Decadal changes in ocean properties revealed by ARGO floats

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[1] This paper demonstrates that CTD data from autonomous profiling floats can be used to detect basin-scale changes of water properties on decadal, and potentially shorter, timescales. In the western Indian Ocean at 32°S, the properties of Subantarctic Mode Water have changed such that between 1987 and 2002, salinity has increased by 0.04 at certain temperature levels. Although in this case detailed and high-accuracy data are available from a research cruise, we demonstrate that floats have the following value: real-time float data are of sufficient accuracy to reveal changes in ocean properties on timescales of a decade or less; floats achieve spatial and temporal coverage not possible with research ships, providing vital supporting evidence for the interpretation of cruise CTD data. Floats therefore provide a mechanism for monitoring changes during the interval between dedicated research cruises and for identifying areas in which further cruises are likely to be fruitful.
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1. Introduction

[2] The international Argo program (www.argo.net) currently has more than 1500 floats operating across all ocean basins. Each float carries a CTD, and on a pre-set cycle, usually 10 days, reports a temperature and salinity profile from the ocean surface down to a maximum depth of 2000 metres. Some floats have a lesser maximum depth and some floats visit that depth only on a subset of profiles with intermediate profiles being shallower. Argo data are freely available on internet sites, usually within 48 hours of acquisition. The data discussed in this paper were collected up to May 2003 from the first Argo floats deployed in the subtropical Indian Ocean; these floats profile to 2000 metres every 10 days.

[3] The UK Argo program has deployed 30 Argo floats in the vicinity of 32°S in the Indian Ocean. Five floats were deployed opportunistically in 2001 and 25 more on RRS *Charles Darwin* Cruise 139 in March–April 2002 [*Bryden et al.*, 2003a]. Hardware faults, now identified and rectified in subsequent instruments, have led to a number of premature failures within the first 15 profiles. Of the original 30, 16 floats were working well after 12 months.

[4] In this paper we compare float data with shipboard CTD data from two research cruises on RRS *Charles Darwin*. Cruise 28 in November 1987 [*Toole and Warren*, 1993] and Cruise 139 in March/April 2002. Each cruise occupied a section from Durban to Fremantle. Comparison with the 2002 data will show the quality and accuracy of the float data. Comparison with the 1987 data will show how the ocean changed in the intervening 15 years. We focus on changes in the large volume of Subantarctic Mode Water that exists at 9–13°C in the South Indian Ocean thermocline.

2. Data

[5] Figure 1 shows the two cruise tracks and the tracks of 23 floats from which data are discussed below. West of about 80°E the two cruise tracks were identical. East of 80°E the 2002 cruise followed a track south of Broken Plateau, a topographic feature rising to within 1000 metres of the sea surface, and which presented problems to analysis of the 1987 data. After deployment (on the 2002 cruise) some floats have migrated by up to 500 km in latitude. Data from these floats will allow us to assess the meridional variability of water mass properties.

[6] Figure 2 shows two θ-S diagrams, divided at 80°E. The float data show plenty of scatter in the upper ocean: to be expected since the data span a complete seasonal cycle. At around 12°C the curve is tight: we are sampling a large and homogeneous reservoir of thermocline and mode waters. At 4 to 5°C we see the salinity minimum of Antarctic Intermediate Water. In Figure 2a there is scatter at this depth (900 to 1200 metres), which comes from mixing with much saltier Red Sea Water [*Beal et al.*, 2000]. In Figure 2b there is variability at the depth of Indian Deep Water, which is found at about 1500 metres with a nitrate maximum and an oxygen minimum.

[7] We concentrate our analysis on the tightest part of the θ-S curve, which is the Subantarctic Mode Water (SAMW), and examine salinity at the SAMW minimum of potential vorticity (PV). The properties of the PV minimum in the 1987 and 2002 section data were examined by *McDonagh et al.* [2005]. Here we use the gross structure of potential temperature of the PV minimum from those data sets and centre our analysis at the θ = 13°C isotherm from Africa to 70°E, moving linearly to 11°C at 80°E and 9°C at 112°E. We show that at this depth the changes in ocean properties are homogeneous over large spatial scales and that decadal variability is significant compared with interannual variability.

[8] Figure 3 summarises the CTD data from the two cruises and from the floats. The values are changes with respect to 1987 CTD station data, plotted at the longitude where floats were deployed. Note that there is always a 2002 CTD station at a float deployment. All CTD and float salinity data are interpolated onto potential temperature levels. Figure 3 was obtained as follows: CTD stations for 1987 and 2002 were identified that fell within a three degree longitude window, centred on the location of the first profile of each float. Typically this would include between four and

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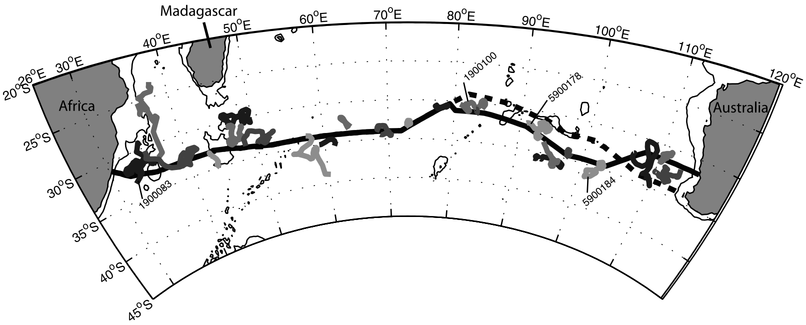

Figure 1. Tracks of 1987 (dashed line) and 2002 (solid line) cruises. Float tracks are shown in shades of grey. The 2000 metre depth contour is also shown. Some floats are identified by World Meteorological Organisation (WMO) number.

six stations from each CTD section. We include all data from each of the floats, regardless of latitude, providing between 10 and 50 profiles. For each float deployment location, the 1987 stations are averaged to provide a θ-S reference profile. Each station or float profile is compared with the appropriate reference, and described by a single mean salinity offset in a 1°C window centred on the SAMW reference temperature. At each deployment location, the collection of single-profile offsets are displayed as a mean and standard deviation, shaded according to data source.

[9] Consider the possible sources of error. The errors in individual shipboard CTD profiles, which have been adjusted to high-quality salinity bottle data, can be assumed to be significantly smaller than 0.01. Thus the spread in the dashed or solid black bars represents ocean spatial variability. The spread in the float data (grey bars) represents the combination of ocean space and time variability, and float CTD sensor drift. The most likely cause of offsets between grey and solid black bars is float salinity offsets. We note that east of 80°E, nearly all floats appear to be fresh compared with cruise CTD data, by an amount 0.01 to 0.015. No such bias is apparent west of 70°E. Since we present unadjusted float data, exactly as reported by the instrument in real time, a bias of this magnitude in the sensor data is not impossible. However since the floats were all from the same manufacturing batch, it seems odd that the bias should have such a clear geographical distribution. We note also that the temperature surface on which the offset is determined changes by 4°C east of 70°E, and the reference salinity on that surface changes by more than 0.50. It is possible therefore that our technique for selecting data, while consistently applied to all three datasets, has aliased the background gradient to produce an artificial bias between the 2002 float and cruise data in the eastern basin. In the western basin, the reference salinity on θ = 13°C increases smoothly by 0.02 between 35°E and 70°E, which is small compared with the decadal changes. We emphasise that horizontal (especially east-west) gradients have been

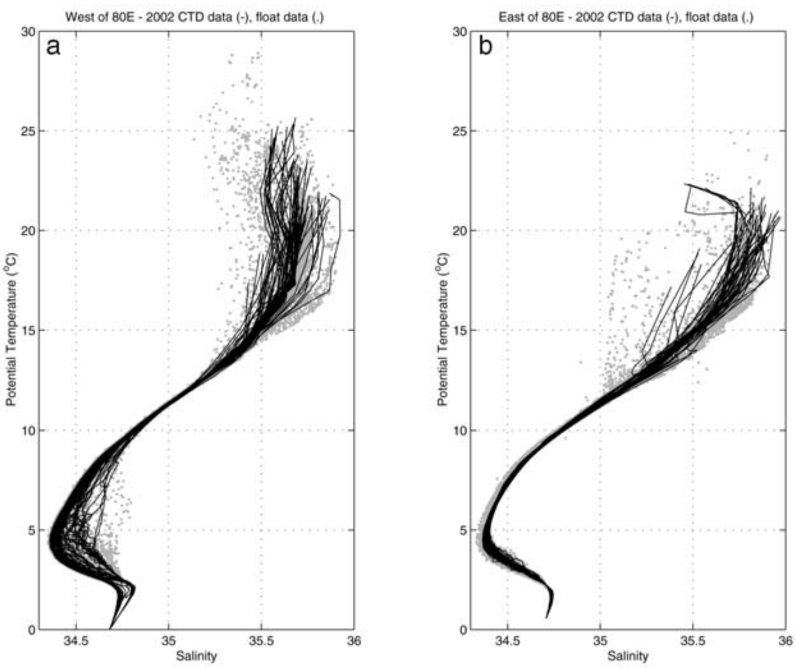

Figure 2. Potential temperature vs. salinity diagrams for float profiles (grey dots) and 2002 cruise CTD profiles (black lines). (a) Floats deployed west of 80°E. (b) Floats deployed east of 80°E.

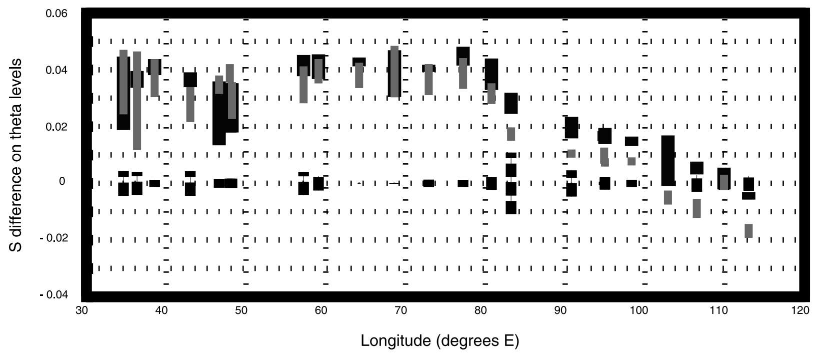

Figure 3. Mean offset and standard deviation of salinity on an isotherm at depth of Subantarctic Mode Water stratification minimum. Changes since 1987. Key is dashed line: 1987 cruise; solid black: 2002 cruise; grey line: floats. For details of calculation, see text.

dealt with by simple averaging, rather than linear interpolation or a more sophisticated objective mapping. Procedures that make better allowance for such gradients are being developed as part of the Argo Delayed-Mode Quality Control (DMQC) system, and are being implemented at DMQC centres during 2005. Application of such procedures during the DMQC process will reveal whether the difference between float and 2002 CTD data east of 80°E in Figure 3 is real, or an artefact of sampling or instrumental bias.

[10] The challenge of providing a delayed-mode calibrated float data set remains a topic of current research. Systematic application of procedures agreed at the Argo DMQC workshop held in April 2005 will lead to greater confidence in the absolute accuracy of float data. Only one float, 5900184, had a salinity sensor which shows obvious drift in its early data: it is drifting towards fresher values. Accordingly, we take only the first 10 profiles, which appeared to be stable.

[11] It is immediately apparent that at this PV minimum, the 2002 data are up to 0.04 more saline than the 1987 data on isotherms, and that this change is highly uniform at the western end of the section. As the temperature of the PV minimum decreases east of 80°E the salinity difference at the PV minimum also decreases. This is consistent with the study of *McDonagh et al.* [2005] that considered the changes between the 1987 and 2002 CTD data over the temperature range 5 to 17°C in more detail. They found that the maximum change across the eastern end of the section occurred everywhere at the temperature of the warmest mode water rather than at the PV minimum. However, the floats add significantly to the description of the changes. When comparing two zonal CTD sections, there is always the question of latitudinal variations. Are we seeing a genuine decadal change, or a combination of advection and a north-south gradient? Furthermore, east of 80°E the sections do not coincide. However, the latitudinal dispersion of the floats shows that, at least over 5 degrees of latitude, latitudinal variation is small compared with changes between the 1987 and 2002 sections. Conveniently, floats 1900100 at 82°E and 5900178 at 92°E span the 1987 and 2002 cruise tracks.

[12] Furthermore, the float data span 12 months since the deployment cruise: variability at this depth over this timescale is again small compared with the decadal change. We emphasise that the one standard deviation scatter on the float data includes variability from all sources: ocean time and space variability as well as instrument relative error within profiles and instrument temporal sensor drift.

3. Conclusions

[13] Some of the decadal changes reported in greater detail by *McDonagh et al.* [2005] from the 2002 CTD station data can equally well be inferred from float data. Indeed, the changes on the western part of the CTD section were noticed before the cruise from float 1900083, deployed in August 2001. In this case, the cruise was already planned before the floats revealed the ocean changes. However, in other ocean regions it is very likely that decadal changes revealed by float data will enable further investigation by research cruises developed in response to float results. Use of float data to measure interannual variability and longer-term trends will indicate the timescale on which it is appropriate to revisit oceans with more comprehensive measurement techniques.

[14] As pointed out in the discussion of Figure 3, the float data supplement the CTD data by revealing that neither interannual nor latitude variability are responsible for the changes observed on the section. This makes the result from the analysis of CTD data incontrovertible. Furthermore, floats will continue to monitor changes on this section. McDonagh et al.'s analysis includes identifiable changes since 1995, a period of just seven years. Such changes can now be determined using floats in the Argo program.

[15] The real-time data from this batch of floats provides salinity with an absolute accuracy of order 0.01, sufficient to detect these quite small ocean changes. We note in passing that this region of the Indian Ocean was identified by *Banks et al.* [2000] as an area in which anthropogenic climate change runs of a coupled climate model HADCM3 produced a large signal to noise ratio. The low spatial and interannual variability revealed by the float data makes this a favourable area for detecting small ocean trends on decadal time scales. Comprehensive discussion of the trends and oscillations revealed by CTD and bottle data over the period from 1936 to the present is provided by *Bryden et al.* [2003b] and *McDonagh et al.* [2005].

[16] **Acknowledgments.** Support was provided by the Natural Environment Research Council under grant NER/A/S/2000/00438 (E.L.M.) and under the core strategic research project Ocean Variability and Climate (B.A.K.).

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