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X. Carton, P. L'Hegaret, R. Baraille. Mesoscale variability of water masses in the Arabian Sea as revealed by ARGO floats. *Ocean Science*, 2012, 8, pp.227-248. 10.5194/os-8-227-2012 . hal-00690880

**HAL Id: hal-00690880**

**<https://hal.science/hal-00690880>**

Submitted on 24 Apr 2012

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

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Received: 17 May 2011 – Published in Ocean Sci. Discuss.: 16 June 2011

Revised: 8 March 2012 – Accepted: 19 March 2012 – Published: 30 March 2012

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

The Red Sea Outflow Water (RSOW) is concentrated in the Southwestern Gulf of Aden, in particular when a cyclonic gyre predominates in this region. Salinities of 36.5 and temperatures of 16 °C are found in this area at depths between 600 and 1000 m. RSOW is more dilute in the eastern part of the Gulf, where intense and relatively barotropic gyres mix it with Indian ocean Central Water. RSOW is also detected along the northeastern coast of Socotra, and fragments of RSOW 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 sea-level anomaly measured by altimetry is strong, at regional scale. The finer scale details of the float trajectories are not sampled by altimetry and are often related to the anomalous water masses that the floats 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 °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 were also observed in the Arabian Sea between 18 and 20° N and 63 and 65° E in summer, showing that this water mass can escape the Gulf of Oman southeastward, during that season.

Kinetic energy distributions of floats with respect to distance or angle share common features between the two regions (Gulf of Aden and Arabian Sea), in particular peaks at 30, 50 and 150 km scales and along the axis of monsoon currents. Hydrological measurements by floats are also influenced by the seasonal variations of PGW and RSOW in these regions.

## 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 the Indian continental shelf and west by the shallower Gulf of Aden. The Arabian Sea is bounded south by the Carlsberg Ridge (see Fig. 1). Southwest of the Arabian Sea, the Somali Basin has the largest depths (deeper than 5000 m; Tomczak and Godfrey, 2003). This oceanic region is connected to two evaporation basins, the Persian Gulf (with depths shallower than 90 m and mean depth of 25 m), and the Red Sea (with maximum depths near 2740 m and mean depth of 490 m). These two basins produce salty waters which flow into the Arabian Sea (see below).

The circulation and water masses in the Arabian Sea 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. In the Arabian Sea, the surface oceanic currents form a cyclonic gyre in January, which weakens in March (Kindle and Arnone, 2001). During the winter monsoon, the mixed layer deepens strongly offshore, a priori due to convective overturning in mid-basin, while the dominant Ekman transport is shoreward (Lee et al., 2000). The summer monsoon winds blow to the Northeast from June to October. They are usually stronger than the winter monsoon winds and lead to faster currents. During the summer monsoon, a swift northeastward current (the East Arabian Current) flows south of the Arabian Peninsula, and forms the northern part of the regional anticyclonic gyre.

During the summer monsoon, upwelling occurs on the Southern coast of Oman, near Ras al Madrakah-Ras ash Sharbatat (Shi et al., 2000). Moreover, between early May and end of October, a jet-front system forms at Ras al Hadd

(southeast of Oman), as cool upwelled waters of the Southern Omani coast meet the warmer waters of the Gulf of Oman (Böhm et al., 1999). The associated southeastward jet is confined between two counter-rotating eddies (one cyclonic to the north and an anticyclonic one to the south).

During the same period, the northeastward Somali Current is also strongly intensified (Schott and Fisher, 2000). It is then accompanied offshore by a large anticyclonic eddy, the “Great Whirl”. During summer, the monsoon winds also generate upwelling along the Somali coast. The cold and fresh upwelled waters (with temperatures of 17–18 °C) are in strong contrast with the oceanic surface waters (temperatures of 28–29 °C). Note that upwellings are also observed along the southwestern coast of India during the summer monsoon.

Furthermore, the Arabian Sea is a region of strong evaporation (the  $E - P$  budget is on the order of  $150 \text{ cm yr}^{-1}$ ). Thus, surface salinity as high as 36 can be found in its northern part.

The circulation in the Gulf of Aden, and in the Gulf of Oman, is more complex, formed of local cyclonic and anticyclonic gyres (Bower et al., 2002; Fratantoni et al., 2006; Bower et al., 2000; Pous et al., 2004b). In the Gulf of Oman, one or two large cyclonic gyres have been identified by these authors. In November, due to winds blowing along the axis of the Persian Gulf, and which also affect the Gulf of Oman, upwelling can appear along the Iranian coast in the Gulf of Oman (and in the Persian Gulf, Pous et al., 2004a, b). In the Gulf of Aden, the Somali Current Ring and the Gulf of Aden Eddy appear at the end of the summer and winter monsoons respectively, and the Gulf of Aden eddy propagates westward into the Gulf while the Somali Current Ring remains relatively stationary at the entrance of the Gulf. Recently, Bower and Furey (2011) have shown the existence of two other eddies in the Gulf of Aden: the Lee Eddy and the Summer Eddy which form early during the summer monsoon due to strong winds blowing through the Socotra Passage.

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, PGW and the Red Sea Outflow Water, RSOW) 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; Pous et al., 2004b; Bower et al., 2005). The Red Sea Water enters the Gulf of Aden with a temperature close to 22 °C and a salinity close to 40. These values decrease to 16 °C and 36 once this water has mixed with surrounding waters (Indian ocean Central Water, ICW) and the RSOW settles at depths of 600 to 900 m in the Arabian Sea; from there, it follows the East African coast southward. Near 30° S, the RSOW is found at depths of 1000 to 1100 m. The Persian Gulf Water has similar temperature and salinity values (22 °C and 40) in the northern part of the Straits of Hormuz. Strong mixing with Indian Ocean Surface Water (IOSW) decrease the thermohaline characteristics of the outflowing water to

about 20 °C and to 37.5 in the Gulf of Oman where the equilibrium depth of PGW is about 200–250 m; the PGW characteristics decrease to 17 °C and 36.2 in the northern Arabian Sea where its equilibrium depth is about 300 m (Prasad et al., 2001).

The other water masses in the region are the ICW, which originates from the Subtropical Convergence and lies in and above the thermocline (Tomczak and Godfrey, 2003). Its temperature range is 17 °C to 5 °C from top to bottom, and its salinity varies from 35.5 to 34.8. It also bounds the warm and salty outflow water masses of the Northern Arabian Sea on their Southeastern side.

Below the ICW, lies the Indian Deep Water (IDW, at depths between 1500/2000 m and 3800 m, with potential temperature of 2.5 °C and salinity of 34.8) and finally the Antarctic Bottom Water (AABW), below 3800 m depth, with potential temperature of 0.3 °C and salinity of 34.7.

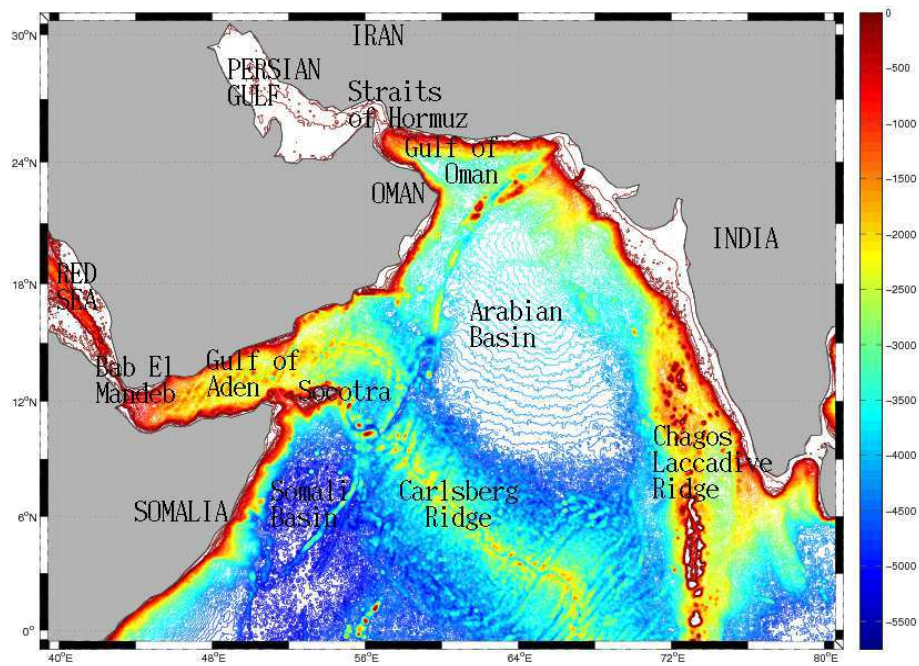
In this paper, we will investigate the regional and mesoscale variability of the upper water masses (above 2000 m depth) with hydrological data gathered by ARGO floats. ARGO is an international program for the monitoring of the global ocean, which relies on hydrological data collection by about 3000 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 days (a few floats for 5 days only). Then 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 their 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

ARGO float data were obtained from the ARGO Regional Center for the Indian Ocean (INCOIS, Indian Government). In the database, 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 the Gulf of Aden. A total of



**Fig. 1.** Bathymetry of the Arabian Sea (from ETOPO1 database).

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, ETOPO1 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. Delayed-time sea-level anomalies (SLA, with  $1/3 \times 1/3^\circ$  resolution on a Mercator grid and with daily interpolation), computed with respect to a 7-year mean of the sea surface topography, are used here to determine the correlation with the float motion.

For each float, we shall show the vertical/alongpath section of temperature and salinity, and we shall try to relate the major thermohaline anomalies with the water masses described in the introduction. We shall also plot the trajectories superimposed on the bathymetry or on SLA. To establish quantitative correlations between the float trajectories and the bathymetry, we shall compute the angle between the trajectory and the isobaths at each position, and plot this angle versus time.

For each float, we shall compute Lagrangian velocities from the distance and time-lag between two surfacings; these surfacings can be consecutive, or separated by two cycles or more. We shall plot the kinetic energy distribution thus obtained with respect to the distance covered by the float, or

with respect to the orientation of its trajectory. Note that the orientation is given between  $-90^\circ$  and  $+90^\circ$ , with the origin on the eastward axis. The direction of the flow (e.g. eastward or westward for a zero degree angle) is here less important. For instance, energy in both northeastward and southwestward directions reflects the influence of monsoon currents.

Also, our analysis of the floats energy assumes that the flow field has global homogeneity, isotropy and stationarity. These hypotheses will be tested by computing the energy distributions for several floats (thus having different starting points and different trajectories), and for different periods of the year.

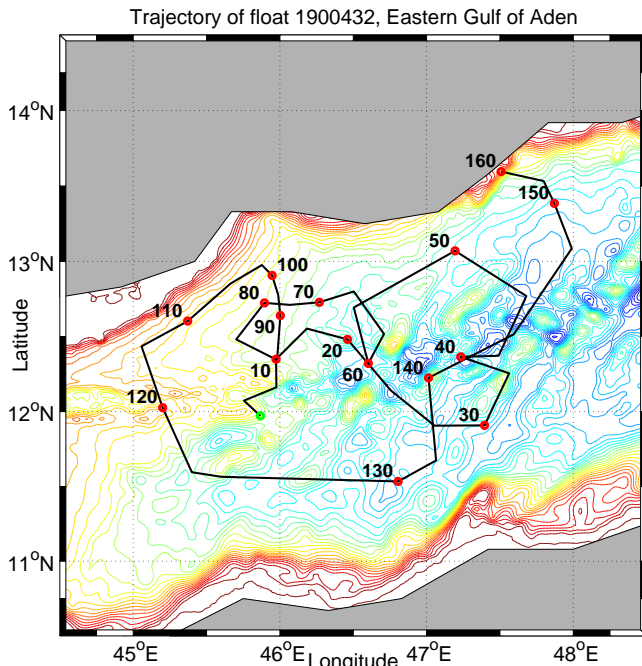
### 3 Gulf of Aden

#### 3.1 Float 1900432

Float 1900432 was released 8 April 2007 near  $45^\circ 52' E$ ,  $11^\circ 58' N$ , and its mission ended on 17 October 2007 near  $46^\circ 40' E$ ,  $13^\circ 24' N$ . We terminated the analysis of its data on the 23 September 2007 since the last hydrological measurements were not realistic. The 4-day cycle of the float allowed the observation of short-term loops.

Its motion, shown on figure 2 was mostly cyclonic. Firstly, the trajectory was northeastward from about  $46^\circ N$ ,  $12^\circ E$  to  $46^\circ 30' E$ ,  $12^\circ 30' N$  for 20 days. Then the float performed one large cyclonic loop with diameter of about 100 km, for 40 days, in the area spanning  $46^\circ 30' E$  to  $47^\circ 30' E$  and  $11^\circ 50' N$  to  $13^\circ 05' N$ ; this large loop was followed by two small cyclonic loops at  $12^\circ 30' N$  near  $46^\circ 40' E$  and  $45^\circ 50' E$ , between

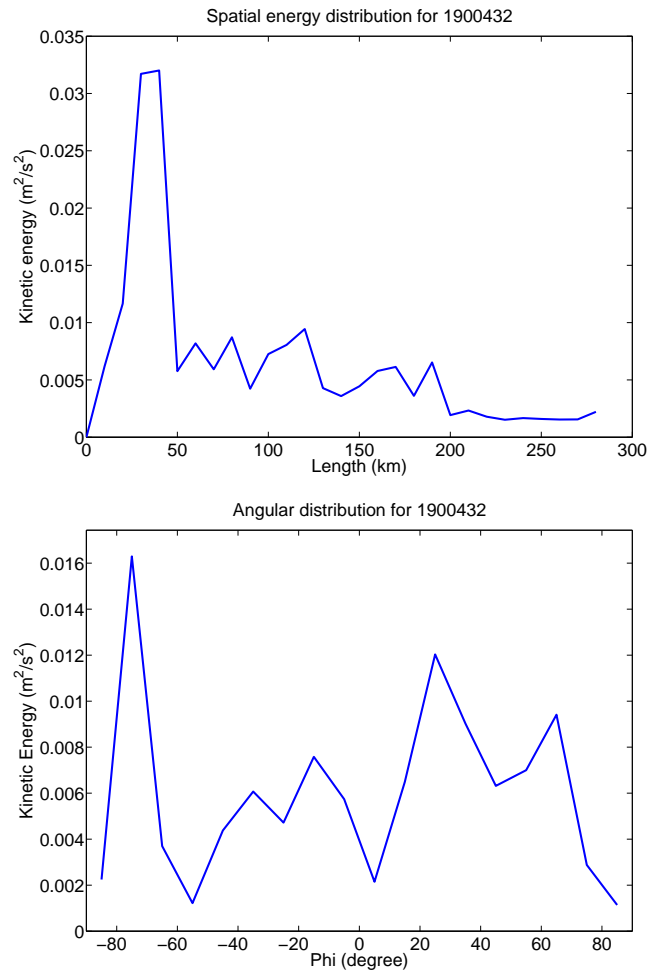




**Fig. 2.** Trajectory of float 1900432 in the Gulf of Aden, superimposed on bathymetry; the green dot is the starting point of the trajectory; positions every 10 days are indicated by a red dot.

days 56 and 100 of the mission. Then a larger loop (with diameter of about 100 km) was performed cyclonically until day 128 (in the area between 12° N and 13° N and between 46° E and 45° E). Finally, the float drifted northeastward to 48° E, 13° N and then northwestward to 47°30' E, 13°30' N. Velocities ranged between 4 and 20 cm s<sup>-1</sup>.

The kinetic energy distribution with respect to horizontal displacement is shown in Fig. 3; this distribution shows four relative maxima (we consider that a wide peak in the curve, or two peaks very close to each other constitute a single maximum). The largest kinetic energy ( $K \approx 0.03 \text{ m}^2 \text{ s}^{-2}$ ) is found at horizontal scales of 40 km, most likely, in relation with the two small loops with swift motion of the float; a second relative maximum is formed of two peaks, at 60 and 80 km horizontal scales; this can be related to the fast and small zonal motions of the float and to the cycloidal motion superimposed on the large loops in its trajectory; the third relative maximum occurs for 120 km horizontal scales, in relation with the large loops themselves. Finally, the peak at 170–190 km can be associated with the large zonal motion of the float. In the large loops, the float velocity was about 5 cm s<sup>-1</sup>. This value is in agreement with Bower and Furey's findings (2011): the velocities in the RSOW are weaker in the western Gulf of Aden (5 cm s<sup>-1</sup>) than in the eastern gulf (15 cm s<sup>-1</sup>). Unfortunately, the time-life of the float was too short to test the invariance of this spectrum to the period of the year (this point will be addressed in more details in Sect. 5 of the paper). One can only state that the larger scale



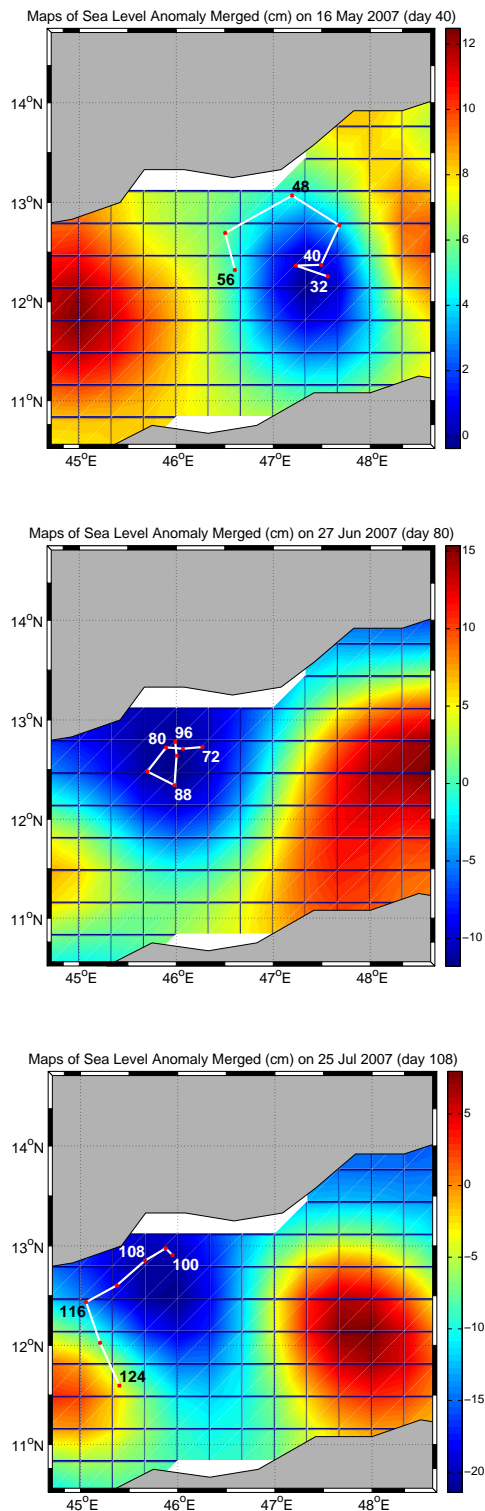
**Fig. 3.** Distribution of Lagrangian kinetic energy (in  $\text{m}^2 \text{s}^{-2}$ ) with respect to horizontal displacement (top) and to the orientation of the displacement (bottom), for float 1900432.

motions occurred at the end of the mission, that is, in late summer, early fall.

This figure also shows the energy distribution versus the angle of the flow. This distribution has two peaks at  $\phi = +25^\circ$  and  $-15^\circ$  corresponding to the along-gulf displacements, and at  $\phi = +65^\circ$  and  $-75^\circ$  corresponding to across-gulf displacements. Obviously, energy is also found at other angles (e.g. at  $\phi = -35^\circ$ ) since several loops were present in the trajectory.

The float motion superimposed on the bathymetry is shown in Fig. 2. The angle between the trajectory and the isobaths was computed and plotted versus time (figure not shown). This angle was often larger than 45°; it was smaller than 20° only at days 80–90 and 110–120. This confirms that the correlation between isobaths and float trajectories was weak except close to the continental slope.

The float motion is now compared with the surface flow, given by the SLA. On day 40 of the mission (16 May), two large gyres, one cyclonic east of 46°30' E and one



**Fig. 4.** From top to bottom, sea-level anomaly (SLA) maps of 16 May, 27 June and 25 July 2007 (days 40, 80 and 108 of the mission). The trajectory of float 1900432 is superimposed on each map. Red dots correspond to the position of this float every 4 days; the number close to the dots is the mission day shown only every 8 days for clarity.

anticyclonic west of this longitude, were present in the SLA map (see Fig. 4). The float trajectory, superimposed on this SLA map, indicates that part of the large loop performed by the float from days 20 to 60, circled the cyclonic gyre. The small indentation in the trajectory between days 32 and 40 of the mission (8 May and 16 May) may be due to a positioning error, or to small scale flow not sampled by altimetry.

On 27 June (day 80 of the mission), the surface circulation was cyclonic west of 47° E and anticyclonic east of that longitude. The float trajectory nearly circled the core of the cyclonic gyre. One month later (25 July or day 108 of the mission), the anticyclonic gyre had retreated to the southeast and the flow was cyclonic over most of the region; again the float circled anticlockwise around the cyclonic region and then followed the southwestward flow between the cyclone and the anticyclone.

Thus, the float motion was consistent with the surface circulation indicated by the SLA. Indeed, gyres in the Gulf of Aden have a noticeable barotropic component (Bower et al., 2002; Bower and Furey, 2011).

The water masses sampled by the float during its vertical profiles are now identified on the vertical sections of temperature and of salinity along the trajectory of float 1900432 (see Fig. 5).

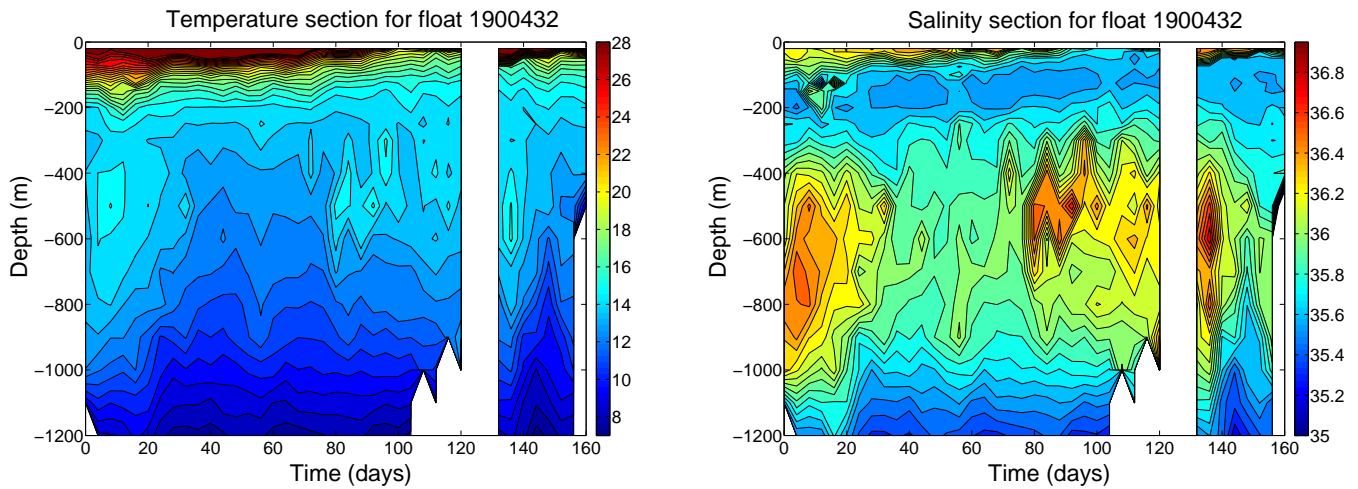
From day 0 to 24 of the mission, the float encountered a warm and salty water mass, at depths between 400 m and 1000 m, with temperature ranging between 12 °C and 16 °C and salinity between 35.8 and 36.5. The maximum temperature was slightly shallower than the maximum salinity (at 400–600 m versus 500–700 m). This water mass was clearly Red Sea Outflow Water. Very warm and salty waters were again found with peaks between days 80 and 100, and then at days 130–140. Thus RSOW was mostly confined west of 47° E. Deep data were missing at days 108–116 and no hydrological data were returned at days 120 to 128, hence the gap observed in the temperature and salinity sections.

On the contrary, east of 47° E, cooler and fresher water was found in the 300–800 m depth range, with temperature lying in the 9–13 °C interval and salinity between 35.5 and 35.8. This water was more likely ICW, mixed with RSOW, to account for the slightly larger salinity than that of pure ICW. This water was contained in the large cyclone which lay around 47° E, 12°30' N at day 40 of the mission. This confirms the conclusion drawn by Bower and Furey (2011) that westward drifting eddies can transport ICW into the Gulf of Aden and mix it with RSOW there.

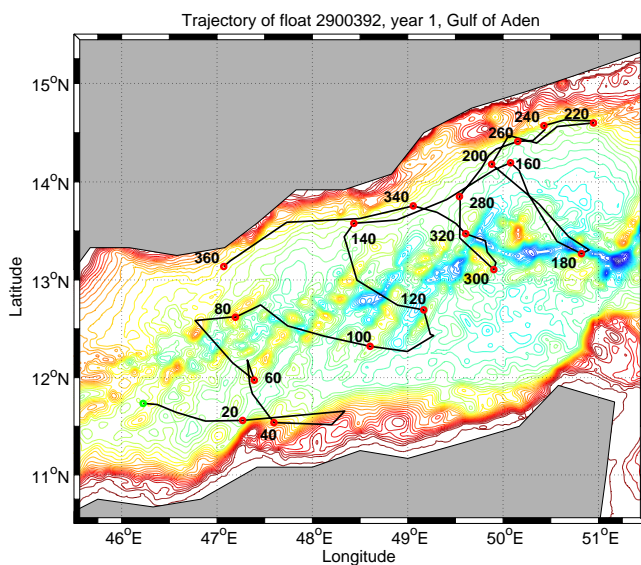
Finally, the thermocline waters became thinner during the 6 months of the record, either because of wind-induced vertical mixing, or of lateral turbulent mixing, or because of the presence of cooler water close to the northern coast.

### 3.2 Float 2900392

Float 2900392 was released 30 September 2005 near 46°13' E, 11°44' N. In February 2010, when this study was



**Fig. 5.** (Left) Vertical section of temperature (in °C) along the trajectory of float 1900432 in the Gulf of Aden; (right) vertical section of salinity.



**Fig. 6.** Trajectory of float 2900392 in the Gulf of Aden, superimposed on bathymetry, year 1; the green dot is the starting point of the trajectory; positions every 20 days are indicated by a red dot.

initiated, this float was still active. Only the first two years of its mission are presented here (in two segments of one year each). This float had a 5-day cycle.

During year 1, the float drifted eastward for a month from  $46^{\circ}13' \text{ E}$  to  $48^{\circ}15' \text{ E}$  along  $11^{\circ}40' \text{ N}$  (see Fig. 6). Then, it followed three loops, one anticyclonic, one cyclonic and then a large anticyclonic one at  $49\text{--}50^{\circ} \text{ E}$ , and later it moved up to  $51^{\circ} \text{ E}$ ,  $14^{\circ}40' \text{ N}$ . Finally it came back swiftly southwestward along the coast of Yemen (again with a cyclonic loop). Clearly, the float trajectory was a combination of motion around gyres and of fast along-gulf displacement near the northern shore (during the fall intermonsoon).

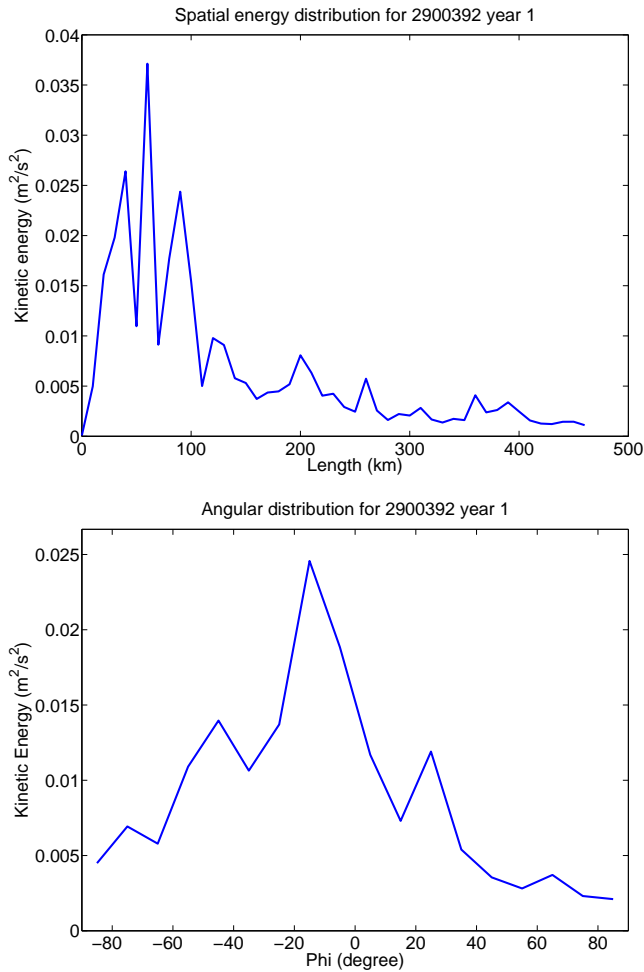
Only a weak correlation of the float trajectory with the isobaths was found, except in the last stage of the float evolution (between days 330 and 350 when the angle between the trajectory and the isobaths was smaller than  $10^{\circ}$ ).

In the energy distribution (see Fig. 7), a wide peak at 30–40 km horizontal scale corresponds to the small scale loops in the float trajectory, two peaks at 60 and 90 km can be related to the meanders in the trajectory, and we associate smaller peaks at 200 and 260 km with the large excursions of the float along the gulf axis. In the angular distribution of the energy, two peaks are found at  $-15^{\circ}$  and  $+25^{\circ}$  (as for float 1900432); this corresponds to displacements mostly along the Gulf axis. A peak at a  $-45^{\circ}$  angle can be related to the swift float motion at days 120–135, 160–200 and 300–340.

Altimetric data were used to determine the surface circulation (see Fig. 8). On day 115 of the mission (25 January 2006), a strong cyclonic gyre was present near  $48^{\circ}30' \text{ E}$  and  $12^{\circ}30' \text{ N}$ ; this gyre had a tail on its southeastern side. The float trajectory was anticlockwise and followed this tail. On day 160 of the mission (8 March 2006), the circulation near  $49^{\circ}30' \text{ E}$  and  $13^{\circ} \text{ N}$  was strongly anticyclonic; the float trajectory was clockwise and then followed the southeastward flow between this anticyclonic gyre and the cyclonic one on its eastern flank. Finally, on day 325 of the mission (23 August 2006), the regional gyre circulation was again cyclonic over the central part of the Gulf of Aden. The float trajectory was clearly anticlockwise around this gyre. This confirms the deep influence of the regional gyres observed in the altimetry.

The thermohaline section along the float trajectory is displayed in Fig. 9. During the first 100 days, the float sampled warm and salty RSO. Again, the temperature and salinity maxima were about  $16^{\circ} \text{ C}$  and 36.5, located respectively at depths between 400 and 500 m and between 500 and 600 m. This thermohaline anomaly diminished as the float moved

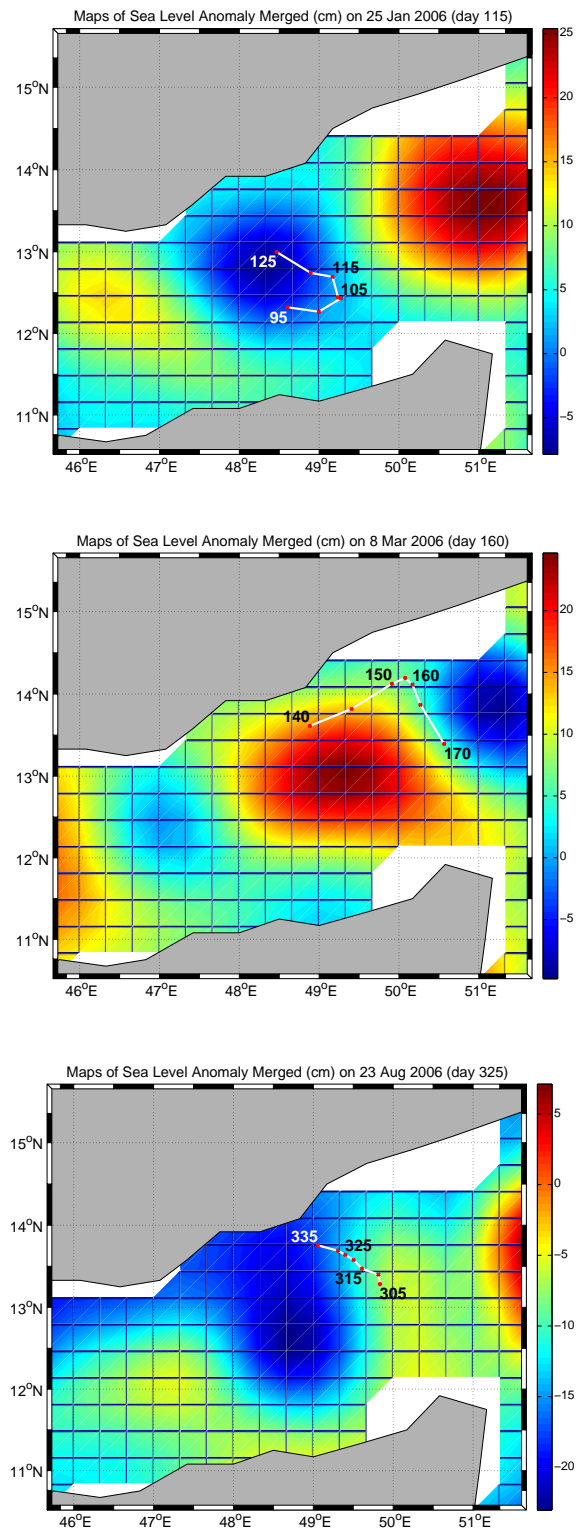




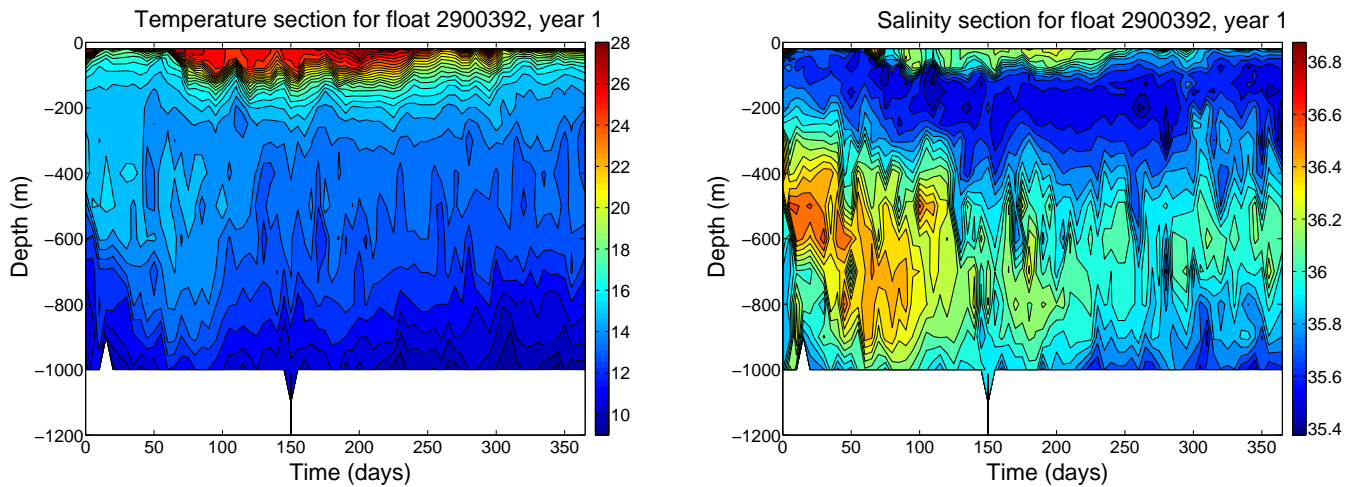
**Fig. 7.** Distribution of Lagrangian kinetic energy (in  $\text{m}^2 \text{s}^{-2}$ ) with respect to horizontal displacement (top) and to the orientation of the flow (bottom), for float 2900392.

eastward, in particular after day 120 when the trajectory exhibited the large anticyclonic loop. Clearly, RSOW lay in the southwestern part of the Gulf of Aden at that time. Then, the temperature and salinity measured by the float at 600 m depth were on the order of  $12^\circ\text{C}$  and 35.8. Again, these values were slightly above ICW characteristics, indicating mixing with RSOW. The surface layer became cooler and fresher in summer and warmer and saltier in winter when the winds were weaker (an observation similar to that of float 1900432).

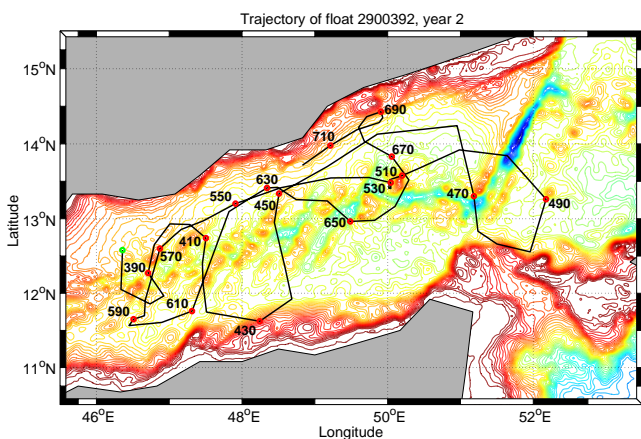
During year 2, the float followed a series of cyclonic and anticyclonic meanders, with a large cyclonic loop around  $48^\circ \text{E}$ ,  $12^\circ 30' \text{N}$  for about 30 days (see Fig. 10). Then, the float moved rapidly northeastward for 20 days and performed a cyclonic loop between  $51^\circ \text{E}$  and  $52^\circ \text{E}$ , and  $12^\circ 30' \text{N}$  and  $13^\circ 30' \text{N}$ , for about 40 days. Then the float drifted back southwestward, nearly to its starting point in less than 4 months. From there, it followed three meanders, alterna-



**Fig. 8.** From top to bottom, sea-level anomaly (SLA) maps of 25 January, 8 March and 23 August 2006 (days 115, 160 and 325 of the mission). The trajectory of float 2900392 is superimposed. Dots indicate the position of the float every 5 days. Mission days are indicated next to the dots.



**Fig. 9.** Vertical sections of temperature (in °C, left) and of salinity (right) along float 2900392 trajectory for year 1.



**Fig. 10.** Trajectory of float 2900392 in the Gulf of Aden, superimposed on bathymetry, year 2; the green dot is the starting point of the trajectory; positions every 20 days are indicated by a red dot.

tively cyclonic, anticyclonic and cyclonic, up to 50° E, 14° N and finally drifted back southwestward again. This trajectory illustrates the combination of fast along-gulf currents, especially near its northern coast (with a reversal of direction between winter monsoon and spring intermonsoon), and of large cyclonic and anticyclonic gyres at the center of this gulf.

Correlation of the float motion with the isobaths orientation was again weak, except close to days 450 and 550 when the float moved along the northern coast.

The kinetic energy distribution (not shown) has peaks at 40, 80, 140 and 400 km, corresponding respectively to the small and medium size gyres or meanders, for the first three, and to the fast along gulf motion at days 500–600, for the latter. The energy distribution versus the angle has maxima at +20° and –80°, which are the along-gulf and across-gulf orientations.

The altimetric maps agree with this circulation (see Fig. 11): in November 2006, the surface gyre was cyclonic above the first cyclonic loop of the float. In January 2007, the float first moved clockwise around the anticyclone at 50° E, 13°30' N; then the float performed a cyclonic loop at 1000 m depth under a cyclonic surface gyre, located near 52° E, 14° N. Finally, a clear correlation can also be established between the anticyclonic loop of the float near 48–50° E and 13–13°30' N, and an anticyclonic surface gyre in July 2007.

Again (see Fig. 12), thermohaline sections along the float trajectory show that warm and salty water lay in the western part of the Gulf around cyclonic gyres a depths close to 600 m. This water had the same thermohaline maxima as in year 1 (about 16.5 °C and 36.5 at respectively 500–600 m depth and 600–700 m depth), and thus was a priori RSOW. Colder and fresher water (with temperature of 10–12 °C and salinity of 35.5–35.8) was sampled by the float at days 500–550 and 650–700, in the northeastern part of the gulf. Again this water was ICW mixed with RSOW by the large gyres.

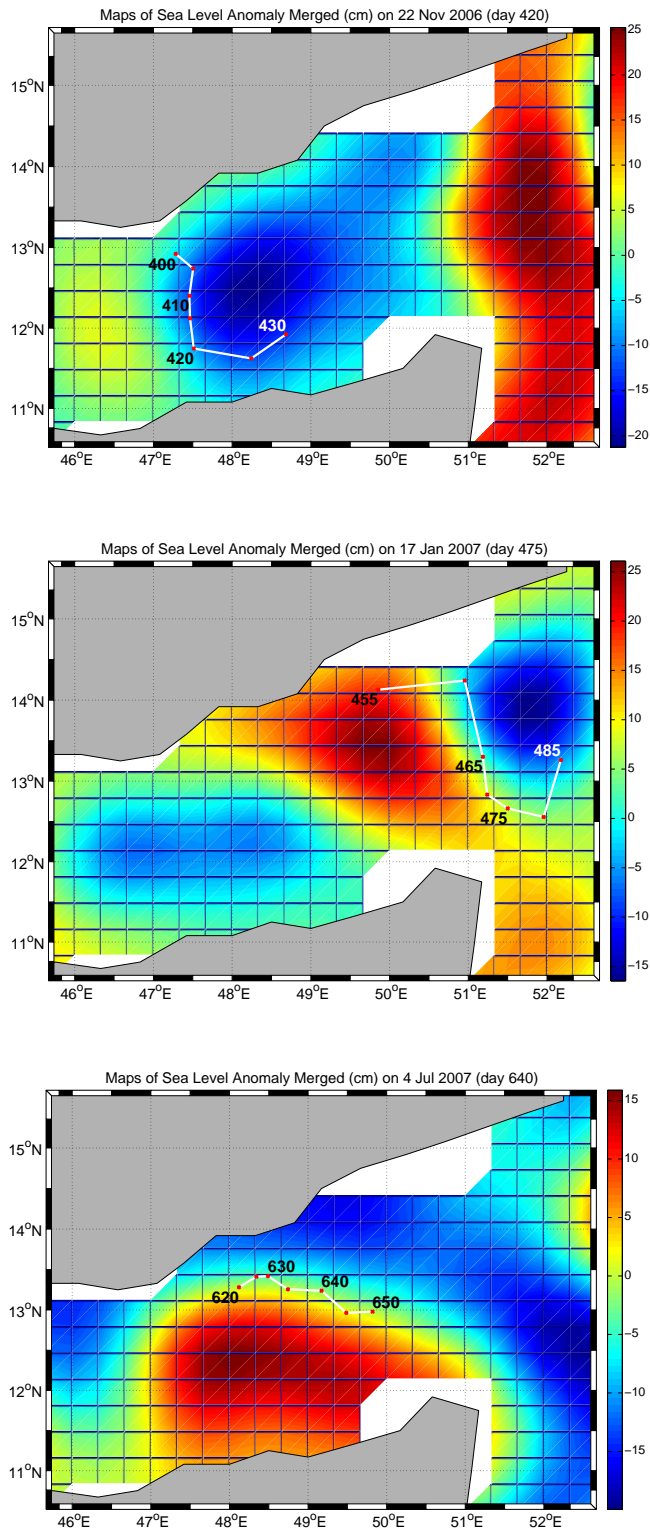
## 4 Arabian Sea

### 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 days.

During the first year, the float drifted northeastward to 56° E, 13° N and then northwestward to 54°30' E, 14° N within about 100 days (see Fig. 13). It remained stationary near this position for about two months, then it performed a cyclonic loop between this position and 56° E and 15° N. After day 250, it followed a large anticyclonic loop (with strong zonal predominance) up to 58° E and to 17°30' N for





**Fig. 11.** From top to bottom, sea-level anomaly (SLA) maps of 22 November 2006, 17 January 2007 and 4 July 2007 (days 420, 475 and 640 of the mission). The trajectory of float 2900392 for year 2 is superimposed. Dots indicate the position of the float every 5 days. Mission days are indicated next to the dots.

the last three months of its first year. The three main peaks of the kinetic energy distribution (not shown) are at 50, 90 and 160 km. Another peak lies at 220 km. The smaller scales correspond to the motion of the float from day 50 to 250; the larger scale motions occur at days 0 to 50 and 250 to 350. The angular distribution has maxima at  $+25^\circ$  and  $+45^\circ$  and at  $-55^\circ$ . This can be simply correlated with the trajectory, the former two for the drift at days 0–50 and 250–350 and for the orientation of the loop at days 150–200, and the latter for the segments of trajectory at days 250–260 and 300–310.

The temperature and salinity sections along the trajectory show evidence of a cooling and of a freshening of the surface layer in August and September 2006 (days 140 to 200 of the mission), a priori in relation with strong summer monsoon winds (see Fig. 14).

At depths between 300 and 800 m, a core of cold and fresh water was sampled by the float between days 0 to 20, 180 to 210 and 260 to 270. With temperatures of 8 to 12 °C and salinities of 35.1 to 35.4, this was likely ICW.

At depths between 400 and 900 m, two cores of warm and salty Red Sea Outflow Water were present from day 30 to 60, and from day 140 to 160. The first warm core was located east of Socotra, near the continental slope; this core of RSOW flowed around the island. The salinity and temperature at 700 m depth were about 35.9 and 12 °C. Similar maxima were found again near day 160, at the same depth, as the float was much farther north (near  $55^\circ 30' E$ ,  $14^\circ 10' N$ ). At that time, the float performed a cyclonic loop, and a cold core was sampled on the northern part of this loop. We interpret these two events as the advection of a detached fragment of RSOW by a cyclonic gyre.

Finally, in January–February 2007, a weak signature of Persian Gulf Water ( $T \sim 18^\circ C$ ,  $S \sim 35.9$  at depths near 200–300 m) was sampled by the float, as it came near Ras al Madrakah (near  $57^\circ 50' E$ ,  $19^\circ N$ ).

In the altimetric map, a cyclonic surface signature was present between days 180 and 210 when the float followed a cyclonic trajectory near  $55^\circ 30' E$ ,  $14^\circ 20' N$  (see Fig. 15). Early January 2007, the anticyclonic loop of the float near  $57^\circ E$ ,  $16^\circ N$  was also related to an anticyclonic sea level anomaly. Though the correspondence between float trajectory and SLA was not as strong as in the Gulf of Aden, the deep motion of the float could still be correlated with the surface motion at horizontal scales of 100 to 200 km, in this region.

During year 2, float 2900104 performed successively a cyclonic, an anticyclonic and a cyclonic loop, for about 40 days each, in a general northeastward direction (towards Ras ash Sharbatat (near  $57^\circ E$ ,  $18^\circ N$ ; see Fig. 16)). After about 150 days, the float followed a cyclonic loop northwestwards this cape (for about 3 months), and then an anticyclonic loop northeastward for about two months. The end of its trajectory (for year 2) was southwestward.

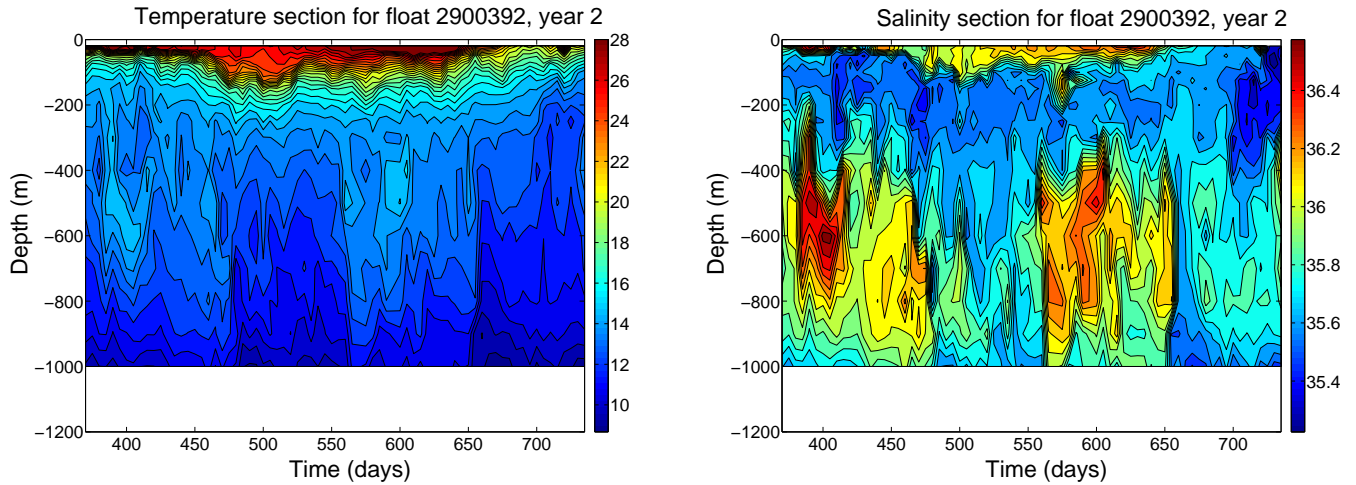


Fig. 12. Vertical sections of temperature (in °C, left) and of salinity (right) along float 2900392 trajectory for year 2.

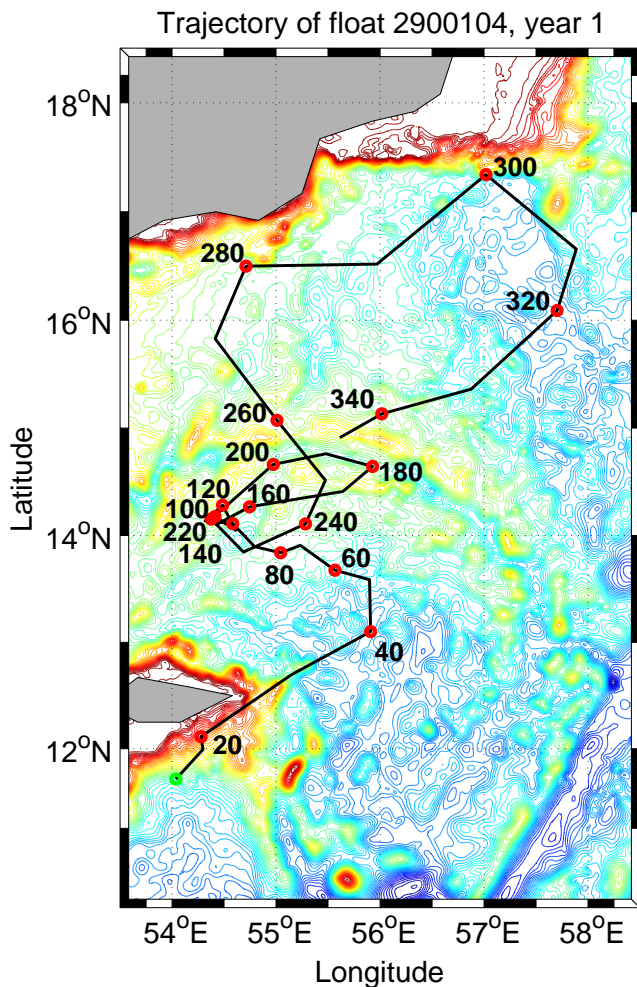


Fig. 13. Trajectory of float 2900104 in the Arabian Sea, superimposed on bathymetry, year 1; the black dot is the starting point of the trajectory; positions every 20 days are indicated by a red dot.

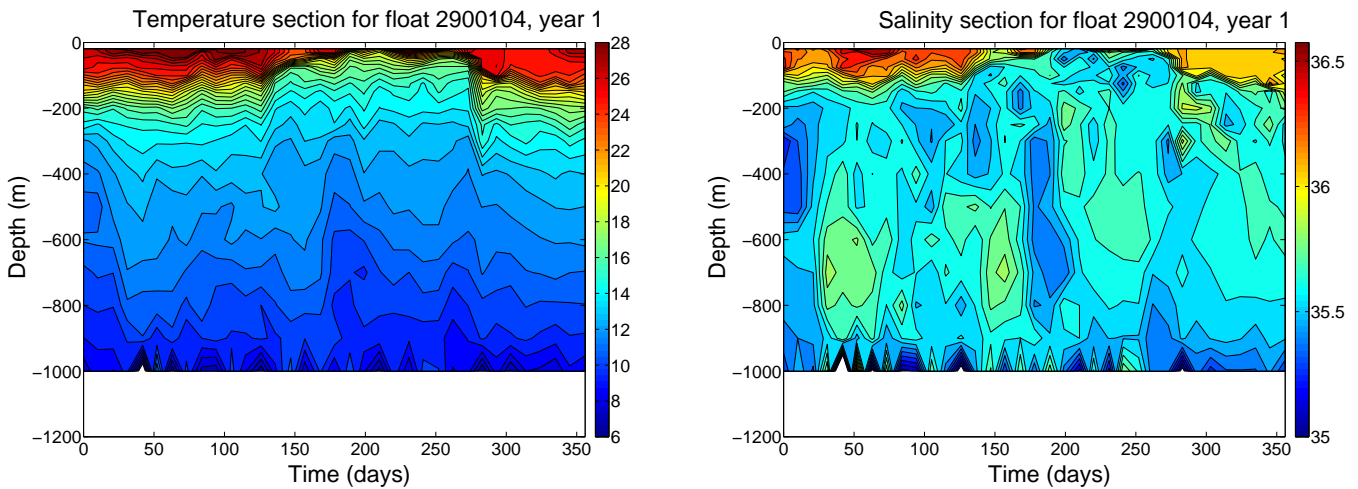
The energy peaks (not shown) are located at 50, 80, 120, 160 km horizontal scales, and with a smaller amplitude, at 220, 270, 320 and 410 km. The former four peaks correspond to the float motion between days 500 and 650 while the latter four correspond to the larger scale displacements near the beginning and end of this second year of mission (days 365–500 and 650–730). The energy distribution with respect to the orientation (not shown) peaks by far at a 25° angle, corresponding to the large scale ENE-WSW displacements of the float with the monsoon currents.

Only a weak correlation was found between this float trajectory and bathymetry, except at days 400–450 and 600–650, but mostly over the abyssal plain. In fact, the correlation over the abyssal plain may be due to regional gyres (at 100 km scale), which remain east and west of Ras al Madrasah for long periods of time. When a float is trapped in these gyres, it remains over the abyssal plain and does not cross isobaths.

For this float, surface-depth correlations of motions were found at horizontal scales of 200 km, but those at 50 km scale were not always clear. At larger horizontal scales, (400–500 km), the float trajectory reflected the monsoon currents.

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. 17). This water mass was thus found east of Ras ash Sharbatat and south of Ras al Madrasah, for the first two periods, and south of Ras ash Sharbatat for the latter. The stronger salinities for PGW were found in November and in January.

This indicates that (a) PGW can flow southwestward 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.



**Fig. 14.** Vertical sections of temperature (in °C, left) and of salinity (right) along float 2900104 trajectory for year 1.

Colder and fresher waters were also identified at 200 m depth around day 550 (early September 2007) and day 620 (mid November 2007). Indeed, in September, upwellings can develop near Ras ash Sharbatat and bring colder and fresher waters upward.

On the contrary, in November, isotherms rose above 300 m depth, but dived below 600 m depth. This structure of the isotherms, the values of temperature and salinity at depths between 300 and 600 m, and the anticyclonic loop in the float trajectory, point towards the existence of a deep anticyclone of ICW at that time and location. This anticyclone may have been generated earlier by the instability of the northeastward current along the southern coast of Oman (see also Lee et al., 2000).

#### 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 degrees east.

Its initial trajectory was mostly southwestward, in accordance with the monsoon current direction (see Fig. 18). On this global drift, two cyclonic loops were superimposed, one between days 35 and 50 and near 55° E, 14° N, the other one between days 80 and 100 and near 52°30' E, 14° N. After 100 days, the float drifted back to the Northeast along the coast of Oman, perhaps in relation with an early reversal of the monsoon current.

The energy distribution with distances (not shown) has peaks at 30, 100 and 150 km horizontal scales, in agreement with the small and large loops and with the ENE-WSW displacements. In the angular distribution, the energy maxima lie at +30°, -35°, +65° and -75°. The first orientation is

clearly related to the large-scale motion with the monsoon currents.

The angle between the trajectory and the isobaths (see Fig. 19) was most often small because the float crossed few topographic anomalies or flows along the continental slope. Nevertheless, the bottom topography did not seem to steer the float motion, but the currents with surface expression, or the anomalous water masses, did (see below).

The temperature and salinity sections of this float show the presence of PGW at 200 m depth during the first 20 days of the mission, south of Ras ash Sharbatat (near 57° E, 18° N); this was most likely a fragment detached from the PGW outflow (see Fig. 20). Between days 32 and 50 (during the first loop in the trajectory), no deep thermohaline maximum appeared. But a noticeable RSOW signature was visible during the second loop and once the float drifted eastward, along the continental slope, towards 54°40' E, 16° N.

Again, there was a good correlation of the float trajectory with the SLA (see Fig. 21). Both cyclonic loops circled around surface depressions (days 36 and 72 of the mission) and the final clockwise motion of the float wrapped around a surface elevation (days 92 of the mission).

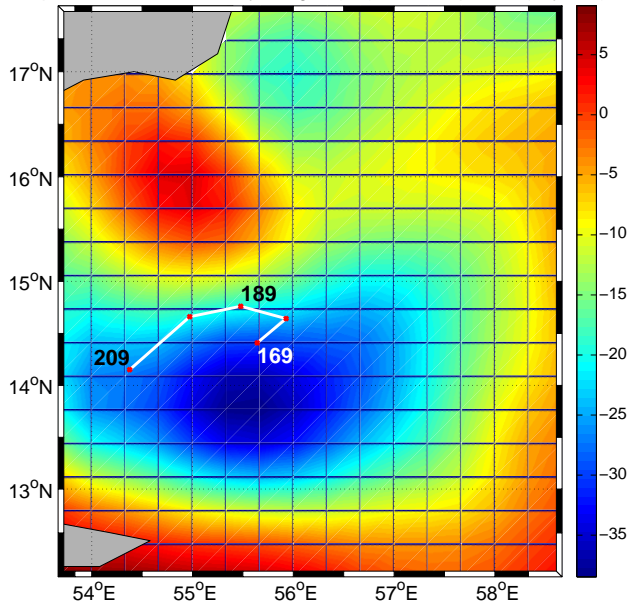
#### 4.3 Float 2900394

This float was released on 27 June 2005 at 62°33' E, 20°50' N but a positioning problem occurred for the first 10 days. Then, the trajectory was correct, but a major drift occurred in temperature data for 40 days. Therefore the data were analysed only from day 50 onward. This float had a 5-day cycle.

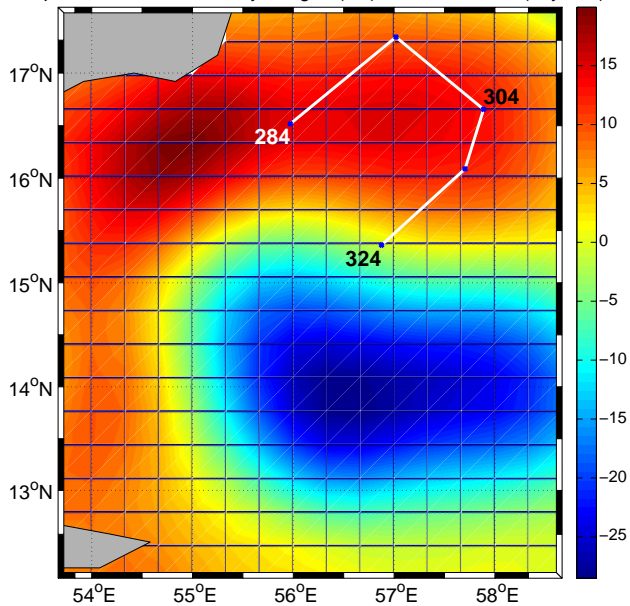
Float 2900394 performed a series of anticyclonic loops between 63°30' E and 64°30' E and 19°30' N and 21° N for about 240 days starting from day 50 (see Fig. 22). The abrupt shift to the south between days 175 and 185 may be a positioning problem. Then, to the end of year 1, the



Maps of Sea Level Anomaly Merged (cm) on 20 Sep 2006 (day 189)



Maps of Sea Level Anomaly Merged (cm) on 10 Jan 2007 (day 304)

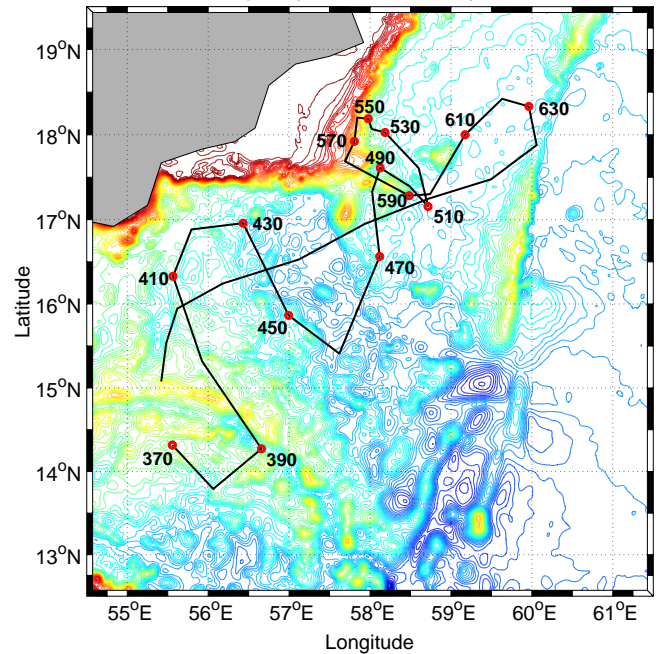


**Fig. 15.** Altimetric maps of 6 September 2006 (day 189 of the mission) and of 7 January 2007 (day 304 of the mission), with the trajectory of float 2900104 superimposed. Dots indicate the position of the float every 10 days.

float followed an anticyclonic trajectory from 64° E, 20° N to 65°30' E, 19° N and back to 63°30' E, 18°30' N.

The angle between the trajectory and the bathymetry varied rapidly with time, and did not indicate a durable correlation. The energy distribution with distance indicates a peak at 25 km, related to the small loops performed by the float (not shown). Its distribution with respect to the angle has peaks at

Trajectory of float 2900104, year 2



**Fig. 16.** Trajectory of float 2900104 in the Arabian Sea, superimposed on bathymetry, year 2. A red dot indicates the position of the float every 20 days.

$\pm 85^\circ$ , related to the meridional motion. Other peaks at  $\pm 20^\circ$  and  $\pm 40^\circ$  have smaller amplitudes.

The thermohaline anomalies identified during this period were located between 150 and 350 m depths (see Fig. 23). Warm and salty water (17–18°C, 36.2–36.4) was observed at days 50–100, 150–240 and 270–320. This was clearly PGW and it was concentrated near 20–21° N, 63°30' E–64°30' E. Considering the float motion, this may have been an eddy of PGW. On the contrary, a cold and fresh anomaly was sampled around day 340. This water may have originated from the Ras al Madrasah upwelling which was active then.

The altimetric maps during the September 2005–April 2006 period, in the 63–65° E, 18–21° N region, did 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 were more related to the deep, warm and salty water masses, that it encountered.

During the second year, the trajectory of float 2900394 was 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. 24). This repeated southeastward drift of float 2900394 indicates the presence of a current in this direction, in summer, from the mouth of the Gulf of Oman. This current is a priori the Ras al Hadd jet. The correlation with altimetry was more durable for the large cyclonic motions. The vertical sections of temperature and of salinity showed again three blobs of PGW at days 420–510, 550–600, 650–680 (see Fig. 25). During the first time

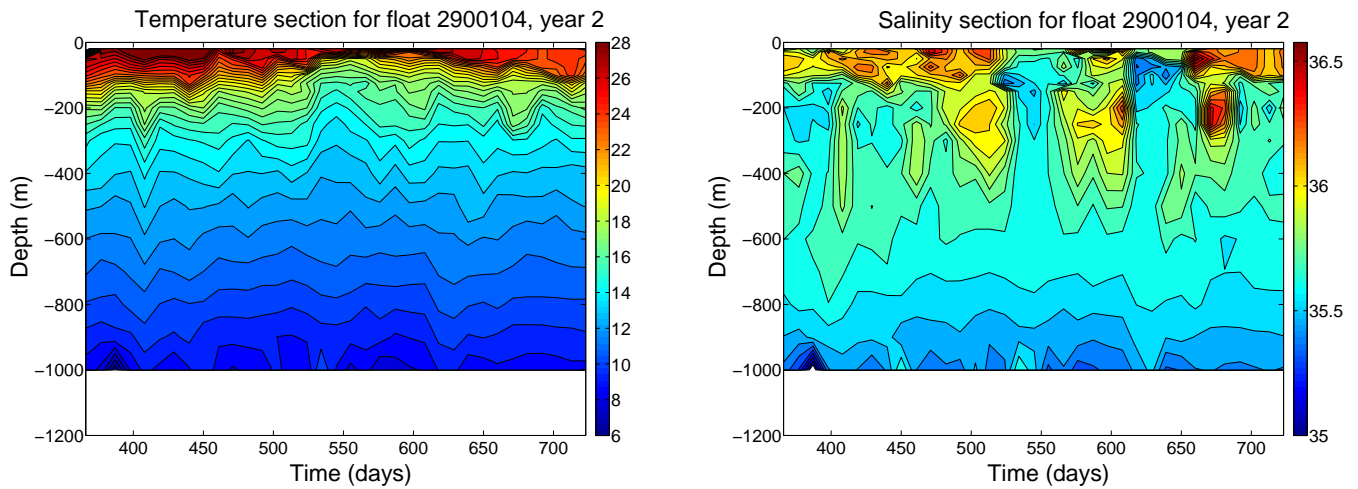


Fig. 17. Vertical sections of temperature (in °C, left) and of salinity (right) along float 2900104 trajectory for year 2.

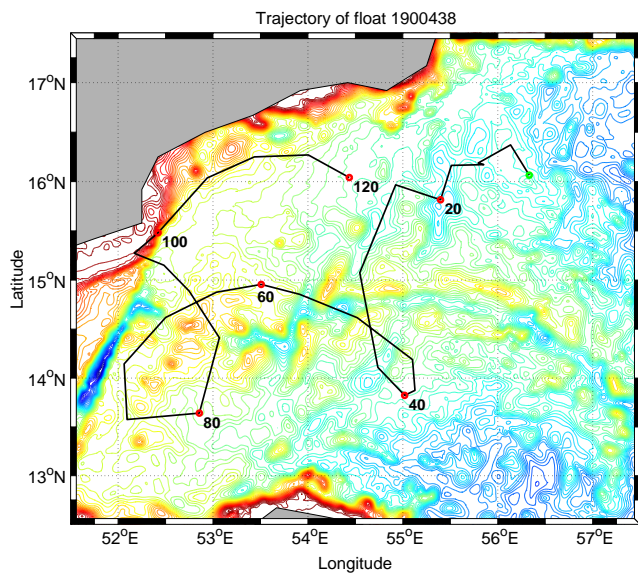


Fig. 18. Trajectory of float 1900438 in the Arabian Sea, superimposed on bathymetry. A green dot indicates the initial position of the float; red dots mark the position of the float every 20 days.

interval, a small anticyclonic loop was achieved by the float; two cyclonic loops were performed during the two other periods.

### 5 Discussion

Here, we discuss two points which concern all floats: the dependence of the spatial distribution of kinetic energy with respect to location or time, and the correlation of temperature and salinity measurements by the floats with the regional climatology.

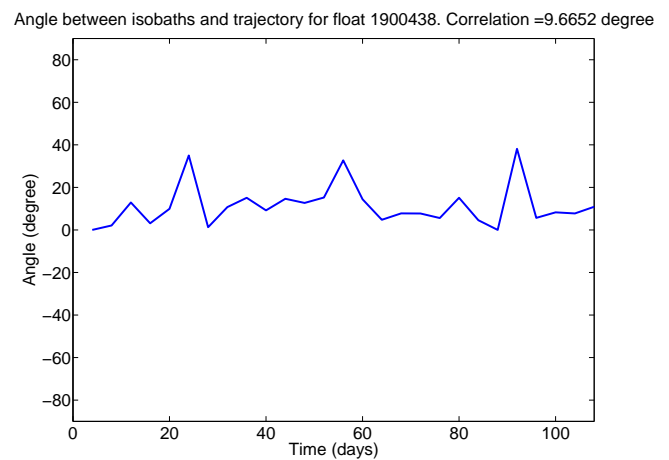


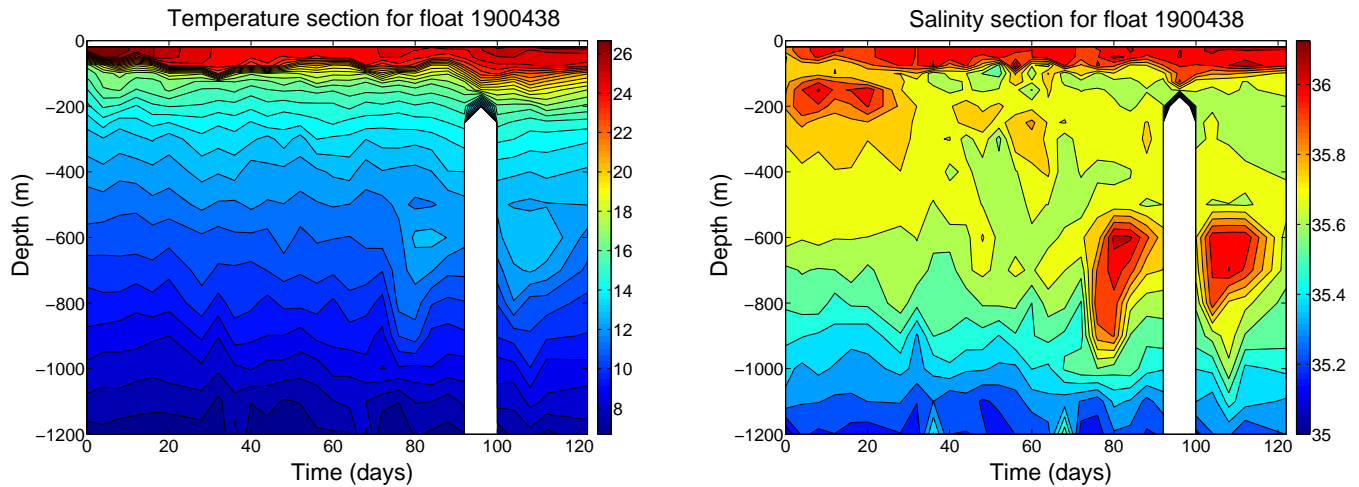
Fig. 19. Angle between the isobaths and the trajectory of float 1900438 with respect to time.

Firstly, we study the homogeneity, isotropy and stationarity of the kinetic energy distributions.

In the Gulf of Aden, these distributions for the two floats concerned, for each year, and even for each season, showed the following: The distribution with respect to the distance had three peaks, at 30, 60 and 160 km, this latter being slightly less marked during the summer. The annual distributions with respect to the angle had peaks at  $\pm 20^\circ$ ,  $+60^\circ$ ,  $-40^\circ$ , and  $-80^\circ$ , while the seasonal distribution had peaks at  $+20^\circ$ ,  $+60^\circ$  in summer and at  $-20^\circ$  and  $-80^\circ$  in winter.

From this we can conclude that the same scales of motion were present in both seasons and at different locations in the Gulf, mostly due to the gyres which occupied it. Though our database is limited, so that conclusions are difficult to draw for the orientation of the trajectories with respect to seasons, we observed twice a westward-southwestward current (angle of  $+20^\circ$ ) along the coast of Yemen at the end of





**Fig. 20.** Vertical sections of temperature (in °C, left) and of salinity (right) along float 1900438 trajectory.

the winter monsoon. This can be related with the presence of cyclones at this location, already described by Bower and Furey (2011).

In the Arabian Sea, the peaks in the distribution of kinetic energy with respect to distance were found at 30, 60, 100 and 150 km, except for float 2900394 for which the energy was concentrated by far at the 20–25 km scale. The peaks at scales of 60 and 100 km were related to gyre motion.

Concerning the orientation of motion, the energy peaks at  $+20^\circ$  to  $+40^\circ$  were present for all floats. This peak was usually related to large scale displacements on seasonal time scales (related to monsoon currents). Other peaks were related to gyre motions or to local currents such as the Ras al Hadd jet.

Therefore, there was similarity in the dominant scales of motion between floats in the Arabian Sea, but also between the Arabian Sea and the Gulf of Aden.

Secondly, we compare the vertical sections of temperature and salinity obtained by the floats to the climatological temperature and salinity maps at 300 and 600 m depth (the depth of PGW and RSOW or ICW). These maps are given in appendix (see Figs. A1 and A2).

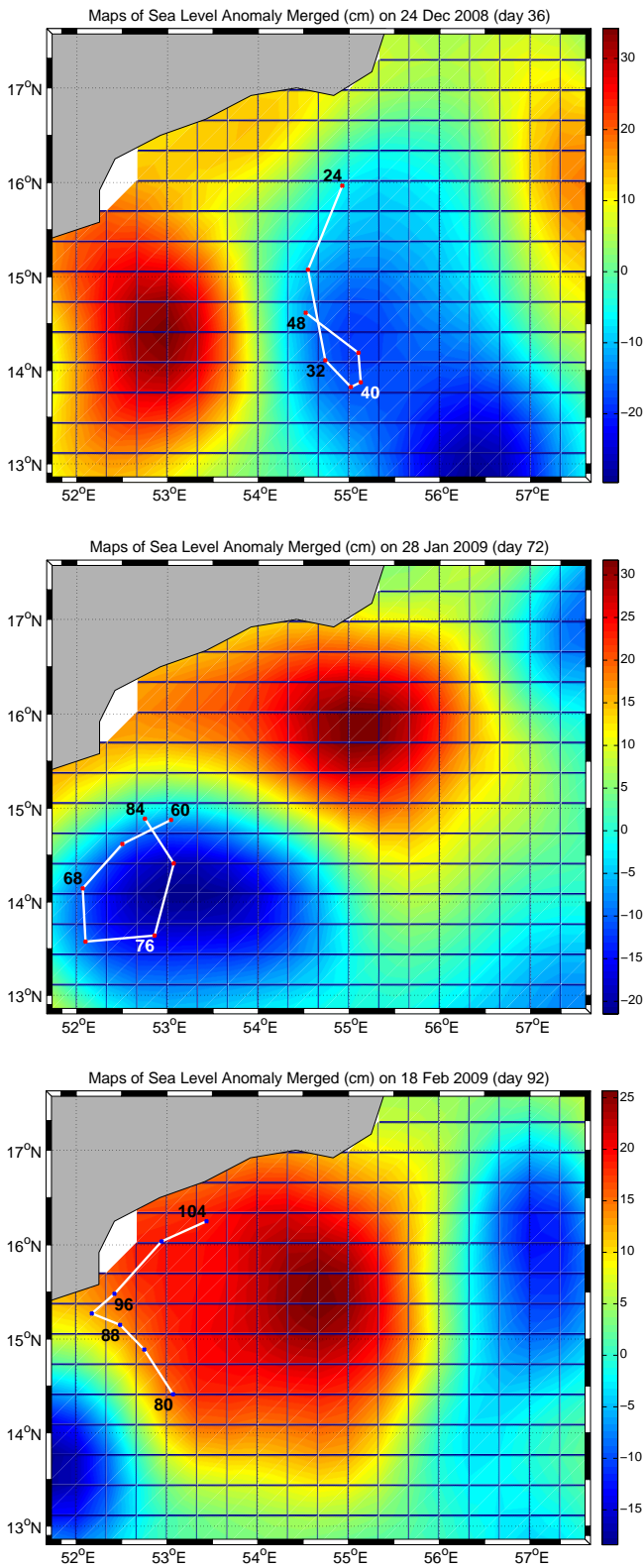
In the Gulf of Aden, the climatological maps show a zonal gradient of temperature and salinity, which intensifies in May. This gradient is shifted eastward and is weaker in November. During the 160 days of its mission, float 1900432 measured a maximum thermohaline gradient near  $46^\circ 30' E$  as in the climatology. Float 2900392 evolved mostly east of this longitude and was thus located in a region of weaker salinity anomaly. From January to May, the climatology indicates that the warm and salty water at 600 m depth and east of  $46^\circ 30' E$ , extends eastward along the coast of Yemen. Later in the year, this eastward extension occurs rather along the coast of Somali. For years 1 and 2, float 2900392 resided more often in the northern part of the Gulf of Aden. Thus it showed stronger salinity anomalies from September to

March than later in the year. During year 2, float 2900392 showed salinity maxima at days 400 and 600 at its westernmost position in the Gulf (near  $47^\circ E$ ).

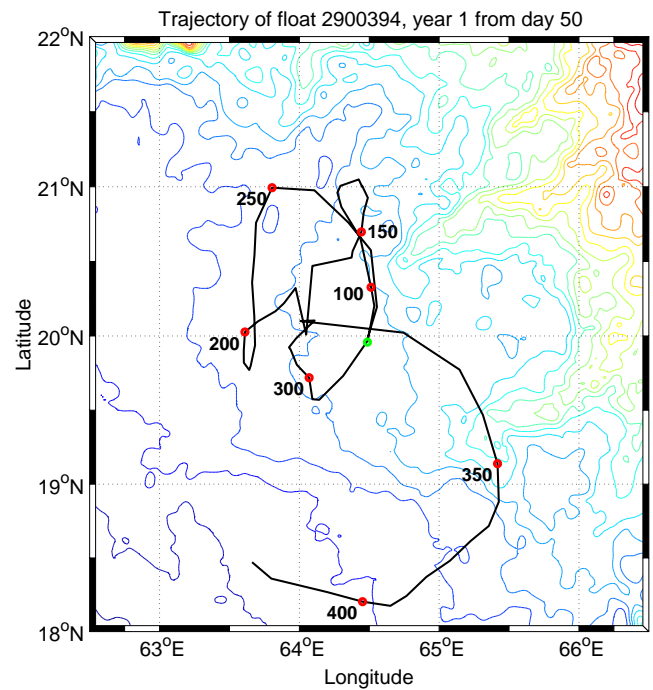
In the Arabian Sea, a positive salinity anomaly is observed in the climatology north of Socotra, at 600 m depth; this anomaly is most marked in July. Float 2900104 also indicated a salinity anomaly near  $14^\circ N$ ,  $54\text{--}56^\circ E$  at this depth and in May–September (year 1). The same float measured a PGW anomaly near Ras al Madrasah in mid January (year 1); the climatological salinity map at 300 m also shows a wide extent of the PGW plume at this location in January (see Fig. A). Float 2900104 showed again strong salinity anomalies at 300 m depth in early August, mid November and in January (year 2). Climatology indicates that this is the period of maximum extent of PGW along the southern coast of Oman. PGW was also measured by float 1900438 off Ras ash Sharbatat in November; this corresponds to the large extent of PGW in the climatology at that time. The same float sampled RSOW near  $53^\circ E$  and  $14\text{--}15^\circ N$  in January, again at a time of wide extent of RSOW along the coast of Yemen, in the climatology. Finally, float 2900394 sampled PGW near  $64^\circ E$ , both during year 1 (near  $20\text{--}21^\circ N$ ) and during year 2 (near  $16\text{--}17^\circ N$ ), except in March–May. Climatology indicates that PGW extends south of  $20^\circ N$  at  $64^\circ E$  except in March–May.

## 6 Conclusions

The data from five profiling floats in the Gulf of Aden and in the Arabian Sea have been analysed. Their trajectories and thermohaline anomalies at depth have been compared with surface motions, with bathymetry and with climatological water masses.



**Fig. 21.** From top to bottom, sea-level anomaly (SLA) maps of 24 December 2008, 28 January and 19 February 2009 (days 36, 72 and 92 of the mission) with the trajectory of float 1900438 super-imposed. Dots correspond to the position of this float every 4 days. Mission days are indicated next to the dots.



**Fig. 22.** Trajectory of float 2900394, for year 1 from day 50, super-imposed on bathymetry. A green dot indicates the initial position of the float; red dots mark the position of the float every 50 days.

Clearly, if a strong correlation between surface and deeper motions could often be established at 100–200 km scale, loops with 30–40 km diameter, performed by the floats were not sampled by altimetry, due to its resolution. Some of these small loops could be correlated with thermohaline anomalies at the same scale and at the depth of PGW or of RSOW. The float trajectories also reflected the large-scale wind-induced circulation.

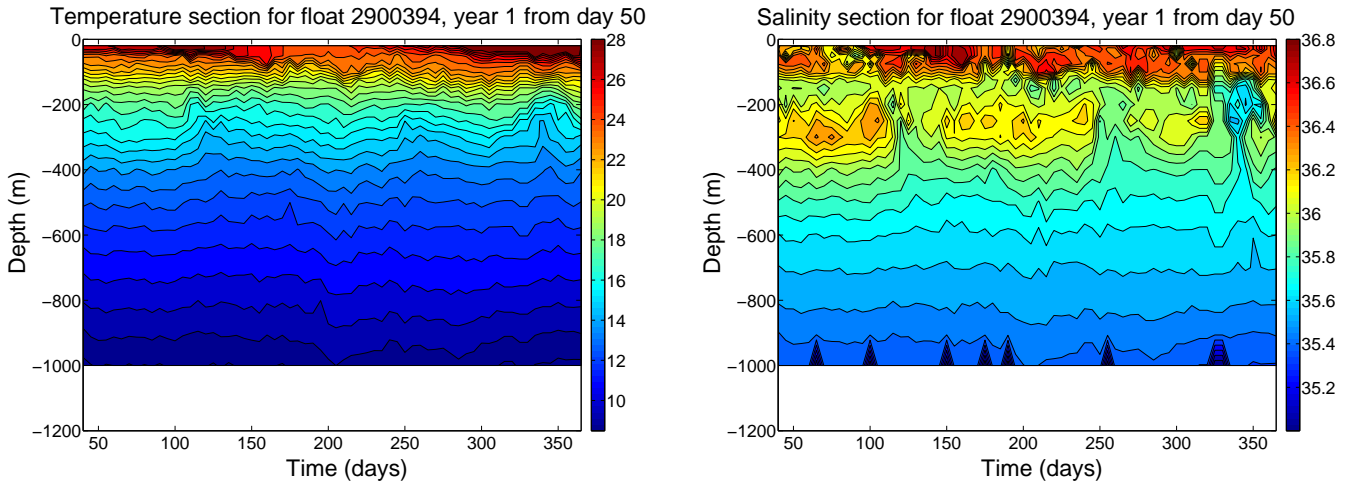


Fig. 23. Vertical sections of temperature (in °C, left) and of salinity (right) along float 2900394 trajectory for year 1 from day 50.

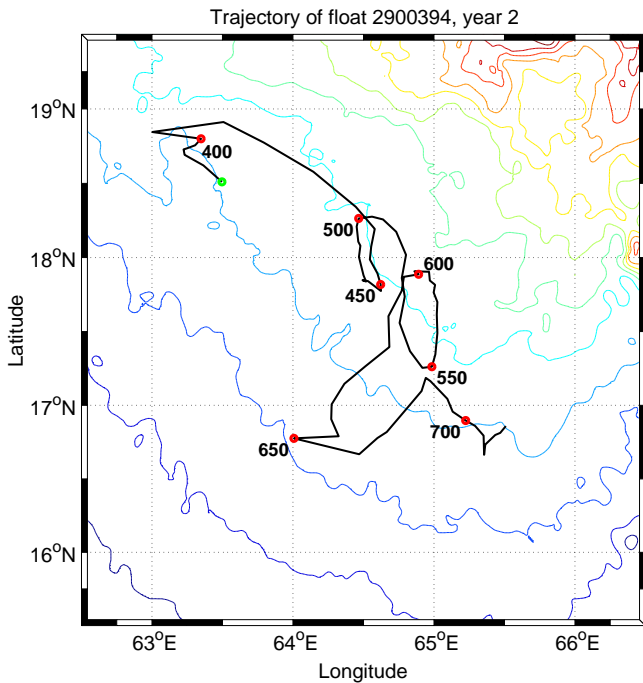


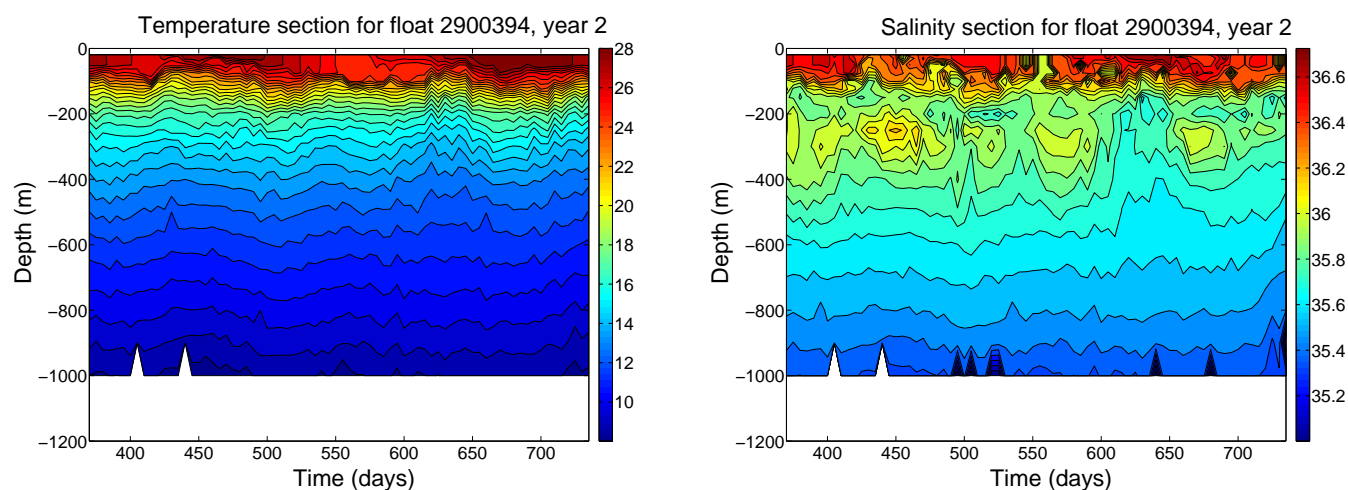
Fig. 24. Trajectory of float 2900394, for year 2, superimposed on bathymetry. A green dot indicates the initial position of the float; red dots mark the position of the float every 50 days.

In summary, the circulation in the Gulf of Aden is clearly composed of cyclonic and anticyclonic gyres at regional scale, observed in SLA, as mentioned in the literature, and with a barotropic character. The circulation in the Arabian Sea is also influenced by mesoscale gyres near the coast of Oman, which are well observed in altimetric data. More south, the circulation is complex and the float trajectories are less well correlated with SLA.

The scale and angular distribution of kinetic energy represents quite faithfully the different elements of the float trajectories. This distribution has common features from float to float or from year to year in a given region.

The correlation of the float trajectories with bathymetry was poor, except in one case; but this event may have been related to a quasi-stationary gyre located in a region of weak bathymetric anomalies.

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 by the floats was the appearance of colder and fresher water masses at 200 m depths, a priori related to upwelling events. Deeper cold and fresh water masses (e.g. between 500 and 800 m depths) were observed under the form of deep eddies or fragments of ICW.



**Fig. 25.** Vertical sections of temperature (in °C, left) and of salinity (right) along float 2900394 trajectory for year 2.

Intense thermohaline anomalies were measured at the depths of PGW or of RSOW.

In the Gulf of Aden, temperature and salinity peaks of 16 °C and 36.5 were observed in the RSOW. The RSOW signal measured by floats intensified notably when the float circulated cyclonically in the western Gulf of Aden. This was well related to climatology also. The float recordings allowed us to identify the outflow of RSOW from the Gulf of Aden on the continental slope near 55° E and 13° N. It also showed evidence of detached fragments of RSOW north of that location (near 14°30' N).

In the Arabian Sea, temperature and salinity peaks of 19 °C and 36.5 were observed in the PGW at 300 m depth. The PGW signal was observed near Ras al Hadd and Ras al Madrasah/Ras ash Sharbatat. This indicates that, under favorable conditions of monsoonal currents (in winter), the PGW outflow can veer around Ras al Hadd and extend southwest along the southern coast of Oman. Our observations also showed little PGW west of Ras ash Sharbatat. On the contrary, during summer, the PGW was exported southeastward from the Gulf of Oman; the Ras al Hadd jet was likely to focus this export in this direction.

Again, the seasonal variations of RSOW and PGW extent were observed in the float measurements in the Arabian Sea.

Further work should investigate this water mass distribution with more floats.

## Appendix A

### Climatological maps of temperature and salinity at 300 and 600 m depth

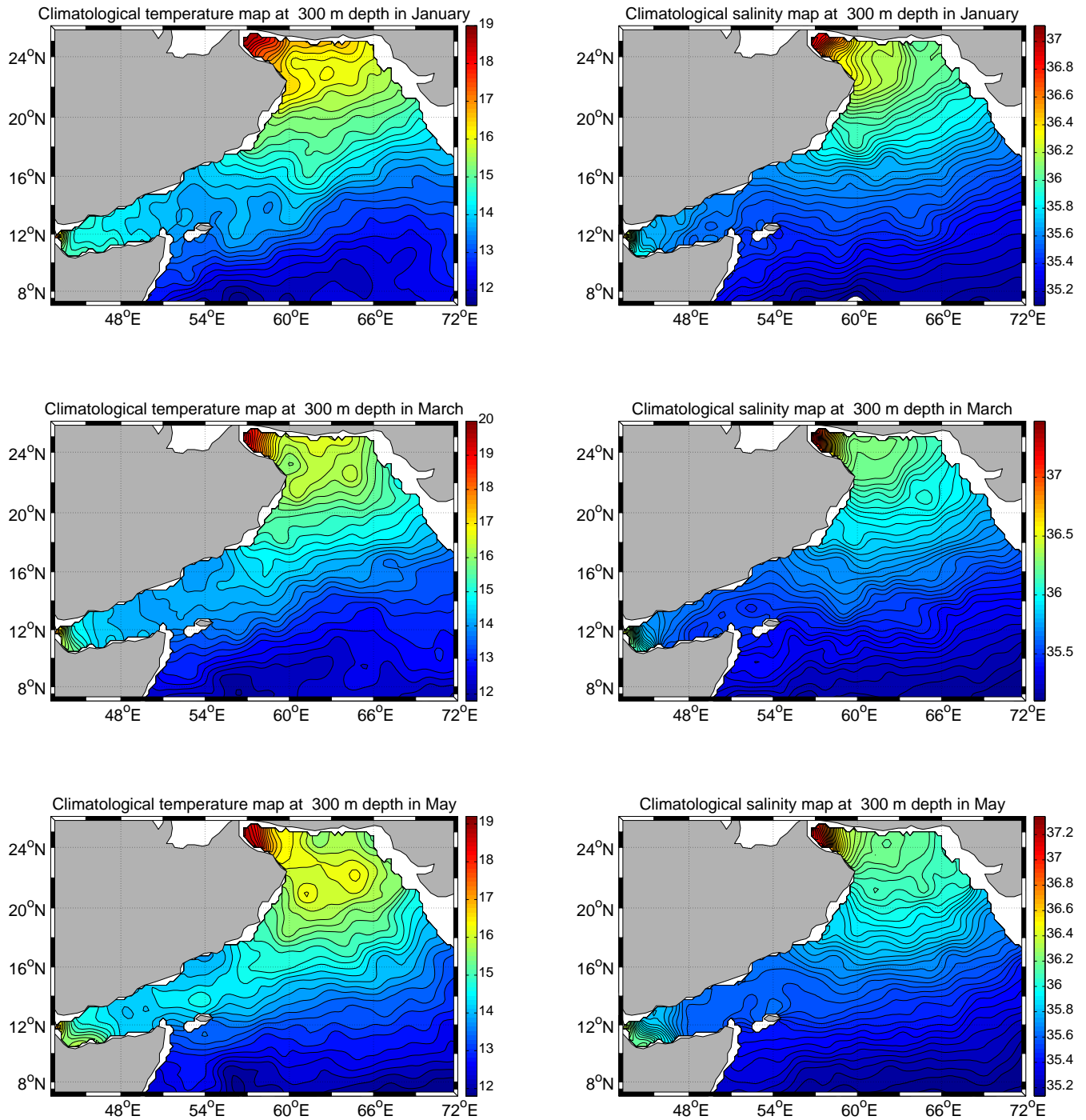
*Acknowledgements.* The authors are grateful to one referee whose fine remarks and suggestions considerably improved the presentation and contents of this paper. The authors thank the ARGO program (ARGO Regional Center for the Indian Ocean, INCOIS, Indian Government) for providing the hydrological data of the profiling floats, to the CNES/AVISO center (France) for the altimetric maps, and to the NGDC/MGG (USA) for the ETOPO2 bathymetry. Thanks are due to Amy Bower for fruitful discussions and suggestions. This work was supported by DGA under the “COMINO” and “SYNBIOS” projects.

Edited by: J. A. Johnson



The publication of this article is financed by CNRS-INSU.





**Fig. A1.** (Continued from previous page) Horizontal maps of temperature (in °C, left) and salinity (right) at 300 m depth for January, March, May, July, September, November (from top to bottom), from the climatology.



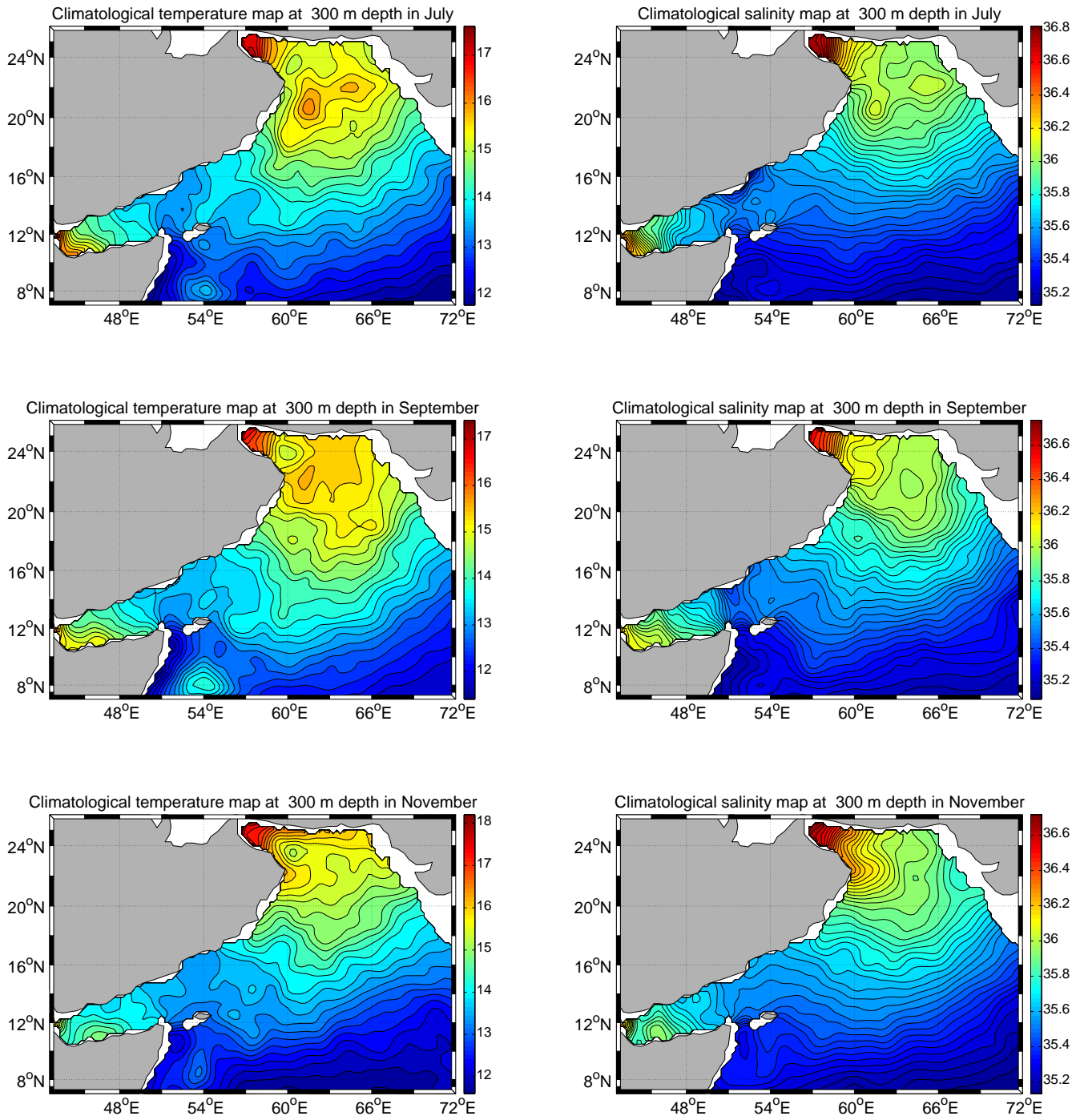
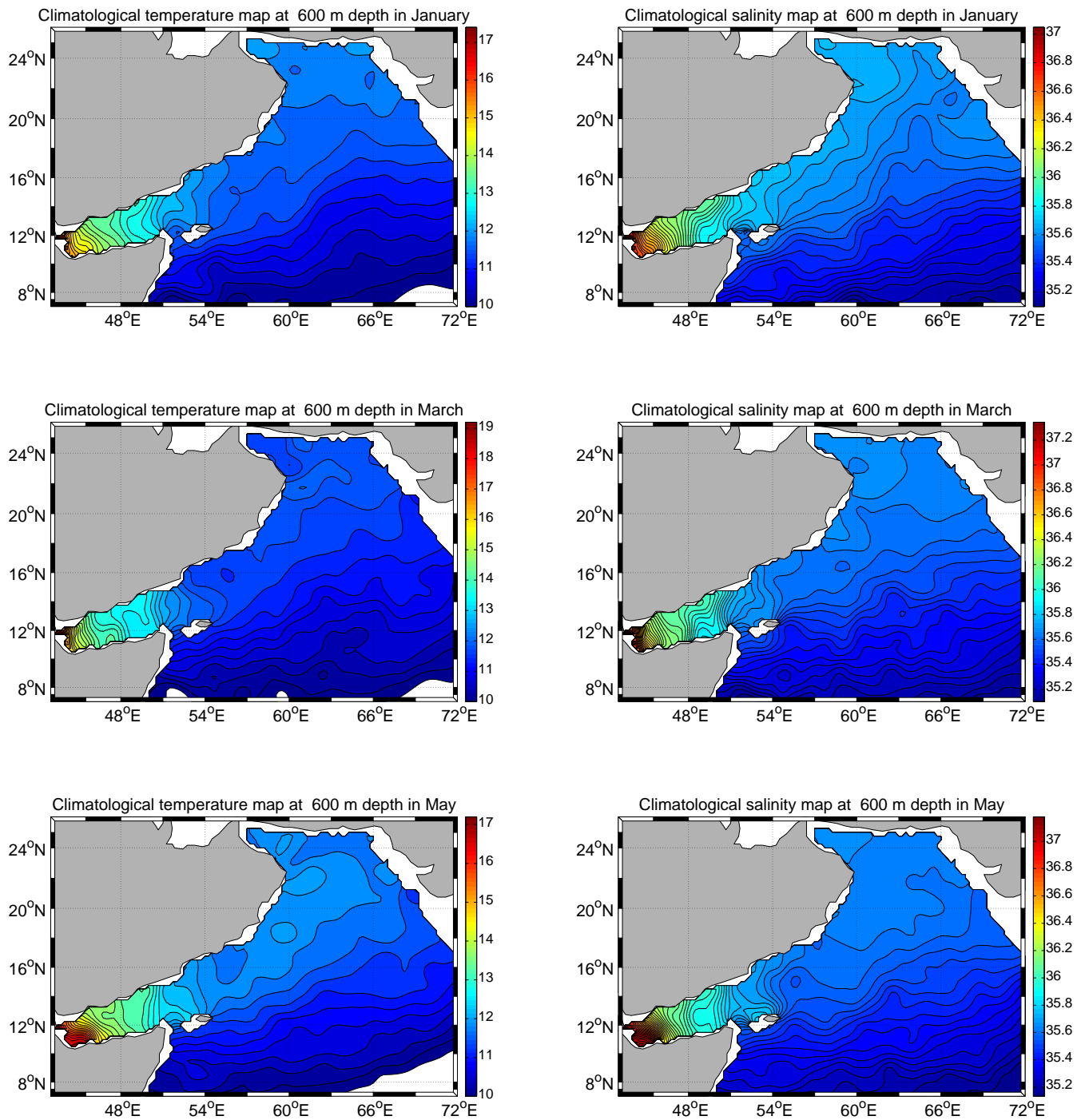


Fig. A1. Continued.



**Fig. A2.** (Continued from previous page) Horizontal maps of temperature (in °C, left) and salinity (right) at 600 m depth for January, March, May, July, September, November (from top to bottom), from the climatology.

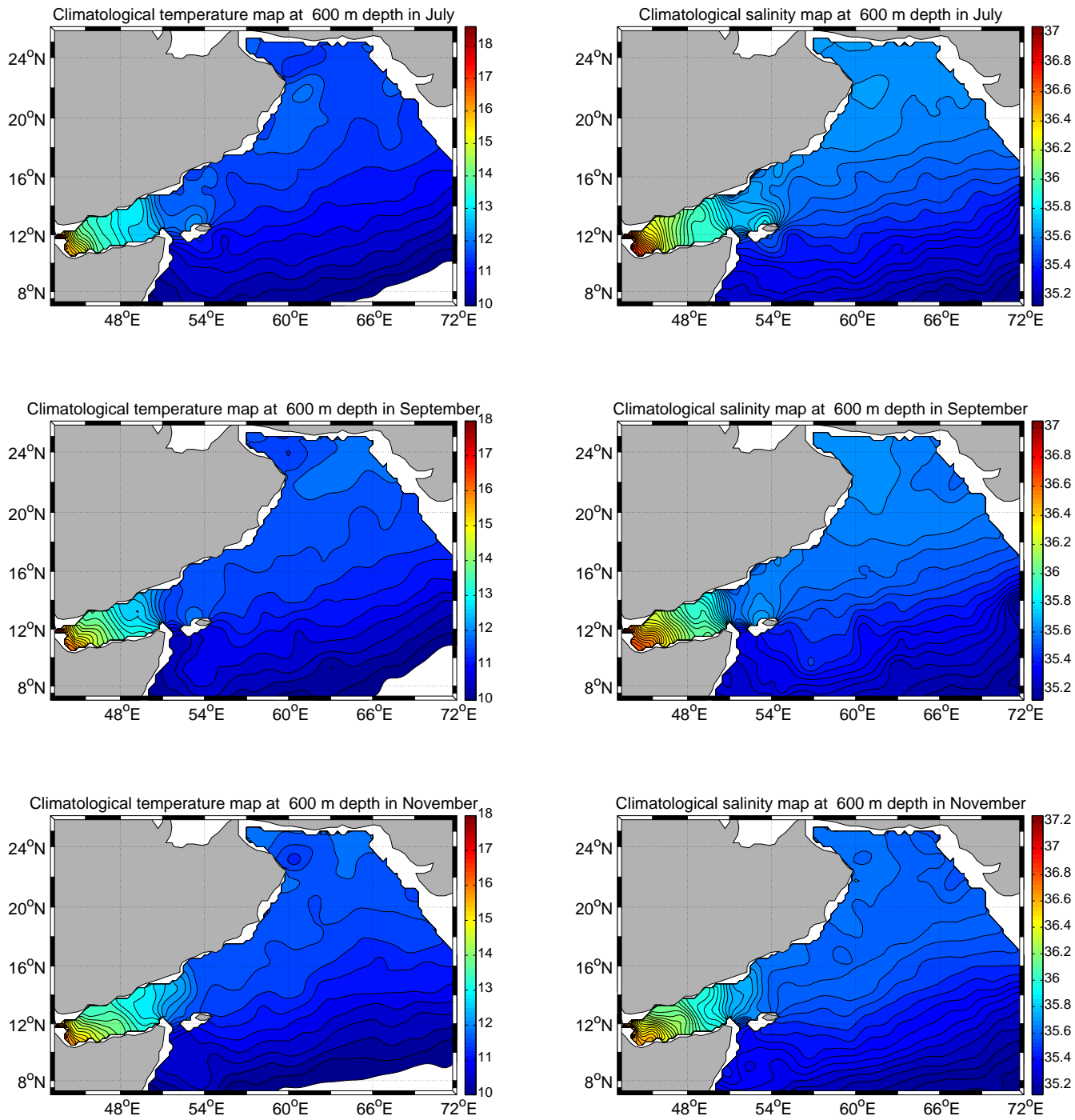


Fig. A2. Continued.

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