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  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 13: Southern Ocean and ACC

Outline

- Southern Ocean and the Antarctic Circumpolar Current (ACC)

  $\rightarrow$ largest/strongest current in the world

- beyond the homogeneous gyre example

  $\rightarrow$ wind forcing and Ekman overturning cell (+ existence of counter overturning cell)

  $\rightarrow$ thermal wind shear relation (cf. Lec. 7 + 8)

  $\rightarrow$ stratification + form stress

  $\rightarrow$ baroclinic instability (see Lec. 17)

  $\rightarrow$ influence on MOC (see next Lec.)

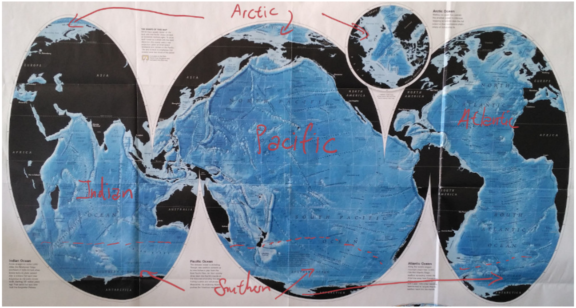
Key terms: ACC, Ekman + eddy overturning cell, thermal wind, (interfacial/topographic) form stress, baroclinicity

Recap: Southern ocean (slide from Lec 2)

Oceans separated horizontally by continental land masses

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

  $\rightarrow$ Southern ocean slightly different...



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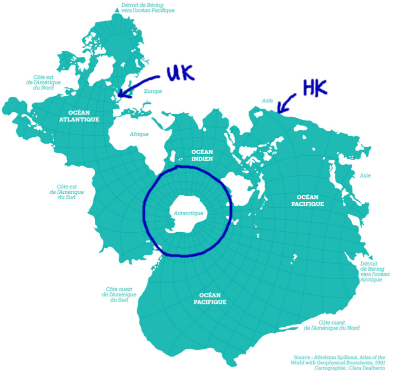

Figure: Spillhaus projection with a focus on the oceans and, in particular, of the Southern Ocean. See diagram for origin of diagram.

- **unblocked** latitudes, no zonal landmass boundaries

  → dynamical implications? (see later)

  → paleoclimate consequences? (see OCES 4001)
- forced by SH mid-latitude prevailing Eastward wind (Westerlies)
- connected to all other major ocean basins

Recap: Southern ocean

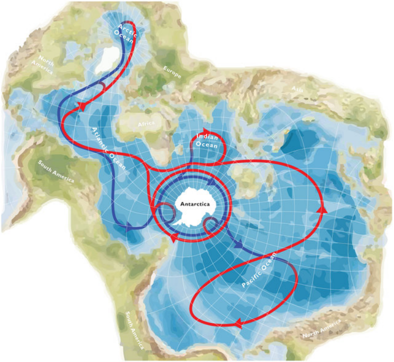

Figure: Spillhaus projection with a focus on the oceans and, in particular, of the Southern Ocean, with a schematic of the MOC put on (red = warm surface waters, blue = cold deep/abyssal waters). From Mike Meredith (BAS), from his Challenger Medal ceremony talk in 2018.

- **Antarctic Circumpolar Current** (ACC)

  → world's largest current, transport of ≈ 130 Sv (1 Sv = 10^6 m^3 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

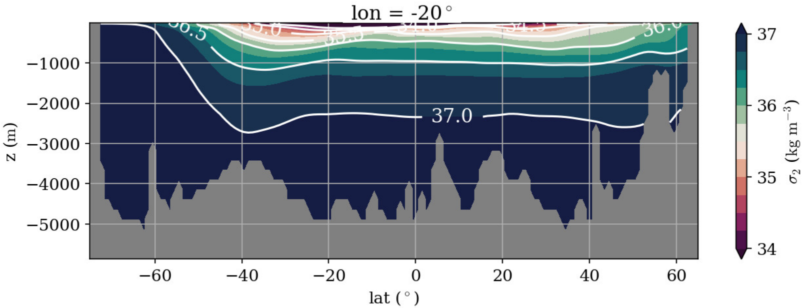

Figure: Meridional section in the Atlantic of σ_2. See `plot_eos.ipynb`. Strongly tilting isopycnals present in the Southern Ocean, in contrast to relatively flat isopycnals in the basins.

- meridional section plot of σ_2 (see Lec. 6)
- strongly tilting isopycnals (see Lec. 6) in Southern Ocean
- wind coming out of page
- $\rightarrow$ 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 feautres

  $\Rightarrow$ **take out** momentum (see Lec 10) via topographic form stress

  (see later)

Forcings around the Southern Ocean

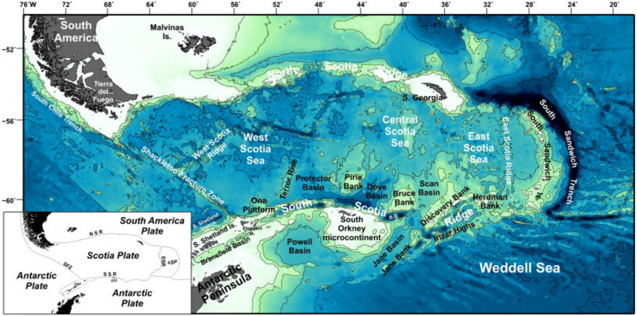


Figure: Bathymetry around the Drake passage. Figure modified from Civile *et al.* (2012), *Tectonophysics* (top half of their Fig. 1)

Some notable bathymetric features:

- Drake passage, a choke point for the ACC
- Kerguelen plateau, a wide ridge (not shown here)

$\rightarrow$ 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	ACC: reasonably "fast", but broad
$\approx$ 30 Sv transport	$\approx$ 130 Sv transport
depth-independent theory ok?	depth-independent theory "fails"
	e.g. Gill (1968) *J. Fluid Mech.*
	but see Marshall *et al.* (2016) *Ocean Modell.*
Sverdrup balance OK	eddies important

- despite differences, dynamical concepts shared between the two

again, dynamics important!

Ekman driven circulation

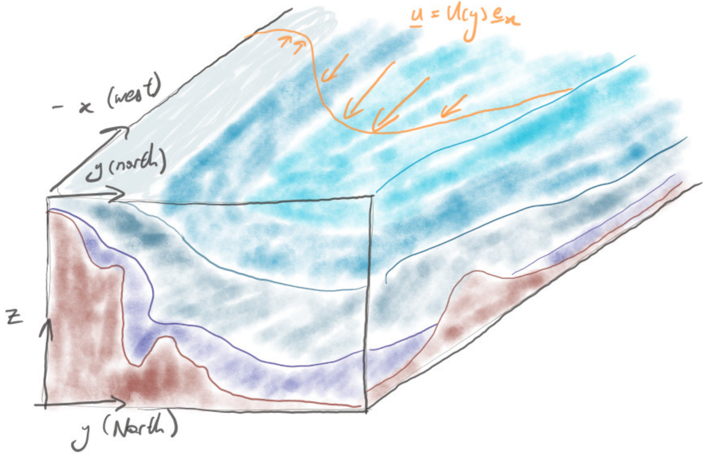
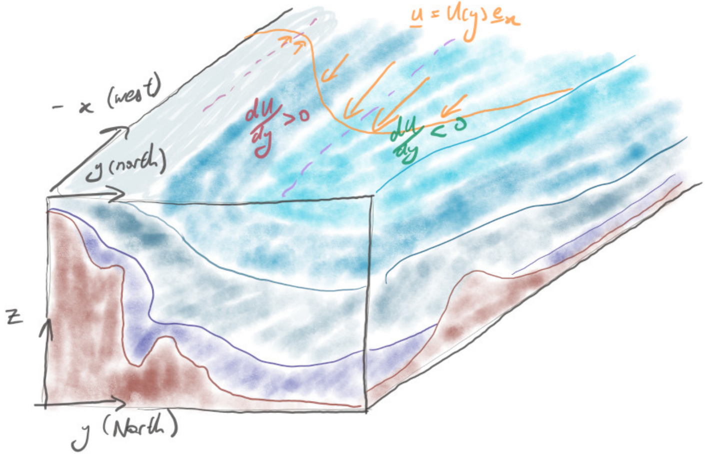


Figure: Schematic of wind forcing over Southern Ocean and associated Ekman circulation (recall Lec. 9). $f < 0$ because we are in the Southern Hemisphere. Diagram based on Olbers ref here

Ekman driven circulation



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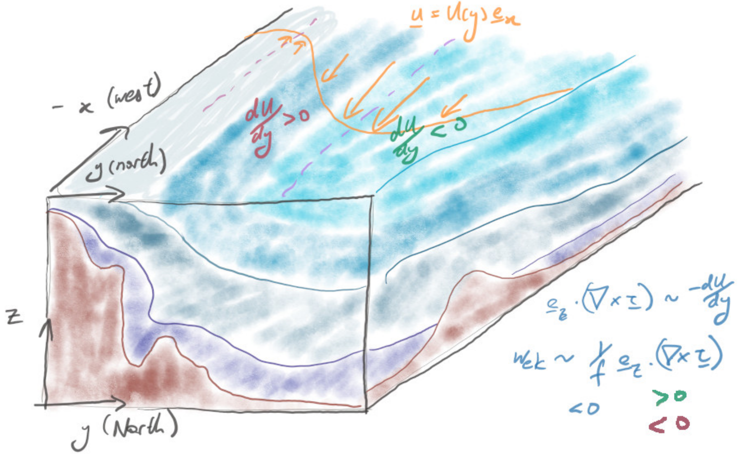

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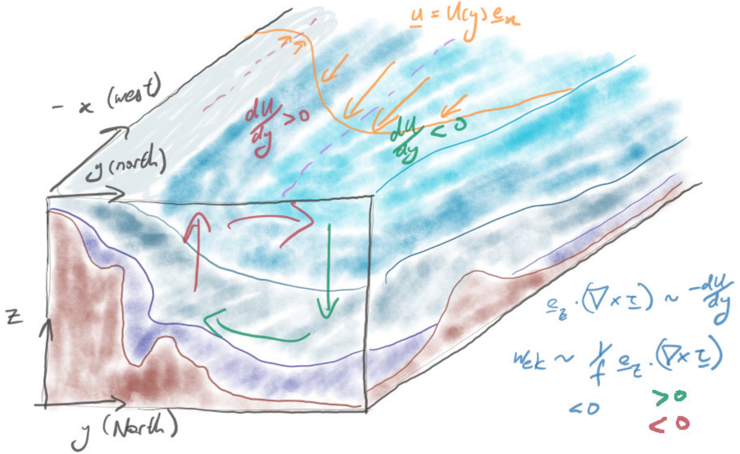

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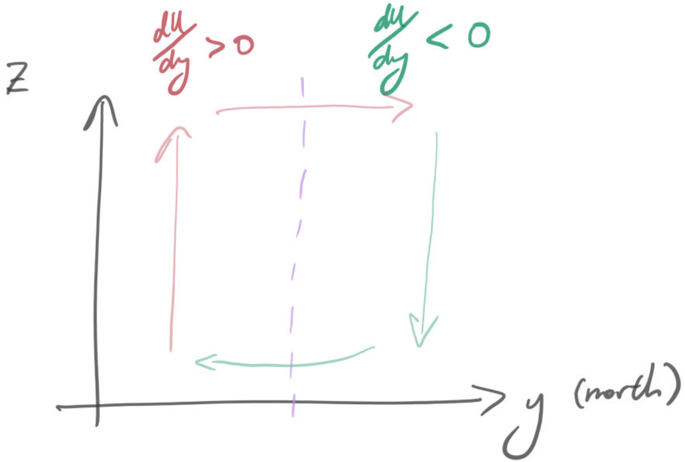

Figure: Ekman overturning and its consequences.

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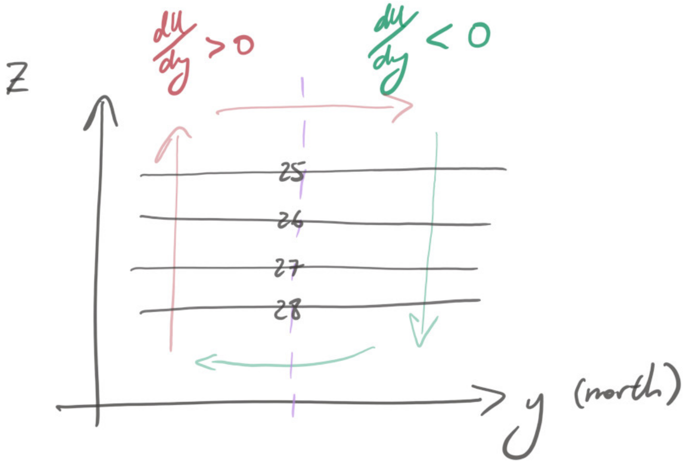

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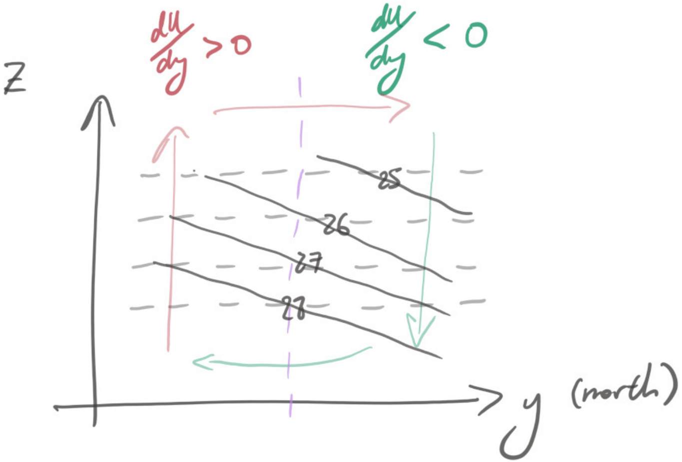

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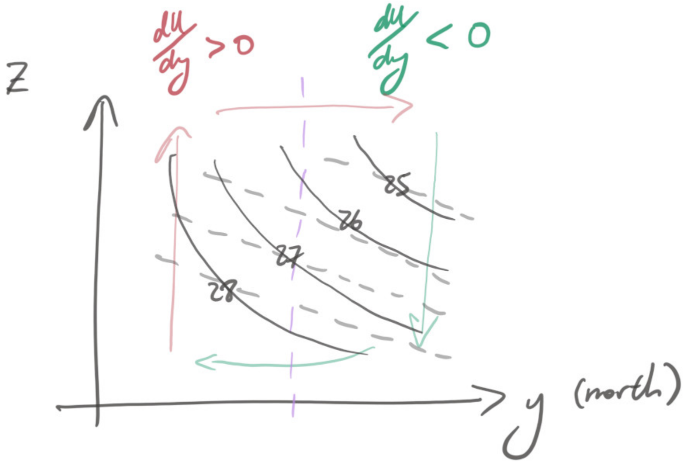

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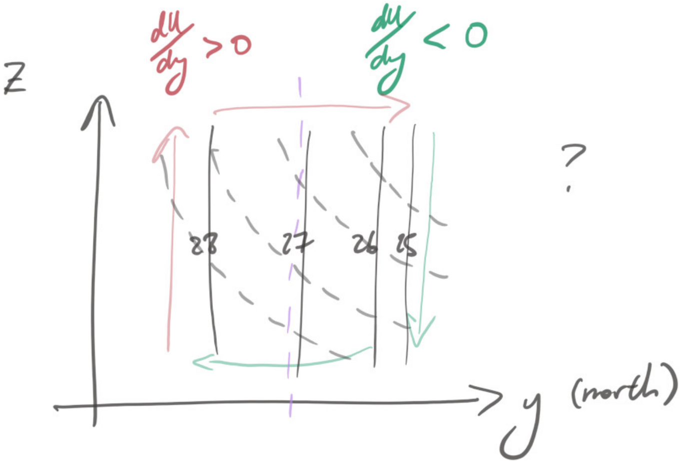

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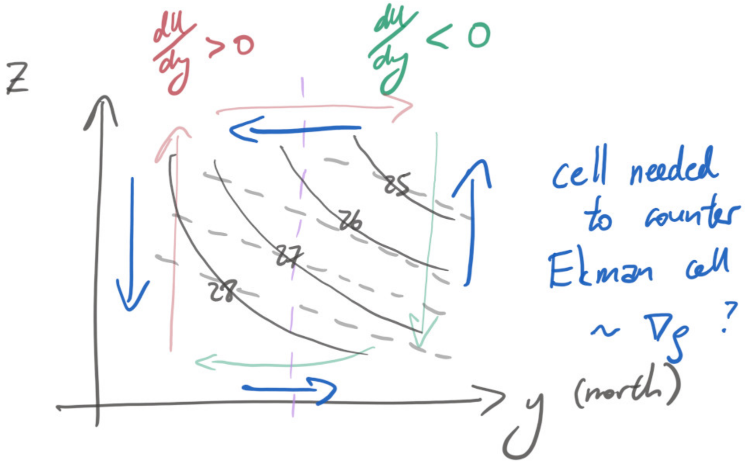

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Thermal wind relation

SO stratification control, how is it related to ACC?

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

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- eliminate pressure to get

$$\boxed{f\boldsymbol{e}_z \times \frac{\partial \boldsymbol{u}_g}{\partial z} \overset{!}{=} \frac{g}{\rho_0}\nabla\rho}$$

Thermal wind relation

$$f\boldsymbol{e}_z \times \frac{\partial \boldsymbol{u}_g}{\partial z} \overset{!}{=} \frac{g}{\rho}\nabla\rho$$

- thermal wind relation (ignoring some shenanigans for now) says that

  horizontal gradients in ρ $\sim$ vertical gradients in $\boldsymbol{u}_g$

- tilting isopycnals implies there a geostrophic flow

  $\rightarrow$ system needs to be rotating

  $\rightarrow$ more tilt $=$ stronger flow

  $\rightarrow$ 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

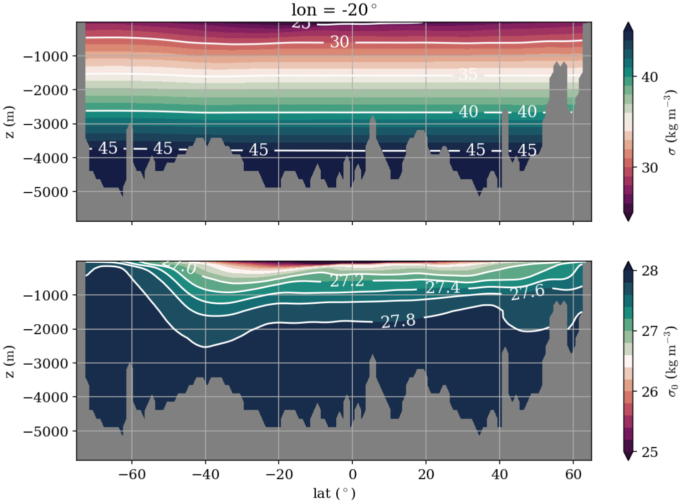

Figure: Meridional section in the Atlantic of (top) in-situ density and (bot) σ_0. See `plot_eos.ipynb`. σ_0 implies there is a thermal wind coming out of the page in the Southern Ocean (because $f < 0$), consistent with what we know. On the other hand, in-situ density σ implies basically nothing is 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)

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  → hydrostatic + geostrophic balance (Lec. 7 + 8)

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  → consistent with E-ward wind momentum input
- 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)

  $\rightarrow$ but how? (topographic form stress)

  $\rightarrow$ 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

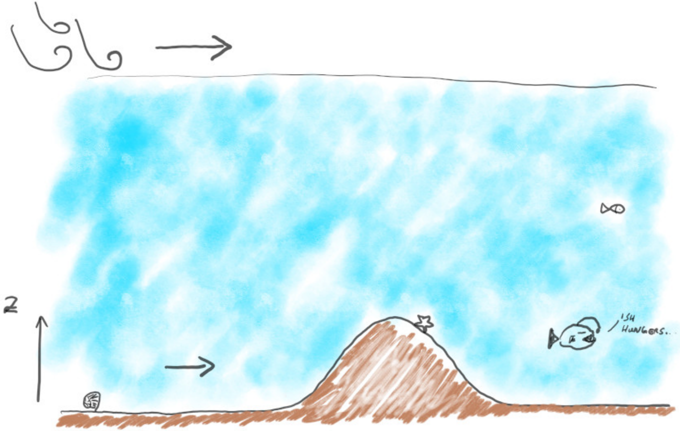
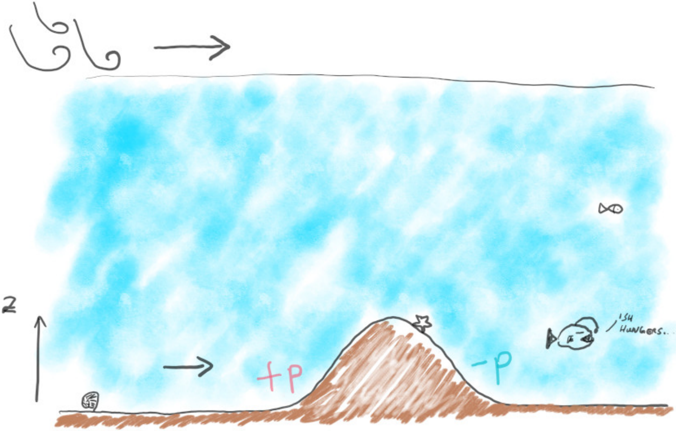


Figure: Schematic of (interfacial + topographic) form stress.

Form stress



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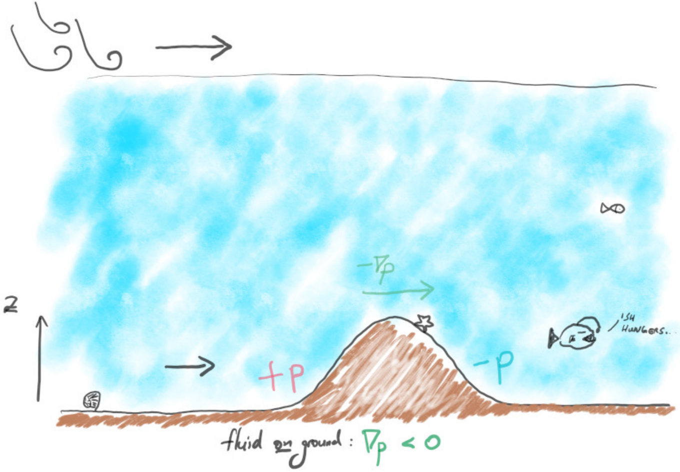

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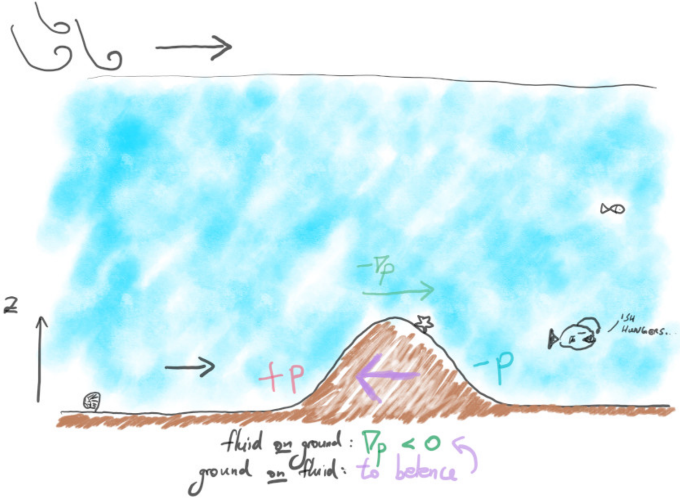

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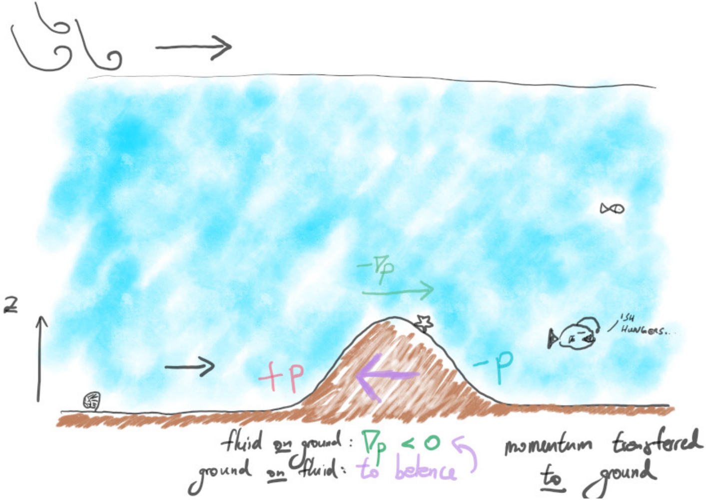

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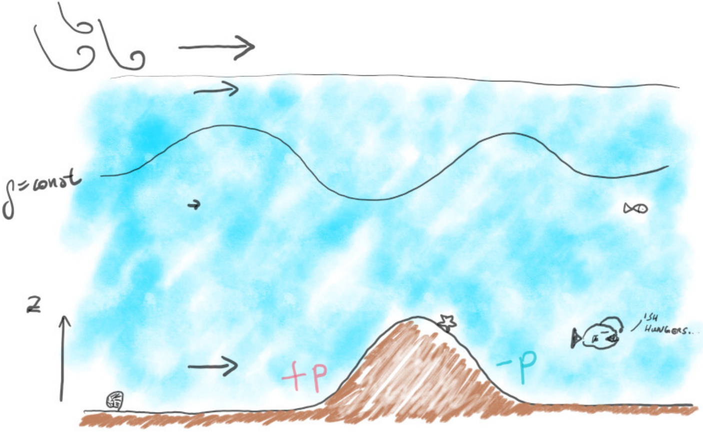

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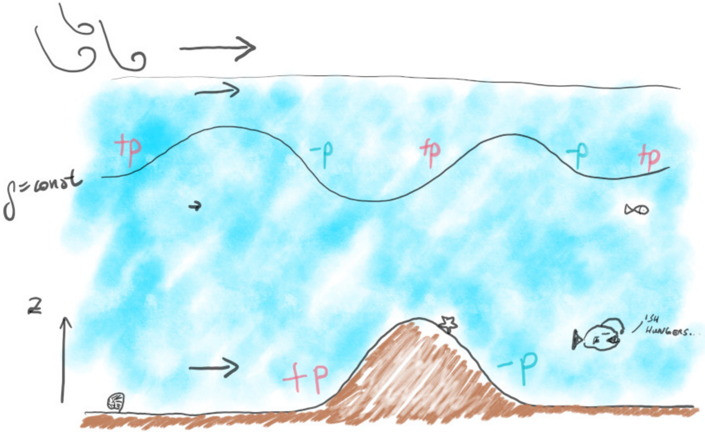

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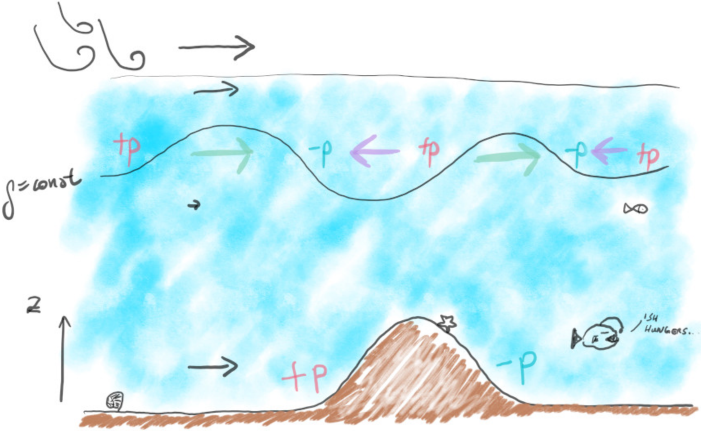

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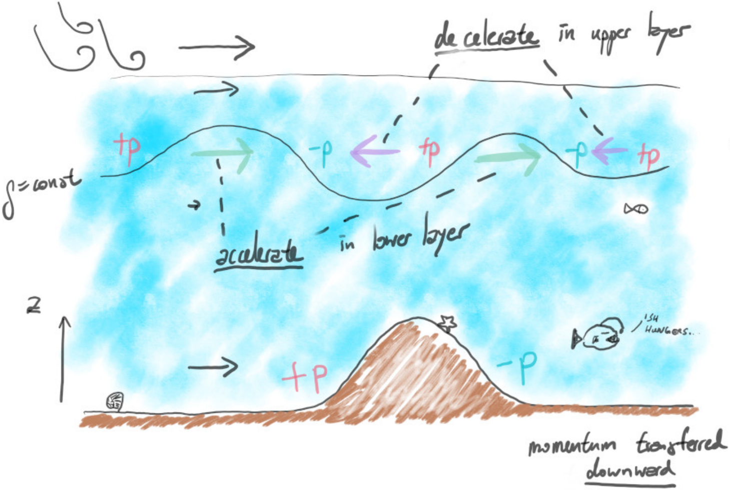


Figure: Schematic of (interfacial + topographic) form stress.

f/H contours (recall Lec. 12)

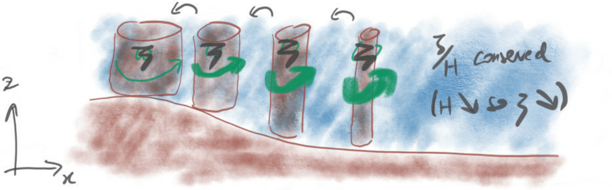


Figure: Conservation of $q = \omega/H$ (assuming $|\omega| \gg |f|$ for illustration). As H decreases, the spinning gets faster to compensate so that q is conserved.

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

- planetary f + relative $\omega = \boldsymbol{e}_z \cdot \nabla \times \boldsymbol{u}$ vorticity, scaled by fluid depth H

  $\rightarrow$ on large-scales $|\omega| \ll |f|$ (homework exercise)
- geostrophic flow **wants** to travel along $q \approx f/H$ contours

  $\rightarrow$ to conserve angular momentum

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

f/H contours

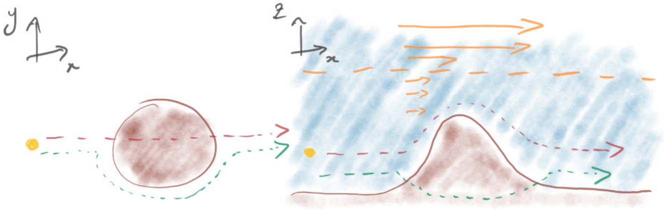


Figure: Some consequences of f/H contours.

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

f/H contours

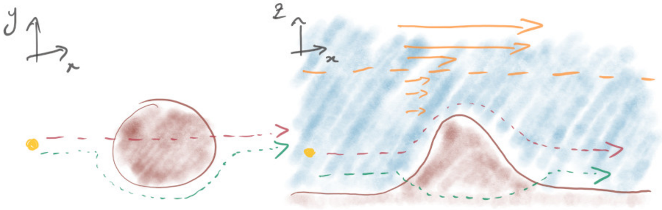


Figure: Some consequences of f/H contours.

- if bathymetric feature tall enough ($H < H_{\text{ref}}$), f/H contours can be blocked

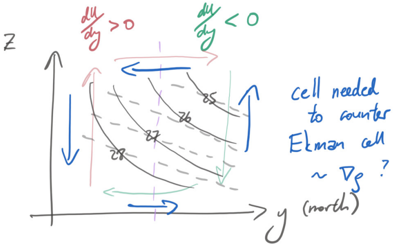
  $\rightarrow$ significant "pressing" onto bathymetry

  $\rightarrow$ strong ∇p so stronger topographic form stress

  $\rightarrow$ **strong** deceleration, topographic influence significant

  $\rightarrow$ 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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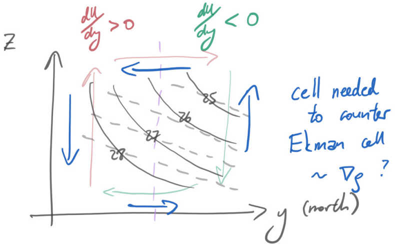

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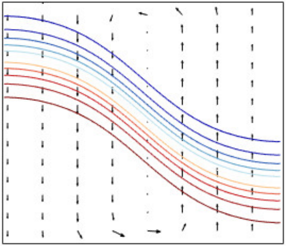
baroclinic instability

- sloping isopycnals ∼ vertically sheared flow (thermal wind)
- sheared flow ⇒ instability (see Lec. 17)

  → **reduce** vertical shear ∼ **flatten** isopycnals



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

eye candy

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

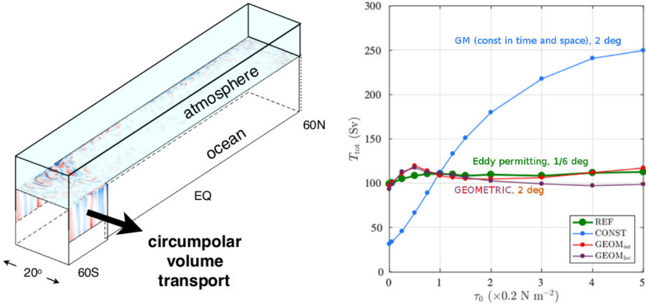


Figure: Idealised sector model from Munday, Johnson & Marshall (2013), *J. Phys Oceanogr.* and results on ACC transport (related to Southern Ocean overturning) sensitivity with changes of wind depending on mesoscale parameterisation, from Mak *et al.* (2018), *J. Phys Oceanogr.*.

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

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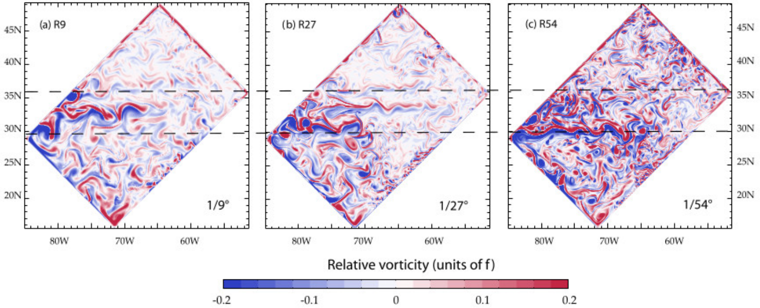

Figure: Snapshots of surface relative vorticity of a double gyre model at different resolutions. From Lévy *et al.*, (2010), *Ocean Model.* (modified from their Fig. 3).

- 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!