How Ocean Mixing Can Influence Global Sea Level and Climate

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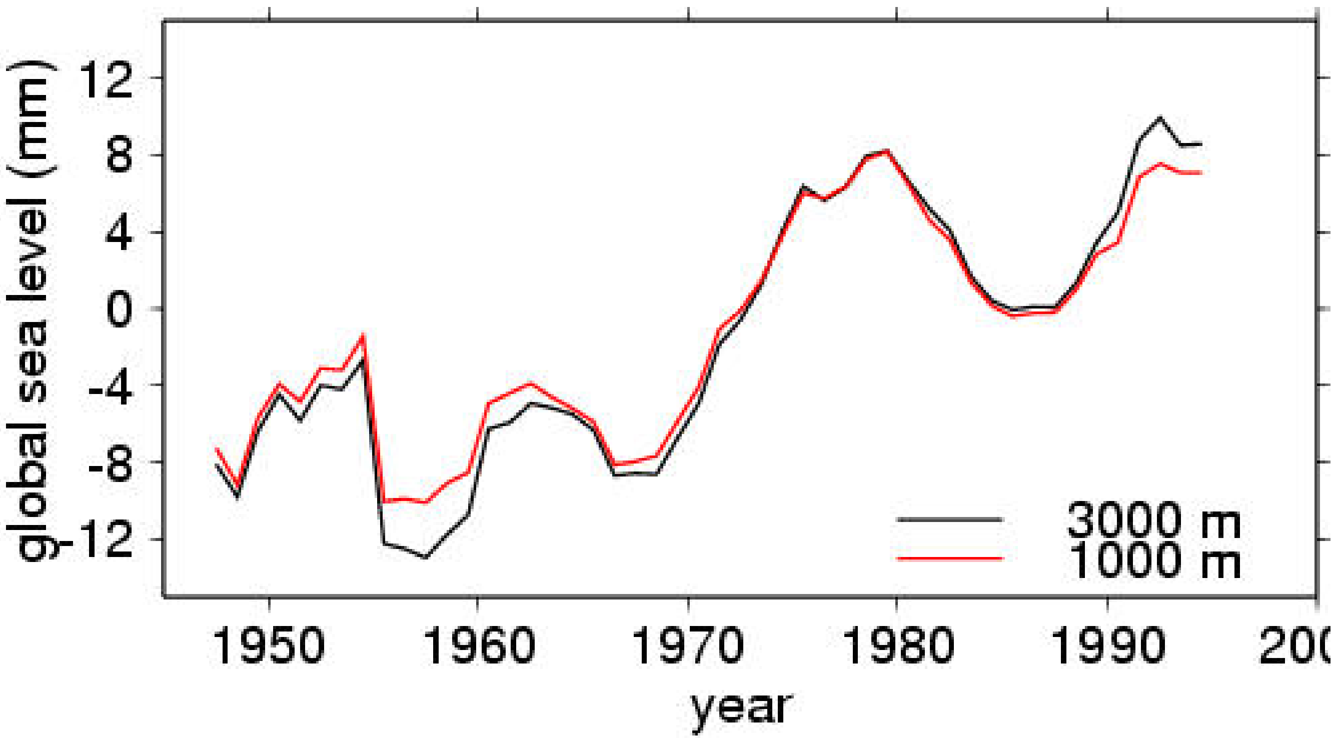
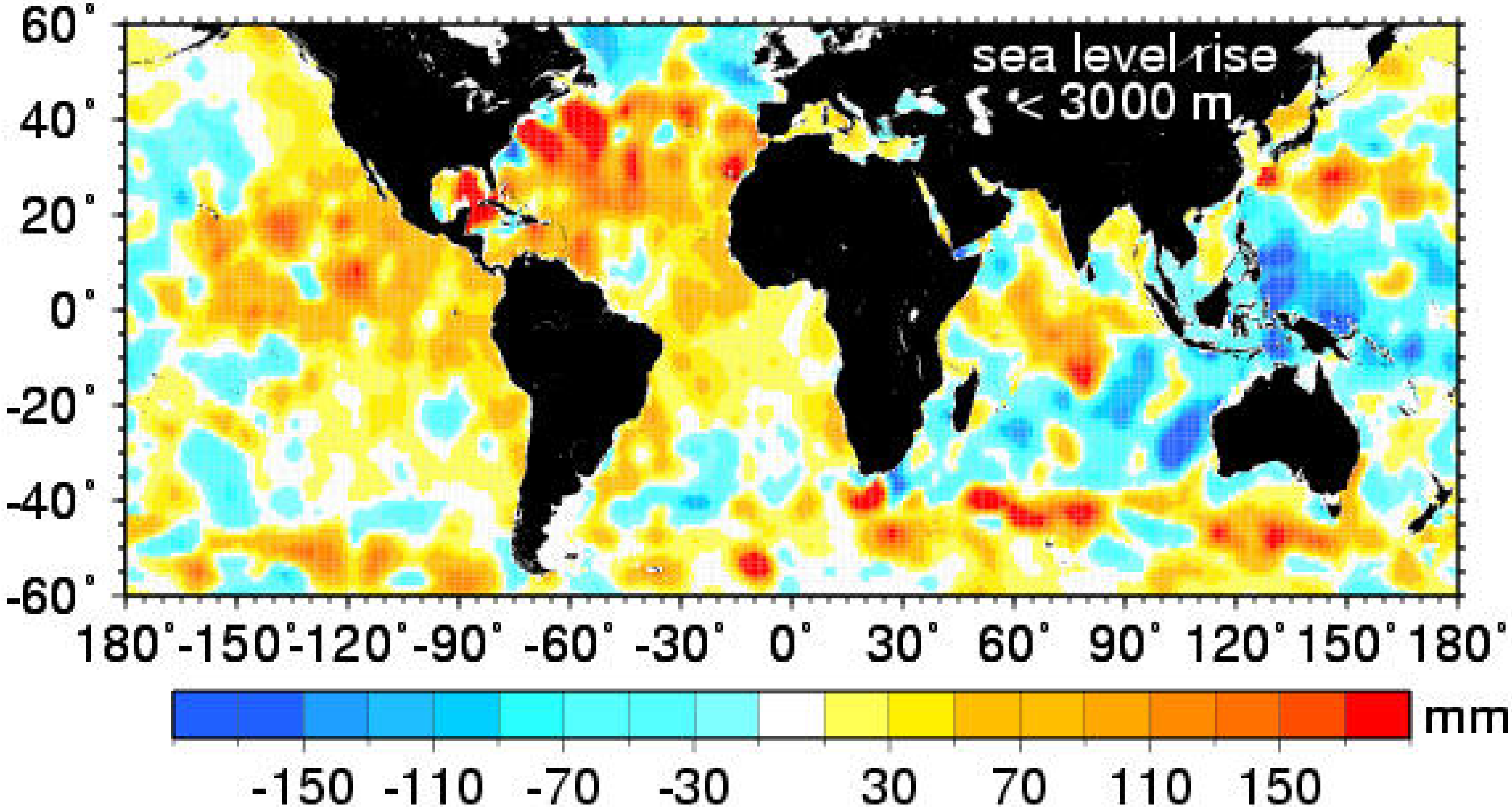
20th Century Steric Sea Level Rise



Levitus, 1998

Steric Sea Level Rise (spatial distribution)



Levitus, 1998: 1947 to 1994

Causes and Uncertainties in Sea Level Rise

Total Sea Level Rise: 1.84±0.35 mm/year

[Douglas, 2001; Peltier, 2001]

Steric sea level rise: 0.55 mm/year

[Antonov, 2002]

Ice melt: 0.2 mm/year to 0.6 mm/year

[IPCC: Church et al., 2001]

Missing sea level rise: 0.7 to 1.1 mm/year

Objectives: How Can Mixing Influence Sea Level?

- Mixing heat within the ocean
  no flux across boundaries
- Mixing heat/CO_2 downwards into the ocean
  heat/gas input from atmosphere
- Other implications of mixing
  water mass transformation

Computing sea level: dependence on density

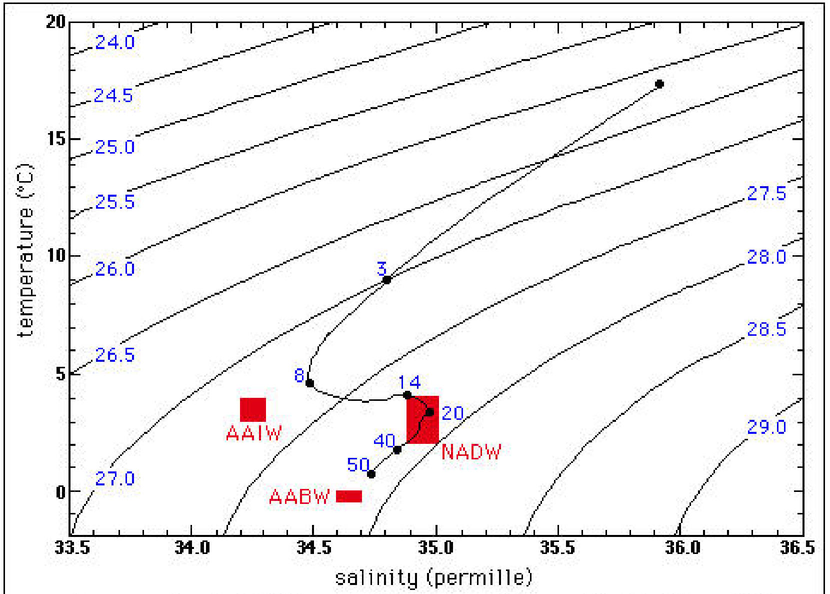
$$\text{sea level} = \int_{z_o}^{0} g\rho dz \qquad \rho = \rho(T, S, p)$$

In practice:

$$\Delta\text{sea level} = \frac{1}{g}\int_{p_o}^{p_s} \Delta\delta dp$$

where δ is specific volume anomaly.

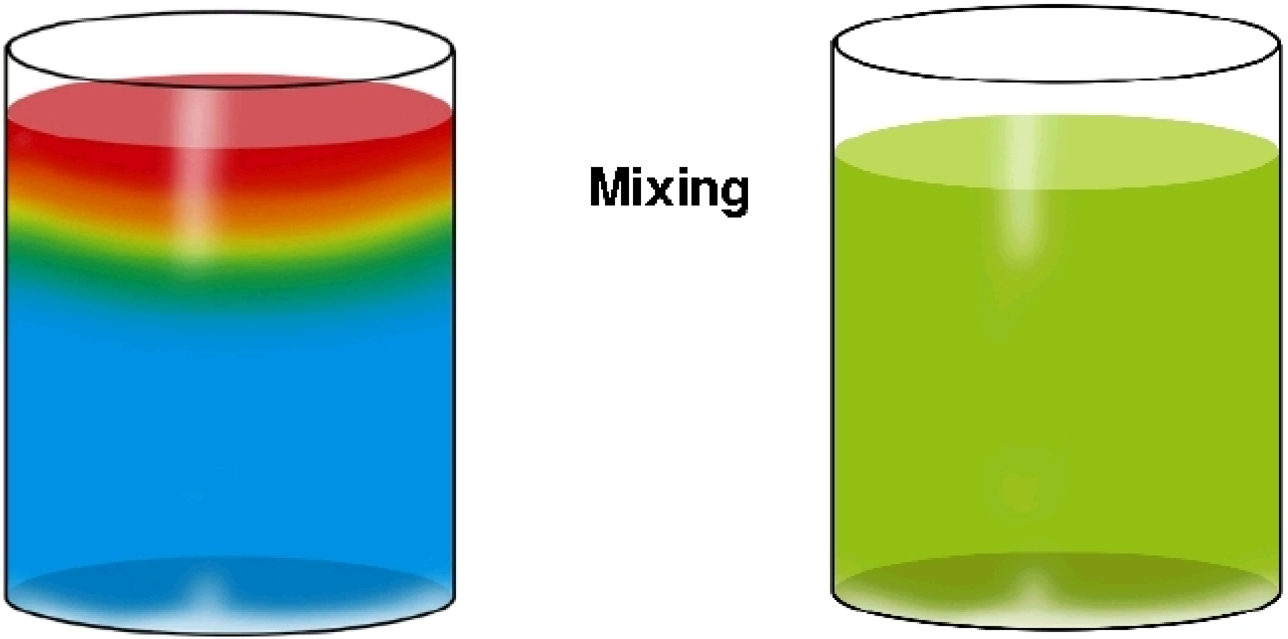
T-S diagram: The effects of cabbeling



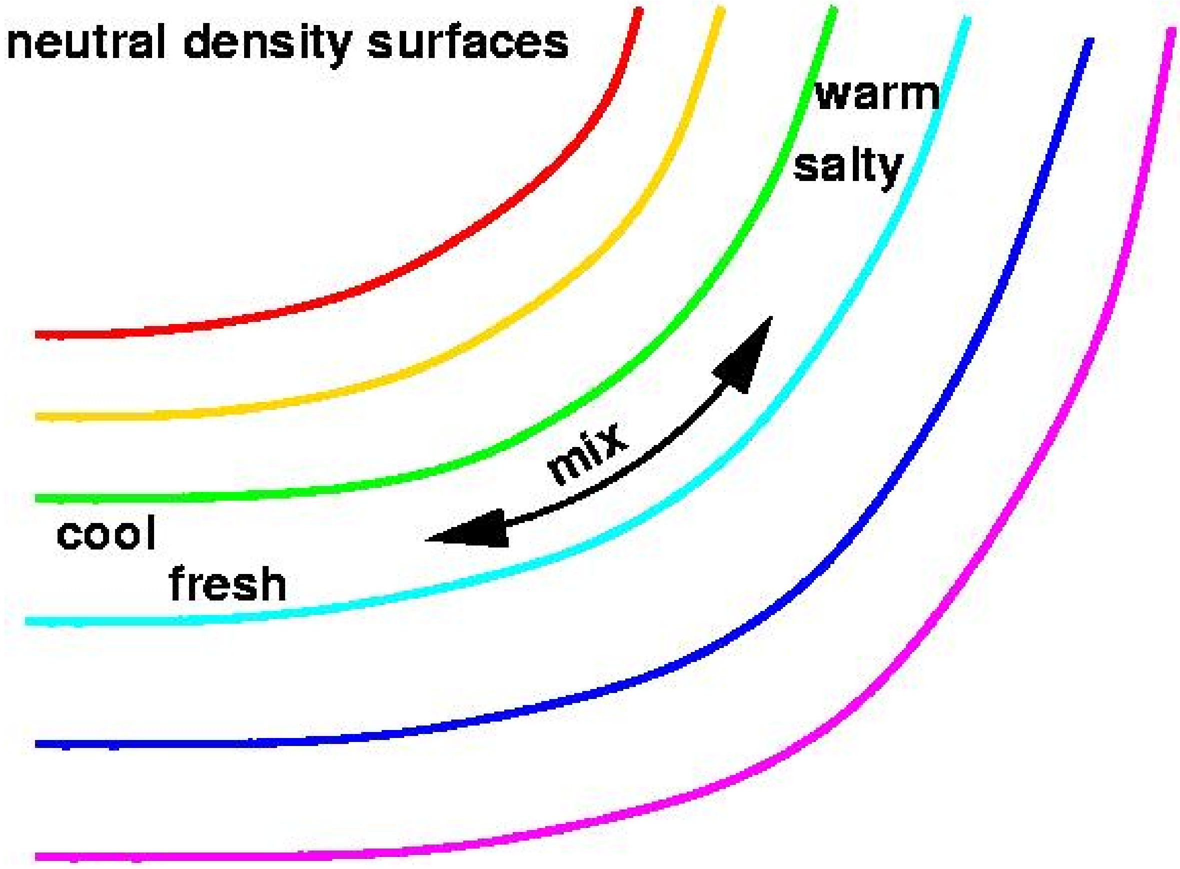
An example of a T-S diagram for observations at depths from 150 m to 5,000 m at 9°S latitude in the Atlantic Ocean. Dots represent individual seawater samples; numbers indicate depths in hundreds of meters. Red boxes represent the major subsurface Atlantic water masses. AABW = Antarctic Bottom Water; NADW = North Atlantic Deep Water; AAIW = Antarctic Intermediate Water.

T, S, and p all contribute to ρ.

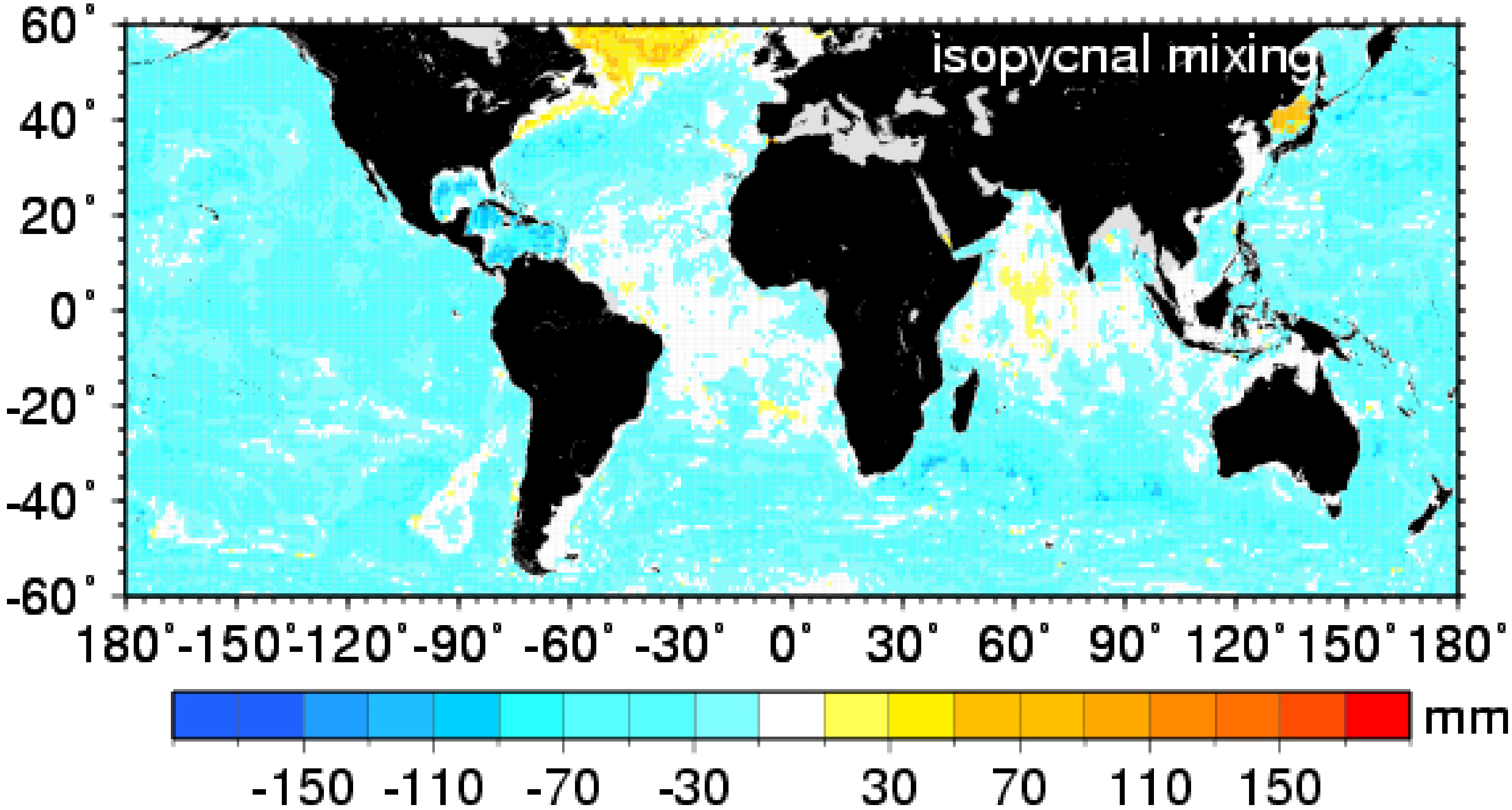
Mixing lowers sea level



Homogenize temperature and salinity along density surfaces



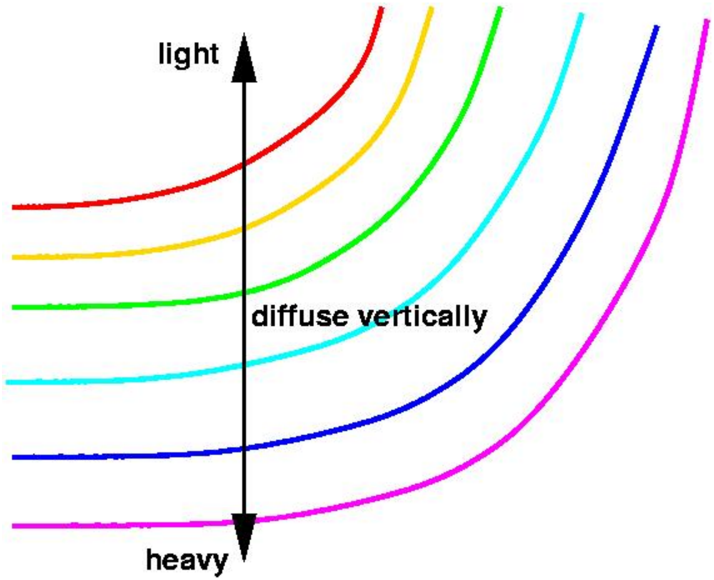
Along-isopycnal diffusion of heat in the ocean



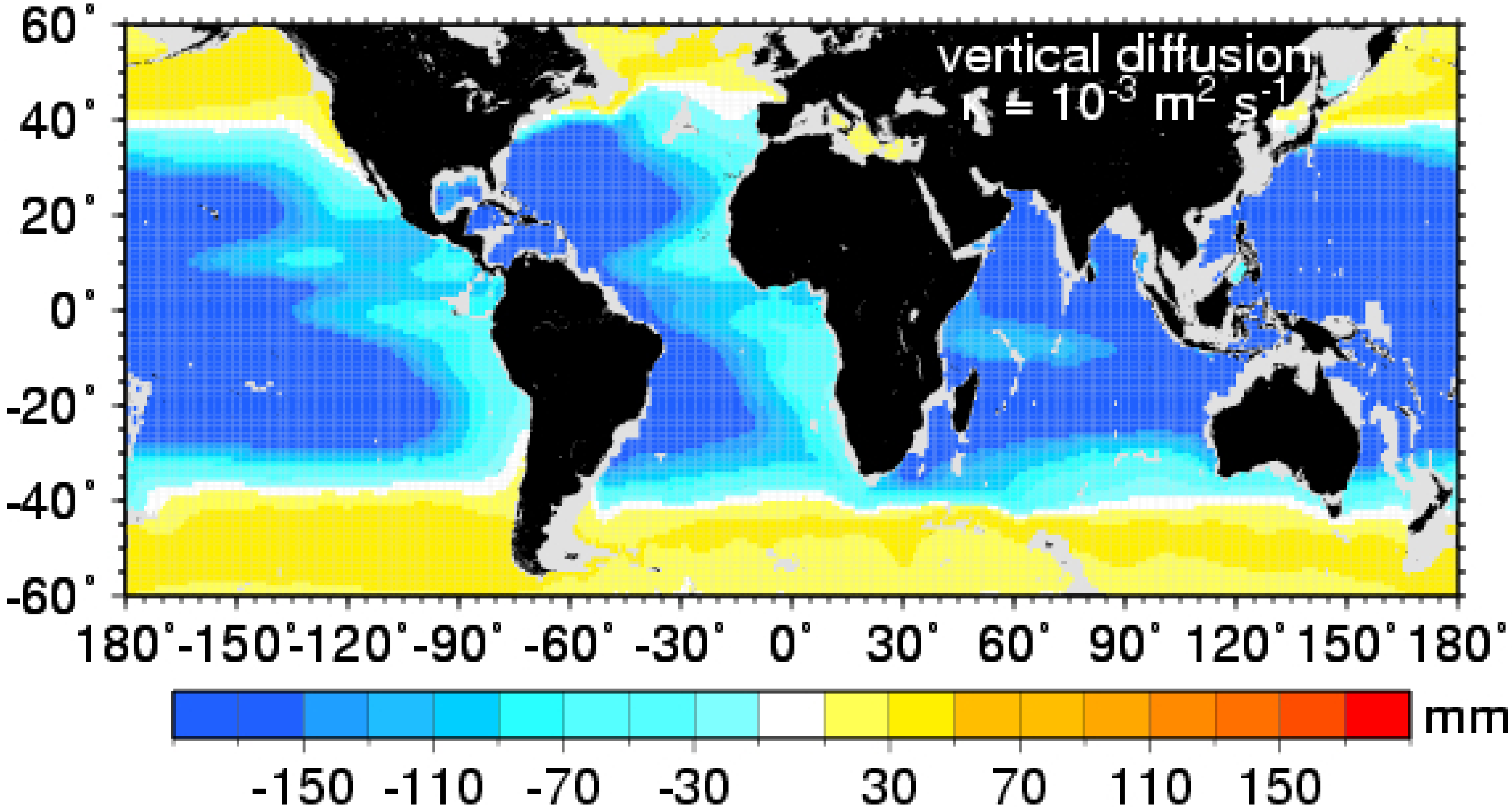
Vertical mixing of heat

$$\frac{\partial \theta}{\partial t} = -\kappa \frac{\partial^2 \theta}{\partial z^2} \quad \text{with} \quad \left.\frac{\partial \theta}{\partial z}\right|_{z=0} = \left.\frac{\partial \theta}{\partial z}\right|_{z=3000m} = 0.$$

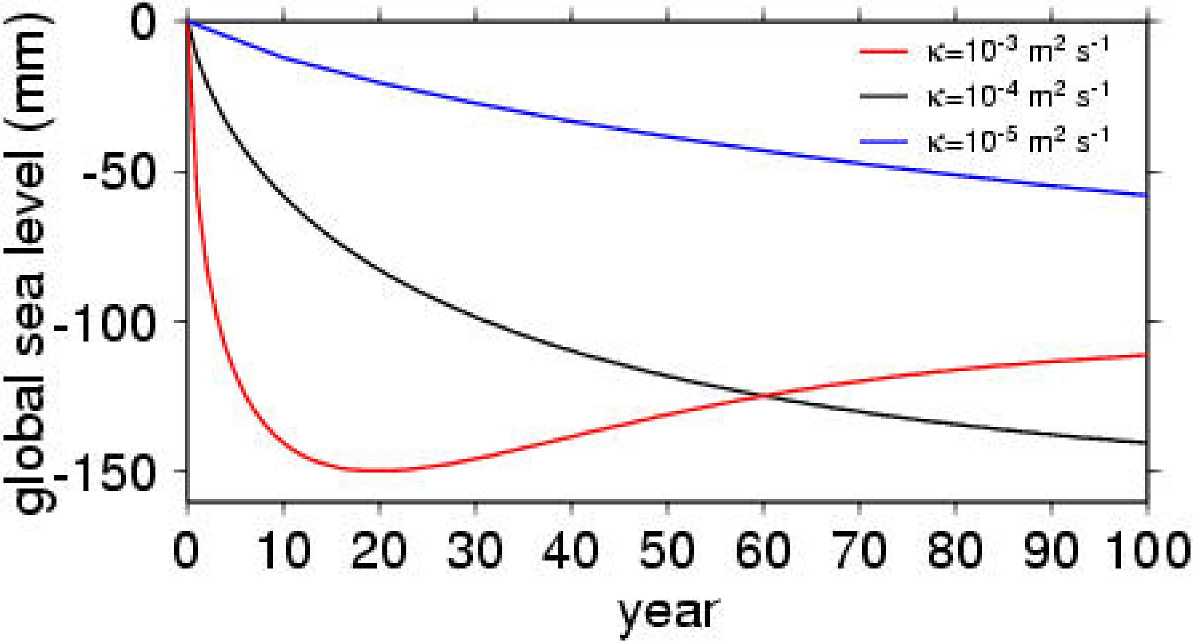
No input of heat or salt. Just vertical mixing.



Impact of vertical mixing



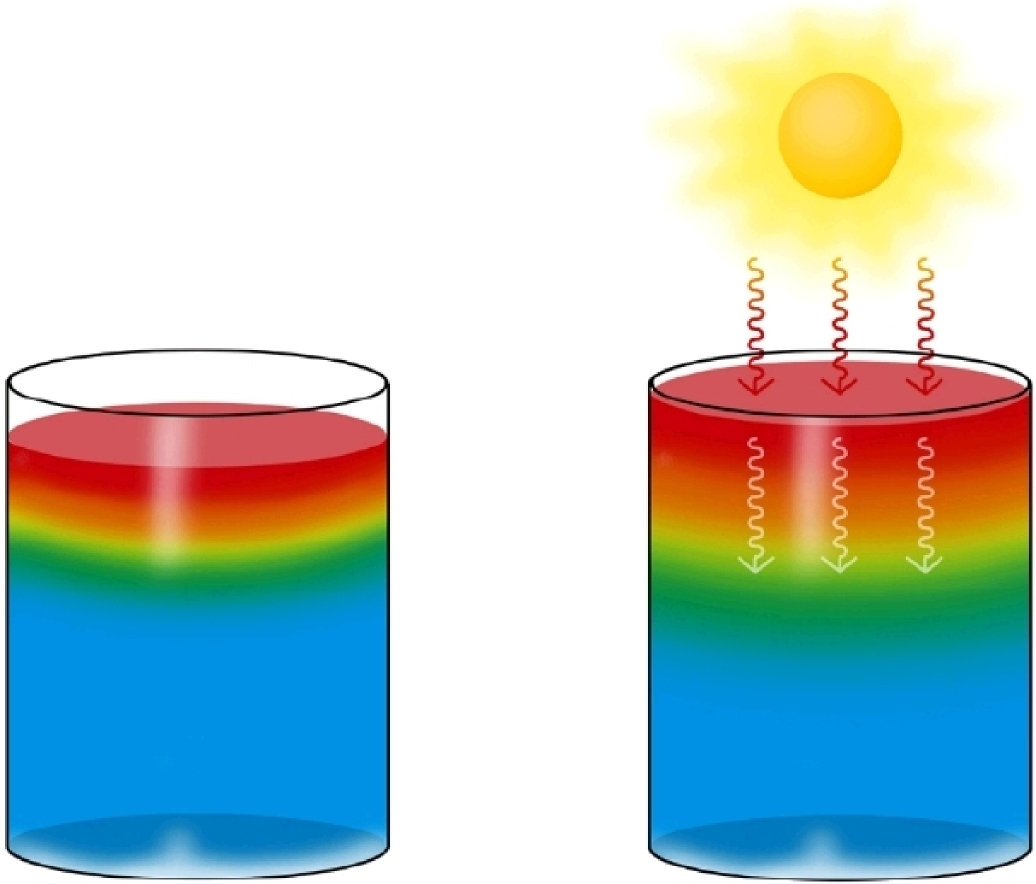
Evolution of global sea surface due to vertical mixing



Implications

- Vertical and horizontal mixing rates can influence sea level estimate uncertainties. Mixing lowers sea level.
- Serious implications for tracking sea level rise: mapping T and S is like mixing, and can lower sea level. More data means more mixing.
- If no additional heat causes problems, what happens when the atmosphere over top is changing as well?

Impact of mixing on sea level in a climate model

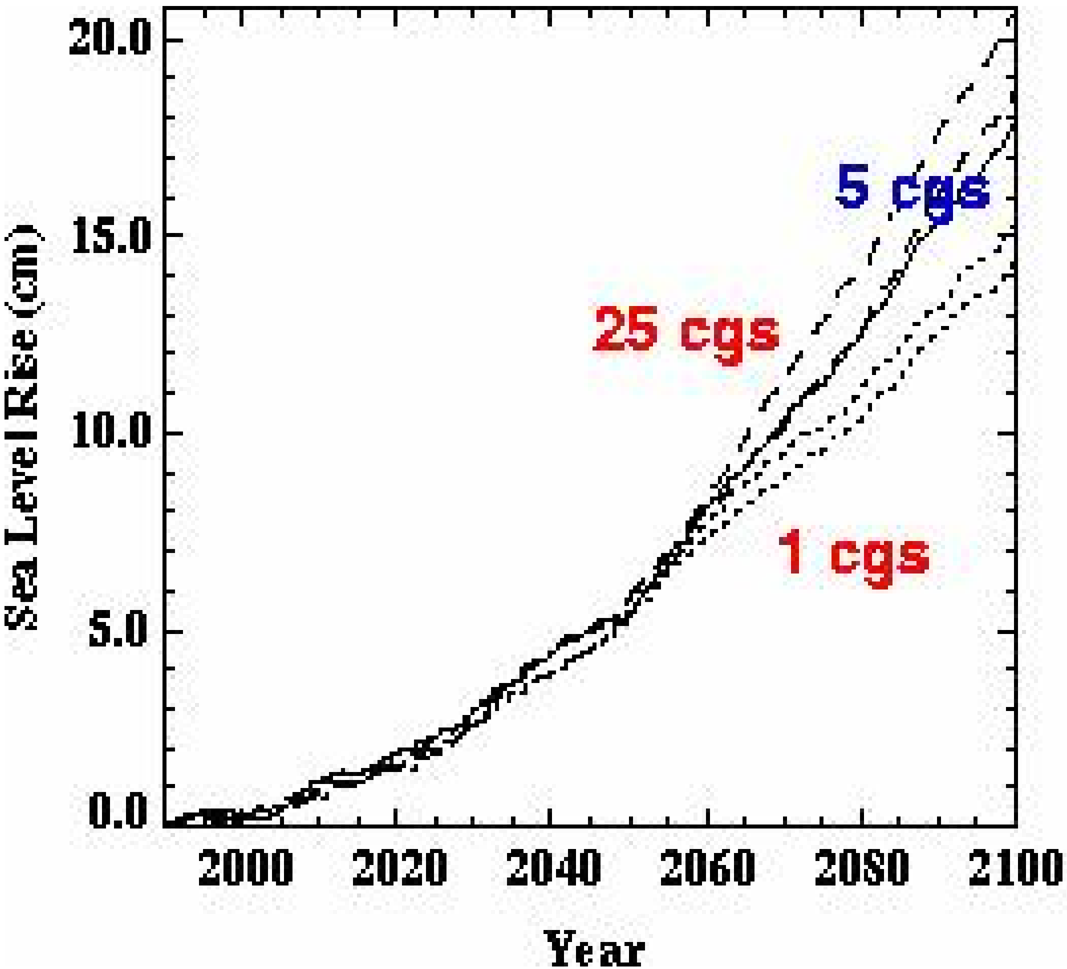


Sokolov et al. (1997, 1998): Sea level rise depends on mixing rate

Couple Atmosphere-Ocean Model

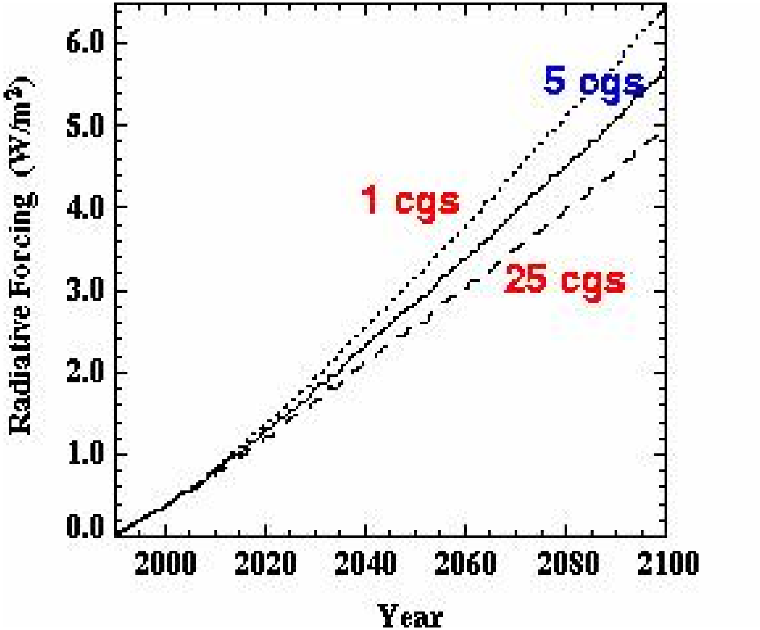
- 2-D Climate-Chemistry in Atmosphere
- Zonal mean ocean with mixed layer
- Heat uptake by ocean:
  - $K_v = 1$ cm^2 s^{-1}
  - $K_v = 5$ cm^2 s^{-1}
  - $K_v = 25$ cm^2 s^{-1}
  - carbon diffusion coefficients = 1.5 K_v

Sokolov et al. (1997, 1998): Sea level rise depends on mixing rate

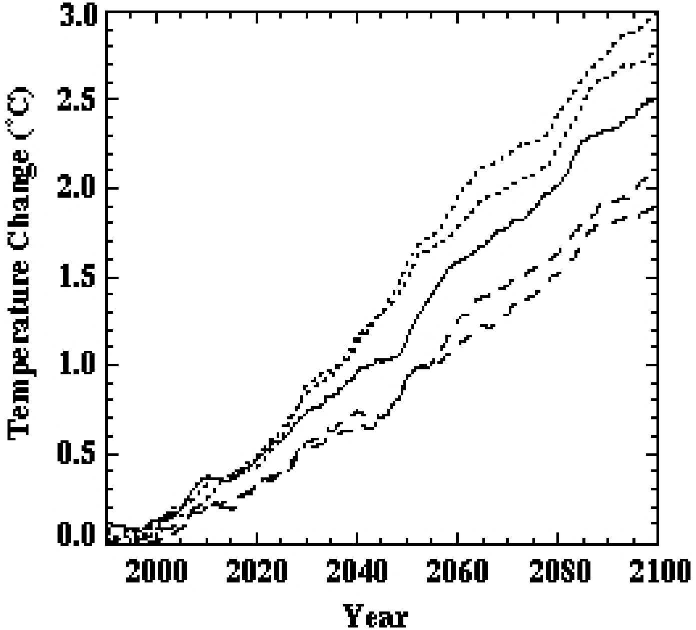


Sokolov et al. (1997, 1998)

Radiative forcing



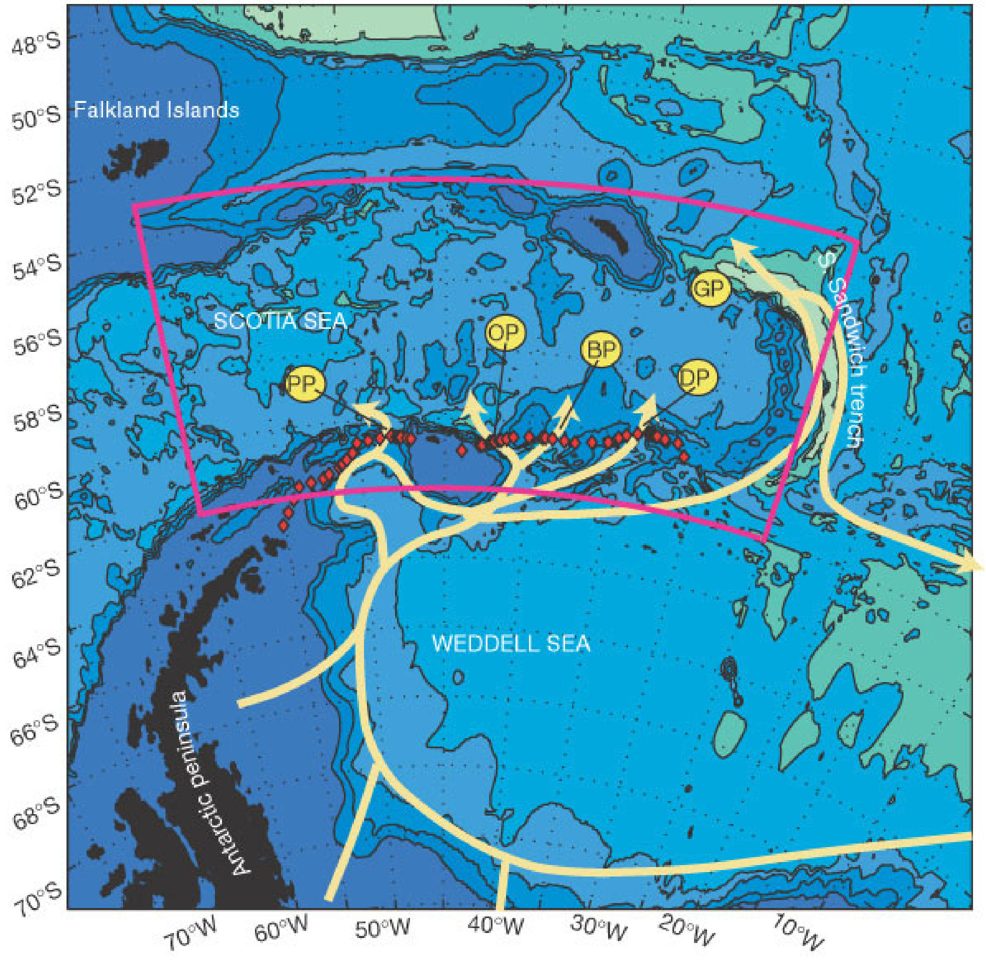
Temperature rise



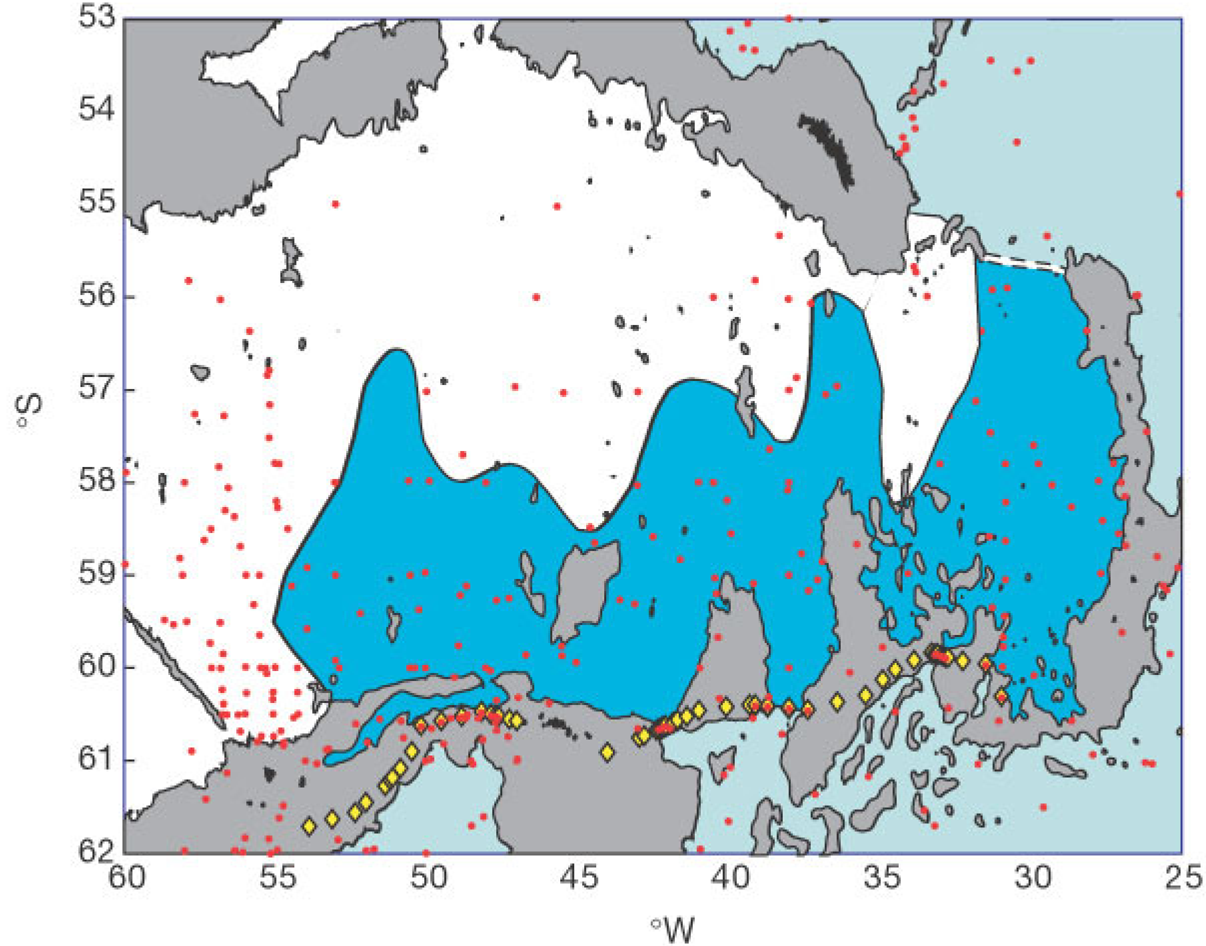
Upper ocean vs deep ocean

- Sea level changes due to mixing mostly related to upper ocean
- Roughness related mixing largest in deep ocean
- What are deep ocean implications for variable mixing?

Heywood et al. (2002)



Heywood et al. (2002): extent of $\gamma = 28.31$ *water*



Heywood et al. (2002)

$$V(\theta_u - \theta_i) = -AK\frac{\partial\theta}{\partial z}$$

where

V is volume transport

θ_u is upwelling potential temperature

θ_i is inflowing potential temperature

A is area

K is diapycnal diffusivity

$K = 39 \pm 10$ to 79 ± 45 cm^2 s^{-1}

Summary

- Mixing the ocean lowers sea level, even without cooling or evaporation
- When heat and CO_2 can diffuse into ocean, high mixing corresponds to deep penetration of heat. That increases sea level (and increases CO_2 storage in ocean.)
- Mixing also influences rate of bottom water changes, as well as indirectly affecting dynamics.

Mixing rates will influence forecasts for future climate.