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Lagrangian water mass tracing from pseudo-Argo, model-derived salinity, tracer and velocity data: An application to Antarctic Intermediate Water in the South Atlantic Ocean

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ABSTRACT

We use the tracer and velocity fields of a climatological ocean model to investigate the ability of Argo-like data to estimate accurately water mass movements and transformations, in the style of analyses commonly applied to the output of ocean general circulation model. To this end, we introduce an algorithm for the reconstruction of a fully non-divergent three-dimensional velocity field from the simple knowledge of the model vertical density profiles and 1000-m horizontal velocity components. The validation of the technique consists in comparing the resulting pathways for Antarctic Intermediate Water in the South Atlantic Ocean to equivalent reference results based on the full model information available for velocity and tracers. We show that the inclusion of a wind-induced Ekman pumping and of a well-thought-out expression for vertical velocity at the level of the intermediate waters is essential for the reliable reproduction of quantitative Lagrangian analyses. Neglecting the seasonal variability of the velocity and tracer fields is not a significant source of errors, at least well below the permanent thermocline. These results give us confidence in the success of the adaptation of the algorithm to true gridded Argo data for investigating the dynamics of flows in the ocean interior.

1. Introduction

Argo data provide invaluable and remarkable information about the ocean structure over the first 2000 m of the water column, especially in basins that were, until recently, poorly sampled by field experiments (Roemmich et al., 2009). The standard lifestyle of an Argo float is the following: it drifts passively for 8–9 days at depth 1000 m, it dives down to 2000 m and then samples the water column up to the surface where it can emit data to satellites, before it returns to its parking level. Since the early results proposed by Wong and Johnson (2003), many efforts have been made in using Argo temperature and salinity measurements over the vertical, especially in basins that remained poorly observed until the intensive deployment of Argo floats. Among the recent studies that deal with the South Atlantic (the regional focus of our work) Dong et al. (2011) analysed the performance of a coupled general circulation model with respect to the reproduction of the meridional overturning circulation and meridional heat transport, with and without assimilation of Argo data. Garzoli et al. (2013) combined cruise data and Argo profiles to infer the variability these two quantities over 2002–2011. Wu et al. (2011) could relate the spatial distribution of turbulent diapycnal mixing at depths 300–1800 m to the interaction of the Antarctic Circumpolar Current with the topography by making full use of high-resolution vertical profiles. Sato and Polito (2014) focused on the identification and formation of South Atlantic subtropical mode waters. They showed that most of the eddies sampled by an Argo profile and with marks of these mode waters were anticyclonic.

Probably more marginally because more complicated, some other studies have attempted to make the most of the displacements of autonomous floats at depth, knowing that only the successive positions of the instruments at the sea surface are trackable (e.g., Davis, 2005; Park et al., 2005; Lebedev et al., 2007; Katsumata and Yoshinari, 2010; Menna and Poulain, 2010). In each study, the extrapolation of the start and end of the deep displacement from the successive surface positions is an essential step. Recently, Gray and Riser (2014) used a velocity analysis at the Argo parking depth to produce a reference velocity field for geostrophic calculations at other depths. A few years ago, the Laboratoire de Physique des Océans in Brest (France) undertook a comprehensive processing of the Argo data collected over the

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world ocean to produce an atlas (named ANDRO, for Argo New Displacements Rannou and Ollitrault) of deep displacements based on Argos-tracked surface locations, and fully checked and corrected for possible errors found in the public Argo data files because of wrong decoding or instrumental failure (Ollitrault and Rannou, 2013).

It is tempting to blend absolute velocity information from a dataset like ANDRO and geostrophic velocity profiles obtained over the vertical with the thermal wind equation, as done for instance successfully by Gray and Riser (2014) in their global analysis of the Sverdrup balance. Then, the resulting gridded absolute geostrophic velocity field might be a good candidate for the investigation of water mass displacements and conversions, in the style of the analyses performed on the output of an ocean general circulation models (OGCM), by combining Lagrangian trajectories and the knowledge of in situ temperature and salinity (e.g., Blanke et al., 2006). Unfortunately, the ocean interior is not purely geostrophic, and oceanic variability develops at time scales ranging from a few hours (i.e., internal waves) to several years (i.e., decadal variability) (Ferrari and Wunsch, 2010). Gridded climatologies of temperature and salinity and of the mean absolute geostrophic velocity field correspond to independent calculations, which may result in the poor rendering of the genuine temperature and salinity modifications along three-dimensional movements. The physical reality of the modifications is however essential because they relate to the sudden or progressive conversion of a water mass into another. The study of such water mass transformations refers essentially to the close combination of tracer and velocity information, and a Lagrangian analysis of gridded mass and velocity annual fields may not be so accurate unless special care is brought to the calculations and to the interpretation of the results.

We will not discuss the process of gridding scattered velocity and tracer information though this is of course a crucial step when working with genuine Argo data, and we take the availability of gridded datasets for granted. Our paper aims at testing the successful derivation of a fully non-divergent three-dimensional velocity field by using here, for convenience, synthetic velocity and tracer data calculated and gridded by an OGCM. Our methodology uses only model data that mimic the gridded information that can be retrieved from the profiles and displacements of the Argo profilers. Therefore, we are confident that it will be easily transposable to true, gridded Argo data, while beneficiating from the present results inferred from equivalent and thorough model-based calculations. For instance, the sensitivity of water mass tracing experiments to the inclusion or exclusion of seasonal variability in the gridded dataset can be investigated in the model, knowing that Argo-derived gridded products consist predominantly of annual mean climatologies that disregard the seasonal scales of ocean variability. Section 2 presents the model simulation that provides pseudo-like Argo information, i.e., the horizontal velocity field at 1000 m and the vertical profiles of temperature and salinity. Section 3 introduces a retrieval algorithm for the full three-dimensional velocity and tracer fields, and discusses some key hypotheses in the light of known patterns of the circulation of intermediate waters. Section 4 details the validation of the Lagrangian experiments that can be carried out with these fields, with reference to results obtained with the original velocity and tracer model data. Our concluding remarks follow in Section 5.

2. Model and method

The numerical simulation we choose for our study is a somewhat realistic description of the world ocean circulation (see detailed description in Blanke et al. (2002)). The model that generated it (the OPA model, Madec et al., 1998) was used mostly as a dynamic interpolator of the mass field derived from an observational climatology of salinity and temperature (Levitus, 1982). The domain simulation extends from 78°S to 90°N with a 2° zonal resolution at the equator and a meridional grid interval that varies from 0.5° at the equator to a maximum of 2° in the tropics. There are 31 levels in the vertical with the highest resolution (10 m) in the upper 150 m. The simulation is forced by a daily climatology obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) 15-year (1979–1993) reanalyses, and smoothed by an 11-day running mean. The restoring term to the Levitus climatology appears as a Newtonian damping in the temperature and salinity equations of the OGCM. The intensity of the restoring is given by the inverse of a characteristic time scale that varies with depth and with the distances from the surface, the coast, and the equator (Madec and Imbard, 1996). The simulation is equilibrated (there is no substantial drift in the tracer and velocity fields after ten years of integration) and the internal sources and sinks of heat and salt introduced by the Newtonian damping balance exactly the surface heat and evaporation-minus-precipitation fluxes that are almost zero when integrated over the global domain. The restoring (together with the climatological atmospheric forcing) is here an essential ingredient to allow useful comparisons with circulation schemes deduced from observations (e.g., Blanke et al., 2001; Friocourt et al., 2005). It does not interact directly with the model turbulent mixing and bottom boundary layer schemes since it is not applied near the coastlines or within the mixed layer. The restoring can still be considered as part of the model physics (at it intends to mimic the effects of poorly performing subgrid scale parameterizations), with a non-local redistribution of heat and salt (unlike lateral and vertical mixing that do conserve heat and salinity through exchanges between adjacent grid cells).

The model horizontal resolution and the time scales kept for variability (monthly averages) compare favourably with the resolution of the gridded atlases one can calculate from in situ Argo data (e.g., Hosoda et al., 2008; Roemmich and Gilson, 2009; von Schuckmann et al., 2009). Of course, at this resolution, the model does not sample the full spectrum of variability of the real ocean: submonthly and subgrid scale movements are only parameterized with physical schemes that account for the mean effect of turbulent lateral and vertical mixing. By comparison, the gridded atlases calculated with Argo data average all the scales of variability truly experienced by the drifters.

One model level for tracers and horizontal velocities lies at 1033 m and matches appropriately the parking depth of most Argo drifters. Therefore, in this study, we use the annual mean currents modelled at this depth in the South Atlantic Ocean as a reference absolute velocity field. The annual mean values of temperature and salinity are combined to define an average mass field on which the thermal wind equations are applied to derive geostrophic velocity components. The surface wind stress that forced the model is used to estimate the annual mean Ekman circulation that can be added on the total horizontal velocity field. These three stages represent a set of operations that can be applied to true Argo-derived gridded datasets and available wind stress climatologies. The full monthly varying model velocity and tracer fields are kept for reference Lagrangian experiments, to which all comparisons will be made.

The focus is here on the South Atlantic Ocean because the northward spreading of Antarctic Intermediate Water (AAIW) from the Subantarctic Front to the North Atlantic has long been a subject of intense interest (Wüst, 1935; Talley, 1996) and has been addressed in the recent years by major research projects, e.g., GoodHope (Ansorge et al., 2005; Speich and Arhan, 2007) and SAMOC (Garzoli et al., 2007). Our study builds especially on the