JÜLICH Forschungszentrum

GCS Gauss Centre for Supercomputing

Southern Ocean eddy compensation examined with a high-resolution ocean model

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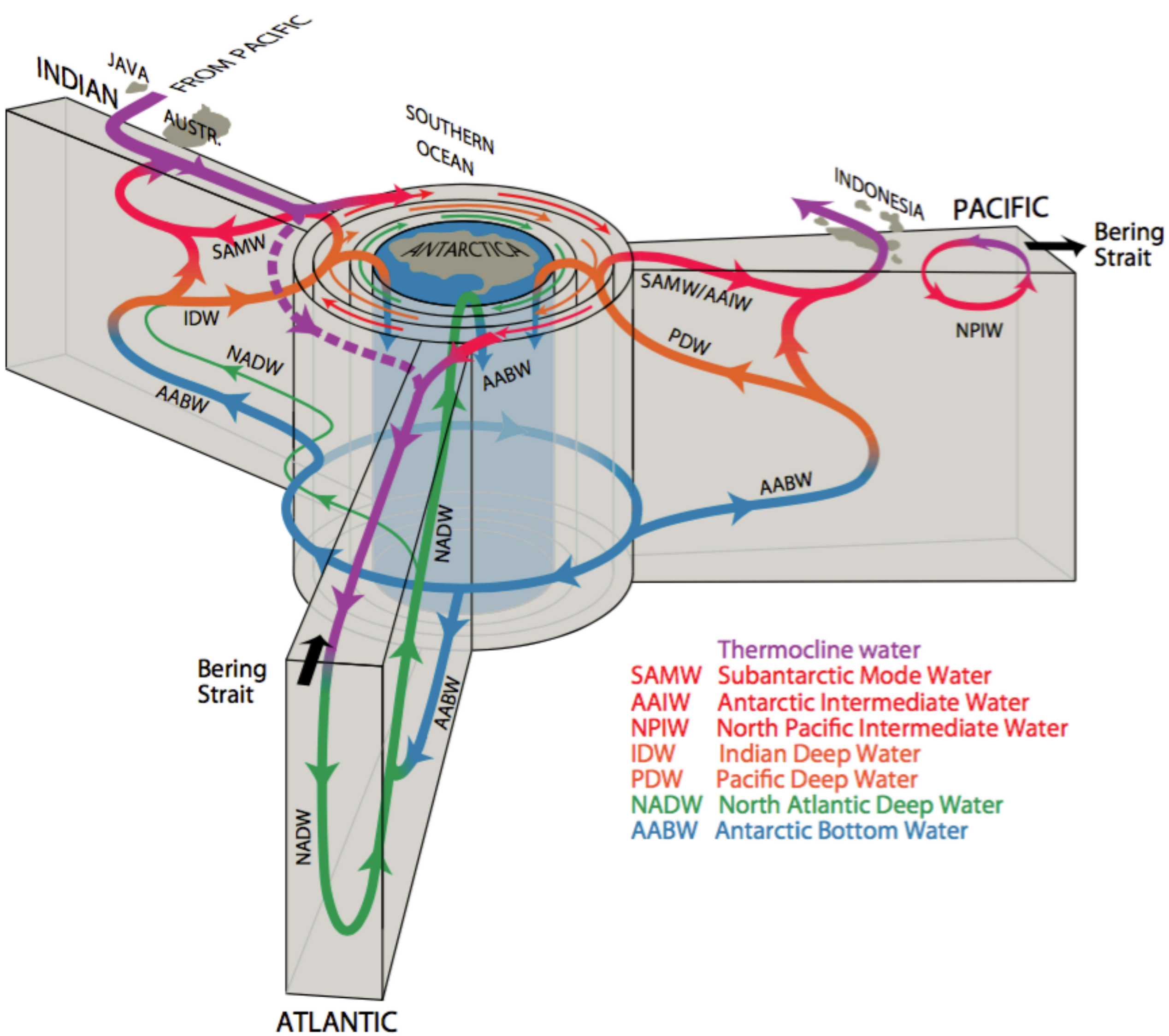
TeamOcean NBI

UHH

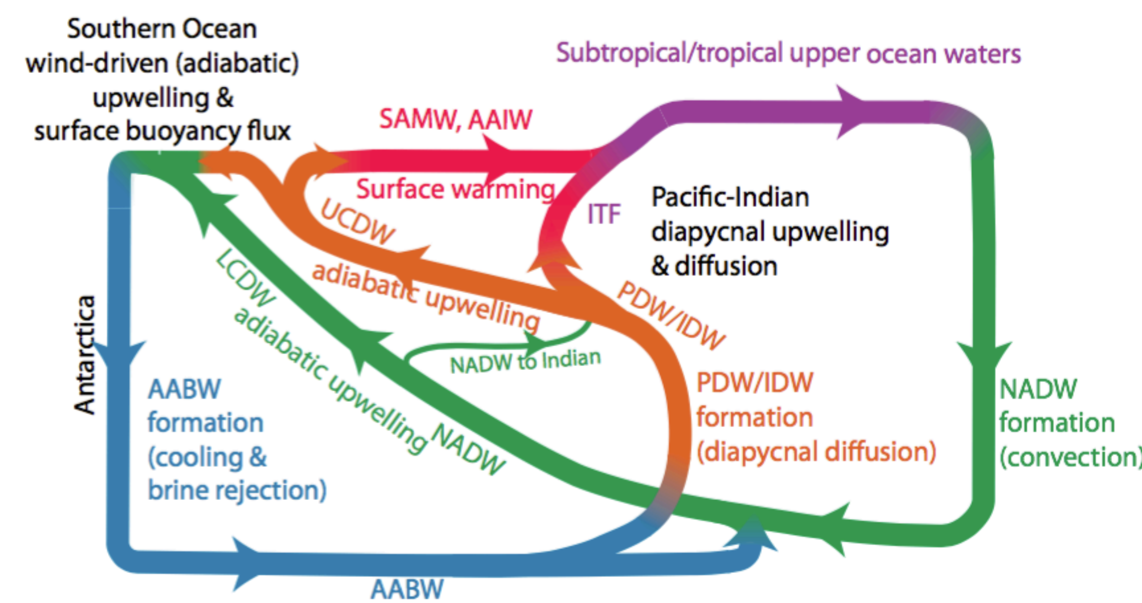
ice 2 ice

Global overturning circulation

3D schematic



Collapsed 2D view



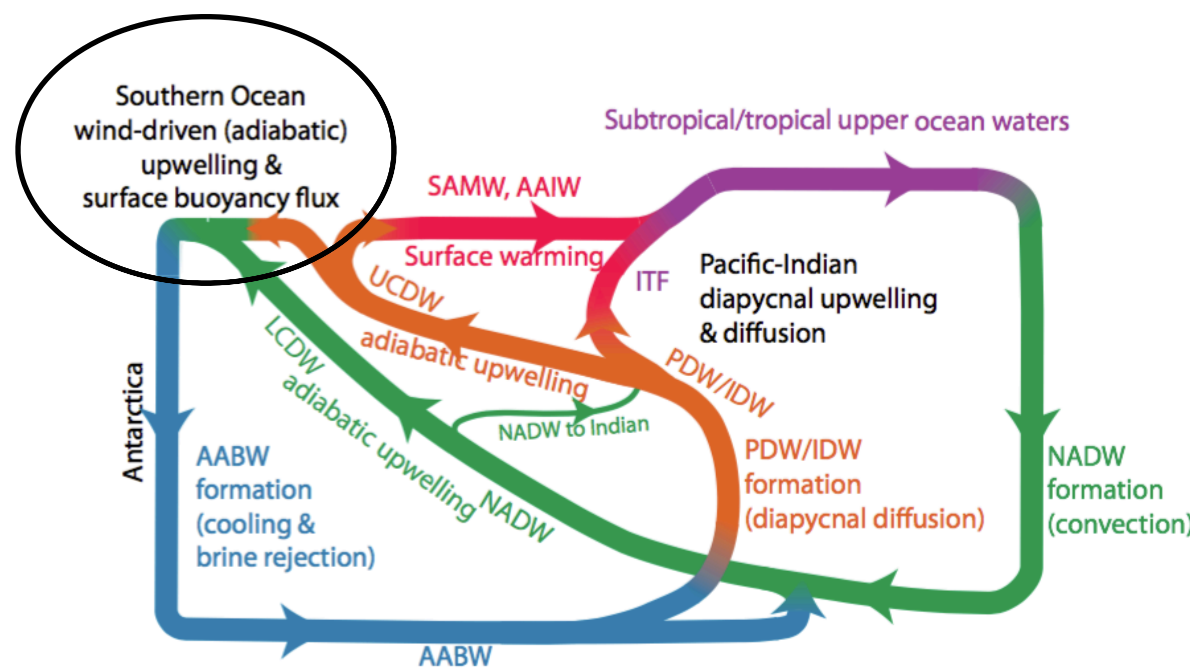
Atmospheric and oceanic circulation reduces equator-to-pole temperature contrast

From Talley, L. D. (2013), closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and Transports. Oceanography 26(1):80-97.

Global overturning circulation

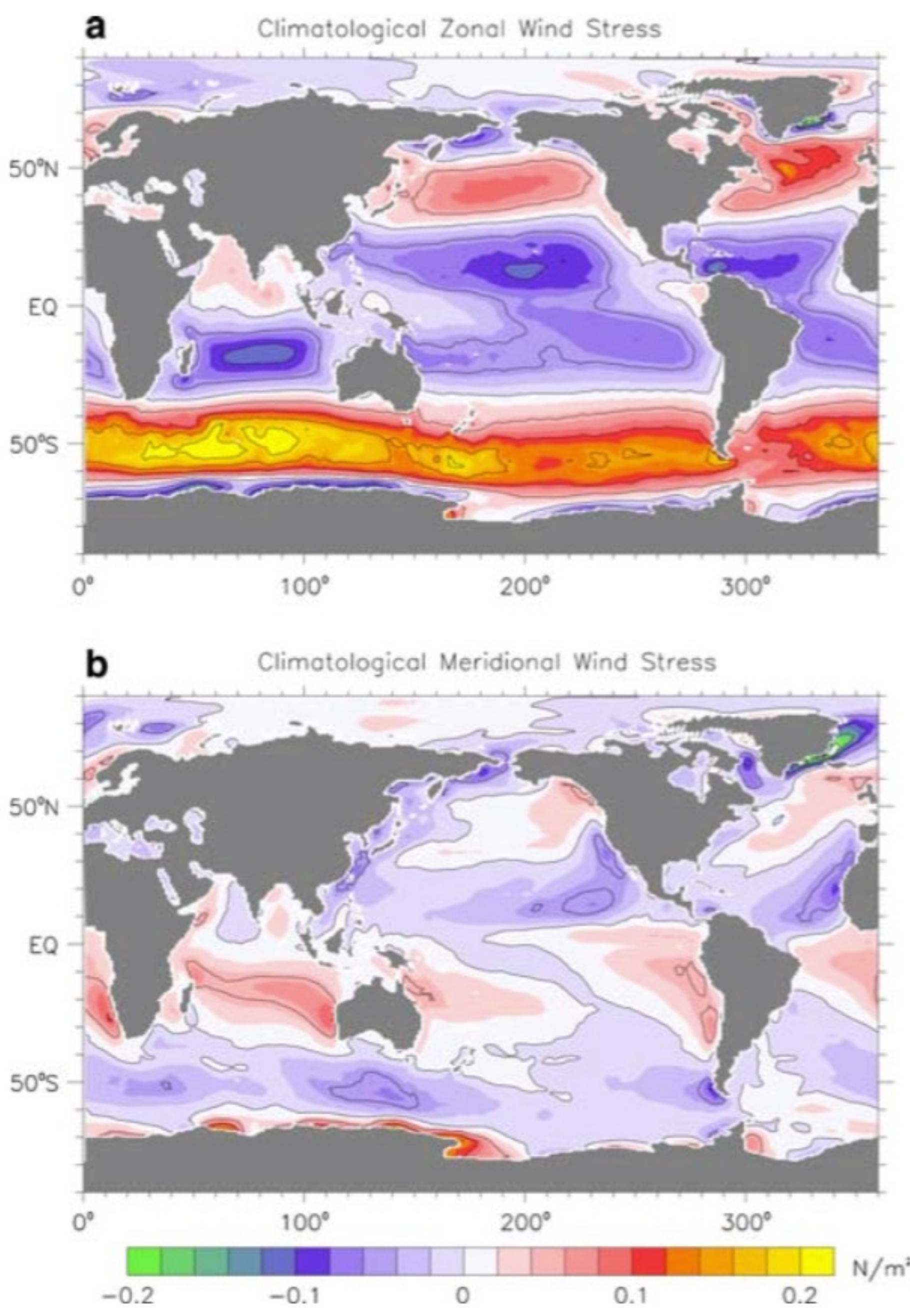
Collapsed 2D view

- Southern Ocean uptake of anthropogenic CO_2 (~40%) and heat (~75%) substantial.
- Hypothesised to play a major role in glacial-interglacial transitions.
- Provides closure to the global overturning circulation.



From Talley, L. D. (2013), closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and Transports. Oceanography 26(1):80-97.

What forces the ocean circulation?

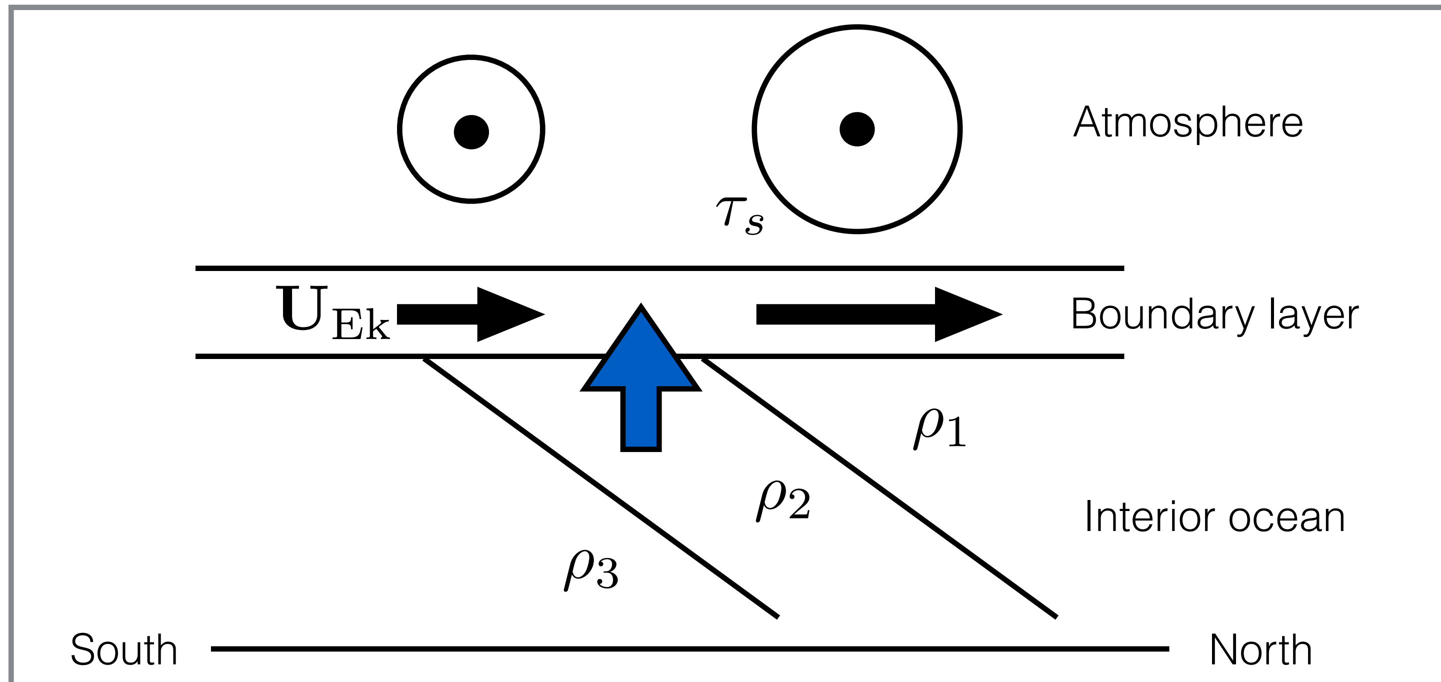


Climatology of wind stress on surface ocean. From Large and Yeager (2008).

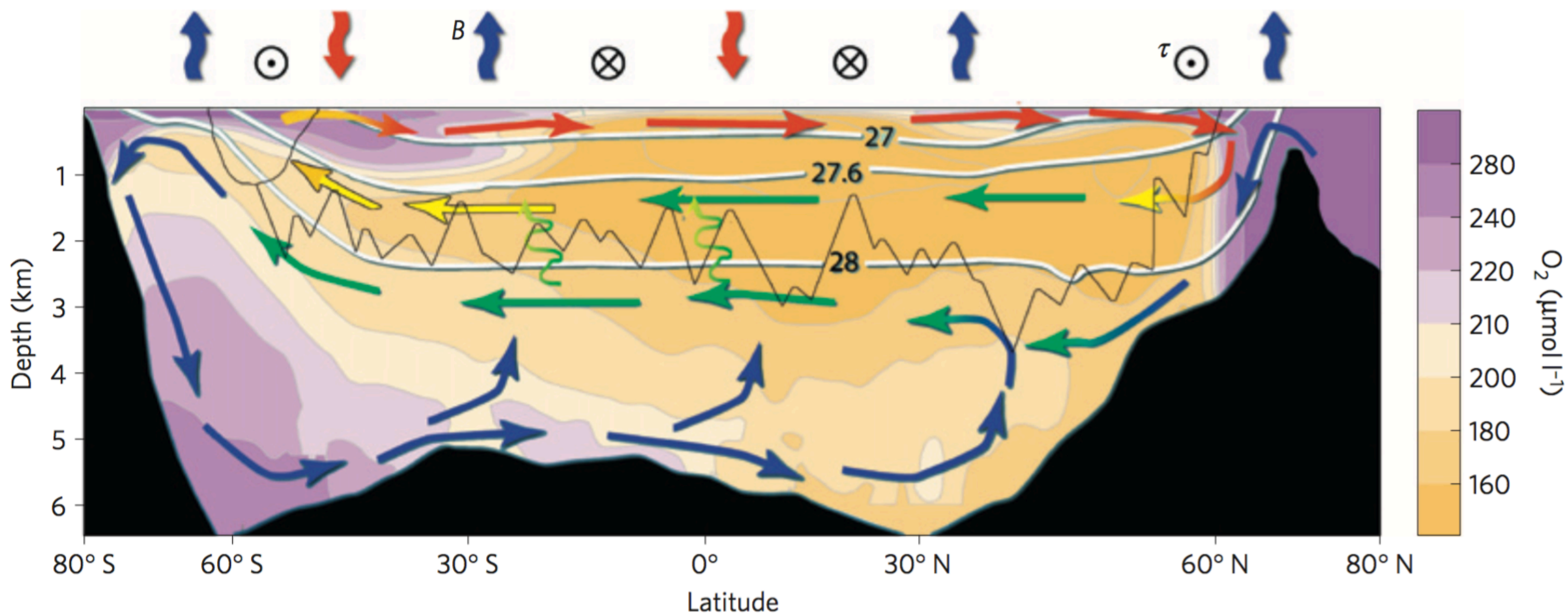
- Solar insolation
- Atmospheric winds
- Precipitation + evaporation
- Interaction with sea and land ice
- River run-off, etc.

Simple momentum balance in the ocean surface boundary layer:

$$\int_{-D}^{0} f\mathbf{k} \times \mathbf{u}_{\mathrm{Ek}}\, \mathrm{d}z = \int_{-D}^{0} \frac{1}{\rho}\frac{\partial \tau}{\partial z}\, \mathrm{d}z \Rightarrow \mathbf{U}_{\mathrm{Ek}} = -\frac{\mathbf{k} \times \tau_s}{\rho f}$$



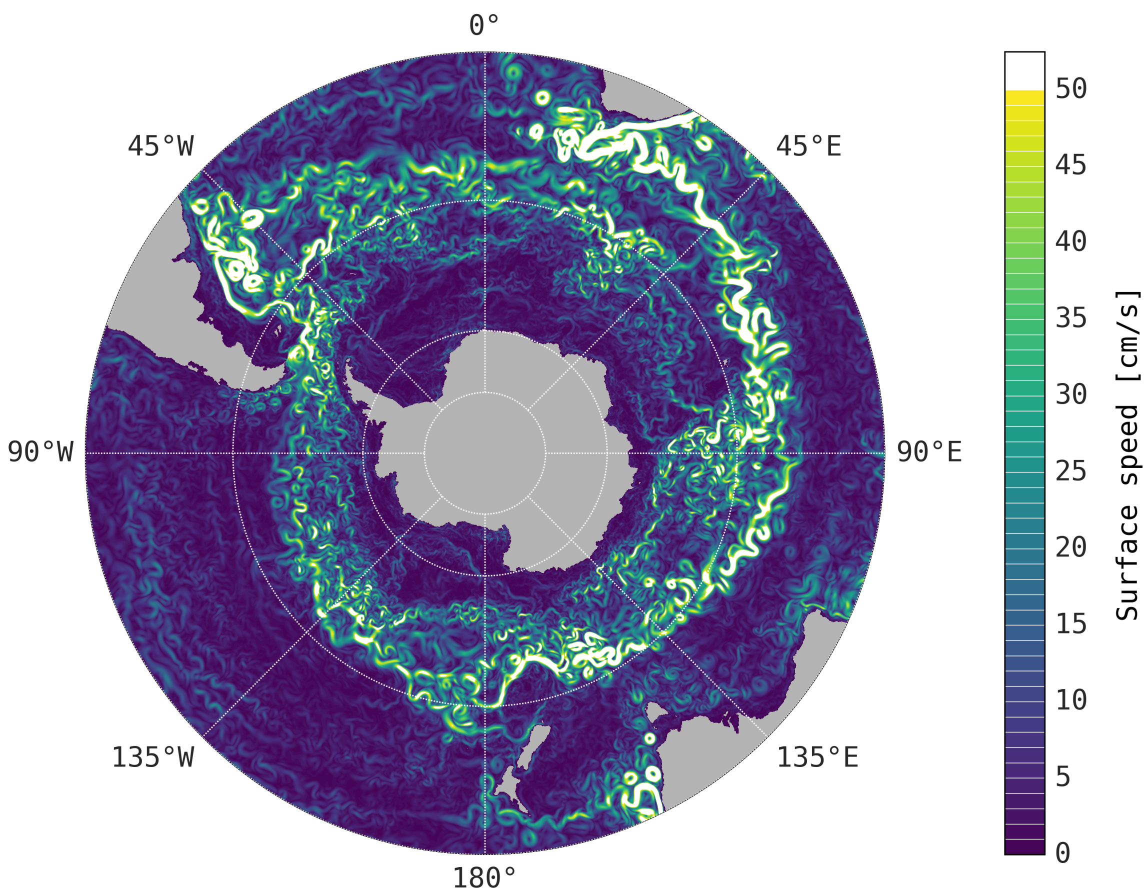
Ocean density structure



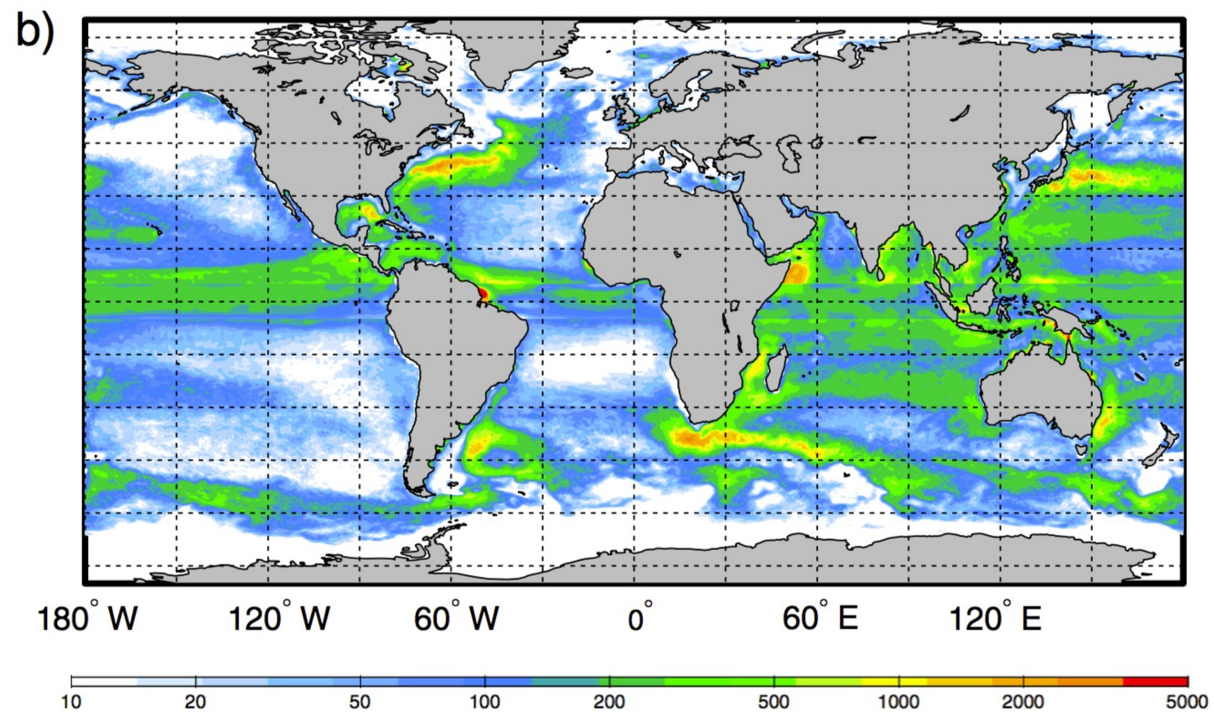
Schematic borrowed from Marshall and Speer (2012), Nature Geoscience

- Southern Ocean winds lift surfaces of constant density.
- The circulation of water in the interior ocean is approximately along surfaces of constant density (adiabatic circulation).
- Hence the Southern Ocean is an important region for the ventilation of the deep ocean!

Eddies in the Southern Ocean



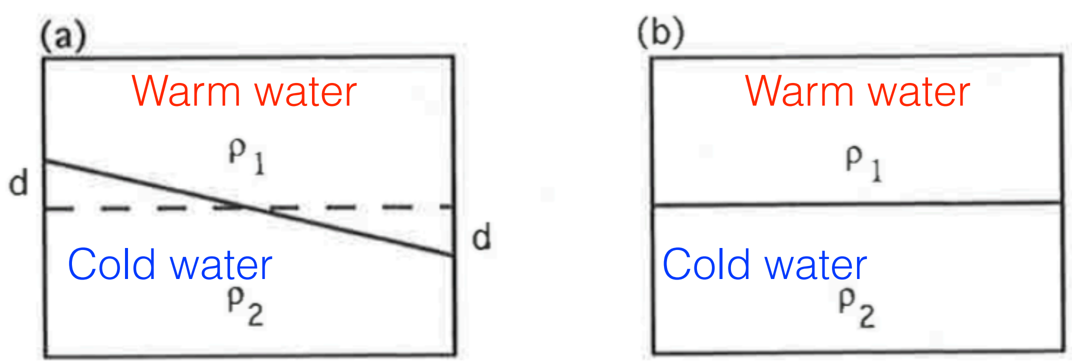
Snapshot of surface ocean velocity magnitude from a high resolution ocean model.



From Roullet et al. (2014). Kinetic energy associated with eddies as seen from satellite. Unit is cm^2/s^2.

- Eddies, equivalent to storm systems in the atmosphere, are a result of baroclinic instabilities in the large-scale circulation.
- In both the ocean and the atmosphere, the eddies account for a substantial part of the poleward heat transport.

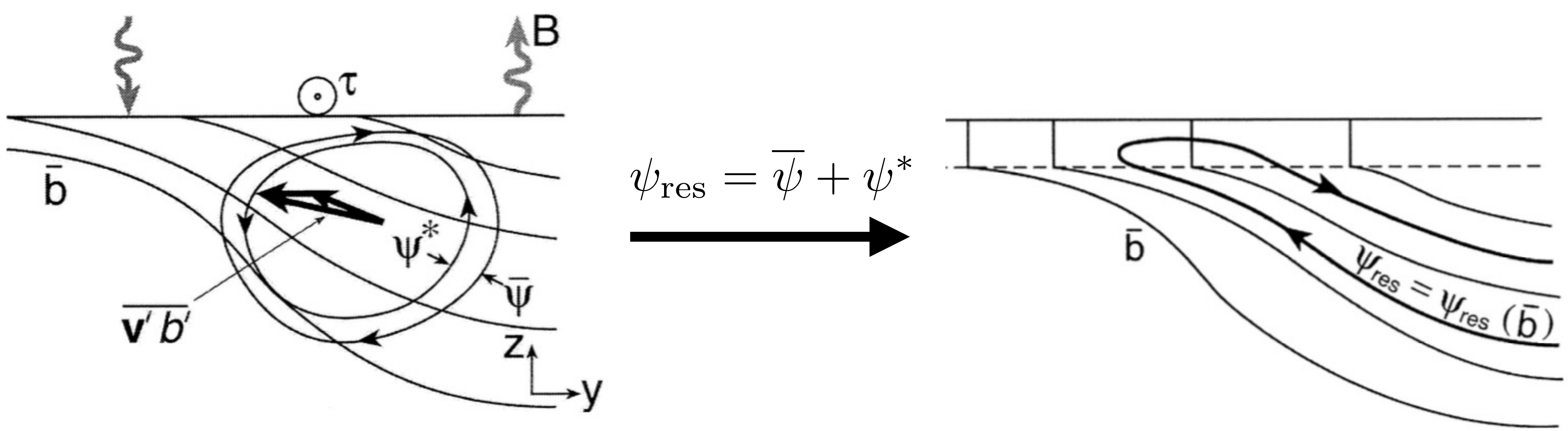
Eddy-induced circulation



Situation (a) holds more potential energy that situation (b).

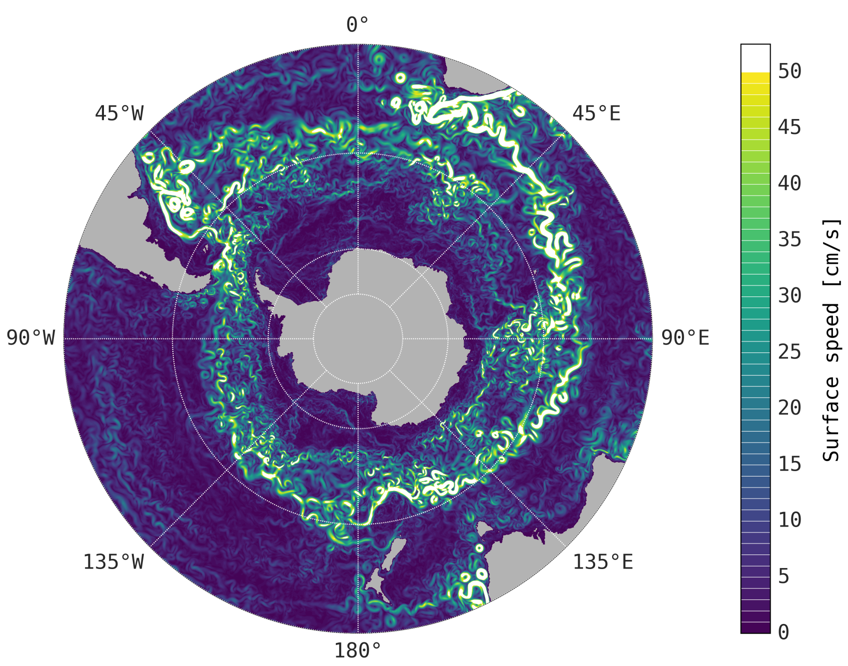
From Knauss (1997)

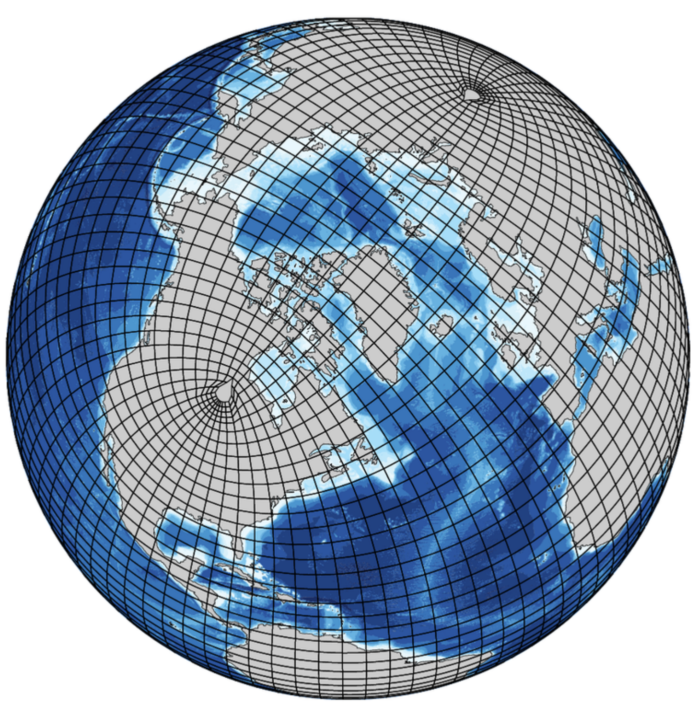
- Baroclinic instabilities transform potential energy into eddy kinetic energy.
- Eddies act to flatten surfaces of constant density.
- They compensate the wind-driven circulation.



From Marshall and Radko (2003)

Representing the eddy-induced circulation in ocean models





Observations

- Characteristic eddy length scale ~10^1-10^2 km
- Characteristic eddy time scale ~ A couple of months

Commonly-used ocean models

- Horizontal grid resolution ~ 10^2 km around equator and 10^1-10^2 km at higher latitudes
- Model time step ~ 10^3 s
- Temporal resolution of model output ~ 1 month

The characteristic eddy length scale challenges the modelling community!

Parameterising eddies

$$\psi_{\text{res}} = \overline{\psi} + \psi^* \qquad \overline{\psi} = -\frac{\tau_s}{f\rho}$$

Parameterisation —> $\psi^* = \kappa s_\rho \qquad s_\rho = -\frac{\frac{\partial \rho}{\partial y}}{\frac{\partial \rho}{\partial z}} = \left(\frac{\partial z}{\partial y}\right)_\rho$ Slope of density surface

This closure is based on the idea that eddies remove large-scale potential energy from the ocean (Gent and McWilliams (1990)). This has proven a successful closure!

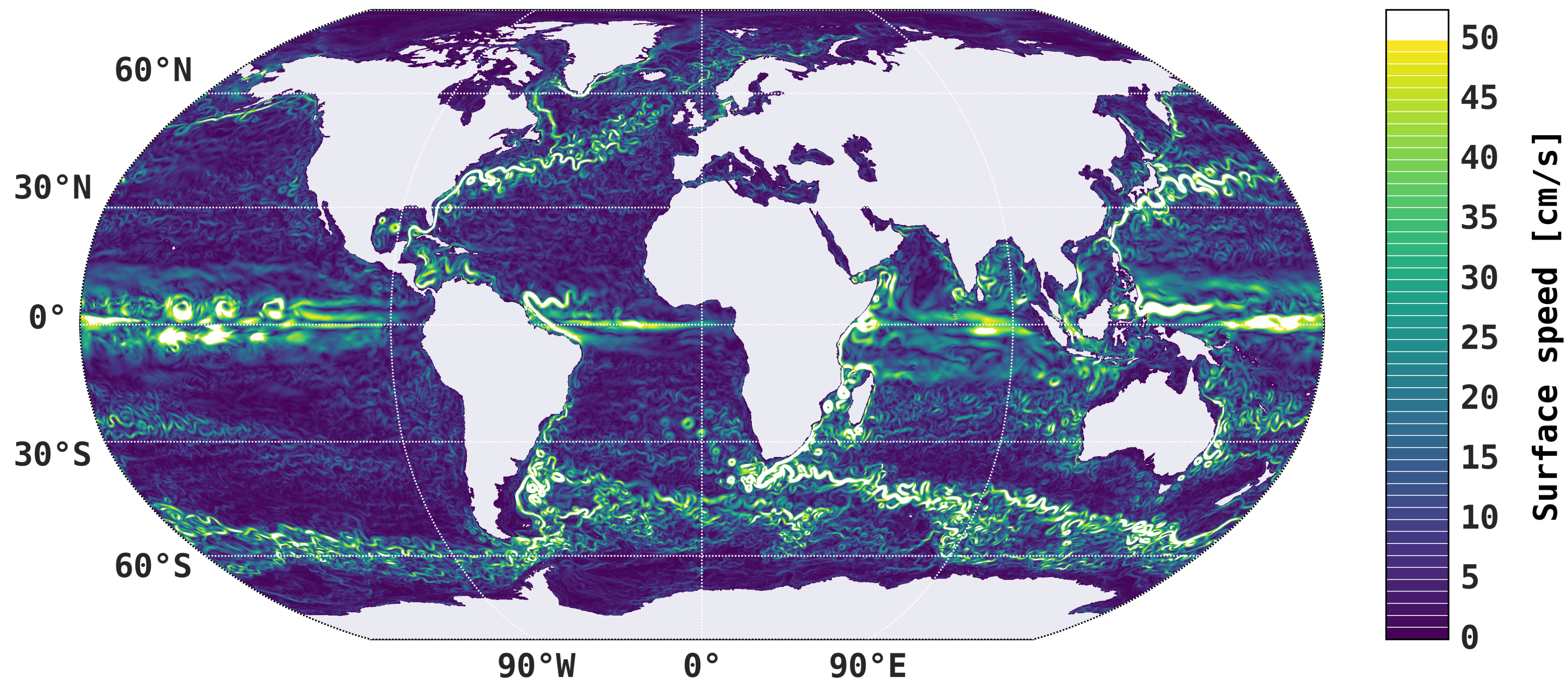
How are we to formulate kappa? This is an active research area.

$$\kappa = \frac{N^2}{N_{\text{ref}}^2}\kappa_{\text{ref}}, \quad N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}$$

This closure is default in the Community Earth System Model (CESM), a commonly-used climate model.

This research project

How well does the parameterisation mimic Southern Ocean eddy effects seen in an ocean general circulation model with explicit ocean eddies?



Snapshot of ocean surface velocity magnitude from a high-resolution model.

Ocean general circulation model

Community efforts!

$$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} = -\frac{1}{\rho_0}\nabla_2 p + \mathbf{F}$$

Horizontal momentum balance

$$\frac{D\mathbf{v}}{Dt} = \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{u} \cdot \nabla)\,\mathbf{v}$$

Material derivative

$$\frac{\partial p}{\partial z} = -\rho g$$

Hydrostatic balance

$$\nabla \cdot \mathbf{u} = 0$$

Continuity

$$\rho = \rho(T, S, p)$$

Equation of state

$$\frac{DS}{Dt} = A_H \nabla^2 S + \frac{\partial}{\partial z} A_v \frac{\partial}{\partial z} S$$

Tracer equations

+ numerous parameterisations of unresolved physics (e.g. breaking of internal waves, vertical mixing, baroclinic instability, isopycnal mixing, convection)

CESM model setup

High resolution ocean model (documented in Small et al. (2014))

- Active ocean + sea-ice model
- 0.1 deg. horizontal resolution
- 62 vertical levels
- Global domain
- Realistic basin geometry and bottom topography
- Prescribed meteorological boundary conditions (Large and Yeager (2008))
- Initial conditions from observations

The resolution results in ~10^8 grid points. Hence integration of the model is a HPC task.

Low resolution ocean model (documented in Gent et al. (2011))

Same as above except

- ~1 deg. horizontal resolution
- Eddies parameterised in accord with previous slides

This model is much cheaper to integrate forward and is run at UCPH.

High-resolution ocean modelling with JUQUEEN

JUQUEEN

- Allocated ~75 mio. core-h since May 2015.
- Model run on 4096 cores.
- One model year / ten days.

Capable of transferring 2.5 TB / day.

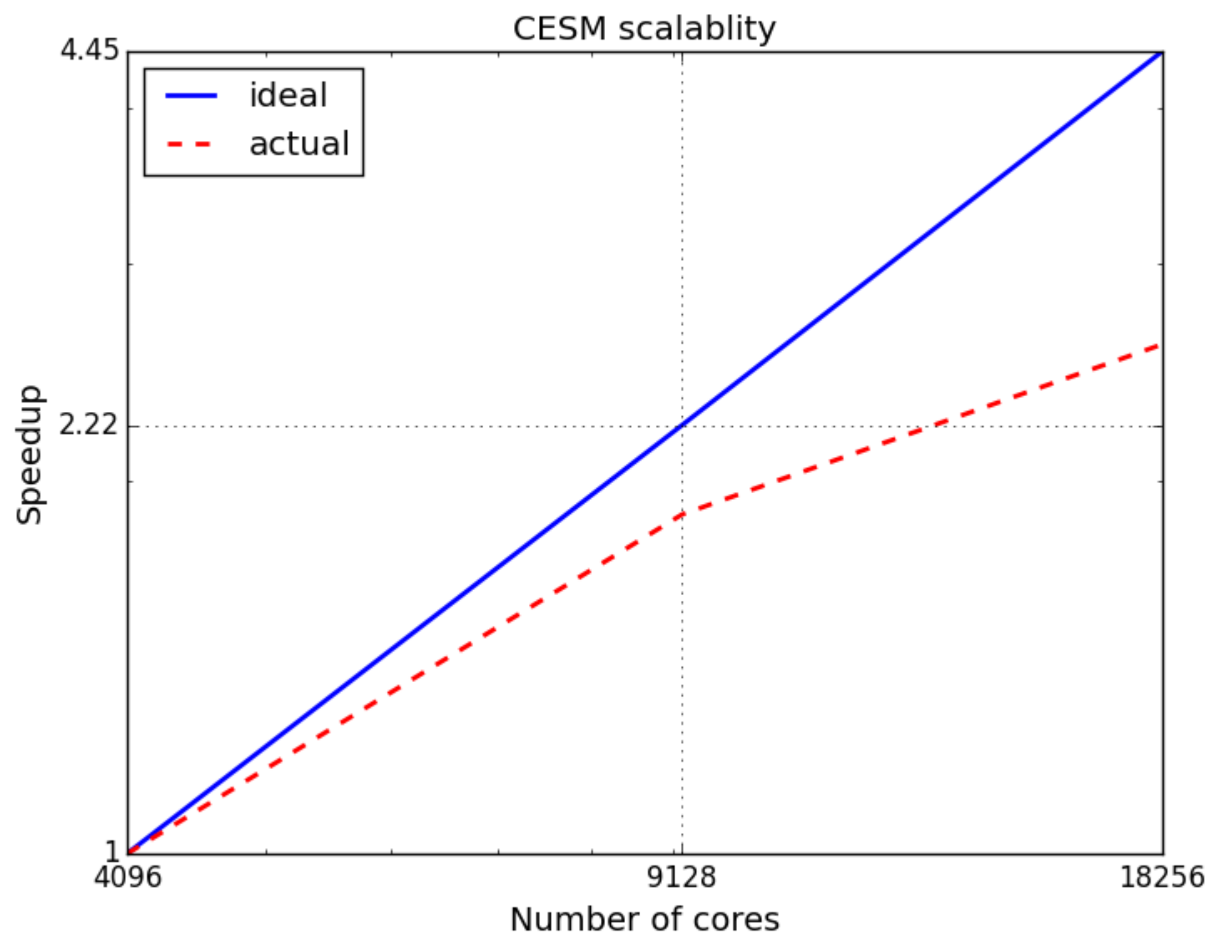
ERDA

- Electronic Research Data Archive (ERDA).
- Collaboration with e-science at UCPH.
- Model output on the local mass storage: ~700 TB.

Local computation resources

A SSH-FS connection to ERDA allows for fast data processing.

Scalability and bottlenecks



- Integrating the model using 9128 cores was considered, but data transfer Jülich —> ERDA would become a bottleneck.
- Bottlenecks with 4096 cores: sea-ice model and coupling to forcing fields every 15th model minute.

Simulation overview

High res.

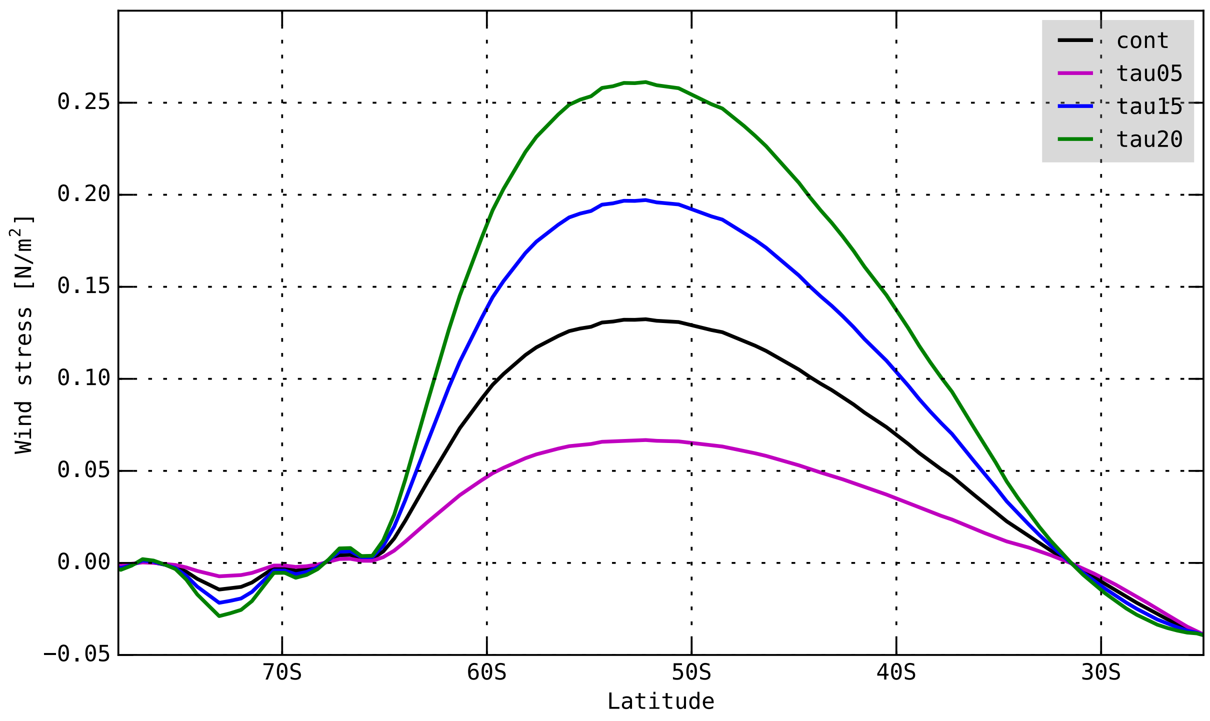
Control simulation, 26 years duration

- → 50% wind stress increase, 16 years duration
- → extended control, 16 years duration
- → 50% wind stress decrease, 16 years duration

Low res.

Control simulation, 300 years duration

- → 100% wind stress increase, 100 years duration
- → 50% wind stress increase, 100 years duration
- → extended control, 100 years duration
- → 50% wind stress decrease, 100 years duration



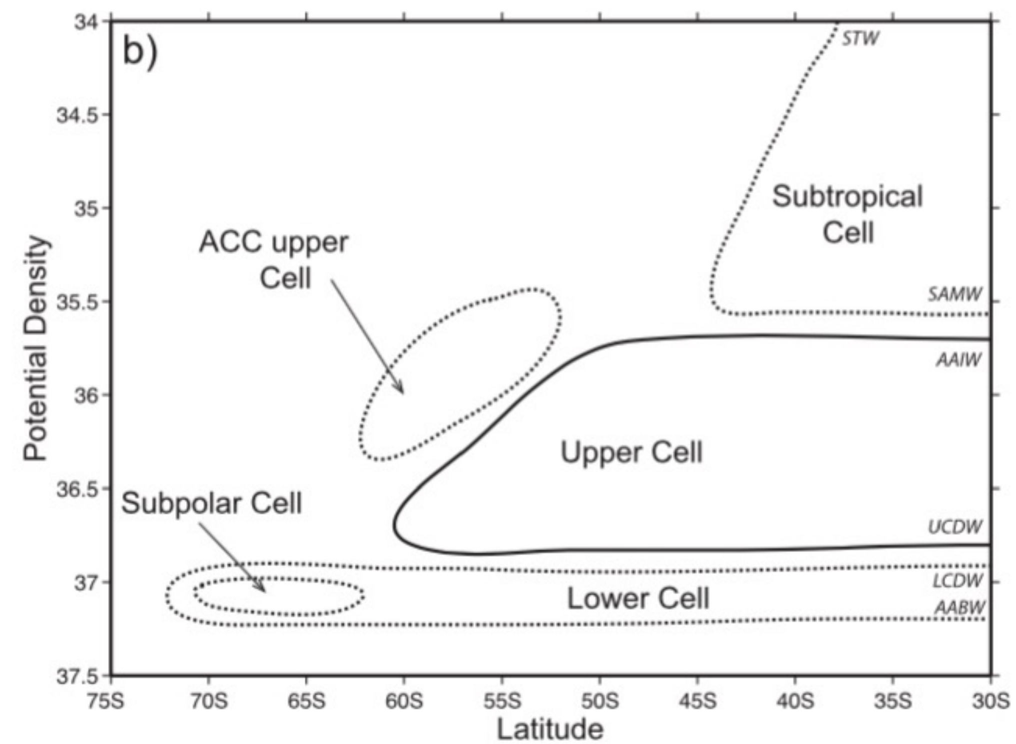
Overturning metrics

Procedure for high resolution model

$$\overline{\psi_I}(\theta,\sigma) = \overline{\oint_0^{2\pi} \int_{\eta_B(\phi,\theta)}^{\eta(\phi,\theta,t)} v(\phi,\theta,z,t)\,\mathrm{d}z\, R\cos(\theta)\ \mathrm{d}\phi}$$

$$\Psi_I(\theta,\overline{\sigma}) = \oint_0^{2\pi} \int_{\eta_B(\phi,\theta)}^{\overline{\eta}(\phi,\theta)} \overline{v}(\phi,\theta,z)\,\mathrm{d}z\, R\cos(\theta)\ \mathrm{d}\phi$$

$$\psi_I^* = \overline{\psi_I} - \Psi_I$$



Farneti et al. (2015)

Procedure for coarse resolution model

$$\overline{\psi_I} = \overline{\oint_0^{2\pi} \int_{\eta_B}^{\eta} v\,\mathrm{d}z\, R\cos(\theta)\ \mathrm{d}\phi} + \overline{\oint_0^{2\pi} \int_{\eta_B}^{\eta} v_{\mathrm{GM}}\,\mathrm{d}z\, R\cos(\theta)\ \mathrm{d}\phi}$$

$$\overline{(\cdot)} = \frac{1}{T}\int_0^T (\cdot)\ \mathrm{d}t$$

$$T = 10\,\mathrm{years}$$

$$\mathrm{Output\ res.} = 1\,\mathrm{month}$$

Overturning comparison

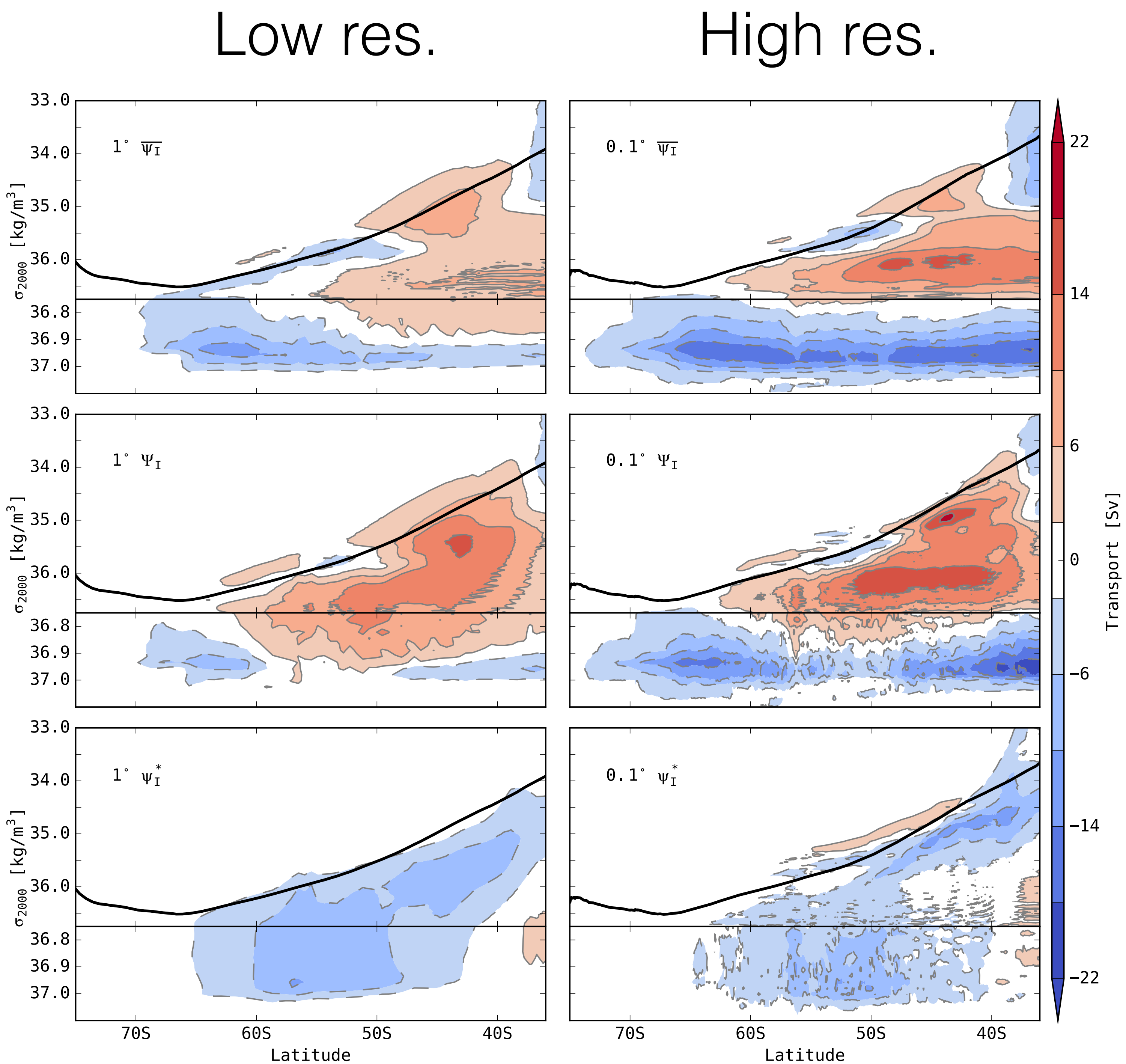
Total

=

Mean-flow

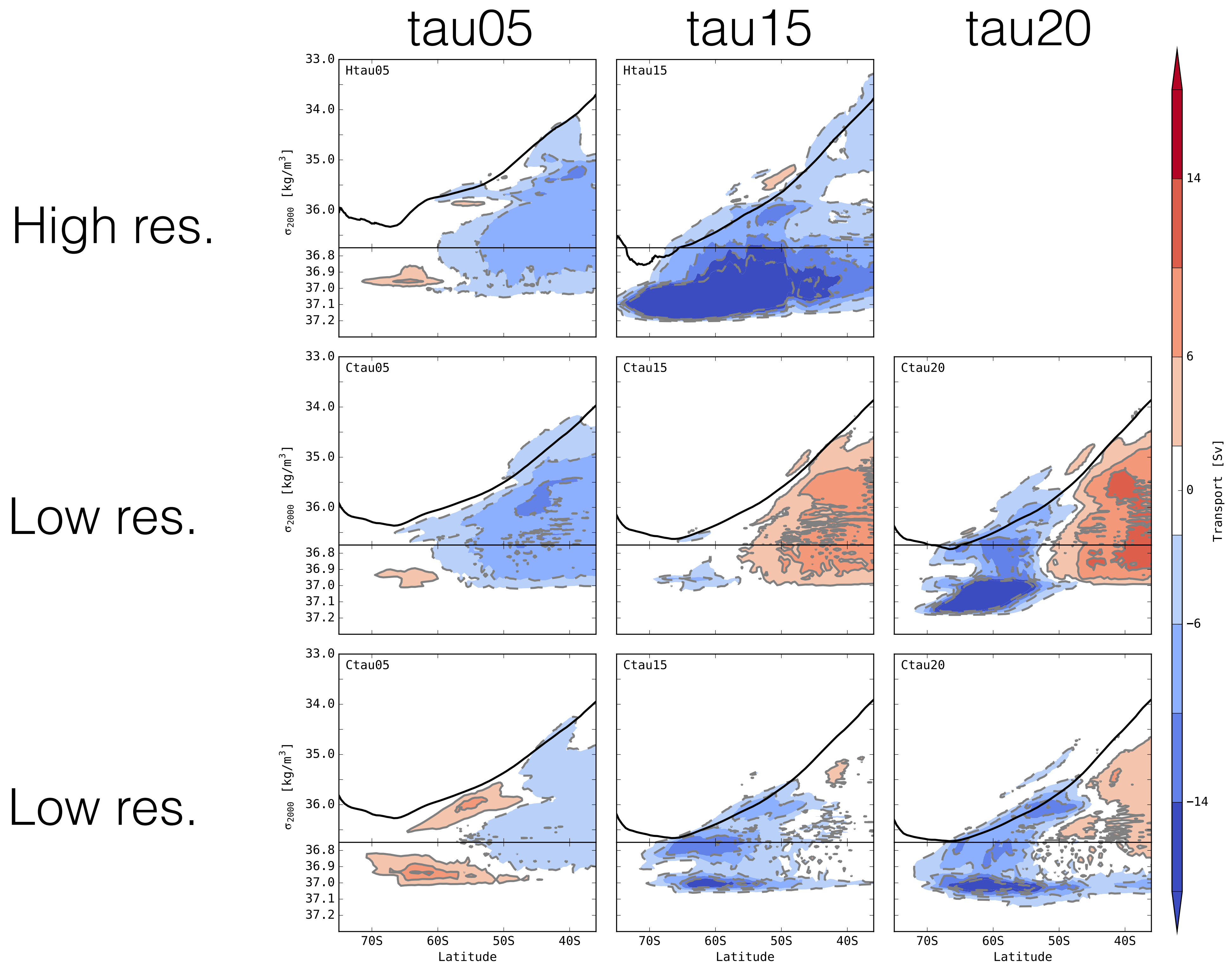
+

Eddy-induced



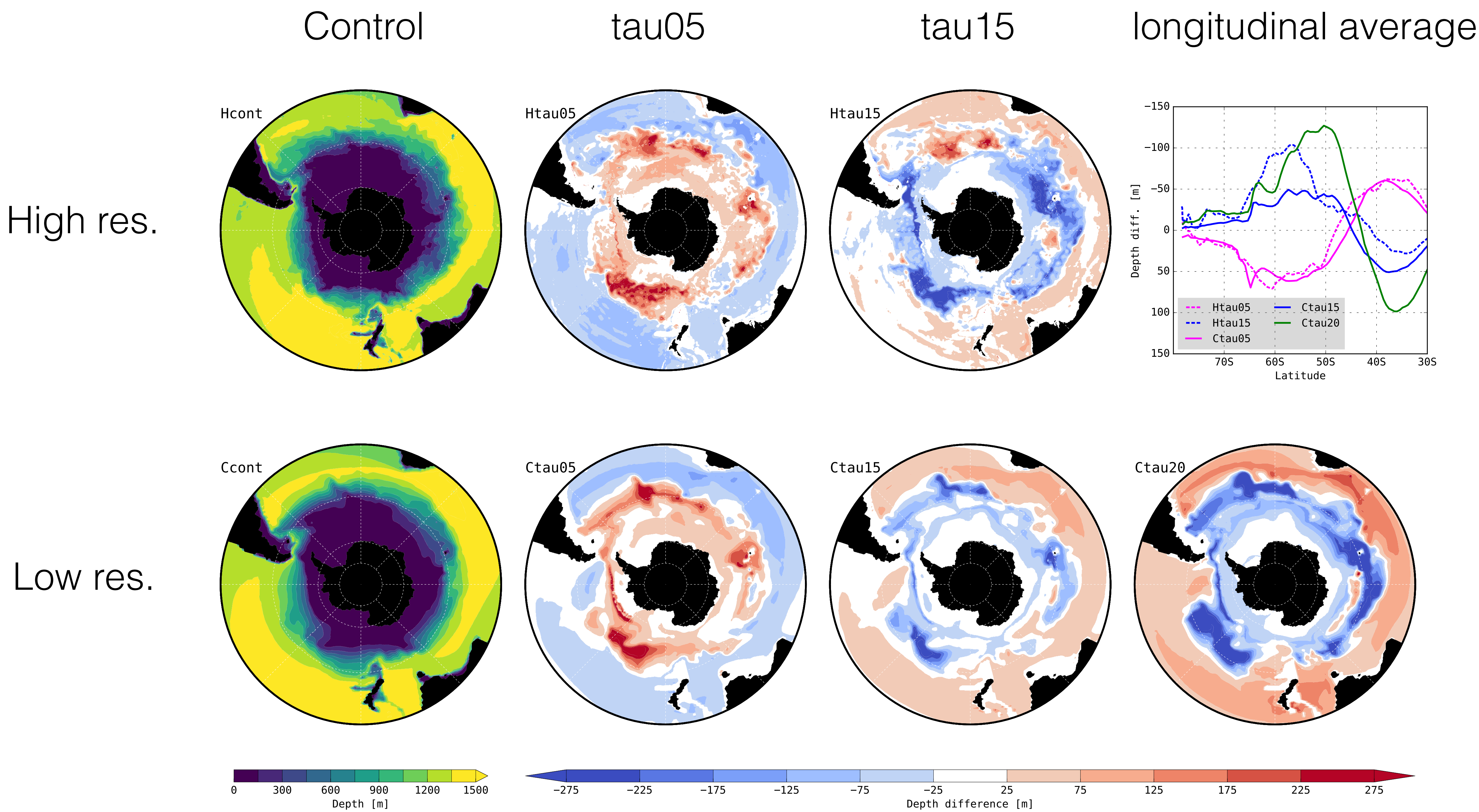
1Sv = 10^6 m^3/s

Changes in overturning

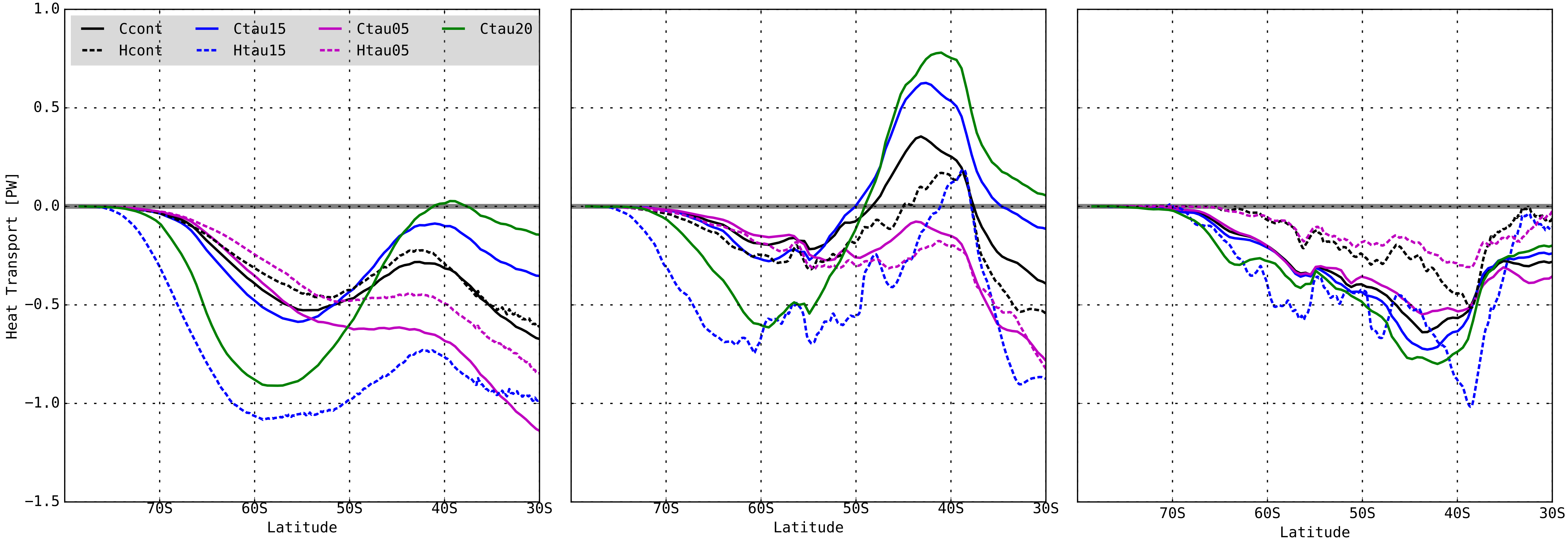


1Sv = 10^6 m^3/s

Density structure changes



Northward heat transport



Total = Mean + Eddy

Conclusions

- The eddy-induced circulation is more surface-intensified in the high-resolution model —> Different total overturning between the models.
- Model sensitivity to 50% wind stress decrease independent of model resolution on two decade timescale.
- Disparate model response with 50% wind stress increase indicates more complex dynamics than anticipated.
- The equilibration time-scale is longer than two decades, possibly centennial —> a need for longer simulations.

If you want to know more, please see Poulsen et al. (2018), Parameterized and resolved Southern Ocean eddy compensation, *Ocean Modelling*, **124**, 1-15.

Thanks for listening!