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Evaluation of oceanic transport parameters using transient tracers from observations and model output

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ABSTRACT

A method is presented to find the age distribution of ocean waters, the transit-time distribution (TTD), by combining an eddying global ocean model's estimate of the TTD with hydrographic observations of CFC-11, temperature, and salinity. The method uses a mixture model of an assumed form of the TTD, an inverse Gaussian (IG), and an established Bayesian statistical method. All known significant sources of uncertainty are propagated to arrive at estimates of two oceanic transport parameters associated with the IG TTD, the mean age (Γ) and either the half-variance (Δ^2) or the Peclet number ($Pe = \Gamma^2/\Delta^2$). It is found that the uncertainties on Γ do not overlap zero in most locations using only CFC-11, temperature, and salinity. However, the uncertainty on the other IG parameter does not overlap zero in only a few locations. With the inclusion of another transient tracer (^{3}He/^{3}H), the uncertainty on this other IG parameter does not overlap zero in just a few additional locations in the deep North Atlantic Ocean. Neither a single- nor mixture-IG representation is adequate for representing the full TTD in the ocean, particularly in the Southern Ocean.

Differences between the IG parameters estimated using the model's tracers as data (BayesPOP) and those estimated using tracer observations as data (BayesObs) provide information about the sources of model biases, and give a more nuanced picture than can be found by comparing the simulated CFCs with observed CFCs. Using the differences between each of the oceanic transport parameters from BayesObs and those from BayesPOP with and without a constant *Pe* assumption along each of the hydrographic cross-sections considered here, it is found that the model's eddy mixing biases often lead to larger model errors than the model's mean advection time biases. It is also found that mean advection time biases in the model can be statistically significant at the 95% level where mode water is found in the Southern Ocean.

1. Introduction

Transient tracers in the ocean are used to determine the time since water was last in contact with the sea surface – often referred to as the ideal mean age of the water (Khatiwala et al., 2001; Waugh et al., 2003; Waugh et al., 2004; Hall et al., 2007). After entering the ocean, a transient tracer is both advected and diffused by the ocean circulation and mixing, with the interpretation of an age of a water parcel complicated by mixing (Mecking et al., 2004). Thus, the age that is inferred from transient tracers based on their atmospheric histories is often referred to as the "apparent age" (Mangerud and Gulliksen, 1975; Warner et al., 1996; Tanhua et al., 2004). The apparent pCFC-ages, also referred to as the "tracer age" for CFCs (Waugh et al., 2003; Zhang et al., 2005), are derived by taking the measured CFC concentrations, converting them into partial pressures by dividing by their (temperature and salinity dependent) solubility (Warner et al., 1985), and finding the year in the atmospheric time series (Walker et al., 2000) that matches this partial pressure. ^{3}He/^{3}H ages can be found from an analytical expression for radionuclides (Jenkins, 1987) because ^{3}H decays to ^{3}He with a half-life of 12.43 years. For both CFCs and ^{3}He/^{3}H, the apparent age is a single number, but any given water parcel is made up of water that originated in many different places and times so that any given water parcel can be considered to have a continuous spectrum of ages with a mean age that is generally different from the apparent age. Because of mixing and the non-linear time-dependence of the atmospheric concentrations of tracers, tracer-specific ages are different from the mean age of a water parcel as well as different from each other (e.g., Waugh et al., 2003; Mecking et al., 2004).

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The concept of a transit-time distribution, or TTD, can be used to quantify the continuous spectrum of ages in a water parcel. The TTD was introduced as a marginal distribution that is obtained from the boundary-propagator Green's function, or joint distribution of locations and times since a water parcel was last ventilated by Holzer and Hall (2000). A TTD can then be interpreted as a probability, or mass fraction, of a water parcel starting somewhere at the surface getting to a given interior location over a certain time interval. While it is more difficult to interpret the properties of the flow where a TTD is wide, a narrowly peaked TTD corresponds to a steady, advectively dominated flow.

Several previous studies (Waugh et al., 2003, 2004; Hall et al., 2007) have approximated the three-dimensional TTD with the inverse Gaussian (IG) function. The TTD is always related to the Green's function for the tracer transport equation, but only the exact TTD for the constant coefficient (steady circulation and constant mixing), one-dimensional advection–diffusion equation, acting along isopycnals, can be expressed analytically as an IG function (Abramowitz and Stegun, 1965; Wunsch, 2002). When the IG approximation is made, the problem then becomes one of estimating the parameters of the IG. However, since the IG may not be a good approximation to the three-dimensional TTD in many locations, a method that incorporates observations has been developed and used to derive a TTD that does not assume an IG functional form. This method, the Maximum Entropy Method (MEM), determines the full boundary propagator, and therefore the TTD, from observations of transient tracers by transforming the distribution estimation problem into a system with an equal number of equations and unknowns (Khatiwala et al., 2009; Holzer et al., 2010; Holzer and Primeau, 2010; Khatiwala et al., 2012). Using the MEM, a mean age and a TTD width (or half-variance) are found, and some known sources of uncertainty are quantified. However, additional information, such as using the IG approximation as an initial guess for the shape of the TTD, is known to affect the TTD estimate from the MEM (e.g., Holzer et al., 2010a).

Several previous studies (Khatiwala et al., 2001; Primeau, 2005; Peacock and Maltrud, 2006; Haine et al., 2008; Maltrud et al., 2010) have used the boundary impulse response function (BIR) method, whereby the TTD is obtained using an ocean general circulation model from a forward integration of an idealized tracer input set to a non-zero value for one year and then set to zero thereafter (i.e., a top hat input). At each location in the ocean interior and as a function of time, the BIR method sets the values of this tracer equal to the BIR TTD. Since a numerical model can provide constraints on the TTD that observations cannot, we aim to combine the information provided by both a numerical model and observations keeping in mind that the model circulation fields themselves contain biases.

Here, we combine the TTD calculated in a high-resolution numerical model using the BIR method with observations of transient tracers to find a Bayesian estimate of the two parameters of the assumed IG form of the TTD as well as the TTD itself. This allows us to quantify the information provided by observations and improve upon the model's IG parameters and TTD. Bayesian analysis has been used, for example, in an oceanographic application to estimate ventilation ages in the last glacial maximum compared to the Holocene with radiocarbon data by DeVries and Primeau (2010). In Bayesian analysis, three distributions need to be defined: a likelihood (measure of how well the model fits the data), a prior (initial guess for the target distribution of the quantity of interest before the Bayesian analysis is performed), and a posterior (final target distribution of the quantity of interest). There are three different posteriors in our application here: two are the probability densities for each of the IG parameters and one is the TTD itself.

The specific objectives of this manuscript are as follows. First, to determine whether the IG form used in previous studies (Waugh et al., 2003; Waugh et al., 2004; Hall et al., 2007) accurately approximates the full TTD of the real ocean, we compare our posterior TTD estimates with an IG that has parameters equal to the IG parameter posterior estimates. Second, in order to investigate where there are significant model biases and whether these biases can be attributed to specific processes, we compare the IG parameters derived from the simulated transient tracers and the IG parameters derived from the observed transient tracers.

We focus on subregions of the North Atlantic and Southern Oceans, and particular attention will be paid to the mode and intermediate water masses in the Southern Ocean. Mode and intermediate water masses play an important role in storing heat and carbon dioxide in the ocean (Sarmiento et al., 2004) and they are composed, in part, of water parcels that have relatively recently interacted with the atmosphere (Sloyan and Rintoul, 2001). While mode waters are typically formed during the wintertime in regions with relatively deep mixed layers (McCartney, 1977; McCartney, 1982), intermediate waters reside below the mixed layer for a longer period of time than thermocline waters before being eroded and are a mixture of thermocline and deeper water masses (Sloyan et al., 2010). The dominant processes responsible for the formation of a mode or intermediate water mass either include convection via air-sea fluxes, Ekman transport across frontal zones, lateral eddy (horizontal) mixing (Iudicone et al., 2011), and diapycnal (vertical) mixing (e.g., Antarctic Intermediate Water, or AAIW; Sloyan et al., 2010), or deep convection (e.g., Subantarctic Mode Water, or SAMW; Sallée et al., 2006). Ocean model simulations have suggested that lateral eddy mixing and diapyncal mixing are also important for erosion of water masses in the Southern Ocean (Downes et al., 2011; Urakawa et al., 2012).

This manuscript is organized as follows: In Section 2, we describe the observational and model data used to inform our Bayesian TTD estimates. In Section 3, we review TTDs and summarize our Bayesian TTD estimation method. Lastly, we detail our results in Section 4 and make suggestions for further research.

2. Data and the numerical model

We focus on several hydrographic sections (Table 1, Fig. 1): SR03 between 135°E and 147°E from Tasmania (44°S) to Adélie Land of Antarctica (67°S); P16 along 150°W from 17°S to Antarctica (67°S); I06 along 30°E from South Africa (42°S) to Antarctica (60°S); A16 along 20°W from Iceland (63°N) to 34°N (which is the southernmost point of ^{3}He/^{3}H observations to the depths we consider); and A05 along 24.5°N from 14°W to about 79°W in the North Atlantic Ocean. These three hydrographic sections were occupied during both the World Ocean Circulation Experiment (WOCE) and again during the Climate Variability and Predictability (CLIVAR)/CO$_2$ Repeat Hydrography Program (bottle data available through http://cchdo.ucsd.edu/). Each of these sections has at least three repeated occupations in which CFCs (and sometimes ^{3}He/^{3}H as well) were measured. We will also examine A20, a section that runs along 53.5°W in the North Atlantic, in order to compare our estimates of the mean ages with those estimated by Holzer et al. (2010).

AAIW is defined by a distinct local minimum in salinity and SAMW is defined by a distinct local minimum in large-scale potential vorticity. To determine the location of AAIW in the water column, we consider each vertical profile of salinity and define AAIW as present where the salinity, S, is less than $S_{max,AAIW}$, and potential densities, ρ_θ, are in the range, $27.05 \leqslant \rho_\theta \leqslant 27.40$ kg m^{-3}, north of 50°S (Sloyan and Rintoul, 2001). Here, $S_{max,AAIW}$ is defined