What drives the Ocean's Super Residual Circulation?

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UNIVERSITY of TASMANIA AUSTRALIA

CSIRO

QMS QUANTITATIVE MARINE SCIENCE

IMAS INSTITUTE FOR MARINE AND ANTARCTIC STUDIES

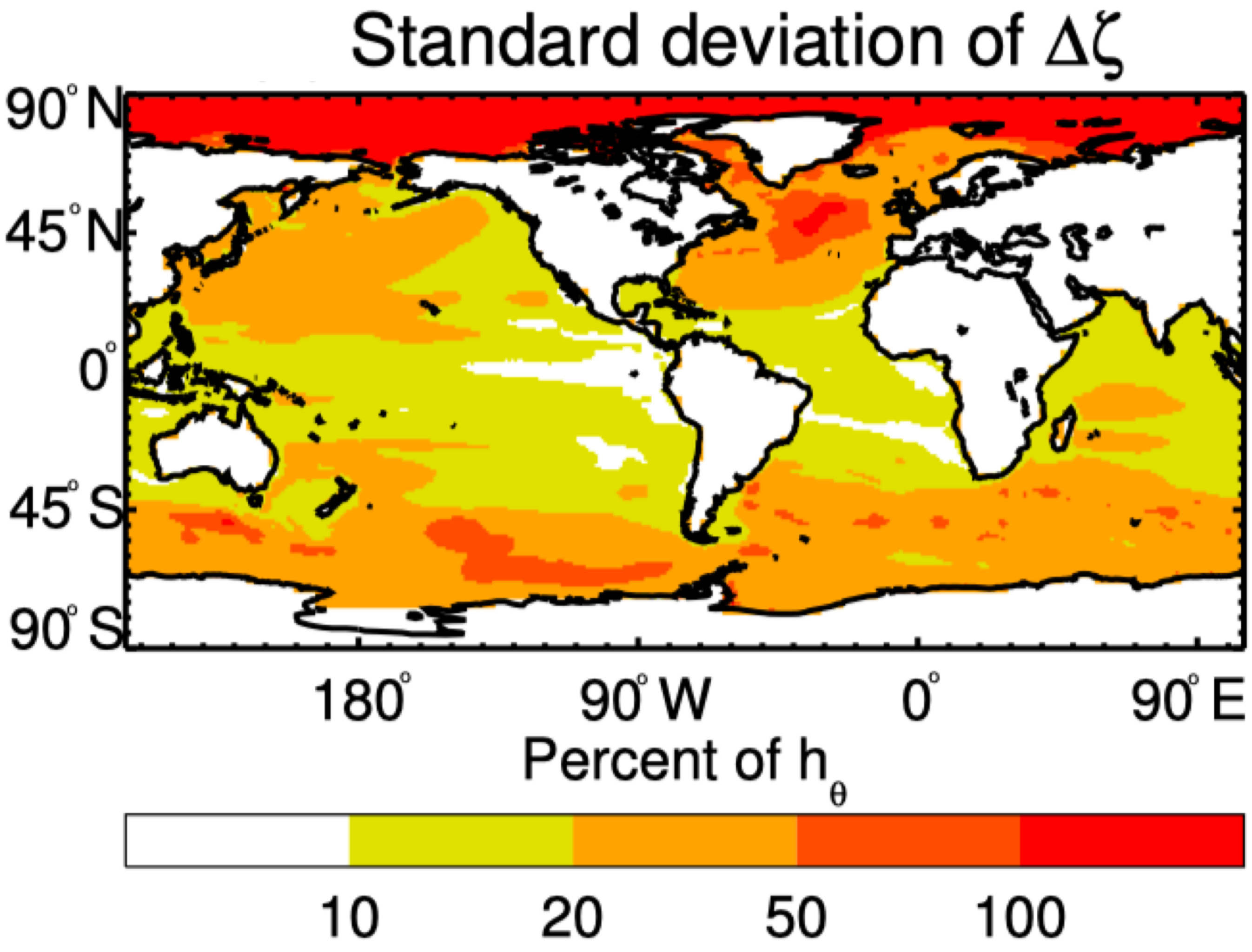
ARC CENTRE OF EXCELLENCE FOR CLIMATE EXTREMES

Earth Systems and Climate Change Hub

National Environmental Science Programme

COSIMA Virtual Workshop May 2020

Motivation



Spread in projected sea level change among models largely due to differences in ocean heat uptake and vertical heat transport (Kuhlbrodt and Gregory 2012)

Vertical heat transport: traditional budget approach

$$\frac{\partial T}{\partial t} = -\nabla \cdot (uT) + \nabla \cdot (K_{eddy}\, T) + \nabla \cdot (K_{small}\, T) + \frac{F}{\rho_0 C_p}$$

$$\boxed{\begin{aligned} -\nabla \cdot (uT) &= ADV + MESO \\ \nabla \cdot (K_{eddy} \nabla T) &= ISO \end{aligned}}\; + SUB$$

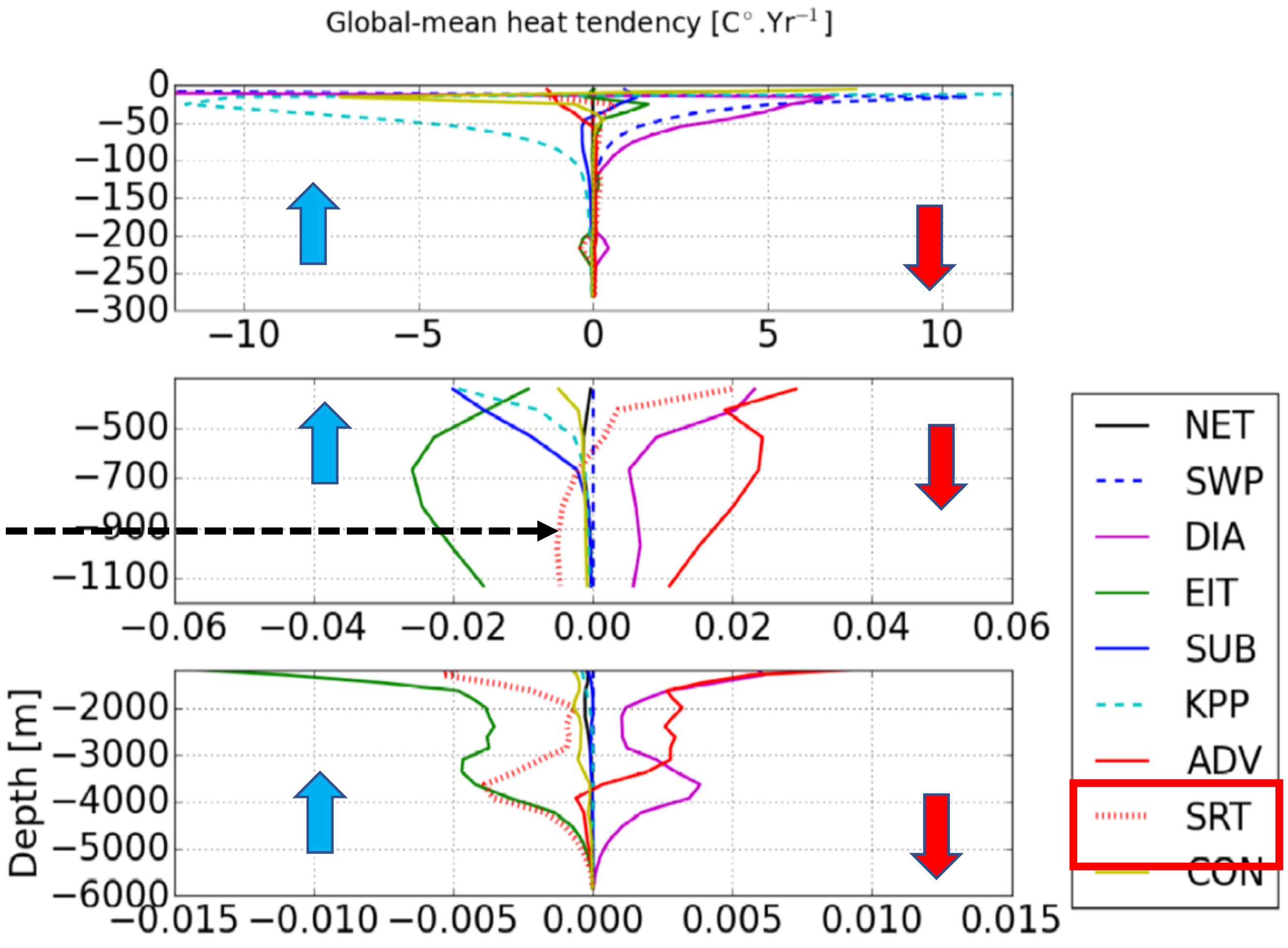
Super Residual Transport (SRT)

$$\nabla \cdot (K_{small} \nabla T) = DIA + KPP + CON + SIGMA_{DIFF}$$

$$F = SFC + SWP + PME + RIV + FRZ$$

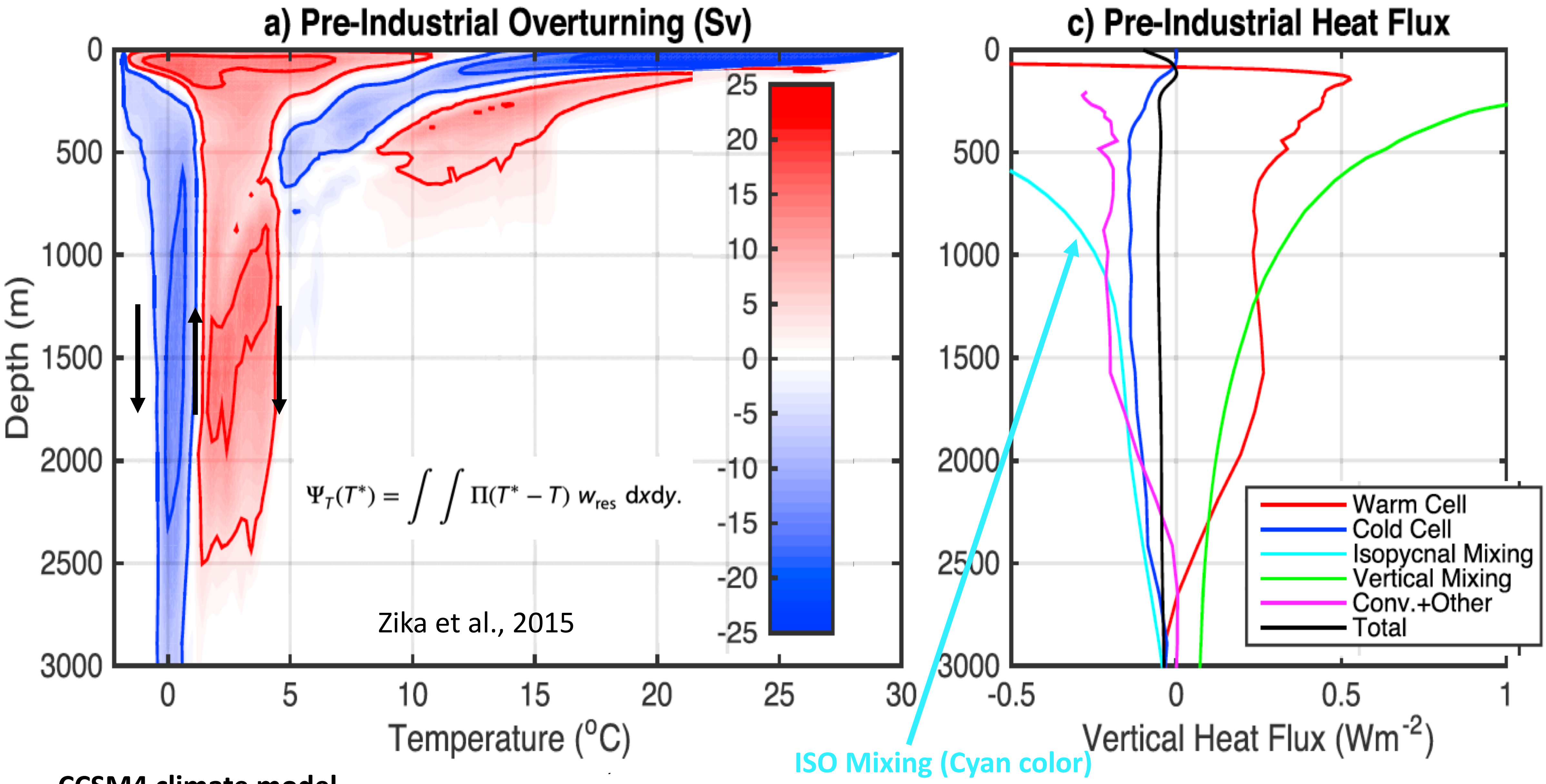
SRT Transports heat downward in the upper ocean and upward in the deep ocean

Limitation: cannot separate different parts of ocean circulation



Dias et al., 2020

Residual circulation and heat transport by each cell and diabatic processes



CCSM4 climate model

Key objectives

- Quantify the contribution of different components of ocean circulation to vertical heat transport
- Quantify what physical processes drive different components of ocean circulation and their associated heat transport
- Define the Super Residual Circulation (SRC) by combining resolved Eulerian and eddy advection with eddy mixing

Residual and Diathermal Circulation in ACCESS-OM2

Residual Circulation (Zika et al., 2015)

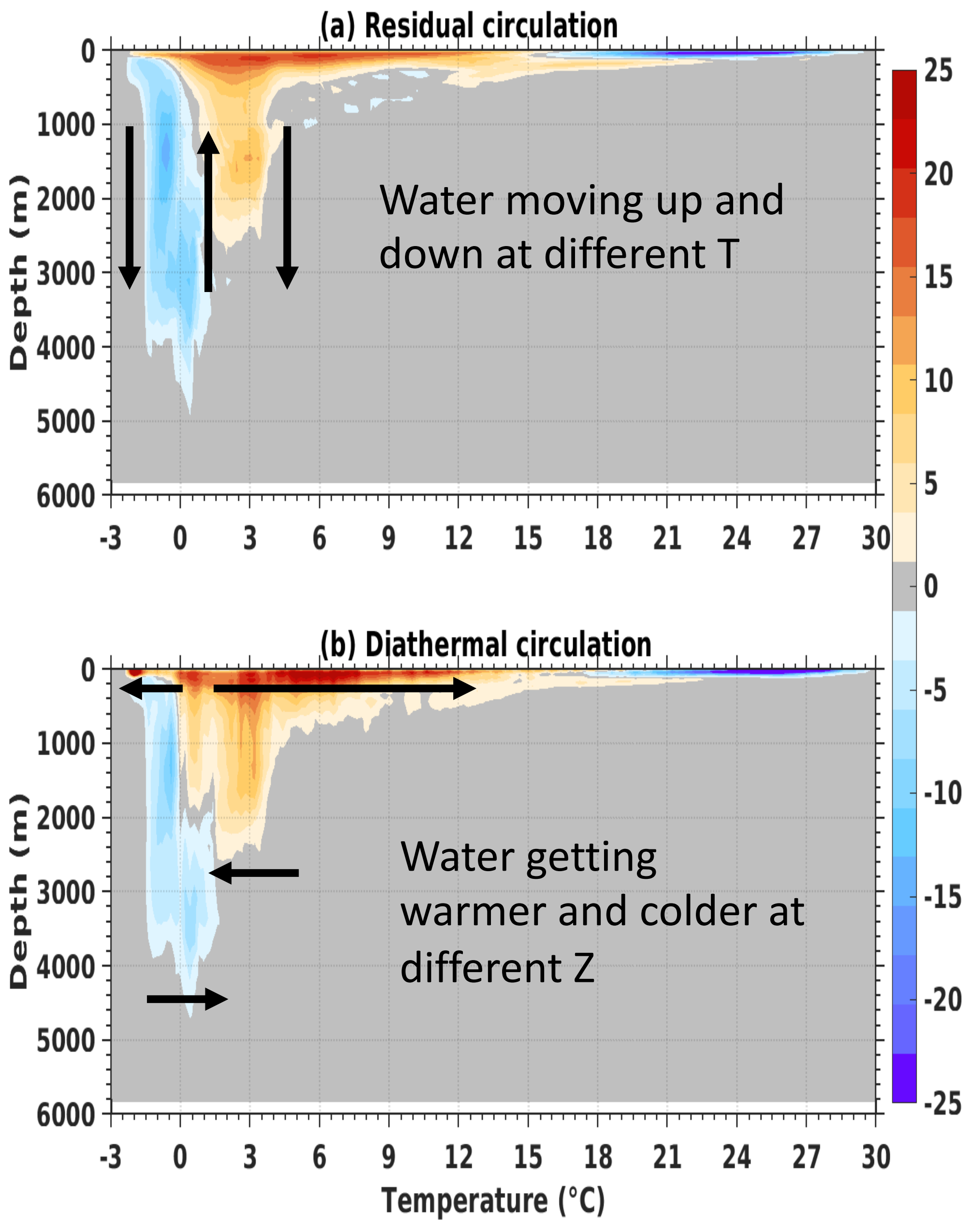
$$\psi(T^*, Z^*) = \iint_{\substack{T<T^* \\ Z=Z^*}} w\, dA.$$

Diathermal circulation (brand new!!!)

$$\psi^{dia}(T^*, Z^*) = \iint_{\substack{Z<Z^* \\ T=T^*}} \left(\frac{\partial T}{\partial t} + \nabla \cdot (uT) \right) / \ |\nabla T|\, dA$$

$$= \frac{\partial}{\partial T} \iint_{\substack{Z<Z^* \\ T<T^*}} \frac{\partial T}{\partial t} + \nabla \cdot (uT)\, dV$$

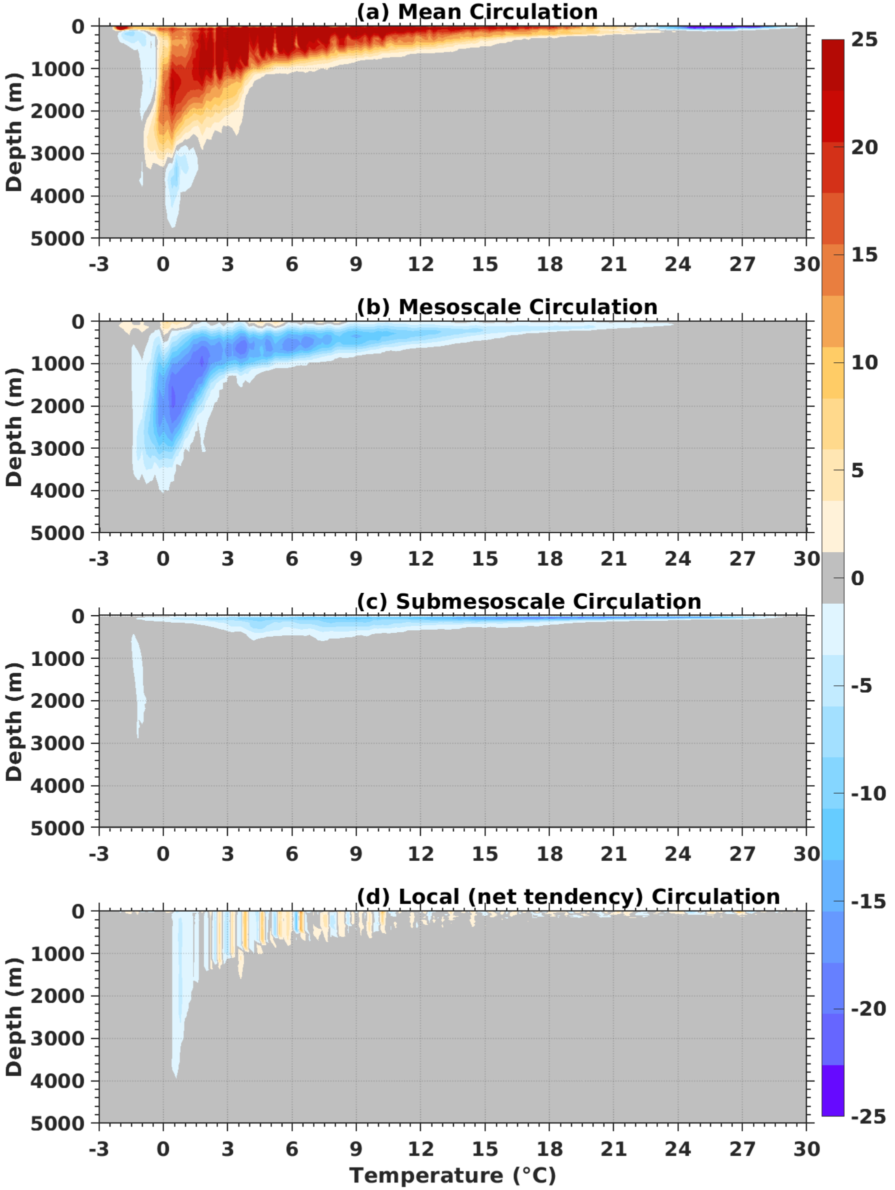
$$= -\frac{\partial}{\partial T} \iint_{\substack{Z<Z^* \\ T<T^*}} \nabla \cdot \left(K_{eddy} \nabla T\right) + \nabla \cdot \left(K_{small} \nabla T\right) + \frac{F}{\rho_0 C_p}\, dV.$$



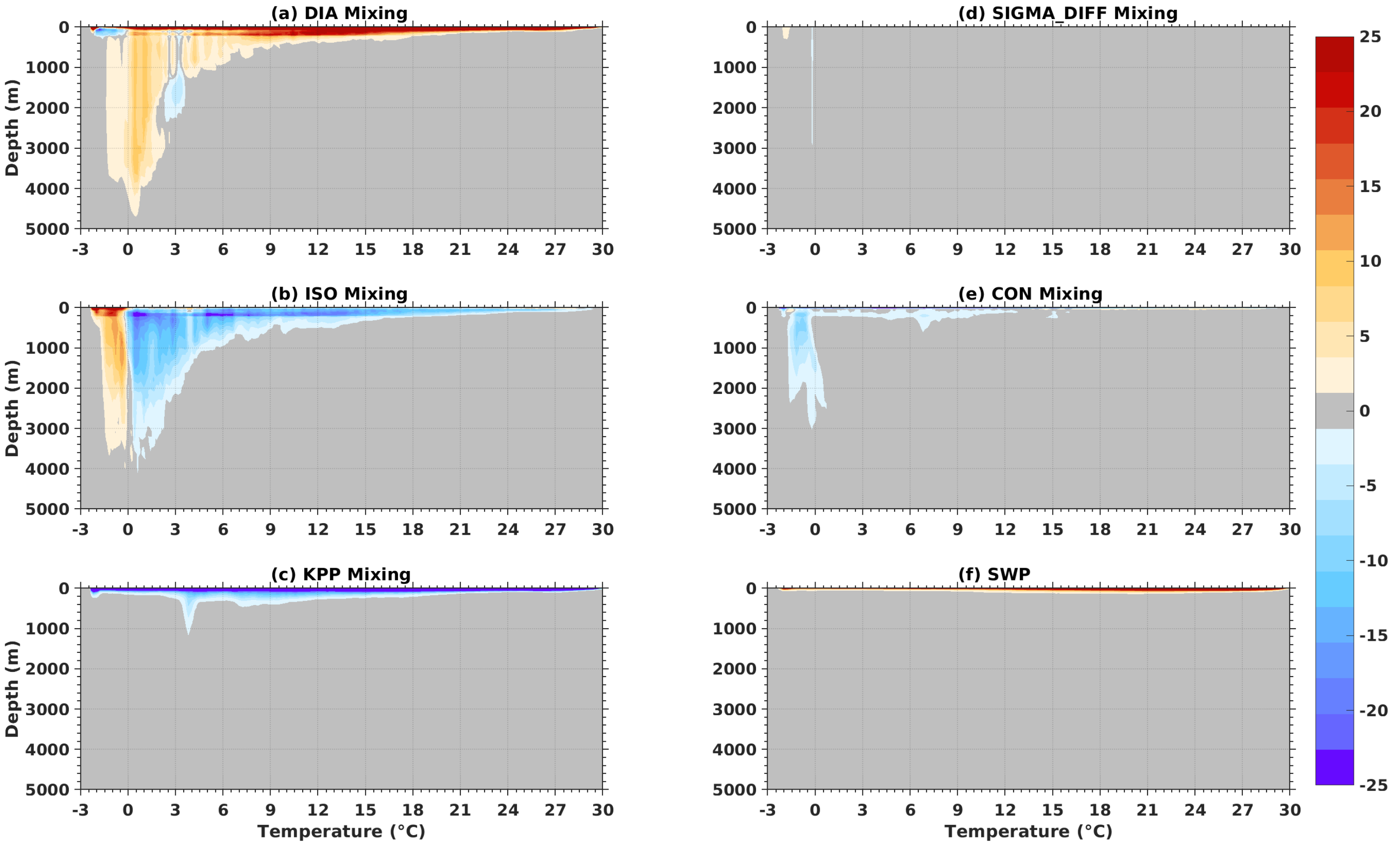
Diathermal circulation reveals influence of both diabatic and advective processes!

Contribution of different processes to diathermal circulation

Advective processes (Kinematics)



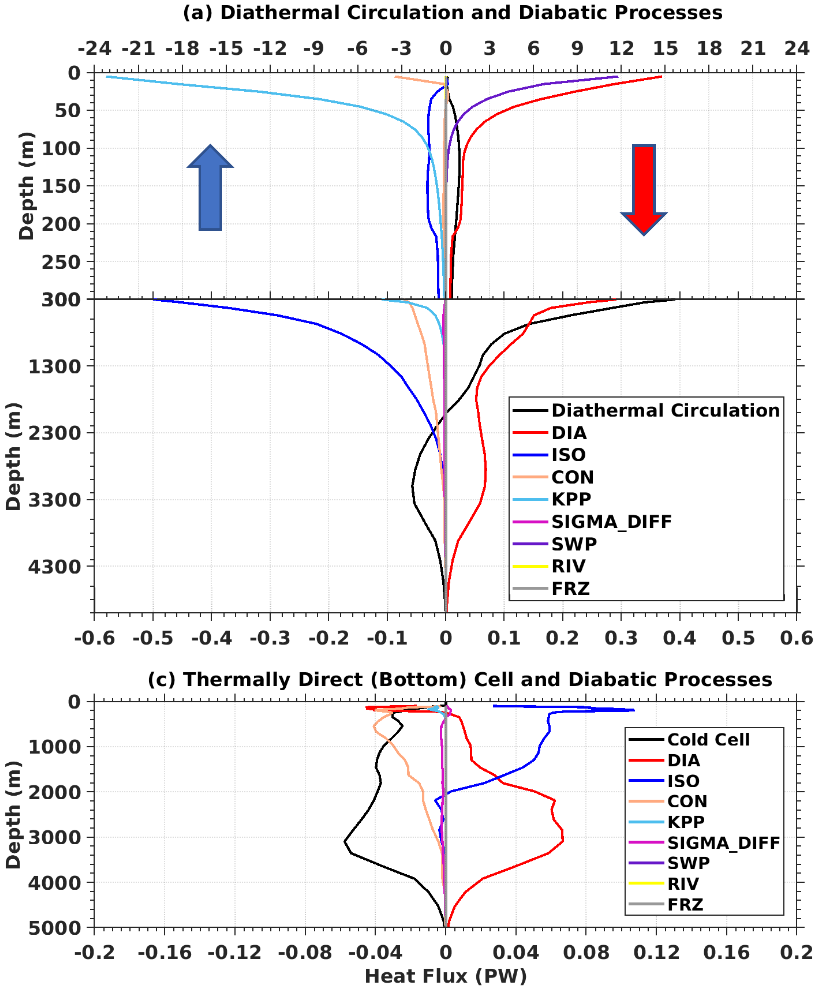
Diabatic processes (thermodynamics)



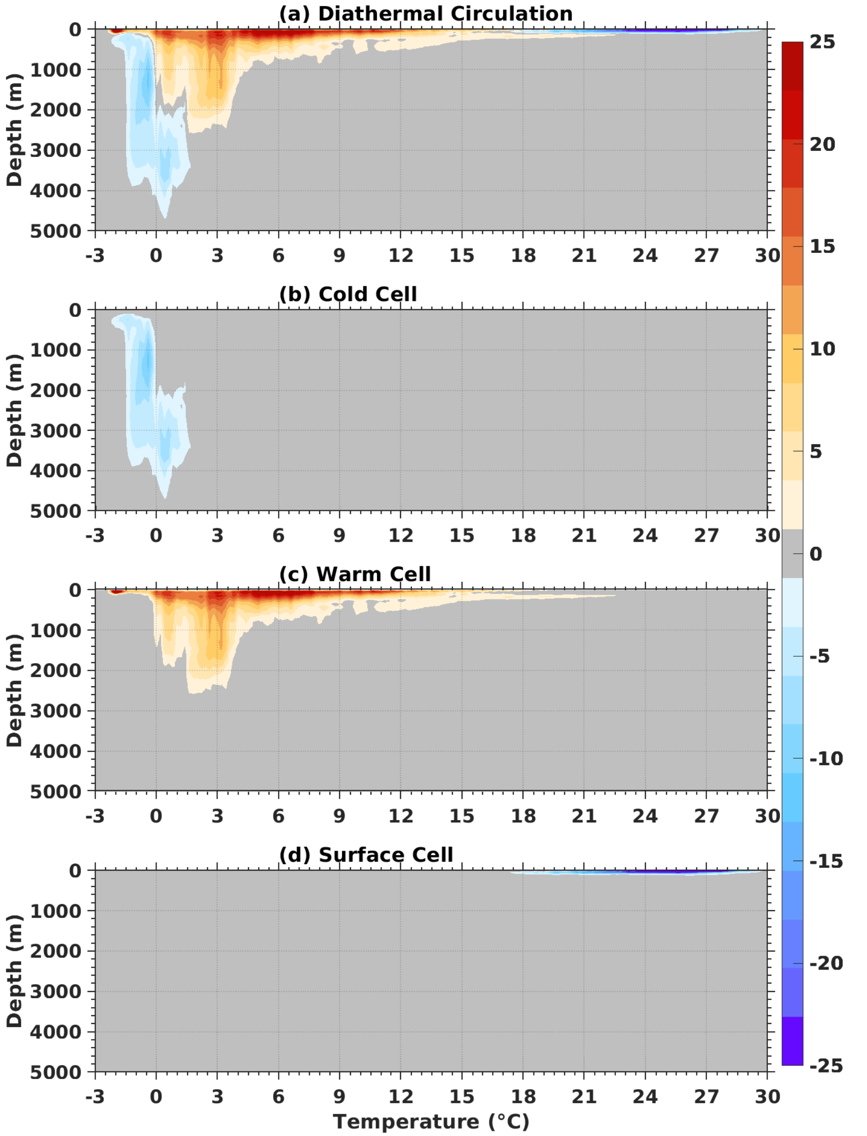
In this framework advective and diabatic processes perfectly balance.

Heat transport by individual cells and the role of diabatic processes

Heat transport by individual cells



Individual circulation cells

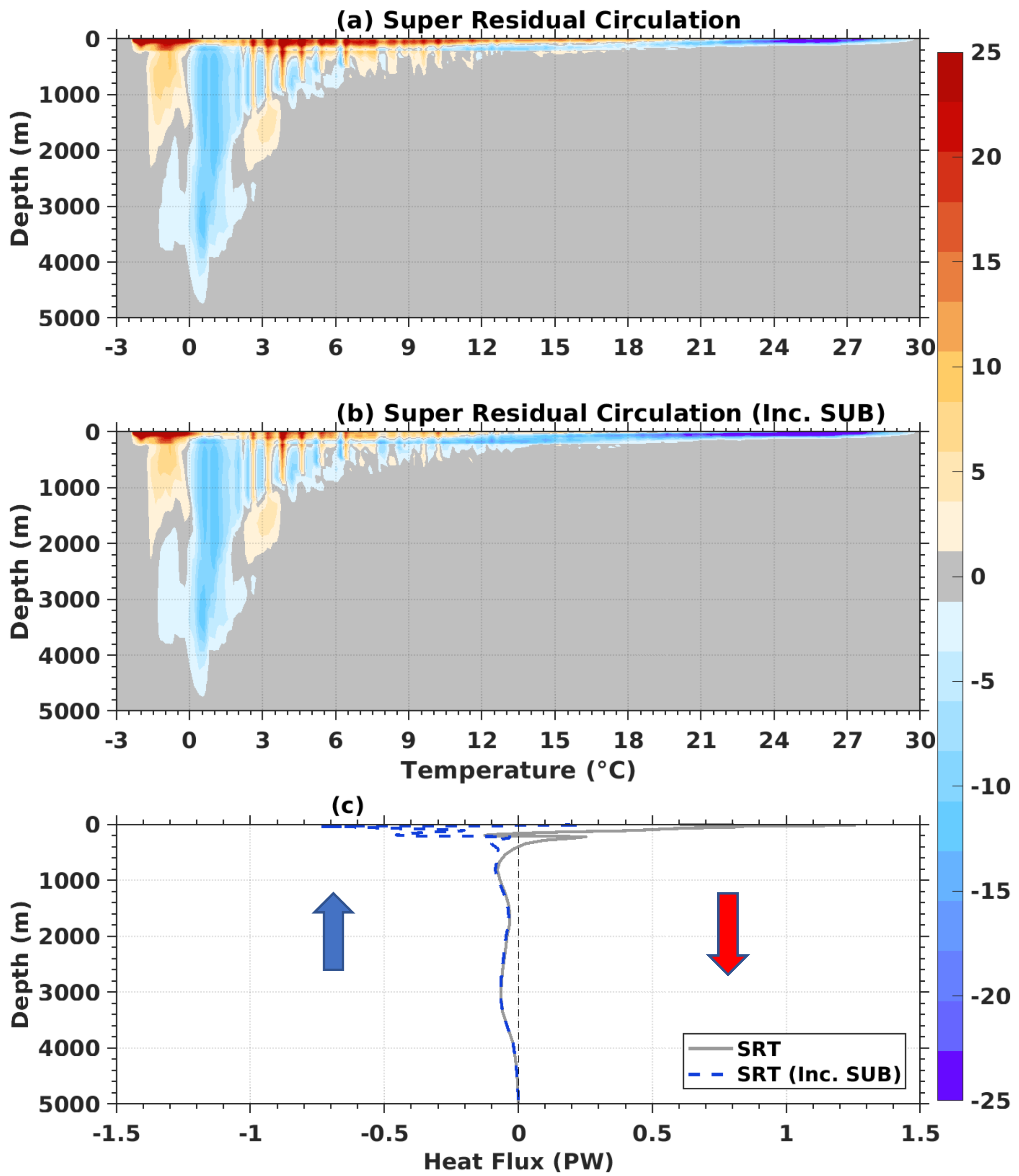


$$T_H = C_p \, \rho_0 \int \psi \, d\,T$$

Super Residual Circulation (SRC)

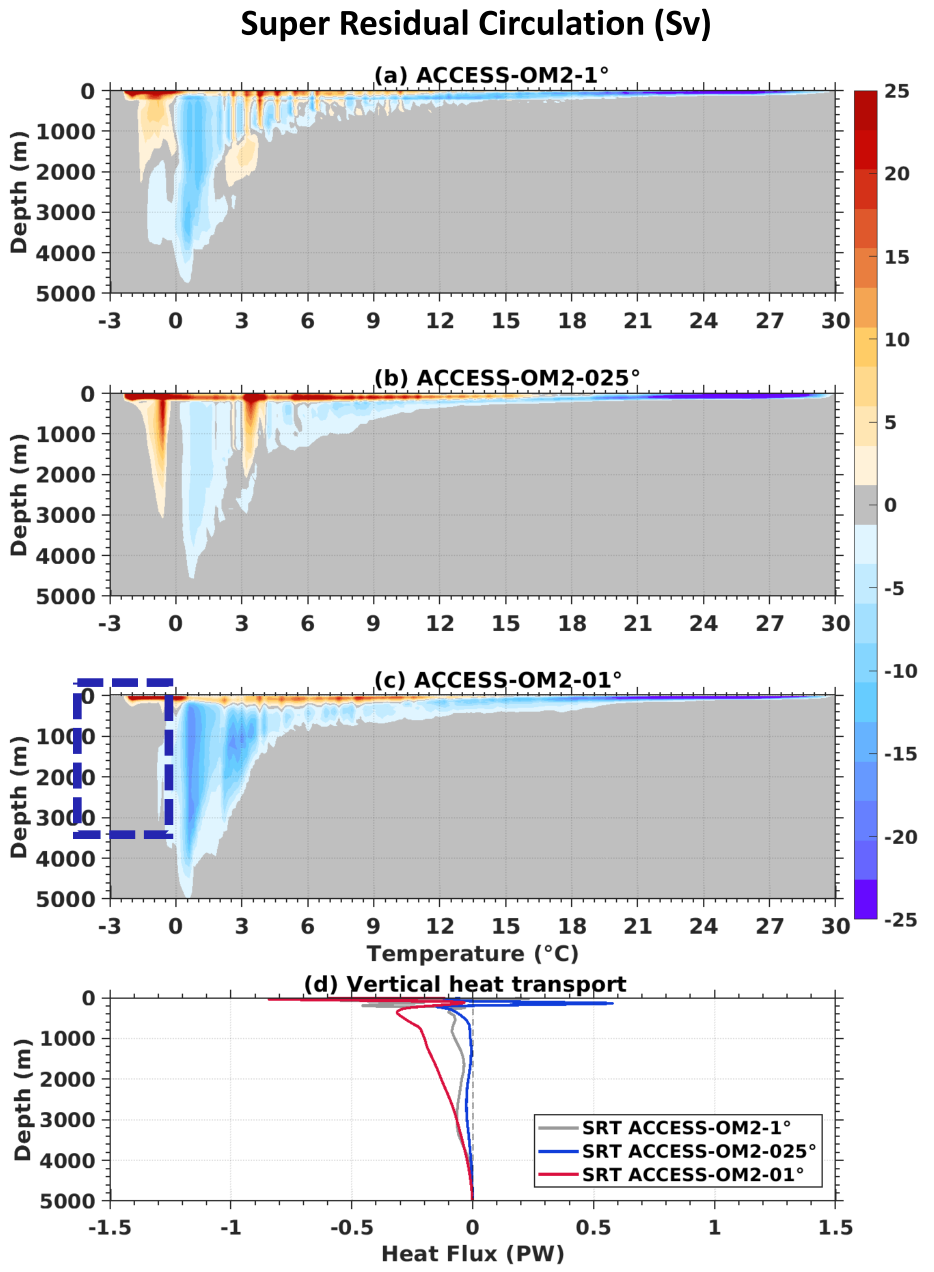
$$\psi^{SRC}(T^*, Z^*) = \frac{\partial}{\partial T} \iint_{\substack{Z<Z^* \\ T=T^*}} \nabla \cdot (\boldsymbol{u}T) + \nabla \cdot \left(K_{eddy}\, T\right) dV$$

- The SRC is dominated by a thermally direct cell.
- The SRC describes 15Sv of water sinking through the 1000m depth surface at about 0°C which is warmed to 2°C by diabatic processes before upwelling.
- The SRC describes Stommel and Arons' and Munk's classical model of the deep circulation.



Super Residual Circulation (SRC) in 1º, 0.25º & 0.1º ACCESS-OM2

- SRC is dominated by a thermally direct cell in ACCESS-OM2-1º, 0.25º and 0.1º.
- ACCESS-OM2-1º and 0.25º has two thermally in indirect cell (warm cell) in colder temperature (< 4ºC) which is not present in ACCESS-OM2-0.1º .
- Upper 200 m has similar thermally direct and thermally indirect cell in all configurations.
- SRC in ACCESS-OM2-0.1º transport 3 time more heat upward than ACCESS-OM2-1º & 0.25º at 1000 m.



Conclusions

- Using advective tendencies, we have presented the diathermal circulation in temperature and depth (T-Z) coordinates which exactly describes contributions to vertical heat transport.
- We have revealed the diathermal circulation and the role of different diabatic processes in its individual overturning cells.
- For the first time, we have introduced the Super Residual Circulation (SRC) which combines Eulerian and eddy advection with isopycnal mixing processes.
- The SRC is dominated by a thermally direct cell with cold water sinking and warm water upwelling consistent with classical descriptions of deep ocean circulation.
- ACCESS-OM2 1^{o}, 0.25^{o} and 0.1^{o} are looks qualitatively similar although 0.1^{o} does not capture the warm cell in temperature $< 0^{o}$ in the subsurface.
- The SRC allows a direct comparison between models with different resolutions and different partitions between resolved and parameterized processes.

Thank you

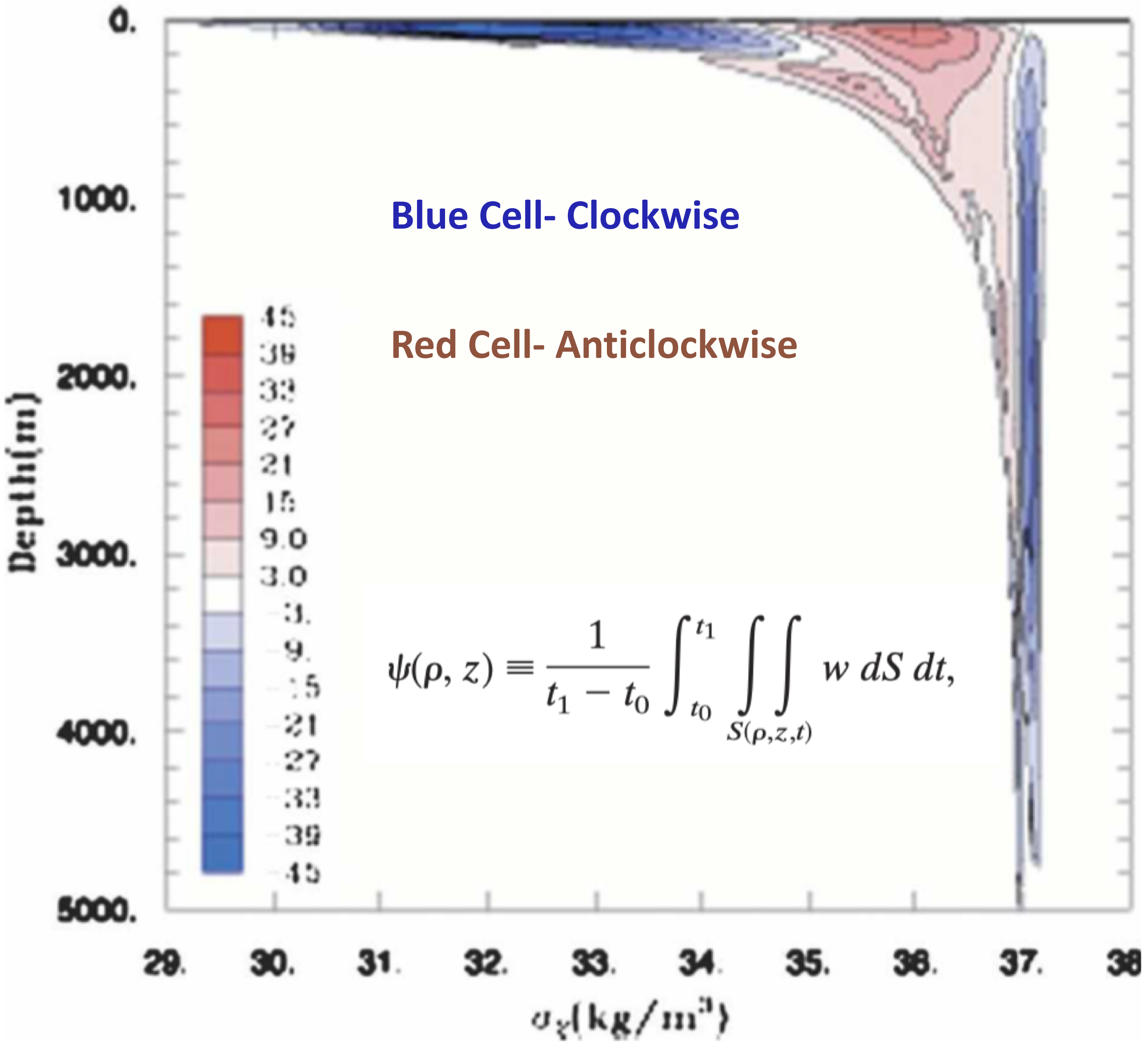
Novel water mass framework in depth density coordinates

Key Findings

- ❑ Nycander et al. (2007) found three cell in depth and density coordinate and called them as

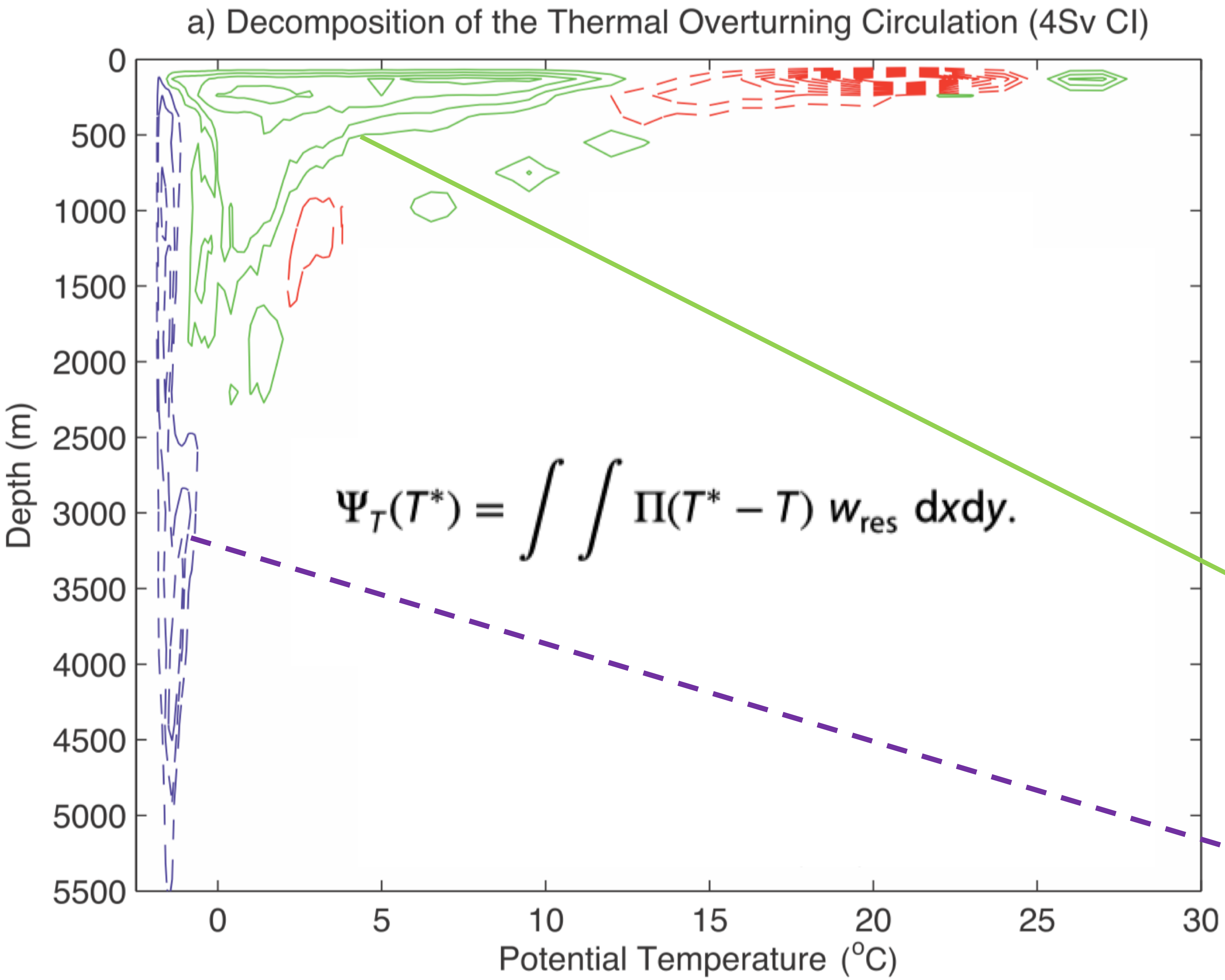
- Cold Cell : Thermally direct (Buoyancy driven) (blue)

- Warm Cell : Thermally indirect (Wind driven) (red)



Nycander et al. (2007)

Novel water mass framework depth temperature coordinates



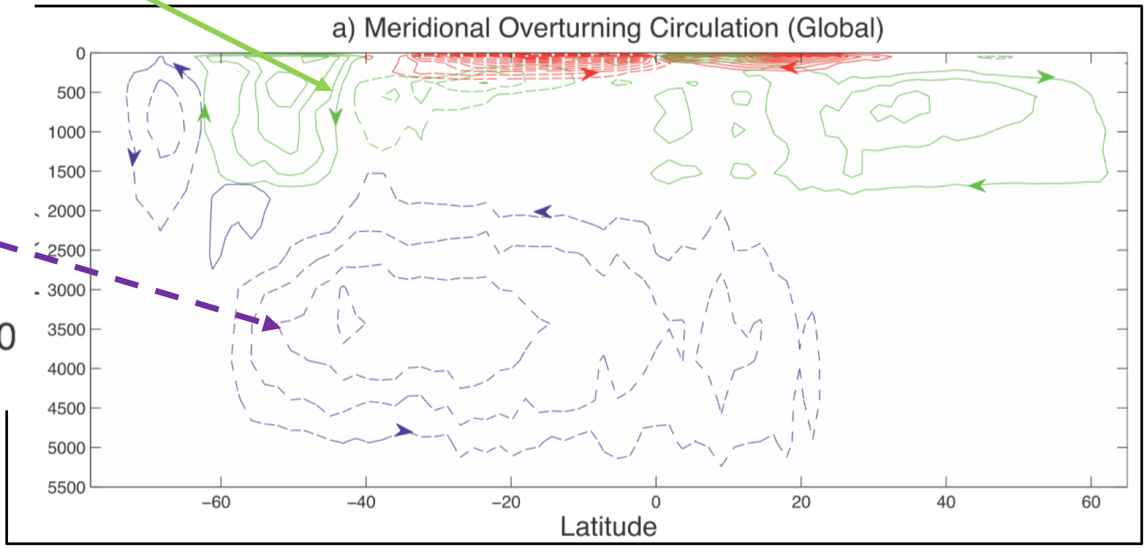
$$\Psi_T(T^*) = \int\int \Pi(T^* - T)\, w_{res}\, dxdy.$$

Uvic. ESM climate model

Zika et al., 2013a

Key findings:

- **Warm Cell link with Interhemispheric overturning Cell (green color)**
- **Cold Cell link with Antarctic Bottom Water (Abyssal) Cell (blue color)**
- **Surface Cell link with tropical and subtropical gyre Cell (red color)**



Residual and Diathermal Circulation in ACCESS-OM2

Residual Circulation (Zika et al., 2015)

$$\boldsymbol{\psi}(\boldsymbol{T}^*, \boldsymbol{Z}^*) = \iint_{\substack{T<T^* \\ Z=Z^*}} \boldsymbol{w}\, \boldsymbol{dA}.$$

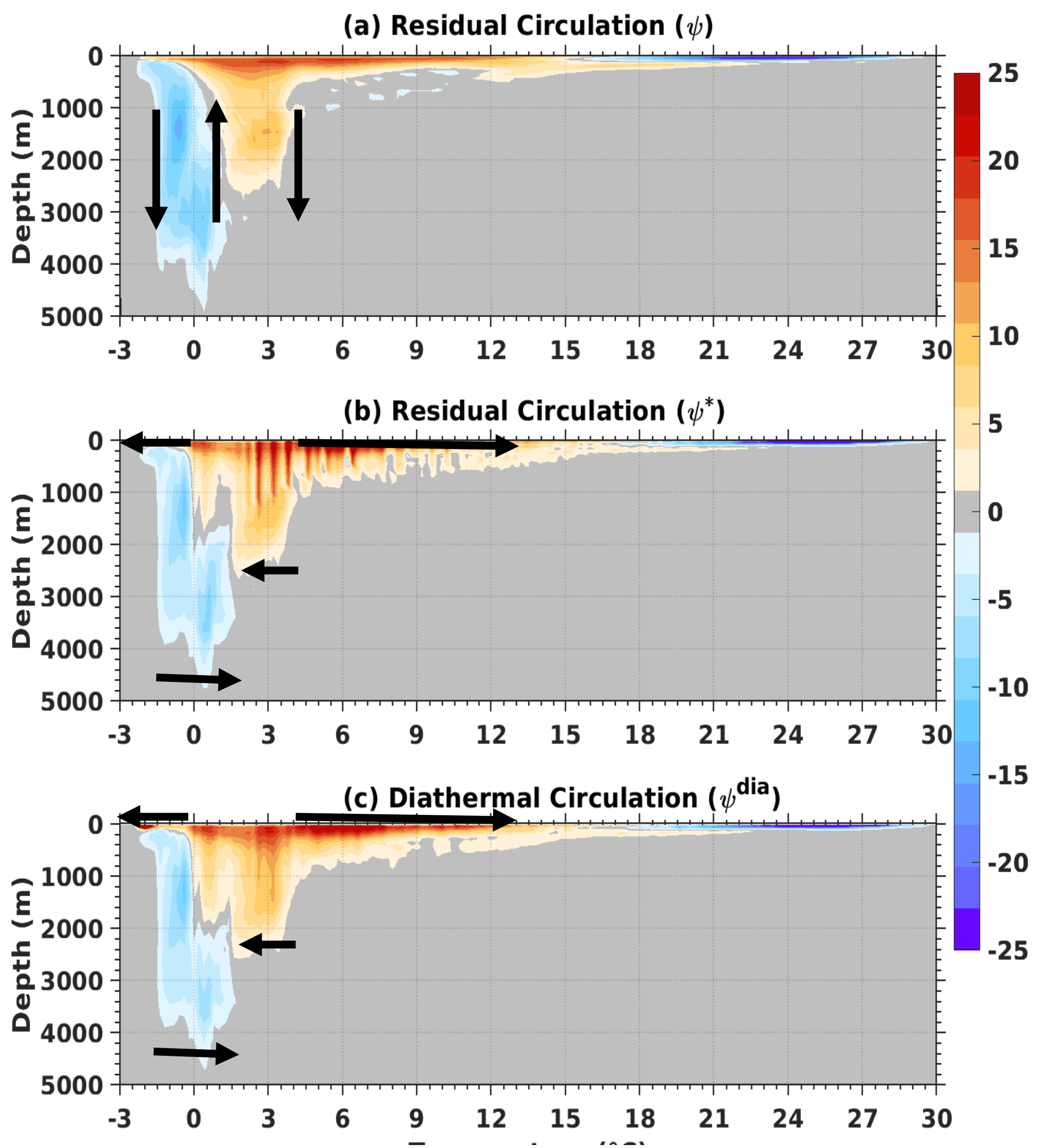
$$\boldsymbol{\psi}^*\,(\boldsymbol{T}^*, \boldsymbol{Z}^*) = \frac{\partial}{\partial \boldsymbol{T}} \iint_{\substack{Z<Z^* \\ T<T^*}} \boldsymbol{\nabla}\cdot(\boldsymbol{uT})\, \boldsymbol{dV}$$

Diathermal circulation (brand new!!!)

$$\boldsymbol{\psi}^{dia}\,(\boldsymbol{T}^*, \boldsymbol{Z}^*) = \frac{\partial}{\partial \boldsymbol{T}} \iint_{\substack{Z<Z^* \\ T<T^*}} \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} + \boldsymbol{\nabla}\cdot(\boldsymbol{uT})\, \boldsymbol{dV}$$

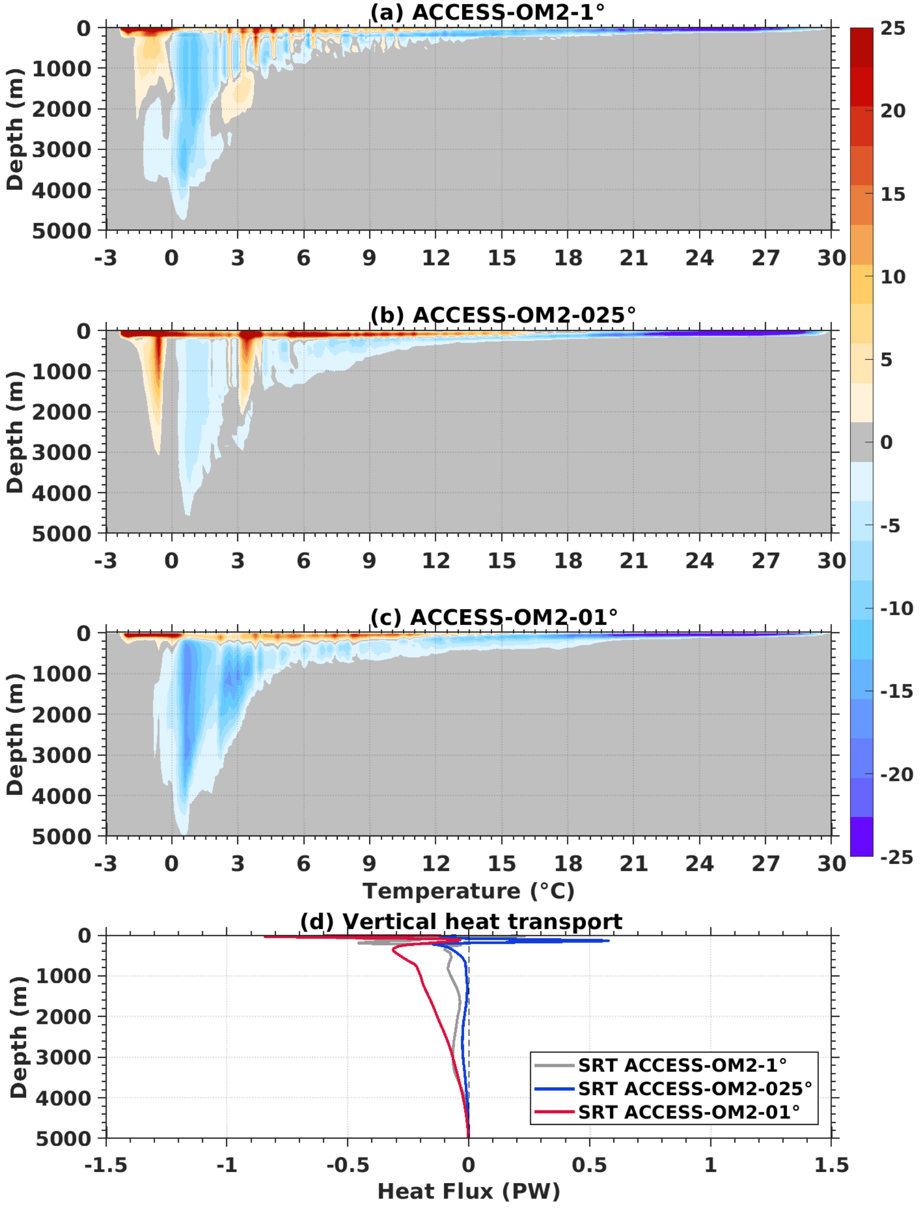
$$= -\frac{\partial}{\partial \boldsymbol{T}} \iint_{\substack{Z<Z^* \\ T<T^*}} \nabla\cdot\left(\boldsymbol{K}_{\boldsymbol{eddy}} \nabla \boldsymbol{T}\right) + \nabla\cdot\left(\boldsymbol{K}_{\boldsymbol{small}} \nabla \boldsymbol{T}\right) + \frac{\boldsymbol{F}}{\boldsymbol{\rho_0 C_p}}\, \boldsymbol{dV}.$$

- Diathermal circulation reveals influence of both diabatic and advective processes!

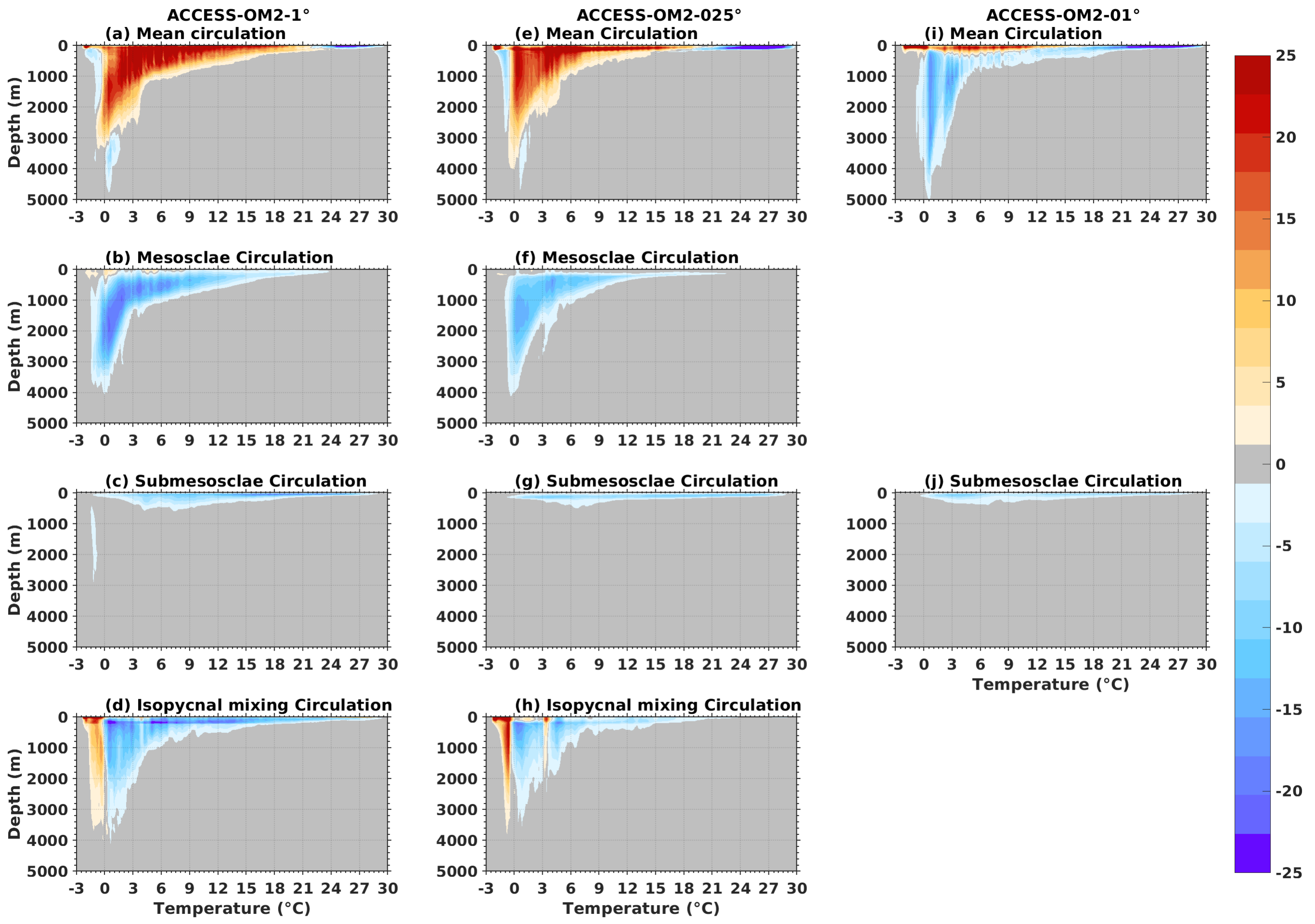


Super Residual Circulation (SRC) in 1º, 0.25º & 0.1º ACCESS-OM2

Super Residual Circulation (Sv)



Individual Advective Contribution to Super Residual Circulation (Sv)



- ACCESS-OM2-1º and 0.25º have two thermally direct cell in colder temperature which is not present ACCESS-OM2-0.1º .
- All configuration in the upper 100 m has similar thermally direct and thermally indirect cell