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OCES 2003 : Descriptive Physical Oceanography

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

Lecture 13: Southern Ocean and ACC

Outline

- ▶ Southern Ocean and the Antarctic Circumpolar Current (ACC)
 - largest/strongest current in the world
- ▶ beyond the homogeneous gyre example
 - wind forcing and Ekman overturning cell (+ existence of counter overturning cell)
 - thermal wind shear relation (cf. Lec. 7 + 8)
 - stratification + form stress
 - baroclinic instability (see Lec. 17)
 - influence on MOC (see next Lec.)

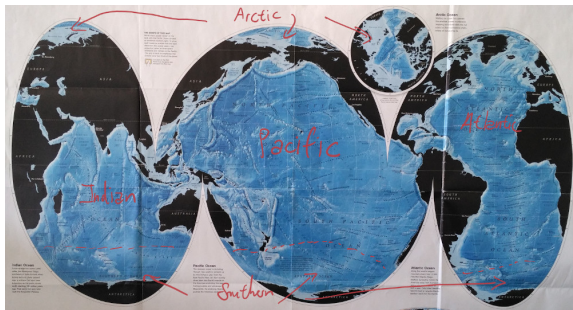
Key terms: ACC, Ekman + eddy overturning cell, thermal wind, (interfacial/topographic) form stress, baroclinicity

Recap: Southern ocean (slide from Lec 2)

Oceans separated horizontally by continental land masses

- constraints on dynamics + circulation (contrast this to atmosphere)

→ Southern ocean slightly different...



Recap: Southern ocean

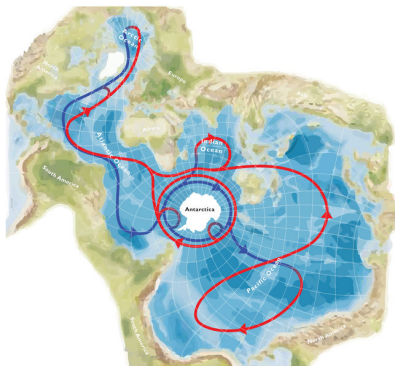


Figure: Spillhaus projection with a focus on the oceans and, in particular, of the Southern Ocean, with a schematic of the MOC put on (red = warm surface waters, blue = cold deep/abysal waters). From Mike Meredith (BAS), from his Challenger Medal ceremony talk in 2018.

- ▶ **Antarctic Circumpolar Current (ACC)**
 - world's largest current, transport of $\approx 130 \text{ Sv}$ ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$)
 - very **turbulent/unstable** region (see Lec. 17)
- ▶ **subpolar gyres** on Antarctic side
 - cyclonic (clockwise in SH), e.g. **Ross + Weddell**
- ▶ **central role in global MOC** (see Lec. 14)

Recap: stratification

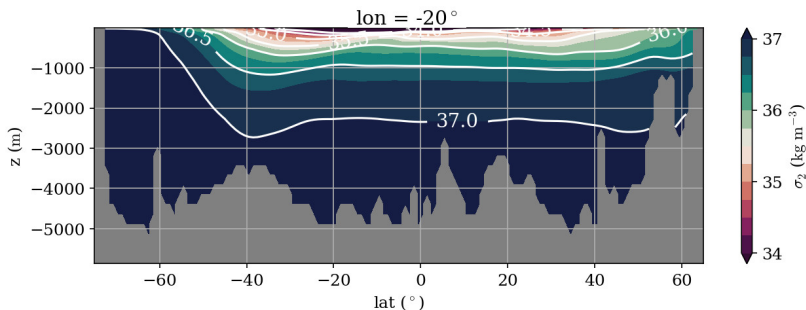


Figure: Meridional section in the Atlantic of σ_2 . See `plot_eos.ipynb`. Strongly tilting isopycnals present in the Southern Ocean, in contrast to relatively flat isopycnals in the basins.

- ▶ meridional section plot of σ_2 (see Lec. 6)
- ▶ strongly tilting isopycnals (see Lec. 6) in Southern Ocean
- ▶ wind coming out of page
- ▶ → but sign + profile of wind stress curl? (see Lec. 9)

Forcings around the Southern Ocean

buoyancy/thermodynamic forcing:

- ▶ T_{air} **cold** (high latitudes), heat **loss** from ocean
- ▶ \Rightarrow buoyancy **loss** (water getting denser)

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mechanical forcing:

- ▶ mid-latitude prevailing Eastward winds (Westerlies)
 \Rightarrow **E-ward** momentum injection
- ▶ bathymetric features
 \Rightarrow **take out** momentum (see Lec 10) via **topographic form stress**

(see later)

Forcings around the Southern Ocean

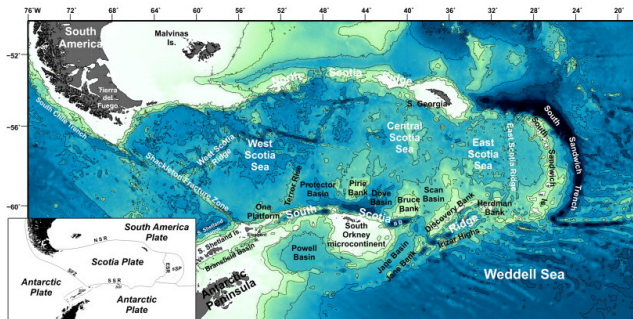


Figure: Bathymetry around the Drake passage. Figure modified from Civile *et al.* (2012), *Tectonophysics* (top half of their Fig. 1)

Some notable bathymetric features:

- ▶ **Drake passage**, a choke point for the ACC
- ▶ **Kerguelen plateau**, a wide ridge (not shown here)
→ water depth can vary from 4000 to 1000 m (recall **PV conservation** Lec. 12)

gyres vs. ACC

gyres	ACC
bounded latitudes	unblocked latitudes
	cf. atmosphere
WBC: intense narrow current ≈ 30 Sv transport	ACC: reasonably “fast”, but broad ≈ 130 Sv transport
depth-independent theory ok?	depth-independent theory “fails” e.g. Gill (1968) <i>J. Fluid Mech.</i> but see Marshall <i>et al.</i> (2016) <i>Ocean Modell.</i>
Sverdrup balance OK	eddies important

- ▶ despite differences, **dynamical** concepts shared between the two

again, **dynamics** important!

Ekman driven circulation

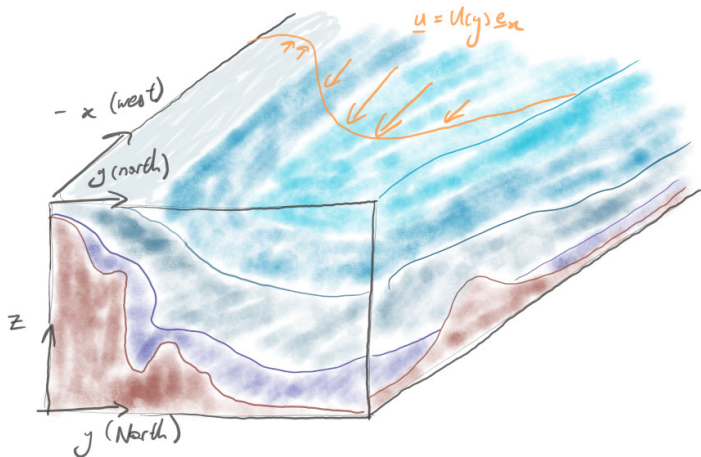


Figure: Schematic of wind forcing over Southern Ocean and associated Ekman circulation (recall Lec. 9). $f < 0$ because we are in the Southern Hemisphere. Diagram based on Olbers [ref here](#)

Ekman driven circulation

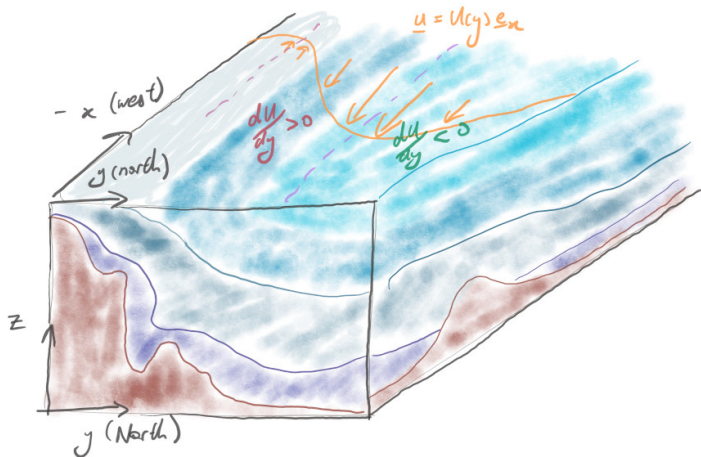


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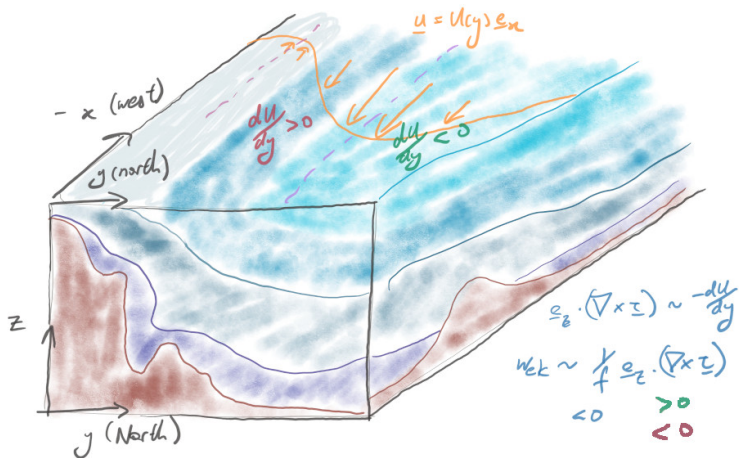


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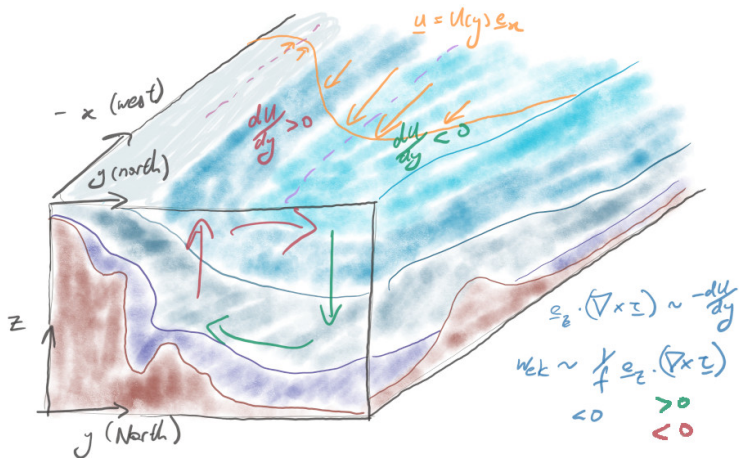


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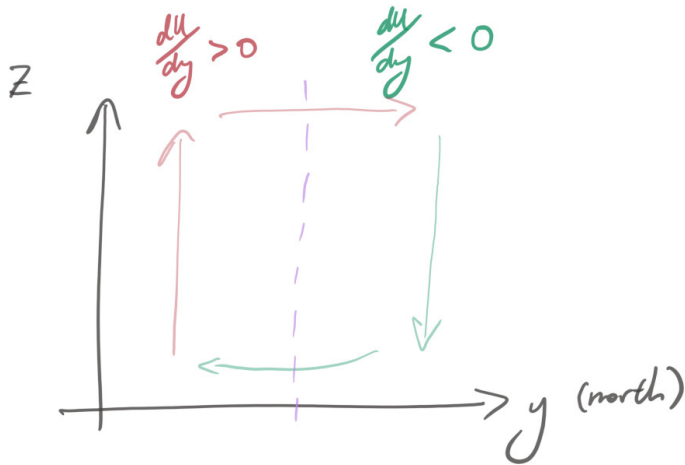


Figure: Ekman overturning and its consequences.

Ekman driven circulation

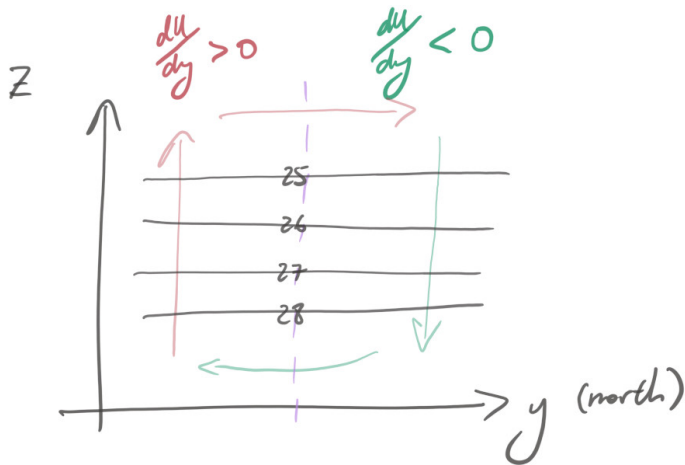


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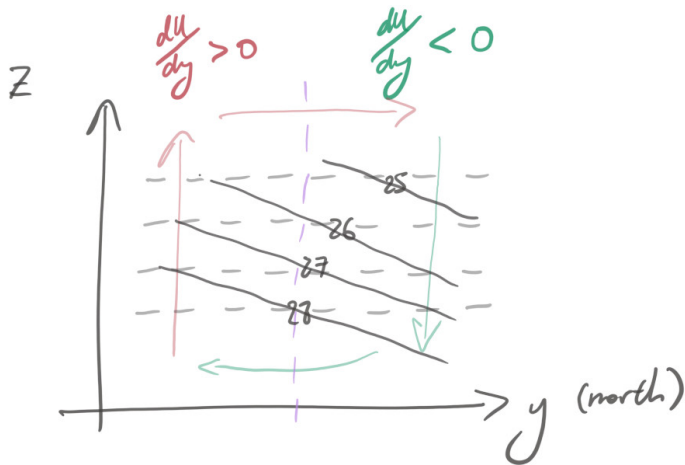


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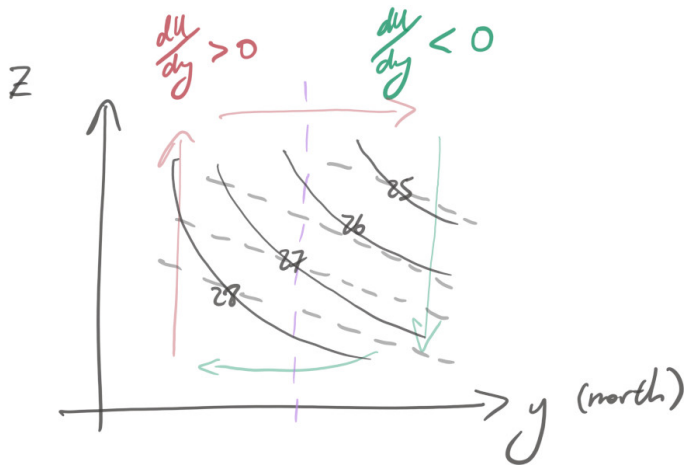


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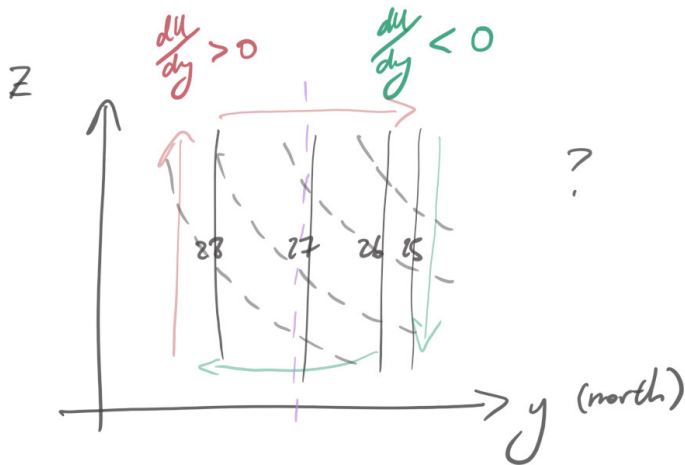


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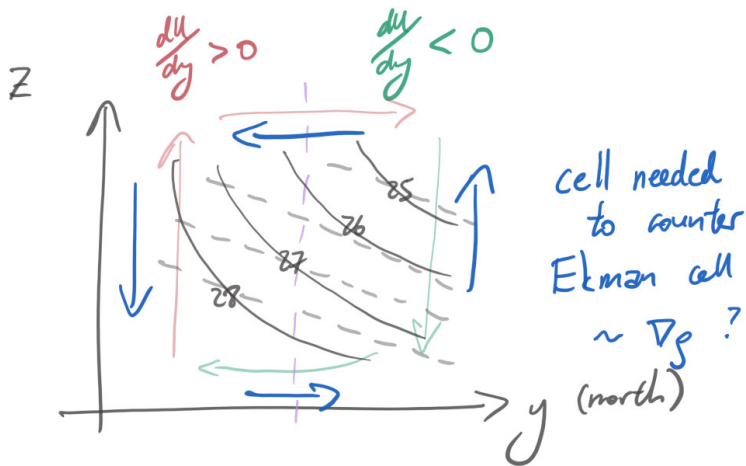


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- eliminate p , so take ∇ of hydrostatic balance and $\partial/\partial z$ of geostrophic balance (shenanigans here!):

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- eliminate pressure to get

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$$f \mathbf{e}_z \times \frac{\partial \mathbf{u}_g}{\partial z} \stackrel{!}{=} -\frac{g}{\rho} \nabla \rho$$

- ▶ **thermal wind relation** (ignoring some shenanigans for now) says that
horizontal gradients in $\rho \sim$ vertical gradients in u_g
- ▶ tilting isopycnals implies there a geostrophic flow
 - system needs to be rotating
 - more tilt = stronger flow
 - direction depends on tilt and hemisphere (because f changes sign)
- ? combine with SSH to get **vertical profile** of geostrophic flow? (see Lec. 20, OCES 3203, maybe OCES 3301)

Thermal wind relation

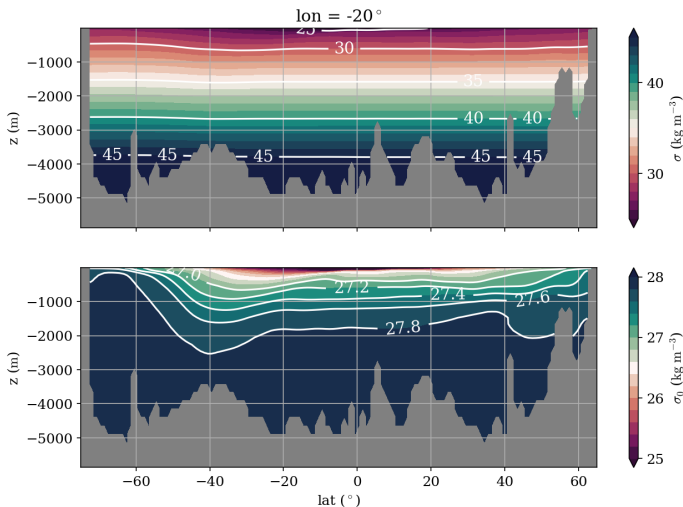


Figure: Meridional section in the Atlantic of (top) in-situ density and (bot) σ_0 . See `plot_eos.ipynb`. σ_0 implies there is a thermal wind coming out of the page in the Southern Ocean (because $f < 0$), consistent with what we know. On the other hand, in-situ density σ implies basically nothing is going on, which we know is not true.

2/3 way point

- ▶ wind puts momentum in + induces an **overturning** via **Ekman suction/pumping** (Lec. 9)
 - **steepens** isopycnals (Lec. 5 + 6)
 - cannot continue indefinitely (otherwise **convectively unstable**), existence of **counter overturning cell** (see later)
- ▶ **thermal wind shear relation**
 - hydrostatic + geostrophic balance (Lec. 7 + 8)
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- ▶ **baroclinic** theory here, **vertical structure** + **stratification** involved
 - cf. homogeneous gyre theory, but ideas here also apply somewhat there

Form stress

How is momentum removed?

- ▶ removal at bottom (momentum input by wind \sim momentum removal at ocean floor loss to land)
 - but how? (**topographic form stress**)
 - role of **PV conservation**? (Lec. 12)
- ▶ how is it **transferred** vertically? (**interfacial form stress**)

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in essence **pressure gradients** (Lec. 7)

Form stress

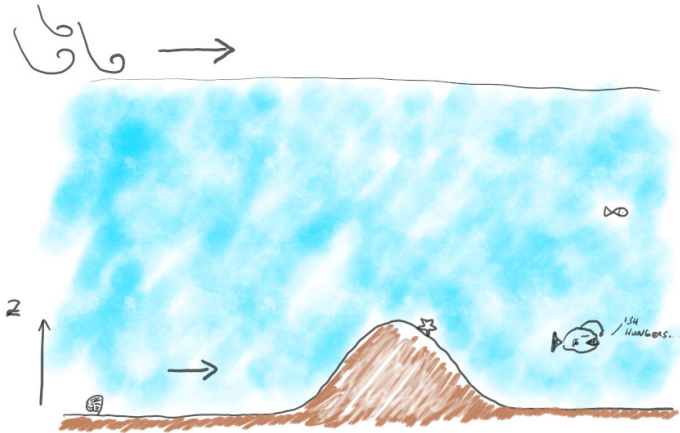


Figure: Schematic of (interfacial + topographic) form stress.

Form stress

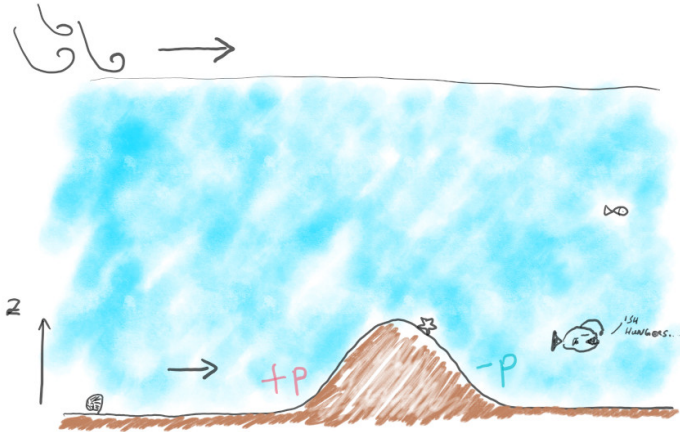


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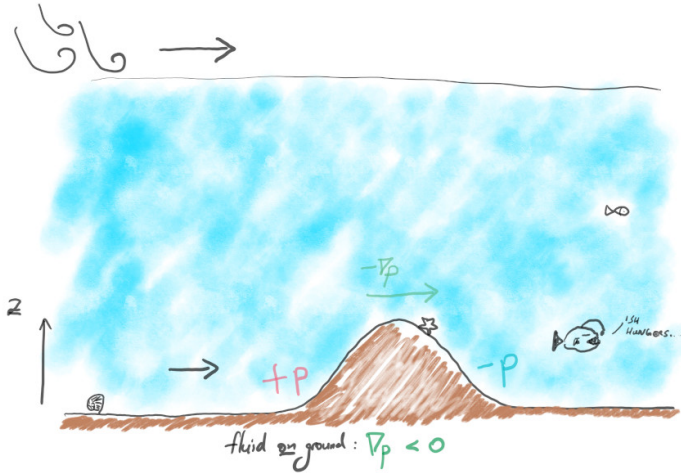


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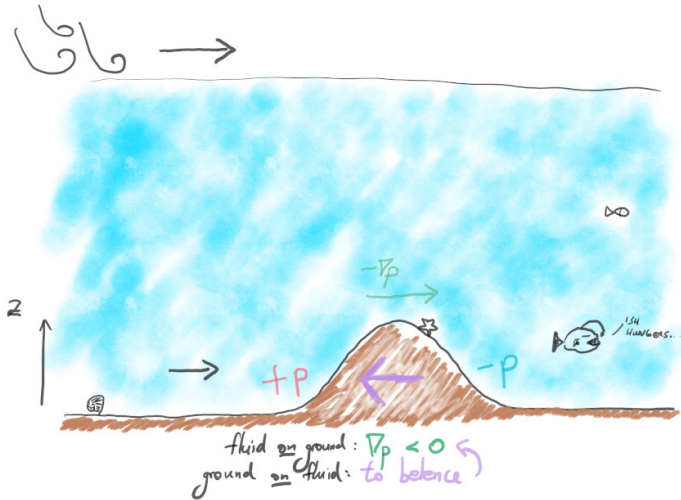


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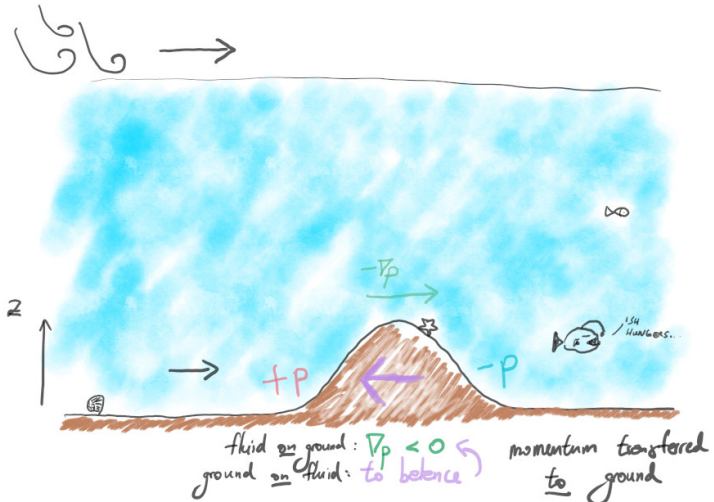


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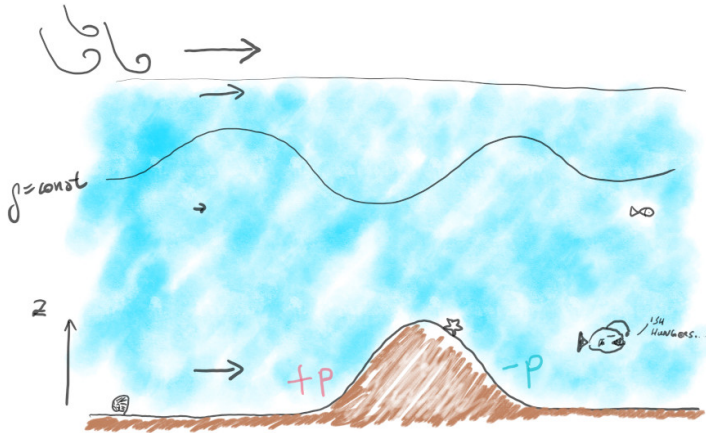


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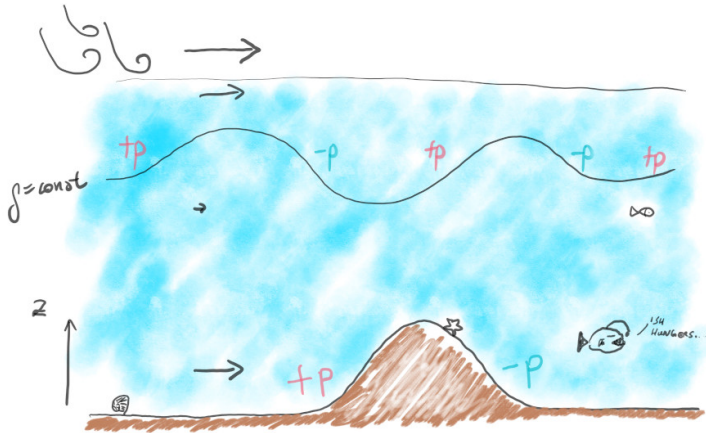


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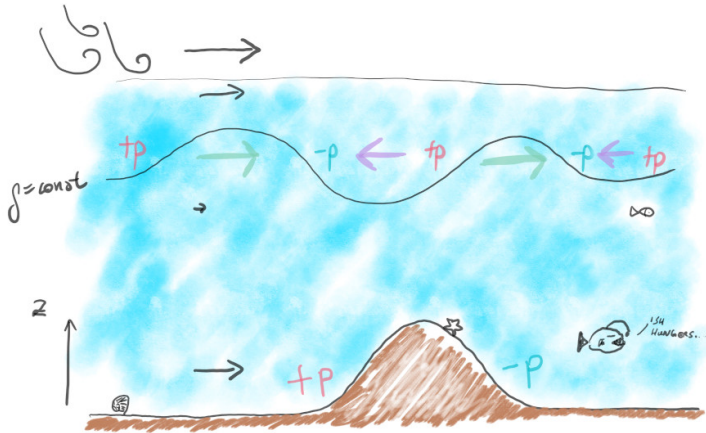


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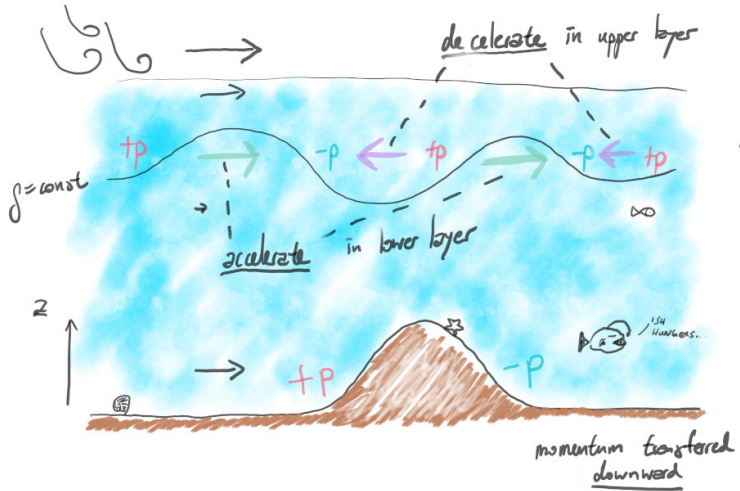


Figure: Schematic of (interfacial + topographic) form stress.

f/H contours (recall Lec. 12)

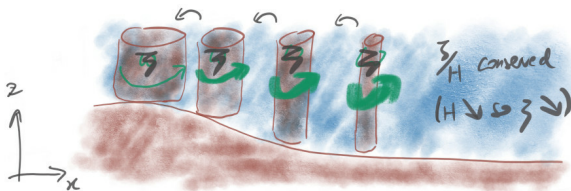


Figure: Conservation of $q = \omega/H$ (assuming $|\omega| \gg |f|$ for illustration). As H decreases, the spinning gets faster to compensate so that q is conserved.

Recall PV was loosely defined as (Lec 12) $q = (f + \omega)/H$

- ▶ **planetary** f + **relative** $\omega = \mathbf{e}_z \cdot \nabla \times \mathbf{u}$ vorticity, scaled by fluid depth H
 → on large-scales $|\omega| \ll |f|$ (homework exercise)
- ▶ geostrophic flow **wants** to travel along $q \approx f/H$ contours
 → to conserve **angular momentum**

Q. at given latitude, f is fixed by H might not be, so whats the consequences?

f/H contours

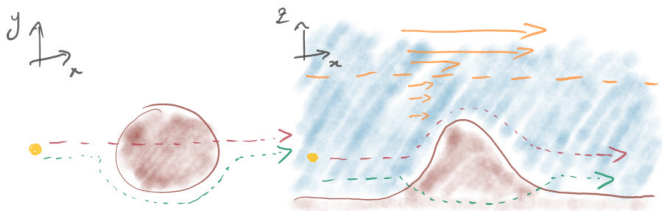


Figure: Some consequences of f/H contours.

- ▶ if bathymetric feature not that tall ($H \approx H_{\text{ref}}$), just go **over**
 - not that much “pressing” onto bathymetry
 - weaker ∇p so smaller topographic form stress
 - **weak** deceleration, weak topographic influence
- ▶ theories neglecting baroclinicity + topography results in ACC transport being ridiculously large

f/H contours

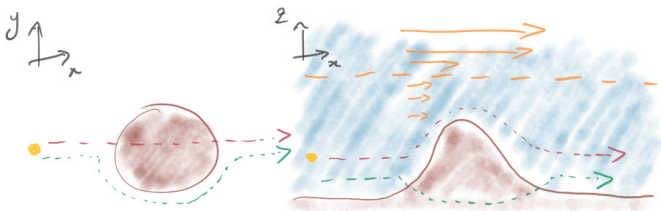
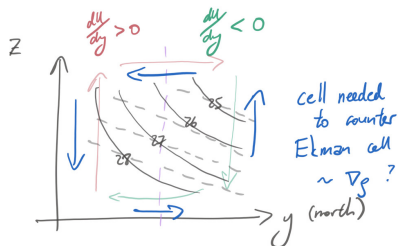


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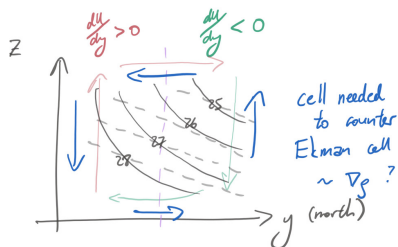
- ▶ if bathymetric feature tall enough ($H < H_{\text{ref}}$), f/H contours can be **blocked**
 - significant “pressing” onto bathymetry
 - strong ∇p so stronger topographic form stress
 - **strong** deceleration, topographic influence significant
 - e.g. Drake passage, Kerguelen plateau

Quick brief on baroclinic instability (more in Lec. 17)



- ▶ what is the source of the counter overturning cell?
 - strength probably needs to be related to **isopycnal slopes**

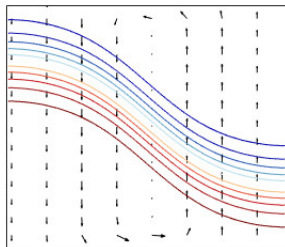
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baroclinic instability

- ▶ sloping isopycnals \sim vertically sheared flow (thermal wind)
- ▶ sheared flow \Rightarrow instability (see Lec. 17)
→ **reduce** vertical shear \sim **flatten** isopycnals



Quick brief on baroclinic instability (more in Lec. 17)

eye candy

Quick brief on baroclinic instability (more in Lec. 17)

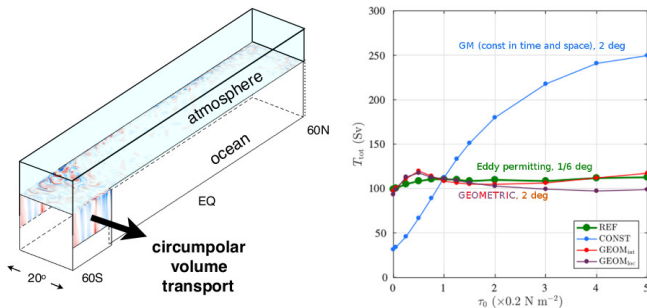


Figure: Idealised sector model from Munday, Johnson & Marshall (2013), *J. Phys Oceanogr.* and results on ACC transport (related to Southern Ocean overturning) sensitivity with changes of wind depending on **mesoscale parameterisation**, from Mak *et al.* (2018), *J. Phys Oceanogr.*.

- **residual** of Ekman and eddy cell affects SO stratification
 - affects ACC transport through thermal wind
 - can have **global** effect via isopycnal connectivity to all ocean basins (see Lec. 14)

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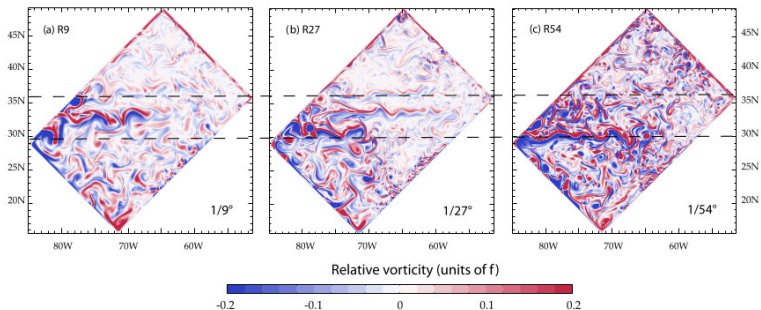


Figure: Snapshots of surface relative vorticity of a double gyre model at different resolutions. From Lévy *et al.*, (2010), *Ocean Model*. (modified from their Fig. 3).

- important in gyres too (see Lec. 12)
 - shaping the WBC, **bio-physical interaction**, momentum transfer etc.

Summary

- ▶ Southern Ocean the “center” of the global ocean
 - unblocked latitudes
 - stratification here can influence **global** stratification (and in turn global **MOC**, ocean heat content etc.) (see Lec. 14)
- ▶ ACC largest current in the world
 - tilting isopycnals, **thermal wind relation** (geostrophic + hydrostatic balance) (more in Lec. 20)
 - **Ekman** vs. **eddy** overturning cell, **residual** affecting overall stratification
 - role of **form stress** and **f/H contours**
 - **baroclinic eddies** a source of form stress + flattens isopycnals (more in Lec. 17)

Key role of **dynamics, applicable to ACC + gyres!**