

## **Tidal Asymmetry in the Mandovi and Zuari Estuaries, the west coast of India**

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### **ABSTRACT**

Harmonic analysis of the observed and simulated tides in the Mandovi and Zuari estuaries along the west coast of India was carried out. Tidal constituents derived from the above process were analysed in order to study the tidal asymmetry in these estuaries. Sea level observations during March – April 2003 at 13 stations in the Mandovi and Zuari estuaries were used for the harmonic analysis. Simulations of tides were carried out using a hybrid network numerical model. The model could well simulate the amplitude and phase of five major tidal constituents ( $K_1$ ,  $O_1$ ,  $M_2$ ,  $N_2$ ,  $S_2$ ) in almost all stations in the Mandovi and Zuari estuaries. Both observations and simulations show that the amplitude and phase of major diurnal and semi-diurnal constituents increase towards the upstream regions. The increase of this predominant species towards the upstream regions shows that the Mandovi and Zuari estuaries are not frictionally dominated estuaries since amplification due to geometrical effect cancels the decay in amplitude due to friction.

The rapid increase of the first and second harmonics of  $M_2$  and compound tides inside the estuaries shows the non-linear response of the Mandovi and Zuari estuarine systems to the tidal forcing.  $M_4/M_2$  amplitude ratio indicates that the tide is subjected to more asymmetry in the Zuari than that in the Mandovi. The increase of the first harmonic of  $M_2$  and decrease of relative surface phase ( $2M_2-M_4$ ) inside the Mandovi and Zuari estuaries show that these estuaries are flood dominant estuaries.

**ADDITIONAL INDEX WORDS:** *Numerical model, tidal constituents, harmonic analysis, west coast of India.*

## INTRODUCTION

Tidal spectrum consists of large number of constituents and the amplitude and phase of these constituents are subjected to distortion when they propagate from ocean to estuaries. Bottom friction, channel geometry and other physical processes cause tidal distortion in an estuary. The mutual interference of an astronomical tide and shallow water tide can give rise to tidal asymmetry (KANG and JUN, 2003).

Tides in the west coast of India (Figure 1a) are semi diurnal mixed and large variation in the tidal range is noticed between southern end and northern end. At Cochin backwaters, tidal range is about 1 m whereas at Gulf of Khambhat and Gulf of Kutch, the tidal ranges are about 8 m. The Gulf of Khambhat experiences tides that are the highest vertical tidal range observed along the west coast of India.

Though many studies (UNNIKRISHNAN et al., 1999; SHETYE, 1999; UNNIKRISHNAN and LUICK, 2003, SUNDAR and SHETYE, 2005) were conducted in order to understand the variation of major diurnal and semi diurnal constituents in the Gulfs/Estuaries on the west coast of India, no detailed study was undertaken to know the variations of overtides ( $M_4$ ,  $M_6$ ) and compound tides ( $MS_f$ ,  $MK_3$ ,  $MN_4$ ,  $MS_4$ ) inside these Gulfs/Estuaries. The overtides and compound tides have major role on the tidal asymmetry inside the Gulf/Estuaries. Tidal asymmetry can change the duration of flood and ebb in an estuary. Tidal asymmetry has important effects on both the geological evolution of shallow estuaries and the navigability of estuarine channels (AUBREY and SPEER, 1985).

In order to study the variations of overtides and compound tides and their role on tidal distortion, we chose the Mandovi and Zuari estuaries on the west coast of India since these estuaries represent the other estuarine systems on the west coast of India in terms of tidal characteristics, channel convergence, heavy fresh water discharge into Arabian Sea etc. The Mandovi and Zuari estuaries play a vital role on the regional economy as these channels are exclusively used for the transportation of Iron and Manganese ores from their upstream regions to the nearest Port, Mormugao (see Figure 1a), which is one of the major ports in India. A narrow canal, Cumbarjua, interconnects these two estuaries. The cross-sectional area of the Mandovi and Zuari estuaries decrease towards the upstream regions and average depth of each of these estuaries is 5 m.

Mandovi and Zuari estuaries are called “monsoonal” estuaries since these estuaries receive heavy freshwater influx ( $\sim 400 \text{ m}^3\text{s}^{-1}$ ) during southwest monsoon (June - September). However, in most part of the year except June - September, these estuaries are well mixed and the tidal influence reaches up to 50 km from the mouth of these two estuaries (SHETYE et al., 1995). The tidal range in the Mandovi and Zuari estuaries is about 2.0 m.  $M_2$  (Principal lunar semi-diurnal constituent) is the dominant constituent in these estuaries. The amplitude of  $M_2$  is about 55 cm, which is four times higher than  $N_2$  (Larger Lunar elliptic) and three times higher than  $S_2$  (Principal solar semi-diurnal constituent). The dominant diurnal constituents are  $K_1$  (Luni-solar declinational) and  $O_1$  (Lunar declinational). In the present study, we used a hybrid network model to simulate the observed tides during March - April 2003. Thereafter, the harmonic analysis of observed and simulated tides was done. The tidal constituents derived from the harmonic analysis were analysed in order to study the non-linear response of the Mandovi and Zuari estuarine systems to the tidal forcing.

## **MATERIALS AND METHODS**

### **Bathymetry and tide data**

Bathymetry maps (1968-1969) of minor ports survey organization, Ministry of Shipping and Transport, Govt of India were digitized to obtain the bathymetry data for the Mandovi, Zuari and Cumbarjua. Sea level measurements were carried out at 13 locations in the Mandovi and Zuari estuaries and the Cumbarjua canal. There are six stations in the Mandovi estuary; five stations in the Zuari estuary and two stations in the Cumbarjua Canal where the tide pole measurements were carried out during 10 March-13 April 2003. The sea level obtained from the above observations was used for the model comparison.

### **Numerical model**

For the simulation of tides, we used a hybrid network numerical model, which was modified form of a vertically averaged 2D numerical model (UNNIKRISHNAN et al., 1999). This model was used for the simulation of tides and salinity distribution in the Mandovi and Zuari estuarine network (MANOJ and UNNIKRISHNAN, communicated). The hybrid network model consists of a 2D model that was used for simulating tides at the downstream regions in the Mandovi and Zuari estuaries. As mentioned above, the cross sectional area of the Mandovi and Zuari estuaries

decrease rapidly towards the upstream directions and the Cumbarjua Canal connects these two estuaries at the upstream regions. Hence for the simulation of tides at these narrow upstream regions, we developed an area averaged 1D model using the formulation given by HARLEMAN and LEE (1969). The 2D and 1D models were coupled at distance about 15 km from the mouth of the Mandovi and Zuari estuaries (Figure 1c). Finite difference explicit scheme was used to solve the momentum and continuity equations in the model. The model uses an Arakawa C grid and leapfrog technique to march in time. A Cartesian coordinate system was considered where x and y-axis are positive towards east and north respectively.

We give a brief description of the equations used in the model

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}(uU) + \frac{\partial}{\partial y}(vU) = -g(h + \eta) \frac{\partial \eta}{\partial x} + fV + A_H \nabla^2 U - C_D \frac{U \sqrt{U^2 + V^2}}{(h + \eta)^2} \quad (2)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}(uV) + \frac{\partial}{\partial y}(vV) = -g(h + \eta) \frac{\partial \eta}{\partial y} - fU + A_H \nabla^2 V - C_D \frac{V \sqrt{U^2 + V^2}}{(h + \eta)^2} \quad (3)$$

$$b \frac{\partial \eta}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \quad (4)$$

$$\frac{\partial Q}{\partial t} + \frac{2Q}{A} q - \frac{2bQ}{A} \frac{\partial \eta}{\partial t} = -gA \frac{\partial}{\partial x}(z_0 + h + \eta) - g \frac{Q|Q|}{AC^2R} \quad (5)$$

The expression for stability criterion of the present numerical scheme is given below

$$\Delta t \leq \frac{(\Delta x \Delta y)}{\sqrt{2g(h + \eta)}} \quad (6)$$

$$\eta_{i,t+\Delta t} = \eta_{i,t-\Delta t} - 2 \left( \frac{\Delta t}{\Delta x b_i} \right) (Q_{i,t} - b_i (U_{i-1,j,t})) \quad (7)$$

Equation 1 & 4 are the continuity equations in 2D and 1D models respectively; Equation 2 & 3 are the transport form of momentum equations in the x and y directions and Equation 5 represents the area-averaged form of 1D momentum equation. Equation 6 is the Courant-

Friedrichs-Lewy (CFL) stability criterion. Equation 7 shows the formulation of 2D and 1D coupling.  $\Delta x$  and  $\Delta y$  are the space increments in the x and y-axis respectively. Both  $\Delta x$  and  $\Delta y$  were taken as 500 m.  $\Delta t$  is time interval, which was taken as 15 seconds in the model. The coefficient of horizontal diffusion of momentum,  $A_H$ , was chosen as  $500 \text{ m}^2\text{s}^{-1}$ . There was no considerable variation of amplitude at different stations in the estuaries when the bottom drag coefficient,  $C_D$ , in the model was allowed to vary from 0.001 to 0.003, however, the value of 0.002 gave better match with that of observations. Hence we used 0.002 as a constant value for bottom drag coefficient in the downstream regions of the model. At the upstream regions, the channel's bathymetry plays an important role on tidal amplitude. So the Manning coefficient in the 1D model was allowed to vary from 0.015 to 0.035.

### **Boundary conditions**

The tide for forcing the model at the open boundary was predicted from the known tidal constituents at Dona Paula (see Figure 1b) using TASK-2000 (Tidal Analysis Software Kit 2000). The no-slip boundary conditions were applied along the closed boundaries. At western boundary (open boundary), the predicted tide was prescribed as function of time. Model was initialized to zero surface elevation and velocity. Even in April, there is a small fresh water influx ( $10 - 15 \text{ m}^3\text{s}^{-1}$ ) into the Mandovi and Zuari estuaries from the upstream ends; hence we introduced a freshwater influx of  $10 \text{ m}^3\text{s}^{-1}$  at the upstream end boundaries of the Mandovi and Zuari.

The model was run for 42 days (3 March - 13 April 2003) to simulate the tides at 13 stations in the Mandovi and Zuari estuaries. The model was spun up over a period of 7 days (3 March – 9 March 2003). The simulated tides of the remaining days (10 March – 13 April 2003) were compared with those observed.

## **RESULTS**

Observed and simulated tides at 13 stations in the main channels of the Mandovi and Zuari and in the Cumbarjua are plotted in the Figure 2 and it shows that the model has reproduced the tide observations reasonably well in almost all stations. Verem station in the Mandovi is about 5 km from the ocean point (here after all the distances mentioned are with respect to the ocean point)

where the tidal range is 1.5 m and 2.3 m during neap and spring tide respectively. The tidal amplitude remains almost same at Britona (9 km), Akkada (20 km), Volvoi (33 km) and Usgao (41km) with slight increase in amplitude towards the upstream regions. But when the tide reaches at Ganjem (50 km) an upstream station in the Mandovi, the amplification of tide is visible ( $< 0.5$  m) only during spring tide. Similarly, the amplitude at Dona Paula (0 km), Cortalim (12 km), Borim (21 km) and Sanvordem (45 km) also remain unchanged. But the amplitude gets distorted at Sanguem (55 km). The simulation of tides at Banastarim (15 km) and Madkai (24.5 km) in the Cumbarjua are also well reproduced by the model.

### **Harmonic analysis of observed and simulated tide**

To get a clear idea about the non-linear response of an estuarine system to the tidal forcing, it is important to decompose the tide into harmonic constituents so that it becomes easy to analyse the major and minor harmonic constituents and explain the non-linear response of the estuarine system to the tidal forcing. We used 35-day data of tidal amplitude for the harmonic analysis and this one-month data was sufficient to resolve major diurnal and semi diurnal constituents, overtides and compound tides. The harmonic analysis of both observed and simulated tides were done using TASK-2000 software. In order to find the difference between observation and model simulation, we computed the complex difference module that gives synthetic information of the difference in both amplitude and phase between the observation and simulation.

The mean difference of this module over major diurnal and semidiurnal constituents, overtides and compound tides was also calculated in order to get the mean estimate of the accuracy of the model at each station. Amplitudes and phases of observed and simulated tidal constituents and the complex difference module are given in Table 1 - 3. The five major diurnal and semi diurnal constituents in the Table 1 - 2, are plotted in the Figure 3. The overtides and compound tides are shown in the Figure 4 and 5 respectively. As discussed earlier,  $M_2$  is the dominant tidal constituent with amplitude more than 50 cm both in the Mandovi and Zuari estuaries. The other dominant constituents are  $K_1$ ,  $S_2$ ,  $O_1$  and  $N_2$  (see Table 1 - 2).

### **Major diurnal and semi diurnal constituents**

Figure 3 shows the observed and simulated amplitudes and phases of five major tidal constituents. The observed amplitude of  $M_2$  in the Mandovi is 53 cm at Verem and the amplitude

increases about 63 cm at Usgao. Thus, the increase of  $M_2$  tide when it reaches the upstream regions is about 10 cm. In the Zuari, the amplitude of  $M_2$  is about 54 cm at Dona Paula and the amplitude increases about 69 cm at Sanvordem.  $K_1$ ,  $S_2$ ,  $O_1$  and  $N_2$  are also increase towards the upstream regions. Now if we look at the simulations of these constituents, At Verem, Britona and Akkada, the simulation of amplitude of  $M_2$  is reasonably good. But at Volvoi and Usgao, the model underestimates  $M_2$ . In the Zuari, the model reproduces  $M_2$  reasonably good from Dona Paula to Sanvordem (see the right top panel of Figure 3). The simulation of the amplitudes of  $O_1$ ,  $N_2$  and  $S_2$  are also reasonably good both in the Mandovi and Zuari. The model underestimates the amplitude of  $K_1$  at upstream regions. But the model has reproduced the phase increase of diurnal and semi diurnal constituents towards the upstream regions reasonably well in the Mandovi and Zuari. The mean difference of major constituents at different stations except Ganjem and Sanguem in the Mandovi and Zuari are within the limits of model accuracy (see Table 1-2). The difference found at Ganjem and Sanguem is very high and the reasons are explained in the discussion section.

### **Overtides and compound tides**

The overtides are plotted in the Figure 4, which shows the longitudinal variation on the amplitude and phase of  $M_4$  and  $M_6$  towards the upstream regions. The simulations of overtides are reasonably good in the Mandovi and Zuari. Both observation and simulation show the rapid increase of  $M_4$  inside the Zuari. The amplitude and phase of  $M_6$ , which is the second harmonics of  $M_2$ , also increases inside these two estuaries. The amplitude of  $M_6$  is better simulated than  $M_4$  in both these estuaries.

The Figure 5 shows that  $MS_f$  (Lunisolar synodic fortnightly constituent) is a significant compound tidal constituent in the Mandovi and Zuari with its amplitude about 3 cm (see Table 1 and 3) at the downstream regions and increases about 5 cm at the upstream regions. Two other important compound tides are  $MK_3$  (ter-diurnal tide, derived from the interactions of  $M_2$  and  $K_1$ ) and  $MN_4$  (quarter-diurnal tide which is the result of  $M_2$  and  $N_2$  interactions). The amplitude and phase of  $MK_3$  steadily increase inside the estuaries. The simulation of the amplitude and phase of  $MN_4$  is well matched with that of observed in the Mandovi and there is a reasonably good match in the Zuari. The simulation of the amplitude of  $MS_4$  (quarter-diurnal compound tide which is the

result of  $M_2$  and  $S_2$  interactions) also has a reasonable match in the Zuari but the model overestimates the amplitude in the Mandovi. The mean difference of overtides and compound tides increases marginally from mouth to upstream stations.

#### **$M_4/M_2$ amplitude ratio and relative surface phase ( $2M_2-M_4$ )**

The  $M_4/M_2$  amplitude ratio and relative surface phase ( $2M_2-M_4$ ) help to measure the non-linear distortion of tides inside the estuaries. The type of tidal (flood-dominant vs. ebb dominant) depends on the relative phasing of  $M_4$  to  $M_2$  (Aubrey and Speer, 1985; Speer and Aubrey 1985; Friedrichs and Aubrey 1988). The observed amplitude ratio,  $M_4/M_2$  is almost steady in the Mandovi estuary (see Table 4) and it steadily increases in the Zuari from mouth to upstream regions. The model overestimates  $M_4/M_2$  at the upstream regions in the Mandovi and the simulation of  $M_4/M_2$  are overall good in the Zuari (see Table 5). The relative surface phase decrease towards upstream regions both in the Mandovi and Zuari estuaries.

## **DISCUSSION**

The model sensitivity to horizontal diffusion of momentum was checked. The coefficient value was allowed to vary between  $100 \text{ m}^2\text{s}^{-1}$  and  $700 \text{ m}^2\text{s}^{-1}$ . The increase in amplitude and phase of the constituents towards the upstream regions was better simulated for the value of  $500 \text{ m}^2\text{s}^{-1}$ . The changes in friction from 0.001 to 0.003 did not show any significant impact on the amplitude and phase, however the value, 0.002 gave better agreement between observed and simulated. The tidal amplitude remains almost same with slight increase in the upstream direction in the Mandovi and Zuari estuaries over a long stretch. The previous studies in the Mandovi and Zuari estuaries show that tidal amplitude remains unchanged over a distance of 40 km from the mouth and then decays rapidly over the next 10 km (SHETYE et al., 1995; UNNIKRISHNAN et al., 1997). Mandovi and Zuari estuaries are strongly converging channels and this leads to the amplification of tides in the upstream direction. The momentum balance in this type of estuaries is primarily between pressure gradient and friction (FRIEDRICHS and AUBREY, 1994), the decay in amplitude due to friction gets canceled by amplification, which leaves the amplitude, unchanged over 40 km in Mandovi and Zuari estuaries from the mouth. Tidal amplitude gets decayed in last 10 km in these estuaries. UNNIKRISHNAN et al., (1997) showed that the decay in amplitude at the



upstream regions is due to the influence of freshwater influx. The influence of freshwater influx is visible even in April at Ganjem.

### **Increase of Amplitudes and phases of major constituents**

Harmonic analysis of the tide shows that the predominant species of tidal constituents increase inside the estuaries (see Figure 3). As we saw above, the Mandovi and Zuari estuaries are not frictionally dominated estuaries; the frictional nature of the estuary is demonstrated by the significant decay of all semi diurnal and diurnal constituents, with associated large phases (AUBREY and SPEER, 1985). The previous studies (UNNIKRISHNAN et al., 1999; SHETYE, 1999; UNNIKRISHNAN and LUICK, 2003) show that major diurnal and semi-diurnal constituents increase inside the Gulfs of Khambhat and Gulf of Kutch due to resonance and geometric effects. SHETYE, (1999) showed that the large amplification in semi diurnal constituents in the Gulf of Kutch is due to the proximity of their periods to the period at which the Gulf resonates. Though we have not estimated the role of co-oscillation of incident and reflected waves on amplitude and phase in the Mandovi and Zuari estuaries, it can be seen from the Figure 4 and 5 that the amplitude and phase variations of the tidal constituents towards the upstream regions are not linear, which is a strong indication of the presence of a reflected wave in these estuaries. Hence the amplification of semi-diurnal constituents in the Mandovi and Zuari can be mainly attributed to the balance between pressure gradient and friction as mentioned above. The superimposition of incident and reflected wave could be the other cause of increase of the semi-diurnal constituents at the upstream directions.

### **Amplitude and phase increase of overtides and compound tides**

Non-linear response to the tidal forcing is reflected in the increase of high frequency  $M_2$  overtides compound tides and a forced low frequency  $MS_f$  constituent throughout the estuary (AUBREY and SPEER, 1985). The increase of  $M_4$  towards the upstream regions in an estuary indicates flood dominance. The  $M_4$  increases both in the Mandovi and Zuari estuaries. Similarly, the amplitude and phase of  $M_6$  increase inside the estuaries. The increase of  $M_6$  inside the estuaries can be attributed to the quadratic friction (BLANTON et al., 2002). It can be seen from the Figure 5 that the non-linear increase of compound tides towards the upstream regions. Both observation and simulation show the consistent increase of amplitude of  $MS_f$  in the Mandovi

though the model slightly underestimates the amplitude in the downstream regions. But the observed amplitude increase of MSf inside the Zuari is not consistent. The amplitude of  $MN_4$  in the Mandovi and  $MS_4$  in the Zuari decrease in the middle of these estuaries and then steadily increase in the upstream directions. This rapid increase in amplitude and phase of the first and second harmonics of  $M_2$  and the non-linear increase of compound tides show the non-linear nature of the Mandovi and Zuari estuarine systems to the tidal forcing.

The complex difference module calculated at different stations in the Mandovi and Zuari shows that the mean difference over major diurnal and semi diurnal constituents, overtides and compound tides gradually increase from downstream region to the upstream regions. The difference in  $M_2$  is also high towards the upstream stations. For the present study, we used a 2D square grid, which is not well adapted to the irregular configuration of coastlines. The meandering effects of channels influence the amplitude and phase of tide entering into the estuary. The higher difference found in some stations between observed and simulated could be due to the above reasons. Now if we look at the difference calculated at Ganjem and Sanguem, the differences are very high between observed and simulated tidal constituents. Apart from the above reasons, there are other factors such as freshwater flow and higher channel elevation with respect to mean sea level, which also prevent tide from these upstream stations. The freshwater inflow into the Mandovi is more than that of Zuari. Thus, the tidal characteristics get distorted more at Ganjem than at Sanguem. Tide is visible at Ganjem only during spring tide. Hence the harmonic analysis of tidal signal measured at Ganjem did not resolve the amplitude and phase of tidal constituents accurately. The model could not simulate the observed tide accurately. This could be due to the in accurate freshwater input, improper representation of channel elevation with respect to the mean sea level and also could be due to the square grid used in the present model. Similarly at Sanguem also, tide get distorted (see Figure 2).

The increase of  $M_4/M_2$  amplitude ratio towards the upstream regions except Ganjem in the Mandovi estuary is marginal (see Table 4). The  $M_4/M_2$  is 0.01 at Verem and 0.03 at Usgao. This increase of  $M_4/M_2$  from mouth to upstream regions shows that the tide does not get distorted much towards upstream regions in the Mandovi where as at Ganjem, tide is completely gets distorted that is evident from the very high amplitude ratio, which is about 0.5. In the Zuari, tidal

amplitude gets distorted towards the upstream regions with continues increase of  $M_4/M_2$  from 0.02 to 0.1 (see Table 5). The observations of the relative surface phase decrease from 222 degree at Verem to 6.8 degree at Ganjem in the Mandovi. In the Zuari, the observation of relative surface phase decrease from Dona Paula to Cortalim, but from Cortalim to Sanvordem, the relative surface phase increases and again it decreases at Sanguem (see Table 4 and 5). But the model shows the decrease of relative surface phase towards the upstream directions both in the Mandovi and Zuari with exceptions at Akkada and Usgao. Now if we look at the relative phase relationship between  $M_4$  and  $M_2$ , a flood-dominant system has sea surface phase of 0 to 180 degree with maximum flood at 90 degree and ebb-dominant system has sea surface phase of 180 to 360 degree with maximum ebb at 270 degree (FRIEDRICHS and AUBREY, 1988). If we assume a linear relationship in the relative phase mentioned above, a relative surface phase of about 220 degree at Verem and Dona Paula and about 6 degree at Ganjem and about 23 degree at Sanguem show that the relative surface phase decreases towards the upstream regions. The decrease of a relative surface phase towards upstream directions is an indication of flood-dominance. The analysis of sea level observations (see Figure 2) also shows the flood-dominance in the Mandovi and Zuari estuaries. Overall, the increase of  $M_4$  and decrease of relative surface phase inside both in the Mandovi and Zuari show that these estuaries are flood-dominated. But there are some mudflats at the upstream regions in the Zuari estuary, which can increase the duration of ebb, which indicates that the Zuari estuary is a less flood dominant than the Mandovi estuary.

## CONCLUSIONS

Harmonic analysis of observed and simulated tides was done in order to examine the nonlinear nature of the estuarine system to the tidal forcing in the Mandovi and Zuari estuaries. The observations and model results show the consistent increase of amplitude and phases of major diurnal and semi diurnal constituents inside these estuaries. The increase of major tidal constituents inside the estuaries show that the Mandovi and Zuari estuaries are not frictionally dominated estuaries since the frictional effect is decayed due to geometric effect. The increase of overtides and compound tides inside the estuaries show the non-linearity of these estuaries to the tidal forcing. The  $M_4/M_2$  amplitude ratio shows that tidal distortion at the upstream regions in the Mandovi is marginal whereas in the Zuari, the  $M_4/M_2$  amplitude ratio steadily increases in the upstream direction. This higher amplitude ratio indicates strong tidal distortion in the Zuari.

## Appendix

$U = u(h + \eta)$  is the transport along the x-axis

$V = v(h + \eta)$  is the transport along the y-axis

Where  $u$  and  $v$  are vertically averaged velocities over a water column of height,  $(h + \eta)$

$h = f(x, y)$ , Depth

$\eta = f(x, y, t)$ , Tide

$t$  = time

$g$  = Acceleration due to gravity

$f$  = Coriolis parameter

$A_H$  = Coefficient of horizontal diffusion of momentum

$C_D$  = Bottom drag coefficient

$b$  = Width of the channel

$q$  = Freshwater influx per unit channel length

$Q$  = Along channel transport

$R$  = Hydraulic radius

$C$  = Chezy coefficient

$z_0$  = Distance between the bottom of the channel and an arbitrary level surface well below the bottom.

$A$  = Cross-sectional area of the channel

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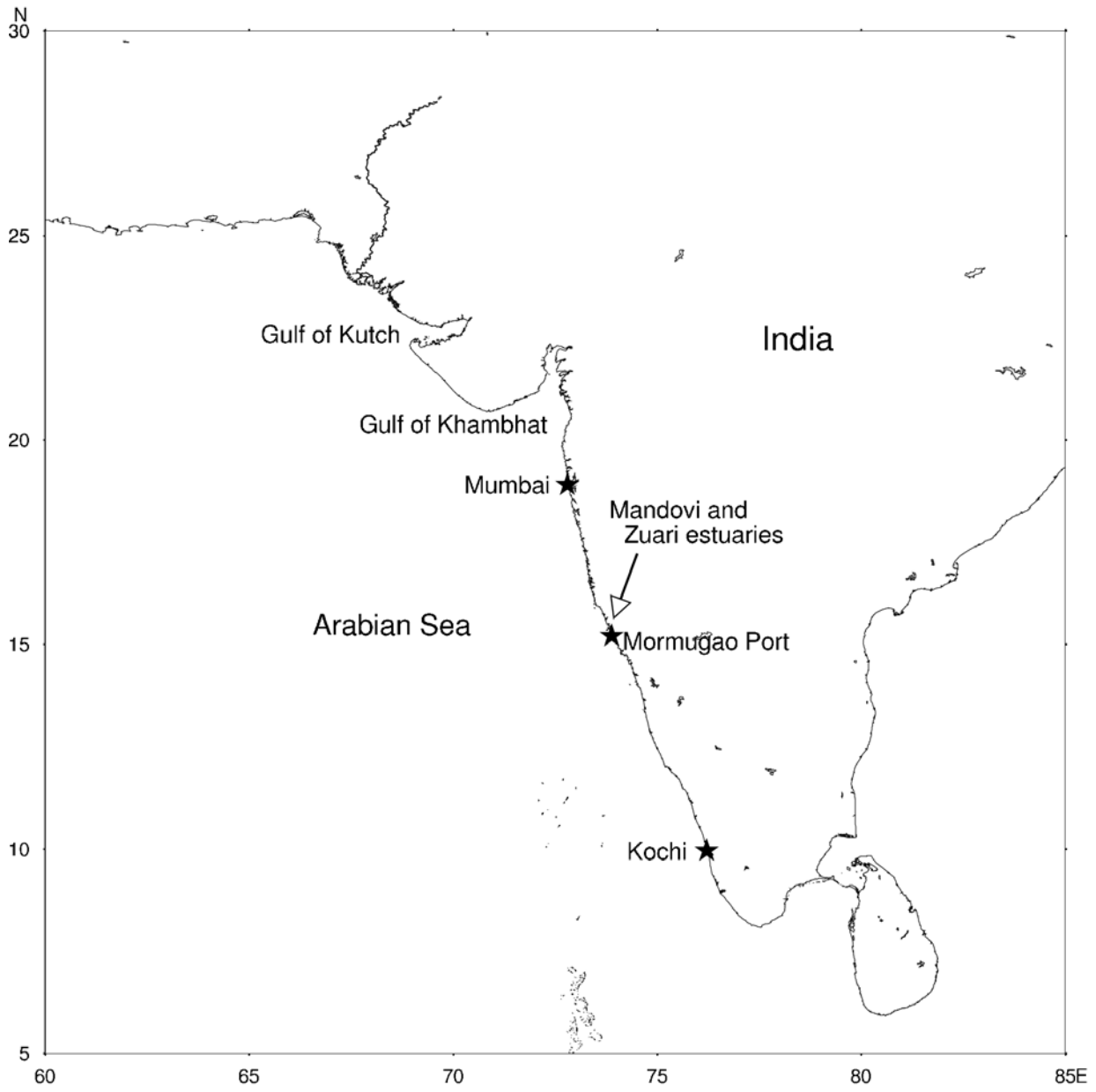
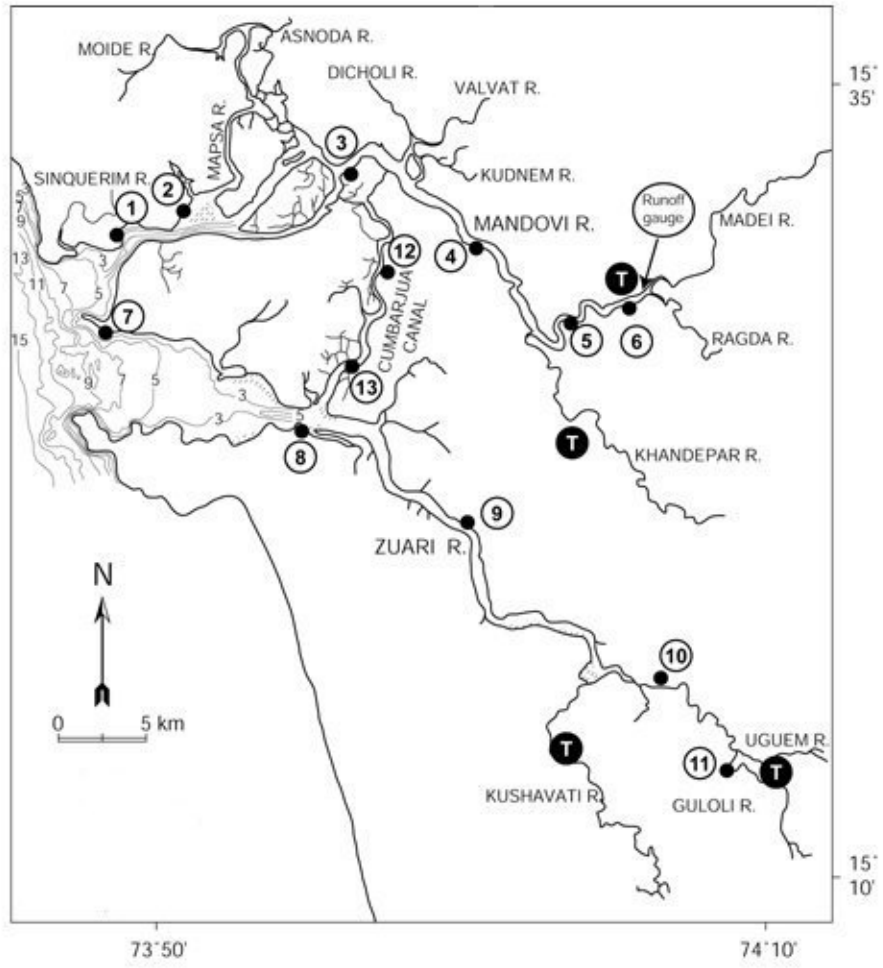


Figure 1a





- ① Verem ② Brittona ③ Akkada ④ Valvoi ⑤ Usgaon ⑥ Ganjem ⑦ Dona Paula
- ⑧ Cortalim ⑨ Borim ⑩ Sanvordem ⑪ Sanguem ⑫ Banastarim ⑬ Madkai

Figure 1b

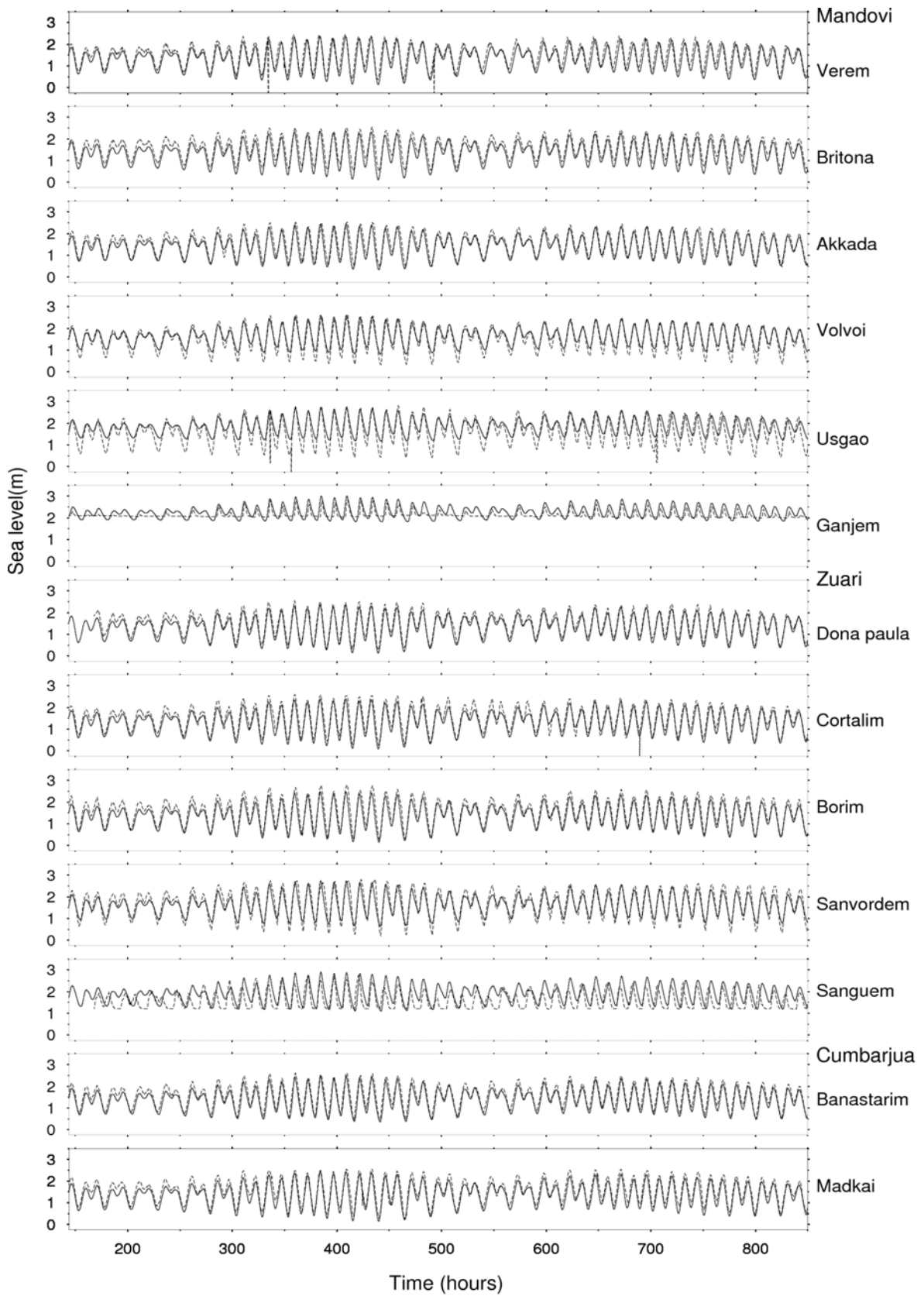


Figure 2

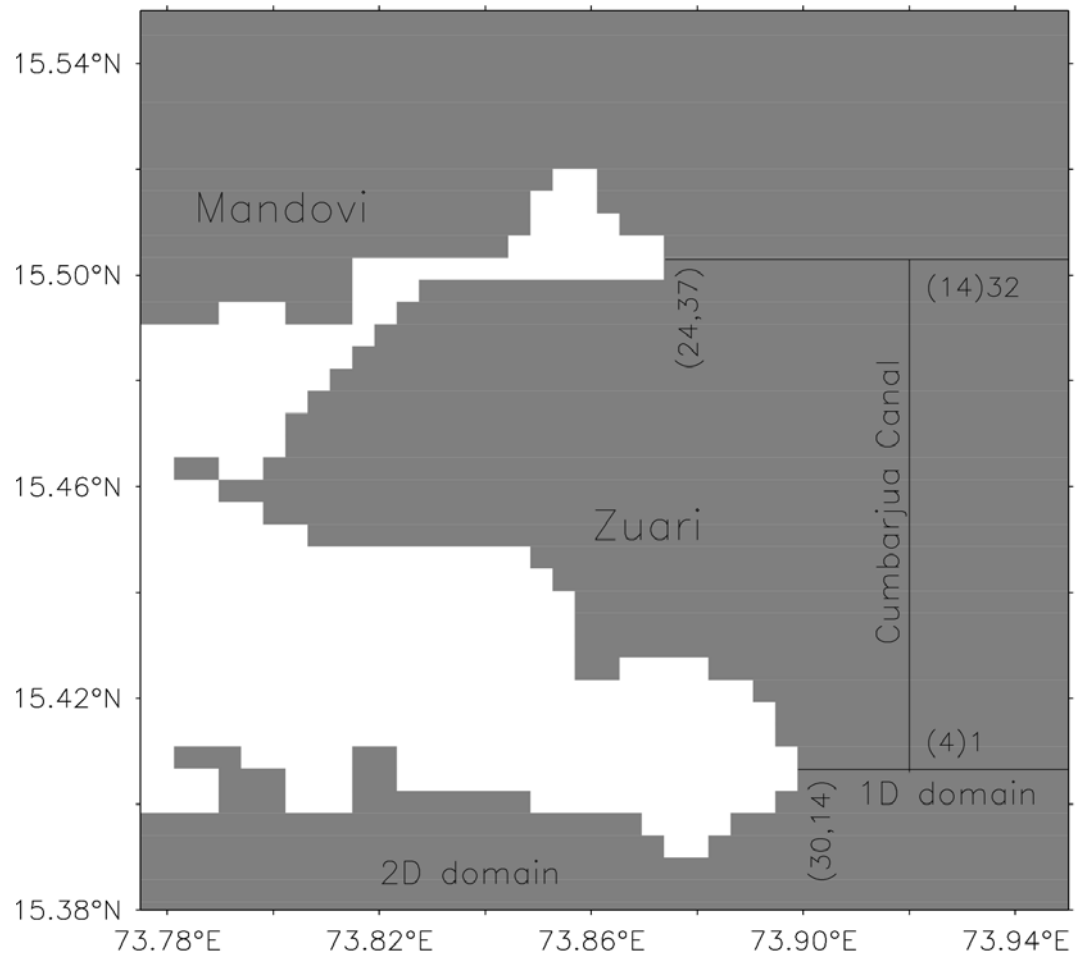


Figure 1c

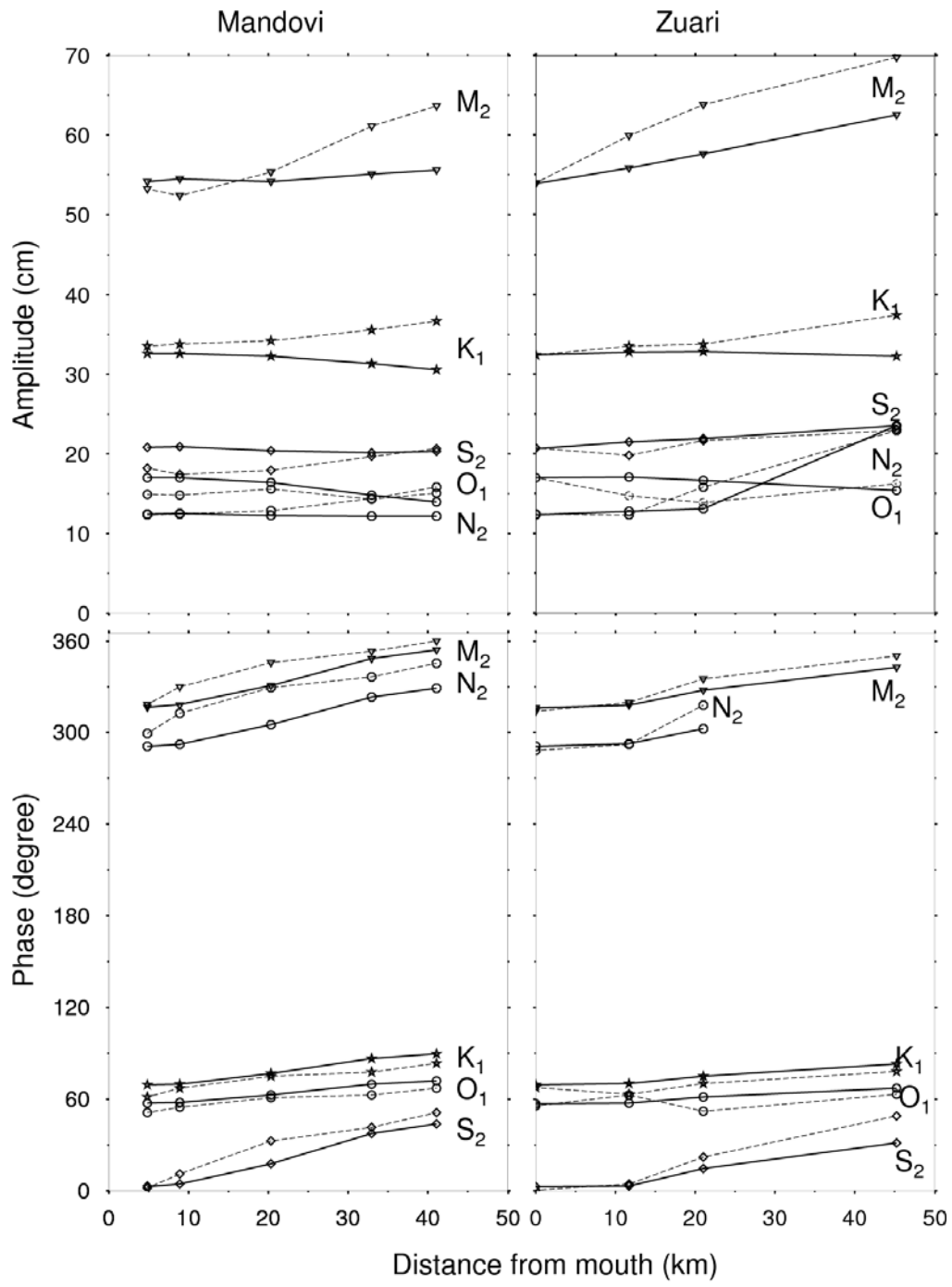


Figure 3

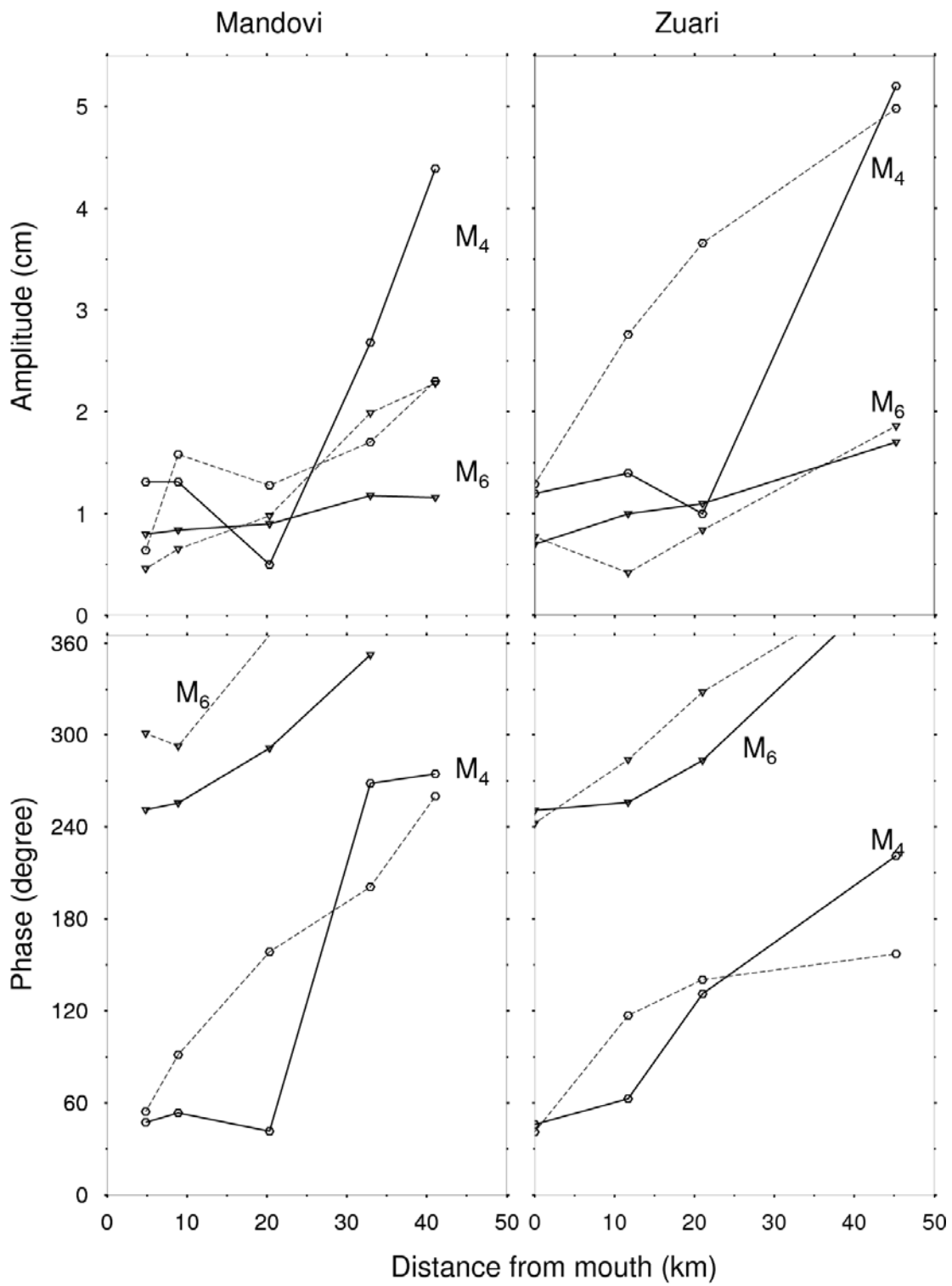


Figure 4

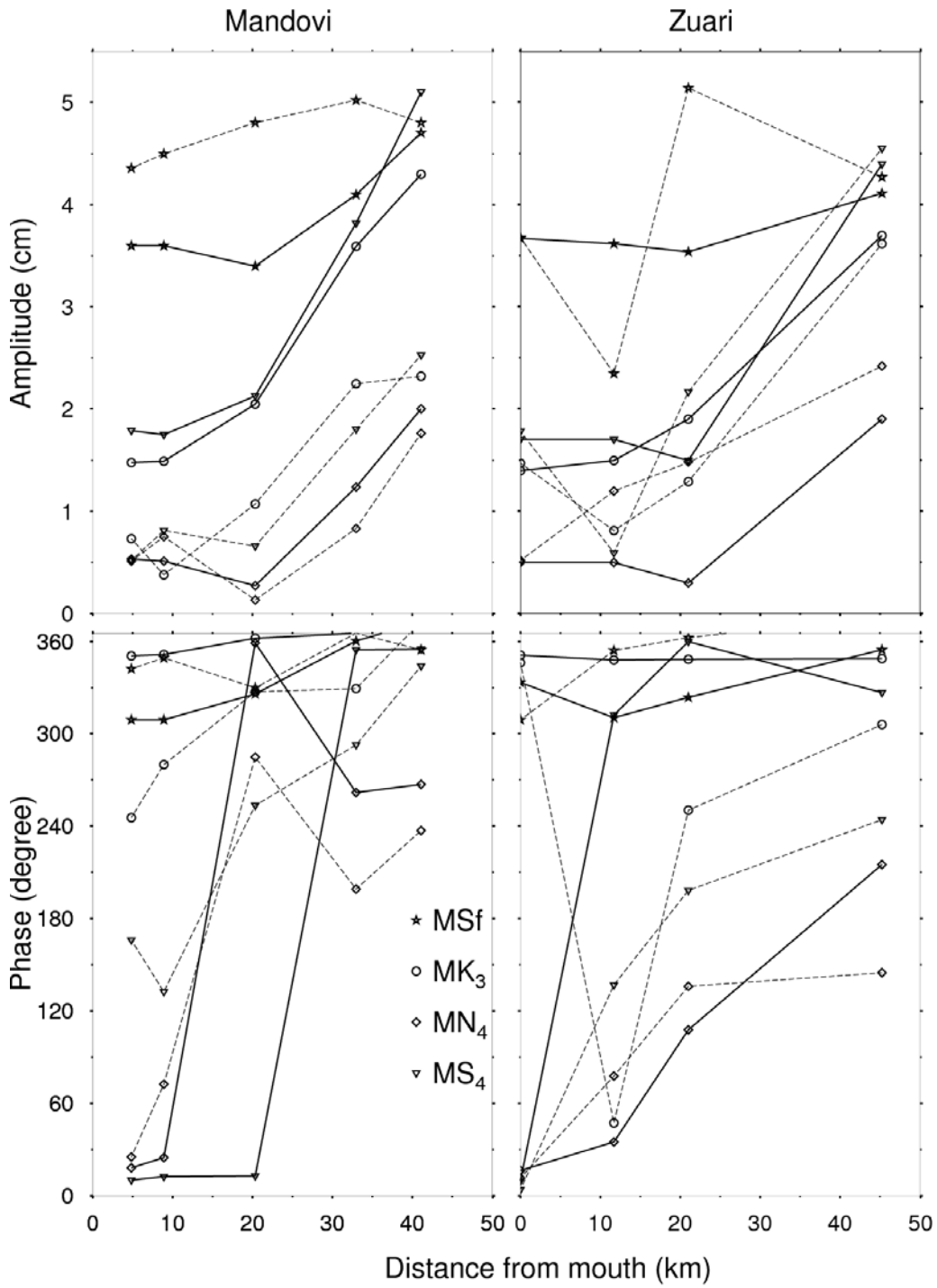


Figure 5

Table 1. Amplitudes (Amp), phases (Pha) and complex difference module (Diff) of tidal constituents in the Mandovi. The number in bracket next to the station name is the distance from the mouth of the estuary

Const.(cm)	Verem [5]			Britona [9]			Akkada [20]			Volvoi [33]			Usgao [41]			Ganjem [50]			
	Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	
<b>O<sub>1</sub></b>	<b>Amp</b>	<b>14.9</b>	<b>17</b>	<b>2.66</b>	<b>14.7</b>	<b>17</b>	<b>2.45</b>	<b>14.5</b>	<b>16.4</b>	<b>1.97</b>	<b>14.3</b>	<b>14.7</b>	<b>1.79</b>	<b>15</b>	<b>13.5</b>	<b>1.92</b>	<b>2.3</b>	<b>12.5</b>	<b>13.36</b>
	<i>Pha</i>	51.2	57.1		54.7	57.8		60.8	62.7		62.7	69.6		67.1	71.9		327.9	75.1	
<b>K<sub>1</sub></b>	<b>Amp</b>	<b>33.5</b>	<b>32.5</b>	<b>4.54</b>	<b>33.7</b>	<b>32.6</b>	<b>2.01</b>	<b>34.1</b>	<b>32.2</b>	<b>2.11</b>	<b>33.5</b>	<b>31.3</b>	<b>5.43</b>	<b>36.6</b>	<b>30.5</b>	<b>7.09</b>	<b>6.1</b>	<b>28.6</b>	<b>22.64</b>
	<i>Pha</i>	61.5	69.2		67	69.9		75	76.6		77.5	86.3		83.2	89.4		82.1	93	
<b>N<sub>2</sub></b>	<b>Amp</b>	<b>12.3</b>	<b>12.4</b>	<b>1.83</b>	<b>12.4</b>	<b>12.5</b>	<b>4.3</b>	<b>12.8</b>	<b>12.3</b>	<b>5.31</b>	<b>14.3</b>	<b>12.1</b>	<b>3.72</b>	<b>15.8</b>	<b>12.1</b>	<b>5.36</b>	<b>2.8</b>	<b>11.6</b>	<b>8.8</b>
	<i>Pha</i>	299.5	291		312.3	292.4		329.1	304.8		336.3	323.2		345.1	329.0		333.9	335	
<b>M<sub>2</sub></b>	<b>Amp</b>	<b>53.2</b>	<b>54.2</b>	<b>1.73</b>	<b>52.4</b>	<b>54.4</b>	<b>10.88</b>	<b>55.3</b>	<b>54.2</b>	<b>14.33</b>	<b>61.1</b>	<b>55.1</b>	<b>7.92</b>	<b>63.6</b>	<b>55.6</b>	<b>10.01</b>	<b>12.1</b>	<b>53.9</b>	<b>42.71</b>
	<i>Pha</i>	318.2	316.7		329.6	318.1		345.5	330.5		353.3	348.2		0	354.2		20.92	1.1	
<b>S<sub>2</sub></b>	<b>Amp</b>	<b>18.2</b>	<b>20.8</b>	<b>3.05</b>	<b>17.4</b>	<b>20.9</b>	<b>4.19</b>	<b>17.9</b>	<b>20.4</b>	<b>5.58</b>	<b>19.6</b>	<b>20.1</b>	<b>1.44</b>	<b>20.6</b>	<b>20.3</b>	<b>2.69</b>	<b>5.7</b>	<b>19.7</b>	<b>4</b>
	<i>Pha</i>	358.1	2.8		11.1	4.2		32.5	17.5		41.3	37.4		51	43.5		48.9	49.9	
Mean diff for major consti.				<b>2.76</b>			<b>4.77</b>			<b>5.86</b>			<b>4.06</b>			<b>5.41</b>			<b>18.3</b>
<b>M<sub>4</sub></b>	<b>Amp</b>	<b>0.6</b>	<b>1.3</b>	<b>0.71</b>	<b>1.5</b>	<b>1.3</b>	<b>0.93</b>	<b>1.2</b>	<b>0.5</b>	<b>1.5</b>	<b>1.7</b>	<b>2.8</b>	<b>2.51</b>	<b>2.3</b>	<b>4.3</b>	<b>2.16</b>	<b>6.4</b>	<b>6.1</b>	<b>10.09</b>
	<i>Pha</i>	25.1	18.1		72.2	24.5		284.8	359		199.2	261.6		237.2	267.2		35	287.4	
<b>M<sub>6</sub></b>	<b>Amp</b>	<b>0.4</b>	<b>0.8</b>	<b>0.62</b>	<b>0.6</b>	<b>0.8</b>	<b>0.48</b>	<b>0.9</b>	<b>0.9</b>	<b>1.08</b>	<b>1.9</b>	<b>1.1</b>	<b>1.49</b>	<b>2.2</b>	<b>1.1</b>	<b>1.42</b>	<b>2.6</b>	<b>1.2</b>	<b>1.84</b>
	<i>Pha</i>	301	251		292.5	255.5		5	291.1		44	352.2		67.5	33.7		44.5	84.2	
Mean diff for overtide consti.				<b>0.67</b>			<b>0.71</b>			<b>1.29</b>			<b>2</b>			<b>1.79</b>			<b>5.97</b>
<b>MSf</b>	<b>Amp</b>	<b>4.3</b>	<b>3.6</b>	<b>2.34</b>	<b>4.5</b>	<b>3.6</b>	<b>2.88</b>	<b>4.8</b>	<b>3.4</b>	<b>1.43</b>	<b>5.0</b>	<b>4.1</b>	<b>0.97</b>	<b>4.8</b>	<b>4.7</b>	<b>1.46</b>	<b>4.1</b>	<b>5.4</b>	<b>1.93</b>
	<i>Pha</i>	342.1	309.1		349.0	309.2		329.8	326.0		005.1	000.4		354.3	011.9		40	22.6	
<b>MK<sub>3</sub></b>	<b>Amp</b>	<b>0.7</b>	<b>1.4</b>	<b>1.72</b>	<b>0.3</b>	<b>1.4</b>	<b>1.33</b>	<b>1.0</b>	<b>2.0</b>	<b>1.31</b>	<b>2.2</b>	<b>3.5</b>	<b>2.15</b>	<b>2.3</b>	<b>4.3</b>	<b>2.01</b>	<b>3</b>	<b>4.9</b>	<b>4.74</b>
	<i>Pha</i>	245.5	350.6		279.9	351.3		326.9	1.8		329.1	5.1		12.7	9.4		86.8	17.9	
<b>MN<sub>4</sub></b>	<b>Amp</b>	<b>0.5</b>	<b>0.5</b>	<b>0.06</b>	<b>0.7</b>	<b>0.5</b>	<b>0.52</b>	<b>0.1</b>	<b>0.2</b>	<b>0.2</b>	<b>0.8</b>	<b>1.2</b>	<b>1.09</b>	<b>1.7</b>	<b>2.0</b>	<b>1</b>	<b>2.5</b>	<b>2.8</b>	<b>3.84</b>
	<i>Pha</i>	25.1	18.1		72.2	24.5		284.8	359		199.2	261.6		237.2	267.2		12.55	279.8	
<b>MS<sub>4</sub></b>	<b>Amp</b>	<b>0.5</b>	<b>1.7</b>	<b>2.17</b>	<b>0.8</b>	<b>1.7</b>	<b>2.22</b>	<b>0.6</b>	<b>2.1</b>	<b>2.45</b>	<b>1.8</b>	<b>3.8</b>	<b>3.34</b>	<b>2.5</b>	<b>5.1</b>	<b>2.69</b>	<b>5.8</b>	<b>6.5</b>	<b>6.36</b>
	<i>Pha</i>	166	10.2		132.6	12.1		253.4	12.6		292.9	354.4		344.1	355.1		63.31	1.4	
Mean diff for comp tide consti.				<b>1.57</b>			<b>1.74</b>			<b>1.35</b>			<b>1.89</b>			<b>1.79</b>			<b>4.22</b>

Table 2. Same as Table 1. but for the Zuari estuary.

Const.(cm)		Dona Paula [0]			Cortalim [12]			Borim [21]			Sanvordem [45]			Sanguem [55]		
		Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff	Obs	Mod	Diff
<b>O<sub>1</sub></b>	<b>Amp</b>	<b>16.9</b>	<b>17</b>	<b>0.44</b>	<b>14.7</b>	<b>17.1</b>	<b>2.78</b>	<b>13.9</b>	<b>16.7</b>	<b>3.72</b>	<b>16.2</b>	<b>15.4</b>	<b>1.43</b>	<b>7.6</b>	<b>9.7</b>	<b>14.86</b>
	<i>Pha</i>	55.6	57.04		62.6	57.5		52.1	61.3		62.9	67.2		190.6	72.7	
<b>K<sub>1</sub></b>	<b>Amp</b>	<b>32.4</b>	<b>32.4</b>	<b>0.79</b>	<b>35.5</b>	<b>32.7</b>	<b>4.97</b>	<b>38.8</b>	<b>32.8</b>	<b>6.73</b>	<b>37.4</b>	<b>32.2</b>	<b>5.9</b>	<b>17.9</b>	<b>22.9</b>	<b>37.08</b>
	<i>Pha</i>	67.7	69.1		63.1	70		70	74.9		78.3	82.9		220.9	90.6	
<b>N<sub>2</sub></b>	<b>Amp</b>	<b>12.4</b>	<b>12.4</b>	<b>0.61</b>	<b>12.3</b>	<b>12.8</b>	<b>0.5</b>	<b>15.8</b>	<b>13.1</b>	<b>4.79</b>	<b>13.9</b>	<b>14</b>	<b>5.18</b>	<b>12.1</b>	<b>9.9</b>	<b>4.25</b>
	<i>Pha</i>	288.1	290.9		292.3	292.5		318	302.2		339.3	317.9		308.5	327.6	
<b>M<sub>2</sub></b>	<b>Amp</b>	<b>54</b>	<b>53.9</b>	<b>2.17</b>	<b>59.9</b>	<b>55.9</b>	<b>4.31</b>	<b>63.8</b>	<b>57.7</b>	<b>10.09</b>	<b>69.7</b>	<b>62.6</b>	<b>11.36</b>	<b>42.6</b>	<b>44.5</b>	<b>29.91</b>
	<i>Pha</i>	313.7	316		319.6	318		335	327.4		350.1	342.4		317.2	357.3	
<b>S<sub>2</sub></b>	<b>Amp</b>	<b>20.7</b>	<b>20.7</b>	<b>1.05</b>	<b>19.8</b>	<b>21.5</b>	<b>1.76</b>	<b>21.6</b>	<b>21.9</b>	<b>2.79</b>	<b>22.9</b>	<b>23.5</b>	<b>7.12</b>	<b>13.6</b>	<b>17.1</b>	<b>14.95</b>
	<i>Pha</i>	359.7	2.6		3.1	4.4		22	14.7		48.8	31.2		345.9	42.8	
Mean diff for major consti.				<b>1.01</b>			<b>2.87</b>			<b>5.62</b>			<b>6.2</b>			<b>20.21</b>
<b>M<sub>4</sub></b>	<b>Amp</b>	<b>1.2</b>	<b>1.2</b>	<b>0.11</b>	<b>2.7</b>	<b>1.4</b>	<b>2.21</b>	<b>3.6</b>	<b>1.0</b>	<b>2.62</b>	<b>4.9</b>	<b>5.2</b>	<b>5.34</b>	<b>6.3</b>	<b>5.1</b>	<b>2.05</b>
	<i>Pha</i>	40.8	46		117.1	62.5		140.6	131		157.3	221		251	267.9	
<b>M<sub>6</sub></b>	<b>Amp</b>	<b>0.7</b>	<b>0.7</b>	<b>0.1</b>	<b>0.4</b>	<b>1.0</b>	<b>0.67</b>	<b>0.8</b>	<b>1.1</b>	<b>0.77</b>	<b>1.8</b>	<b>1.7</b>	<b>0.11</b>	<b>1.7</b>	<b>1.3</b>	<b>1.22</b>
	<i>Pha</i>	242.4	250.6		284	256		327.9	283.6		44.3	42.5		63.3	108.9	
Mean diff for overtide consti.				<b>0.1</b>			<b>1.44</b>			<b>1.69</b>			<b>2.72</b>			<b>1.64</b>
<b>MSf</b>	<b>Amp</b>	<b>3.6</b>	<b>3.6</b>	<b>0</b>	<b>2.3</b>	<b>3.6</b>	<b>2.51</b>	<b>5.1</b>	<b>3.5</b>	<b>3.22</b>	<b>4.2</b>	<b>4.1</b>	<b>1.54</b>	<b>10.3</b>	<b>5.1</b>	<b>5.44</b>
	<i>Pha</i>	308.9	308.9		354	310.1		2.4	323.7		15.7	354.3		16.3	28.9	
<b>MK<sub>3</sub></b>	<b>Amp</b>	<b>1.4</b>	<b>1.4</b>	<b>0.11</b>	<b>0.8</b>	<b>1.5</b>	<b>1.29</b>	<b>1.2</b>	<b>1.9</b>	<b>2.39</b>	<b>3.6</b>	<b>3.7</b>	<b>2.68</b>	<b>5.2</b>	<b>3.4</b>	<b>7.37</b>
	<i>Pha</i>	346.3	351		47.4	348		250.3	348.5		305.8	348.8		133.2	16.8	
<b>MN<sub>4</sub></b>	<b>Amp</b>	<b>0.5</b>	<b>0.5</b>	<b>0.05</b>	<b>1.2</b>	<b>0.5</b>	<b>0.9</b>	<b>1.4</b>	<b>0.3</b>	<b>1.14</b>	<b>2.4</b>	<b>1.9</b>	<b>2.51</b>	<b>3.9</b>	<b>2.3</b>	<b>1.65</b>
	<i>Pha</i>	11.3	16.4		77.7	34.7		135.7	107.7		144.7	215		258.3	266	
<b>MS<sub>4</sub></b>	<b>Amp</b>	<b>1.7</b>	<b>1.7</b>	<b>0.17</b>	<b>0.5</b>	<b>1.7</b>	<b>2.03</b>	<b>2.1</b>	<b>1.5</b>	<b>3.56</b>	<b>4.5</b>	<b>4.4</b>	<b>5.87</b>	<b>4.2</b>	<b>5.4</b>	<b>5.18</b>
	<i>Pha</i>	3.9	9.6		136.8	12.3		198	0		244.3	326.8		283.8	347.7	
Mean diff for comp tide consti.				<b>0.08</b>			<b>1.68</b>			<b>2.58</b>			<b>3.15</b>			<b>4.91</b>



Table 3. Same as Table 1. but for the Cumarjua canal

		Madkai [15]			Banastarim [24.5]		
Const.(cm)		Obs	Mod	Diff	Obs	Mod	Diff
<b>O<sub>1</sub></b>	<b>Amp</b>	<b>14.3</b>	<b>15.9</b>	<b>3.77</b>	<b>14.1</b>	<b>16.7</b>	<b>5.44</b>
	<i>Pha</i>	<i>56.4</i>	<i>69.4</i>		<i>42.6</i>	<i>60.5</i>	
<b>K<sub>1</sub></b>	<b>Amp</b>	<b>34.5</b>	<b>32.7</b>	<b>7.7</b>	<b>34.8</b>	<b>32.6</b>	<b>2.2</b>
	<i>Pha</i>	<i>72</i>	<i>84.8</i>		<i>73.5</i>	<i>73.7</i>	
<b>N<sub>2</sub></b>	<b>Amp</b>	<b>13.3</b>	<b>11.8</b>	<b>1.78</b>	<b>14.4</b>	<b>12.8</b>	<b>1.63</b>
	<i>Pha</i>	<i>322.4</i>	<i>318</i>		<i>298.5</i>	<i>299.7</i>	
<b>M<sub>2</sub></b>	<b>Amp</b>	<b>55.7</b>	<b>54.8</b>	<b>2.39</b>	<b>57.6</b>	<b>56.3</b>	<b>1.33</b>
	<i>Pha</i>	<i>340.4</i>	<i>342.7</i>		<i>325.4</i>	<i>325.1</i>	
<b>S<sub>2</sub></b>	<b>Amp</b>	<b>18.4</b>	<b>19.9</b>	<b>2.2</b>	<b>19.6</b>	<b>21.4</b>	<b>2.17</b>
	<i>Pha</i>	<i>26.4</i>	<i>31.2</i>		<i>15.4</i>	<i>12</i>	
Mean diff for major consti.				<b>3.57</b>			<b>2.55</b>
<b>M<sub>4</sub></b>	<b>Amp</b>	<b>2</b>	<b>3</b>	<b>4.73</b>	<b>0.5</b>	<b>1</b>	<b>0.77</b>
	<i>Pha</i>	<i>116.9</i>	<i>257.9</i>		<i>149.6</i>	<i>101.2</i>	
<b>M<sub>6</sub></b>	<b>Amp</b>	<b>1.5</b>	<b>0.8</b>	<b>0.72</b>	<b>0.3</b>	<b>1.1</b>	<b>0.8</b>
	<i>Pha</i>	<i>318.2</i>	<i>308.7</i>		<i>270.6</i>	<i>274.2</i>	
Mean diff for overtide consti.				<b>2.72</b>			<b>0.78</b>
<b>MSf</b>	<b>Amp</b>	<b>5</b>	<b>3.6</b>	<b>2.87</b>	<b>6.5</b>	<b>3.5</b>	<b>3.5</b>
	<i>Pha</i>	<i>3.2</i>	<i>328.9</i>		<i>343</i>	<i>321.3</i>	
<b>MK<sub>3</sub></b>	<b>Amp</b>	<b>0.9</b>	<b>3.7</b>	<b>3.27</b>	<b>1.8</b>	<b>1.7</b>	<b>3.05</b>
	<i>Pha</i>	<i>295.8</i>	<i>351</i>		<i>228.3</i>	<i>349.7</i>	
<b>MN<sub>4</sub></b>	<b>Amp</b>	<b>0.8</b>	<b>1.2</b>	<b>1.97</b>	<b>0.2</b>	<b>0.3</b>	<b>0.15</b>
	<i>Pha</i>	<i>99.3</i>	<i>259.2</i>		<i>47.6</i>	<i>73.5</i>	
<b>MS<sub>4</sub></b>	<b>Amp</b>	<b>1</b>	<b>3.8</b>	<b>4.46</b>	<b>0.5</b>	<b>1.4</b>	<b>1.9</b>
	<i>Pha</i>	<i>210.1</i>	<i>336</i>		<i>193.9</i>	<i>8.6</i>	
Mean diff for comp tide consti.				<b>3.14</b>			<b>2.15</b>

Table 4. Amplitude ratio of  $M_4/M_2$  and relative surface phase ( $2M_2-M_4$ ) in the Mandovi

	Verem [5]		Britona [9]		Akkada [20]		Volvoi [33]		Usgao [41]		Ganjam [50]	
	Obs	Mod	Obs	Mod	Obs	Obs	Obs	Mod	Obs	Mod	Obs	Mod
$M_4/M_2$	<b>0.01</b>	<b>00.02</b>	<b>0.03</b>	<b>0.02</b>	<b>0.02</b>	<b>0.009</b>	<b>0.02</b>	<b>0.04</b>	<b>0.03</b>	<b>0.07</b>	<b>0.52</b>	<b>0.11</b>
$2M_2-M_4$ (degree)	222.32	226.01	207.72	222.58	172.72	259.61	145.61	68.21	100.11	73.67	6.84	74.8

Table 5. Same as Table 4. but for the Zuari

	Dona Paula[0]		Cortalim [12]		Borim [21]		Sanvordem [45]		Sanguem[55]	
	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
$M_4/M_2$	<b>0.02</b>	<b>0.02</b>	<b>0.04</b>	<b>0.02</b>	<b>0.05</b>	<b>0.01</b>	<b>0.07</b>	<b>0.08</b>	<b>0.14</b>	<b>0.11</b>
$2M_2-M_4$ (degree)	222.62	226	162.17	213.55	169.42	163.88	182.98	103.76	23.4	86.7