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Quality of temperature and salinity data from Argo profiling floats in the Bay of Bengal

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In the present study, temperature and salinity from APEX -*Argo floats with reported SPB* (Argo-SPB) and salinity from *normal floats without any reported SPB* (Argo-N) in the BoB have been subjected to quality check (QC). Method used for QC depends on time-space de-correlation scales (TSD-scales) of temperature and salinity in the BoB at selected potential temperature (θ) surface (10 ^{o}C). High quality shipboard CTD observations in the BoB have been used to identify TSD-scales of temperature and salinity. Observed TSD scales for salinity (temperature) at θ surface of 10 ^{o}C are 5 days and 60 km (8 days and 80 km). QC has been performed on matchups between Argo and shipboard CTD observations falling within the identified TSD- scales. QC on Argo-SPB could not identify any significant systematic bias/error, except for a single profile (cycle No. 48) of float-4900675. In the case of Argo-N, significant error is found in most of the salinity profiles from the float-2900268.

[**Keywords:** Argo, Ship-CTD, BoB, TSD scale, θ-S diagram]

Introduction

Argo profiling floats provide high quality vertical profiles of temperature and salinity in the global ocean. More than 5000 Argo floats have been deployed and the array is now providing nearly 100000 temperature- salinity profiles per year[1]. With life times of 3-5 years, the floats measure salinity and temperature from the surface to a pre-determined depth. Argo data are available within 24 hours of collection through Data Assembly Centres (DACs). Because 90% of the Argo floats have electrode-type conductivity cell (see Sea-Bird online at http:/www.seabird.com/), the „„prolonged and unattended"" presence in the ocean make them susceptible to fouling–biofilm formation inside the cell, which alters the conductivity and thereby salinity measurements. Reports based on post-deployment calibrations of conductivity cells from six recovered floats have shown no significant drift[3,7]. One of the earlier studies[14] reports the long-term drift in the salinity of Argo floats that completed 5 years (<.01 PSU per year) is insignificant to affect the objective of the Argo program in understanding the climate variability. Barker[1] has reported depth biases in APEX float in the global Ocean due to SPB. The depth biases cause temperature and salinity artefacts in the data. Therefore, it is important to check the Argo salinity for possible long term drift that cause systematic bias in the observed salinity. Although the delayed mode Argo data available in DACs have undergone different levels of QC (real-time & delayed mode), the objective of the present study is to re-assess the quality using high quality shipboard CTD observations in the BoB. For this purpose, we use the TSD-scales in selecting matchups of shipboard and Argo CTD as in the earlier study[14] . Temperature from Argo-N has not been reported for any biases. Therefore, in the present study, temperature and salinity from Argo-SPB and salinity from Argo-N in the BoB have been subjected to QC. Throughout this study, APEX -*Argo floats with reported SPB* are referred to as „Argo-SPB" and *normal floats without any reported SPB* are referred to as 'Argo-N'

Materials and Methods

TSD scales of temperature and salinity in the BoB

The subsurface waters of the BoB are very uniform in all parts of the Bay north of 5 ^{o}N and are referred as the Indian Equatorial Intermediate Water (IEIW). This uniform (near-linear) salinity structure makes it possible to validate Argo salinity at deeper layers, at 5 and 10 ^{o}C θ surfaces. Although the deeper 5 ^{o}C θ surface is more appropriate (less natural variability) compared to the10 ^{o}C θ surface, a large number of floats have depth limit to consider only 10 ^{o}C θ surface. For identifying the appropriate TSD scales in the BoB, high quality shipboard CTD archive available in the WOA-09 (World Ocean Atlas 2009) and IODC (Indian Oceanographic Data Centre) is used. Argo data have not been used in deriving TSD for temperature and salinity as the same is subjected to QC. CTD data coverage maps of WOA-2009, IODC and Argo are shown in figure 1A, 1B and 1C, respectively. Figure 1D shows the composite θ-S (potential temperature-salinity) plot for shipboard CTD (red filled circles) and Argo (Green filled circles).

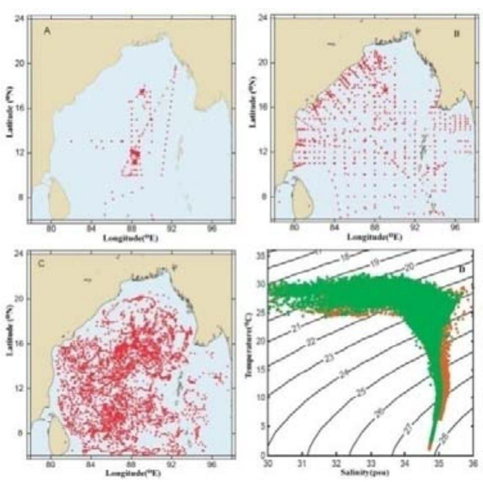

Figure 1(A)-Coverage of ship-board CTD observations from WOA-2009, (B) Same as figure 1A but for IODC, (C) Same as figure 1A but for Argo (till April 2012), (D) θ-S plot for the composite ship-board CTD (WOA09+IODC; red filled circles) and Argo (green filled circles).

The derived parameter SALD[14] (Salinity Difference between two neighboring observations within the TSD scales) is used for identifying drift/biases in Argo salinity. Neighboring observations within the TSD scale are referred as "matchups" in this study. This method was successfully used in finding drift/biases in Argo data from the Sea of Japan and the Northwest Pacific[14]. SALD derived from quality controlled CTD observations from ship are used for finding the TSD scales of salinity at deeper theta surface. Maximum and minimum SALD values obtained from ship observations of CTD are used in the quality analysis of Argo salinity. SALD derived at theta surface of 10 ^{o}C is shown in figure 2A. Grey filled circles in figure 2A show SALD dependence on distance between matchups (Km) and red filled circles show SALD dependence on time lag between matchups (days). As depicted in figure 2A, for a time scale of 5 days and space scale of 60 km the regression coefficients are nearly zero and not significant at 99 % confidence level. Similar to the TSD scales of salinity, the same has been derived from the shipboard CTD observations for temperature at θ surface of 10 ^{o}C. For temperature, TSD-scales are found to be 8 days and 80 km, respectively (Figure 2B). Temperature difference (at 5 or 10 ^{o}C θ surfaces) between "matchups" within the TSD scales is referred to "TED".

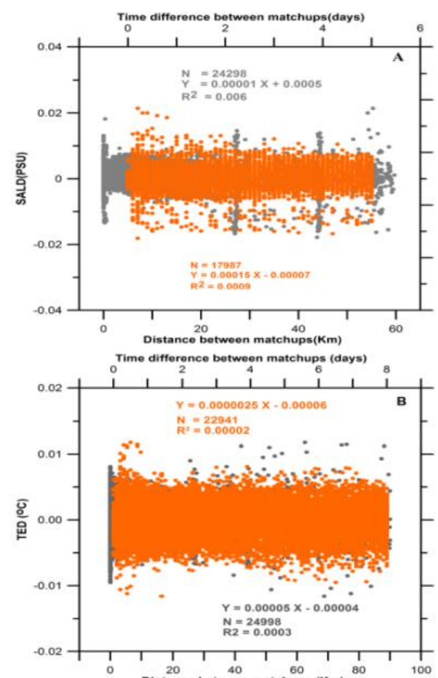

Figure 2(A)-Time-space de-correlation scales (TSD-scales) for salinity (SALD) at 10 ^{0}C θ derived from ship observations of CTD from the Bay Of Bengal (BoB), B) same as in figure 2A, but for temperature (TED).

Results

Quality of temperature and salinity from Argo-SPB

There are three types of Argo floats deployed in the global Ocean, namely APEX, SOLO and PROVOR. Maximum percentage of deployed floats is APEX (62%), followed by SOLO (26 %) and remaining 12 % is PROVOR. As reported in a previous study[1], there are 7 floats in the BoB which are having SPB. Since SPB is independent of depth, the same shall cause systematic bias in the subsurface temperature and salinity. As the float measures absolute pressure for getting the gauge pressure, the absolute pressure has to be corrected for atmospheric surface pressure (SP). There are APEX floats with positive and negative drift in SP. If drift is positive, it could be corrected once SP values are recorded. If it is negative drift, the pressure transducer is designed in such a way that the SP is truncated to zero. If the drift values are recorded, it is possible to correct for the drift. However, for many floats deployed prior to 2009 the drift values have not been recorded and therefore, the depth data from these floats will remain as uncorrected (~20%). In SOLO and PROVOR, the correction for surface pressure has been done automatically. Potential temperature versus salinity (θ-S) plot for profiles from pressure affected Argo floats as reported is shown in figure 3A.

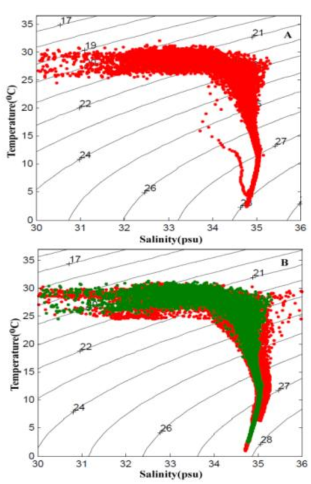

Figure 3(A)-θ-S plot for profiles from Argo-SPB in the BoB, B) θ-S plots of total profiles from Argo-SPB overlaid on the θ-S of ship-board CTD (WOA09+IODC).

The θ-S values for profile-48 from the float 4900675 are obviously wrong as shown in figure 3A. In order to check the gross quality of profiles from pressure affected floats, composite plots of θ-S from these floats are compared with the same from shipboard CTD observations in figure 3B. θ-S plots from both pressure affected Argo floats and shipboard CTD observations are well comparable at subsurface levels.

Argo-SPB versus shipboard CTD matchups

Matchups between Argo-SPB and shipboard CTD observations are selected to check the quality of temperature and salinity profiles from the former. Since the minimum temperature of these profiles (Shipboard and Argo CTD) is about 2°C, SALD and TED have been derived at θ surface of 10 and 5 °C from the above matchups as reported in section-2 and the same is presented in figure 4A and 4B, respectively.

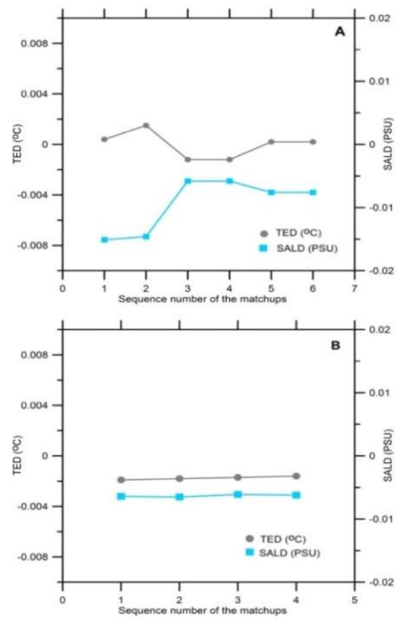

Figure 4(A)-SALD and TED at θ surface of 10 °C derived from matchup profiles between Argo-SPB and shipboard CTD. Mean of TED and SALD are 0.00002 °C and 0.009 PSU, respectively. B) Same as in figure 6A, but for θ surface of 5 °C.In this case, mean of TED and SALD are 0.0018 °C and 0.0063 PSU, respectively.

While the observed mean variability of SALD at θ surface of 10 °C is ~ 0.009 PSU, at 5 °C the same is much lesser (~0.002 PSU). There is no significant difference in the TED variability at θ surface of 10 and 5 °C (0.002 °C). SALD and TED variability are much lesser than the accuracy of Argo salinity and temperature. Therefore, the temperature and salinity from Argo-SPB in the BoB do not exhibit any significant biases in the subsurface level. This is further illustrated in figure 5A, where the red and green profiles represent matchups between shipboard and Argo-SPB observations. In the subsurface layers (figure 5A), the matchup profiles exhibit exact overlap without showing any visible bias.

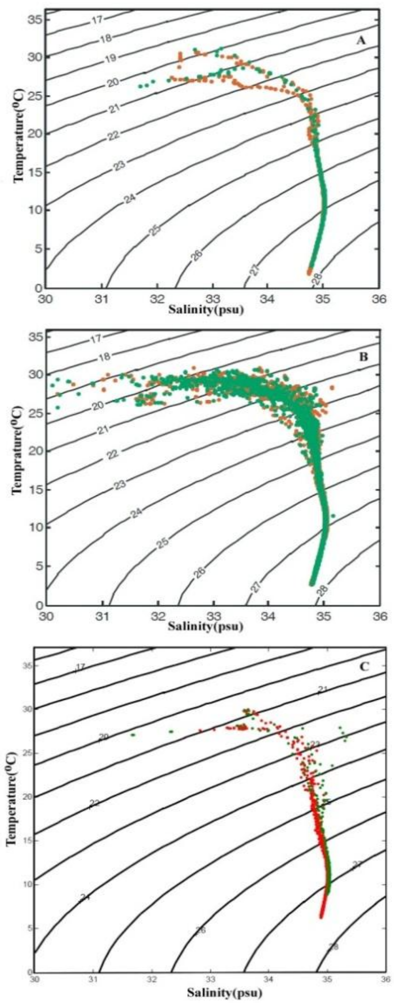

Figure 5(A)-θ-S plot of matchups between Argo-SPB (green) and ship-board CTD (red), B) Same as in figure 5A, but for matchups between Argo-SPB and Argo-N, C) Same as in figure 5A, but for Argo-N and ship-board CTD.

Argo-SPB versus Argo-N matchups

Matchups between profiles from Argo-SPB and Argo-N are used further to check the quality of temperature and salinity in the former. For this purpose, profiles from Argo-N which have undergone QC with shipboard CTD in the present study have been used. SALD and TED derived at θ surface of 10 and 5 °C from the matchups are shown in figure 6A and figure 6B (SALD-blue line and TED-grey line). As seen in figure 6A, the mean and standard deviation (σ) of TED are -0.0007 °C and 0.002 °C, respectively and that of SALD are 0.004 PSU and 0.015 PSU. At θ surface of 5 °C (figure 6B), the mean and σ for TED are 0.0006 °C and 0.002 °C, respectively. Whereas, the same for SALD are 0.015 PSU and 0.002 PSU. The observed SALD and TED variability in figure 6A and 6B show no visible bias in temperature and salinity from Argo-SPB. This is further demonstrated in θ-S plot of matchups profiles between Argo-SPB (red) and Argo-N (green) as shown in figure 5B.

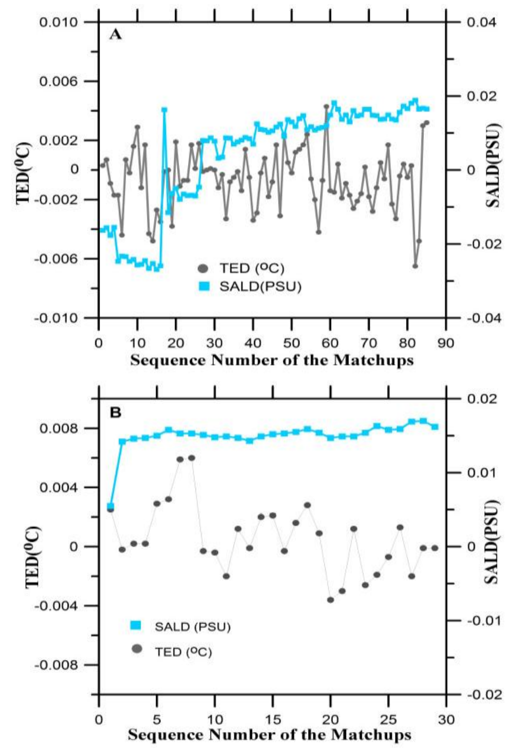

Figure 6(A)-SALD and TED at θ surface of 10 °C derived from matchup profiles between Argo-N and Argo-SPB. The mean and standard deviation (σ) of TED are -0.0007 °C and 0.002 °C, respectively and that of SALD are 0.004 PSU and 0.015 PSU. B) Same as in figure 6A, but for θ surface of 5 °C. The mean and σ for TED are 0.0006 °C and 0.002 °C, respectively. Whereas, the same for SALD are 0.015 PSU and 0.002 PSU.

Quality of salinity from Argo-N

As discussed in the introduction, majority of Argo floats have electrode-type conductivity cell. Long residence of the floats in the ocean make conductivity cells susceptible to fouling–biofilm formation inside the cell, which alters the conductivity and thereby salinity measurements. Therefore, we have analysed delayed mode data from Argo-N only for quality of salinity.

Argo-N versus shipboard CTD matchups

Matchup profiles between Argo-N and

shipboard CTD observations satisfying the TSD-scales of 5 days and 60 km have been identified to find SALD values at 10 °C θ surface. Figure 5C shows the θ-S plot of matchup profiles between shipboard (red) and Argo-N (Green). Argo-N and shipboard CTD shows very coherent temperature and salinity variability at deeper layers. Figure 7 shows SALD derived from Argo-N versus shipboard CTD matchups given in Table-1.

Table 1- Details of matchups between shipboard, Argo-N and Argo-SPB observations

Details of matchups between shipboard and Argo-N observations			
Cruise No.	No. of stations	Float No.	No. of profiles
1711	3	2900093	2
1715	1	2900093	2
954	11	2900107	1
Details of matchups between shipboard and Argo-SPB observations			
Cruise No.	No. of stations	Float No.	No. of profiles
1746	1	4900674	2
28033	2	4900675	2
Details of matchups between Argo-N and Argo-SPB observations			
Argo-N. Float No.	No. of profiles	Argo-SPB Float No.	No. of profiles
2900107	16	2900755	16
2900106	1	2900876	1
2900107	5	4900673	9
2900093	20	4900675	19
5901373	14	4900675	24

The observed variability of SALD (~0.027 PSU) is well within the maximum and minimum values of SALD derived from matchups of shipboard CTD observations, shown in figure 2. However, the SALD values in figure 7 show a mean bias of -0.027 PSU. Since the SALD is derived by subtracting Argo-N salinity from that of shipboard CTD, the negative bias implies that Argo-N salinity is higher than the shipboard CTD salinity. As shown in Table-1, the shipboard CTD observations in the matchups between Argo are from two ships (ORV Sagar Kanya and FORV Sagar Sampada) and have deployed different CTD systems. Shipboard CTDs have undergone onboard calibration. If the bias is in the shipboard CTD observations, it is quite unlikely for both the CTD systems to have similar bias of the same order (~0.02 PSU).

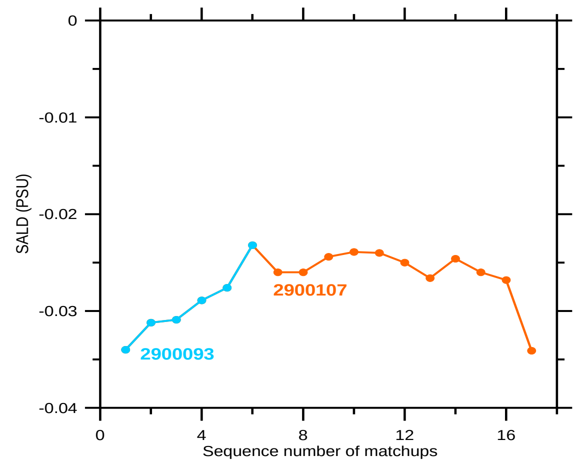

Figure 7-Scatter plot of SALD from matchups between Argo-N and shipboard CTD, in this case, the mean and σ of SALD are -0.0272 PSU and 0.0034 PSU, respectively

Therefore, the observed negative bias in SALD (figure 7) could be due to the higher salinity values from Argo compared to that from shipboard CTDs. Although the SALD variability at 10 °C θ surface from shipboard CTD alone is of the same order (figure 2), it is not systematic as seen in figure 7 and strengthen the possibility of saltier Argo observations. Different Argo floats shall have different initial biases and such biases could be either positive or negative.[3,7,14]. In the case of these two floats (2900093 and 2900107) shown in Table-1, it appears that both the floats have positive bias (saltier observations).

Argo-N versus Argo-N matchups

Comparison of matchup profiles from individual float and matchups between different floats shall identify random or systematic error/bias in the Argo data. SALD derived from matchups between different floats shall give information on float-to-float initial biases in salinity. Scatter plot of SALD derived from such matchups between Argo-N floats is shown in figure 8A. SALD associated with the float-2900268 are showing values much higher than the SALD derived from CTD observations from ship alone (figure 2), implying possible error in the salinity profiles from float-2900268. To explore this possible error further, salinity of all profiles from float 2900268 at 10 °C θ has been compared with the same from three calibrated floats (2900267, 2900093 and

2900107) as shown in figure 8B. Floats 2900093 and 2900107 have been calibrated with shipboard CTD observations (shown in figure 7) and 2900267 have matchups with both 2900093 and 2900107. Salinity from float 2900268 at θ surface of 10 °C is much lower than that of other floats in figure 8B (2900267, 2900093 and 2900107).

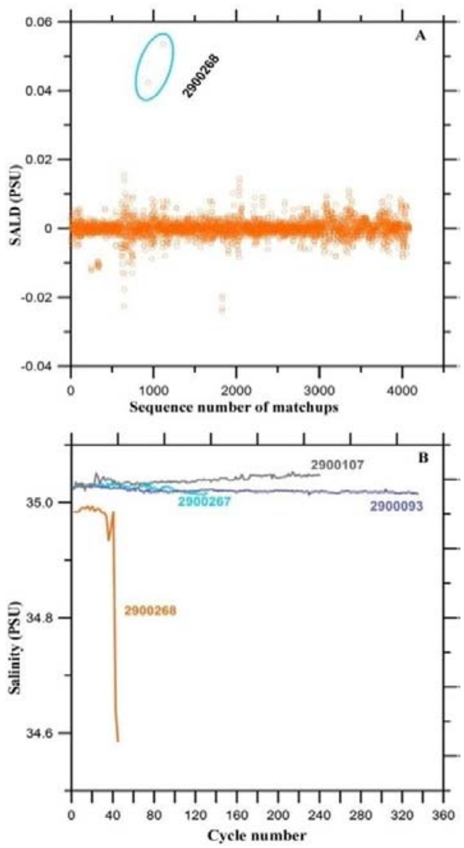

Figure 8(A)-Scatter plot of SALD from matchups between Argo-N and Argo-N. The large SALD > 0.04 PSU is from the matchups involving the float 2900268. B) Comparison of salinity at θ surface of 10 °C from 2900268 with calibrated float (2900267). 2900267 have been calibrated with another float which is calibrated with CTD observations from ship.

The float 2900268 was deployed in the southern Bay along with the float 2900267 and drifted towards north up to ~ 17 °N where it failed to ascent (Probably due to fresh water induced high stratification[10]). Although the float collected data from 91 cycles, the delayed mode QC by DACs considered only data from 48 cycles with good quality flag as seen in figure 8B. In order to understand about any inherent initial bias in the salinity of float 2900268, the θ-S from the float is overlaid on the same from shipboard CTD observations in the BoB (figure 9B). While θ-S from 47 and 48 cycles of 2900268 falls well outside the intermediate water mass of BoB, the former from remaining cycles (1-46) falls within the range of BoB intermediate water mass. However, the float 2900267 and 2900268 were located initially in the same location (figure 9A) and the observed significant difference in salinity at θ surface of 10 °C in figure 8B shall be due to some initial bias.

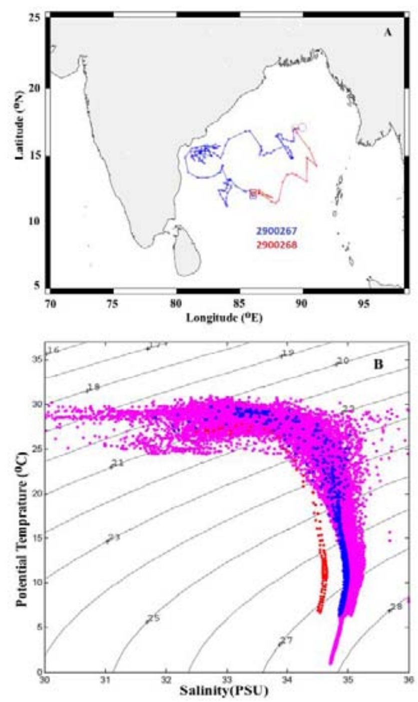

Figure 9(A)-Trajectories of floats 2900268 and 2900267, the open rectangle shows initial position and open circle shows last locations. B) θ-S plot of data from the float 2900268 (Blue and red) overlaid on the same from shipboard CTD observations in the BoB (Magenta).

Therefore, data from this float could be considered with some apprehension on the quality and be flagged with appropriate quality flag.

Discussion

Both in “real” and “delayed mode” quality control various objective methods are employed by DACs[2,8,18]. One of the earlier studies[17] inter-compared objective methods used by various DACs and reported large inconsistencies in methods used and results obtained in the delayed-mode QC. Reasons for such inconsistencies could be due to the lack of good quality background data and also due to difficulty in delineating sensor drift from long-term water mass change. As seen in the results of present study, there are no visible error/biases in the Argo data in the BoB, except for a single profile from the float-4900675 (Argo-SPB) and profiles form the float-2900268 (Argo-N). In both these cases, the observed SALD values are larger compared to the BoB water masses in the intermediate levels. The subsurface waters of the BoB are very uniform in all parts of the Bay north of 5 ^{o}N and are referred as the Indian Equatorial Intermediate Water (IEIW) and this make it possible to identify the large SALD values as errors. However, identification of systematic biases becomes difficult when the bias is comparable to the observed variability. Since the systematic biases are independent of depth (uniform from surface to last observed depth), the SALD and TED values at θ surface of 10 and 5 ^{o}C (presented in section-3 &4) are capable of identifying salinity and temperature biases at these levels. Since the observed SALD and TED values are of the order of the expected accuracies of Argo salinity and temperature (0.01 PSU and 0.005 ^{o}C, respectively) it is reasonable to conclude that there is no significant biases/error in the observed data from the BoB to affect the objective of the Argo program in understanding the climate variability.

In the QC analysis, we have selected the θ surface of 10 and 5 ^{o}C because most of the Argo floats in the BoB have parking depth of 500 m. There are some floats with parking depth of 1000 m. There are not enough shipboard CTD matchups to resolve the TSD scales at θ surface 5 ^{o}C. Since the TSD scales are larger at deeper surfaces, the same at θ surface 10 ^{o}C could be considered for the θ surface of 5 ^{o}C. In the QC analysis, the shipboard CTD are from three ships, namely ORV Sagar Sampada, ORV Sagar Kanya and ORV Roger Revelle. The consistent SALD and TED values at θ surface of 5 ^{o}C in figure 4B derived from matchups involving different shipboard CTD minimize the possibility of any bias in shipboard CTD and the observed very small SALD (0.006 PSU) and TED (0.001 ^{o}C) could be attributed to Argo, implying that SPB in Argo has no significant effect on subsurface temperature and salinity. The initial biases vary from float to float and such biases could be either positive or negative[7,3,14]. As discussed in section-3, comparison of matchup profiles from individual float and matchups between different floats shall identify random or systematic error/bias in the Argo data. SALD derived from matchups between different floats shall give information (if exists) on float-to-float initial biases in salinity. This is illustrated in figure 10A and 10B. Scatter of SALD from matchup profiles from same float (figure 10A) is lower than the same from different floats (figure 10B). The observed difference in the scatter provides significant information on the existing initial salinity biases of the floats (involved in the matchups). Since the difference in scatter between SALD in figure 10A and 10B is very small, the floats involved in matchups of different floats have no significant initial biases. Knowledge on the water mass characteristics of BoB based on earlier studies could also be used for a broad assessment of the quality of Argo data in the BoB. The low salinity surface water mass which is identified[15] as the Bay of Bengal Low Salinity Water (BBLSW), which has well marked north-south gradient in σt[5] with the Northern Dilute Water (NDW), transition water and the Southern Bay of Bengal Water (SBBW). While the density of NDW varies from 18-19 σt, for SBBW the density range is 21-22 σt. The surface transition water is a mixture of BBLSW and SBBW with density range of 19-21 σt. In the subsurface layer (50-100 m) the Arabian Sea High Salinity Water (ASHSW) is present. While the ASHSW is observed only in the southern Bay and off Sri Lanka during winter monsoon, it penetrates into the northern Bay (up to 14 ^{o}N) during the summer monsoon [6,12].

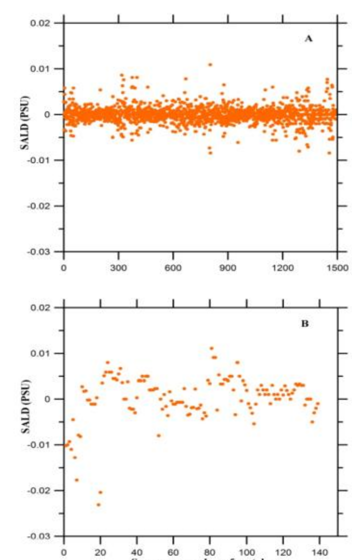

Figure 10(A)-Scatter plot of SALD derived from matchups of Argo profiles from same floats. B) Same as in figure 10A, but for different floats.

The subsurface saline water (> 35.0 PSU) layer is the Intermediate High Salinity Water (IHSW) of the BoB wherein the Persian Gulf and Red Sea Water enter the BoB [9,11,16,19,20]. The Arabian Sea High salinity water also enters the BoB during winter. A layer of high salinity water (35.0~35.1 PSU) in the depth interval of 200~900 m between 26.0 and 27.4 σt isopycnals also has been observed[13]. θ-S plots from Argo floats shown in figure 1D and figure 3 show all the water masses identified in the BoB.

Conclusion

The quality of delayed mode data from Argo profiling floats in the BoB and that available at Argo Data Assembly Centers (DACs) has been examined. Temperature and salinity from APEX -Argo floats with surface pressure biases (Argo-SPB) and salinity from normal floats (Argo-N) in the BoB have been subjected to QC. The QC method depends on TSD-scales of temperature and salinity in the BoB at selected θ surfaces (10 and 5 ^{o}C). High quality shipboard CTD observations in the BoB have been used to identify TSD-scales of temperature and salinity. QC has been performed on matchups between Argo and shipboard CTD observations falling within the identified TSD scales. Observed TSD scales for salinity (temperature) at θ surface of 10 ^{o}C are 5 days and 60 km (8 days and 80 km). QC has been performed on matchups between Argo and shipboard CTD observations falling within the identified TSD-scales. QC on Argo-SPB could not identify any significant systematic bias/error, except for a single profile (cycle No. 48) of float-4900675. In the case of normal floats, significant error is found in most of the salinity profiles from float-2900268. Except for the observed errors involving these two floats (2900268 and 4900675), our quality analysis demonstrates high quality of Argo data in the BoB, including the data from floats with SP biases. Considering the long-term presence of the Argo floats in the ocean, it is important to assess the quality of data at different levels for improving upon the data quality. DACs performing the delayed mode QC may not have full access to the high quality shipboard CTD data as background information for the BoB as, knowledge on the regional water masses is an important factor in the quality assessment.

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