Oil spill trajectory prediction at proposed Vadhavan port and assessing the probable spread and drift towards Tarapur Atomic Power Station (TAPS) on hypothetical basis

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Abbreviations

DSL: Demeaned Sea Level

ESSO : Earth System Science Organization

GNOME: General National Oceanic and Atmospheric Administration Operational Modeling Environment

HSL: Hypothetical Spill Location (19.9343° N, 72.5389° E)

IHROM: INCOIS High Resolution Ocean Model

ILROM: INCOIS Low Resolution Ocean Model

INCOIS : Indian National Centre for Ocean Information Services

IOSTPS : INCOIS Oil Spill Trajectory Prediction System

JNPT: Jawaharlal Nehru Port Trust

OGCM: Ocean General Circulation Model

RMSE : Root Mean Square Error

TAPS: Tarapur Atomic Power Station

WC: West Coast

Abstract

Development of a new modern all weather deep draft port is proposed by the Government of India at Vadhavan site (located at Palghar district of Maharashtra state). According to techno economic feasibility studies this is a suitable site. Tarapur Atomic Power Station (TAPS) is just 12 km far in the south. TAPS is currently operational and all the four units are feeded with sea water using two intake channels and two outfall channels. A study was carried out by INCOIS as per the request from JNPT, to assess, whether any accidental oil spillage within the proposed Vadhavan port limit can affect the intake and outfall zone of TAPS. A Hypothetical Spill Location (HSL) was chosen (19.9343ºN, 72.5389ºE) within the port limit. INCOIS Oil Spill Trajectory Prediction System with GNOME was set for the study region with a known quantity (700 Tons) of Fuel oil. The trajectory model was forced with high resolution ocean currents and wind fields. After the analysis and validation of the input forcing parameters, the trajectory model was used to generate the oil spill trajectory pattern during spring and neap tide days of the year 2017. The drift pattern was generated upto 54 hrs after the spillage in each case. It was observed from the hypothetical simulation, that, the intake and outfall zones of TAPS are affected during certain instances. Based on this hypothetical study (during 2017), the spilled oil from the HSL should be contained within 18 to 36 hrs, so that the intake and outfall zones of TAPS will not get affected. However, in case of accidental oil spills, within the port limit, the drift pattern has to be simulated on nowcast and forecast basis using oil spill trajectory prediction models.

1. Introduction

With the ever increasing marine traffic it became necessary for expansion and updation of the major ports in India. The new generation cargo liners are demanding more berth length and more channel depth for smooth operation. Deepening and widening of the main harbor channel & Jawaharlal Nehru (JN) Port channel was attempted to facilitate cargo ships to enter with a draft of 14.0 meters. It is not economical to increase draft beyond 15.0 meters in JN port as well as further development and expansion of the port are constrained by natural and topographical limitations. To fulfill the requirement of the main line container ships and other large bulk carriers having draft of 17.0 - 18.0 meters, Jawaharlal Nehru Port Trust (JNPT) Management and the administrative Ministry of Shipping, Govt. of India have come to a conclusion to develop a new port on the Maharashtra coast in the hinterland region of JNPT, where deeper depth of 20 meters closer to coastline is available. Based on pre feasibility and techno economic feasibility studies, Vadhavan site in Dahanu Taluka, Palghar district of Maharashtra state, open coast facing the Arabian Sea, has been chosen for development of a new modern all weather deep draft port. The proposed boundary of the proposed port is as follows:

"A line drawn from the coast at

Point A: Lat 19° 54' 26" N, Lon 72° 40' 34" E along the coast northward to

Point B: Lat 19°57' 59" N, Lon 72°42'18" E including banks and shores upto high-water-marks and creeks within the line as far as navigable and into the sea westward to

Point C: Lat 20°0' 0" N, Lon 72°30'0" E then southward to

Point D: Lat 19° 54' 5" N, Lon 72°30' 0" E and back to coordinate (A) on the coast."

The port limit extends up to bathymetry of 26 meters in the deeper western part and having an area of 170 Square-Kilometer. The operational Tarapur Atomic Power Station (TAPS) is approximately 12 km in the south direction. The proposed port limit and the location of TAPS is shown in Fig. 1. There are currently four units running in TAPS and there are two water intake channels and two outfall channels stretching into the ocean. Now Jawaharlal Nehru Port Trust has been directed by the Ministry of Shipping, as per suggestion of the Department of Atomic Energy to investigate the effect of oil spill, by doing the trajectory prediction of spilled oil, in case of an unfortunate incident within the proposed port limit, to know whether the intake and outfall zone of TAPS will get affected or not.

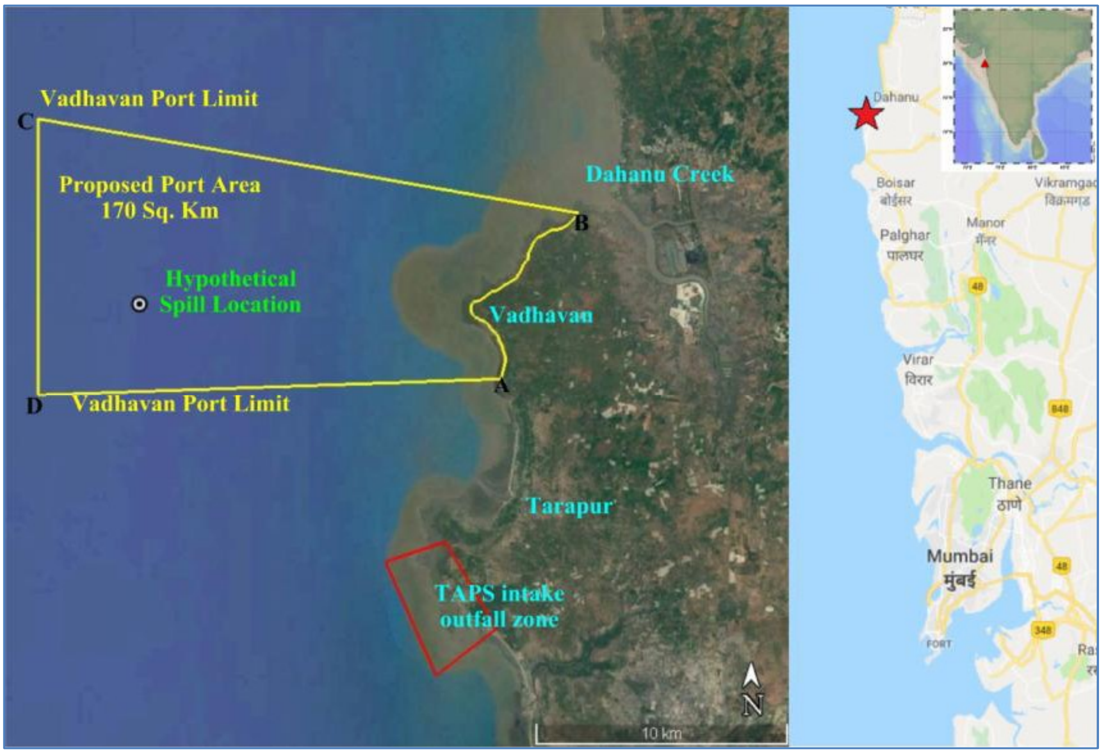


Fig. 01. Location of the proposed Vadhavan Port and operational Tarapur Atomic Power Station (TAPS).

2. Objective of the study

As per the request from JNPT, INCOIS proposed an oil spill trajectory prediction study to assess, whether the intake and outfall zone of TAPS will get affected, in case of any accidental oil spillage within the proposed Vadhavan port limit. The sub tasks identified to carry out the oil spill trajectory prediction study are as follows:

- Generation of Spatio - temporal gridded datasets of Met-ocean parameters such as atmospheric winds and ocean currents for the study region.
- Validating the tidal cycles generated by the Ocean General Circulation Model, for the time frame of this study.

- Setting up the oil spill trajectory model using INCOIS oil spill trajectory prediction system for the study region.
- Generation of trajectory (drift) patterns, from the Hypothetical Spill Location (19.9343° N, 72.5389° E) which is within the port limit during spring and neap tidal cycles of the year 2017.
- To assess, whether the hypothetical spills within the proposed port limit will affect the intake and outfall zone of TAPS.

3. Generation of Spatio-temporal met-ocean parameters

3.1 Extraction of wind fields

The modeled daily atmospheric wind velocity fields are obtained from INCOIS-Ocean State Forecast laboratory. The wind velocity parameters are extracted for the study region (here West Coast of India). The wind -rose plot is generated at the HSL to study the intra-annual variability of surface winds during the year 2017. Fig 02 represents the month wise rose plot of wind fields at the hypothetical spill location for the year 2017. The wind pattern varied, significantly during the Indian summer monsoon i.e during June, July, August and September (JJAS) period.

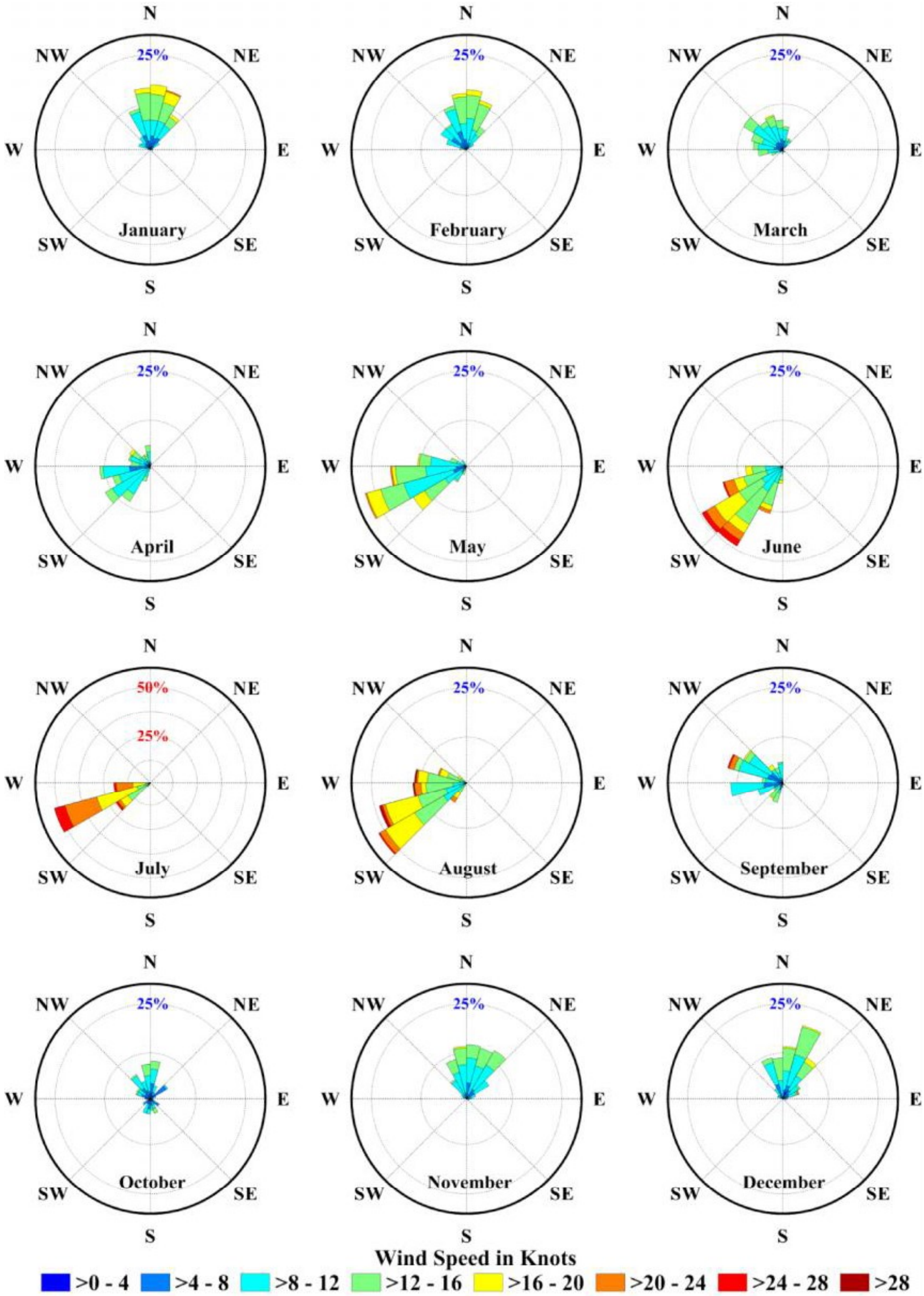


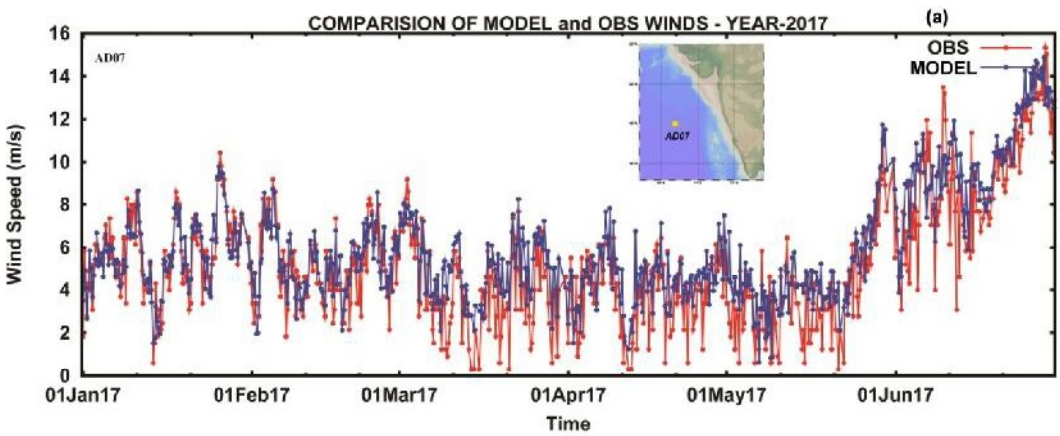
Fig. 02. Month wise wind rose plot of winds at HSL for 2017. Note the difference in scale during the month of July. Meteorological convention is followed representing the "from" direction of wind.

Intra- annual variation in the wind speed and direction (Fig. 02.) at the HSL during various seasons of the year 2017 is noted. During Jan -Feb, the winds are Northerly. North-westerly winds are noted during March. During April -May, winds are West-Southwesterly. During June -August, South-westerly winds are noticed. West- North-westerly winds prevailed during September. During October - December, Northerly winds prevailed.

3.2. Wind field validation using Moored buoy

Wind fields were compared with that of INCOIS - Real Time Automatic Weather Station (IRAWS) mounted on board ships and found to have lesser Root Mean Square Error, RMSE *(Harikumar et al. 2012).* Further, the wind fields of 2017 were validated with that of INCOIS Moored buoy AD07 (66.89° E, 14.98° N).

Fig. 03(a,b). shows the time series plot of simulated and observed wind velocity fields. The statistical parameters of this validation are also shown in *Table 1.*



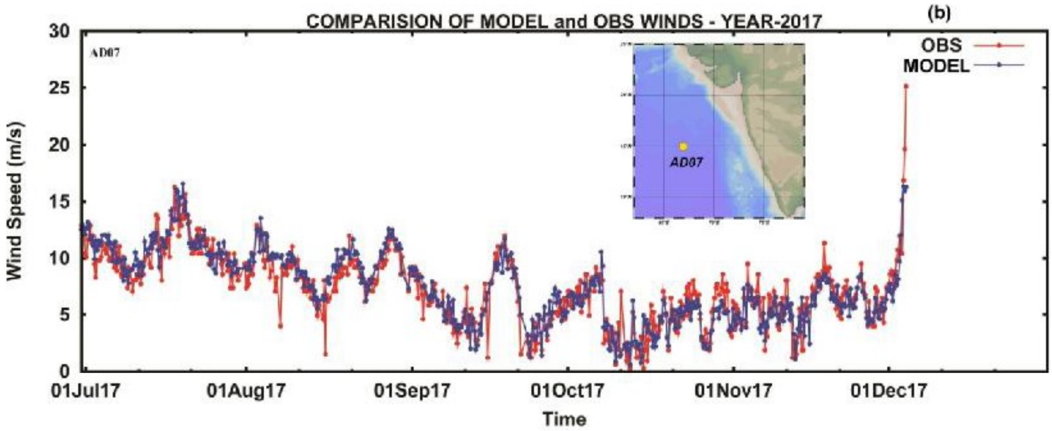


Fig.03(a,b): Comparison of wind speed obtained from Moored buoy (AD07) and model during Year 2017. The inner panel figure shows the location of AD07.

Table 01: Statistical comparison of wind speed obtained from Moored buoy (AD07) and model during Year 2017.

Location	N	MEAN (ms^{-1})		RMSE (ms^{-1})	BIAS (ms^{-1})	Correl Coeff.
		OBS	MODEL			
AD07 (66.89º E, 14.98º N)	1250	6.25	6.65	1.35	0.4	0.90

3.3 Generation of Ocean currents

Ocean circulation pattern is generated by Ocean General Circulation Model of INCOIS, which is a free surface, terrain following model that solves a set of primitive equations in an orthogonal curvilinear coordinate system in the horizontal direction and stretched terrain following sigma coordinates in the vertical direction.

INCOIS has set up a Low Resolution Ocean Model (ILROM) for simulating ocean state parameters in the Indian Ocean basin. To perform better simulation in the Arabian Sea region, INCOIS has set up a High Resolution Ocean Model (IHROM) in high horizontal resolution and is currently used to simulate ocean state parameters for the west coast on operational basis. It has been setup to improve the prediction skills of coastal features, particularly the coastal circulation. This is an improved setup of a well validated model, published in peer reviewed scientific journal *(Francis et al, 2013).* The configuration details can be found in technical document *[No.ESSO/INCOIS/ISG/TR/01(2017)]* which is available for ready reference. Especially for this Vadhavan study, IHROM was set for the spatial resolution of $1/48^0$ (~2.23 km) in horizontal and 40 sigma levels in vertical. The temporal resolution of the IHROM has been increased six folds from 06 hrs to 01 hr. The IHROM model is run for the period of January 2017 to December 2017 for generating the tide incorporated ocean currents. The vertical stretching parameters are chosen such that the vertical resolution is highest in the upper part of the ocean. The south and west boundaries of the IHROM setup is open and nudged to the daily-averaged values obtained from a relatively low resolution (9 Km) basin-scale model (ILROM). For realistic tide simulation,10 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, Mf and Mm) derived from the TPXO 7.0 global tidal model *(Egbert and Erofeeva, 2002)* are used in this setup. The domain of the present setup is 65^0 E - 77.5^0 E & 08^0 N - 25.5^0 N and is shown in *Fig. 04.*

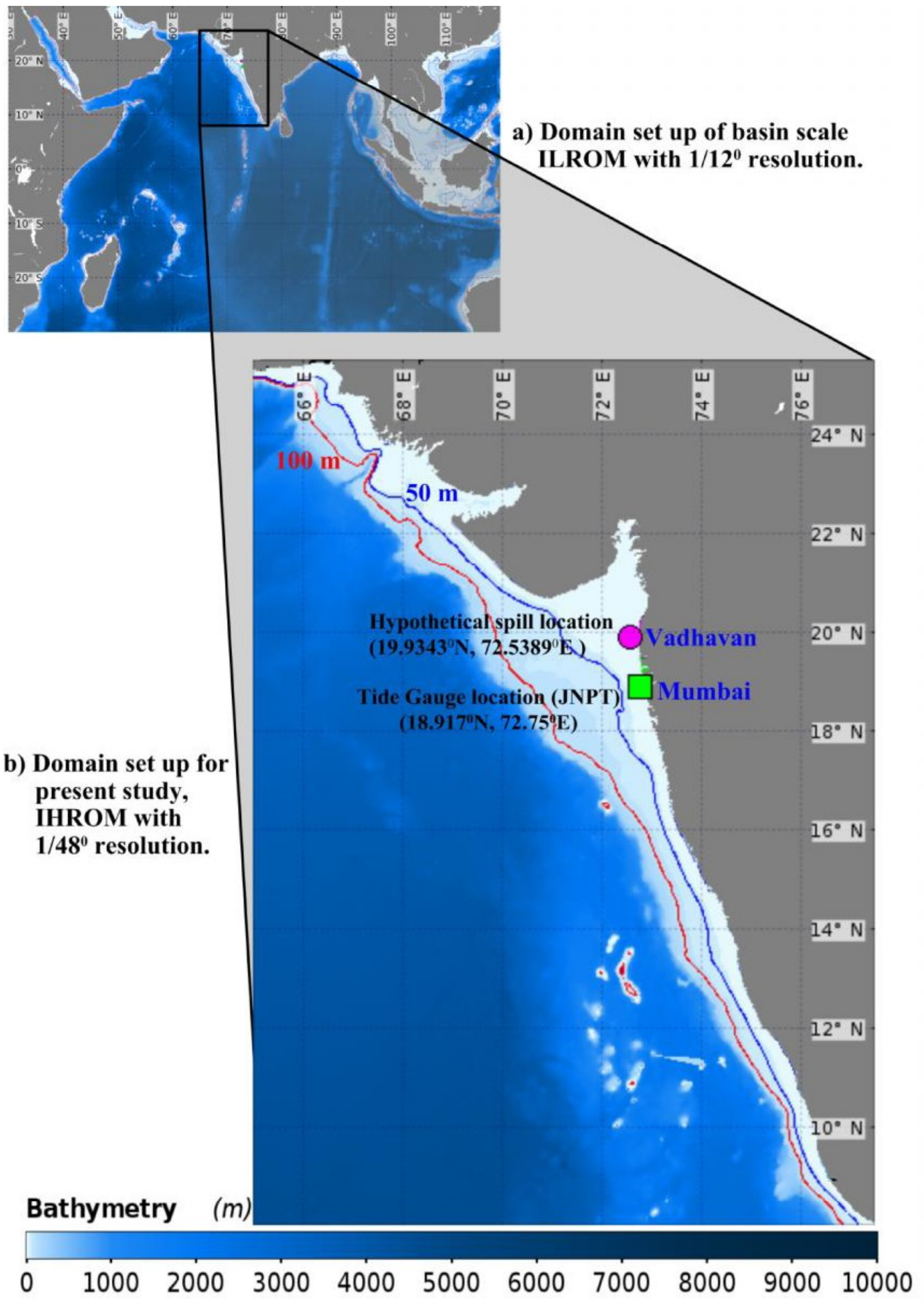


Fig. 04. a) Domain of ILROM and b) domain of IHROM used in this study. Modified etopo2 ocean bathymetry is used in this study.

3.4. Validation of demeaned sea level using tide gauge data

To evaluate the performance of IHROM generated ocean currents during the tidal cycles, the modeled Demeaned Sea Level (DSL) was compared with that of the INCOIS mounted tide gauge station at JNPT. A typical modern tide gauge station (*Fig. 05.*) contains 3 types of sensor for sea level measurement a) Pressure Gauge b) Acoustic Sensor c) RADAR Sensor. RADAR sensors are well validated, well accepted as per the Global Sea Level Observing System (GLOSS) guideline and have less error fluctuations *(Miguez et al., 2012)* and are remotely sensed.

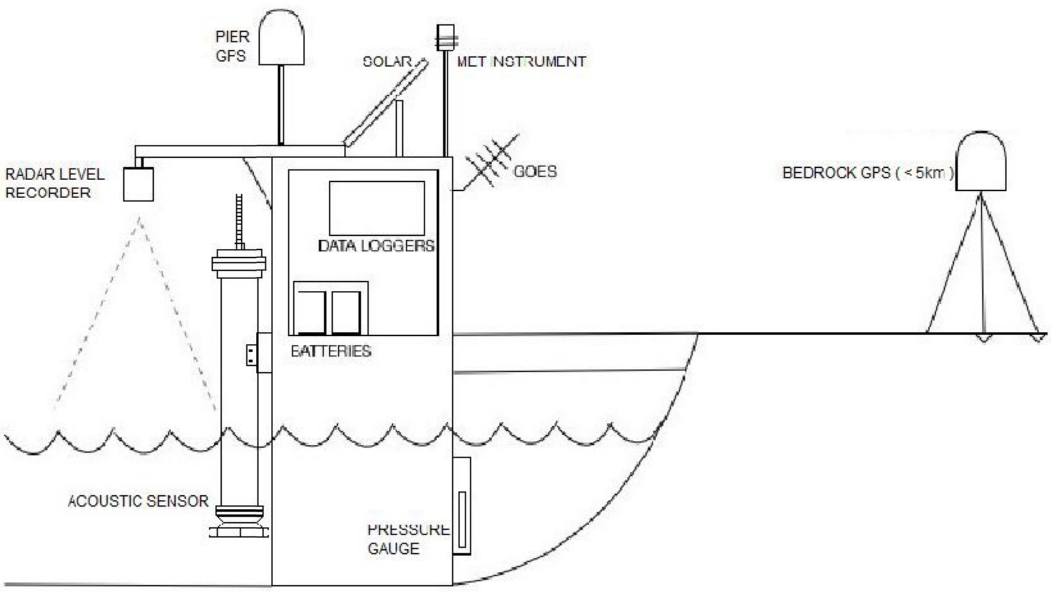


Fig. 05. Schematic of a typical tide gauge station.

As a component for monitoring Tsunamis, storm surges and supporting navigational requirement of ports, INCOIS set up a tide gauge station to study the diurnal variation in the sea level near JNPT at 72.75° E, 18.917° N. This station also records data using these three types of sensors. Three sets of Demeaned Sea Level (DSL) data were compared as shown in *Fig. 06.* The correlation coefficient and slope of linear fit equation between them was found to be very close to 1. *Fig. 06.* can be referred for correlation coefficient values between Acoustic Sensor & RADAR Sensor data (0.998) and between Pressure Gauge & Radar Sensor data (0.997) and also for the coefficients of linear fit.

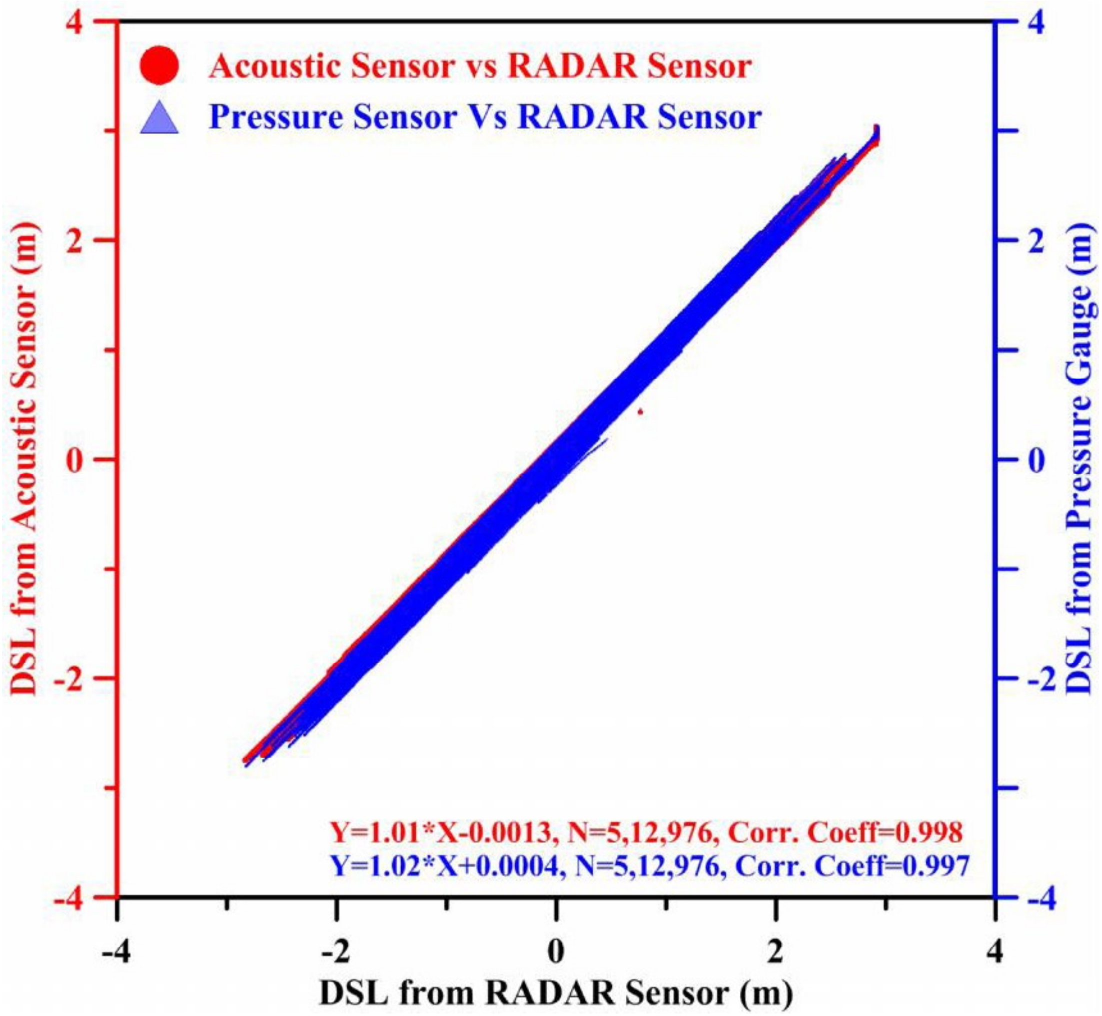


Fig. 06. Comparison of DSL between RADAR, Acoustic & Pressure Sensors of the INCOIS mounted JNPT tide gauge station for the year 2017. DSL estimated for every minute is used for the comparison

During final validation RADAR sensor data was used, and henceforth in-situ tide gauge data will be referred to the RADAR sensor data only. Model simulated DSL was validated using the tide gauge recorded DSL data. The evaluation was carried out specially for this project during the period 0000hrs of 01-Jan -2017 to 2300 hrs of 31- Dec -2017. Monthly time series charts are presented on hourly basis to compare the model simulated and in-situ recorded DSL. They are shown in the following figures (*Fig. 07-10.*).

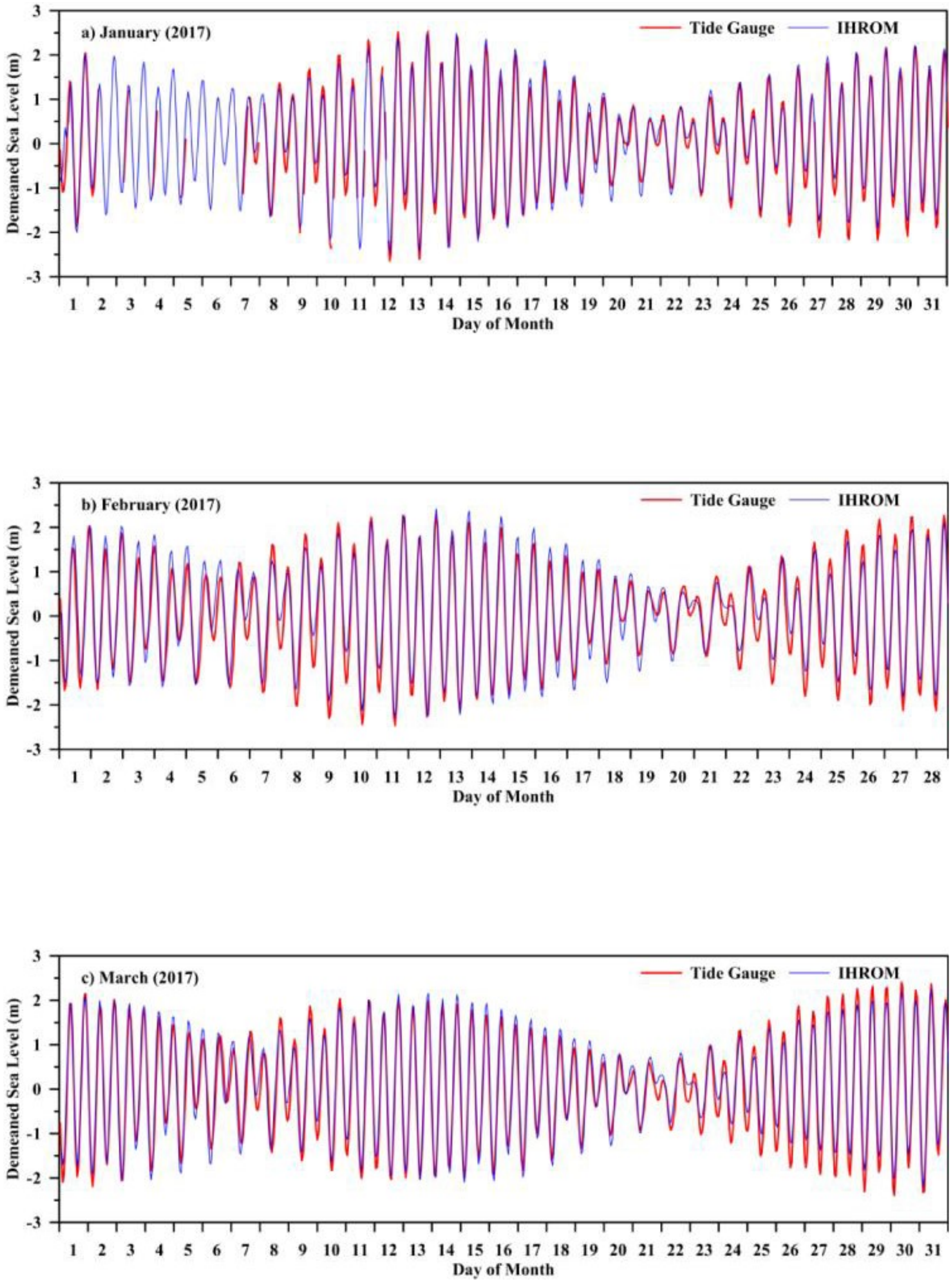


Fig. 07. Comparison between IHROM simulated DSL with that of JNPT tide gauge for January, February and March of 2017.

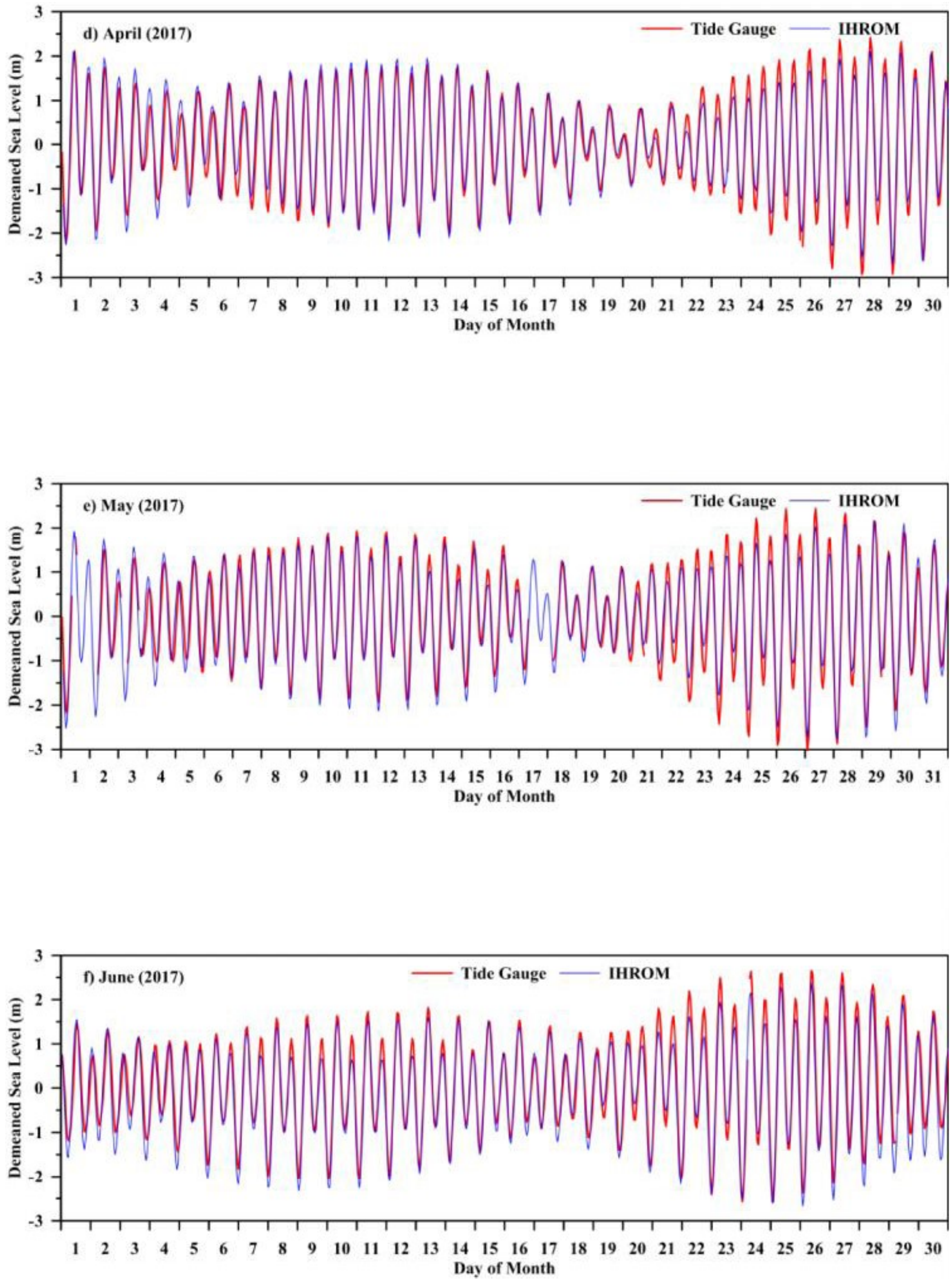


Fig. 08. Comparison between IHROM simulated DSL with that of JNPT tide gauge for April, May and June of 2017.

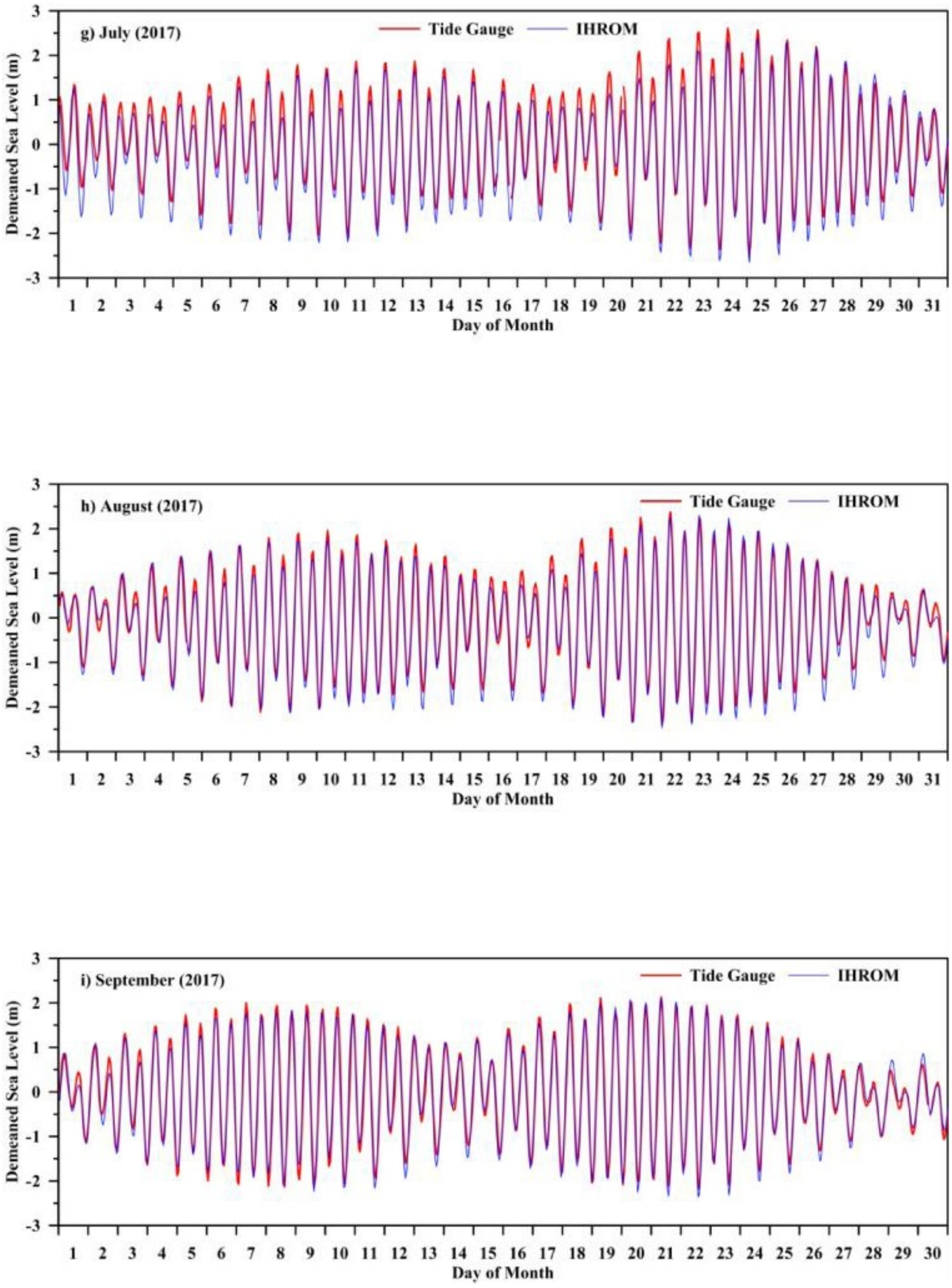


Fig. 09. Comparison between IHROM simulated DSL with that of JNPT tide gauge for July, August and September of 2017.

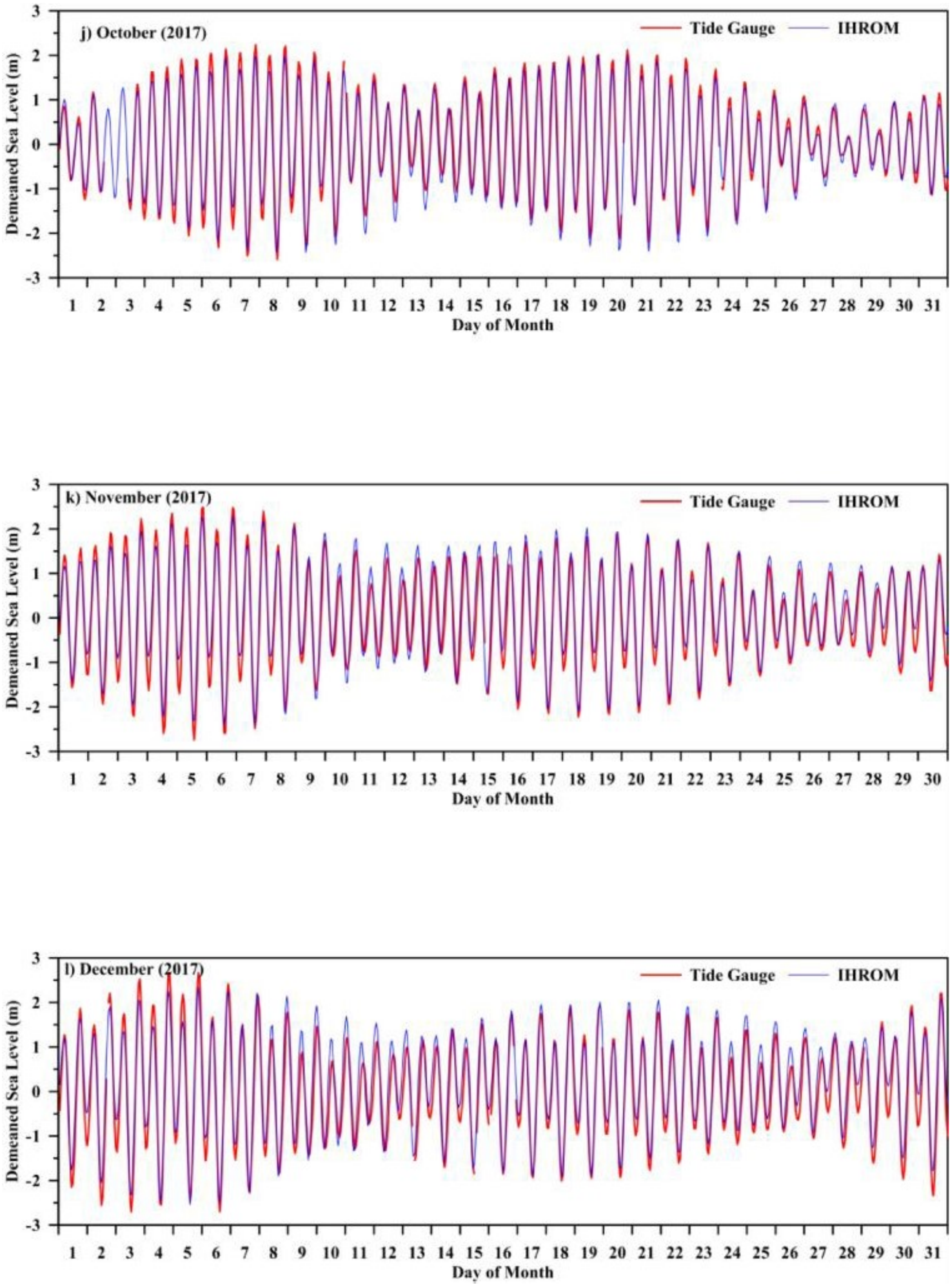


Fig. 10. Comparison between IHROM simulated DSL with that of JNPT tide gauge for October, November and December of 2017.

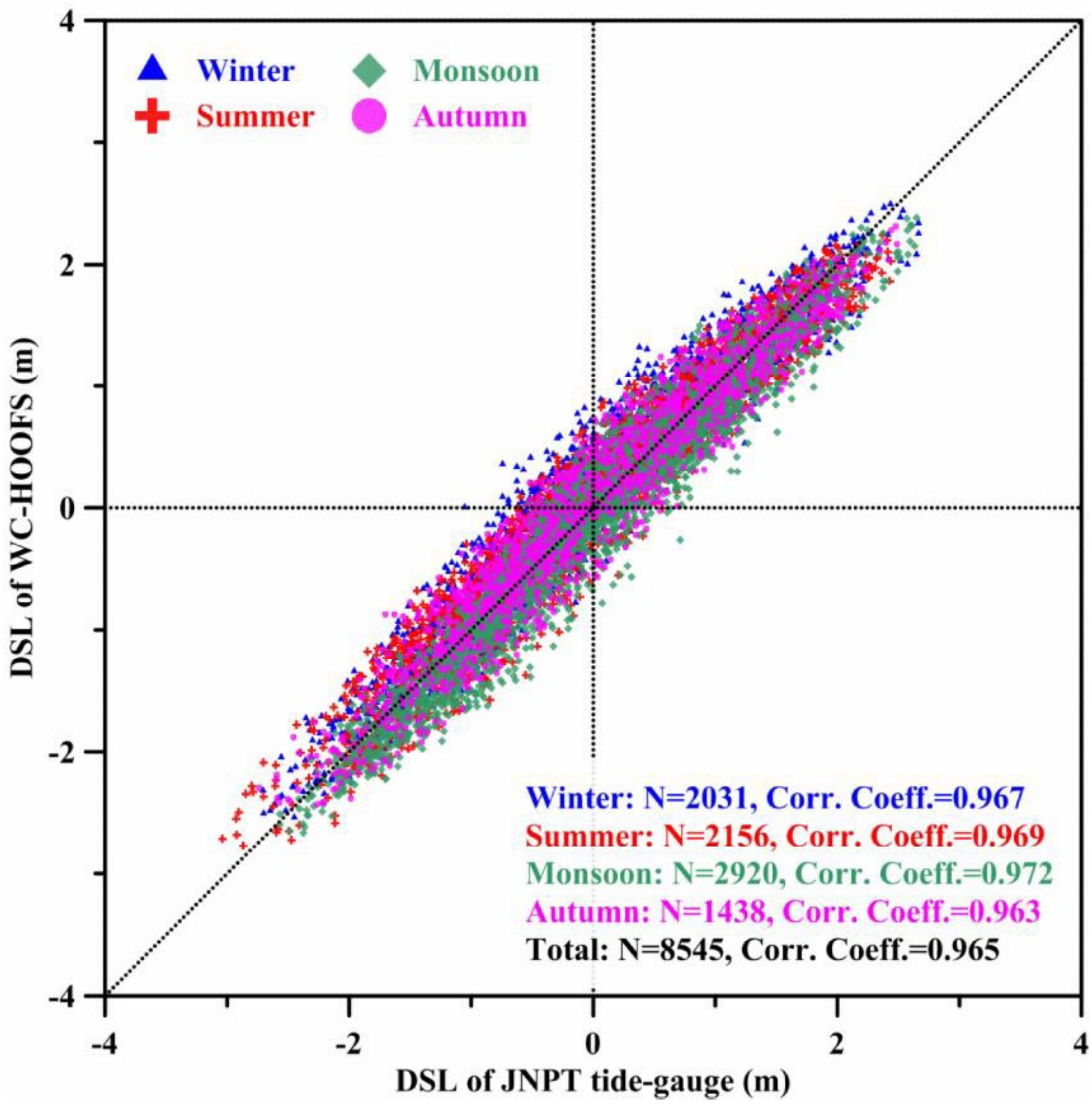


Fig. 11. Scatter plot of season wise DSL of IHROM vs JNPT radar tide gauge.

The model data set comprised 8,760 data points (24x365) on hourly basis, whereas the tide guage has 8,549 data points. Hence the available 8,549 data points were utilized for the comparison. A scatter plot between the insitu and model simulated DSL is shown in *Fig. 11.* Season wise correlation & annual correlation were estimated and shown in Figure 11. From this statistical estimation, a better agreement was noticed between IHROM simulated and Tide gauge recorded DSL.

Table 02: Month wise statistical comparison between the modeled and observed DSL at JNPT during 2017

Month	RMSE (m)	Correl. Coeff.	Bias(m)
January	0.26	0.98	-0.10
February	0.30	0.97	-0.11
March	0.26	0.98	-0.08
April	0.28	0.97	-0.06
May	0.30	0.96	0.00
June	0.31	0.97	0.14
July	0.30	0.97	0.16
August	0.22	0.98	0.06
September	0.22	0.98	0.01
October	0.26	0.97	0.04
November	0.32	0.96	-0.15
December	0.36	0.96	-0.20
Year 2017	0.29	0.96	-0.02

From the above table, a high correlation between the modeled and observed DSL is noticed. The study region comes under the macro-tidal regime, as the tidal heights are over 4m. Tidal currents dominate the processes in macro-tidal areas. The tides at JNPT, come under the category of mixed, predominantly semi-diurnal nature, as it experiences two high and two low tides of different heights every day. The principal tidal constituents M2, S2, K1 and O1 have amplitudes of 125.3, 50.9, 42.0 and 19.4 cm, respectively in the region.

3.5. IHROM ocean surface currents at the hypothetical spill location

The zonal (U) and meridional (V) component of the current/velocity field were obtained from IHROM simulation. After extraction of U & V, magnitude of current and the meteorological direction of the current was estimated. The current speed was found to be varying from 0.004 to 2.154 ms^{-1} with an average of 0.749 ms^{-1} during 2017. Month wise maximum, minimum and mean current speed is tabulated in Table 3. Fig. 12. to Fig. 23. shows month wise time series plot of the zonal & meridional component of the current, magnitude & direction of the current at the HSL during 2017.

Table 03: Month wise maximum, minimum and mean surface current speed depth at the HSL

Year 2017	Min Current Speed (ms^{-1})	Max Current Speed (ms^{-1})	Mean Current speed (ms^{-1})	Date of maximum current speed
January	0.014	1.812	0.726	13-Jan-2017
February	0.011	1.788	0.731	11-Feb-2017
March	0.012	1.983	0.768	30-Mar-2017
April	0.011	1.908	0.734	11-Apr-2017
May	0.013	2.038	0.742	28-May-2017
June	0.017	2.113	0.770	27-Jun-2017
July	0.024	2.157	0.773	25-Jul-2017

Year 2017	**Min Current Speed (ms^{-1})**	**Max Current Speed (ms^{-1})**	**Mean Current speed (ms^{-1})**	**Date of maximum current speed**
August	0.015	2.115	0.755	23-Aug-2017
September	0.011	2.123	0.765	20-Sep-2017
October	0.019	1.983	0.745	08-Oct-2017
November	0.004	2.067	0.742	05-Nov-2017
December	0.016	2.051	0.736	05-Dec-2017
Year 2017	0.004	2.157	0.749	25-Jul-2017

Table 03. indicates higher values of maximum current magnitude as well as average value of magnitude during the southwest summer monsoon period (JJAS).

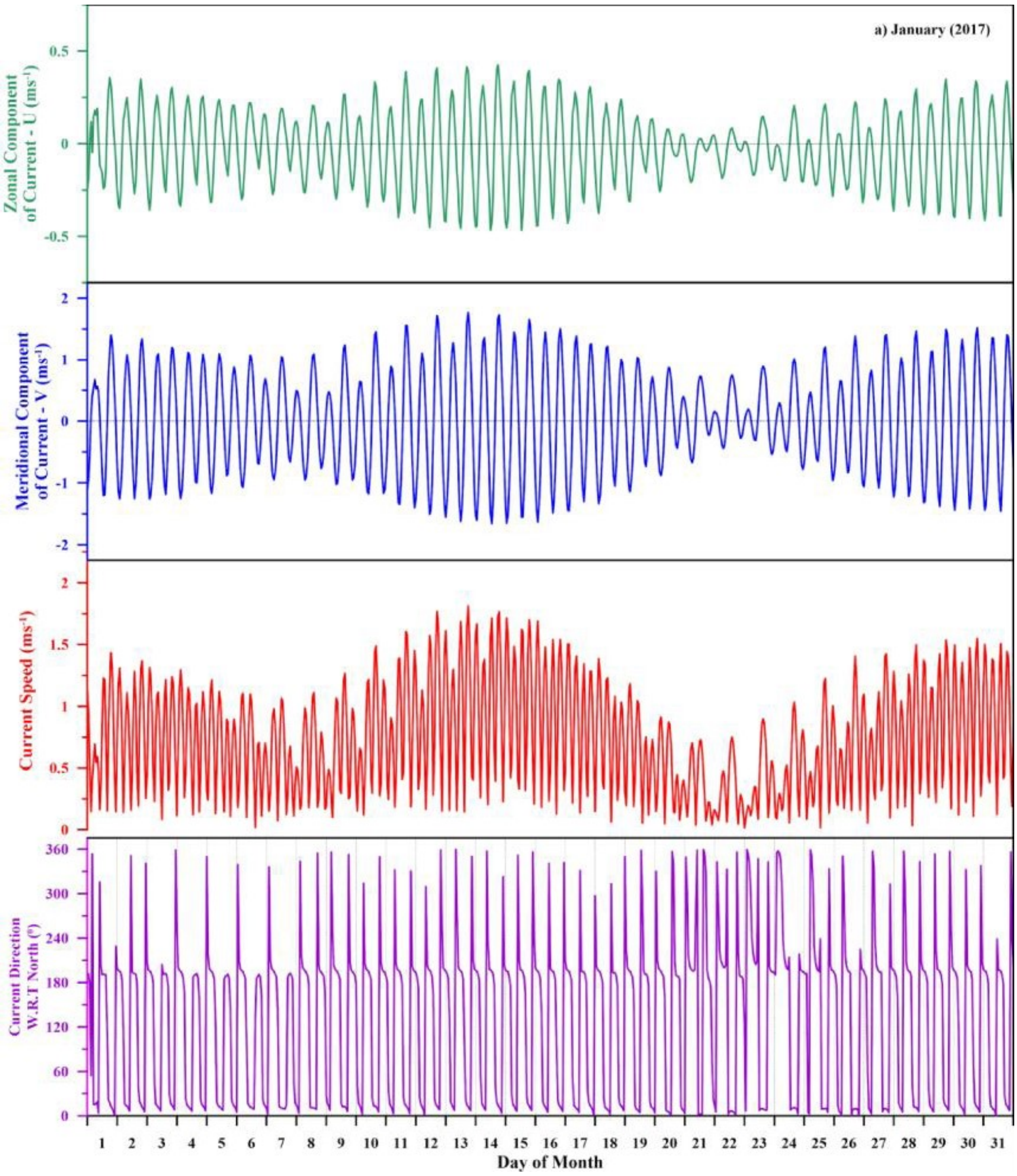


Fig. 12. Time series plot of IHROM simulated zonal and meridional components of current, current speed & direction at HSL for January, 2017.

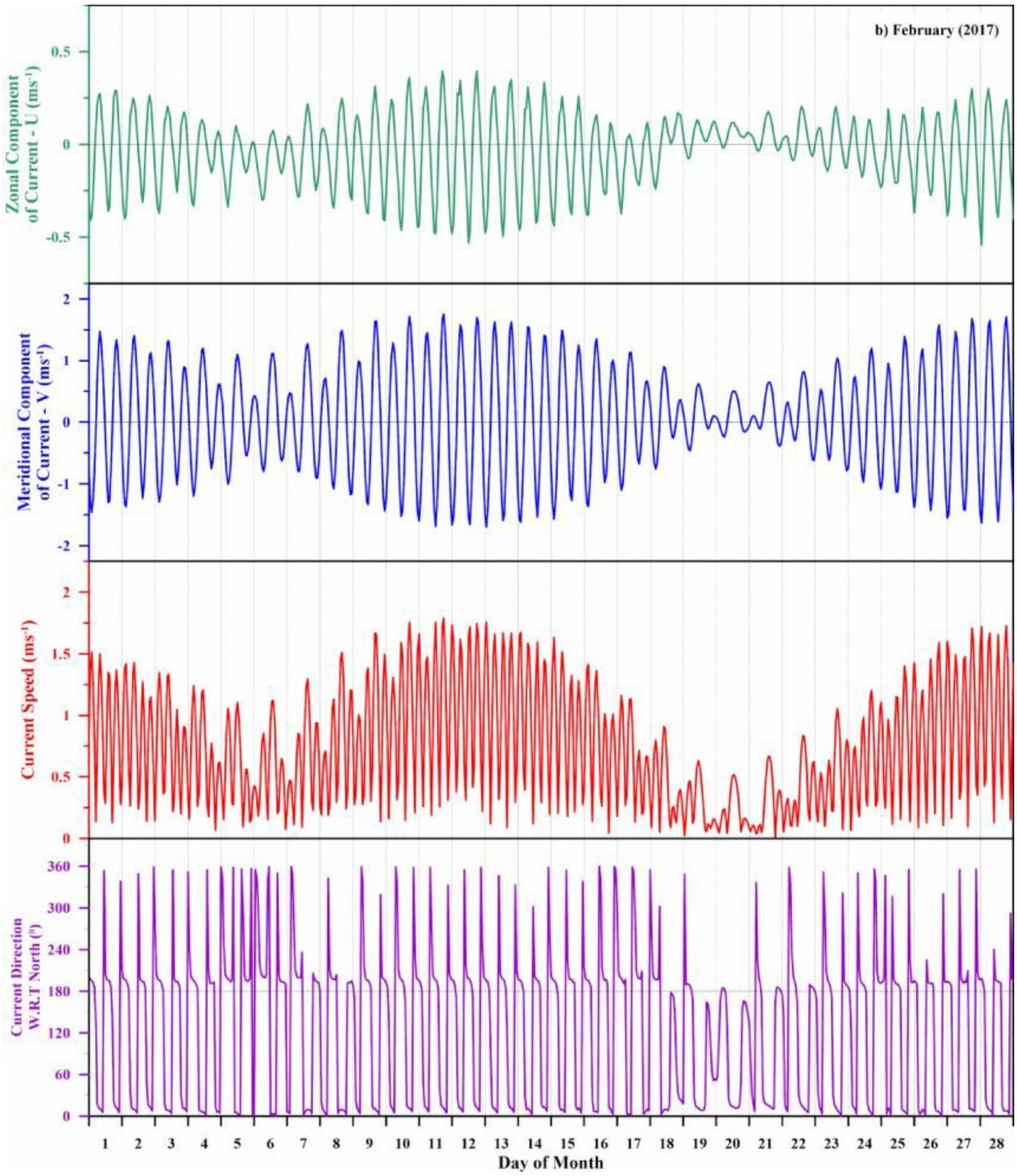


Fig. 13. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for February, 2017.

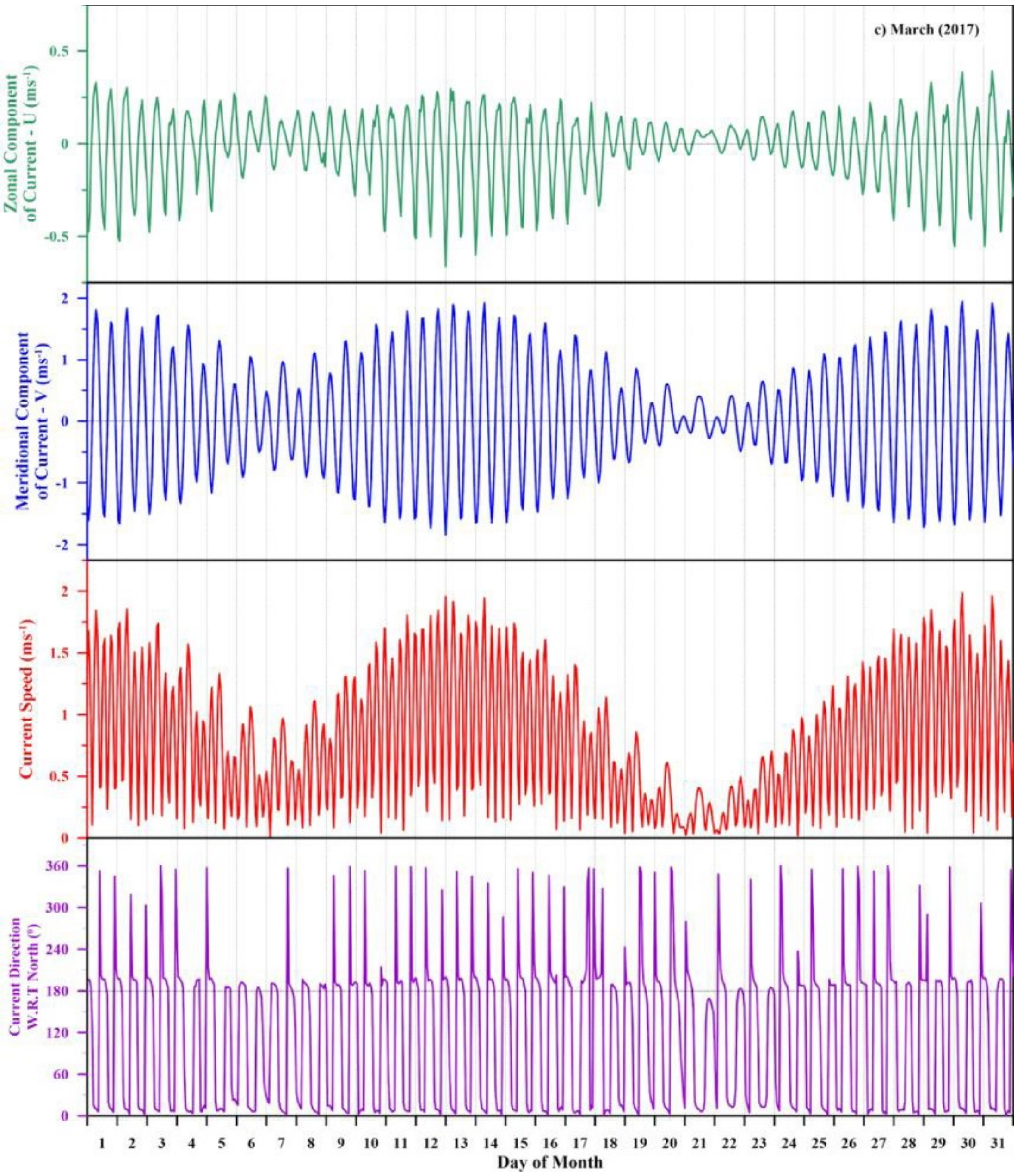


Fig. 14. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for March, 2017.

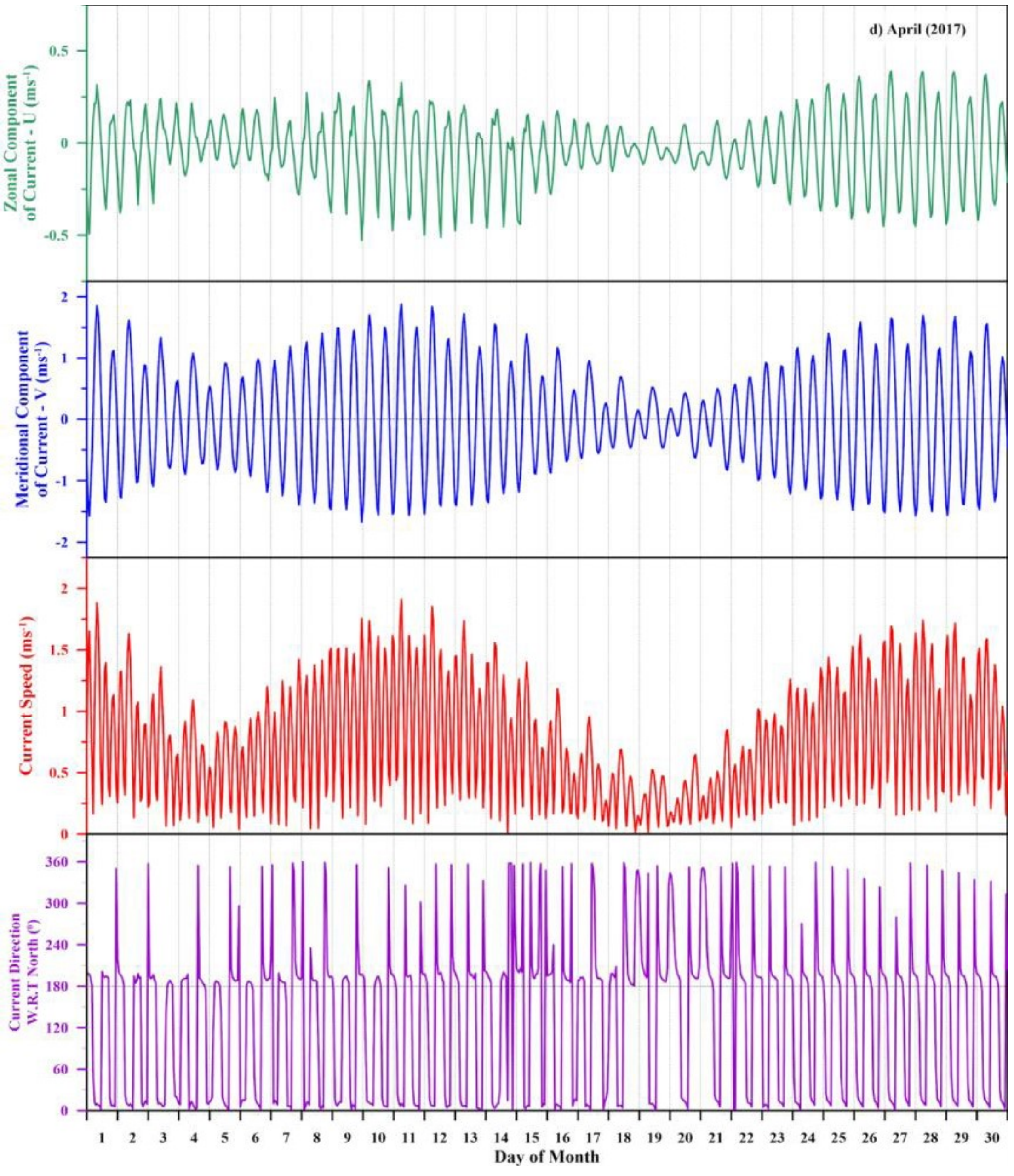


Fig. 15. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for April, 2017.

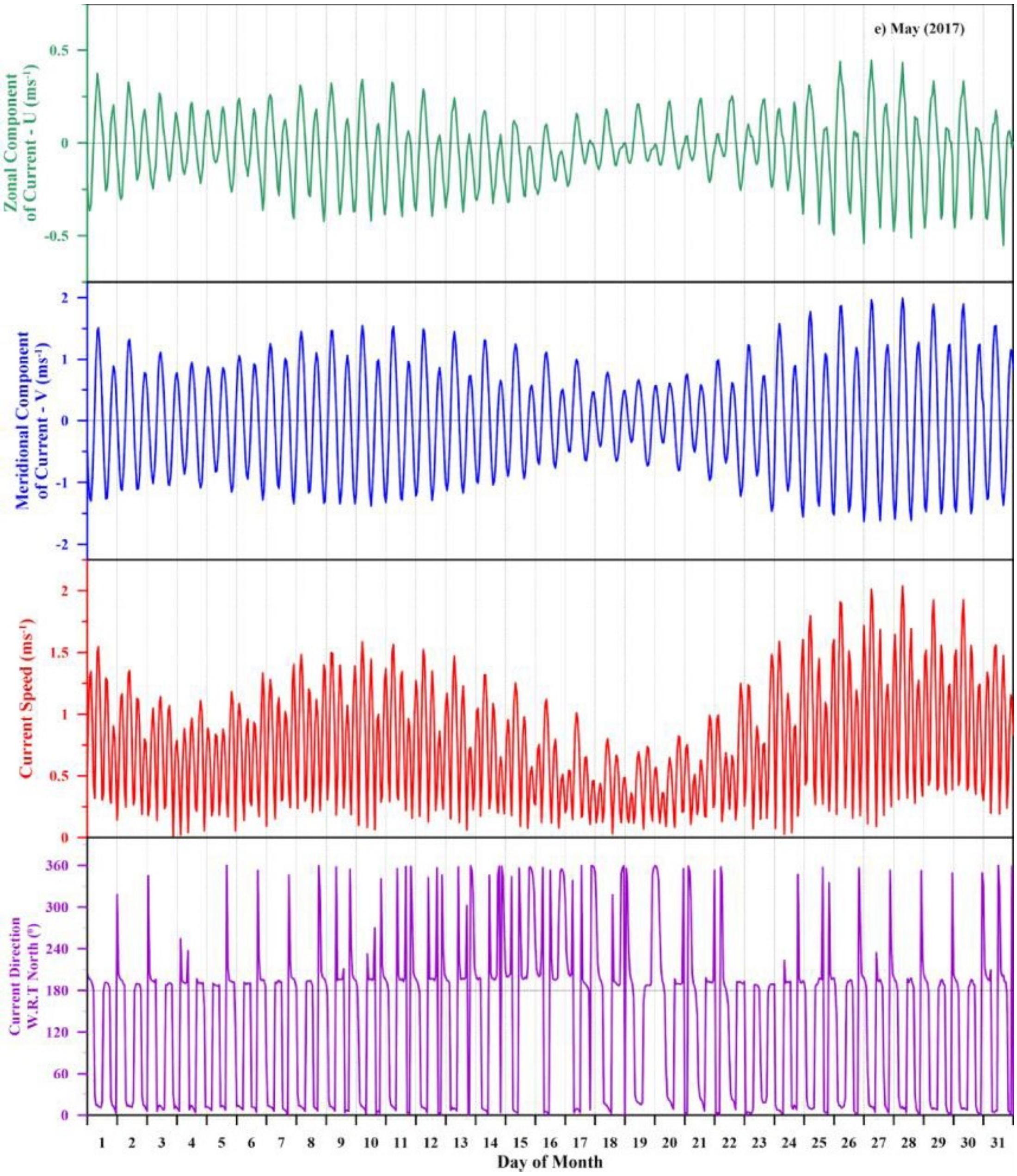


Fig. 16. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for May, 2017.

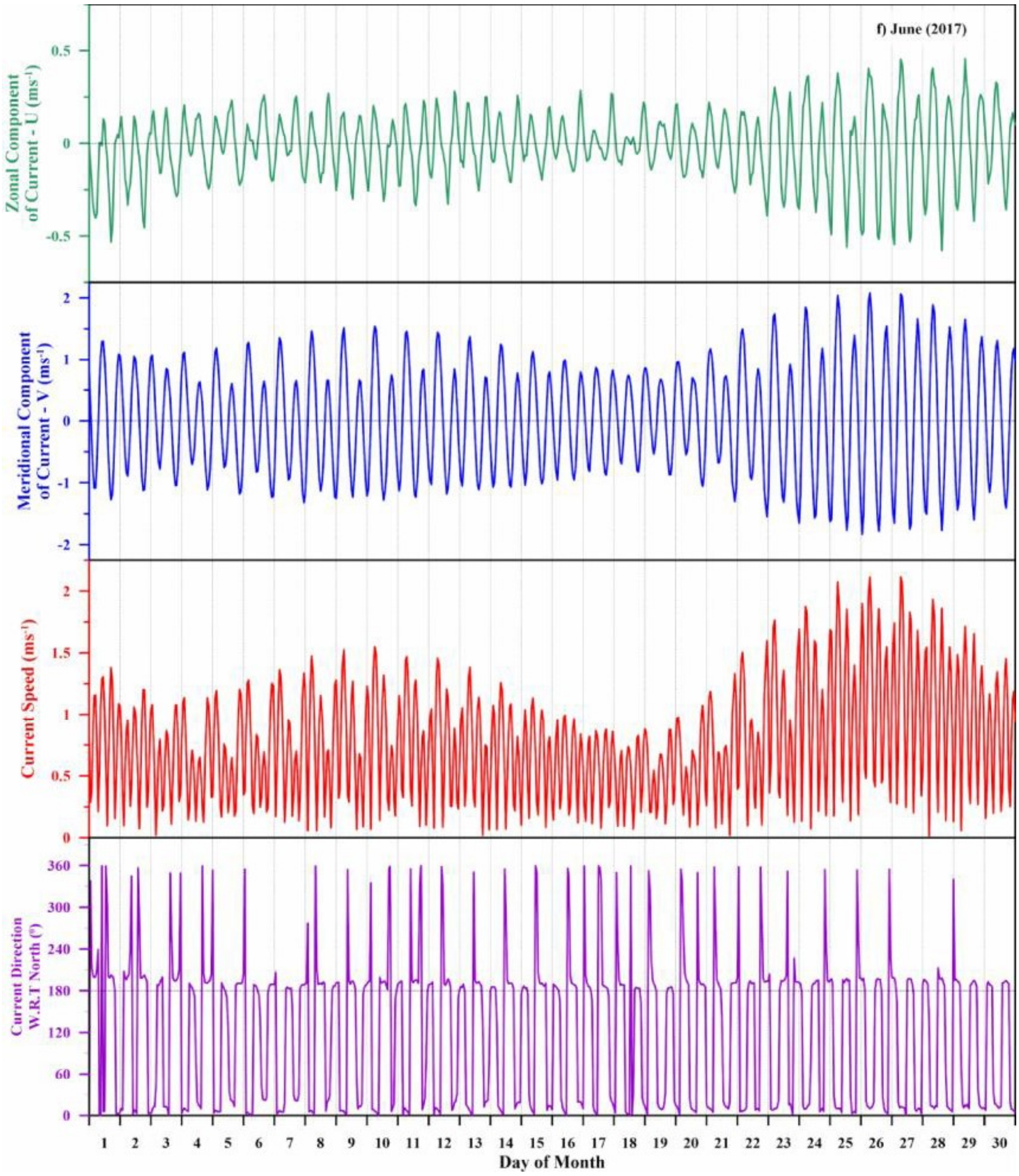


Fig. 17. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for June, 2017.

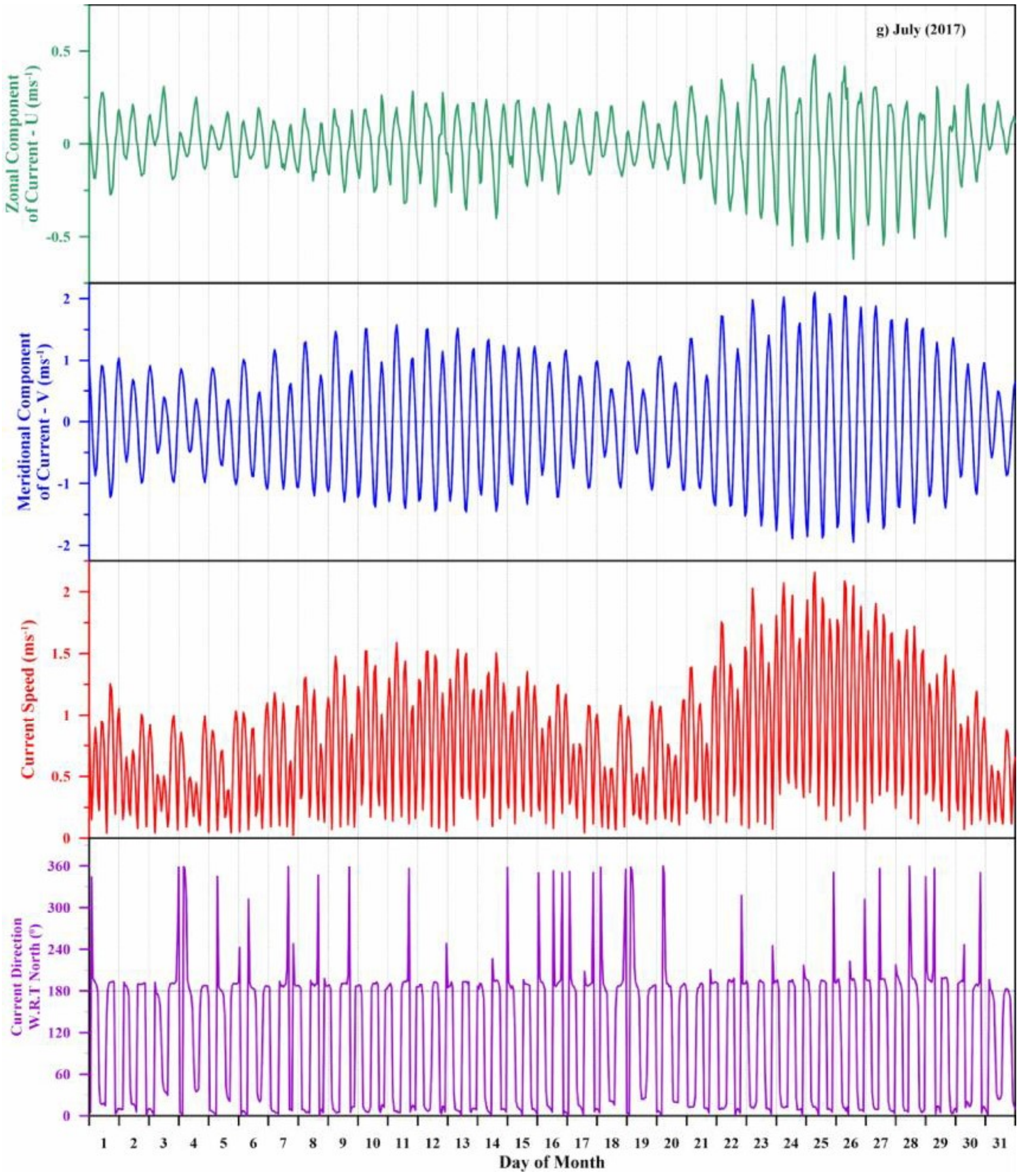


Fig. 18. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for July, 2017.

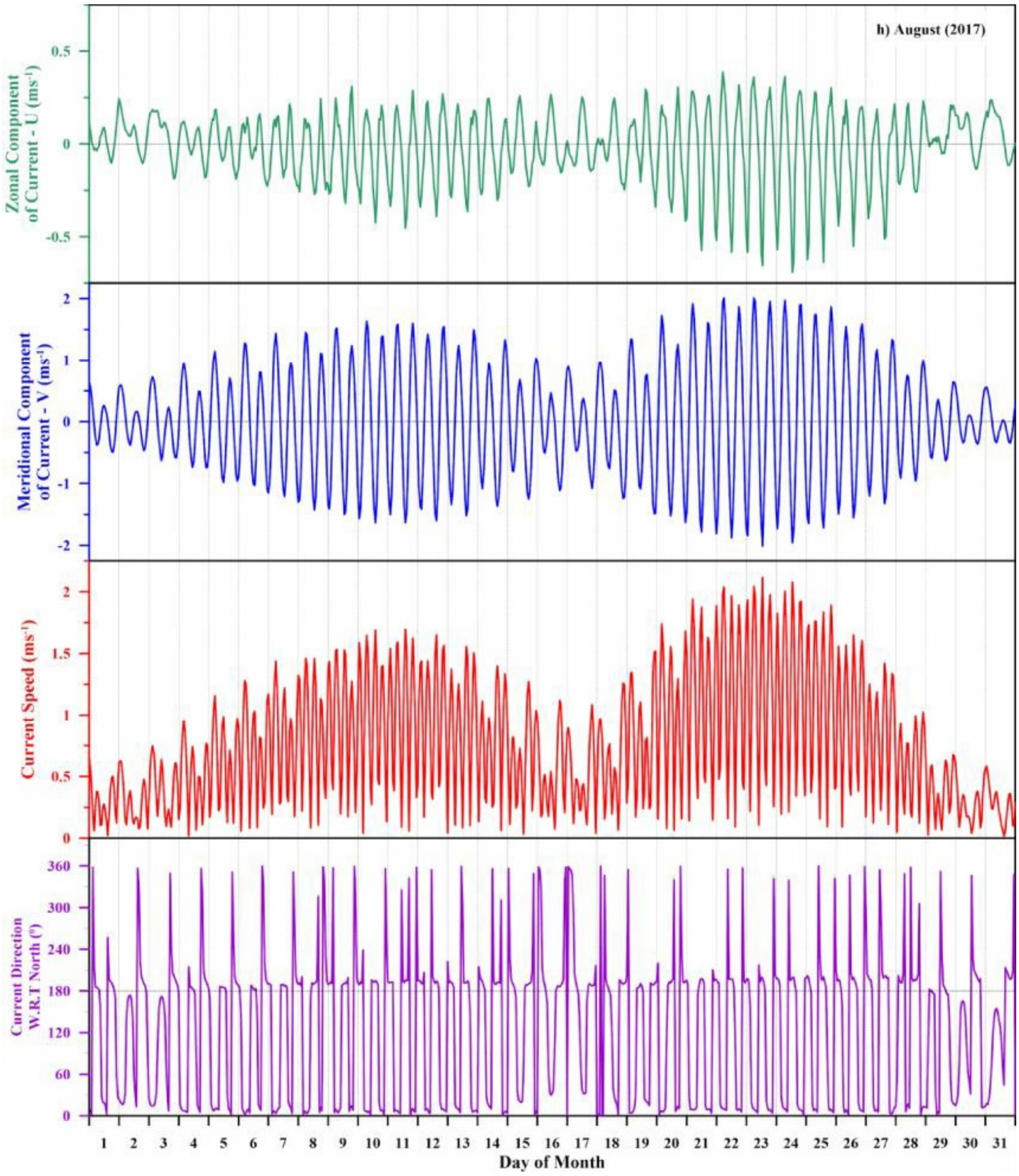


Fig. 19. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for August, 2017.

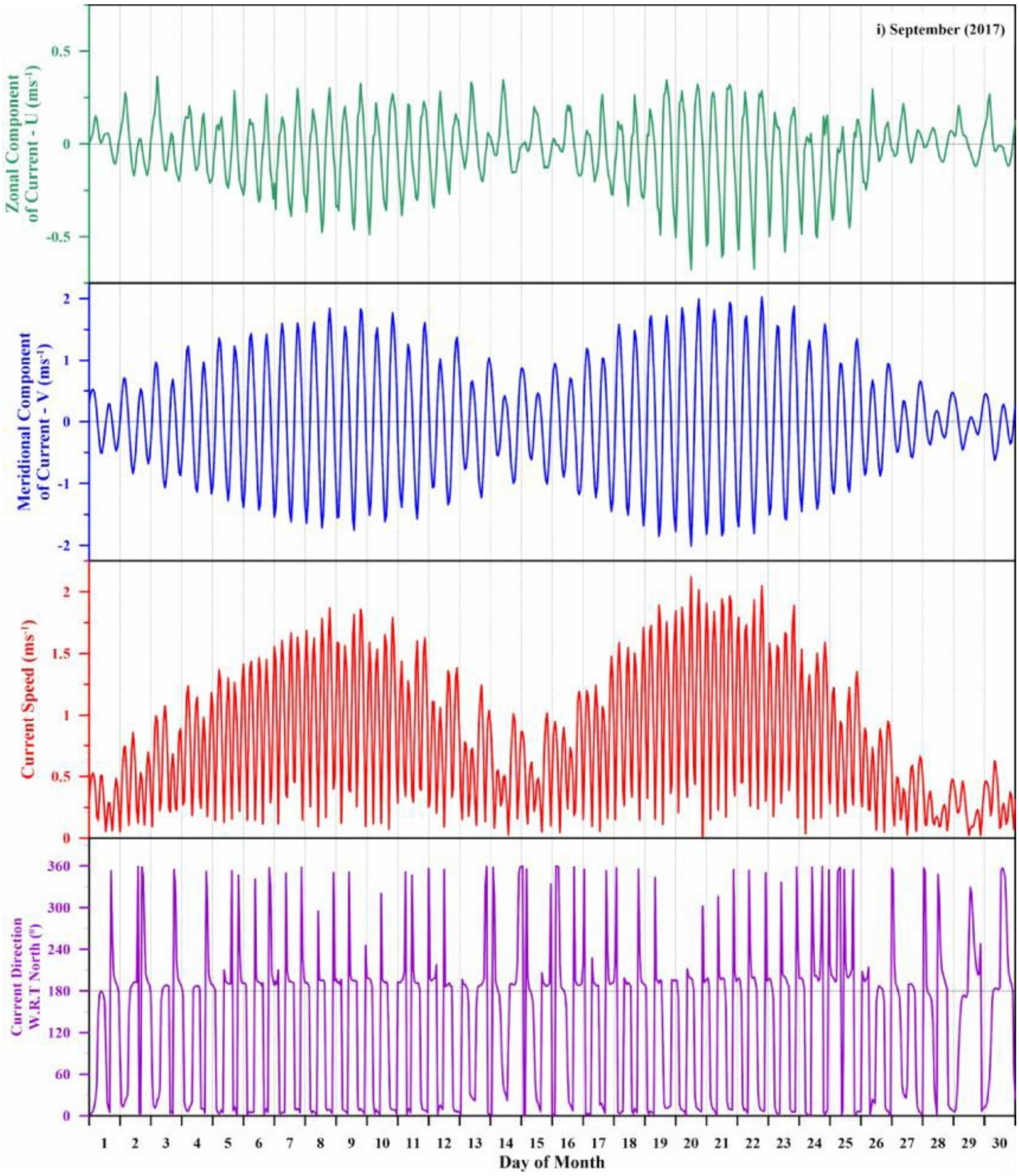


Fig. 20. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for September, 2017.

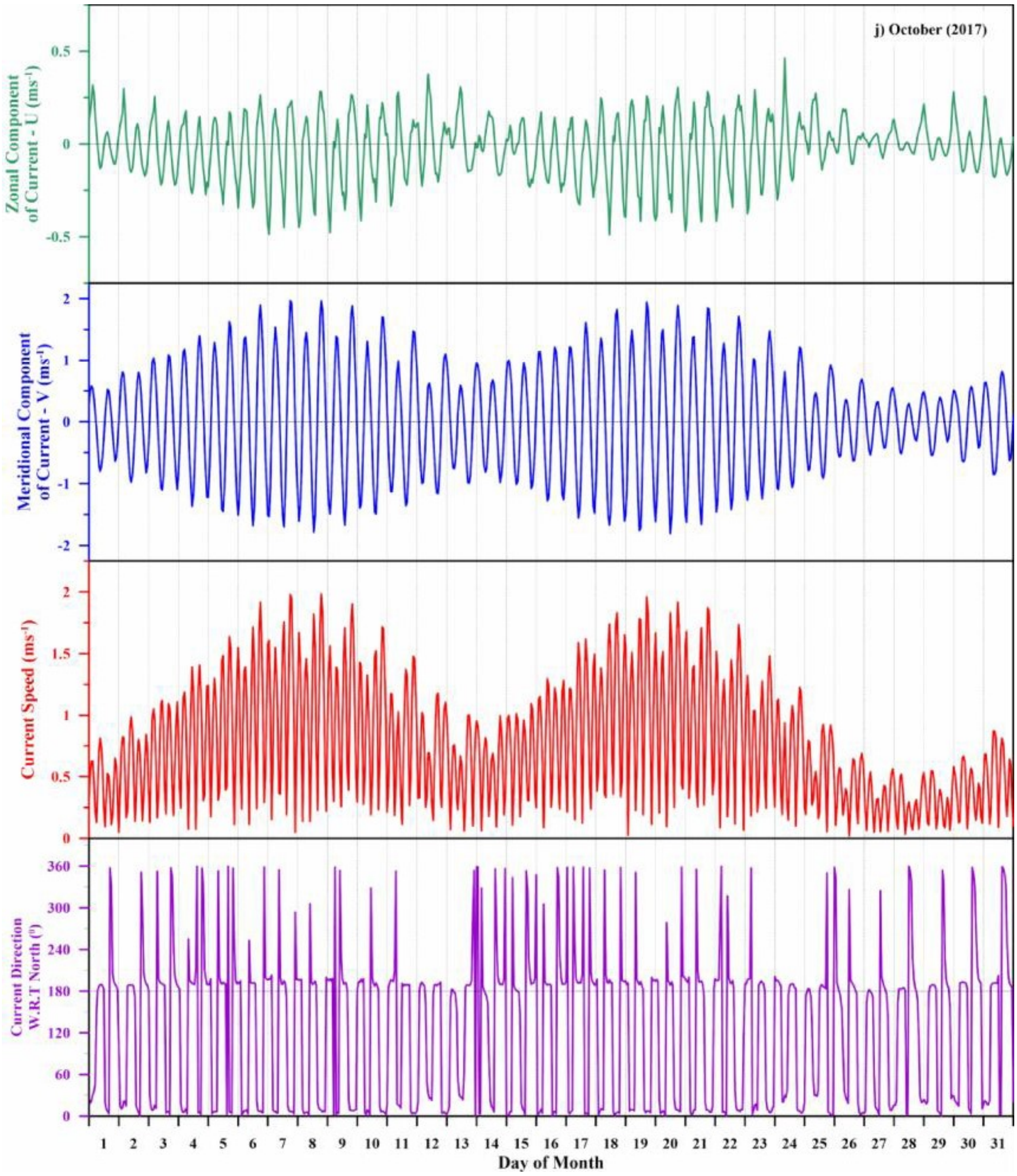


Fig. 21. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for October, 2017.

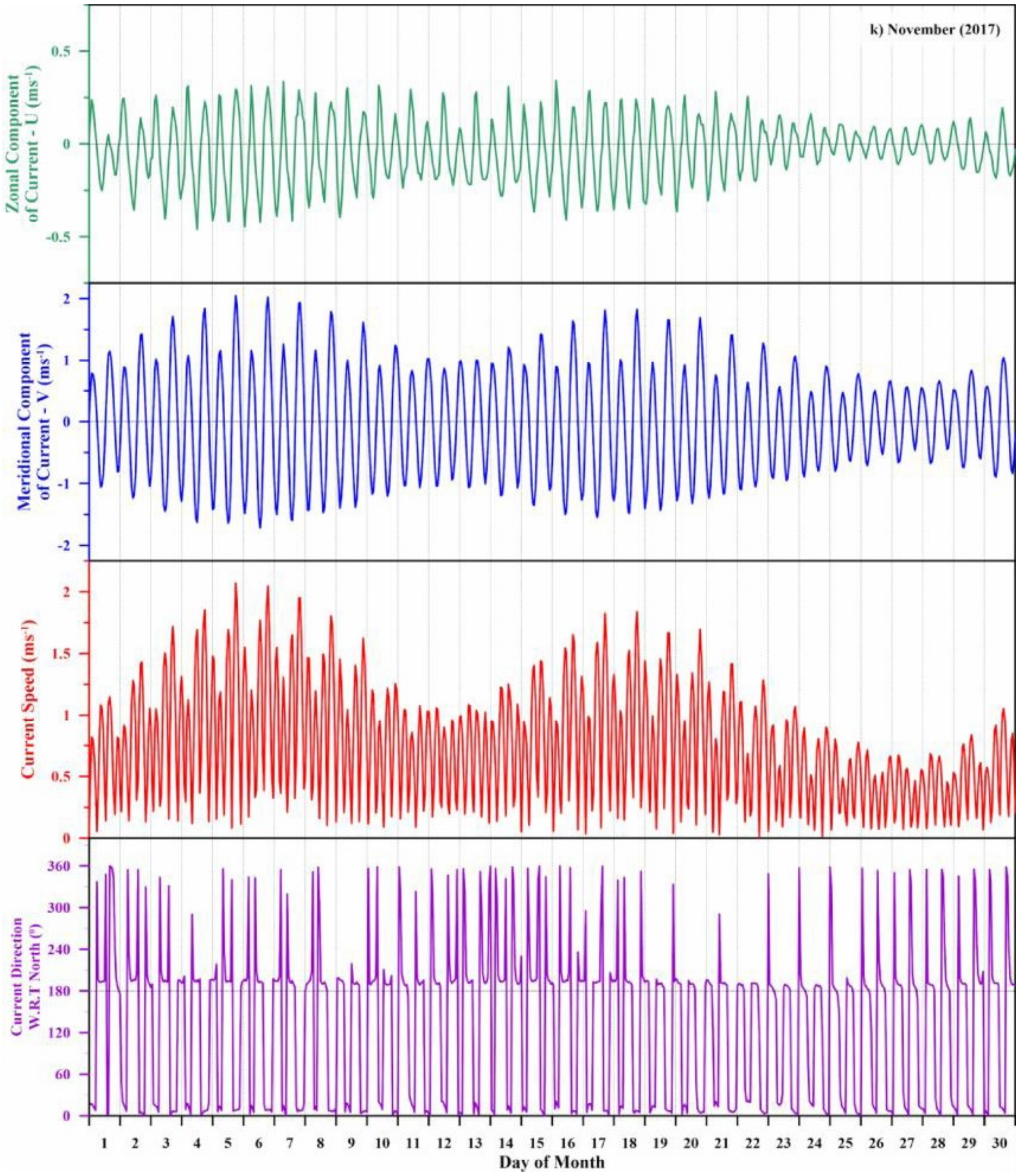


Fig. 22. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for November, 2017.

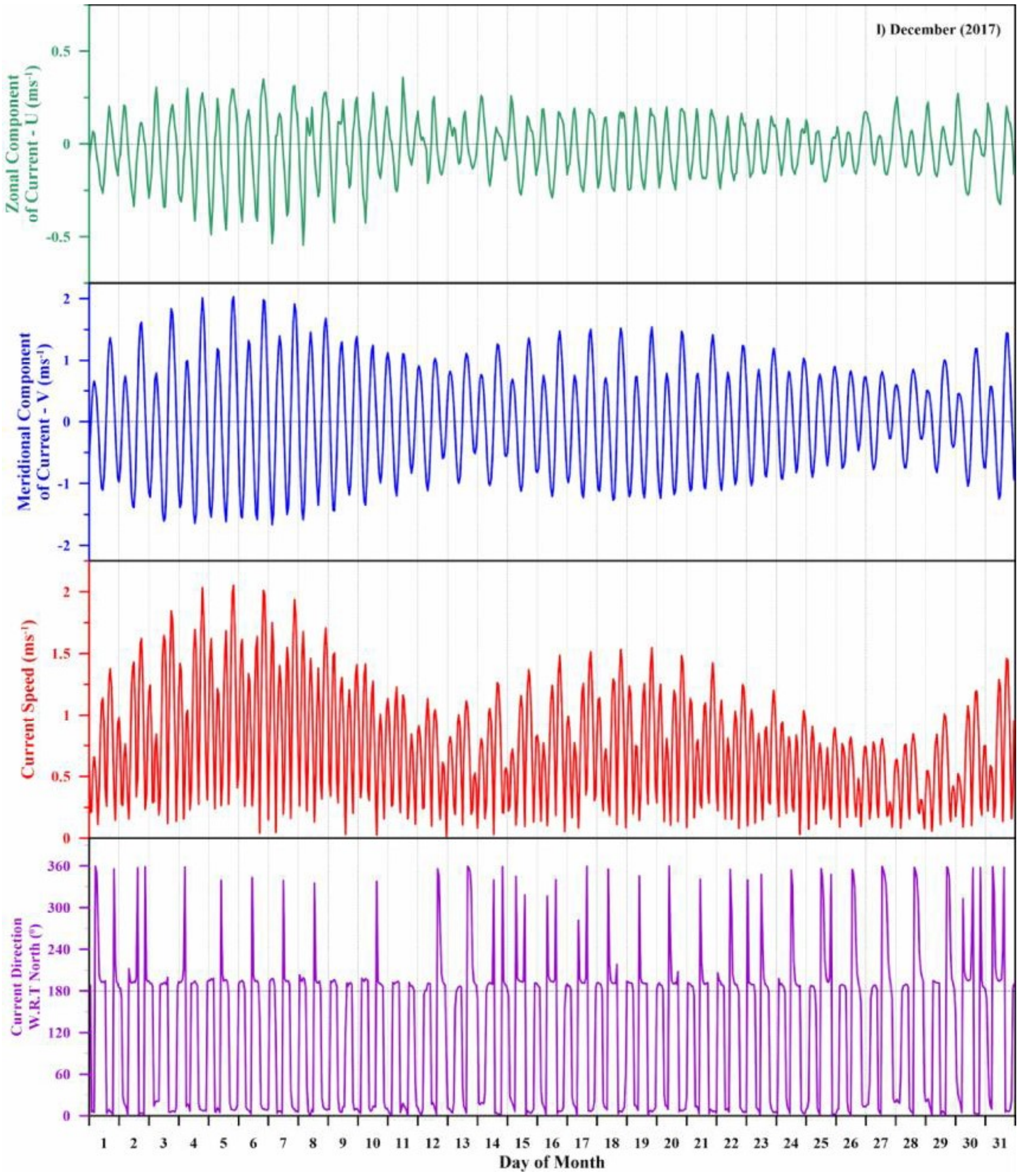


Fig. 23. Time series plot of IHROM simulated zonal and meridional components of current, current speed and direction at HSL for December, 2017.

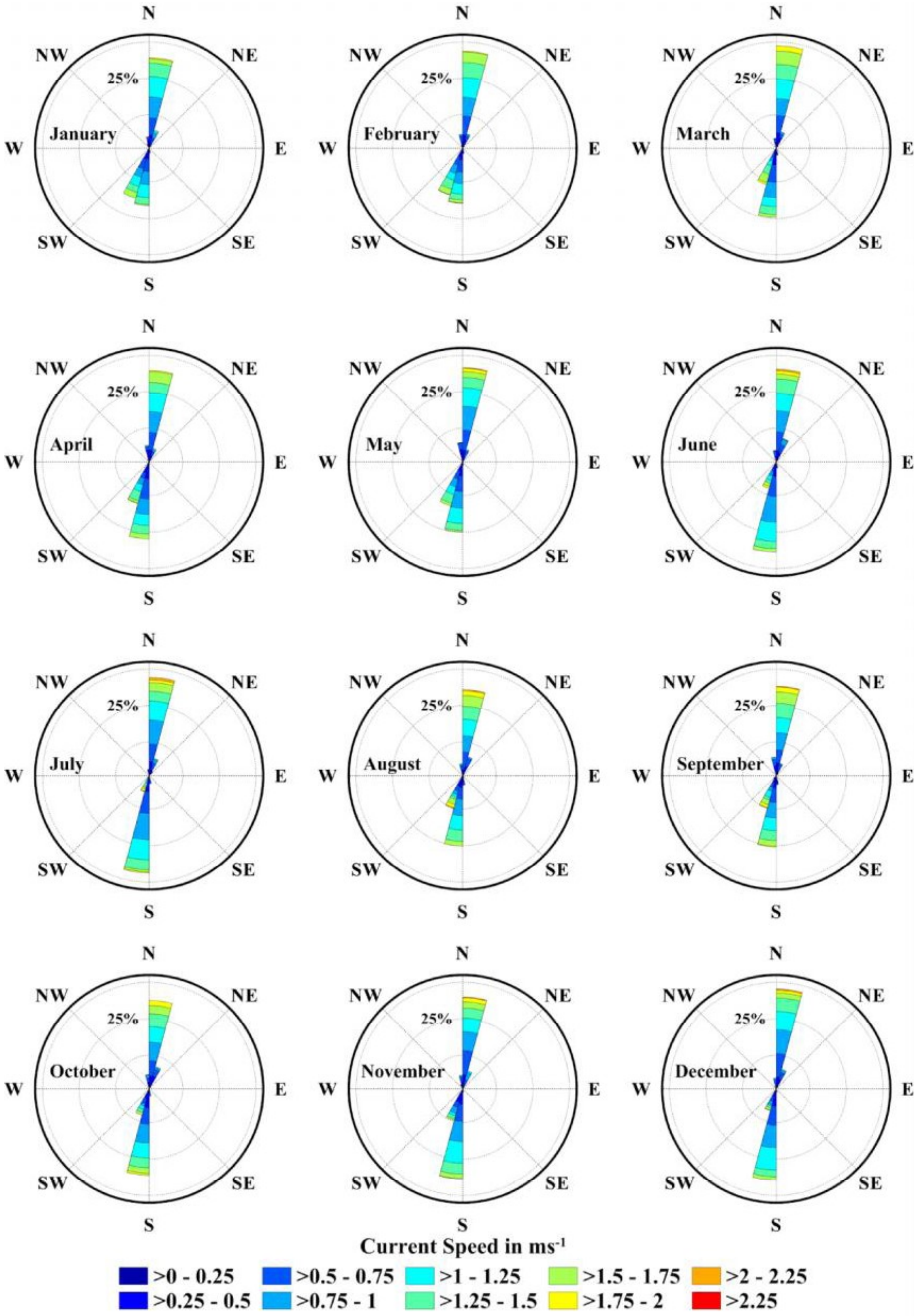


Fig. 24. Month wise current rose plot of IHROM simulated surface currents at HSL for 2017. Oceanographic convention is followed, representing the "towards" direction.

Figures 07-10, shows the monthly comparison between the simulated Demeaned Sea Level (DSL) of IHROM and observed DSL of JNPT Tide Gauge. It is noted the spring and neap tide cycles are well captured by the IHROM. From rectilinear form of the current rose plot (*Fig. 24)*, it is evident that the ocean current at the HSL is mainly governed by flooding and ebbing tidal cycles, suggesting strong tidal dominations.

4. Oil spill trajectory prediction

Indian National Centre for Ocean Information Services (INCOIS), Hyderabad has developed a numerical modeling setup with oil spill trajectory model GNOME called INCOIS Oil Spill Trajectory Prediction System (IOSTPS) to predict the trajectory of the spilled oil pollutant, based on prevailing winds and ocean currents in the region of spill. The trajectory model was operationalised at INCOIS by setting it in diagnostic mode for Indian ocean. The diagnostic mode allows the user to set their own scenario. The model estimates the movement of spilled oil as the vector sum of wind speed, current speed and diffusion turbulence. The resultant of these forcings at each and every time step gives the impetus for the oil to drift *(Zelenke et al. 2012)*. The displacement along the x and y direction is computed as follows *(Zelenke et al 2012)*.

$$\Delta x = \frac{u*\Delta t}{\frac{111,120.00024}{cos y}} \text{ ---------------- } 1$$

$$\Delta y = \frac{v*\Delta t}{111,120.00024} \text{ -------------- } 2$$

Where

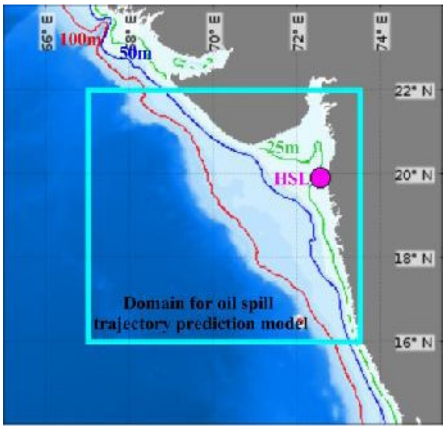
Δx - Zonal displacement by movers, Δy - Meridional displacement by movers, Δt - time elapsed between time steps.

u,v are the velocity of the forcing parameters.

y- is the latitude in radians

Prasad et al. (2014) explained the detailed methodology adopted for predicting the trajectory of spilled oil and its validation for Mumbai oil spill incidents. Recently, *Prasad et al. (2018)* have carried out an assessment of Heavy Furnace Oil (HFO) spill trajectory prediction. It was for the spill that occured due to the collision between BW Maple, an outbound Liquefied Petroleum Gas (LPG) tanker and an inbound chemical tanker MT Dawn Kanchipuram, collided about two nautical miles (13.2282°N, 80.3633°E) off Kamarajar Port, Ennore on Jan 28, 2017.

4.1 Oil Spill trajectory prediction from HSL for the proposed Vadhavan port

Domain : 67° E to 73.5° E, 16° N to 22° N	
Pollutant : Fuel oil (700 Tons)	
HSL : 72.5389° E,19.9343° N	
Trajectory model run period:	Spring and neap tidal cycles of all months during 2017

In the present study the wind fields obtained from INCOIS ocean state forecast laboratory were validated with in situ data obtained from the Automatic Weather Stations (AWS) installed on board ships. The Root Mean Square error was found to be less than 2.6 m s^{-1} *(Harikumar et al. 2012)*. In another study, it was found that, the correlation between the modeled wind fields and that of the Moored buoy was 0.90 (Figure 03 & Table 01).

The ocean current pattern was obtained from INCOIS High Resolution Ocean Model especially for the west coast. The circulation pattern was generated every hour and utilized for oil spill trajectory prediction.

The INCOIS oil spill trajectory prediction system was set with all the generated met-ocean parameters for the period 01-Jan -2017, 0000 hrs to 31-Dec -2017, 2300 hrs. To study the intra- annual variation in the oil spill drift pattern, the generated trajectory was therefore extracted during the spring and neap tide days of each and every month and plotted in ArcGIS, a geographical information system tool. The variation in the drift patterns is shown in Figures 25 to 48.

The plots corresponding to the alphabets a, b, c represents the spring tide phase at the end of 18th, 36th, 54th hour, respectively. The plots corresponding to the alphabets e, f, g denotes the neap tide phase at the end of 18th, 36th, 54th hour, respectively.

The trajectory maps were generated for every 18 hour interval during the spring and neap tide phases of all months during 2017.

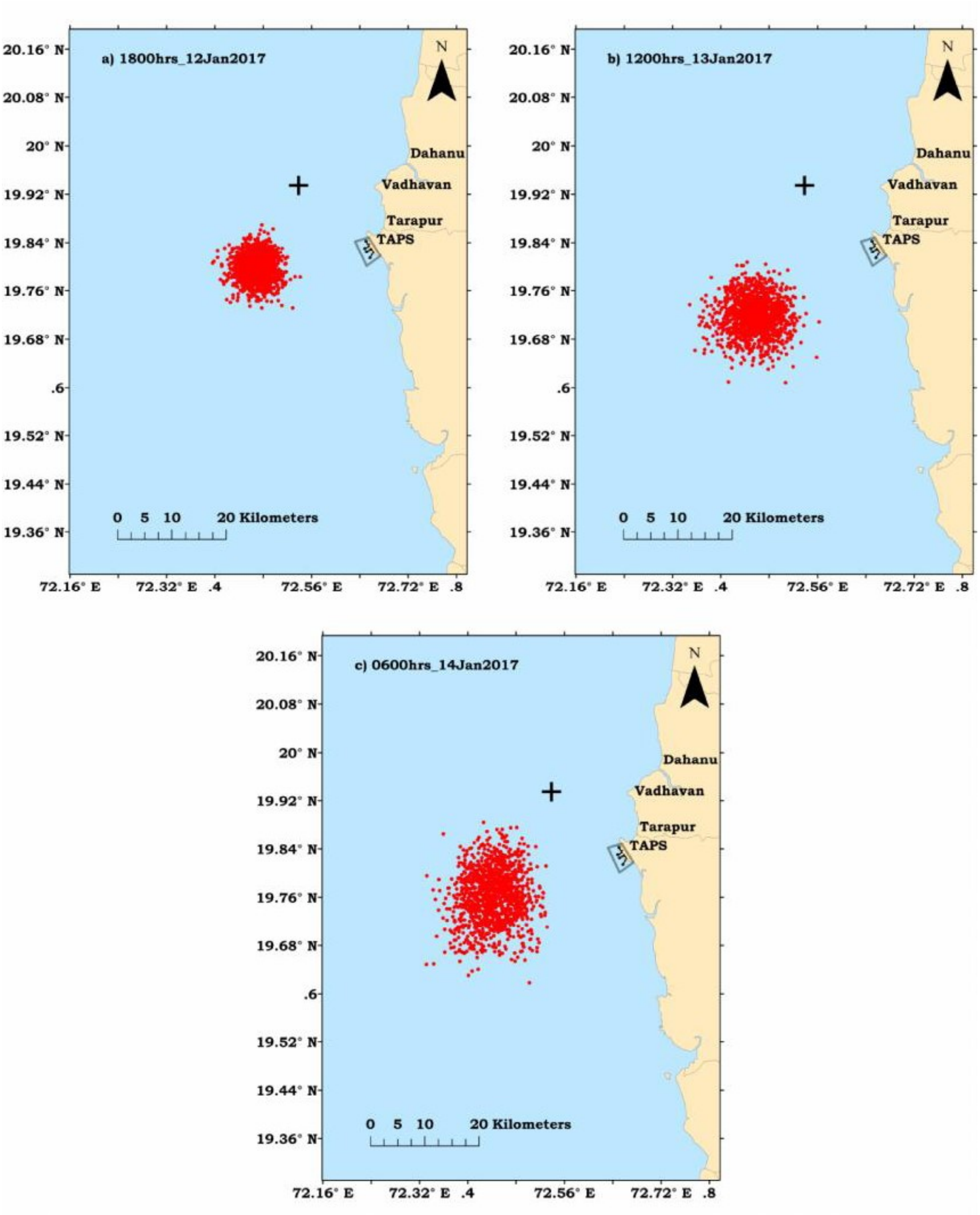


Fig. 25. Simulated oil drift pattern during spring tide days - Jan 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

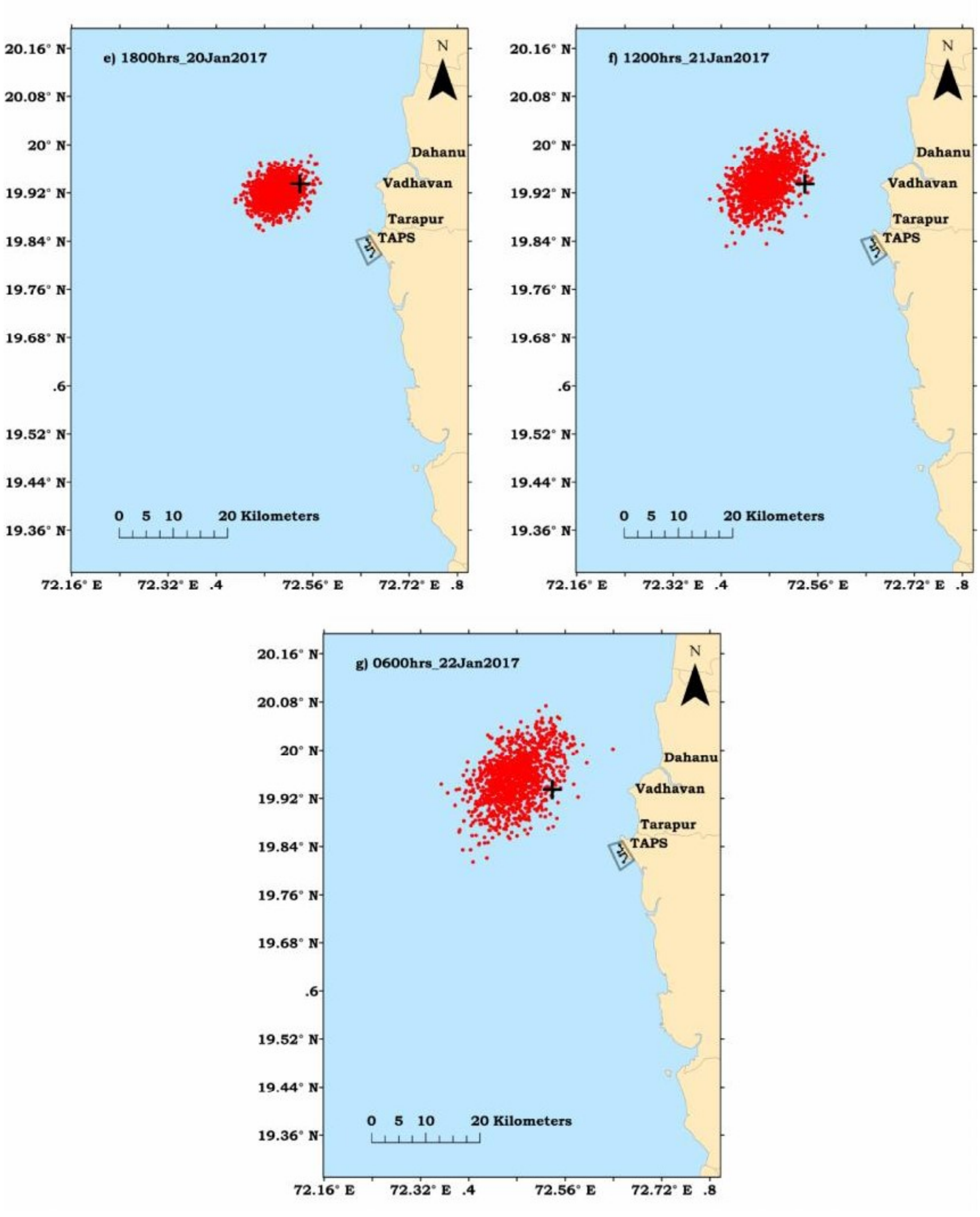


Fig. 26. Simulated oil drift pattern during neap tide days - Jan 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

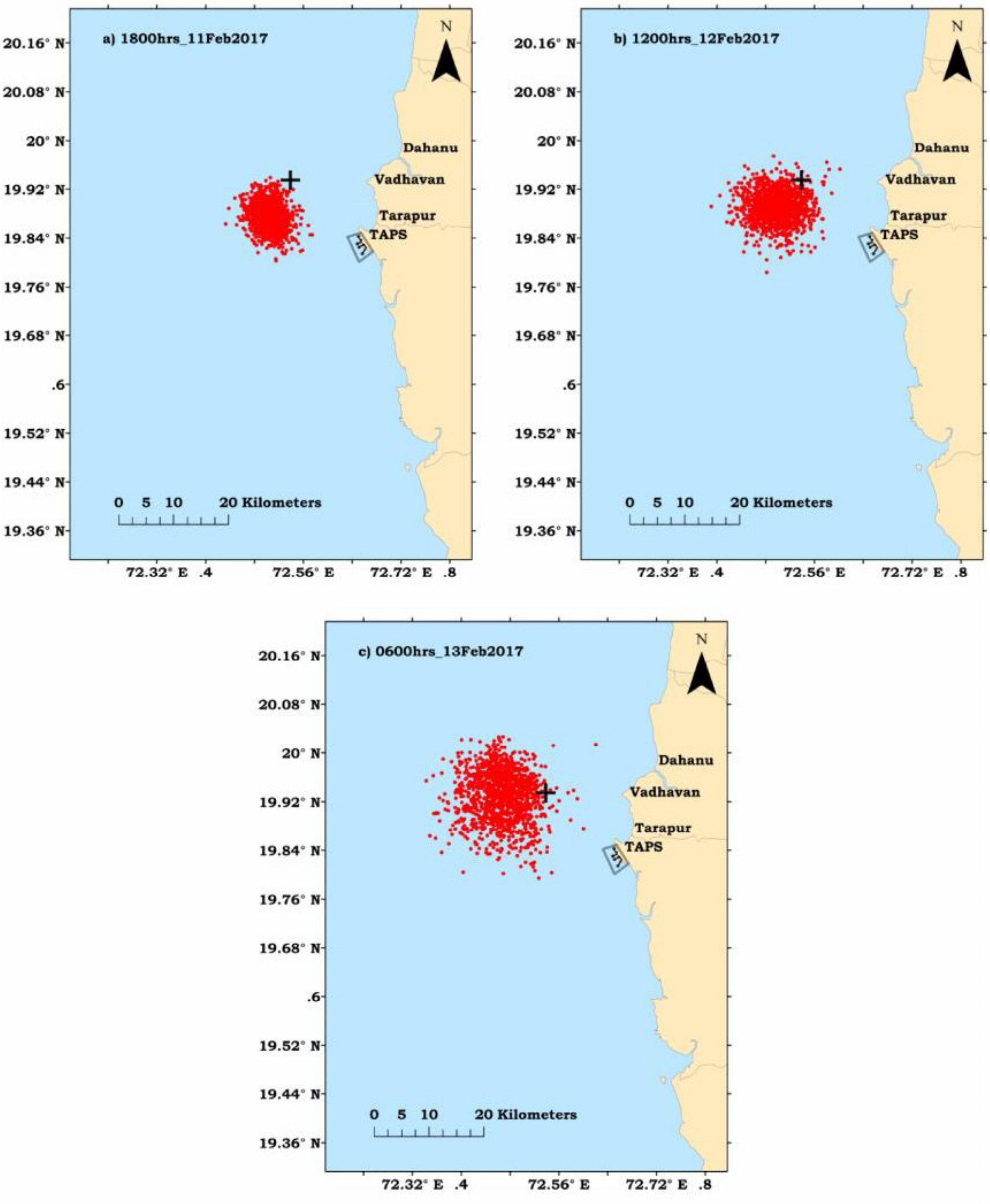


Fig. 27. Simulated oil drift pattern during spring tide days - Feb 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

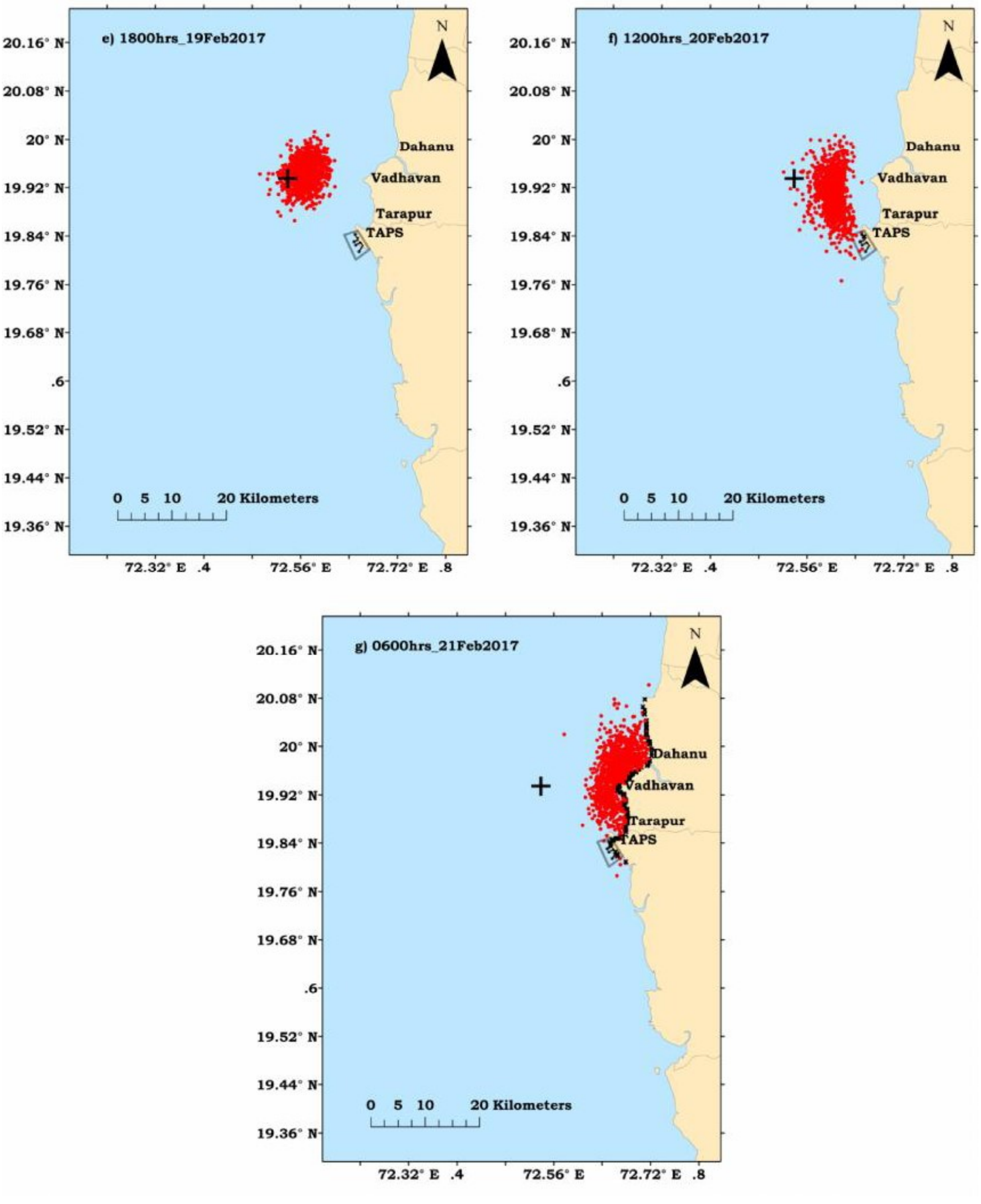


Fig. 28. Simulated oil drift pattern during neap tide days - Feb 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

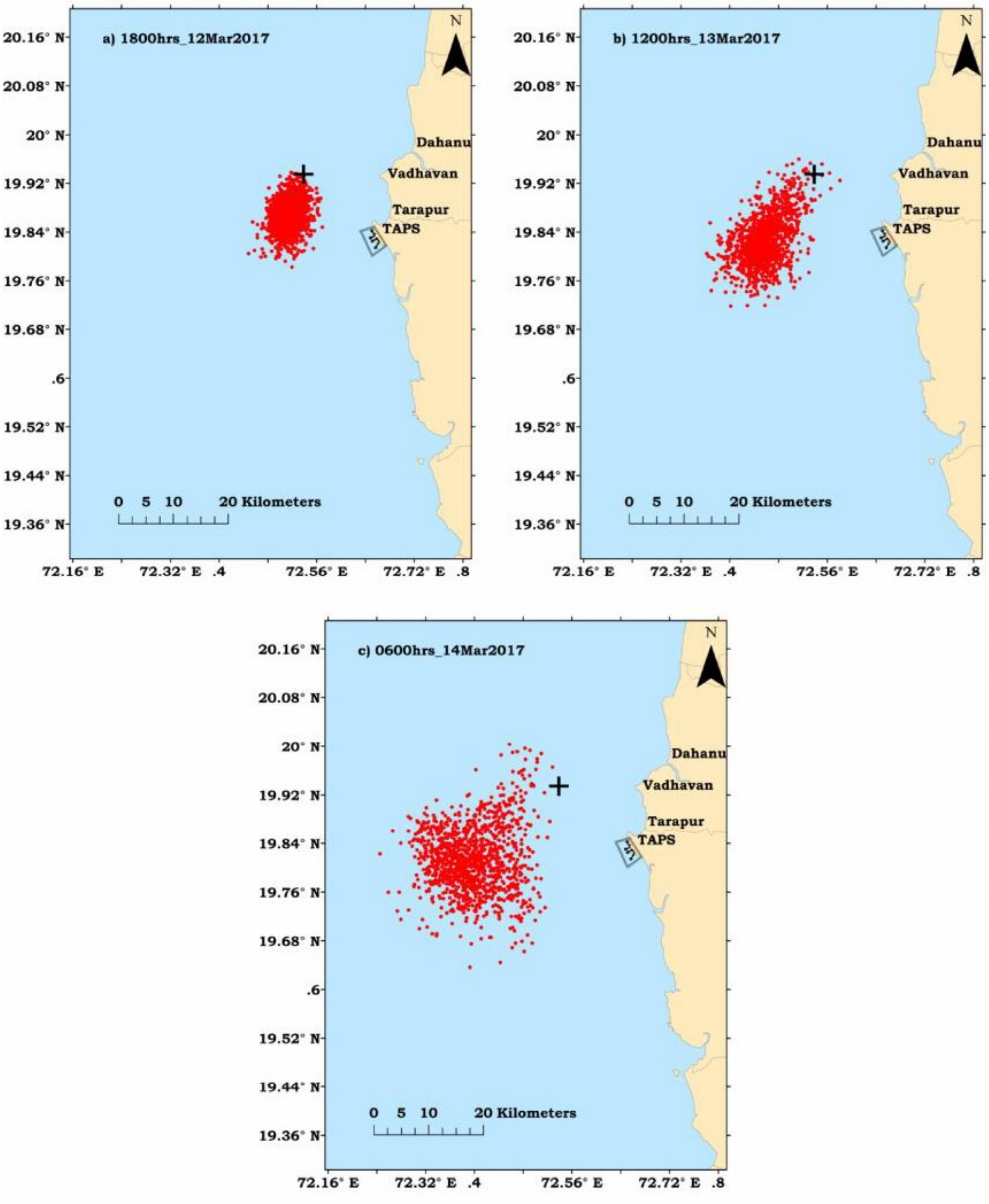


Fig. 29. Simulated oil drift pattern during spring tide days - March 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

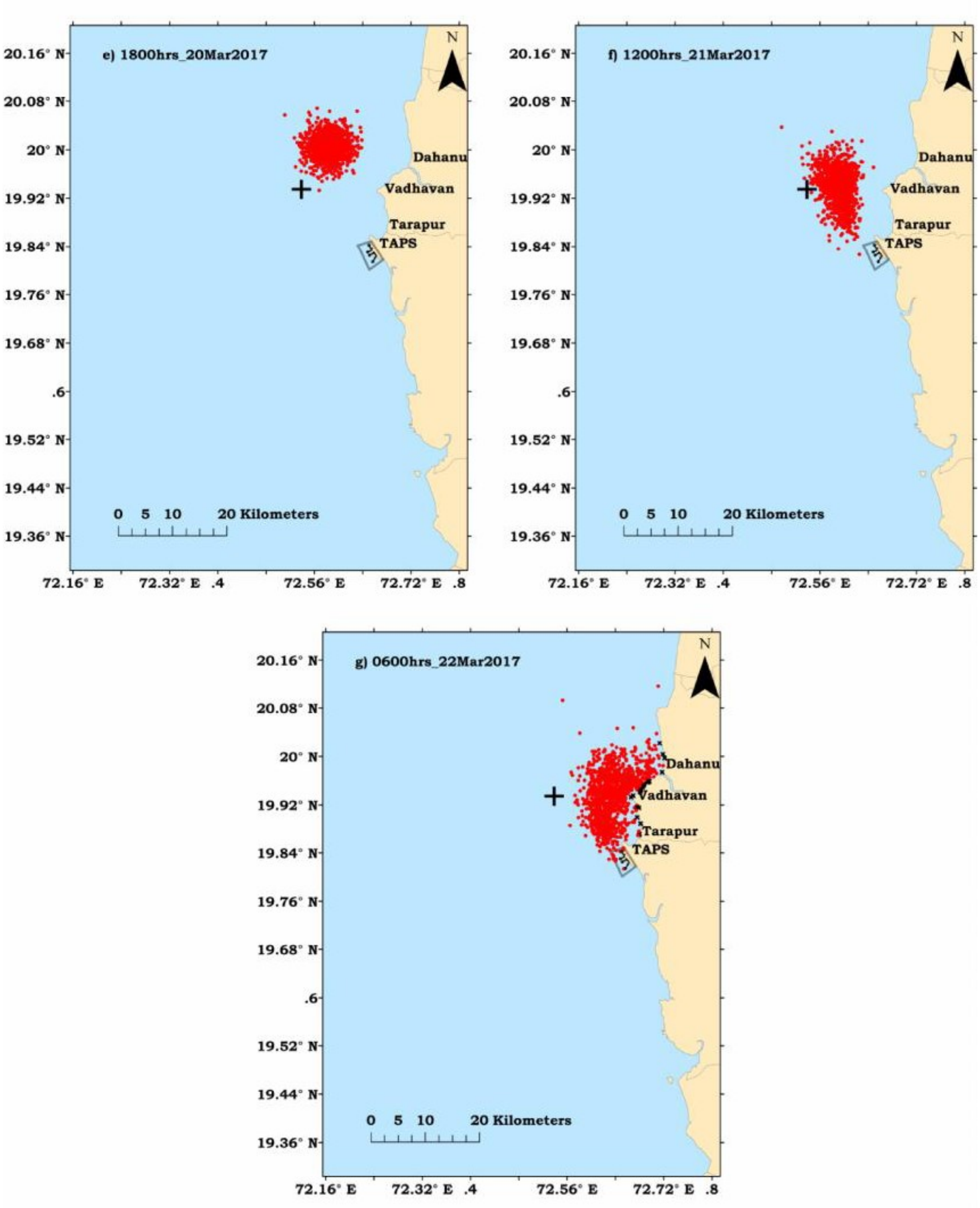


Fig. 30. Simulated oil drift pattern during neap tide days - March 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral. The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

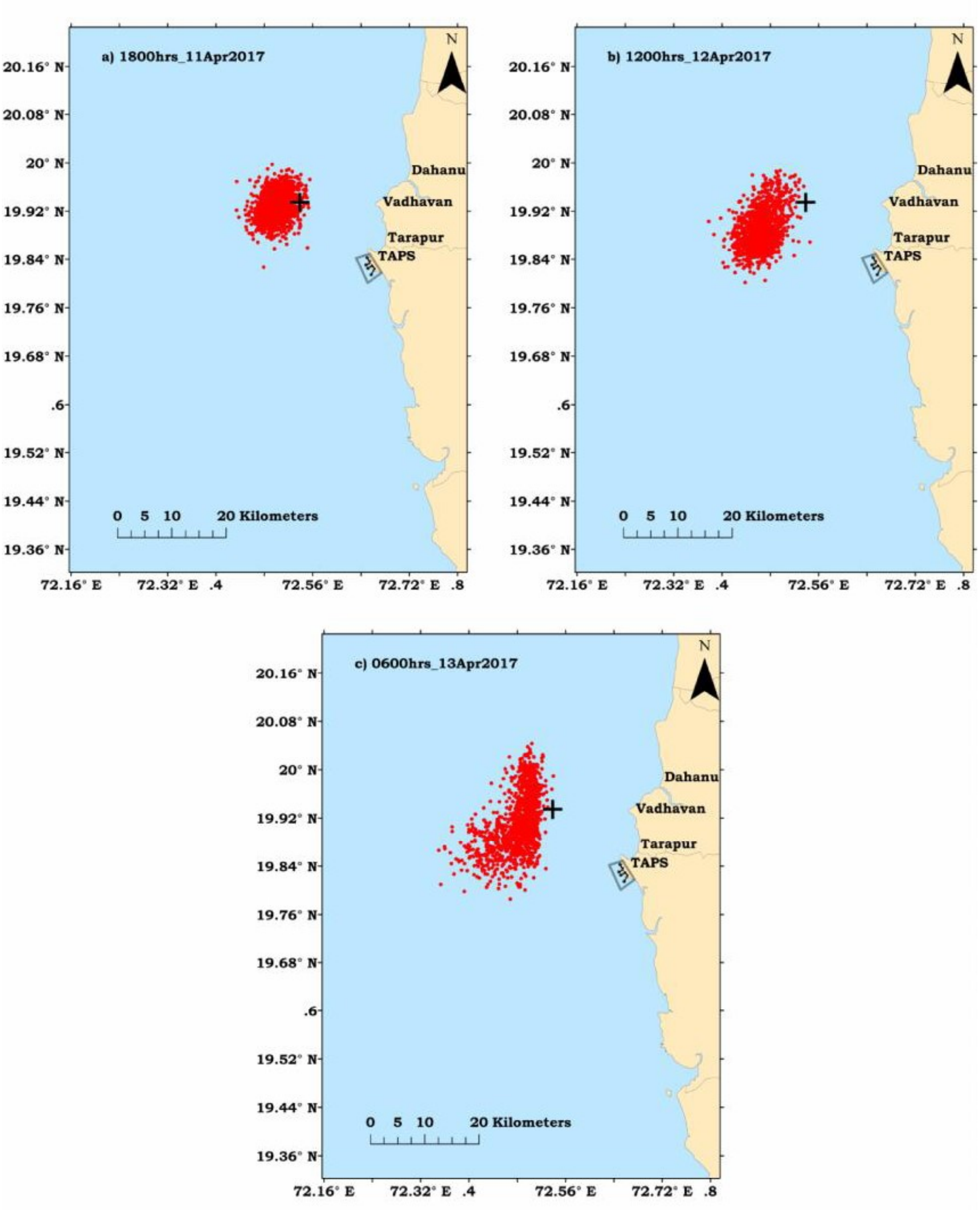


Fig. 31. Simulated oil drift pattern during spring tide days - April 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

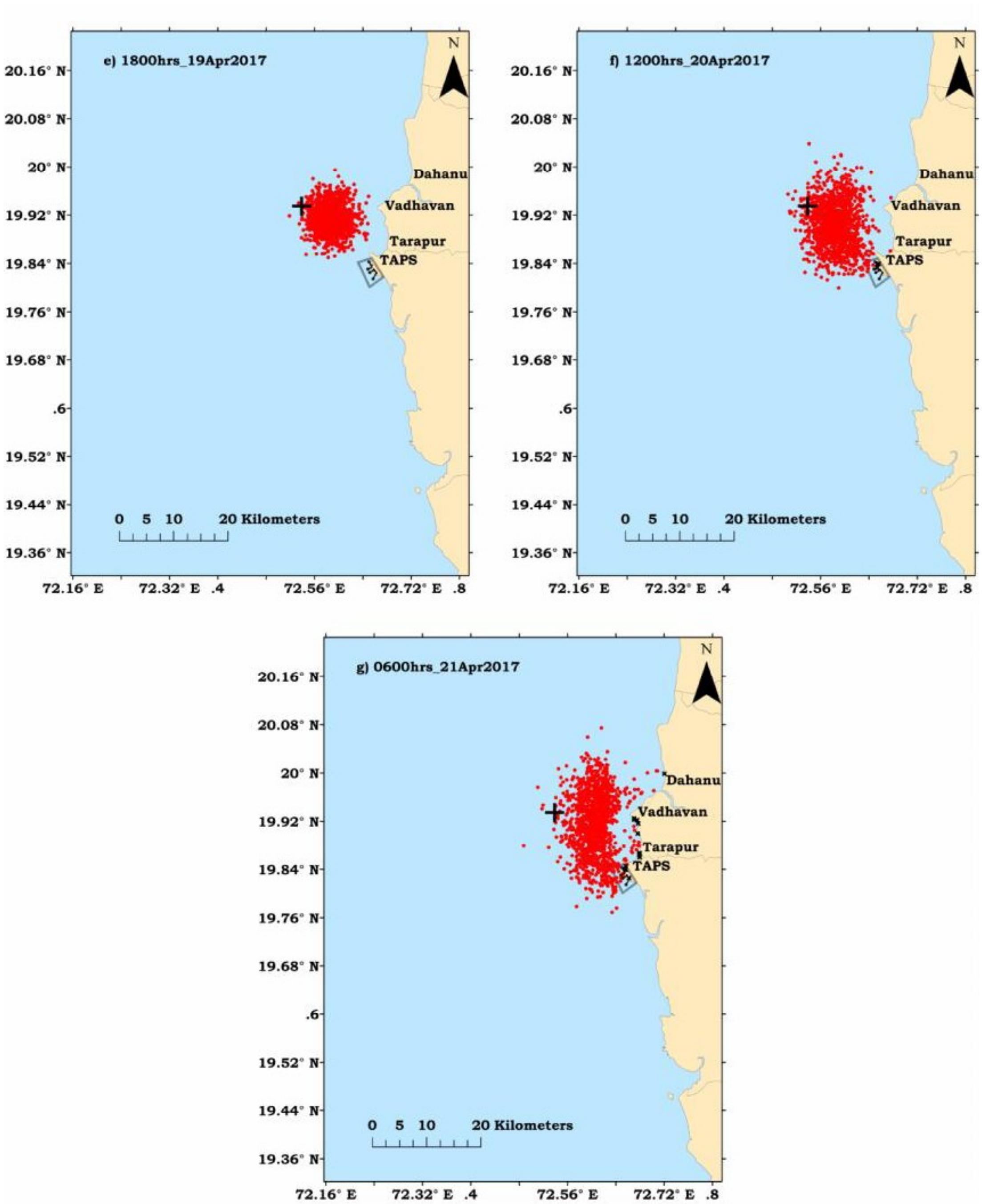


Fig. 32. Simulated oil drift pattern during neap tide days - April 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

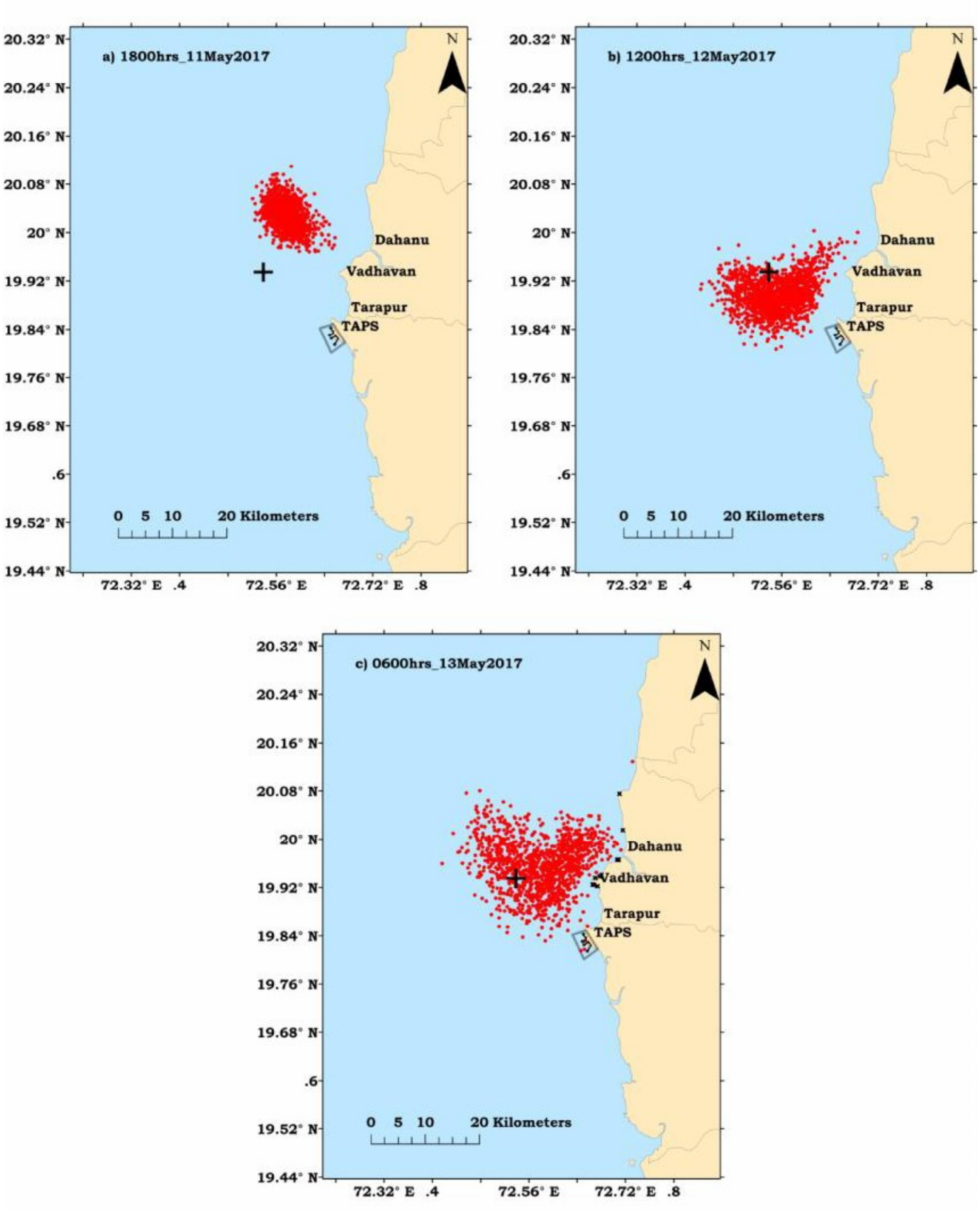


Fig. 33. Simulated oil drift pattern during spring tide days - May 2017. In all the panels, black plus sign denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

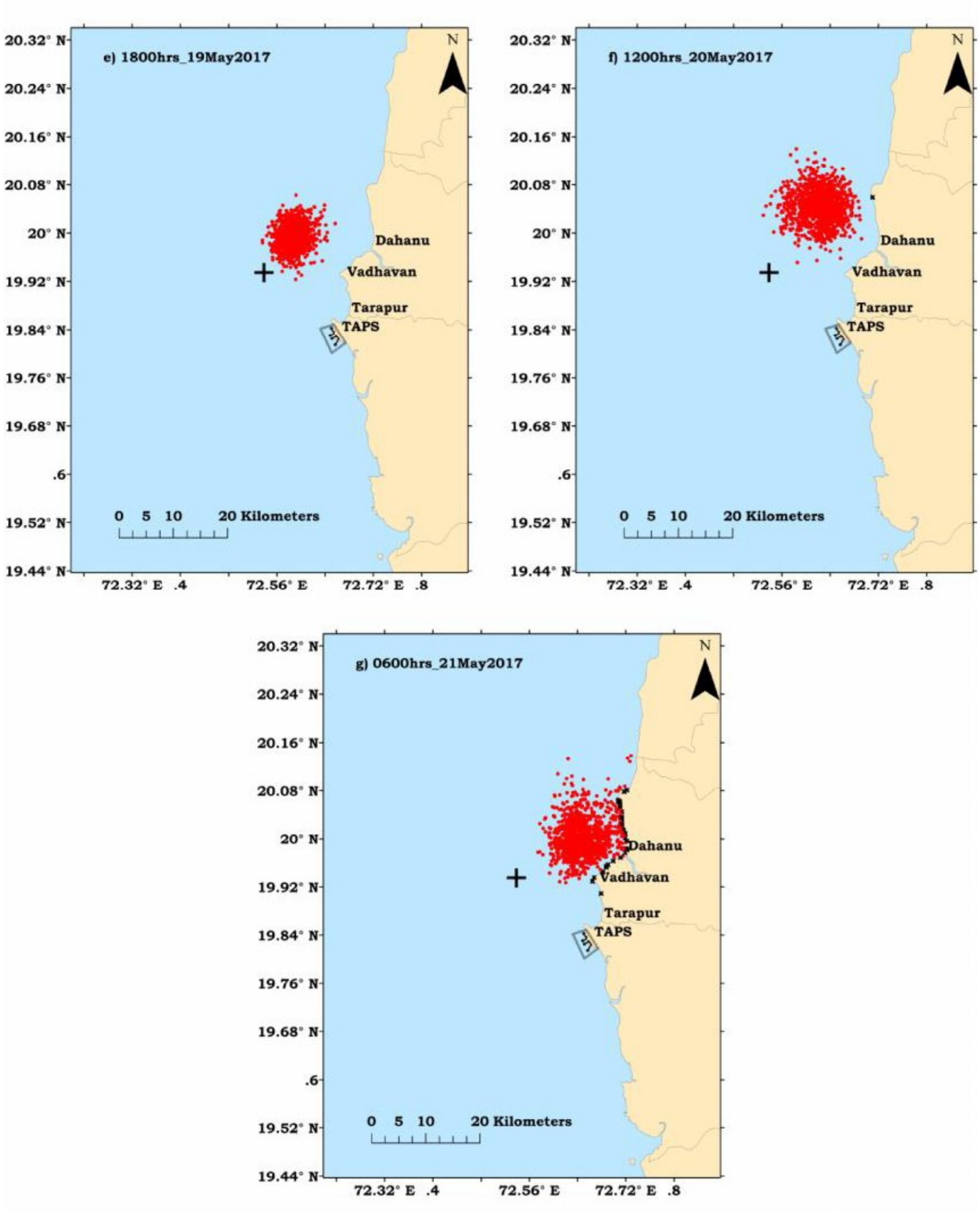


Fig. 34. Simulated oil drift pattern during neap tide days - May 2017. In all the panels, black plus sign denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

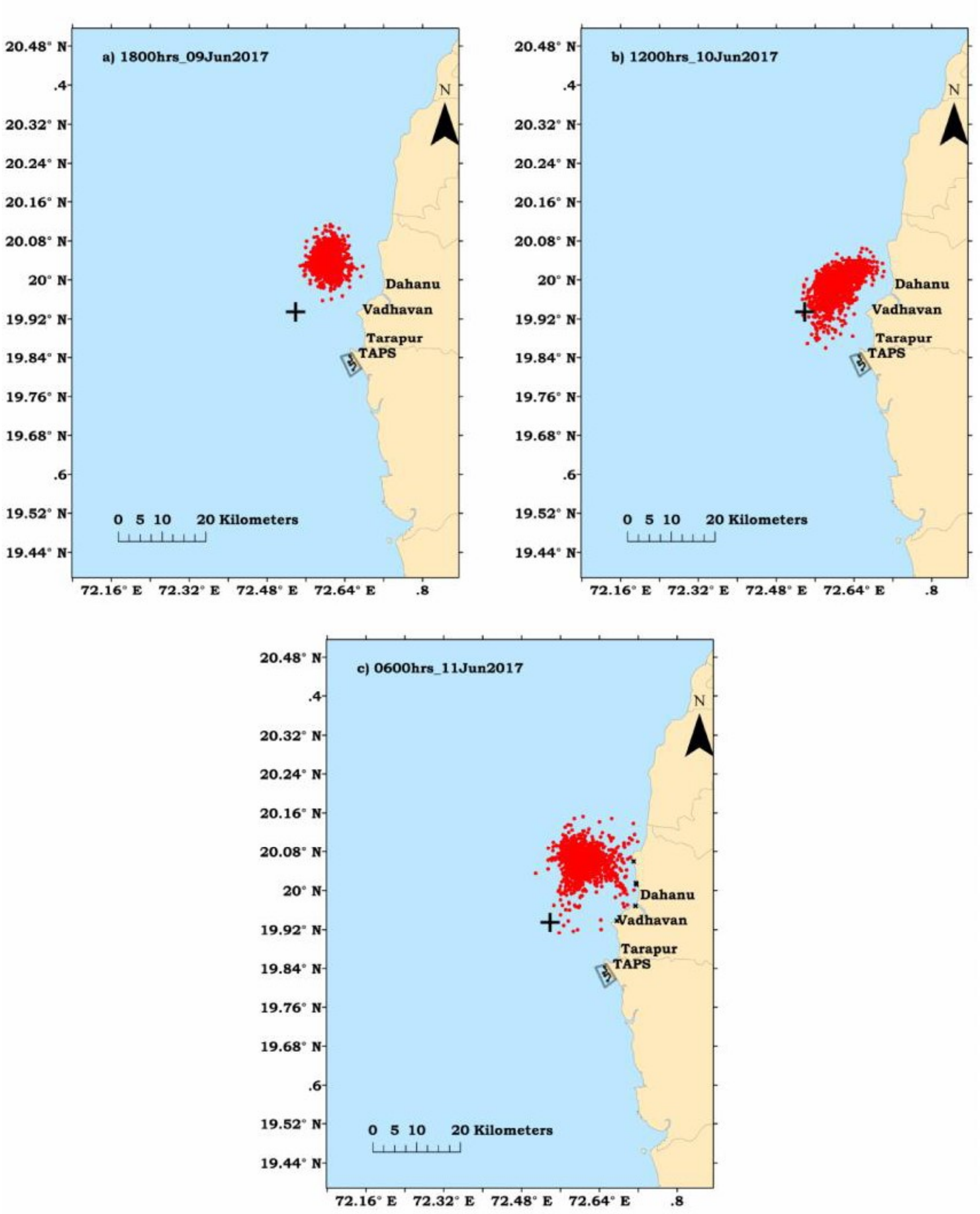


Fig. 35. Simulated oil drift pattern during spring tide days - June 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

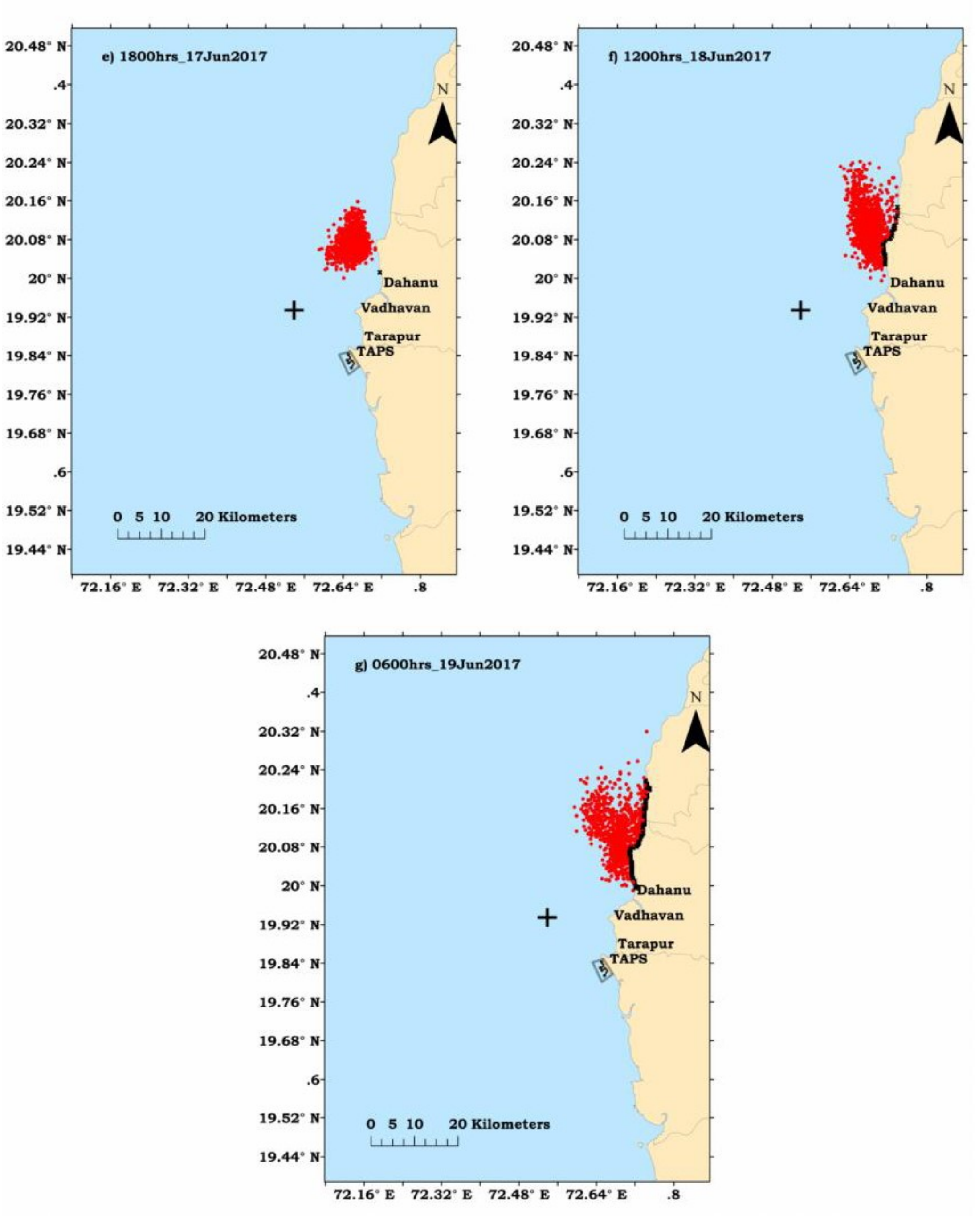


Fig. 36. Simulated oil drift pattern during neap tide days - June 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

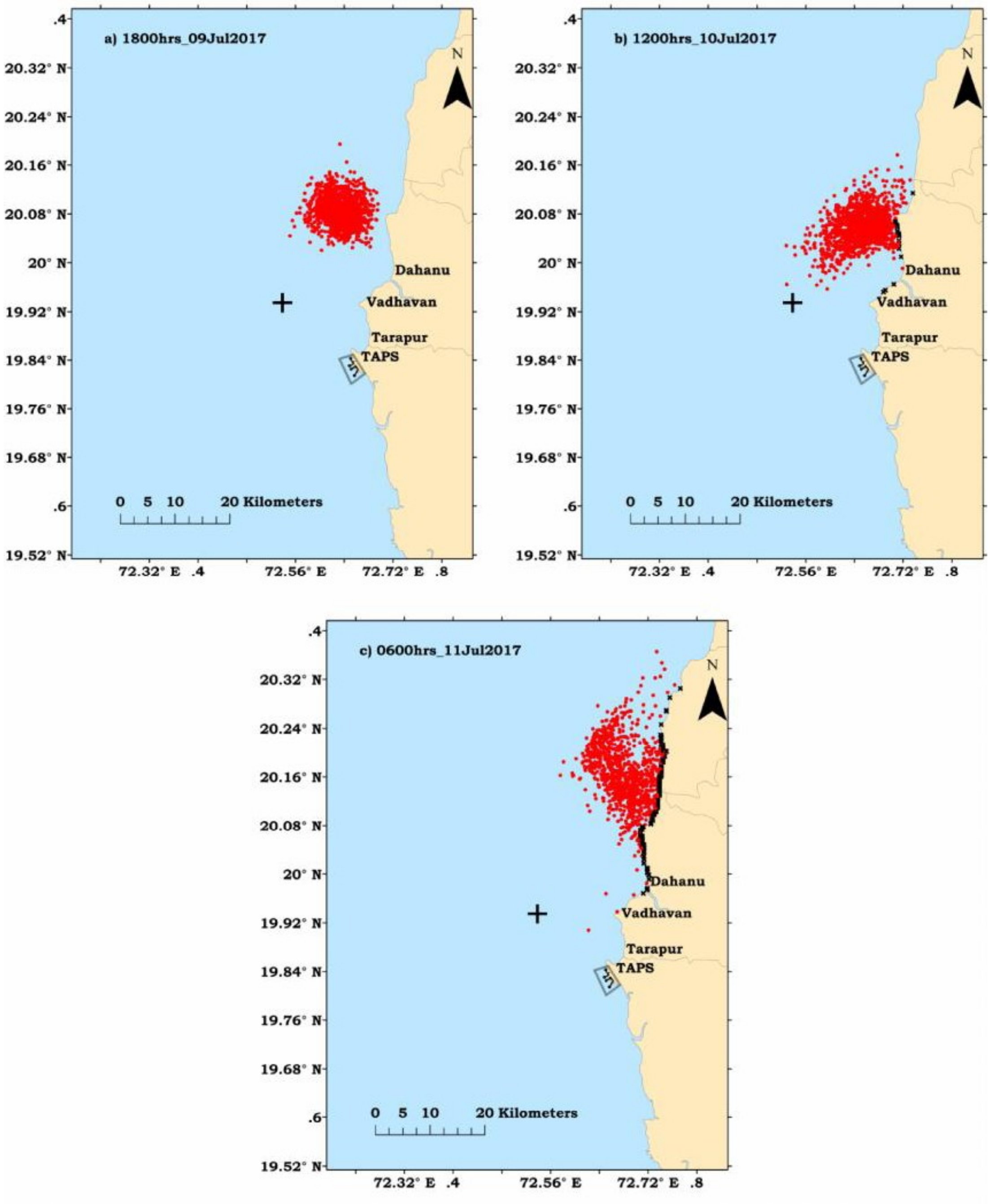


Fig. 37. Simulated oil drift pattern during spring tide days - July 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral. The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

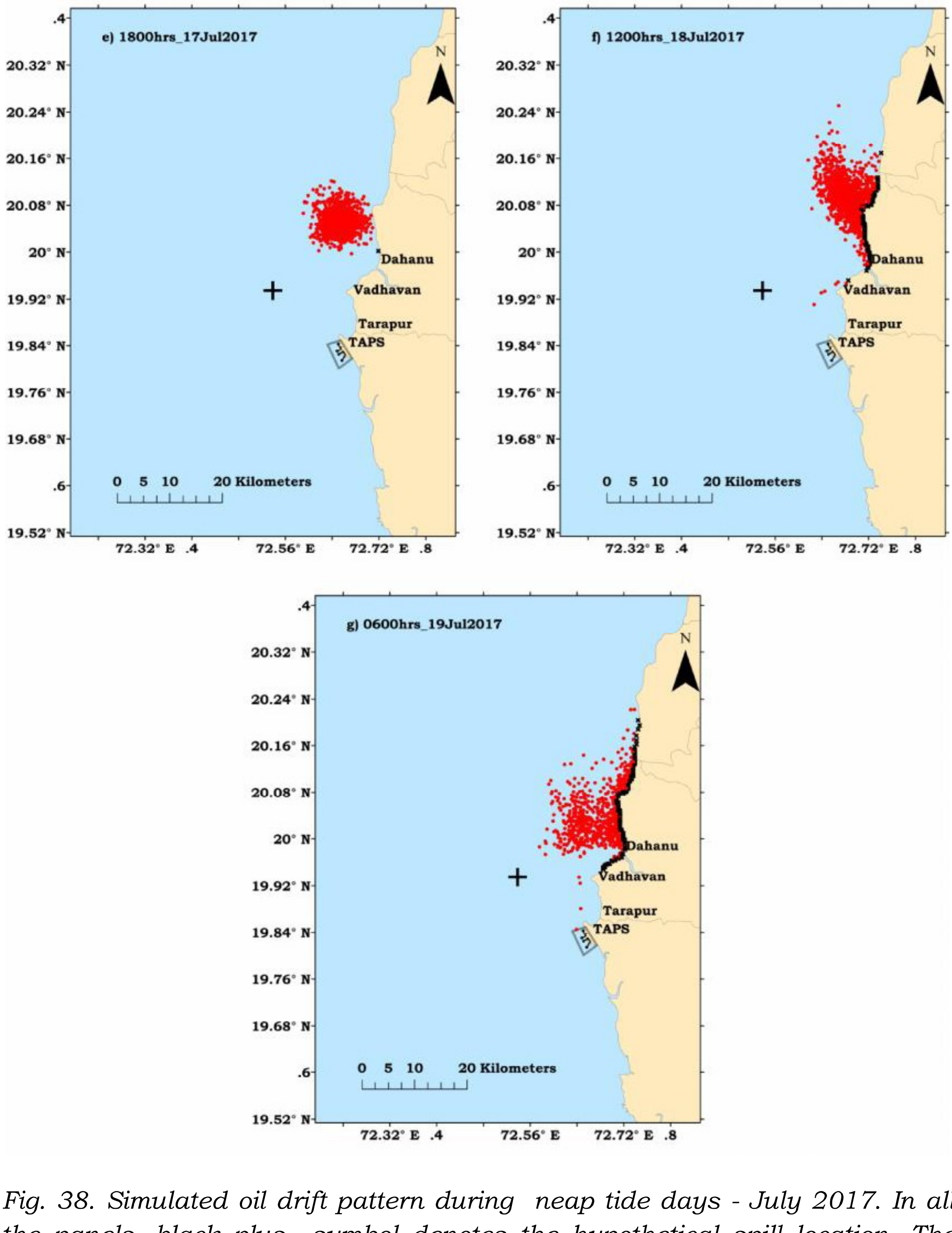


Fig. 38. Simulated oil drift pattern during neap tide days - July 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral. The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

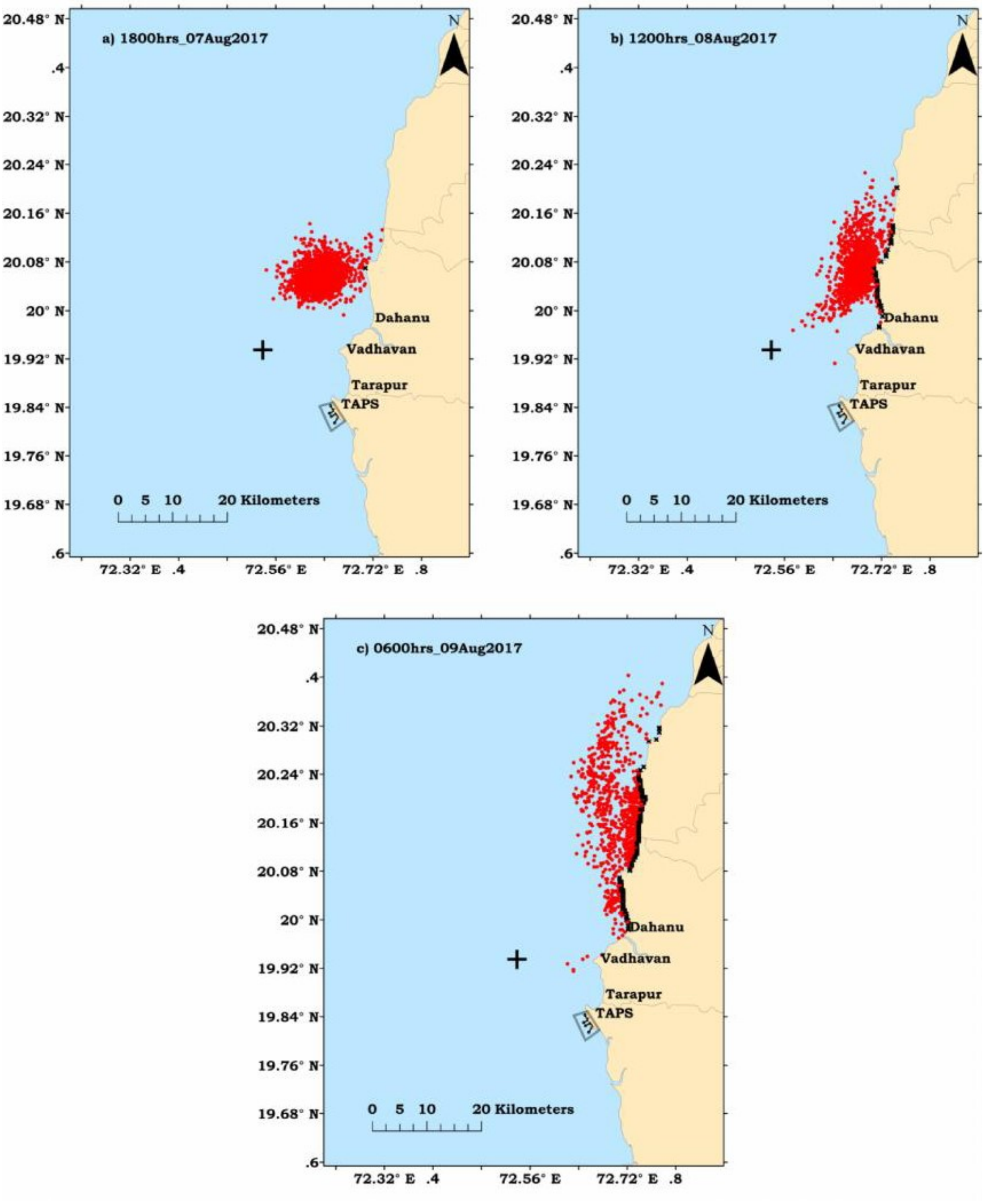


Fig. 39. Simulated oil drift pattern during spring tide days - Aug 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

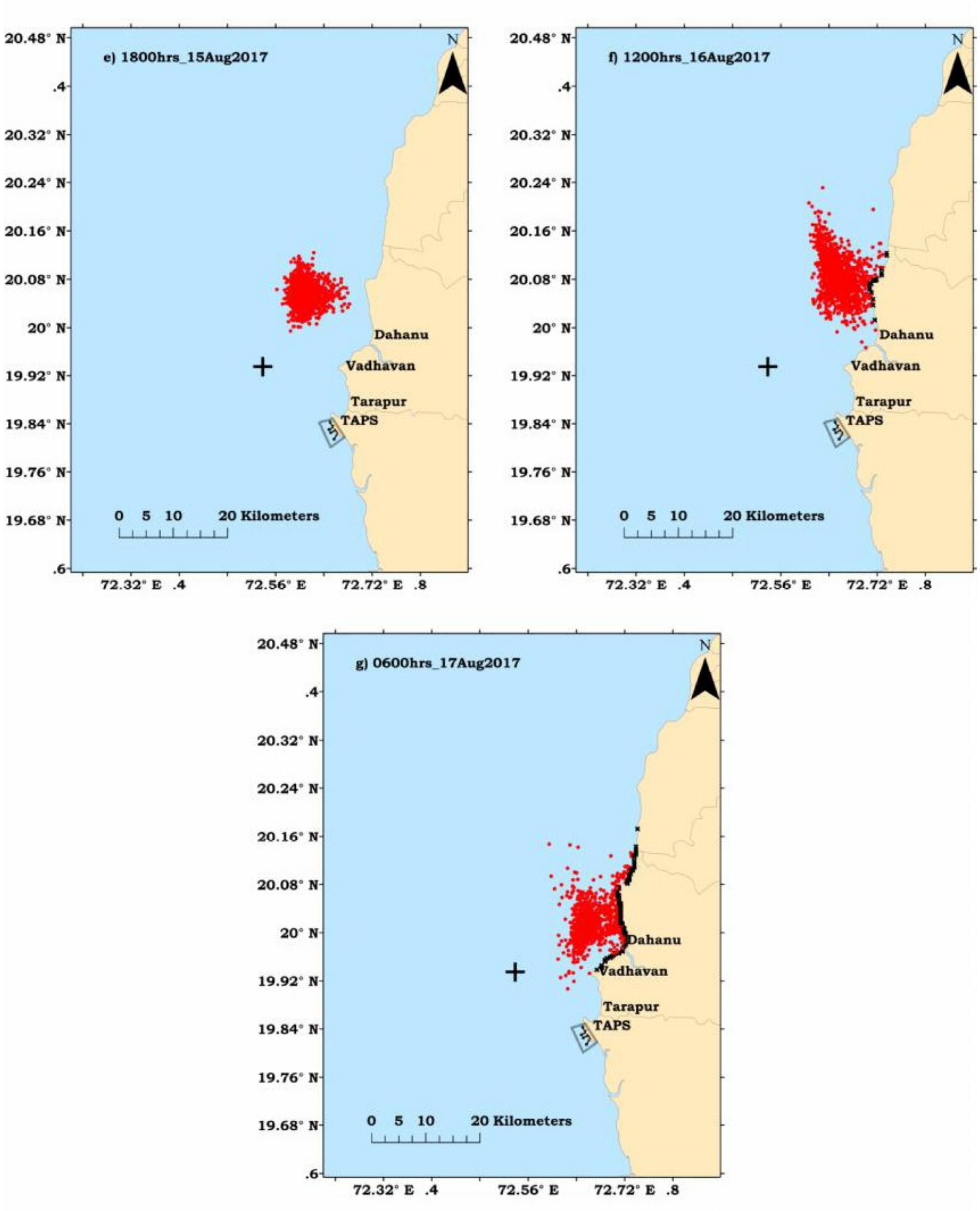


Fig. 40. Simulated oil drift pattern during neap tide days - Aug 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

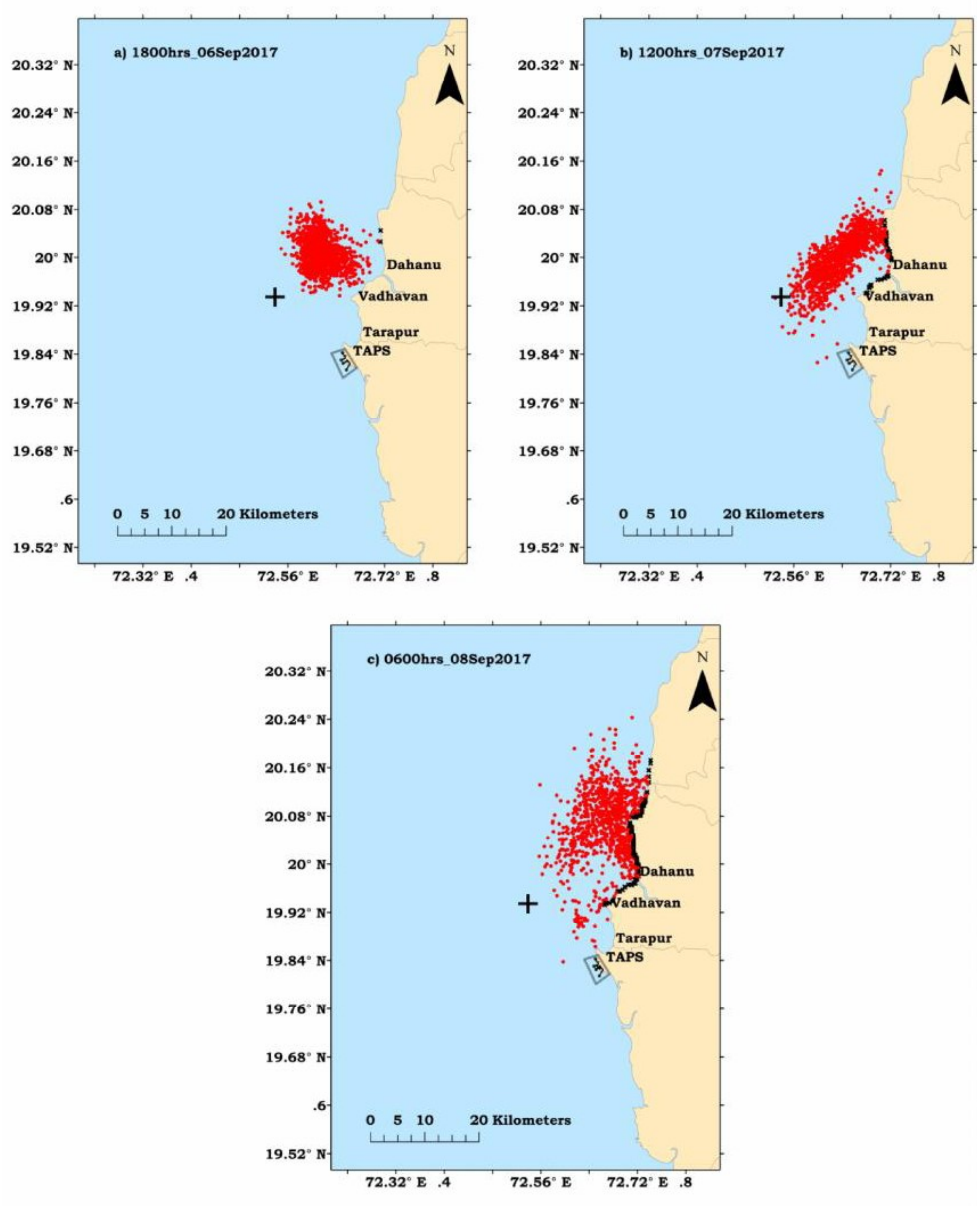


Fig. 41. Simulated oil drift pattern during spring tide days - Sep 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and beached status of oil particles respectively.

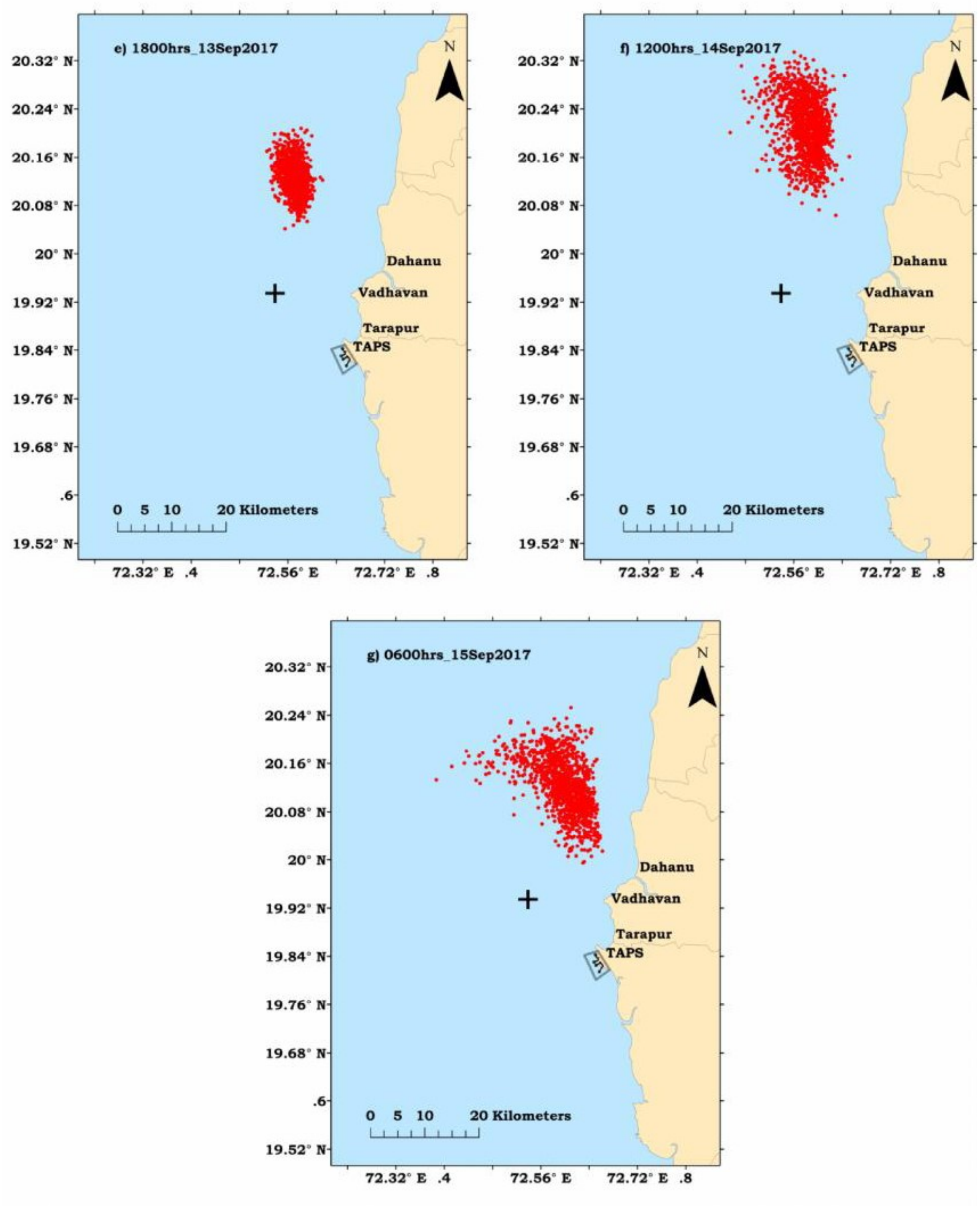


Fig. 42. Simulated oil drift pattern during neap tide days - Sep 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral. The red dots indicate the floating status of oil particles.

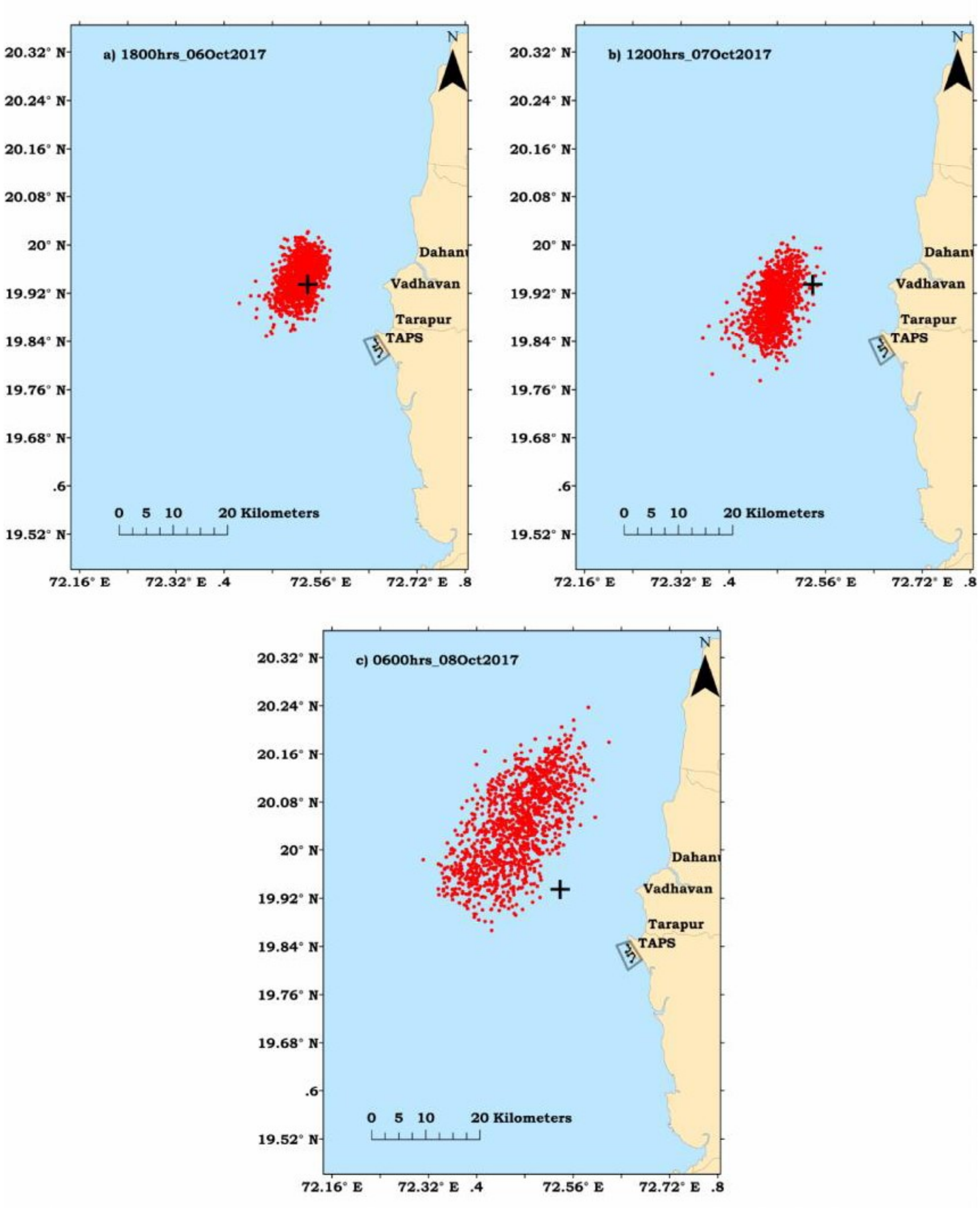


Fig. 43. Simulated oil drift pattern during spring tide days - Oct 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral. The red dots indicate the floating status of oil particles.

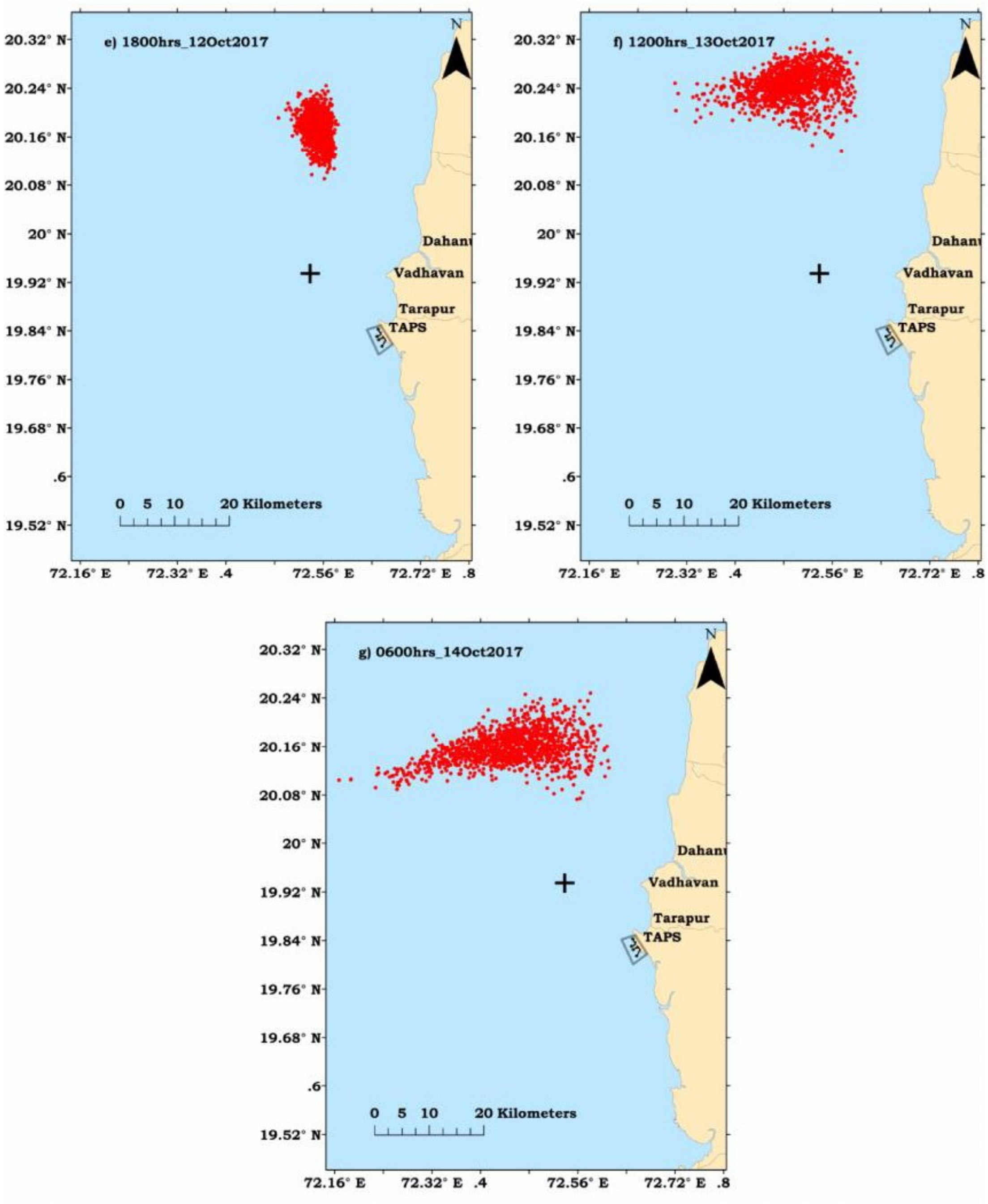


Fig. 44. Simulated oil drift pattern during neap tide days - Oct 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

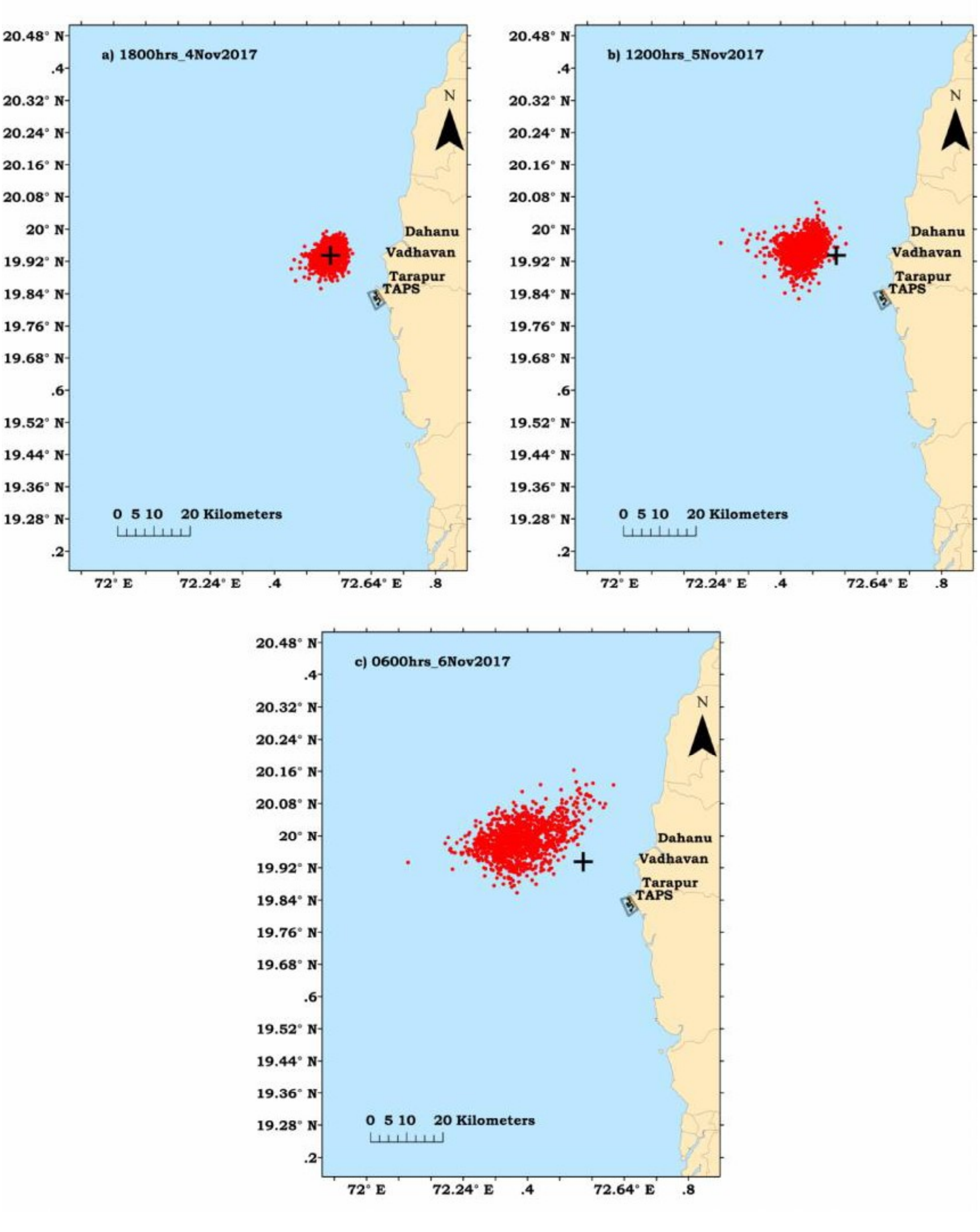


Fig. 45. Simulated oil drift pattern during spring tide days - Nov 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

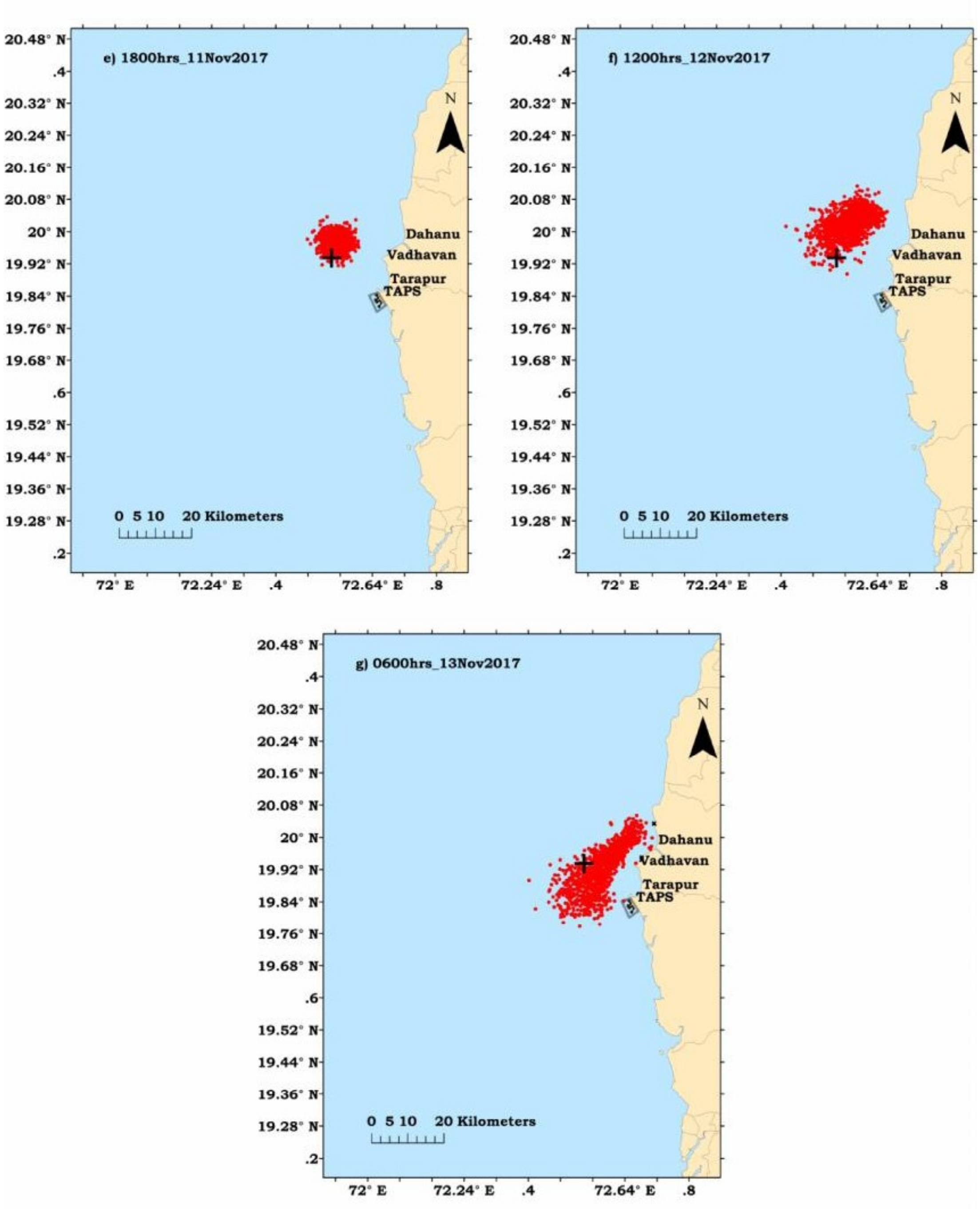


Fig. 46. Simulated oil drift pattern during neap tide days - Nov 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots and black X symbols indicate the floating and the beached status of oil particles respectively.

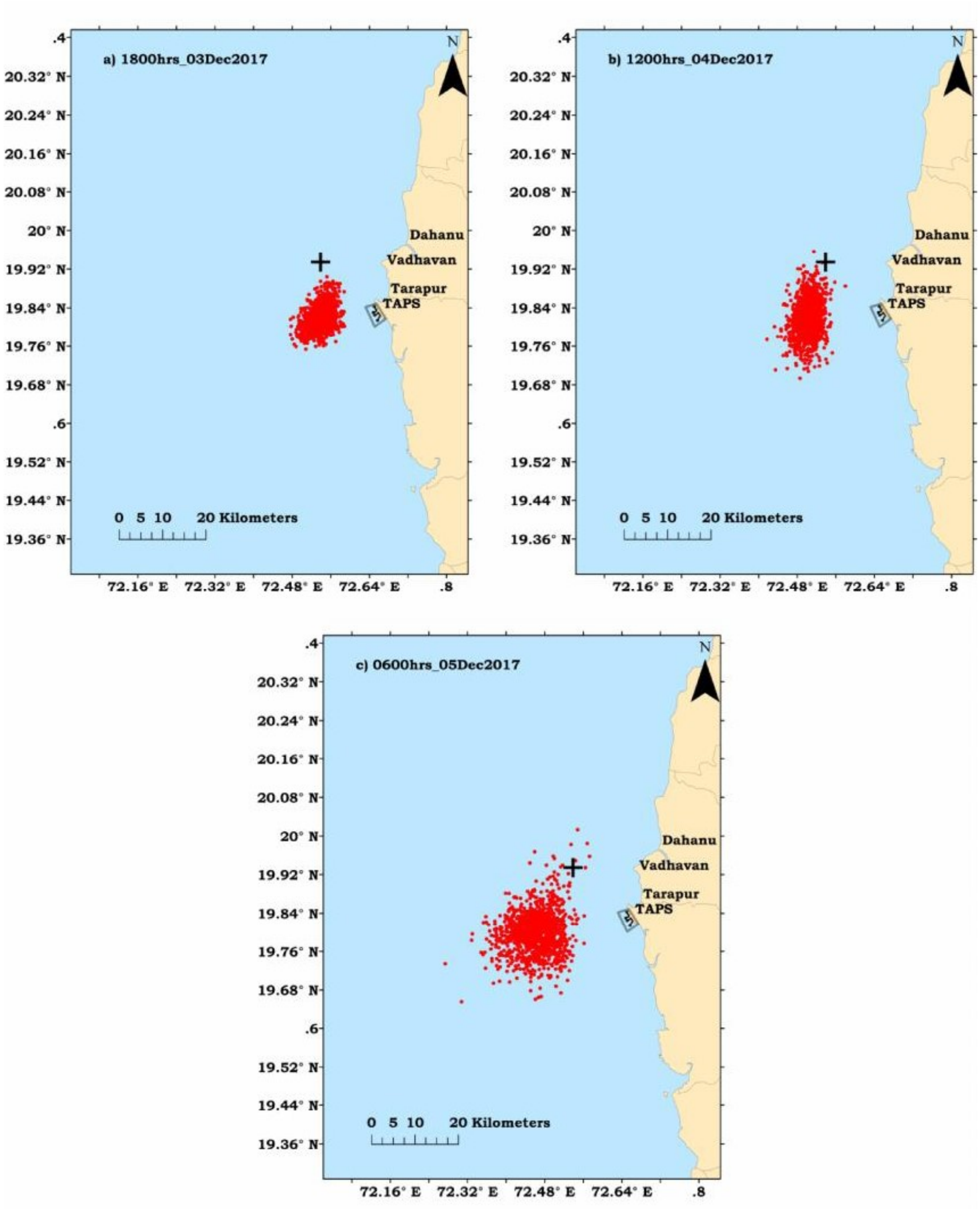


Fig. 47. Simulated oil drift pattern during spring tide days - Dec 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral. The red dots indicate the floating status of oil particles.

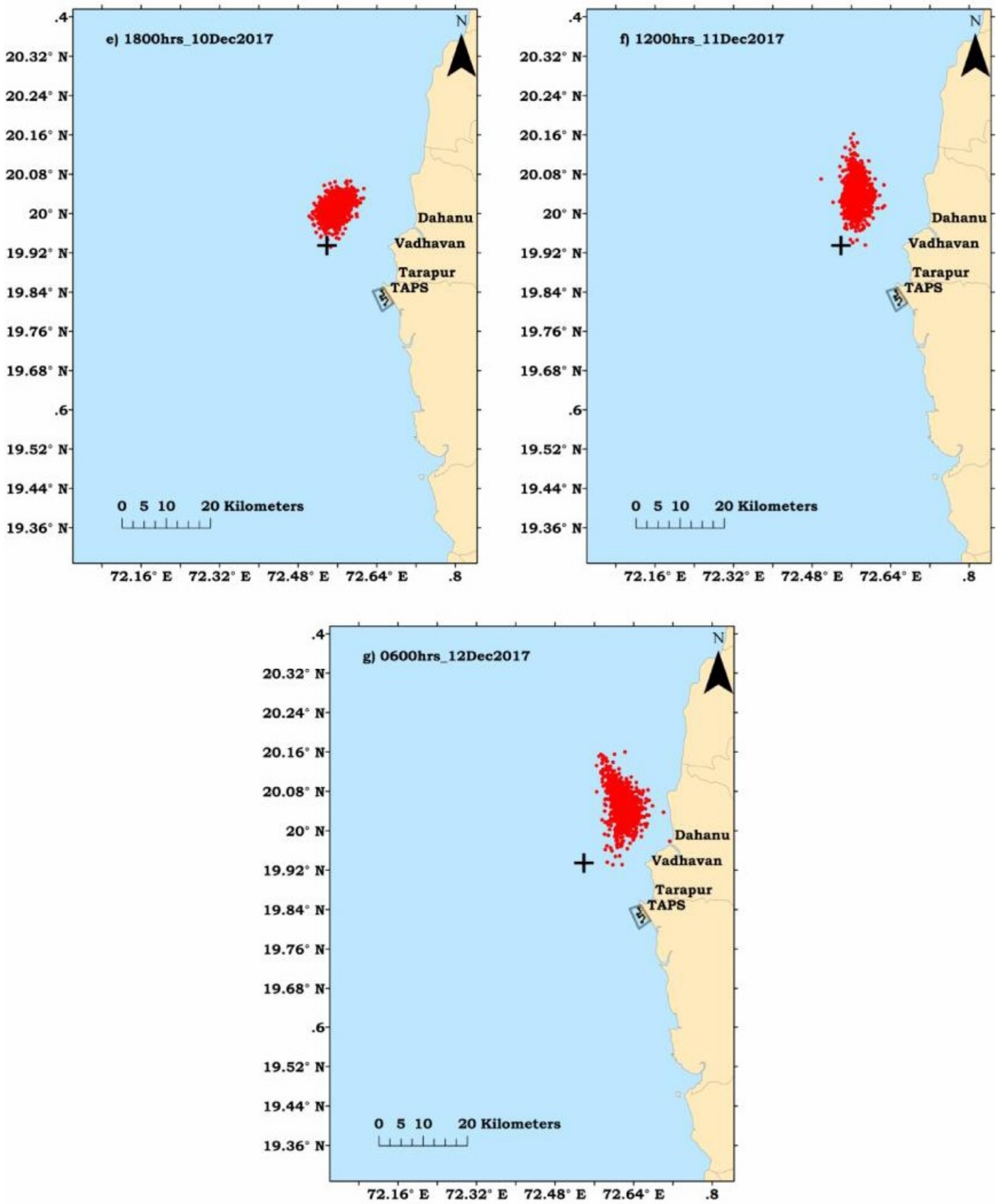


Fig. 48. Simulated oil drift pattern during neap tide days - Dec 2017. In all the panels, black plus symbol denotes the hypothetical spill location. The TAPS intake and outfall zone is represented by a quadrilateral.The red dots indicate the floating status of oil particles.

5. Interpretation of simulated oil spill drift patterns

Based on the oil spill trajectory prediction (Figures 25-48), an impact chart is prepared, which indicates the period of impact due to the spilled oil spread and drift to TAPS. Table 03, displays the period of impact during the spring and neap tide days of 2017. Letter N and Y denotes, "No impact" and "Impact" status on TAPS respectively.

Table 04: Impact Chart - Probable period of impact at TAPS

S. No	Month	Type of tide	Date/time (0000 to 2400 hrs)	18 th Hr	36 th Hr	54 th Hr
01	January	spring	12 to 14 Jan (2017)	N	N	N
02		neap	20 to 22 Jan (2017)	N	N	N
03	February	spring	11 to 14 Feb (2017)	N	N	N
04		neap	19 to 21 Feb (2017)	N	Y	Y
05	March	spring	12 to 14 Mar (2017)	N	N	N
06		neap	20 to 22 Mar (2017)	N	N	Y
07	April	spring	11 to 13 Apr (2017)	N	N	N
08		neap	19 to 21 Apr (2017)	N	Y	Y
09	May	spring	11 to 13 May (2017)	N	N	Y
10		neap	19 to 21 May (2017)	N	N	N
11	June	spring	09 to 11 Jun (2017)	N	N	N
12		neap	17 to 19 Jun (2017)	N	N	N

S. No	Month	Type of tide	Date/time (0000 to 2400 hrs)	18 th Hr	36 th Hr	54 th Hr
13	July	spring	09 to 11 Jul (2017)	N	N	N
14		neap	17 to 19 Jul (2017)	N	N	N
15	August	spring	07 to 09 Aug (2017)	N	N	N
16		neap	15 to 17 Aug (2017)	N	N	N
17	September	spring	06 to 08 Sep (2017)	N	N	N
18		neap	13 to 15 Sep (2017)	N	N	N
19	October	spring	06 to 08 Oct (2017)	N	N	N
20		neap	12 to 14 Oct (2017)	N	N	N
21	November	spring	04 to 06 Nov (2017)	N	N	N
22		neap	11 to 13 Nov (2017)	N	N	N
23	December	spring	03 to 05 Dec (2017)	N	N	N
24		neap	10 to 12 Dec (2017)	N	N	N

N- No Impact, Y- impact

6. Conclusions

The INCOIS oil spill trajectory prediction system was set for the region of study, including the Vadhavan Port limits and TAPS. The trajectory model was run during the spring & neap tidal cycles of year 2017, from a hypothetical spill location with a known quantity (700 Tons) of fuel oil. The intra-annual (monthly) variation, in the drift pattern of spilled fuel oil, especially during the spring and neap tide days of year 2017 was studied.

As far as this hypothetical study (during 2017) is concerned, the spilled oil from the Hypothetical Spill Location (HSL) should be contained within 18 to 36 hrs, so that the intake and outfall zones of TAPS will not get affected.

In case of accidental oil spills, within the port limit, the drift pattern has to be simulated on nowcast and forecast basis using oil spill trajectory models.

To combat or contain the spilled oil pollutant within the port limit, the port has to be equipped with necessary oil spill response facilities. It is also advised to monitor the port area (after establishment) using a continuous oil spill monitoring system.

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