Final Report Grant DE-SC0007066 and DE-SC0006848
Mode and Intermediate Waters in Earth System Models

The focus of this grant was on diagnosing the physical mechanisms controlling upper ocean water mass formation and carbon distribution in Earth System Models (ESMs), with the goal of improving the physics that controls their formation. In particular, our goals were to address the following scientific questions:

Q1. What physical mechanisms control the formation process and water mass pathways?
Q2. Can high-end coupled climate models capture these processes, and if not, what numerical tools and parameterizations can improve their representation?
Q3. What role do mode and intermediate waters play in regulating the distribution of carbon, oxygen and nutrients in the mean and global warming states?

To this end, we set ourselves three overall objectives which we broke down into four specific tasks as mapped out below:

Objectives	Tasks
1. Quantify the relative contributions of different processes in forming mode and intermediate waters.	1. Implement water mass transformation diagnostics 2. Compare diagnosed transformation rates for the mean state with observational and model based studies
2. Evaluate whether biases in biogeochemical tracers arise from biases in the physical or biogeochemical solutions.	3. Model evaluation of biogeochemical tracers linked to water mass pathways
3. Elucidate how changes in winds, surface forcing, and eddy processes affect both mode and intermediate water pathways and biogeochemical cycling.	4. Sensitivity experiments
Implications of the proposed objectives: evaluation of carbon distribution	

A description of our accomplishments is given below, organized according to the four tasks, with a final section on our evaluation of the carbon distribution. Major accomplishments include:

1. the development and implementation of model code to carry out runtime diagnostics of water mass transformation in the GFDL model (see Section I). The diagnostics played a central role in several papers described in Section II.
2. an analysis of the influence of model resolution on water mass origin and fate, and the role of eddies in ocean heat transport. These studies relied on three coupled earth system models developed at GFDL with ocean components that had 1°, 0.25°, and 0.1° horizontal resolution (see Section III. A.)
3. a series of sensitivity studies of the influence of lateral mixing on ocean climate and biogeochemistry (see Section III. B.).
4. a model analysis of how climate variability affects the large-scale climate and biogeochemistry of the ocean (see Section III. C.).
5. model simulations and analysis of how anthropogenic carbon enters the ocean and is then redistributed by water mass formation and transformation (see Section IV.)

The research funded under this grant led to 10 published papers and 2 submitted papers, with 3 additional papers in preparation and 3 papers from related efforts that were direct outgrowths of this project.

I. Task 1: implement water mass transformation diagnostics

A thorough water mass analysis utilizes a transformation framework in density space, the coordinate in which water masses flow with the least amount of work. In a zonal, single density layer view, the exchange between water masses can be described as a balance between: (i) the lateral flux of heat and freshwater at the ocean surface (as overlying atmospheric buoyancy fluxes influence the shifting of density outcrops), (ii) the northward/southward volume transport across a designated meridional boundary, and (iii) the expansion/deflation of the density layer between the surface outcrop and this meridional boundary. Whilst several studies have presented water mass transformation methods (first introduced by Walin 1982) in fully coupled and ocean-ice model configurations, the results were estimated in density space offline. Offline calculations potentially miss important nonlinear effects associated with high-frequency changes in isopycnals, particularly related to mesoscale eddy dynamics and subgrid scale processes. In addition, water mass transformation includes non-linear mixing processes, such as cabbeling and thermobaricity, that are difficult to accurately quantify offline. This difficulty is particularly true in the Southern Ocean, where heat and salt fluxes arising from mesoscale eddy parameterizations encounter the deep mixed layers with steeply sloping isopycnals. In short, the oceanographic community needs a set of diagnostics that could be generated online in depth-coordinate models.

The first major task in this DOE grant (Task 1) was to implement such diagnostics into a widely used coarse-resolution model, the NOAA/GFDL Earth System Model (GFDL-ESM2M; Dunne et al. 2012). Stephen Griffies at NOAA/GFDL, in collaboration with Stephanie Downes, Jaime Palter and Anand Gnanadesikan formulated the diagnostics, and a pedagogical summary can be found in the current GFDL-Modular Ocean Model version 5 (MOM5) manual (Chapter 36 in Griffies et al. 2012). The diagnostics carefully separate the water mass transformation into contributions from mixing sources including internal waves, diffusion, advection, geothermal heating, overflows, cabbeling and thermobaricity.

These diagnostics are publicly available to the modeling community. However, this work exposed some significant issues with the diagnostic framework; two problems in particular remain unresolved. The first is the type of density coordinate system (neutral density, potential density) that should be used, something we as an oceanographic community have not been able to agree upon. The second is how to attribute property changes due to an individual process to the appropriate water mass. For this reason it was felt to be premature to include these diagnostics in the NCAR CESM, as originally planned. However the studies described below detail the use of the novel water mass diagnostics in the GFDL climate model to estimate individual mixing processes (without a full budget closure required).

II. Task 2: Compare diagnosed transformation rates for the mean state with observational and model based studies

The overall objective with which this task is associated is to **quantify the relative contributions of different processes in forming mode and intermediate waters**. While we did address this objective in several studies described in the subsections below, we were unable to do all the specific observational and model based comparisons originally proposed in Task 2, in part because another group scooped us on some of our plans (for example to analyze transformation rates in the CMIP5 models); and in part because one of the postdocs supported under this grant who was critical to this work (Stephanie Downes) left early in the grant period for a position at ANU in Australia (where, however, she did continue with related work described below).

A. Buoyancy transfer throughout the water column

Using the newly developed online transformation diagnostics, Palter et al. (2014; J. Clim) explored the impact of individual mixing terms (mesoscale and submesoscale, overflows, and terms in the nonlinear equation of state) in transporting buoyancy throughout the water column. Regionally, vertical diffusion of buoyancy is not entirely balanced by advection, and it is the residual of these terms that this study focused upon. Under a scenario of doubled CO_2 forcing, slowing down of both the upper and lower overturning circulation cells, and the interaction between these cells, allowed surface warming signals to quickly be transported to the deep ocean, with the mixing terms often neglected in similar studies playing a significant role.

B. Allied effort on mode and Intermediate water mass formation

The introduction of water mass diagnostics in MOM5 led to other research supported by related grants. In one particular example, for upper ocean water masses, such as mode and intermediate waters, the water mass transformation diagnostics framework did not include the transport of water masses from the mixed layer (where they gain their temperature and salinity signatures), known as subduction. Thus Stephen Griffies expanded the MOM5 water mass diagnostics via collaboration with Eun Young Kwon (currently at Seoul National University; previously a postdoc in Sarmiento's group at Princeton University) to include said subduction diagnostics. Previous studies had indicated that the small-scale eddy contribution to the subduction rates across the mixed layer base were non-negligible in the flux of Southern Ocean mode and intermediate waters into the ocean interior. Kwon, Downes, Sarmiento et al. (2013; JPO) demonstrated in a high resolution version of the GFDL model, as well as in a high resolution data assimilation model, that the seasonal eddy subduction accounted for up to 40% of the annual mean subduction rate due to transformation within the pycnocline as the density outcrops migrated meridionally. The flux of anthropogenic carbon through the mixed layer base is directly related to the seasonal variation in the subduction of mode and intermediate water .

C. Allied effort on Antarctic Bottom Water formation

A grad student at ANU worked in part under the supervision of Stephanie Downes (and input from Griffies) to explore Antarctic Bottom Water formation, export, and exchange with regards to overflow parameterisations routinely implemented in global climate models (Snow et al., 2015; Ocn. Modell.). The authors developed an Atlantic sector model version of the NOAA/GFDL Modular Ocean Model version 5 (MOM5) with realistic topography. The MOM5 water mass transformation diagnostics developed by Griffies were used to show that the ratio of bottom water advection and downslope tracer transport along the Antarctic continental shelf varied depending on choice of overflow parameterisation.

III. Task 3: Model evaluation of biogeochemical tracers linked to water mass pathways; and Task 4: Sensitivity studies

Mode and intermediate water masses have a significant role in global biogeochemical cycling. These waters are responsible for supplying a significant fraction of nutrients to tropical ecosystems. They also encompass a major fraction of the ~16 Mkm^3 where water column denitrification removes nitrate from the ocean. Finally, mode and intermediate waters contain significant amounts of anthropogenic carbon dioxide. All of these phenomena depend not only on the volume of mode and intermediate water but the rate at which these waters, particularly in low latitudes, exchange with high latitudes. A particular focus here has been the role of mesoscale processes, particularly along-isopycnal stirring, in setting these rates and thus in modulating the distribution of nutrients, oxygen, and anthropogenic carbon dioxide. Additionally, we have examined how variability in convective regions may connect to variability in carbon and oxygen.

A. Model resolution sensitivity studies

During the period of this grant, we had available to us and were able to analyze the results of several simulations carried out at GFDL with three different coupled earth system models having a 1° coarse resolution ocean model, an intermediate eddy permitting 0.25° ocean model, and an eddy rich 0.1° horizontal resolution model.

1. Effect of the ocean mesoscale on mode and intermediate waters origin and fate

The origin, structure and fate of Southern Ocean intermediate and mode waters were investigated by carrying out a water mass transformation analysis in a density framework. The water mass volume, location and physical properties in a GFDL climate model with a high-resolution (eddying) ocean were compared to a physically-identical model which is only modestly eddying, to assess the effect of increased ocean resolution, and hence a well-developed mesoscale eddy field, on these characteristics. Preliminary results include that mesoscale eddy mixing processes lead to a reduction of the volume of mode and intermediate waters (confirming previous results; Lachkar et al., 2009), and reduce the contribution of lighter subtropical surface waters to intermediate and mode water densities relative to denser upwelled circumpolar deep waters. Both of these results are relevant for the sequestration of anthropogenic carbon and heat in mode and intermediate waters. The differences in the surface formation and destruction of waters compared to a data-assimilating model (the Southern Ocean State Estimate, SOSE), and a similar comparison between a state-of-the-art coarse resolution (i.e. non-eddying) global climate model to the high-resolution model are under current investigation. It is expected that this work will lead to a manuscript being submitted to a peer-reviewed journal (Frenger et al., in prep).

2. Role of transient mesoscale eddies in ocean heat transport

Eddies have been recognized as crucial contributors to oceanic heat transport. In Griffies et al. (2015), we characterized impacts on heat in the ocean climate system from transient ocean mesoscale eddies, making use of the hierarchy of three climate models with coarse, eddy permitting, and eddy rich ocean resolutions. Analysis of the ocean heat budget reveals that ocean mesoscale eddies act to transport heat upward in a manner that partially compensates (or offsets) the downward heat transport from the time-mean currents. This study illustrates the need for better representing or parameterizing the vertical transport of heat by mesoscale eddies in order to accurately simulate ocean water masses and to reduce climate model drift.

B. The role of lateral mixing in the Earth System and ocean biogeochemistry

In coarse resolution models, it is necessary to parameterize mesoscale and submesoscale mixing. Lateral mixing is generally parameterized with a diffusion coefficient A_{Redi}. Although the value of this coefficient in the subtropical gyres has been estimated to range between 1500 and >5000 m^2/s using floats and tracers, most numerical models use much smaller values (ranging between a 150-2000 m^2/s). The reasons for this disagreement and the impacts of it have not been clear.

Model sensitivity studies show that changes in the lateral mixing impact a broad range of processes. As reported in Pradal and Gnanadesikan (2014), large changes were found in regional sea surface temperatures, with higher mixing destabilizing polar haloclines, preventing sea ice formation and leading to basin-scale warmings of several degrees C. Insofar as models are often tuned to physical circulation, lower mixing coefficients in the North Pacific may be preferred to avoid developing an overly strong overturning circulation there -- but this may then impact low-latitude biogeochemistry which requires a higher mixing coefficient.

In previous work on ocean biogeochemistry (Gnanadesikan et al., Biogeosciences, 2012), we had established that lateral mixing was the dominant mechanism by which mode and intermediate waters supplied oxygen to the oxygen minimum zones in the GFDL Earth System Model. This spurred us to examine the extent to which the disagreements in the value of this coefficient could have impacts on the volume census of hypoxic waters. We developed a series of model simulations with different spatiotemporally constant values of A_{Redi} ranging from 400 to 2400 m^2/s. This range brackets many of the climate models used in CMIP5. In Gnanadesikan et al. (2013), we established that these simulations produced an order of magnitude range in the volume of the most hypoxic waters. Low values, such as are found in the mode and intermediate waters in the NCAR CESM, are associated with overly large volumes of intensely hypoxic waters. In our lowest mixing model, waters with oxygen concentrations below 10 M, a level at which denitrification occurs, fill 39 Mkm^3 as opposed to the observed values of 5-6 Mkm^3. By contrast the model with A_{Redi}= 2400 m^2/s has a value of 3 Mkm^3. This result has spurred considerable interest from the NCAR CESM ocean working group in breaking apart the thickness and tracer mixing parameterizations.

At the Ocean Sciences Meeting in 2014, Pradal and Gnanadesikan (2014)'s work was presented as a Tutorial talk, with one of the major messages being that a better way of specifying spatially-variable mixing coefficients was needed. Discussions with Ryan Abernathey led to our testing two such distributions, one based on satellite altimetry and the other a zonal mean version of this parameterization. Implementing this parameterization into our coarse coupled climate model, we have found it to impact a wide range of processes, but in ways that are by no means simple. In Gnanadesikan, Pradal and Abernathey (2015a) we showed that the level of mixing could explain about half of the modeled range in anthropogenic carbon uptake, with the more realistic mixing parameterization taking up more carbon than our control in the North Pacific, but less in the Southern Ocean. In Gnanadesikan, Pradal and Abernathey (2015b) we show that there are important impacts of this mixing on deep ventilation, which show up in the modeled fields of radiocarbon and mantle Helium. However, the relationship between these tracers (which has important implications for global geochemistry and constraints on the dynamics of the Earth's mantle) is relatively constant. A manuscript looking at the impact of the mixing coefficient on carbon pumps (Gnanadesikan, Pradal and Abernathey, 2015c) shows that it exerts a significant control on the magnitude of biological carbon storage, with higher mixing leading to lower storage, but that this change is significantly compensated by changes in the solubility pump.

C. Climate variability

Another major focus of our work has been looking at how variability, particularly in the convective regions where mode, intermediate, and deep waters are formed, affects the large-scale climate and biogeochemistry of the planet.

In Gnanadesikan et al. (2014), we examined the Atlantic Multidecadal Variability, showing that within the GFDL ESM2G model it is associated with convective variability in the Greenland and Labrador Sea that is driven by salinity anomalies and leads to changes in biogeochemical cycling. These changes though, differ significantly between West Greenland (where warmer waters lead to more nutrients all through the growing season), the Labrador Coast (where warmer waters lead to earlier sea ice melt and an earlier bloom initiation, but not to a change in productivity). These differences may explain different fisheries responses to salinity anomalies associated with the overturning.

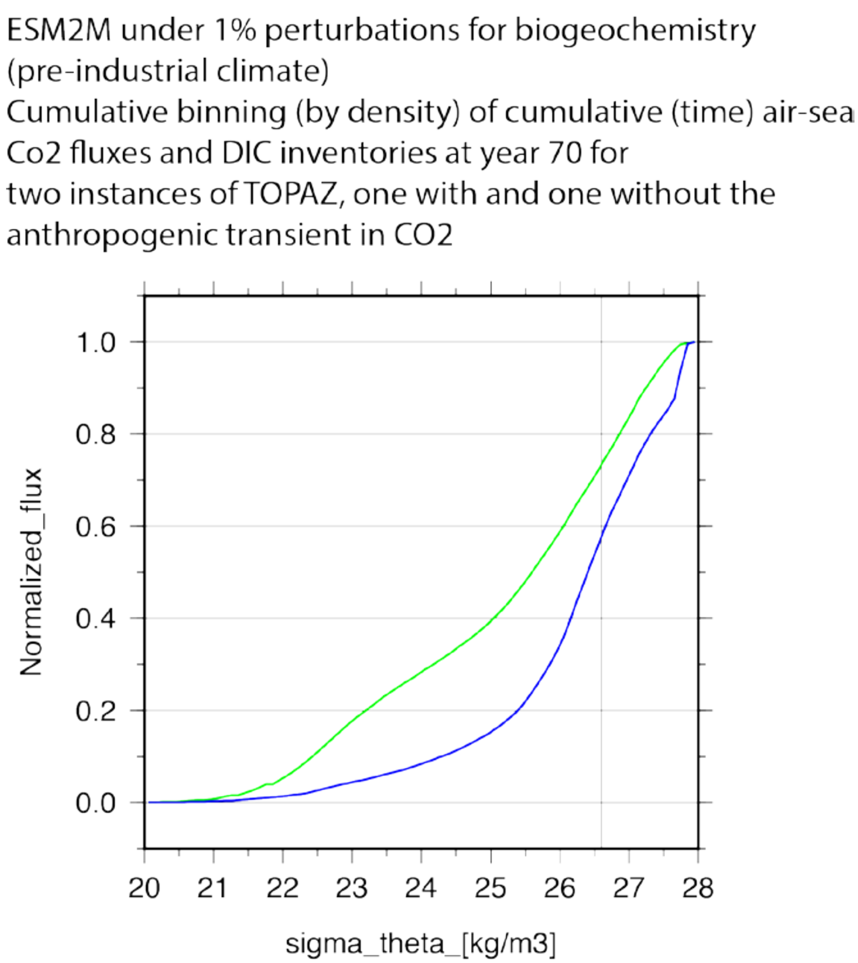
In Gnanadesikan et al. (in rev.) we examine the variability in convection in the Southern Ocean and contrast it with tropically-driven decadal variability. Southern Ocean convective variability is associated with a tradeoff between deep and mode/intermediate water formation, but also with changes in the planetary radiation balance and sea level rise. Tropical variability is not. The results show how SST trends can become decoupled from planetary radiation balance and SSH trends.

A_{Redi} also has impacts on climate variability. Gnanadesikan et al. (2015, subm. int. rev.) shows that increasing A_{Redi} increases the amplitude of El Nino, despite lateral mixing exerting more damping on El Nino. The reason for this is a combination between a trade-off between damping to lateral and vertical mixing, and the fact that increased mixing warms the cold tongue, producing an atmospheric state that is inherently more unstable. A review paper (Gnanadesikan, Koszalka, Abernathey and Pradal, in prep.) is currently in the final stages of preparation and will be submitted to JGR-Oceans. Work to analyse why the different models show no difference in climate sensitivity and how they differ in their response to ozone forcing is currently underway, supported by an NSF FESD grant.

IV. Implications of the proposed objectives: evaluation of carbon distribution

What are the pathways by which anthropogenic carbon (Cant) enters the ocean and what is the water mass signature of CO_2 uptake? To address these questions, a new simulation was conducted with GFDL's coupled earth system model ESM2M with constant pre-industrial boundary conditions for atmospheric CO_2, with an idealized representation of the atmospheric boundary condition for the anthropogenic transient in atmospheric CO_2. For the model run, two instances of the TOPAZ biogeochemistry model have been run online, one with an idealized 1%/year increase above pre-industrial atmospheric CO_2 levels over 70 years (until CO_2 doubling, i.e., increasing CO_2 and constant climate), and the other with constant pre-industrial atmospheric CO_2 (i.e., constant CO_2 and constant climate) Anthropogenic carbon for this case is defined as the difference in the carbon variables between the two instances of TOPAZ.

The attached figure shows as a function of potential density two fields from the model represented at the time of CO_2 doubling (at the end of 70 years). The blue



line shows the normalized cumulative inventories as a function of density, and a vertical line at σ_0=26.6 denotes the density corresponding the base of the directly ventilated thermocline. This result reveals that 60% of the global Cant inventory resides in subtropical mode waters and other waters lighter than σ_0=26.6. Of order 20% of the global Cant inventory resides in the combined subpolar and intermediate water masses, with another 20% residing in deep waters.

The normalized cumulative (in time) air-sea fluxes binned by surface density is also shown cumulatively (by density) over the full 70-year period, representing the density at which Cant has crossed the air-sea interface. This curve reveals relatively significant uptake for lighter waters, with approximately 73% of the global uptake of Cant occurring over densities less than σ_0=26.6. This result is important, as it implies that nearly ¾ of the Cant uptake via gas exchange is occurring over the densities of waters corresponding the shallow overturning Subtropical Cell structures.

The discrepancy between cumulative inventories (60% of the global total by σ_0=26.6) and cumulative fluxes (73% of the global total by σ_0=26.6) represents a significant diapycnal exchange of Cant from lighter densities to higher densities subsequent to uptake by gas exchange. This exchange implies an important role for densification of Cant-rich waters, as a means to provide Subantarctic Mode Water densities with elevated Cant inventories, which we hypothesize occurs in western boundary current extension waters.

It is interesting to note that the central role of subtropical mode water for Cant uptake relative to denser water masses is even more pronounced with GFDL's ESM2M than what was found in the analysis of Iudicone et al. (2015) with the French NEMO-PISCES model. Additional analyses of a suite of CORE-II-forced runs with MOM5-TOPAZ was found to be largely consistent with the coupled behavior in ESM2M, and thus the behavior revealed in the figure is not interpretable as an artifact of coupling.

Work is currently underway to evaluate an analogous simulation with the 1%/year increase in atmospheric CO_2 impacting atmospheric radiation, again with two instances of TOPAZ so as to define in a consistent way the anthropogenic Cant transient for that run. With the 1%/year increase in radiation, this new run provides warming to the physical state of the coupled model, with this impacting not only stratification but also the buffering capacity of seawater. The way in which these interact to impact the density signature of Cant uptake via gas exchange and Cant storage in the ocean interior, relative to the unperturbed physical state discussed above, will provide a means to evaluate the mechanisms sustaining carbon-climate feedbacks in the model, within a water mass framework. It is expected that this work will lead to a manuscript being submitted to a peer-reviewed journal (Rodgers et al., in prep).

V. Additional related studies

A. Anthropogenic carbon uptake in the Southern Ocean

A large proportion of the global anthropogenic CO2 uptake is found to accumulate in Mode and Intermediate waters of the Southern Ocean. In Majkut et al. (2014), we provided a review of the current estimates of the carbon sink in the Southern Ocean based on observations and models (both ocean only models and Earth System Models) and highlighted the uncertainties due to the scarcity of observations. We then used an observational system simulation experiment, based on GFDL-ESM2M historical simulation, to show that an observational programme based on 150–200 vertically profiling floats, would provide a significant step toward a better understanding of the Southern Ocean CO2 uptake.

B. Assessment of a reduced-tracer biogeochemical model in an Earth System Model

In Galbraith et al. (in press), we presented a novel biogeochemical model with three prognostic tracers, miniBLING, that we compare to two other biogeochemical models: BLING, another reduced-tracer model with six prognostic tracers, and TOPAZ, a state-of-the-art model with 30 prognostic tracers. The three models are embedded in an Earth system model (GFDL ESM2M) and run simultaneously. We show that the reduced-tracer models perform similarly in the representation of the mean state and response to climate change. This study illustrates that reduced-tracer models are applicable to a broad range of major biogeochemical concerns.

Publications

Published or accepted

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In preparation

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