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Summer monsoon response of the northern Somali Current, 1995

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Abstract. Preliminary results on the development of the northern Somali Current regime and *Great Whirl* during the summer monsoon of 1995 are reported. They are based on the water mass and current profiling observations from three shipboard surveys of R/V *Meteor* and on the time series from a moored current-meter and ADCP array. The monsoon response of the GW was deep-reaching, to more than 1000m, involving large deep transports. The northern Somali Current was found to be disconnected from the interior Arabian Sea in latitude range 4°N – 12°N in both, water mass properties and current fields. Instead, communication dominantly occurs through the passages between Socotra and the African continent. From moored stations in the main passage a northward throughflow from the Somali Current to the Gulf of Aden of about 5 Sv was determined for the summer monsoon of 1995.

1. Introduction and background

The Somali Current is known to develop in different phases in response to the onset of the southwest monsoon [e.g. *Swallow et al.*, 1983; *Schott et al.*, 1990]. During the early phase of the monsoon, in May to early June, it crosses the equator and turns offshore at about 3°N. Part of it recirculates southward across the equator, forming a *Southern Gyre*, part of it flows eastwards at low latitudes. A marked cold-water wedge develops at the shore-ward shoulder of the offshore flow, 3°N – 5°N.

With the onset of the first strong southwest monsoon winds, typically in early to mid-June, a strong anticyclonic gyre, the *Great Whirl* (GW), develops in latitude range 5°N – 9°N, with a second cold wedge at its northwestern flank, where the flow turns offshore. The generation mechanism of the GW was determined to be by baroclinic Rossby waves, generated by the strong offshore anticyclonic windstress curl [*Schott and Quadfasel*, 1982]. The further development remained obscure. It seemed like there might have been years during which the two-gyre system of GW / *Southern Gyre* broke down and a single boundary current existed from the equator to the Horn of Africa [*Schott*, 1983], but the observational evidence for these occurrences was not very satisfactory. A third anticyclonic gyre appears to be typical for the late phase of the southwest monsoon. It is located northeast of the island of Socotra and therefore called the *Socotra Gyre* (SG) [*Bruce*, 1979]. Nothing is known yet on its generation mechanism.

In the latest observations prior to the WOCE 1995 expedition, carried out in summer 1993 [*Fischer et al.*, 1996], two important features of the northern Somali Current system were observed, that had not been previously reported: first, a significant northward flow (of some 13 Sv) through the passage between the island of Abd al Kuri and the mainland (for location and topography see Figures 1, 2), called *Socotra Passage* in the following; and second, a band of northward warmwater flow east of the GW, that provided inflow of low-latitude waters both into the SG and into the *Socotra Passage*. This meridional warmwater band, traceable by satellite SST anomalies from 4°N – 13°N, appeared to decouple the GW from the interior of the Arabian Sea, allowing exchanges between the waters off Somalia and the Arabian Sea at large only through the Socotra Passage and the shallows between Abd al Kuri and Socotra([*Fischer et al.*, 1996]).

To investigate the development of the northern Somali Current and its exchanges with the interior of the Arabian Sea, three shipboard surveys were carried out off Somalia during April to September 1995 with R/V *Meteor* two of which are shown in Figure 1. Further, a moored array of current meters and upward-looking ADCPs was deployed across the northern Somali Current south of Socotra (Figure 2).

In the following, preliminary results on the development of currents and transports of the northern Somali Current regime during the summer monsoon of 1995 will be briefly reviewed on the background of the above described earlier findings.

2. Shipboard observations

Shipboard water mass observations consisted of Neill-Brown CTDO_2 and Freon measurements, current profiles were obtained by shipboard and lowered ADCP and by Pegasus profiler. Unfortunately the surveys had to be kept outside the Somali EEZ.

2.1. The early monsoon onset

The summer monsoon onset 1995 off northern Somalia was characterized by a first burst in the second half of May, then slackening into late May, and final onset of full-strength monsoon winds around 10 June, about a week later than in 1993 and 1994 (Kindle, *pers. communication, 1997*). The near-surface current patterns of the surveys in June/July and Aug./Sept. are shown in Figures 1 a,b, where water masses are indicated by salinity classes. Both maps reveal a water mass distinction between the near equatorial and the northern circulation regimes. In June, the southern offshore-flowing branch, at 1°N to 3°N, was strongly

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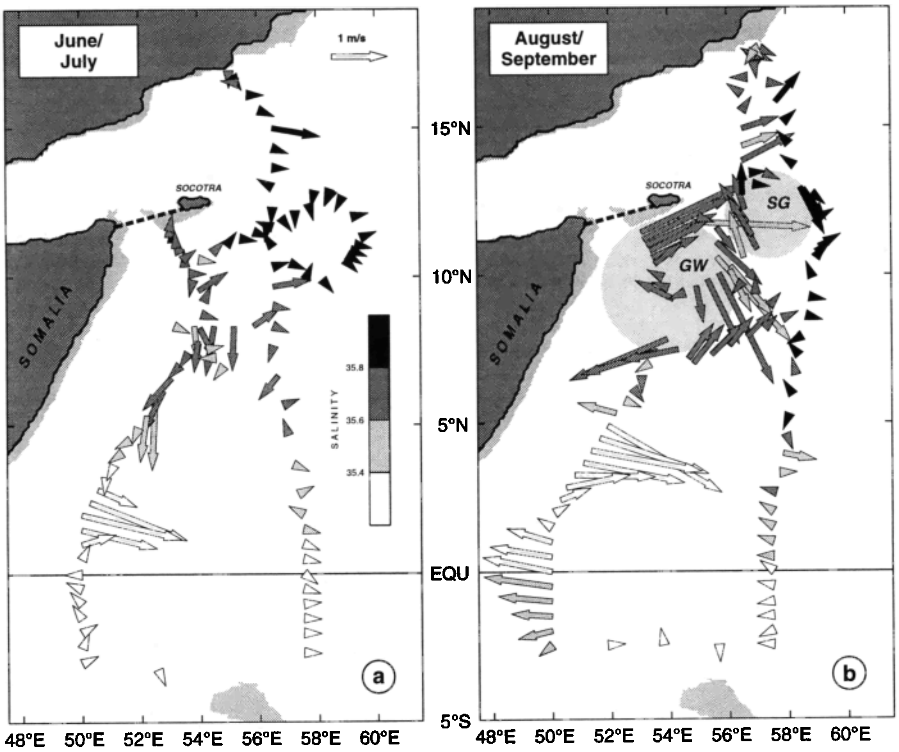

Figure 1. Near surface currents at 25 m from shipboard ADCP measurements during R/V *Meteor* cruises of June/July 1995 (a) and August/September 1995 (b). Water masses are characterized by salinity classes shown by shading grades; approximate locations *Great Whirl* (GW), *Socotra Gyre* (SG) are shown as shaded circles.

developed, with westward equatorial flow across 50°E indicating the recirculation of the *Southern Gyre*. The GW is just beginning to spin up during the second survey. It is interesting to note that during the northern part of the survey, 26–29 June, strong eastward flow was found north of Socotra, at a transport of about 13 Sv above σ_Θ=25.0 (Figure 3), that was not a recirculation of the westward flow just to the south of it, at 11°N to 13°N, which only carried about 4 Sv, but must in its major part have originated out of the northern Somali Current regime through northward advection between Socotra and the mainland.

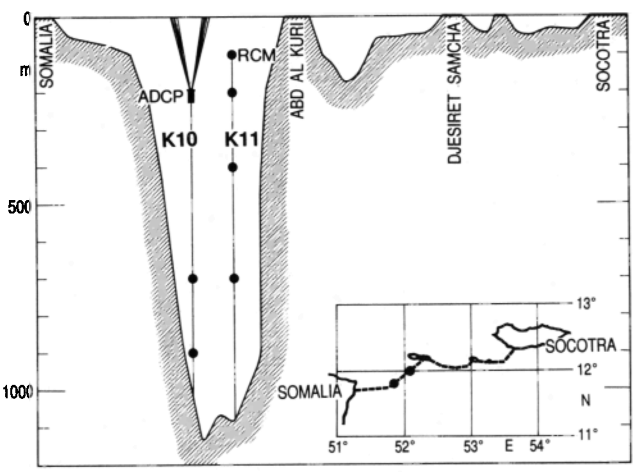

Figure 2. Topography between Somalia and Socotra across the shallows of the Socotra shelf (see inset). Also included are the moored instruments (moorings K10 and K11) in the deep Socotra Passage.

2.2. The fully developed SW Monsoon

During the third *Meteor* survey, in late August, the *Southern Gyre* was even stronger than in the preceding month, with strong recirculation. Indications for significant offshore recirculation of the *Southern Gyre* had also been deduced from earlier drifter observations of the fully developed southwest monsoon by *Schott et al.* [1990]. The GW was fully developed during the Aug.-

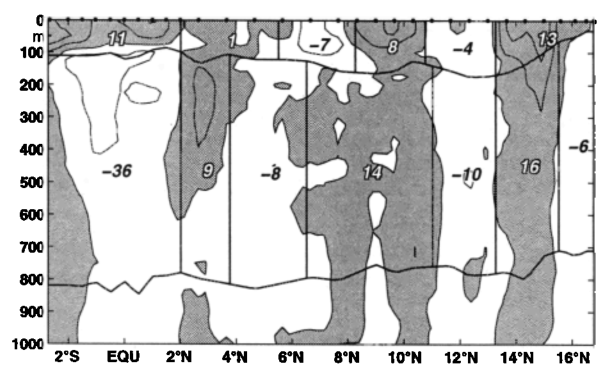

Figure 3. Combined VMADCP-, LADCP and Pegasus currents across eastern section (see Figure 1) of the R/V *Meteor* cruise in June/July 1995; offshore flow is shaded, contour interval is 25 cm s^{-1}.Two isopycnals are marked, σ_Θ=25.0 and σ_Θ=27.3, and layer transports for current cores are given in Sv ($10^6 m^3 s^{-1}$).

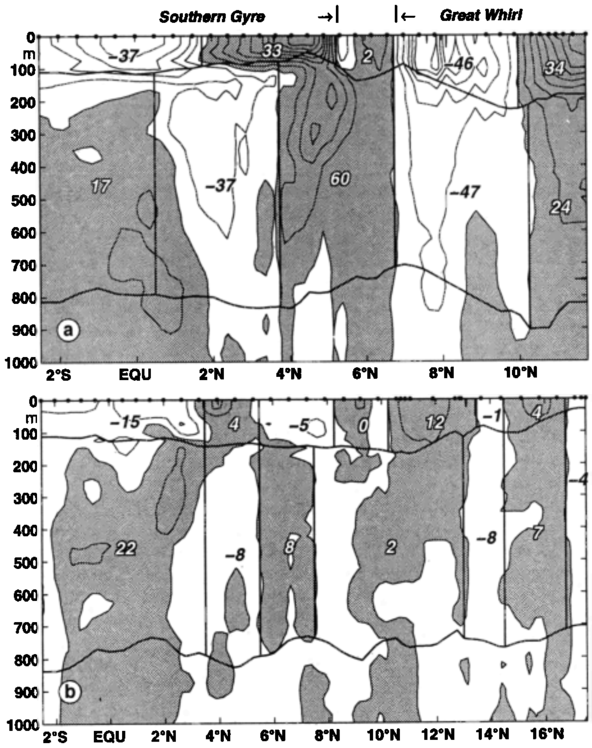

Figure 4. As in Figure 3, but for R/V *Meteor* cruise in August/September 1995; (a) across western section, (b) across eastern section(see Figure 1).

Sept. survey, with velocities at the surface in excess of 2.5 m s^{-1}(Figure 1b). In difference to the same time period in 1993, when about 200 km of still water separated the GW from the Socotra shallows [*Fischer et al.*, 1996], the GW was now jammed against the southern slopes of Socotra. East of Socotra, the *Socotra Gyre* (SG) was now developed. As in June, eastward near-surface flow was occurring again north of the SG, in latitude range 13°N – 16°N during 15–16 September.

Currents and transports past the western and the eastern section of the August survey are shown in Figures 4a,b respectively. The GW has a transport of 50 Sv above σ_Θ=25.0, and currents exceeding 10 cm s^{-1}were still observed at levels below 1000 m depth. This results in a doubling of the GW transport between about 200 m and 800 m, again different from the 1993 observations, where the GW was much shallower. The difference between the currents of the western and the eastern sections is striking (Figure 4): nothing of the vigorous nature of the GW is reflected at that eastern section. Currents there were weak (Figure 4b) and salinities higher (Figure 1) than in the GW, suggesting a decoupling of the GW from the interior of the Arabian Sea in the latitude range 4°N – 12°N. East of the GW, a band of northward flow was found (Figure 1) , as it was in Aug. 1993, supplying inflow to the SG. Above σ_Θ=25.0 a band of 12 Sv of eastward flow crosses the eastern section at 10°N – 13.5°N (Figure 4b) that is partially delivering the outflow from the SG eastward.

3. Moored current measurements

The moored array was originally planned, as WOCE array ICM-7, to be deployed across the northern Somali Current near 9.5°N at the continental margin. Due to the nonexistence of a Somali government this was not possible and the next best solution was to deploy it normal to the topographic slope off Socotra with some coverage also of the *Socotra Passage.* To provide an idea on the development of the circulation in the array area, monthly mean vectors of the near-surface flow for May to October 1995 are shown in Figure 5. They are determined from the upward-looking ADCP profiles compensated for mooring motion. June to July shows the spin-up of the GW. The northward expansion of the GW during the southwest monsoon is clearly visible, with the strongest currents just south of Socotra in its end phase, in September, and the known continuance of the GW after the end of the summer monsoon.

Two moorings, one of them with an upward-looking ADCP for the shallow near–surface flow (Figure 2), were dedicated to the passage, and after it was found on the deployment cruise that the passage depth was larger than anticipated, additional instrumentation was inserted into the deeper part of the moorings.The transport time series from the two moorings shows northward throughflow during almost the entire year, even for most of the winter monsoon season (Figure 6). The low value at the beginning corresponds to the LADCP section made on 28-29 March 1995. The transport mean for June – Aug. 1995 was 5 Sv.

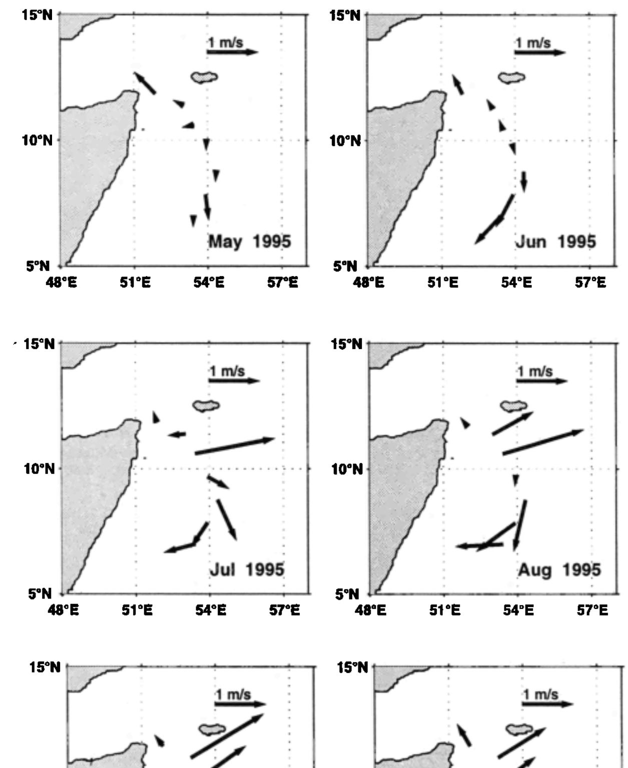

Figure 5. Monthly mean current maps from moored ADCPs interpolated to 50 m depth; scaling vector is included.

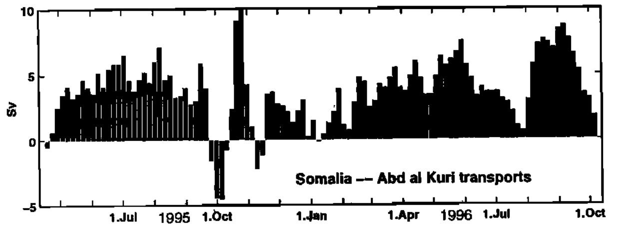

Figure 6. Northward transports (Sv) through the Socotra passage from 10-day mean current meter records.

This was, however, not the entire flow between Socotra and the mainland. The shallows between Socotra and Abd al Kuri have depths of mostly over 100 m (Figure 2) and significant flow can escape there.

4. Conclusions

The study of the Somali Current by shipboard observations during the summer of 1995, and by a moored array (recovered late Oct. 1996) also throughout the summer monsoon of 1996, will allow quantification of previously not well measured circulation features in the NW Arabian Sea. At this time, some of the preliminary findings are:

- The GW appears to be disconnected from the interior of the Arabian Sea in the latitude range 4°N - 12°N. East of it a band of northward warm water flow was found, connecting low latitudes with the SG, confirming similar observations made in 1993.
- Communication of the northern near coastal Somali Current regime with the Arabian Sea in the fully developed summer monsoon is dominantly through the passage and shallows west of Socotra. The net transport through the *Socotra Passage* is northward throughout most of the year.
- The monsoon response of the GW 1995 was deep-reaching, to 1000 m, while in 1993 GW currents were already decayed significantly near 300 m depth.
- The northern boundary of the GW in 1995 was located much more northward than in previous observations and pressed against the Socotra shelf in the late southwest monsoon phase.

Further analysis will combine the shipboard observations shown here with those of other groups, with the moored currents and with satellite SST and altimetry measurements to delineate the seasonal behaviour of the northern Somali Current in relation to local and remote forcing, and to determine the degree of interannual variability of that circulation system.

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