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Article

Water Masses and Flow Fields of the Southern Ocean Measured by Autonomous Profiling Floats (Argo floats)

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Abstract : Using data from Argo floats collected in the Southern Ocean, we describe water mass properties and flow fields at intermediate levels (1000 m and 2000 m levels). Water mass properties from Argo floats, which are consistent with those from previous hydrographic surveys, reflect the movement of the floats well even without quality control on the Argo data. Since the flow fields from the Argo floats do not cover the entire Southern Ocean, we could not obtain a general circulation pattern, especially at the 2000 m level. We, however, can confirm the general eastward tendency due to ACC largely following the topography.

Key words : Southern Ocean, Argo float, water mass, intermediate level flow

1. Introduction

The collection of high quality hydrographic data is technically and logistically demanding. Thanks to advances in float technology, the establishment of a real-time global ocean-monitoring network has become feasible. In 2001, in conjunction with the Climate Variability and Predictability (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE), the International Argo Program was launched. Through the program, a global array of floats was initiated. The main scientific goal of the Argo Program is to provide an enhanced real-time capability for measurement of temperature and salinity through the upper 2000 m of the oceans and to contribute to a global description of the seasonal cycle and interannual variability of the upper ocean thermohaline circulation (ARGO Science Team 2000).

Upon deployment at the surface, an Argo float dives down to a predetermined drifting (or parking) depth, which is not more than 2000 m as sketched in Fig. 1. After drifting with the flow at the parking depth for a fixed period time, which is usually set at 10 days, the float rises to the surface, measuring the temperature and salinity of the water through which it ascends with the CTD mounted on the top of the float. The ascending or descending motion of a float is induced by controlling its buoyancy using the bladder located at the bottom of the float and the hydraulic pump housed inside the float. At the surface, its location is determined by satellites, and the float transmits the hydrographic profile data to satellites repeatedly for about 10 hours. The float then dives down to the parking depth to continue another cycle. Satellites relay the data to land stations, where the data would be distributed to various users around the globe almost in real time.

Argo floats could be deployed from various vehicles including hundreds of commercial vessels and aircrafts. Once deployed, the floats continue to operate unattended as the name "autonomous float" suggests. Most of the data collected by Argo floats are managed by Global Data Centers (GDAC) (ftp://ftp.ifremer.fr/ifremer/argo and ftp://usgodae1.fnmoc.navy.mil/pub/outgoing/argo) and are available through the Internet (Pouliquen 2002) almost in real time.

The Southern Ocean is known to play an important role in controlling the global thermohaline circulation and Earth's climate (Gordon 2001 for example). Nevertheless, the Southern Ocean is poorly understood compared to other parts of the global ocean, mainly due to the paucity

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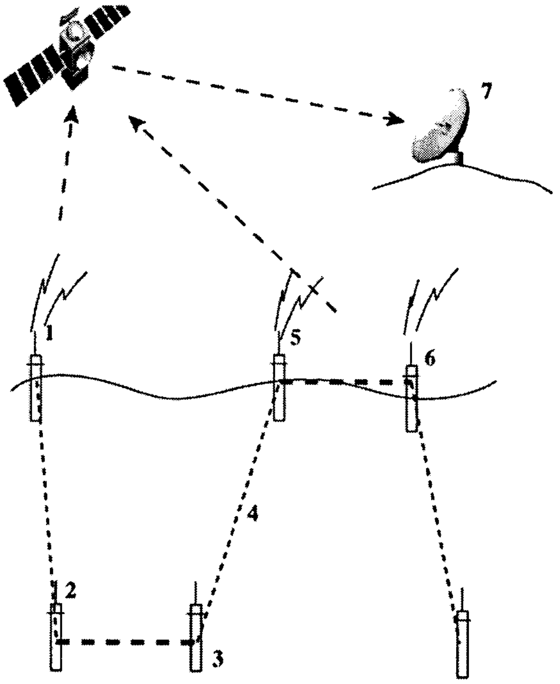

1. Float deployed by a ship or an aircraft.
2. Drift for preset days (about 9 days) with ocean currents.
3. Oil pumped from the internal reservoir to inflate the external bladder causing float to rise.
4. Temperature and salinity profile recorded during ascent.
5. Up to 12 hours at surface to transmit the data to satellite.
6. Oil pumped back to the internal reservoir and a new cycle begin.
7. Data sent to users.

Fig. 1. Operation cycle of an Argo float.

of observational data, especially during the Austral winter. Since Argo floats collect temperature and salinity profiles, and Lagrangian flow data irrespective of weather conditions easily, they can be useful in areas such as the Southern Ocean, which cannot be reached easily with research vessels.

Since 2001, KORDI has participated in the International Argo program and deployed Argo floats into the East Sea and the Southern Ocean. Currently, only five countries including Korea have been deploying floats into the Southern Ocean and the number of floats operating in the Southern Ocean is quite small compared with that from other oceanic zones. Therefore, our efforts for the Southern Ocean have been useful in providing valuable data to the international community.

In this paper, we describe the intermediate level circulation pattern, and temperature and salinity distributions in the Southern Ocean using data from Argo floats. In addition to the Argo data from the KORDI Argo floats, data from other nations participating in the International Argo Program are utilized. The structure of this paper is as follows. In Section 2, we describe data, and data acquisition. In Section 3, velocity fields from drift data at 1000 m and 2000 m levels are described. In this section, water mass properties are also described. Brief summaries are given at the end.

2. Data

We have downloaded data collected to the south of 30°S from GDAC's and utilized them in this paper in addition to the data from the KORDI Argo floats, most of which, of course, are available at GDAC's.

Once floats are deployed, it is almost impossible to retrieve the float and calibrate the CTD. Therefore, the accuracy of salinity is one of the main issues in Argo data. If we are interested in interannual variations or a precise classification of water masses, we might have to go through a precise calibration. In this study, we intend to describe water masses along with flow patterns observed by the Argo floats in general, and we do not need to go through such a calibration. In fact, Oh *et al.* (2004) showed that the accuracy of salinity measured by recent Argo floats could be better than 0.01 psu without any calibration.

3. Results

Flow fields

Since we cannot track floats once they dive down below the surface, we cannot determine the trajectories at the parking depths directly. When we estimated velocities at the parking depths from each float, we crudely assume that the last known location and the time before the dive (point 1 in Fig. 1) was the same as those found at the starting point of a drift at the parking depth (point 2 in Fig. 1), and the first known location and time after ascent (point 5 in Fig. 1) are the same as those of the final point of the drift (point 3 in Fig. 1). This, of course, is a crude estimate, because the float would drift while ascending and descending due to the ambient flows, but it has been shown that such a crude estimate served the purpose quite well (Johnson *et al.* 2004; Park *et al.* 2004). Since it is not easy to investigate the drift of the floats individually, we have divided the area into 3° by 3° bins and performed a bin average. During the average, the bins with three or more pieces of data are considered, and the resulting velocity fields at 1000 m and 2000 m levels are shown in Figs. 2 and 3, respectively. Since the velocity fields are

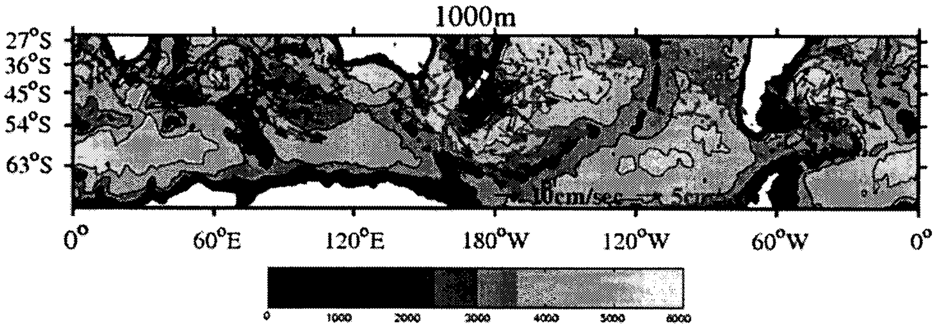

Fig. 2. Velocity fields at 1000 m estimated using 6657 velocity data from Argo floats. The color shading represents the bottom topography in the 1000 m interval.

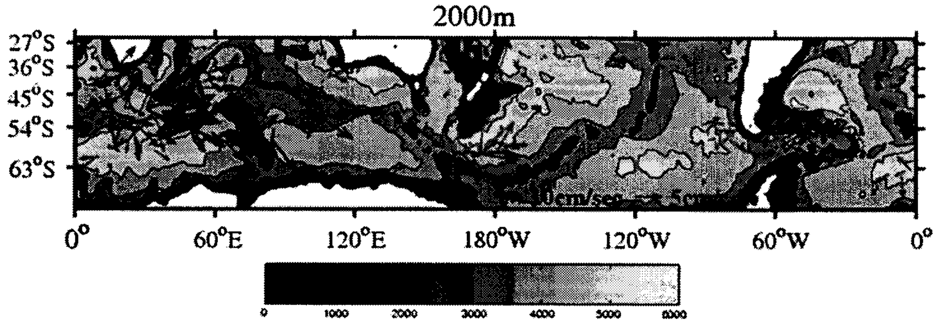

Fig. 3. The same as in Fig. 2, but at 2000 m with 2958 velocity data.

from Lagrangian drifters deployed at selected locations, the distribution of the velocity vectors is not even. Even though we do not have enough data to describe the general circulation pattern as in Gille (2003), the high variability of the Southern Ocean currents is well represented. For comparison, a schematic map of major currents in the southern hemisphere south of 20°S from Rintoul *et al.* (2001) is shown in Fig. 4.

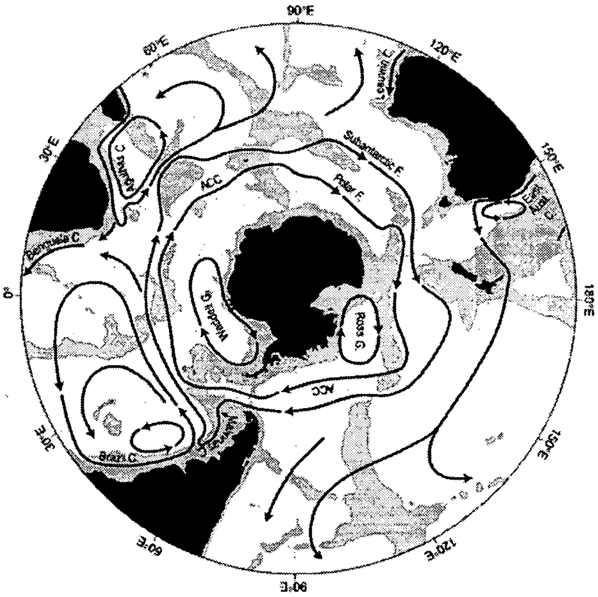

Fig. 4. A schematic map of major currents in the southern hemisphere oceans south of 20°S from Rintoul *et al.* (2001).

Fig. 2 shows that over the Indian Ocean, there is not much data in high latitudes to investigate the structure of the ACC clearly, but to the south of 45°S the water moves to the east mainly following the topography as also reported by others (Gordon *et al.* 1978; Chelton *et al.* 1990; Gille 1994, 2003). Around the tip of Africa, strong flows are observed. The flows must be associated with strong boundary currents (the Agulhas and Benguela Currents), but we do not have enough data to describe the structure of the flows clearly.

To the south of Australia, there is a flow following the 4000 m isobath between 50-70°S as the Polar Front. In mid-latitudes of the South Pacific (between 30-40°S) the flow is northward in general as the general wind driven circulation theory predicts (Pedlosky 1987). Estimating the interior meridional mass transport would be an interesting extension of this simple descriptive work. To the south of New Zealand, there is a northeastward flow

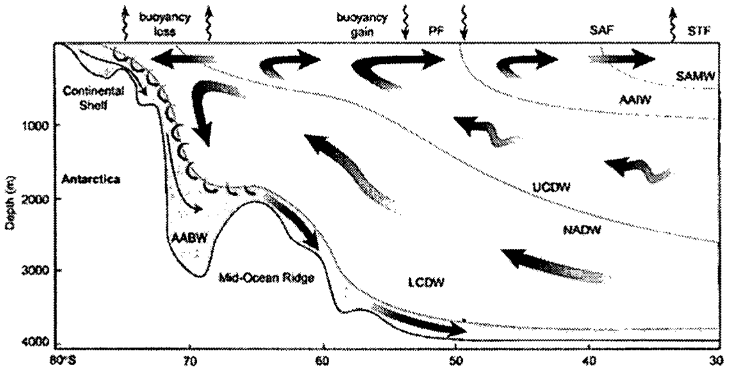

Fig. 5. Schematic of meridional circulation and water types in the Southern Ocean from Speer *et al.* (2000). AABW stands for Antarctic Bottom Water, LCDW Lower Circumpolar Deep Water, UCDW Upper Circumpolar Deep Water, AAIW Antarctic Intermediate Water, SAMW Sub Antarctic Mode Water, PF the Polar Front, SAF the Subantarctic Front, and STF the Subtropical Front.

following the 5000 m isobath as the Subantarctic Front, but there is not enough data to substantiate the flow clearly. Around New Zealand, the flow field is quite complicated and fast possibly due to the complex bottom topography.

Over the Atlantic sector, the subtropical gyre consists of the westward drift between 30°S and 34°S in the interior, and the southward Brazil Current along the western boundary as well known by the wind driven general ocean circulation theory (Pedlosky 1987). Between 45°S and 55°S, the Malvinas Current flows to the north along the western boundary and meets the Brazil Current leading to the large meridional excursion of the Subantarctic Front. At the Drake Passage between 55°S and 65°S, the flow is mainly eastward following the Polar Front although there are high spatial variabilities.

Most of the floats are configured to park at 1000 m-depth level, and only minor data are available at the 2000 m level. Even though it is hard to describe the general features of the flow pattern, it is clear that the eastward tendency is dominant to the south of 50°S as can be seen in Fig. 3. The individual trajectories, however, are useful in explaining water properties observed by the floats as described next.

Water mass properties

Since Argo floats provide hydrographic profiles, one can use Argo data to investigate water mass properties and their changes. In this section, we describe water mass properties in the Southern Ocean using the data obtained using the KORDI Argo floats. The data set comes from to the south of Australia and across the Drake Passage. To help make comparisons with earlier results, a schematic of meridional circulation and water type from Speer *et al.* (2000) is shown in Fig. 5.

A potential temperature and salinity (Θ-S) diagram using the profiles from the floats deployed to the south of Australia is shown in Fig. 6, and the trajectories of the floats at parking depths (2000 m) are shown in Fig. 7. In Fig. 6, the data from the floats that has (or had) been operated for more than 5 months with more than 15 profiles collected are presented here, but in Fig. 7 the trajectories of all the floats deployed to the south of Australia are shown. A Θ-S diagram and the trajectories from the floats deployed across the Drake Passage are shown in Figs. 8 and 9, respectively. In the Θ-S diagrams, we used the raw data, i.e., data without quality control. If we are to investigate changes in the water properties found downstream precisely, we might need to do quality control. Here, we are to identify the main water masses, and data collected without quality control serves the purpose well as can be seen from the Θ-S diagrams.

As shown in Fig. 6, to the south of Australia, the profiles from the southernmost float (WMO ID 5900475) show a strong signature for AABW in the deep layer, LCDW in the middle layer, and cold fresh waters at the surface as we can expect from Fig. 5. Since we do not have oxygen data, we cannot differentiate LCDW from UCDW clearly, however (Callahan 1972). Note that some of the profiles were taken during the Austral winter to the south of 65°S, which are very hard to obtain from a research vessel. As we move to the north, first AABW (WMO ID 5900471) and then LCDW (WMO ID 5900473) disappear at depth. In the surface layer, while the cold and fresh water disappears (WMO ID 5900471), SAMW starts to appear (WMO ID 5900473). In the middle layer,

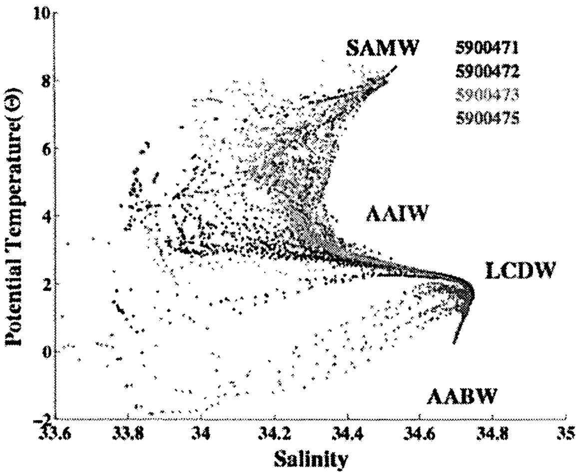

Fig. 6. Potential temperature and salinity (Θ-S) diagram using the profiles from the floats deployed to the south of Australia. The numbers represent WMO ID's of the floats. The data from the floats that have (or had) been operated for more than 5 months with more than 15 profiles collected are presented here. Acronyms are as in Fig. 5.

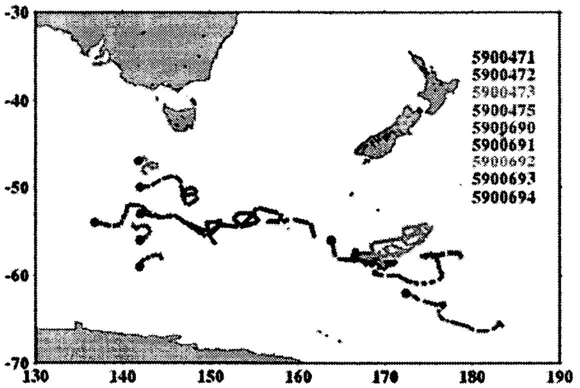

Fig. 7. The trajectories of the floats deployed to the south of Australia at the parking depths of 2000 m. Here the trajectories of recently deployed floats are shown in addition to those of the floats used in Fig. 6. The numbers represent WMO ID's.

AAIW emerges (WMO ID's 5900473 and 5900472) with the distinct salinity minimum as consistent with Fig. 6.

The profiles obtained across the Drake Passage also show water masses consistent with their trajectories and similar temperature and salinity distributions to those of earlier studies (Fig. 8). Profiles obtained further to the south show a stronger signature of AABW expectedly, and cold and fresh SAAW (Sub-Antarctic Water) near the surface. Compared to those deployed to the south of Australia, the profiles shown in Fig. 8 were taken further

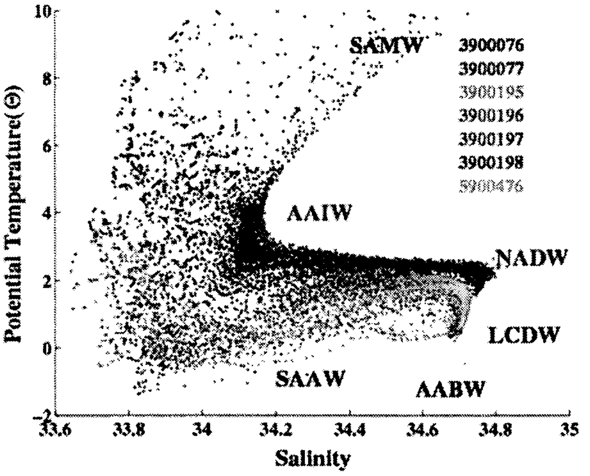

Fig. 8. The same as in Fig. 6, but for the floats deployed across the Drake Passage. Here SAAW stands for Sub-Antarctic Water.

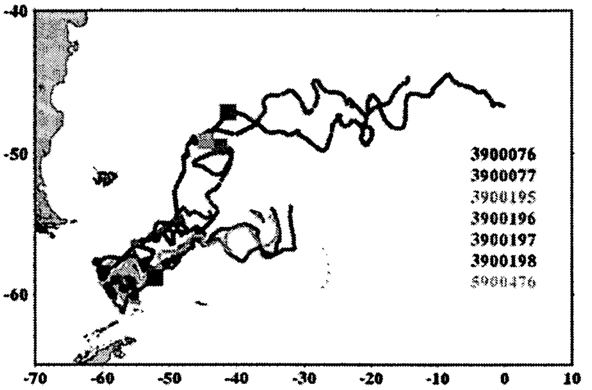

Fig. 9. The same as in Fig. 7, but for the floats deployed across the Drake Passage. The colored squares on the trajectory of WMO ID 3900077 present the locations of the profiles shown in Fig. 10.

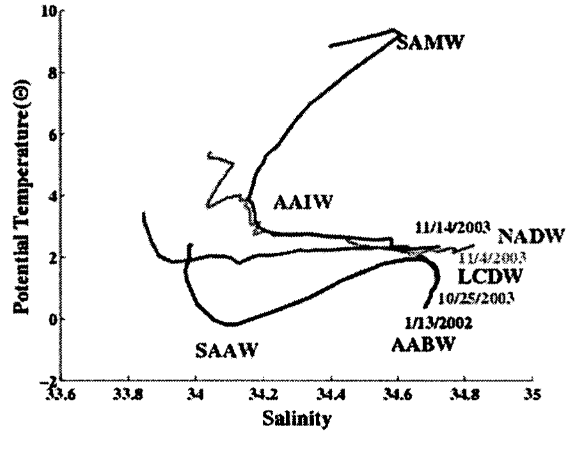

Fig. 10. Θ-S diagrams of selected profiles from WMO ID 3900077.

to the north and the signature of AABW is weaker, i.e. saltier and warmer. Unlike the floats deployed to the south of Australia, the floats deployed across the Drake Passage moved across the PF or SAF, and the water mass properties change rapidly downstream as shown in Fig. 10. The Θ-S diagrams in Fig. 10 are prepared from selected profiles of WMO ID 3900077, whose locations are marked with colored squares in Fig. 9. As it moves to the north across the PF, AABW and SAAW disappears at depth and at surface, respectively. The float then crossed SAF during the next cycle and the 70th profile (November 4, 2003) does not show LCDW. The profile instead shows NADW with the salinity maximum in the deep layer, and AAIW in the middle. In the 71st profile that was taken ten days later, SAMW, which is located further to the north, was observed at the surface. Note that AAIW is fresher in the Atlantic sector than in the Pacific Sector as we can see from the comparison of Figs. 7 and 9, as consistent with earlier studies (McCartney 1982).

4. Summaries

Argo floats, which provide hydrographic profiles as well as Lagrangian trajectories autonomously for about 3 years, can be a very useful tool for studying oceans, such as the Southern Ocean, that are hard to reach by conventional research vessels. In this paper, we described water mass properties and intermediate level flow fields of the Southern Ocean using Argo data.

The water masses and changes measured by the floats are consistent with earlier studies despite a lack of quality control concerning the data. This implies that Argo data could be useful in investigating water properties. The flow fields at 1000 m and 2000 m levels show the eastward tendency, due to the ACC in general, but there is not enough data to describe the general circulation pattern, especially at the 2000 m level. Since the Argo Program will be carried out over for the next few years, in a few more years, we will obtain enough drifter data to understand the Southern Ocean circulation better.

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