

Coastal circulation along the central west coast of India during cyclone Phyan: measurements and numerical simulations

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Abstract

Measurements and numerical simulations carried out off Mumbai coast for the period 22nd October- 22nd November 2009 showed significant variations in water level and currents during cyclone Phyan. Changes in the meridional component of the current velocity were found to be highly significant during Phyan. The strong southward flow due to the cyclone resulted in a complete nullification of a flood current and continued the net flow towards south for approximately 18 h. This enhanced the ebb flow by about 0.12 m/s off Worli and 0.16 m/s off Satpati. The shift in the cyclone generated currents towards north resulted in an enhancement of flood current by 0.3 m/s off Worli and 0.2 m/s off Satpati. During the first 7 hours of Phyan, a strong current system associated with an anti-cyclonic eddy was formed off Mangalore, which propagated towards north upto Ratnagiri and disappeared while the cyclone entered the land. Water level variations of 0.38 m and 0.44 m were observed due to Phyan off Worli and Satpati, respectively. Positive and negative surges, that is, a fall in water level upto -20 cm and a rise upto 20 cm, were observed during Phyan, and these were associated with shift in the wind direction.

Keywords: tides; cyclones; hydrodynamics; storm surges; west coast of India; northeast monsoon.

1. Introduction

Coastal areas are prone to natural disasters such as cyclones, storm surges and tsunamis, and they generate serious threat to the coastal environment. The region between 10°S and 15°N gives rise to extreme weather conditions ranging from depressions to severe cyclones (Sadhuram et al. 2006). Over the north Indian Ocean, cyclones tend to form between April and December, with peaks in May/June and November (Obasi 1977). Several studies have been carried out in the north Indian Ocean to understand the response of extreme weather events (e.g., Sinha 1987; Gopalakrishna et al. 1993; Sundar et al. 1999; Chinthalu et al. 2001; Madsen and Jakobsen 2004; Subrahmanyam et al. 2005; Rajesh et al. 2005; Sanil kumar et al. 2008). Storms and depressions are less prevalent in the Arabian Sea compared to the Bay of Bengal (Dube et al. 1997).

The general circulation in the north Indian Ocean is influenced by seasonally reversing monsoon winds (Shetye et al. 1991). Transfer of water masses between the Bay of Bengal and the Arabian Sea takes place due to eastward summer monsoon current (SMC) during southwest (SW) monsoon and westward winter monsoon current (WMC) during northeast (NE) monsoon (Shankar et al. 2001). Currents along the west coast of India are dominated by tides, which are mixed with dominant semi-diurnal constituents (Shetye et al. 1991; Unnikrishnan et al. 1999). Tidal range increases from south to north due to broadening of the continental shelf (Kunte et al. 2000, Unnikrishnan 2010).

Storms introduce significant variability in water levels and currents along the coastal regions (Sinha 1987). Occurrence of extreme events combined with high tide results in large sea level elevation (Unnikrishnan et al. 2006). The sea surface slope across the continental shelf formed by the gradients in water levels is directly proportional to wind stress and inversely proportional to water depth. A perturbation in water level during a storm is mainly due to wind stress. Spatial variation in winds generates convergences and divergences in current flow. Under the influence of Coriolis effect, alongshore component of winds can push the water away from or towards the coast, which can lead to a fall or rise in water level (Neil 1981).

Studies on the effect of cyclones on hydrodynamic response along the west coast of India are very limited. Variations in met-ocean parameters at different locations along the west coast of India and Kavaratti Island lagoon were studied by Joseph et al. (2011) for the cyclone Phyan. They reported that the storm surges along the west coast of India are moderate during this period. Byju et al (2011) studied the physical and biological response of the Arabian Sea to Phyan. They identified rapid cooling in the sea surface temperature (SST), enhancement of chlorophyll *a* and two-fold increase in net primary productivity (NPP). As there were two current meter moorings off Mumbai (Figure 1b) during the passage of Phyan, it

was possible to validate the hydrodynamic model results, and study the dynamic response of the coastal region to this extreme event. The present work primarily aims at estimating water level variations and studying coastal circulation off Mumbai, the central west coast of India, utilising the results of measurements and model simulations.

2. The cyclone Phyan

Phyan formed in the Arabian Sea (Figure 2) during November 2009 with an estimated fall in the central pressure from 1000 hpa on 9th November 2009 at 1430 h (IST) to 988 hpa (at Harnai, Mumbai) on 11th November 2009 at 1030 h (IMD 2009). In association with active NE monsoon surge, initially a low pressure area was formed off Kanyakumari on 7th November 2009. It gradually intensified into a depression, and lay centered over southeast and east central Arabian Sea (about 70 km west of Amini Divi, Lakshadweep) on 9th November at 1430 h. It moved initially in a north-northwestward direction, recurved north-northeastwards, and intensified into a deep depression at 0830 h and a cyclonic storm ‘Phyan’ at 2330 h on 10th November 2009 (Figure 2). It crossed north Maharashtra coast off Mumbai at 1530 h on 11th November at 1530 h, weakened into a deep depression at 1730 h and further into a depression at 2330 h. The sustained maximum wind speed at the surface was about 22.5m/s on 11th November 2009.

Location for figures 1 and 2

3. Data used

Surface currents (speed and direction) were measured (10 minutes interval) at two nearshore locations (15m water depth) off Satpati and Worli along the Mumbai coast (Figure 1b) during 22nd October 2009 – 22nd November 2009 using Aanderaa Recording Current Meters (RCM 9 LW) (AADI, 2006). The RCM 9 LW has an accuracy of ± 0.15 cm/s for current speed and upto $\pm 7.5^\circ$ for direction. The current speed and direction have been converted into u (zonal) and v (meridional) velocity vectors. Simultaneously, water level off Satpati and Worli was measured using Sea Level Gauge, designed and developed by the National Institute of Oceanography (NIO), Goa.

Wind velocity vectors (u and v components) available at IFREMER/CERSAT were used for the hydrodynamic model simulations. These are QuikScat data (Ebuchi et al. 2002) blended to the operational ECMWF winds, available at $0.25^\circ \times 0.25^\circ$ spatial grids in every 6 hours and quality of this data was checked by validating with buoy winds (Bentamy et al. 2006).

4. Model setup and validation

Hydrodynamic model was setup to simulate flow pattern along the west coast of India (large domain) and off Mumbai (nested domain) using MIKE 21 HD – a two dimensional hydrodynamic model developed by DHI Water & Environment (DHI, 2008). This model has been used earlier to study the circulation characteristics of the Gulf of Kachchh, along the west coast of India (Vethamony et al. 2005; Babu et al. 2005). The large domain covers the region bounded by latitudes 7°N - 22° 32' N and longitudes 67° 12'E - 77° 21'E with 220 x 411 grids (rectangular), having a resolution of 5 km x 5 km in the X and Y directions, respectively (Figure 1a). The nested domain covers the Mumbai coastal region (18° 45' - 20° 12' N and 71° 59' E - 73° 07' E); 300 x 400 grids having a resolution of 500 m x 500 m (Figure 1b). The model bathymetry was generated using ETOPO 5 data obtained from the National Geophysical Data Center (NGDC, USA) for deep waters and digitized hydrographic chart data (Sindhu et al. 2007) for the nearshore regions.

Location for figures 3 and 4

The south, west and north boundaries of the large domain are kept open with an eastern land boundary (Figure 1a). The tidal elevations along the open boundaries have been predicted using the Global Tide Model (Andersen 1994; Andersen 1995; Andersen and Woodworth, 1995). These predicted tides have been applied as boundary conditions for model simulations. The time step (Δt) for the computation has been set to 60 s, which produces a Courant number of 2.56, and that satisfies the stability criteria of the model simulations. The IFREMER/CERSAT blended wind vectors were linearly interpolated to each grid (for both domains). The output parameters (fluxes, water levels and current velocities) were obtained for every 30 min. The tidal elevations simulated in the large domain have been validated with those predicted using tidal constituents provided by the International Hydrographic Bureau, Monaco (Anonymous 1930) at the standard Ports: Mumbai, Ratnagiri, Goa and Mangalore along the west coast of India. The tidal elevations simulated in the large domain and those predicted using tidal constituents at Mumbai, Ratnagiri, Goa and Mangalore show a good match (Figure 3), indicating that the model forced with GTM tides successfully reproduces tidal currents in the large domain.

The fluxes and levels at the boundaries of the small domain (Figure 1b) were transferred to the nested model to simulate currents off Mumbai. For the validation, water levels and current velocities (u and v velocities) simulated off Satpati and Worli were extracted and compared with measurements, and they compare very well (Figure 4). The scatterplot between measured and simulated current velocities (Figure 5) shows that the parameters are least scattered. The correlation coefficient, r.m.s. error and bias estimated for u -velocity are 0.63, 0.07 and 0.01, respectively off Satpati and 0.73, 0.10 and 0.00, respectively off

Worli, whereas those estimated for v-velocity are 0.89, 0.28 and 0.00, respectively off Satpati and 0.86, 0.17 and 0.04, respectively off Worli.. The low correlation coefficient for u-velocity could be due to the constraints in the model's west boundary, where the wind generated currents are not given as the boundary condition, hence it would have some influence on the zonal (east-west currents). Also, the zonal velocity component is much lower compared to the meridional component.

Location for figures 5 and 6

5. Results and discussion

The wind regime along the west coast of India during NE monsoon is composed of NE monsoon winds and local sea breeze from NW. It has been observed that during weak NE monsoon, the sea breeze becomes stronger and NW winds dominate (Figure 6). During the evolution of Phyan, the synoptic and local winds became very weak; the cyclone was centered about 120 km south of Worli. Normally, wind speeds at Worli and Satpati will be below 4.5 m/s during this period in the absence of any extreme weather event, and that also with the dominance of zonal component. However, during Phyan, the wind speeds reached upto 22.5 m/s with dominance of meridional component (v-velocity).

In general, currents and variations in water levels along the west coast of India are generated predominantly by tides, followed by residual effects. The residual variations are due to winds and remote forcing (Shetye et al. 2008). However, during this period, the residuals obtained from the measurements provide no indication of remote forcing. During NE monsoon season, wind has very minor role in causing water level variations or influencing the current system along the west coast of India. On the other hand, the situation was different when the cyclone Phyan approached the Mumbai coast: a fall in water level, of the order of -20 cm (on 10th November) and a rise in level of the order of +20 cm (on 11th Nov) were observed (Figures 7a and 7b). The change in wind direction during different phases of Phyan made positive and negative surges in this region. Strong winds parallel to the shore, where the shore is to the right of the wind flow cause positive surges, and where the shore is to the left of the flow cause negative storm surges (Neil 1981).

The diurnal variation in the winds (land - sea breeze system) leads to significant changes in the coastal currents off Mumbai coastal region, apart from tidal currents. The analysis of measured currents off Mumbai show diurnal variation, which is evident from the residual of the zonal currents (Figures 7c and 7d). This is due to the impact of sea breeze, which generates an eastward current when it is active. When the sea breeze weakens, the eastward current gradually diminishes and reverts back to the normal conditions, and currents generated by the seasonal winds (NE monsoon) flow westward. It was found that

the diurnal patterns were absent during the passage of cyclone and retained after the cyclone. Significant changes were observed in the meridional component of the currents off Worli and Satpati during Phyan. Those variations are higher off Worli, as this location is relatively closer to the Phyan track.

Location for figures 7 and 8

In general, the currents off Mumbai are tide dominated, and flow towards NE while flooding and SW while ebbing (Figures 8a and 8b), and very close to the coast the currents are northerly and southerly while flooding and ebbing, respectively. However, when the NE monsoon winds are stronger or a cyclone occurs, we do find change in the current pattern. For example, NE wind causes a reduction in flow magnitude while flooding since the wind generated current opposes the tidal flow. Further, an increase in current speed is observed while ebbing as the currents generated by winds and tides are in the same direction (Figures 8c and 8d). This indicates that the NE monsoon winds enhance the ebb flow and reduce the flood flow. When the sea breeze is active, an eastward flow towards the coast is observed and this causes diurnal variations in the residual currents.

At the initial stage of the cyclone (09-10th Nov), the meridional component of the cyclone generated currents off Worli was towards south. This reduced the net northward flow by 0.2 m/s while flooding and enhanced the net southward flow by 0.12 m/s while ebbing. Subsequently, during 11-12th Nov, when there was a northward shift in the cyclone, the cyclone generated currents enhanced the net northward flow by 0.3 m/s while flooding, and reduced the southward flow by 0.35 m/s while ebbing. The meridional component of the cyclone generated currents off Satpati (Figure 7f) was initially towards north and later (after 12 h) shifted towards south. This shift in the cyclone direction occurred between two consecutive flooding and thereby, altered the current pattern. Initially, the cyclone generated currents enhanced the net flow with an increase of 0.16 m/s for the first flood and later reduced by 0.2 m/s for the second flood. When Phyan developed, a strong current system associated with an anti-cyclonic eddy was formed off Mangalore, south west coast of India. As the cyclone progressed, the eddy moved northward upto off Ratnagiri region, and disappeared when the cyclone moved towards the land.

The spatial variations in water levels and currents off Worli and Satpati are also significant during cyclone Phyan. The water levels simulated at locations W1, W2 and W3 and S1, S2 and S3 (locations are marked in Figure 8a) are shown in Figures 9a and 9d. Water level differences of the order of 0.38 m and 0.44 m have been obtained between W3 and W1 and between S3 and S1, respectively. The large difference in water level off Satpati is due to wider continental shelf compared to the same off Worli. The continental shelf at the southern tip of the Mumbai region is narrow and increases significantly while moving towards

the north. The northern part is characterized by Gulf of Khambhat - a semi-enclosed basin, where the tidal range increases significantly towards the upstream (Unnikrishnan 2010).

Similar to water levels, the meridional component of the currents was highly influenced by Phyan. During normal conditions, the northward (flood) and southward (ebb) flows are stronger when we move towards the coast. However, during Phyan, the southward flow was stronger at locations W2 and W3, compared to W1 since the winds were relatively weak closer to the coast (Figure 9c). Hence, a strong southward flow is obtained at an area approximately 50 km away from the coast of Worli (W2). Due to the effect of strong southward flow, a flood current during 11th November 2009 (10 – 17 h) disappeared at the locations W2 and W3, whereas it was present at W1 with low magnitude (Figure 9c). The intensity has reduced further while moving towards north. A maximum difference of 0.4 m/s in the meridional component of the currents was observed between W2 and W1. Off Satpati also, the strong southward flow during Phyan was observed between S1 and S2 compared to S3 (Figure 9f). The flood current during 11th November 2009 mentioned above was completely absent off Satpati also. Here again, a difference of 0.21 m/s in the meridional component of currents off Satpati was observed between S2 and S3.

Location for figure 9

In general, the eastward and westward flows (zonal components) are nearly the same in magnitude at all the locations off Worli. However, during Phyan the westward flow (ebb) decreased while moving away from the coast and the minimum flow is observed at W3 (Figure 9b). The maximum difference in magnitude of the westward flow between W1 and W3 during Phyan was 0.14 m/s. Surprisingly, it was found that during a particular ebb period (15– 22 h of 11th November 2009), the westward flow at W3 was nearly zero. This indicates that zonal component of the cyclone generated currents was towards east, which significantly reduced the westward ebb flow, and enhanced the eastward flood flow. Off Satpati, both eastward and westward flows decrease towards the coast during normal conditions (Figure 9e). However, during the cyclone the eastward flow was nearly the same at all locations and the westward flow increases while moving away from the coast (Figure 9d). It was found that the maximum difference in westward flow between S1 and S3 during normal conditions was 0.19 m/s, and, it was 0.32 m/s during Phyan.

4. Conclusions

Coastal circulation and surges during the cyclone Phyan have been analyzed using measurements and numerical simulations. Studies on water level variation and coastal circulation during extreme weather events along the west coast of India are very limited, and the results discussed in the present study provide

a potential evaluation of oceanic phenomenon during such events. The observed negative and positive surges as well as considerable enhancement and reduction in the net flow off Mumbai in accordance with the passage of cyclone is very important to plan the coastal activities along the Mumbai coast. Since, the cyclone occurred during the NE monsoon season, the associated diurnal pattern in the currents disappeared during the passage of Phyan and was retained after the cyclone.

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Figure captions

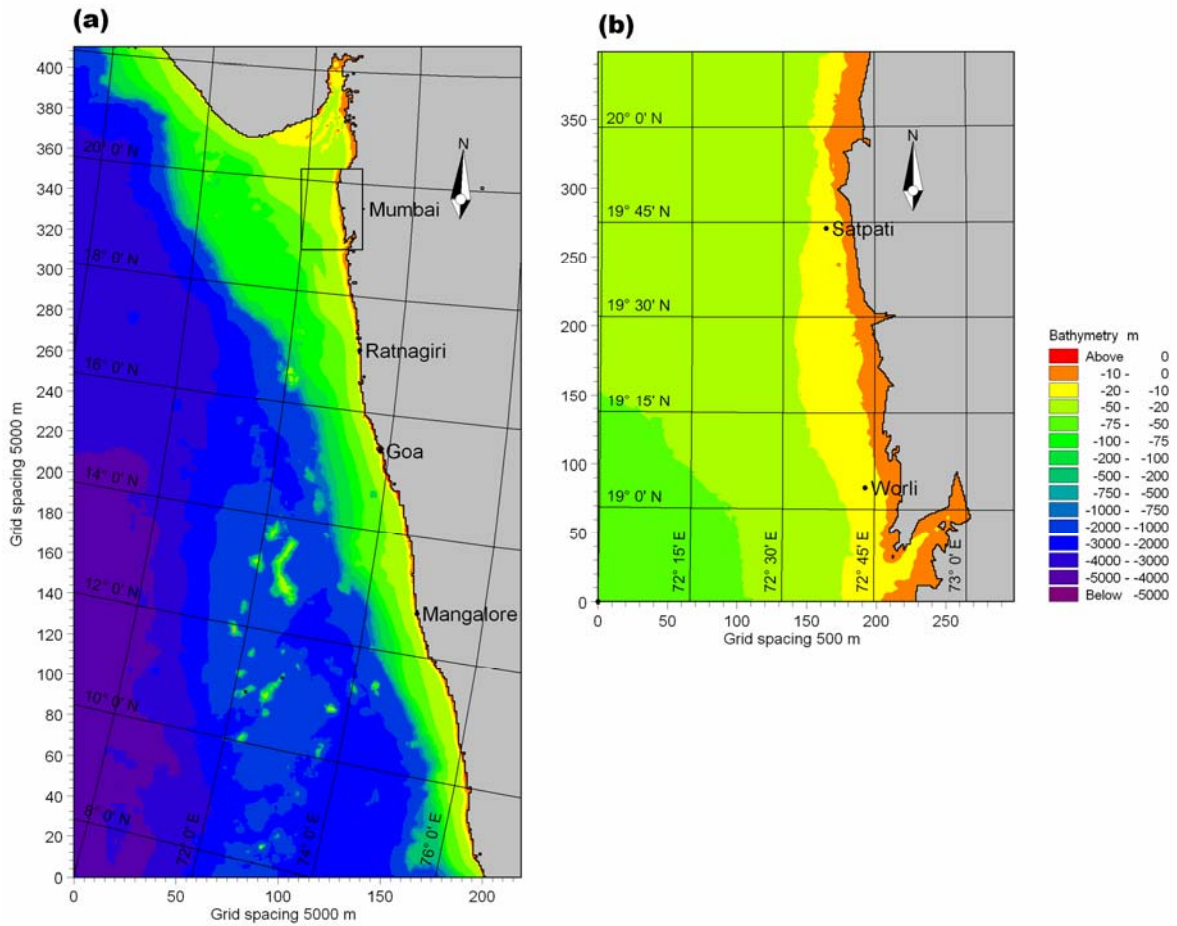


Figure 1. (a) Large domain for the west coast of India and (b) nested small domain for the Mumbai coast. Measurement locations (Worli and Satpati) are marked in the small domain.

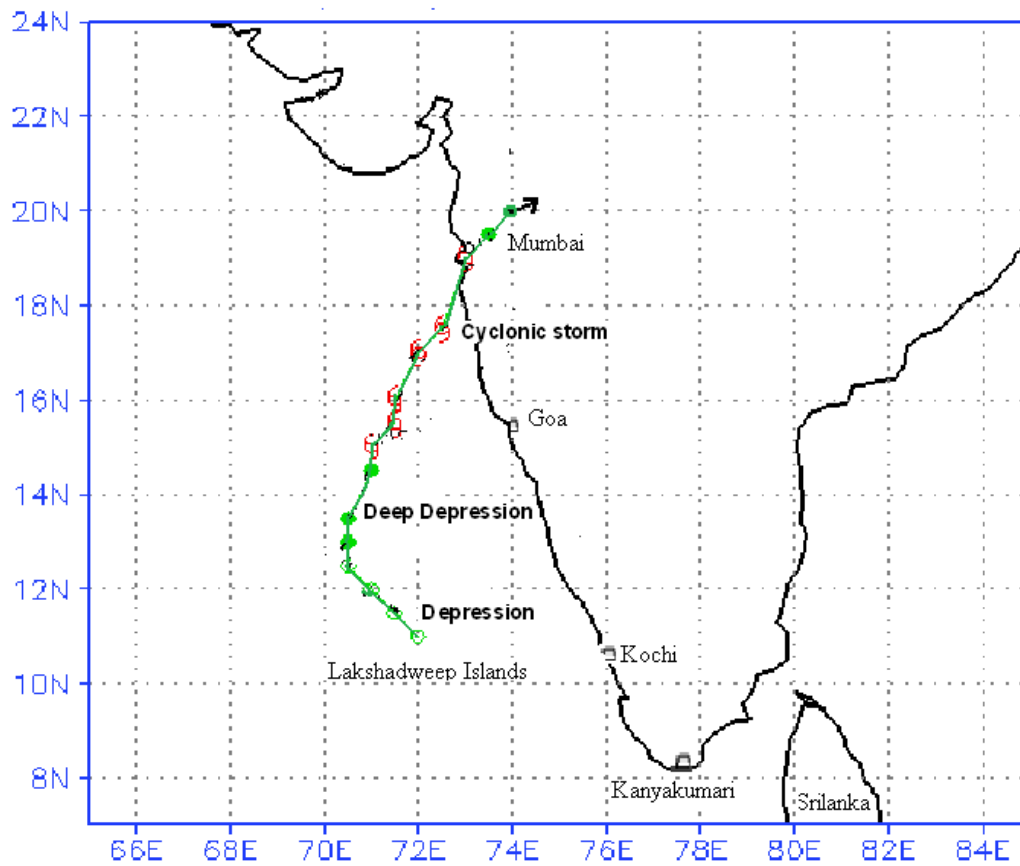


Figure 2. Track of the cyclone Phyan (courtesy: India Meteorological Department).

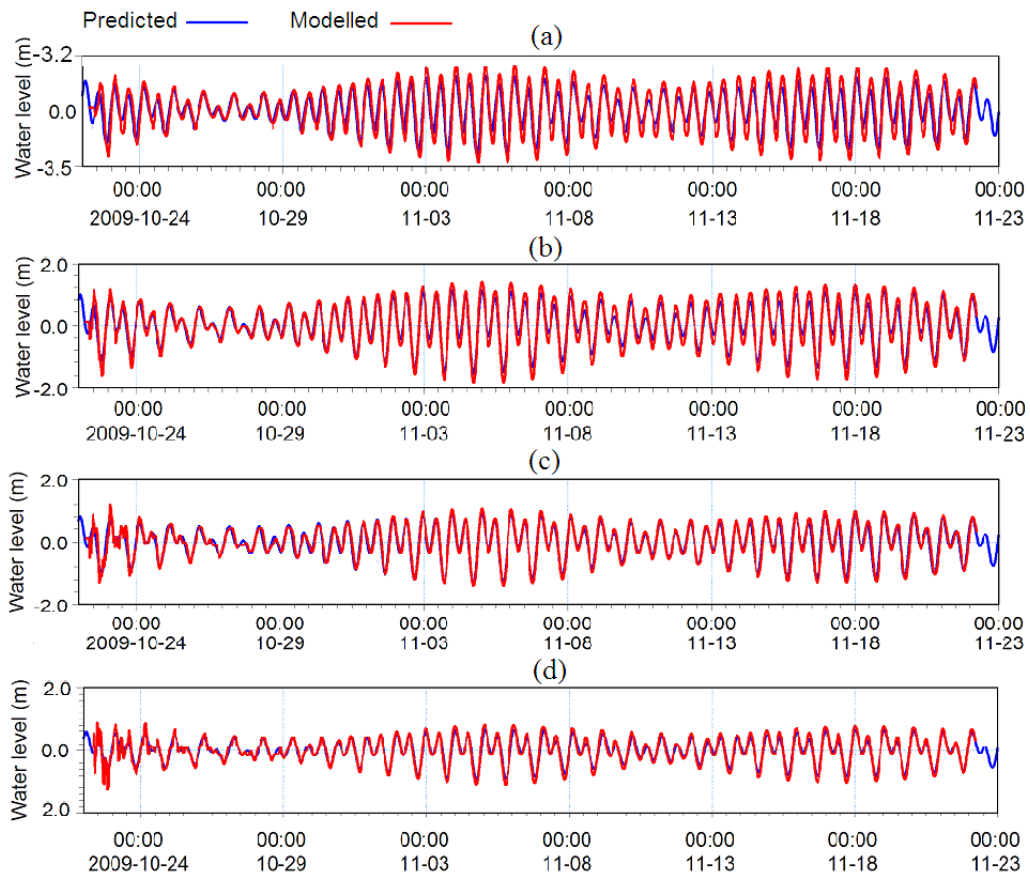


Figure 3. Comparison between predicted (using tidal constituents) and simulated (in the large domain) tidal elevations off (a) Mumbai, (b) Ratnagiri, (c) Goa and (d) Mangalore

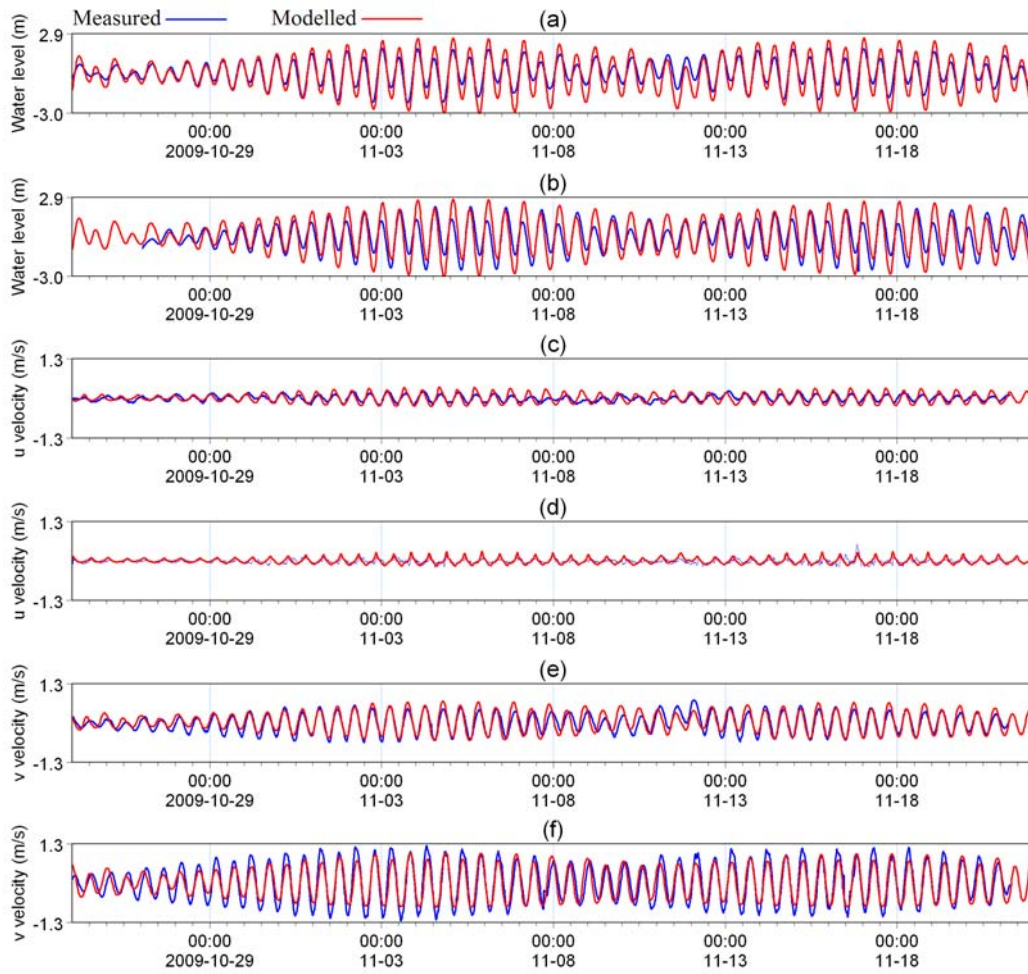


Figure 4. Comparison between measured and modelled water levels and currents: (a) water levels off Worli, (b) water levels off Satpati, (c) u-velocity off Worli, (d) u-velocity off Satpati, (e) v-velocity off Worli and (f) v-velocity off Satpati.

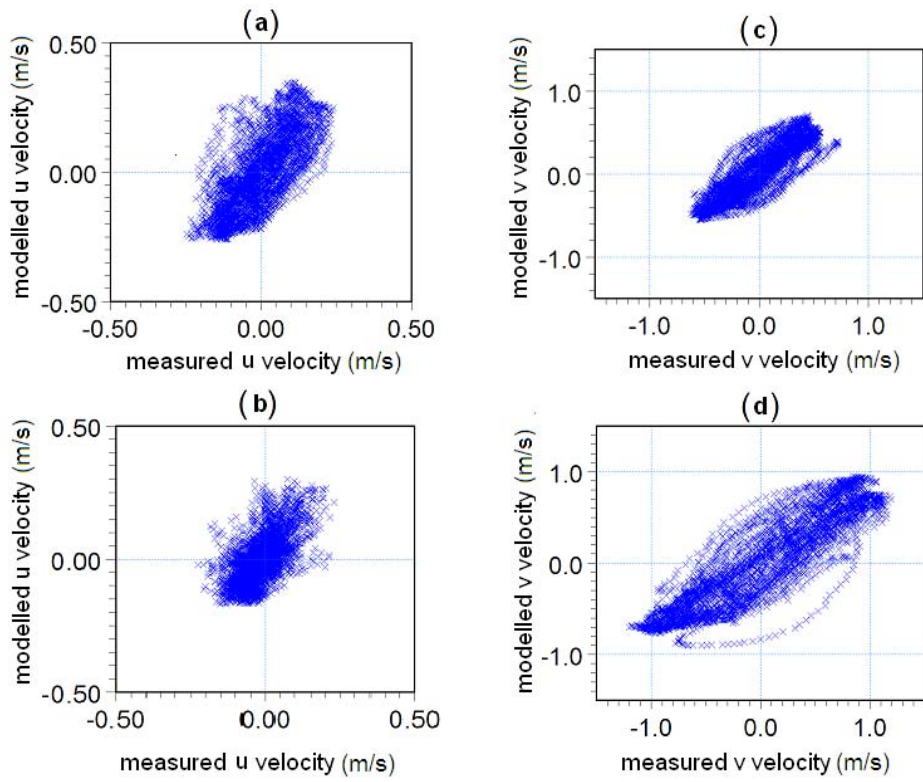


Figure 5. Scatter of measured and modelled current velocities: (a) u-velocity off Satpati, (b) u-velocity off Worli (c) v-velocity off Satpati and (d) v-velocity off Worli.

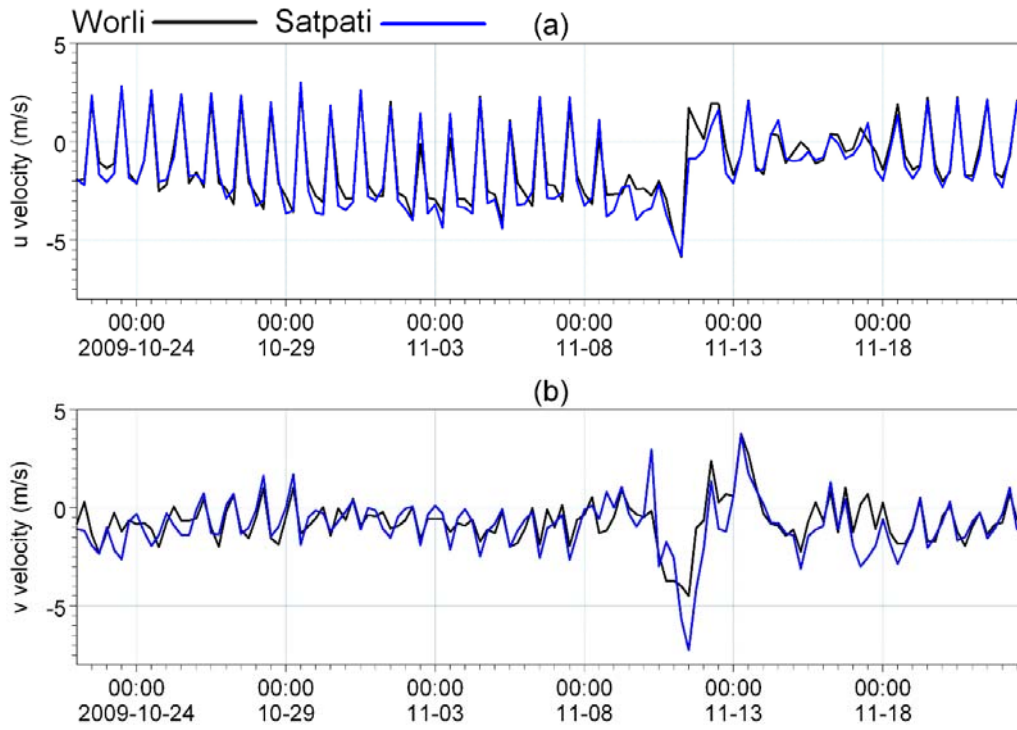


Figure 6. IFREMER/CERSAT blended wind speeds off Worli and Satpati: (a) u-velocity and (b) v-velocity.

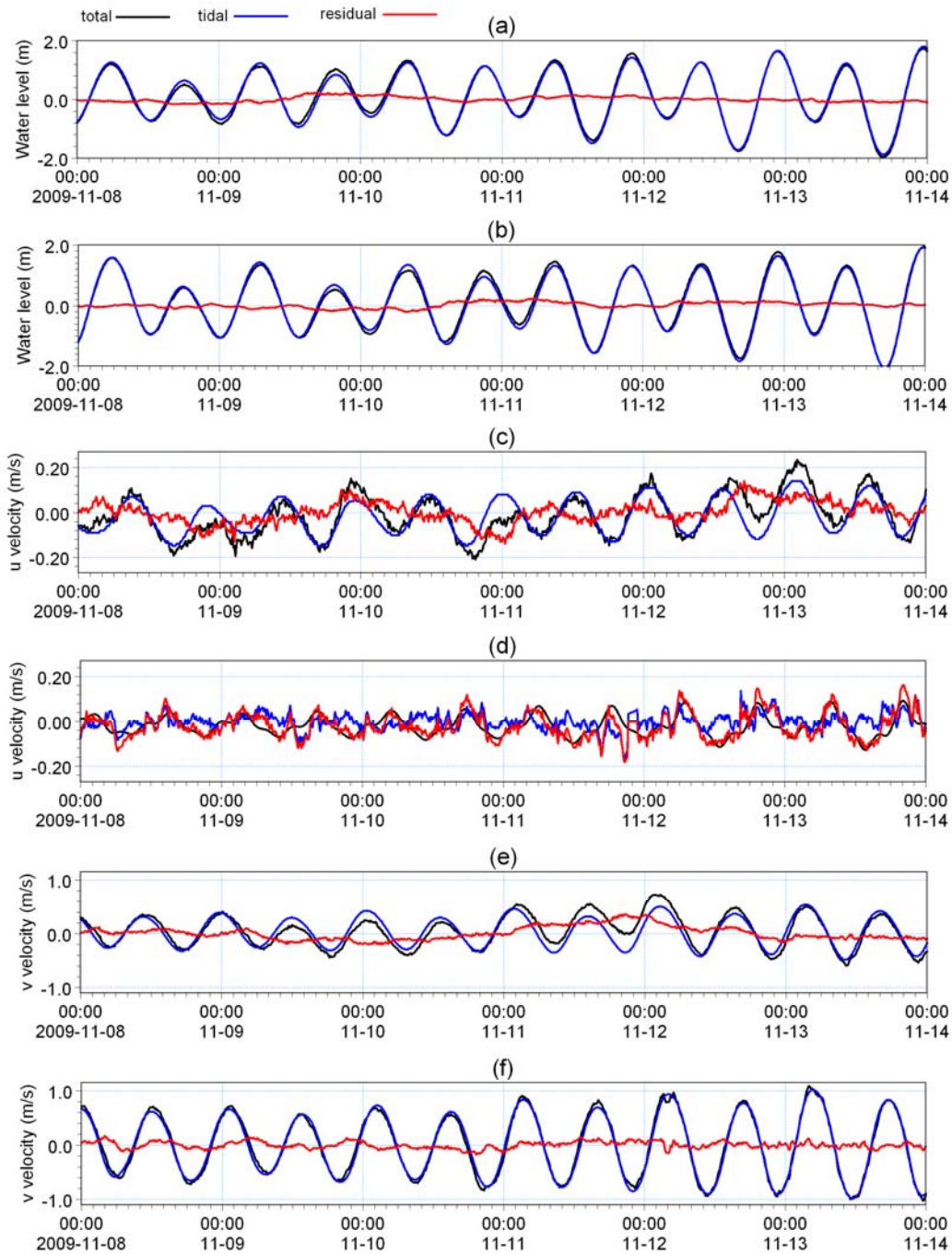


Figure 7. Total, tidal and residual water levels and current velocities measured off Mumbai: (a) water levels off Worli, (b) water levels off Satpati, (c) u-velocity off Worli, (d) u-velocity off Satpati, (e) v-velocity off Worli and (f) v-velocity off Satpati.

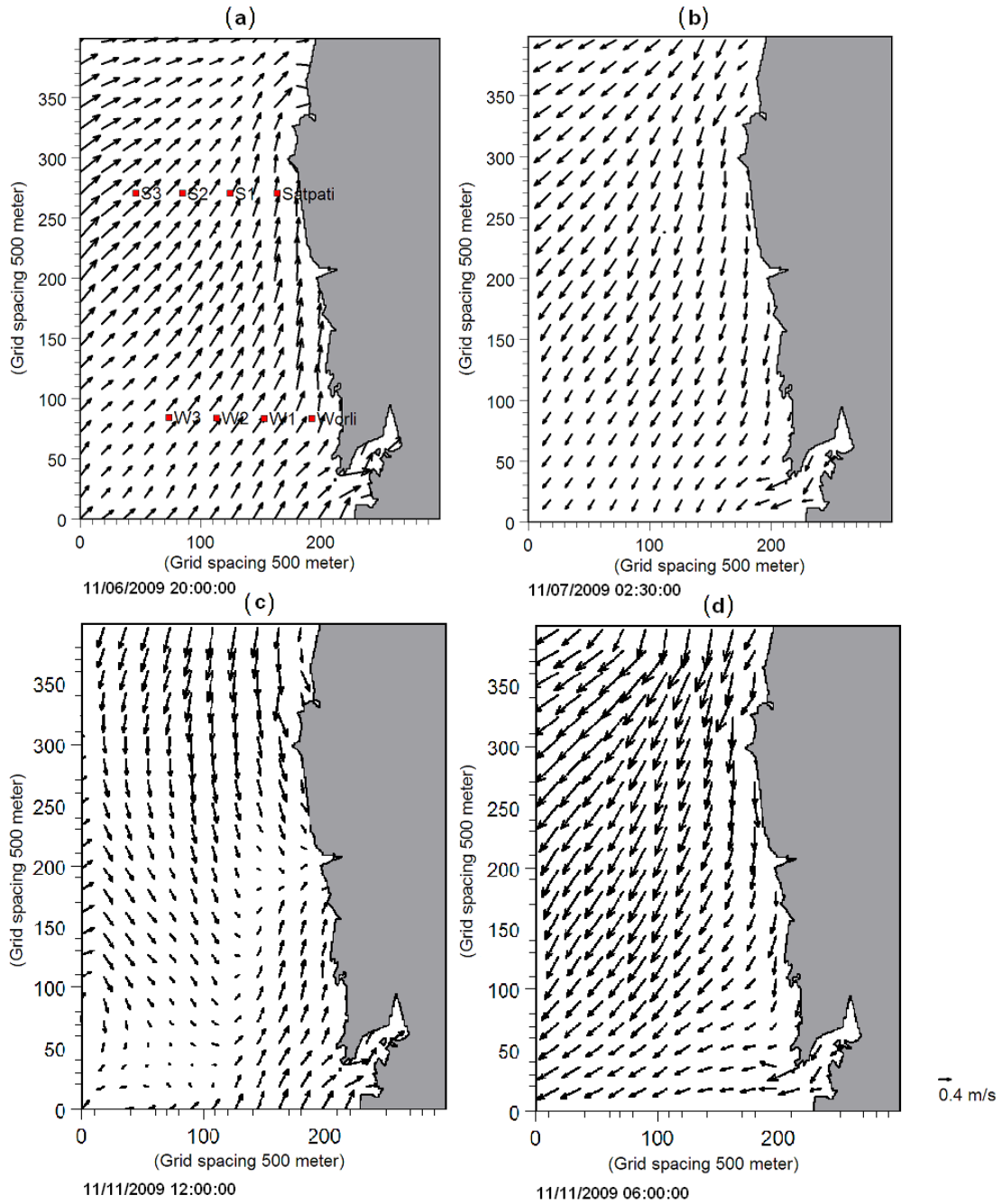


Figure 8. Current vectors off Mumbai: (a) flood during NE monsoon, (b) ebb during NE monsoon, (c) flood during Phyan and (d) ebb during Phyan.

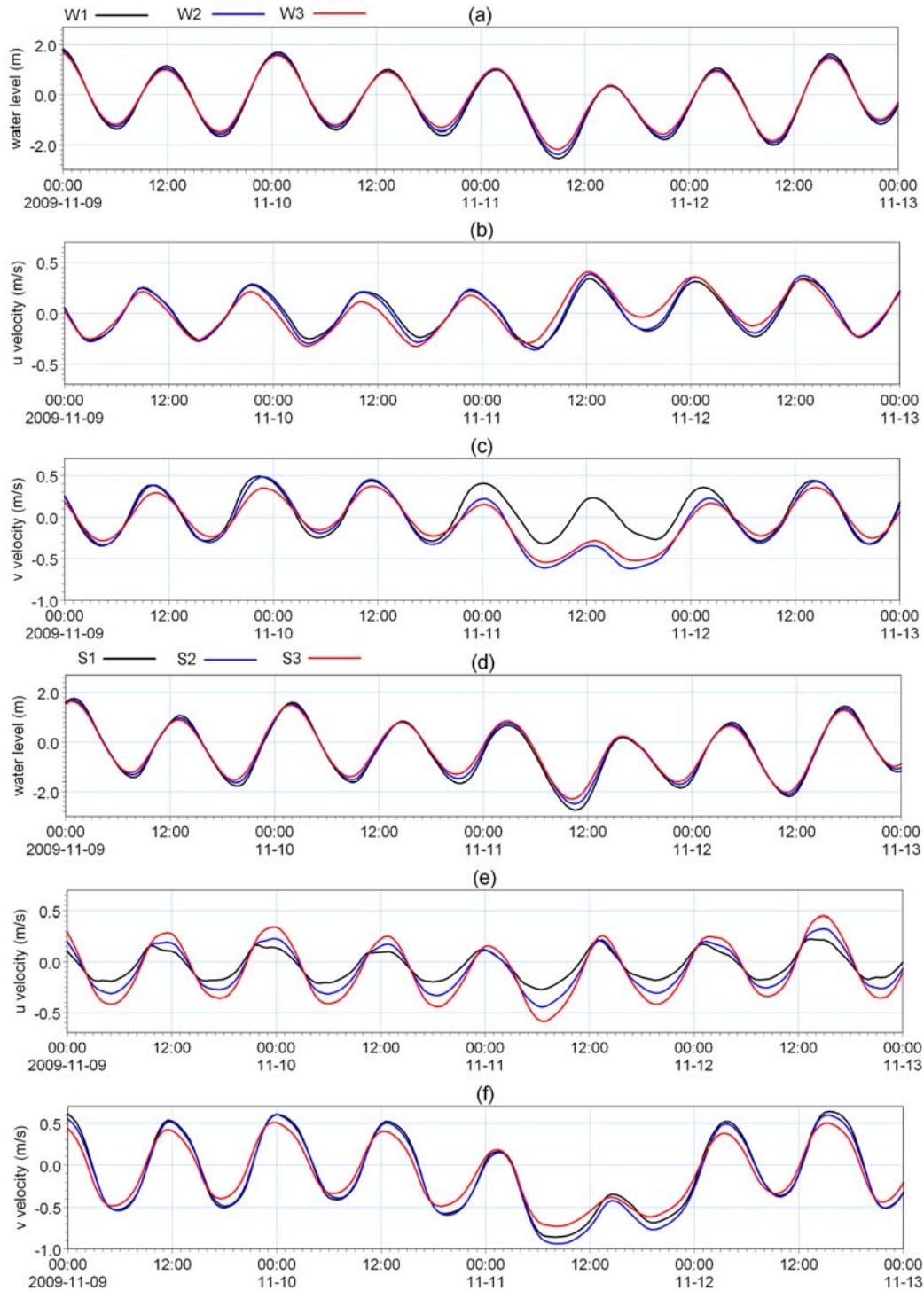


Figure 9. Water levels and zonal and meridional components of currents simulated at different locations off Worli (W1, W2 and W3) and Satpati (S1, S2 and S3): (a) water levels off Worli, (b) water levels off Satpati, (c) u-velocity off Worli, (d) v-velocity off Worli, (e) u-velocity off Satpati and (f) v-velocity off Satpati.