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JOINT ASSIMILATION OF DRIFTER AND ALTIMETER DATA IN AN INDIAN OCEAN CIRCULATION MODEL

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ABSTRACT

Joint assimilation of drifter and altimeter data in a model of the Indian Ocean has been explored. The year 2007 has been chosen for the study, since in this year there was a relatively higher concentration of drifter trajectories in this region. Drifter data have been assimilated using nudging scheme, while altimeter data have been assimilated using statistical interpolation. A control run without any assimilation has also been used as a reference. Skill of this joint assimilation has been tested by comparing against satellite derived observations of sea level and surface current. The known statistical yardsticks of correlation and root mean square error have been used to judge the skill. The assimilation has been found to exhibit a significant positive impact in both these cases.

Keywords: *Data assimilation, Drifter data, Indian Ocean circulation model*

INTRODUCTION

In recent times there has been an explosion of ocean measurements, whether *in situ* or remotely sensed. Numerical circulation models have also attained a high degree of sophistication such that realistic hind casts with these models are now feasible. Although there are many state-of-the-art ocean circulation models, the model predictions soon diverge from reality because of various imperfections such as incomplete physics, inaccurate initial and boundary conditions etc. Assimilation of data in these models tends to bring back the model trajectories towards reality. The most important parameter, from the point of view of assimilation, is undoubtedly the satellite altimeter-derived sea level. Over the years, a number of studies has been devoted to this research topic [1]. Although assimilation of sea level data can lead to a significant improvement in the predictability of sea surface current, e.g., via the geostrophic route (at least away from the equator), assimilation of currents obtained from the positions of drifting buoys can cause a more direct effect. The use of such Lagrangian information to improve the model prediction of sea surface currents is an active research topic [2,3]. However, compared to the case of altimeter data assimilation, there are just a handful of studies investigating assimilation of drifter data [2,4,5]. Also, most studies have considered idealized problems. Thus, [6] considered assimilation of drifter data in an idealized ocean model, while [7] considered idealized twin experiments. In contrast, refrenced1 and 5 are concerned with assimilation of real drifter data along with satellite data in the Princeton model for the Gulf of Mexico. Till recently there had not been any study devoted to the assimilation of drifter data in an Indian Ocean circulation model. An effort has been made to fill this gap to a certain extent [see 5]; however, the improvement in hindcast and forecast capability was not very dramatic possibly because of the paucity of the number of deployed drifters. It was also suggested that, apart from the deployment of a sizable number of drifters, further improvement may come from joint assimilations of drifter and altimeter data. The present study is carried out in that spirit and it thus can be considered as a natural extension of [5], and also of another recent study by a few of the present authors [8] in which assimilation of altimeter data in the same model was investigated.

We have followed the previous studies [2,4] for assimilating drifter data in combination with satellite altimeter data in a circulation model of the north Indian Ocean. The goals are to produce ocean analyses and to evaluate these analyses by comparing them with *in situ* and remotely sensed observations.

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DATA AND MODEL

There were 15 buoys in this time period, although not all the buoys were operational during the entire period. The data are distributed via the Indian National Centre for Ocean Information Services (INCOIS). The drifting buoy position information has been downloaded from the relevant website. The drifting buoys are satellite-tracked buoys at the ocean surface The data consist of an unevenly spaced time series of position fixes (often 1 to 8 observations per day per buoy) determined by the CLS Argos system with an accuracy of approximately +/- 300 m [9].

Apart from the data from drifting buoys, satellite-derived sea level anomaly (SLA) maps for 2007 from the Archiving, Validation, and Interpretation of Satellite Oceanography (AVISO) have also been used. This is a merged product from several altimeters. These are obtained at daily intervals throughout the year. The data are available at 0.33° resolution. They were further averaged to 0.5° x 0.5° for use in the model. OSCAR surface current is a product derived from various satellite sensors [10]. These data are available at 5-day intervals at a spatial resolution of 1° x 1°. The data describe ocean currents at 15 m depth. Since within this depth the model currents do not vary significantly, the model surface currents have been used for comparison with OSCAR currents. However, the model currents have been extracted such that the dates coincide with OSCAR dates and have been averaged to the same OSCAR resolution.

The model used is the Princeton Ocean Model (POM) configured for the Indian Ocean [5,8]. It is a sigma coordinate model. For the present study, the model domain extends from 20°S–25°N and 40 – 100°E. The horizontal resolution of the model has been set to 0.5 x 0.5 deg. The vertical grid uses 26 sigma levels. The external time step used is 30 sec and the internal time step used is 1200 sec. The model bottom topography is derived from the 2 minute resolution ETOPO 2 database. Lateral boundary conditions contiguous to coastlines are handled automatically by the land masks. Velocities normal to the land boundaries are set to zero. The landward tangential velocities in the horizontal friction terms are also set to zero. The boundaries at the north and west are treated as closed boundaries, while the southern boundary is open. The region from 5-20°S in the eastern side is set as open boundary. Sommerfield type radiation boundary condition is used at the open boundaries. Along the eastern boundary, velocity is specified for the Indonesian Through Flow (ITF). Monthly averaged river flux values from UNESCO database (http: //dss.ucar.edu) have been used. The river fluxes are specified via lateral boundary conditions at the grid cells containing the river locations Tides, however, are not included in our model.

The model has been spun up from rest using climatological winds and fluxes. By computing domain averaged kinetic energy, it was found out that steady annual cycle is established only after 30 years of spin up. After this initial spin, an interannual run has been performed for the years 2001-2006. Here, the model was forced by daily fields of net short and long wave radiation, precipitation and specific humidity obtained from the National Center for Environmental Prediction (NCEP). The data are available at 1.875° spatial resolution and have been further averaged to 0.5° using bilinear interpolation.to match the model resolution. For the daily wind forcing, analyzed winds from QuikSCAT scatterometer for the same time period have been used. The data are obtained from the website [19]. This was done, since it has been shown earlier [11], that this is a better wind product for simulating Indian Ocean circulation features using POM. The interannual run was to set the stage for the assimilation in the year 2007. The same set of forcings was used for the assimilation run in 2007.

METHODOLOGY

ASSIMILATION OF DRIFTER DATA

We first describe the technique used for assimilating drifter data. The positions of the drifters were smoothed using Gaussian–filter time scale of 24 h to eliminate tidal and inertial currents [12] and were sub-sampled at 3-h time intervals. The details are given below.

The following successive correction analysis scheme [13] was considered:

$$f_g^{\,k} = f_g^{\,k-1} + W_g(f_o - f_o^{\,k-1}) \quad (1)$$

$$f_o^{\,k} = f_o^{\,k-1} + W_o(f_o - f_o^{\,k-1}) \quad (2)$$

Here $\mathbf{f}_g^{\,k}$ and $\mathbf{f}_o^{\,k}$ are data vectors (buoy positions) representing the analysis following k iterations evaluated on analysis and observation points, respectively. $\mathbf{W}_g$ and $\mathbf{W}_0$ are matrices containing weighting factors for interpolating increment variables onto the analysis and observation points, respectively,

The iteration cycle is initialized using

$$\mathbf{f}_g^{\,0} = \langle f_g \rangle , \qquad f_o^{\,0} = \langle f_o \rangle ,$$

where $\langle f_g \rangle$ and $\langle f_o \rangle$ represent a " mean" field , evaluated on analysis and observation points. The weights are generated using Gaussian function model [13].

Afterwards the velocity components $\mathbf{v}_n^{\,o}(m)$ were computed from smoothed drifter positions $\boldsymbol{r}_n^{\,o}(m)$, $n = 1,2, \ldots, N$ = number of drifters, at time $t = m\,\Delta t$, $m = 1,2, \ldots, M$, where Δt is the time step, as:

$$\mathbf{v}_n^{\,o}(m) = (\boldsymbol{r}_n^{\,o}(m) - \boldsymbol{r}_n^{\,o}(m-1)) / \Delta t \quad (3)$$

The assimilation scheme is the nudging scheme and is identical to the one used earlier [2,4]:

$$\frac{\partial \mathbf{u}}{\partial t} = (\text{physics}) - \sum_{n=1}^{N} \lambda_n (\mathbf{u} - \mathbf{v}_n^{\,o})/N \quad (3)$$

$$\lambda_n = (1/t_a) \exp(-s_n^{\,2}/R^2_{\text{nudge}}) \exp(-(t-t_n^{\,o})/t_d) \exp(z/z_d) \quad (4)$$

where physics consists of several forces like coriolis force, gravity, friction etc., s_n is the distance between the model grid point and the n th drifter's position and $(t-t_n^{\,o})$ is the difference between the assimilation and observation time. The strength of the nudging is determined by the assimilation time scale t_a, while t_d is the damping time scale. The spatial length scale $R_{\text{nudge,}}$ in effect, determines how far the influence of a particular buoy location is spread at the assimilation time. The exp (z/z_d) term, where $z_d = 10$ m, is used to restrict the effect of the assimilation to approximately near surface. The t_d should correspond approximately to Lagrangian correlation time scale and we have simply used the value advocated previously [2,4]. Thus we use $t_d = 1$ day. The assimilation time scale equals the model's internal time step, which is 1200 s. For simplicity we assume that $s_n = 0$. In other words, distance between the observation point and the nearest grid point at that particular observation time is neglected. Physically, the nudging equation signifies the fact that the model's velocity **u** at a grid cell is mainly influenced by the recent nearby drifters.

ASSIMILATION OF ALTIMETER DATA

Although there are many sophisticated techniques of altimeter data assimilation, simple schemes like statistical interpolation are widely employed for analyses and operational forecasts [14,15].

The technique adopted here was advocated quite a few years ago [15] and was used for assimilating along-track sea surface height anomalies (SSHA). It has been modified subsequently for the assimilation of SSHA maps [16] and this modified scheme has been used in the present study. The satellite altimeter derived SSHA is projected into the subsurface temperature field using pre-computed correlation functions derived from a multi-year (2001-2007) integration of the model used in the study. The resulting temperature field is then added to the model mean temperature field to yield an estimate of the observed temperature T^{obs}. After each assimilation time step (1day, in our case), the model temperature is replaced by assimilated temperature T^a, given by

$$T^a = T^m + P\,(T^{obs} - T^m) \quad (6)$$

where P, the optimal weight function , is given by the formula

$$P = C_{fg}\,(1 + C_{fg} - C_T^{2})^{-1} \quad (7)$$

$$C_T = \langle (\mathrm{d}T\mathrm{d}\eta) \rangle / [\langle (\mathrm{d}T)^2 \rangle \langle (\mathrm{d}\eta)^2 \rangle]^{1/2} \quad (8)$$

In Eqn (7), C_{fg} is a first-guess error parameter whose value lies between 0 and $C^{max} = 2$, and C_T is the correlation between sea level anomalies dη and sub-surface temperature anomalies dT. As noted earlier [17]. if the data coverage is uniform, which is true in our case, this parameter can be taken as a constant. We arrived at the optimum value of 0.8 by trial and error.

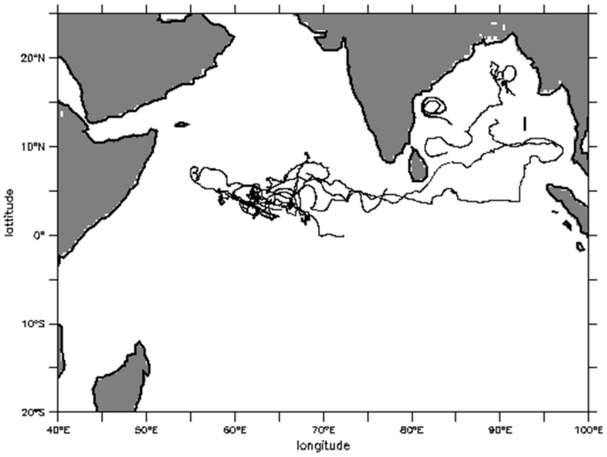

Figure 1 : "spaghetti" plot of the drifter tracks during 2007

ASSIMILATION RESULTS

In Fig. 1 we show a spaghetti plot of the drifter tracks in the period of study. The assimilation run was initialized on 1st January and ended on 31st December of 2007. The first drifter entered the model domain on 3rd January. The skill of the assimilation can be judged by comparing the analyzed ocean state (produced as a result of assimilation) with observations. Accordingly, daily SLA maps obtained from AVISO were used for validating the analysis. Strictly speaking, these maps can not be called independent, since they have been used in assimilation. Nevertheless, it has to be clearly understood that the assimilation approach is not a direct one. Sea level anomalies are first projected to subsurface temperatures and optimal interpolation is used to assimilate these temperatures causing modification of large-scale density field. This density modification causes modification of the current field, which is locally refined by drifter assimilation. Only after this refinement the analyzed current gives rise to an improved estimate of the temperature and salinity fields which are used by the model equations to calculate analyzed sea level. It is thus natural to expect that the analyzed sea level will not be identical to the observed one used for assimilation. Hence, it is interesting to compare the analyzed sea level

with the observed one. A similar comparison between the observed sea level and the sea level simulated in a control run without assimilation will enable us to judge the relative merit of assimilation. The root mean square errors (RMSE) of this quantity in the two simulations (control and assimilation) are displayed in Fig. 2. It can be immediately seen that there is an overall improvement, and this improvement is quite substantial. A significant fraction of the area of the study is dominated by very low RMSE (2-6 cm) in the assimilation case. In the free run there was a region in the southern part of the basin with very high RMSE (more than 16 cm). This RMSE has decreased to ~ 6 cm, which is a significant improvement. Apart from RMSE, another important aspect of any statistical comparison is the correlation between two sets of results (in this case simulations and observations). Accordingly, in Fig. 3 we show these correlation maps. Again it can be seen that there is a large improvement, distributed quite evenly. We have also spatially averaged the respective RMSEs and the correlations to quantify the overall average improvement. The RMSE decreased from 11.3 cm to 9.0 cm while the correlation improved from 0.5 to 0.68.

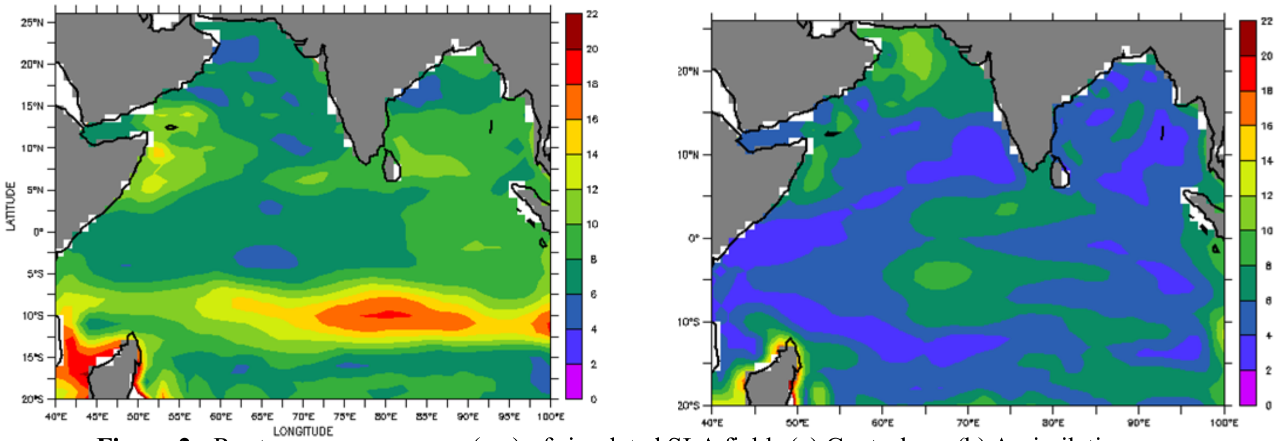

Figure 2 : Root mean square error (cm) of simulated SLA fields (a) Control run (b) Assimilation run

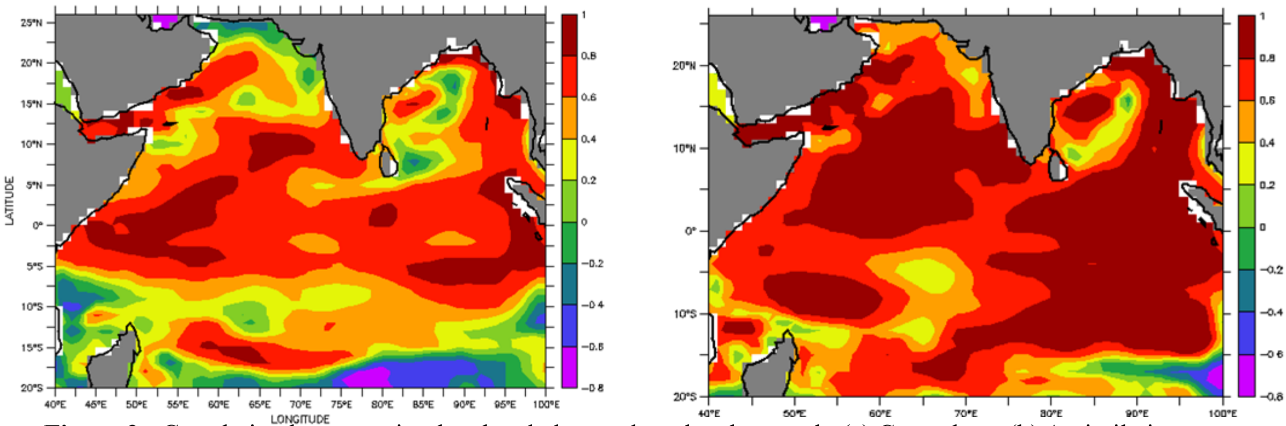

Figure 3 : Correlation between simulated and observed sea level anomaly (a) Control run (b) Assimilation run

It would be quite interesting to evaluate the impact of assimilation directly on the model derived surface currents. As mentioned earlier, apart from large–scale modification of this current, caused by assimilation of altimeter data, there is additional local refinement caused by drifter assimilation. In order to obtain a complete picture of the impact of assimilation, a basin scale comparison with independent observation is called for. Fortunately we had at our disposal OSCAR surface current [10] derived using data from several satellite sensors.

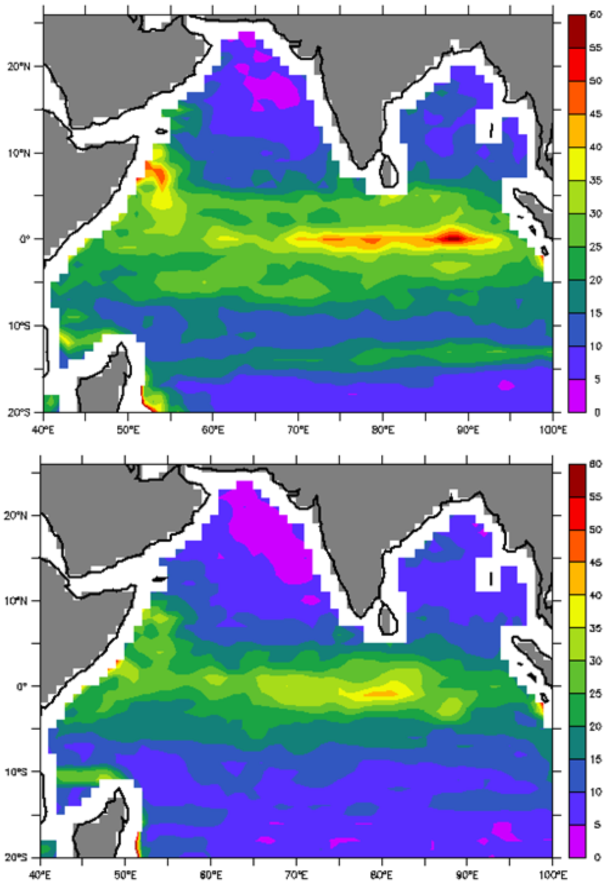

Figure 4 : Root mean square error (cm s^{-1}) of simulated surface current speed (a) Control run (b) Assimilation run

In Fig. 4 we show the RMSE for the current speeds in the control and assimilation runs, computed with respect to the OSCAR currents. It is immediately apparent that there is an overall improvement in simulation of the current speed also, and notably so, in the central and equatorial Indian Ocean, northern Arabian Sea and southern Indian Ocean. Since OSCAR current is an independent set of observations, it was interesting to employ another standard statistical yardstick, viz., correlation, for evaluating the impact of assimilation. In Fig. 5 the correlation maps are shown for the two runs. Again, a distinct overall improvement is visible in the case of assimilation run. Similar to the case of the sea level, in this case also we have spatially averaged the respective RMSEs and the correlations in order to quantify the overall average improvement. The RMSE decreased from 18.7 cm/sec to 14.3 cm/sec, while the correlation improved from 0.18 to 0.29.

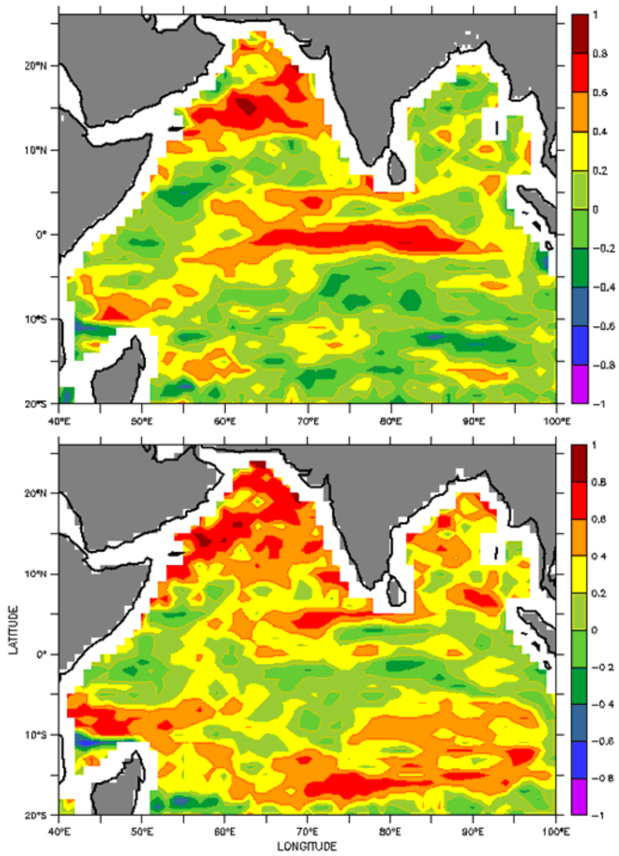

Figure 5 : Correlation between simulated and observed surface current speed (a) Control run (b) Assimilation run

Daily means of model subsurface temperature obtained from these two experiments have been compared with Argo profiles of temperature. Figure 6 shows the scatter plots of simulated temperature with Argo temperature at 50m depth. Correlation is 0.50 in the case of control run which improves to 0.59 in the case of assimilation run. The RMSE is reduced from 2.13 to 1.74 deg C at the same depth.

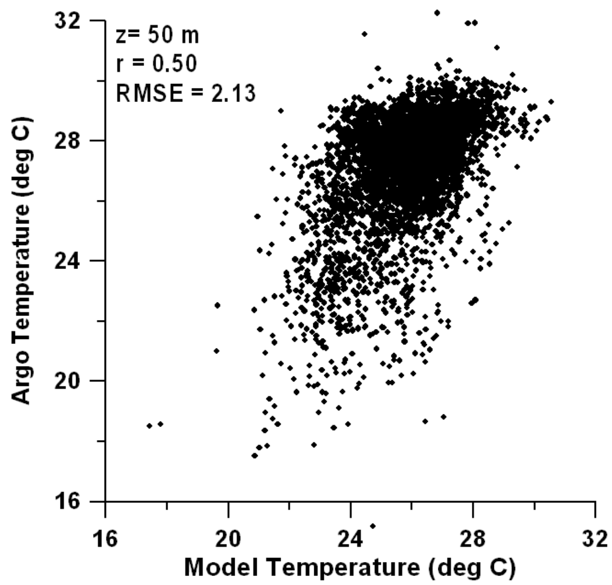

Figure 6 (a)

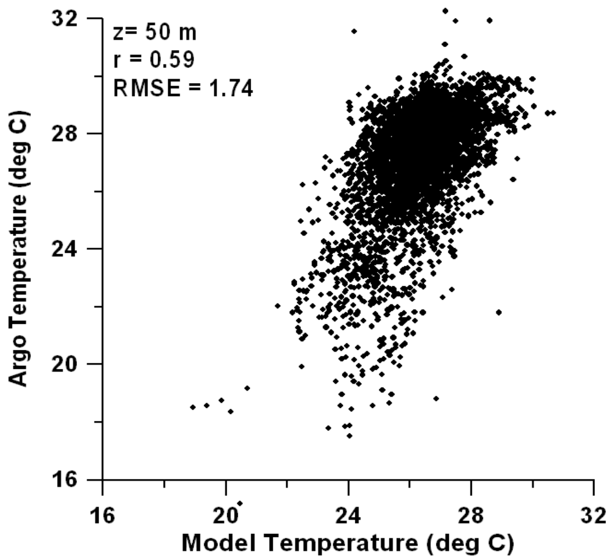

Figure 6 (b)

Figure 6 : Scatter plots of model temperature versus Argo temperature at levels 50m (a) control run (b) assimilation run

CONCLUSIONS

In this paper, we have explored the joint assimilation of drifter and altimeter data in a circulation model of the Indian Ocean. To the best of our knowledge and belief, this is the first study of its kind related to joint assimilation of altimeter and drifter data in an Indian Ocean circulation model and is a natural extension of the previous study of the authors [5] concerned with drifter data assimilation.

The assimilation can be summarized in the following manner. The altimeter assimilation causes large scale modification of subsurface density through a change in subsurface temperature field. The subsequent change in large scale current field is locally refined by drifter assimilation Skill of the assimilation has been ascertained by comparing the sea level anomalies and surface currents simulated in the control and assimilation runs with satellite as well as *in situ* data. The skill has been assessed both in terms of root mean square error and correlation. Assimilation has been found to exhibit a positive impact on the simulations of both sea level anomaly and currents. Unfortunately, very few drifters were available in the Indian Ocean during the period of study. We conjecture that the result would have been more impressive, had there been a more sizable number of drifters, of the order of a few hundreds, like. e.g., in the Gulf of Mexico. In spite of this limitation, the result seems to be quite encouraging. Apart from the deployment of more drifters, further improvement in result may come from the use of more sophisticated schemes of assimilation for drifter as well as for altimeter data. The data used in the present work are downloaded from the websites [18, 19]

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