Motivation: Observations and models suggest warming of the deep ocean on decadal time scales

From Domingues et al. 2008. Results for the deep ocean based on an ocean reanalysis product from Kohl et al. 2007.

- In observations and climate models, the deep ocean provides a major sink of heat on decadal time scales (Palmer et al. 2011). Accounting for deep ocean heat uptake is critical to closing global sea level and energy budgets.
- Variability in thermosteric sea level below 1700 m is 10-20% as large as surface ocean variability with much larger values in regions of high eddy activity (Ponte 2012), particularly the Southern Ocean.
- With evidence mounting in support of an important role for the deep ocean in heat uptake on decadal time scales, it is essential that we understand the mechanisms that transport tracers to the deep ocean, their variability, and response to warming.

Question: What controls the penetration of buoyancy to the deep ocean?

Here we use an Earth System Model (GFDL’s ESM2M) and compare the steady state buoyancy budget under preindustrial forcing to the buoyancy budget following a 1% to doubling of CO₂.

Model Description

- GFDL’s Earth System Model with MOM4 model (ESM2M)
- Boussinesq ocean initialized from Levitus; results shown after more than 2000 years of spin-up.
- Control run: Internal climate variability only; CO₂ run: 1% to doubling of atmospheric CO₂ concentrations
- Vertical mixing includes background diffusion, boundary fluxes, and parameterized convection (i.e. stabilizing gravitational instabilities)
- Neutral tracer diffusion and Gent McC Williams slope diffusion, with diffusivity coefficient = 600 m² s⁻¹. Neutral diffusion transitions exponentially to horizontal diffusion adjacent to land boundaries and where neutral slopes exceed 1,000.
- New diagnostics calculate the density tendency for every process that effects T and S in every time step (Griffies, 2012) ocean

Global integrals of the steady-state buoyancy budget

Resolved advection supplies nearly as much buoyancy to the deep ocean as vertical diffusion. This supply of buoyancy is balanced principally by mesoscale advection, with nonlocal convection playing a major role only above 400 m.

(a) Zonal average steric sea level budget terms for the full water column. Heat gained at low latitudes would raise steric sea level by 200 mm yr⁻¹. In steady state, this steric sea level source is balanced by its advection to high latitudes, where heat is lost to the atmosphere.

(b) The zonal average deep ocean (>1270 m) steric sea level budget terms confirm an advective-diffusive balance at low latitudes, as imagined by Munk (1966). In the Southern Ocean, both advection and diffusion supply buoyancy to the deep ocean and are balanced by the destruction of buoyancy via cabbeling, thermobaricity, and convection. In the North Atlantic, vertical diffusion supplies buoyancy to the deep ocean faster than elsewhere; this buoyancy supply is balanced by advection, convection, and mixing with dense marginal sea water masses.

(c) The impact of advection on the deep ocean buoyancy budget is separated into components from the large scale mean flow (resolved by our model) and the parameterized mesoscale and submesoscale advection. Resolved advection provides a large source of buoyancy to the deep ocean at high latitudes, which is largely balanced by the mesoscale and submesoscale transport.

Steady state steric sea level budgets

A schematic of the steady-state zonal mean buoyancy budget. Low latitude atmospheric buoyancy input is transported to high latitudes. At high latitudes, buoyancy losses to the atmosphere promote convective mixing and dense water formation in marginal seas. Here, isopycnal gradients of T, S, and P lead to the thermobaric destruction of buoyancy. The resultant dense water formed is advected to lower latitudes in the large-scale circulation. Vertical mixing balances the low latitude advective buoyancy sink.

Transients response of steric sea level to a doubling of CO₂

Changes in the global integrals of buoyancy due to a doubling of CO₂. Most of the buoyancy added to the deep ocean is due to an increase in the delivery of buoyancy by the resolved advection. The vertical diffusive supply of buoyancy slows slightly in the warmer simulation; the global integral of buoyancy tendency due to other subgrid-scale processes changes little in the deep ocean.

A schematic of the changes to the zonal mean buoyancy budget and resultant steric sea level rise. Buoyancy forcing becomes more positive mainly at the equator and high northern latitudes, but buoyancy accumulates mostly at mid-latitudes due to changes in the advective buoyancy transport.

References


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