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# OCES 2003 : Descriptive Physical Oceanography

(a.k.a. physical oceanography by drawing pictures)

## Lecture 12: Gyres 2 (Western intensification)

# Outline

- ▶ (wind driven?) gyres
- ▶ depth-independent model with no topography: vorticity balance
  - boundary acting as sink of vorticity
  - **Western intensification** and WBCs
- ▶ complications (extras, or things of interest)
  - topography
  - depth-dependence
  - buoyancy forcing

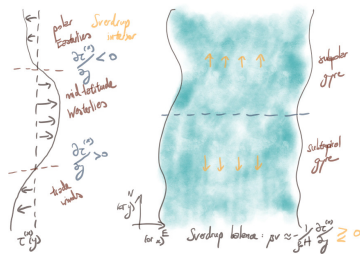
**Key terms:** Western Boundary Currents (WBC), vorticity balance, western intensification

# Recap: Sverdrup balance

## ► Sverdrup balance (in meridional)

$$\beta v \approx F_{\tau}(x, y) = -\frac{1}{\rho_0 H} \frac{\partial \tau^{(x)}}{\partial y}$$

→ Coriolis balancing **wind stress curl**



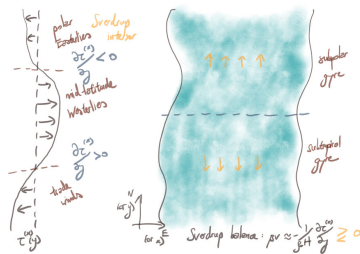
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## What happens at boundaries?

- **friction** important over boundary layer, Sverdrup balance breaks down
- **boundary condition** fixes (more or less) direction of flow  
→ intensification has to be on the **West**

# Single (subtropical) gyre: vorticity balance

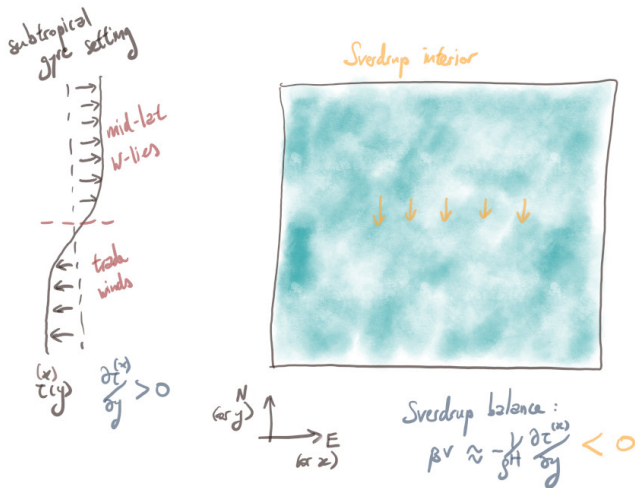


Figure: Schematic for NH subtropical gyre.

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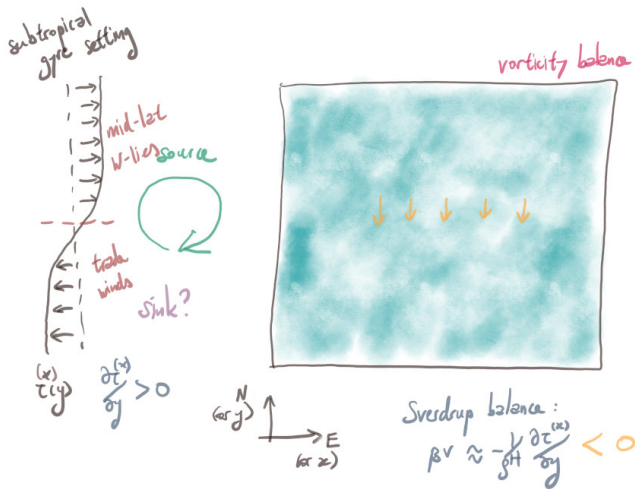


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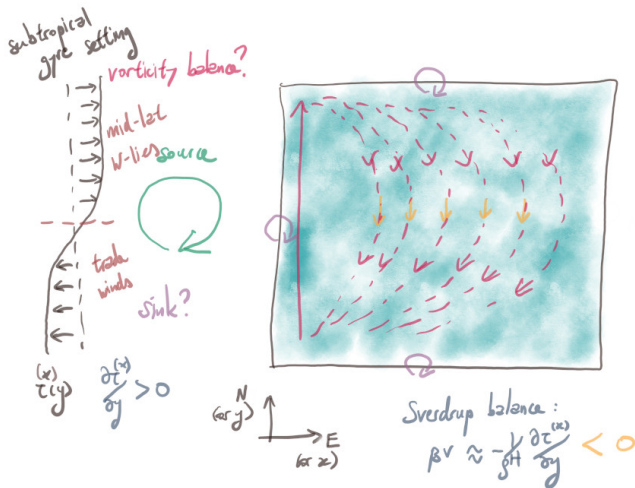
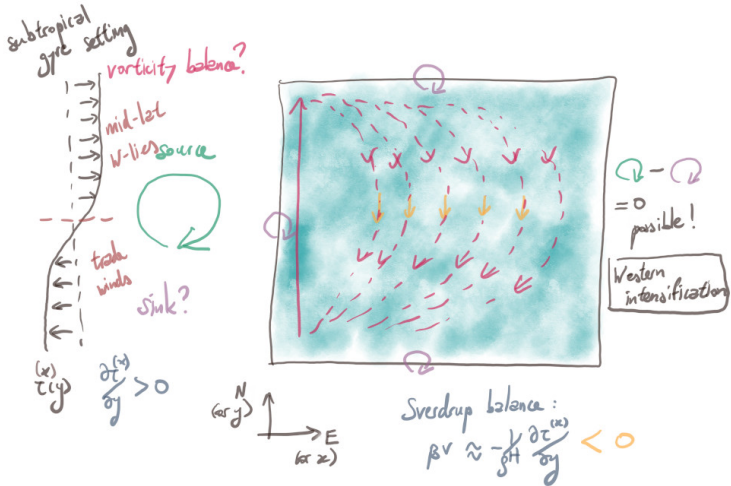


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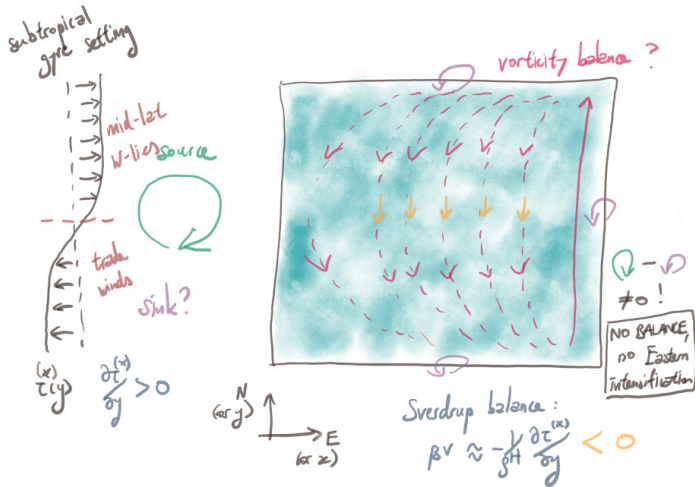


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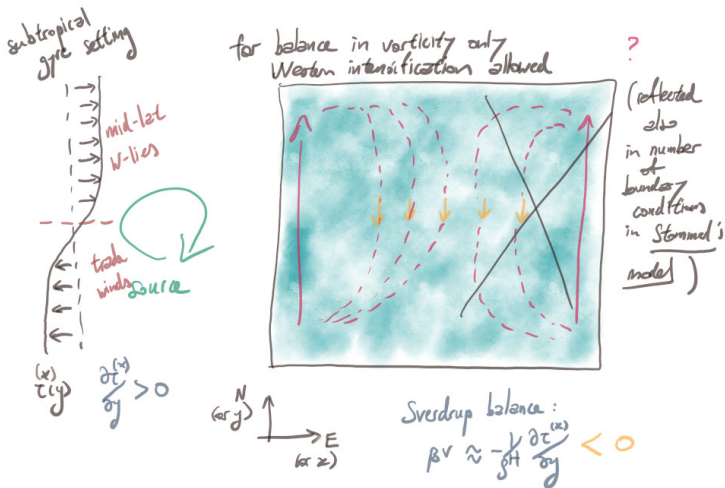
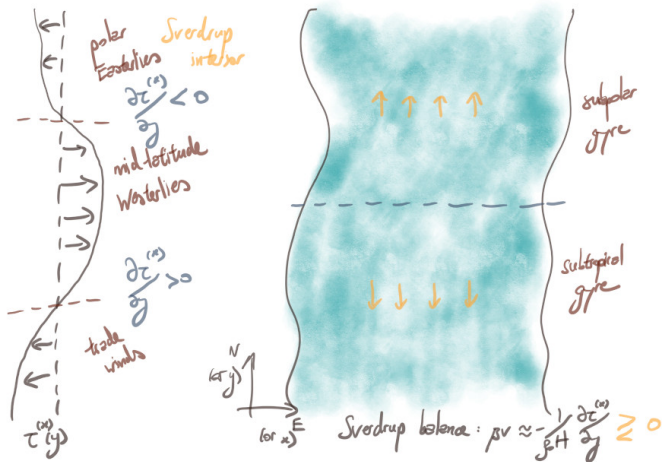


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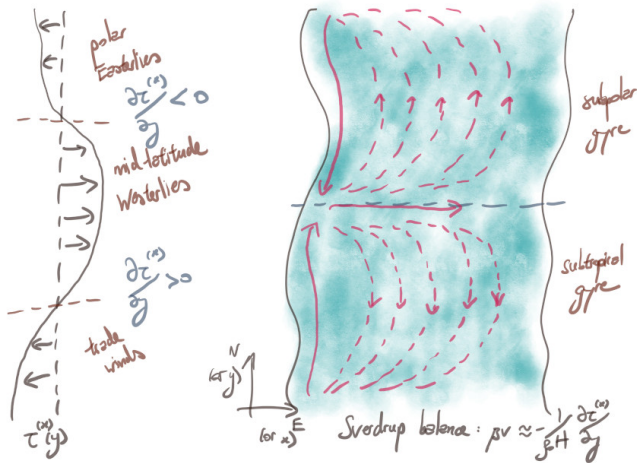


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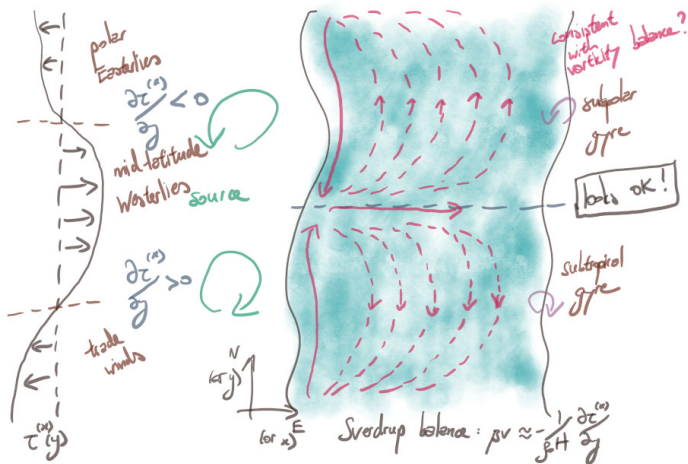


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# Summary of arguments

In this depth-independent (cf. **barotropic**) model of the gyre:

- ▶ **Sverdrup balance** (wind stress curl  $\sim$  Coriolis) tells you what interior flow you have
  - links also with **con/divergence** (up/downwelling)
- ▶ boundary conditions fixes **flow orientation** and has to be **Western intensification**
  - energetically unfavourable (wind blowing against the detached current)
  - only the Western Boundary can be a sink of the input vorticity

Aside:

- ▶ Stommel's original model only allows for one boundary condition to put on
  - have to put on the West, asymptotic matching for solution (see maybe OCES 3203)
  - see Ch. 14 of Vallis (2006), *Atmospheric and Ocean Fluid Dynamics* for more

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→ those that are not deep are mostly influenced by **Ekman suction** (more in Lec. 21 + 22)

→ model here made **assumptions** (e.g. depth-independence) to give a **deep** theory

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Value of the model/theory to be measured by:

- ▶ does it work?
- ▶ did you learn something from it?
- ▶ does it tell you what you might want to consider next?



# Extras

Other discrepancies:

- ▶ no asymmetry between subtropical and subpolar gyres  
→ subtropical gyre more prominent in observations
- ▶ WBCs and resulting near-surface transport goes **polewards**  
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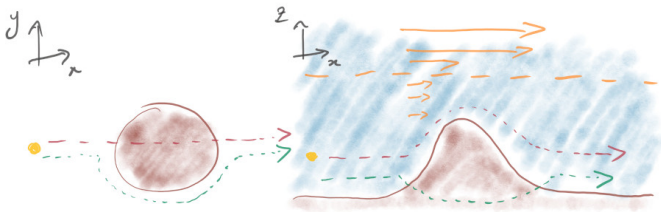
Model assumptions:

1. no bathymetry
2. depth-independence (cf. **barotropic** but I try not to use that term)
3. wind-driven

## Extras: topography

The ocean has bathymetric features

- ▶ go around or go over? depends on **energetics!**

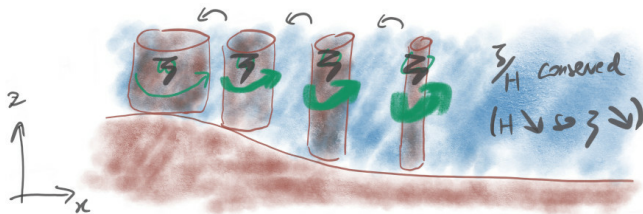


**Figure:** Possible paths when facing an obstacle: go over or go around. Depending on  $H$  as well one might be more preferable than the other. Note also that the strong flow above the obstacle is intuitively not strongly influenced by the obstacle (despite measures such as **JEBAR** stating otherwise; see e.g. Cane, Kamenkovich & Krupitsky, 1998, *J. Phys. Oceanogr.*).

- ▶ influence not throughout depth because **baroclinicity**  
→ despite things like **JEBAR** stating otherwise...

## Extras: topography

- ▶ fluid wants to try and conserve **angular momentum**
  - contrast this with **linear** momentum  $p$
  - related to **vorticity**, but as  $q = (\omega + f)/H$  (**potential vorticity**, PV)



**Figure:** Conservation of  $q = \omega/H$  (assuming  $|\omega| \gg |f|$  for illustration). As  $H$  decreases, the spinning gets slower to compensate so that  $q$  is conserved.

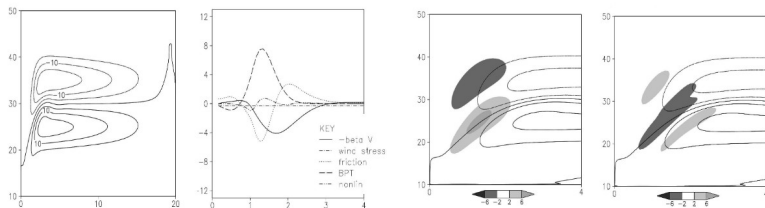
- ▶ cf. ballerina effect (or the spinning-chair-with-leg-sticking out effect)

# Extras: topography

over slopes we now have more things coming into play

(e.g. Salmon, 1998; Hughes & de Cuevas, 2001, *J. Phys. Oceanogr.*)

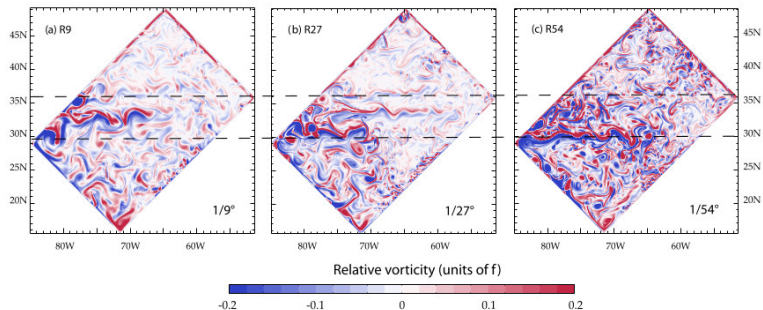
- ▶ **bottom pressure torque** (related to PV conservation)
- ▶ **bottom drag** (instead of friction as before)



**Figure:** Results from a depth-independent gyre model with a slope on the west, showing (a) streamfunction, (b) balances between terms, (c) bottom pressure torque forcing, and (d) frictional forcing. Adapted from Jackson, Hughes & Williams, 2006, *J. Phys. Oceanogr.* (their Figs. 1–4). Also see Williams & Follows (2011), Ch. 8.3.

## Extras: vertical variations + baroclinicity

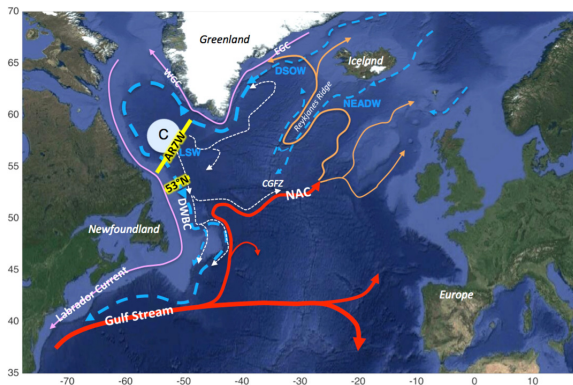
- ▶ there are of course vertical gradients in general ocean flow  
→ related to stratification through **thermal wind shear relation** (see next Lec.)  
→ allows for **baroclinic instability** (more in Lec 13 + 17)



**Figure:** Snapshots of surface relative vorticity of a double gyre model at different resolutions. From Lévy *et al.*, (2010), *Ocean Model*. (modified from their Fig. 3).

## Extras: vertical variations + baroclinicity

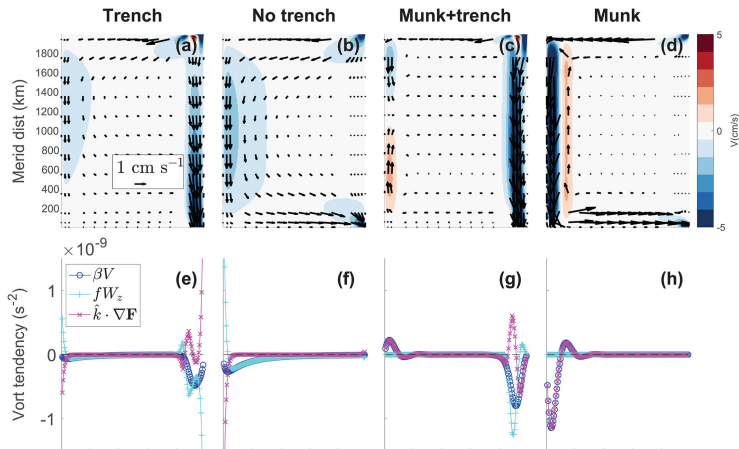
- ▶ deep WBCs but going the other way (see again in Lec. 14)
  - similar type of argument above (e.g. Stommel & Arons, 1960, *Deep-Sea Res.*)
  - modifications by **topography** (steering), **mixing** (re-circulations) etc.



**Figure:** Schematic of WBC (Gulf stream, the red line) and the deep WBC (the blue-dashed line). From Handmann *et al.*, 2018, *J. Geophys. Res: Oceans* (their Fig. 1).

# Extras: vertical variations + baroclinicity

► deep EBCs? (Yang, Tziperman & Speer, 2020, *Geophys. Res. Lett.*)

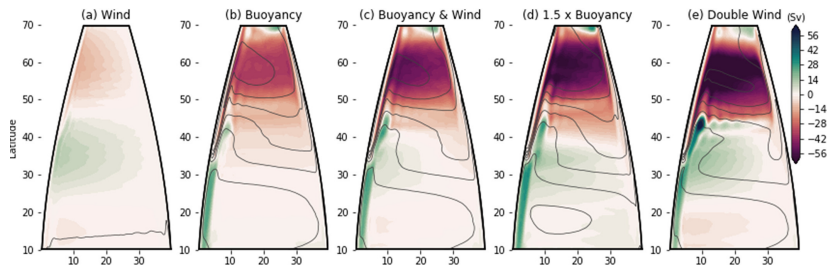


**Figure:** Meridional flow and vorticity budget and bathymetry (rows) from Yang, Tziperman & Speer, 2020, *Geophys. Res. Lett.* (modified from their Fig. 3).



## Extras: buoyancy forcing

- ▶ classical theory of wind-driven gyres, but what about **thermodynamic/buoyancy** forcing?



**Figure:** Barotropic streamfunction (rows) for a few experiments, showing the barotropic streamfunction (as shading) and the SST (as gray lines). From Hogg & Gayen (2020), *Geophys. Res. Lett.* (modified from their Fig. 3).

- ▶ **subpolar** gyre particularly affected by buoyancy forcing
- ▶ **eddies** seem to be needed (cf. Colin de Verdière, 1988, *J. Mar. Res.*)

# Summary

**Simple** (but by no means **complete**) theory for **gyre circulation**

- ▶ depth-independent, wind-driven with no topography
- ▶ **Sverdrup interior** fixes interior flow
- ▶ **vorticity balance** fixes orientation and gives **Western intensification**

→ vorticity input by wind can **only** (!) be removed at the West (in this model...)

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- ▶ start from some assumptions, just roll with it (carefully and logically) and see where it takes you...  
→ just pictures and considering whether things are pos/negative above (wasn't too bad right?)

**Theories are not static and do evolve!**

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If things in the **simple** theory doesn't work, either

- ▶ the logic was wrong (!)
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  - **topography** (e.g. Hughes & de Cuevas, 2001, *J. Phys. Oceanogr.*)
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**“All models are wrong, but some are useful”**

– attributed to George Box