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# Potential outcomes of glider data assimilation in the Solomon Sea: Control of the water mass properties and parameter estimation

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ABSTRACT

Steerable underwater gliders are a recent addition to ocean observing systems. Gliders were deployed in the Solomon Sea to improve our knowledge of this potentially important region for Pacific climate. In this study, we explore the potential use of glider data assimilation to control some properties of the ocean state estimation, chosen here to be Solomon Sea thermohaline misfits due to an erroneous tidal-mixing parameterization. Ocean observing system simulation experiments involving several scenarios of glider deployment show that the fleet design can strongly impact the control efficiency. A fairly good control of the Solomon Sea mass field can be achieved with a somewhat unrealistic fleet of 50 gliders. With a more realistic configuration of 10 gliders, the performance depends on the space and time distribution of the vehicles. Substantial control is achieved when glider trajectories are coordinated to collect information-rich data. As a complement, glider data assimilation was used to directly correct the model: the uncertain tidal mixing parameter is estimated through assimilation of data provided by the 10 coordinated gliders using an ensemble simulation method. This promising strategy allows an accurate estimation of the parameter and therefore yields an efficient correction of the errors in Solomon Sea thermohaline properties.



## 1. Introduction

Ocean observing systems have been tremendously enhanced in the last two decades, in particular thanks to the advent of satellites dedicated to the observation of the ocean in the 1990s (especially altimetric satellites such as Topex/Poseidon, ERS, Envisat, Jason1-2) and to coordinated programs of profiler floats (such as ARGO) in the 2000s. Still, oceans clearly remain largely underobserved. Therefore, a major issue for oceanography from both research and operational points of view is an improvement of the existing observing systems and development of new means, or even new concepts, of oceanographic observation.

Among the recently developed ocean observing systems, gliders offer rich opportunities (Testor et al., 2010), especially in coastal regions, mainly because their technology is relatively simple, inexpensive and allows piloting (which is the basic advance of gliders over floats). The fundamental concept of gliders was suggested by Stommel (1989), who described them as floats that *"migrate vertically through the ocean changing ballast … steered horizontally by gliding on wings …broach the surface six times a day to … transmit their accumulated data and receive instructions telling them how to steer through the ocean … [at a] speed [of] generally half a knot."* We refer the reader to Rudnick et al. (2004) for more details on glider technology. These autonomous underwater vehicles notably provide high-resolution along-track temperature and salinity data.

At the same time, ocean general circulation models (OGCMs) have benefited from major developments and become essential means to understand and study the ocean dynamics, and also to integrate observations through data assimilation. One application of data assimilation is to study or even optimize the potential use of observing systems by simulating the corresponding observations. Such experiments, called Observing System Simulation Experiments (OSSE), have originally been developed for meteorological studies (e.g., Arnold and Dey, 1986) and extended to oceanic purposes in many circumstances (e.g., Oke et al., 2009; Ubelmann et al., 2009). One fundamental principle of OSSEs is to assume that the control simulation, also called the "true ocean", is realistic and representative of the real ocean. Observations are extracted from this control run, using space and time distributions of observations as close as possible to the real ones. In the case of gliders, extracted data consist of vertical profiles of temperature and salinity down to several hundreds of meters and the extraction is performed along the gliders' trajectories. These synthetic observations are used via data assimilation to constrain another numerical simulation that differs from the control one through the presence of error sources. Typically, error sources in the simulated ocean are related to forcings, uncertainties in parameterizations, or even simply to the initial conditions of the simulation because of the intrinsic non-linear and chaotic behavior of the ocean.

In this context, the essential purpose of the present study is to explore the potential outcomes of glider data assimilation in the specific

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OSSEs methodological framework on one hand to control numerical simulations according to different simple deployment scenarios of glider fleets and on the other hand to estimate key parameters of physical processes parameterized in OGCMs.

The choice of the region of study has been primarily motivated by the investigations currently carried out in the Solomon Sea region under the framework of the international SPICE[1] program endorsed by the World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR). The Solomon Sea is suspected to be a region of climatic importance since the South Pacific low-latitude western boundary currents (LLWBCs) transit through this basin, located north of the Coral Sea, before joining the equatorial region (Fig. 1). These LLWBCs are seen as a major contributor to the Equatorial Undercurrent (EUC) and to the equatorial cold tongue by both observational (Tsuchiya, 1981; Tsuchiya et al., 1989) and model tracer studies (Blanke and Raynaud, 1997; Fukumori et al., 2004). With the South Pacific being a source of decadal variability (e.g. Giese et al., 2002; Holland and Raphael, 2006; Luo et al., 2003), the connections between the subtropics and the tropics through the western boundary route of the South Pacific are thought to play a major role in El Niño–Southern Oscillation (ENSO) low-frequency modulation. Despite its importance in understanding climate variability, until recently few studies have focused on the Solomon Sea because of the lack of observations and the difficulty of modeling a region of such complex bathymetry. Using historical data, Fine et al. (1994), Sokolov and Rintoul (2000) and Qu and Lindstrom (2002) investigated the water masses in the western South Pacific. Recently, the mean thermocline circulation in the Solomon Sea and its annual cycle have been analyzed using a numerical simulation (Melet et al., 2010a) and SADCP data (Cravatte et al., 2011). The surface circulation and sea level variability were analyzed using altimeter data (Melet et al., 2010b). Climatological equatorward pathways of Solomon Seawater and modifications in the corresponding water masses were diagnosed in a Lagrangian framework using numerical simulations (Melet et al., 2011, hereafter M11).

To improve our understanding of this remote and poorly observed region, data are being collected notably with a program of repeated glider surveys since 2007 that will be sustained for the next few years. The complex bathymetry and strong currents of the Solomon Sea provide further incentive for exploring this region with flexible devices, such as gliders, whose horizontal positions are, to a large extent, controlled. Indeed, other means of observation encounter different difficulties: standard altimetric products are hampered by the complex geography and presence of many coastal regions and islands so that a specific reprocessing of altimetric data is needed in these regions (Melet et al., 2010b); classical profiler floats cannot be steered so that damage risks related to the strong regional currents preclude an even slightly synoptic data coverage; direct in-situ observations via oceanographic cruises are difficult in this remote region; relatively few XBT lines provided by ships of opportunity cross the Solomon Sea, etc.

Among the uncertainties in current OGCMs parameterizations particularly relevant for the Solomon Sea, the ones associated with the vertical turbulent mixing associated with the breaking of internal tides represent a notable source of errors. Indeed, strong tidal energy dissipation occurs in this region, as shown by different observational (Egbert and Ray, 2000) and numerical studies (Arbic et al., 2004; Jayne and StLaurent, 2001; Niwa and Hibiya, 2001; Simmons et al., 2004), which may lead to enhanced mixing. Incidentally, it has recently been shown that including a parameterization of the mixing induced by internal tides in the Solomon Sea yields significant modifications in the mass field (M11), in better agreement with observations (CARS climatology, Ridgway et al., 2002). Therefore, we chose

[1] Southwest Pacific Ocean Circulation and Climate Experiment program, available online at http://www.clivar.org/organization/pacific/pacific_SPICE.php.

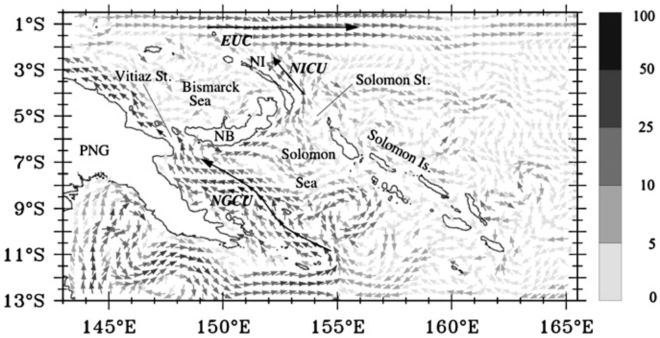


**Fig. 1.** Solomon Sea velocity field (cm/s) averaged between 0 and 600 m in the $1/12^{c}irc$ model for January, 1993. PNG stands for Papua New Guinea, NB for New Britain, NI for New Ireland.

to define the source of error in our idealized experiments to be the intensity of the vertical turbulent mixing due to the breaking of internal tides. This proved to be a significant source of misfits for the corresponding modeled circulations and a quite relevant error to be controlled. In addition, mixing is not easily accessible from observations although it is a key parameter of ocean models. The prospect of being able to estimate this parameter with data assimilation is therefore quite promising.

The main objectives of the present study are therefore to exploit two complementary data assimilation possibilities in an OSSE framework for glider observations in the Solomon Sea, consisting of:

- A direct exploration of several scenarios of more or less idealized deployment of fleets of gliders to assess their ability to control the water mass thermohaline characteristics.
- A direct estimation of uncertain parameters, chosen here to be related to the internal-tide driven mixing, by introducing the error or one of its components in the control vector of the assimilation scheme.

The paper is organized as follows: First, the methodology is presented in Section 2, with in particular the development of a new multigrid data assimilation methodology. In Section 3, the potential control of the mass field errors through glider data assimilation is assessed in different scenarios to address the following issues: What is the impact of the number of gliders and of the possibility to pilot them? In Section 4, we take advantage of the idealism of the experiments and of the functionality of the data assimilation method to introduce model error in the control vector. Since the source of error is known to be the value of the parameter of the mixing related to internal tides, can this parameter be estimated by assimilating glider data? Conclusions and perspectives are provided in Section 5.

## 2. Methodology

As indicated previously, the capability of glider data to control model errors is assessed in the following by performing several OSSEs whose characteristics are detailed in Table 1. The relevance and structure of the misfits introduced in the false ocean, compared to the control simulation, through uncertainties of the tidal mixing parameterization will be discussed in the next section. Because the control run is perfectly known in the rather idealistic OSSE experimental context, it is possible to assess the efficiency of the observing system and to optimize the deployment of the sensors and the complementarity of data.

To implement these OSSEs, a proper numerical configuration set up is needed, which includes a validated numerical simulation, a data assimilation methodology and a methodology to represent or mimic the data sampling in a realistic way.