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An Isopycnal Box Model with predictive deep-ocean structure for biogeochemical cycling applications

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ABSTRACT

To simulate global ocean biogeochemical tracer budgets a model must accurately determine both the volume and surface origins of each water-mass. Water-mass volumes are dynamically linked to the ocean circulation in General Circulation Models, but at the cost of high computational load. In computationally efficient Box Models the water-mass volumes are simply prescribed and do not vary when the circulation transport rates or water mass densities are perturbed. A new computationally efficient Isopycnal Box Model is presented in which the sub-surface box volumes are internally calculated from the prescribed circulation using a diffusive conceptual model of the thermocline, in which upwelling of cold dense water is balanced by a downward diffusion of heat. The volumes of the sub-surface boxes are set so that the density stratification satisfies an assumed link between diapycnal diffusivity, κ_d, and buoyancy frequency, N: $\kappa_d = c/(N^{\alpha})$, where c and α are user prescribed parameters. In contrast to conventional Box Models, the volumes of the sub-surface ocean boxes in the Isopycnal Box Model are dynamically linked to circulation, and automatically respond to circulation perturbations. This dynamical link allows an important facet of ocean biogeochemical cycling to be simulated in a highly computationally efficient model framework.

1. Introduction

The surface mixed-layer origins of ocean water have been recently estimated for the real ocean (DeVries and Primeau, 2011): approximately 40% of the ocean is ventilated through the Southern Ocean Polar region (SOP), approximately 16% through the Southern Ocean Sub-Polar region (SOSP), and approximately 29% through Northern High Latitude regions (NHL). The remainder of the ocean is ventilated through other surface ocean regions (Fig. 1), such as the low latitudes. Dividing the total surface area of the ocean, A_{total}, into N discrete regions, the fraction of the global ocean that last made contact with the surface ocean in region n, $f(A_n)$, is written (Primeau, 2005),

$$f(A_n) = \iint_{A_n} H_{new}(x,y)dxdy \Big/ \iint_{A_{total}} H_{new}(x,y)dxdy \tag{1}$$

where x and y are co-ordinates in the longitudinal and latitudinal directions respectively, and $H_{new}(x,y)\delta x\delta y$ is the volume of the ocean that last made contact with the surface ocean within the surface area element $\delta x\delta y$ at location x, y, such that $H_{new}(x,y)$ has dimensions of length.

Biogeochemical cycling is sensitive to the regional ventilation properties of the ocean. Biogeochemical tracer concentrations vary across the surface ocean, causing global ocean storage of preformed tracers to be related to the regional ventilation properties. For an arbitrary preformed tracer χ, the global mean concentration is given by,

$$\bar{\chi} = \left(\iint_{A_{total}} \chi(x,y)H_{new}(x,y)dxdy\right) \Big/ \iint_{A_{total}} H_{new}(x,y)dxdy \tag{2}$$

where an overbar indicates a whole-ocean mean. Global ocean storage of the preformed component of many biogeochemical tracers significantly affects aspects of biogeochemical cycling within the atmosphere–ocean system. For example, on centennial timescales atmospheric CO_2 is exponentially related to both the global ocean storage of preformed phosphate (Goodwin et al. (2008) and Marinov et al. (2008); where Ito and Follows (2005) derived an initial linear approximation) and to mean ocean potential temperature (Omta et al., 2011; Goodwin et al., 2011); where global preformed phosphate is determined by the efficiency of the soft tissue pump and seawater potential temperature is considered a preformed

Abbreviations: SOP, Southern Ocean Polar; SOSP, Southern Ocean Sub-Polar; NHL, Northern High Latitude.

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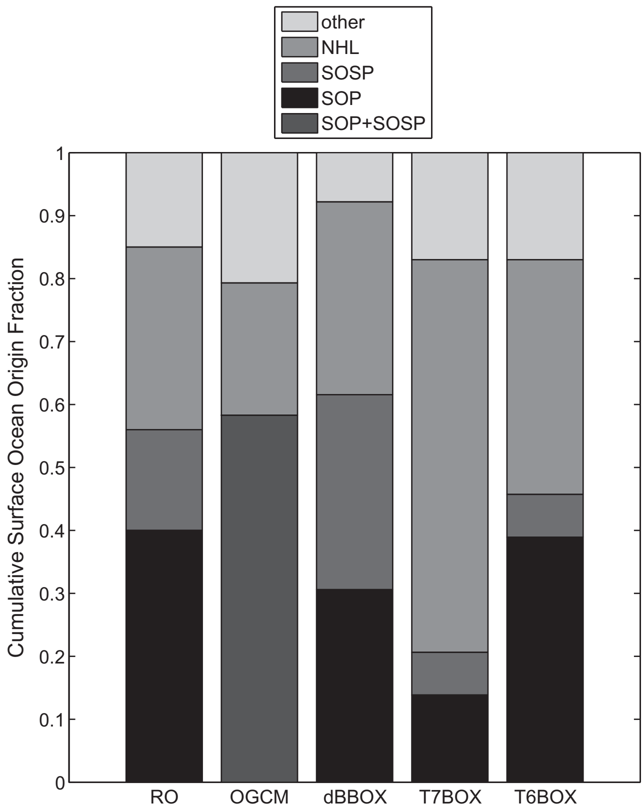

Fig. 1. The surface origin fractions of global ocean water for: an estimate of the real ocean, 'RO' (Devries and Primeau, 2011); an Ocean General Circulation Model, 'OGCM' (Primeau, 2005); the box model of de Boer et al. (2010), 'dBBOX'; and the 7-box and 6-box models of Toggweiler (1999), 'T7BOX' and 'T6BOX' respectively. The box models of de Boer et al. (2010) and Toggweiler (1999) are all set up with 15 Sv downwelling each from the Southern Ocean Polar region (SOP), Southern Ocean Sub-Polar region (SOSP), and Northern High Latitudes (NHL). The Primeau (2005) OGCM is spun up to preindustrial conditions, and the Devries and Primeau (2011) analysis is an observationally and dynamically constrained estimate for the real ocean. Note that the Primeau (2005) OGCM analysis records only one fraction regarding water from the whole Southern Ocean region (SOP + SOSP).

tracer. Atmospheric CO_2 is also a function of the global ocean storage of preformed titration alkalinity, via a more complicated relationship (Omta et al., 2011). A significant alteration to the global ocean storage of a preformed tracer is the result of either a change to regional surface ocean tracer concentrations, $\chi(x,y)$, or to the fractions of the ocean ventilated through each region, $\iint_{A_n} H_{new}(x,y)dxdy$, (Eqs. (1) and (2)). This study presents a new 'Isopycnal Box Model' motivated to simulate the biogeochemical effects of changes to the fraction of the ocean ventilated by each surface region with computational efficiency.

Consider how regional ventilation properties are set in different types of numerical ocean model. In General Circulation Models (GCMs) the volume of the ocean ventilated through each surface region (Eq. (1)) is internally solved according to the physical representations within the model and the prescribed boundary conditions, which determine ocean circulation and the volumes of the different water masses. For conventional Box Models, such as those based around Sarmiento and Toggweiler (1984), the volume of the ocean ventilated through each surface box is trivially determined by the prescribed ocean box volumes and the prescribed ocean circulation transport terms. Box volume and circulation terms are set independently by the Box Model user. This independence allows a Box Model to be tuned to a desired regional ventilation profile for a given circulation. However, box volumes tuned to achieve realistic regional ventilation for one circulation state may have to be retuned to achieve realistic regional ventilation for another circulation state (i.e. the box volumes may not be appropriate if the circulation terms are altered). Considered dynamically, both the compositions and volumes of different water masses are determined by the ocean circulation state. Altering the circulation terms in a Box Model while maintaining constant box volumes (e.g. Toggweiler, 1999) assumes that only the compositions of water masses are determined by the circulation state, but that water mass volumes are invariant. In contrast, altering the box volumes (e.g. Skinner, 2009) while maintaining constant circulation transport rates assumes that only the water mass volumes are determined by the overall circulation state, but that the compositions of the water masses are invariant.

Box Models are often used for ocean biogeochemical simulations due to their computational efficiency, allowing multi-millennial timescales to be simulated over a wide range of parameter space. The link between the appropriate box volumes and ocean circulation volume transport terms questions the use of Box Models for biogeochemical simulations in instances when either the circulation or box volumes are altered in isolation: a change to circulation should be accompanied by a corresponding change to box volumes. Here, an Isopycnal Box Model is presented that internally calculates the sizes of the sub-surface ocean boxes as a function of the prescribed circulation using physical constraints. A diffusive model of the thermocline is adopted, in which upwelling of cold dense water is balanced by downward diffusion of heat. Boxes of fixed potential density lie approximately horizontally, and are vertically arranged in density order. The box-sizes are adjusted to determine the density stratification, which satisfies a relationship between diapycnal diffusivity, κ_d, and the buoyancy frequency, N.

This manuscript is set out in the following way. Section 2 demonstrates the importance of setting box volumes for determining regional ventilation by comparing the Box Models of Toggweiler (1999) and de Boer et al. (2010) using identical prescribed circulations. Section 3 presents and describes the new Isopycnal Box Model with internally solved deep ocean structure. The regional ventilation in the Isopycnal Box Model is examined. Section 4 discusses the implications of the new Isopycnal Box Model, comparing its qualities with conventional 'prescribed volume' Box Models.

2. Regional ventilation in 'prescribed volume' Box Models

To demonstrate the importance of the Box Model volumes and configuration in determining the regional ventilation, a standard circulation is applied to different Box Models and the steady state values for $f(A_n)$ are calculated for each surface region, Eq. (1). The steady state ventilation fractions for each region, $f(A_n)$, are calculated analytically from the imposed box volumes, volume fluxes and volume exchanges of the Box Models using the following principles: (i) at steady state the fraction of water in Box A originating from Box B is the sum of the volume flux and volume exchange from Box B to Box A, divided by the sum of the total volume fluxes and volume exchanges entering Box A from all neighbouring boxes. (ii) The water in any surface box is considered to originate entirely from that surface box.

The 6 and 7-Box Models of Toggweiler (1999) are compared with the 5-Box Model of de Boer et al. (2010) (Fig. 2). The standardised circulation applied to all three models includes 15 Sv downwelling associated with the Meridional Overturning Circulation (MOC) from the Northern High Latitude surface box (NHL), 15 Sv downwelling of Antarctic Bottom Water (AABW) from the Southern Ocean Polar box (SOP), and 15 Sv downwelling of Antarctic Intermediate Water (AAIW) from the Southern Ocean Sub-Polar box (SOSP). The fate of the subducted water is as per the original model circulation in each case (Fig. 2). Where the Box Model originally included an exchange between the low latitude surface