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Can we reconstruct mean and eddy fluxes from Argo floats?

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ABSTRACT

The capacity of deep velocity estimates provided by the Argo float array to reconstruct both mean and eddying quantities, such as the heat flux, is addressed using an idealized eddy resolving numerical model, designed to be representative of the Southern Ocean. The model is seeded with 450 "virtual" Argo floats, which are then advected by the model fields for 10 years. The role of temporal sampling, array density and length of the float experiment are then systematically investigated by comparing the reconstructed velocity, eddy kinetic energy and heat-flux from the virtual Argo floats with the "true" values from the model output. We find that although errors in all three quantities decrease with increasing temporal sampling rate, number of floats and experiment duration, the error approaches an asymptotic limit. Thus, as these parameters exceed this limit, only marginal reductions in the error are observed. The parameters of the real Argo array, when scaled to match those of the virtual Argo array, generally fall near to, or within, the asymptotic region. Using the numerical model, a method for the calculation of cross-stream heat-fluxes is demonstrated. This methodology is then applied to 5 years of Argo derived velocities using the ANDRO dataset of Ollitrault & Rannou (2013) in order to estimate the eddy heat flux at 1000m depth across the Polar Front in the Southern Ocean. The heat-flux is concentrated in regions downstream of large bathymetric features, consistent with the results of previous studies. 2 ± 0.5 TW of heat transport across the Polar Front at this depth is found, with more than 90% of that total concentrated in less than 20% of the total longitudes spanned by the front. Finally, the implications of this work for monitoring the ocean climate are discussed.

1. Introduction

Deep drifting floats, such the satellite tracked Argo floats and the Autonomous Lagrangian Circulation Explorer (ALACE) floats, or acoustically tracked Sound Fixing and Ranging (SOFAR) and RAFOS floats, provide direct measurements of the oceanic currents as they move with the flow. These floats provide the only direct measurements of the ocean's subsurface currents with broad spatial coverage and have been instrumental in shaping our comprehension of the structure of the ocean's interior (Roemmich et al., 2009; Riser et al., 2016). They have been shown to be capable of producing accurate and rich maps of the time mean interior currents (Davis, 1991a; Gille, 2003a; LaCasce, 2008; Ollitrault and Colin de Verdiére, 2014) and measurements of features not readily inferred from remotely sensed surface measurements, such as deep jets and boundary currents (Richardson and Fratantoni, 1999; Fratantoni and Richardson, 1999; van Sebille et al., 2011; 2012). With the continued development of the Argo program, and the improved geographical and temporal coverage of the global ocean that comes with it, it is reasonable to ask: are we capable of observing robust, quantitative statistics of the oceanic meso-scale with current float deployments?

As a way of introducing the problem, Fig. 1a shows all Argo float positions in the Southern Ocean (south of 30°S) within 5 days of the 25th of December 2009. We have determined the mean distance between each of the points plotted in Fig. 1a and their closest neighbor is approximately 160 km. Fig. 1b shows the trajectory of a single float, (World Meteorological Organization number #5900777) over its lifetime. Numerous scales of motion are present in this trajectory, from very tight loops with a radius of order a few kilometers, to larger meanders with a effective radius of several hundred kilometers. The time series of float position is *non-stationary* (that is, the statistical properties of the motion change with time) and, although the Argo float has remained operational for approximately four years, the trajectory is limited to a relatively small part of the ocean, drifting only a few degrees throughout its operational life. As such, this float has repeatedly sampled the same geographic region.

Clearly, Argo float #5900777 'sees' a number of features important to general circulation, including mesoscale eddies superimposed over a larger scale flow field. However, the geographic region sampled by this float is limited. Thus, we pose the question: what characteristic must an

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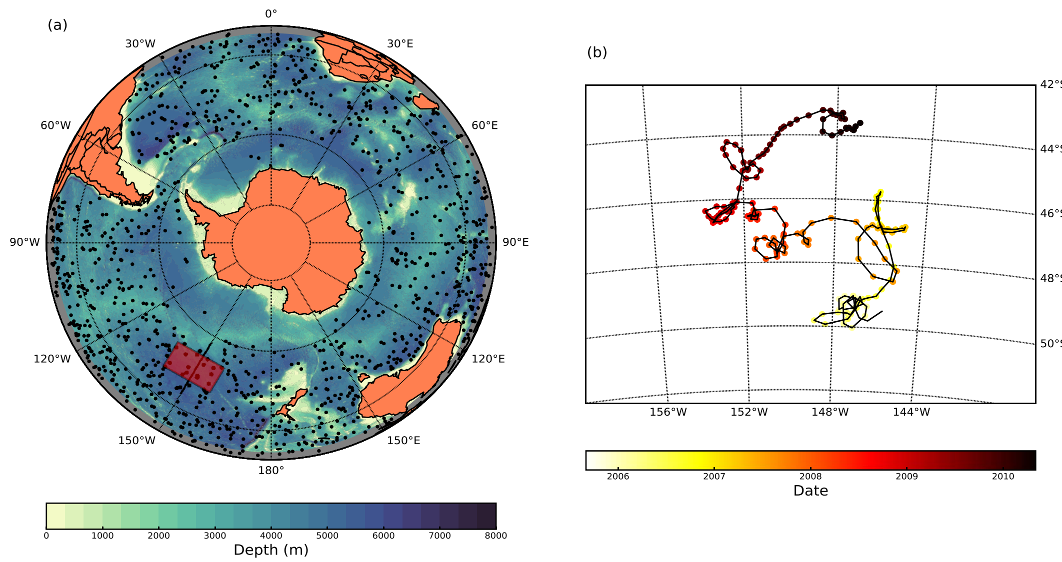

Fig. 1. Spatial coverage of Argo floats in the Southern Ocean. (a) All reported Argo float positions at 1000db, within 5 days of the 25th of December, 2009 (points), overlayed over the topography from the ETOPO01 dataset (colored contours); (b) zoom on the highlighted region in panel (a), showing the trajectory of float # 5900777 from the 26th of April 2005 to the 26th of December 2009.

array of these floats have in order to resolve the oceanic meso-scale?

Argo floats, by their design, present several challenges for the accurate measurements of deep currents. Argo floats must resurface to transmit their data, leaving the currents inferred from their displacement subject to errors such as delays in the surface location fix, shear in the water column and surface drift (Ollitrault and Rannou, 2013). Although a substantial amount of work has been undertaken to determine and control these errors in the measurement, less work has been devoted to understanding the limitations of sampling and the sampling density, particularly when compared with the large amount of work undertaken to understand the limitations of the surface drifter array (Davis, 1982; 1987; 1991a; 1991b; LaCasce, 2008). Surface drifters and Argo floats have several substantial differences in their sampling characteristics. Due to the fact that surface drifters do not need to complete a dive cycle, they report a position fix every 1-–2 hours (Elipot et al., 2016), which is much more frequent than the standard Argo position fixes of once every 5–15 days (with the vast majority of floats reporting a position every 10 days). Additionally, the surface drifter dataset has far denser sampling statistics than the Argo array. As such, work performed using surface drifters may not translate directly to Argo floats.

In this study, we use a combined empirical/observational approach to study the influence that sampling, both spatial and temporal, have on the ability to reconstruct deep flows and the eddy fluxes associated with meso-scale motions, treating the Argo float array as a array of "moving current meters" (Davis, 1991b). To do this, we will use a an idealized Observing System Simulation Experiment (OSSE). OSSEs have become relatively common in climate science since the 1980s (Hoffman and Atlas, 2016). The basic principle of an OSSE, described in Hoffman and Atlas (2016), is to take the output of a numerical model as the "truth" and then sample this output with synthetic observations. With the luxury of knowing the "truth" from the numerical model, the utility of synthetic observing system can then be rigorously evaluated.

We will study the errors associated with the length of time between dive and resurfacing of the floats, the spatial density of the Lagrangian array and the duration of the float experiment will be in place by systematically modifying the density and time span of the virtual float array, as well as the sampling characteristics of the float derived velocities. Specifically, an idealized, eddy resolving numerical model of the Southern Ocean is "observed" using "virtual" Argo floats. By comparing the Lagrangian derived estimates of mean velocity, eddy kinetic energy and heat flux to the "exact" results from the model solution, we will demonstrate the utility and shortcomings of these Lagrangian measurements. We will then use the understanding of the limitations of the Lagrangian derived velocities gained from the model output in order to estimate the eddy heat flux in the Southern Ocean from the existing array of Argo floats. We limit our focus to the Southern Ocean for two primary reason: it is the principle region of study for both authors of this paper; and the lack of available "traditional" observations from ships means that a detailed investigation of the Argo floats' capacity to resolve meso-scale statistics is warranted. However, the results obtained here are expected to apply quite generally.

The capacity of the Argo array to effectively represent important oceanic variables, including current velocity, has already been subject to several OSSEs. For example, Kamenkovich et al. (2011) used a "virtual" Argo float array, designed to resemble the Argo array as it was at the time of publication, to sample the output of a numerical model of the North Atlantic. The virtual Argo float array performance was assessed in two model configurations: with and without mesoscale variability present. Kamenkovich et al. (2009); 2011) found that the presence of mesoscale eddies had a profound effect on the virtual Argo array's data coverage, as eddies tend to efficiently disperse floats, leading to broader spatial coverage. Puzzlingly, they find that poor data coverage is not consistently correlated with high reconstruction errors. In contrast, errors are generally higher in regions dominated by strong advection, such as the western boundary currents and the ACC. Focusing on the Southern Ocean, Majkut et al. (2014) used a virtual array of Argo floats equipped with biogeochemical sensors sampling output from the GFDL-ESM2M climate model to demonstrate the potential for these floats to provide useful data from the real ocean, and to suggest sampling strategies for future deployments. Roach et al. (2016) used virtual Argo and RAFOS arrays, advected in the data assimilating Southern Ocean State Estimate (SOSE) model to assess the fidelity of estimates of lateral diffusivity calculated with the real Argo array. However, to our knowledge, no study has investigated the influence of float sampling, array density or experiment time-span on the resulting reconstruction error, nor have the capacity of Argo floats to estimate quadratic quantities, such as heat flux, been rigorously assessed. In this paper it is our intention address these topics.

The remainder of this article is organized as follows: Section 2 discusses the spatial and temporal sampling characteristics of Argo floats and the effects of each on the estimation of underlying flow fields.