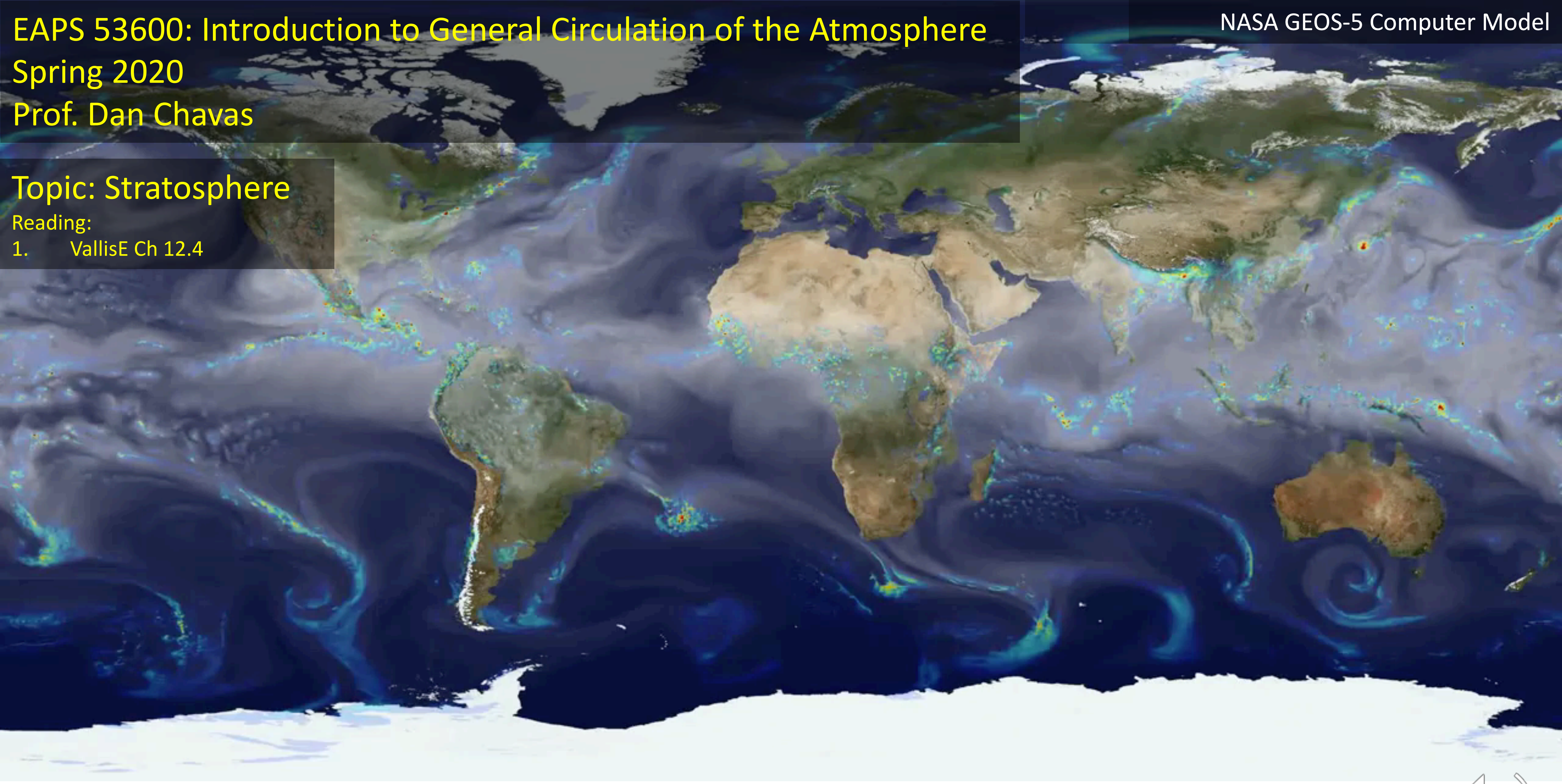
EAPS 53600: Introduction to General Circulation of the Atmosphere
Spring 2020
Prof. Dan Chavas

NASA GEOS-5 Computer Model

Topic: Stratosphere
Reading:
1. VallisE Ch 12.4



White: total precipitable water (brigher white = more water vapor in column)
Colors: precipitation rate ($0 - 15\frac{mm}{hr}$, red=highest)

Source: https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=30017

Learning outcomes for today:

- **Describe the basic structure of temperature and circulation in the stratosphere and its seasonality**
- **Explain how the stratospheric circulation is affected by tropospheric eddies**
- **Explain the two dominant modes of variability in the stratospheric circulation**

Structure of the stratosphere

Temperatures if the atmosphere didn't move: radiative-equilibrium

(though this is based on the observed distribution of ozone, which depends on the circulation)

Driven by summertime solar absorption by ozone

Zero absorption (polar night)

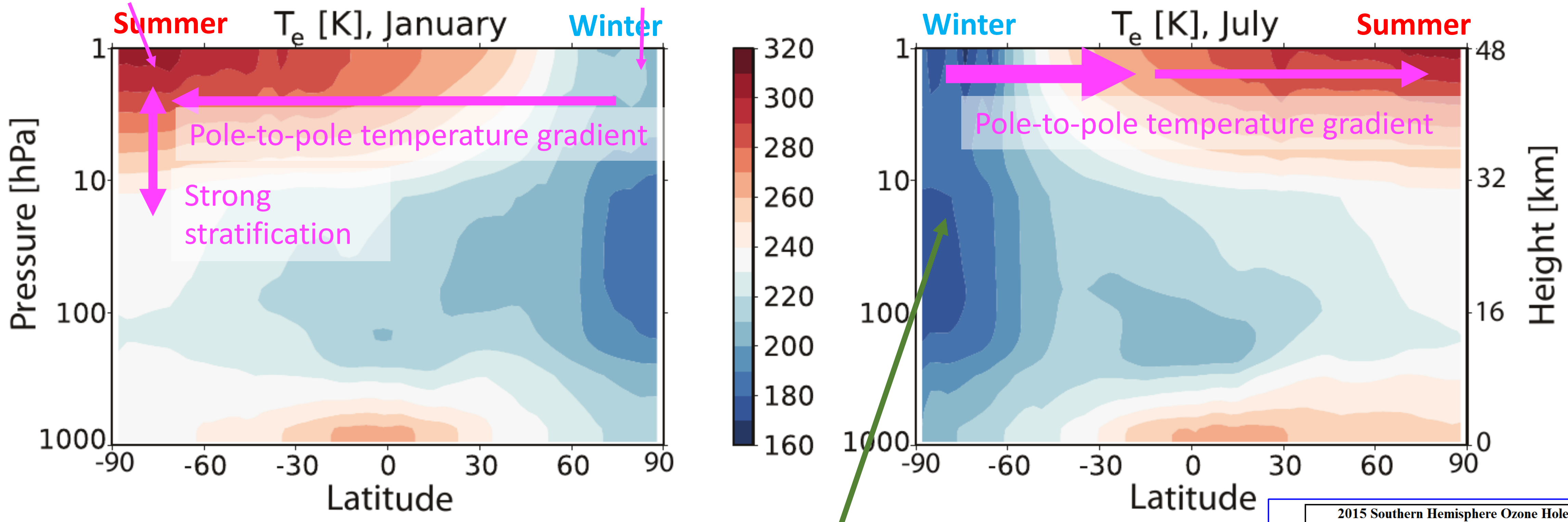
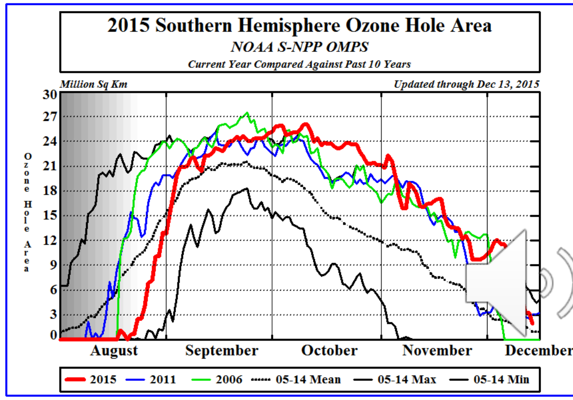


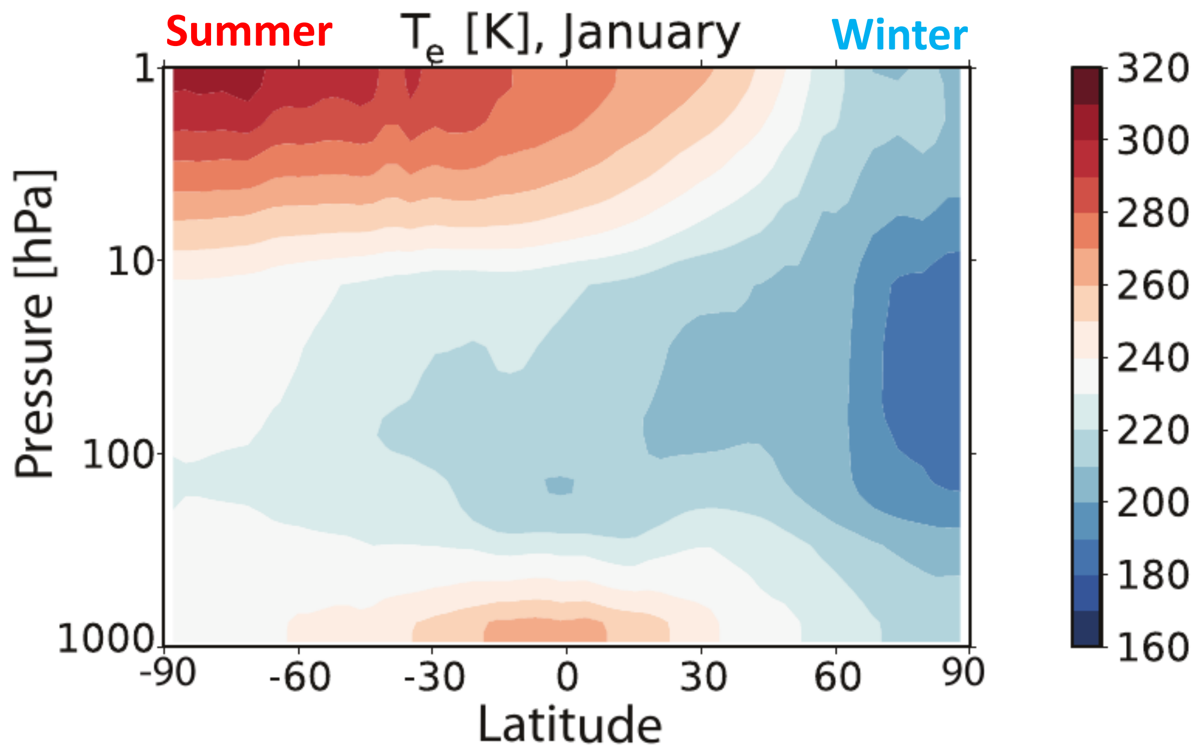
Fig. 12.10:

Note: the ozone hole develops here, in Spring (sept/oct)

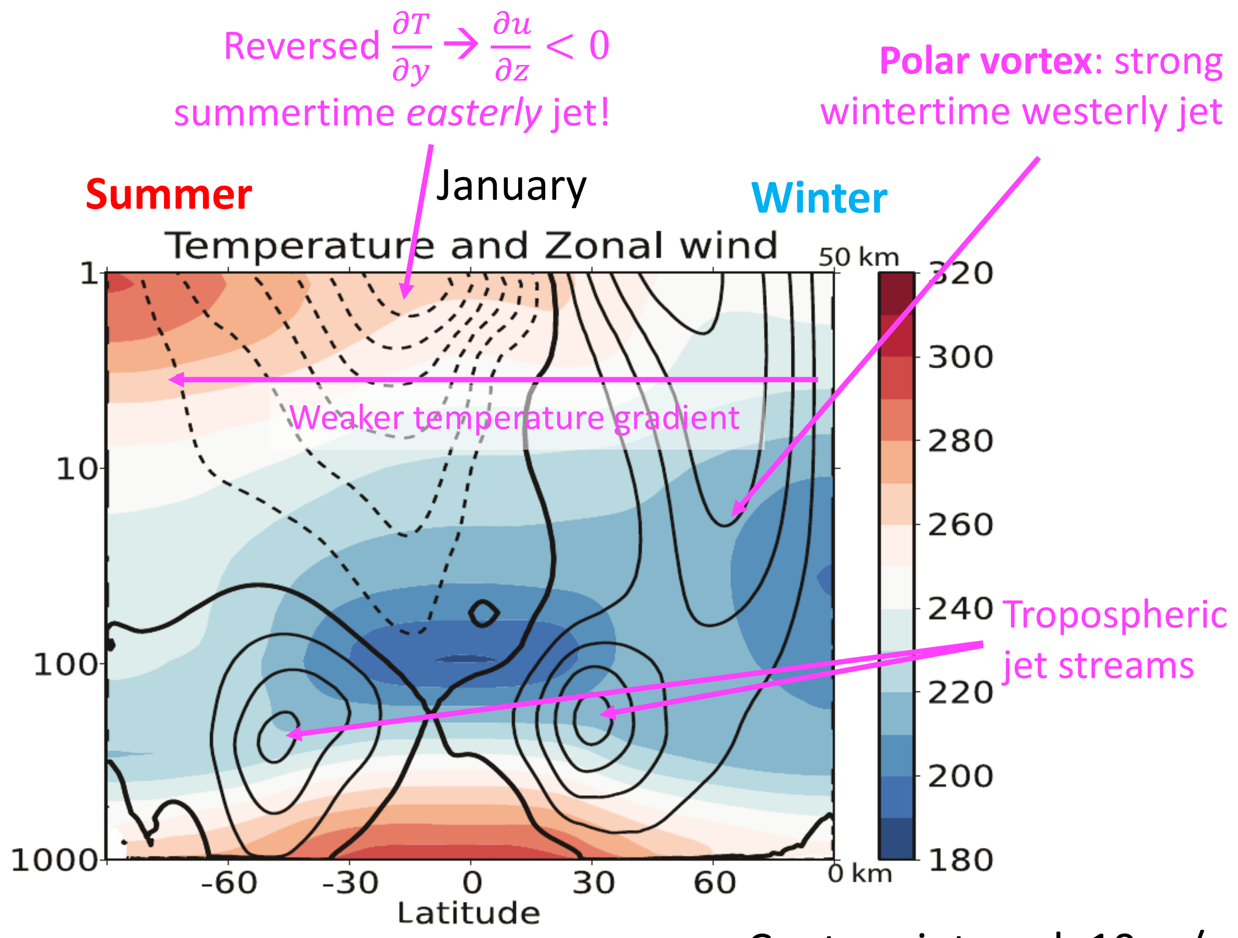
- Polar stratospheric clouds form at extremely cold temperatures.
- These clouds provide a surface that catalyzes ClO production from Cl-containing compounds.
- In spring, the sun comes out and melts these clouds, releasing ClO into the air to destroy O_3.



Radiative equilibrium



Observations



Contour interval: 10 m/s

Fig. 12.10: The **weaker meridional temperature gradient** in observations indicates a **poleward heat transfer by the stratospheric circulation**.

Fig 12.11

Dynamics (motion) of the stratosphere

What makes the stratosphere move?

- **Strongly stratified – vertical motion generally inhibited**

  $N \sim 2 * 10^{-2}\ s^{-1}$ – 2x more stable than troposphere

- **Baroclinic instability <u>not</u> a significant driver of motion in the stratosphere**

Fastest growing wavelength scales with L_d which is ~4x longer than in the troposphere ($L_d \sim 4000\ km$)

$$L_d = \frac{NH}{f}$$

$H \sim 20\ km$ – 2x deeper than troposphere
N – 2x more stable than troposphere

Eady growth rate is significantly smaller than in the troposphere

$$\sigma_E = 0.31 \frac{\Lambda H}{L_d}$$

$\frac{H}{L_d}$ is 2x smaller than troposphere (from above)
Wind shear Λ : similar

There is no obvious change in the PV gradient to support counter-propagating Rossby waves like there is in the troposphere.

Hence, the stratosphere is generally <u>baroclinically stable</u>.

- **The primary driver for motion? It comes from below**

Rossby waves
Gravity waves

Generated in the troposphere, propagate upwards, and break in the stratosphere

Horizontal circulation

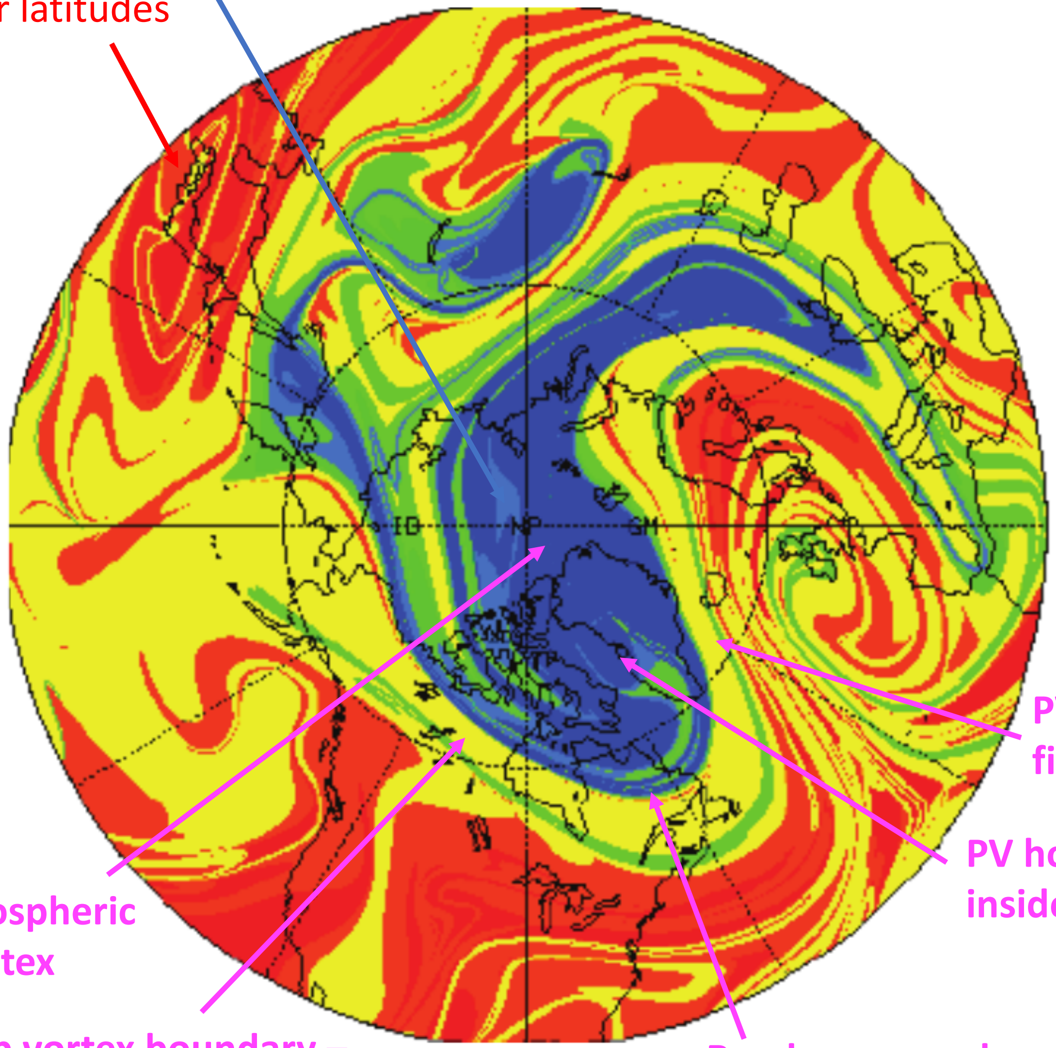
Very strong stratification → quasi-2D flow

Analog: the rotating tank

blue dye near
cold north pole

red dye at surrounding
warmer latitudes

Color = potential vorticity
(a tracer)



NH stratospheric polar vortex

Sharp vortex boundary – inhibits mixing

Rossby waves along boundary

PV homogenized inside vortex

PV stretched and filamented outside

$$\frac{\partial q}{\partial t} + u \cdot \nabla q = 0 \qquad q = \nabla^2 \psi + \beta y + \cancel{\frac{\partial}{\partial z}\left(\frac{f_0^2}{N^2}\frac{\partial \psi}{\partial z}\right)}$$

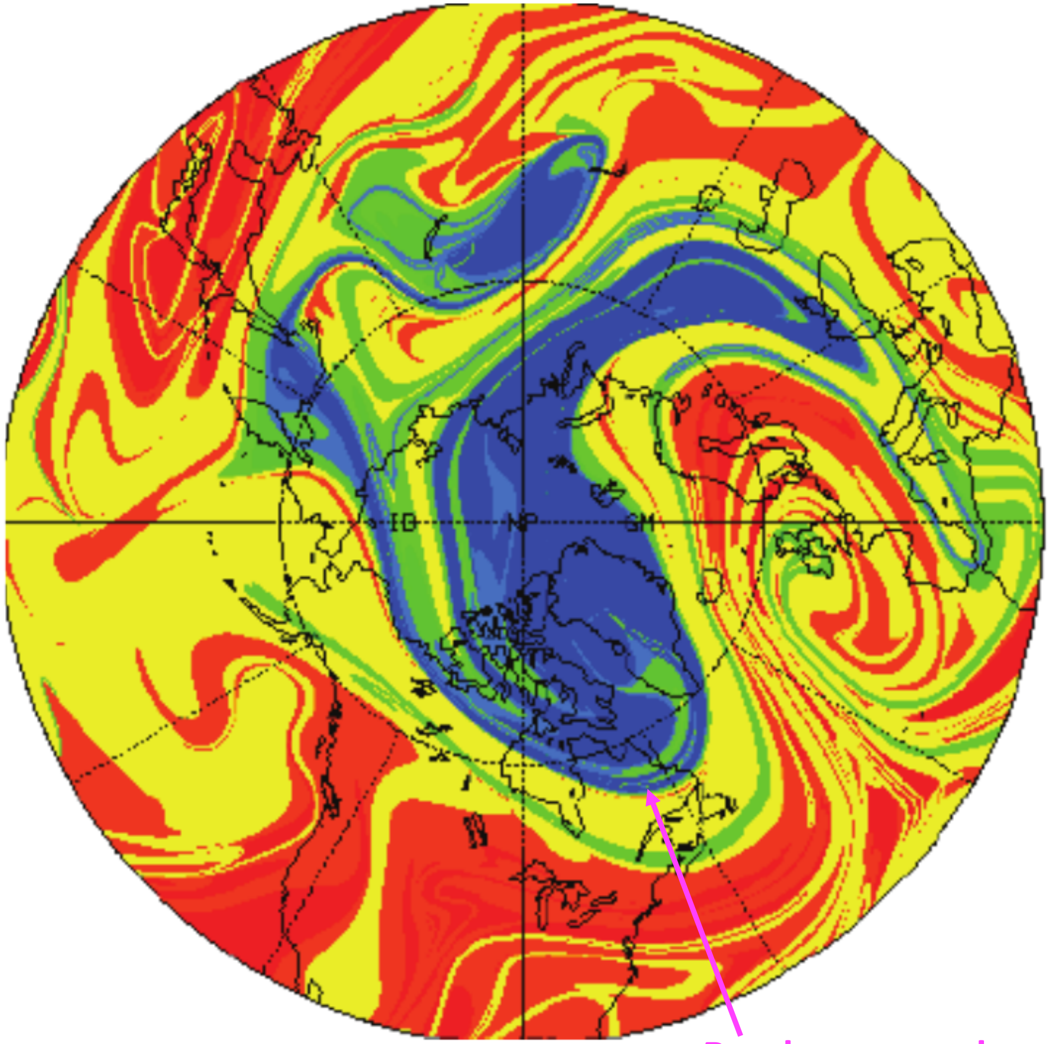
If N^2 is large enough, this can be neglected

Generally, this assumption holds for length scales smaller than the deformation radius: $L < L_d$

Fig 12.12: The tracer distribution in the northern hemisphere lower stratosphere on 28 January 1992. The tracer was initialized on 16 January by setting it equal to the potential vorticity field calculated from an observational analysis, and then advected for 12 days by the observed winds.

Very strong stratification → quasi-2D flow

Color = potential vorticity
(a tracer)



Rossby waves along boundary

What generates this (Rossby) wave activity?

Rossby waves propagate upwards from the troposphere below.

However, only waves with **relatively long wavelengths** are allowed, satisfying:

$$0 < U < \frac{\beta}{k^2 + l^2}$$

(see VallisE Ch 6.4.2)

Baroclinic eddies from the troposphere stir the stratosphere!

Rossby waves propagate upwards from the troposphere and break in the stratosphere

Wave breaking = wave activity dissipation = EP flux convergence

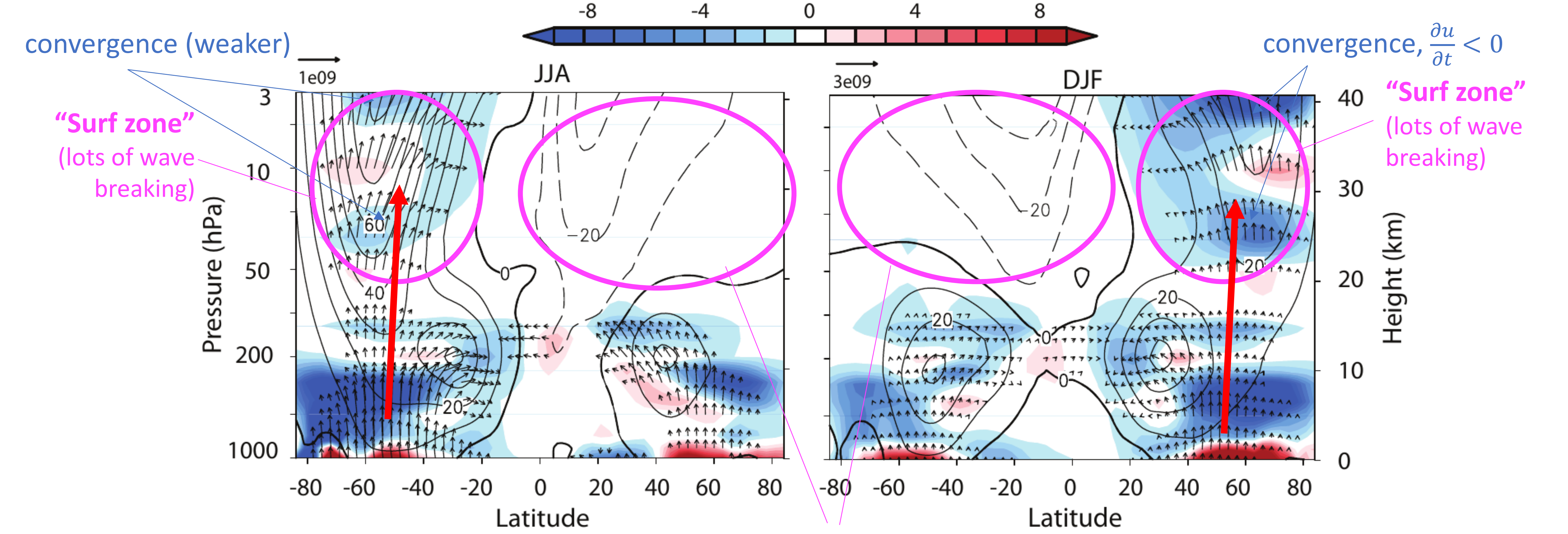
$$\frac{\partial \bar{u}}{\partial t} = f_0 \bar{v}^* + \overline{v'q'} + \bar{F} \qquad \overline{v'q'} = \nabla \cdot \boldsymbol{\mathcal{F}}$$

Arrows = EP Flux vectors ($\boldsymbol{\mathcal{F}}$)

Colors = EP flux divergence ($\nabla \cdot \boldsymbol{\mathcal{F}}$)

Contours = mean zonal wind ($\overline{u}$)

Recall: Rossby wave energy follows the EP flux vectors



Nothing in the summer hemisphere!

The zonal wind is easterly – **upward wave propagation is not allowed**! (See VallisE Ch 6.4.2)

Fig. 12.9:

Overturning circulation

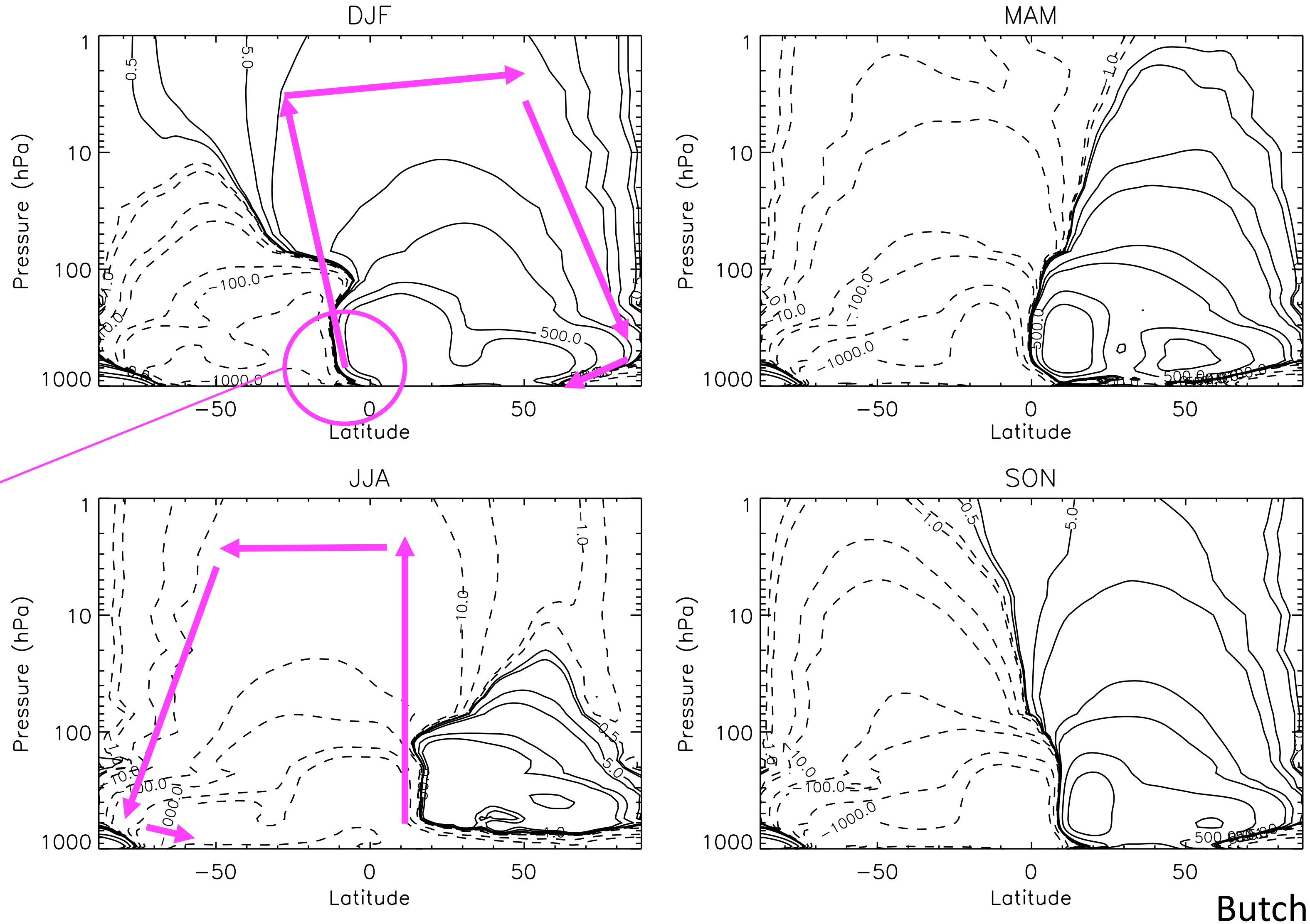
(eddy-driven residual, driven by breaking waves)

Brewer-Dobson circulation: a residual, eddy-driven overturning circulation

A stratospheric extension of the tropospheric residual circulation

Strongest in the winter hemisphere.
Because that's when tropospheric wave activity is stongest.

Notice: this circulation brings air into the stratosphere **from the tropical troposphere**!



Butchart (2014, RG)

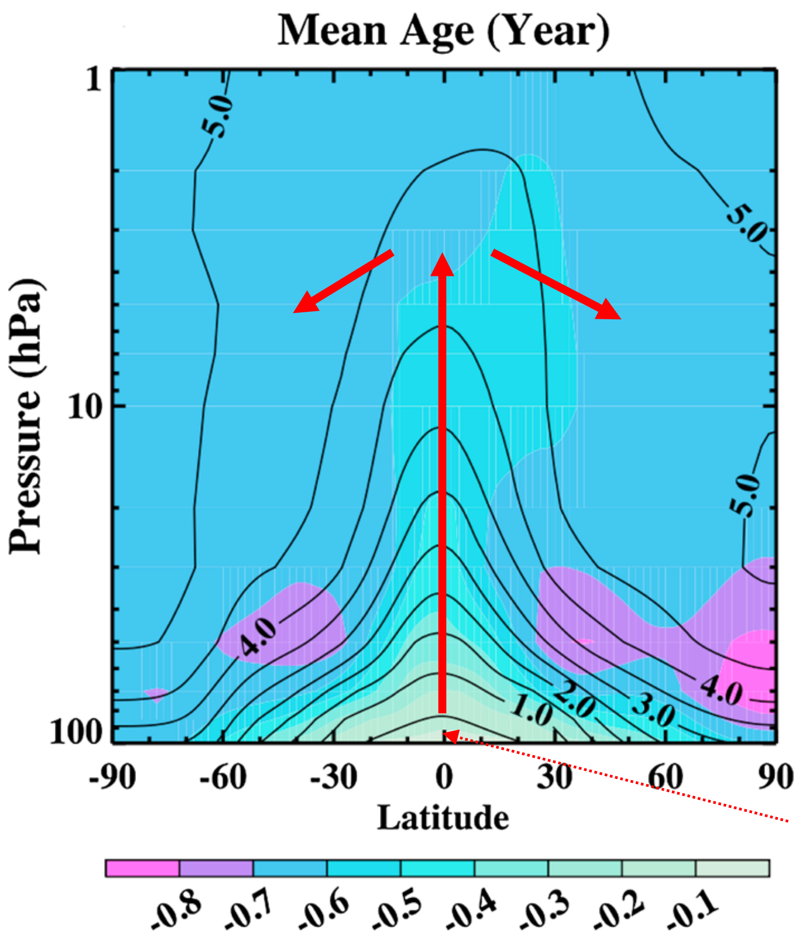
Figure 5. Seasonal mean TEM stream function, ψ, from ERA-Interim for 1989–2009. Contours have units of kg m^{-1}s^{-1} and are spaced logarithmically. Dashed contours represent negative values. Figure 3 from *Seviour et al.* [2012].

Brewer-Dobson circulation: a residual, eddy-driven overturning circulation

This is a **Lagrangian** circulation (again, not an Eulerian mean).

This means the circulation **carries tracers and pollutants**, such as ozone and aerosols, with it.

Note: this is why **large volcanoes in the tropics** are particularly important as a source of **sulfate aerosols in the stratosphere**.

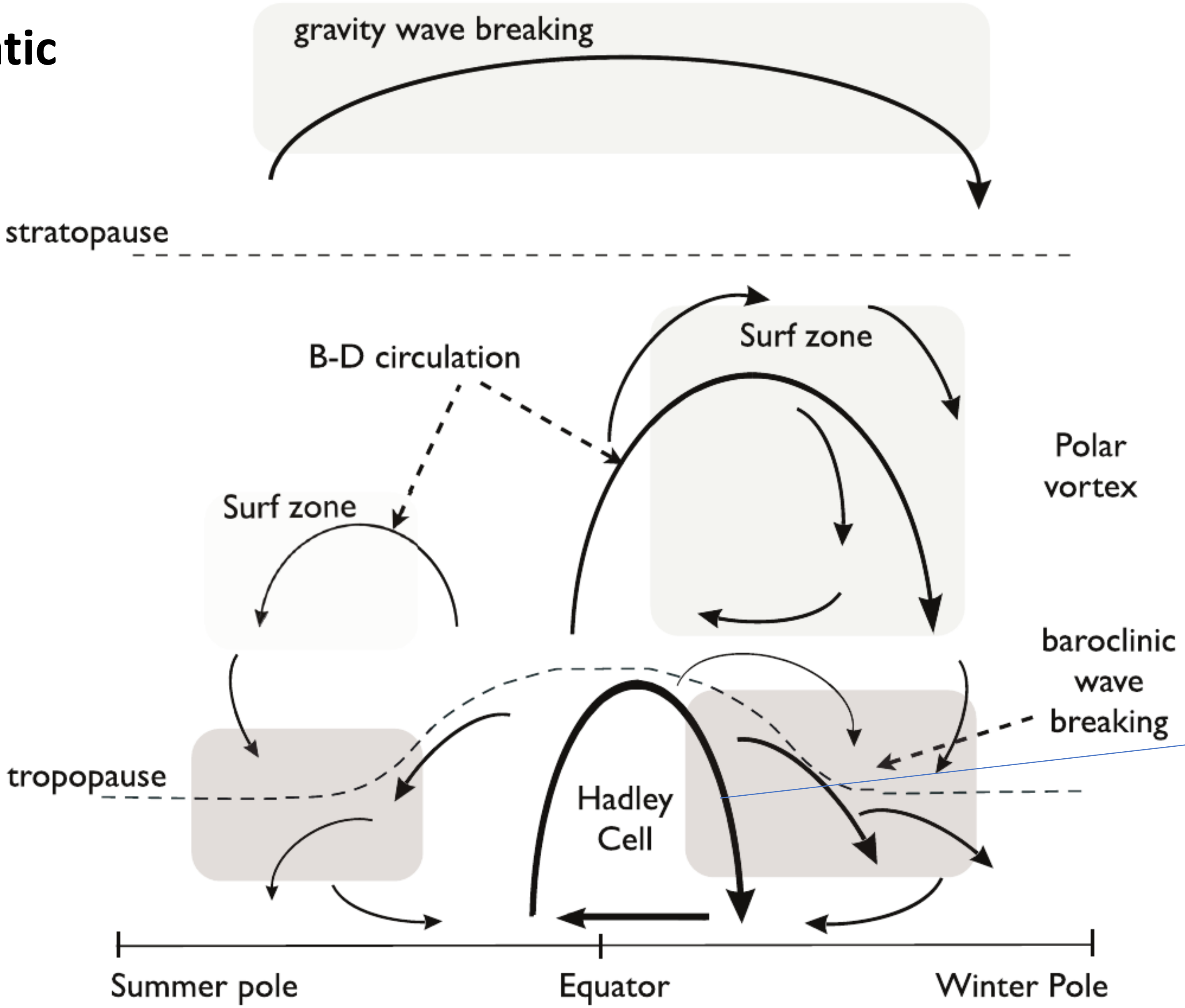


Set age = 0 here
(entry point into stratosphere)

Figure 3. Annual mean age of air in years simulated by a CCM for the year 2000 (contours) and the simulated change in age from 2000 to 2080 (colors). Figure 2a from *Li et al.* [2012]. ©American Geophysical Union. Used with permission.

Butchart (2014, RG)

Summary schematic



Solid arrows indicate the residual circulation.

Note: only in the Hadley cell is the residual circulation comprised primarily of the actual Eulerian-mean. Elsewhere, the eddy forcing is dominant.

Fig. 12.13:

Stratospheric vs. tropospheric polar vortex

(not the same thing!)

WHAT IS THE POLAR VORTEX AND HOW DOES IT INFLUENCE WEATHER?

DARRYN W. WAUGH, ADAM H. SOBEL, AND LORENZO M. POLVANI

There are separate stratospheric and tropospheric planetary-scale circumpolar vortices, with differing structure, seasonality, dynamics, and impacts on extreme weather.

Waugh et al (2017, BAMS)

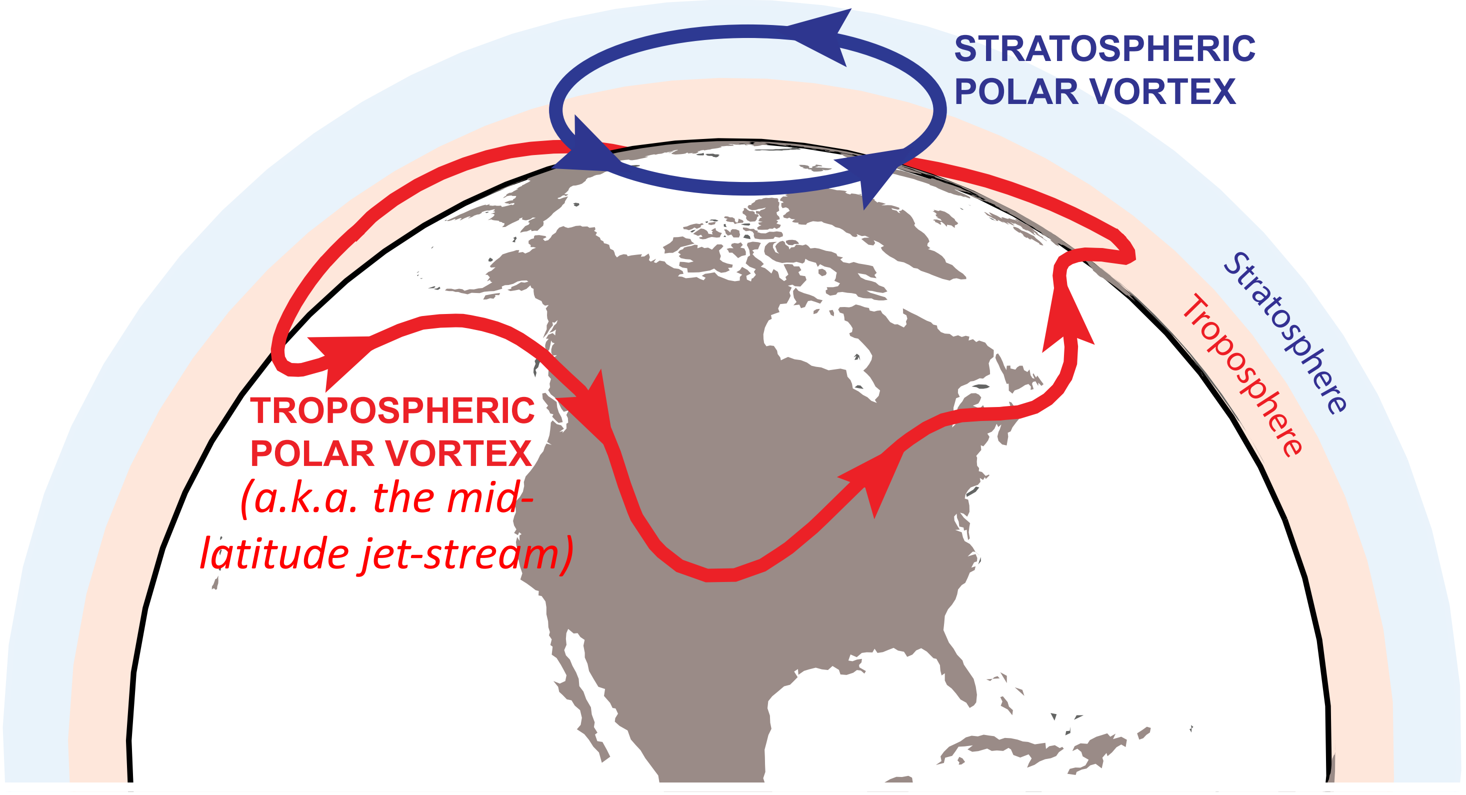


Fig. 1. Schematic of stratospheric and tropospheric polar vortices.

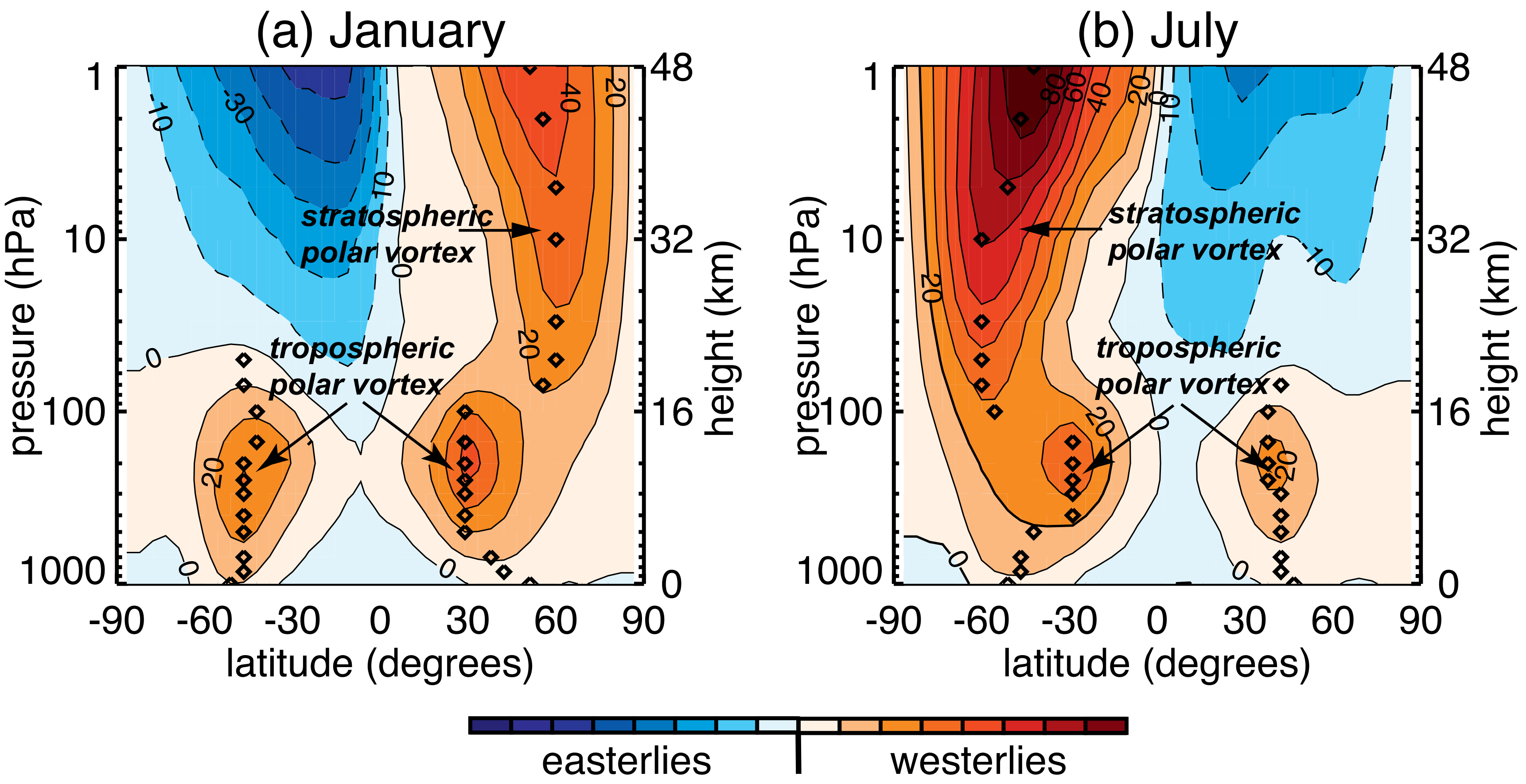


FIG. 2. Climatological zonal-mean zonal wind in Jan and Jul. The diamonds mark the hemispheric maximum of the zonal wind at each pressure level and the approximate edge of the polar vortex for that hemisphere. Data source: National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) analyses.

Stratospheric polar vortex

Tropospheric “polar vortex”

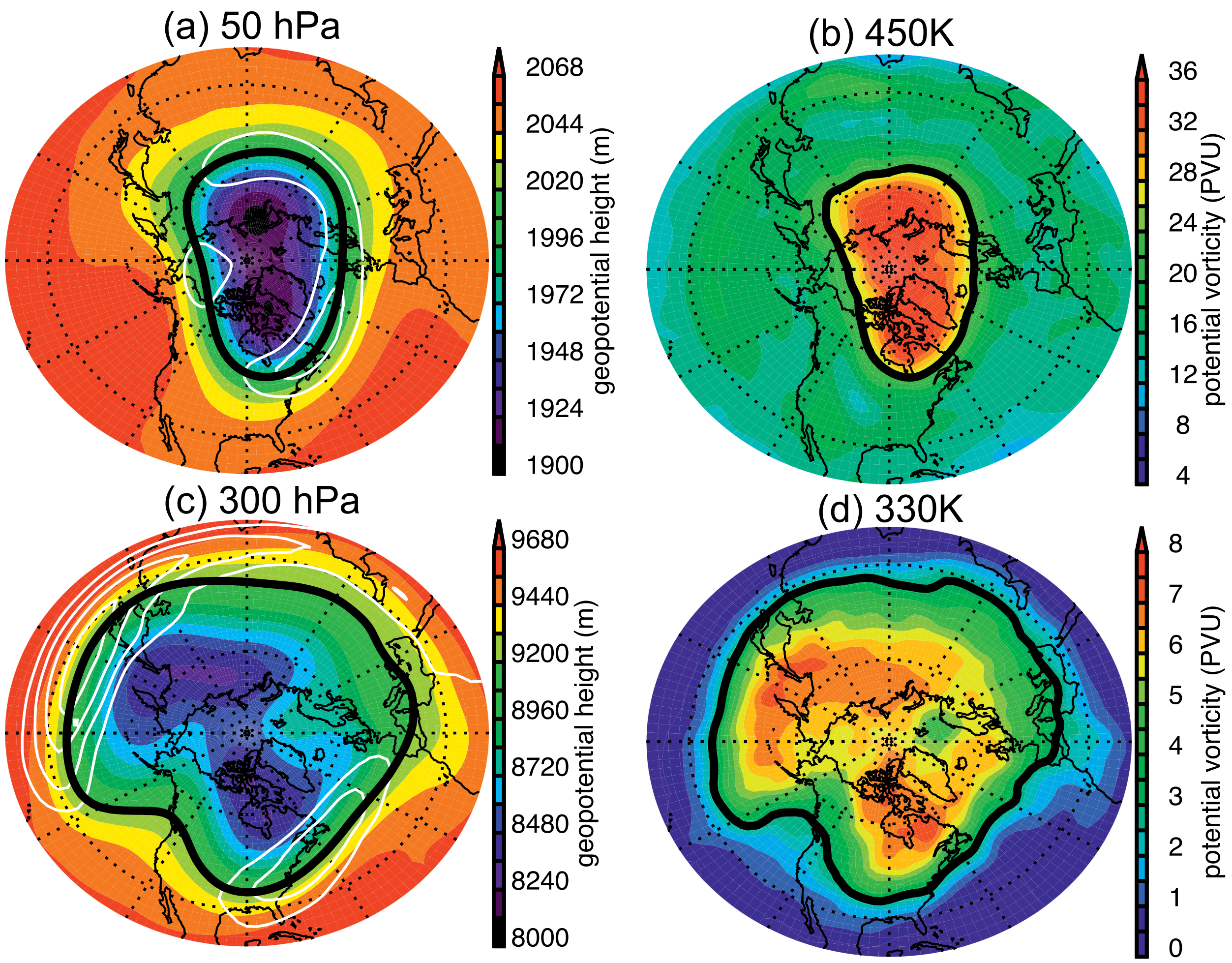


FIG. 3. Maps illustrating the (a),(b) stratospheric and (c),(d) tropospheric vortices in Jan 2014 using (left) geopotential height (shading) and zonal winds (white contours for 30, 40, 50, and 60 m s^{-1}) at (a) 50 and (c) 300 hPa and (right) potential vorticity at (b) 450 and (d) 330 K. The thick black contours illustrate the edge of the vortices defined using geopotential height or potential vorticity. Data source: National Centers for Environmental Prediction (NCEP) reanalyses.

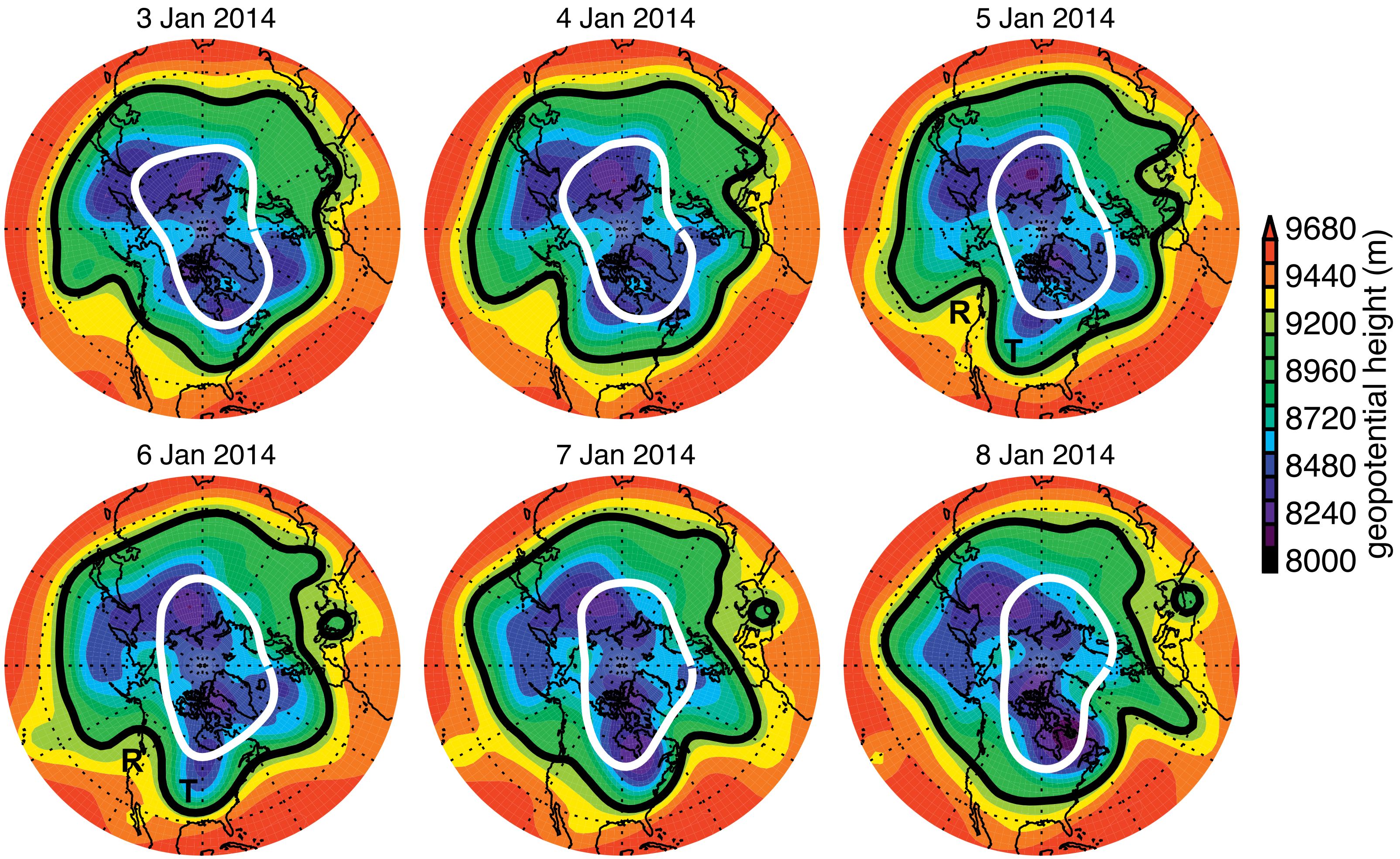


FIG. 4. Maps of 300-hPa geopotential height for 3–8 Jan 2014. Black contours mark the tropospheric vortex edge at 300 hPa and white contours mark the stratospheric vortex edge at 50 hPa. The R and T on 5 and 6 Jan indicate the location of ridge and trough, respectively, discussed in the text. Data source: NCEP reanalyses.

Can variability in the stratospheric wintertime polar vortex affect tropospheric weather?

Yes.

Dominant mode of variability in the stratospheric polar vortex?

“Sudden Stratospheric Warming” (SSW)

- Generated by especially strong upward propagating Rossby wave activity. Enhanced wave breaking temporarily weakens the polar vortex and makes it more susceptible to breaking down.
- Largely a Northern-Hemisphere phenomenon.

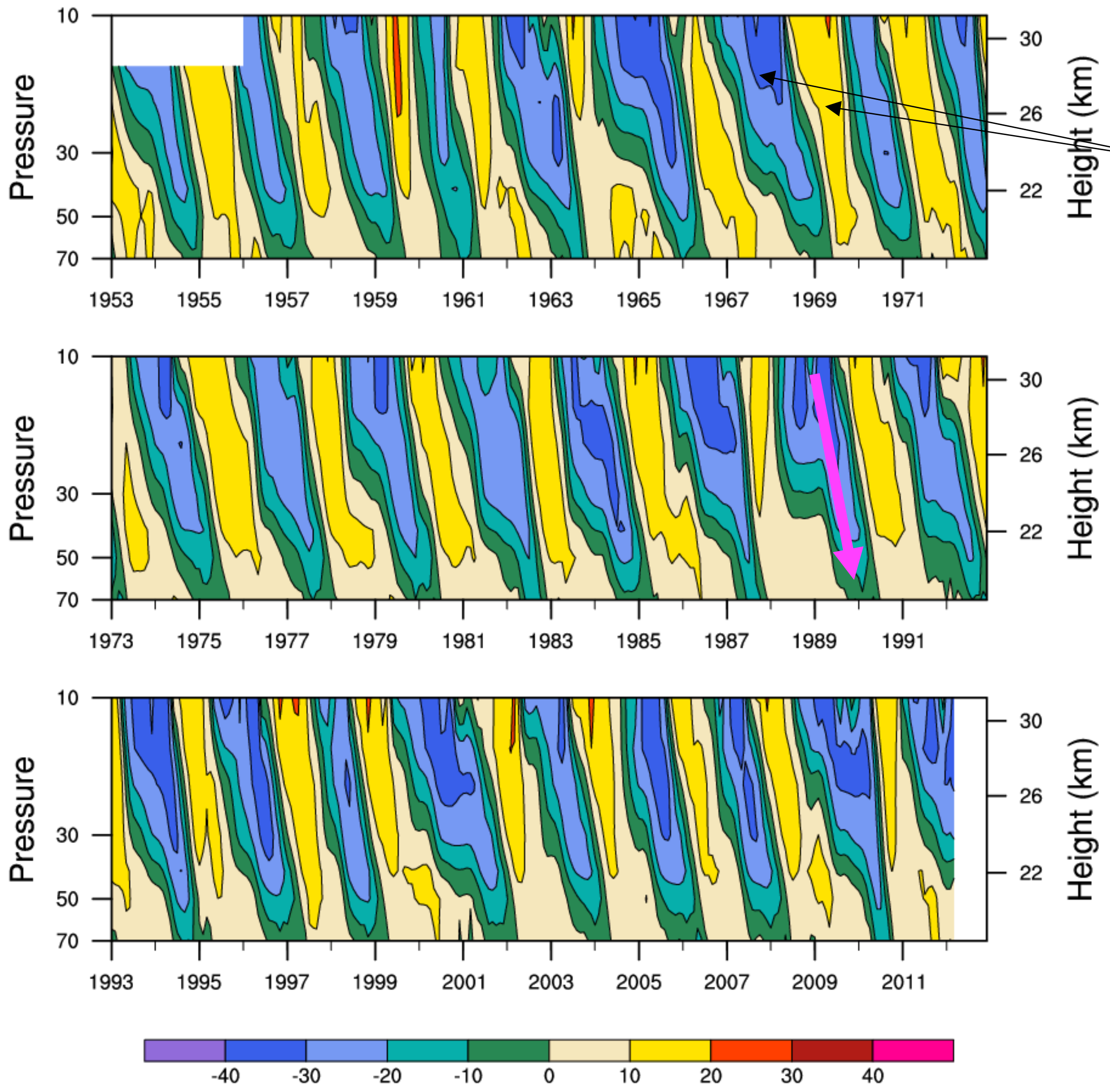
Met Office

https://www.youtube.com/watch?v=VnlFFaF_l7I

A second mode of variability: Quasi-biennial oscillation (QBO)

Monthly-mean zonal wind near Equator

3 radiosonde stations: Canton Island, Gan/Maledive Islands, Singapore



("almost every 2 years")

- Oscillation of the equatorial zonal wind in the stratosphere
- Switches between **easterlies** and **westerlies**
- Mean period: ~28 months
- Easterly phase amplitude is about twice as strong as that of the westerly phase
- Develops at the top of the lower stratosphere and propagate downwards
- Dissipated at the tropical tropopause

What drives this oscillation?

Principally **upward propagating Kelvin waves** from the tropical troposphere.

https://climatedataguide.ucar.edu/climate-data/qbo-quasi-biennial-oscillation

Now go to Blackboard to answer a few questions about this topic!