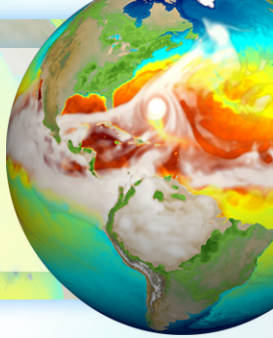
Surface-flux driven water mass transformation analysis in E3SM simulations



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Outline

Importance of Southern Ocean and Sea-ice

Water Mass Transformation framework

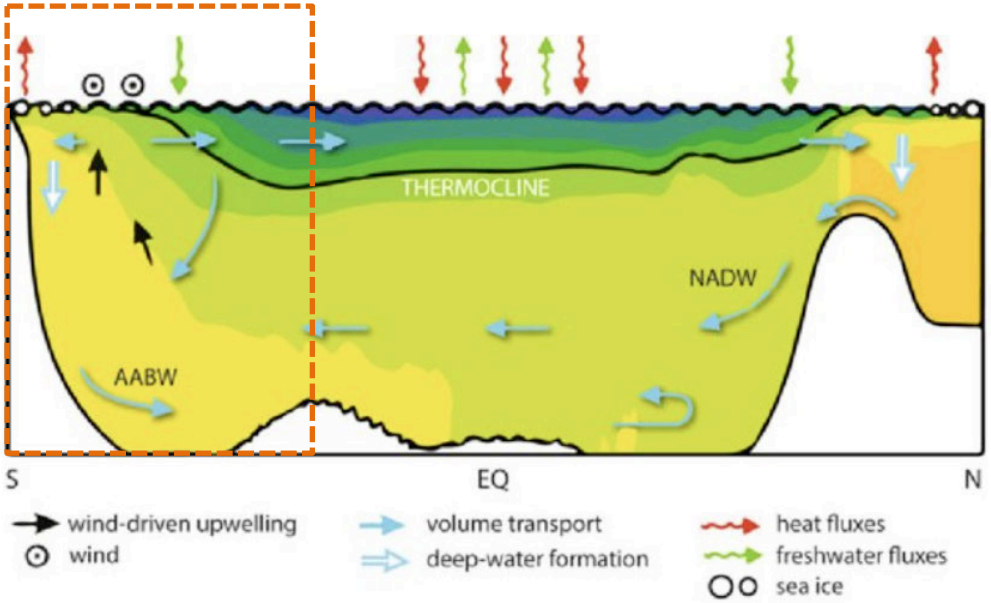
Application (I) to Southern Ocean in E3SM simulations

Application (II) to dense water formation in Antarctic coastal polynyas

Application (III) to Labrador Sea bias in E3SM simulations

Southern Ocean

Atlantic Meridional Overturning Circulation (AMOC)



- Significant sink for atmospheric heat, anthropogenic carbon dioxide
- Producing the densest water mass in global ocean, Antarctic Bottom Water (AABW)

From Kuhlbrodt et al. 2007, Violante et al., 2017

Marshall and Radko (2003) : Residual Mean

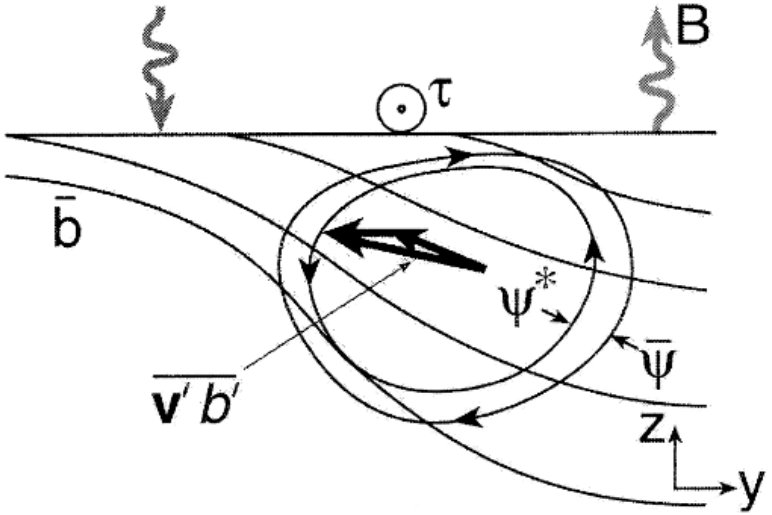


Fig. Schematic diagram of the Eulerian mean $\bar{\psi}$ and eddy-induced transport ψ^* component of the Southern Ocean meridional overturning circulation driven by wind and buoyance fluxes.

Southern Ocean overturning is a residual between opposing **Ekman (clockwise)** and **eddy-driven (counterclockwise)** cells

$$\psi_{res} = \bar{\psi} + \psi^*$$

Ekman flow *Eddy-driven flow*

Marshall and Radko (2003) : Residual Mean

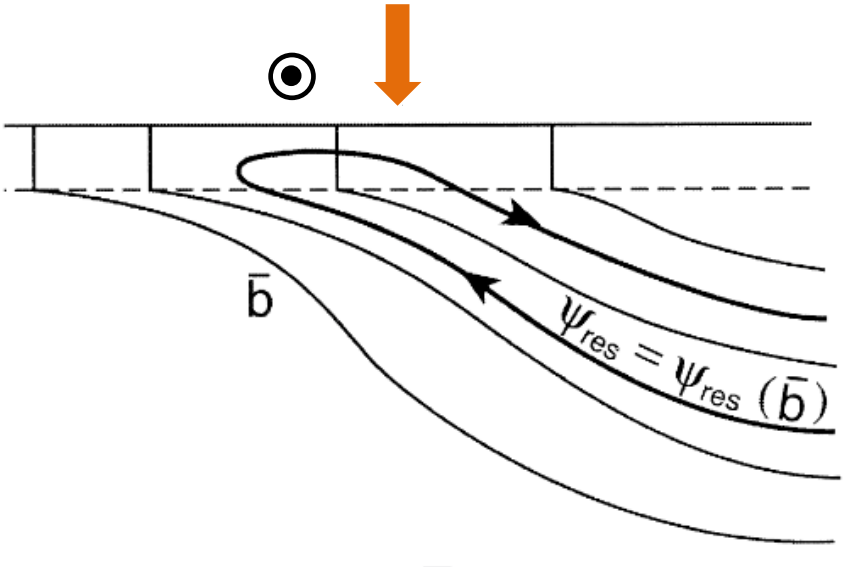


Fig. The residual flow $\psi_{res} = \bar{\psi} + \psi^*$ is assumed to be directed along mean buoyancy surfaces $\bar{b}$ in the interior but to have a diapycnal component in the mixed layer of depth (denoted by the horizontal dotted line).

"Buoyancy budget" of surface layer controls the strength of the residual overturning

Buoyance budget: Heat vs. Freshwater

Potential Density Equation

$$\frac{d\sigma}{dt} = \frac{d\sigma}{d\Theta}\mathcal{D}(\Theta) + \frac{d\sigma}{dS}\mathcal{D}(S)$$

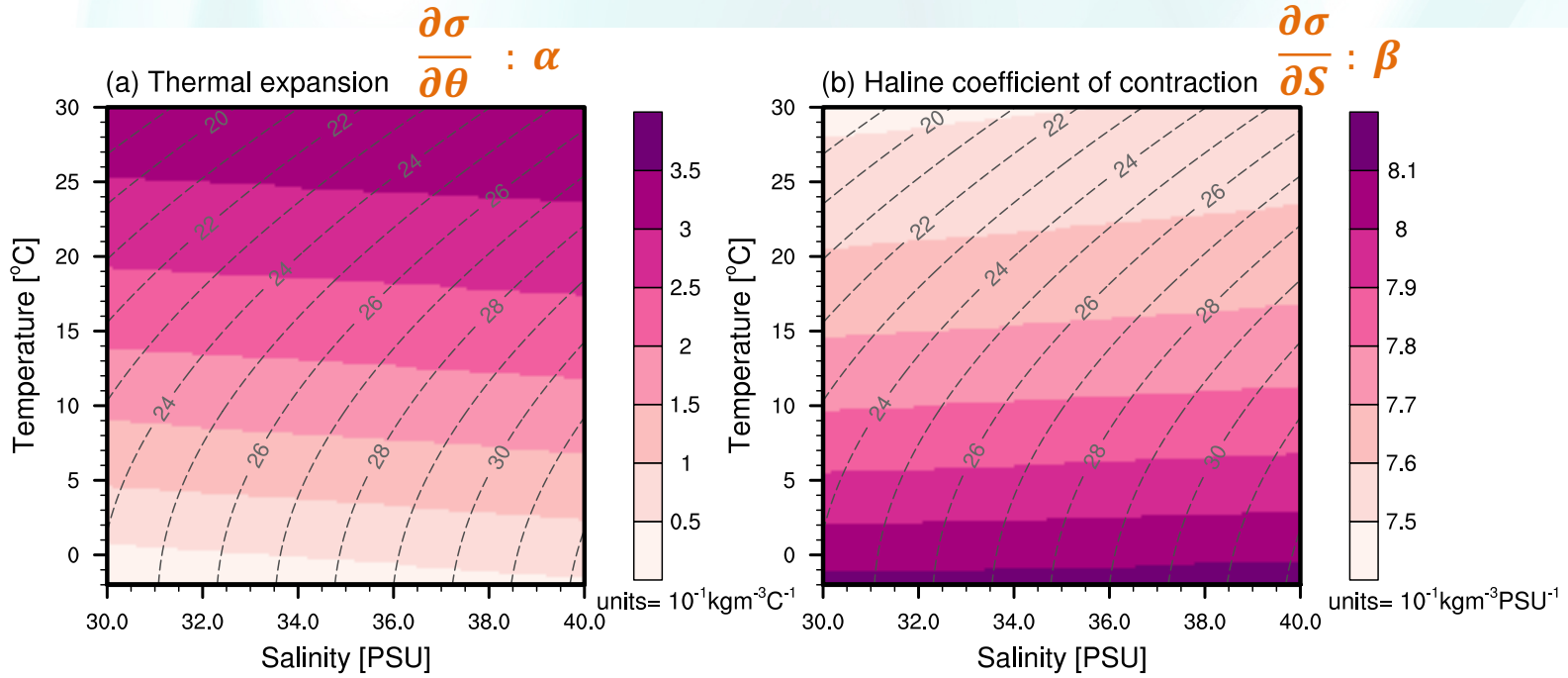
Thermal expansion

Haline coefficient of contraction

$$\frac{d\Theta}{dt} = \mathcal{D}(\Theta)$$ *: Temperature change over time*

$$\frac{dS}{dt} = \mathcal{D}(S)$$ *: Salinity change over time*

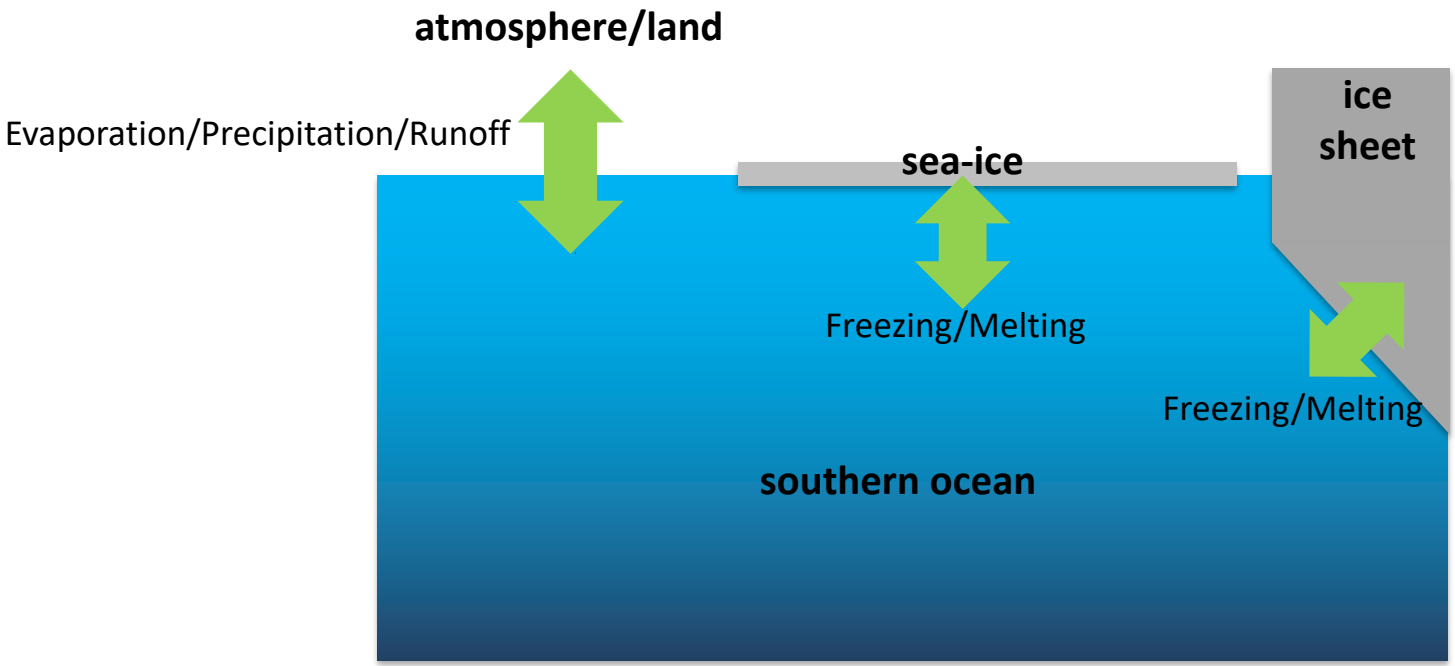
Buoyance budget: Heat vs. Freshwater



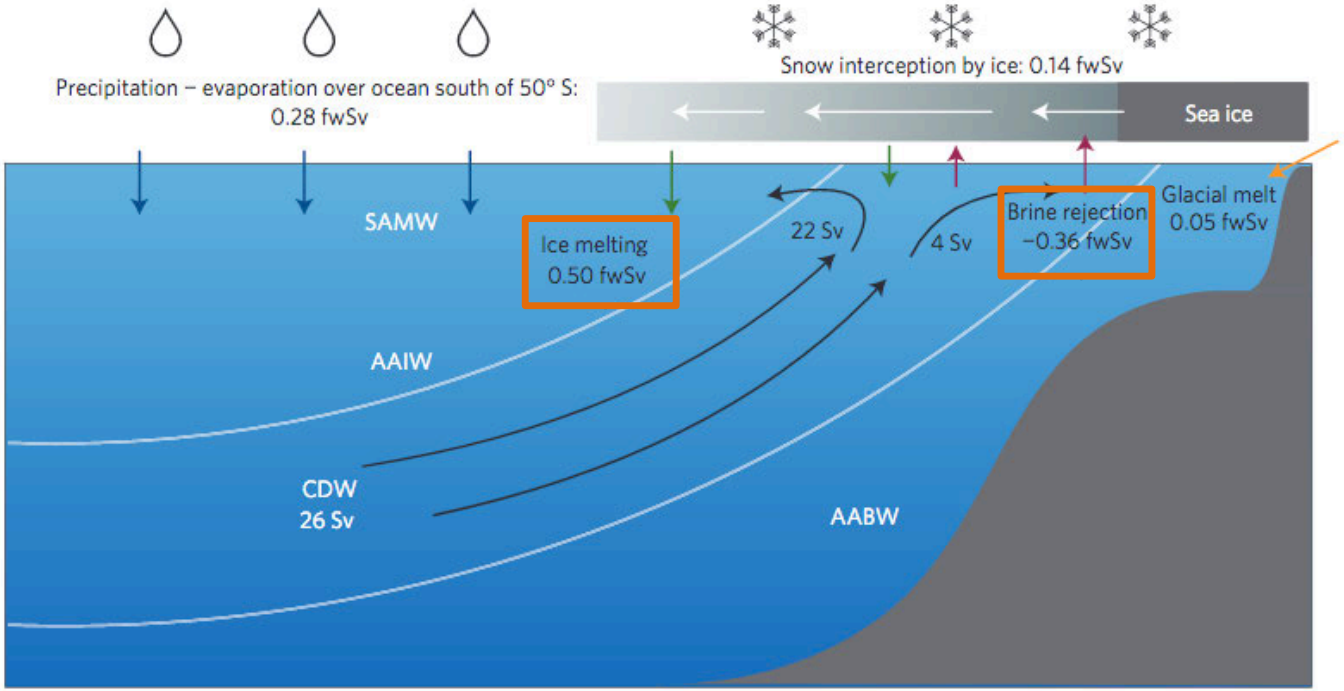
“Relatively low latitudes”

“Relatively high latitudes”

Several sources of freshwater flux



Abernathey et al. (2016) Freshwater flux exchange (SOSE)

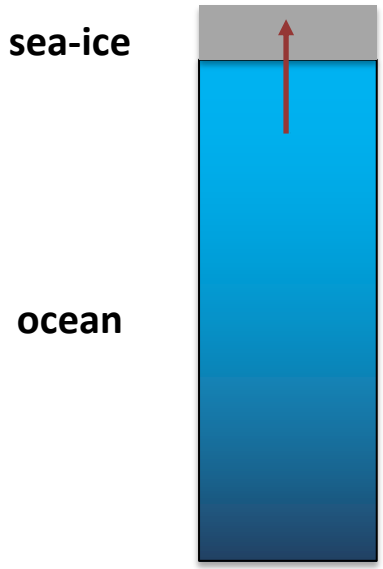


1 fwSv = $10^6 m^3$ freshwater $s^{-1} \cong 3.15 \times 10^4$ Gt freshwater / year

SOSE: Southern Ocean State Estimate, 6yrs (2005-2010) high-res ocean data assimilated product (Mazloff et al. 2010)

Surface freshwater fluxes (sea-ice/ocean interaction)

Winter: brine rejection, freshwater transports to sea-ice
salinity goes up

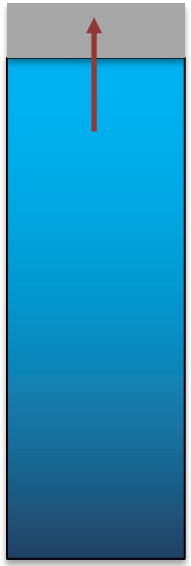


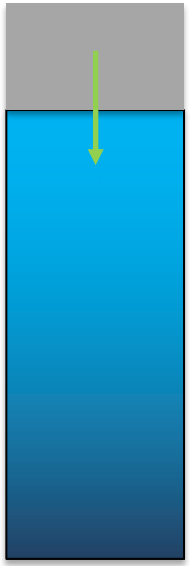
Surface freshwater fluxes (sea-ice/ocean interaction)

Winter: brine rejection, freshwater transports to sea-ice
salinity goes up

sea-ice

ocean





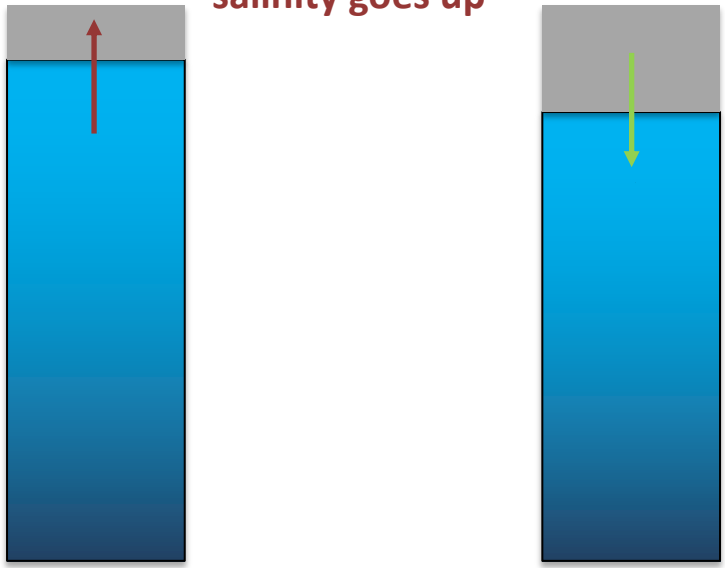
Summer: freshwater transports to ocean
salinity goes down

Surface freshwater fluxes (sea-ice/ocean interaction)

Winter: brine rejection, freshwater transports to sea-ice
salinity goes up

sea-ice

ocean



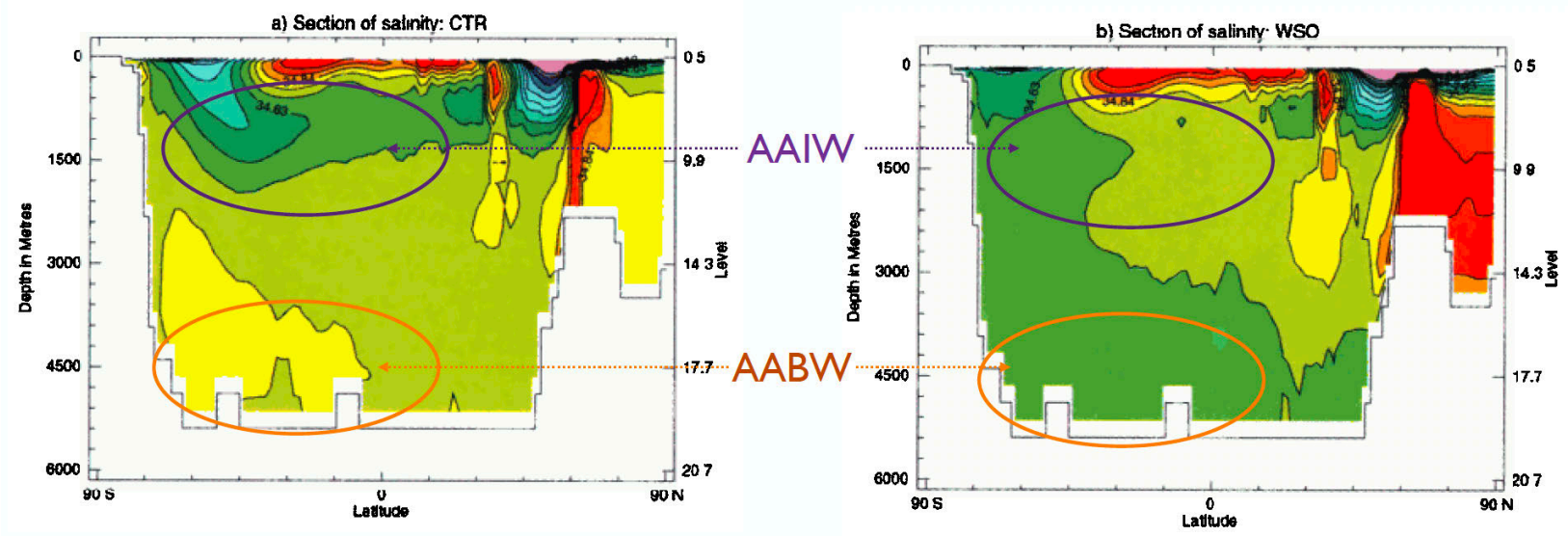
Summer: freshwater transports to ocean
salinity goes down

Occurs at high latitudes → Occurs at low latitudes

There should be wind-driven sea-ice movement!

Sea-ice's role in AABW and AAIW (Saenko and Weaver 2001)

fully coupled ocean and sea-ice | **removed sea-ice component**



- *intermediate model with coarse resolution ocean (MOM2), 2D atmosphere, and dynamic /thermodynamic sea-ice model*

"Sea-ice" is very important in Southern Ocean water masses!

Water Mass Transformation (Walin 1982, Abernathey et al. 2016)

- Powerful way to characterize the role of different processes in driving ocean circulation (overturning).
- "**Water mass**" refer to a body of water with similar temperature, salinity, and/or density properties.
- "**Water mass transformation**" is considered to be a process which some properties of a water parcel are changed.
- Depending on the nature of the transformation, the density of the water parcel might be changed continuously.
  → Density changes ultimately affect the ocean dynamics (ocean circulation).
- To aid in our investigation of SO interactions between the atmosphere, ocean, sea ice, and ice shelves, we applied **WMT** analysis.

$$\underbrace{\Omega(\sigma_k, t)}_{\text{Total WMT}} = \underbrace{-\frac{1}{(\sigma_{k+1} - \sigma_k)} \iint_A \left(\frac{\alpha Q_{net}}{\rho_0 C_p}\right) dA}_{\text{Net surface heat flux}} + \underbrace{\frac{1}{(\sigma_{k+1} - \sigma_k)} \iint_A \left(\frac{\beta S F_{net}}{\rho_0}\right) dA}_{\text{Net surface freshwater flux}}$$

$$F_{net} = F_{A \to O} + F_{I \to O}$$

$F_{A \to O}$: *Atmosphere to Ocean*

$F_{I \to O}$: *Sea ice to Ocean (formation and melting)*

Water Mass Transformation (Walin 1982, Abernathey et al. 2016)

- *Water-mass transformation rates:*

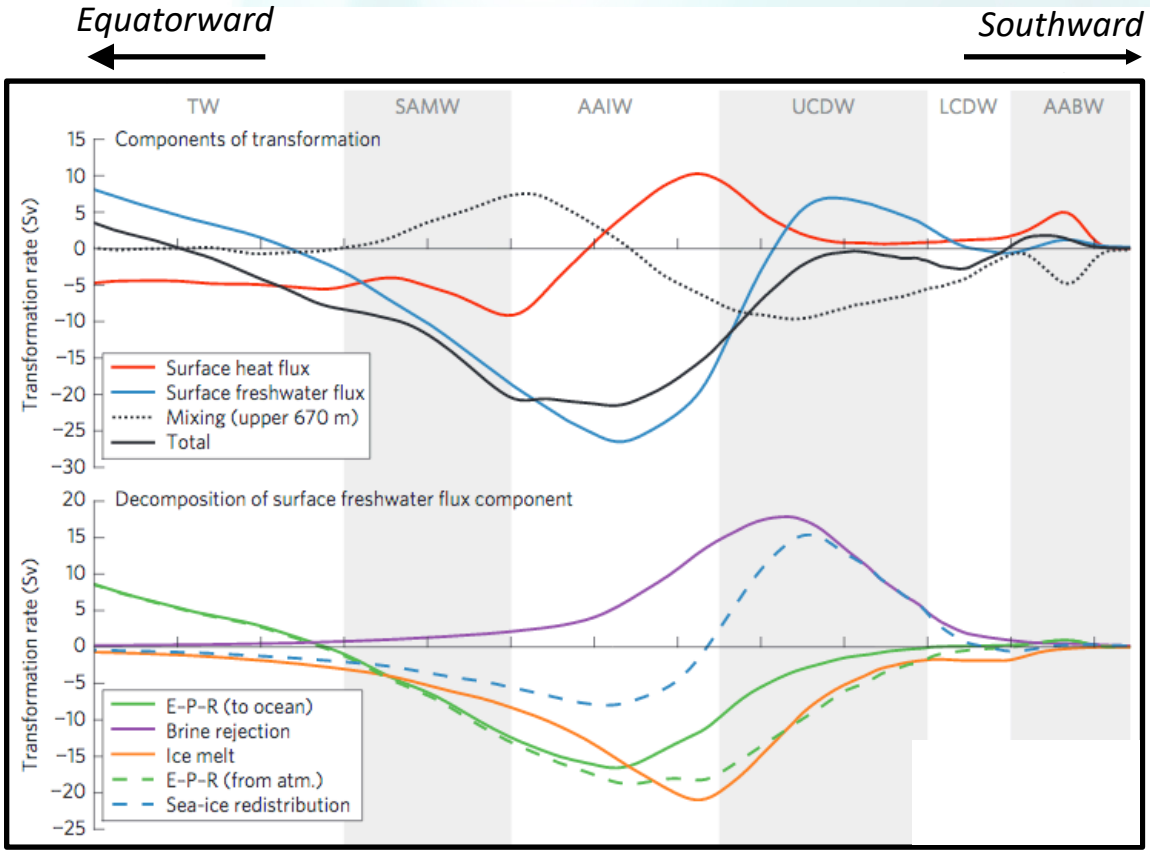
$$\Omega(\sigma_k, t) = -\frac{1}{(\sigma_{k+1} - \sigma_k)} \iint_A \left(\frac{\alpha Q_{net}}{\rho_0 C_p}\right) dA + \frac{1}{(\sigma_{k+1} - \sigma_k)} \iint_A \left(\frac{\beta S F_{net}}{\rho_0}\right) dA$$

- *Water-mass formation rates:*

$$\mathrm{M}(\sigma_k) = -[\overline{\Omega(\sigma_{k+1})} - \overline{\Omega(\sigma_k)}]$$

	Positive	Negative
Transformation rates	Denser Lose buoyancy	Lighter Gain Buoyance
Formation rates	Water convergence Downwelling motion	Water divergence Upwelling motion

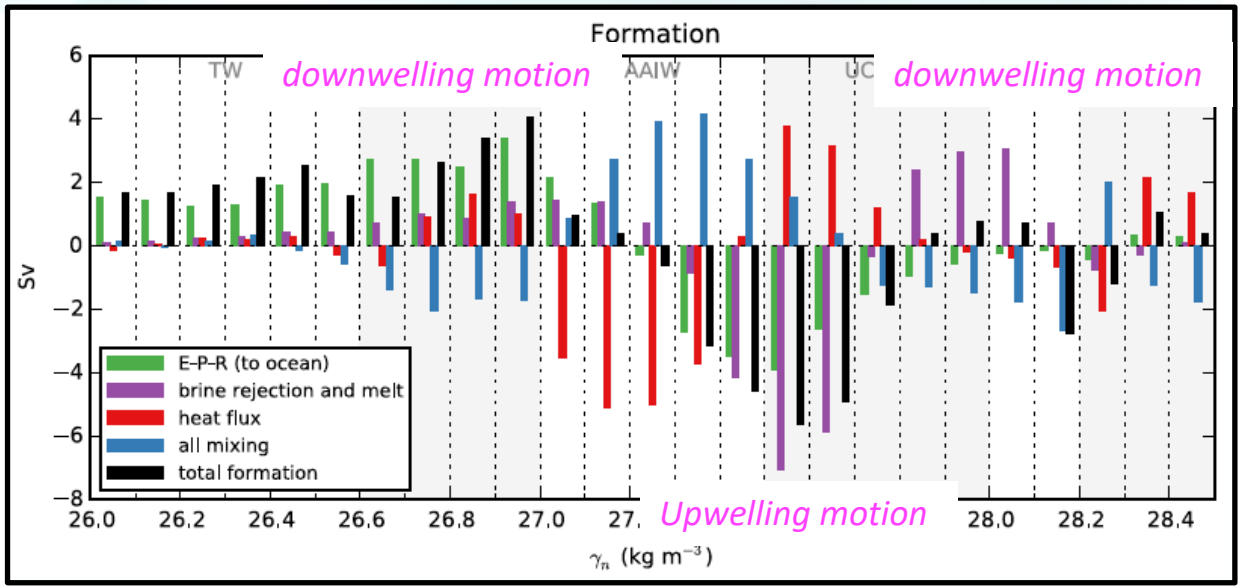
Water Mass Transformation (Abernathey et al. 2016, SOSE)



- *Surface freshwater flux term is dominant*
- *Heat flux is secondary to freshwater flux*

- *Sea-ice formation/melting is dominant*
- *brine rejection peaks in UCDW range*
- *sea-ice melting peaks in AAIW range*

Water Mass Formation Rates (Abernathey et al. 2016, SOSE)



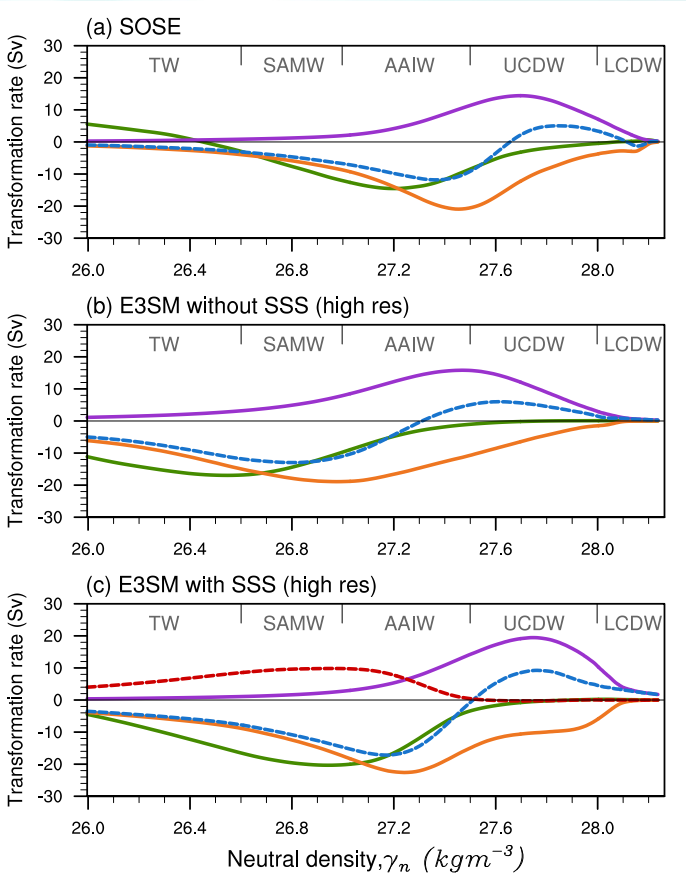
- *Destruction (upwelling motion) of UCDW and some AAIW dominated by **"sea-ice"***
- *Precipitation, heat flux, and sea-ice melting contribute to production of SAMW*
- *Heat flux term makes AABW → limitation of SOSE data, real ocean transformation rate in AABW mainly caused by brine rejection!*

Application (I) to Southern Ocean in E3SM simulations

	SOSE	E3SM (Ocean and Sea-ice stand-alone)
Resolution	1/6° x 1/6°	30to10
Periods	6 years (2005-2010)	20 years

SOSE: Southern Ocean State Estimate, 6yrs (2005-2010) high-res ocean data assimilated product (Mazloff et al. 2010)

Water Mass Transformation in Southern Ocean

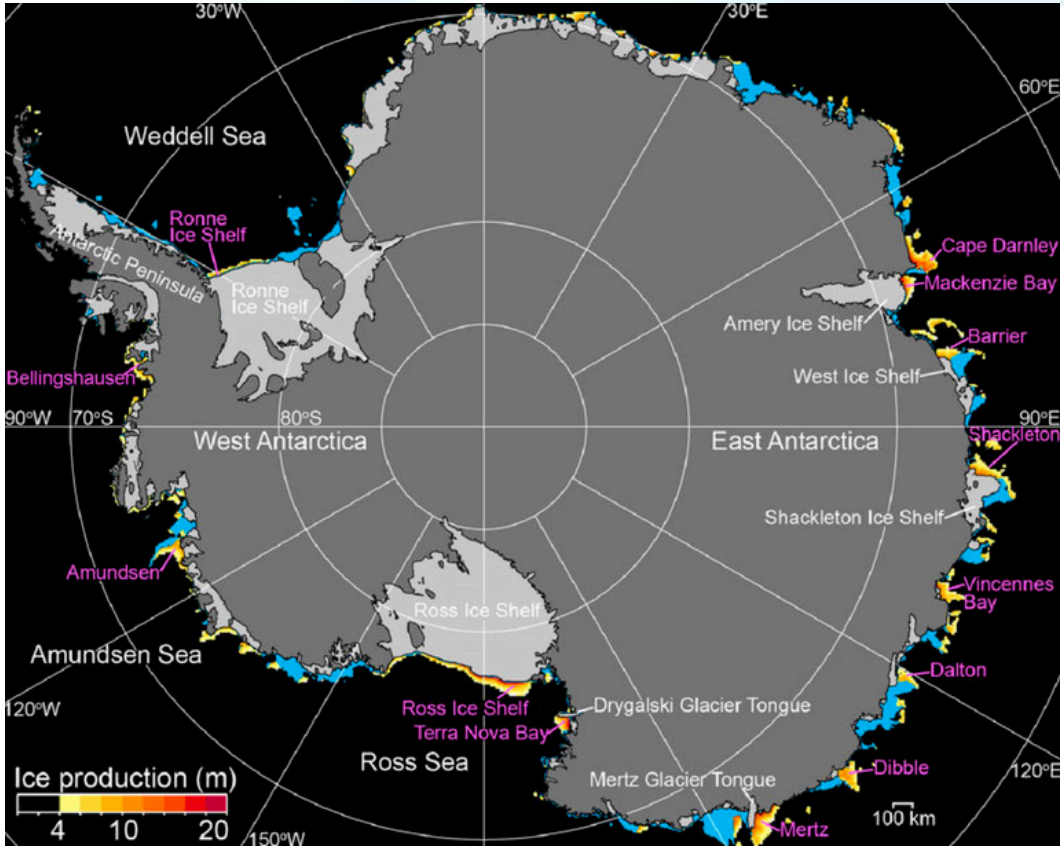


Sea-ice formation (brine rejection)
Sea-ice melting
Sea-ice formation and melting
E-P-R
Salinity restoring

Application (II) to dense water formation in coastal polynyas

	LR tuned HR E3SM	HR E3SM (Caldwell et al. 2019)
Resolution	Low Res. 60to30	High Res. 18to6
Periods	30 years (26-55)	30 years (26-55)

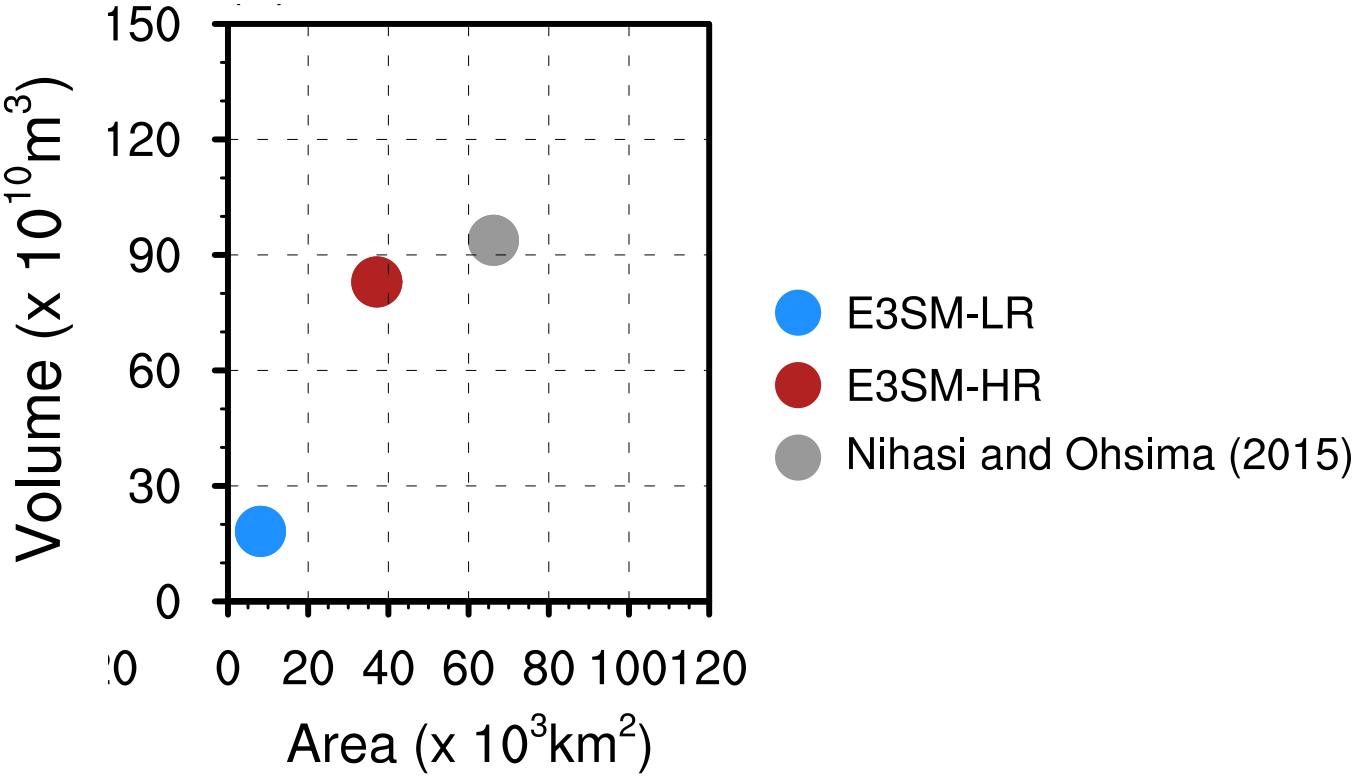
Sea-ice production in coastal polynyas



- Small in area compared to the total sea-ice zone (<3%)
- High Sea-ice production (10% of total sea-ice volume)
- Important climate impact on atmospheric mesoscale motions by transporting latent heat from ocean
- Impact on strong water mass transformation → AABW

From Nihashi and Ohshima, 2015

Sea-ice production in Antarctic coastal polynyas

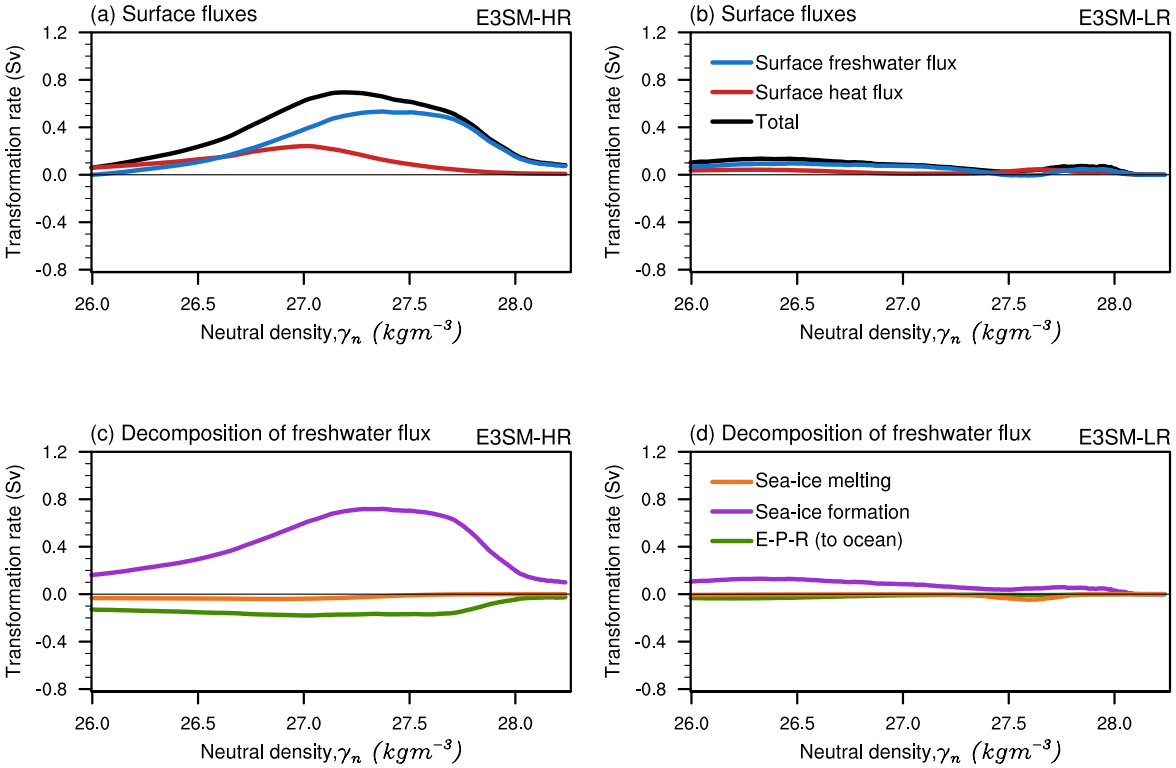


Jeong et al. (in prep)

Water Mass Transformation in coastal polynyas

HR

LR



- Dense water-mass transformation in HR
- Major role of surface freshwater flux

- **Brine rejection term is dominant**
- However, it occurs at relatively low density ranges → it is related to fresh bias along the Antarctic coast in HR

Jeong et al. (in prep)

Application (III) to Labrador Sea bias in E3SM simulations

	LR tuned HR E3SM	HR E3SM (Caldwell et al. 2019)
Resolution	Low Res. 60to30	High Res. 18to6
Periods	30 years (26-55)	30 years (26-55)

Labrador Sea bias in E3SM simulations

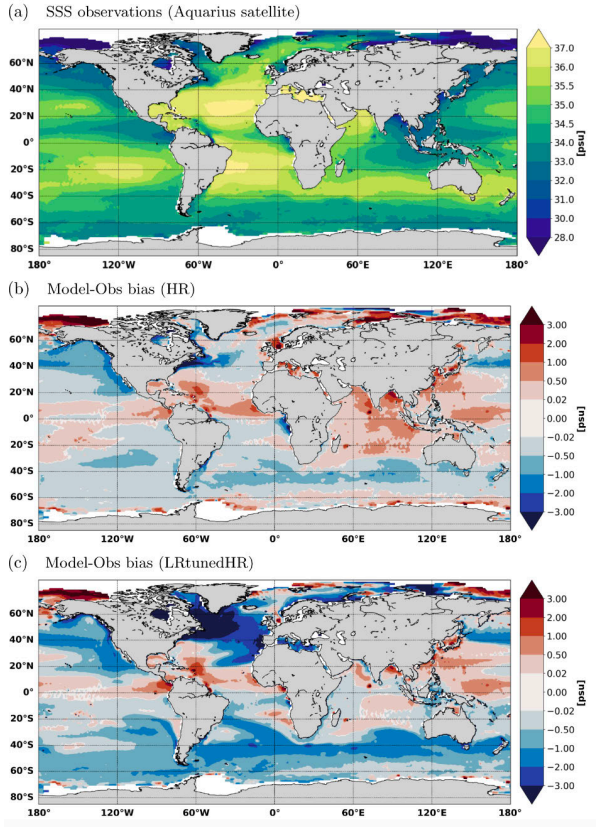
Sea Surface Salinity

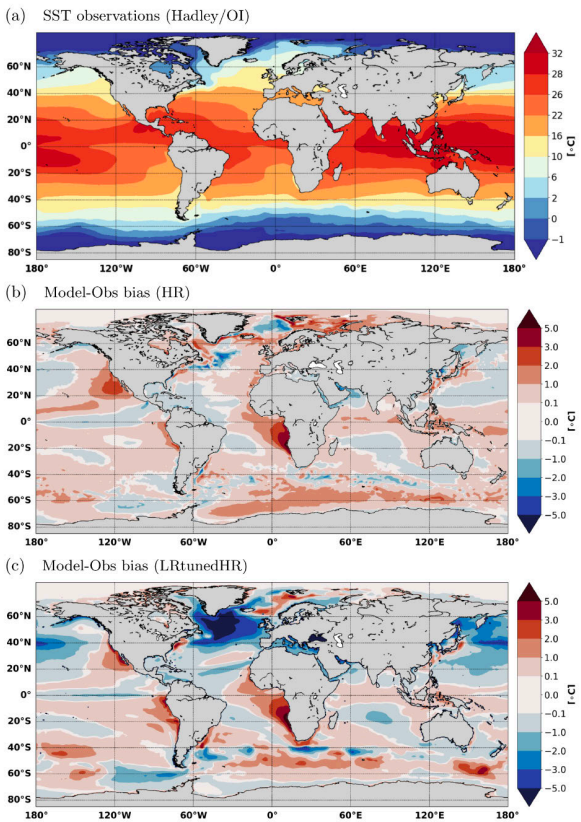
Sea Surface Temperature

OBS

HR - OBS

LR - OBS

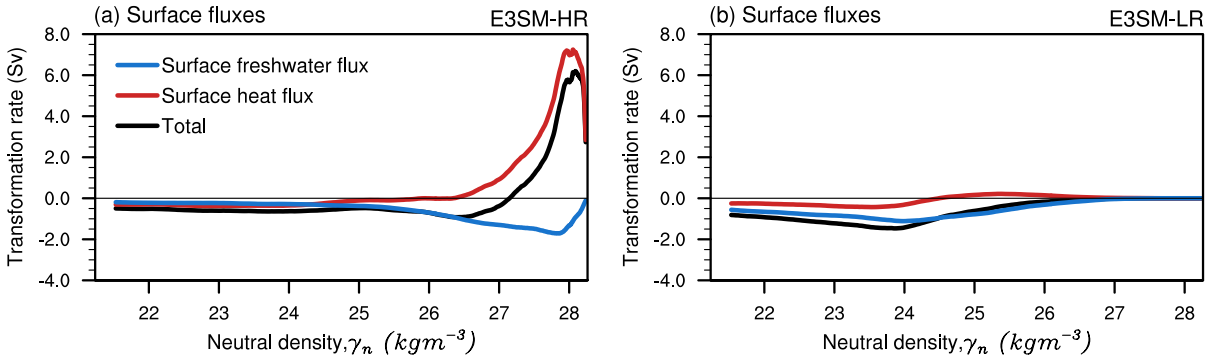




From Caldwell et al. 2019

Water Mass Transformation in E3SM simulations

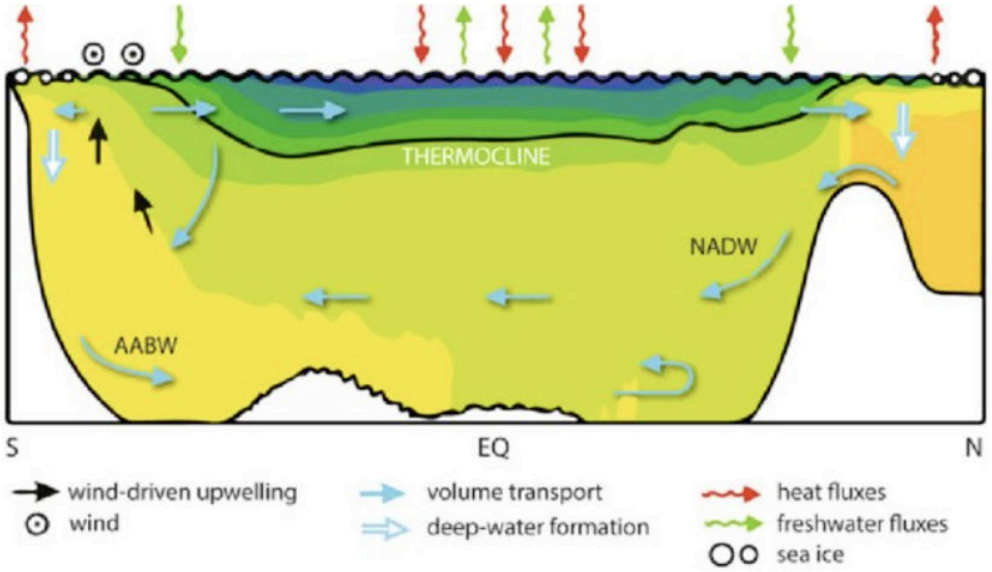
HR **LR**



- Dense water-mass transformation in HR
- Major role of heat flux loss (to the atmosphere) rather than surface freshwater flux term

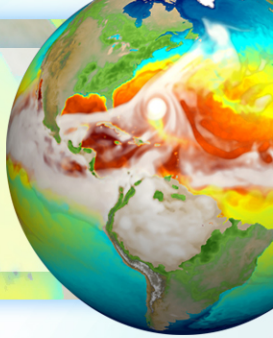
- However, no dense water-mass transformation in LR

Atlantic Meridional Overturning Circulation (AMOC)



From Kuhlbrodt et al. 2007, Violante et al., 2017

Thank you



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