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Co-Tidal maps for the Coastal oceans around India

INDIAN SPACE RESEARCH ORGANISATION

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15	Sea level is an essential climatic variable (ECV). It has been measuring precisely through satellite altimeter. There are several oceanic processes contribute variability of sea level with tide being the major contributor. As tide is periodic and highly predictable, its contribution can be removed from the altimetric measurement for further investigation of sea level variability. We proposed a regional tidal solution for the Indian coastal oceans which may serve as the accurate tidal corrections for the along-track sea level data measured by satellite altimeter such as SARAL-ALTIKa. This solution is derived based on regional implementation of barotropic version of Princeton Ocean Model driven by FES99 global tidal solution at the open boundaries. *Key words:* Tides; satellite altimeter; tide gauge; India coast; SARAL-ALTIKa; FES2012	

Contents

Co-Tidal maps for the coastal oceans around India

1. Abstract

Sea level is an essential climatic variable (ECV). It has been measuring precisely through satellite altimeter. There are several oceanic processes contribute variability of sea level with tide being the major contributor. As tide is periodic and highly predictable, its contribution can be removed from the altimetric measurement for further investigation of sea level variability. We proposed a regional tidal solution for the Indian coastal oceans which may serve as the accurate tidal corrections for the along-track sea level data measured by satellite altimeter such as SARAL-ALTIKa. This solution is derived based on regional implementation of barotropic version of Princeton Ocean Model driven by FES99 global tidal solution at the open boundaries.

2. Introduction

The long-term sea level records from the past satellite altimeter missions such as TOPEX-POSEIDON (Jason 2) and ENVISAT etc. helped in understanding several aspects of circulation and its change in response to the climate variability (Cazenave et al. 1998[7]; Cabanes et al. 2001[4]; Fu 2010[12]; Salim et al. 2012[25]). Sea level exhibits change in all the time scales: diurnal to seasonal to inter-annual and decadal scales (Sakova et al. 2006[23]). It has been increasing linearly at the rate of 3.2 mm/yr (Cazenave and Nerem 2004[8]; Holgate and Woodworth 2004[13]) owing to the warming of the global oceans (Carton et al. 2005[5]). Altimeter-measured sea level Anomaly (SLA) often used to infer surface geostrophic currents in deep ocean regions (Liu et al. 2012[17]). These data were used to describe the major large scale circulation patterns in the regional and global oceans (Johnson et al. 2007[14]). In recent years the applications of satellite altimeter were extended for the coastal and marginal seas (Durand et al., 2009[9]; Vingnudelli et al. 2011[30]; Liu et al., 2014[18]; Troupin et al., 2015[28]).

SARAL (Satellite with ARgoes and ALtimeter) is a cooperative altimeter mission of Indian Space Research Organisation (ISRO) and Centre National d'études Spatiales (CNES) Space Agency of France which is complementary to Jason 2 and ENVISAT missions, launched on 25 February 2013. It carried the payload AltiKa, a Ka band altimeter along with dual-frequency (at Ka and C) radiometer that allows the measurements of satellite height from the sea surface (h_s) to be corrected for the effects due to the signal passing through the wet troposphere. The coupled Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and a laser retro-reflector (LRR) system allow us to determine the satellite's position in the orbit precisely (H_s). The instantaneous sea surface height (SSH) can be determined (at an accuracy of 2-3 cm) from the accurate measurements of altimeter heights from the earth's center of mass (H_s) and ocean surface (h_s). Depending on the actual use of the SSH data, the various geophysical signals such as the ocean tides, the inverse barometric effect due to atmospheric pressure fluctuations, the dynamic topography due to ocean currents, and the geoids due to the gravity field may be regarded as the signal itself or as error sources in the SSH observations. Liu et al. 2012[17] treated tides as noise in altimeter measured sea level data when they studied the sub-tidal current variations and geostrophic currents in the west Florida shelf.

Present tidal corrections of the altimeter observations are based on FES2012 global tide model (Carrère et al., 2012[6]). Tide in the ocean is defined as the periodic rise and fall of the sea surface driven by the differential change in gravitational force due to the moon and the sun. Tides in the open oceans can be predicted accurately by existing global numerical hydrodynamic models (Andersen et al., 1995[1], 2006[2]; Egbert and Erofeeva, 2002[10], Lefèvre et al. 2002[15]; Lyard et al. 2006[19]). In contrast, tidal predictions by these models in the coastal and estuary regions are associated with large uncertainty mainly due to complex geometry and bathymetry of the regional oceans. In order to complement the global tidal model, several regional tidal models are also developed to simulate tides in coastal ocean (Unnikrishnan et al. 1999[29]; Lefevre et al. 2002[10]).

In view of the above, the main goal of this study is to build a regional tide model for the Indian coastal oceans for two purposes: (i) to assess the global tide models and (ii) to complement the global tidal solutions for the altimeter along track sea level tidal correction in the study region.

3. Data and Methodology

3.1 Data

3.1.1 Tide gauge data

The long-term records of sea level measured at 20 coastal tide gauge stations around India (Figure 1) have been used in this study. These were maintained by the survey of India and the retrieved data were shared with National Oceanographic Data Centre (NODC) of Indian National Centre for Ocean Information Services (INCOIS), Hyderabad. Prior to use these data, we applied following correction for the phase angles of the tides in order to convert them from standard local time zone to the reference of Greenwich Mean Time (GMT).

$$G_i = g_i + \frac{360^0}{P_i} Z_n g_i$$

Where g_i and G_i are phase angles of the tidal constituent, i, with reference to the local time and GMT respectively. P_i is the period of the tide (in hours) and Z_n is the time zone of the location. The present study region belongs to zone number 5. Thus, 75° and 150° corrections required for diurnal and semi-diurnal tides, respectively.

The same procedure is followed for the regional tidal model solution to convert them to GMT reference in order to compare with FES tidal solutions and use in extraction of x-track tidal level corresponding to the SARAL-ALTIKa observations for the Indian coastal oceans.

3.1.2 Satellite data

Six along track data of cycle 1 of SARAL-ALTIKa (as shown in Figure 1): three tracks on the Western continental shelf (T468, T382, and T668) and three tracks on the eastern continental shelf (T023, T309, and T967) have been used for this analysis.

3.2 Method

3.2.1 Regional Tidal model

Regional tidal model used in this study is based on barotropic mode of the Princeton Ocean Model (POM). The POM is the terrain following (sigma or s-co-ordinates) Ocean General Circulation Model (OGCM) originally developed by Blumberg and Mellor (1987) [6]. It has been used for wide range of ocean applications: for predicting barotropic tides to complex baroclinic circulations, coastal to open ocean processes, real time forecast system to climate change predictions. The model solves finite difference analogs of the primitive equations, with a non-linear equation of state relating density to temperature and salinity. The model employs a C grid in the horizontal and a terrain following sigma coordinate for the vertical. The horizontal time differencing is explicit whereas the vertical differencing is implicit. The model has a free surface and a split time step: the external mode portion of the model is two-dimensional and uses a short time step based on the Courant-Friedrichs-Levvy (CFL) condition and the external wave speed, whereas the internal mode is three-dimensional and uses a long time step based on the CFL condition and the internal wave speed. Earlier on we used this model for simulating tidal propagation and characterizing seasonal circulation in the northwestern continental shelf of India (Nayak et al. 2014[21] and Salim et al. 2015[24]).

The POM is configured for the Indian coastal domain between the longitudinal range 68°E and 90°E and latitudinal range 6^0N and 24 ^{0}N (Figure 1). It consists of uniform Cartesian coordinate system at 5 km (~2 min) spatial resolution with 660 levels along longitude, 540 levels along the latitude. The bathymetry data used for this purpose is taken from modified version of ETOPO-2 (www.nio.org). The time step for the external barotropic mode is taken as 6 s. The model run is carried out for 75 days by forcing with the time varying tidal level at western, southern, and eastern boundaries at every external barotropic time step. The simulated results are saved at 3-minute interval. Excluding the first 10 days, remaining 65 days model output were used in the study. The first 10 days spin up period is enough for the model to reach a stable state. Data to specify tidal level at three open boundaries of the study domain were extracted from the global FES99 tide model (Lefèvre et al. 2002[15]) at every 6 minute interval which is interpolated in to the model time step inside the modeling procedure.

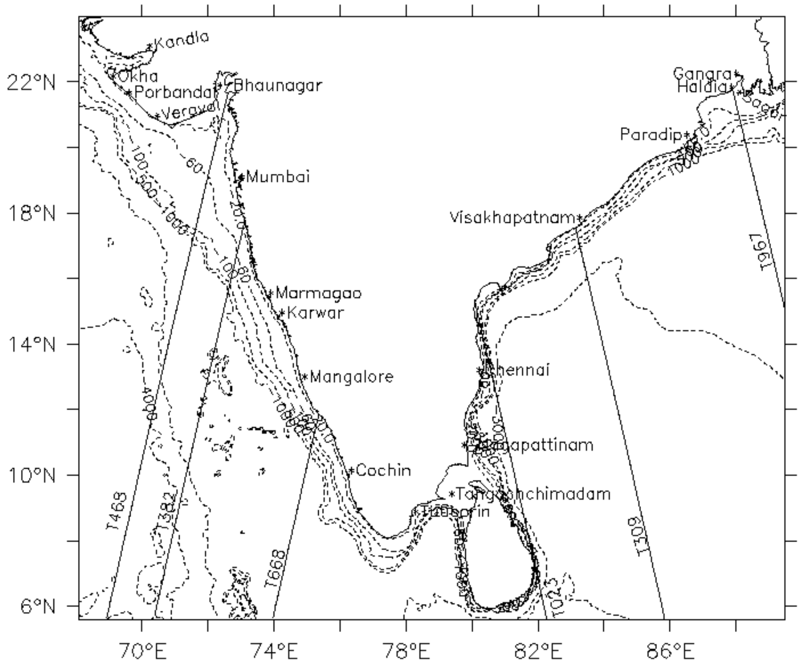

Figure 1: Study region along with six SARAL-ALONG track data (solid lines) and twenty coastal tide gauge stations (marked with *) for which long-term sea level records are available for analysis in this study. Dash contours represent the bathymetry of the region.

A number of sensitivity experiments were carried out for tuning the co-efficient of bottom friction (CBF) so that model solution suitably matches with the tide gauge measurements near the coastal regions and FES99 co-tidal maps (spatial pattern of amplitude and phase of major tides) in the open oceans regions beyond the continental shelf break. The values for the CBF for the final model run is taken as follows: 0.00085 for region with depth less than 50 m, 0.0012 within 50-200 m depth contours, 0.0015 within 200-1000m, and 0.002 for the region beyond the 1000 m depth contour. Tidal harmonics (here major five components M2, S2, N2, K1 and O1) of the simulated tidal levels were estimated using least square procedure (Foreman, 1978[11]).

3.2.2 FES tidal solutions

The FES99, FES04, and FES2012 are global tidal solutions prepared by CNES, France by assimilated tide gauge and satellite (T/P and ERS) sea level observations data in to a Finite Element Model of the Global Oceans (Lefèvre et al. 2002[15]; Lyard et al. 2006[19], Carrère et al., 2012[6]). These are distributed at the public domain along with TOPEX/SSH observations to scientific and research community. The spatial resolution of FES99 is $1/4^0$ while it is $1/8^0$ for the FES04 and $1/16^0$ for the FES2012 solutions. The FES2012 is considered to be an improved version of FES04, mainly accounts for the ice coverage in Polar Regions, inclusion of additional long-period nonlinear waves and most recent bathymetry and coast line. These tidal solutions are used for different oceanographic applications: tidal correction for satellite measured SSH data (Schaeffer et al. 2012[26], Salim et al. 2012[25]); used as forcing in the coastal circulation model to study residual and mean circulation in the northwestern continental shelf of India (Nayak et al. 2014[21]; Salim et al. 2015[24]), assessment of regional coupled tide and circulation model and to study the role of ocean bottom morphology on long period gravity waves and mixing in the deep oceans etc. (Provost and Lyard, 2003[22]).

4 Results and Error estimation

4.1 Co-tidal charts based on regional solution

The co-tidal charts comprising spatial patterns of amplitude and phase contours of major tides: M2, S2, K1 and O1 for the study region extracted from the regional tidal model are presented in Figure 2. For the comparison purpose, the amplitude maps of these major tides based on regional model, and based on FES99 and FES2012 models are also presented (see Figure 2a, 2b, and 2c). The FES04 and FES2012 are identical in the study region, and hence forth the FES2012 solutions are used along with FES99 in the analysis. M2 co-tidal lines (contour of equal phase) mostly parallels the latitudinal lines (perpendicular to the coast lines) on the western continental shelf. M2 phase decreases from 200^0 at the southern side to 150^0 at the northern side at 16^0N latitude.

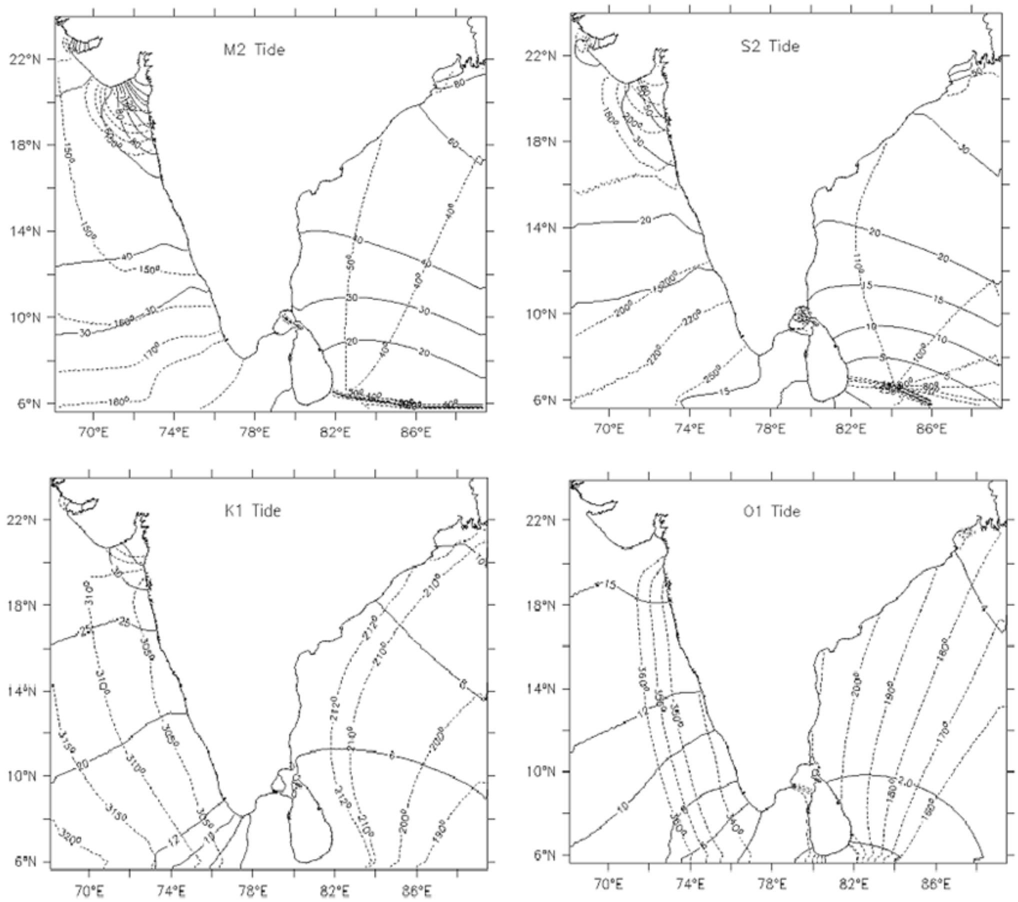

Figure 2: Tidal charts for Indian coastal oceans based on POM2D simulated tidal levels. Continuous lines represent amplitude (in cm) contours and dash lines represent phase (in degree) contours. The tidal phases are reference to the GMT.

On the north to this on the open ocean, the phase remains the same as 150^0. This suggests that M2 tide propagate perpendicular to the co-tidal lines that further implies that tidal waves propagate parallel to the coastlines on the western continental shelf of India.

M2 co-range lines (contour of equal amplitudes) on the south eastern Arabian Sea parallel longitudes (and normal to the coast lines) with small values 30 -40 cm. On the north eastern region, it undergoes slow amplification over the continental slope until the shelf break. In the northwestern continental shelf of India, especially inside the Gulf of Khambhat and Gulf of kutchh, strong amplification, more than 4 times (40 to 200 cm) was observed. Strong amplification of semidiurnal tides in these regions is resulted from the quarter wavelength resonance of the tides owing to their inherent geometrical settings (Nayak and Shetye, 2003[20]). On the eastern continental self and western Bay of Bengal, co-range lines mostly parallel the longitudinal lines (normal to the coast line of India) with small amplitude 20 cm in the southwestern Bay of Bengal. The gradual amplification of M2 tides observed from south to north along the eastern continental shelf of India with more than 100 cm amplitude observed on the head of the Hooghly estuarine system.

Spatial pattern of S2 tidal chart is similar to M2 tide; however, S2 amplitude is almost half of M2. On the other hand, diurnal tides have small amplitudes, 35 cm and 18 cm at the shelf break respectively for K1 and O1 tides, and they exhibit slow amplification towards the inner gulf. At the gulf head, amplitudes are 65 cm and 30 cm respectively.

The estimated tidal amplitudes based on regional model (Figure 2a) although highly resemble with FES tidal solutions (Fes99 in Figure 2b and FES2012 in Figure 2c) from open ocean to the shelf-break, there exist significant difference in the northwestern and northeastern continental shelf regions of India. In these places shelf is wider and gradually narrower towards the coast forming converging channels: the Gulf of Khmabhat and Gulf of Kuchh in the western shelf and the Hooghly Estuary in the eastern shelf. Numerous studies suggested that the semi-diurnal tides (M2 and S2) undergo strong amplification in these regions (Shetye et al. 1999[27] and Nayak and Shetye, 2003[20]). In the present study, the regional model estimated expected large amplification of M2 and S2 tides (up to 350 cm and 100 cm) along the axis of the converging channel (Gulf of Khambhat and Gulf of Kutchh) while the FES99 solutions estimated moderate amplification (up 150 for M2 and 60 cm for S2) and FES2012 highly underestimating the features. It will be discussed subsequently that FES2012 highly under estimating the observed feature of M2 and S2 tides. It is believed that there must be some problem with global FES2012 tidal model associated with input bathymetry data or assimilation of tide gauge observation in to the model.

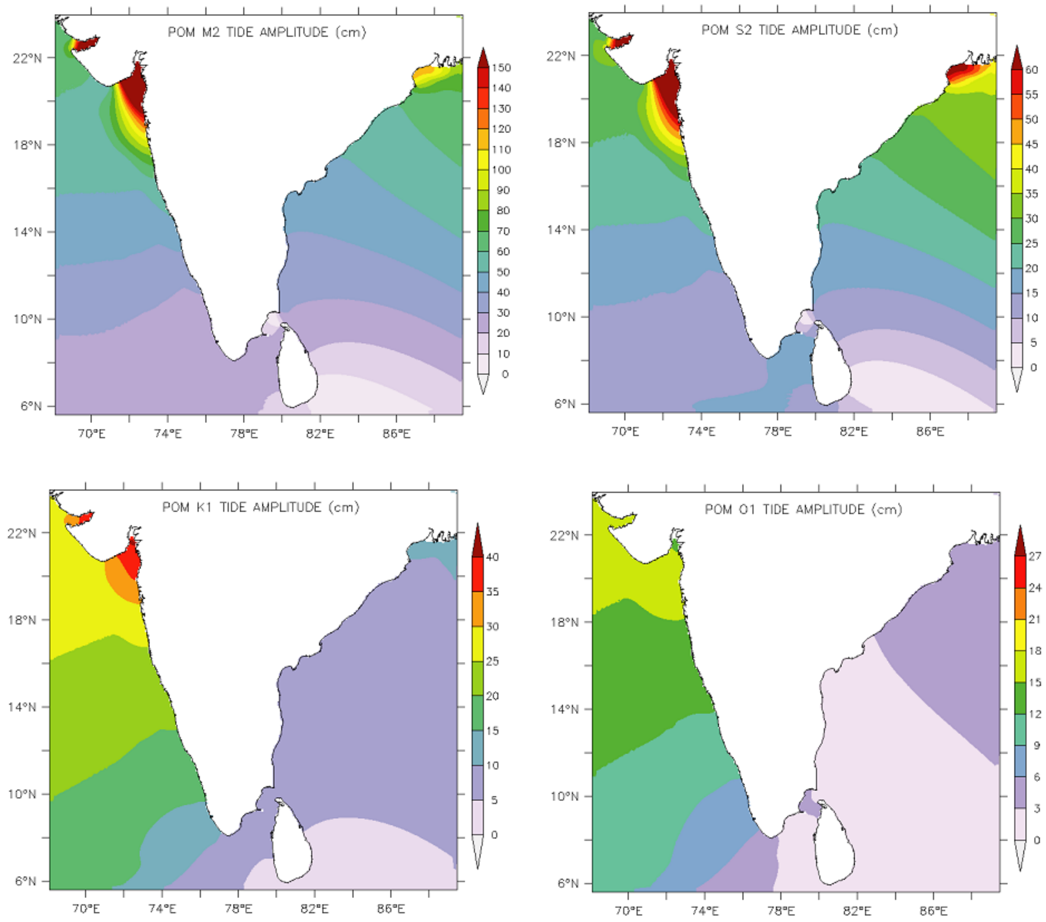

Figure 2a: Amplitude of major tides M2, S2, K1, and O1 in the study region based on POM2D simulated tidal levels.

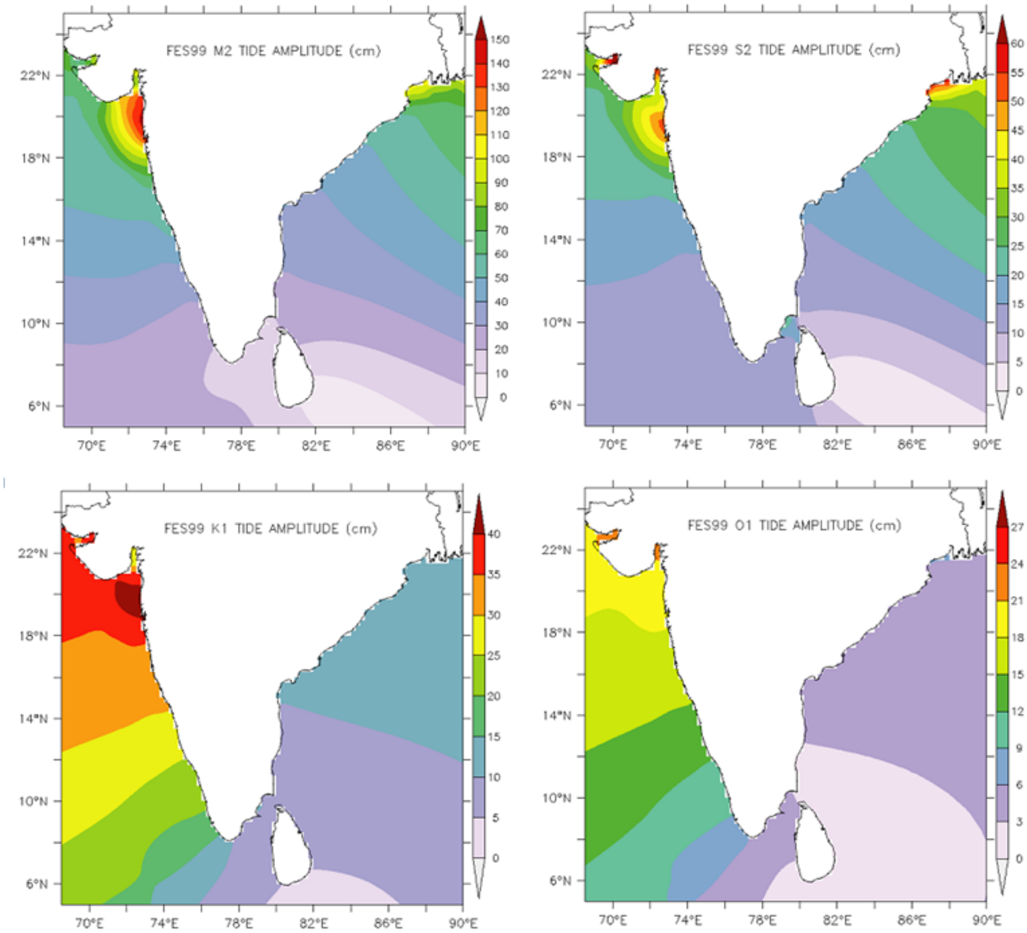

Figure 2b: Amplitude of major tides: M2, S2, K1, and O1 in the study region based on FES99 tide model.

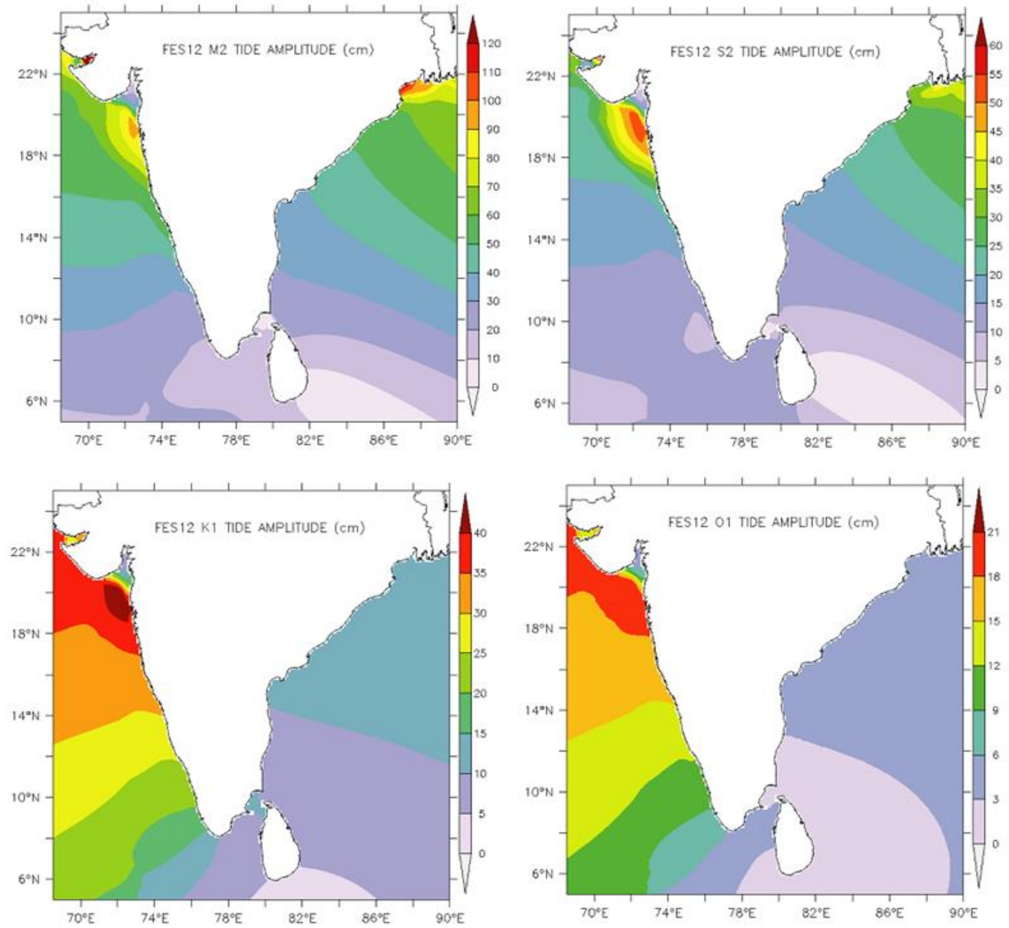

Figure 2c: Amplitude of major tides: M2, S2, K1, and O1 in the study region based on FES2012 tide model.

4.2 Error estimation

To provide a quantitative assessment of modeled tidal levels, the root mean square error (rmse) for each tidal constituent at each coastal tide-gauge station is estimated using the following equation:

$$rmse = \sqrt{\frac{1}{T}\left(A_{obs}Cos\,(\omega t - \varphi_{obs}) - A_{mod}Cos\,(\omega t - \varphi_{mod})\right)^2}$$

where (A, φ) are the complex form of amplitude and phase obtained from observation and modelled tidal levels. T is temporal segments. The rmse is often used in model evaluation (e.g. Liu et al., 2007 [16])

As shown in Figure 3, the rmse associated with different tidal solutions exhibit large values at the stations located inside the Gulf of Kutchh and the Gulf of Khambhat on the northwestern continental shelf (stations 2, 5, and 6) and at the stations located on the north-eastern continental shelf (18,19,20). These regions have wider, converging and shallow continental shelves. The rmse associated to regional solutions are significantly lower than that of the FES counters parts.

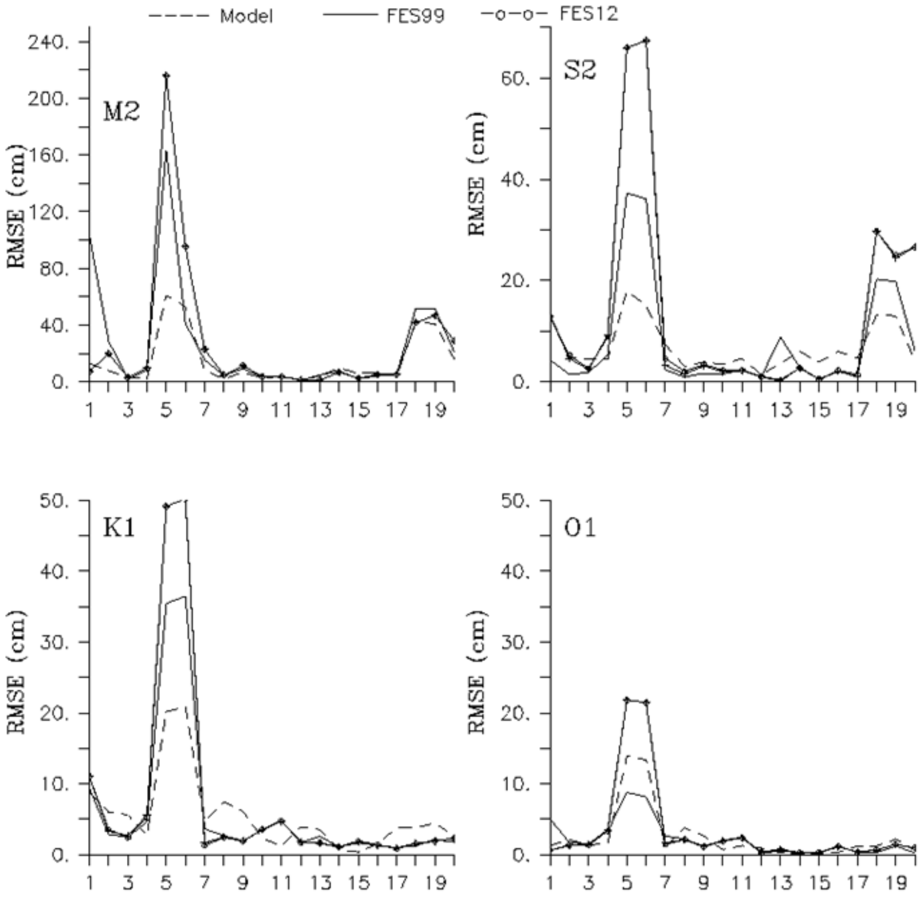

Figure 3: Root mean square errors (RMSE) associated with global FES tidal solutions and with regional model.

5 Along-track SARAL-ALTIKA sea level tidal corrections

As an application we used regionally developed tidal components to assess SARAL-ALTIKA tidal corrections in the coastal oceans around India. We selected six tracks from cycle 1 of SARAL-ALTIKA (Figure 1): three tracks on the western continental shelf (T468, T382, and T668) and three tracks on the eastern continental shelf (T023, T309, and T967) for the analysis. The two tidal corrections taken here with along-track sea level observations are FES2012 (Tsol1) and GOT4.8 (Tsol2). These data for the selected tracks along with the extracted tides based on FES99 and regional POM model are presented in the Figure 4.The tracks on the western continental shelf are from coast to the open oceans and on the eastern continental shelf are from open ocean to the coastal regions. Note that the track wise regional tidal correction generated here includes astronomical diurnal and semi-diurnal tidal components from the present model (POM) and others from the FES99 solutions.

The track T468 exhibits significant differences among different tidal corrections while it goes over the northwestern continental shelf of India. Beyond the continental slope towards the open ocean, it does not show any difference (see also the Figure 1). Tsol1 and Tsol2 are mostly identical except the region proximity to the coast: upstream region of the Gulf of Khambhat(GK). The FES99 tidal level has 50 cm lower than the Tsol1 tidal level on the continental shelf region. POM based regional solution (TPOM) however varied similar to Tsol2 and FES99, there exist significant difference. TPOM inside the GK (indices between 20 and 45) is lower than Tsol2, and mostly resembled with FES99. In the continental shelf domain (indices between 45 and 80) it approaches Tsol2. Here we believe that TPOM is better than other solutions as it compares well with the tide gauge observations.

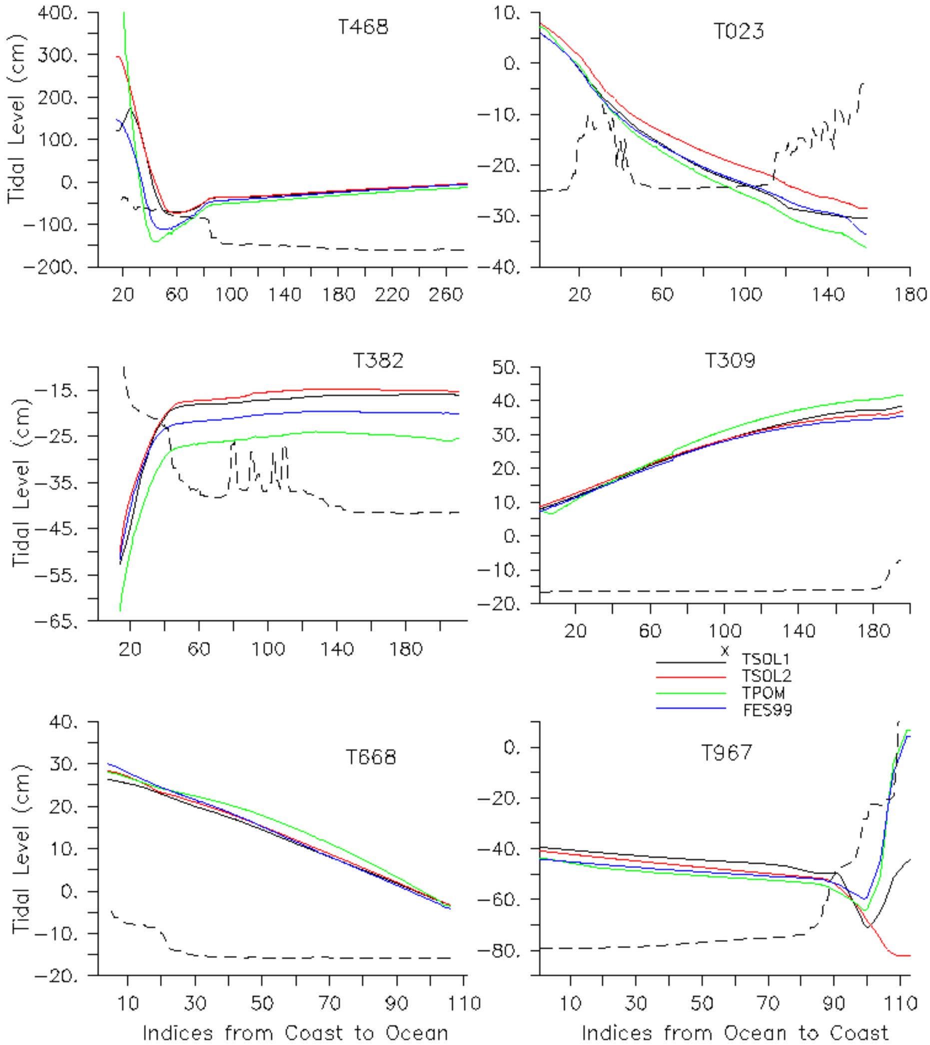

Figure 4: Tidal levels corresponding to SARAL-ALTIKa along track data, based on different models. TSol1 and Tsol2 are for correction1and correction 2 available in SARAL data records. TPOM is corresponding to POM based regional correction and FES99 is the correction based on FES99 solutions.

The track T382 passes over the regions with significant variable bathymetry (see Figure 1). The portion of the track for which x < 40 is belong to continental shelf, and the domain with 40 < x< 120 belong to shallow seas around the Lakshadweep. For this track tidal level estimated by Tsol1 and Tsol2 are identical. The FES99 remains the same as Tsol1 within the continental shelf region (x <35). It then diverges to lower value by 10 cm within the continental slope region and remains parallel to the Tsol1. TPOM although maintain similar shape, it constantly estimated 7 cm lower tidal level than the Tsol1. Regarding the track T668 on the southern continental shelf, all tidal models provides the similar results.

The track T023 passes over the eastern continental shelf of India and Sri Lankan coast (Figure 1). Note that the indices (x) started from open ocean sides towards the coast of India. The associated tidal corrections for Tsol1, Tsol2, and FES99 exhibit similar variability and magnitudes. On the other hand TPOM however retain the shape invariant, it remain 5 cm lower than FES solutions in the Indian coastal region (x >100) and almost identical with FES in the Sri Lankan coast and in between (x <100). This is because the region around the Sri-Lanka has narrow and steep Shelf.

For the track T309, all FES based tidal solutions (Tsol1, Tsol2, FES99) parallel each other and also resemble with TPOM solution. The track T967 passes over the northeastern continental shelf of India. The associated tidal corrections over the open ocean domain (x<95) remain parallel for all the tidal models. There exist large differences among different tidal solutions over the continental shelf regime (95< x<115). TPOM increases from -60 cm to 10 cm and which is same for FES99. On the other hand, Tsol1 increases from –75 cm to -35 cm and Tsol2 decreases from -45 cm to -75 cm.

6 Conclusions

The tidal charts based on POM based regional tidal solutions are generated and are very similar to FES tidal solutions however there exist large differences in the magnitude of semi-diurnal tidal amplitudes over the coastal regions with wide and converging continental shelf areas such as the Gulf of Khambhat and the Hooghly estuary.

Comparison against SARAL-ALTIKA along track data we observed that FES tidal corrections are reasonably accurate for open ocean regions beyond the continental shelf, while they may have associated with significant uncertainty near the coastal regions especially on the converging shelf areas. Regarding the performance of regional tide, it is working well for all part of our study domain including the coastal oceans adjacent to the Gulf of Khambhat and the Hooghly estuary and open oceans beyond the shelf region. Since this regional model is indirectly developed from the FES99 tidal solution and it has almost similar characteristics of FES99 solution, we better claim that this product should be used for reprocessing of SARAL-Along track data for the coastal oceans around India. Even much better tidal solutions can be derived through this procedure by selecting suitable bottom friction coefficient and using better bathymetry of the region.

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