Dynamics of the Atlantic meridional overturning circulation and Southern Ocean in an ocean model of intermediate complexity

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Outline

1. Introduction

2. Model

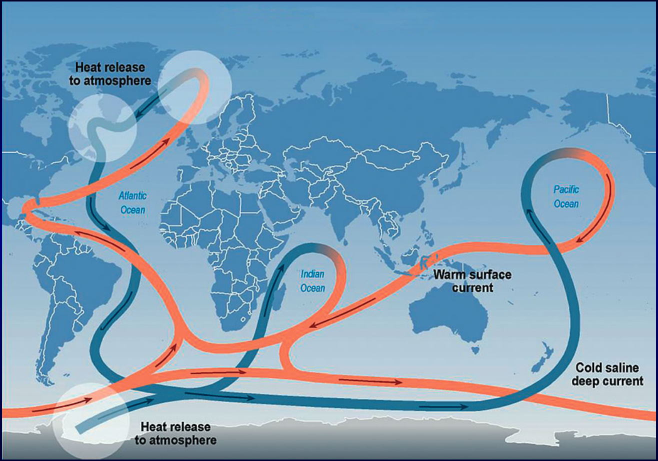
3. Solutions

4. Summary

Background

McCreary et al. 2016. Dynamics of the Atlantic meridional overturning circulation and Southern Ocean. . . . *Prog. Oceanogr.* `http://dx.doi.org/10.1016/j.pocean.2016.01.001`.

"Great Conveyor"

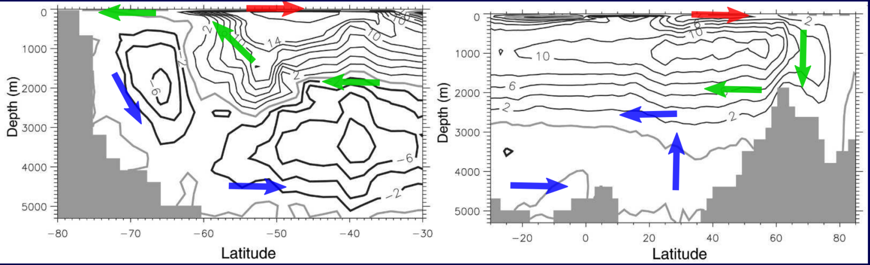


(IPCC)

Deep MOC

Meridional overturning streamfunctions:

Southern Ocean Atlantic



Saenko & WJ Merryfield (2005).

- “Deep” and “Bottom” cells.

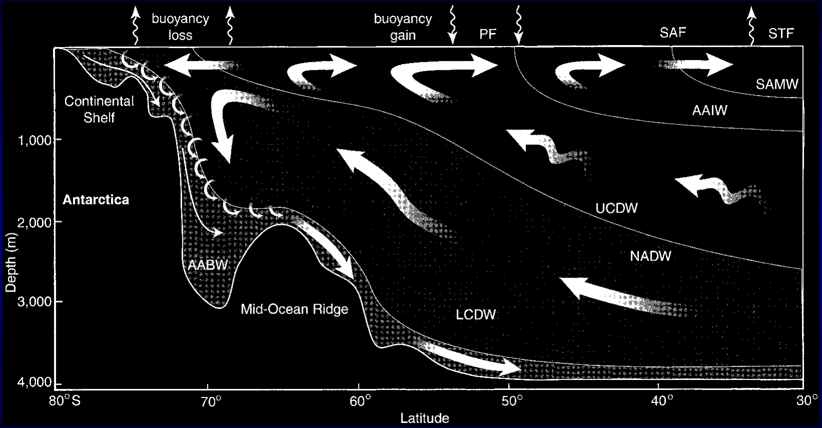
MOC (cont'd)

What is the meridional overturning circulation (MOC)?

- Near-surface water flows poleward, getting denser (colder or saltier or both);
- sinks to great depths;
- gets less dense by internal diffusion and comes back to the sea surface or dynamically upwells to the sea surface and gets less dense by surface flux.

For the deeper cell, diffusion is critical. For the upper cell, probably it's not.

Upwelling in the Southern Ocean



Speer et al. (2000)

Issues

- What determines the location and strength of the sinking?
- What determines the location and strength of the upwelling?

Issues

For the upper cell: How do the SO winds affect/control the MOC strength? What do mesoscale eddies do?

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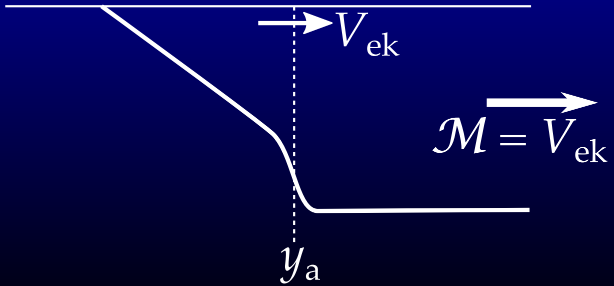
- Eddy compensation: Eddy-induced transport opposing Ekman drift.



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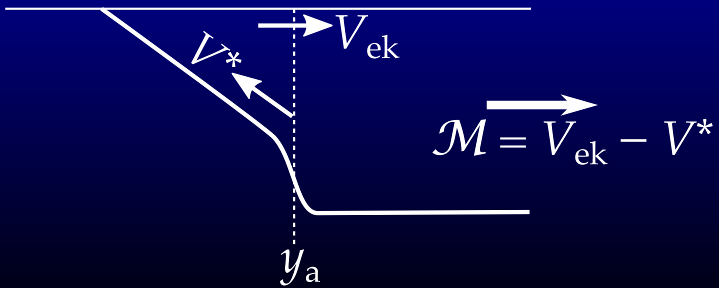


Issues

For the upper cell: How do the SO winds affect/control the MOC strength? What do mesoscale eddies do?

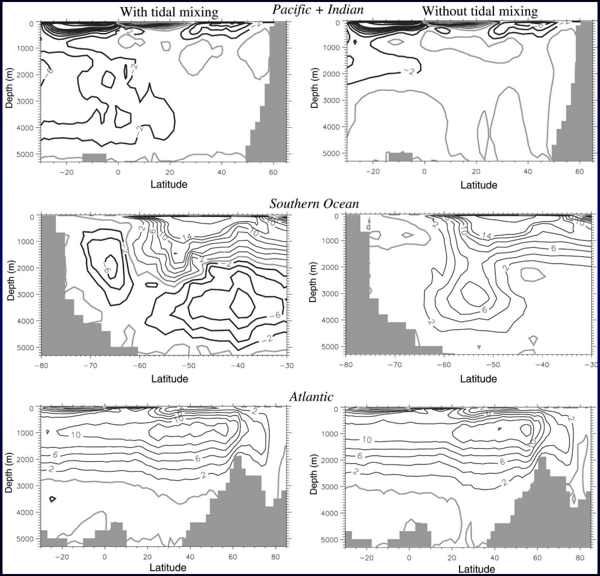
- Eddy compensation: Eddy-induced transport opposing Ekman drift.
- Eddy saturation of $\mathcal{M}$?: Stronger winds, weaker response.

Issues

For the upper cell: How do the SO winds affect/control the MOC strength? What do mesoscale eddies do?

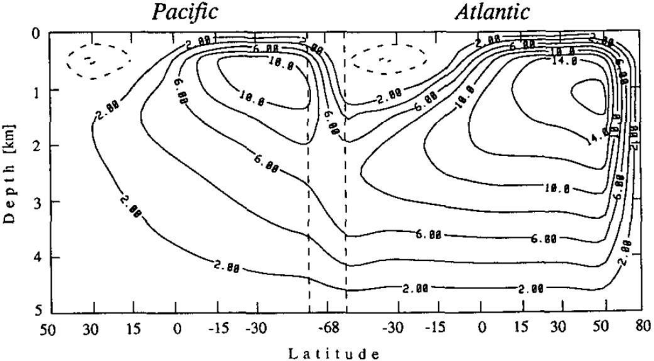
- Eddy compensation: Eddy-induced transport opposing Ekman drift.
- Eddy saturation of $\mathcal{M}$?: Stronger winds, weaker response.
- (Eddy saturation of ACC strength?)

Full OGCM



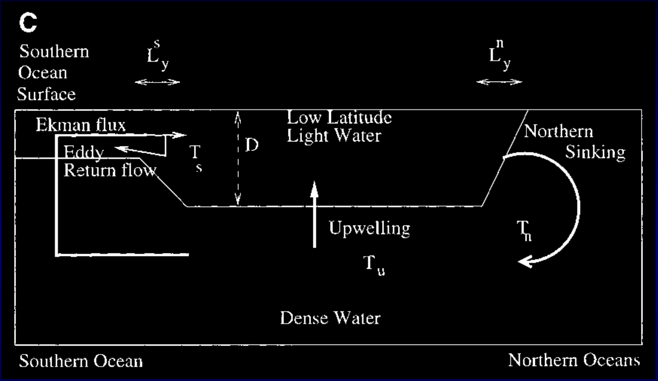
Saenko & WJ Merryfield (2005). Two cells.

Zonally-averaged models



Stocker & Wright (1991)

Box models



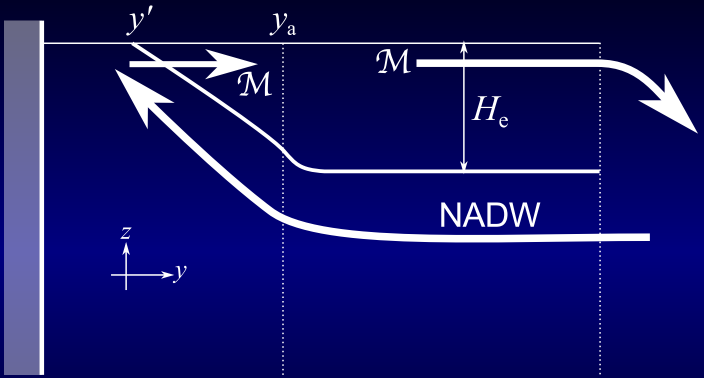
Gnanadesikan (1999)

Needs empirical parameterizations and scalings.

Various models

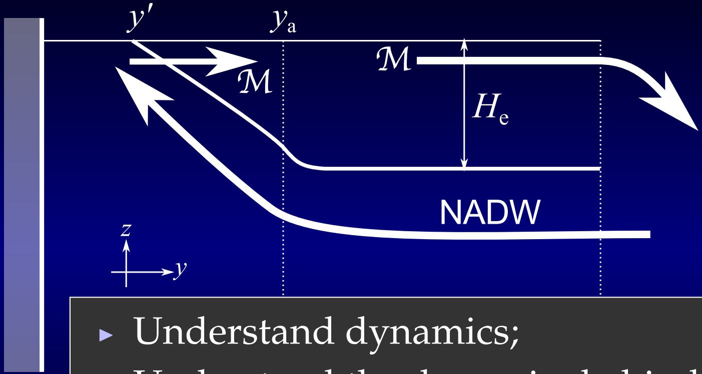
- OGCMs are too complex.
- Zonally-averaged models are still too complex and probably missing important dynamics.
- Box models are missing important dynamics.

Layer model



- thermocline + intermediate = upper layer
- deep + bottom = lower layer

Layer model



- Understand dynamics;
- Understand the dynamics behind the empirical parameterizations;
- Replace scalings with more precise formulae;
- Propose new formulae.

Outline

Governing equations

Start from the standard $1\frac{1}{2}$-layer model:

$$\boldsymbol{u}_t + f\boldsymbol{k}\times\boldsymbol{u} = -g'\nabla h + \boldsymbol{\tau}/h,$$
$$h_t + \nabla\cdot(h\boldsymbol{u}) = w_{\mathrm{e}}$$

Time average:

$$f\boldsymbol{k}\times\overline{\boldsymbol{u}} = -g'\nabla\overline{h} + \tilde{\boldsymbol{\tau}}/\overline{h},$$
$$\nabla\cdot(\overline{h}\overline{\boldsymbol{u}}) + (\overline{h'\boldsymbol{u}'}) = \overline{w_{\mathrm{e}}}.$$

GM parameterization:

$$\overline{h}\boldsymbol{u}^* \equiv \overline{h'\boldsymbol{u}'} = -\kappa_{\mathrm{GM}}\nabla\overline{h}.$$

Governing equations (2)

"Residual" velocity: $\hat{\boldsymbol{u}} \equiv \overline{\boldsymbol{u}} + \boldsymbol{u}^*$. Continuity eq. is simply

$$\boldsymbol{\nabla} \cdot (\overline{h}\hat{\boldsymbol{u}}) = \overline{w_{\mathrm{e}}}.$$

Momentum eq. becomes

$$\begin{aligned} f\boldsymbol{k} \times \overline{h}\hat{\boldsymbol{u}} &= -g'\boldsymbol{\nabla}P + \tilde{\boldsymbol{\tau}} - f\boldsymbol{k} \times \kappa_{\mathrm{GM}}\boldsymbol{\nabla}\overline{h} \\ &= -g'\boldsymbol{\nabla}P + \tilde{\boldsymbol{\tau}} - f\boldsymbol{k} \times \frac{\kappa_{\mathrm{GM}}}{g'\overline{h}}\left(\tilde{\boldsymbol{\tau}} - f\boldsymbol{k} \times \overline{h}\overline{\boldsymbol{u}}\right) \\ &= -g'\boldsymbol{\nabla}P + \tilde{\boldsymbol{\tau}} - \frac{\nu}{f}\boldsymbol{k} \times \tilde{\boldsymbol{\tau}} - \nu\overline{h}\hat{\boldsymbol{u}} + \nu\overline{h}\boldsymbol{u}^*, \end{aligned}$$

where $P \equiv g'\overline{h}^2/2$ and $\nu \equiv \kappa_{\mathrm{GM}}f^2/(g'\overline{h})$.

Governing equations (3)

Finally,

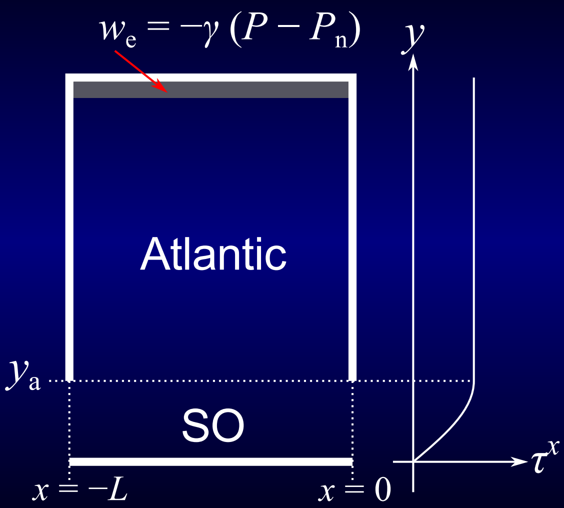
$$f\boldsymbol{k} \times \boldsymbol{U} \approx -g'\nabla P - \nu \boldsymbol{U} + \boldsymbol{\tau},$$
$$\nabla \cdot \boldsymbol{U} = w_{\mathrm{e}},$$

where $\boldsymbol{U} \equiv \overline{h\boldsymbol{u}} = \bar{h}\hat{\boldsymbol{u}}$ and $P \equiv g'\bar{h}^2/2$.
$\boldsymbol{U}$ is the "residual" transport and
$\nu \equiv \kappa_{\mathrm{GM}} f^2/(g'\bar{h})$ = const.

$$w_{\mathrm{e}} = \begin{cases} -\gamma'(\bar{h} - h_{\mathrm{m}}) & \text{where } \bar{h} < h_{\mathrm{m}}\text{: "mixed layer"}, \\ -\gamma(\bar{h} - h_{\mathrm{n}}) & \text{at } y = y_{\mathrm{n}}\text{: "sinking"}, \\ w_{\mathrm{d}} & \text{elsewhere: diff. upwelling.} \end{cases}$$

We consider the limit $\gamma, \gamma' \to \infty$.

Model configuration



$$\tau^y = 0$$
$$w_d = 0$$

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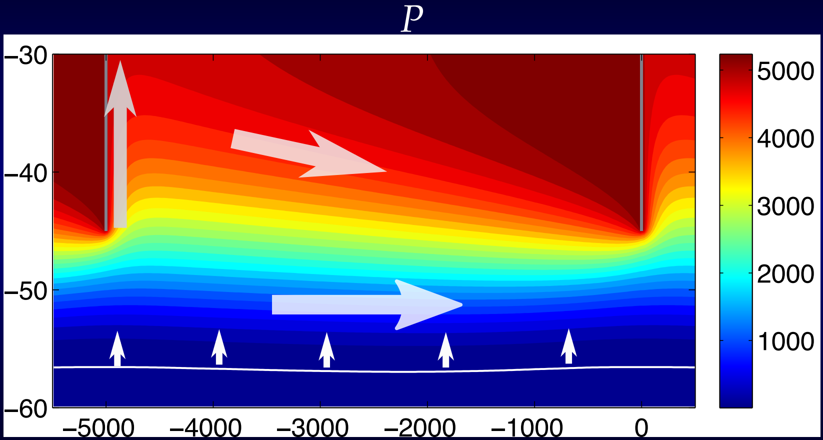
Numerical solution



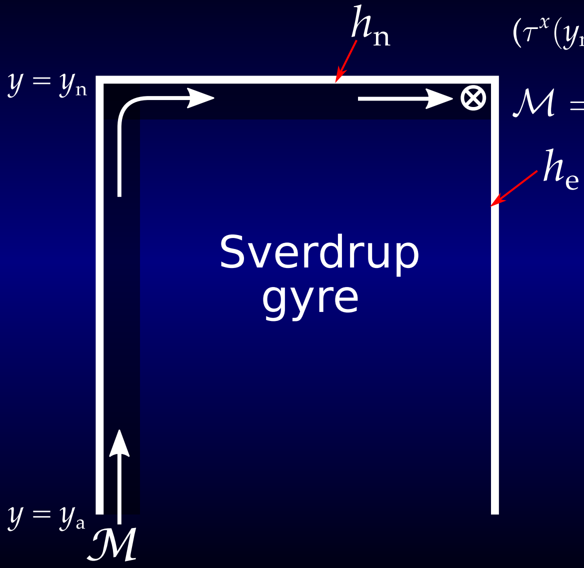
Atlantic: Interior solution

North of y_a in the interior, the Sverdrup solution

$$P = P_e - \frac{f^2}{\beta} \int_0^x \mathrm{d}x \left(\frac{\tau^x}{f} \right)_y$$

is an excellent approximation.

Atlantic: Boundary layers



($\tau^x(y_n) = 0$ is assumed.)

$$\mathcal{M} = \frac{P_e - P_n}{f(y_n)}$$

Atlantic: Constraints

$$P = P_{\mathrm{e}} - \frac{f^2}{\beta} \int_0^x \mathrm{d}x \left(\frac{\tau^x}{f} \right)_y$$
$$\mathcal{M} = \frac{P_{\mathrm{e}} - P_{\mathrm{n}}}{f(y_{\mathrm{n}})}$$

Remember that $P = g' \overline{h}^2 / 2$.
$\Longrightarrow$ If P_{e} is known, everything is determined.

Southern Ocean: Interior solution

South of y_a, a zonally-uniform solution exists:

$$-fV = -\nu U + \tau^x, \quad fU = -P_y, \quad V_y = 0$$

because $w_e = 0$.

$$V = \mathcal{M}/L = \text{const.}, \quad U = \frac{f}{\nu}\left(\frac{\tau^x}{f} + \frac{\mathcal{M}}{L}\right),$$

$$P = P_a + \int_y^{y_a} dy\, \frac{f^2}{\nu}\left(\frac{\tau^x}{f} + \frac{\mathcal{M}}{L}\right).$$

Southern Ocean: Interior solution

How to determine $\mathcal{M}$ (or V) in the SO? Note that

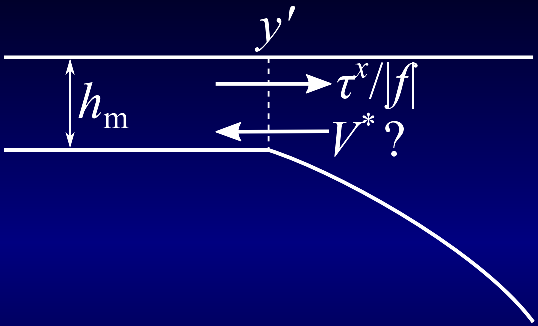
$$U = -\frac{P_y}{f} = -\frac{g'}{f}\overline{h}\,\overline{h}_y = \frac{g'}{f}\overline{h}\frac{V^*}{\kappa_{\mathrm{GM}}} = \frac{f}{\nu}V^*.$$

Therefore

$$V = \frac{\nu}{f}U - \frac{\tau^x}{f} = V^* - \frac{\tau^x}{f}$$

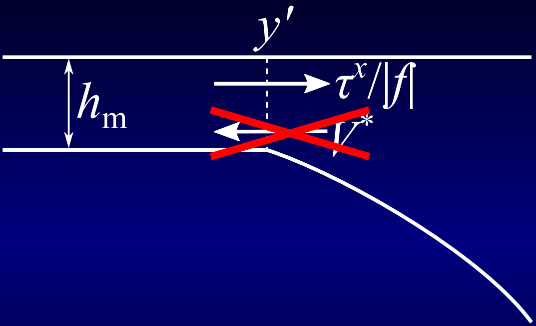
as expected!

Southern Ocean: Interior solution



$\overline{h}_y$ can be discontinuous at y'. We in fact included ρ_y and parameterized V^* due to mixed-layer (submesoscale) eddies. But we concluded $V^* \simeq 0$ when h_m is small.

Southern Ocean: Interior solution



Therefore,
$V = \mathcal{M}/L \simeq -\tau^x/f$
at y'.

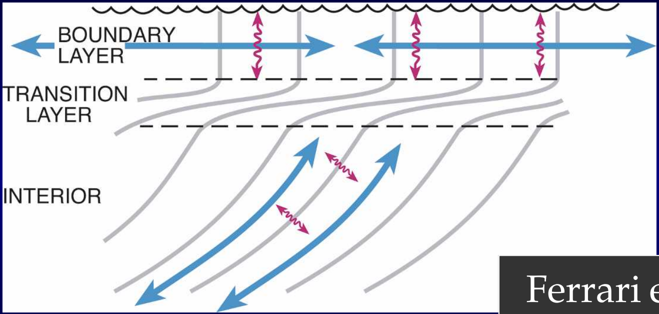
$\overline{h}_y$ can be discontinuous at y'. We in fact included ρ_y and parameterized V^* due to mixed-layer (submesoscale) eddies. But we concluded $V^* \simeq 0$ when h_{m} is small.

Southern Ocean: Outcrop

Is y' fixed?

Southern Ocean: Outcrop

Is y' fixed? No!



Ferrari et al. (2008)

Some authors fix y', depriving the system of one deg. of freedom $\rightarrow$ letting V^* a free parameter instead!

Southern Ocean: Constraints

So, y' is a free parameter in the SO solution.

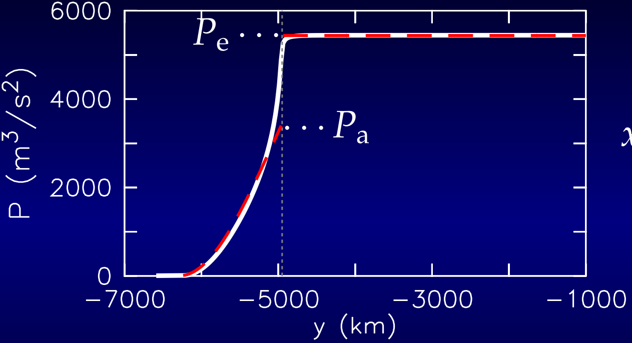
$$
\begin{aligned}
y' &\Rightarrow \mathcal{M}/L = -\tau^x(y')/f(y') \\
&\Rightarrow g'h_\mathrm{m}^2/2 = P(y') \\
&\qquad\qquad = P_\mathrm{a} + \int_{y'}^{y_\mathrm{a}} \mathrm{d}y\, \frac{f^2}{\nu}\left(\frac{\tau^x}{f} + \frac{\mathcal{M}}{L}\right) \\
&\Rightarrow P_\mathrm{a}.
\end{aligned}
$$

Then, the solution is determined:

$$
V = \mathcal{M}/L = \text{const.}, \quad U(y) = \frac{f}{\nu}\left(\frac{\tau^x}{f} + \frac{\mathcal{M}}{L}\right),
$$

$$
P(y) = P_\mathrm{a} + \int_{y}^{y_\mathrm{a}} \mathrm{d}y\, \frac{f^2}{\nu}\left(\frac{\tau^x}{f} + \frac{\mathcal{M}}{L}\right).
$$

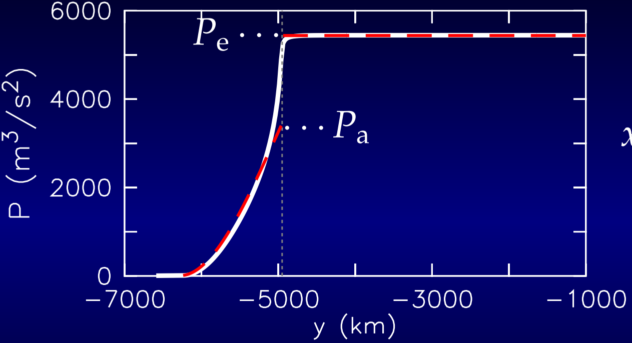
Zonal boundary layer



$x = 0$

Solve for the zonal boundary layer.

Zonal boundary layer



$x = 0$

Solve for the zonal boundary layer.

After a lot of algebra,

$P_e - P_a = \Pi(\nu, \mathcal{M}, \tau^x(y_a), \tau^x_y(y_a^+), \tau^x_{yy}(y_a^+))$.

Integral constraints

- Sinking: $\mathcal{M} = F(P_{\mathrm{e}})$.
- Upwelling: $\mathcal{M} = -L\,\tau^x(y')/f(y')$.
- Outcrop: $y' = Y[P_{\mathrm{a}}, \mathcal{M}, \nu, \tau^x(y)]$.
- Zon. bndry layer:
  $P_{\mathrm{e}} - P_{\mathrm{a}} = \Pi(\nu, \mathcal{M}, \tau^x(y_{\mathrm{a}}), \tau^x_y(y^+_{\mathrm{a}}), \tau^x_{yy}(y^+_{\mathrm{a}}))$

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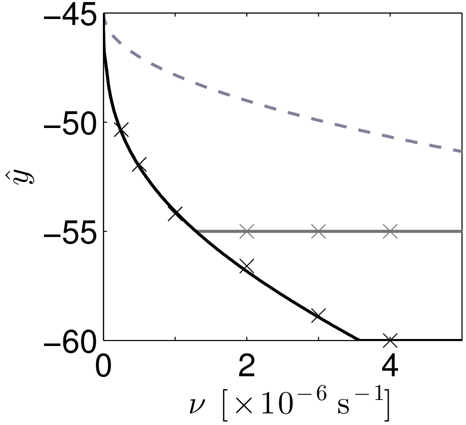
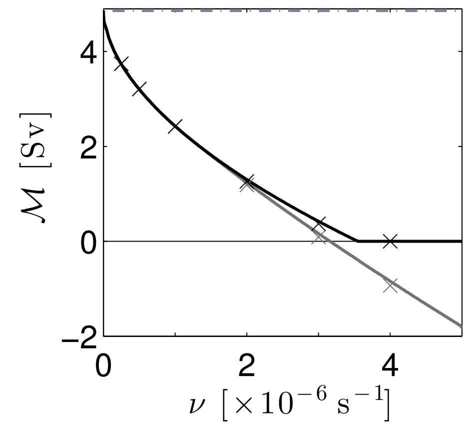
$\Rightarrow \mathcal{M}, y', P_\mathrm{e} =$ func. of $[\tau^x(y), \nu, L]$.

Impacts of ν



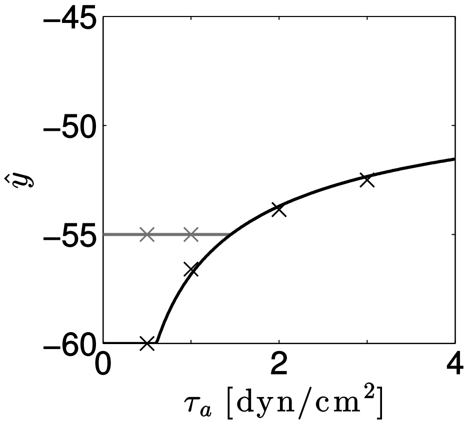
- Location of outcrop (y').

Impacts of ν



- Location of outcrop (y').
- Outcrop determines $\mathcal{M}$. $\mathcal{M}$ decreases only because outcrop shifts southward.

Impacts of τ



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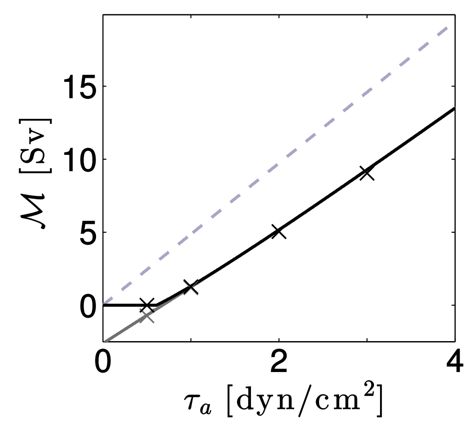
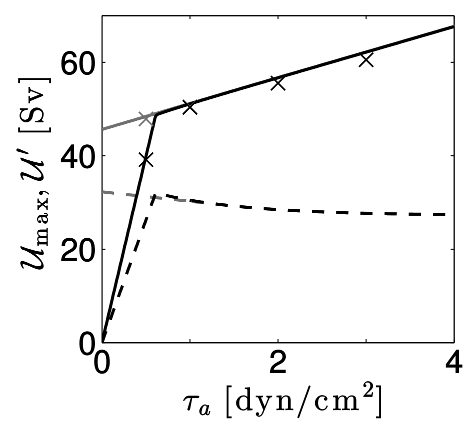
Impacts of τ



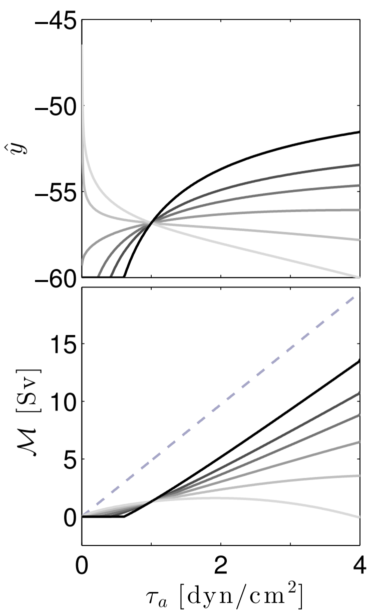
- Location of outcrop (y').
- "Eddy compensation": At y', $\mathcal{M} \approx -\tau^x/f$, $V^* \approx 0$. But, at y_a, $|\tau^x/f| > \mathcal{M}$, the difference being LV^*.

Impacts of τ



- Location of outcrop (y').
- "Eddy compensation": At y', $\mathcal{M} \approx -\tau^x/f$, $V^* \approx 0$. But, at y_a, $|\tau^x/f| > \mathcal{M}$, the difference being LV^*.
- "Strength of ACC": $\overline{U}^x = -\overline{P}^x_y/f = (\tau^x - |f|\mathcal{M}/L)/\nu$.

Impacts of τ



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- "Strength of ACC": $\overline{U}^x = -\overline{P}^x_y/f = (\tau^x - |f|\mathcal{M}/L)/\nu$.
- "Eddy saturation": If $\nu \propto (\tau^x)^n, \ldots$.

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- $\mathcal{M}$ = Ekman drift at y'.
  - "Eddy compensation" $= V_{\text{ek}}(y_{\text{a}}) - V_{\text{ek}}(y')$.
  - V^* (eddy-induced transport) weakens $\mathcal{M}$ through poleward shift of y'.

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  - V^* (eddy-induced transport) weakens $\mathcal{M}$ through poleward shift of y'.
- The ACC strength depends weakly on τ primarily because of $\mathcal{M}$.
- "Eddy saturation" can be parameterized by $\nu \propto \tau^{\alpha}$.

Extra slides

Parameterization of sinking

- Present study: $w_{\mathrm{e}} = -\gamma(P - P_{\mathrm{n}})$
  $\Rightarrow \mathcal{M} = (P_{\mathrm{e}} - P_{\mathrm{n}})/f$.
- A box ocean: $\mathcal{M} \approx 0.8 P_{\mathrm{e}}/f$
  (Schloesser et al. 2014).

Generally, P_{a} is smaller in the latter.
$\Rightarrow$ larger $\mathcal{M}$ (y' shifting north) and smaller U in ACC (smaller pressure gradient across ACC).