Salinity variability in the Arabian Sea

Sudheer Joseph
Indian National Centre for Ocean Information Services, Hyderabad, India

Howard J. Freeland
Institute of Ocean Sciences, Sidney, British Columbia, Canada

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[1] Argo floats deployed in the Arabian Sea provided an opportunity to look at the temporal variability of the core-depth of Arabian Sea High Salinity Water mass (ASHSW) at three locations in the north, central and southern Arabian Sea. These three locations show distinctly different variability patterns. At the northern location we see a prominent semi-annual cycle, whereas at the central location an annual cycle dominates. Comparison with TOPEX/JASON sea level data shows that this difference can be attributed to the influence of Rossby waves at the central location. In the southern Arabian Sea the variability in core depth is also dominated by an annual-mode, but there are 2 high frequency components near the Madden-Julian Oscillation frequencies. Thus the salinity distribution in the Arabian Sea apparently is influenced by both remote forcing and ocean atmospheric coupling. **Citation:** Joseph, S., and H. J. Freeland (2005), Salinity variability in the Arabian Sea, *Geophys. Res. Lett.*, *32*, L09607, doi:10.1029/2005GL022972.

1. Introduction

[2] Water masses with specific temperature and salinity characteristics are created by surface processes and ocean-atmosphere interactions at specific locations. Water masses and their formation processes in the Arabian Sea (AS) have been described by many authors [*Kumar and Prasad*, 1999; *Beal et al.*, 2000; *Prasad and Ikeda*, 2002a, 2002b; *Stramma et al.*, 2002], few of which [*Kumar and Prasad*, 1999; *Prasad and Ikeda*, 2002a, 2002b] describe the formation processes and spreading based on Climatology and modelling. Because of the intense variability associated with the monsoon cycle, water mass structure in the upper layers of the AS show enormous variability in space and time. Most authors identify two water masses in the AS known as the Arabian Sea Water (ASW) and Arabian Sea High Salinity Water Mass (ASHSW). *Donguy and Meyers* [1996] define a surface water mass with salinity S $35.5 < S < 36.5$, and $\theta > 22°C$ as ASW. *Morrison* [1997] defines ASW as the water mass with a salinity maximum at a σ_θ of 25.0 kg m^{-3}. *Kumar and Li* [1996] suggested characteristic temperature, salinity, and σ_θ for this water mass as 26.345°C, 36.387, and 24.082 kg m^{-3} respectively, with the denser fractions of ASHSW having σ_θ greater than 25.0 kg m^{-3}. Thus the ASW may be viewed as a denser fraction of ASHSW [*Morrison*, 1997]. In this paper we follow the definitions of *Kumar and Prasad* [1999] and *Prasad and Ikeda* [2002b, 2002a] and identify the core depth of ASHSW as the sub-surface maximum in the upper 200 meters [*Kumar and Prasad*, 1999].

[3] Several factors contribute to the existence and variability in the ASHSW:

1. Low salinity waters of southern origin can be advected into the region by the Somali and North Equatorial Current [*Morrison*, 1997].
2. During the south west monsoon period, the waters that upwell along the Arabian coast can have low salinities resulting from poleward advection associated with the Somali current [*Morrison*, 1997].
3. Precipitation and runoff from rivers in the eastern AS contribute to the formation locally of low salinity waters, which in turn augment the subsurface maximum, the identifying feature of the ASHSW.

[4] During the NE Monsoon, the cold and dry winter winds from Asia, combined with Ekman pumping, cause subduction of high-salinity surface waters of the northern AS [*Morrison*, 1997; *Schott and Fischer*, 2000]. This causes wide spread formation of ASHSW with a salinity maximum just beneath the mixed layer at a σ_θ of 25 [*Morrison*, 1997]. The continual availability of Argo data from 2001 to present prompted us to examine the variability of the core depth of ASHSW which occupies the uppermost layer of the Arabian Sea.

2. Data and Methods

[5] The data used in this study are high quality temperature and salinity profiles acquired as part of project Argo. Deployments in the AS started in late 2001 (see Figure 1). Usually Argo floats sample during their ascent phase and stop sampling 3–4 meters below the sea surface. However, in some cases sampling ends up to 8 or 9 meters below the surface. For this study we accepted profiles provided the shallowest sample was less than 10 metres below the surface. The data were periodically downloaded from the Ifremer web site (http://www.ifremer.fr/coriolis/cdc/default.htm) and in most cases have been subjected only to a cursory real time quality check, as prescribed by the Argo data management manual. Apart from this all profiles were visually checked for obvious problems. Delayed mode quality control is presently available only for a limited number of profiles. However, drifts in sensor calibrations will have minimal effect on the present study because we are concerned primarily with vertical gradients rather than absolute values of salinity. The data were linearly interpolated to one meter intervals before analysis for the core depth of the ASHSW. Dynamic height anomaly data sets of

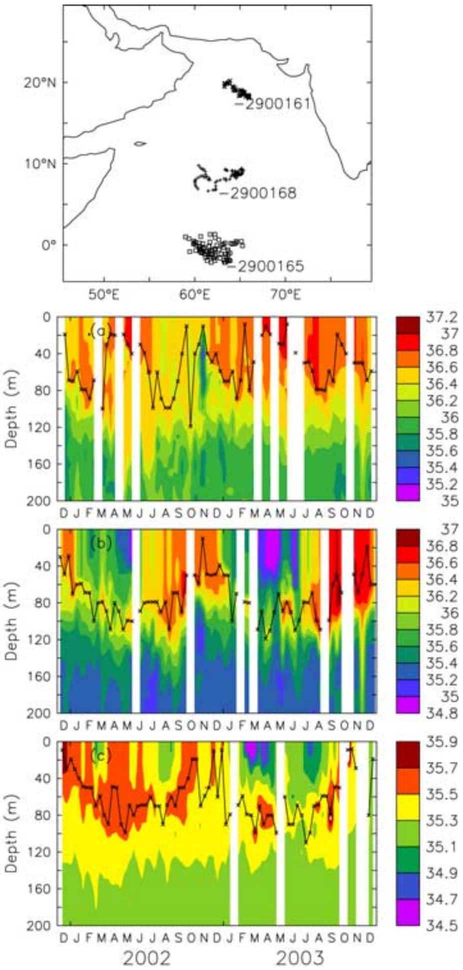

Figure 1. Time depth section of Salinity from the 3 float locations. The black line with symbols indicates the core depth of the ASHSW.

Topex/Jason satellite were obtained (http://www-aviso.cnes.fr) and were used for verifying the frequencies exhibited by the float based core depth data.

3. Northern AS: Float-2900161

[6] Throughout this paper Argo floats are indicated by their WMO numbers, which are never repeated and unique for a float. Float-2900161 was launched in 2001 at 20°N, 64°E and moved only a few degrees during the two years it reported data, which contrasts markedly with the other two floats used (Figure 1). This float also has reported the highest salinity among the 3 floats selected for this study reaching extrema of 36.91 psu on the 27 May 2002 and 37.02, on 1 June 2003 at the core of the ASHSW which is located near 20 and 40 meters depth respectively (Figure 2). During the time of peak salinity, the temperature and σ_θ were 31.18°C and 22.84 in 2002 and 29.69°C and 23.27 in 2003 (Figure 2). By June of each year the core depth appears to be deepening due to the influx of fresh water. This fresh water influx derives from rain as well as advection of low salinity water from the Oman upwelling region through the Ras al Hadd Jet which lies above the ASHSW core [*Morrison*, 1997]. By September of each year the core had risen close to the surface (Figure 1a). From the second half of October until December the core depth shoals, which is in agreement with the results of *Kumar and Prasad* [1999] and *Prasad and Ikeda* [2002a]. Their observations from climatological data suggest that the ASHSW first becomes evident in the northern AS during November, near the surface. Its formation is attributed to evaporative cooling caused by the north-eastern monsoon winds [*Prasad and Ikeda*, 2002a]. One of the interesting features of the ASHSW core at this location is that, irrespective of the presence of the core at a deeper or shallower level, it is in communication with the atmosphere through waters of similar salinity (Figure 1a). Starting in December and continuing through January the core descends to a depth of more than 80 meters. From March to the middle of June, the core is observed near 20 meters depth and by end of June it deepens to 100 meters. A close look at the core depth variability in its entirety suggests the presence of annual and semi annual cycles (Figure 1a). This is supported by a Fourier decomposition showing moderate annual and prominent semi-annual components of the periodogram (Figure 3a). The periodogram indicates that 39% of the total variance is contained in the semi-annual and 6% in the annual component. This simple picture is spoiled slightly by a single deep spike visible in the core depth time series in October 2002. The salinity maximum associated with this is extremely weak and possibly has nothing to do with the ASHSW. Doubtless the presence of this spike decreases the fraction of variance accounted for in the semi-annual cycle. In order to corroborate this result we obtained Topex/Jason data for the same period and averaged it over the profiling locations of Float-2900161. The Fourier decomposition of these data shows that the semi-annual mode (28% of variance) of variability is less prominent than the annual mode (44% of variance) (Figure 3d) but does, however, have significantly more power than at the other two locations.

4. Central AS: Float-2900168

[7] This float acquired its profiles in the region 5–9°N and 60–65°E. Here the maximum salinity recorded at the

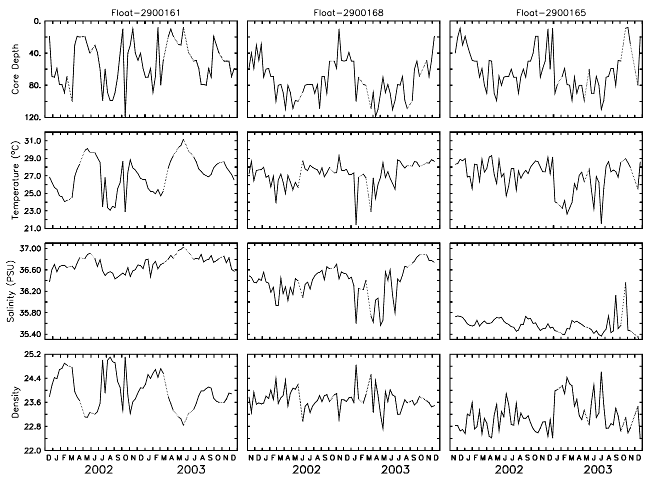

Figure 2. Property variation at the core depth of the ASHSW for 3 floats. Dashed lines indicate missing data.

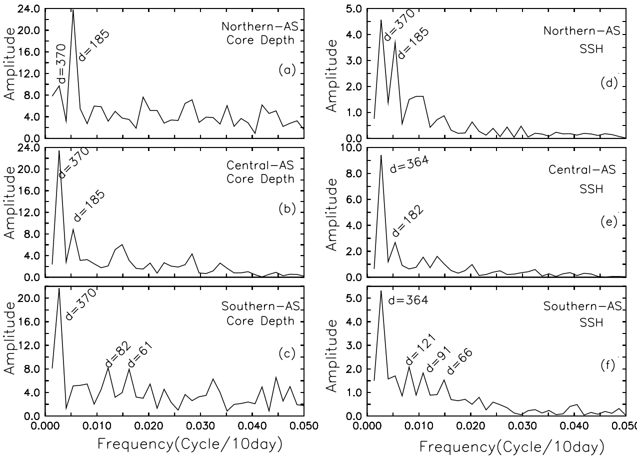

Figure 3. Periodograms of the core depth and Topex/Jason Sea surface height averaged over the respective float locations.

core is 36.66 & 36.86 (with corresponding temperature and density of 27.36, 28.05, 23.85, 23.80)(Figure 2) occurring on 23 September 2002 and 9 October 2003 respectively (Figure 1b). At this time the core is about 50 to 60 meters deep. By the end of December it has deepened reaching a maximum depth of 90–100 meters around April to May (Figure 2). During the Nov.-Dec. period the core is ventilated but by the end of January it is detached from the surface by a cap of low salinity water (Figure 1b). The Fourier decomposition (Figure 3b) of the core depth shows clear dominance by an annual cycle accounting for 60% of the total variance. A second prominent peak is seen at the semi-annual period but accounting for only 8% of the variance. This is a striking contrast with the northern float 2900161, which showed semi annual dominance. This change in prominence of the annual mode can be attributed to the influence of westward propagating Rossby waves as reported by *Brandt et al.* [2002]. The Fourier decomposition of Topex/Jason data averaged over the profiling locations of Float-2900168 shows 79% variance for annual mode, (Figure 3e) and shows a strong resemblance with the core depth plot. This gives credibility to our argument concerning the influence of annual Rossby waves in regulating the depth of salinity maximum.

5. Southern AS: Float-2900165

[8] Float 2900165 profiled in the equatorial Indian Ocean between 60–65°E near the equator. Here the ASHSW has a rather feeble presence compared to the other two sites. This probably is due to equatorial mixing processes and the large distance from it's origin. But the influence of the ASHSW can be seen as a high salinity patch near the surface during the Nov.–Dec. period and at a greater depth, reaching about 100 meters, during May–June (Figure 2). The maximum salinity observed in the core is 35.73 on 8 September 2002 and 24 October 2003. The corresponding temperature and density were 27.63 and 23.07 in 2002 and 28.97 and 23.10 in 2003 (Figure 2). This site shows a smaller range of salinity variability compared to the other two floats probably due to the stirring of equatorial current systems. However in September, October, and November of 2003 salinity fluctuations (Figure 2) appear that are quite different from those seen at the other two floats. In Figure 1c we observe the ASHSW core near the surface during Nov.-Dec. During February, March and April, a low salinity patch is discernible near the surface, and was stronger in 2003 than in 2002 (Figure 1c). This could be due to an intrusion of Bay of Bengal Water [*Shankar et al.*, 2002]. A second episode of low salinity occurred during July-August, contributed by the monsoonal rainfall/hydrological inputs and was stronger in 2003 than in 2002 (Figure 1c). A Fourier decomposition of the core depth data at this site (Figure 3c) shows dominance of the annual mode, which accounts for 54% of variance.The semi-annual mode contributes a very low percentage of variance 3% and is likely not significant. In fact two other modes contribute more to the total variance, one at a period of 62 days (7% of variance) and an 82 day oscillation with 6% variance (Figure 3c). These 2 peaks are likely related to the Madden-Julian oscillation, which has a periodicity ranging from 35 to 90 days [*Hendon*, 2000]. Fourier decomposition of Topex/Jason data (Figure 3f) at this location is comparable to the core depth data in the following aspects. Topex/Jason SSH data shows 51% of variance for annual mode and just 5% variance for the semi-annual mode. There are three other prominent modes of 121 days with 8% of variance, 91 days with 6% of variance and 66 days with 5% of variance. The poorer match of the float data and the Topex/Jason data at this locality could be due to the more dynamic nature of this equatorial site.

6. Discussion and Conclusion

[9] The Arabian Sea is a highly evaporative basin and temperature is assumed to have a dominant control of the density structure. Most observations from this basin include only temperature, salinity data being comparatively sparse. The formative processes and distribution of ASHSW was described by a few workers [e.g., *Kumar and Prasad*, 1999; *Prasad and Ikeda*, 2002a; *Stramma et al.*, 2002]. In this study we focused on an unexplored aspect, the remote forcing on temporal variability of it's spreading depth. The climatic forcing of the salinity field is often attributed to freshwater forcing by, rain fall or river runoff. Our observations in the AS show that the core depth, and therefore the salinity distribution, is forced by the reversing monsoons both remotely and through fresh water inputs. In the Northern AS (2900161) the semi-annual mode dominates over the annual mode. We consider this as predominantly due to fresh water influx [*Morrison*, 1997]. At the site of 2900168 in the central AS the forcing is mainly of remote origin, as here the mode of variability is showing almost the same percentage of variance as that of the Rossby wave [*Brandt et al.*, 2002] at 60%. In the southern site (float-2900165) the influencing factors are complex and the equatorial current system has a major role in the distribution of properties. Though the variance at the southern site is dominated by the annual mode the amplitude is less compared to that at the central AS (54%). Two high frequency components with 6% and 7% of variance each appear in the periodogram and could be due to the Madden Julian Oscillation. Thus the salinity variability at

this location is influenced by circulation, and ocean atmosphere coupling. Though the present study uses limited data from a limited area, it provides a view of what will be achieved in studies when much more float data, including salinity, becomes available on the basin scale. With increasing density of Argo observations we will be able to examine the salinity field with hitherto unimagined resolution. This will reveal the intricate relationships between the Indian Monsoon system and oceanic feedback mechanisms and so contribute to understanding, modeling and predicting this complex system.

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H. J. Freeland, Institute of Ocean Sciences, P.O. Box 6000, Sidney, BC, Canada V8L 4B2.

S. Joseph, Indian National Centre for Ocean Information Services, P.O. BOX 21, Hyderabad-55, AP, India. (sjo@incois.gov.in)