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Tracing ventilation source of tropical pacific oxygen minimum zones with an adjoint global ocean transport model

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ABSTRACT

To better understand the changes in the ventilation of Oxygen Minimum Zones (OMZs) in the Eastern Tropical North Pacific (ETNP) and South Pacific (ETSP), we use an adjoint global transport model to trace the surface locations of their source waters. The transit times for surface waters to reach the OMZs are obtained for steady-state transport. For the ETNP OMZ, 26% of the water volume makes last contact with the atmosphere in the Equatorial North Pacific with mean transit time of 109 years. Mid-latitude North and South Pacific make comparable volumetric contributions (17% and 18% respectively), but have mean transit times that differ by a factor of 2 (186 and 382 years, respectively). The combined contribution of the Southern Ocean and North Atlantic accounts for 16% of the ETNP OMZ volume. The mean transit time from these remote regions is in excess of 2500 years. For the ETSP OMZ, 29% of water volume originates from the surface of the equatorial South Pacific with a mean transit time of 65 years while 36% originates from the mid-latitude South Pacific with a mean transit-time of 157 years. The relative contribution of the two regions indicates that the meridional ventilation pathway from the mid- latitudes is of equal importance as the ventilation via eastward equatorial current system. The mean transit-times computed here help clarify the timescales with which advective- diffusive processes link changes in surface ocean processes to the OMZs of the Eastern Tropical Pacific.

1. Introduction

The world's largest Oxygen Minimum Zones (OMZs) are located at intermediate depths in the Eastern Tropical Pacific due to a combination of factors including a sluggish circulation (Reid, 1965) attributable to blocked geostrophic contours (Luyten et al., 1983), high local respiration rates (Helly and Levin, 2004), and also because of the integrated respiration along the path of the 'conveyor' (Paulmier and Ruiz-Pino, 2009). Accurate simulations of the ETP OMZs are important for earth system models (ESMs) because changes in the size and intensity of the OMZs are critical to the Earth's carbon and nitrogen cycles (Paulmier and Ruiz-Pino, 2009; Kalvelage et al., 2013). The OMZs are also responsible for a significant fraction of global emissions ofthe trace greenhouse gases N_{2O} and CH_4, which have more powerful positive radiative forcing effects than CO_2 (Wright et al., 2012).

At present, numerical models have large biases in their representation of the tropical Pacific OMZs leading to large uncertainties in how they will respond to ongoing climate warming (Bopp et al., 2013; Cocco et al., 2013; Cabré et al., 2015). For example, most CMIP5 models simulated one large eastern tropical OMZ that joins the North Pacific (ETNP) and south Pacific (ETSP) OMZ where the observations indicate two core areas of suboxic waters. In addition, the area and volume of the ETSP OMZ are vastly overestimated (Cabré et al., 2015). The simulation of OMZs in ESMs is challenging because it requires an accurate representation of the delicate balances among different physical and biogeochemical processes (Cabré et al., 2015).

The ventilation of the equatorial Pacific has received significant attention over the past several decades, including studies based on both tracer observations and ocean models (Quay et al., 1983; Wyrtki et al., 1981; Bryden and Brady, 1985; Druffel, 1987; Toggweiler et al., 1991; Fine et al., 2001; Montes et al., 2010). Hydrographic data shows that the upwelled water mass in the Eastern Equatorial South Pacific originates in the lower layers of the equatorial undercurrent, which in turn flows from the western South Pacific and circumpolar regions (Toggweiler et al., 1991). According to Karstensen et al. (2008), the geographical location of the tropical Pacific OMZs appear to be determined to first order by patterns of upwelling, regions of general sluggish horizontal transport at the eastern boundaries, and to a lesser extent by regions with high productivity. However, the sources, variability, and fate of many of the currents ventilating the ETP OMZs remain unresolved.

In the tropical Pacific, eastward equatorial currents are thought to

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be the most likely proximate sources (Stramma et al., 2010). But the waters transported by these equatorial zonal jets ultimately originate from surface ventilation occurring at high-latitudes in both hemispheres. The North Pacific Intermediate water (NPIW), Antarctic intermediate water (AAIW) and subantarctic mode water (SAMW) have all been shown to feed the equatorial current systems that ventilate the Eastern Tropical Pacific (Shimizu et al., 2004; Sloyan et al., 2010; Jones et al., 2016). However, the timescales associated with the advective-diffusive transport and the extent to which they contribute to maintaining the size and extent of the OMZs remain unknown.

Source water properties, such as nutrient and oxygen concentrations can affect the position, size and extent of the ETP OMZs as they travel to these regions. In order to better understand and project the future evolution of the ETP OMZs, it is useful to perform an in-depth analysis of the origin and transport timescales of the the OMZ waters. In this study, we use an adjoint global transport model to trace the source waters of the OMZs(defined as $O_2 < 20\text{mmol/m}^3$ for the purpose of this study). We define the source as the location at which the water residing in the OMZs was last in contact with the sea surface.

To perform the calculation we use transport matrices extracted from the Community Earth System Model (CESM) ocean component, POP2; this provides information that can not be easily deduced from hydrographic observations. The POP2 model can successfully reproduce the large scale features of the observed inventory of chlorofluorocarbons (CFCs) (Danabasoglu et al., 2012). The model is also able to simulate the bomb ^{14}C uptake signal and the ^{13}C Suess effect reasonably well (Jahn et al., 2015). Although there are some known biases in the modelled circulation, such as a North Pacific ventilation that is too weak (Moore et al., 2013), the POP2 circulation performs well in comparison to the ocean component of other CMIP5 Earth system models (Cabré et al., 2015).

Tracer transport matrices are very useful for deriving the equilibrium state of different biogeochemical tracers (Bardin et al., 2014; Fu and Primeau, 2017) without the need to perform long time integration of the transport equations. Transport models based on transport matrices are also useful for diagnosing the ventilation of the ocean in terms of transit-time distributions (TTDs) and some of their low-order moments (Primeau, 2005; Holzer et al., 2010; Holzer and Primeau, 2010). For the ETNP and ETSP OMZ, we attempt to obtain the integrated ventilation information and answer some key questions such as: 1) Whatsurface regions make the largest contribution to the ventilation of the waters in the ETNP and ETSP OMZs? 2) What are the timescales for the needed advective- diffusive transport? 3) How different are the source waters that ventilate the ETNP and ETSP OMZs?

2. Model and methods

2.1. Global transport model

The “parent” ocean model from which we constructed the time-averaged tracer-transport operator is based on a prognostic simulation of the CESM ocean component, POP2 (Smith et al., 2010). The POP2 configuration we used has a dipolar grid with the North Pole displaced into Greenland, and with the transition from the Mercator grid starting at the Equator (Smith et al., 2010). The POP2 model has a nominal resolution of 1 degree. There are $N_x = 320$ computational grid points in the nominally north-south direction and $N_y = 384$ grid points in the nominally east-west direction. In the vertical there are $N_z = 60$ depth levels with a 10 m spacing for the top 16 layers and a spacing between levels increasing to 250 m near the bottom. In total, the model has 4,241,988 wet grid points.

The dynamical model was “spun-up” from rest for 250 years using the Common Ocean-ice Reference Experiments (CORE) climatological forcing (Griffies et al., 2009; Large and Yeager, 2009), in which the same seasonal cycle is repeated every model year. The relatively short dynamical spin-up is based on a tradeoff between the availability of computational resources and the time needed for the transients in the momentum equations to decay. Although the model is still drifting after the 250-year spin-up, the relative change in the magnitude of the major currents has substantially decreased and is typically less than 0.1% per year. After the spin-up, the dynamical ocean model was run for an additional year during which we saved all quantities needed to construct the model's advection-diffusion transport operator in matrix form with a monthly time resolution (Bardin et al., 2016). The monthly transport operators were then averaged to produce an annual mean transport operator.

2.2. Surface fraction of last-contact places and mean ventilation age

An Eulerian water parcel can be partitioned according to where and when its fluid elements were last in contact with the sea surface. The partitioning produces a normalized distribution function (Primeau, 2005; Holzer and Primeau, 2010), $\mathscr{L}(r_s, \tau|r)$, in which (r_s, τ) is the time and place of last contact with the sea surface and in which the conditioning argument r denotes the location of the fluid parcel which we take to be in one of the Tropical Pacific OMZs. As shown in Primeau (2005) and Holzer et al. (2010), the joint distribution, $\mathscr{L}(r_s, t_s - t|r)$ for the last-passage time (t_s) and last- place of surface contact can be expressed in terms of the propagator of surface boundary conditions $\mathscr{L}(r_s, t_s - t|r) = \widetilde{G}(r, t; r_s, t_s)$, where $\widetilde{G}$ is the solution to:

$$\frac{\partial \widetilde{G}}{\partial t} + \mathbb{T}^{\dagger}\widetilde{G} = -\kappa\Lambda\widetilde{G} \tag{1}$$

where

$$\Lambda = \begin{cases} 1, & \text{in the upper-most layer,} \\ 0, & \text{elsewhere,} \end{cases} \tag{2}$$

and $\mathbb{T}^{\dagger} = V^{-1}\mathbb{T}'V$ is the adjoint transport operator, with $\mathbb{T}$ being the steady-state advection-diffusion transport operator $\mathbb{T} \equiv \nabla\cdot(U - K\nabla)$. By using the adjoint operator,OMZ waters can be labeled with a tracer and transported backward in time to their locations of last contact with the sea surface. The parameter $\kappa = (3\text{ days})^{-1}$ is the rate constant at which the tracer label is removed when the water is in the surface layer of the model.

The adjoint global transport model allows us to trace the movement of waters in an OMZ backwards in time to the locations where it last had contact with sea surface. In our implementation, the resident waters in the OMZs are traced back to the model's surface layer locations. The resulting pattern of surface contact is referred to as the pattern of ‘source’ locations. The volume fraction of OMZ water that was ventilated from a surface grid-box indexed by (i, j) is given by

$$f_{ij} = \frac{V_{i,j}}{\tau}\delta_{i,j}\int_0^\infty \widetilde{G}(t)dt, \tag{3}$$

where $V_{i,j}$ is the volume of the (i, j)-th surface grid-box and

$$\delta_{i,j} = \begin{cases} 1, & \text{in the}(i, j) - \text{th surface grid box, ;} \\ 0, & \text{elsewhere.} \end{cases} \tag{4}$$

The fraction f_{ij} can be obtained directly from if $\int_0^\infty \widetilde{G}(t)$ is available, which can be obtained by solving the system of linear equations

$$\left[\overline{\mathbb{T}}^{\dagger} + \frac{1}{\tau}\Lambda\right]\int_0^\infty \widetilde{G}(t)\,dt = \widetilde{G}(0) \tag{5}$$

$\widetilde{G}(t = 0)$ is initialized in the OMZ with a concentration chosen so that the total amount of tracer integrates to one at $t = 0$, namely

$$\widetilde{G}(0) = \begin{cases} 1/V_{\mathrm{OMZ}}, & \text{in the OMZ,} \\ 0, & \text{elsewhere,} \end{cases} \tag{6}$$

with V_{OMZ} being the total volume occupied by a given OMZ. The overbar on the transport operator indicates that the annually averaged operator is used for the direct calculation of the zero-th moment of $\widetilde{G}$.