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Do Coupled Climate Models Correctly Simulate the Upward Branch of the Deep Ocean Global Conveyor?

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The large-scale meridional overturning circulation (MOC) connects the deep ocean, a major reservoir of carbon, to the other components of the climate system and must therefore be accurately represented in Earth System Models. Our project aims to address the specific question of the pathways and mechanisms controlling the upwelling branch of the MOC, a subject of significant disagreement between models and observational syntheses, and among general circulation models.

Observations of these pathways are limited, particularly in regions of complex hydrography such as the Southern Ocean. As such, we rely on models to examine theories of the overturning circulation, both physically and biogeochemically.

This grant focused on a particular aspect of the meridional overturning circulation (MOC) where there is currently significant disagreement between models and observationally based analyses of the MOC, and amongst general circulation models. In particular, the research focused on addressing the following questions:

1. Where does the deep water that sinks in the polar regions rise to the surface?
2. What processes are responsible for this rise?
3. Do state-of-the-art coupled GCMs capture these processes?

Our research had three key components: observational synthesis, model development and model analysis. In this final report we outline the key results from these areas of research for the 2007 to 2012 grant period.

The research described here was carried out primarily by graduate student, Daniele Bianchi (now a Postdoc at McGill University, Canada), and Postdoc Stephanie Downes (now a Research Fellow at The Australian national University, Australia). Additional support was provided for programmers Jennifer Simeon as well as Rick Slater.

1. Observational synthesis

The deep overturning circulation can be traced via both physical and chemical tracers. We employed helium-3 (^{3}He) to investigate the flow of deep water originating in the North Atlantic and upwelling in the Southern Ocean. Helium-3 has been less widely used due to the paucity of observations and limited understanding of it source function. Most of the excess helium-3 (relative to the atmospheric equilibrium concentrations) found in the intermediate and deep

layers of the world ocean, is released by hydrothermal activity at the mid-ocean ridge spreading centers.

Bianchi assembled a global ^{3}He dataset from publicly available observations including WOCE, CLIVAR, GEOSECS, INDIGO and TTO cruises, as well as other published data. Observations of δ^3He, and helium concentration were vertically interpolated and objectively mapped on a 1°x1° global grid, to be used for data-model inter-comparison and as improved initial conditions for simulations that require long integration times. The ^{3}He data set was merged with the GLODAP dataset (Key et al., 2004) to aid in water mass analyses performed by another graduate student previously in Sarmiento's group.

Bianchi et al. (2010) used the ^{3}He data synthesis with a suite of ocean general circulation models to constrain the inventories and flux of ^{3}He from the Earth mantle to the oceans. The outgassing flux of ^{3}He is frequently used to normalize estimates of chemical fluxes of elements from the solid Earth, and provides a strong constraint to models of mantle degassing. Bianchi et al. (2010) suggest that the currently accepted flux of 1080 mol/year (Craig et al., 1976; Dutay et al., 2004) is overestimated by a factor of 2. We show that a flux of 527±102 mol year^{-1} is required for ocean general circulation models that produce distributions of ocean ventilation tracers such as radiocarbon and chlorofluorocarbons that match observations. The estimate of the flux of ^{3}He from mid-ocean ridge systems has been used widely in geochemistry, and our new estimate has important implications for the understanding of the dynamics and geochemistry of the Earth's interior. The new source function implied by this work is implemented in the suite of simulations using both the developed coarse coupled model CM2Mc and the ocean-only model (see next section on Model Development).

Downes, in conjunction with senior scientists from Princeton University, Texas A & M University, Florida State university and Scripps Institute of Oceanography, traced deep circulation in the South pacific circulation using hydrographic data (Downes et al., 2012, in press). This was the first time this water mass had been traced. Downes and co-authors used ^{3}He and stratification measures to trace hydrothermal plumes originating from the Pacific-Antarctic Ridge to the Drake Passage (via the Antarctic Circumpolar Current) and to the Ross Sea (via the Ross Gyre). This plume likely contributes to the formation of Ross Sea Antarctic Bottom Water, and may have a significant influence on the long term temperature signature of bottom water.

2. Model Development

Galbraith et al. (2011) developed a coarse-resolution (3ºx3º) coupled climate model, CM2MC, based on a GFDL coupled model. Galbraith was previously a Postdoc in Sarmiento's group; now at McGill University, Canada; he was not supported by this grant, but co-authors of the paper were. The ocean grid has a non-uniform resolution, focusing computational resources at the equator and at mid-to-high latitudes. This model requires roughly one-tenth the computing power

of the standard model, when run with ocean biogeochemical tracers, with only a modest compromise in the large-scale features of the ocean-atmosphere simulation. The physical model was coupled to two new minimum-complexity ocean biogeochemical models in order to examine the linkages between circulation and tracer distribution in the ocean.

The first biogeochemical model includes an idealized representation of the cycling of dissolved nutrients and carbon, and was used in a fully coupled framework to investigate the linkages between climate variability, ocean circulation and radiocarbon distribution on multi-decadal to centennial time scales (Galbraith et al., 2011).

The core of the second biogeochemical model (Biogeochemistry with Light, Iron, Nutrients and Gases, BLING, Galbraith et al., 2010) consists of four tracers (macronutrient, micronutrient, dissolved organic matter and oxygen) with a suite of parameterizations that implicitly represent phytoplankton physiology, ecosystem structure and organic matter cycling. BLING provides an idealized, minimum-complexity biogeochemical model that encapsulates the basic processes represented by more complex ecosystem models, and has been used to study the physical-biogeochemical interplays that control the distribution of nutrients (Duteil et al., 2012) and oxygen (Dutay et al., *in Review*; Bianchi et al., *in Review*) in the ocean. Additionally, due to its extremely low computational cost, BLING is currently being coupled to a fully eddy-resolving global coupled model developed at GFDL to further investigate the physical drivers of carbon, nutrient and oxygen cycling in the ocean.

Finally, the CM2MC model was used to explore the impacts of varying tidal mixing parameterizations on the upwelling of abyssal waters. This model configuration had smaller diffusion coefficients than those used in previous “low mixing coefficient” studies, and a parameterization representing the effects of tide-generated internal turbulence was included. Sensitivity experiments were carried out to investigate the first goal of the proposal: *where does the deep water that sinks in the polar regions rise to the surface?*

In related work, Joseph Majkut (a graduate student in Sarmiento’s group supported by another grant) and Anand Gnanadesikan carried out three simulations using this CM2MC configuration in which the wave energy dissipation and vertical diffusivity were tested: (1) a spatially uniform vertical diffusivity equal to the average of the dissipation (run for 1000 years), (2) wave dissipation reduced by 90% (run for 300 years), and (3) wave dissipation doubled (run for 300 years). Care was taken to make sure the ocean buoyancy and work was kept consistent within the system for each simulation.

Interestingly, the three sensitivity experiments revealed little change (less than 10%) in the biogeochemistry fields, and even less change in the physical circulation. We hypothesize two reasons why the coarse-resolution 3-degree model used may be insensitive to the tidal mixing parameterization. The first is that mixing induced by the KPP mixing scheme (Large et al., 1994) is reaching the abyss and overpowering the internal tidal mixing for the overall density transformation. The second is that numerical mixing is overwhelming the tidal mixing. Viscosity

may also be a contributor.

3. Model Analyses

We assessed the ability of models to reproduce observationally based estimates of water mass formation, transformation, and circulation. In Palter et al. (2010), a study including collaboration with scientists supported by this grant, Jaime Palter (McGill University; formerly at Princeton) explored how nutrients are circulated via the Southern Ocean Mode and Intermediate Water mass pathways. The upper ocean pathway converts deep upwelled waters to lighter pycnocline waters, which are accessible to the ocean's euphotic zone and foster productivity in most of the ocean surface. As also shown in Bianchi's work mentioned above, Palter showed that models with high vertical mixing, high eddy transport, and low Southern Ocean winds, organic nutrients lost by downward sinking at low latitudes are restored through the upwelling and upward mixing of inorganic nutrients across the pycnocline at low latitudes (i.e. a one-dimensional process). By contrast, in models with low vertical mixing, weak GM transport, and stronger Southern Ocean winds, organic nutrients lost across the low latitude pycnocline are restored to the pycnocline primarily in the Southern Ocean and depend on the full three-dimensional meridional overturning circulation for their delivery to the low latitude euphotic zone.

Downes assessed multiple coarse resolution GCMs developed at NOAA/GFDL and an assimilated solution (also coarse resolution) in their ability to represent the export and import of water masses for the Southern Ocean in a density framework. Observationally based estimates of the interaction between the deep and upper overturning cells have been calculated explicitly in isopycnal coordinate inverse models and inferred from geostrophic velocity data across 30ºS. Observationally based studies conclude that the southward flowing Lower and Upper Circumpolar Deep Water are converted to denser, equatorward flowing Antarctic Bottom Water, with no interaction between the upper and deep overturning cells in the Southern Ocean. Downes showed that differences in density structure, parameterization of polar processes, surface heat and freshwater input at high latitudes were strong contributing factors influencing the modeling of Southern Ocean overturning circulation. Downes' research showed that at least half of modeled deep water upwelled in the Southern Ocean.

SUMMARY AND CONCLUSIONS

The goal of this proposal was to test the following two hypotheses

HYPOTHESIS 1: Wind-driven upwelling of Circumpolar Deep Water is the primary mechanism by which the deep water is transported to the surface in the Southern Ocean.
HYPOTHESIS 2: Localized mixing in regions of strong interactions between tides, internal waves, and rough topography is responsible for the buoyancy flux that balances upwelling north of the Southern Ocean

Through the following three primary objectives:

1. To assemble a global gridded dataset of ^{3}He concentrations that can be used to examine three-dimensional patterns of this tracer and compare them with simulations. The dataset

will be made available to the community for use as an additional test for the realism of coupled climate models.

2. To test Hypothesis 1 by evaluating whether our existing set of models in which upwelling occurs predominantly in the Southern Ocean can produce realistic distributions of biogeochemical tracers, including ^{3}He, nutrients and radiocarbon.
3. To test Hypothesis 2 by carrying out simulations in which the mixing is spatially heterogeneous.

We successfully addressed the first objective via research carried out by Daniele Bianchi.
The second objective required testing if wind-driven upwelling was the primary mechanism by which deep waters entered the Southern Ocean and rose to the surface. Palter's and Bianchi's research demonstrated that models with high winds and low mixing support this hypothesis, whereas higher mixing leads to equatorial upwelling of deep waters. Weaker vertical mixing is responsible for the rise of deep waters that sink in the North Atlantic to rise to the surface in the Southern Ocean.

Galbraith's model (CM2MC) was used extensively to test how tidal mixing parameterizations (internal waves/ internal tides) influence the deep ocean overturning circulation. In addition, Downes' work tracing deep circulation with ^{3}He and stratification measures is an important initial step to quantifying how hydrothermal venting may be associated with enhanced deep mixing.

The final scientific question driving this proposal was "Do state-of-the-art coupled GCMs capture these processes?" Downes' research has demonstrated that models need to make substantial improvements in their overturning in basins other than the Atlantic (for which we have the most observations), that buoyancy fluxes driving surface transformation of deep waters need to be better constrained, and that polar processes (icebergs, polynyas, overflows) need improved representation for modeling bottom water formation and export.

Research pertaining to this grant spawned numerous other projects, for example, testing mixing in an isopycnal model, which may reveal different/significant outcomes, compared with our CM2MC mixing experiments. We would also like to incorporate biogeochemistry to complement the physical tracers and act as an alternate method of identifying how mixing distributes upwelled deep waters in the Southern Ocean and at low latitudes.

Downes worked collaboratively with Stephen Griffies (NOAA/GFDL), Jaime Palter and Anand Gnandesikan (Johns Hopkins University; formerly NOAA/GFDL/Princeton) to develop transformation diagnostics in density coordinates (Griffies, 2011). The diagnostics are similar to those developed by Daniele Iudicone who applied the diagnostics to the Southern Ocean (Iudicone et al., 2008). Our global diagnostics calculate the heat and salt tendency terms associated with buoyancy and mixing processes, and bin them into neutral density space at each time step, thus avoiding aliasing problems that can arise from the use of offline monthly diagnostics. The diagnostics include explicitly quantifying non-linear mixing processes such as cabbeling and thermobaricity. These diagnostics have been released as part of the latest version of GFDL's coarse-resolution ($1^{o}x1^{o}$) Modular Ocean Model that is distributed internationally.

Downes and other collaborators will continue to trace deep circulation via hydrothermal plumes in the hopes of quantifying mesoscale vertical mixing and improving geothermal heat flux estimates. The mixing and heat estimates can then be used as additional constraints in the geothermal parameterisations in GCMs.

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(Bold text indicates publications acknowledging the DOE grant)

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