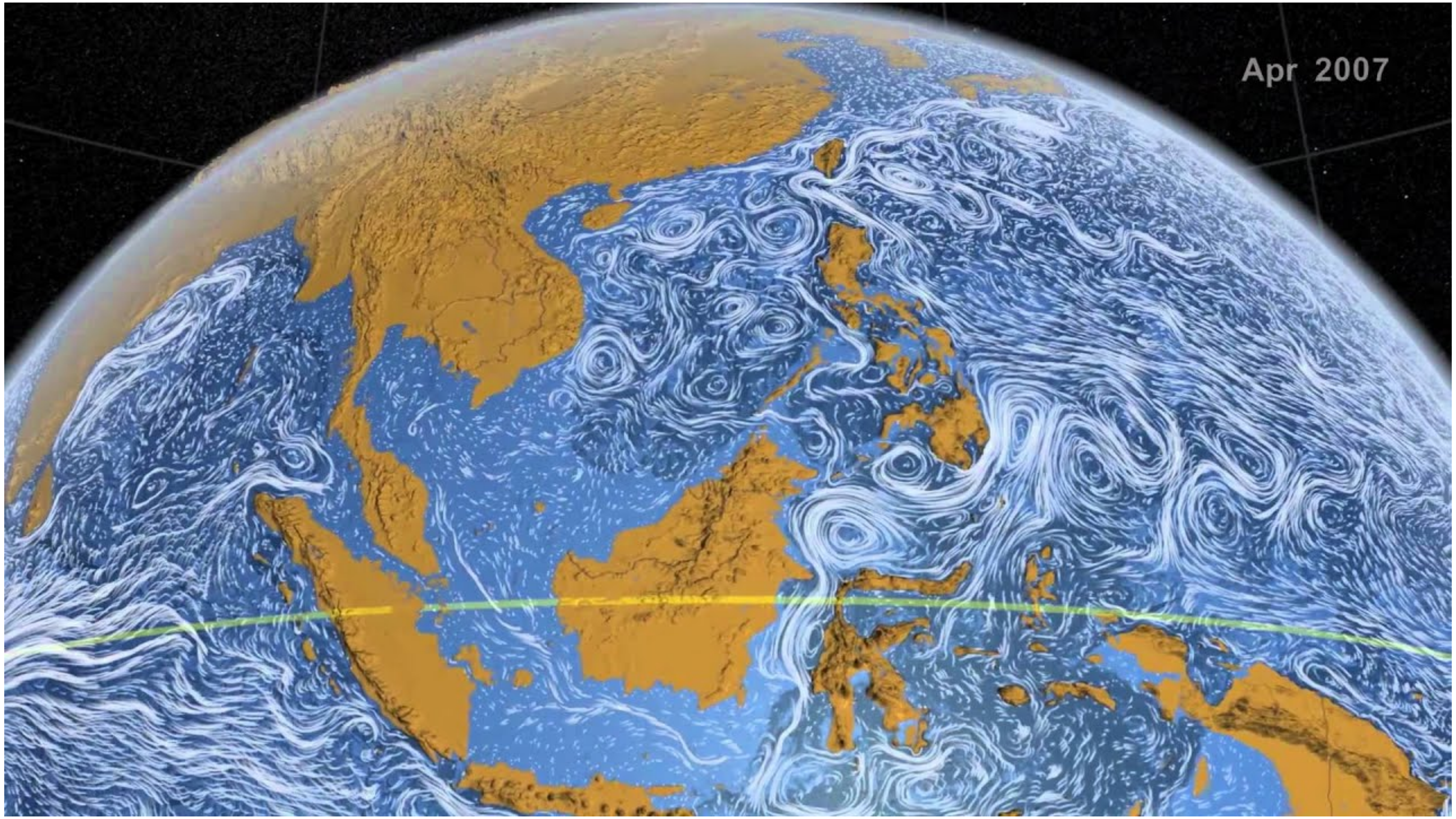
The wind driven ocean circulation

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

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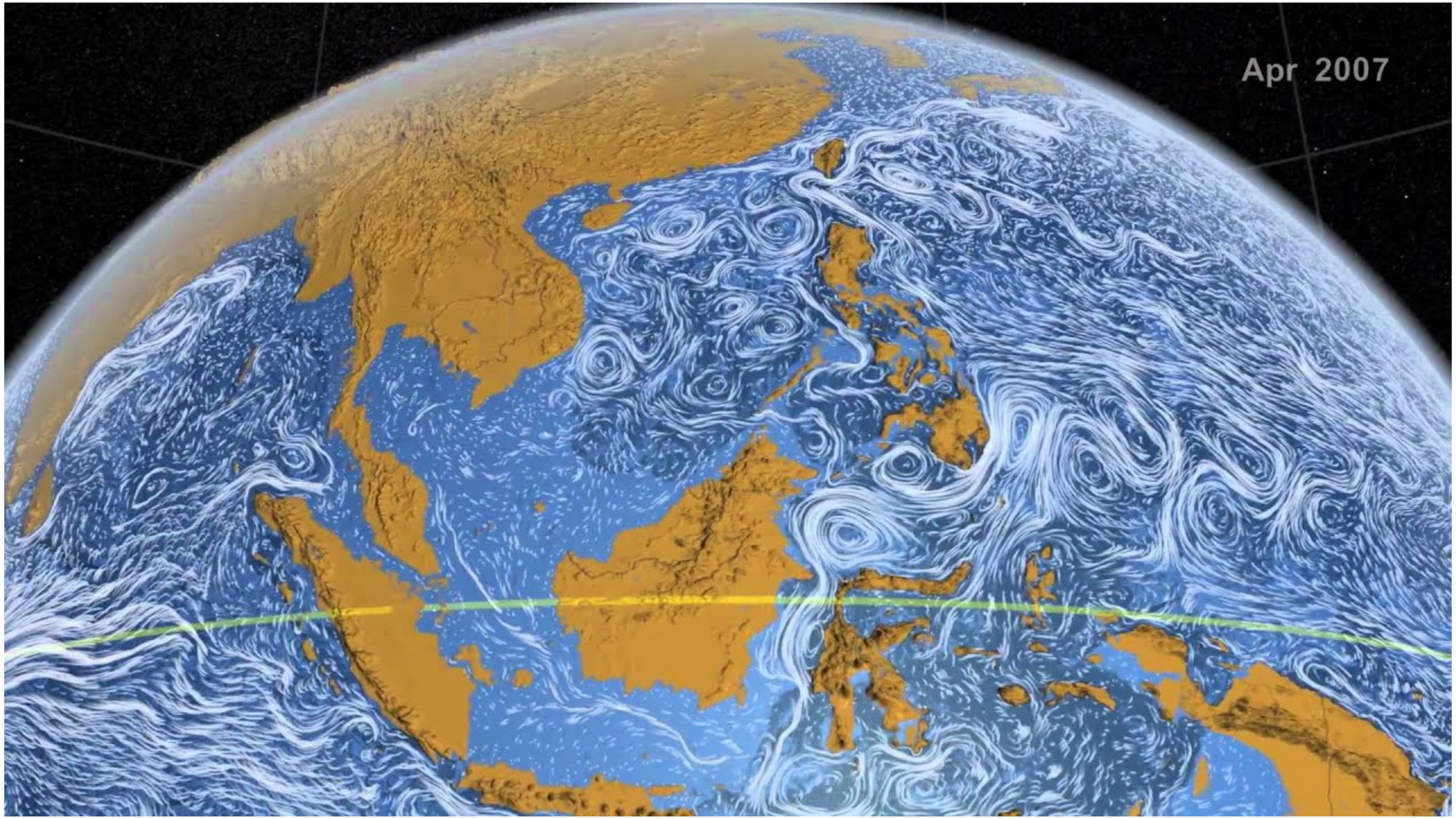

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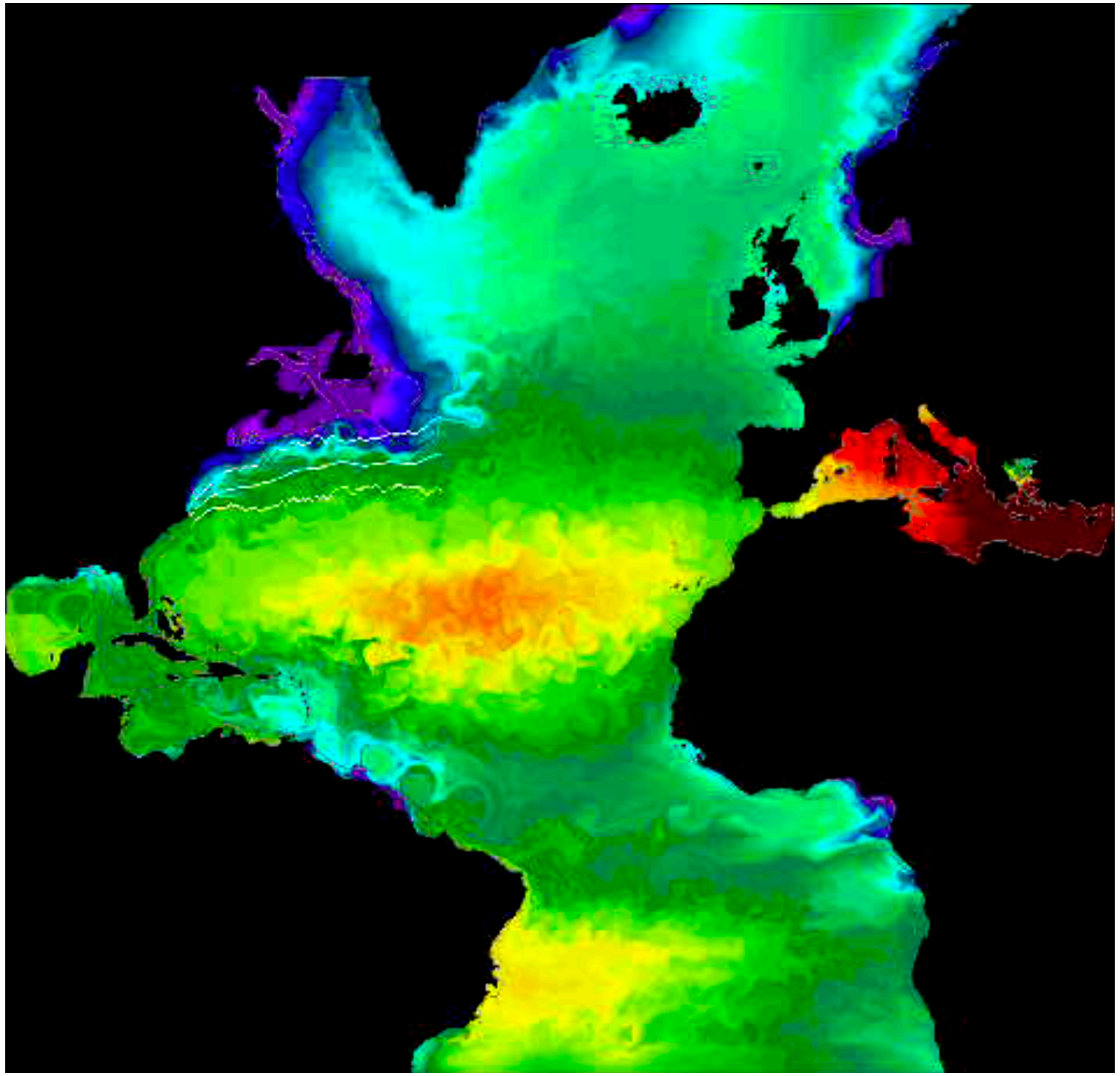
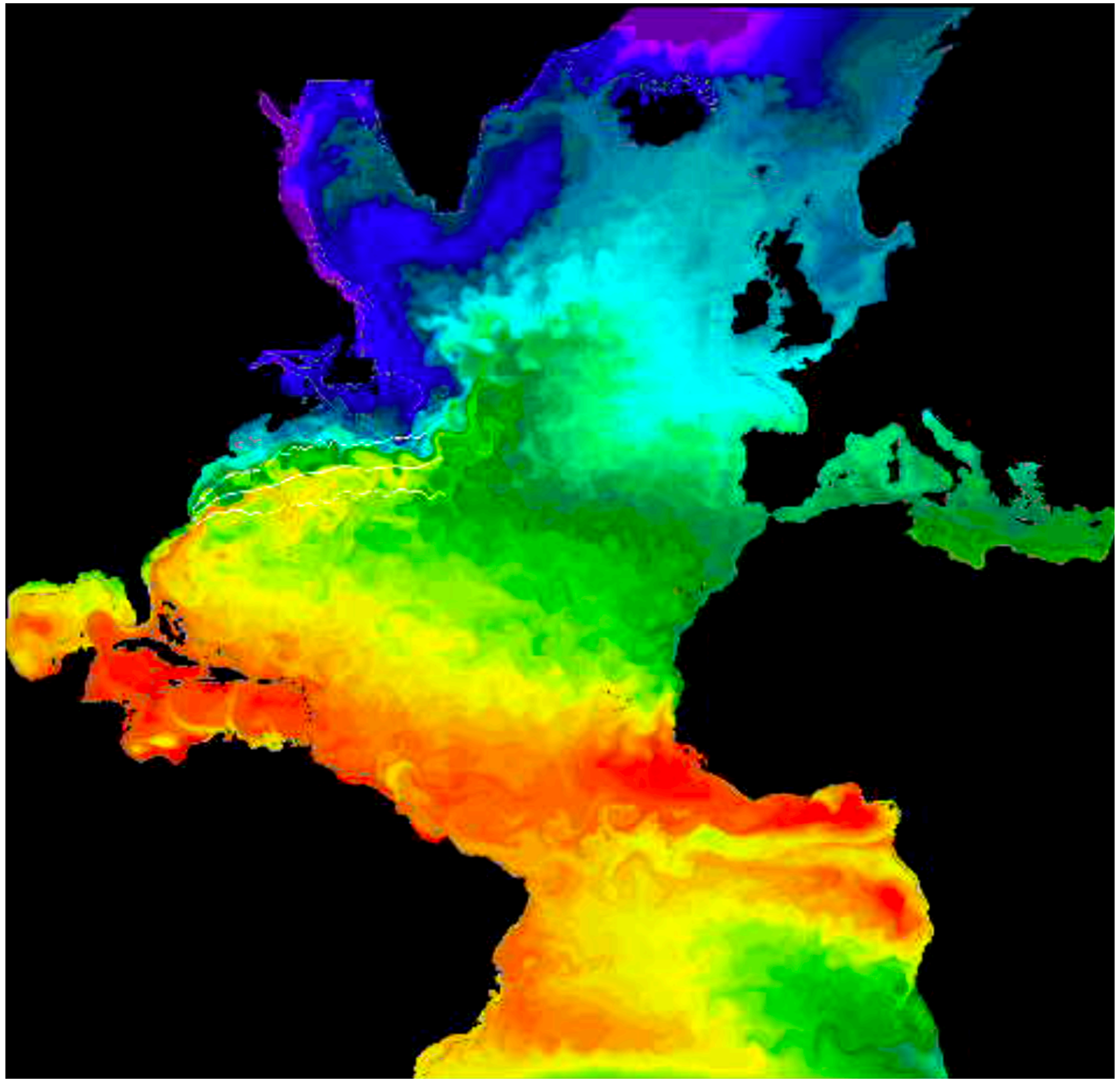


Salinity



Temperature

Animations from MICOM model

notes

1 Momentum equations for the wind-driven circulation, the beta plane
(miniquiz)

2 Vorticity, planetary vorticity
(miniquiz)

Angular momentum and ice skating

https://www.youtube.com/watch?v=FmnkQ2ytlO8

Angular momentum and ice skating

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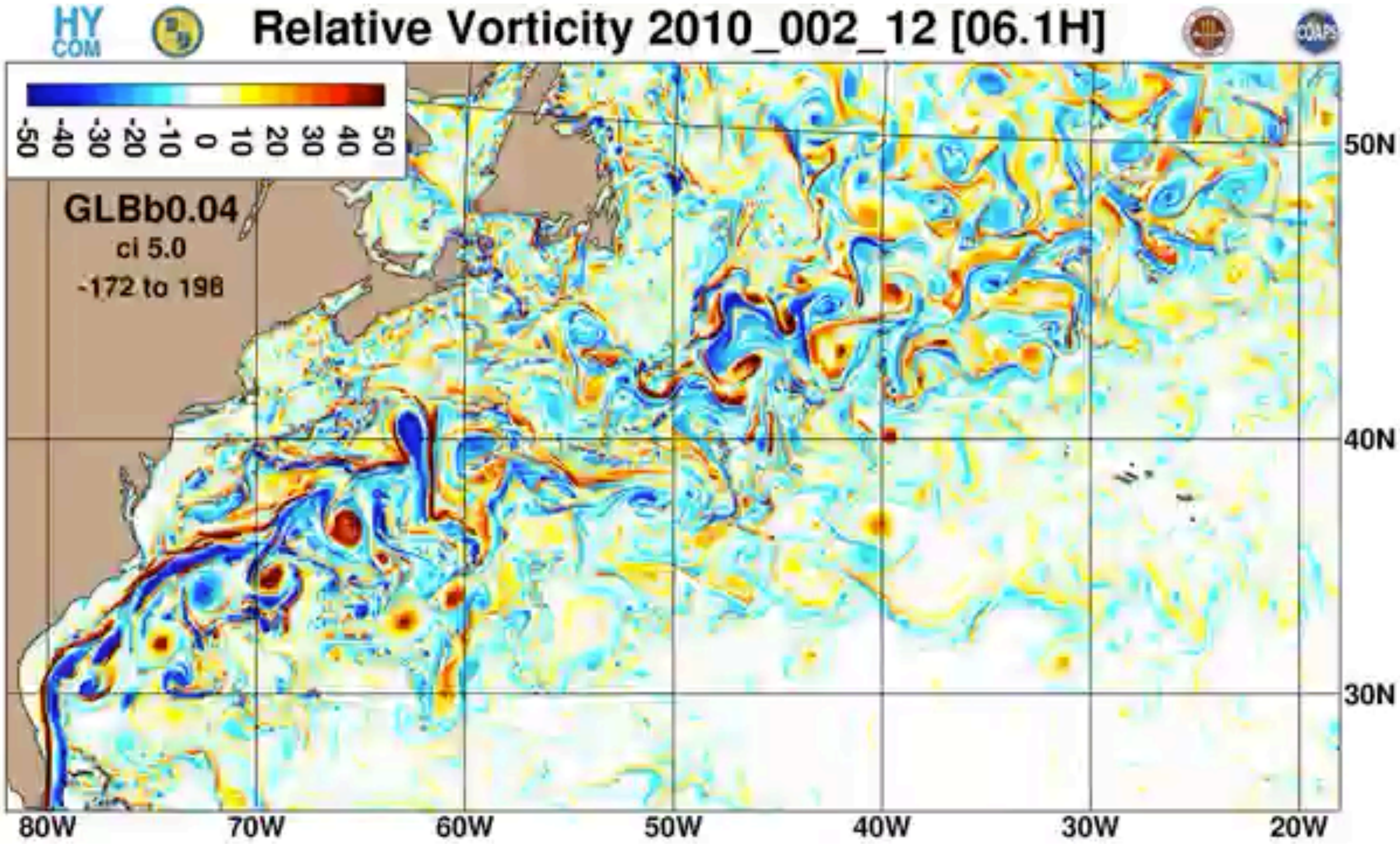
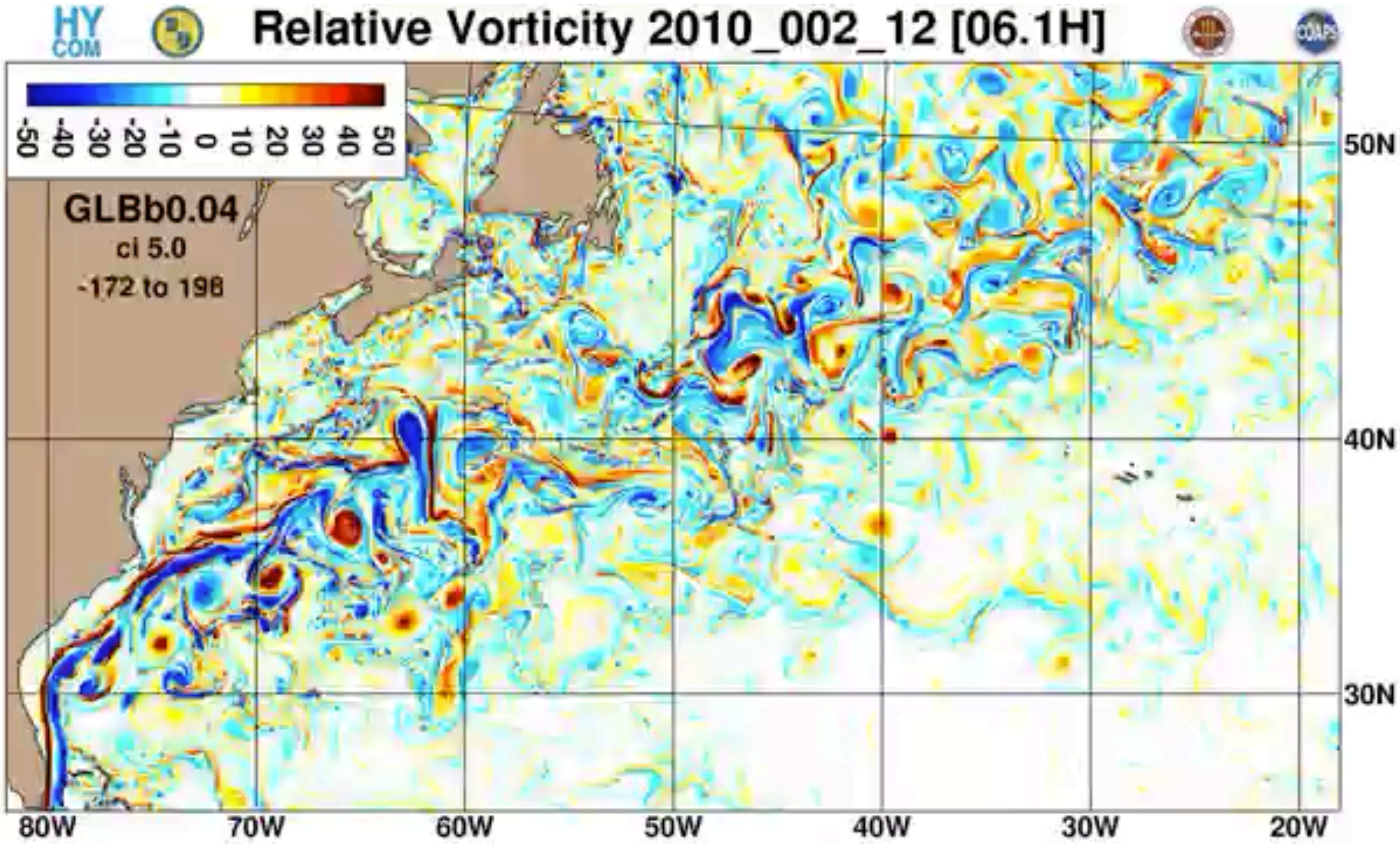
Vorticity in the North Atlantic



relative vorticity in HYCOM model

Vorticity in the North Atlantic



relative vorticity in HYCOM model

Wingtip vortices

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

https://www.boldmethod.com/blog/lists/2017/02/5-factors-that-affect-vortex-strength/

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“vortex cascading” from a drop of milk/ coffee

https://vimeo.com/103705452

“vortex cascading” from a drop of milk/ coffee

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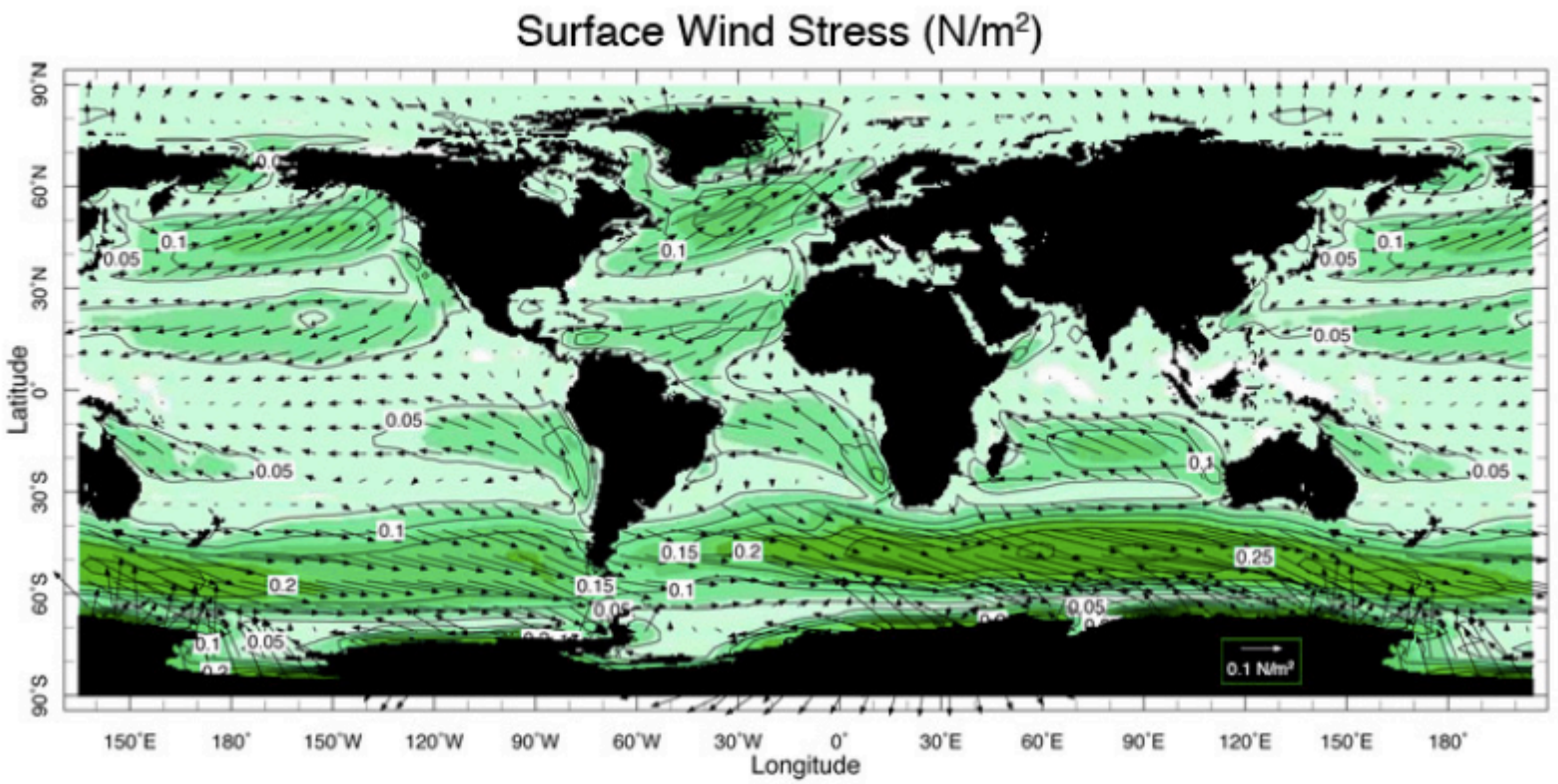
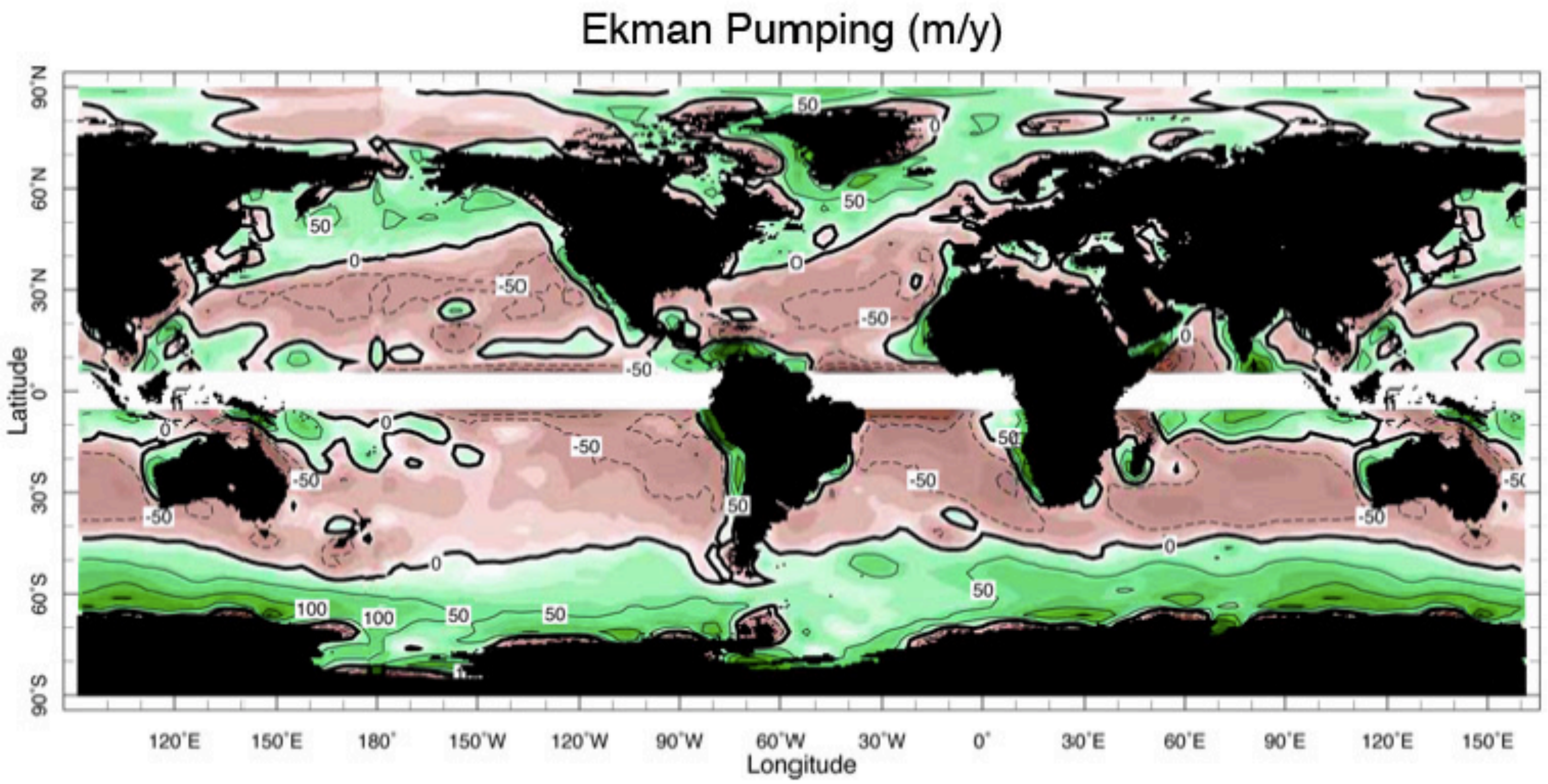
Visualizing vorticity

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

Global wind stress and wind curl





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 $\mathrm{N\,m^{-2}}$. Stresses reach values of 0.1 to 0.2 $\mathrm{N\,m^{-2}}$ under the middle-latitude westerlies, and are particularly strong in the southern hemisphere. The arrow is a vector of length 0.1 $\mathrm{N\,m^{-2}}$. 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 ($\mathrm{m\,y^{-1}}$) 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 $f \longrightarrow 0$ 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.

notes

3 vorticity equation

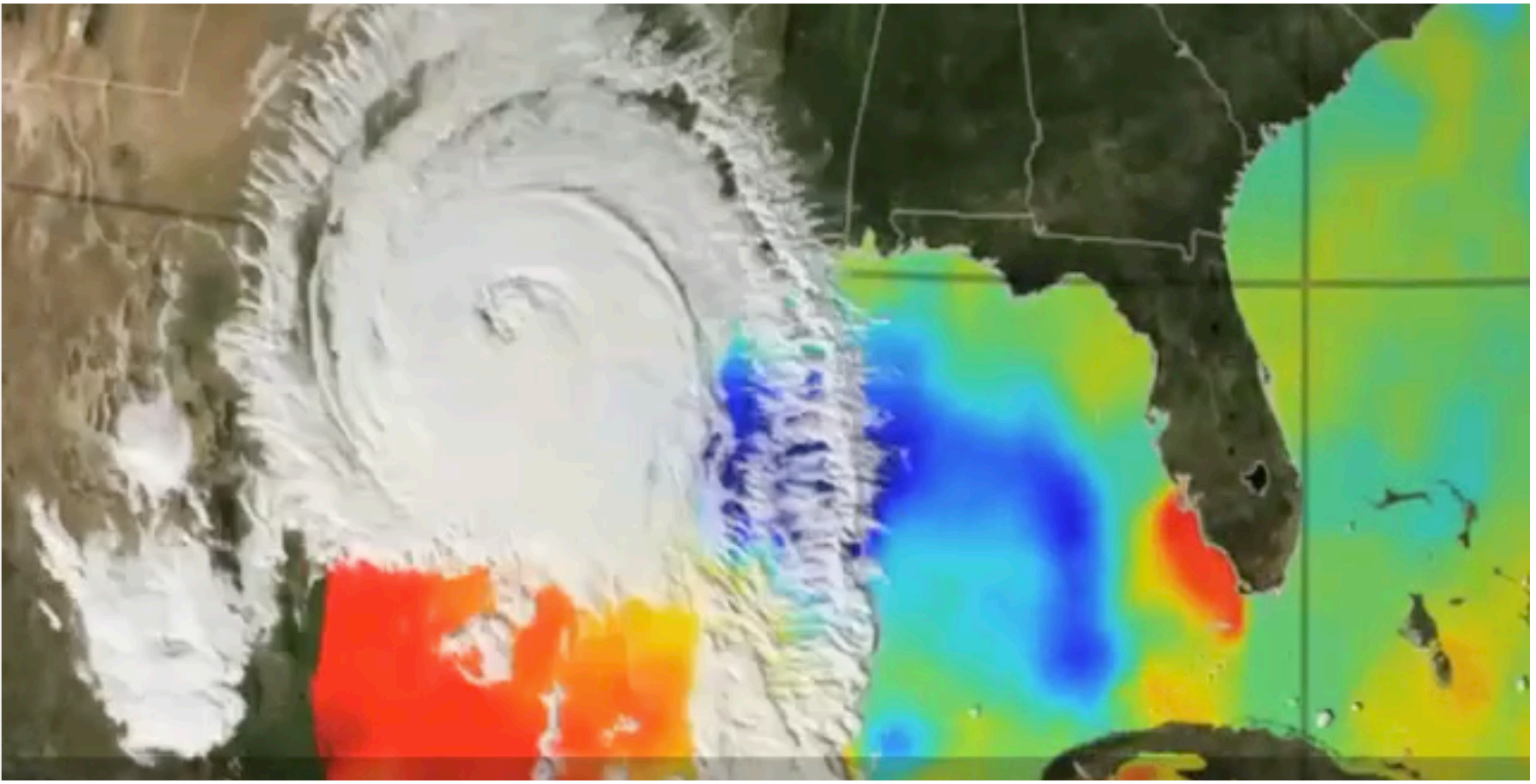
Announcing!

ζ vs ξ

notes

4 vortex decay

Hurricanes weakening over land: vortex decay



https://oceantoday.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

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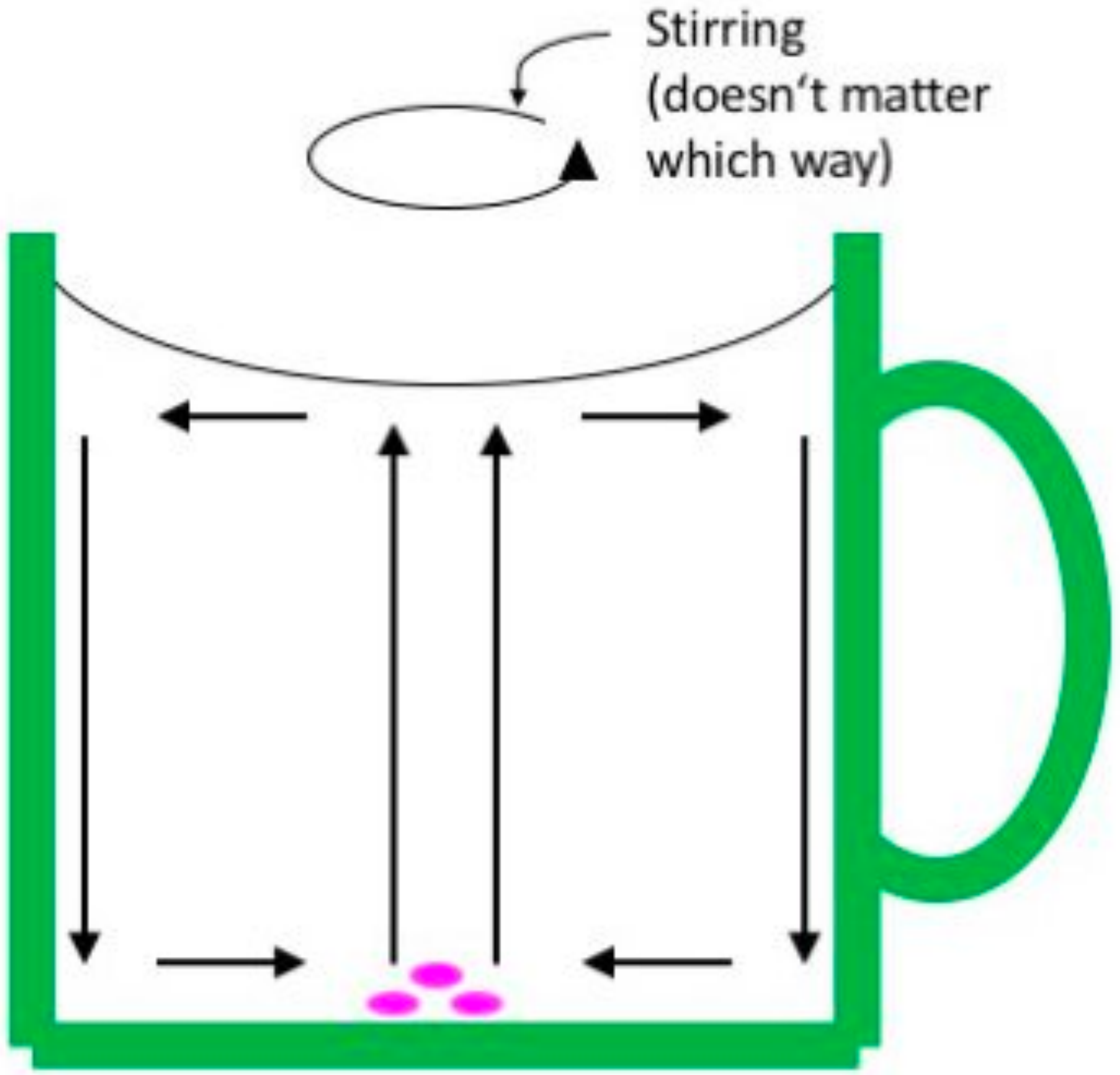
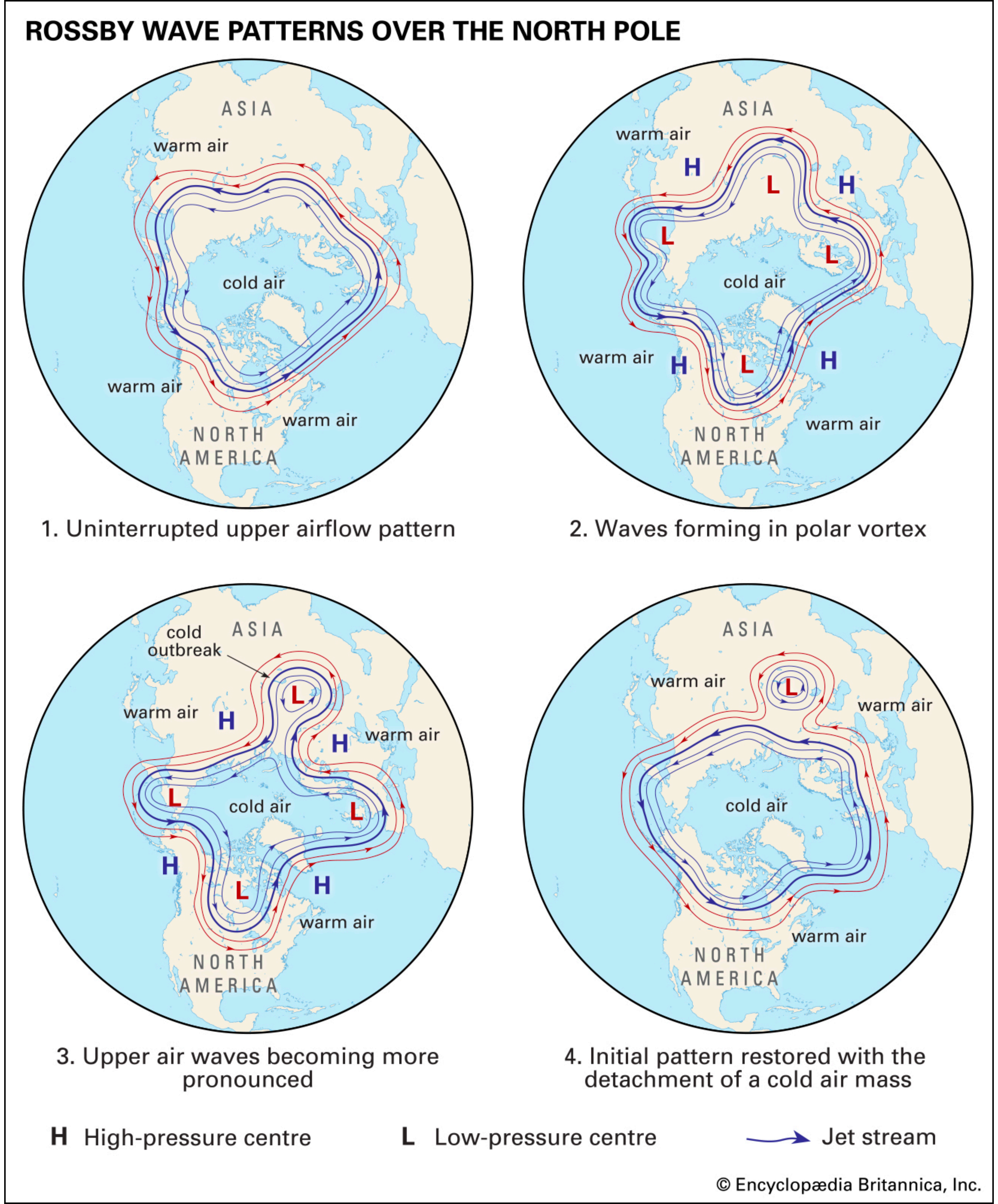


https://mirjamglessmer.com/2019/08/11/demonstrating-ekman-layers-in-a-rotating-tank-high-pressure-and-low-pressure-systems/

notes

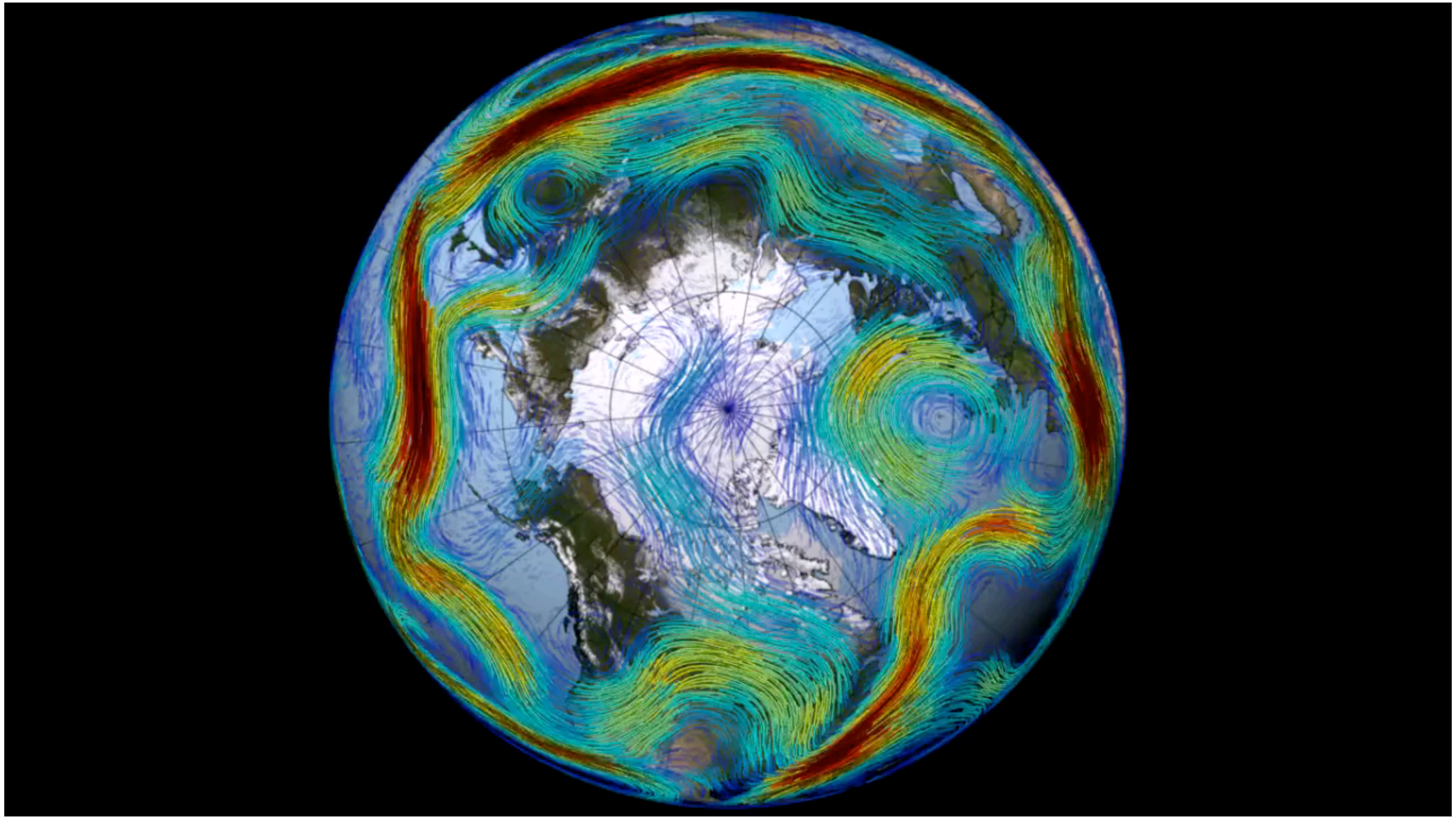
5 Rossby waves



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

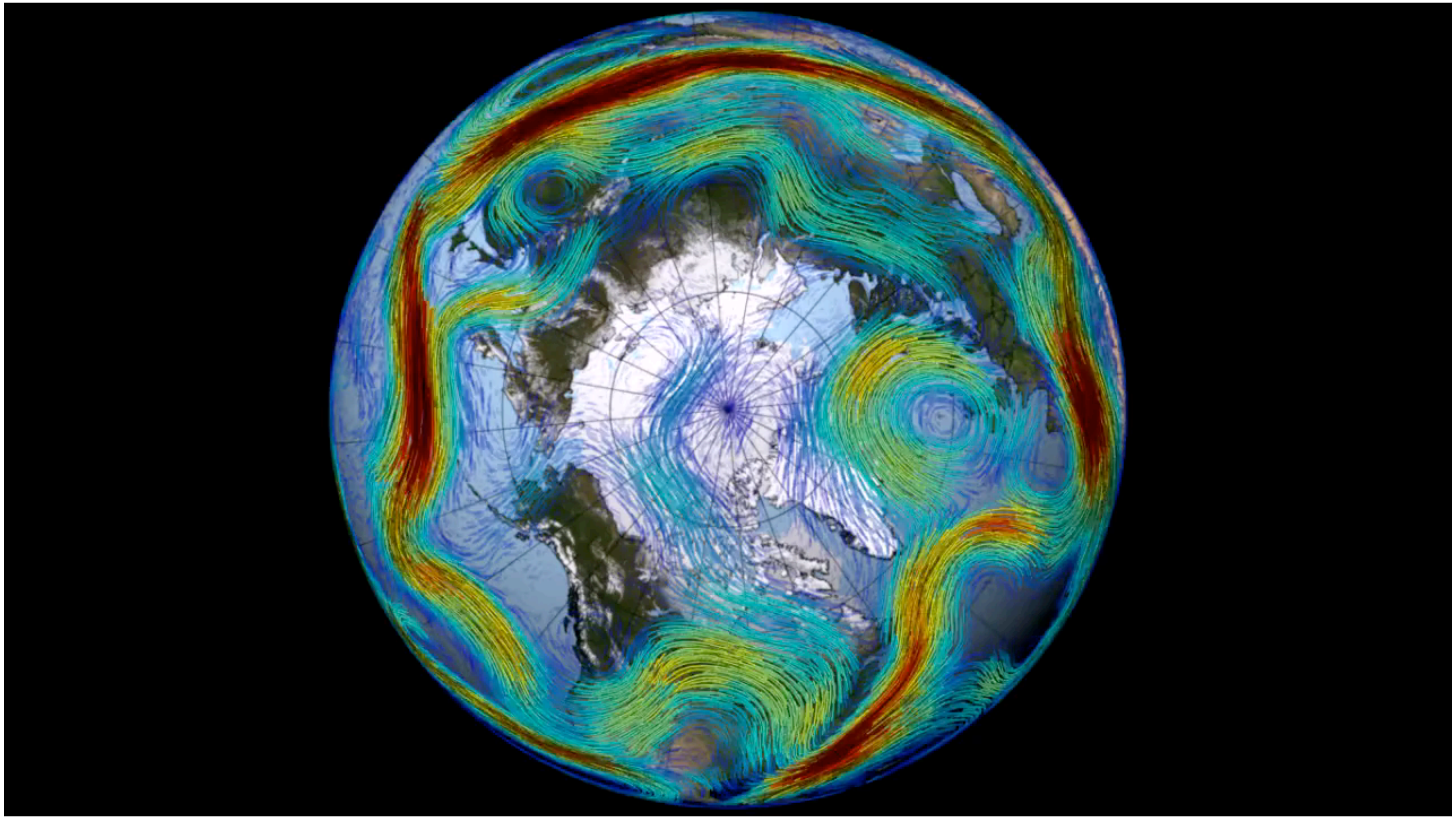
https://www.britannica.com/science/Rossby-wave

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



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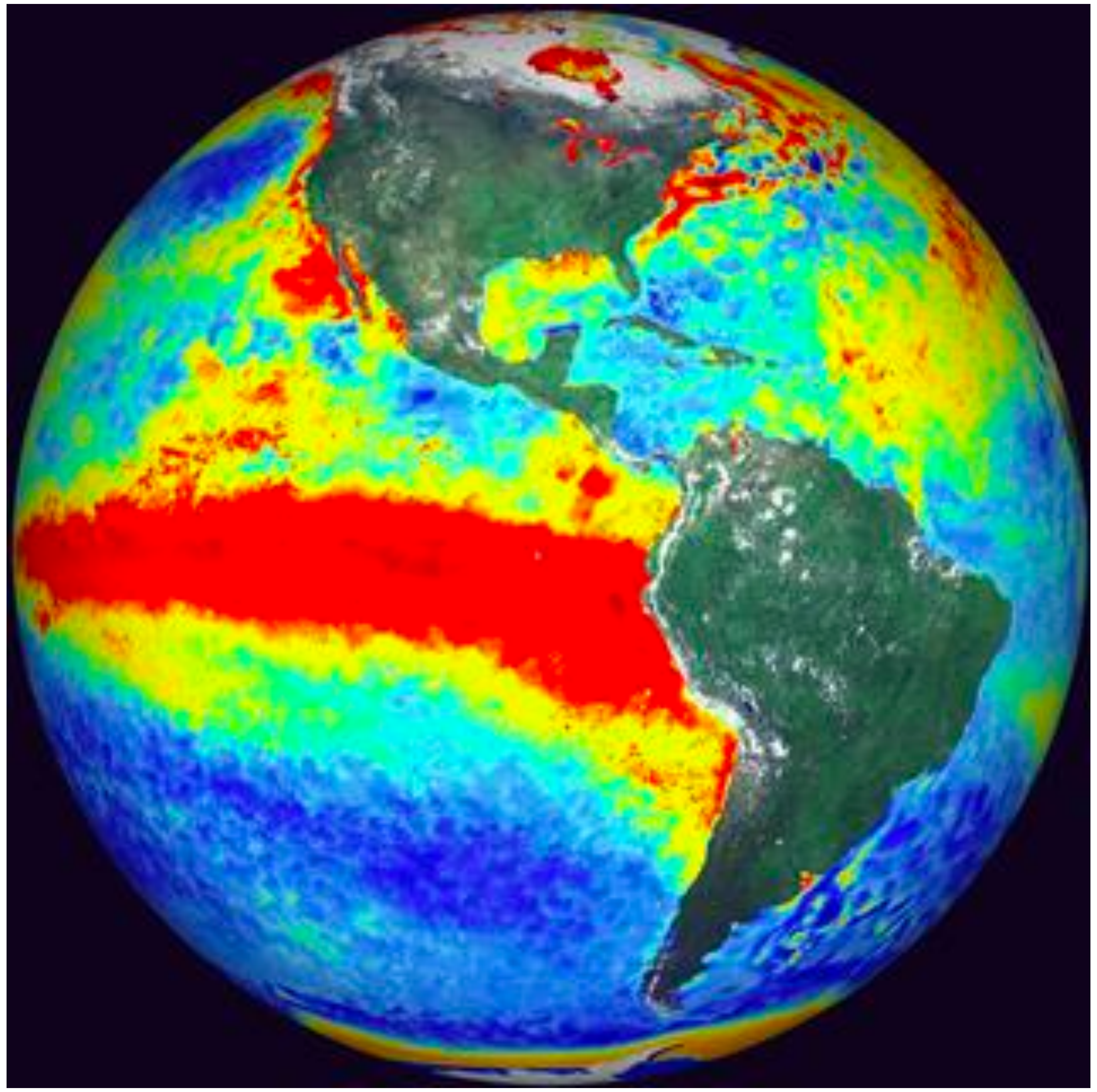
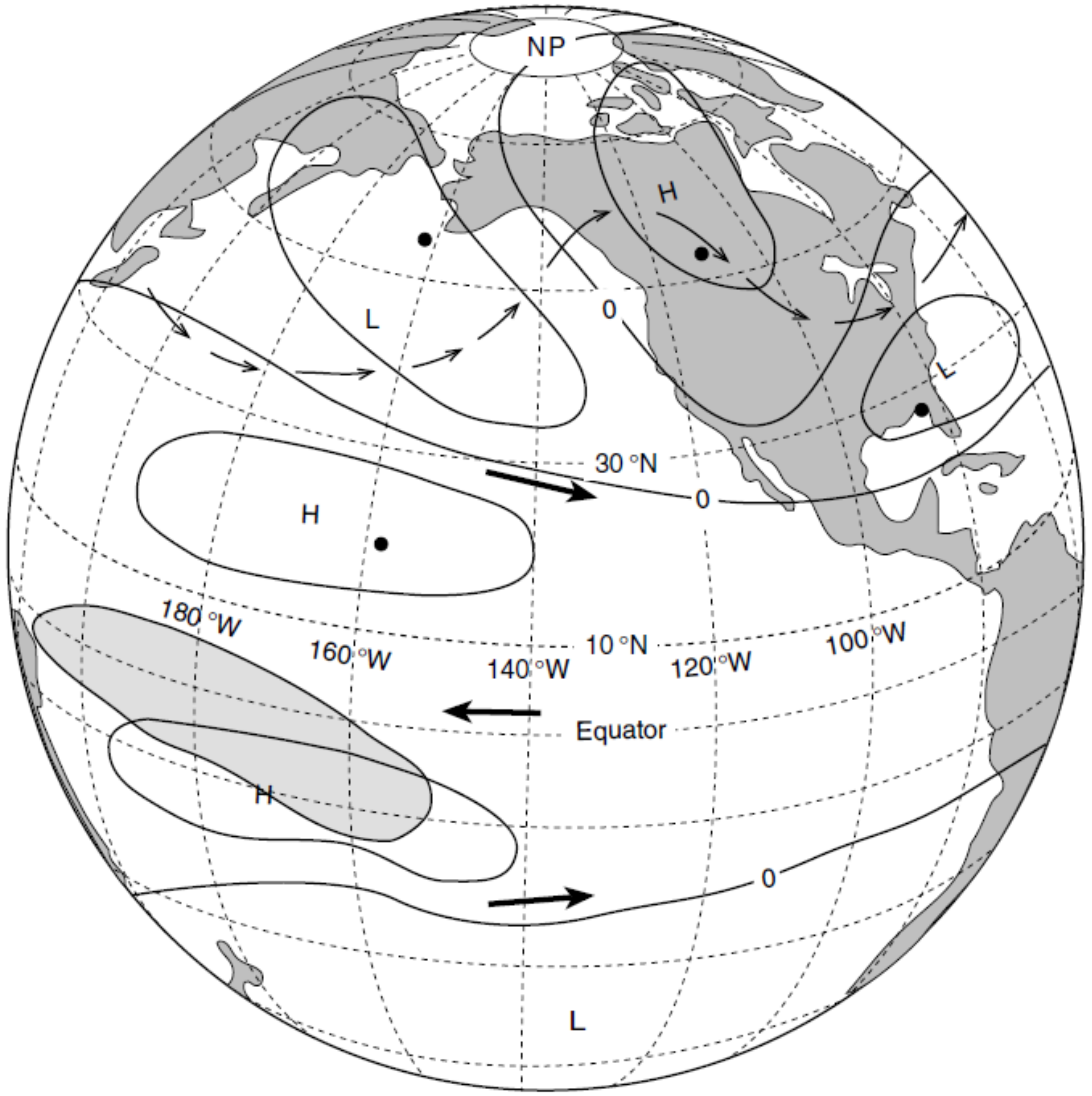
Atmospheric teleconnections: **Rossby wave** train forced by ENSO

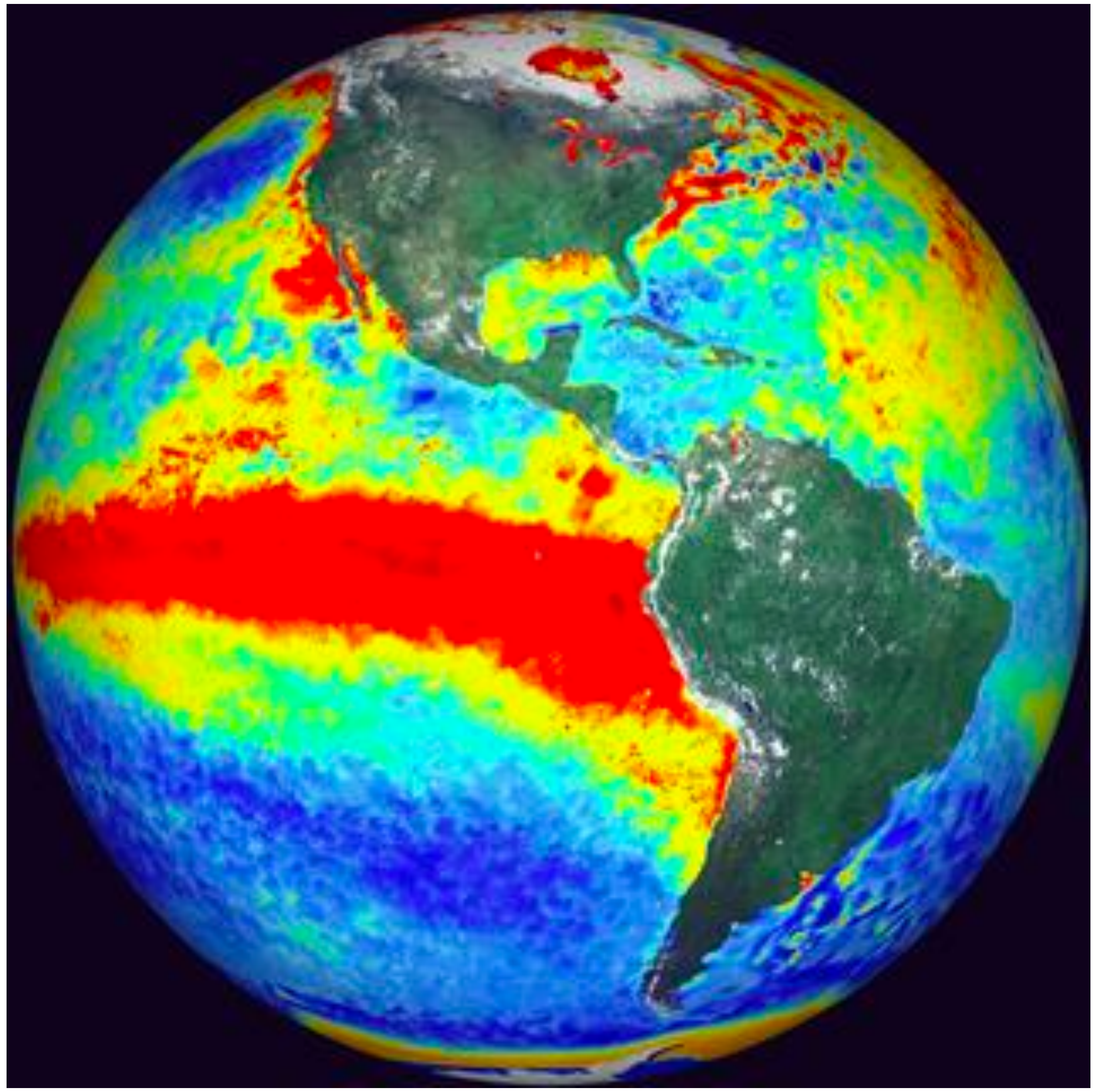


sea surface temperature anomaly during an El Niño event (https://snowbrains.com/noaa-el-nino-update-today/)

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)



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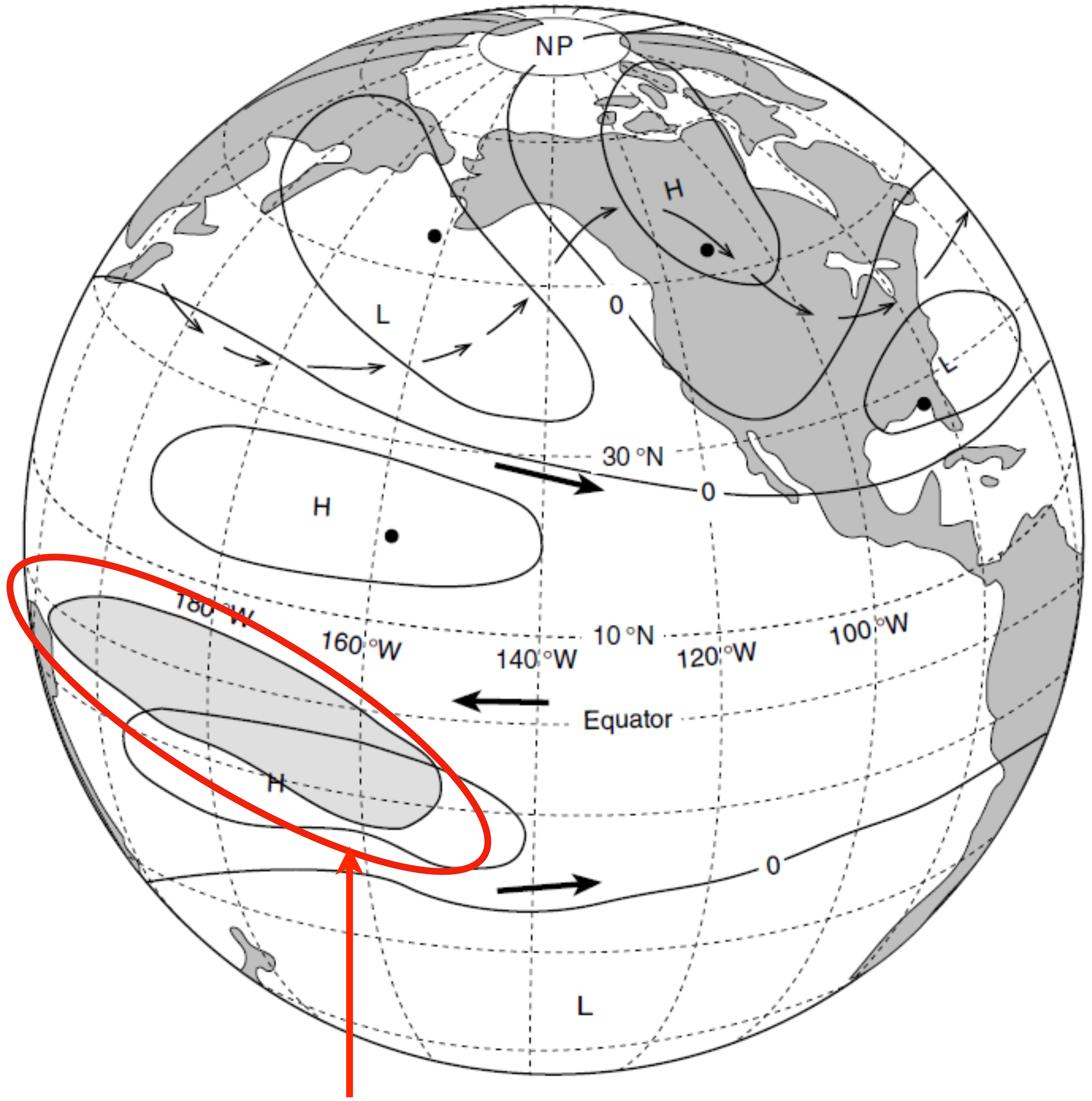

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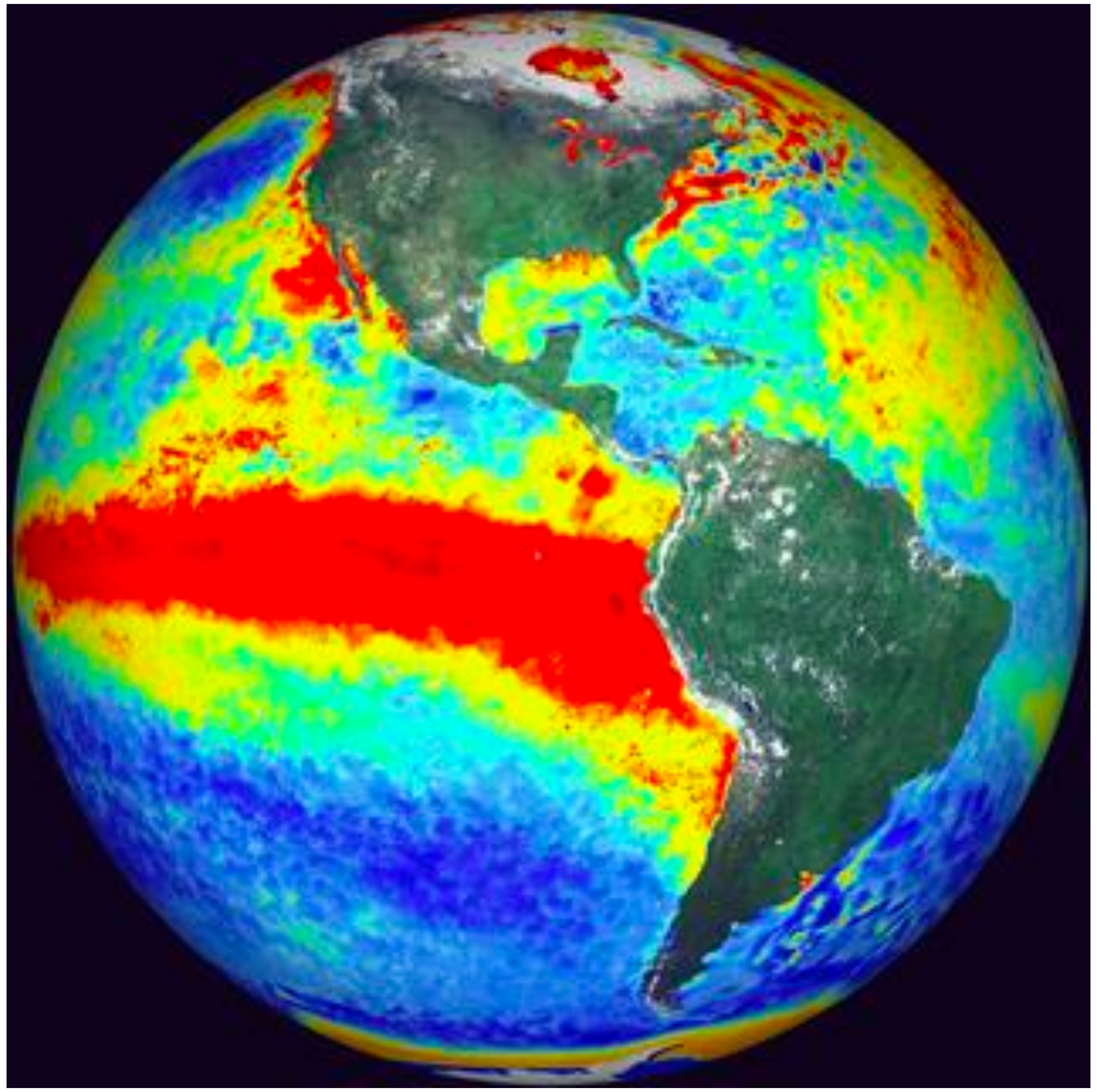
tropospheric stream line distorted by wave
pattern. (Horel & Wallace 1981)

precipitation and atmospheric heating due to El Niño, which forces atmospheric waves



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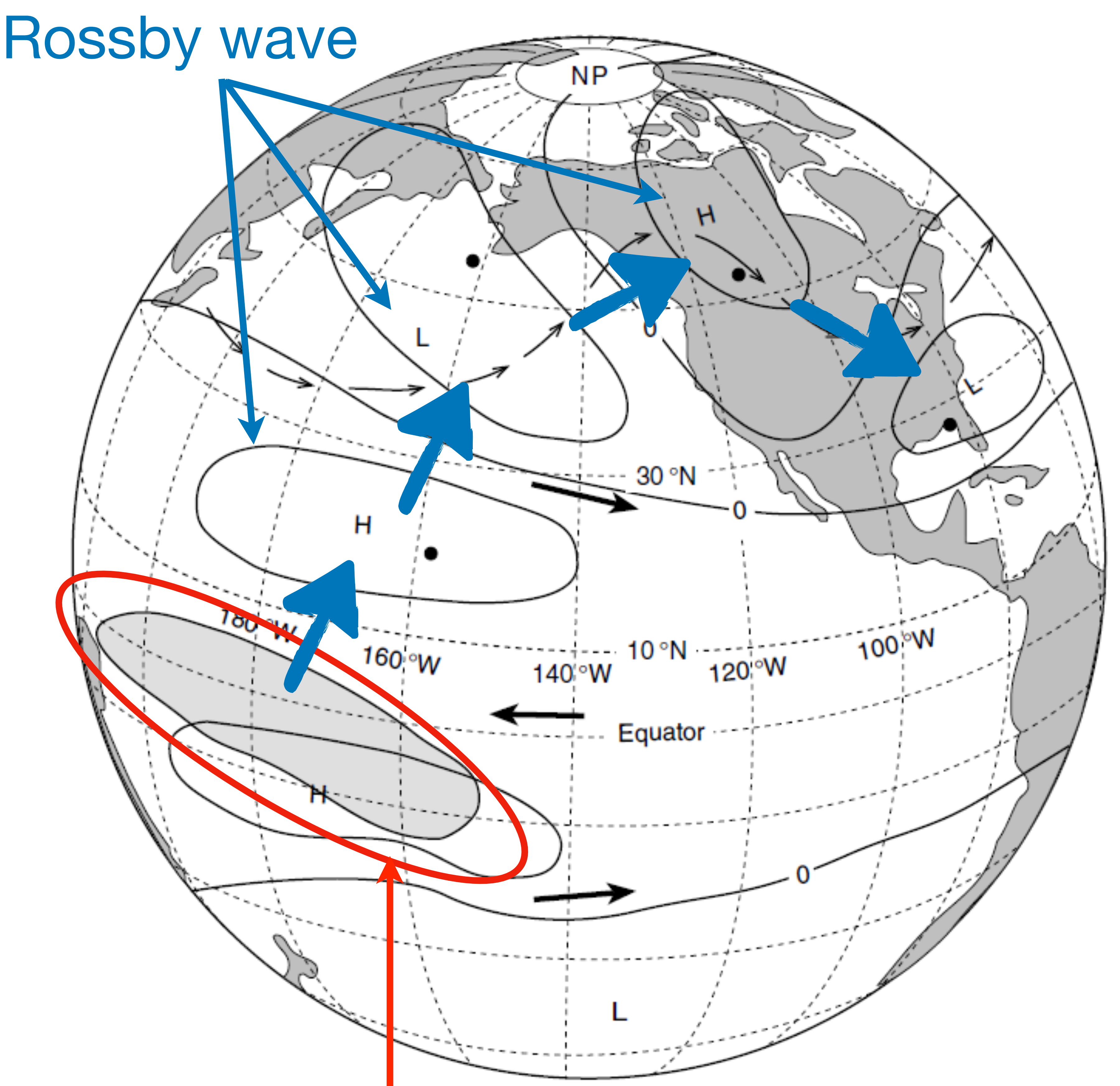

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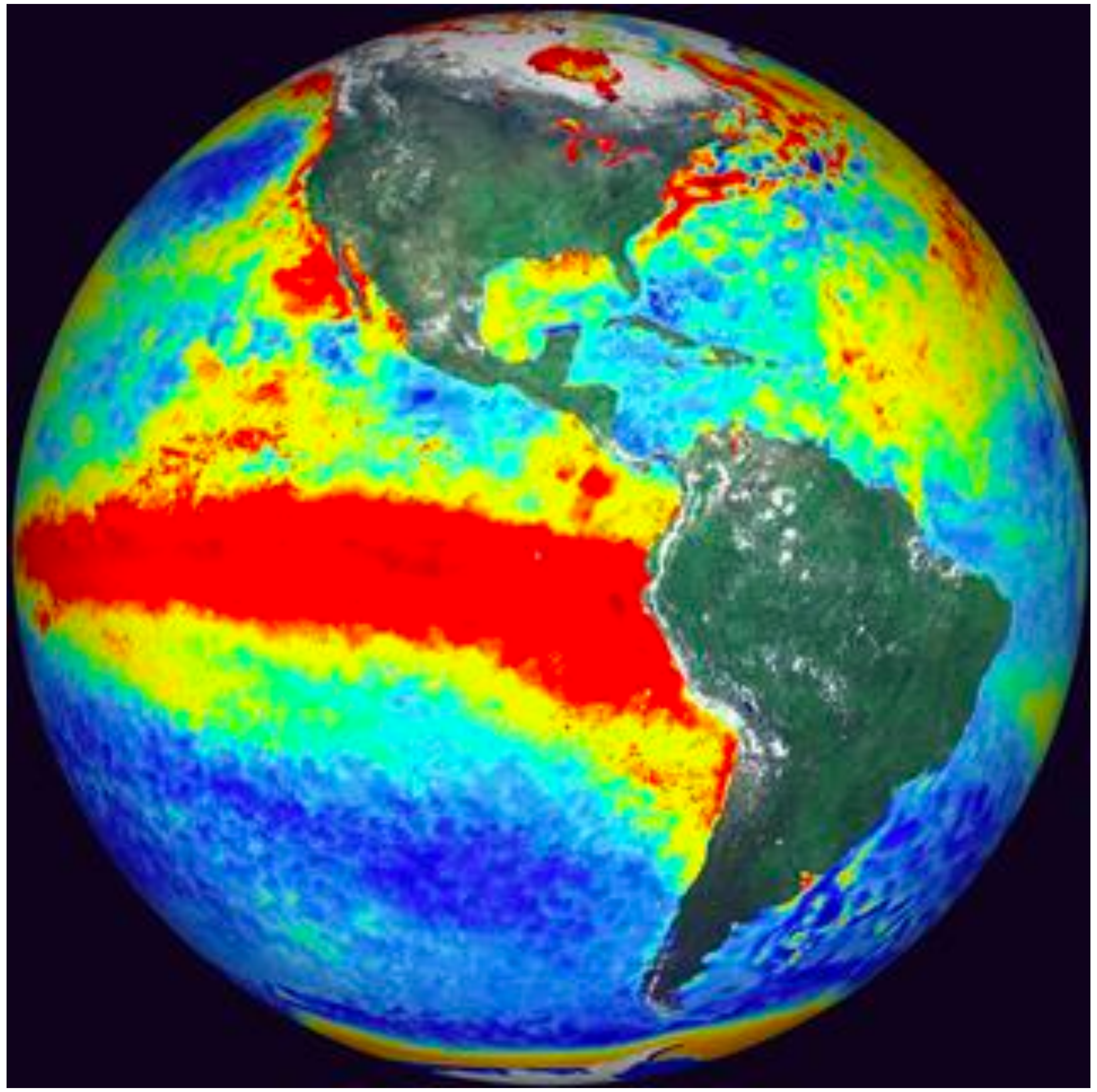
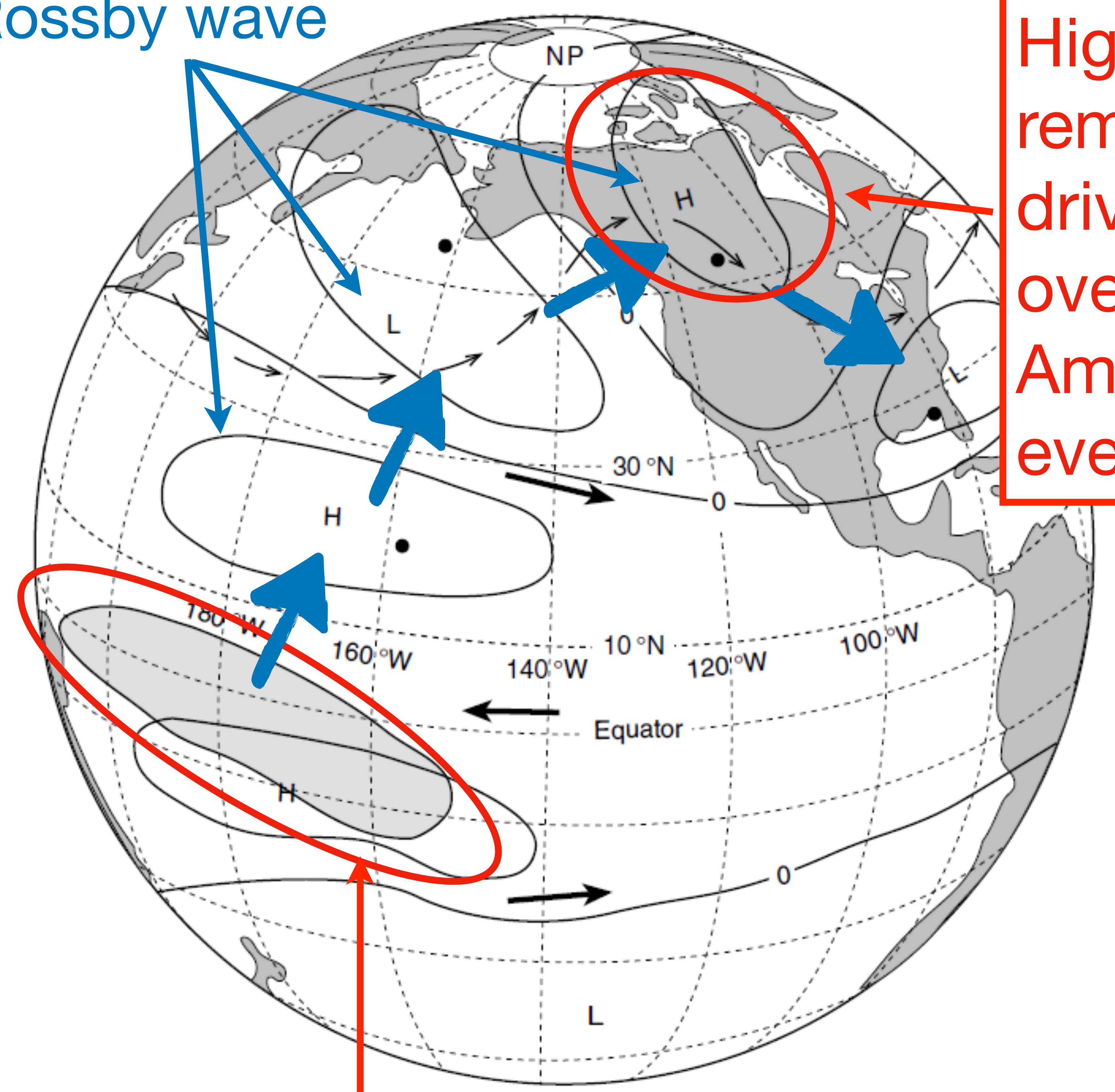


sea surface temperature anomaly during an El Niño event (https://snowbrains.com/noaa-el-nino-update-today/)

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

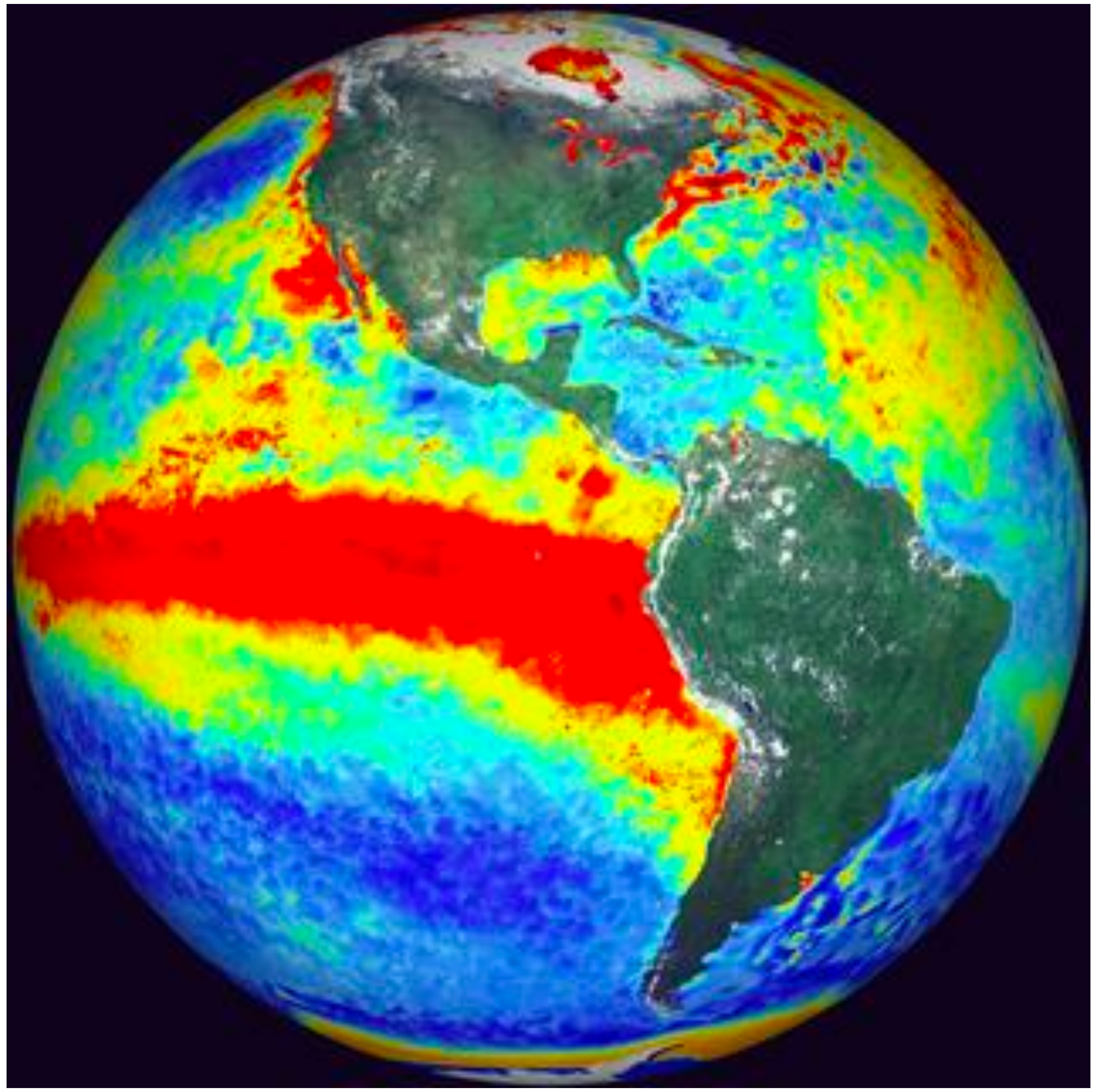
Rossby wave



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

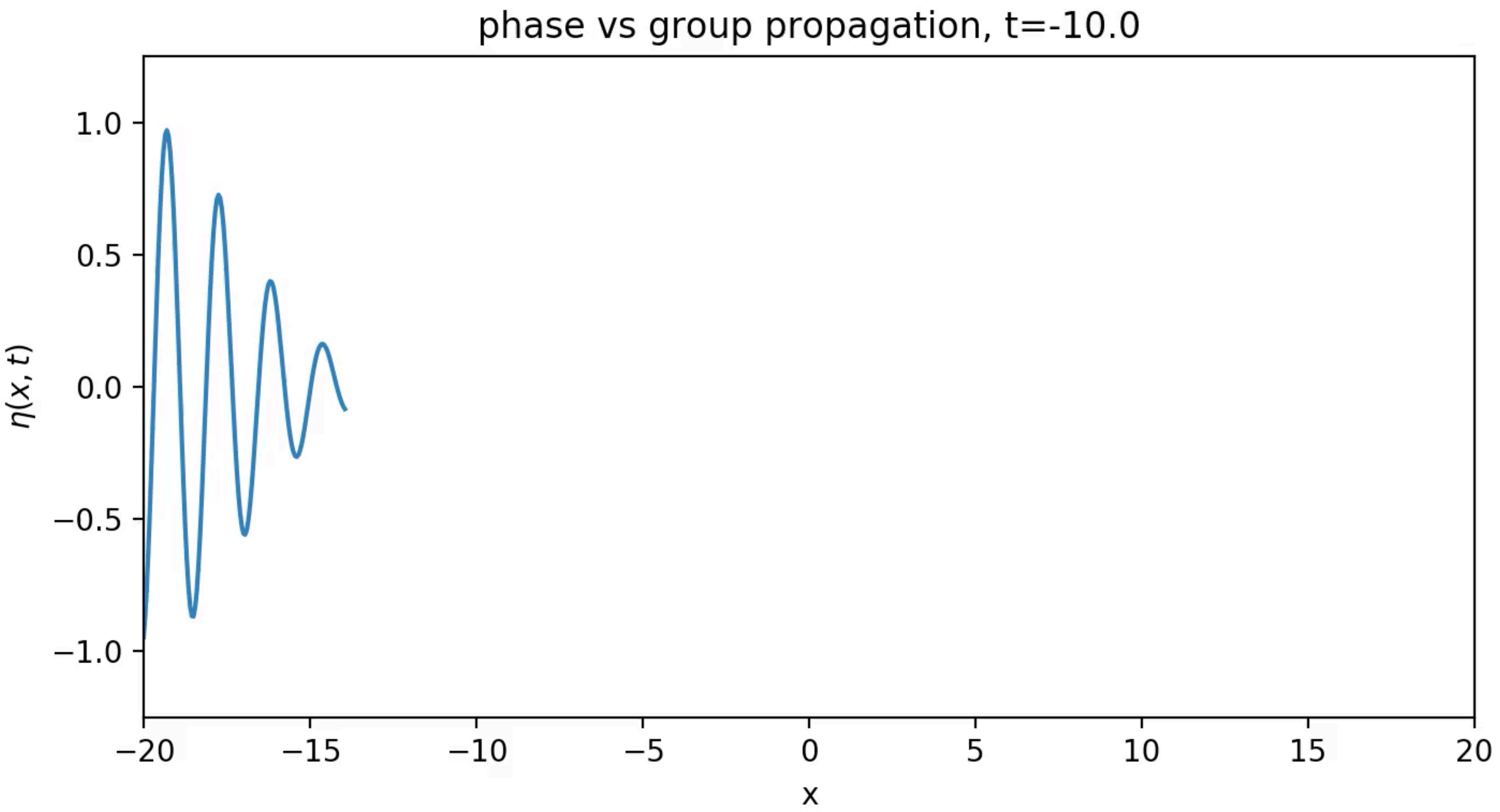
precipitation and atmospheric heating due to El Niño, which forces atmospheric waves

solid contou
atmosphere
shaded are
cloudiness
tropospheric stream line distorted by wave
pattern. (Horel & Wallace 1981)

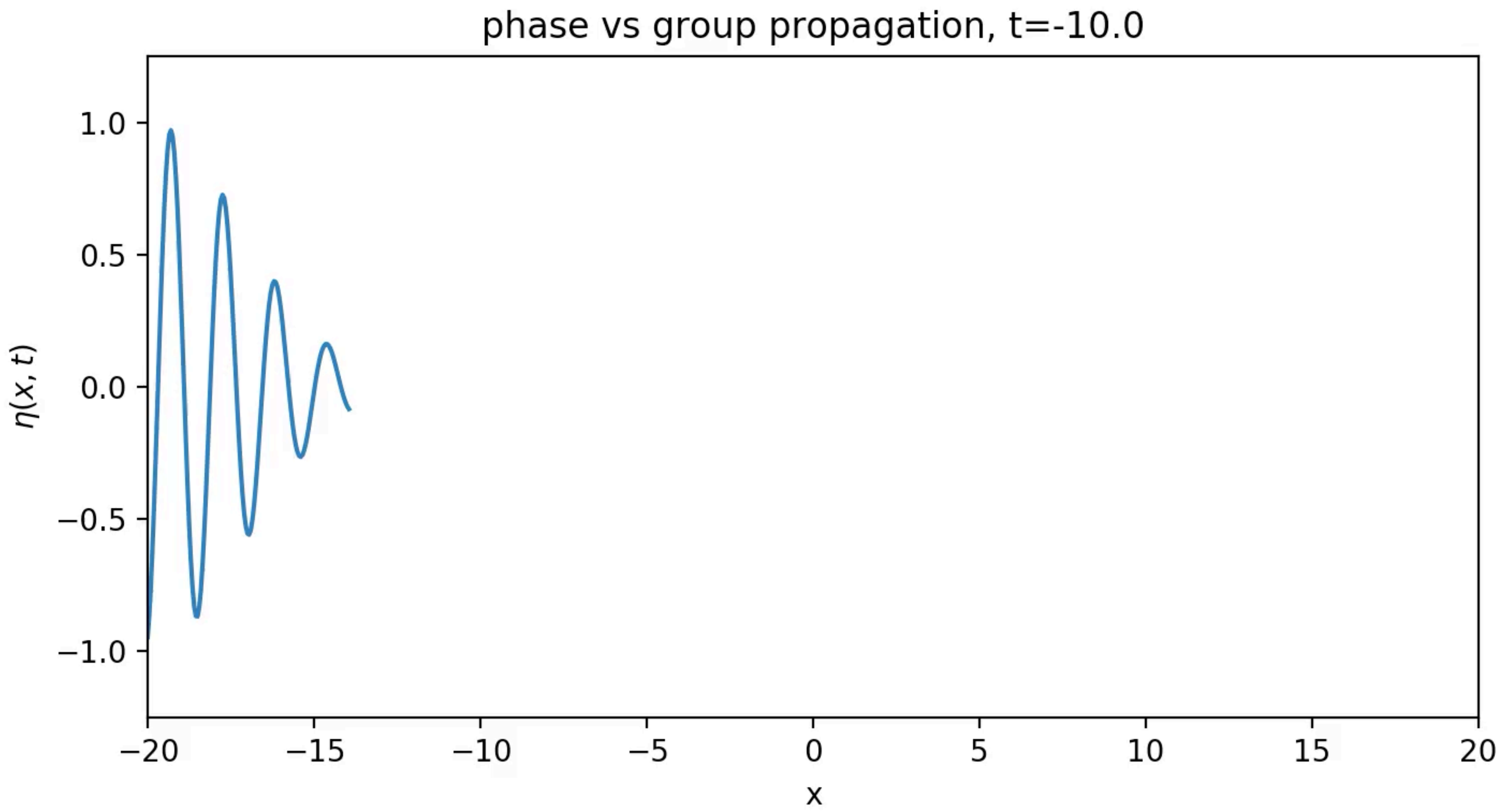


sea surface temperature anomaly during an El Niño event (https://snowbrains.com/noaa-el-nino-update-today/)

Short Rossby waves: eastward group & westward phase velocity



Short Rossby waves: eastward group & westward phase velocity



notes

6 Sverdrup balance

Angular momentum conservation & wind-driven ocean circulation:

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

Moment of inertia:

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

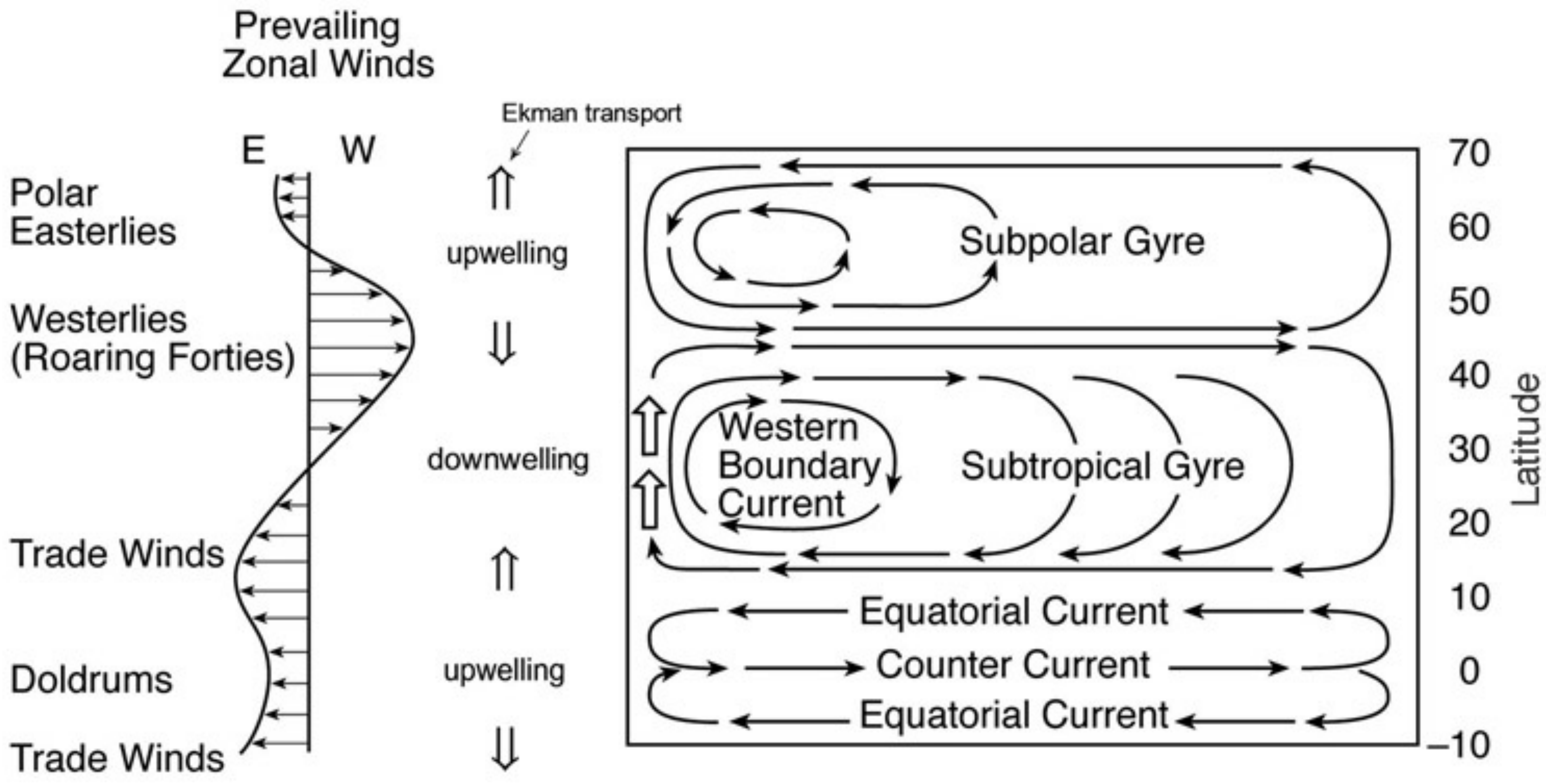
Vortex stretching leads to a smaller moment of inertia & therefore to a faster rotation ω

In the ocean, vorticity is planetary plus relative

$$vorticity = 2\Omega \sin\theta + \zeta$$

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 flow:
wind-driven ocean flow away from the western boundary



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

Schematic

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

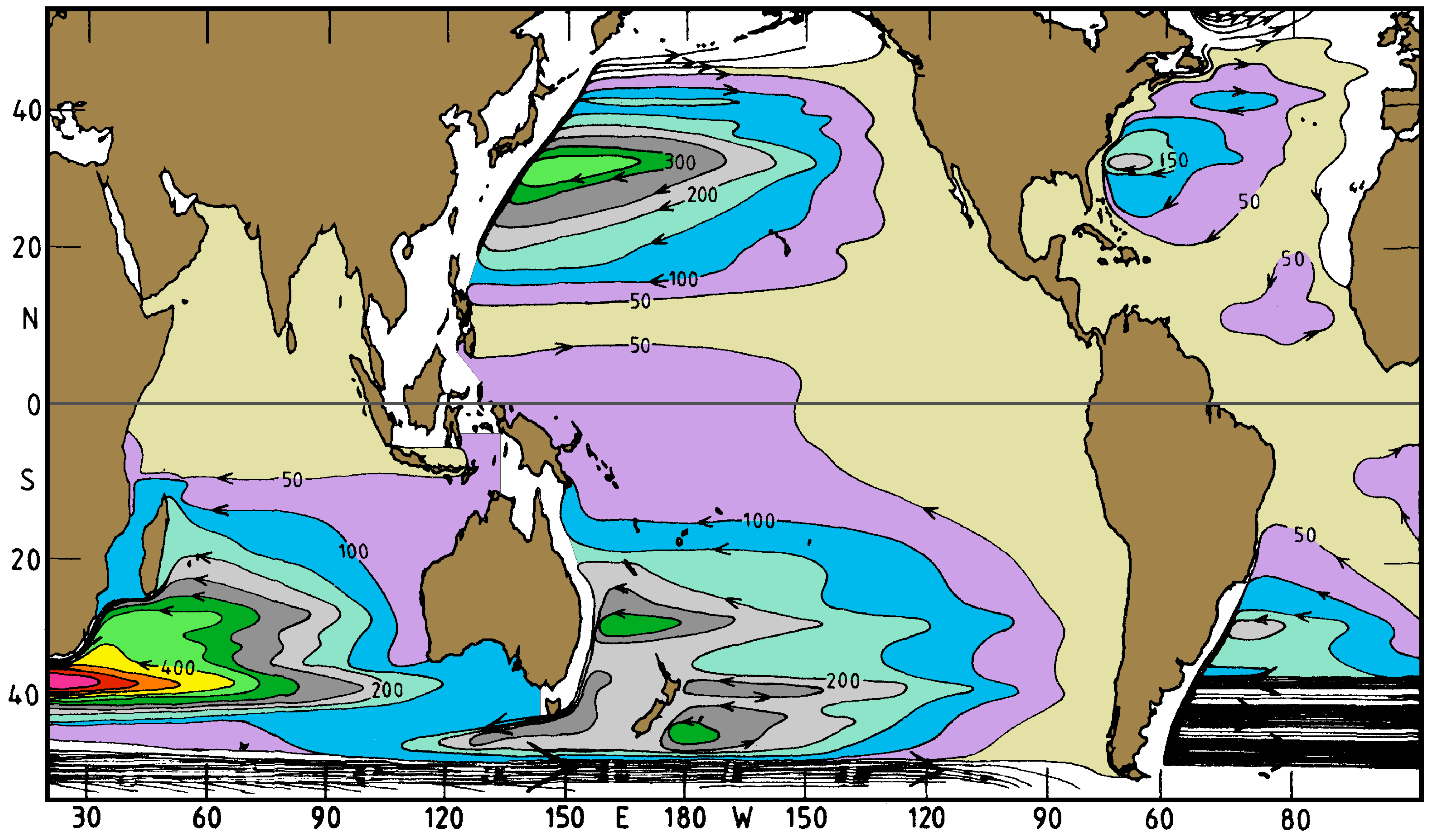


Fig. 4.4. Depth-integrated steric height P, calculated from the right-hand side of the Sverdrup relation (eqn (4.5)), using the data from Hellerman and Rosenstein (1983). Units are 10^1 m^2. For details of the integration procedure see Godfrey (1989).

Sverdrup flow from observed wind stress curl

notes

7 Wind driven circulation: Boundary currents

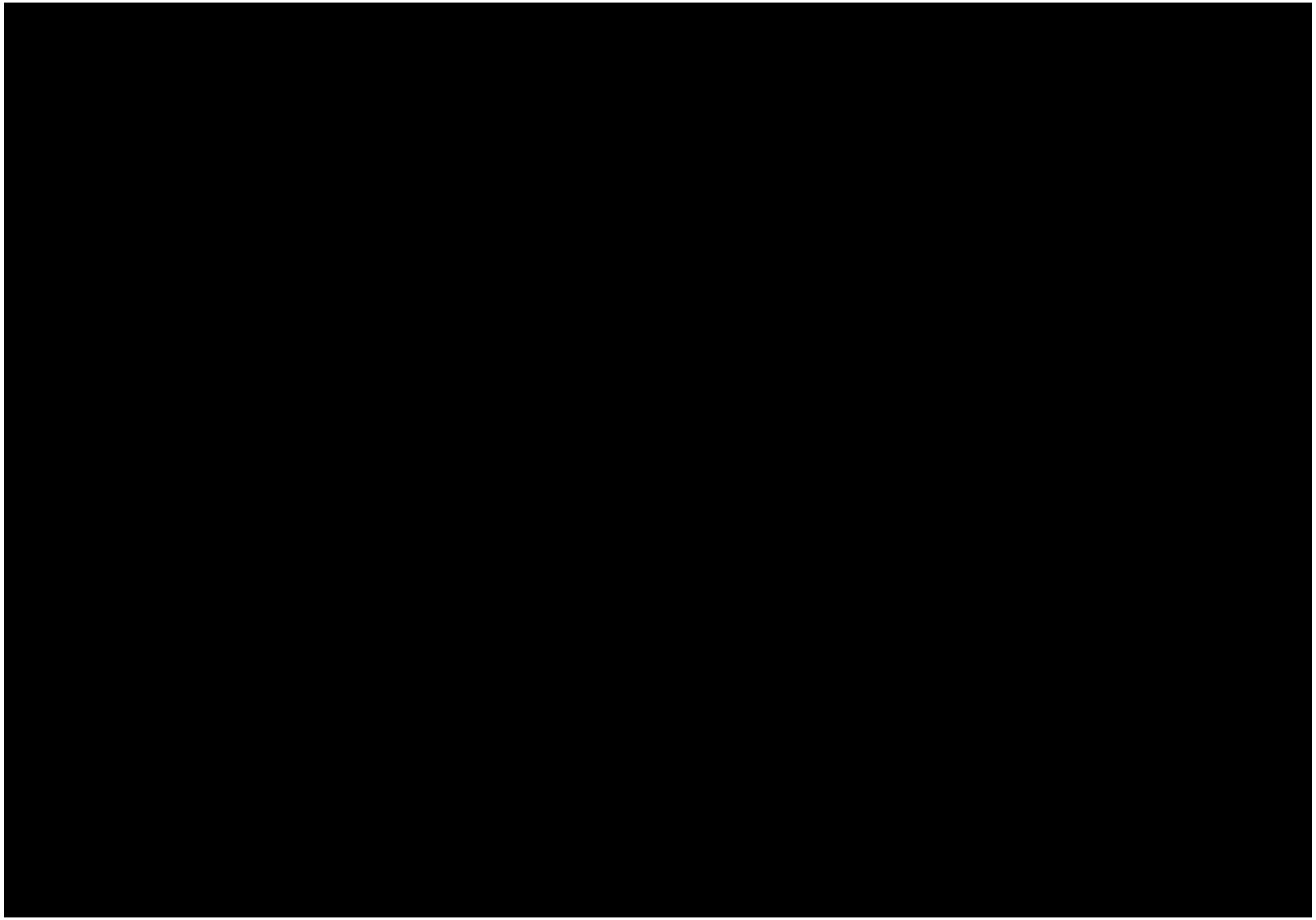
notes

8 Heuristic explanations of western boundary currents based on a vorticity argument:

1) vorticity

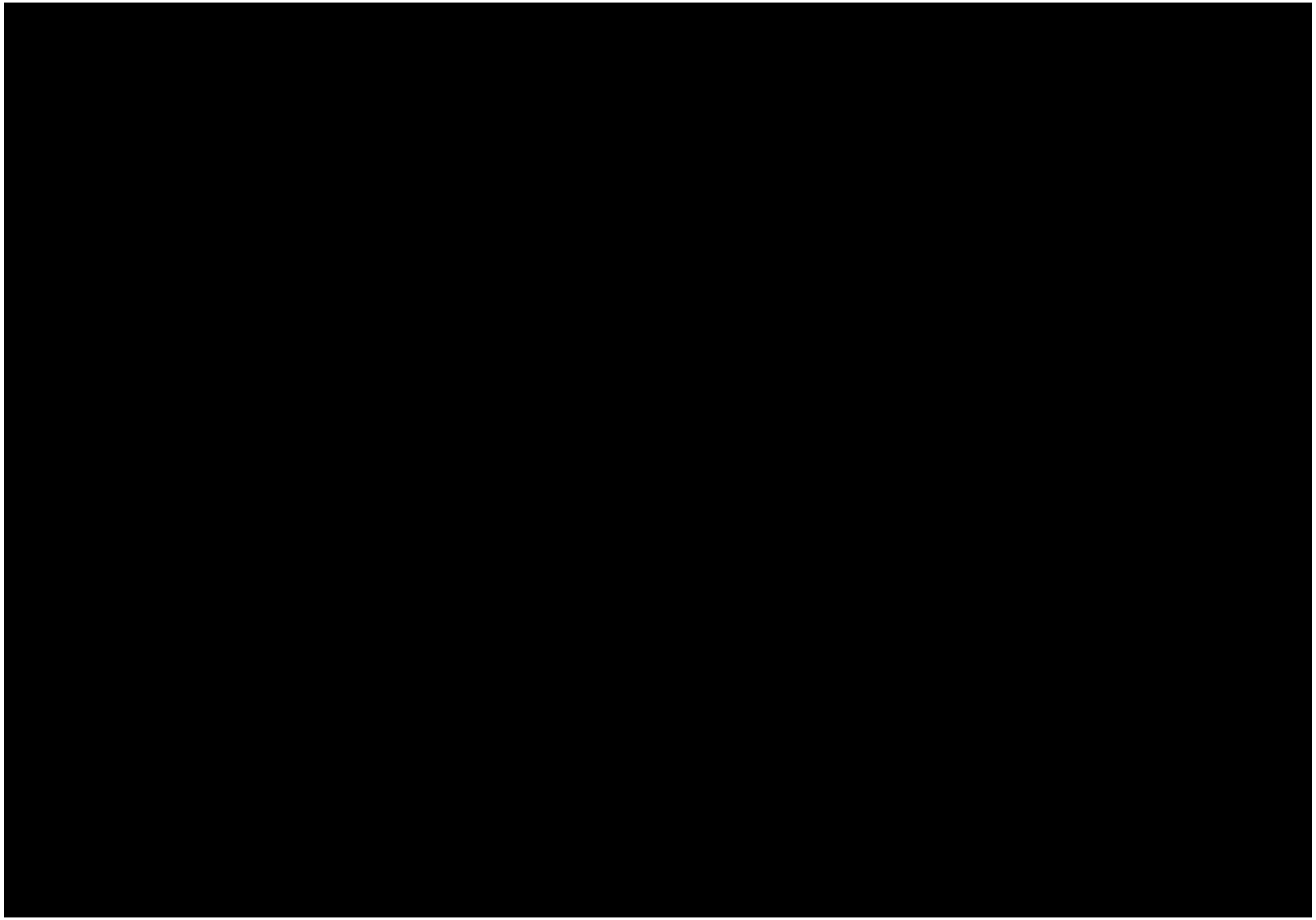
2) Rossby waves

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!

notes
9 Abyssal circulation, Stommel-Arons

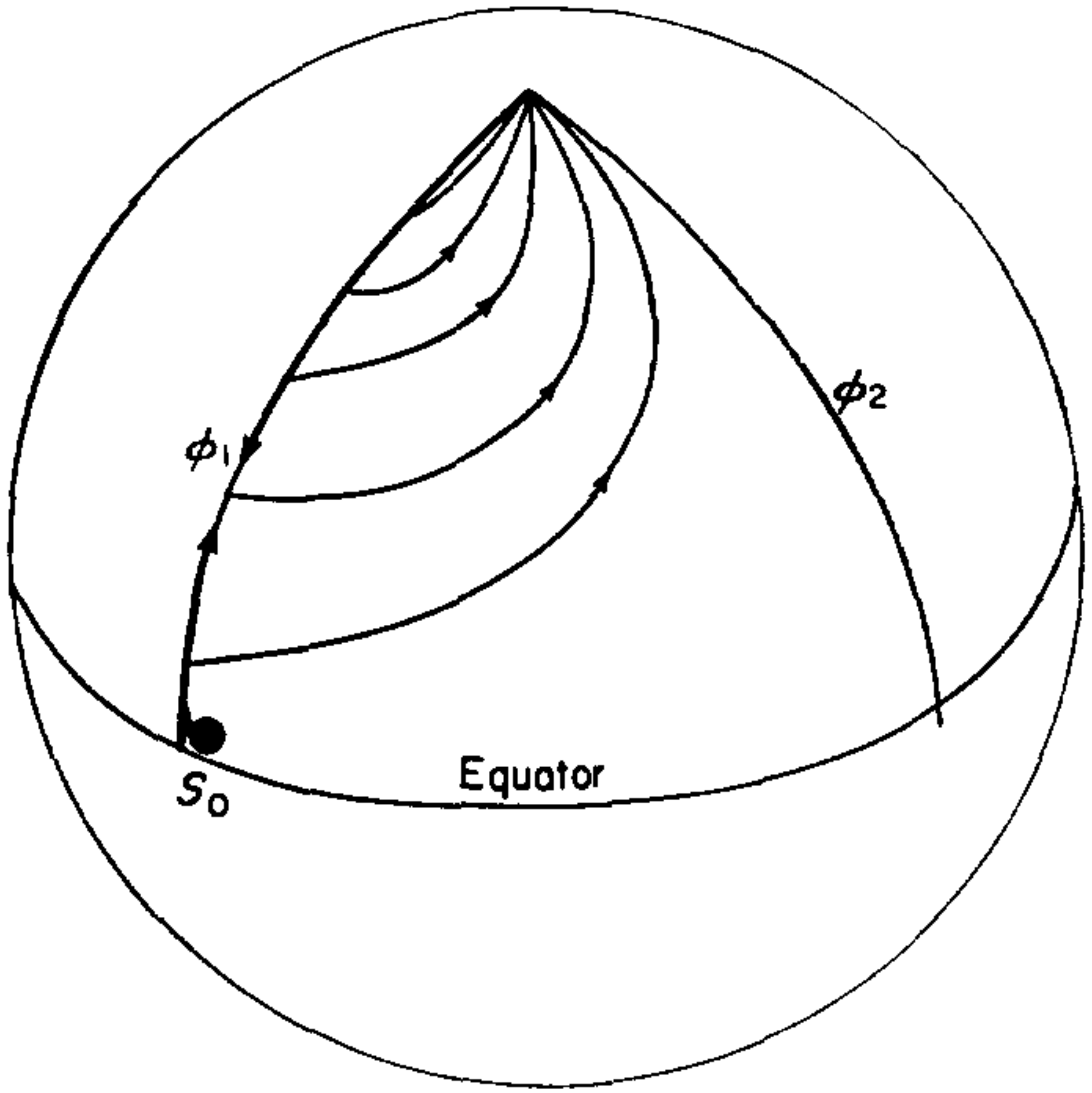


Fig. 8. Circulation pattern in meridionally bounded ocean with concentrated source S_0 (fed by western boundary current from below the equator) and a uniformly distributed sink Qo such that
$S_0 = Q_0 a^2(\phi_2 - \phi_1)$

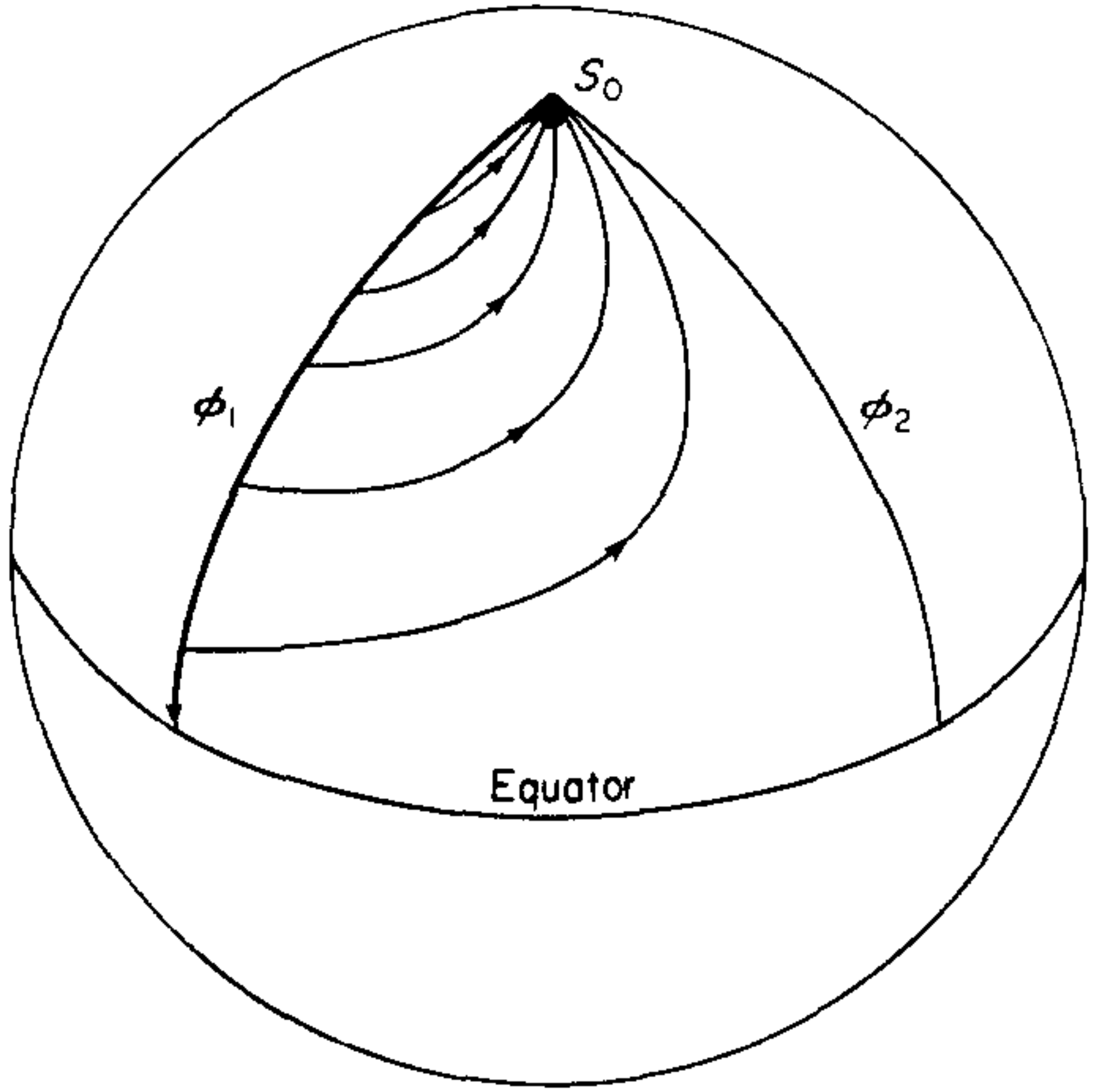


Fig. 6. Circulation pattern in meridionally bounded ocean with concentrated source S_0 at north pole and a uniformly distributed sink Qo such that
$S_0 = Q_0 a^2(\phi_2 - \phi_1)$

Stommel and Arons 1960

Deep Western Boundary Current

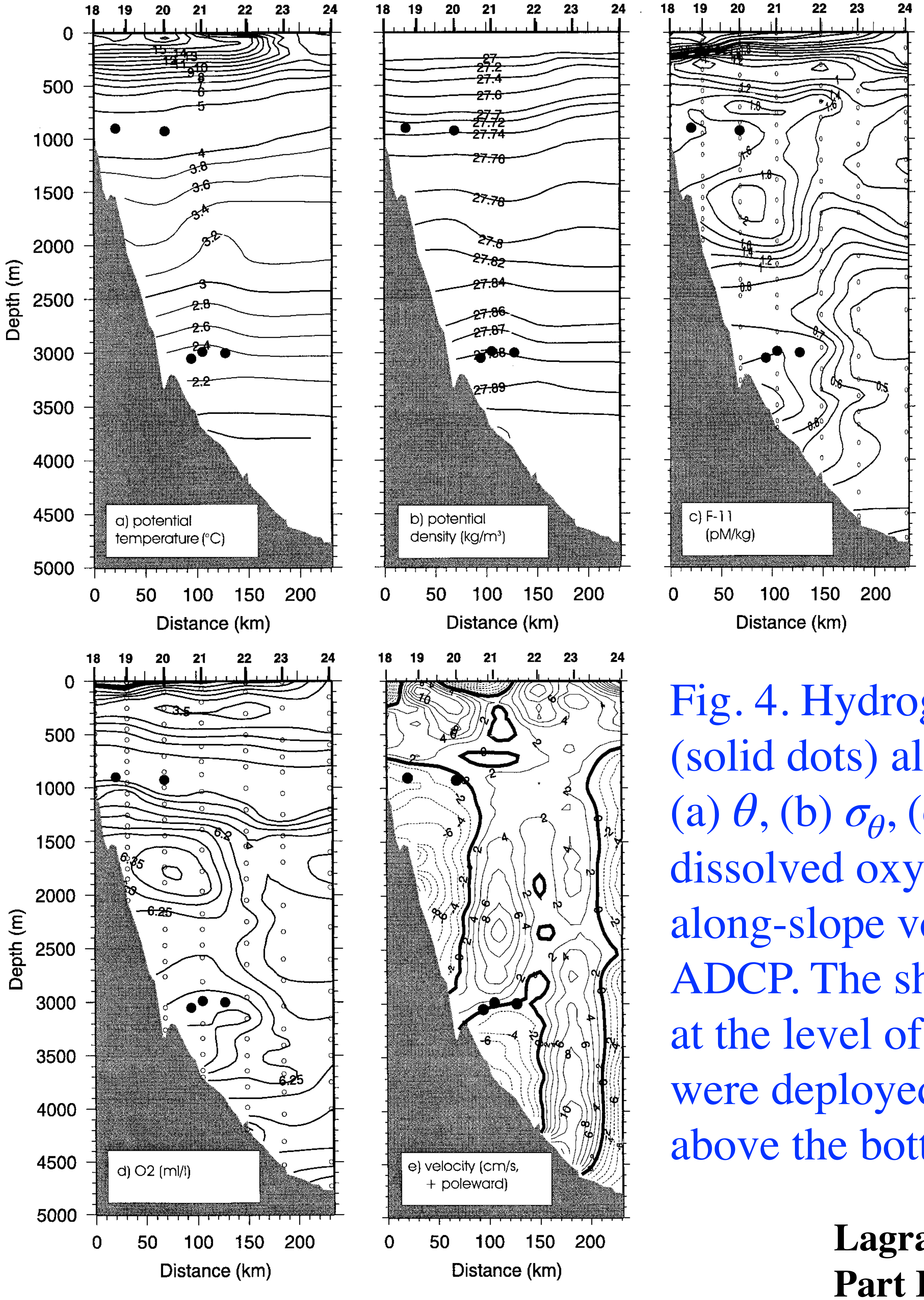


Fig. 4. Hydrography & float launch sites (solid dots) along BOUNCE I Section 3: (a) θ, (b) σ_θ, (c) CFC (F-11), (d) dissolved oxygen, and (e) absolute along-slope velocity from lowered ADCP. The shallow floats were launched at the level of ULSW, and the deep floats were deployed several hundred meters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

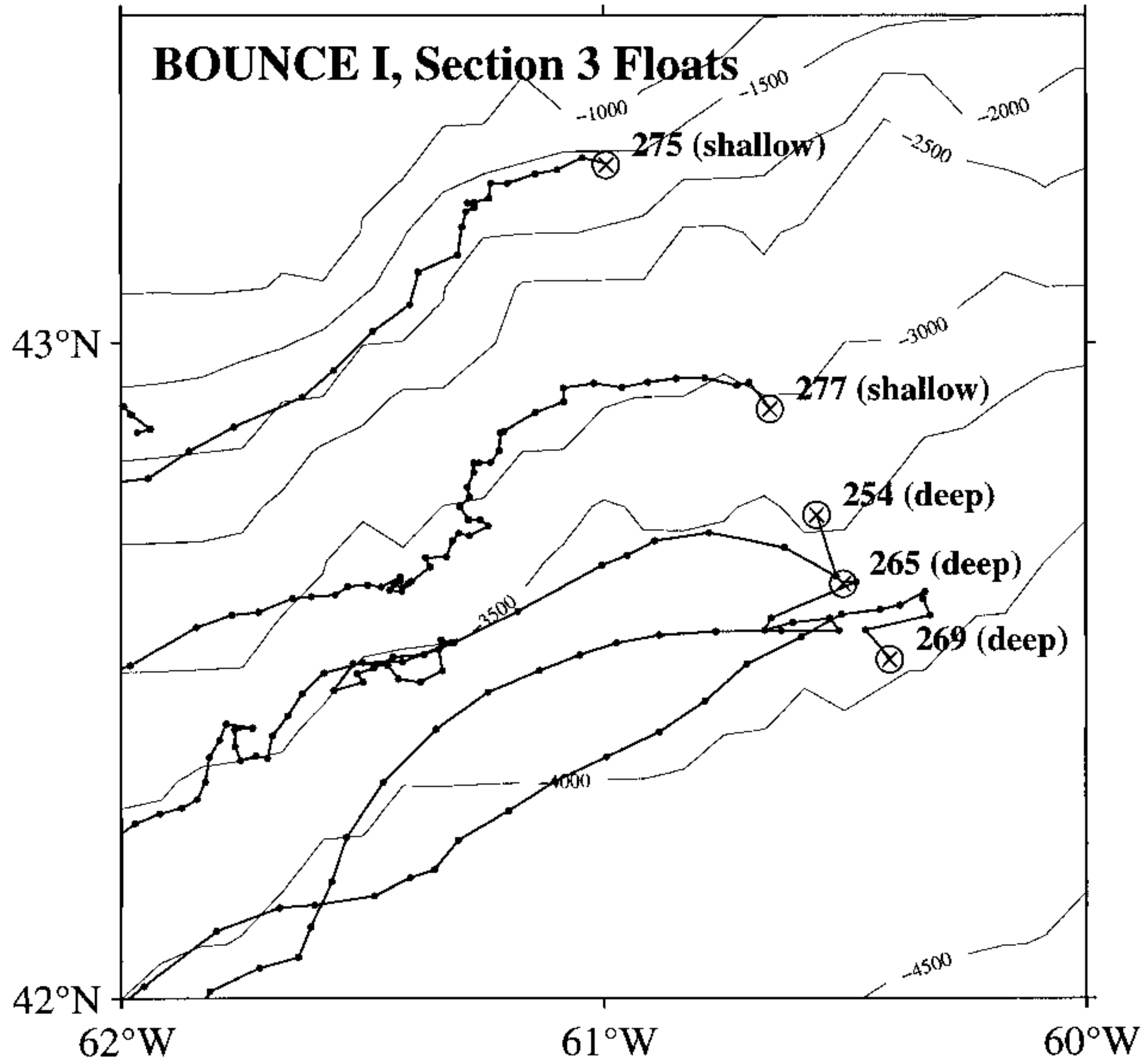


FIG. 5. First part of tracks of five floats deployed along BOUNCE I Section 3, two shallow (275 and 277) and three deep (254, 265, and 269). Dots along tracks indicate daily positions. Launch locations of floats are indicated by circled x's. Bathymetric contours are every 500 m.

Lagrangian Observations of the Deep Western Boundary Current in the North Atlantic Ocean. Part I: Large-Scale Pathways and Spreading Rates. AMY S. BOWER AND HEATHER D. HUNT, 2000

The End