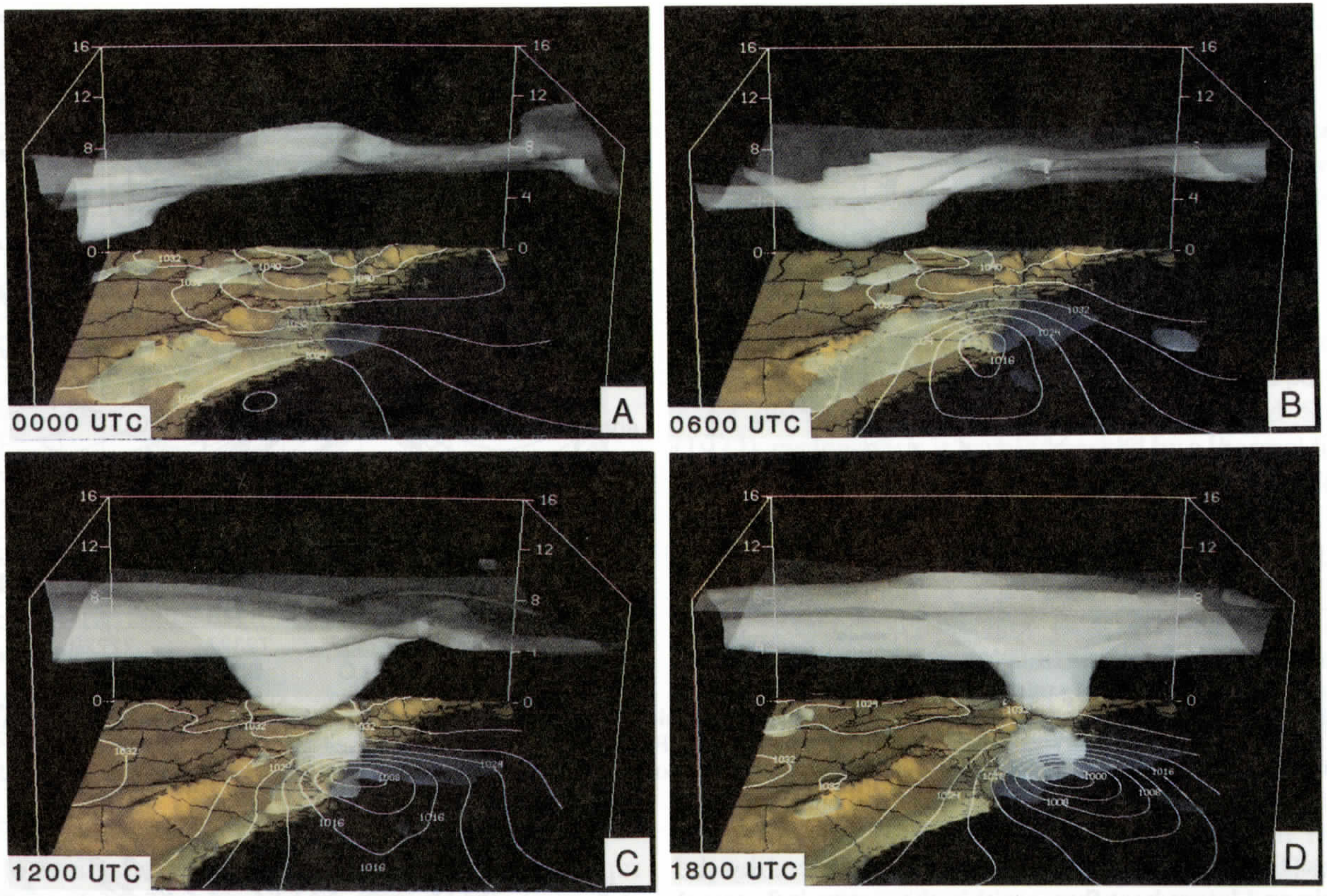
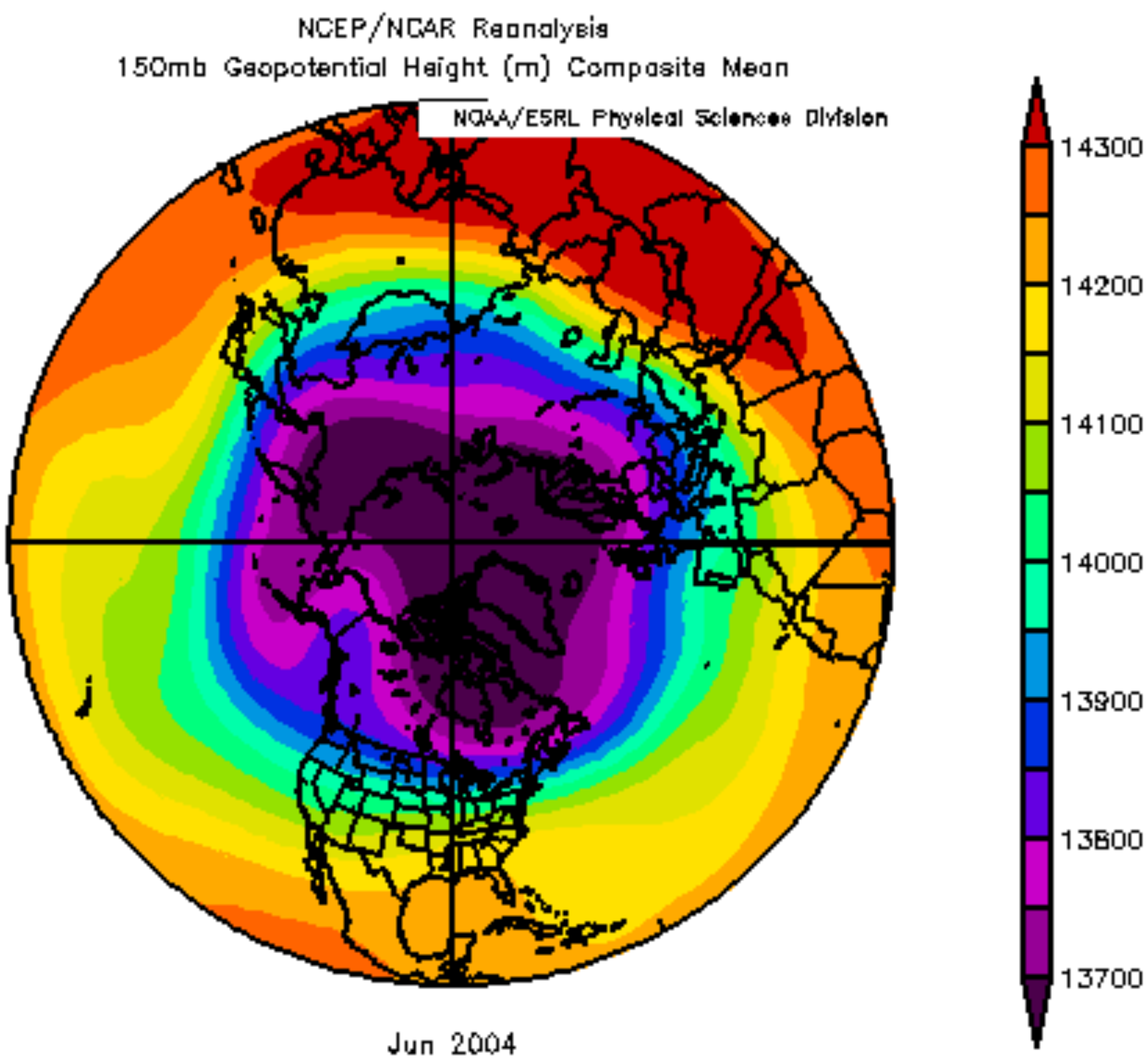
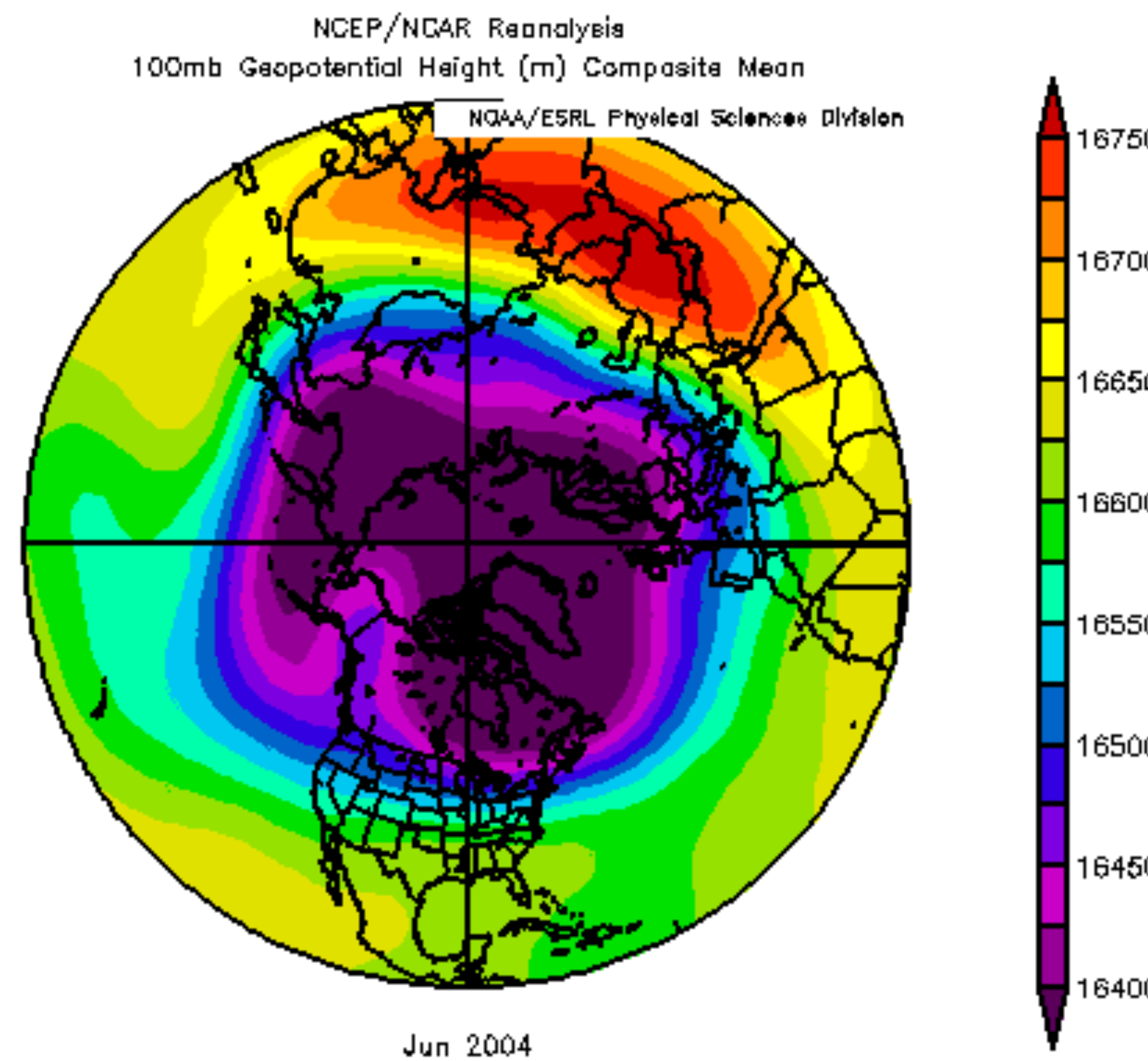



FIG. 6.12. Three-dimensional perspectives, as viewed from the south, of the $2 \times 10^{-5}$ K mb$^{-1}$ s$^{-1}$ IPV surface, and sea-level pressure isobar pattern (mb) derived from the numerical simulation of the Presidents' Day cyclone of Whitaker et al. (1988) for (a) 00 UTC, (b) 06 UTC, (c) 12 UTC and (d) 18 UTC 19 February 1979. The three-dimensional perspectives were derived by William Hibbard using the University of Wisconsin, Space Science and Engineering Center, three-dimensional McIDAS system.

*Ucellini chapter*

# How does the zonal wind control the vertical propagation of Rossby waves into the stratosphere?




150hPa

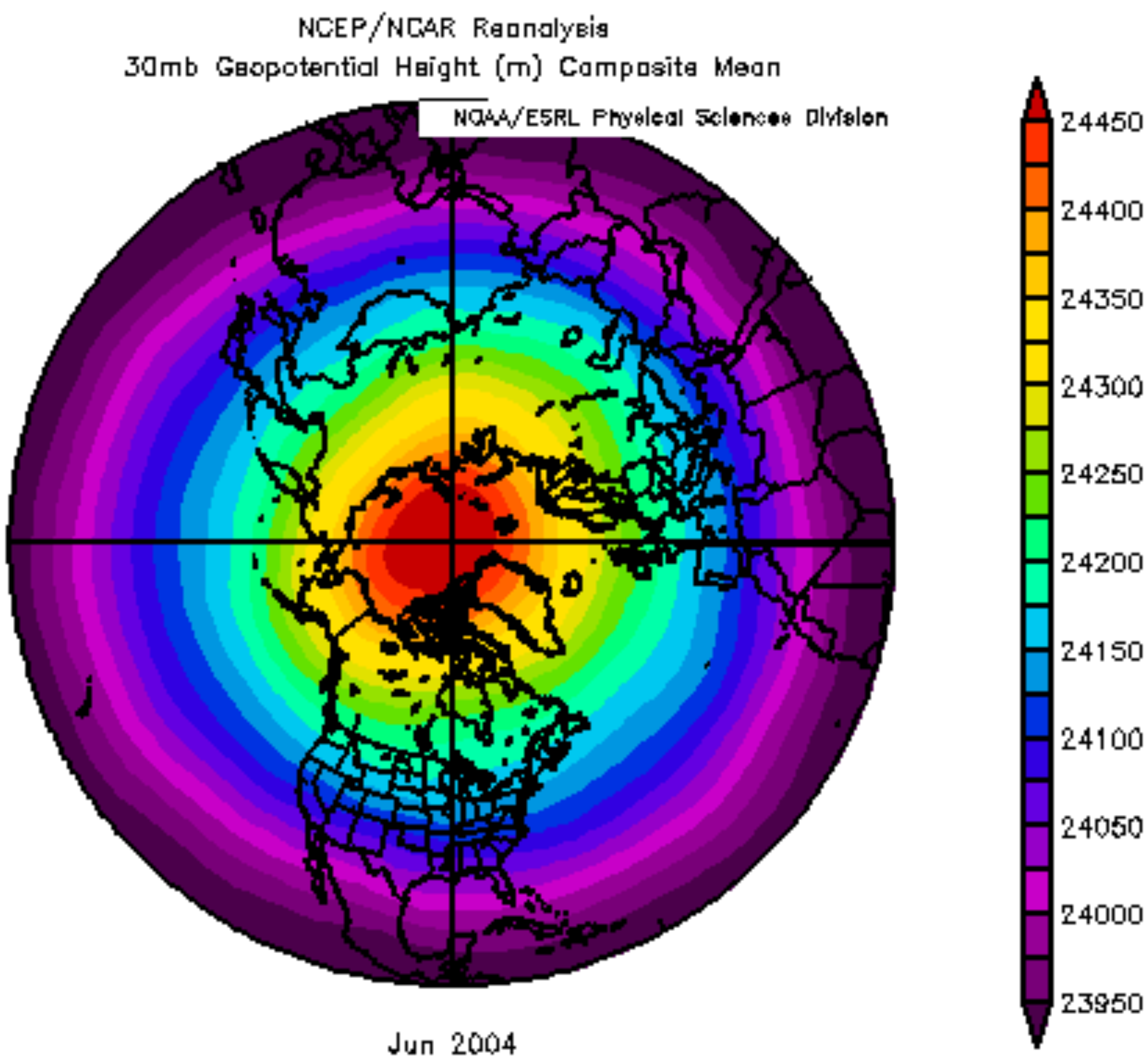
100hPa

## Planetary waves in June 2004

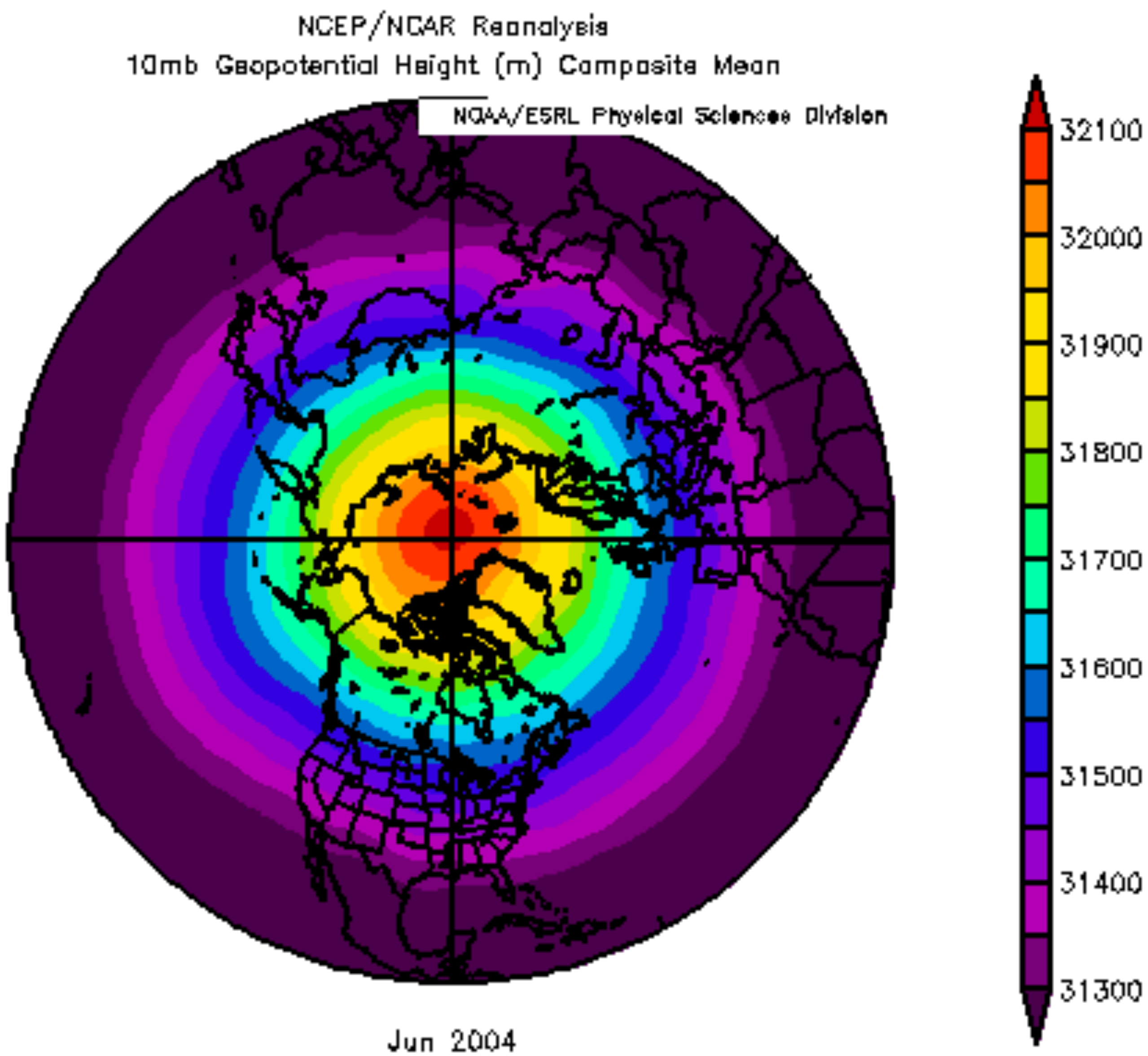


Image courtesy of NOAA/ESRL.

# No planetary waves in the stratosphere at that time




30hPa




10hPa

Image courtesy of NOAA/ESRL.

# Zonal-mean zonal wind (Jun 2004): transition from westerly to easterly flow at 60hPa

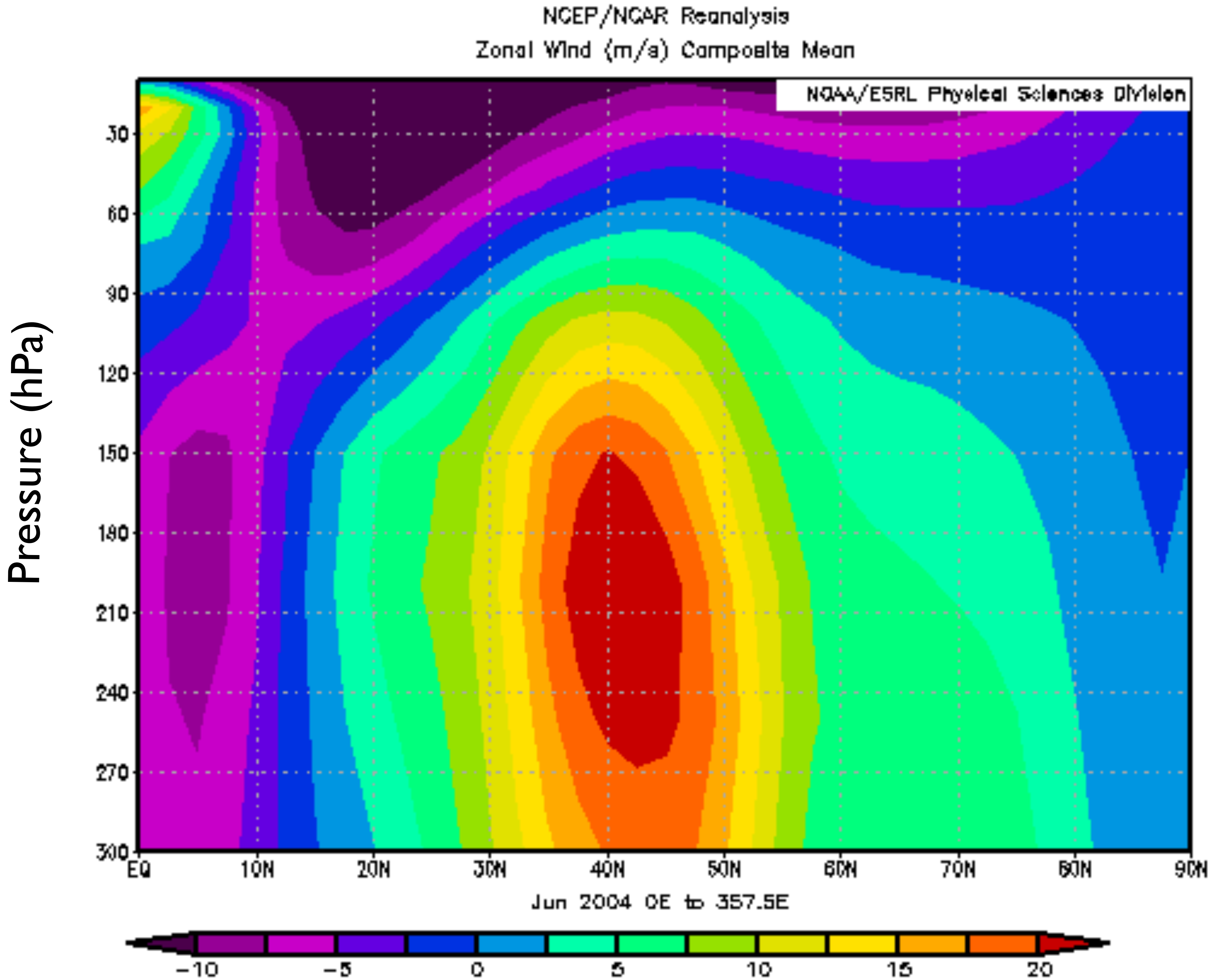
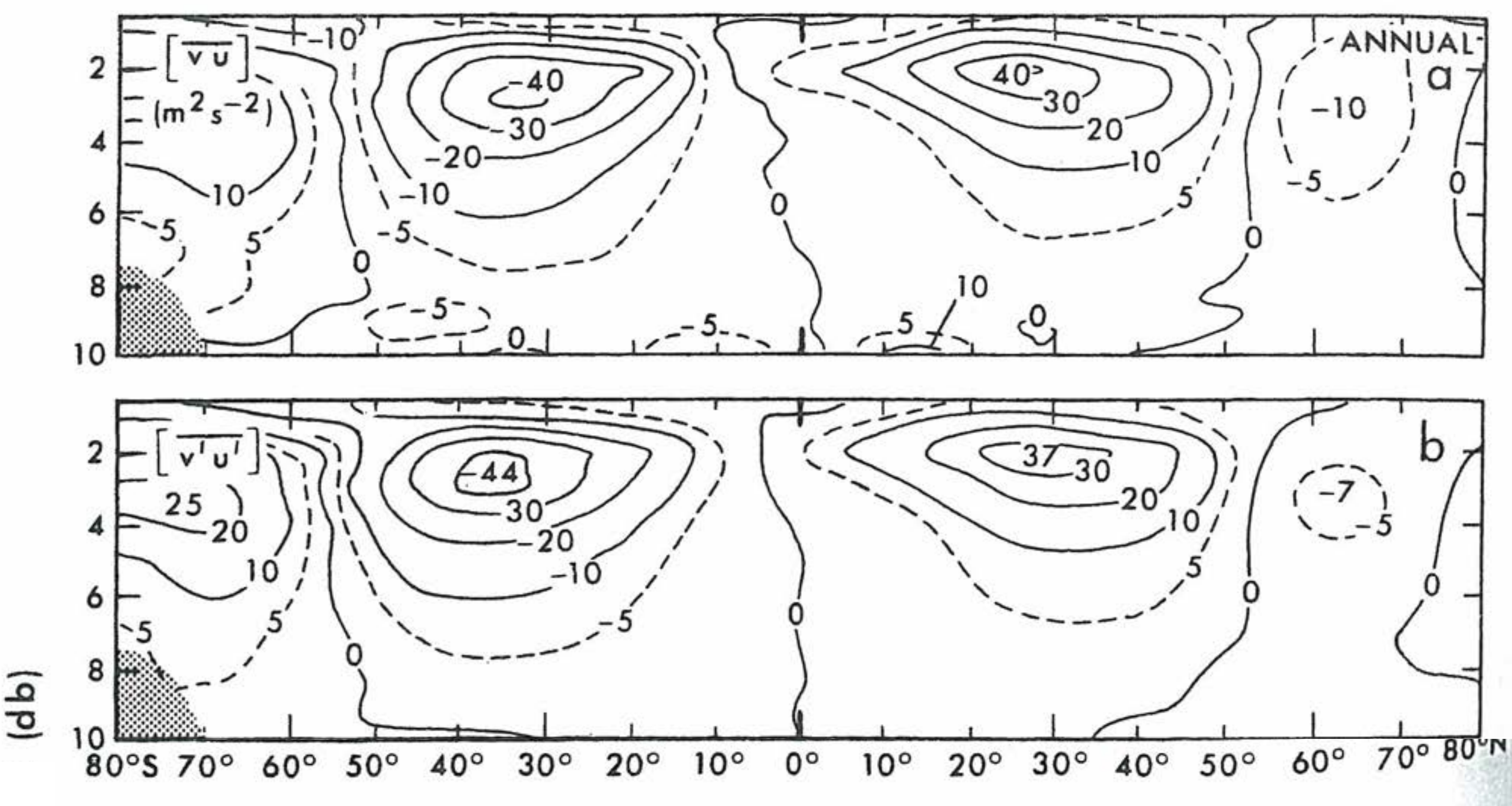



Image courtesy of NOAA/ESRL.

# Role of eddies in the general circulation

# Eddies transport momentum: How does this determine the surface westerlies and affect the Hadley cells?



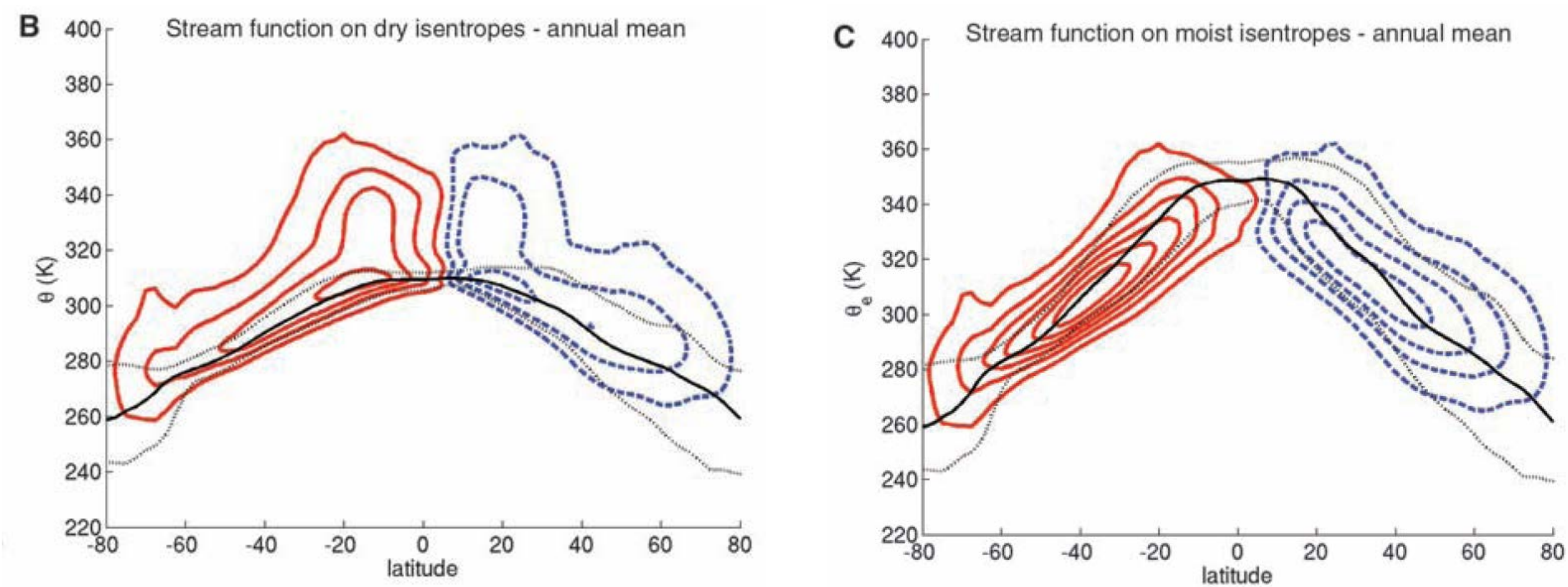

Total

Transient eddies

Northward flux of momentum ($m^2/s^2$)

*Peixoto and Oort, Fig 11.7*

# Why is the mean circulation very different when potential temperature is used as a vertical coordinate?




*(Pauluis et al, Science, 2008)*

We will explore the closely related
Transformed Eulerian Mean (TEM) framework

# How to do well in 12.810

Atmospheric dynamics is fascinating and you will learn about some powerful theories for understanding the circulation of the atmosphere.

Here are some hints about how to get a lot out of the class:

-Attend lectures (of course!) and ask questions or make comments

-Review lectures including derivations after class and ask questions about them at office hours or after class

-Work with other students on your problem sets

-At mid term, start working consistently every week on your class project