Diahaline transport in ocean models

Chris Bladwell

University of New South Wales

c.bladwell@unsw.edu.au

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Overview

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1. Water cycle amplification
2. Water Mass Transformation approach
3. Application of WMT framework to ACCESS-OM2
4. WMT approach to meridional salt transport

Amplification of the water cycle

- The water cycle, the process of evaporation (E) and precipitation (P), is expected to amplify with climate change
- The spatial pattern of $P - E$ correlates with sea surface salinity (SSS)
- SSS can be used to diagnose changes in the water cycle

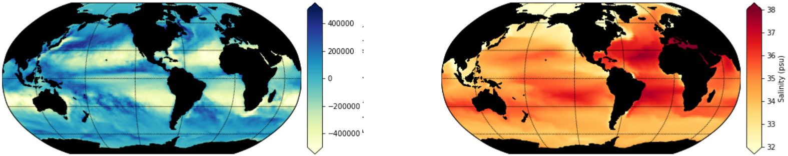
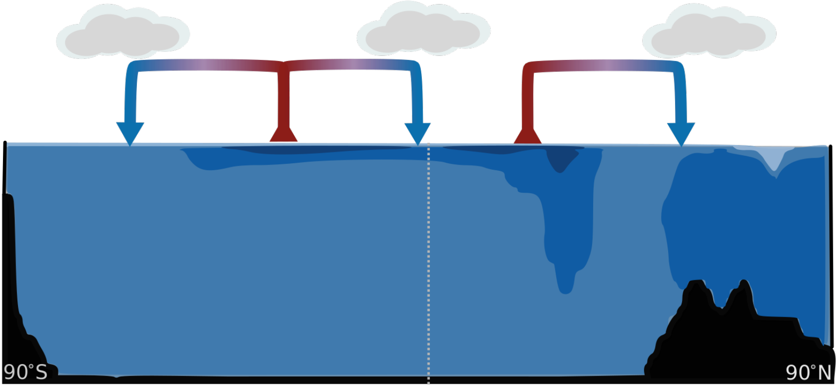


Figure: Left: Annual mean atmospheric freshwater exchanges ($P - E + R$). Right: Annual mean sea surface salinity pattern.

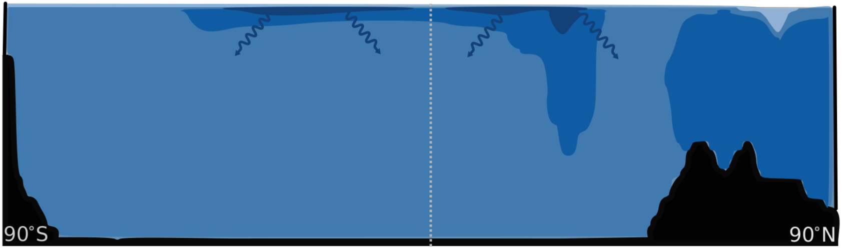
Water cycle and salt transport

- Subtropics dominated by E, tropics and poles dominated by P.
- Freshwater forcing is balanced by oceanic salt fluxes.



Water cycle and salt transport

- Subtropics dominated by E, tropics and poles dominated by P.
- Freshwater forcing is balanced by oceanic salt fluxes.
- Salt fluxes cross isohaline surfaces (surface of constant salinity).



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Volume and salt content

- Salinity, $S(x, y, z, t)$, is g salt$/kg$ seawater.
- Stratify the ocean into isohaline layers $S(x, y, z, t) = S^*$.

Volume and salt mass

The volume of the region of all seawater with $S(x, y, z, t) \leq S^*$ is given by

$$\tilde{\mathcal{V}}(S^*, t) = \iiint_{S \leq S^*} \mathrm{d}x\mathrm{d}y\mathrm{d}z.$$

The salt mass of this region is given by

$$\tilde{\mathcal{S}}(S^*, t) = \iiint_{S \leq S^*} \rho_0 S \mathrm{d}x\mathrm{d}y\mathrm{d}z,$$

where ρ_0 is density.

Salt budget

Evolution of salt mass

The salt mass in the region $S \leq S^*$ evolves according to

$$\frac{\partial \tilde{S}}{\partial t} = -\underbrace{\int_{S=S^*} \hat{\mathbf{n}} \cdot (\rho_0 S(\mathbf{v} - \mathbf{v}^{(S)}))dA}_{\tilde{\mathcal{G}}(S^*,t)S^*\rho_0} + \underbrace{\int_{S\leq S^*} \nabla \cdot \rho\kappa\nabla S dV}_{\tilde{\mathcal{D}}} + Q_S$$

- $\boldsymbol{v}$: fluid velocity
- $\boldsymbol{v}^{(S)}$: velocity of a point on the surface $S = S^*$.
- $\hat{\mathbf{n}}$: the outward normal on this surface
- dA: Area element on the surface $S = S^*$
- $\tilde{\mathcal{D}}$: mixing processes
- Q_S: surface salt flux

Volume budget

Evolution of volume

The volume of the region $S \leq S^*$ evolves according to

$$\frac{\partial \tilde{\mathcal{V}}}{\partial t} = \underbrace{- \int_{S=S^*} \hat{\mathbf{n}} \cdot (\mathbf{v} - \mathbf{v}^{(S)}) \mathrm{d}A}_{\tilde{\mathcal{G}}(S^*,t)} + \underbrace{\int_{S \leq S^*} P - E + R \mathrm{d}x\mathrm{d}y}_{\tilde{\mathcal{P}}(S^*,t)}$$

- $\tilde{\mathcal{G}}$: Diahaline volume transport. In a Boussinesq model, multiplying by a constant density, ρ_0, gives the water mass transformation.
- $\tilde{\mathcal{P}}$: Freshwater forcing

Budget processes

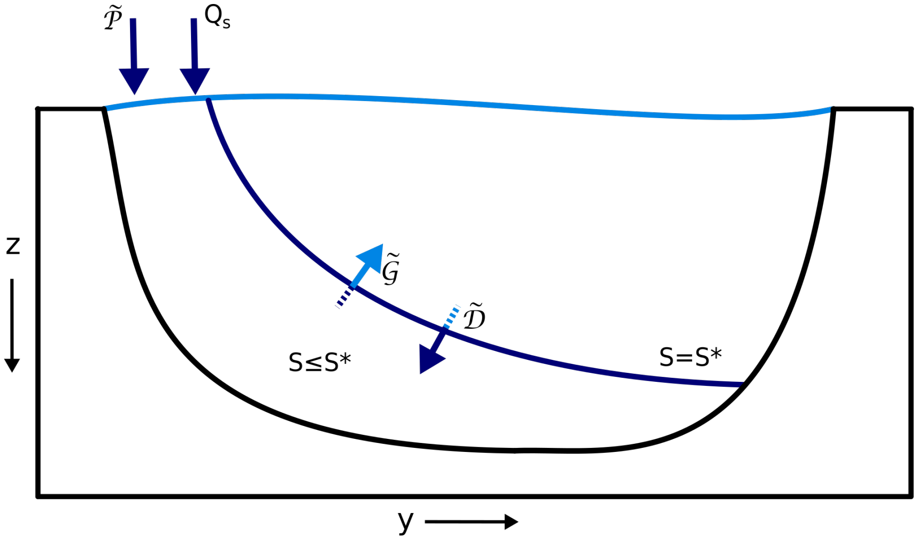

Figure: Schematic of processes involved in diahaline transport.

Internal salt budget

- The distribution of salinity alters through diabatic processes of forcing and mixing
- Water mass transformations are induced by these processes
- We can combine the equations for the evolution of salt mass and volume

Internal salt budget in an ocean model

$$\frac{\partial \tilde{\mathcal{S}}_I}{\partial t} := \frac{\partial \tilde{\mathcal{V}}}{\partial t} S^* \rho_0 - \frac{\partial \tilde{\mathcal{S}}}{\partial t} = \tilde{\mathcal{F}} - \tilde{\mathcal{D}}$$

where

$$\tilde{\mathcal{F}} = \tilde{\mathcal{P}} S^* \rho_0 - Q_S$$

where Q_S is the salt flux through the free surface.

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ACCESS-OM2 coupled ocean-ice model

- Dynamical ocean and ice models and file based atmospheric forcing
- MOM5 ocean model coarse 1° tripolar horizontal grid with 50 depth levels
- YATM RYF forcing 1984-85
- 20 year run

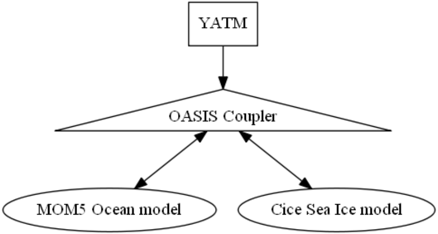

Figure: ACCESS-OM2 coupled model is composed of dynamical ocean and ice models, and YATM file based forcing.

Surface boundary fluxes

- Forcing provides periodic boundary condition
- Salinity restoring and η smoothing introduce non physical diahaline salt flux
- Internal salt tendency forcing,

  $$\tilde{\mathcal{F}} := \tilde{\mathcal{P}} S^* \rho_0 - Q_S,$$

  where Q_S consists of contributions from restoring, η smoothing and coupler exchanges. $0 psu$ exchanged between ocean and sea-ice.

Diffusion in a coarse grid model

- In the 1° ocean model, turbulent and eddy diffusivity are parameterised by
    - Vertical ($\tilde{\mathcal{M}}$): KPP, sigma, mixdownslope
    - Neutral ($\tilde{\mathcal{N}}$): Redi, k33
- Skew-diffusion parameterised subgrid-scale advective transport from mesoscale and submesoscale eddies
- The advection scheme introduces (non-physical) numerical mixing, denoted $\tilde{\mathcal{I}}$
- Therefore, the internal budget can be written

$$\frac{\partial \tilde{\mathcal{S}}_I}{\partial t} = \tilde{\mathcal{F}} - \tilde{\mathcal{D}} = \tilde{\mathcal{F}} - (\tilde{\mathcal{M}} + \tilde{\mathcal{N}} + \tilde{\mathcal{I}})$$

Monthly averaged internal salt budget

1. $P - E$ forces ocean salinity, moving freshwater from high salinity to low salinity
2. Mixing, $\tilde{\mathcal{D}}$, homogenises the ocean, moving salt from high salinity to low salinity
3. Implicit mixing, $\tilde{\mathcal{I}}$, is diffusion of the tracer field caused by numerical advection.

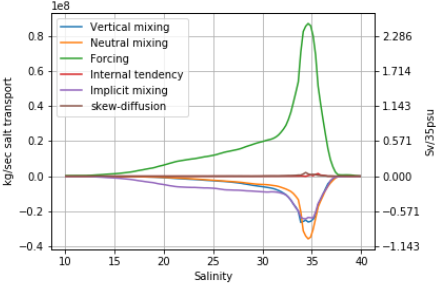

Figure: Monthly averaged internal salt budget of ACCESS-OM2 MOM5 model

Diahaline transport from skew-diffusion

1. Diahaline transport from parametrised GM (mesoscale) skew-diffusion is proportional to the internal salt tendency
2. Small contribution from submesoscale advective transport

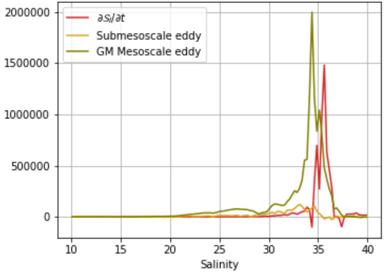

Figure: Monthly averaged diahaline transport from skew-diffusion compared to internal salt tendency in the Access-OM2 MOM5 model

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Meridional processes

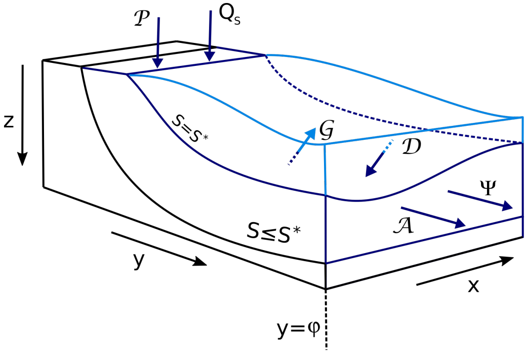

Figure: Processes involved in the meridional transport of salt and fluid across Ψ

Latitude-Salinity space

- The tendency of the volume, $\mathcal{V}(\phi, S^*, t)$, in ϕ-S^* space is given by

  $$\frac{\partial \mathcal{V}}{\partial t} = \mathcal{P} - \mathcal{G} - \Psi$$

  where $v(x, y, z, t)$ is the meridional (northward) velocity component and

  $$\Psi(\phi, S^*, t) = \iint_{S(x,\phi,z,t) \leq S^*} v(x, \phi, z, t) \mathrm{d}x\mathrm{d}z$$

- The salt content, $\mathcal{S}(\phi, S^*, t)$, evolves according to

  $$\frac{\partial \mathcal{S}}{\partial t} = -\mathcal{G}\rho_0 S^* + \mathcal{D} - \mathcal{A}$$

  where

  $$\mathcal{A}(\phi, S^*, t) = \rho_0 \int_0^{S^*} S \frac{\partial \Psi}{\partial S} \mathrm{d}S + \mathcal{A}_{\mathrm{diff}}$$

  and $\frac{\partial \Psi}{\partial S}\mathrm{d}S$ is the northward salt transport between $[S^*, S^* + \mathrm{d}S)$.

Internal meridional salt budget

We are able to define an internal salt budget

$$\frac{\partial \mathcal{S}_I}{\partial t} = \mathcal{F} - \mathcal{D} + \mathcal{A}_I.$$

where $\mathcal{F} = \mathcal{P}\rho_0 S^* - Q_S$ and $\mathcal{A}_I$ is the meridional salt function.

Salt function

The salt function

$$\mathcal{A}_I(\phi, S^*, t) = -\rho_0 \int_0^{S^*} \Psi \mathrm{d}S + \mathcal{A}_{\mathrm{diff}},$$

defines the pathways that salt is transported in the ocean.

Meridional transport figures

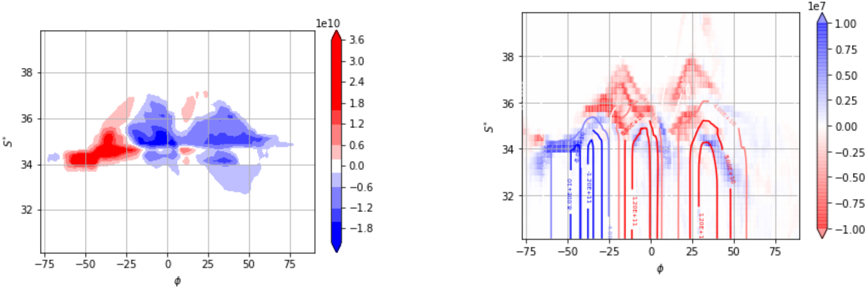

Figure: Left: Streamlines of the meridional streamfunction, $\Psi(\phi, S^*, t)$. Positive contours are anti-clockwise. Right: Contours of the salt function, $\mathcal{A}_I$, showing the pattern of precipitation and evaporation in ϕ-S^* space.

Summary

- Internal salt budget, $\partial\tilde{\mathcal{S}}_I/\partial t$, allows us to quantify the effect of mixing and forcing on the salinity distribution
- We are able to isolate the contribution to diahaline transport from implicit mixing introduced by the numerical advection scheme.
- Latitude-salinity internal salt budget, $\partial\mathcal{S}_I/\partial t$, identifies meridional variation in diahaline fluxes.
- The streamfunction, Ψ, quantifies volume transport in ϕ-S^* space space.
- The salt function, $\mathcal{A}_I$, shows the pathways of salt (freshwater) in ϕ-S^* space.

Thermal forcing

- Intensification of surface salinity pattern has been related to increased thermal forcing
- Thermal forcing perturbation constant 8 W/m^2 long wave radiation
- 1.5°C increased near-surface temperature 10m height

Monthly average internal salt budget of perturbation experiment

1. Constant thermal perturbation
2. Large effect on forcing and tendency
3. Small increased in the maximum mesoscale eddy diffusivity, N.

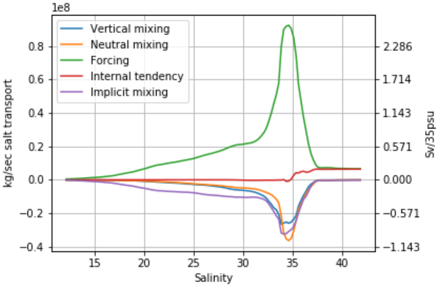

Figure: Monthly averaged internal salt budget of thermal perturbation Access-OM2 MOM5 model

Response of salinity restoring

1. Atmospheric freshwater transport is the same
2. Salinity restoring is negative at high salinity
3. Motivates 'flux' based approach - perturbations without salinity restoring

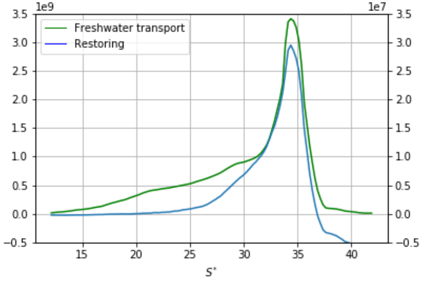

Figure: Precipitation and evaporation of Access-OM2 MOM5 model

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