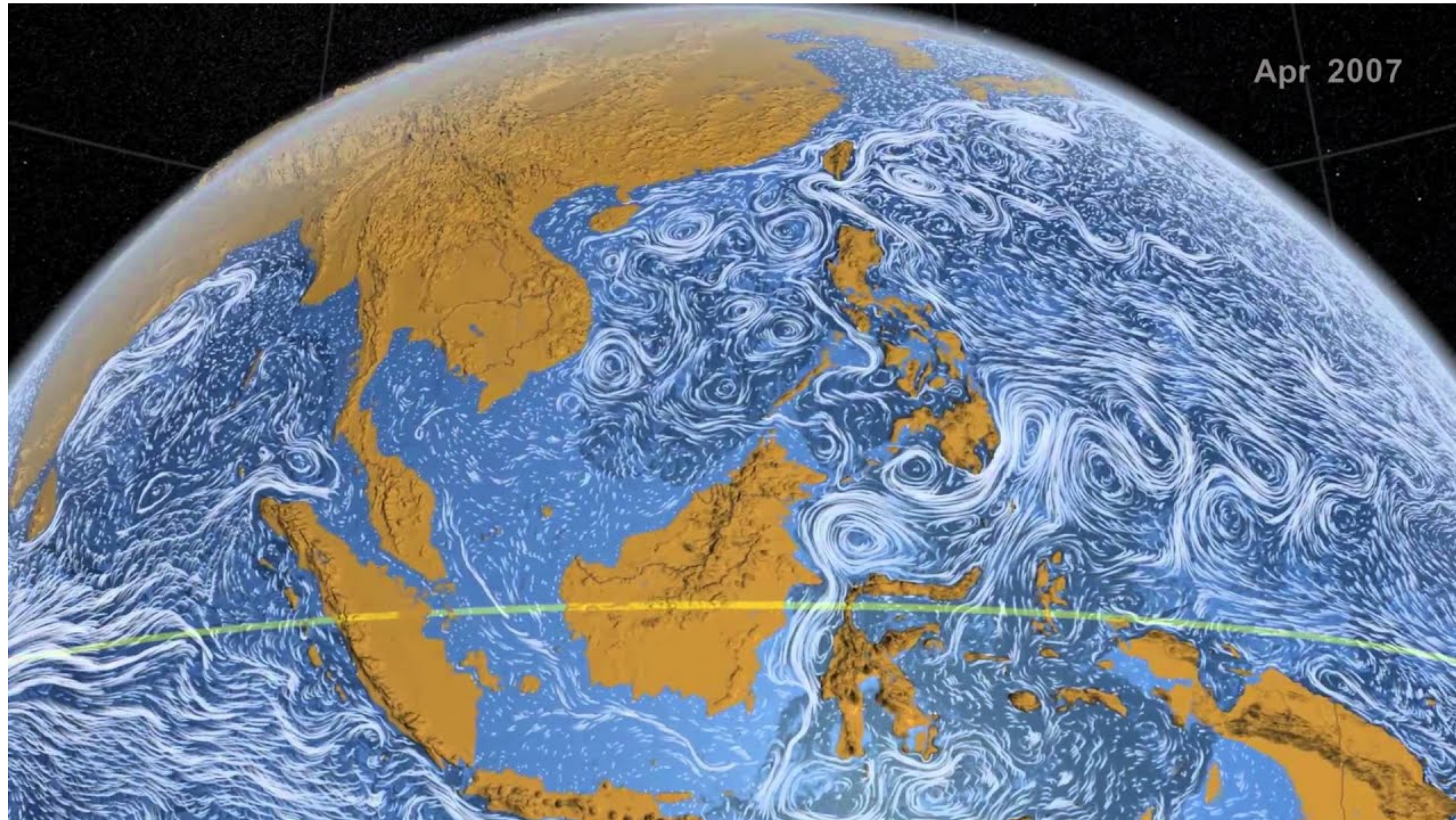


The wind driven ocean circulation

EPS131, Introduction to Physical Oceanography and Climate

Dept of Earth and Planetary Sciences, Harvard University

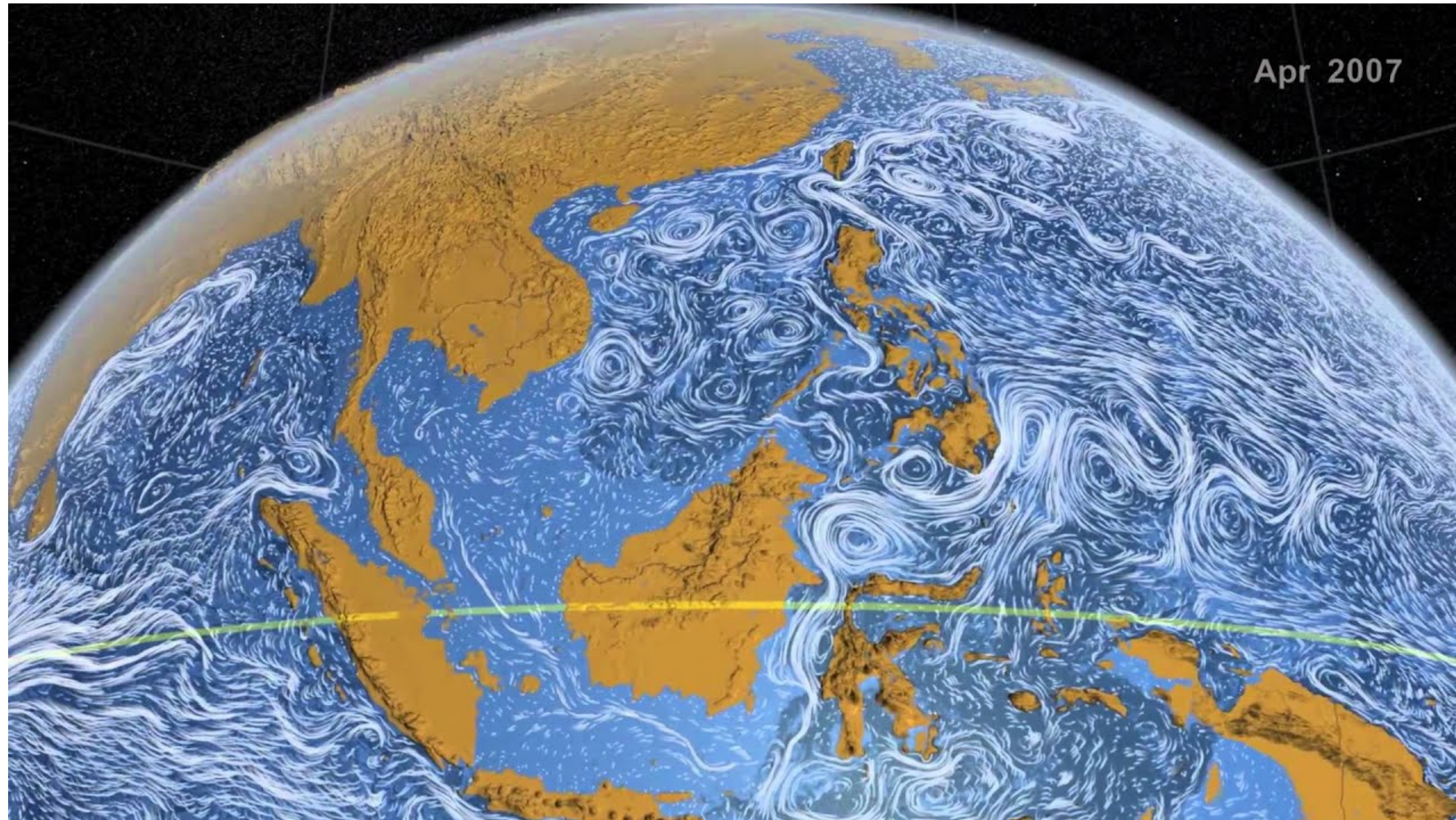


NASA perpetual ocean <https://www.youtube.com/watch?v=CCmTY0PKGDs>

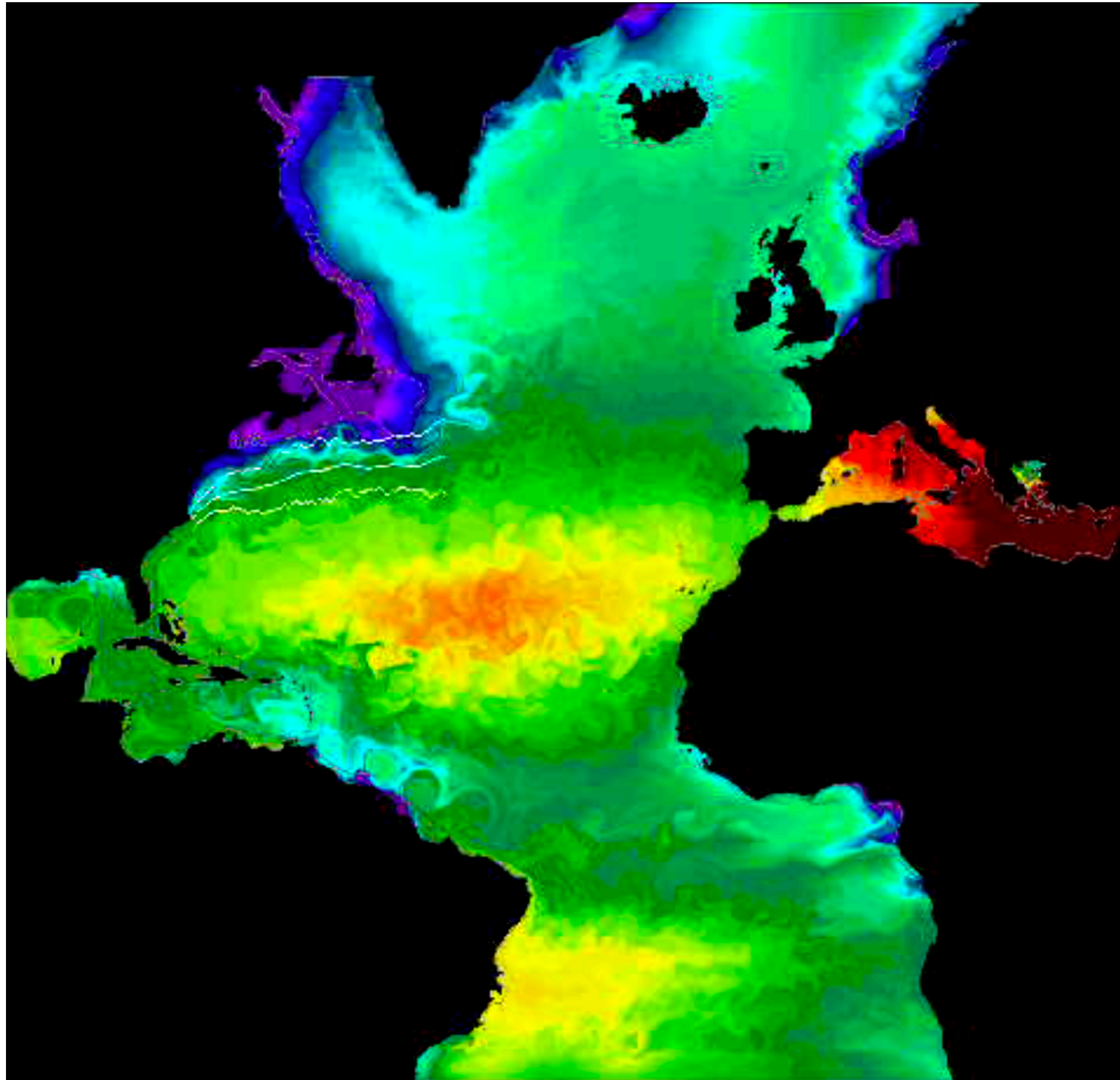
The wind driven ocean circulation

EPS131, Introduction to Physical Oceanography and Climate

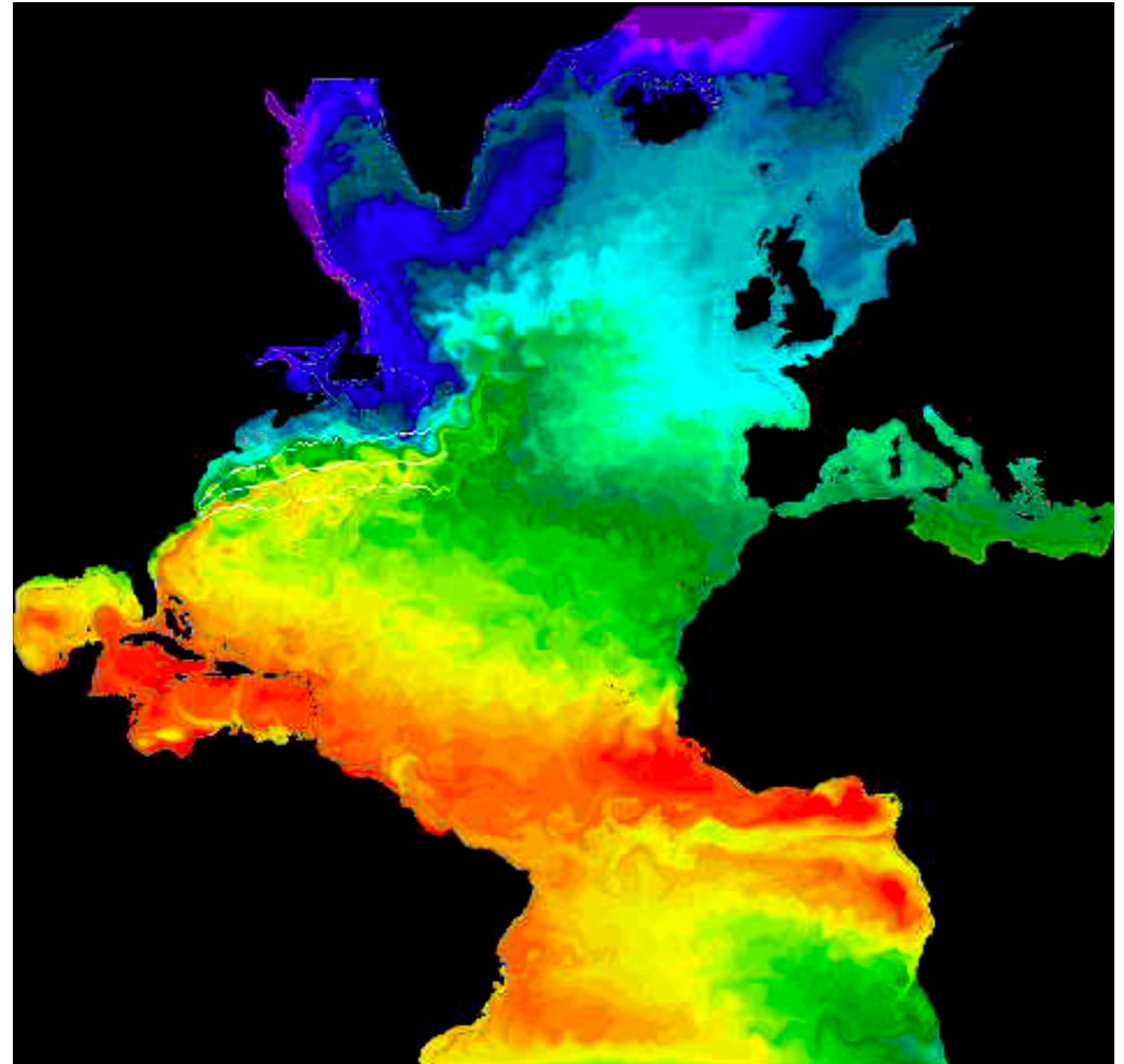
Dept of Earth and Planetary Sciences, Harvard University



NASA perpetual ocean <https://www.youtube.com/watch?v=CCmTY0PKGDs>



Salinity



Temperature

Animations from MICOM model

notes

Outline:

1. Mass conservation (friction, section 6)
2. Ekman pumping (friction, section 7)
3. Beta plane $f = f_0 + \beta y$
4. Momentum equations
5. Outline of derivation of vorticity equation
6. Interpretation of vorticity, planetary vorticity

Use the following 6 slides.

Angular momentum and ice skating



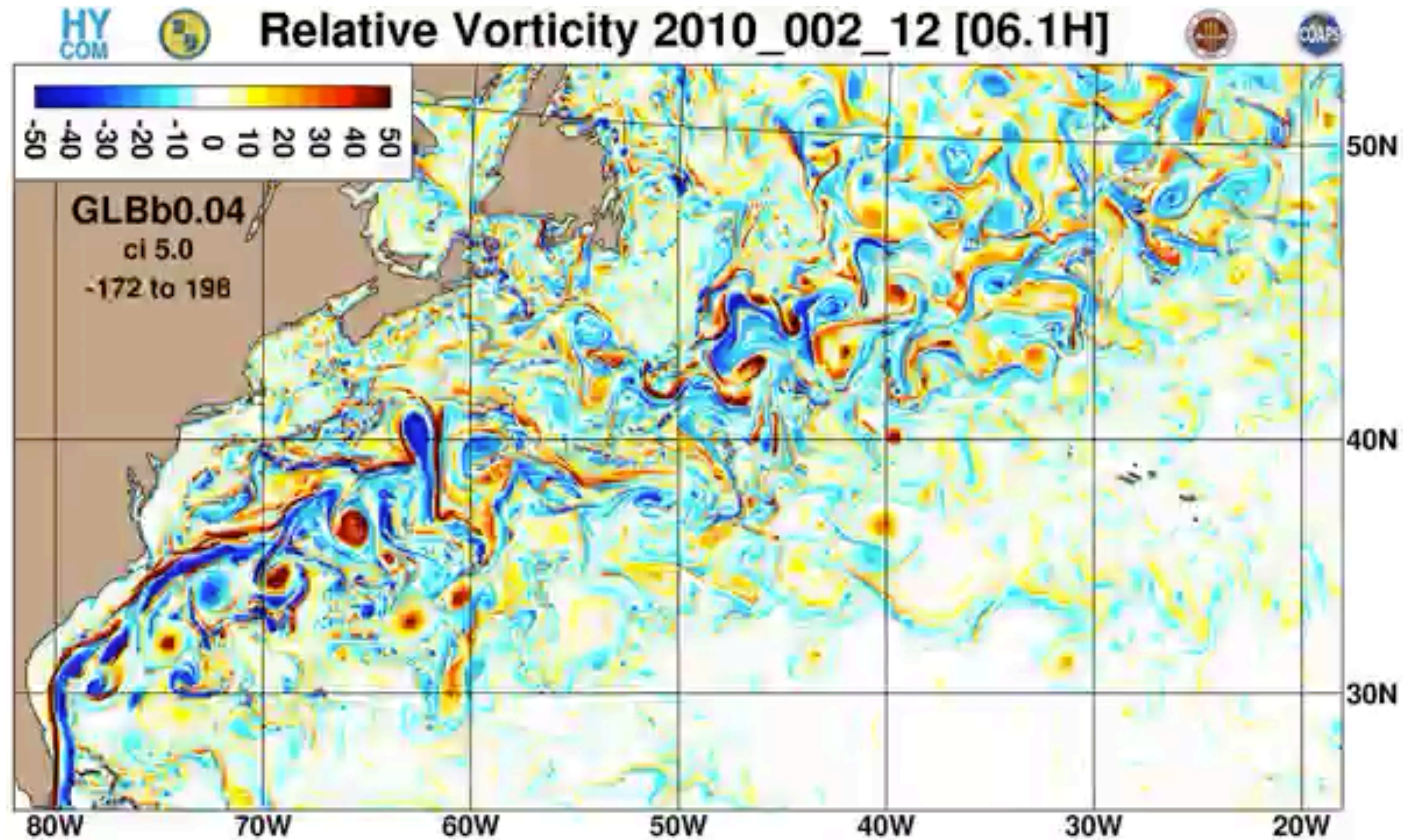
<https://www.youtube.com/watch?v=FmnkQ2ytIO8>

Angular momentum and ice skating



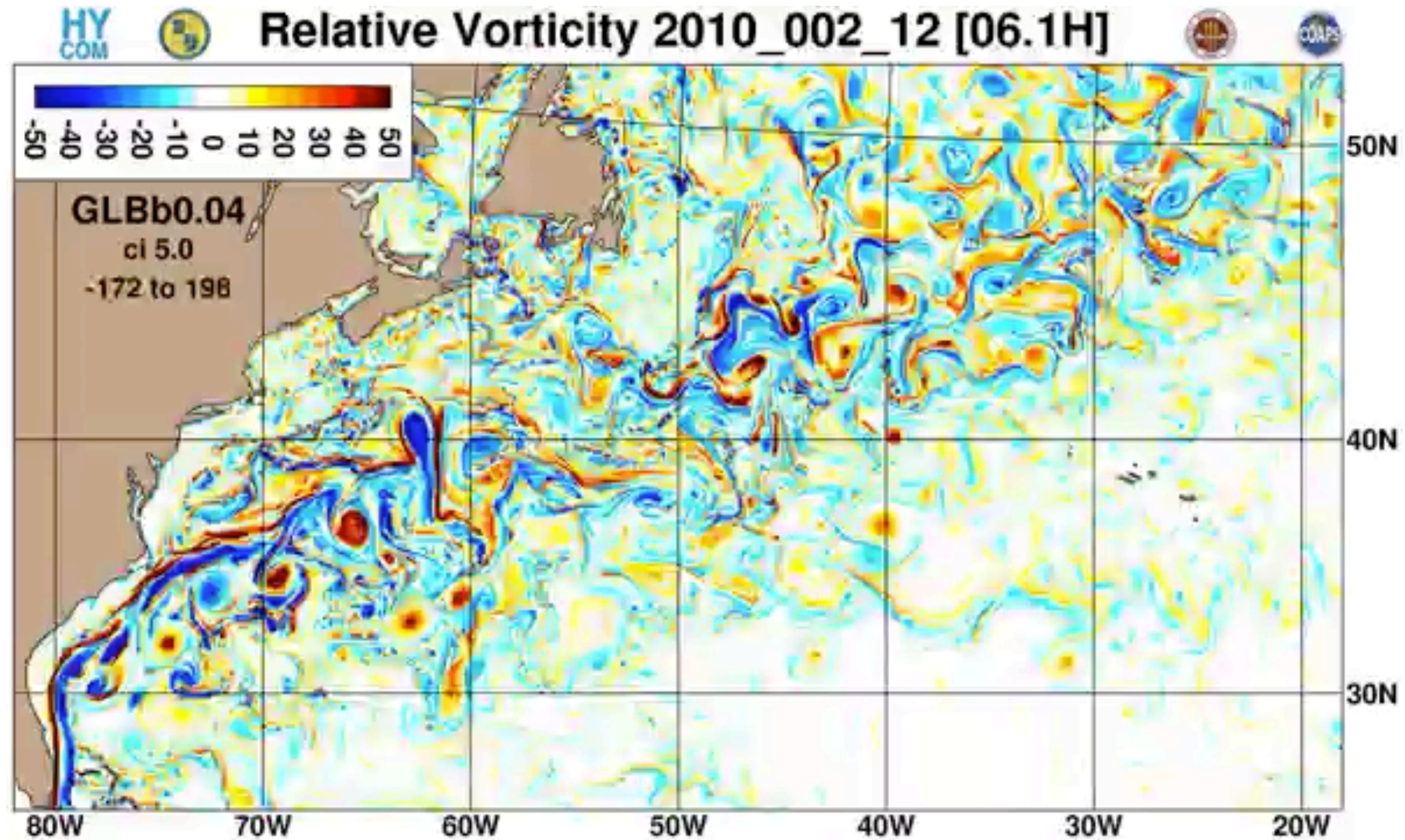
<https://www.youtube.com/watch?v=FmnkQ2ytIO8>

Vorticity in the North Atlantic



relative vorticity in HYCOM model

Vorticity in the North Atlantic



relative vorticity in HYCOM model

Wingtip vortices

**Milestones in Flight History
Dryden Flight Research Center**



C-5A

Wing Vortice Tests at Langley

Circa 1970s



Wingtip vortices, 1990.
PUBLIC DOMAIN/NASA LANGLEY RESEARCH CENTER



Wingtip vortices

**Milestones in Flight History
Dryden Flight Research Center**



C-5A

Wing Vortice Tests at Langley

Circa 1970s



Wingtip vortices, 1990.
PUBLIC DOMAIN/NASA LANGLEY RESEARCH CENTER

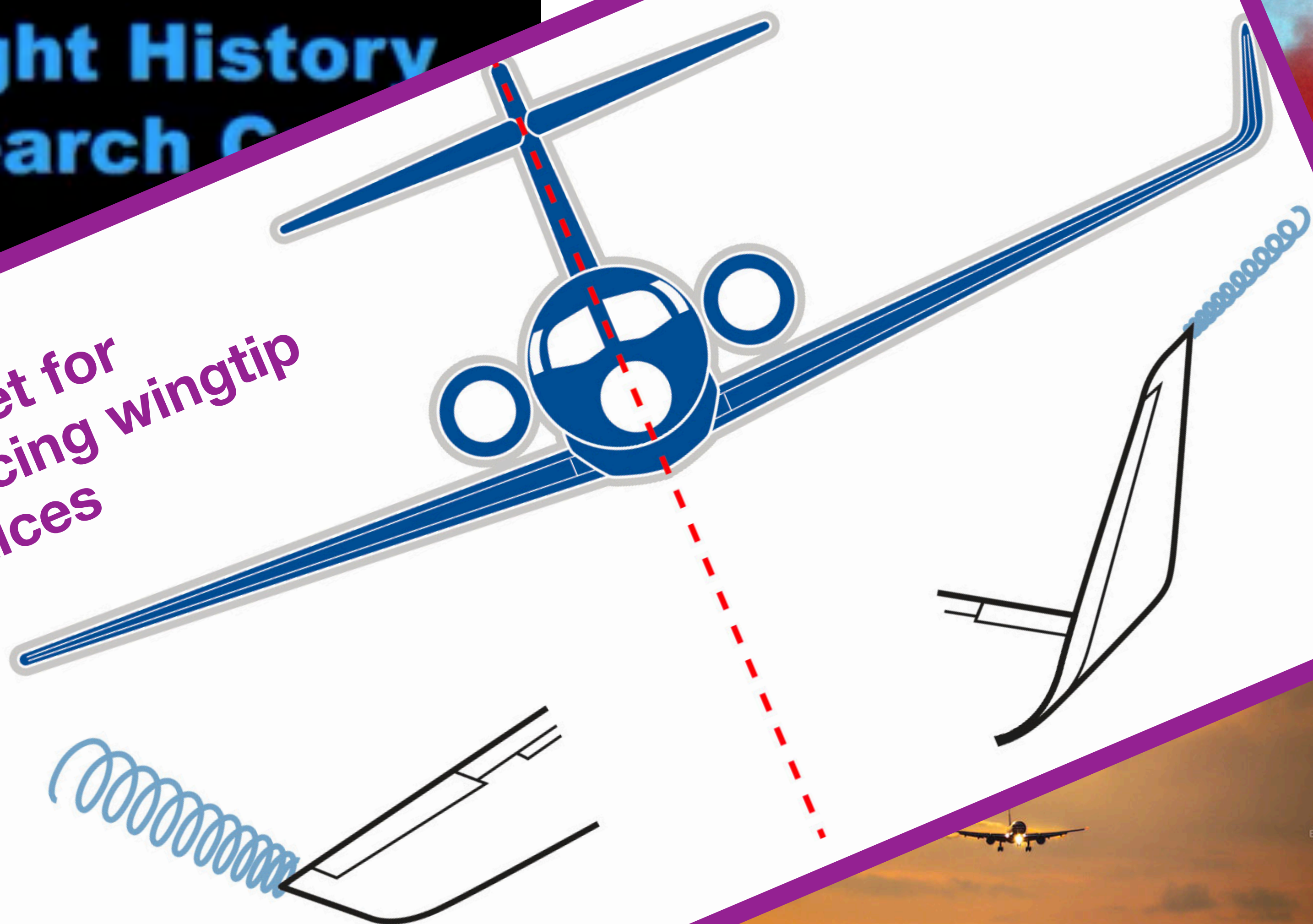


Wingtip vortices

Milestones in Flight History
Dryden Flight Research C



winglet for reducing wingtip vortices



C-5
Wing Vortice Tes
Circa 197



“vortex cascading” from a drop of milk/ coffee



<https://vimeo.com/103705452>

“vortex cascading” from a drop of milk/ coffee



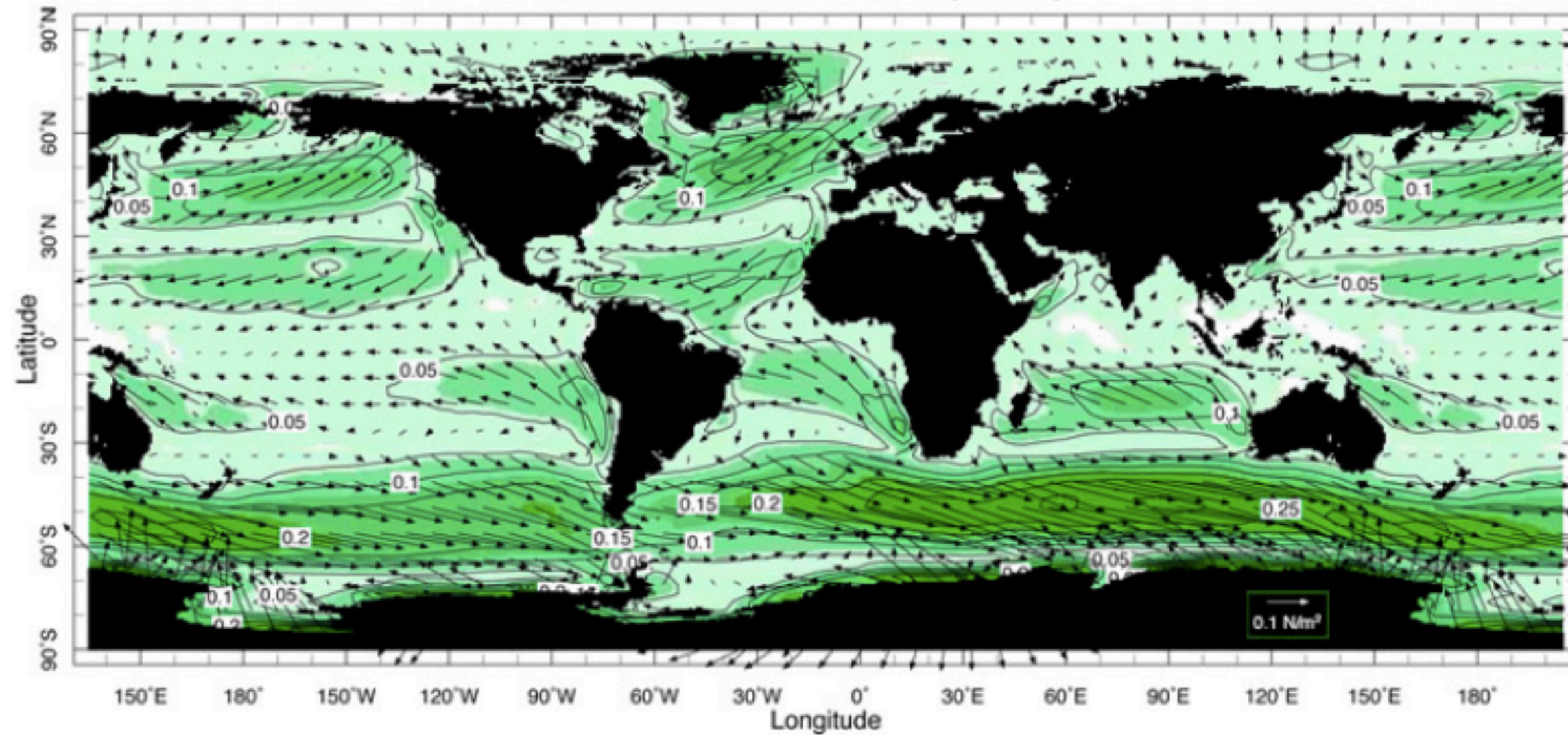
<https://vimeo.com/103705452>

Visualizing vorticity

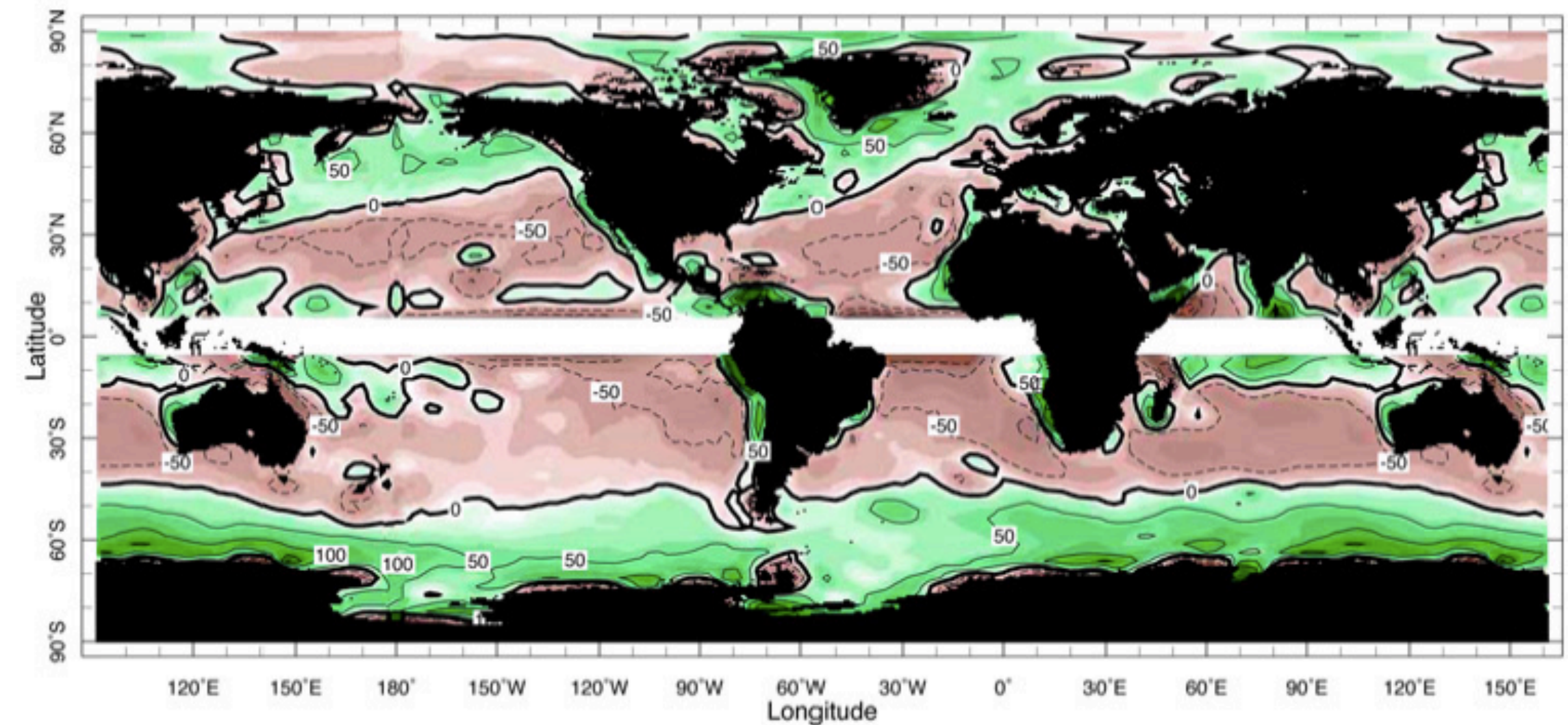
<https://en.wikipedia.org/wiki/Vorticity#Examples>

Global wind stress and wind curl

Surface Wind Stress (N/m^2)



Ekman Pumping (m/y)

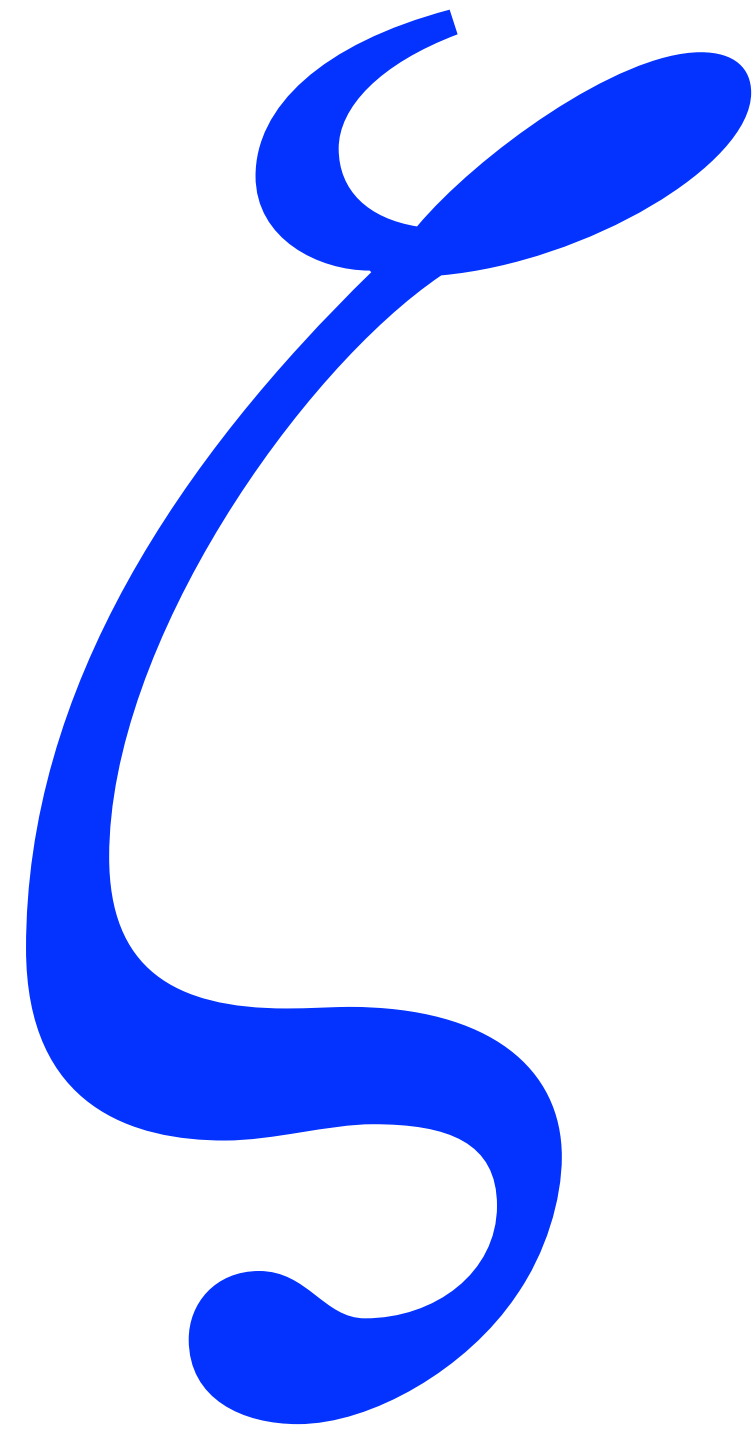


Marshall and Plumb 2008

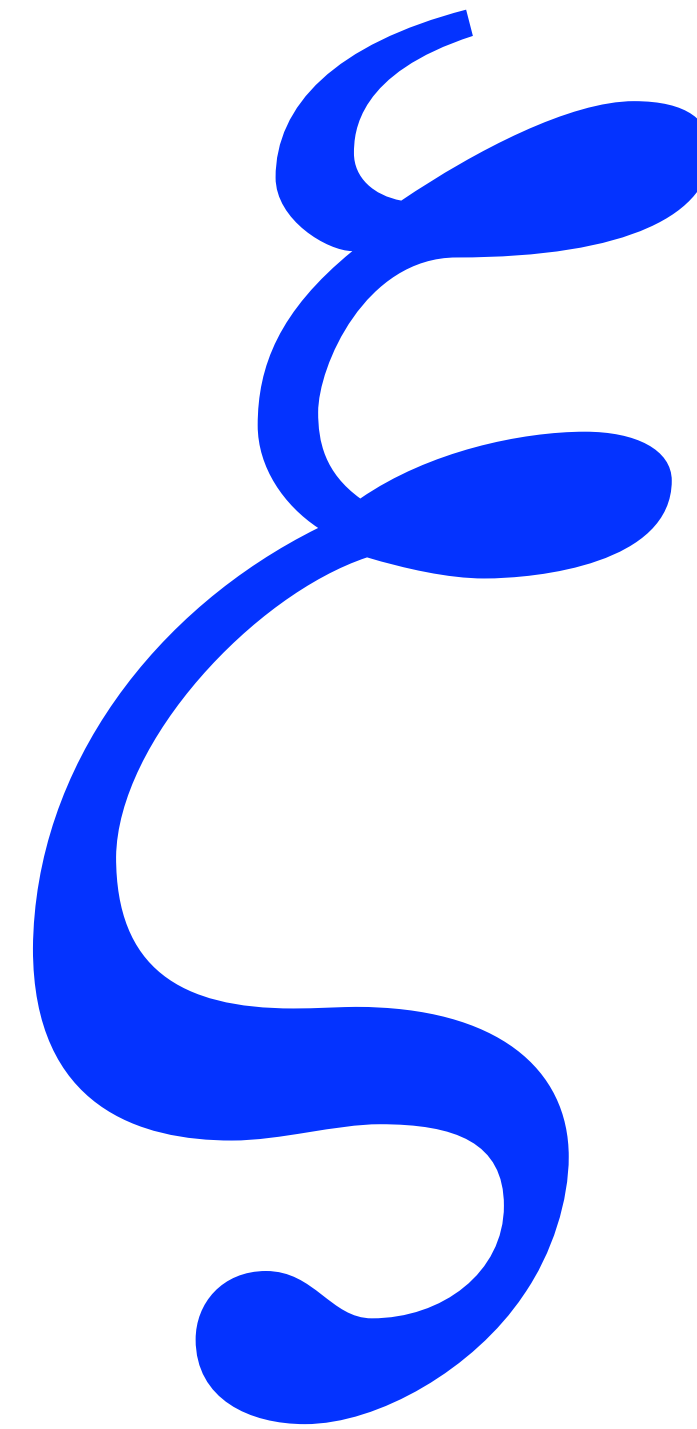
Figure 10.2: Annual mean wind stress on the ocean. A contour of 1 represents a wind-stress of magnitude 0.1 N m^{-2} . Stresses reach values of 0.1 to 0.2 N m^{-2} under the middle-latitude westerlies, and are particularly strong in the southern hemisphere. The arrow is a vector of length 0.1 N m^{-2} . Note that the stress vectors circulate around the high and low pressure centers shown in Fig.7.27, as one would expect if the surface wind, on which the stress depends, has a strong geostrophic component.

Figure 10.11: The global pattern of Ekman vertical velocity (m y^{-1}) computed using Eq.(10.7) from the annual mean wind-stress pattern shown in Fig.10.2. Motion is upward in the green areas, downward in the brown areas. w_{EK} is not computed over the white strip along the equator because $f \rightarrow 0$ there. The thick line is the zero contour. Computed from Trenberth et al (1989) data. The broad regions of upwelling and downwelling delineated here are used to separate the ocean in to different dynamical regimes, as indicated by the colors in Fig.9.13.

Announcing!



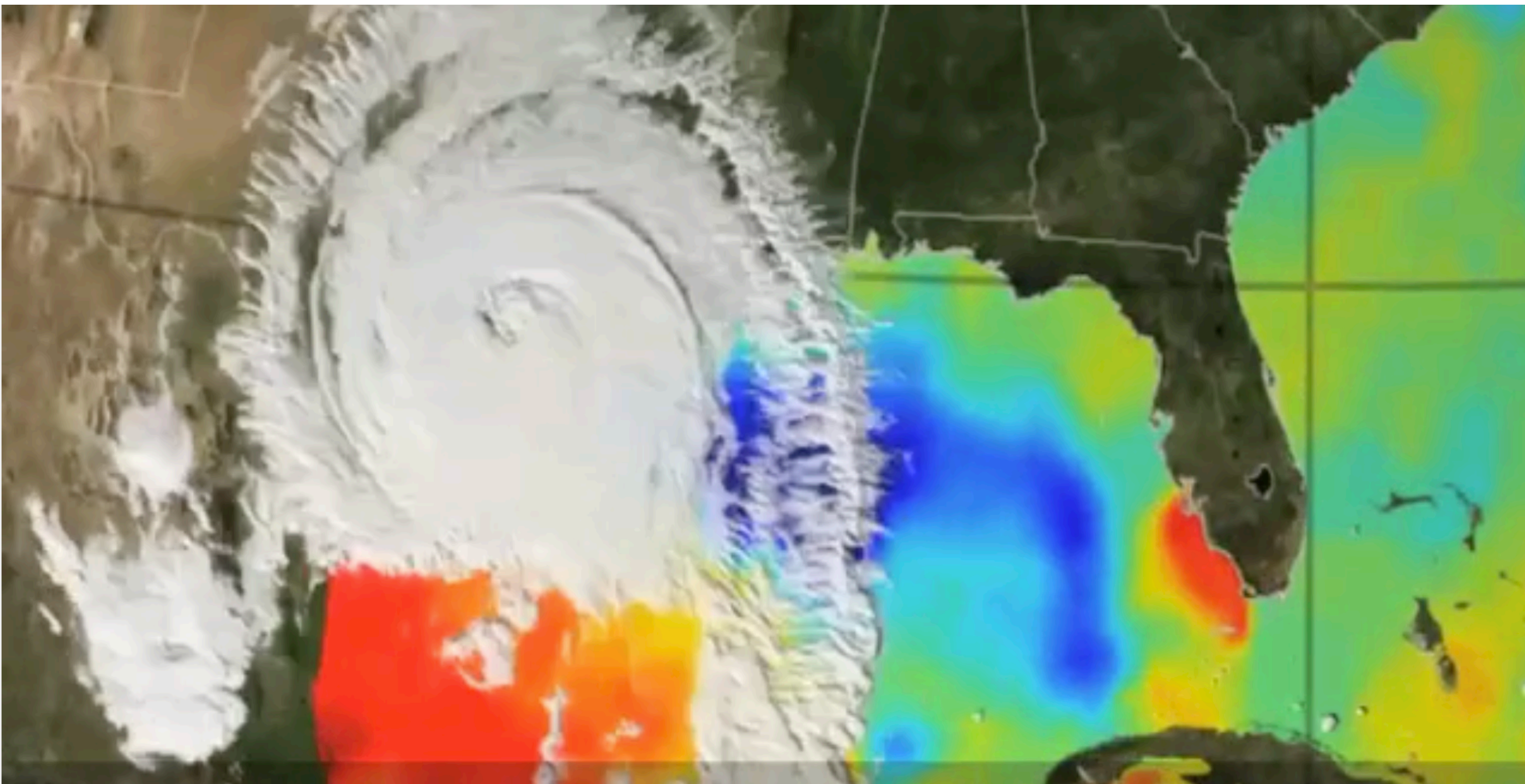
VS



notes

4 vortex decay

Hurricanes weakening over land: vortex decay



<https://oceanoday.noaa.gov/fuelforthestorm/>



<https://www.wmcactionnews5.com/2018/10/11/breakdown-why-hurricanes-weaken-when-moving-across-land/>

Spin-down in a cup of tea: Einstein's tea leaf paradox

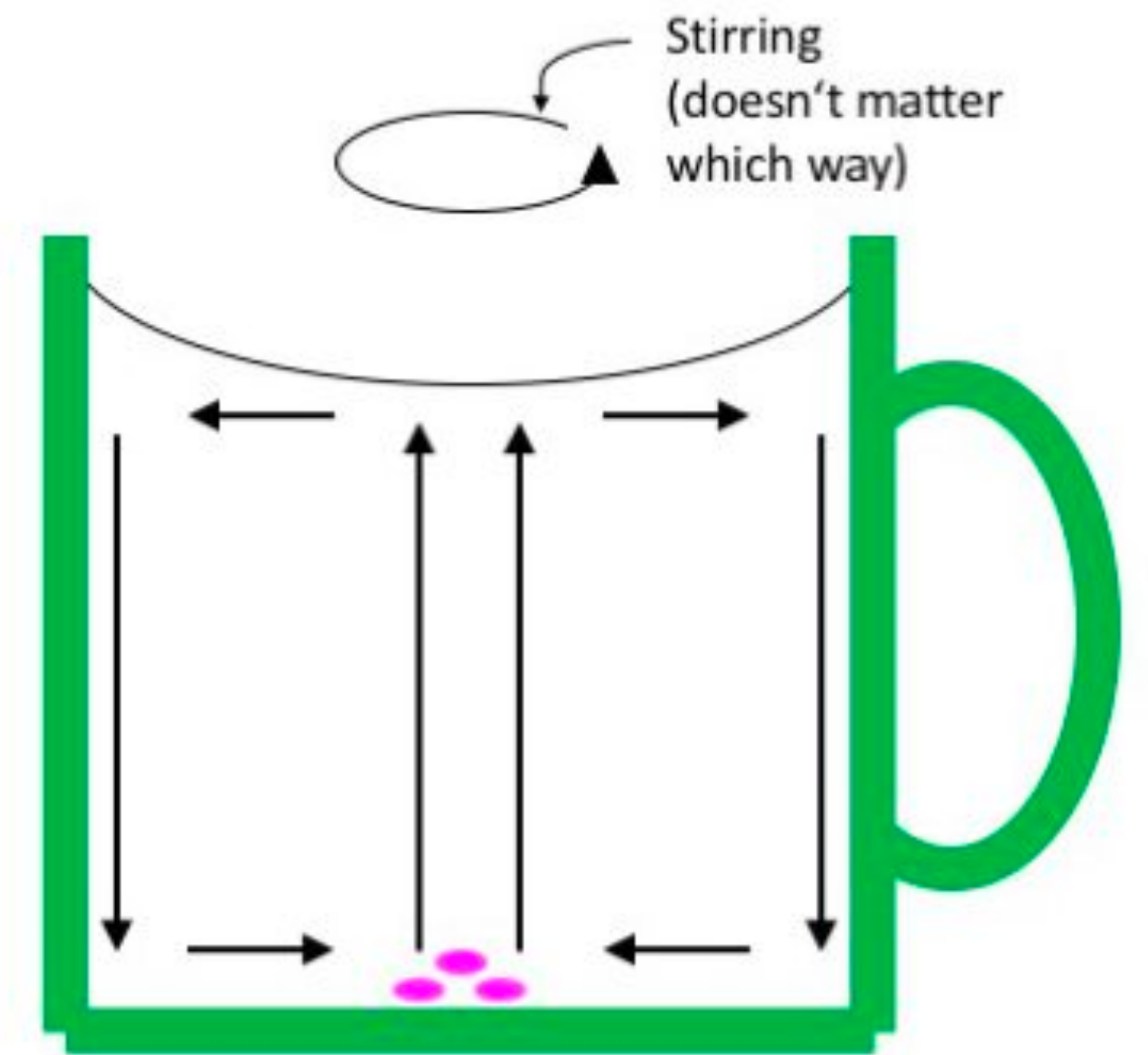


https://www.youtube.com/watch?v=sxAiRe_QWWA

Spin-down in a cup of tea: Einstein's tea leaf paradox



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



<https://mirjamglessmer.com/2019/08/11/demonstrating-ekman-layers-in-a-rotating-tank-high-pressure-and-low-pressure-systems/>

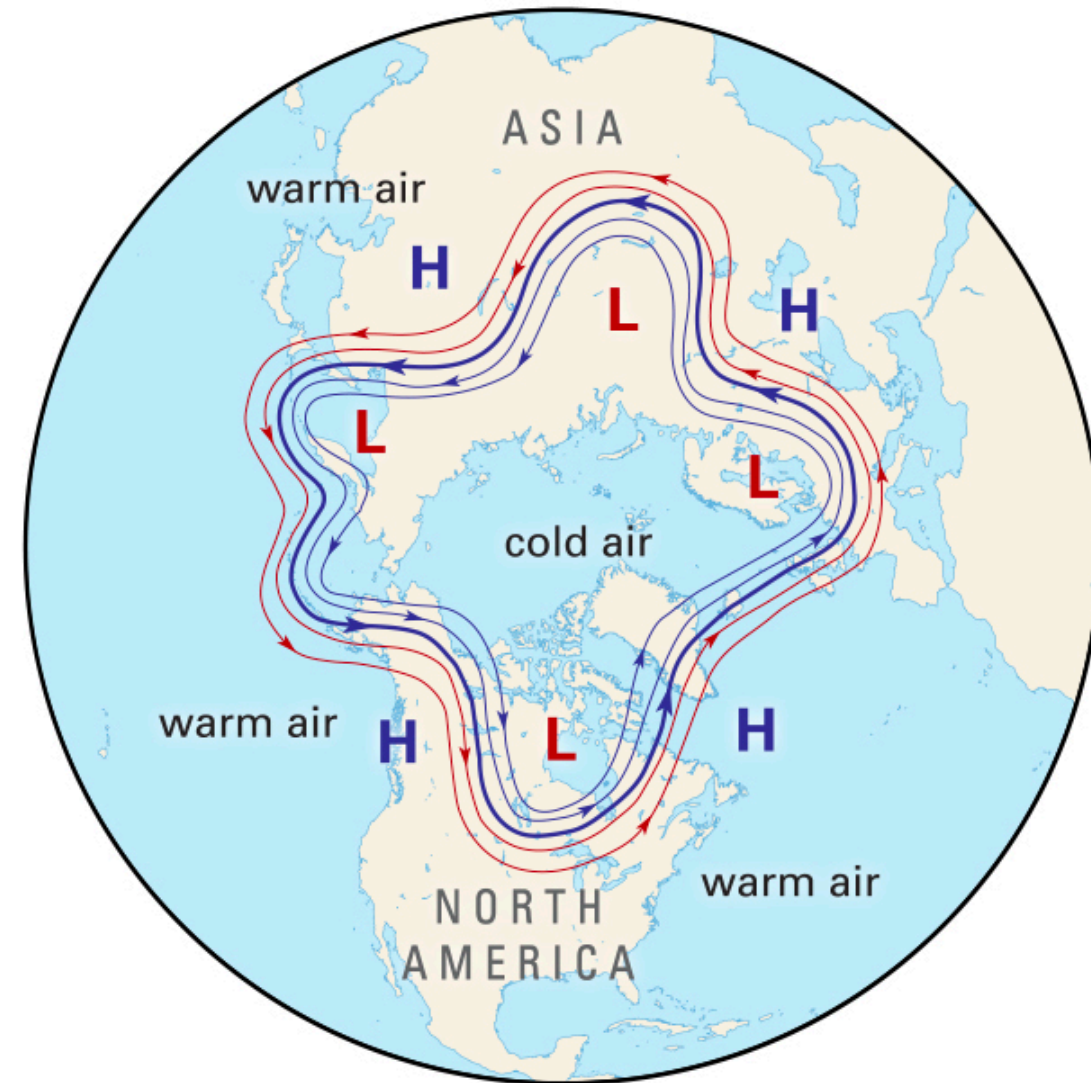
notes

5 Rossby waves

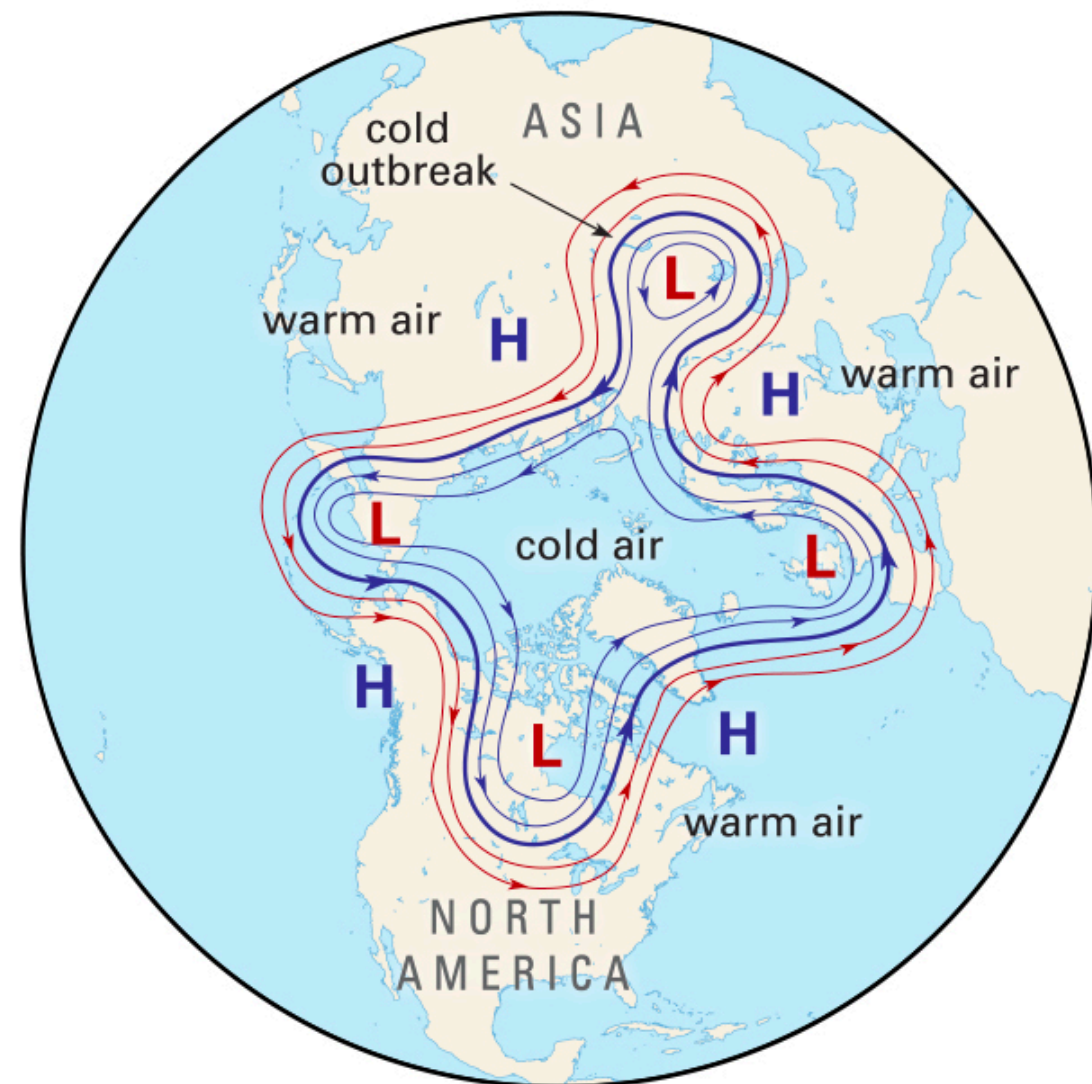
ROSSBY WAVE PATTERNS OVER THE NORTH POLE



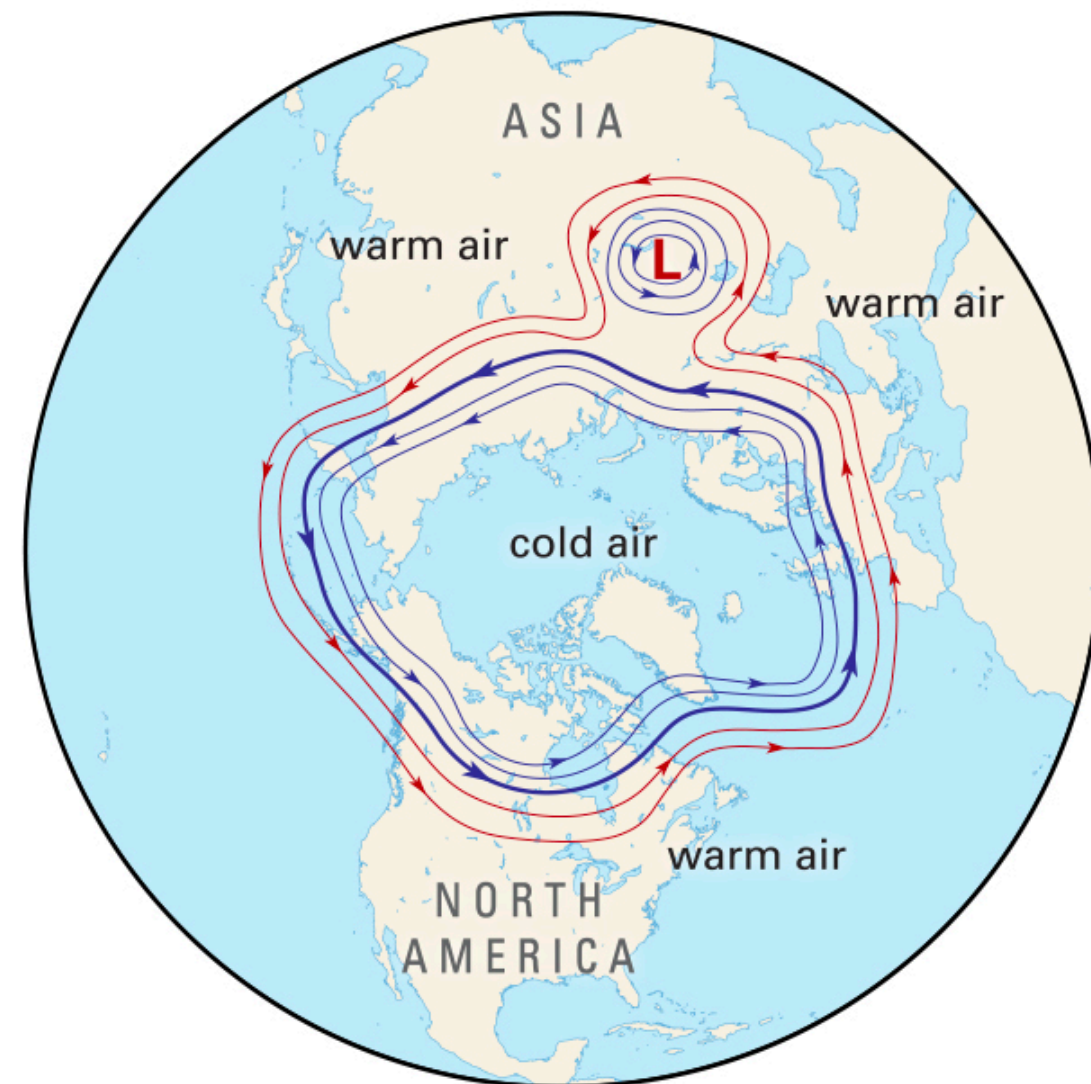
1. Uninterrupted upper airflow pattern



2. Waves forming in polar vortex



3. Upper air waves becoming more pronounced



4. Initial pattern restored with the detachment of a cold air mass

H High-pressure centre

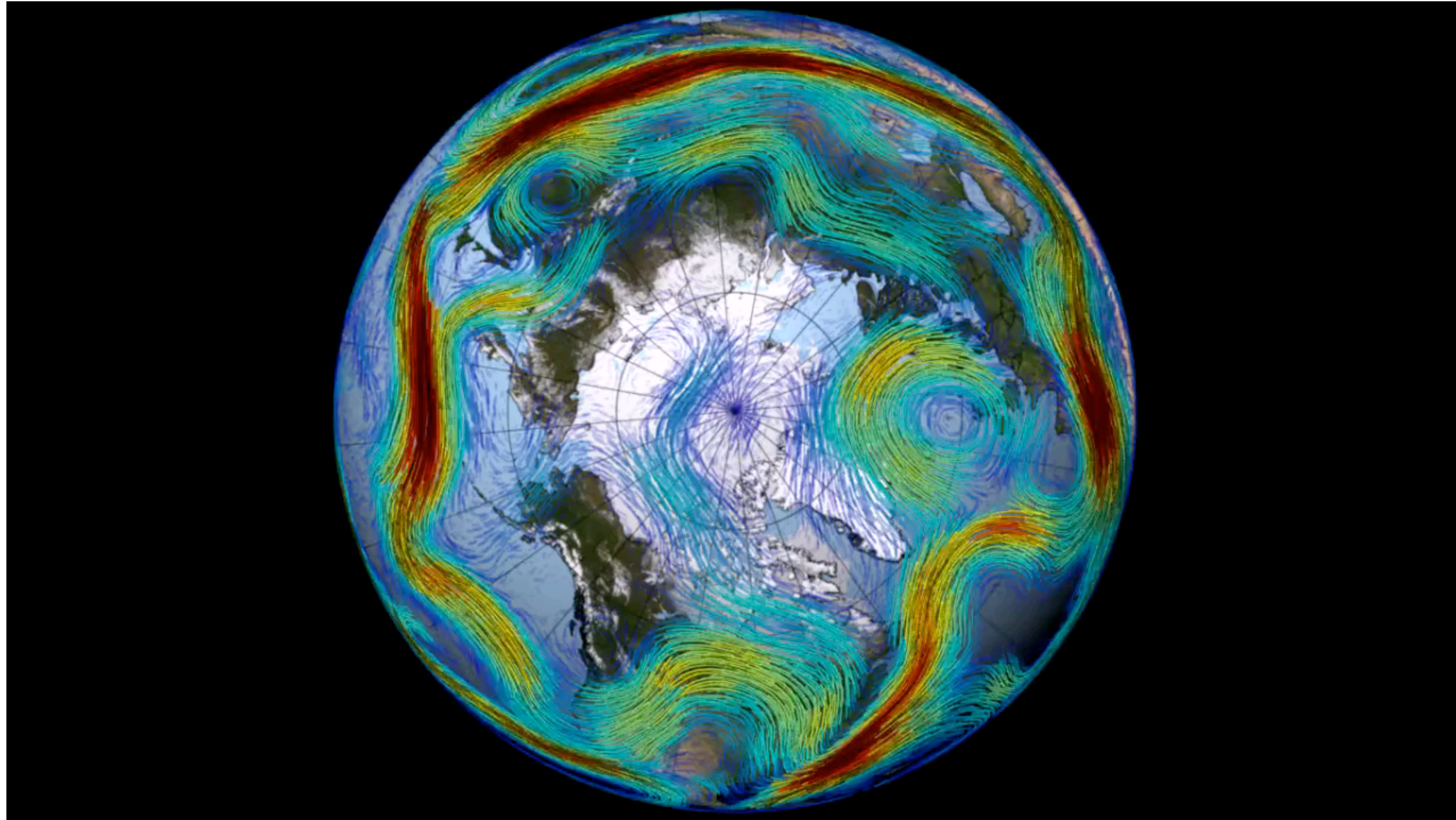
L Low-pressure centre

 Jet stream

Rossby wave patterns over the North Pole depicting the formation of an outbreak of cold air over Asia

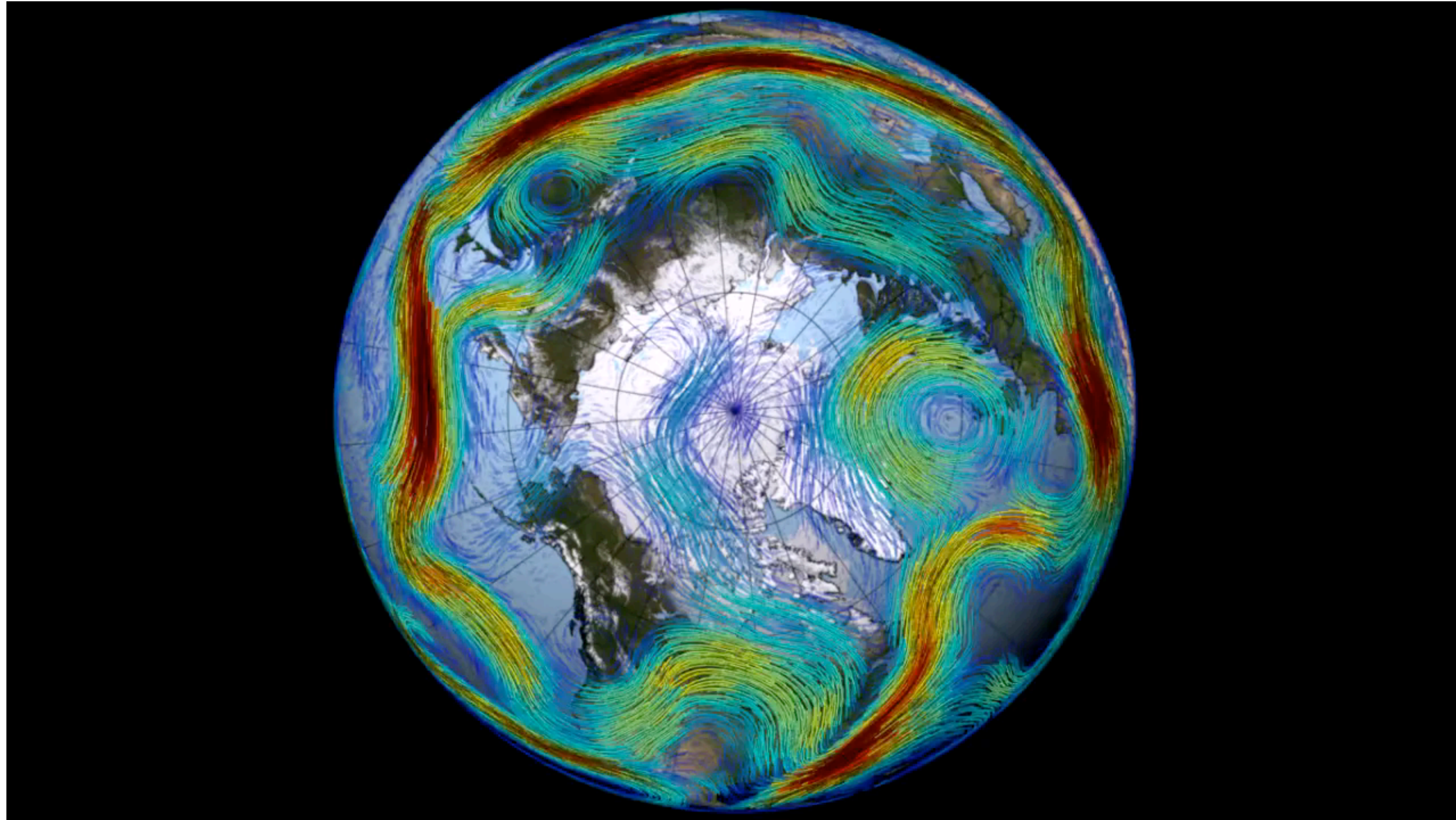
<https://www.britannica.com/science/Rossby-wave>

Rossby waves on the atmospheric jet stream



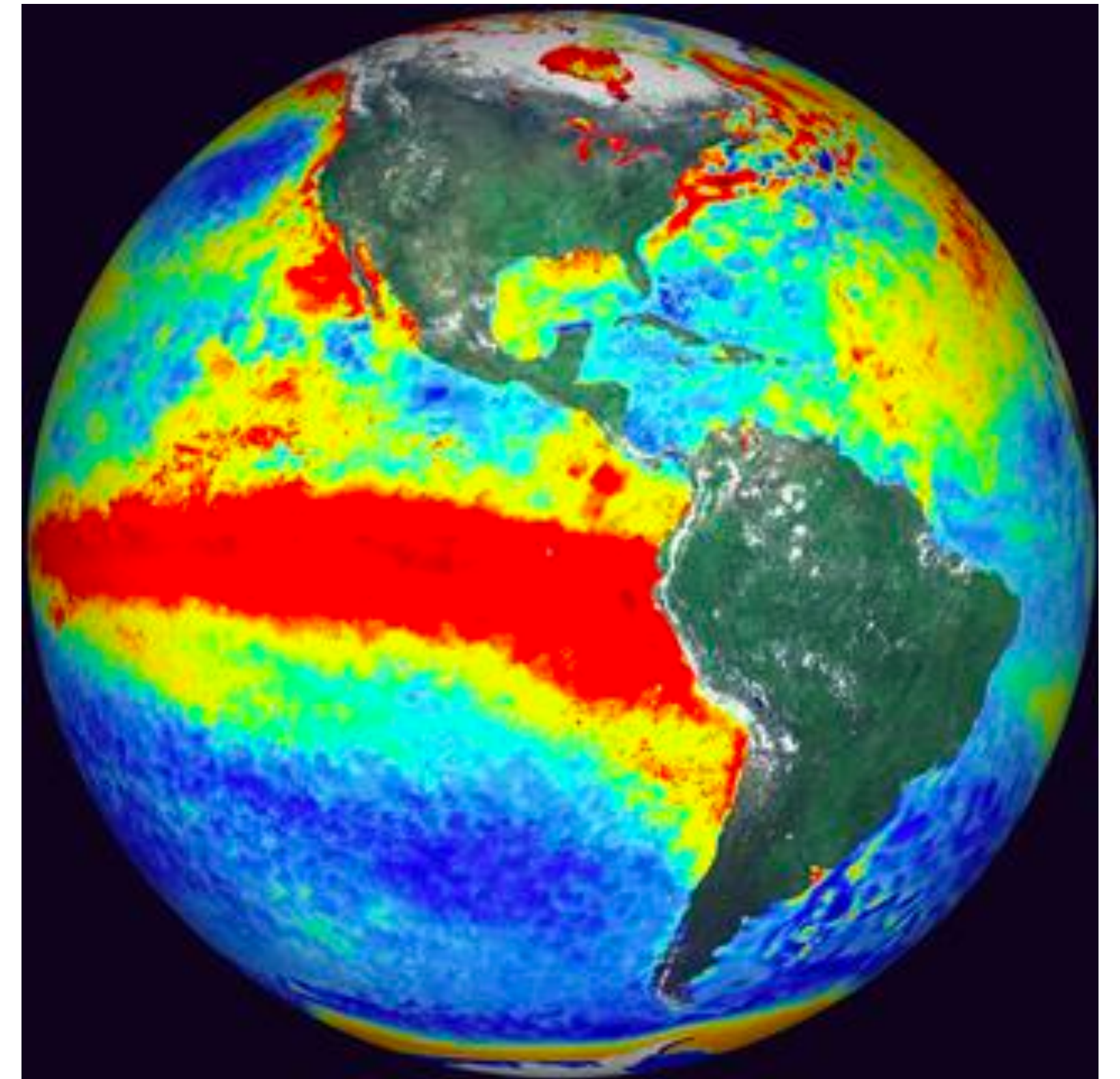
Rossby waves play a significant role in shaping weather. This NASA Goddard animation shows atmospheric waves as indicated by the jet stream. colors: wind speed, from slow (blue) to fast (red).

Rossby waves on the atmospheric jet stream



Rossby waves play a significant role in shaping weather. This NASA Goddard animation shows atmospheric waves as indicated by the jet stream. colors: wind speed, from slow (blue) to fast (red).

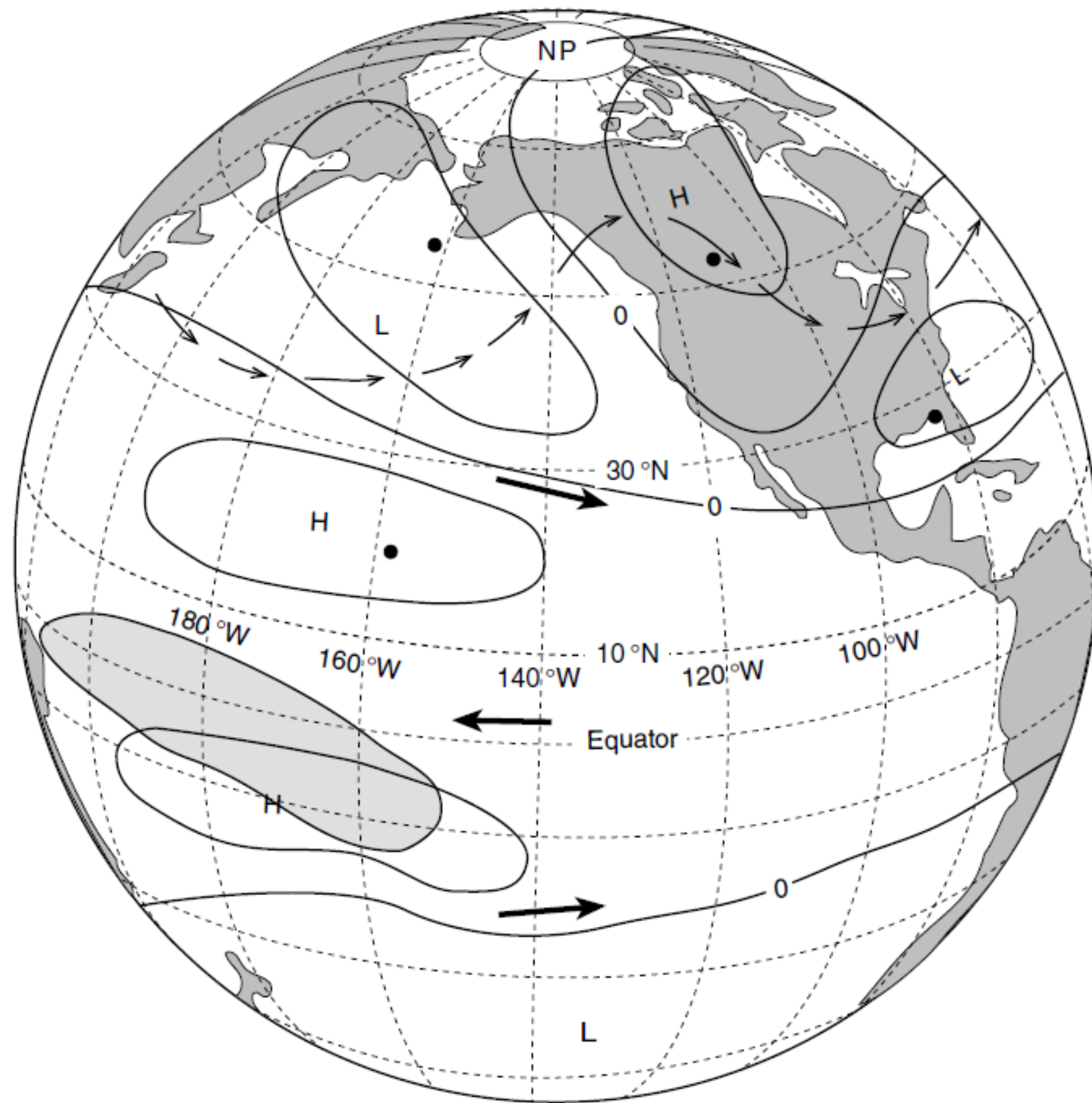
Atmospheric teleconnections: **Rossby wave** train forced by ENSO



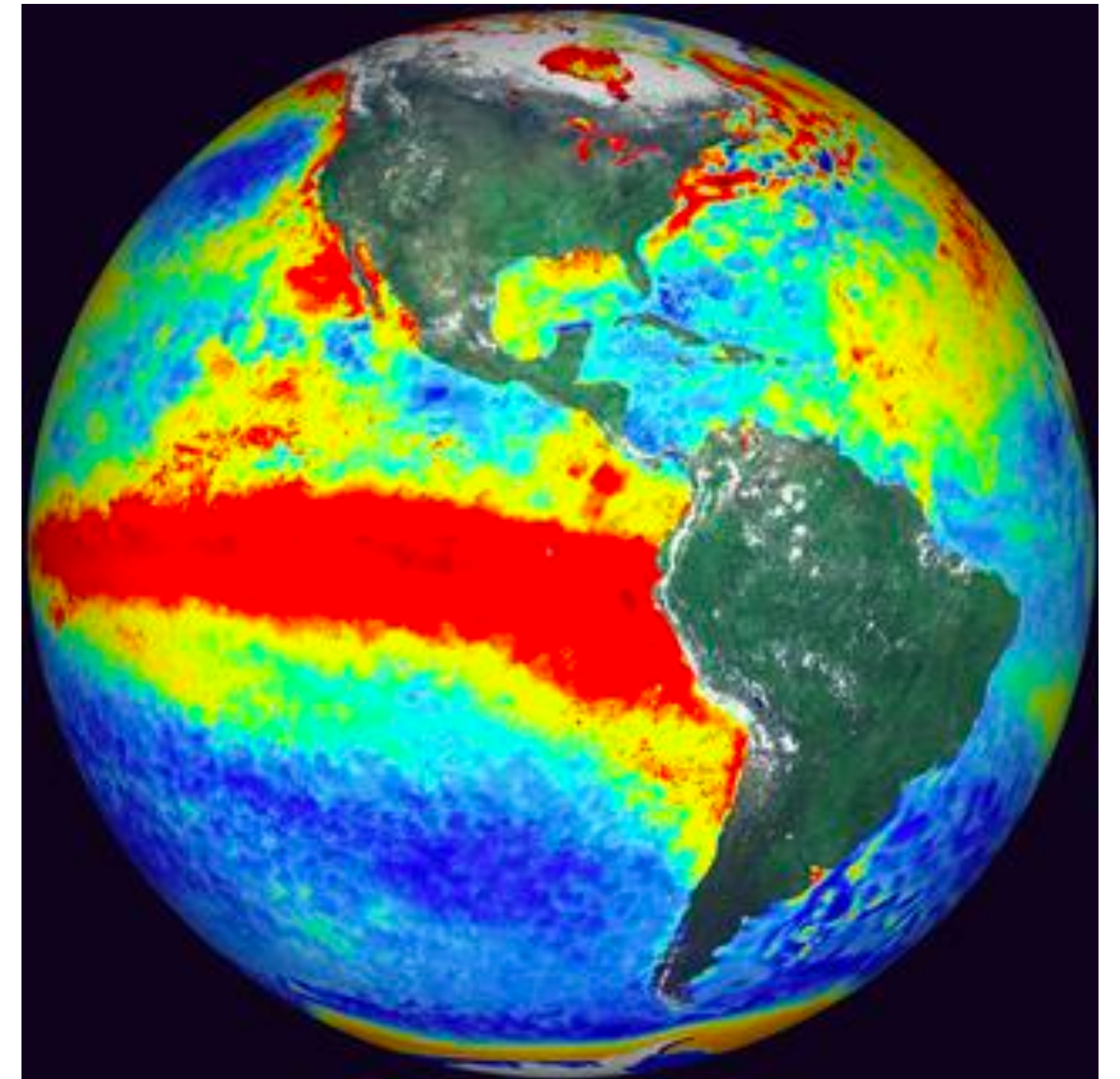
sea surface temperature anomaly
during an El Niño event

(<https://snowbrains.com/noaa-el-nino-update-today/>)

Atmospheric teleconnections: **Rossby wave** train forced by ENSO

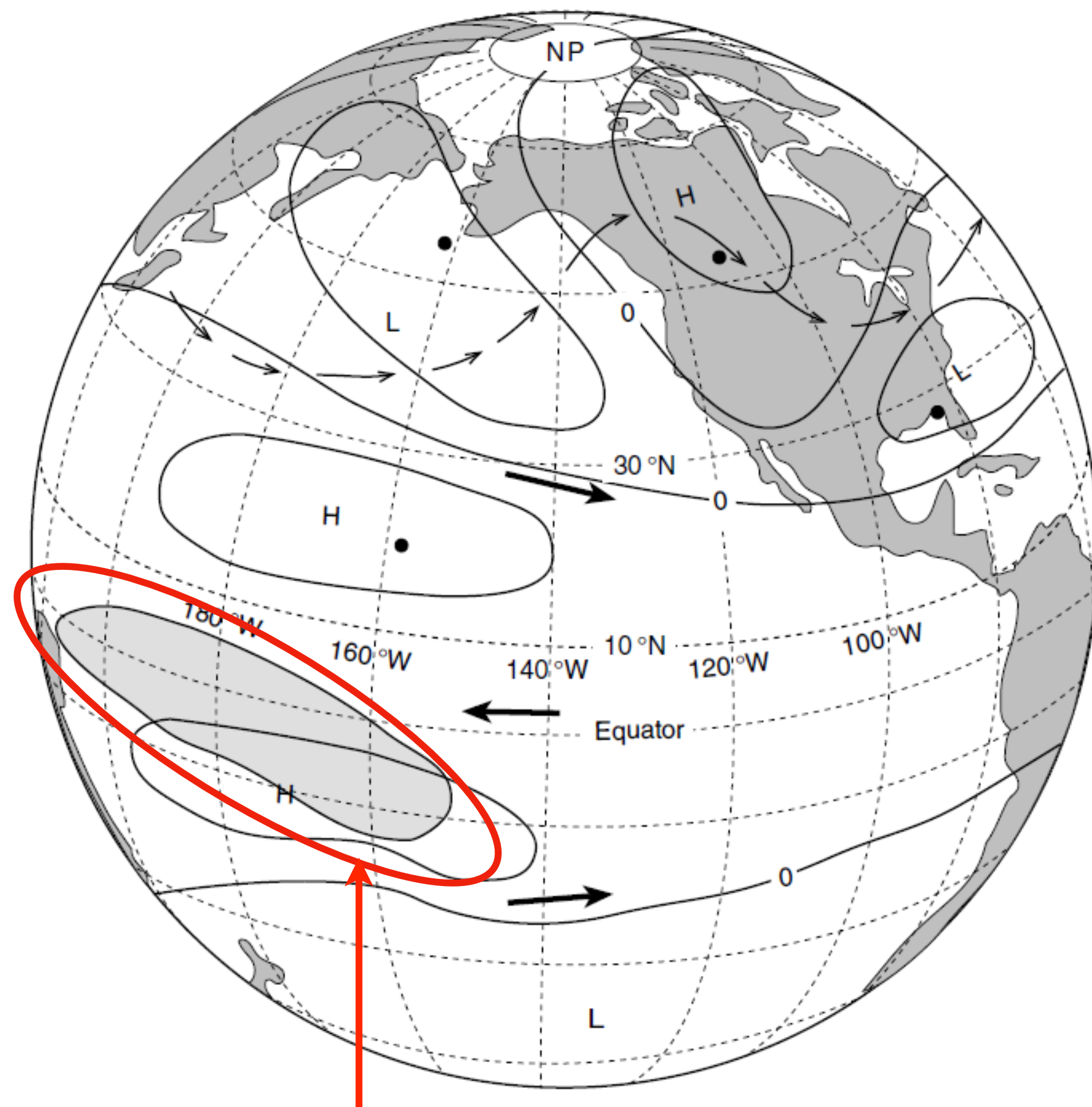


solid contours: schematic upper atmosphere geopotential height anomaly; shaded area at equator: enhanced cloudiness and rain. Light arrows: mid-tropospheric stream line distorted by wave pattern. (Horel & Wallace 1981)

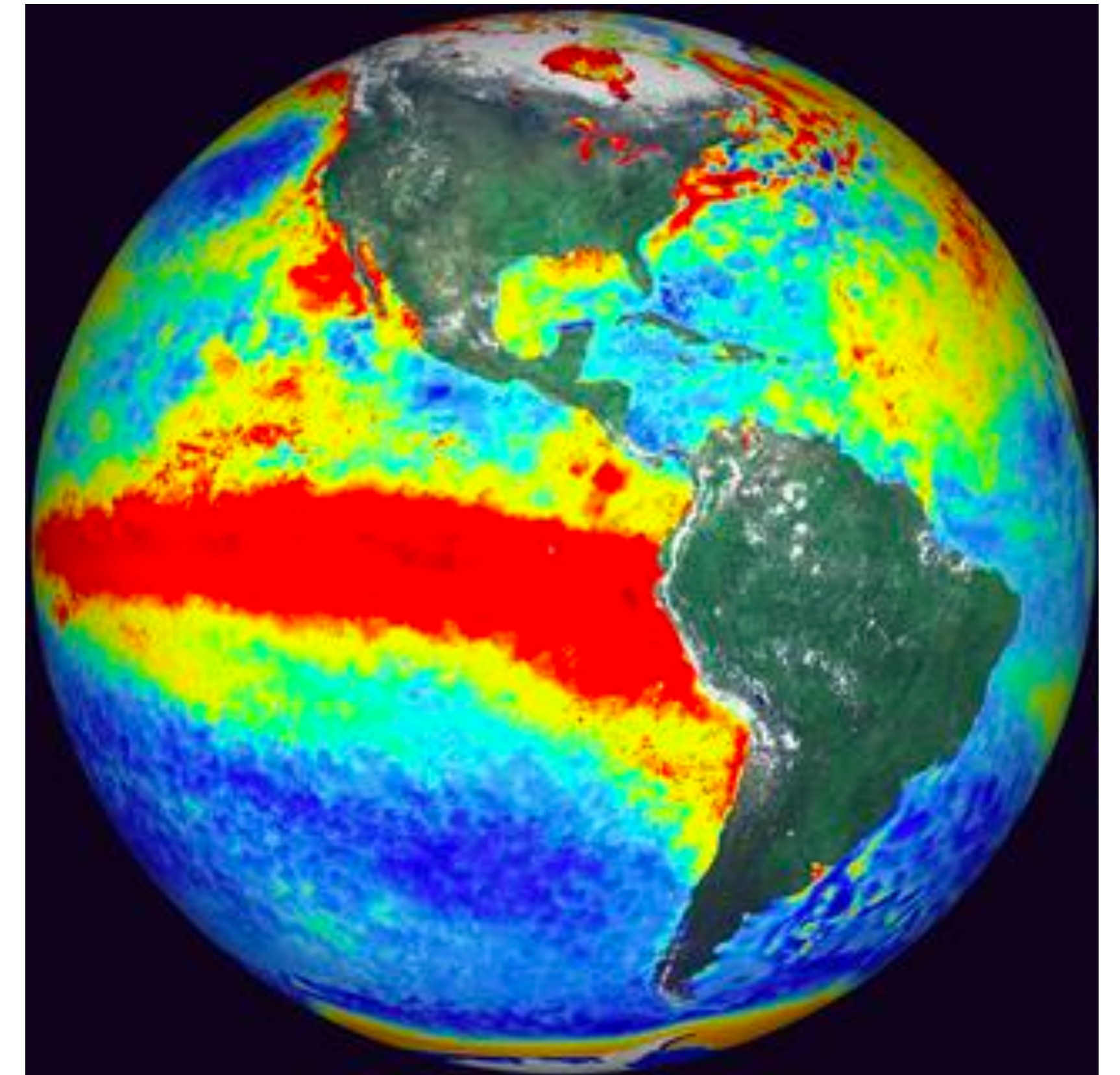


sea surface temperature anomaly during an El Niño event
[\(https://snowbrains.com/noaa-el-nino-update-today/\)](https://snowbrains.com/noaa-el-nino-update-today/)

Atmospheric teleconnections: **Rossby wave** train forced by ENSO



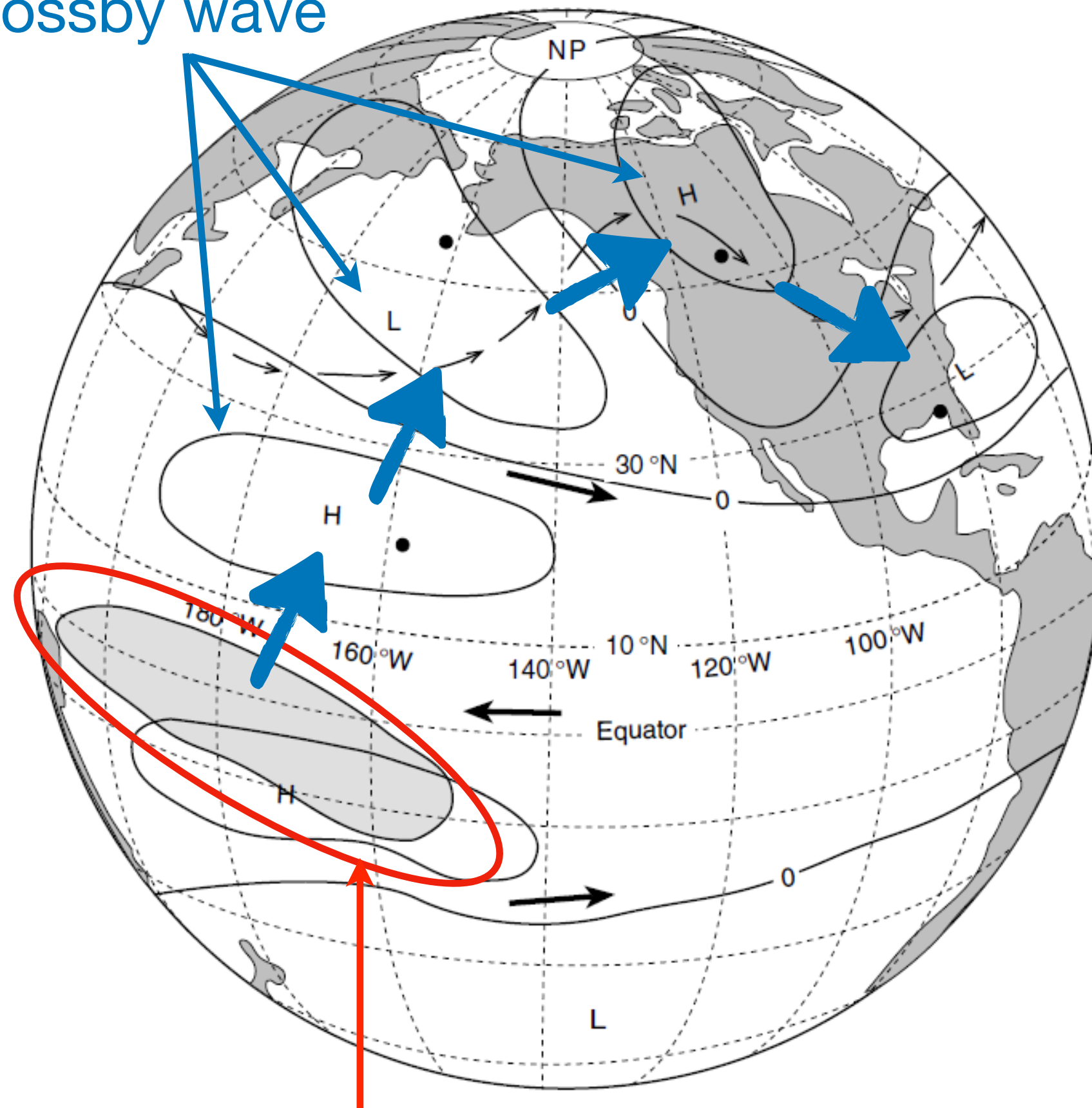
solid contours represent precipitation and atmospheric heating due to El Niño, which forces atmospheric waves. Shaded areas represent cloudiness. The tropospheric streamlines are distorted by the wave pattern. (Horel & Wallace 1981)



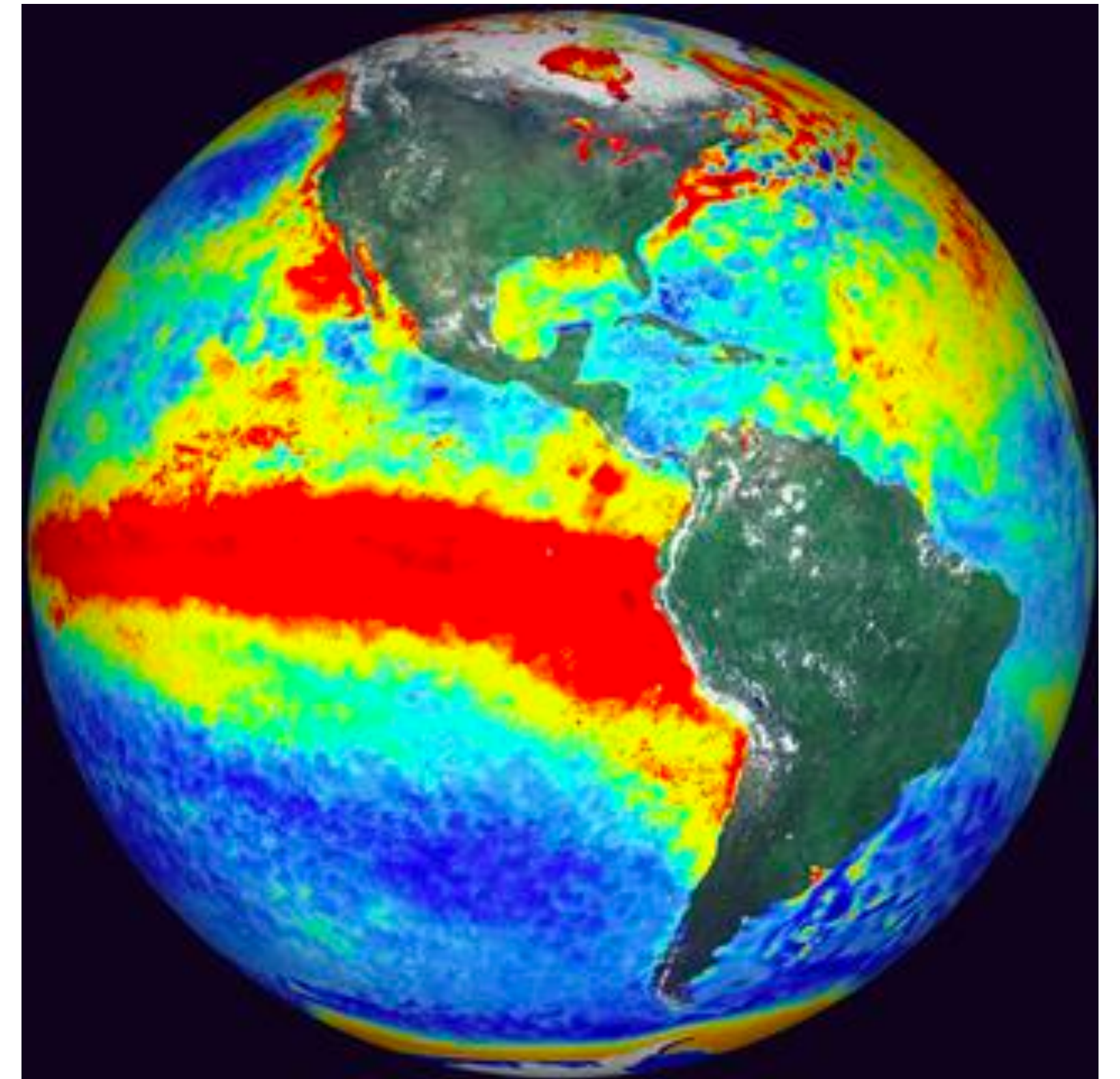
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Atmospheric teleconnections: **Rossby wave** train forced by ENSO

Rossby wave



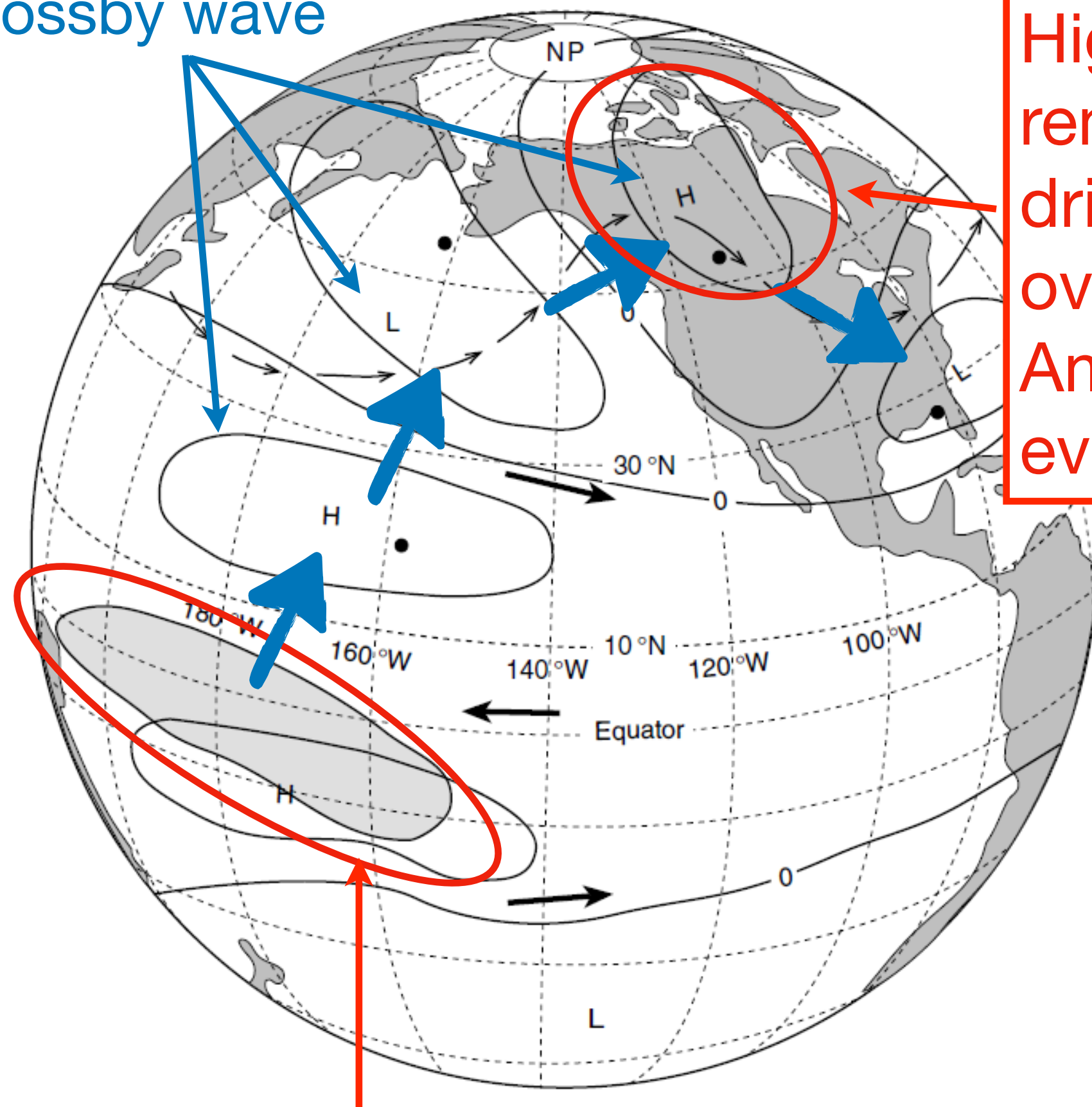
solid contours represent precipitation and atmospheric heating due to El Niño, which forces atmospheric waves. Dashed contours represent cloudiness. The tropospheric streamline is distorted by wave pattern. (Horel & Wallace 1981)



sea surface temperature anomaly during an El Niño event
[\(https://snowbrains.com/noaa-el-nino-update-today/\)](https://snowbrains.com/noaa-el-nino-update-today/)

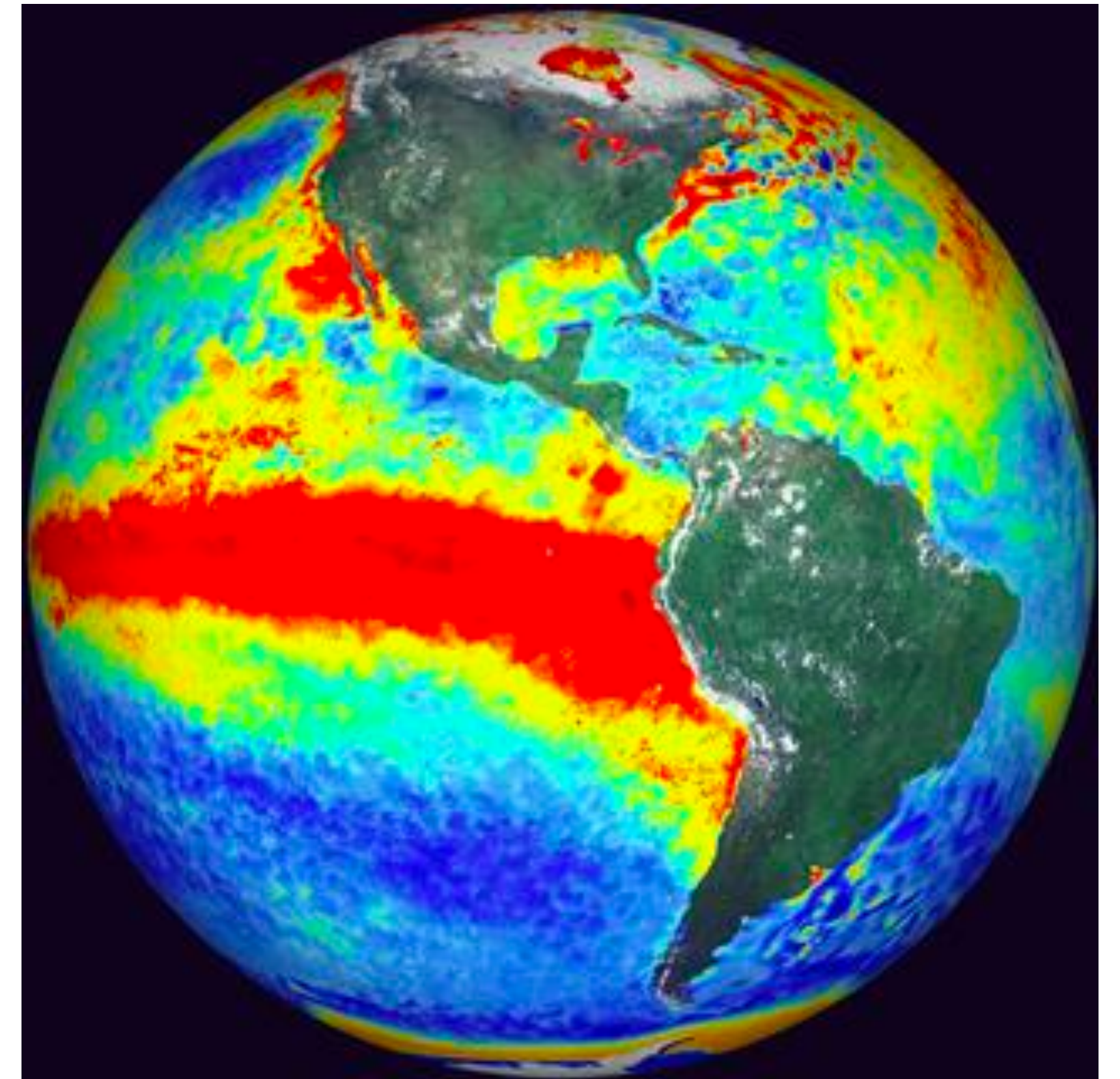
Atmospheric teleconnections: **Rossby wave** train forced by ENSO

Rossby wave



High pressure. Such a remotely forced signal drives drought conditions over south-west North America during La Niña events

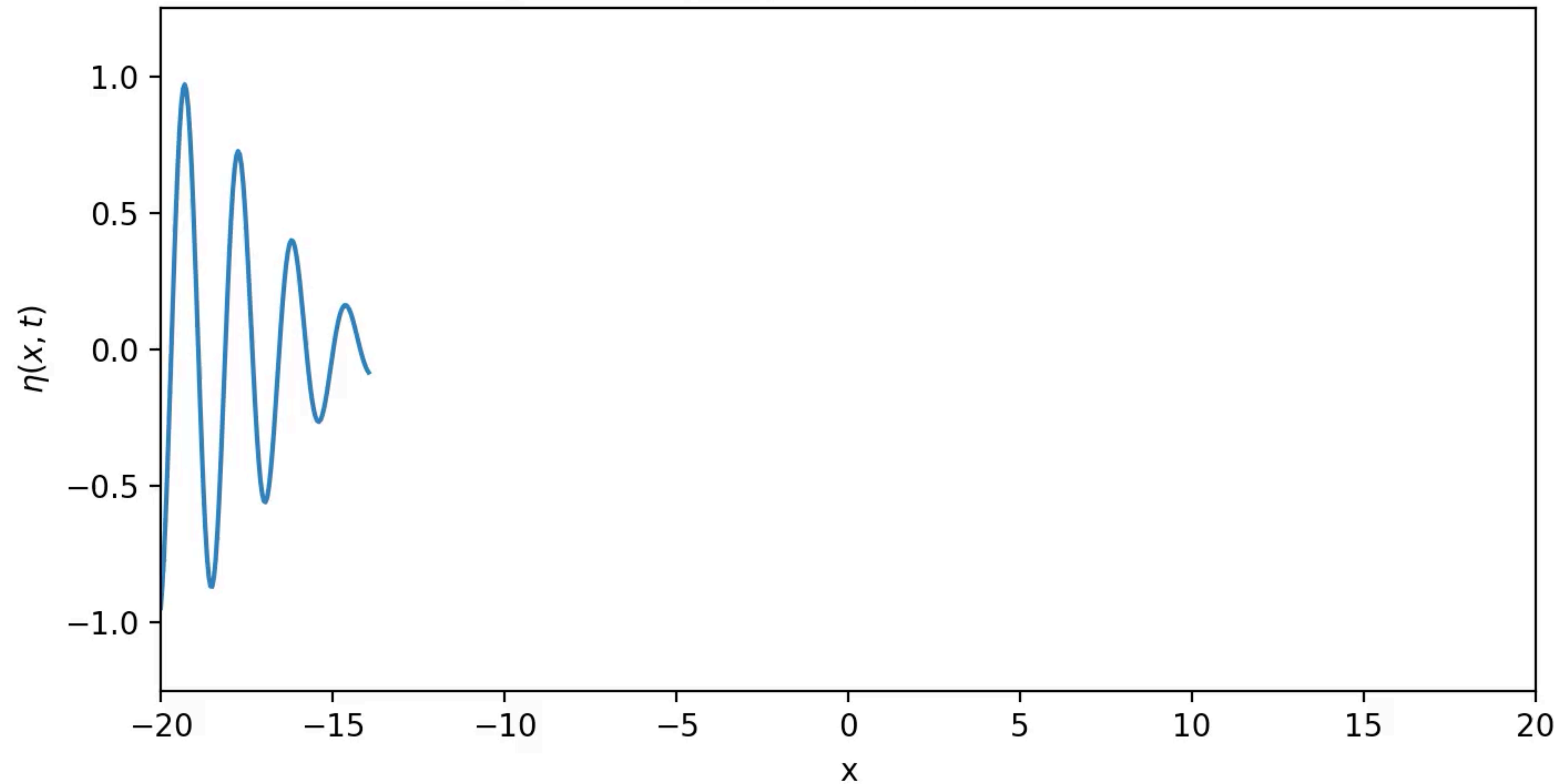
solid contour precipitation and atmospheric heating due to El Niño, which forces atmospheric waves shaded are cloudiness tropospheric streamlines distorted by wave pattern. (Horel & Wallace 1981)



sea surface temperature anomaly during an El Niño event (<https://snowbrains.com/noaa-el-nino-update-today/>)

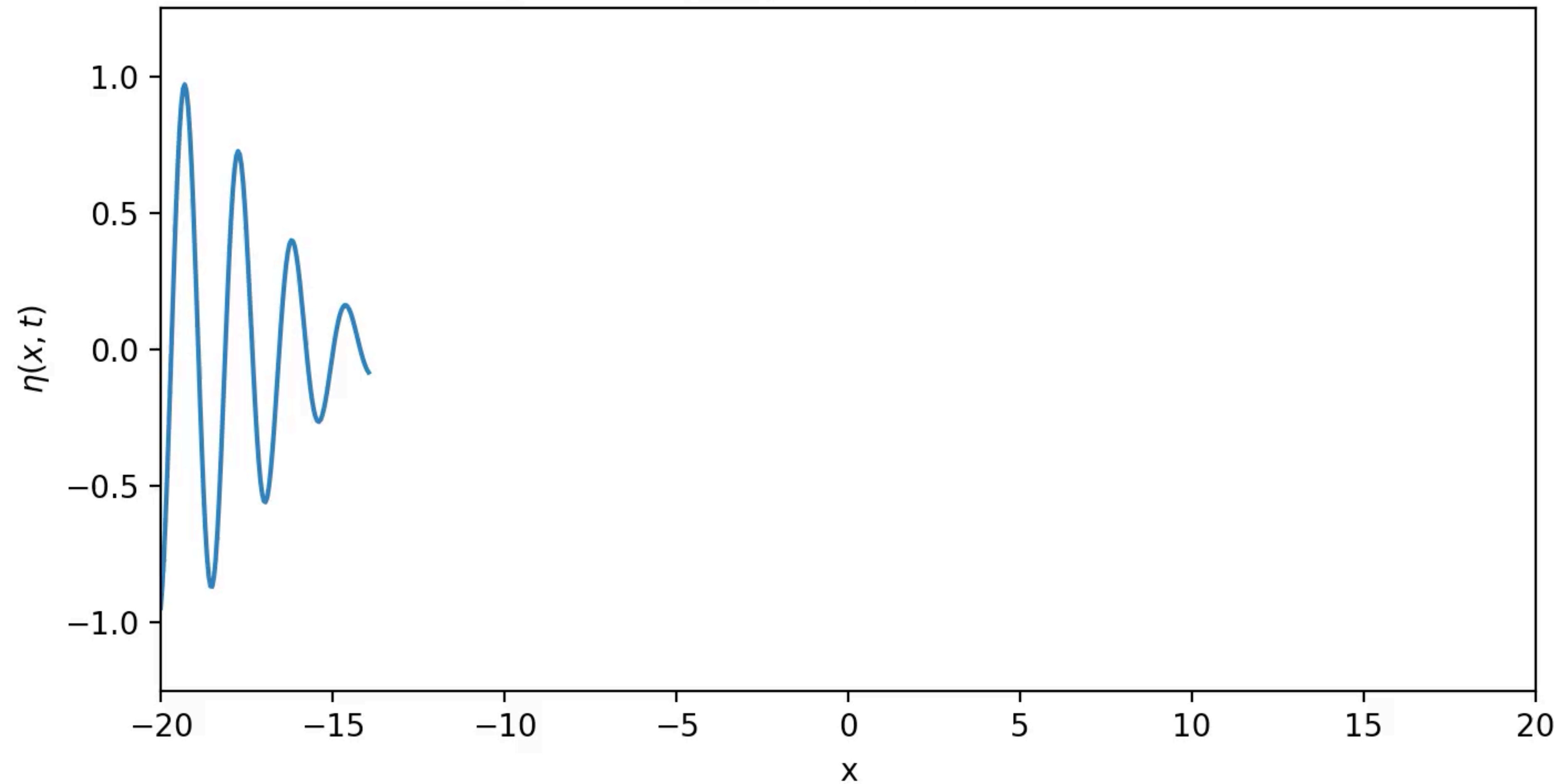
Short Rossby waves: eastward group & westward phase velocity

phase vs group propagation, $t=-10.0$

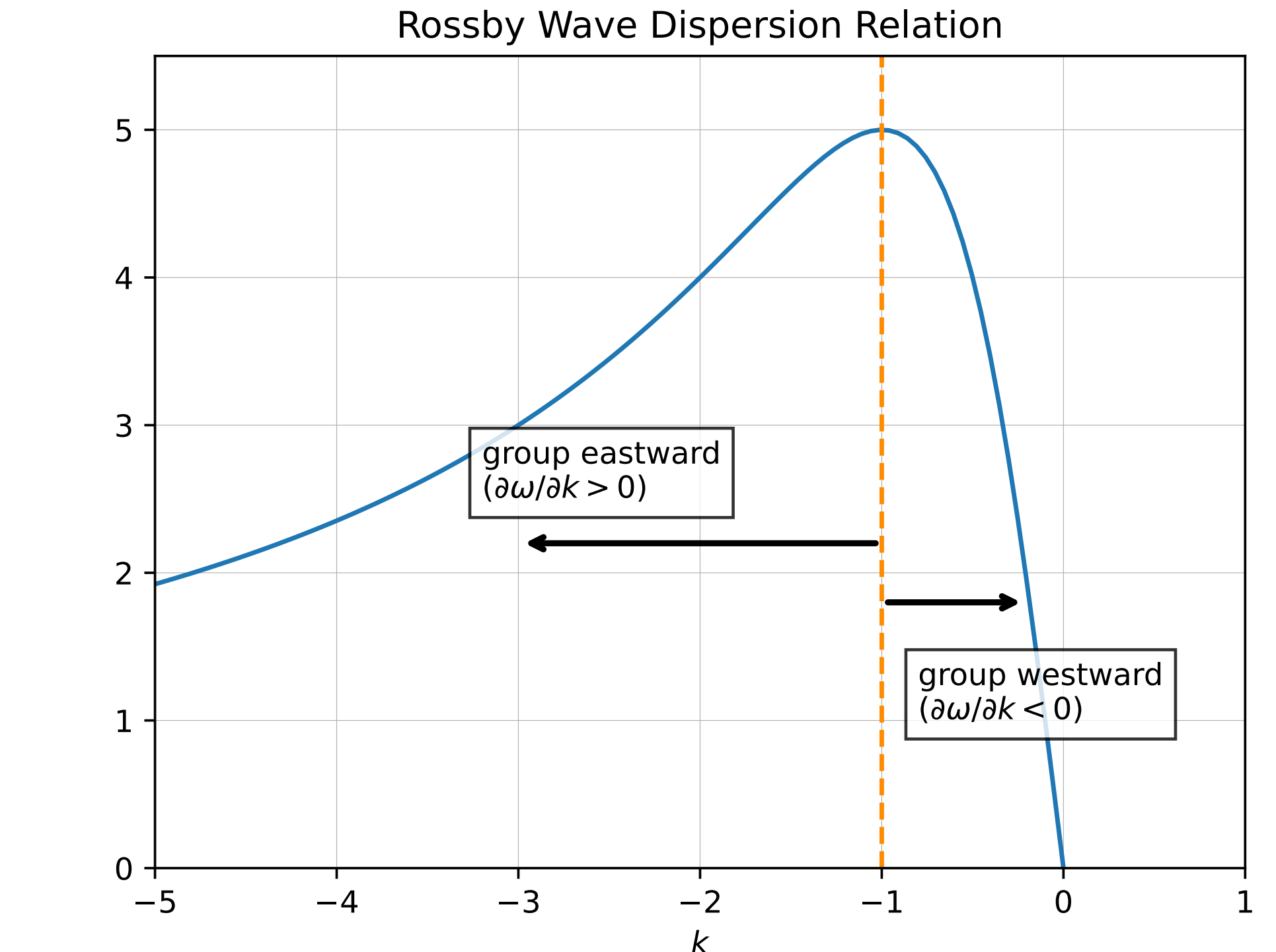
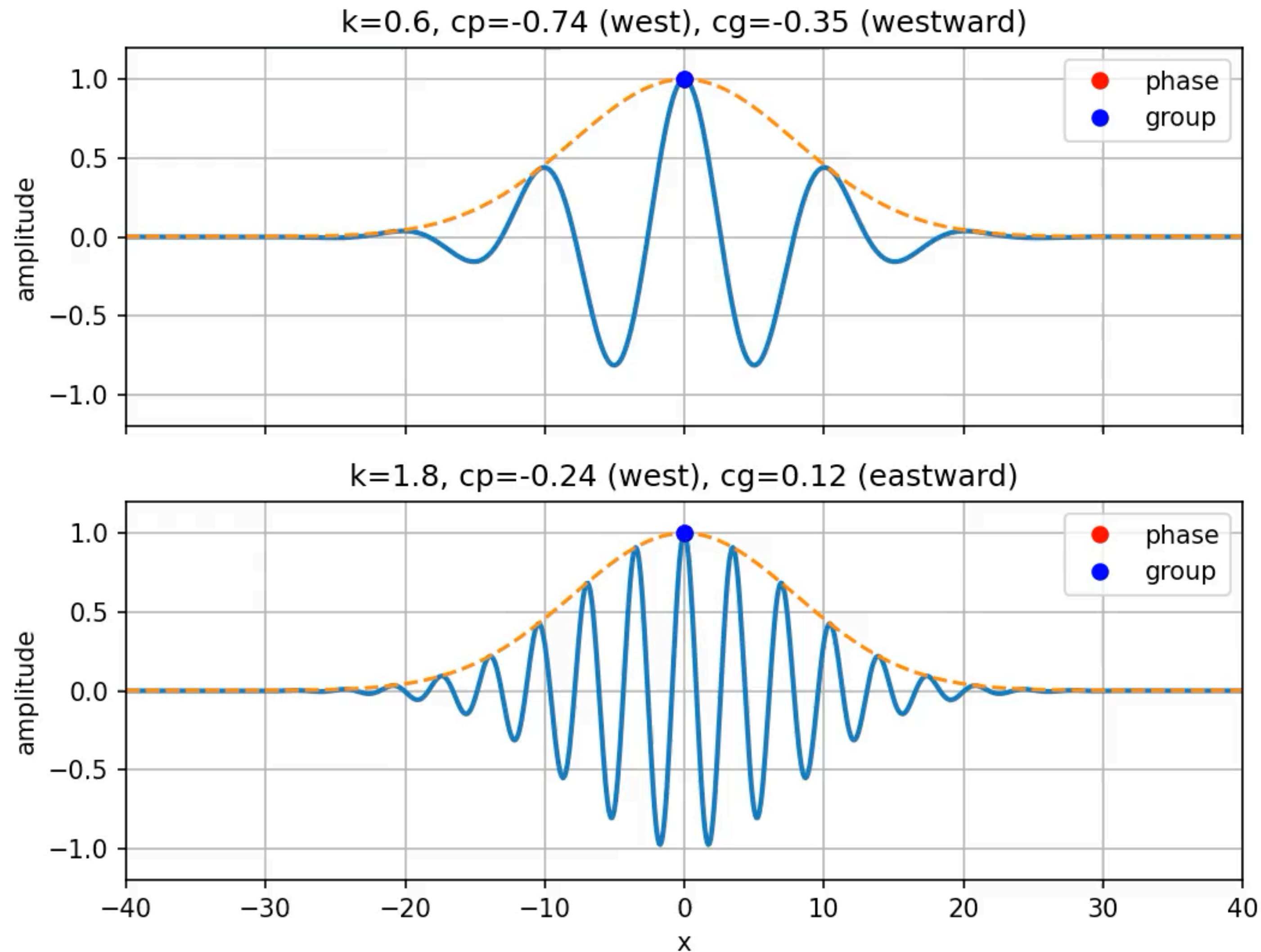


Short Rossby waves: eastward group & westward phase velocity

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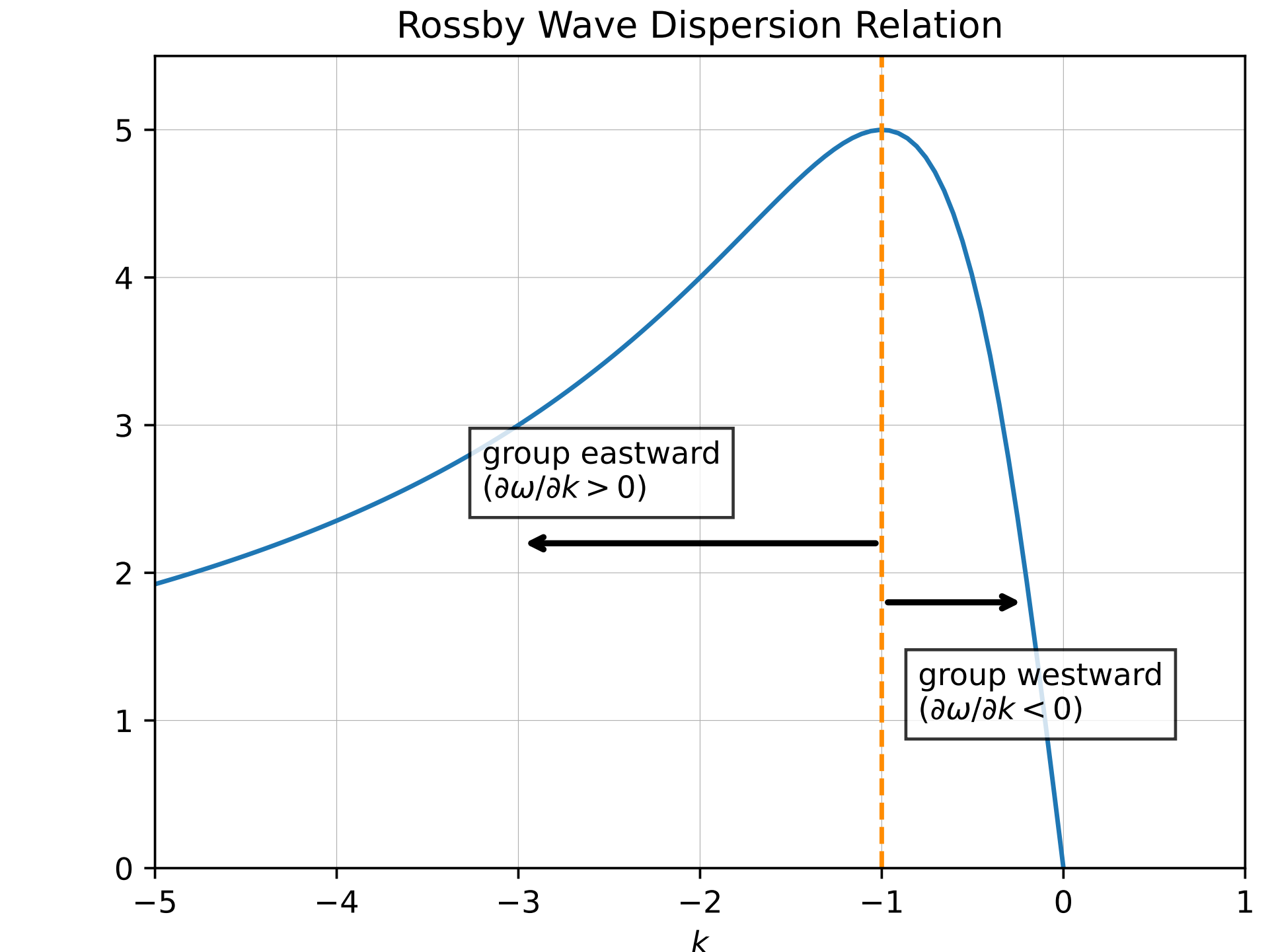
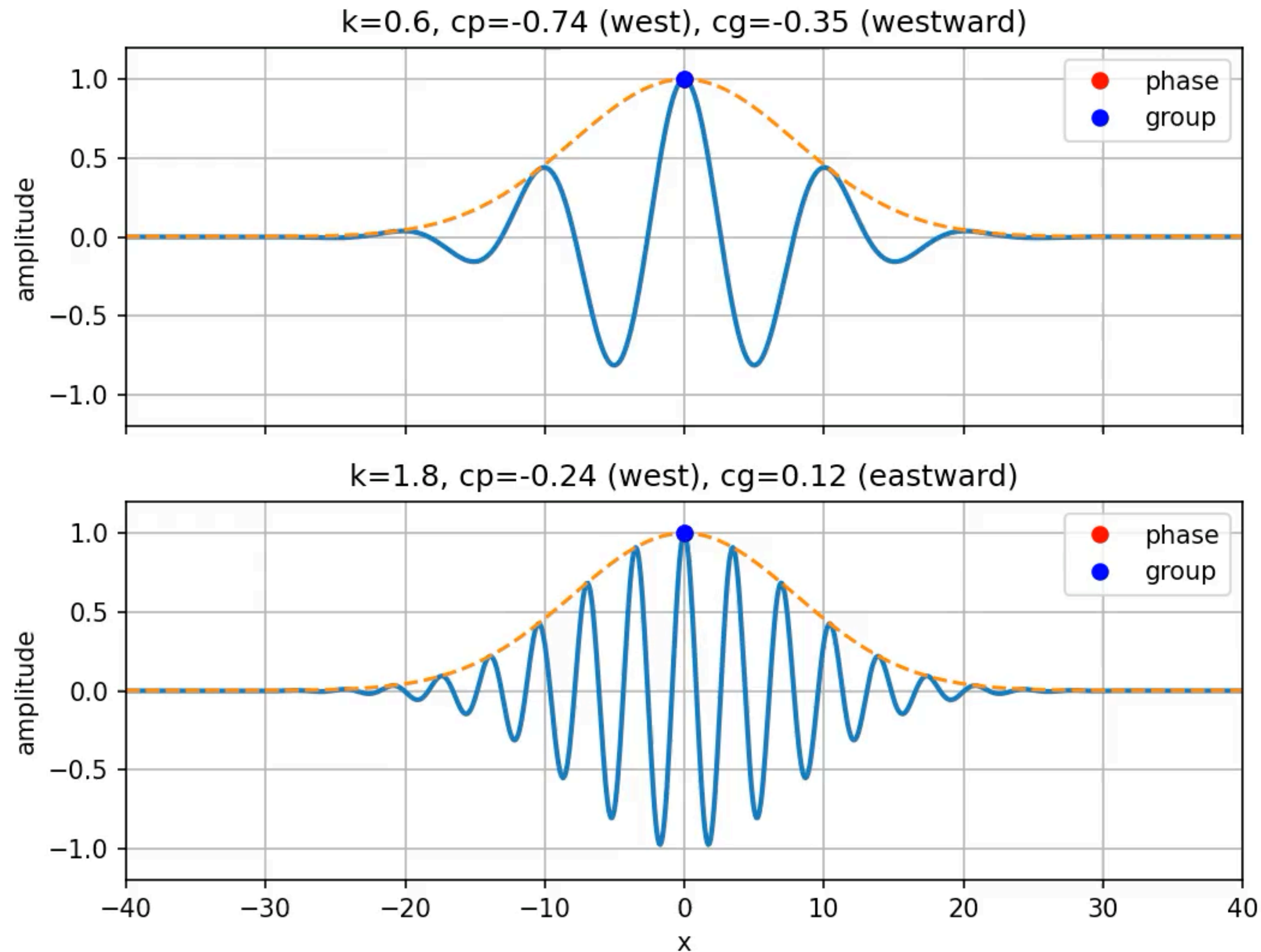
Rossby waves: group vs phase velocity



Dispersion relation: $\omega = -\frac{\beta k}{(k^2 + l^2)^2}$

Group propagation: $c_g^{(x)} = \beta \frac{k - l^2}{(k^2 + l^2)^2}$

Rossby waves: group vs phase velocity



Dispersion relation: $\omega = -\frac{\beta k}{(k^2 + l^2)^2}$

Group propagation: $c_g^{(x)} = \beta \frac{k - l^2}{(k^2 + l^2)^2}$

notes

6 Sverdrup balance

Angular momentum conservation & wind-driven ocean circulation:

$$\text{Angular momentum: } \mathbf{L} = m\mathbf{r} \times \mathbf{v} = I\boldsymbol{\omega}$$

Moment of inertia:

$$I_P = \sum_{i=1}^N m_i r_i^2$$

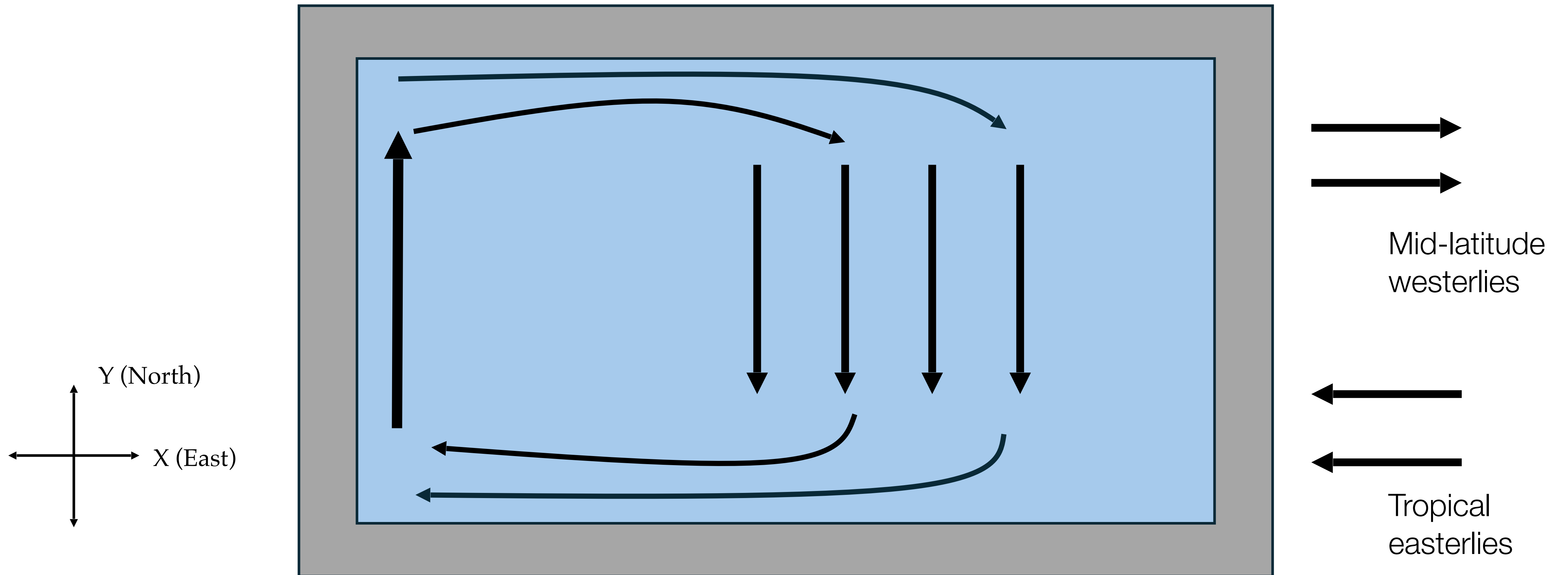
Vortex stretching leads to a smaller moment of inertia & therefore to a faster rotation $\boldsymbol{\omega}$

In the ocean, vorticity is planetary plus relative

$$\text{vorticity} = 2\Omega \sin \theta + \zeta$$

relative vorticity is negligible, hence poleward motion in response to stretching (upward Ekman pumping), and equatorward motion in response to compression (downward Ekman pumping)

Sverdrup Balance

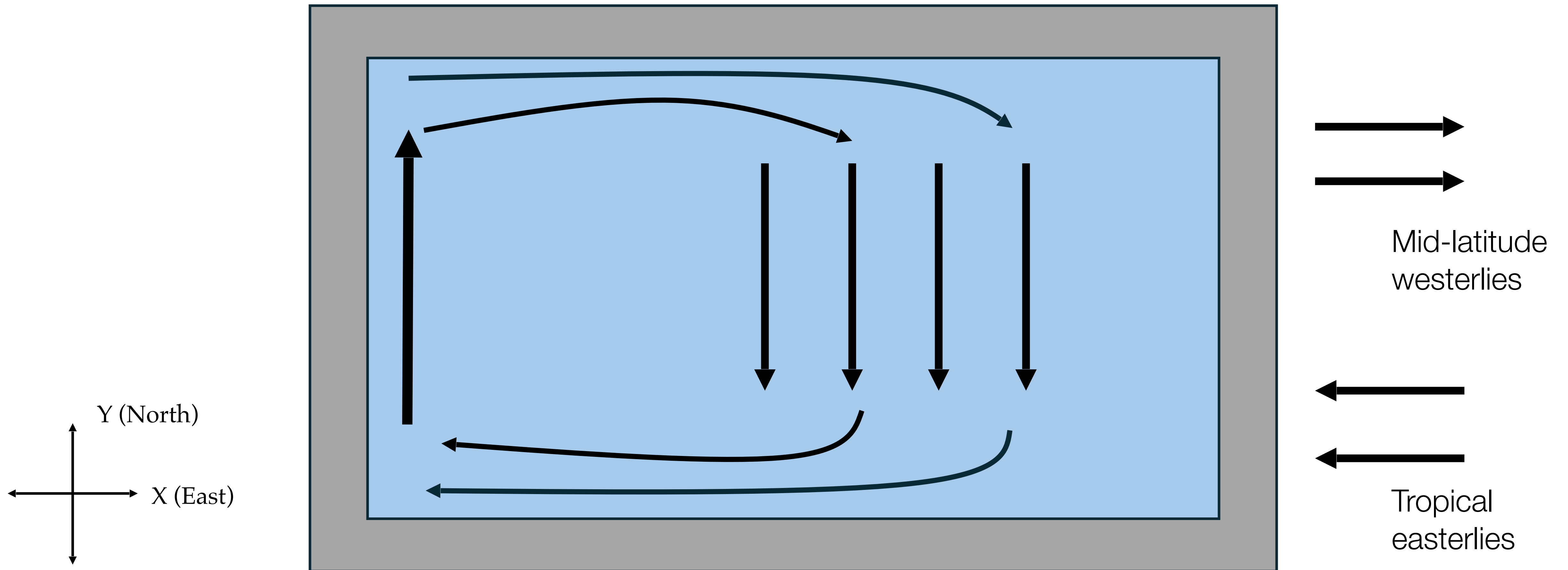


Schematic diagram based on <http://weatherclimatelab.mit.edu/wp-content/uploads/2017/07/chap10.pdf>

We might be tempted to think that trade winds blow eastward so push the ocean westward and the Coriolis turns it into a gyre

Kirstin Koepnick, 2026

Sverdrup Balance

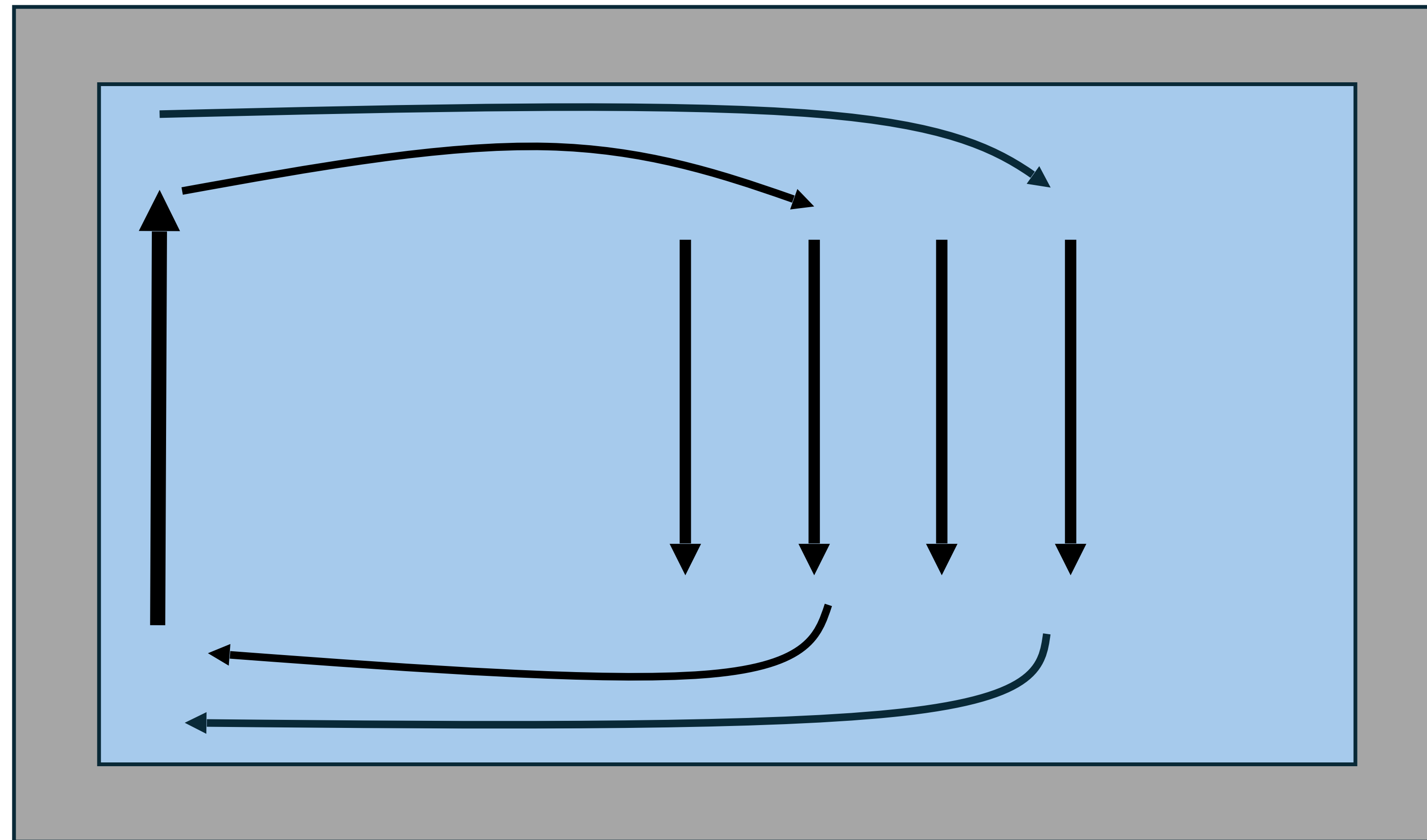
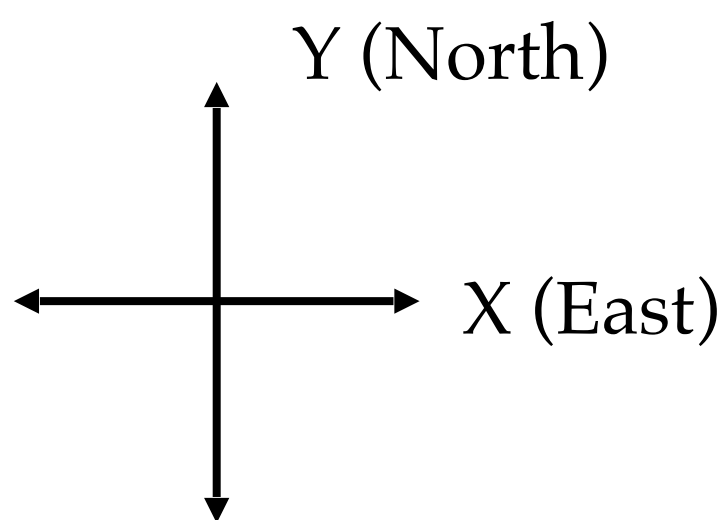


Schematic diagram based on <http://weatherclimatelab.mit.edu/wp-content/uploads/2017/07/chap10.pdf>

~~We might be tempted to think that trade winds blow eastward so push the ocean westward and the Coriolis turns it into a gyre~~

Sverdrup Balance

Winds really only directly move water horizontally in the upper 50 m of the ocean & these gyres are ~1000 m deep!

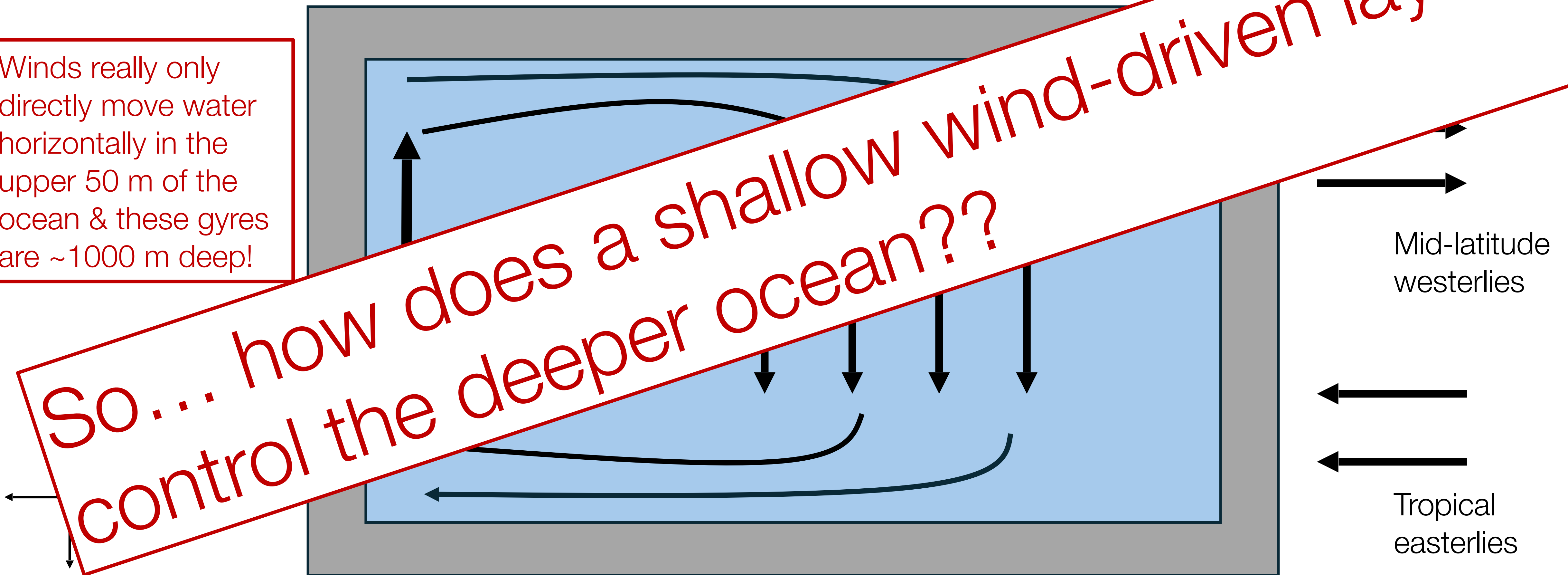


Schematic diagram based on <http://weatherclimatelab.mit.edu/wp-content/uploads/2017/07/chap10.pdf>

~~We might be tempted to think that trade winds blow eastward so push the ocean westward and the Coriolis turns it into a gyre.~~

Sverdrup Balance

Winds really only directly move water horizontally in the upper 50 m of the ocean & these gyres are ~1000 m deep!

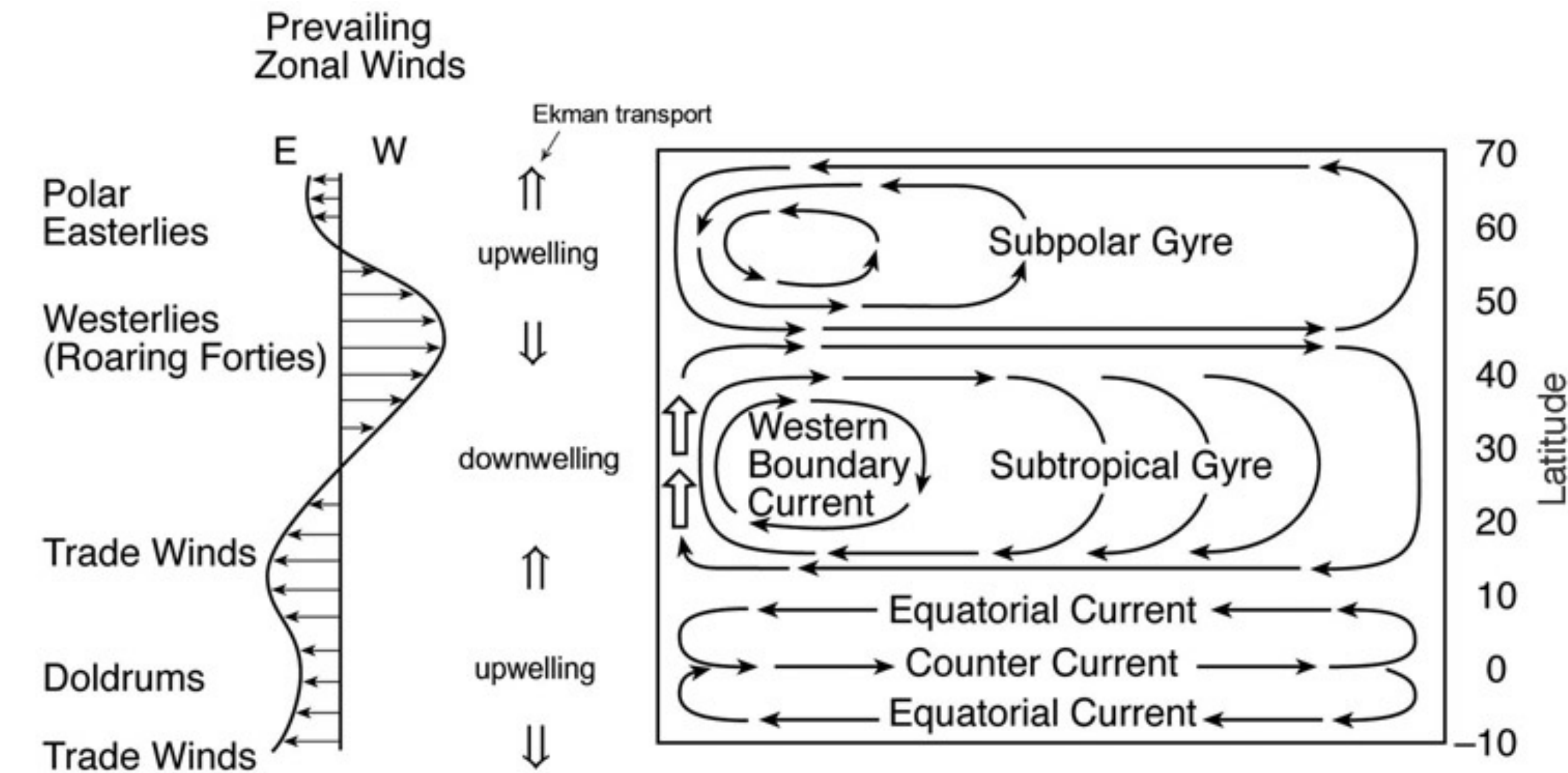


Schematic diagram based on <http://weatherclimatelab.mit.edu/wp-content/uploads/2017/07/chap10.pdf>

~~We might be tempted to think that trade winds blow eastward so push the ocean westward and the Coriolis turns it into a gyre~~

Sverdrup flow:

wind-driven ocean flow away from the western boundary



<http://gyre.umeoce.maine.edu/physicalocean/Tomczak/regoc/pdffiles/colour/single/04P-Ekman.pdf>

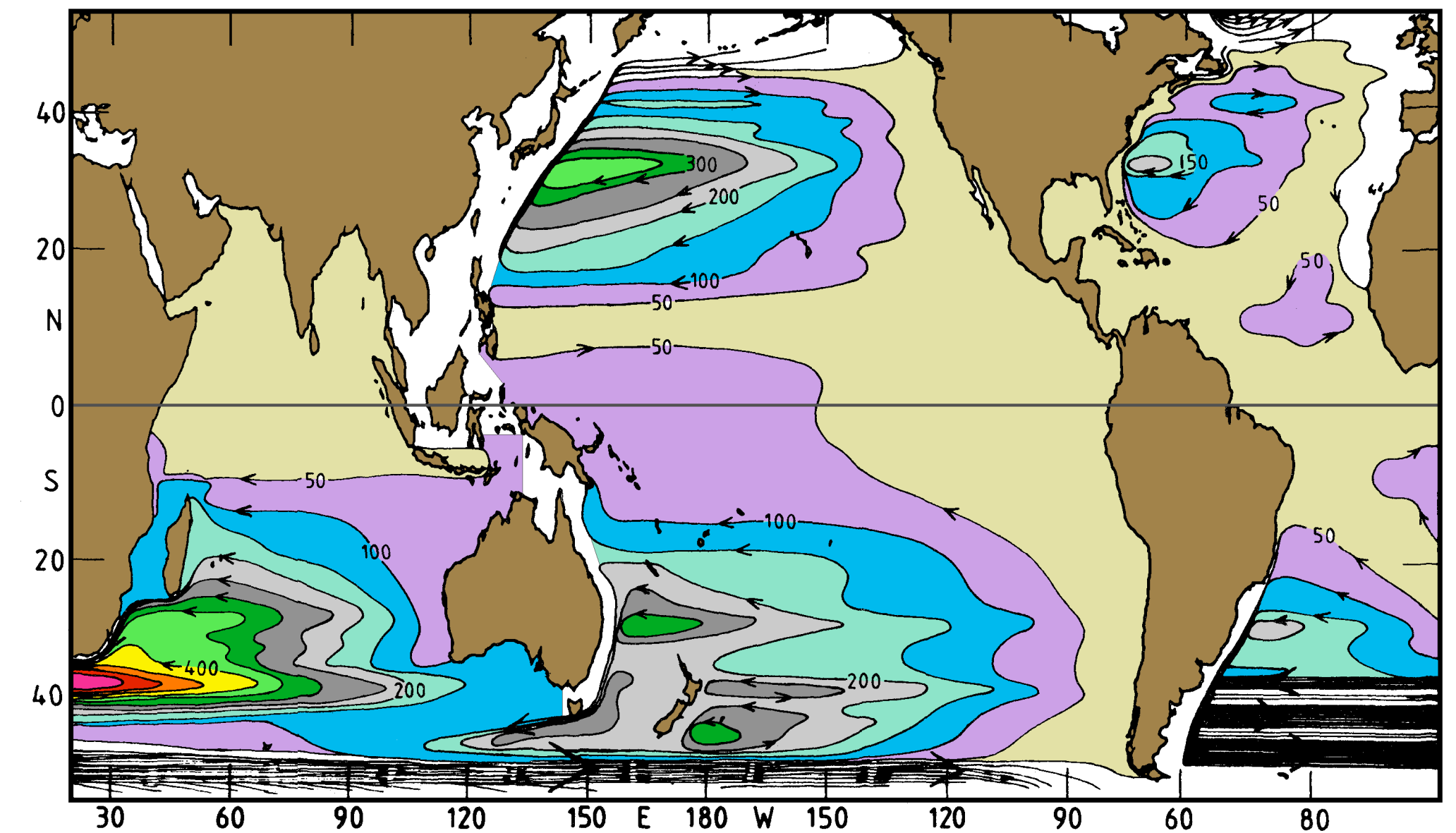


Fig. 4.4. Depth-integrated steric height P , calculated from the right-hand side of the Sverdrup relation (eqn (4.5)), using the data from Hellerman and Rosenstein (1983). Units are 10^1 m^2 . For details of the integration procedure see Godfrey (1989).

Schematic

Sverdrup flow from
observed wind stress curl

<http://weatherclimatelab.mit.edu/wp-content/uploads/2017/07/chap10.pdf>

notes

7 Wind driven circulation: Boundary currents

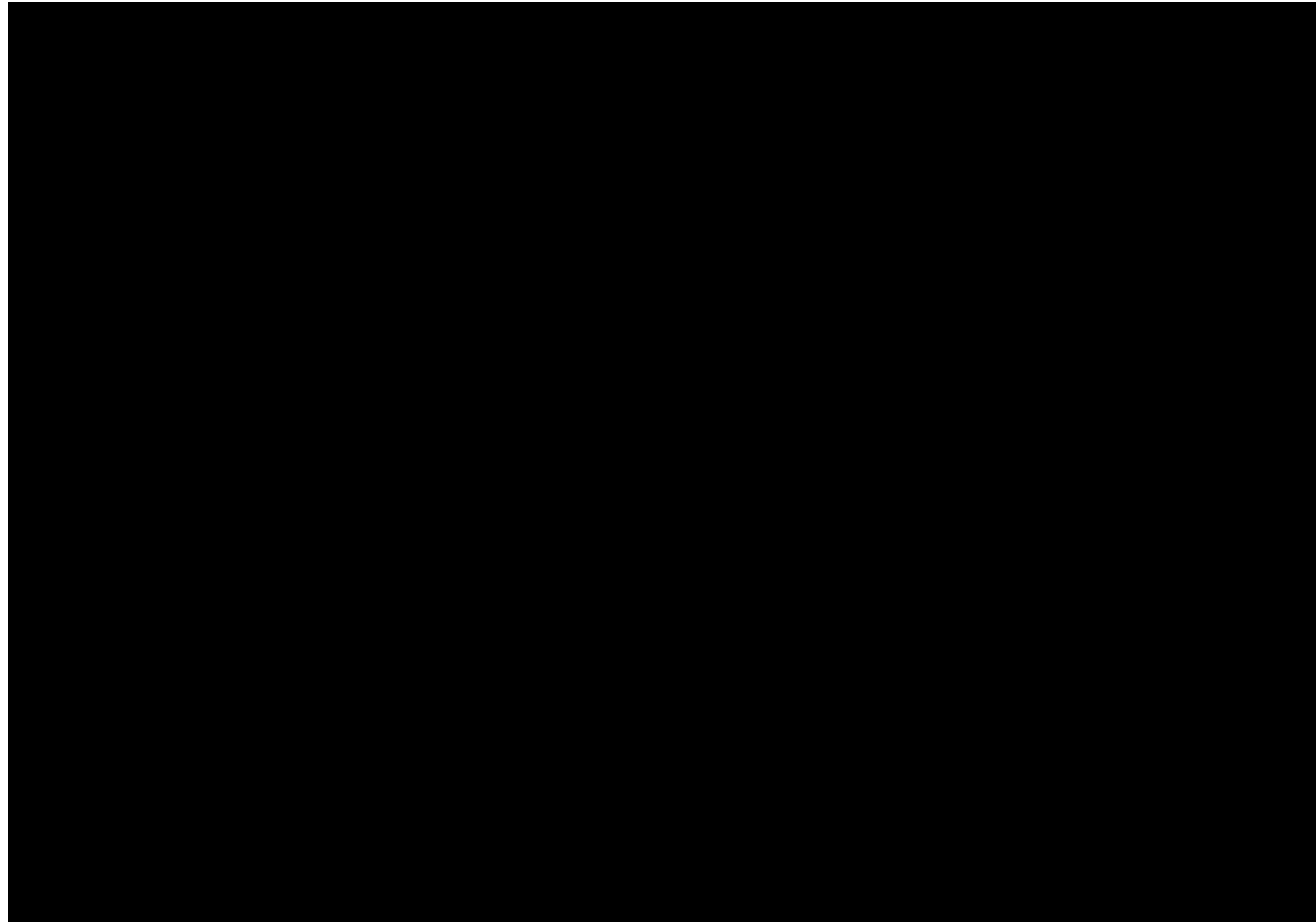
notes

8 Heuristic explanations of western boundary currents based on a vorticity

argument:

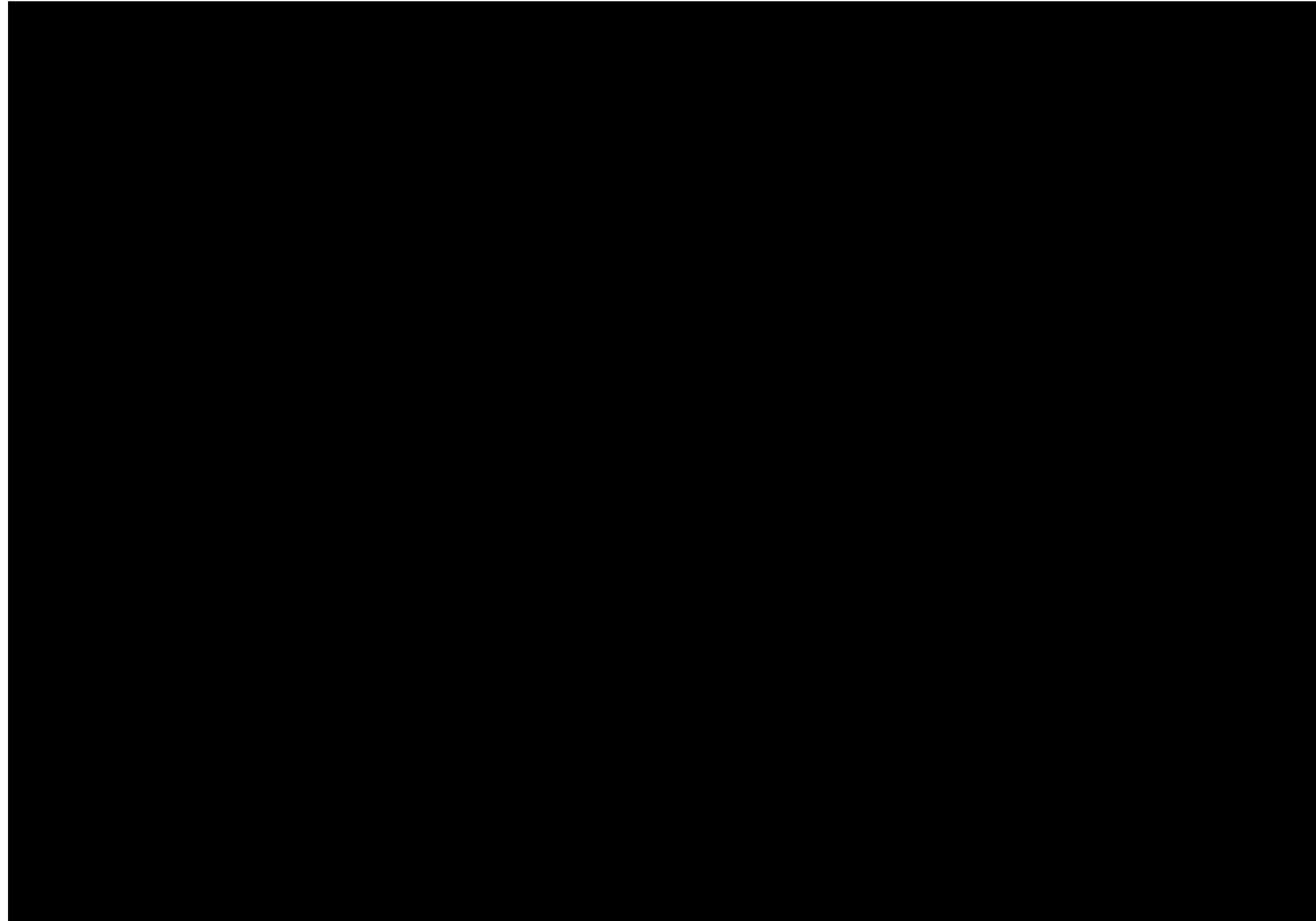
- 1) vorticity
- 2) Rossby waves

And now for another explanation



Make a list of the errors you notice!

And now for another explanation



Make a list of the errors you notice!

9 Abyssal circulation, Stommel-Arons

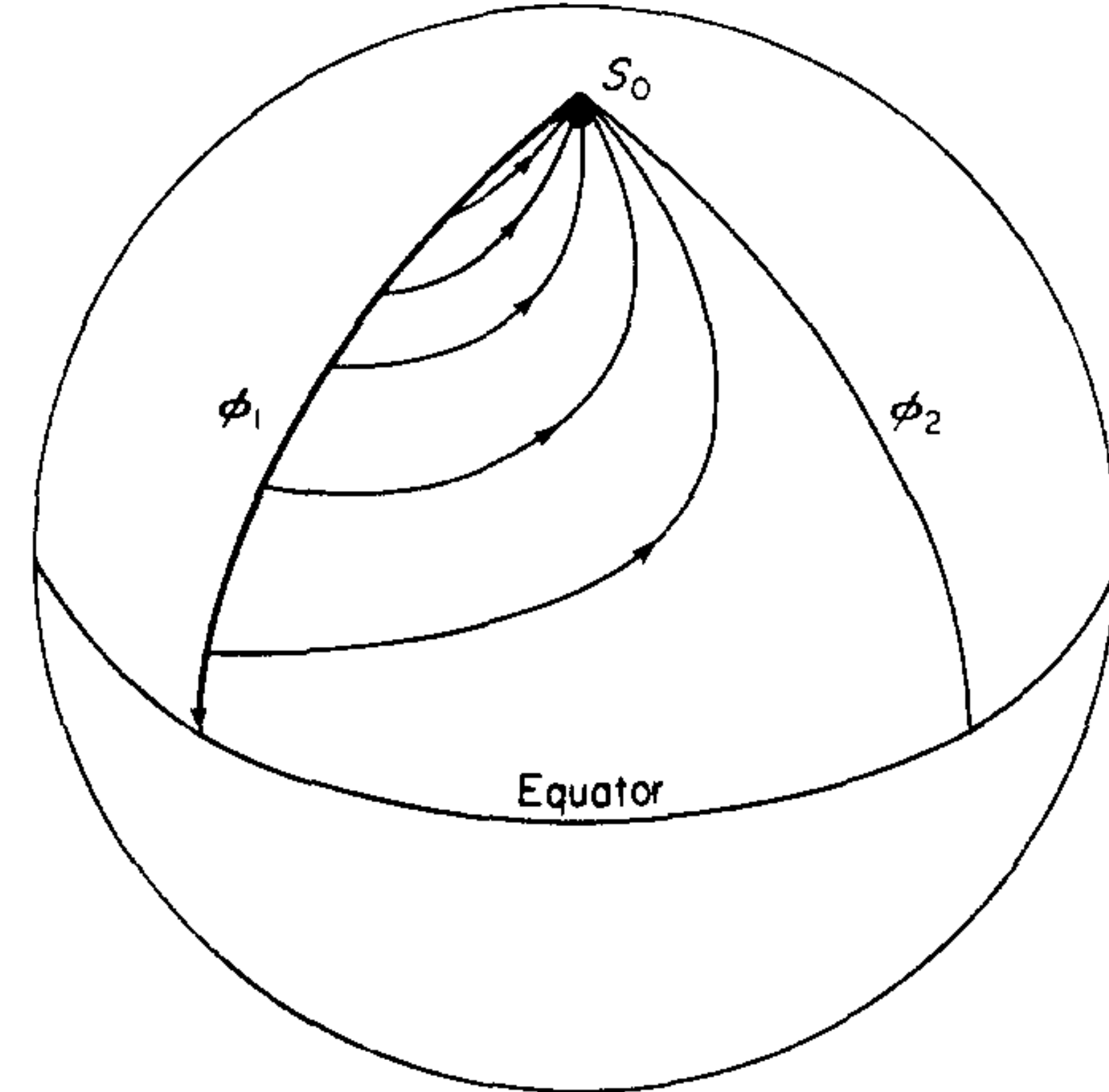
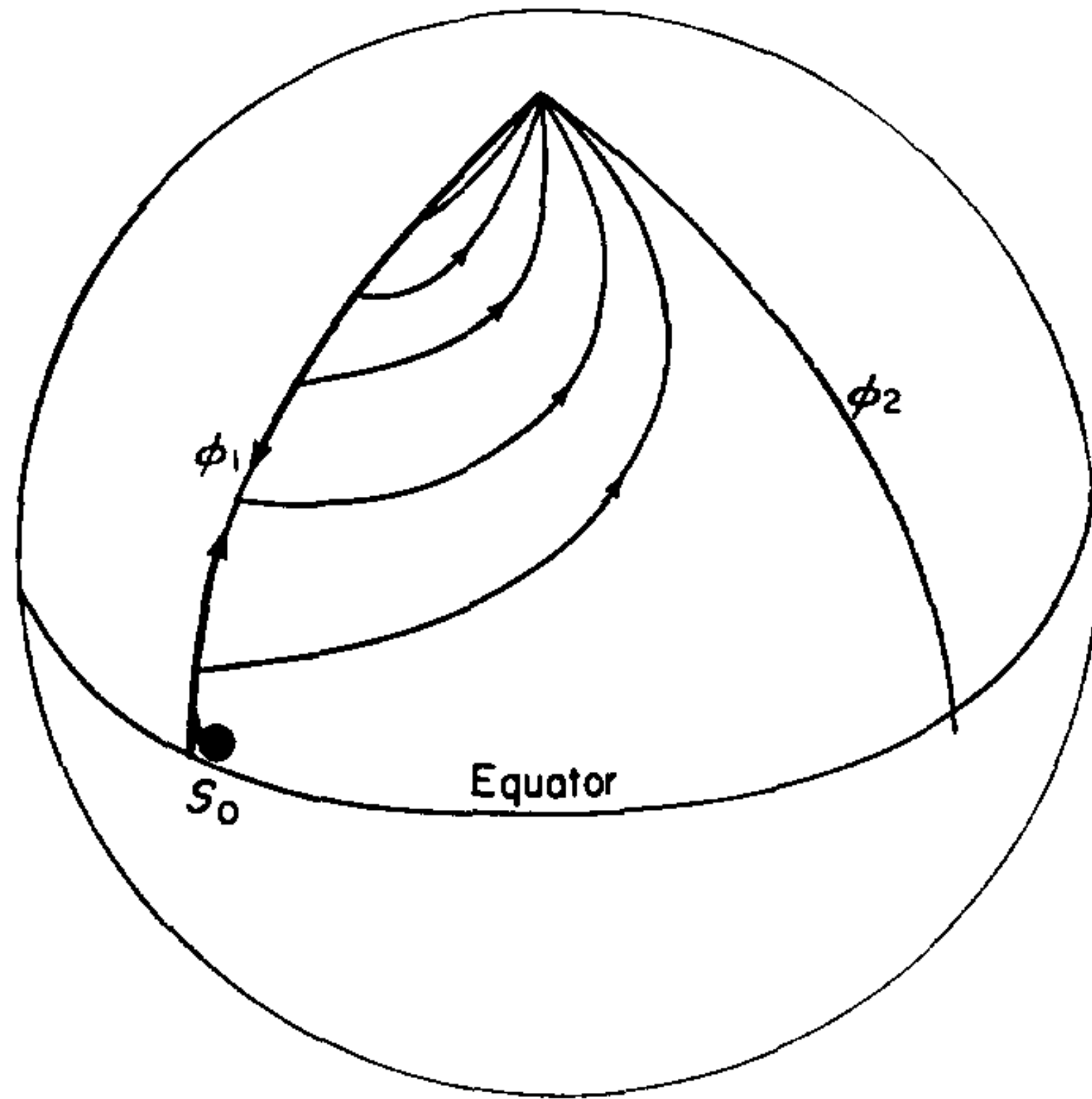


Fig. 8. Circulation pattern in meridionally bounded ocean with concentrated source S_0 (fed by western boundary current from below the equator) and a uniformly distributed sink Q_0 such that $S_0 = Q_0 a^2 (\phi_2 - \phi_1)$

Fig. 6. Circulation pattern in meridionally bounded ocean with concentrated source S_0 at north pole and a uniformly distributed sink Q_0 such that $S_0 = Q_0 a^2 (\phi_2 - \phi_1)$

Deep Western Boundary Current

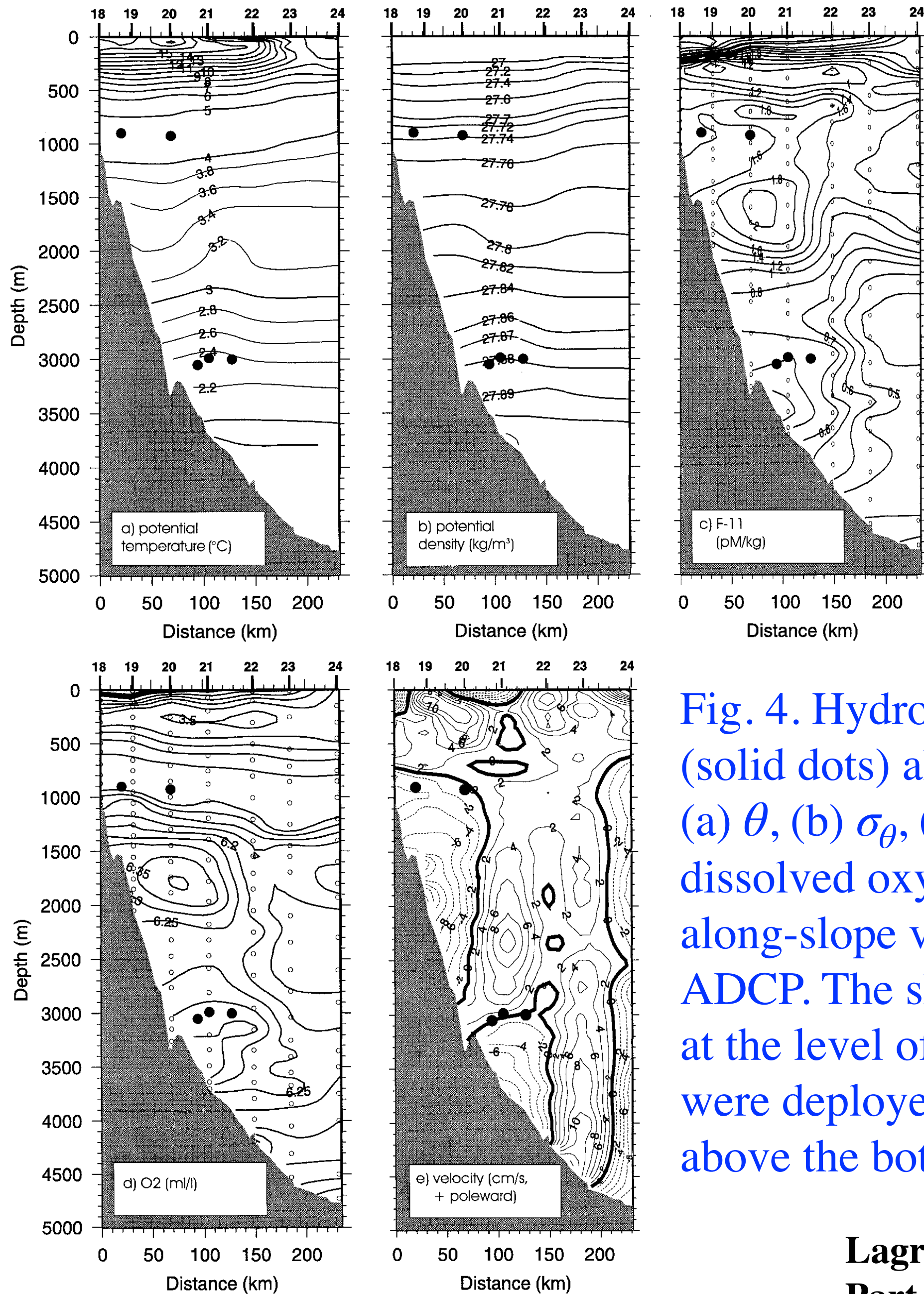


Fig. 4. Hydrography & float launch sites (solid dots) along BOUNCE I Section 3: (a) θ , (b) σ_θ , (c) CFC (F-11), (d) dissolved oxygen, and (e) absolute along-slope velocity from lowered ADCP. The shallow floats were launched at the level of ULSW, and the deep floats were deployed several hundred meters above the bottom in OW.

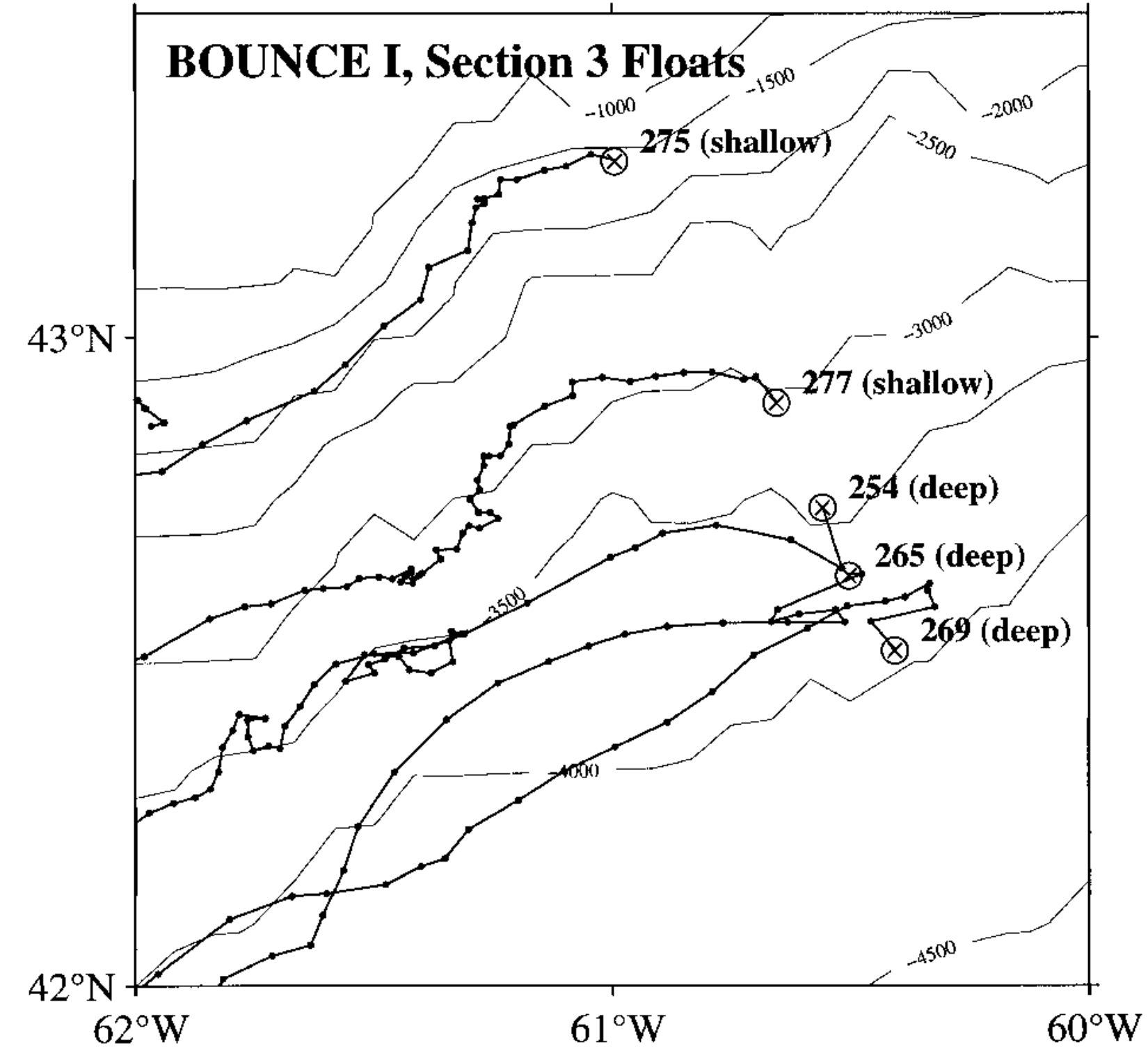


FIG. 5. First part of tracks of five floats deployed along BOUNCE I Section 3, two shallow (275 and 277) and three deep (254, 265, and 269). Dots along tracks indicate daily positions. Launch locations of floats are indicated by circled x's. Bathymetric contours are every 500 m.

The End