

Chapter 2

Data

2.1 Introduction

As mentioned in the earlier chapter, the Gulf of Aden is a data sparse region from an oceanographic point of view. As per the available records, the first measurements of hydrographic parameters (temperature and salinity) in the Gulf of Aden were made during the research cruises of Vityaz during 1886–1889. During this cruise, about 209 profiles were collected from the Indian and Pacific Oceans; of which only 4 were from the Gulf of Aden. The second Expedition in the region was the Italian Expedition during 1923 on board Ammiraglio Magnani. During this cruise, about 144 profiles of temperature–salinity were collected mostly from the Red Sea and Bab el Mandab region. The second Italian cruise during 1924 extended to the western part of the Gulf of Aden. In 1929 the Netherlands Expedition on board Willebrod Snelluis collected about 311 profiles, of which 17 profiles were from the Gulf of Aden during their navigation through the gulf in April 1929. One of the famous expeditions in the Indian Ocean and the Gulf of Aden was the United Kingdom Expedition on board the Mabahiss during 1933–1934. During this cruise, about 119 profiles were collected, of which 19 were from the gulf. After a gap of 15 years, during 1947–1949, Swedish researchers on board the Albatross collected

about 86 profiles including 3 from the Gulf of Aden. Since then, several expeditions in the Indian Ocean have included stations in the Gulf of Aden; especially the International Indian Ocean Expedition (IIOE) during 1960–65. Making use of the hydrographic measurements from the world oceans, Levitus [1982] published a climatological atlas of world oceans. The first atlas published by Levitus [1982] provided the annual oxygen, seasonal salinity and monthly temperature climatologies at 19 standard depth levels (0/1000) at a spatial resolution of $1^\circ \times 1^\circ$ longitude–latitude grid for the world oceans. Though this atlas included areas of the Gulf of Aden, its reliability for this region remained low due to scant data which went into the analysis. The improved versions of this atlas published in 1994 [Levitus and Boyer, 1994; Levitus et al., 1994] and in 1998 [Antonov et al., 1998; Boyer et al., 1998] at $1^\circ \times 1^\circ$ longitude–latitude grid also suffered similar problems due to the low data density in the Gulf of Aden. Moreover, the large interpolation scales (4, 6, and 8 degree in the case of 1998 atlas) used by them while interpolating and mapping the data on to equal sized grids might introduce large errors in a region like Gulf of Aden where the temperature-salinity varies drastically over shorter spatial scales.

To overcome the difficulties in data sparseness, it is prudent to use a variety of data sets available from all sources. This chapter describes the data sets used in this thesis, their source, quality controlling and the processing. The in situ data set, the hydrographic measurements consisting of temperature–salinity and oxygen profiles, were obtained from several sources as described in the next section. Also the measurements made by the sensors mounted on board satellites are used, specially, the sea level heights measured by the satellite based altimeters and the sea winds measured by the sactterometer.

2.2 Hydrographic data

2.2.1 Data source

The available climatology of temperature and salinity for the Gulf of Aden prepared globally appeared to be inadequate to represent several known features, like the inversions in salinity and temperature profiles associated with the Red Sea Water (RSW) in the intermediate levels and the upwelling along the northern coast during summer (see section 2.2.4). Hence, to generate a reliable hydrographic data set, attempts have been made to obtain as many temperature–salinity profiles from the Gulf of Aden from all possible sources. The publicly available data were downloaded from different data centers, and also through personal contacts. The main sources of hydrographic data are:

- The archives of the National Oceanographic Data Center (NODC). NODC data are considered as the main source of data since most of the data (60%) were downloaded from NODC web site. The downloaded data consisted of data obtained using the profiling instrument 'Conductivity–Temperature–Depth (CTD)', 'Expendable Bathythermograph (XBT)' and 'Mechanical Bathythermograph (MBT)' and the 'Ocean Station Data (OSD)', obtained using reversing bottles attached with reversing thermometers. NOCD05 data released in May 2006 [Boyer et al., 2006], as an update to NOCD01 data, was obtained through internet downloads (http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html) for the Gulf of Aden region (between 43 and 55° longitudes and 10 and 18° latitudes). The details of the number of temperature–salinity–oxygen profiles are listed in (Table 2.1). Altogether, 23766 profiles consisting of 23705 temperature profiles, 3993 salinity profiles and 2474 oxygen profiles were obtained from NODC.
- The archives of the Japan Oceanographic Data Center (JODC). A total of 15470 profiles was obtained from JODC, consisting 2142 salinity profiles and 15458 tem-

perature profiles.

- The temperature–salinity–oxygen profiles collected, using CTD, during the Bab el Mandab Experiment (BAM) [Murray and Johns, 1997; Al Saafani and Shenoi, 2004]. These profiles collected during 1995–1997 from the western Gulf of Aden and Bab el Mandab region contained 42 profiles of temperature–salinity–oxygen from the western Gulf of Aden.
- The CTD profiles available from the Netherlands Indian Ocean Programme (NIOP) [Baars, 1994]. 74 profiles of temperature, salinity and oxygen were obtained from this source.
- The data collected during 1984–85 through a survey under the auspices of the Marine Science and Resources Research Center (MSRRC) of Yemen [Stirn et al., 1985]. This data were obtained personally from Dr. Peichura. It consisted of 100 profiles of temperature, salinity and oxygen.

The total number of profiles obtained from the aforementioned sources was 39452; of which 39379 profiles contained temperature, 6351 profiles contained salinity and 2690 profiles contained oxygen (Tables 2.2, 2.3 and 2.4).

Table 2.1 The temperature–salinity–oxygen profiles obtained from National Oceanographic Data Center (NODC05 data sets).

Data type	Total	Temperature	Salinity	Oxygen
CTD	469	469	469	469
OSD	4609	4548	3524	2005
XBT	9655	9655	-	-
MBT	9033	9033	-	-
Total	23766	23705	3993	2474

2.2.2 Quality Control

Since, the profiles were spot measurements in time and space, their distributions were not even either in space or time. Hence, to map them over regular spatial and temporal intervals it is necessary to interpolate them following robust techniques. But before the data are interpolated, it is necessary to subject them to various quality checks. Boyer and Levitus [1994] described a set of quality checks used by them to check the quality of temperature–salinity profiles before subjecting them for interpolation and mapping. Various steps followed to ensure the quality of profiles and the procedure followed to map them on equally spaced spatial grids during each month are described in the following sections.

Position Check

A few profiles appeared in the data sets with wrong positions, say on land. Obviously, these errors occurred due to the wrong entry of station locations. In this step, 31 profiles of temperature, 12 profiles of salinity, and 5 profiles of oxygen having wrong positions were identified and removed (Tables 2.2, 2.3 and 2.4).

Duplicate profile check

Since we have obtained the data from different data centers, it is possible to have the same profile in more than one data source. Thus the second step in the quality check was the removal of duplicate profiles. A duplicate profile is one that contains the identical information to another profile, including position, date, and the data values. The NODC data were used as the reference data set. The profiles found to be repeated in other data sets were then removed. This process removed 16618 profiles of temperature and 2150 profiles of salinity, mostly, from JODC data, and 144 profiles of oxygen (Tables 2.2, 2.3 and 2.4). After the removal of duplicate profiles, 22730 profiles of temperature, 4189 profiles of salinity and 2541 profiles of oxygen were retained. Obviously, the availability

of temperature profiles is larger than (at least 5 times) the availability of salinity profiles in the Gulf of Aden.

Table 2.2 The number of temperature profiles discarded at various stages of quality checks and the number of accepted profiles. See section 2.2.1 for the details on data sources.

Data source	Before quality control	Bad position	Duplicate profiles	Temperature inversion	Accepted
NODC-CTD	469	-	62	-	407
NODC-OSD	4548	5	296	10	4237
NODC-XBT	9655	12	5	22	9616
NODC-MBT	9033	7	958	30	8038
JODC-CTD	328	-	328	-	-
JODC-OSD	3947	7	3780	2	158
JODC-XBT	7223	-	7223	-	-
JODC-MBT	3960	-	3960	-	-
BAM-EXP.-CTD	42	-	-	-	42
NIOP-CTD	74	-	6	-	68
MSRRC-Yem.-CTD	100	-	-	-	100
Total	39379	31	16618	64	22666

Depth inversion and depth duplication checks

After the removal of duplicate profiles, individual profiles of each parameter were checked for duplicate depths and depth inversions. Depth inversion occurs when an observation has a shallower depth than the observation directly preceding it. Depth duplication occurred due to reporting of the same data more than once. In such cases the second observation was flagged and eliminated.

Temperature inversions

Unnecessary temperature inversions can occur due to erroneous recordings or measurements. However, the temperature inversions in the upper layers and locations of a large influx of totally different water masses are not unnatural. For example, in the western Gulf of Aden where a large influx of RSW occurs. Hence, it is necessary to apply this check cautiously. For this reason, the profiles from western Gulf of Aden (west of 47° E) were not subjected to this check. For the profiles from other regions of Gulf of Aden, the temperature inversions were considered unacceptable when the increase in temperature exceeded 0.3 °C per meter between adjacent observations. Boyer and Levitus [1994] had used a similar value to identify the temperature inversions. These checks resulted in the loss of 64 temperature profiles.

Table 2.3 The number of salinity profiles discarded at various stages of quality checks and the number of accepted salinity profiles. See section 2.2.1 for the details on data sources.

Data source	Before quality control	Bad position	Duplicate profiles	Accepted
NODC-CTD	469	-	62	407
NODC-OSD	3524	5	105	3414
JODC-CTD	328	-	328	-
JODC-OSD	1814	7	1649	158
BAM-EXP.-CTD	42	-	-	42
NIOP-CTD	74	-	6	68
MSRRC-Yem.-CTD	100	-	-	100
Total	6351	12	2150	4189

A common approach to identify the inversions in salinity profiles is not possible because of the presence of different water masses. However, any errors that can arise due to erroneous salinities can be checked, though indirectly, through the checks for stability (monotonic increase in density with depth) described later.

Table 2.4 The number of oxygen profiles discarded at various stages of quality checks and the number of accepted oxygen profiles. See section 2.2.1 for the details on data sources.

Data source	Before quality control	Position check	Duplicate profiles	Accepted
NODC-CTD	469	-	62	407
NODC-OSD	2005	5	76	1924
BAM-EXP.-CTD	42	-	-	42
NIOP-CTD	74	-	6	68
MSRRC-Yem.-CTD	100	-	-	100
Total	2690	5	144	2541

Vertical Interpolation

Before checking the temperature–salinity profiles for stability of a water column, they were first interpolated to standard levels. The interpolation of the data to standard levels is necessary because the observed levels differ from one profile to another. The interpolation to 26 standard levels (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1750 and 2000 m) was done using a three point Lagrangian interpolation method based on Scarborough [1966]. This interpolation scheme used one value above and two values below or two values above and one value below the interpolation level. If the observed level reported a value within 5 meters of the surface, then that value is used as the surface value (at 0 m).

Stability check

The station data containing both temperature and salinity were then used to check for the stability of the water column. Spurious inversions in the density values indicate the instability of the water column that is unnatural in most cases. However, minor instability or inversion in density in the upper layers and in the intermediate layers is natural because

of the measurement, made at the time of mixing and stabilization of the water column.

Hence, up to a depth of 30 m, the inversions in excess of $3 \times 10^{-5} \text{ g cm}^{-3}$ in density only were rejected, below this depth, down to 400 m level, inversions in excess of $2 \times 10^{-5} \text{ g cm}^{-3}$ were rejected. No inversions were allowed below 400 m. If the number of unacceptable inversions in each profile is more than two, then the entire profile was eliminated. This check rejected about 950 levels.

Standard deviation check

As a final check, the data retained at each standard level have been subjected to a 'standard deviation check' by grouping the profiles during a month in one-degree spatial grids in the case of temperature and two-degree spatial grids in the case of salinity. This check is expected to discard non-representative data. The monthly mean and standard deviations of temperature (salinity) at each standard level were calculated in each one-degree (two-degree) grid and the individual values were checked against them. When the value at any standard level of the profile exceeded 3 standard deviations, then that was flagged and discarded. This check was performed only when there were enough profiles available within the one-degree (two-degree) grids, say a minimum of three profiles. Hence, the check was not performed when the one-degree (two-degree) grids contained fewer than three profiles. Only 4 one-degree grids in the case of temperature (along the southern side of the gulf) and 3 two-degree grids in the case of salinity had less than 3 profiles (mostly in the eastern gulf). Boyer and Levitus [1994] had used 5 standard deviations in a five-degree latitude by a five-degree longitude grid. Considering the high variability in the temperature-salinity structure in the Gulf of Aden, we have used the smaller grids (two-degree in case of salinity and one-degree in case of temperature) but smaller standard deviation values (3 standard deviations rather than 5). This criteria helped us to retain the small scale features within the Gulf of Aden like the upwelling along the northern side of the gulf. The five-degree grid practiced by Boyer and Levitus [1994] ought to have

smoothed these features unnecessarily.

At the end of the series of quality checks described above, 22666 profiles of temperature, 4189 profiles of salinity and 2541 profiles of oxygen were retained (Tables 2.2, 2.3 and 2.4). The number of oxygen profiles is low compared to the temperature and salinity profiles, hence the oxygen profiles were not subjected to the objective analysis described in the following subsection. The earlier climatologies included 13229 temperature profiles [Stephens et al., 2002] and 1917 salinity profiles [Boyer et al., 2002] for this region. The one-degree spatial grid used for the mapping of temperature by Antonov et al. [1998] and for salinity by Boyer et al. [1998] appears to be inadequate to describe the features in the coastal waters (see for example Figure 2.4). Hence, to describe the observed features in the Gulf of Aden, it is necessary to carry out a similar analysis on 0.5° grids. The number of temperature and salinity profiles available in each 0.5° grid during every month is shown in Figures 2.1 and 2.2. Among the 86 half degree grids, covering the Gulf of Aden, between the longitudes 43° E and 51° E, 2 grids did not have temperature profiles in April and July, 3 grids in May and one grid in September. The number of grids which did not have salinity profiles are more than that of temperature profiles. Nevertheless, considering the distribution of profiles, it is possible to map them over 0.5° grids following the procedures described in Antonov et al. [1998].

2.2.3 Objective Analysis

After the quality control, the data are ready for interpolation and mapping on to equally spaced grids. Since the final numbers of temperature and salinity profiles are sufficiently high in the Gulf of Aden region, we have decided to map them on to 0.5×0.5 grids. An interpolation technique called 'Objective Analysis' is often adopted for the mapping of such data sets [Antonov et al., 1998]. Antonov et al. [1998] used the objective analysis scheme described in Barnes [1964] to prepare the atlas of temperature for the Indian Ocean. The analysis scheme used the data values at standard levels and first-guess values

Figure 2.1 The number of temperature profiles available in $0.5^\circ \times 0.5^\circ$ grids during a month after applying the series of quality checks described in section 2.2.

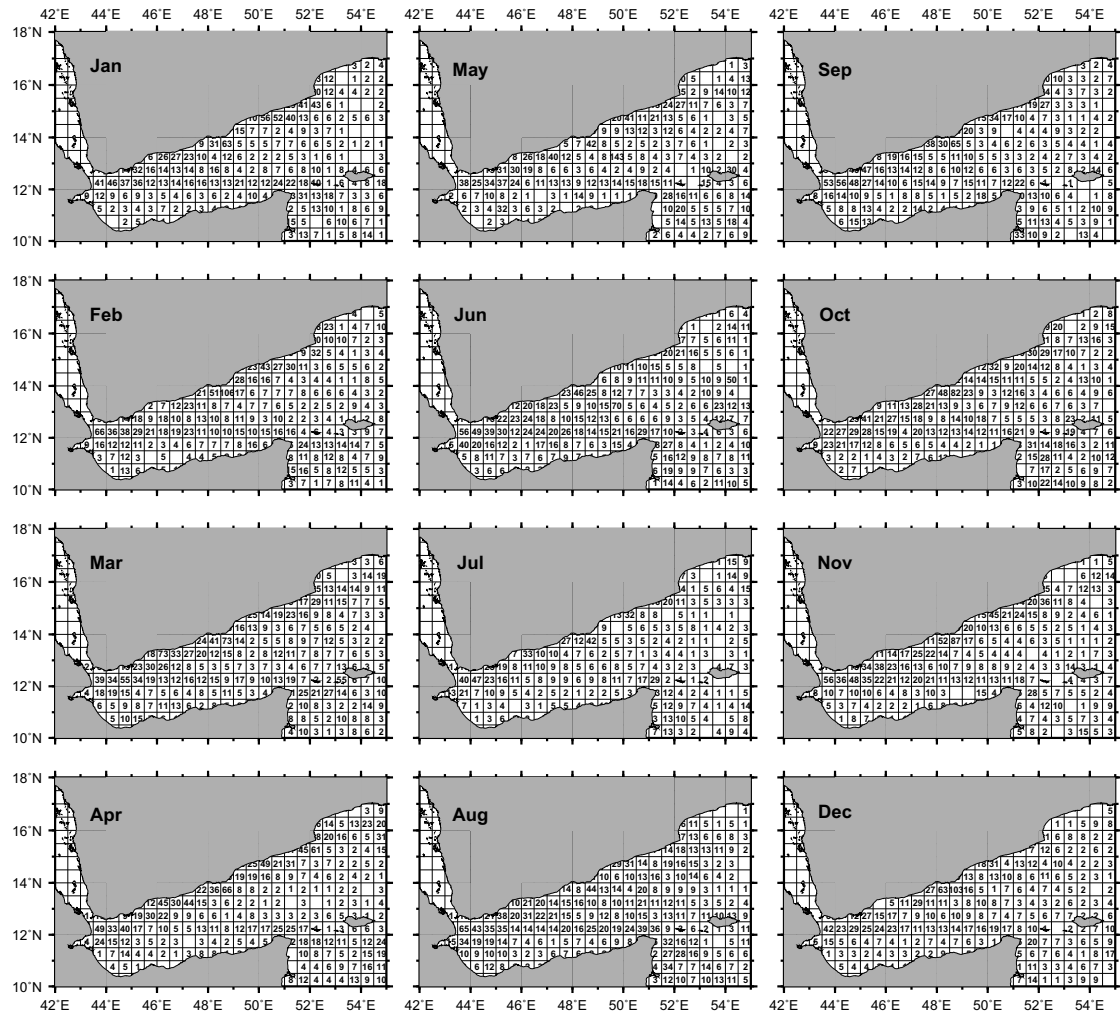
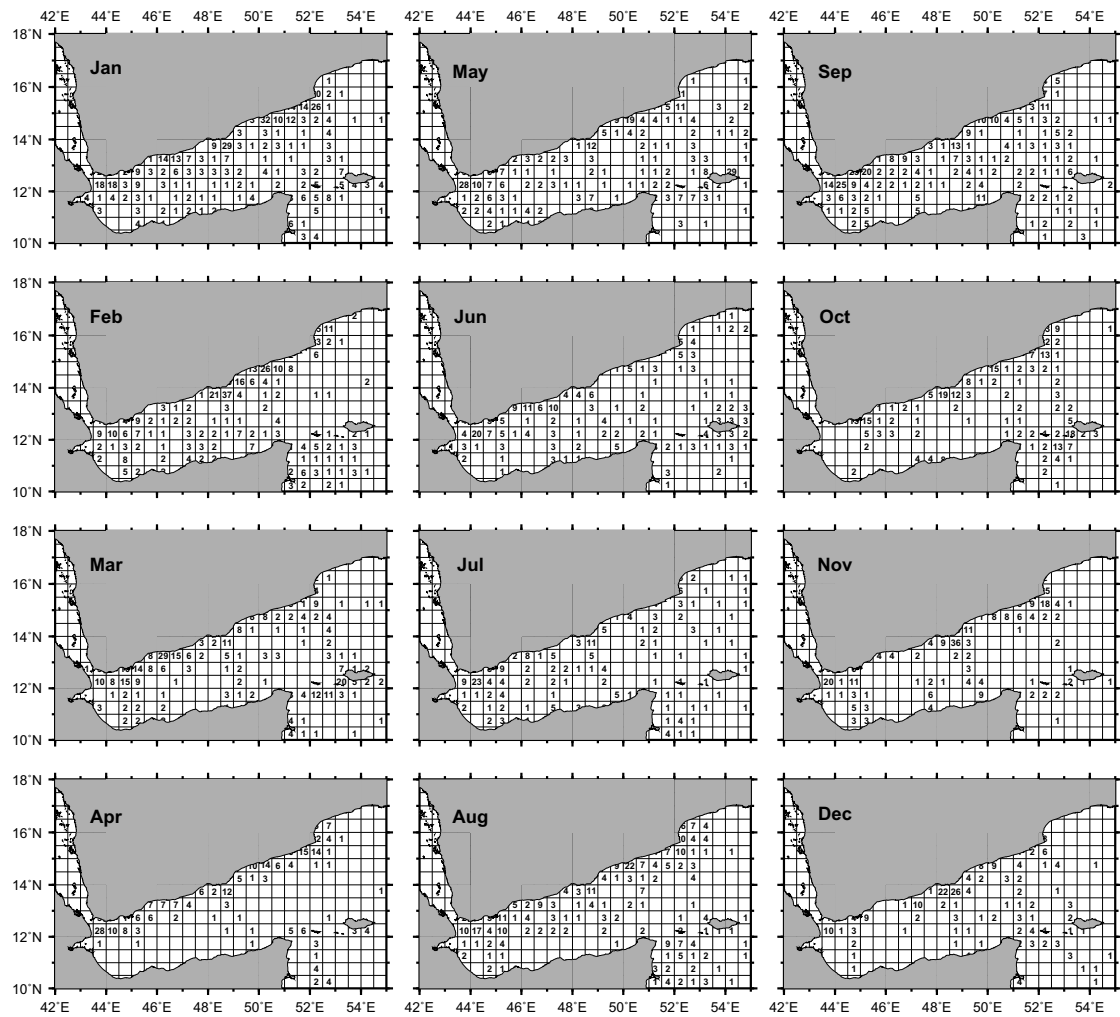


Figure 2.2 The number of salinity profiles available in $0.5^\circ \times 0.5^\circ$ grids during a month after applying series of quality checks described in section 2.2.



for each grid. Antonov et al. [1998] defined the first-guess using the annual 'zonal mean' of the parameter under consideration. For the Gulf of Aden region, this approach caused large errors due to the large variability in the values of temperature and salinity from the western end to the eastern end. The influx of high saline RSW at the western end of the gulf generates sharp zonal gradients rendering the use of zonal means as first-guess values meaningless. On the contrary, the meridional gradients of temperature and salinity in the Gulf of Aden are low. Hence, we have used the meridional means (of each 0.5° longitude bands) as the first-guess values rather than the zonal means.

Together with the first-guess values, the other required inputs for the scheme are the observed values at standard levels regardless of when they were observed. The next input required for the scheme is the 'radius of influence' specifying the distance up to which the interpolation scheme should consider the influence of a particular value. Using these three inputs, the first-guess values, the observed values at standard levels and the radius of influence, the scheme first computes the difference between the observed value and the first-guess value. Later the scheme, corrects the first-guess values at all grid points by applying a distance-weighted mean of all values that lie within the area around the grid point defined by the radius of influence. Mathematically, the correction factor suggested by Barnes [1964] can be written as

$$C_{i,j} = \frac{\sum_{s=1}^n W_s Q_s}{\sum_{s=1}^n W_s} \quad (2.1)$$

where (i, j) are the coordinates of a grid point in the longitude-latitude directions, $C_{i,j}$ is the correction factor at grid point denoted by (i, j) , n is the number of observations that fall within the area around the point i, j defined by the radius of influence, Q_s is the difference between the observed value and the first-guess at the s^{th} point in the influence area, W_s is the weighting function given as $\exp(-Er^2R^{-2})$ for $r < R$ and zero for $r > R$, r is the distance of the observation from the grid point (i, j) , R the radius of influence set

to be 1° for this analysis. E is set to a value 4. Antonov et al. [1998] used a value of $R = 4, 6$ and 8 degrees for the global analysis. For a region like the Gulf of Aden, such a large value of R would introduce undesirable errors because it forces the analysis to use values from the west (where the RSW influx occurs) to obtain a value in the east and vice versa.

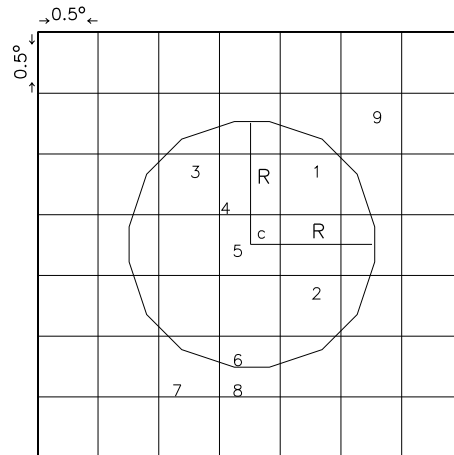
At each grid point the analysis computes the analyzed value $G_{i,j}$ as the sum of the first-guess, $F_{i,j}$, and the correction $C_{i,j}$. ie.

$$G_{i,j} = F_{i,j} + C_{i,j} \quad (2.2)$$

The working of the objective analysis scheme based on the radius of influence is shown in the schematic in Figure 2.3. For the analysis at a particular time for a 0.5×0.5 grid centered at 'c', the procedure includes all observations that fall within the radius of influence R ; in this case, the values at locations 1 to 6. According to the scheme, to compute C_{ij} at location 'c', the value at 5 will be accorded the maximum weightage and the value at 6 will be accorded with minimum weightage. The values at locations outside the radius of influence 'R' (locations 7,8, 9) will have no effect on the C_{ij} at 'c'. If there are no data points within the area defined by the influence radius, then the correction, C_{ij} , will be set to zero leaving the first-guess field unchanged. In such cases, the analyzed value will be the first-guess value itself. This correction procedure is applied at all grid points to produce an 'annual analyzed field'.

The 'annual analysed values' obtained at every grid point were then used as first-guess values for a bi-monthly analysis, again following the same procedure as described above. For the bi-monthly analysis, the mean values in the grids were computed using the data in bi-monthly durations (Jan–Feb, Mar–Apr, May–Jun, Jul–Aug, Sep–Oct, and Nov–Dec). The 'bi-monthly analysed values' thus obtained were then used as the first-guess values and the same procedure was repeated to generate monthly analysed values of temperature and salinity in each half degree grid point in the Gulf of Aden and its vicinity.

Figure 2.3 A schematic showing the grid size and the radius of influence (R) used for the objective analysis scheme. Location 'c' represents the center of $0.5^\circ \times 0.5^\circ$ grid where the interpolated value needs to be assigned. The numbers from 1 to 9 represent the locations where the data are available. According to the scheme, profiles 1-6 located within the radius of influence (R) of 'c' will be considered for interpolation. Maximum weightage will be accorded for Station 5 and minimum for Station 6.



2.2.4 Post objective analysis

After the initial objective analysis, additional checks were performed to identify and rectify the unrealistic features occasionally seen, mostly, in data sparse areas. To eliminate these features, all the data in an area were examined to find the anomalous behaviour, if any, in the profiles. Any suspicious data were then eliminated and the whole procedure of objective analysis was repeated again using the rectified inputs.

The objectively analysed temperature and salinity fields on half degree grids were compared with the previous World Ocean Atlas–1998 (WOA98) of temperature [Antonov et al., 1998] and salinity [Boyer et al., 1998] and also with the new World Ocean Atlas data–2001 (WOA01) of temperature [Stephens et al., 2002] and salinity [Boyer et al., 2002] (Figures 2.4 and 2.5). WOA01 has a spatial resolution of $0.25^\circ \times 0.25^\circ$. Figure 2.4a (panels to the left) shows the horizontal distribution of temperature from three data sets during July. The intense upwelling that occurred along the northern part of the

gulf is not seen in WOA98 (upper panel) due to the coarse spatial resolution ($1^\circ \times 1^\circ$ grid), but is seen clearly in the new climatology (lower panel). It is seen in WOA01, but with lesser intensity (middle panel). The new climatology clearly shows three pockets (marked 1, 2 and 3) of upwelling along the northern coast. These three pockets of upwelling seen along the northern coast of the Gulf of Aden are similar to those reported in Piechura and Sobaih [1986]. Figure 2.4a (panels to the right) shows the same for the month of March where the WOA98 does not show any variations inside the gulf, while the new climatology shows better distribution inside and outside the gulf. Similar horizontal distribution of surface salinity (Figure 2.4b) shows the three pockets of upwelling along the northern coast from the new climatology and the WOA01 and not seen from WOA98. The eastern part (location 3) of WOA01 shows salinity < 34.5 psu, which is very low for the region like Gulf of Aden as compared with 35.7 psu from new climatology. During March (right panels) the new climatology shows also similar distribution of salinity to that of temperature. Figure 2.5a, b and c shows the vertical distribution of salinity, along an east–west section in the Gulf of Aden, during July from the three data sets. The high saline RSW is seen in all data sets in the intermediate layer. The new climatology (Figure 2.5c) shows high salinity RSW in the western end of the gulf with ~ 37 psu, while it is 36.2 psu in WOA98 and 36.4 psu in WOA01. The other advantage of this new climatology is that, it captures the core of RSW at two depth levels in the western part of the Gulf of Aden similar to that reported earlier [Maillard and Soliman, 1986; Bower et al., 2000] using in situ observations. The third advantage of this climatology is that it produces the data to a 2000 m depth (Figure 2.5 panel d) compared to 1500 m in WOA98 and WOA01. The data to 2000 m is useful to describe the bottom water in the Gulf of Aden.

Having shown the advantages of new climatology over the previous climatologies, data sets were also compared with the average values of in situ temperature and salinity in the grids where they existed in the data during a month. Figure 2.6a shows the difference between the temperature in each climatology and the average temperature estimated

from the observed profiles falling in the corresponding grids. The mean of the differences and the standard deviations are lowest for the new climatology. Some of the differences are as high as 6.1 °C for WOA98 and 6.4 °C for WOA01. On the contrary, in the new climatology, very few differences showed higher values (Figure 2.6a, right column). Similarly, higher differences are evident in the salinity fields of WOA98 and WOA01. The differences in excess of 0.5 psu are too many in WOA98 and WOA01 climatologies (Figure 2.6b, left and central columns). On the contrary, the differences, between the analysed value and mean were low for the new climatology (Figure 2.6b, right column).

2.3 Sea level data from satellite based altimeters

The altimeter data, used in this thesis, have been obtained from AVISO (Archiving, Validation, and Interpretation of Satellite Oceanography Data) operations centre. AVISO archives and distributes the satellite altimeter data processed by CLS Space Oceanography Division as part of the European Union Environment and Climate (EU ENACT) project (EVK2-CT2001-00117) with support from CNES (Centre National d'Études Spatiales). AVISO distributes sea surface heights (SSH) and sea level anomalies (SLA) measured by TOPEX/Poseidon (T/P), Jason and ERS-1/2 satellites separately and as a merged product by merging all of them. The T/P was launched in August 1992, and had a repeat cycle of 10 days. ERS-1 was launched in July 1991 with a repeat cycle of 35 days; later ERS-2 replaced ERS-1 in April 1995. As a replacement to T/P, Jason-1 was launched on 7 December 2001 with same repeat cycle of 10 days. Jason-1 was designed to follow the T/P orbit and provide same quality data, if not better. In August 2002, Jason replaced T/P. Although the T/P and Jason satellites have the same repeat cycle (10 days) their ground tracks were separated by a distance of 315 km at the equator; more than the average span of an ocean eddy. On the other hand, the ground tracks of ERS-1 and ERS-2 satellites were separated by a maximum distance of about 80 km. Therefore, merging the T/P-

Figure 2.4 (a) Horizontal distribution of temperature ($^{\circ}\text{C}$) for the months of July and March from the new climatology (lower panels) compared with the temperature of the same months of WOA98 (upper panels) and WOA01 (middle panels).

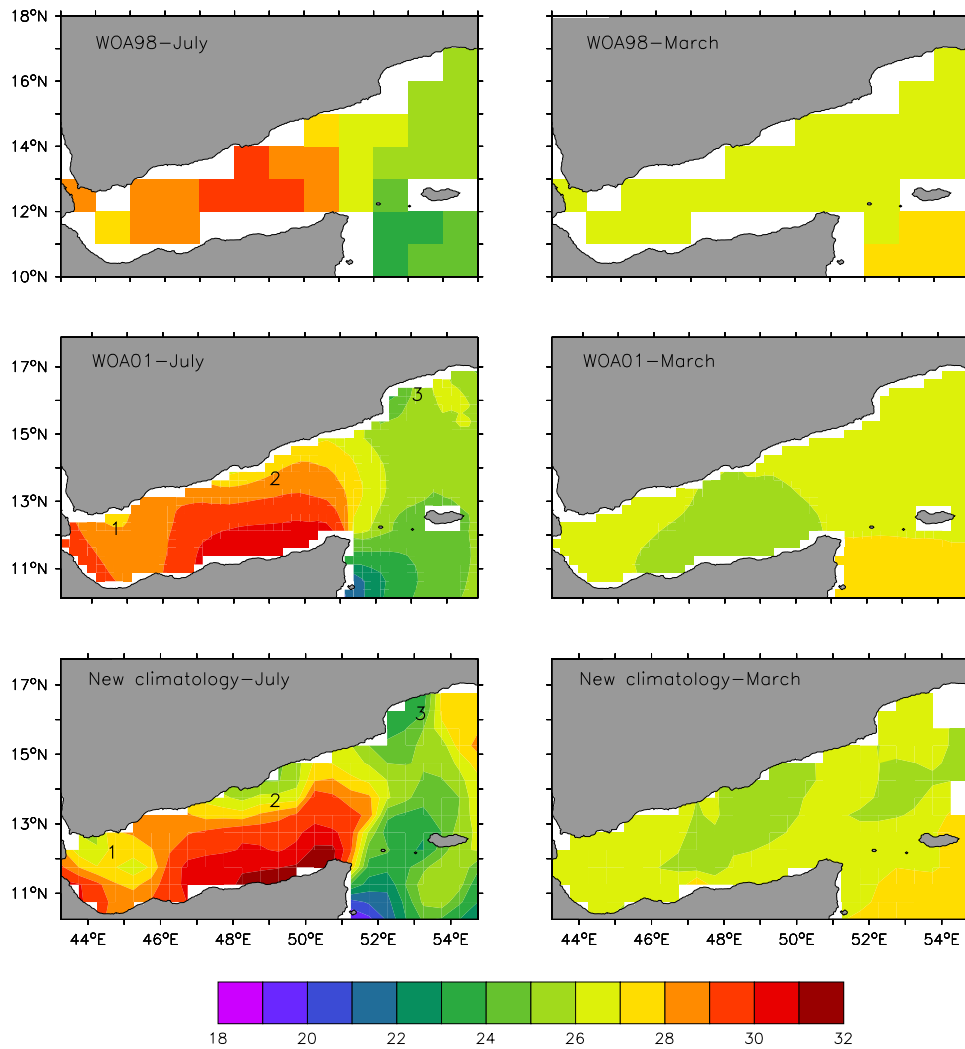


Figure 2.4 (b) Same as Figure 2.4(a) for salinity (psu).

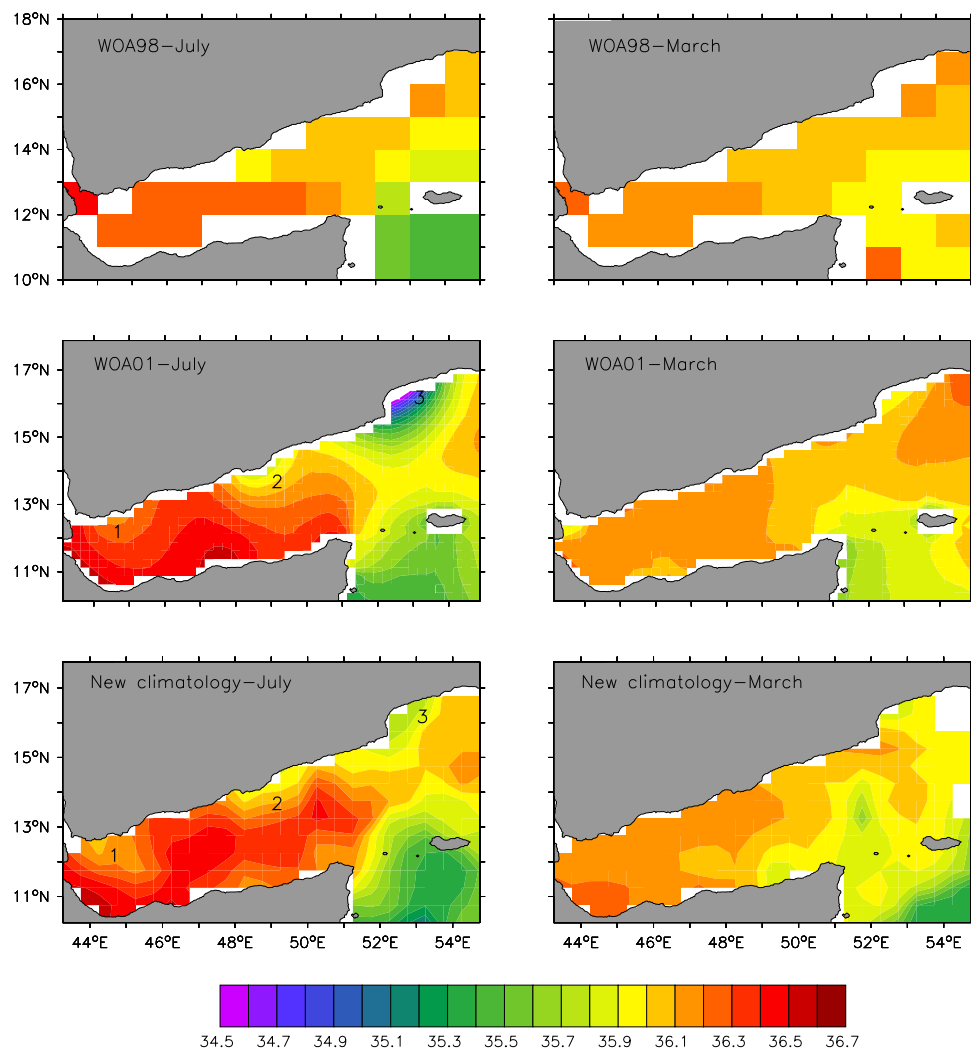


Figure 2.5 A comparison between the vertical distribution of salinity (psu) for the month of July of (a) WOA98, (b) WOA01 and (c) new climatology. The vertical distribution is restricted up to 1500 m because of the maximum coverage of WOA98 and WOA01. The lower panel (d) shows the vertical distribution of salinity from the new climatology extending up to 2000 m. The extension up to 2000 m includes bottom water.

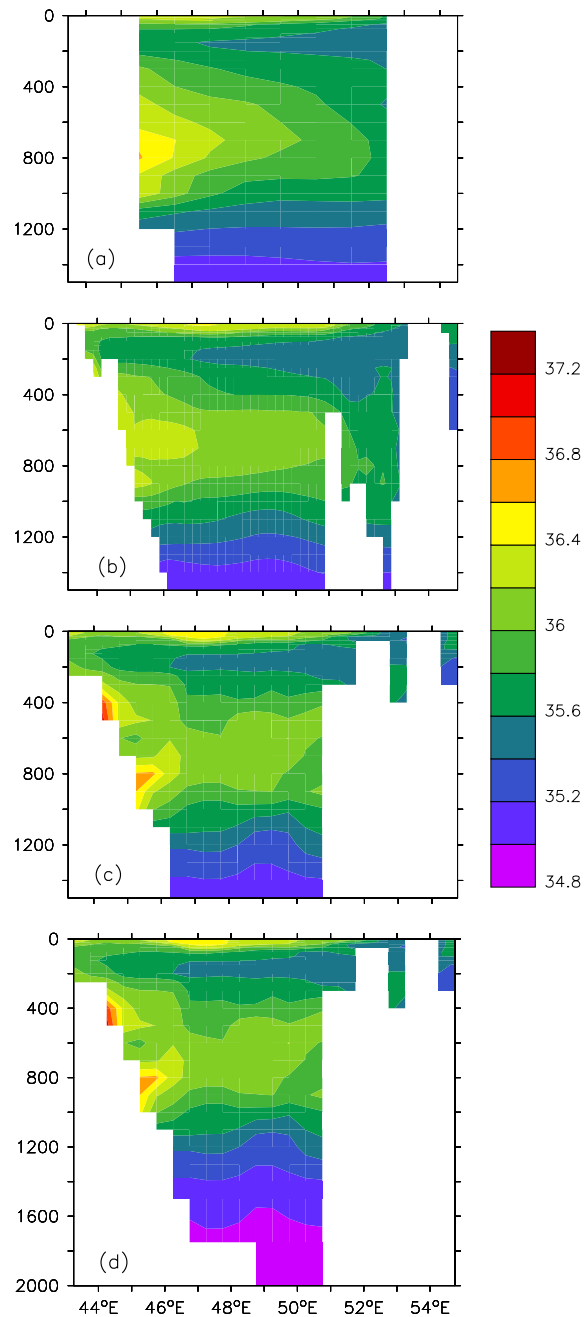


Figure 2.6 (a) The differences between the mean temperature from the observations in a grid and the analysed temperature in the same grid for each data set. The mean, maximum, and standard deviation of the differences are also shown.

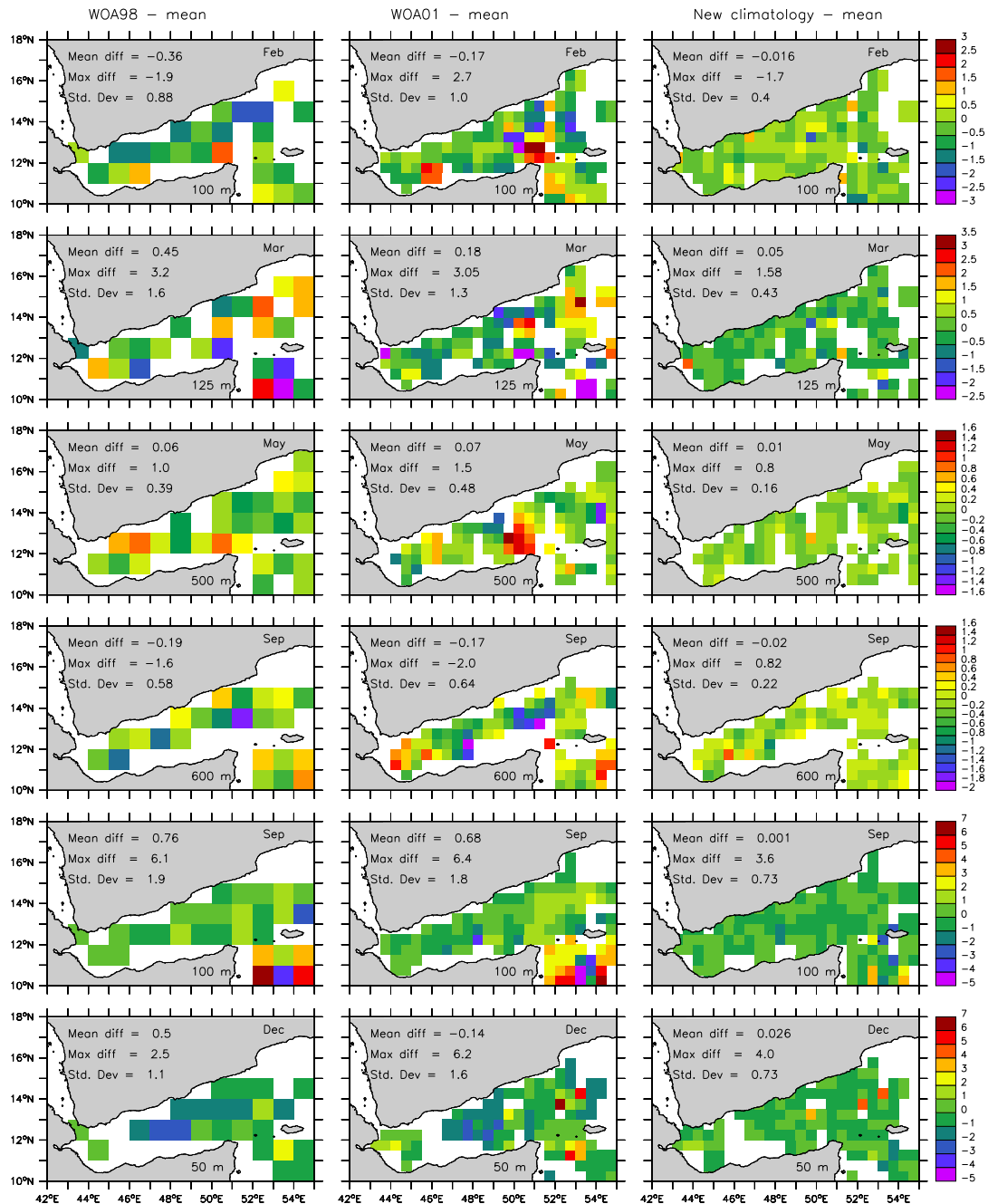
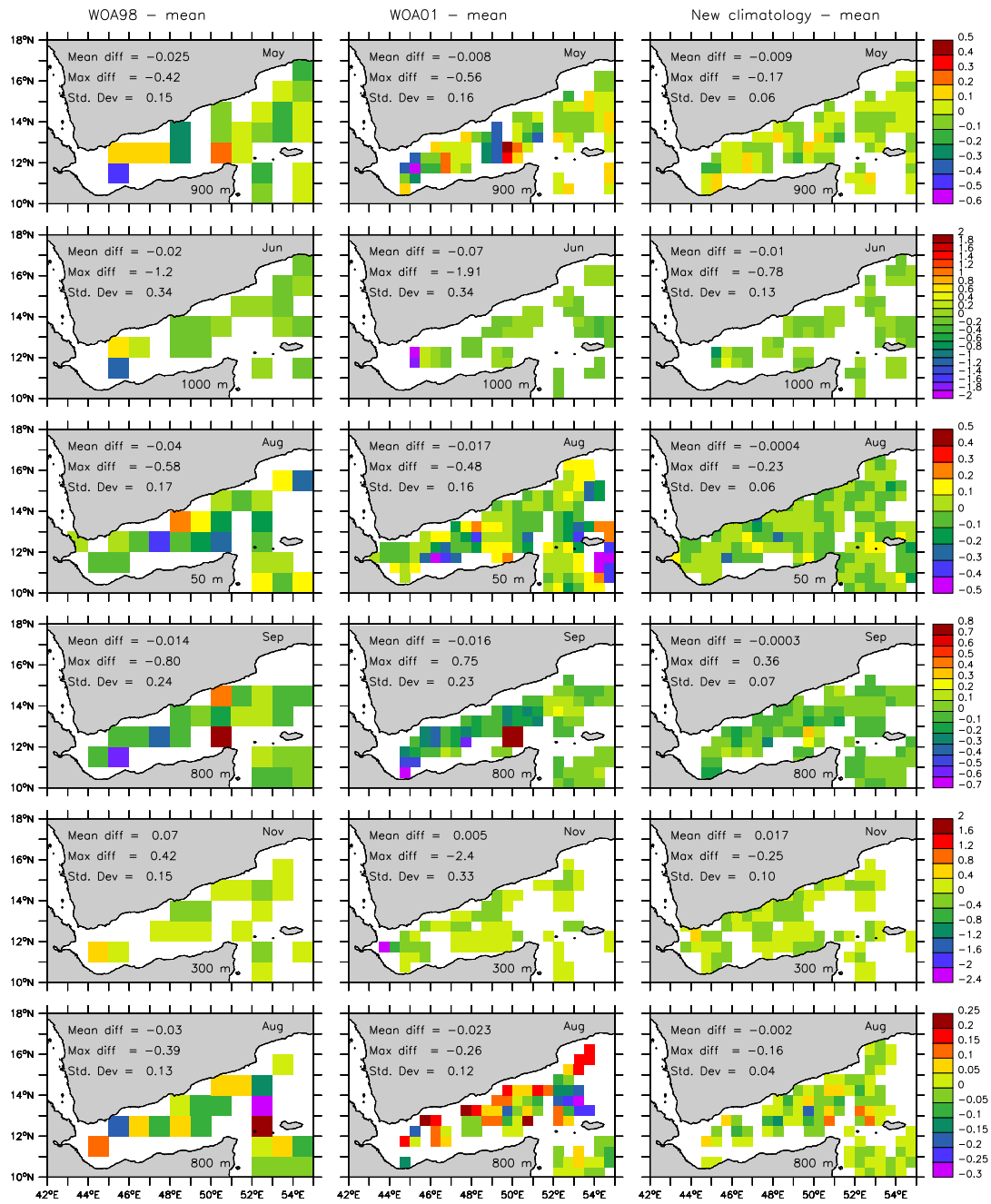


Figure 2.6 (b) Same as 2.6a but for salinity.



Jason and ERS-1/2 altimeter data helped in better resolving the mesoscale variability.

The merged T/P–Jason+ERS data provide more homogeneous and reduced mapping errors than the individual data set [Ducet et al., 2000]. The weekly (7 days) data set of sea level anomaly (SLA) obtained from AVISO spanning over a period of 11 years from 1 January 1993 to 31 December 2003 on a $1/3^\circ$ Mercator projection spatial grid are used in this study. The anomalies of sea level heights (SLA) were obtained relative to a 7-year mean (January 1993 to December 1999). Specific processing was also performed to obtain ERS-1/2 mean consistent with a T/P mean [Anonymous, 2001a].

The data were corrected for instrumental errors, environmental perturbations (wet tropospheric, dry tropospheric and ionospheric effects), ocean wave influence (sea state bias), tidal influence (most recent GOT99 tidal correction [Ray, 1999]), and inverse barometer effect corrected with a variable mean pressure [Dorandeu and Le Traon, 1999]. Tidal and inverse barometer corrections for ERS-1/2 were made to be homogeneous with T/P; the ERS-1/2 orbit was globally adjusted to the more precise T/P orbit [Le Traon and Ogor, 1998].

2.4 Sea surface winds from QuikSCAT scatterometer

QuikSCAT was launched from California, USA on 19 June 1999 with the SeaWinds instrument, a specialized microwave radar, to measure the near-surface wind speed and direction under all weather conditions over the oceans globally. The SeaWinds instrument on QuikSCAT is an active microwave radar designed to measure electromagnetic backscatter from wind roughened ocean surface. QuikSCAT/SeaWinds is a conically scanning pencil-beam scatterometer. See Dunbar et al. [2001] for further details on QuikSCAT scatterometry.

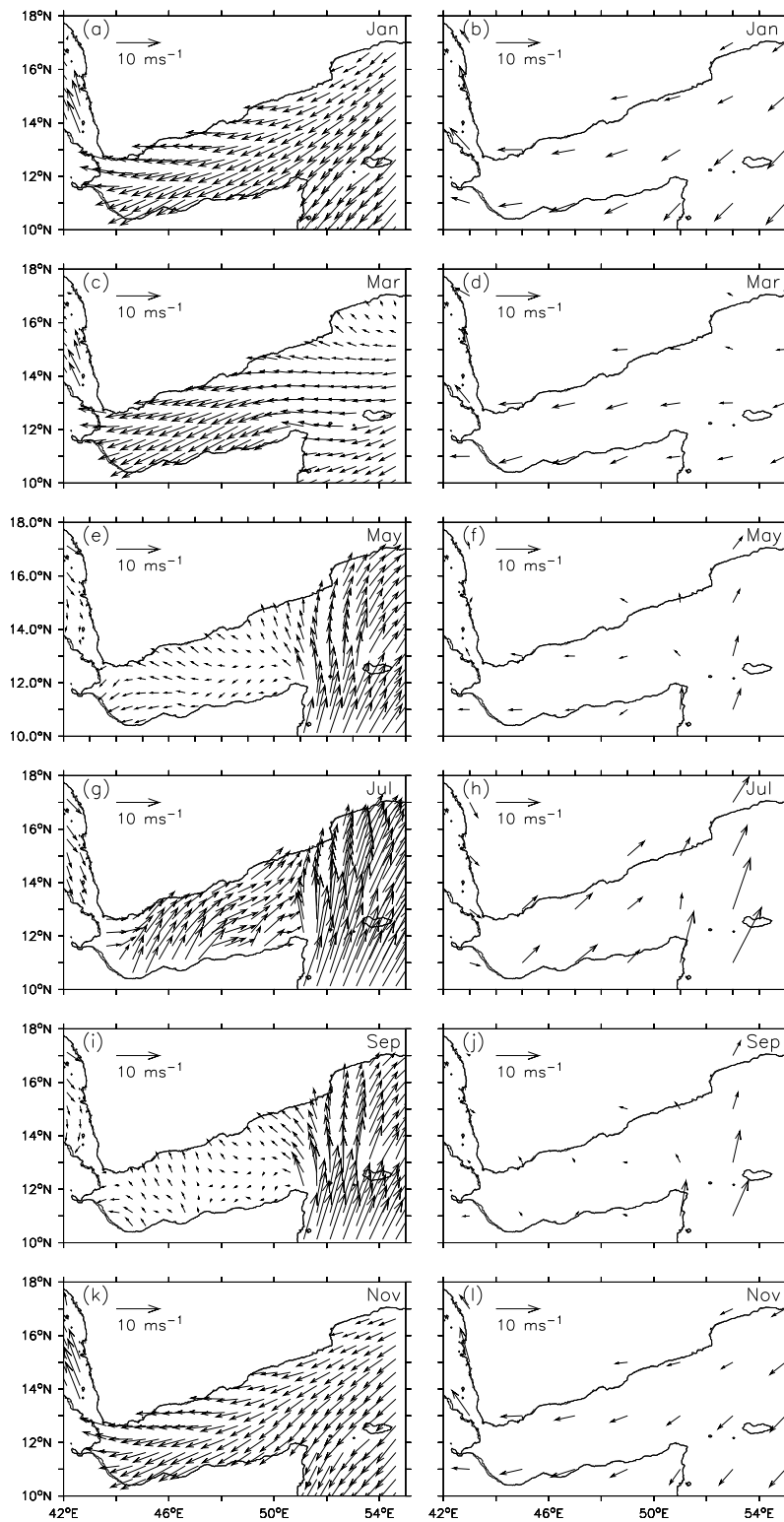
The processed QuikSCAT data is freely distributed by Physical Oceanography Distributed Active Archive Center (PO.DAAC) at NASA Jet Propulsion Laboratory (JPL)

and is available at <http://podaac.jpl.nasa.gov/quikscat/>. For this study, we have obtained the Level 3 data set that consisted of gridded values of scalar wind speed, meridional and zonal components of wind velocity, wind speed squared and time in a fraction of a day [Anonymous, 2001b]. The data used in this research, the Level 3 daily winds, have a spatial resolution of $0.25^\circ \times 0.25^\circ$ for the period from July 1999 till December 2006. The daily data were used to create a monthly climatology of meridional and zonal components of wind velocity. The climatology was then compared with COADS (Comprehensive Ocean–Atmosphere Data Set) climatology available on a spatial grid of $2^\circ \times 2^\circ$ [Woodruff et al., 1993]. COADS was prepared by gathering all possible in situ measurements of winds spanning over a period of 30 years during 1950 to 1979 (Figure 2.7). In general, the magnitude and directions of the wind vectors during each month compare well.

2.5 Ship drift Data

Before the days of satellite–tracked floats and buoys and satellite–based altimeters and scatterometers, scientists relied on ship drift data to map the surface currents in the oceans. In the mid 1800s, Matthew Fontaine Maury of the U.S. Naval Oceanographic Office initiated an effort to assemble navigation charts that included information on currents. He estimated the current speeds based on the ship logs maintained by Naval and merchant ships. In this method, the difference between a ship’s dead–reckoned position (determined from its previous position determined from a navigational fix) is ascribed solely to the effect of surface currents. The U.S. Naval Oceanographic Office continued to record these ship drifts until the mid 1970s. Maximum data on ship drift is available for the period between 1920 and 1940. Most of our knowledge about large–scale ocean circulation patterns and the velocity, kinematics, and seasonal variability of surface currents and eddies are from the ship drift data. One of the earlier compilations of Indian Ocean surface

Figure 2.7 Monthly climatology of surface wind derived from QuikSCAT data (left panels) compared with the $2^\circ \times 2^\circ$ grid COADS climatology (right panels).



currents is contained in the Koninklijk Netherlands Meteorologisch Instituut (KNMI) atlas [Anonymous, 1952], which contains a series of monthly charts at a spatial resolution of $2^\circ \times 2^\circ$ grids. Cutler and Swallow [1984] also produced the surface currents using the ship drift observations from 1854 to 1974 for the Indian Ocean region from 50° E (eastern side of the Gulf of Aden) to 100° E, for every ten days.

In this study, to describe the surface circulation in the Gulf of Aden, we have used the monthly climatology of ship drifts available from National Oceanographic Data Center (NODC), NOAA, on a spatial resolution of 1° longitude \times 1° latitude.