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  `https://github.com/julianmak/academic-notes`

  The repository principally contains the compiled products rather than the source for size reasons.
- Associated Python code (as Jupyter notebooks mostly) will be held on the same repository. The source data however might be big, so I am going to be naughty and possibly just refer you to where you might get the data if that is the case (e.g. JRA-55 data). I know I should make properly reproducible binders etc., but I didn't...
- I do not claim the compiled products and/or code are completely mistake free (e.g. I know I don't write Pythonic code). Use the material however you like, but use it at your own risk.
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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

  $\rightarrow$ boundary acting as sink of vorticity

  $\rightarrow$ Western intensification and WBCs
- complications (extras, or things of interest)

  $\rightarrow$ topography

  $\rightarrow$ depth-dependence

  $\rightarrow$ buoyancy forcing

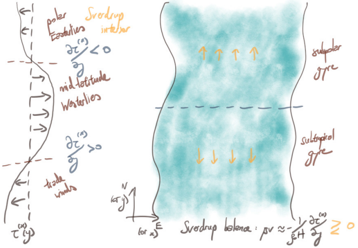
Key terms: Western Boundary Currents (WBC), vorticity balance, western intensification

Recap: Sverdrup balance

- Sverdrup balance (in meridional)

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

$\rightarrow$ Coriolis balancing wind stress curl



$\Rightarrow$ Sverdrup interior, but orientation not fixed

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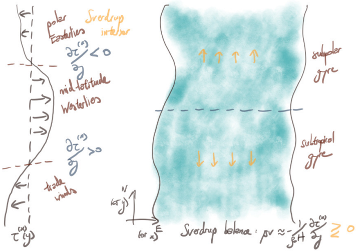


⇒ Sverdrup interior, but orientation not fixed

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 (subtropic) gyre: vorticity balance

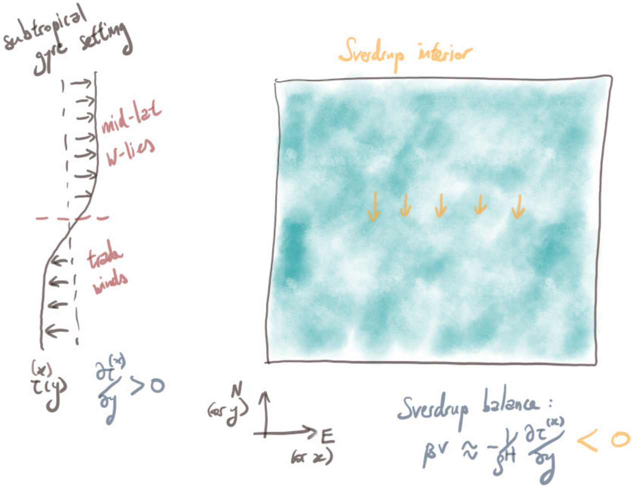
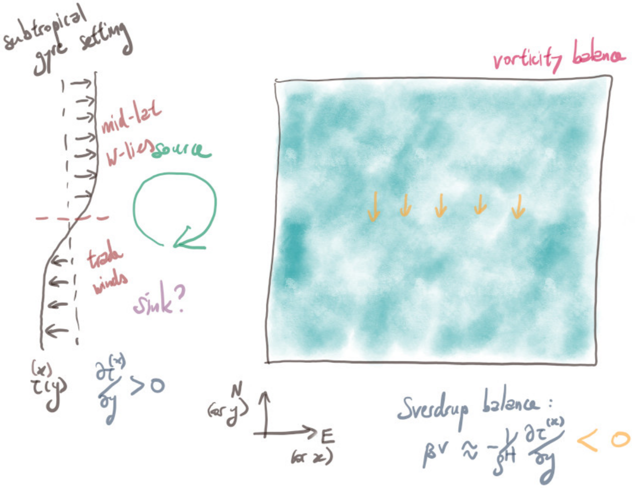


Figure: Schematic for NH subtropical gyre.

Single (subtropic) gyre: vorticity balance



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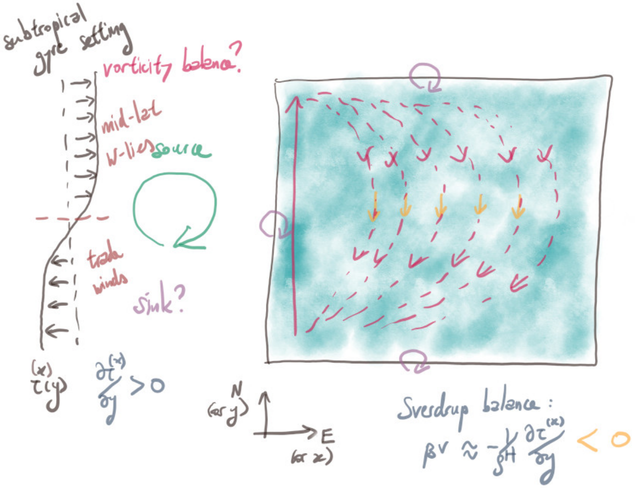

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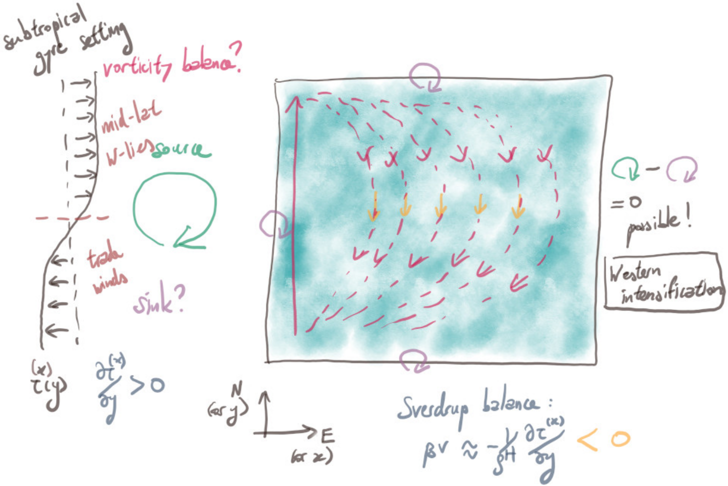

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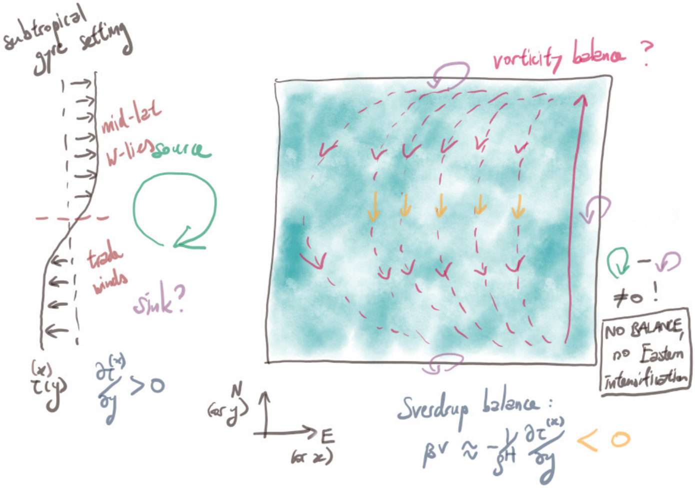

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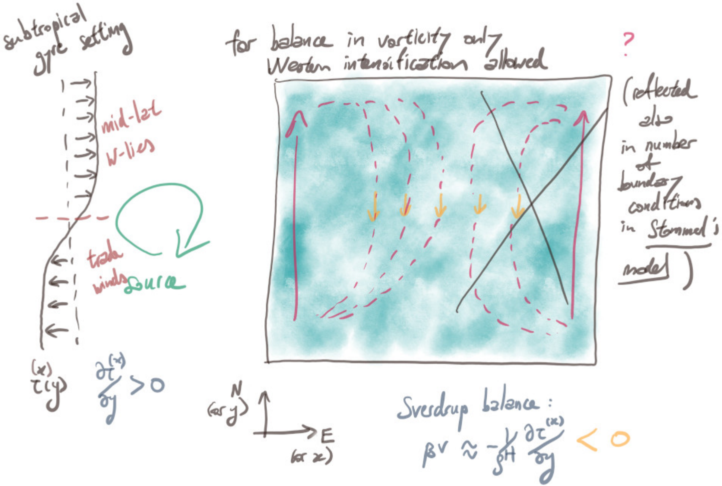

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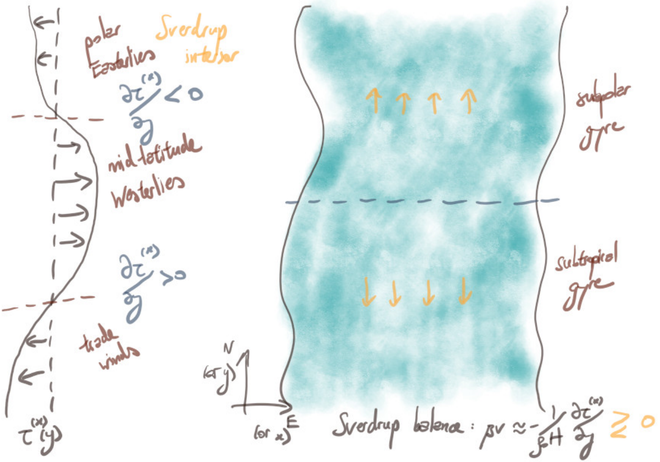
Double (subtropic + subpolar) gyres



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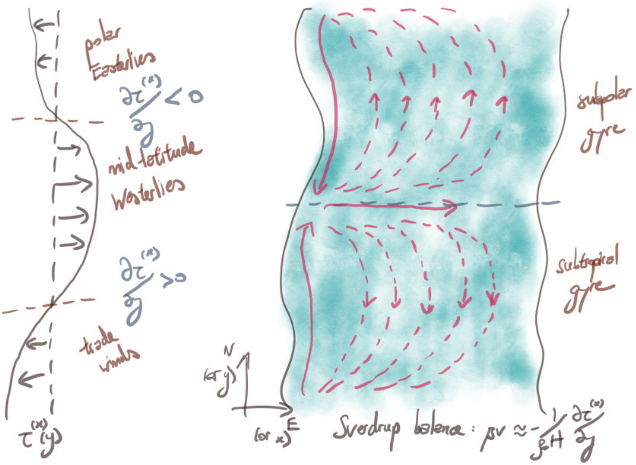
Double (subtropic + subpolar) gyres



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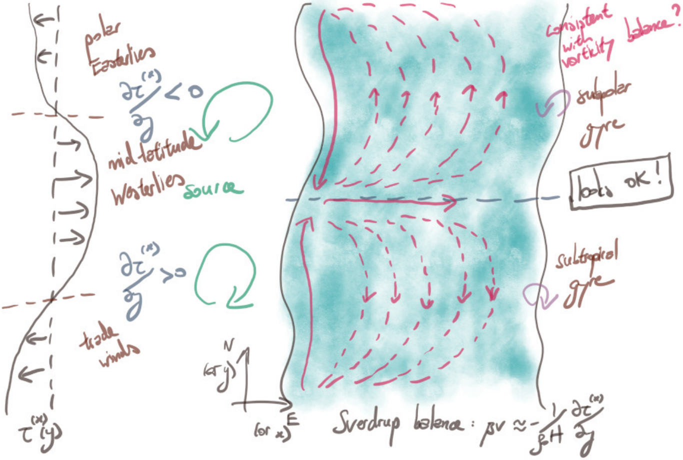

Figure: Schematic for NH double gyre.

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

  $\rightarrow$ links also with con/divergence (up/downwelling)

- boundary conditions fixes flow orientation and has to be Western intensification

  $\rightarrow$ energetically unfavourable (wind blowing against the detached current)

  $\rightarrow$ 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

  $\rightarrow$ have to put on the West, asymptotic matching for solution (see maybe OCES 3203)

  $\rightarrow$ see Ch. 14 of Vallis (2006), *Atmospheric and Ocean Fluid Dynamics* for more

Some notes

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→ EBCs are usually (!) not deep (< 1 km)

→ those that are not deep are mostly influenced by Ekman suction

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

Some notes

Useful lesson: if your argument misses on some aspects, either

- the derivation/logic is **wrong** (!)

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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

  $\rightarrow$ subtropical gyre more prominent in observations
- WBCs and resulting near-surface transport goes **polewards**

  $\rightarrow$ return EQ-ward flow in the east?

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Other discrepancies:

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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!

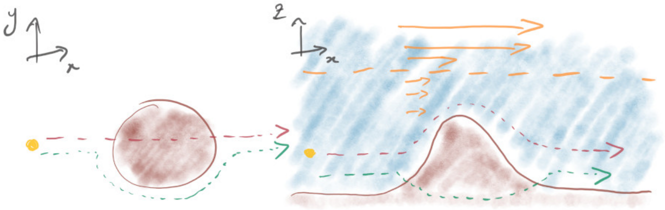

Figure: Possible paths when facing an obstacle: go over or go around. Depending on H as well one might be more preferable than the other. Note also that the strong flow above the obstacle is intuitively not strongly influenced by the obstacle (despite measures such as JEBAR stating otherwise; see e.g.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

- influence not throughout depth because baroclinicity

  $\rightarrow$ despite things like JEBAR stating otherwise...

Extras: topography

- fluid wants to try and conserve angular momentum

  → contrast this with **linear** momentum $\boldsymbol{p}$

  → related to **vorticity**, but as $q = (\omega + f)/H$ (potential vorticity, PV)

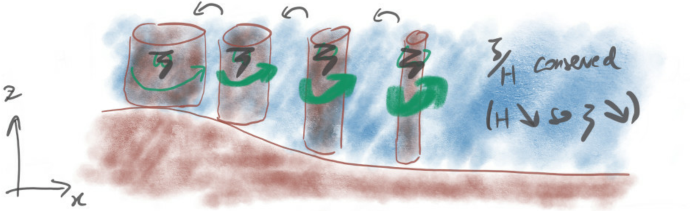

Figure: Conservation of $q = \omega/H$ (assuming $|\omega| \gg |f|$ for illustration). As H decreases, the spinning gets slower to compensate so that q is conserved.

- 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)

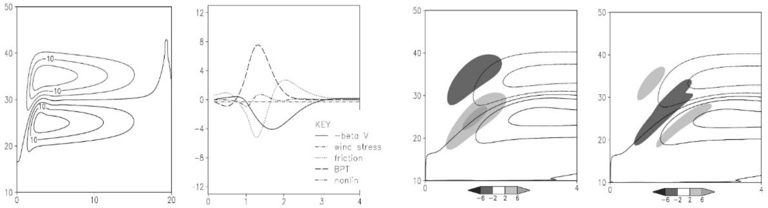

Figure: Results form a depth-independent gyre model with a slope on the west, showing (*a*) streamfunction, (*b*) balances between terms, (*c*) bottom pressure torque forcing, and (*d*) frictional forcing. Adapted from Jackson, Hughes & Williams, 2006, *J. Phys. Oceanogr.* (their Figs. 1–4). Also see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

Extras: vertical variations + baroclinicity

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

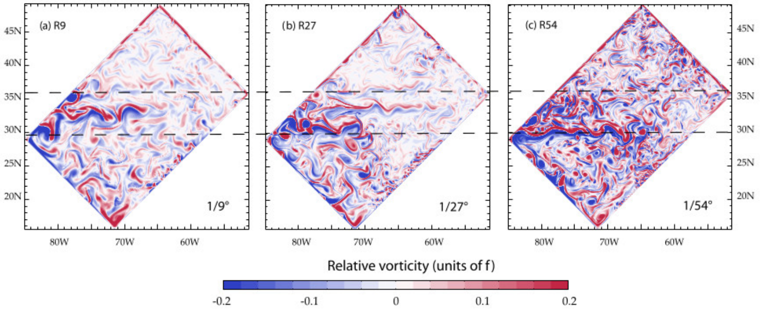

Figure: Snapshots of surface relative vorticity of a double gyre model at different resolutions. From Lévy *et al.*, (2010), *Ocean Model.* (modified from their Fig. 3).

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.

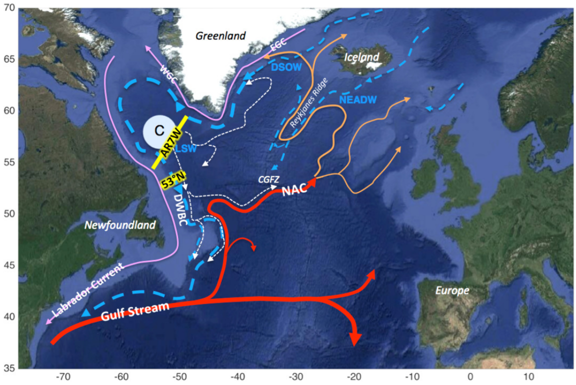

Figure: Schematic of WBC (Gulf stream, the red line) and the deep WBC (the blue-dashed line). From Handmann *et al.*, 2018, *J. Geophys. Res: Oceans* (their Fig. 1).

Extras: vertical variations + baroclinicity

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

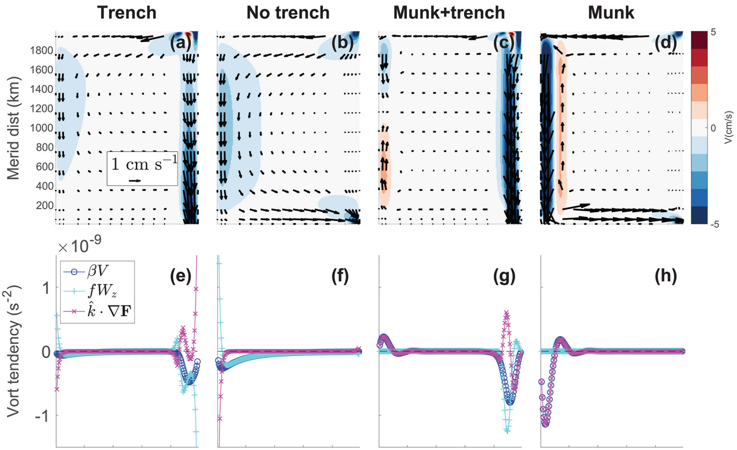

Figure: Meridional flow and vorticity budget and bathymetry (rows) from Yang, Tziperman & Speer, 2020, *Geophys. Res. Lett.* (modified from their Fig. 3).

Extras: buoyancy forcing

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

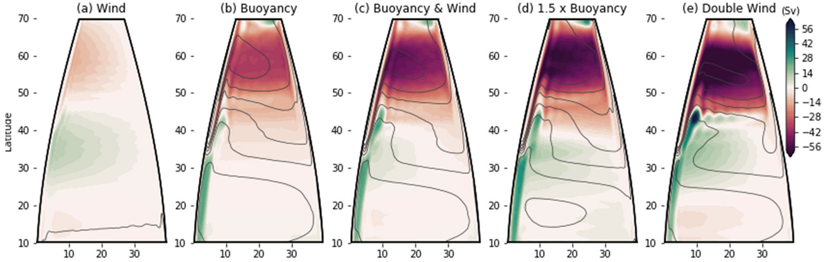

Figure: Barotropic streamfunction (rows) for a few experiments, showing the barotropic streamfunction (as shading) and the SST (as gray lines). From Hogg & Gayen (2020), *Geophys. Res. Lett.* (modified from their Fig. 3).

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

Extras: buoyancy forcing + topography

Q. previous work started from **spun up** state, spin up from rest (i.e. flat state) possible?

- dependency somewhat on whether there is a Southern Ocean opening
- transport on the weak side, but inter-hemispheric circulation
- both wind and thermodynamic forcing important?

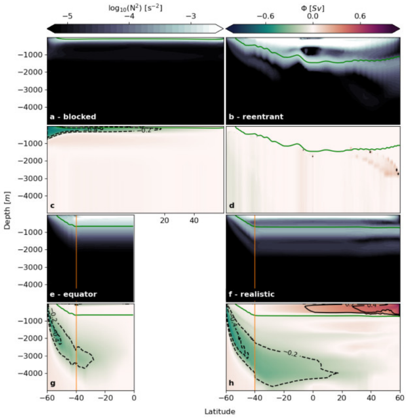

Figure: Meridional section of model stratification under different topographic scenarios. From Klocker *et al.* (2024), *Tellus A* (their Fig. 4).

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

  $\rightarrow$ 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...

  $\rightarrow$ just pictures and considering whether things are pos/negative above (wasn't too bad right?)

Theories are not static and do evolve!

Summary

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

- the logic was wrong (!)
- the theory is too simple and needs more details

  $\rightarrow$ topography (e.g. Hughes & de Cuevas, 2001, *J. Phys. Oceanogr.*)

  $\rightarrow$ depth-dependence (e.g. Yang, Tziperman & Speer, 2010, *Geophys. Res. Lett.*)

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"All models are wrong, but some are useful"

– attributed to George Box