# The Role of Numerical Mixing in AMOC Simulations

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FESOM

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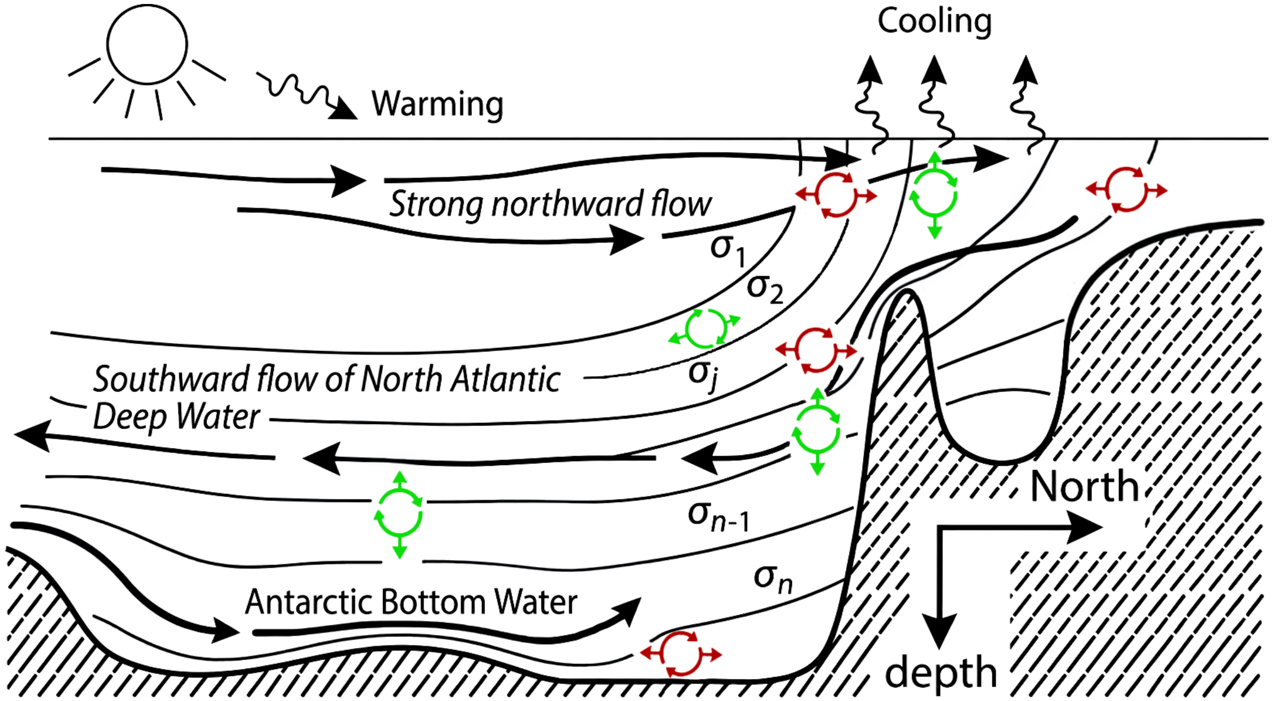
# AMOC in models: accurate signal vs. numerical artifact?

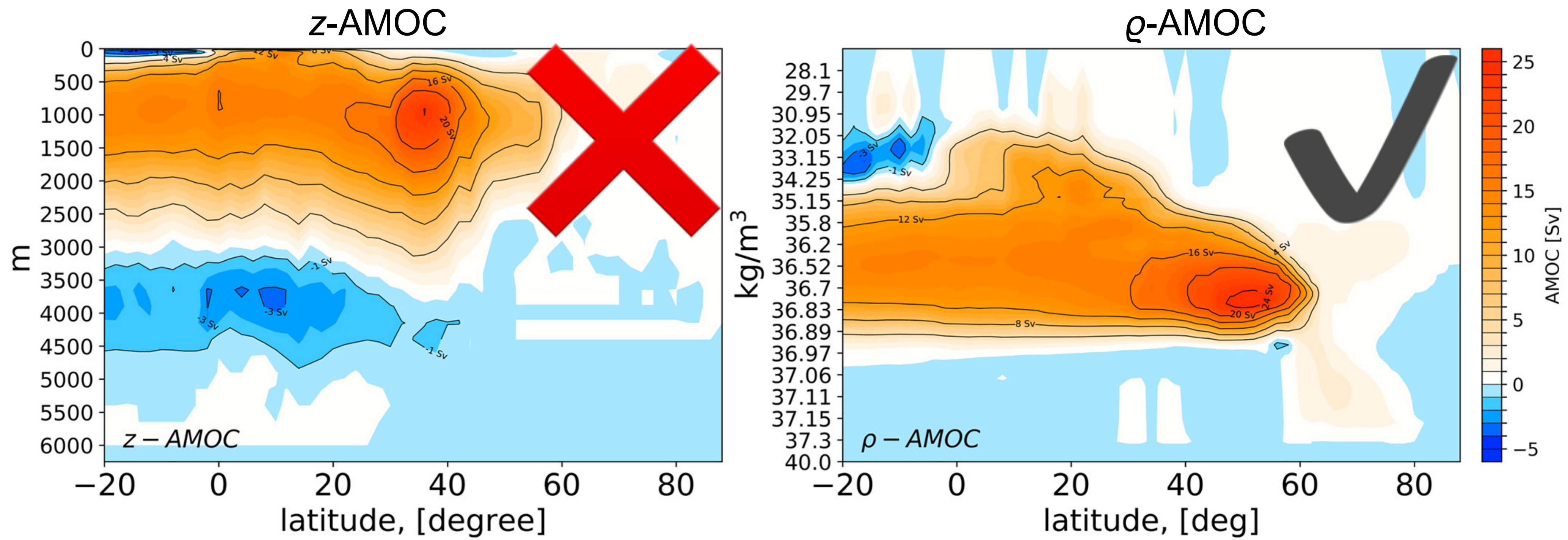



$$R_\rho^{\text{3rd}} \approx -\frac{|u|}{12}\,\delta^3\,\frac{\partial^4 \rho}{\partial x^4}$$

**Numerical mixing is not just a numerical artifact:** it can be comparable in magnitude to explicitly parameterized mixing and is strongest in dynamically active regions that are key to water-mass transformation (eg. Griffies et al. 2000; Ilicak et al., 2012; Klingbeil et al., 2014; Megann, 2018; Holmes et al., 2021).

***Delworth et al. 2012*:** Starting from 1/3° resolution: "We also chose not to use a parameterization of the effects of oceanic mesoscale eddies in this first version of CM2.5, but rather to allow the model to try to simulate eddies explicitly."

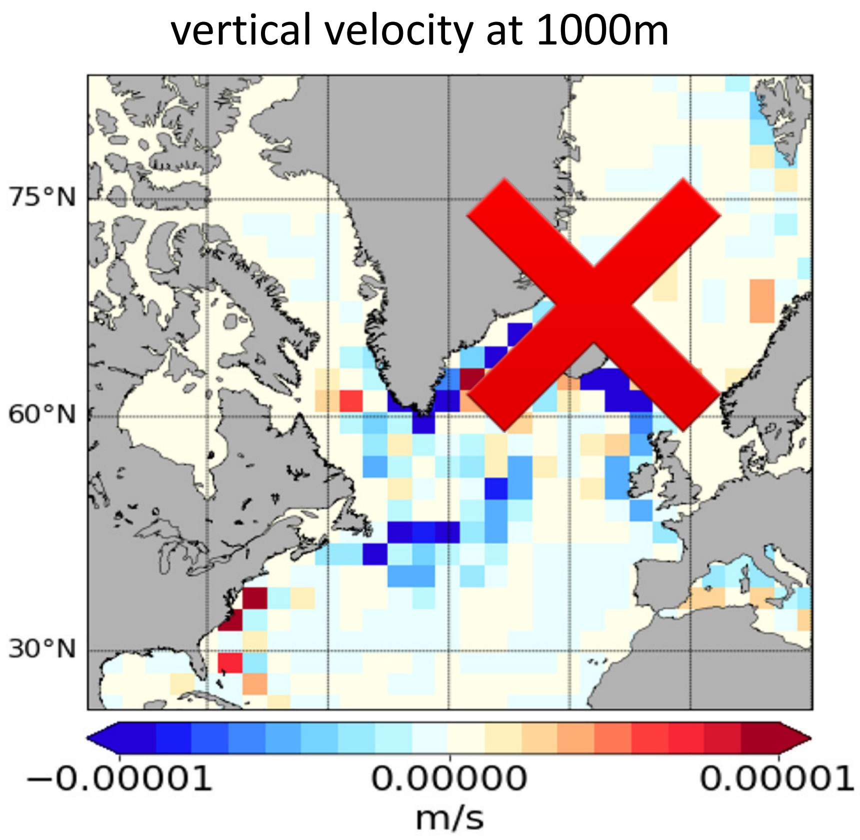
# z & ϱ frameworks

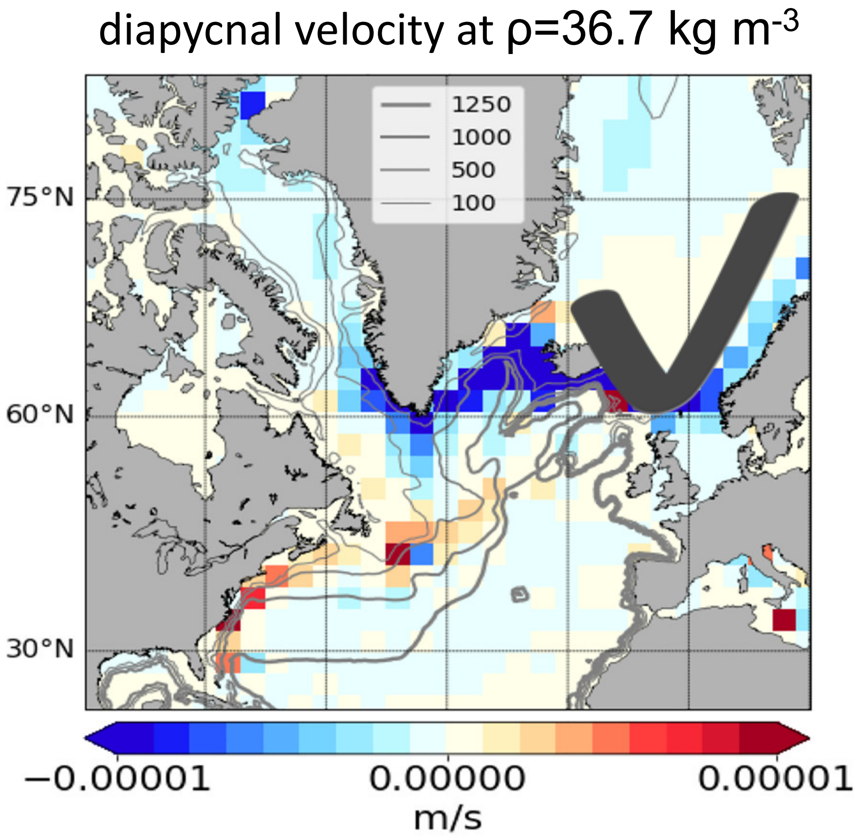



*Sidorenko et al. 2021*

1. Distinct difference between z & ϱ frameworks
2. AMOC maxima is found at different latitudes

# Vertical vs diapycnal velocities




*Sidorenko et al. 2021*

Velocities conservatively remapped onto a 4° × 4° grid

# Full, Physical & Numerical diapycnal velocities

$$w_{\sigma_2}^{\text{full}}(x, y, \sigma_2, t) = \nabla_h \cdot \int_{z,\, \sigma_2' < \sigma_2} \mathbf{u}\, dz$$

$$w_{\sigma_2}^{\text{phys,true}}(x, y, \sigma_2, t) = \frac{\partial}{\partial \sigma_2} \int_{z,\, \sigma_2' < \sigma_2} \left( \frac{\partial \sigma_2'}{\partial \theta}\, \dot{\theta} + \frac{\partial \sigma_2'}{\partial S}\, \dot{S} \right) dz$$

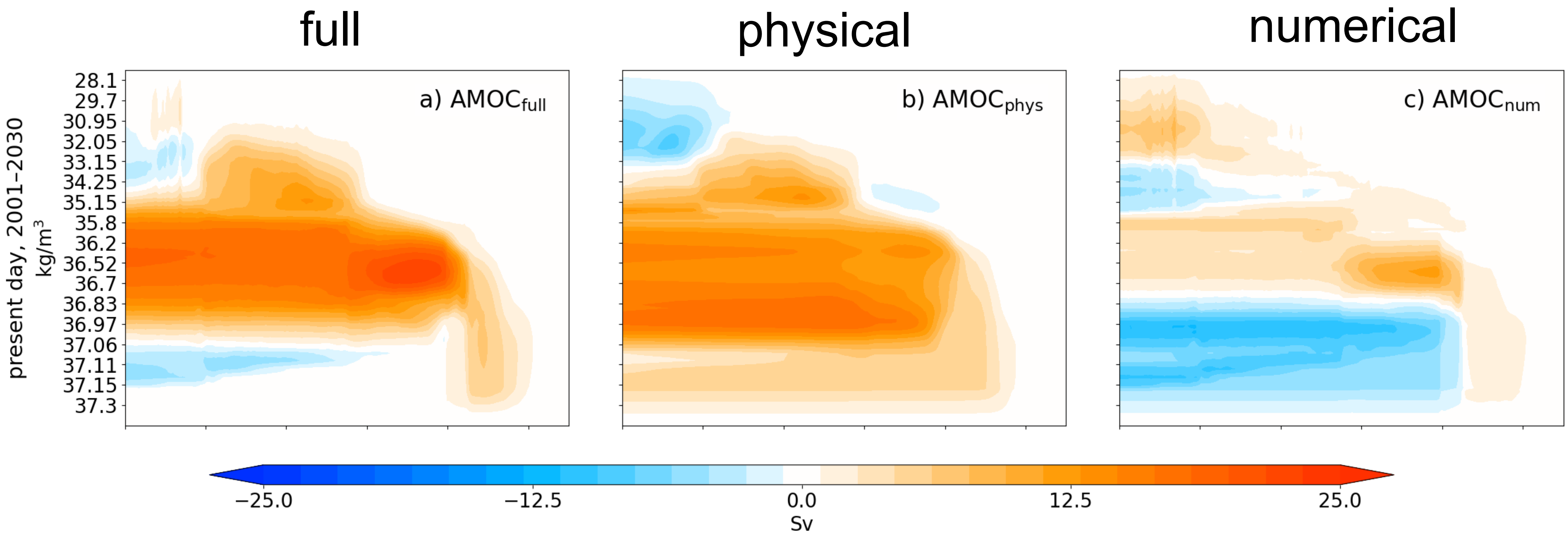
$$w_{\sigma_2}^{\text{full}} = w_{\sigma_2}^{\text{full,true}} + w_{\sigma_2}^{\text{uplift}}$$

$$w_{\sigma_2}^{\text{phys}} = w_{\sigma_2}^{\text{phys,true}} + w_{\sigma_2}^{\text{uplift}}$$

$$w_{\sigma_2}^{\text{num}} = w_{\sigma_2}^{\text{full}} - w_{\sigma_2}^{\text{phys}}$$

see eg. *Walin, G., 1982; Abernathey, R., et al. 2016; Drake, H. F. et al. 2025*

# FESOM2+OpenIFS, RCP 8.5, present day




FESOM resolution: 7km–35 km
OpenIFS resolution: 32 km

**Numerical AMOC is large!**

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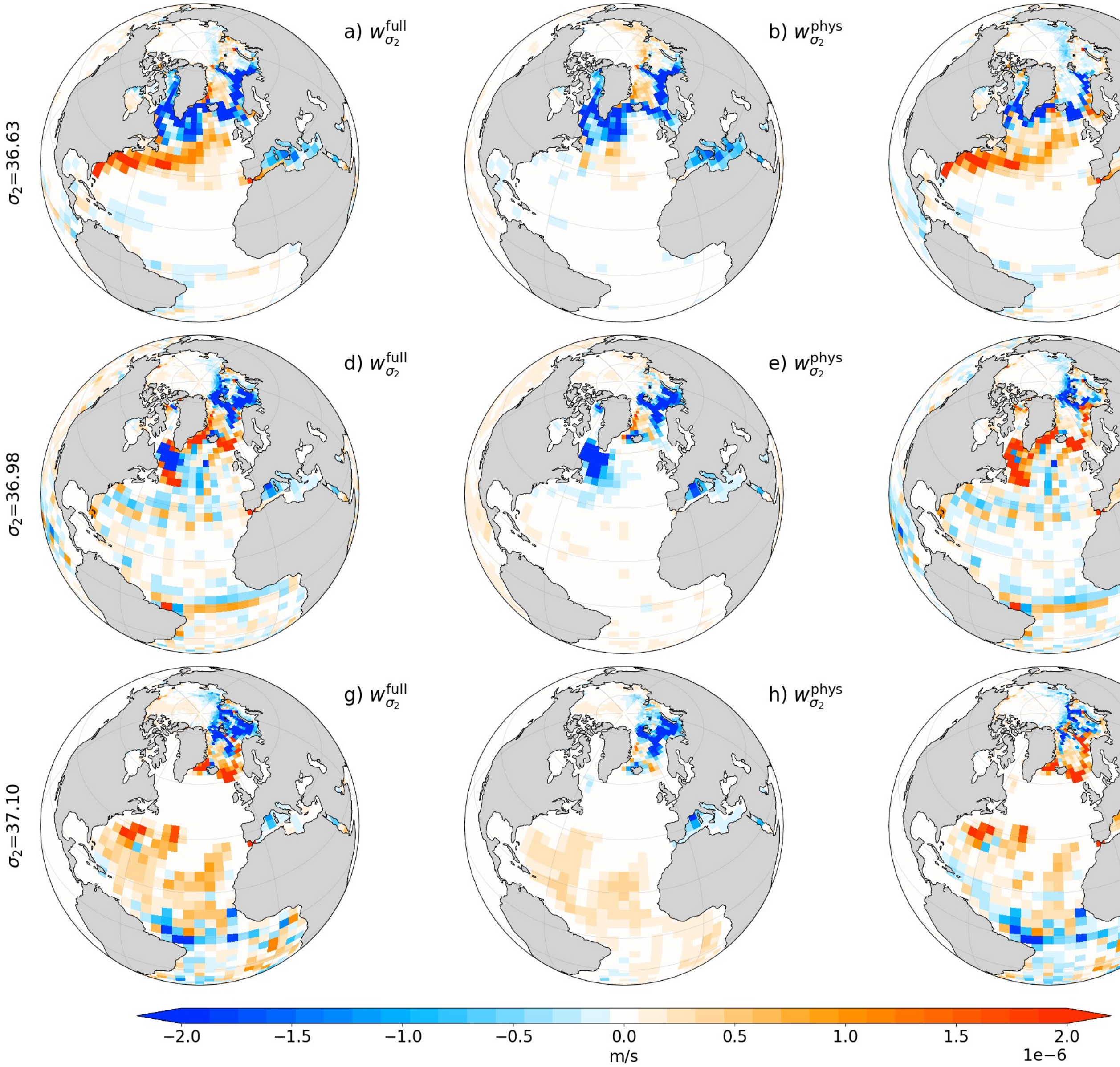
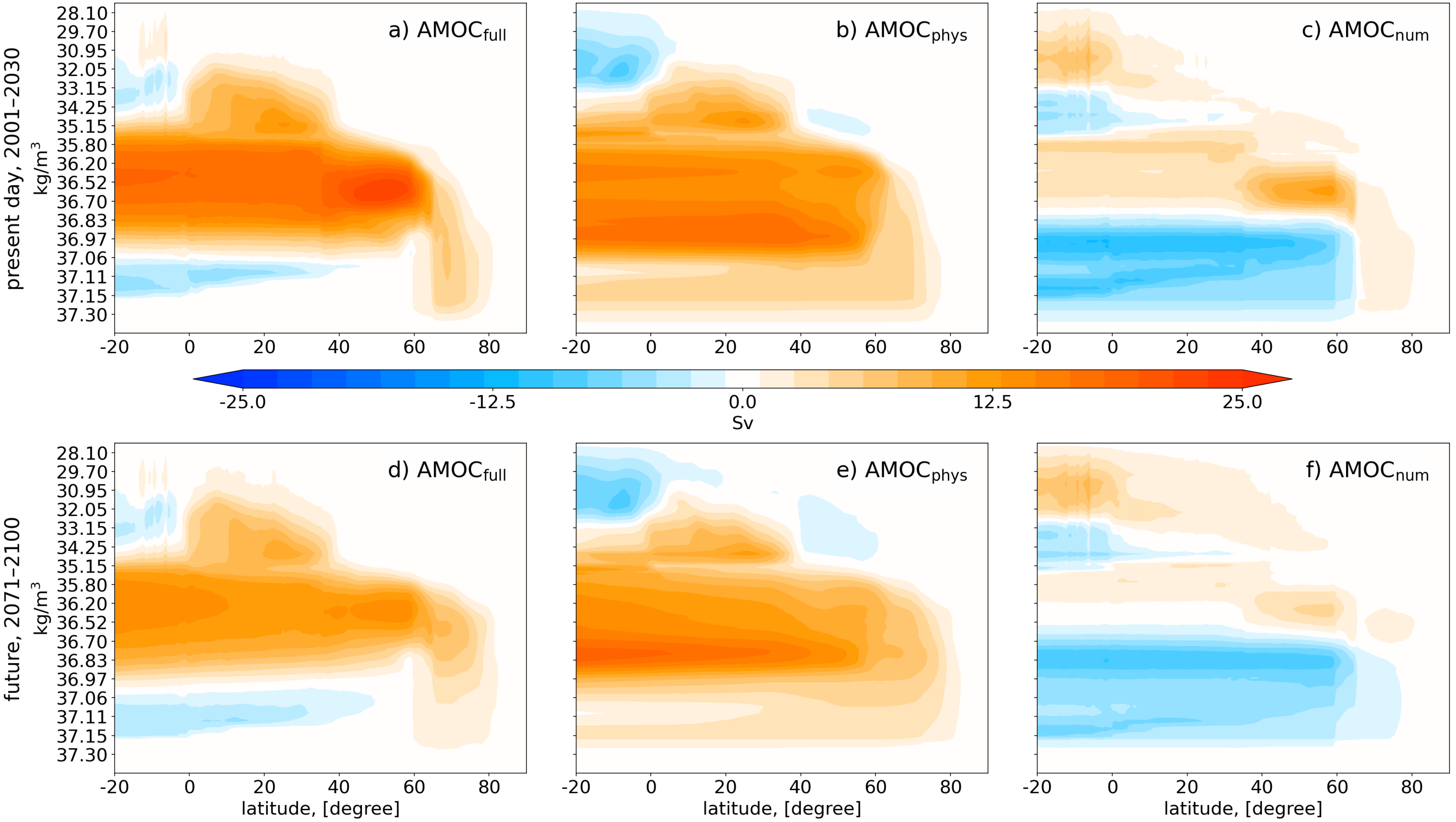
# FESOM2+OpenIFS, RCP 8.5, present day




Numerical-mixing hotspots are prominent along the Gulf Stream and North Atlantic Current, over the Greenland–Scotland Ridge, and around the Labrador Sea boundary.

# FESOM2+OpenIFS, RCP 8.5, future vs. present




Numerical part contributes to decline of AMOC projection!

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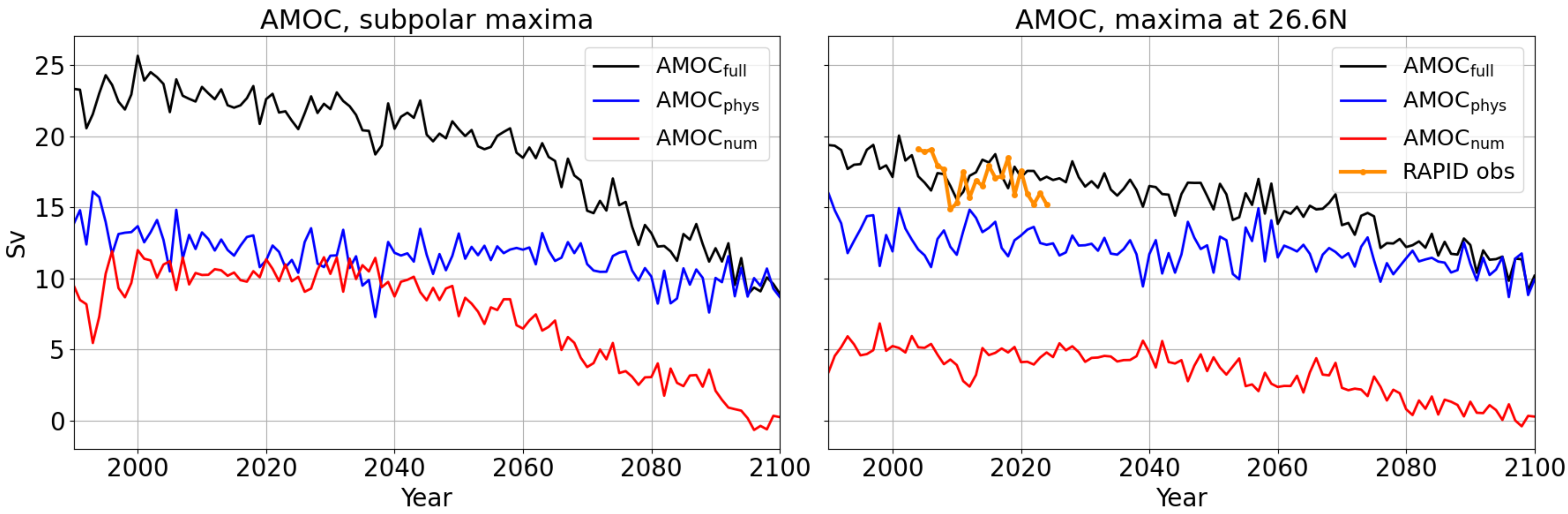
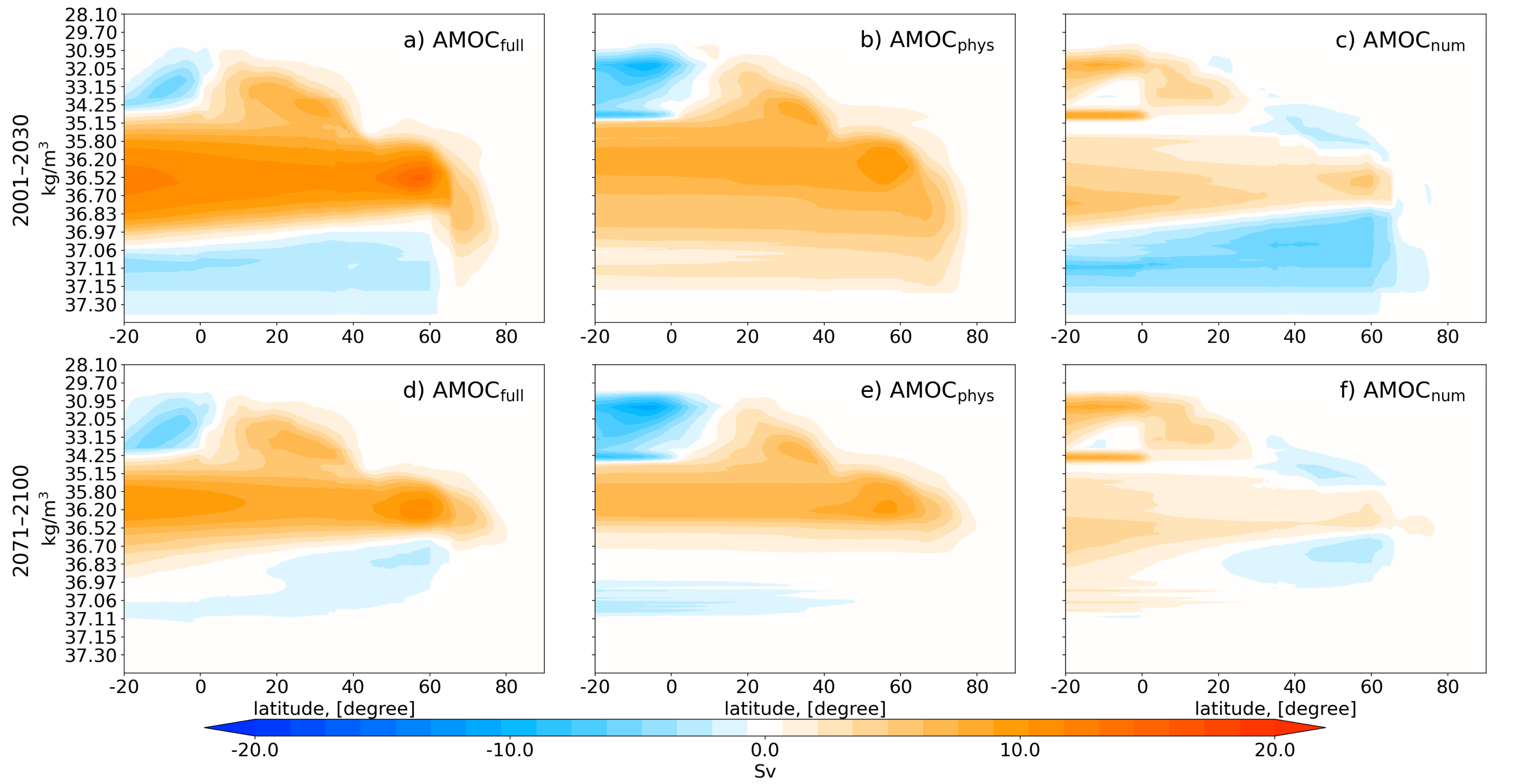
# Physical and numerical AMOCs



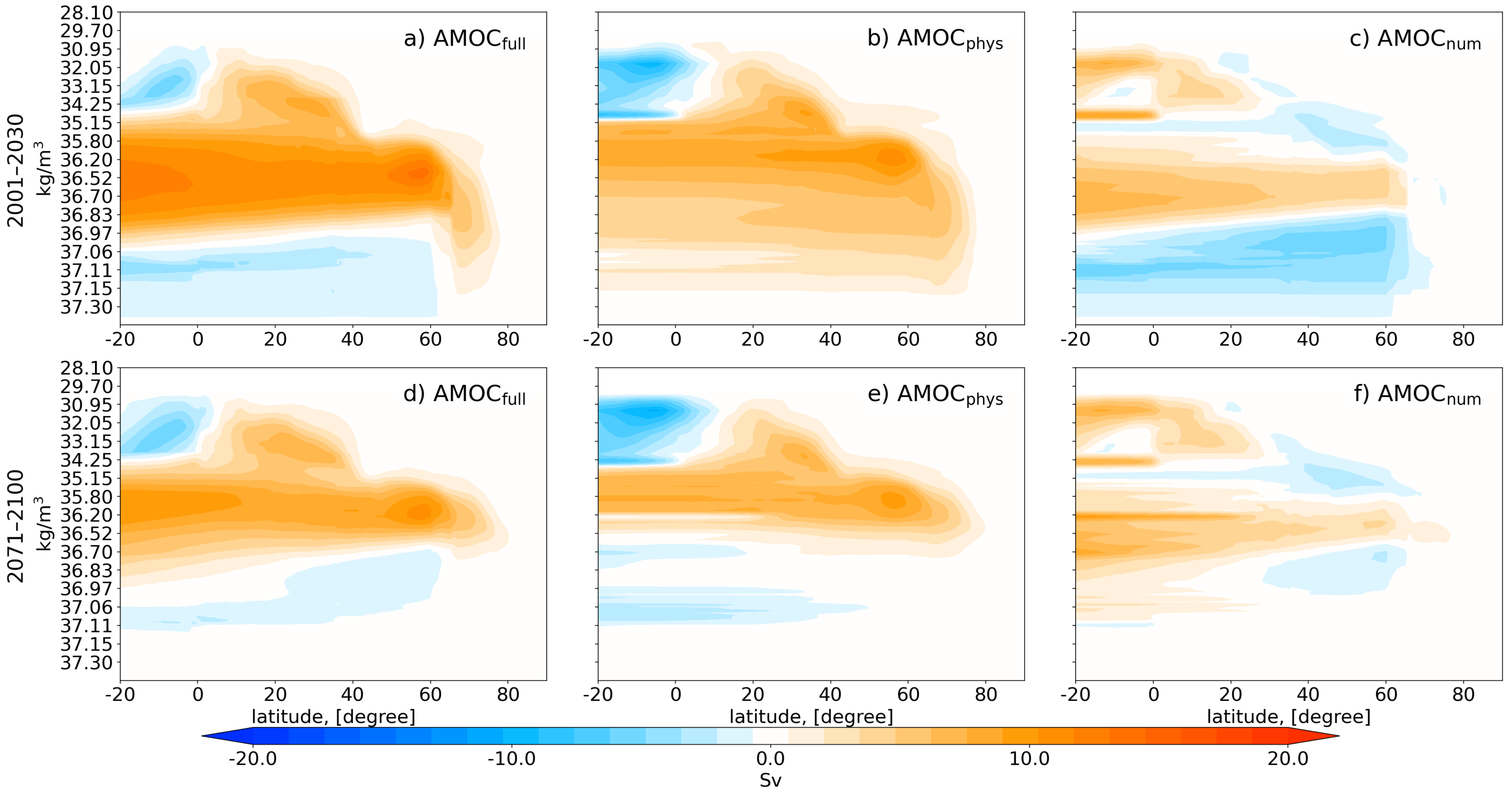

Numerical part dominates the declining trend in AMOC!

# Verification with MITgcm (3rd order)



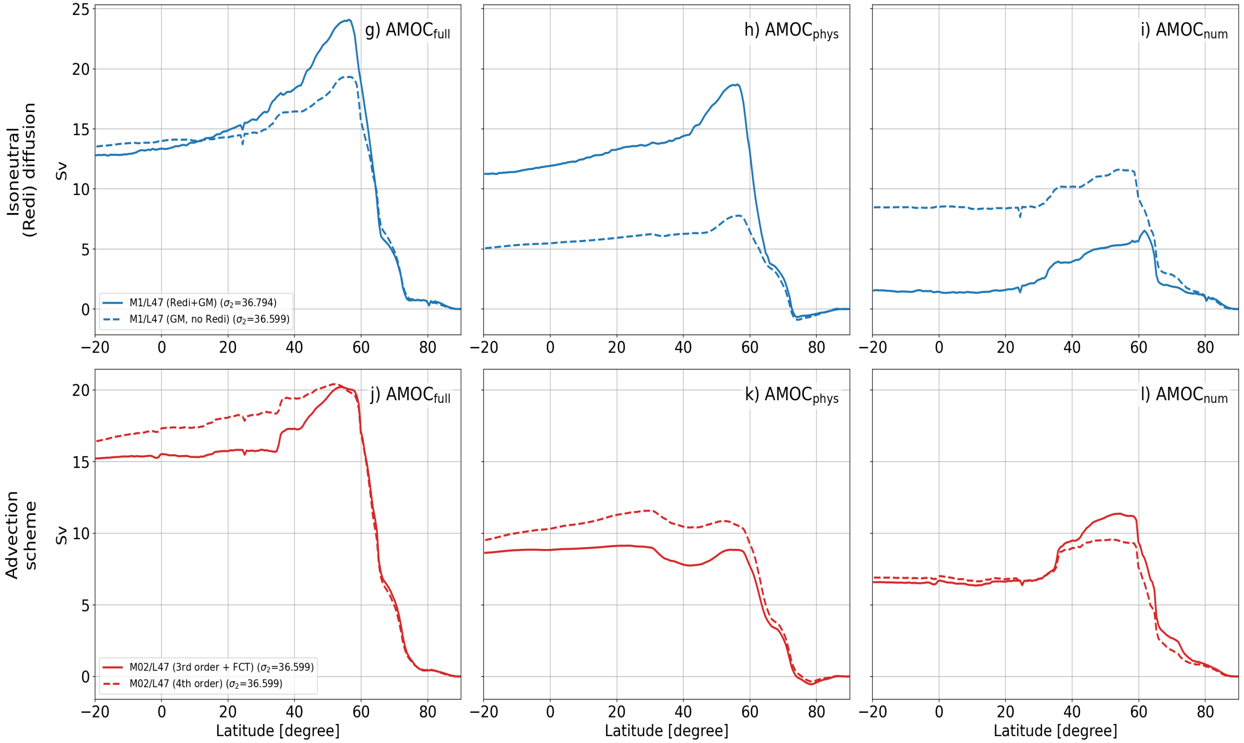

Numerical part dominates the decline in AMOC!

# Verification with MITgcm (7th order)

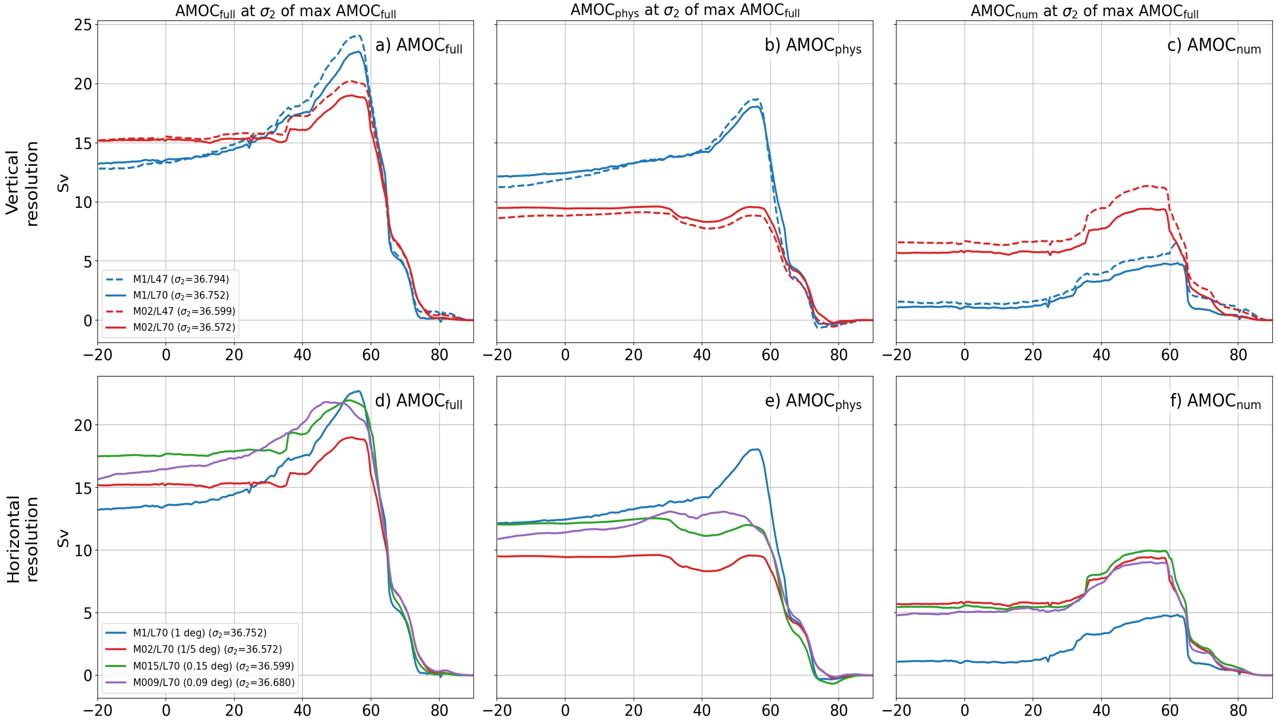



Numerical part dominates the decline in AMOC!

# Forced FESOM simulations

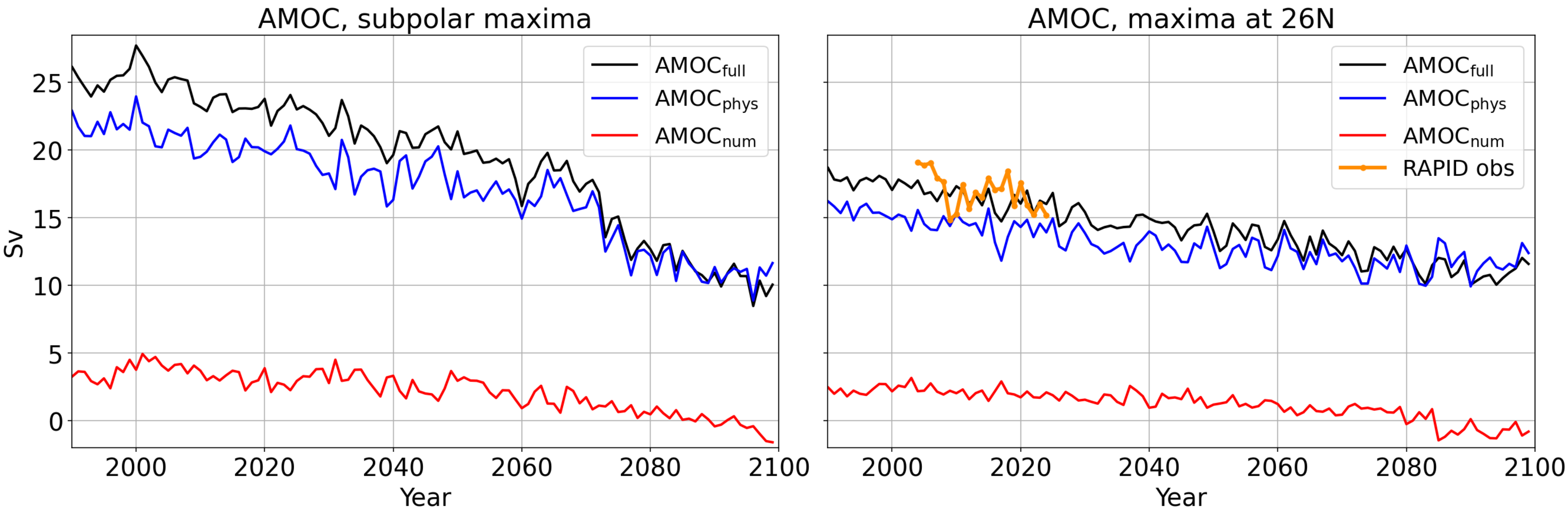



Larger physical mixing leads to smaller numerical one!



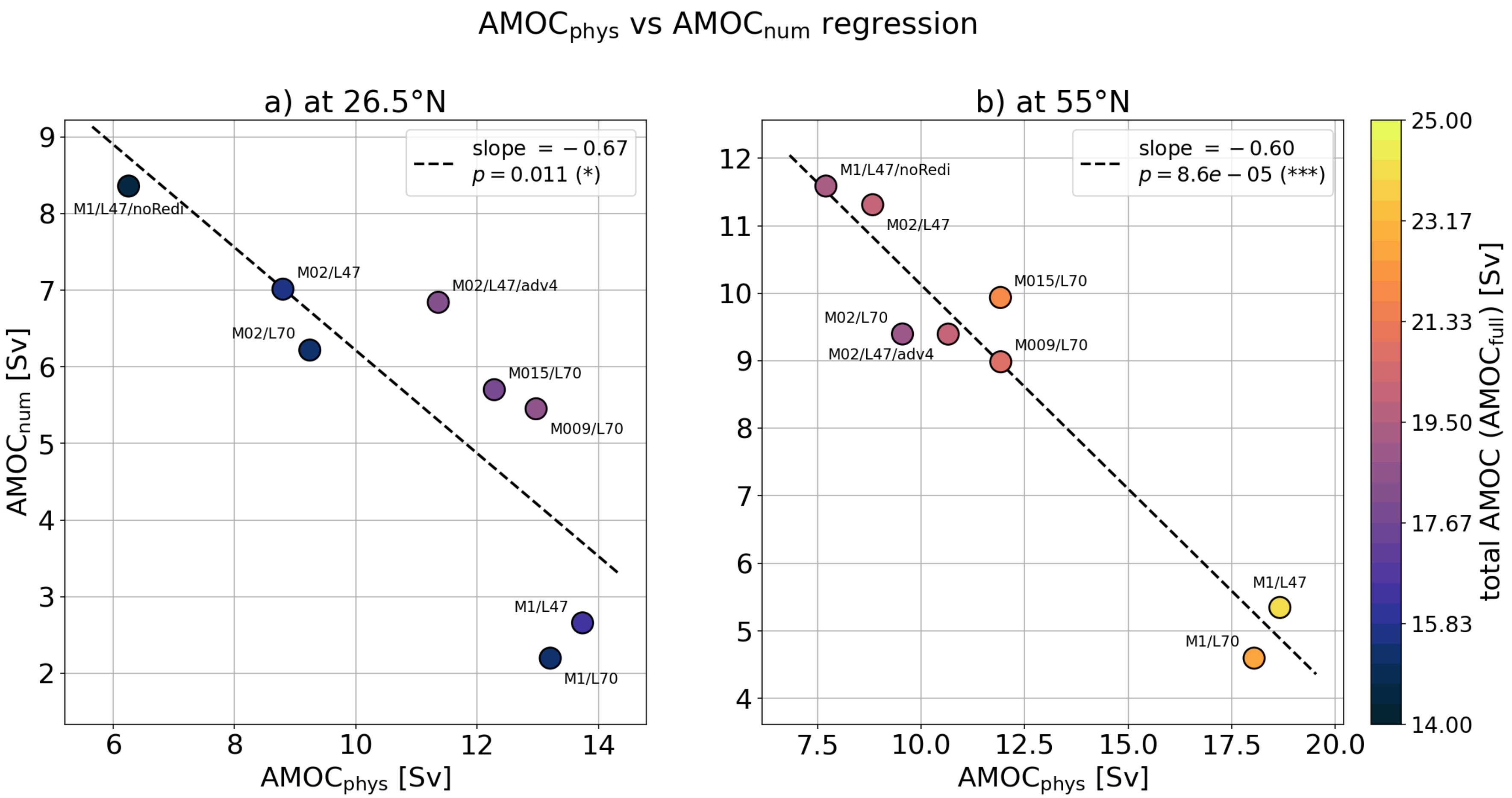

Numerical part never vanishes completely!

# Coarse resolution experiment




FESOM resolution: 20–100 km
OpenIFS resolution: 100 km
**Numerical AMOC is still large!**

# Numerical part is not fully spurious!




Can partly represent unresolved (i.e., unparameterized) physical processes?

# Conclusions

- **Projected AMOC weakening is dominated by a decline in the numerical component**, while the physical component remains comparatively stable.
- **Numerical mixing is not necessarily spurious;** it can partly represent unresolved physical processes.
- **Differences in numerical mixing may contribute to the spread of AMOC projections across climate models.**
- **Understanding, reporting, and controlling numerical mixing is essential for reducing uncertainty in projected AMOC strength and variability.**