



Argo data quality control based on climatological convex hulls

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Abstract (100 words)

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Abstract

This paper discusses a new method of identifying erroneous data in temperature and salinity (T/S) profiles measured by Argo profiling floats. The proposed method uses World Ocean Atlas 2009 (WOA09) climatology to classify good against bad data. An 'n' sided polygon (convex hull) with least area encompassing all the points is constructed based on the Jarvis March algorithm. The mean and standard deviation fields of temperature and salinity obtained from WOA09 corresponding to each standard depth are used for building these polygons. Subsequently Points In Polygon (PIP) principle which is implemented using ray casting algorithm is used to classify the T/S data as within or without acceptable bounds. It is observed that various types of anomalies in the Argo profile data viz., spikes, bias, sensor drifts etc can be identified using this method.

1. Introduction

Argo is an international program aimed at deploying 3000 instruments in the global ocean. Two primary types of floats missions have evolved since the initial float design as described in Davis et al., (1992). In the first mission, the float sinks to a prescribed pressure (typically 1000 dbars) and cycles with a prescribed time period (typically 10 days) and in the second, the floats are programmed to perform drifting and profiling at different depths. In November 2007, the global Argo array of profiling floats has reached its initial target of 3000 operating floats worldwide. The array now provides for the first time a global monitoring of ocean temperature and salinity (T/S) data in real time (Gould et al. 2004).

The primary objectives of Argo program are 1) provide a quantitative characterization of upper-ocean properties, 2) use the float observations to improve interpretation of satellite altimetry data, 3) initialize ocean and coupled forecast models, and 4) provide input to other global ocean analyses (Roemmich et al., 1999). With the core Argo (with temperature and salinity) proved worthy, floats with additional sensors viz., chlorophyll, turbidity, backscattering, nitrates etc are being deployed by various scientific groups. The number of profiles obtained annually by Argo in the world oceans was more than 30,000 in 2003 and this number increased to about 147,833 in 2013. There are around 81,941 CTD casts in World Ocean Database (WOD) which reach deeper than 2000 m and in total there are 115,017 CTD casts in WOD deeper than 1500 m which makes Argo contributing more than historic CTD casts deeper than 1500 m. Argo in conjunction with many other data sets are used in studies related to climate change, sea level rise, ocean heat content, mixed layer processes, assimilation into ocean models (GODAS), generation of better analysis products etc. However some of the studies require that the data from these instruments be of high quality as the results might be sensitive to biases or instrument errors. These errors are to be identified and eliminated or flagged before the data is put to use.

An outlier is an observation that is abnormal compared to its neighbors and lies at an abnormal distance from other values in a random sample from a population. Spatial

outliers are objects with distinct features from their surrounding neighbors in space. Detection of spatial outliers helps reveal important and valuable information from large spatial data sets. In the field of oceanography, for example, spatial outliers can be associated with natural events like cyclones, Indian Ocean Dipole, El Nino and Southern Oscillation or can be associated with errors due to sensor malfunction/degradation. In oceanographic data, outliers are frequently represented in region, i.e., a group of observations from an instrument which is malfunctioning or from a float whose sensors have degraded over period after giving valuable data initially.

Over the past decade, geographic distribution of oceanographic T/S profile data has become more uniform owing to the deployment of Argo profiling floats. From running the ocean models operationally to the preparation of climatologies, oceanographic data is widely put to use. Argo floats deployed by various countries are manufactured by different manufacturers who use different types of pressure and CTD sensors. Each country has their own choice of setting the measurement resolution for obtaining the T/S samples. Owing to different methods of measurements, different instruments and differences in handling the data, there is scope of leaving some bad data unnoticed. Even though the Argo Data Management Team (ADMT) has proposed some quality checks, different organizations/institutions employ additional methods for performing quality checks on data, there can be scope for existence of erroneous data. It would be a cumbersome process to individually pin point these bad data and various methods of handling these erroneous data are developed.

Many quality control procedures were prescribed for quality control of data from Argo floats. The ADMT had prescribed a set of 19 quality checks before the data is distributed to the users (Wong et al., 2014). Further a secondary quality control methods based on scientific analysis called Delayed Mode Quality Control (DMQC) is also in place (Wong et al., 2003; Owens et al., 2009). But not all the data pertaining to global ocean is passed through DMQC. There are also some independent methods of quality control set up by some of the Data Acquisition Centres. Guinehut et al., (2009) proposed a quality control method based on satellite altimetry. Cabanes et al., (2013) described the methods of

quality control of Argo and other in situ data archived at Coriolis Centre. Udaya Bhaskar et al., (2012) proposed a three way quality control methods to qualify the profile data archived at INCOIS. However there are pros and cons with each of these methods. This paper describes a new method to augment the existing procedures, where in profiles from all floats can be treated for their quality with the use of best available climatology.

2. Data and Methods

Argo data pertaining to the Indian Ocean are downloaded from the www.incois.gov.in web site. These data sets have been passed through the real-time quality control procedures proposed by ADMT to be implemented by each Data Acquisition Center and all eligible profiles are passed through delayed mode quality control (Wong et al., 2003). To test the proposed method, real time quality controlled profiles are considered.

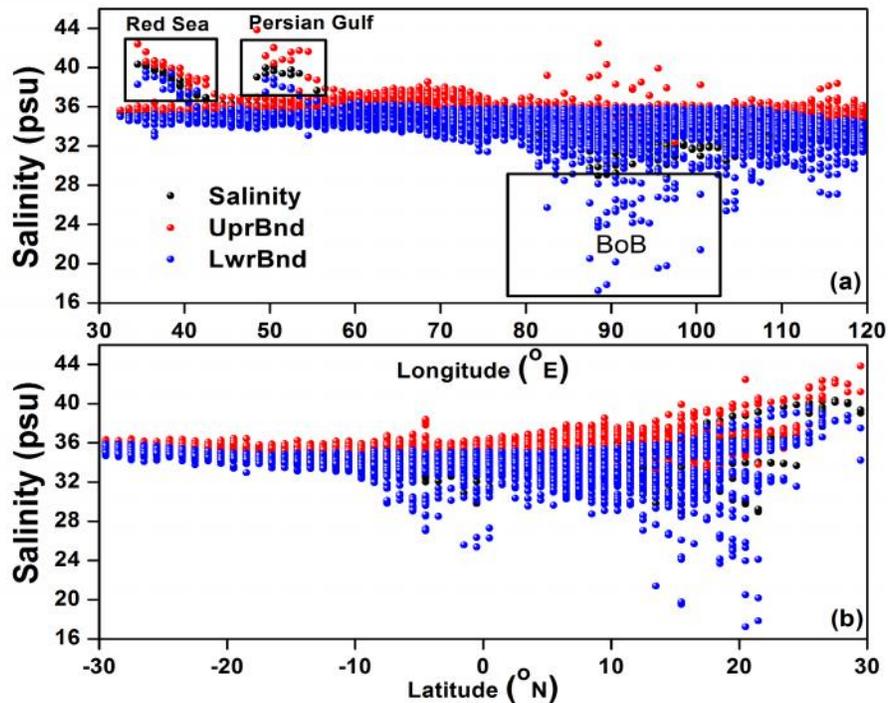


Figure 1. Patterns of salinity in the Indian Ocean when plotted against (a) longitude and (b) latitude corresponding to the depth 0 mts obtained from World Ocean Atlas 2009. Black, blue and red dots represent the mean, (mean - 2*SD), (mean + 2*SD) respectively.

The method is based on the observation that temperature and salinity when plotted against longitude and latitude represent a certain pattern of the parameter variability for that region. Figure 1 shows the salinity patterns for the Indian Ocean when plotted against the longitude (Fig 1a) and latitude (Fig 1b) corresponding to the 0 mts depths obtained from the World Ocean Atlas 2009. From the patterns one can clearly demarcate different types of waters viz., the Red sea, Persian Gulf and Bay of Bengal. Based on this patterns a 'n' sided polygon is derived which is used for performing outlier analysis.

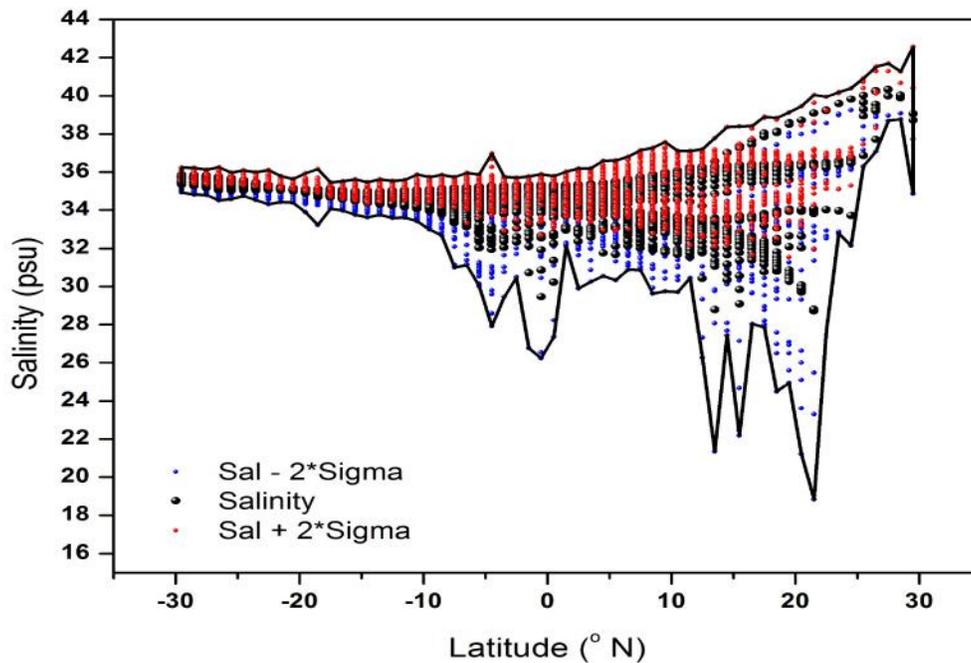


Figure 2. Generation of n-sided polygon (convex hull) based on the mean and 2*standard deviation gridded fields of salinity from World Ocean Atlas 2009. Black, blue and red dots represent the mean, (mean - 2*SD), (mean + 2*SD) respectively.

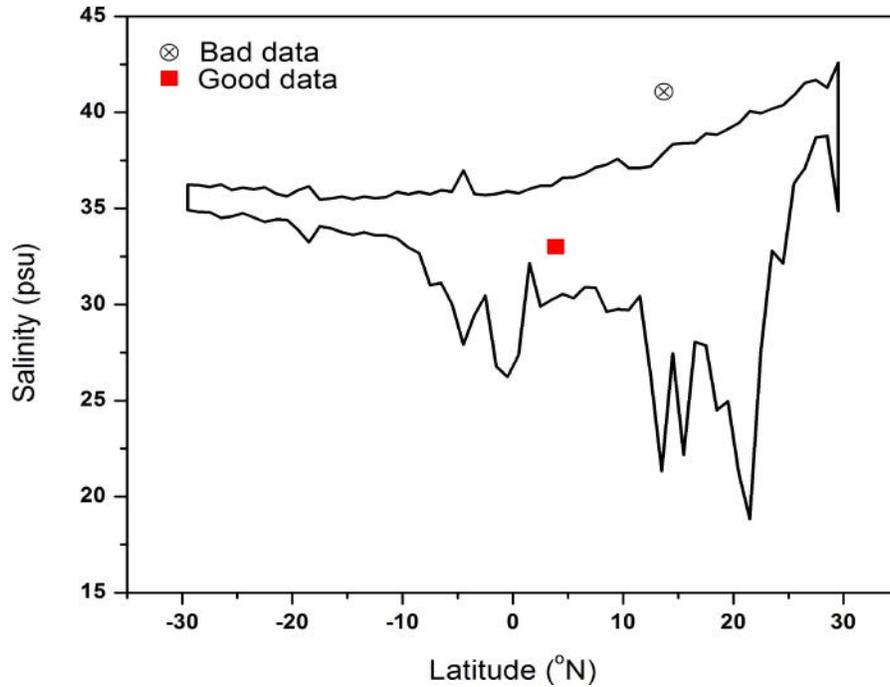


Figure 3. Classification of good and bad data based on PIP and Jordan Curve Theorem.

In the proposed method the principle of convex hull and PIP together are used to identify good vs bad Argo T/S profiles for a specified depth. The steps for application of the proposed method are as follows:

1. Observed Argo temperature and salinity profiles are interpolated using Akima spline (Akima, 1970) to the Levitus standard depths (Levitus, et al, 1994).
2. Use World Ocean Atlas (2009) temperature and salinity data corresponding each standard depth to build a n-sided polygon (convex hull) with least area encompassing the mean and 2*standard deviation fields of temperature and salinity fields with vertices of (latitude, temperature/salinity), (longitude, temperature/salinity). Sample polygon (convex hull) for the 0 meters depth of salinity is shown in Figure. 1.
3. Subsequently the PIP algorithm is used to check if the observed Argo temperature and salinity data (obtained in step 1) falls within or outside this n-sided polygon.
4. Set the quality flags of good(bad) for data falling within(outside) the polygon there by identifying wrong profile data (See Figure. 2).

5. Use the polygon (convex hull) corresponding to the deepest depth (~ 2000 m) to check if the Argo float sensors have any degradation etc.

We wish to mention that our method proposed here is applicable to two dimensions, however this can be extended to three dimensions as well, where in a m dimensional n sided polygons of latitude/longitude and temperature/salinity can be built and the observed profiles from Argo floats can be checked for their correctness. The climatology used for the proposed method is the gridded fields of temperature (Locarnini et al., 2010) and salinity (Antonov et al., 2010) and their standard deviation fields obtained from World Ocean Atlas 2009 (WOA09) of US National Oceanographic Data Centre (NOODC). These climatological mean and standard deviation fields are then used to build polygons (convex hulls) for each standard depths. Since T/S profiles data from Argo floats are not available at regular depths, we first uniformly interpolated them to the same standard depths as provided in WOA09 using Akima spline (Akima et al., 1970). The scattered observations thus obtained from Argo floats are checked to see if they are falling within the corresponding polygon (obtained from climatology for that standard depth) using PIP algorithm. Jarvis March (1973) algorithm also famously called as gift wrapping algorithm was used for constructing polygon (convex hull). This is based on the principle of building a convex hull given n number of points and has a complexity of $O(nh)$ where n is the number of points and h is the number of points on the convex hull. The algorithm used for building the convex hull is described below:

Jarvis March Algorithm:

Given a set P of n points in the plane. we have to compute a convex hull (polygon) of P . We represent the points in P by their Cartesian coordinates, in two arrays $X[1 \dots n]$ and $T[1 \dots n]$ corresponding to the latitude and temperature points obtained from the WOA09. We will represent the convex hull as a circular linked list of vertices in counterclockwise (CCW) order. Jarvis's march starts by computing the leftmost point l , i.e., the point whose x -coordinate (latitude) is smallest, since we know that the left most point must be a convex hull vertex. Then the algorithm repeats the steps with other points in P to find each successive convex hull vertex, starting with l and continuing until we reach l again. The vertex immediately following a point p is the point that appears to be furthest to the

right to someone standing at p and looking at the other points. In other words, if q is the vertex following p , and r is any other input point, then the triple $p; q; r$ is in counter-clockwise order.

```

JarvisMarch(X[1 ... n]; T[1... n]):
    l = 1                (stage 1)
    for i = 2 to n
        if X[i] < X[l]
            l = i
    p = l
    repeat                (stage 2)
        q = p + 1
        for i = 2 to n
            if p != i and CCW(p,i,q)
                q = i
        next[p] = q; prev[q] = p
        p = q
    until p = l

```

Jarvis's March algorithm consists of two stages. During the first stage, it finds the leftmost point by comparing the x-coordinates. After it finds the leftmost point, p is initialized to that point. During the second stage, it finds the point that is furthest clockwise (CW) to p . To do this, it first chooses an arbitrary point q , then it iterates over all points to find the furthest CW point. This is very similar to finding the maximum element in an array but here the comparison is not based on numerical values, but on CCW property. More concretely, i is more CW than q for p if $CCW(p,i,q)=true$. This process ends when p becomes the leftmost point again, at which time the string wraps completely around the set of points.

This simple algorithm is used to build convex hull for all standard depth of climatology. Figure 1 shows a sample n -sided polygon (convex hull) built based on the mean salinity and $2 \times$ standard deviation data obtained from WOA09 for 0 meters depth. The black dots

represents the mean salinity fields, while the red (blue) dots represent the upper(lower) $2 \times$ standard deviation fields respectively. Similar n-sided polygons for each standard depths are generated and used for qualifying the Argo temperature and salinity data. Once this n-sided polygon is constructed, the PIP algorithm is used to check if the observed Argo temperature and salinity data fall inside or outside the polygon.

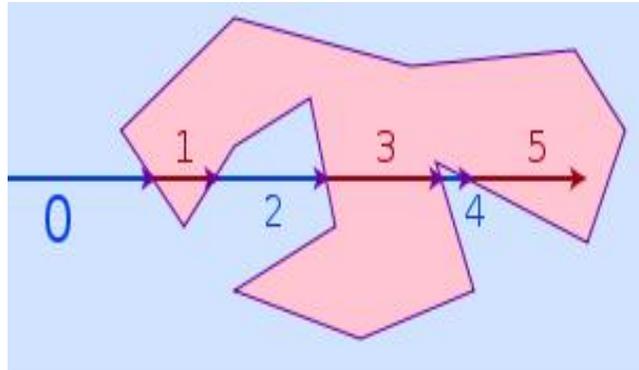


Figure 4. The number of intersections for a ray passing from the exterior of the polygon to any point; if odd, it shows that the point lies inside the polygon. If it is even, the point lies outside the polygon (Chong-Wei et al., 1997).

2.1 Point in Polygon (PIP)

In computational geometry, the PIP problem asks whether a given point in the plane lies inside, outside, or on the boundary of a polygon. It is a special case of point location problems and finds applications in areas that deal with processing geometrical data, such as computer graphics, computer vision, geographical information systems (GIS), motion planning, and Computer Aided Design.

2.2 Implementation of PIP

There are many algorithms available to check whether the given point lies inside the polygon or not like Crossing Test (Shimrat 1962), Angle summation test, Triangle test (Badouel 1990) and Ray Casting Algorithm. In the present work the "Ray Casting Algorithm" was chosen for the purpose of identifying whether a given point lies inside or outside the algorithm. Figure 4 shows a sample test for identifying the point to be within

or outside of polygon. One simple way of finding whether the point is inside or outside a simple polygon is to test how many times a ray, starting from the point and going in ANY fixed direction, intersects the edges of the polygon. If the point in question is not on the boundary of the polygon, the number of intersections is an even number if the point is outside, and it is odd if inside. This algorithm is sometimes also known as the crossing number algorithm or the even-odd rule algorithm, and is known as early as 1962 (Shimrat 1962).

The algorithm is based on a simple observation that if a point moves along a ray from infinity to the probe point and if it crosses the boundary of a polygon, possibly several times, then it alternately goes from the outside to inside, then from the inside to the outside, etc. As a result, after every two "border crossings" the moving point goes outside. This observation may be mathematically proved using the *Jordan curve theorem*.

2.3 Jordan Curve Theorem:

If J is a simple closed curve in \mathbf{R}^2 , then the Jordan curve theorem, also called the Jordan-Brouwer theorem states that $\mathbf{R}^2 - J$ has two components (an "inside" and "outside"), with J the boundary of each (Figure 5). In the words of Jordan "toute courbe [ferm'ee] continue [et sans point multiple]divise le plan en deux r'egions, l'une ext'erieure, l'autre int'erieure, cette derni`ere nepouvant se r'eduire `a z'ero (Jordan, 1893)

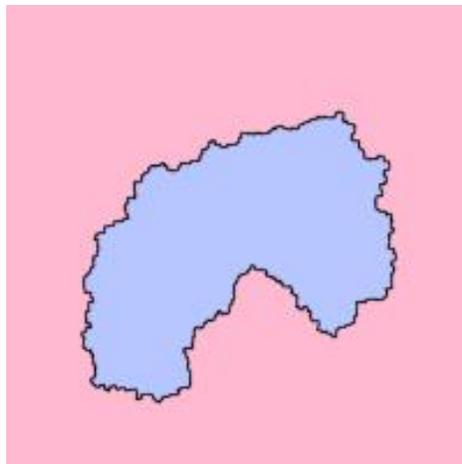


Figure 5. Illustration of the Jordan curve theorem. The Jordan curve (drawn in black) divides the plane into an "inside" region (light blue) and an "outside" region (pink).

In topology, a Jordan curve (simple closed curve) is a non-self-intersecting continuous loop in the plane. The Jordan curve theorem asserts that every Jordan curve divides the plane into an "interior" region bounded by the curve and an "exterior" region containing all of the nearby and far away exterior points, so that any continuous path connecting a point of one region to a point of the other intersects with that loop somewhere.

The algorithm used for implementing the PIP is given below:

Ray casting algorithm:

Let P be a simple convex polygon with vertices p_1, p_2, \dots, p_n and edges e_1, e_2, \dots, e_n and $q_1(x_0, y_0), q_2(x_1, y_1) \dots q_m(x_m, y_m)$ be set of Argo observation points. x_i and y_i represents latitude/longitude and temperature/salinity respectively.

```

begin
  for j = 1 to m
    count = 0
    for i = 1 to n
      if line  $x=x_j$  intersect with  $e_i$ 
        (let  $y_i$  be the y coordinates of the intersection between line  $x = x_j$  and  $e_i$ )
        if  $y_i < y_j$  then
          count = count + 1
        end
      if count is odd  $(x_j, y_j)$  is inside  $P$ 
      else  $(x_j, y_j)$  is outside  $P$ 
    end
  end
end

```

Figure 3 explains a sample scenario of how to determine whether a given data is good (bad) by virtue of it lying within (outside) the n-sided polygon. The biggest advantage of this proposed method is that large number of profiles data can be checked for their quality without manual intervention.

3. Validation of the proposed method

In general temperature and pressure sensors are found to be robust and salinity sensors on Argo floats are susceptible to changes, degradation owing to bio-fouling (Wong et al, 2003). Some of the recorded problems with salinity sensors are offsets, freshening due to Tri-Butyl Tin Oxide (TBTO), drift after a set of cycles etc. Hence we concentrated on checking the quality of salinity data in this section. Climatological means and standard deviations of salinity corresponding to the profiling depth of the floats under consideration are obtained from WOA09 and an n-sided polygon (convex hull) is constructed using Jarvis March algorithm. Argo float time series for the profiling depth values are then obtained and checked against this n-sided polygon using PIP algorithm. If the points fall outside the polygon, the Argo time series is suspected to have a problem (drift, bias, spike etc). Because the climatology is generated using large number of observations spanning decades, a float is suspected to have a problem if the parking depth salinity points fall outside the n-sided polygon which is constructed with a mean \pm 2*standard deviations vertices.

To demonstrate the robustness of the proposed method, 5 typical floats are chosen which represent different problems like drift, offset, grey listed etc. The details of the floats chosen for the validation are given in the table 1.

S.No	WMOID	First Cycle	Last Cycle	Total Cycles	Parking/Profiling depth
1.	2900782	22/06/2007	07/01/2012	167	2000/2000
2.	2900877	11/09/2007	04/09/2012	183	2000/2000
3.	2901340	25/12/2011	19/12/2014	110	2000/2000
4.	2900783	09/07/2007	29/12/2012	201	2000/2000
5.	2900554	06/09/2005	27/06/2009	279	1000/2000

Table 1. Details of the floats chosen for validation of polygon method.

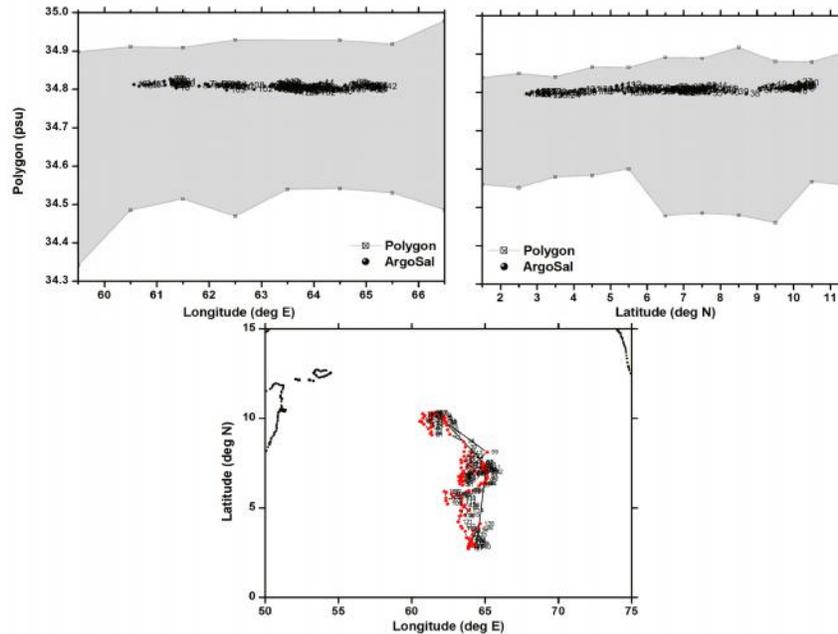


Figure. 6. (a) n-sided polygon (grey shaded region) constructed with longitude, salinity observations corresponding to the profiling depth (2000 m) of float WMOID 2900782. (b) same as (a) but with latitude. (c) Trajectory of the float during its life time.

Some examples of good and anomalous floats are given below together with their positions and n-sided polygons for the profiling depth. The WMO 2900782 travelling southward in the Arabian Sea is a typical example of a good float. All the profiles are observed to be good with the salinities corresponding to the profiling depth falling within the n-sided polygon (Figure. 6).

The second example (WMO 2900877) is contaminated by TBTO fouling which is evident from the fresher salinity profiles initially. The conductivity cell is more susceptible to fouling and associated drift because of the possible change in the dimension of the conductivity cell due to fouling. TBTO is used to improve the anti-fouling in the conductivity cell (Thadathil et al., 2004). Sometime this causes erroneous freshening in the initial profiles until the coating is washed off. Clearly one can see the initial profiles falling outside the n-sided polygon (Fig. 7), thereby indicating the case of the TBTO contamination. Also one can see the few profiles (cycle 33, 43) which are spikes in the time series of the float which are observed to fall outside the polygon.

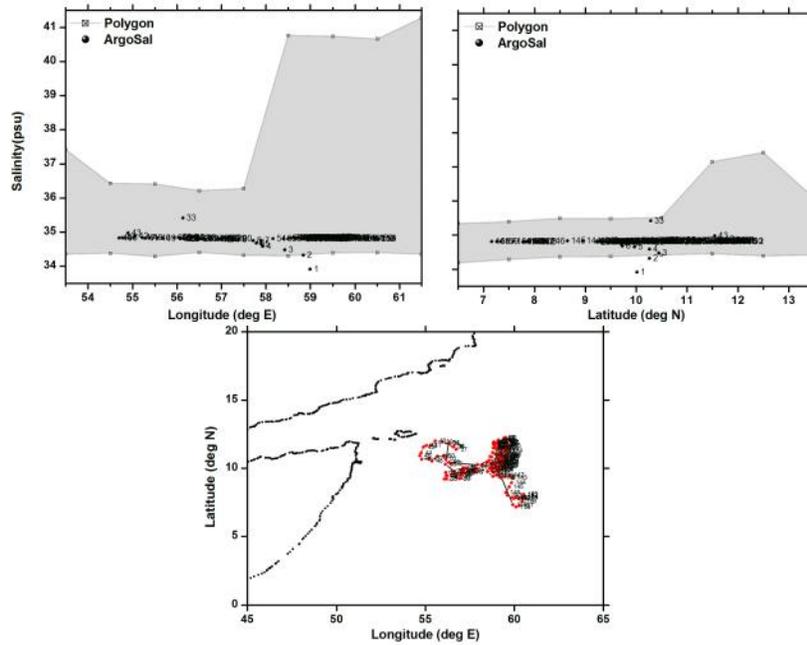


Figure. 7. (a) n-sided polygon (grey shaded region) constructed with longitude, salinity observations corresponding to the profiling depth (2000 m) of float WMOID 2900877. (b) same as (a) but with latitude. (c) Trajectory of the float during its life time.

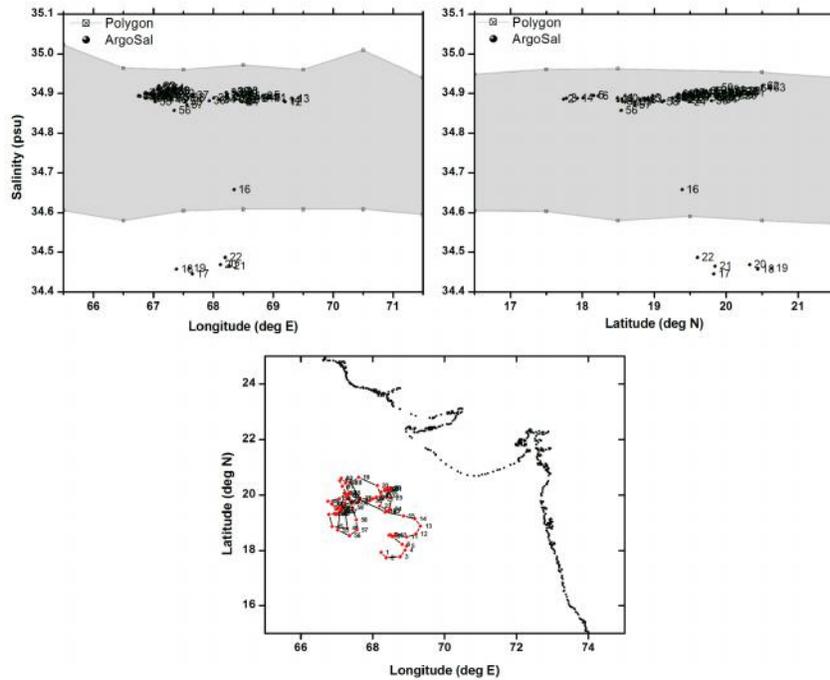


Figure. 8. (a) n-sided polygon (grey shaded region) constructed with longitude, salinity observations corresponding to the profiling depth (2000 m) of float WMOID 2901340. (b) same as (a) but with latitude. (c) Trajectory of the float during its life time.

The third examples of the float is one which is observed to have drift in the salinity sensor only for few cycles. This float is observed to have salinity drift between cycles 16 - 22. This can sometime happen due to worm entering into the conductivity pipe. When the worm is washed out the salinity sensor tends to come back to normalcy. This is clearly observed by the corresponding salinity values at profiling depth of 2000 m falling way outside the n-sided polygon (Fig. 8). This floats seems to have recovered to normalcy after cycle 22. The float with WMO 2900783 in the Bay of Bengal (Fig. 9) shows a typical case of a float whose salinity at profiling depth (2000 m) is completely offset to that of the climatology. All the salinity values corresponding to this float is observed to be falling outside the n-sided polygon right from the cycle 1. This is typical case of a greylisted float.

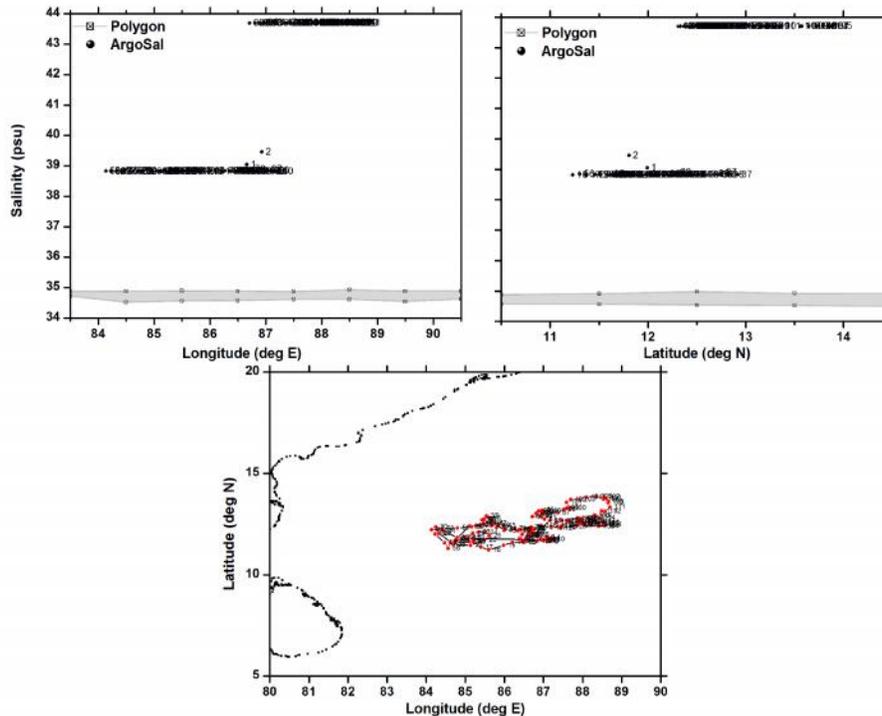


Fig. 9. (a) n-sided polygon (grey shaded region) constructed with longitude, salinity observations corresponding to the profiling depth (2000 m) of float WMOID 2900783. (b) same as (a) but with latitude. (c) Trajectory of the float during its life time.

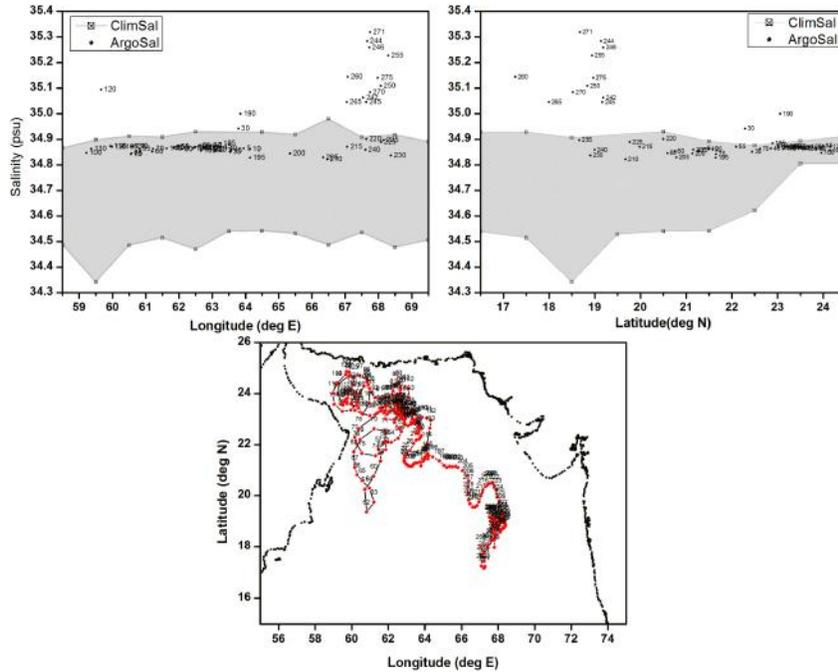


Fig. 10. (a) n-sided polygon (grey shaded region) constructed with longitude, salinity observations corresponding to the profiling depth (2000 m) of float WMOID 2900554. (b) same as (a) but with latitude. (c) Trajectory of the float during its life time.

The last example is that of a float with WMO 2900554 in the Arabian Sea (Fig. 10) whose salinity started to drift starting from cycle 200 onwards. All the salinity values corresponding to these cycles is observed to be falling outside the n-sided polygon from this cycle onwards. The examples discussed above are only a illustration of the possible cases among which the anomalous floats fall in ie., either a spike, offset, drift. These examples demonstrate the usefulness of the proposed method for identifying bad profiles. The biggest advantage of the proposed method is its applicability to suite of float data in a single go.

4. Discussions and Conclusions

A new method for performing quality control of Argo data is proposed. The method is based on building a convex hull and subsequently using Point In Polygon principle. Some of the anomalies viz., spike, drift, offsets etc associated with the Argo profiling float data can be identified. Mean and standard deviation fields from the latest available climatology, WOA09 are used in construction of n-sided polygon. PIP concept is used for

identifying good against bad profiles. The proposed method can be extended to other oceanic regions (viz., Atlantic and Pacific) and checked for its usefulness with other established methods. This method can be considered as a repetitive process as the climatology keeps updating and the floats data is also updated based on other proposed methods by the ADMT. For better results this methods can be augmented with other methods in use like altimetry based QC and objectively analyzed based QC. This method also urges updates to the reference climatology as it forms the backbone of the method.

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