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Salinity drift of global Argo profiles and recent halosteric sea level variation

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ABSTRACT

A salinity sensor drift in the Array for Real-time Geostrophic Oceanography (Argo) float has been identified. In the present study the salinity calibration results for global Argo floats indicate that an upper 900 dbar averaged-positive salinity drift appears during the floats' operating period from January 2001 to December 2010. These offsets are shown to cause an uncertainty in the estimate of the steric height anomaly of up to 17 ± 5%. Based on a multi-grid, three-dimensional, variational method we construct monthly gridded salinity fields using post-calibration Argo salinity profiles for the period 2003–2010. Monthly time series of halosteric height (HSH) for both the global and regional oceans are calculated using gridded salinity fields over the entire 8 years. It is shown that there is a global HSH pattern with a 0.05 ± 0.03 mm/year trend of increasing HSH anomaly relative to the World Ocean Atlas (WOA) 2001 in the upper 900 dbar. Most regions of the North Atlantic Ocean show predominately inter-annual and decadal fluctuations in the HSH anomaly over the observational period. These fluctuations are associated with the Atlantic Oscillation (AO) and/or the Atlantic Multi-decadal Oscillation (AMO). For the Pacific Ocean, inter-annual variability of the HSH anomaly in the Equatorial Pacific Ocean is modulated mainly by the El Niño/Southern Oscillation (ENSO) phenomenon while in the subtropical Northern Pacific Ocean, the wet, cold phase of the Pacific Decadal Oscillation (PDO) modulates the variability of the HSH anomaly, contributing to a positive anomaly observed over the 8 years. For the Indian Ocean, both ENSO and the Indian Ocean Dipole (IOD) influence the inter-annual variability of the HSH anomaly in the Equatorial Indian Ocean. In addition, HSH trends of sub-basin regions are also investigated. We find the most pronounced positive trend occurred in the tropical and subtropical regions of the Southern Indian Ocean with HSH increasing by 0.55 ± 0.08 mm/year, while the most remarkable negative trend occurred in the tropical and subtropical regions of the North Atlantic with HSH decreasing by −0.44 ± 0.04 mm/year.

1. Introduction

Argo floats are deployed to drift freely at a pre-defined parking depth. They are designed to measure temperature, salinity and pressure profiles during each ascent to the sea surface, which occurs roughly every 10 days. At the sea surface they transmit their measurement information by satellite, and then return to their parking depth. Unlike traditional CTD instruments, where in-situ bottle data are usually obtained to enable calibration of the salinity sensor, these floats do not capture independent salinity data for use in calibrating the primary salinity sensor. Argo salinity measurements suffer from sensor drifts and offsets due to bio-fouling (Freeland, 1997), cell contamination (Oka and Ando, 2004), or other technical problems. Unfortunately, it is difficult to calibrate their CTD sensor once deployed in the ocean. In addition, due to the observational nature of these floats, it was determined that only a few can be re-captured and returned to the laboratory for salinity sensor re-calibration. Consequently, various efforts have been made to develop calibration methods utilizing nearby historical hydrographic data. Wong et al. (2003, hereafter referred to WJO) developed a method that can systematically evaluate and correct Argo salinity data with respect to historical data through objective mapping techniques. Böhme and Send (2005; hereafter referred to BS05) found that the WJO method failed in highly variable environments and that it can be substantially improved in regions where the flow is bathymetrically controlled. Their new method, which is largely based on the WJO method, greatly improves the correction in the North Atlantic Ocean. However, the density of the reference database remains a key limiting constraint on this method (Kobayashi and Minato, 2005). When these algorithms are applied to floats drifting in regions with very sparse historical CTD data, such as the Southern Ocean, these existing methods either introduce large errors or provide no estimated correction. Errors are also increased when the float is close to strong hydrological fronts such as the Sub-Antarctic

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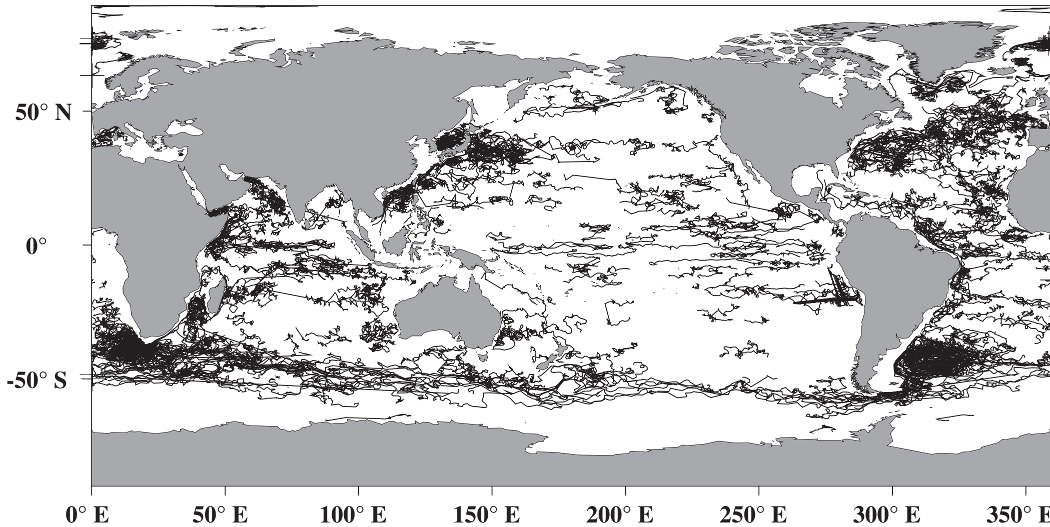

Fig. 1. The spatial distribution of Argo profiles which possess salinity offsets exceeding 0.05 psu during the 2001–2010.

Front in the Southern Ocean. Due to the specific physical attributes in the front region, the existing calibration methods need further improvement. As a result of the significant improvements introduced by the BS05 technique, Owens and Wong (2009; hereafter referred to OW) developed a hybrid correction method merging both the WJO and BS05 methods. The improvements are made in three ways: (1) A piece-wise linear fit is used to estimate the temporally-varying, multiplicative adjustment to the float's potential conductivities; (2) an objective, statistical method is used to choose the breakpoints in the float time series where there are multiple drift trends; and (3) potential vorticity has been added as an optional weighting function that can be switched on and off by users depending on which basin they work in. The OW hybrid method is a comprehensive method, which is now freely available and provides good correction in most parts of the world ocean.

As a part of climate variability studies, Argo data is widely applied to the study of sea level variation. They have been used together with historical hydrographic datasets, the Gravity Recovery and Climate Experiment (GRACE) and altimeter measurements in an attempt to quantify global sea level rise (e.g., Church et al., 2004; Lombard et al., 2007; Willis et al., 2008; Cazenave et al., 2009; Chang et al., 2010). These studies require very high-quality data since the signals of interest are of very low amplitude and are highly sensitive to biases or errors presented in the dataset. Although the Argo array's spatial density does not adequately resolve mesoscale features such as fronts and eddies, Argo does provide an opportunity for estimating regional and global steric sea level changes attributable to temperature and salinity variations in the upper 2000 m of the ocean. However, accurate calibration of the Argo temperature and salinity data is critical for the analysis and prediction of climate change. Recently, a large-scale cold bias found in the Argo data, related to a systematic pressure sensor error, was described by several studies (Lyman et al., 2006; Willis et al., 2007, 2009). This cold bias caused an artificial negative bias on the estimate of the steric height, which distorted the evidence for climate change. In addition, Chang et al. (2009) argued that many floats with artificial salinity offsets have not completed their delayed mode quality control at their respective Data Assembly Centers. This suggests that it is necessary for the complete corrections of salinity sensor drift to be fully incorporated into any research and analysis using Argo data.

An increase of sea level associated with steric expansion has been observed in the Pacific and Atlantic Oceans (e.g., Antonov et al., 2005; Douglass et al., 2006; Cummins and Freeland, 2007) and in the Southern Ocean (e.g., Lombard et al., 2007; Willis et al., 2007). In marginal seas, the contribution of steric component has also been analyzed for the South China Sea (e.g., Cheng and Qi, 2007, 2010). It is worth noting that knowledge of the salinity variability is important to understand observed satellite derived sea level variations, especially in regions where the halosteric component plays a dominant role (Antonov et al., 2002; Munk, 2003). Antonov et al. (2002) indicated that global freshwater changes also

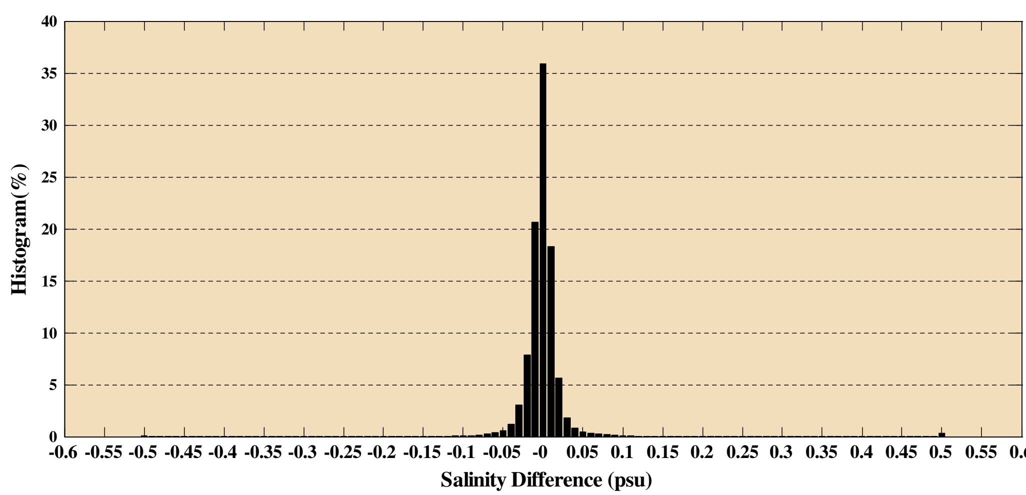

Fig. 2. The histogram of the upper 900 dbar vertical-average salinity difference between pre-calibration and post-calibration for all Argo profiles during the period of 2001–2010.