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Ocean Science Discussions

Mesoscale variability of water masses in the Arabian Sea as revealed by ARGO floats

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Abstract

By analysing ARGO float data over the last four years, some aspects of the mesoscale variability of water masses in the Arabian Sea are described.

The Red Sea Water outflow is strong in the Southwestern Gulf of Aden, in particular when a cyclonic gyre predominates in this region. Salinities of 36.5 and temperatures of 16 $^{\circ}$C are found there between 600 and 1000 m depths. The Red Sea Water is more dilute in the eastern part of the Gulf, and fragments of this water mass can be advected offshore across the gulf or towards its northern coast by the regional gyres. The Red Sea Water outflow is also detected along the northeastern coast of Socotra, and fragments of RSW are found between one and three degrees of latitude north of this island. In the whole Gulf of Aden, the correlation between the deep motions of the floats and the SSH measured by altimetry is strong, at regional scale. The finer scale details of the float trajectories are more often related to the anomalous water masses that they encounter.

The Persian Gulf Water (PGW) is found in the float profiles near Ras ash Sharbatat (near 57° E, 18° N), again with 36.5 in salinity and about 18–19 $^{\circ}$C in temperature. These observations were achieved in winter when the southwestward monsoon currents can advect PGW along the South Arabian coast. Fragments of PGW are found in the Arabian Sea between 18 and 20° N and 63 and 65° E, showing that this water mass can escape the Gulf of Oman southeastward, in particular during summer.

1 Introduction

The Northwestern Indian Ocean is composed of the 3000–5000 m deep Arabian Basin bounded east by the shallower Chagos-Laccadive ridge and by the Indian continental shelf and west by the shallower Gulf of Aden. Southwest, the Somali Basin has the largest depths (deeper than 5000 m; Tomczak and Godfrey, 2002). This oceanic region is connected to two evaporation basins, the Persian Gulf (with depths shallower than

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90 m and a mean depth of 25 m), and the Red Sea (with maximum depths near 2740 m and mean depth of 490 m). The circulation and water masses in the Northwestern Indian Ocean are strongly influenced by the monsoon winds and by the intense air-sea heat fluxes (Johns et al., 2000). The winter monsoon winds blow to the Southwest from December to April. The surface oceanic currents form a cyclonic gyre in January, which weakens in March (Kindle and Arnone, 2001). The summer monsoon winds blow to the Northeast from June to October. During that time, a fast northeastward current (the East Arabian Current) flows south of the Arabian Peninsula, and forms the northern part of the regional anticyclonic gyre. At the same time, the northeastward Somali Current is also strongly intensified (Schott and Fisher, 2000). The circulation in the Gulf of Aden, and in the Gulf of Oman, are more complex, formed of local cyclonic and anticyclonic gyres (Bower et al., 2000, 2002; Fratantoni et al., 2006; Bower et al., 2005; Pous et al., 2004a,b).

The Northwestern Indian Ocean is noticeably influenced by the Persian Gulf and by the Red Sea. These two adjacent seas produce warm and salty waters (the Persian Gulf Water and the Red Sea Water) which penetrate into the Northwestern Indian Ocean via the Gulf of Oman, and the Gulf of Aden, where they equilibrate at depths of 200–300 m and 600–1000 m, respectively (Bower et al., 2000, 2005; Pous et al., 2004a,b). The other water masses in the region are the Indian Central Water, which originates from the Subtropical Convergence and lies in and above the thermocline (Tomczak and Godfrey, 2002). Below this water mass lies the Indian Deep Water (between 1500/2000 m and 3800 m) and finally the Antarctic Bottom Water (below 3800 m).

In this paper, we will investigate the regional and mesoscale variability of the upper water masses (above 2000 m depth) with hydrological data gathered by ARGO floats. ARGO is an international program for the monitoring of the global ocean, which relies on hydrological data collection by about 3000 profiling floats.

These floats are released at the surface at different locations, dive to their 1000 m "parking depth" and most often remain there for 10 d (some floats for 5 d only). Then

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they dive to 2000 m depth and perform a vertical profile of temperature and salinity up to the surface. When the floats surface, they transmit the data to the ARGO centers via satellites. This cycle is then repeated for the lifetime of the float. Once processed, the hydrological data can be mapped along the float trajectories, providing Lagrangian sections of temperature and salinity.

The paper is organised as follows: the dataset is presented and the floats retained for analysis are classified regionally. The long and short-term displacements of the floats are related to the variations of water masses and to the possible presence of mesoscale anomalies. Deep mesoscale displacements are studied in relation with surface motion provided by altimetric maps.

2 Data and methods

At the ARGO Regional Center for the Indian Ocean (INCOIS, Indian Government), 43 floats were identified with a mission beginning north of 12° N (i.e. a surface release north of this latitude). Among them, eight floats were discarded because of too short missions. Two floats were discarded because of erroneous hydrological data. Two floats evidenced positioning or date problems (showing jumps). Finally, thirteen floats were not analysed since most or all of their trajectory lay east of 65° E, while this paper concentrates on the Arabian Sea between the Gulf of Oman and Bab el Mandeb. A total of 20 float trajectories and hydrological datasets were studied. Here, the analysis of 5 floats is presented. When a float performed a multi-year mission, its data were segmented into yearly bins starting at the date of float release. Temperature and salinity were plotted along the trajectories, as vertical sections.

To evidence correlations between the float trajectories and local bathymetric anomalies, ETOPO2 bathymetric maps were extracted from the NGDC database.

To establish relations between motions at 1000 m depth and surface motions, altimetric maps were obtained from the CNES/AVISO satellite data center.

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3 Gulf of Aden

3.1 Float 1900432

Float 1900432 was released 8 April 2007 near 45°52′ E, 11°58′ N, and its mission ended on 17 October 2007 near 46°40′ E, 13°24′ N. We terminated the analysis on 23 September 2007 since the last hydrological measurements are not realistic. The 4-day cycle of the float allows the observation of short-term loops. Its motion, shown on Fig. 1 is cyclonic. Firstly, the trajectory is eastward from 46° E to 47°30′ E for about a month. Then the float performs one large cyclonic loop with diameter of about 100 km, for 24 d, from 47°30′ E to 46°40′ E; this large loop is followed by two small cyclonic loops at 12°30′ N near 46°40′ E and 45°50′ E, between days 56 and 100 of the mission. Then a larger loop (with diameter of about 100 km) is performed cyclonically until day 128 (between 12° N and 13° N and between 46° E and 45° E). Finally, the float drifts northeastward to 48° E and then westward to 47° E. Velocities range between 4 and 20 $\mathrm{cm\,s^{-1}}$.

The sea-level anomaly map of 9 May shows two large gyres, one cyclonic east of 46°30′ E and one anticyclonic west of this longitude (see Fig. 2). The eastern gyre corresponds to the first large cyclonic loop in the float trajectory. The map of 30 June (day 83 of the mission) indicates that the surface circulation is cyclonic west of 47° E and anticyclonic east of that longitude. One month later (25 July or day 108 of the mission), the anticyclonic gyre has retreated to the southeast and the flow is cyclonic over most of the region; this tendency continues until early September (not shown). Thus, the regional-scale motion of the float is consistent with the surface circulation. Indeed, gyres in the Gulf of Aden are relatively barotropic, see for instance Bower et al. (2002). But the finer-scale motions are not simply correlated to the surface motions and must be related to deeper features. For instance, topography may be involved in the change of direction of the float near 46°30′ E, 12°30′ N; the other details of the trajectory must be attributed to deep water mass characteristics.

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These water masses are now revealed by the vertical sections of temperature and of salinity along the trajectory of float 1900432 (see Fig. 3). From day 0 to 24 of the mission, the float is carried in a warm and salty water mass, extending from 400 to 1000 m depth, and with temperature ranging between 12 °C and 16 °C and salinity between 35.8 and 36.5. The maximum temperature is slightly shallower than the maximum salinity (400–600 m vs. 500–700 m). This is clearly the upper core of Red Sea Outflow Water. Very warm and salty waters are again crossed between days 80 and 130, with two main peaks between days 80 and 100, and then 120–130. This can be related to the small loops observed on the trajectory at these dates. One can notice that the RSOW is mostly confined east of 47° E (in the cyclonic gyres). One can also see the general thinning of the warm and salty upper layer during the 6 months of the record, related to seasonal variability.

3.2 Float 2900392

Float 2900392 was released 30 September 2005 near 46°13′ E, 11°44′ N, and its data were collected for this study 26 February 2010 at a location near 59°46′ E, 12°24′ N. It also has a 5-d cycle. Its data are segmented in one-year bins. The first two years are presented here.

During year 1, the float first drifts eastward from 46°13′ E to 48°15′ E along 11°40′ N (see Fig. 4). After a month, it starts performing one anticyclonic loop followed by one cyclonic and one anticyclonic meander, followed by a cyclonic loop, up to 51° E, 14°40′ N. Finally it comes back fairly swiftly southwestward along the coast of Yemen (again with one cyclonic loop).

The altimetric data were used to obtain the surface circulation (see Fig. 5). The map of 23 November 2005 shows a strong northwestward flow between two gyres which can be correlated with the float trajectory at that time. On 18 January 2006, a strong cyclonic gyre is present near 49° E and 13° N, again in agreement with the cyclonic motion of the float. On 8 March, the circulation between 49° E and 50° E and near 13° N is strongly anticyclonic and can explain the anticyclonic loop after the previous cyclonic

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motion. Finally, end of August 2006, the regional gyre circulation is again cyclonic over the central part of the Gulf of Aden. This cyclonic motion can also be correlated with the eastward float trajectory along the coast of Yemen. Again, a correlation can be found between the surface and deep motions in the Gulf of Aden.

The thermohaline section along the float trajectory is displayed in Fig. 6. During the first 100 days, the float samples warm and salty RSOW. Again, the temperature maximum is about 16 °C and the salinity maximum is about 36.5, located respectively at 400–500 m depth and at 500–600 m depth. This thermohaline anomaly diminishes as the float moves eastward.

During year 2, the float first drifts northward to about 47° E, 13° N and then follows a large cyclonic loop around 48° E, 12°30′ N for about 30 days (see Fig. 7). Then, the float moves rapidly northeastward for 20 days and performs a cyclonic loop between 51° E and 52° E, and 12°30′ N and 13°30′ N, for about 40 days. Then the float drifts back southwestward, nearly to its starting point in less than 4 months. From there, it follows three meanders, alternatively cyclonic, anticyclonic and cyclonic, up to 50° E, 14° N and finally drifts back southwestward again.

The altimetric maps agree with this circulation (see Fig. 8): in November 2006, the surface gyre is cyclonic above the first cyclonic loop of the float. In January 2007, a cyclonic surface gyre is located near 51°30′ E, 13°30′ N where the float performs its deep cyclonic loop. Finally, a clear correlation can also be established between the cyclonic loop of the float and a cyclonic surface gyre near 50° E, and 13°30′ N in July 2007.

Again (see Fig. 9), thermohaline sections along the float trajectory show that warm and salty water, with the same thermohaline maxima as for year 1 (about 16.5 °C and 36.5 at repectively 500–600 m depth and 600–700 m depth) is found in the western part of the Gulf, in particular in cyclonic gyres.

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4 Arabian Sea

4.1 Float 2900104

Float 2900104 was released on 14 March 2006 at 54°02′ E, 11°42′ N. Its last data were collected 25 August 2009 at 60°45′ E, 17°10′ N. Here, we present the first two years of its evolution. Its cycle period is 10.5 days.

During the first year, the float drifts northeastward to 56° E, 13° N and then northwestward to 54°30′ E, 14° N within about 3 months (see Fig. 10). It remains stationary near this position for about two months, then performs a cyclonic loop between this position and 56° E and 15° N. Finally, it follows a large anticyclonic motion (with strong zonal predominance) up to 58° E and to 17°30′ N for the last three months of its first year.

The temperature and salinity sections along the trajectory show evidence of a cooling and of a freshening of the surface layer in August, a priori in relation with strong summer monsoon winds (see Fig. 11). At larger depths, two cores of warm and salty water at Red Sea Water depth are visible from day 30 to 60, and from day 140 to 160; a core of cold and fresh water extending down from 300 to 900 m depth exists between days 180 and 210. The first warm core is located near the continental slope of Socotra and is likely to correspond to a branch of the RSW outflow. Indeed, no specific curvature is detected in the trajectory at that time. The salinity and temperature at 700 m depth are about 35.9 and 12 °C.

These maxima are found again near day 160, at the same depth, as the float is much farther north (near 55°30′ E, 14°30′ N). In the following weeks, the float performs a cyclonic loop, and the cold core is sampled on the northern part of this loop. We interpret these two events as the advection of a detached fragment of RSW by a cyclonic gyre. Finally, in January–February 2007, a weak signature of Persian Gulf Water is visible near 200–300 m depth on the salinity section, as the float comes near Ras al Madrakah (near 57°50′ E, 19° N).

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The altimetric map indicates a cyclonic surface signature both between days 180 and 210 and one month later (early December), when the float follows a cyclonic trajectory up to 54°30′ E, 16° N (see Fig. 12). Mid January 2007, the anticyclonic loop of the float near 57° E, 16° N also corresponds to an anticyclonic surface motion in that region. In summary, correspondence between the deep motion of the float and surface motion at 200 km scale can be shown in this region also.

During year 2, float 2900104 performs successively a cyclonic, an anticyclonic and a cyclonic loop, for about 40 days each, in a general northeastward direction (towards Ras ash Sharbatat, see Fig. 13). After about 150 days, the float follows a cyclonic loop northwestward towards this cape (for about 3 months), and then an anticyclonic loop northeastward for about two months. The end of its trajectory (for year 2) is southwestward.

If surface-depth correlation of motions at horizontal scales of 200 km are found, that at 50 km scale is not ubiquitous; mid November 2007, a cyclonic surface signature is found near 58° E, 18° N above the cyclonic loop of the float; but end of December 2007, the anticyclonic loop of the float does not correspond to the altimetric signature. The float trajectory also reflects the regional currents related to the monsoon (northeastward then southwestward).

The temperature and salinity data collected by this float during year 2 show evidence mostly of Persian Gulf outflow Water, especially near days 500, 600 and 680 (about end of July, early November 2007 and mid January 2008, see Fig. 14). This corresponds to positions east of Ras ash Sharbatat and south of Ras al Madrakah, for the first two periods, and south of Ras ash Sharbatat for the latter. The stronger salinities for PGW are found in November and January. This indicates that (a) PGW can flow downstream of Ras ash Sharbatat, though most likely as fragments, (b) this flow intensifies during the transition from summer to winter monsoon, and during winter monsoon, as the large-scale, wind-induced circulation is southwestward.

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Colder and fresher waters are also found at 200 m depth around day 550 (early September 2007) and day 620 (mid November 2007). During the first period, more particularly, upwellings and filaments develop near Ras ash Sharbatat and bring colder and fresher waters upward.

4.2 Float 1900438

Float 1900438 was launched 18 November 2008 at 56°20′ E, 16°04′ N with a 4-day cycle, and its validated data ended 14 March 2009, at 54°26′ E, 16°02′ N. After that date, a 5 month long data gap occurs corresponding to a shift in position by 7° east.

Its initial trajectory is mostly southeastward, in accordance with the monsoon current direction (see Fig. 15); two anticyclonic loops are superimposed on this global drift; one between days 35 and 50 lies near 55° E, 14° N, the other between days 80 and 100 lies near 52°30′ E, 14° N. The temperature and salinity section of this float does not indicate deep maxima during the first loop (see Fig. 16, note that diffuse PGW is visible during the first 20 days of the mission, south of Ras ash Sharbatat; this is most likely a fragment detached from the PGW outflow). On the contrary, a noticeable RSW signal is visible during the second loop and once the float drifts eastward, along the continental slope, towards Ras Marbat (near 54°40′ E, 17° N). The sea surface elevation at that time does not have an anticyclonic signature, so that the trajectory is most likely determined by the deep water masses. This would indicate the presence of an anticyclonic eddy of RSW at that location.

4.3 Float 2900394

This float was released on 27 June 2005 at 62°33′ E, 20°50′ N but a positioning problem occured for the first 10 days. Then, the trajectory was coherent, but a major drift occured in temperature data for 40 days. Therefore the data were analysed from day 50. It has a 5-day cycle.

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Float 2900394 performs a series of anticyclonic loops between 63°30′ E and 64°30′ E and 19°30′ N and 21° N for about 240 days starting from day 50 (see Fig. 17). Then, to the end of year 1, it follows an anticyclonic trajectory from 64° E, 20° N to 65°30′ E, 19° N and back to 63°30′ E, 18°30′ N.

The altimetric maps during the September 2005–April 2006 period, on the 63–65° E, 18–21° N region, do not show durable correlations with the float trajectory, except during the last two months. This suggests that the anticyclonic motions of the float during its first eight months are more related to the deep, warm and salty water masses, that it encounters (see Fig. 18).

During the second year, the trajectory of float 2900394 is mostly southeastward, with one small anticyclonic loop near 64°30′ E, 18° N, and two cyclonic loops near 64°30′ E, 17° N and 65° E, 17°30′ N (see Fig. 19). The correlation with altimetry is more durable for the large cyclonic motions. The vertical sections of temperature and of salinity do not show strong thermohaline anomalies (one blob of rather dilute PGW is noticeable at day 450, see Fig. 20).

5 Discussion and conclusion

Five floats have been analysed in the Gulf of Aden and in the Arabian Sea. Their trajectories and thermohaline anomalies at depth have been compared with surface motions and with the evolution of surface water masses.

Clearly, if a strong correlation between surface and deeper motions can be established at a 100–200 km scale (see also Bower and Furey, 2011), smaller-scale loops performed by the floats are more often related to the presence of thermohaline anomalies or of topographic features. The float trajectories also reflect the large-scale wind-induced circulation. The circulation in the Gulf of Aden is clearly composed of cyclonic and anticyclonic loops at regional scale, as mentioned in the literature, with a barotropic character.

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Concerning the evolution of water masses, the surface temperature and salinity are strongly influenced by the seasonal variations of the wind, or by its sudden intensification. The only deeper-reaching influence of the wind observed here is the appearance of colder and fresher water masses at 200 m depths, a priori related to upwelling events near Ras ash Sharbatat. Deeper cold and fresh water masses (e.g. between 500 and 800 m depths) are more likely to correspond to deep eddies or fragments.

Intense thermohaline anomalies are observed at the depths of PGW or of RSW.

In the Gulf of Aden, temperature and salinity peaks of 16 °C and 36.5 are observed in the RSW. The RSW signal measured by floats intensifies notably when the float circulates cyclonically in the eastern Gulf of Aden. The float recordings allow us to identify the outflow of RSW from the Gulf of Aden on the continental slope near 55° E and 13° N. It also showed evidence of detached fragments of RSW north of that location (near 14°30′ N).

In the Arabian Sea, temperature and salinity peaks of 19 °C and 36.5 are observed in the PGW at 300 m depth. The PGW signal is observed near Ras al Hadd (59°48′ E, 22°30′ N) and Ras al Madrakah/Ras ash Sharbatat. This indicates that, under favorable conditions of monsoonal currents and in the absence of front at Ras al Hadd (the winter situation), the PGW can veer around this cape and extend southwest along the coast. It also indicates that little PGW is observed west of Ras ash Sharbatat. On the contrary, during summer, the PGW is exported southeastward, and the Ras al Hadd front may play a role in focusing this export in this direction. Further work will investigate this water mass distribution with more floats.

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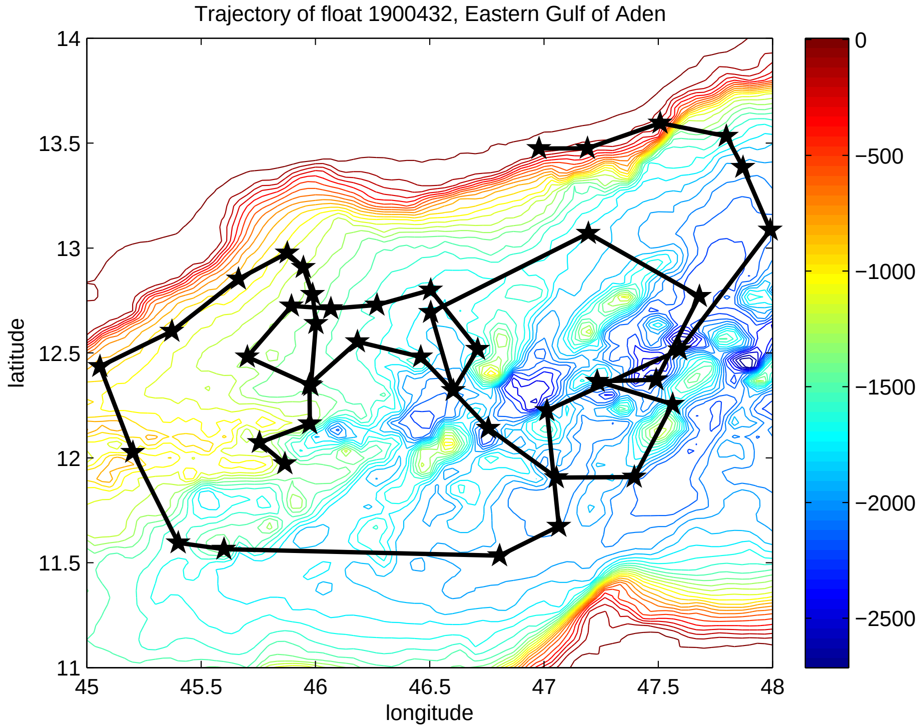

Fig. 1. Trajectory of float 1900432 in the Gulf of Aden, superimposed on bathymetry.

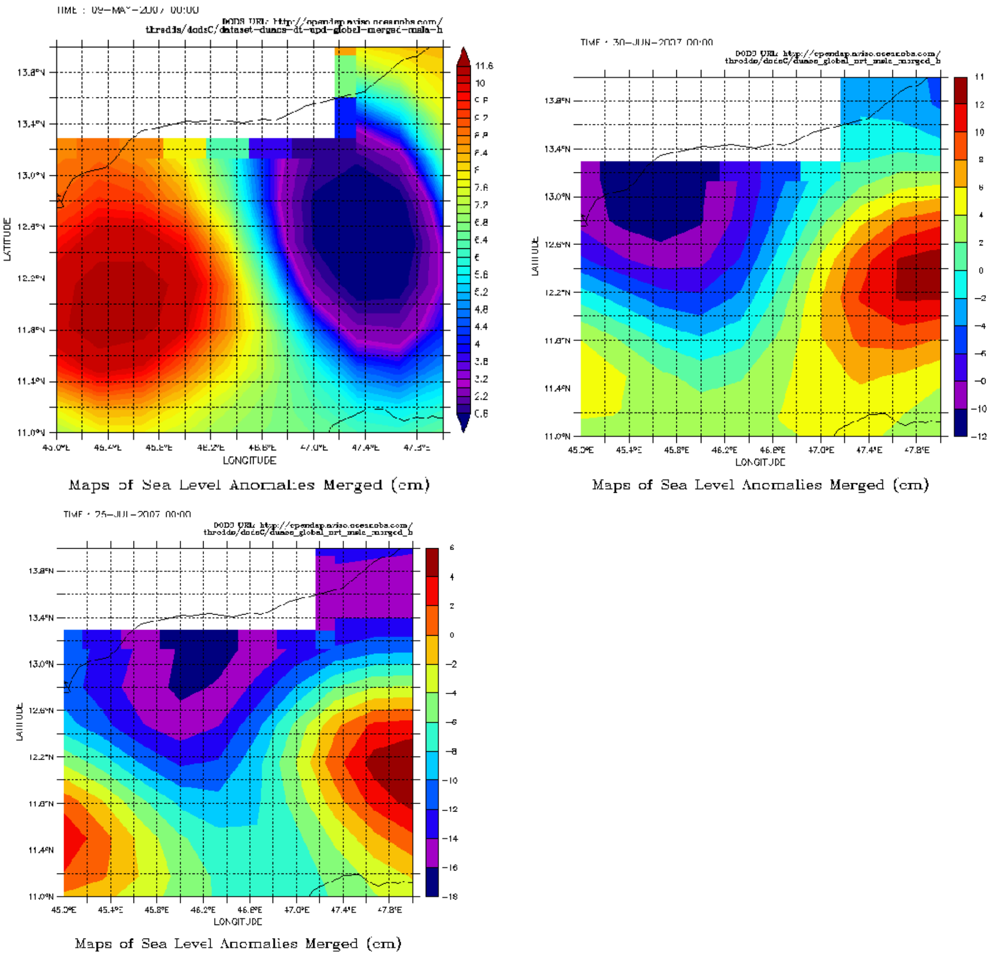

Fig. 2. From left to right and from top to bottom, sea-level anomaly (SLA) map of 9 May, 30 June, 25 July 2007.

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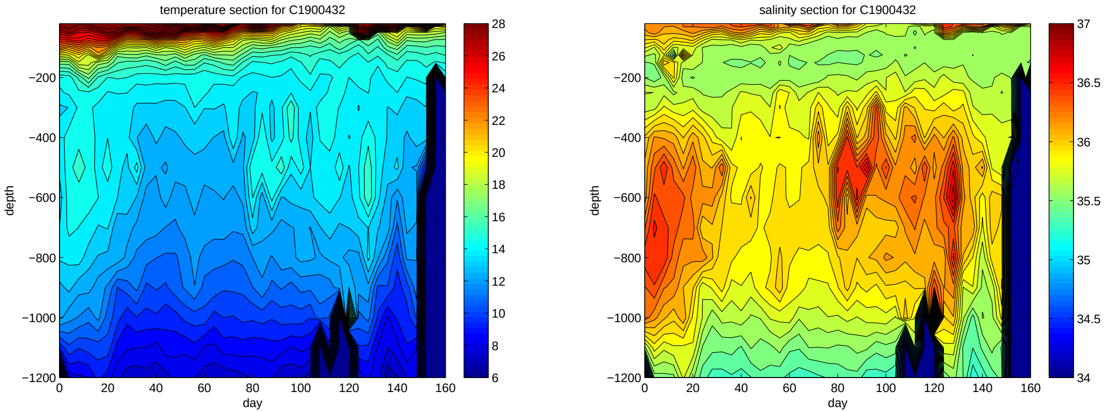

Fig. 3. (left) Vertical section of temperature along the trajectory of float 1900432 in the Gulf of Aden; (right) vertical section of salinity.

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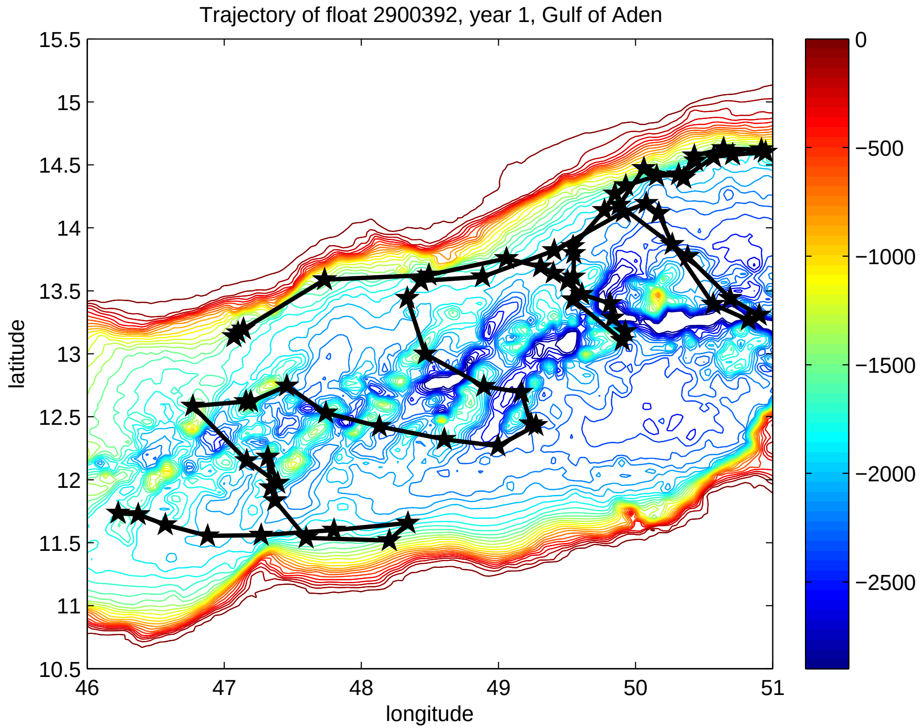

Fig. 4. Trajectory of float 2900392 in the Gulf of Aden, superimposed on bathymetry, year 1.

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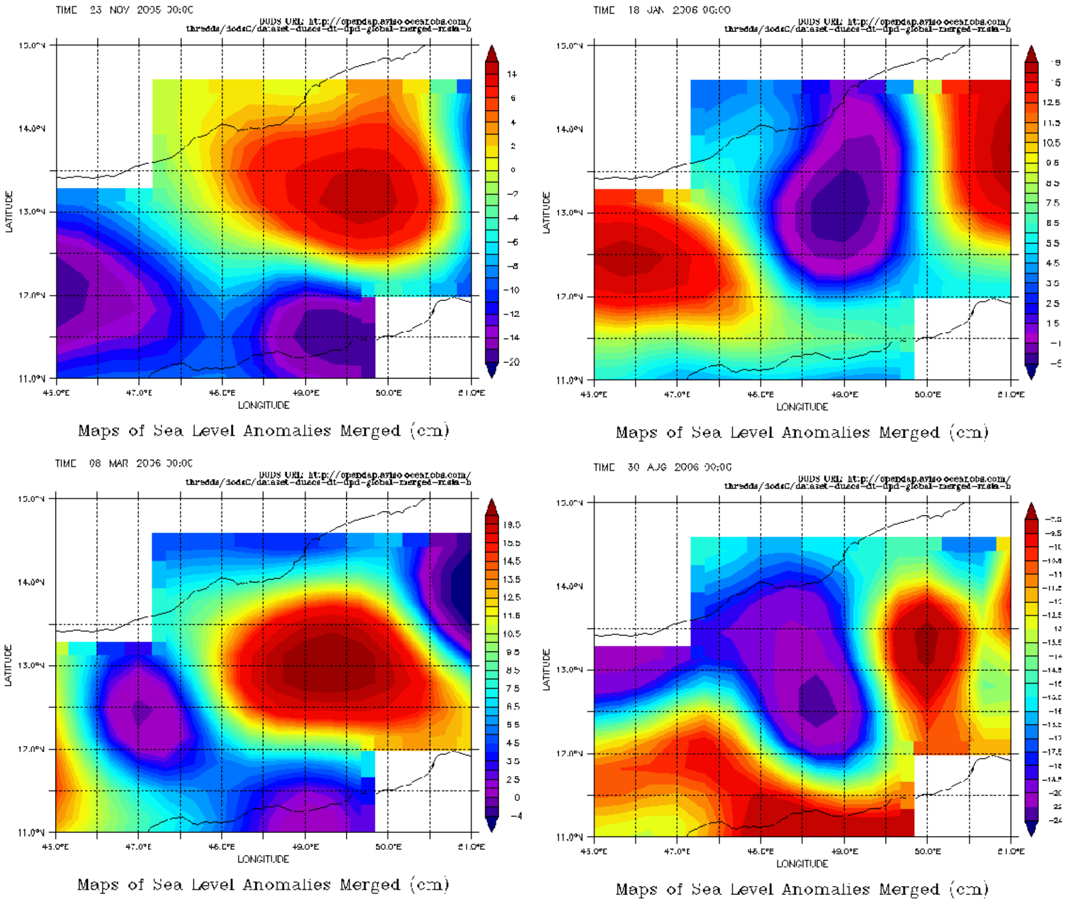

Fig. 5. From left to right and from top to bottom: sea-level anomaly (SLA) maps of 23 November 2005; 18 January, 8 March, 20 August 2006.

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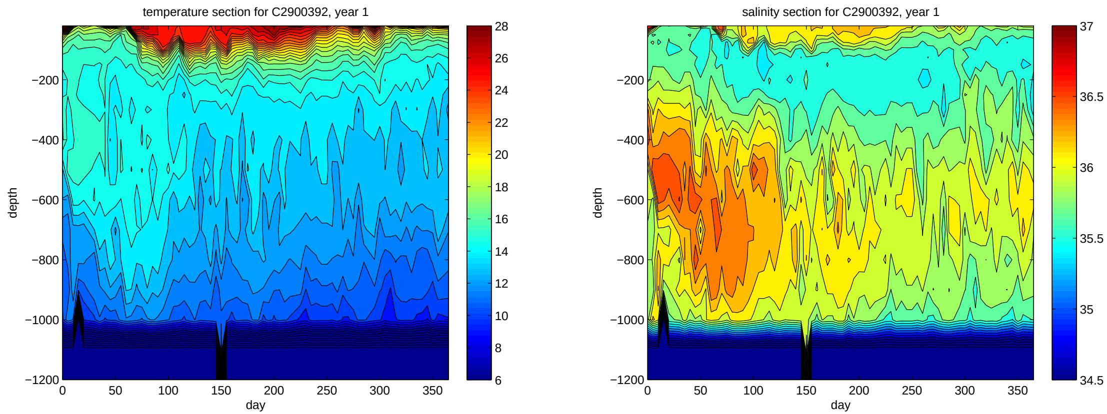

Fig. 6. Vertical sections of temperature and of salinity along float 2900392 trajectory for year 1.

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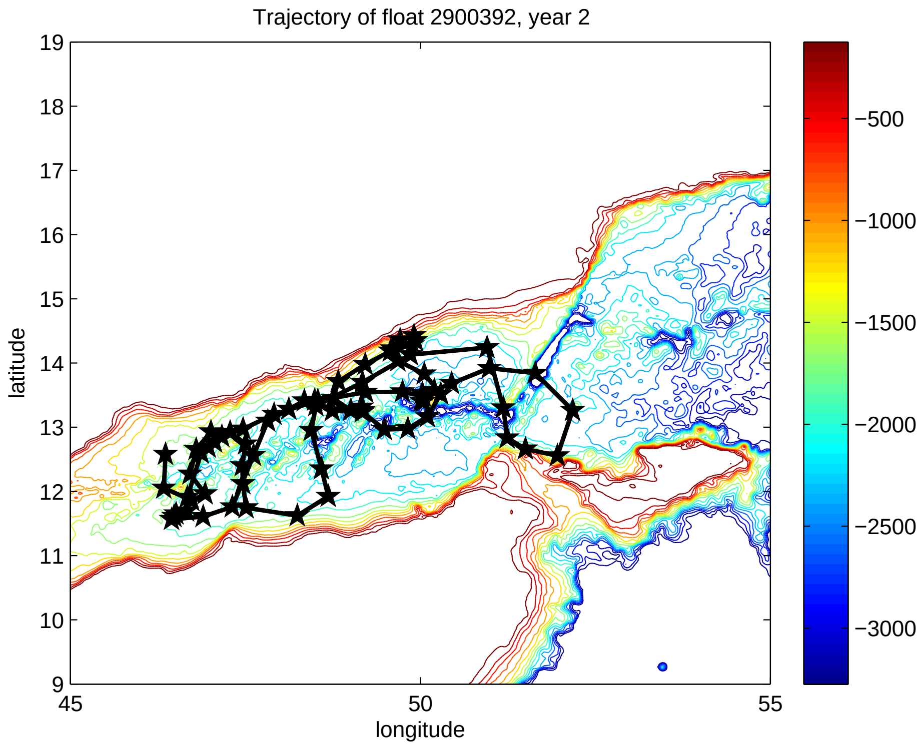

Fig. 7. Trajectory of float 2900392 in the Gulf of Aden, superimposed on bathymetry, year 2.

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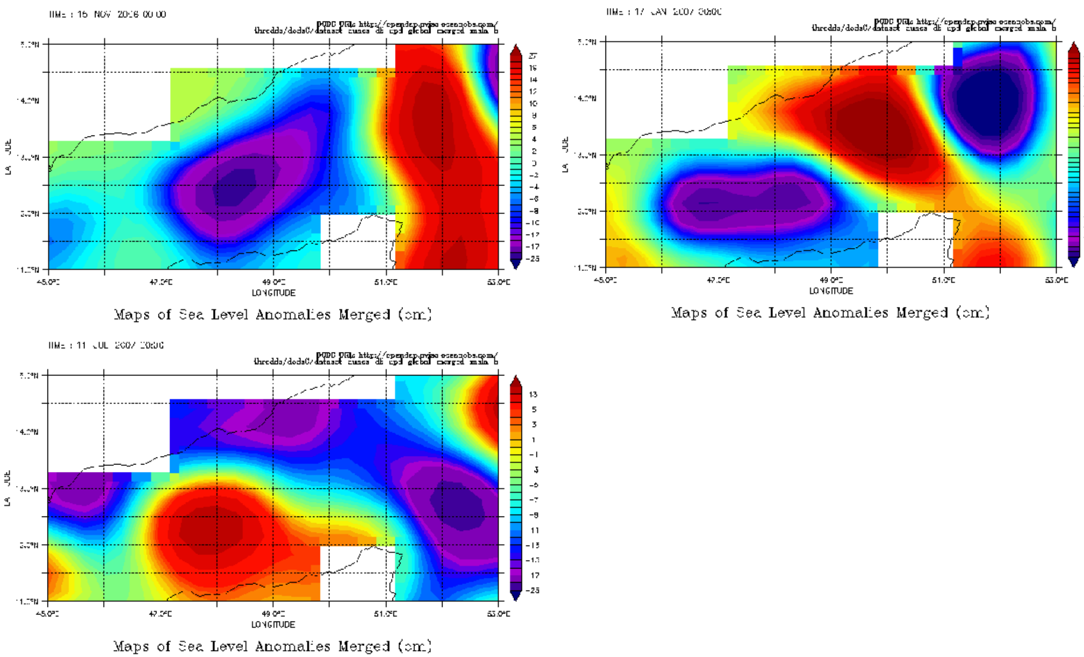

Fig. 8. From left to right and from top to bottom: sea-level anomaly (SLA) maps of 15 November 2006; 17 January, 11 July 2007.

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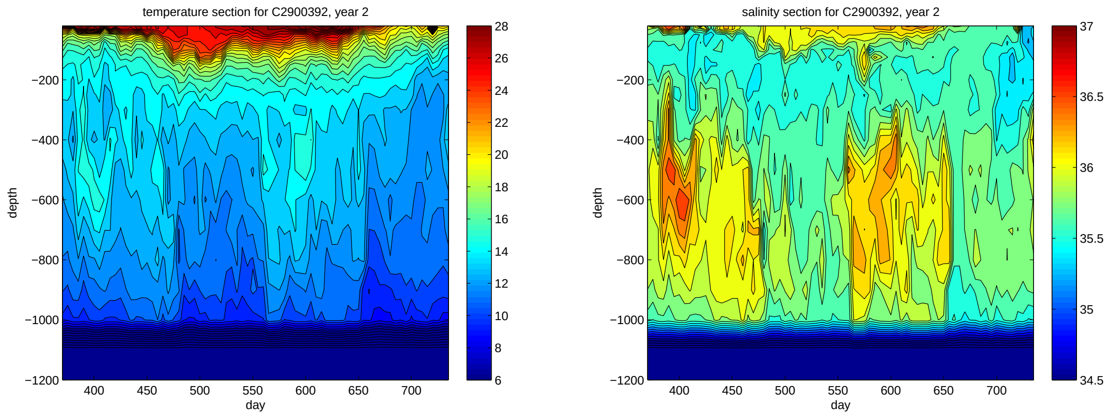

Fig. 9. Vertical sections of temperature and of salinity along float 2900392 trajectory for year 2.

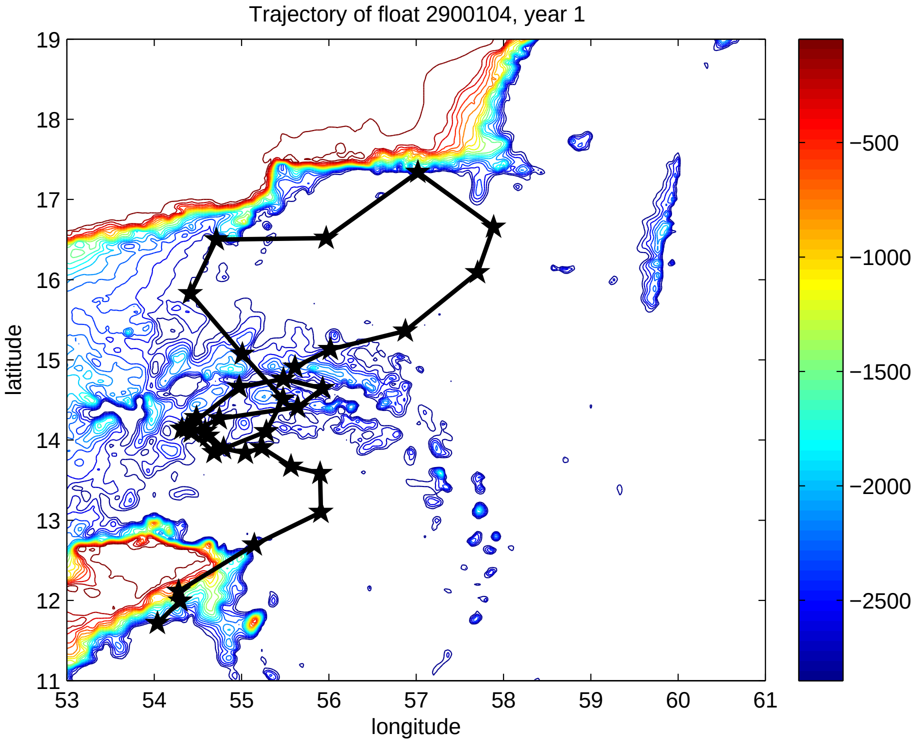

Fig. 10. Trajectory of float 2900104 in the Arabian Sea, superimposed on bathymetry, year 1.

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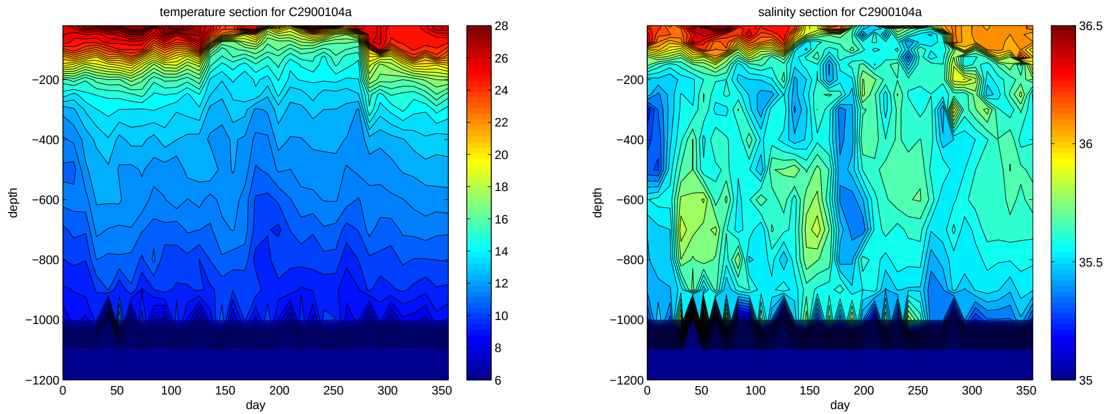

Fig. 11. Vertical sections of temperature and of salinity along float 2900104 trajectory for year 1.

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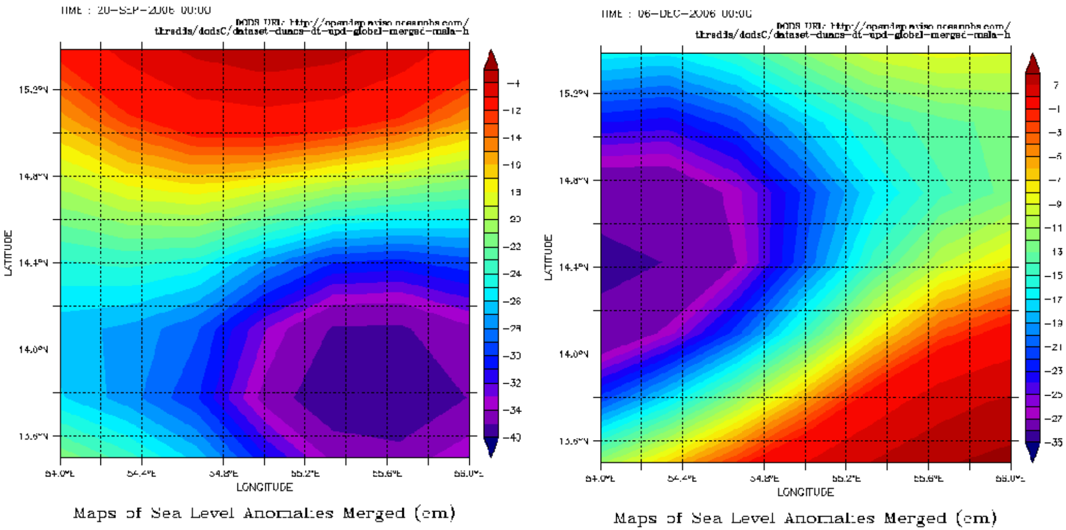

Fig. 12. Altimetric maps on 20 September and 6 December 2006.

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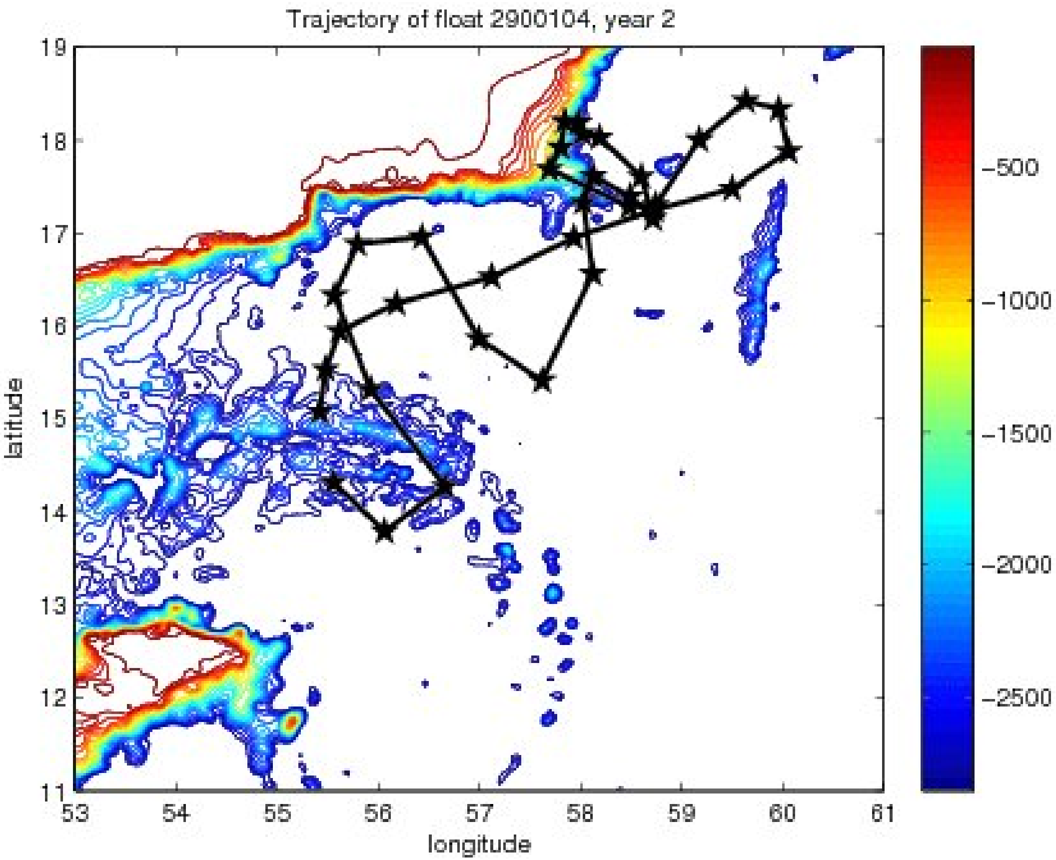

Fig. 13. Trajectory of float 2900104 in the Arabian Sea, superimposed on bathymetry, year 2.

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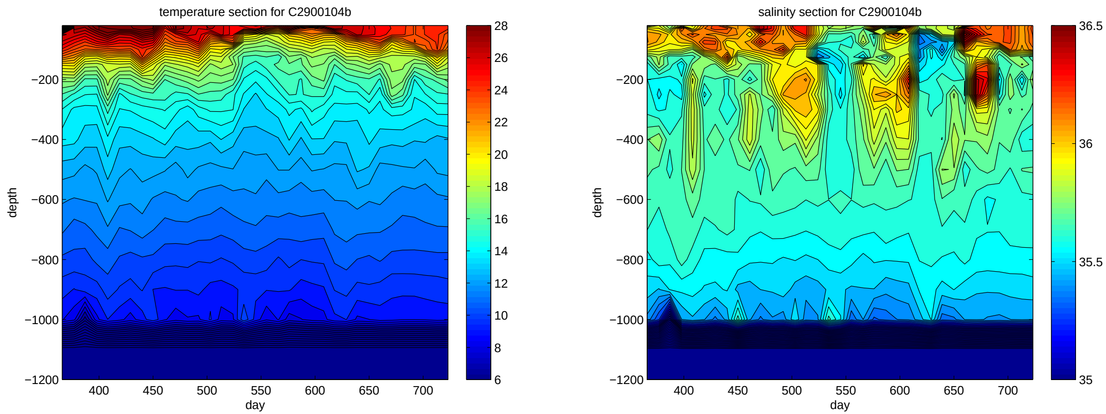

Fig. 14. Vertical sections of temperature and of salinity along float 2900104 trajectory for year 2.

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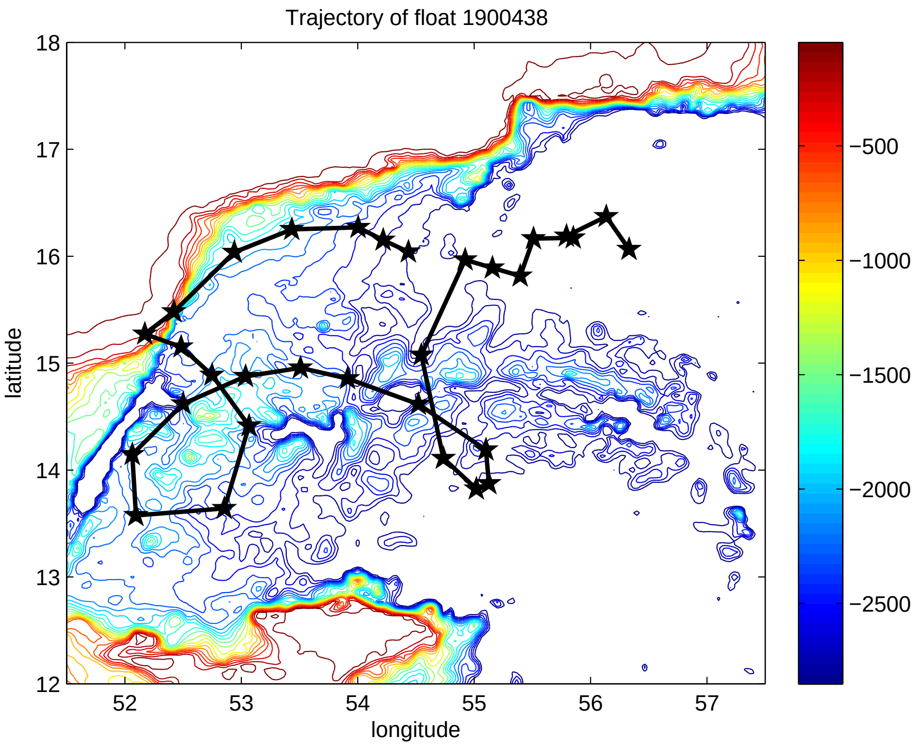

Fig. 15. Trajectory of float 1900438 in the Arabian Sea, superimposed on bathymetry.

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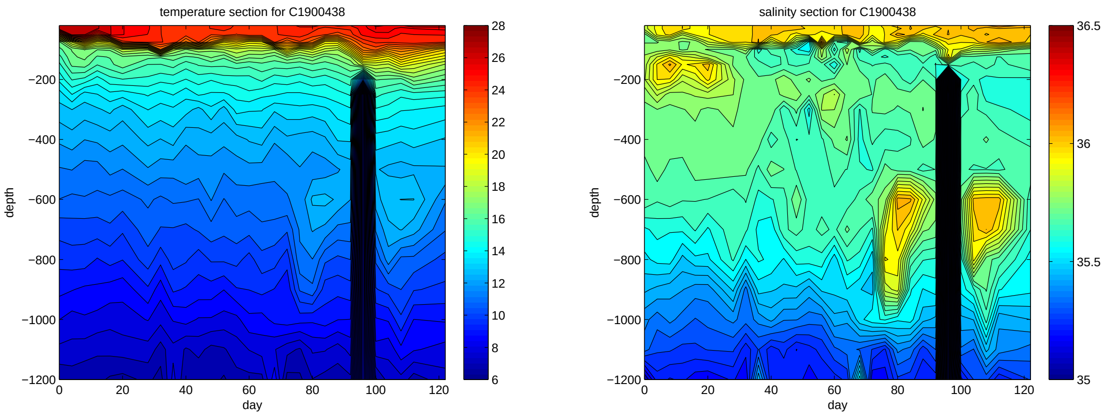

Fig. 16. Vertical sections of temperature and of salinity along float 1900438 trajectory.

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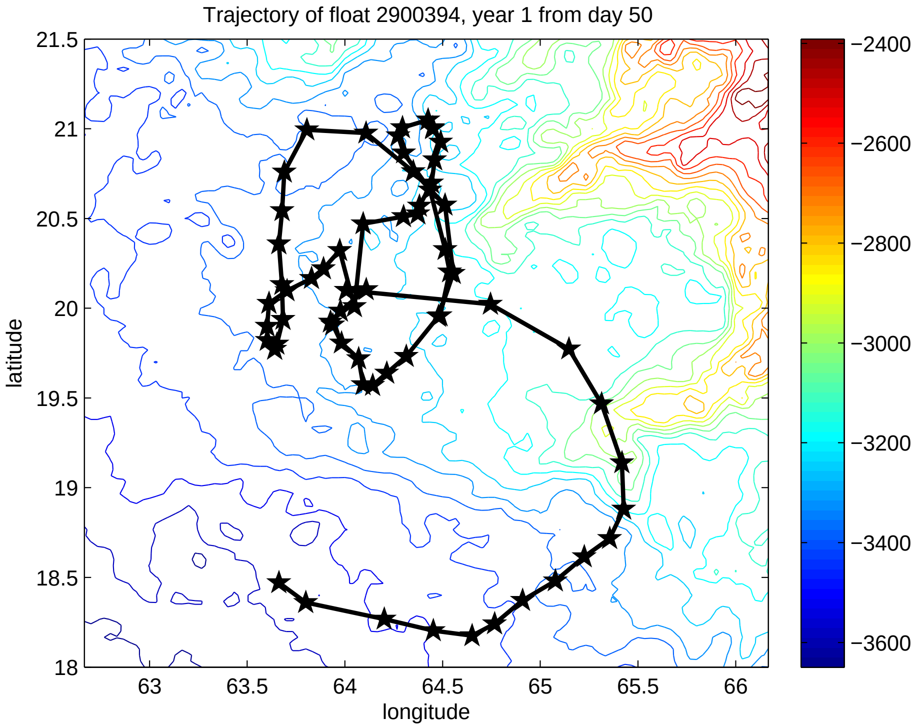

Fig. 17. Trajectory of float 2900394, for year 1 from day 50, superimposed on bathymetry.

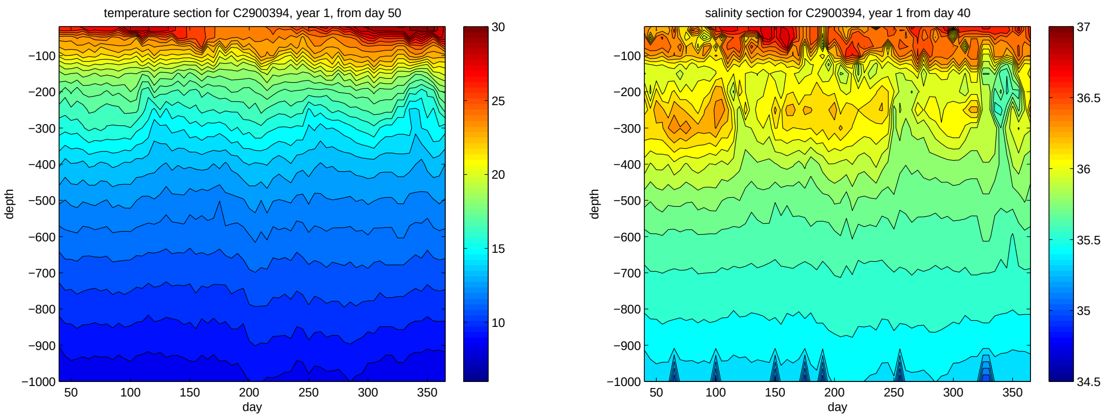

Fig. 18. Vertical sections of temperature and of salinity along float 2900394 trajectory for year 1 from day 50.

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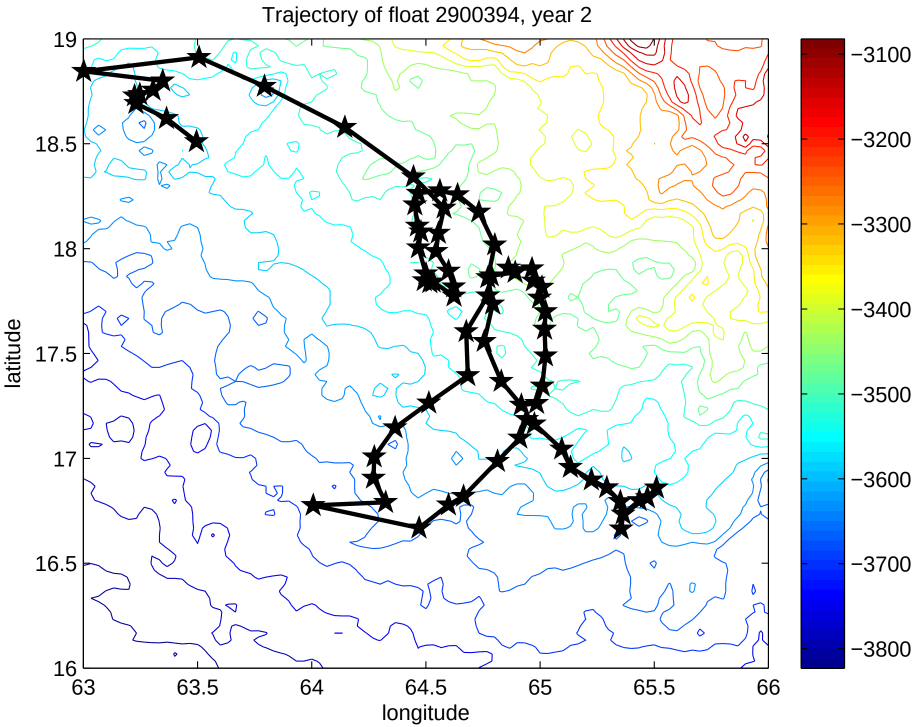

Fig. 19. Trajectory of float 2900394, for year 2, superimposed on bathymetry.

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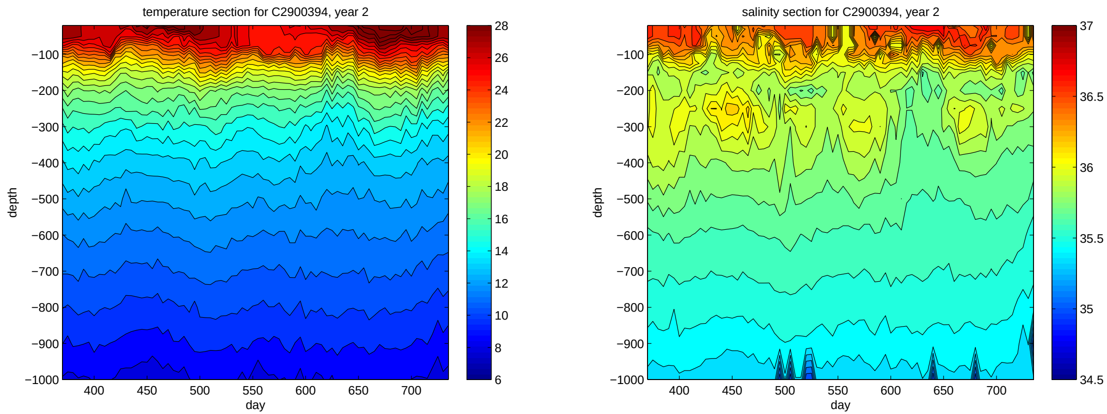

Fig. 20. Vertical sections of temperature and of salinity along float 2900394 trajectory for year 2.

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