

Simulation of trajectories of tar ball transport to the Goa coast

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Abstract

Arrival of tar balls to the Goa coast during pre- and southwest monsoon seasons has been a regular phenomenon in the past few years. In one such event, we observed tar ball deposits along the Goa coast during August 2010, April 2011 and May 2011 when no oil spill was reported in the Arabian Sea (AS). The only source for the formation of tar balls could be the spill/tanker-wash from the tankers passing through the international tanker routes across the AS. Assuming this, an attempt has been made to simulate surface winds, currents and tar ball trajectories for August 2010 using hydrodynamics and particle tracking models. Tar ball particles were released numerically at eight locations in the AS, and five of them reached the Goa coast, matching reasonably well with the observations. The present study confirms our view that the source of these tar balls is the accidental spills or tanker-wash along the international oil tanker route in the AS. A review of the global scenario of tar ball study is also presented in the introduction.

Key words: tar-ball transport, Goa coast, hydrodynamics, particle tracking, tar ball trajectories, international oil tanker route

1. Introduction

Tar ball deposition along the west coast of India (WCI)(for example, along the beaches of Goa, namely, Calangute, Baga and Vagator) has been observed since 1970. A few researchers have studied its chemical properties and the abundance (Nair et al., 1972; Dwivedi and Parulekar., 1974; Qasim., 1975; Dhargalkar et al., 1977; Oostdam, 1984; Kadam, 1988; Sengupta et al., 1993; Kadam and Rokade., 1996; Zakaria et al., 2001, Kaladharan et al., 2004; Chandru et al., 2008). The rate of deposition varies from year to year; only in some years, it is very significant. The deposition of tar balls on the beach is proportional to the quantity of oil spilled in the Sea. The sources of spills in the sea surface are offshore oil exploration, oil tanker accidents, oil-well blowouts, accidental and deliberate release of bilge and ballast water from ships, river runoff, discharges through municipal sewage and industrial effluents. Weathering processes cause approximately half of the spilled oil to disperse within 24 hours, particularly in warm tropical regions. After 24 hours, depending on sea state, water-in-oil emulsion (mousse) may be formed (Sengupta et al., 1993). The stability of this emulsion increases with the salinity of ambient water (Nesterova et al., 1983). The wind causes the suspended matter to adsorb on to the surface of the emulsion. The winds, waves, and turbulence at sea surface cause the emulsion to break into smaller pieces, which eventually become tar balls. Oceanic convergence plays a major role in the formation of tar balls since the convergence zones trap the floating organic and inorganic objects, which act as nuclei around the oil slicks/emulsions and form the tar ball (Heaton et al., 1980). The cyclonic eddy produces the convergence in the ocean while the divergence is due to an anticyclonic eddy. According to the Sand theory, when oil encounters sediment, sand and other shoreline materials, they may adhere together forming tar balls. Some tar balls contain biological communities such as diatoms, bryozoans, blue - green algae, and goose barnacles (Wong et al., 1973).

1.1. Floating tar balls

Depending on the density of the tar balls and seawater, tar balls either float on the sea surface or remain suspended in the water column, and finally, are washed on to the beaches based on the circulation pattern (Sengupta et al., 1993). The floating tar balls decrease in weight and increase in density (Nesterova et al., 1983). The tar balls that float on the sea surface under natural conditions have more stability and degrade very slowly. The basis for this slow destruction is the small ratio of surface area to volume; the surface layer of the tar ball formed by the microbial film of 0.5 to 1mm thickness might be shielding the tar ball (Nesterova et al., 1983). Holdway et al., (1986) conducted a circumnavigation survey for locating floating tar residues and observed that the Pacific, the Atlantic

and the Indian Oceans are minimal in quantities of tar, while semi-enclosed seas such as Mediterranean, Java and Red Seas and West European and Northwest African coastal waters are significant in tar quantity. However, observations of the last few years in the north Indian Ocean show that the tar ball deposits are greater than ever and are deposited along the west coast of India more or less regularly during pre and monsoon seasons. Price and Smith (1986) during the Sindbad Voyage in the Indian Ocean and South China Sea, based on the visual observations of oil slicks and tar balls reported that the occurrence of floating tar balls increases from Malaysia/Indonesia to the Middle East Gulf countries (international tanker route). As the Arabian Sea (AS) is an adjacent region to the Gulf countries, there is a possibility for tar ball formation in the AS, and subsequent deposition along the WCI during the monsoon period as the circulation is towards WCI. The concentration of floating tar balls in the Western Pacific from Tokyo to north of Hawaiian Island was 14 mg/m^2 with an average of 3.8 mg/m^2 (Wong et al., 1973). The observed floating tar residues in the Pacific Ocean are due to tanker washings along the tanker route from the Persian Gulf to Japan (Wong et al., 1976). In Cretan Sea, the deposition varied from 1 to $4280 \text{ } \mu\text{g/m}^2$, with an average concentration of $318 \text{ } \mu\text{g/m}^2$ (Kornilios et al., 1998). In the AS, as a whole, the concentration was in the range of $0\text{-}6 \text{ mg/m}^2$, and along the oil tanker route in the Bay of Bengal, the range was $0\text{-}69.75 \text{ mg/m}^2$; otherwise, the Bay of Bengal is free from floating tar balls (Sengupta and Kureishy., 1981).

According to Butler et al., (1975), the residence time of a tar ball in the ocean is one year. The floating tar balls observed on the sea surface have a residence time of 60-90 days in the AS (Sengupta and Qasim., 1982). Shannon et al., (1983) deduced from the drift card data, that the residence time of tar balls is of the order of months. The above studies show that the residence time of tar ball in the sea may vary from a few months to one year, and differs from region to region based on environmental conditions. Eagle, (1979) measured the concentration of floating tar balls with respect to an oil spill. He conducted monthly cruises around the southwest coast of South Africa and found that that area was free of floating tar, but when there was a spill caused by tanker collision, he observed the movement and dispersion of tar balls.

1.2. Tar ball distribution

The ultimate fate of the floating tar balls is to reach a coast under the influence of prevailing meteorological and oceanographic conditions, provided the circulation is towards the coast and the floating tar balls are also near the coast. However, when the circulation pattern is away from the coast, and the coast is far from the source, the floating tar balls may not reach the coast, and eventually end up in biodegradation. The distribution of tar in the sea depends on the prevailing

winds and surface circulation (Wong et al., 1973). The surface circulation could influence the small scale (75km) and mesoscale (500km) tar distribution (Shaw et al., 1979). For example, along the Lumley beach, West Africa, despite the southwestern monsoonal winds and eastward flowing Guinea current, the maximum deposits occur during June to August (Okera et al., 1974). The occurrence of tar balls along Trinidad and Tobago is a seasonal phenomenon, when the South Equatorial Current dominates circulation of both the Islands. During January to April, the prevailing northwesterly currents and northeasterly winds cause more tar strands on Trinidad than on Tobago. During June to November, when the currents are northerly and winds are southeasterly, larger quantities of tar strands occur on Tobago than Trinidad (Georges and Oostdam., 1983). Kornilios et al., (1998) observed that floating tar balls originating in the Ionian Sea enter the Cretan Sea through Antikithira Strait along with the surface current. The NW Pacific is heavily polluted due to the direct effect of Kuroshio Current system, which transports floating tar balls to the NW Pacific Ocean (Wong et al., 1976). Shannon et al., (1983) observed the movement of tar balls with the Agulhas Current in the southwestern Indian Ocean. The floating tar balls also get transported by the south equatorial current of the Pacific and Indian Oceans (Holdway et al., 1986). Eagle, (1979) noticed that concentration of tar balls was higher in the Gulf Stream and north Atlantic Gyre waters (deep waters) compared to coastal waters. Longshore currents can influence the tar ball transportation. Eagle (1981) conducted a physical experiment by releasing tar balls perpendicular to the shoreline of the beach when the sea was calm; he found that after 5 days, the tar balls moved 43 m from the released point. Nemirovskaya (2011) also noticed that tar balls moved with the alongshore current, especially during storm, and accumulated in the areas of cliffs. When the tar balls are in the surf zone, breakers push them to the shore. The deliverance of tar balls onto the beaches is high due to plunging and surging type of breakers (Tsouk et al., 1985). A survey conducted along the beaches of Qatar revealed that tar ball deposition ranged between 2 and 1132 gmm⁻¹, on an average 290 g m⁻¹. Despite the “Al-Shamal” northwesterly stormy winds, the tar deposition is much higher in the winter season (November to March) along this coastline (Al-Madfa et al., 1999). Sontro et al., (2007) studied the transport mechanism of oil/tar from Coal Oil Point at California, and found that surface currents, winds, swells and sea water temperature can influence tar accumulation at beaches. There is a seasonal variation in beach tar accumulation - higher at Coal Oil Point beaches during summer than in winter. The multiple regression analysis indicated that winds and swells are important factors influencing tar accumulation at Coal Oil Point.

1. 3. Tar ball deposition

It was observed that when a divergence passed through approximately 20 km away from Bermuda, there were no tar deposits, but when a convergence passed, heavy deposition of tar balls were observed (Butler et al., 1998). The size (diameter) of tar balls deposited on the Lumley beach in West Africa ranged up to 8 cm (Okera et al., 1974). Fig.1, shows the locations, where tar ball deposition as well as floating tar balls, were observed.

Fig. 1. is to be inserted here

Dwivedi and Parulekar., (1974) observed that tar ball deposition on beaches of Goa, India, varied considerably with highest deposition of 4480 g/m² on the beach at Sinqerim, Goa during pre-monsoon season. The average deposition along the WCI was 20 g/m² in 1976 - deposition is the heaviest in monsoon months (Dhargalkar, 1977). A tar ball survey among six eastern Caribbean Countries revealed significantly higher concentrations and common occurrences of tar balls on the east and north than the west coasts (Corbin et al., 1993). The rate of deposition along the beaches of Cameroon varied with the seasons. The Down Beach Limbe experienced high deposits of tar balls during February, March and October; the Mile Six Beach during October; while, the Batoke Reference Beach in January. During June-July, all the beaches in Cameroon experience peak percentage of tar balls, and during May and August (rainy season), the least percent of tar balls (Gabche et al., 1998). Kaladharan et al., (2004) observed tar ball deposition at different beaches off Cochin, India during April and May 2001.

Deposition of tar balls along the WCI is becoming a regular phenomenon during pre- and post-monsoon seasons. The average depositions of 28 gm/m² and 20 gm/m² were reported along the WCI during 1975 and 1976, respectively, and the total deposition was approximately 1000 and 750 tones, respectively (Dhargalkar et al., 1977). Present deposition rates along the Goa coast are discussed in Section. 3. The west coast of India is more conducive to tar ball deposition than the east coast; this might be due to the international tanker traffic in the AS. On the west coast, the Goa coast often gets more tar balls than any other region. Some of the sources likely to cause the tar ball deposition along the WCI are: (i) the discharge of tank washings from oil tankers while returning from Mumbai port after unloading their cargo (Reddy and Singbal., 1973), (ii) oil leak from the Mumbai High, the largest offshore oil-producing field of India - insignificant spill could occur during operation or accidents throughout the year, (iii) the Gulf of Kachchh (GoK) has several ports such as Kandla (receiving imported oil from tankers), Adani, Okha and Salaya as well as several Single Point

Moorings (SPMs), where the oil is thrown out from large tankers all the way through under sea pipelines for landward transport of oil, (iv) Asia's largest oil refinery is located at Jamnagar in the GoK, WCI and considering the quantity of oil handled and transported, the area is most vulnerable to oil spills, (v) the Alang-Sosiya Ship-Breaking Yard (ASSBY) located in the Gulf of Cambay, WCI is the biggest ship-breaking yard in Asia, (vi) oil transportation and tanker operations are the major oil sources in the Red Sea and Persian Gulf. All the spilled oil from the above sources spread in the AS and follow the AS circulation pattern and (vi) barges, ships and tankers visit the Mormugao port, which primarily handles iron ore. Earlier, there were incidents of collision that resulted an oil spill. Moreover, Goa is closer to the International tanker route in the AS (Fig. 2a) - a key factor for regular deposition of tar balls along the WCI. Thus, all the spilled oil in the AS, eventually deposit onto the beaches of WCI in the form of tar balls in the summer monsoon season, while the circulation pattern and surface winds are favorable to their transport.

The present study primarily aims at tracking the trajectories of tar balls that were deposited along the Goa coast in August 2010 from the region of origin. No simulation has been performed for the tar balls that were deposited during April and May 2011 because the affected coastal length is less than 5 km (very low compared to the event of 2010) and it is very difficult to get such fine resolution results. We have collected tar ball samples from the beaches of Baga, Calangute and Candolim in North Goa and Velsao, Betalbatim, Colva and Benaulim in South Goa to do further analysis, including fingerprinting using GC-MS to identify their source oil, and this work is in progress.

2. Material and Methods

2.1. Sample collection and analysis

We have followed the method given in the UNESCO manual (Anonymous, 1984) for tar ball sampling during Aug-Sept 2010 and May 2011. Samples were collected from one-meter strip, running across the beach from high tide line to the present water level. As it is difficult to collect the whole tar ball deposit from the entire strip, we collected the samples available in one square meter area from three representative locations in each strip. These tar balls were cleaned following the method of Golik et al., (1981). The tar balls were put in a metal box containing 2mm holes on all sides and bottom and then carried to the sea, where the sand of less than 2mm size was washed off, leaving the tar balls inside the box. Foreign materials were removed before weighing. The average weight of the samples collected from the three representative locations gives the weight of tar ball deposit in one square meter area in that particular strip. The same method was followed for the other

two strips. The average of these three weights is considered as the amount of deposition or the abundance of tar ball of that particular beach.

2.2. Models used

Winds and currents are the major forces which are responsible for the transport of tar balls to the coast. Therefore, we have relied on atmospheric and ocean models to obtain these parameters for each grid point in the model domain. A short description of the models used in this study is given below.

2.2.1. WRF model

Numerical simulations were carried out to generate winds and other atmospheric parameters over the AS using the Weather Research and Forecasting (WRF) model (Shamarock et al., 2008). WRF is based on fully compressible, non-hydrostatic Euler equations, third order Runge-Kutta (RK3) integration scheme and Arakawa C grid. The vertical mixing and diffusion were done by Asymmetric Convective Model with non-local upward mixing and local downward mixing (ACM2) scheme (Pleim., 2007) and surface physics by Pleim-Xiu scheme. In the model, SBU-YLin, a 5-class microphysics scheme with riming intensity was used to account for mixed-phase processes (Lin and Colle., 2011) and Pleim-Xiu Land Surface model (Gilliam and Pleim., 2010). Two-layer scheme with vegetation and sub-grid tiling was used. The Rapid Radiative Transfer Model (RRTM) and Dudhia scheme (Skamarock et al., 2008) were used for long wave and short wave radiations. The global Final analysis data from the National Centers for Environmental Prediction (NCEP) having a spatial resolution of 1° and a temporal resolution of 6 h have been used to provide the initial and boundary conditions to the model. Terrain data have been taken from the US Geological Survey (USGS), which has a resolution of 0.9km.

2.2.2. Modeling Hydrodynamics

The oil residue or a tall ball advects along with surface winds and currents, and their net movement can be simulated using a tracking method. In the present study, currents for the selected domain have been simulated using MIKE21 hydrodynamic model. MIKE21 HD Flow model is a hydrodynamic modeling system for 2D free surface flows. It is widely used for simulation of currents, water level variations, sediment transport, and particle tracking in estuaries and coastal areas. MIKE21 can accommodate high-resolution grid for simulation of water level variations, currents and all other related parameters. It solves 2D shallow water equations of momentum and

continuity equations on a vertically integrated and incompressible mode. The vertical acceleration of the flow is assumed much smaller than the pressure gradient.

A Cartesian coordinate system is used in the model with grid size of 5000m x 5000m to accommodate the tanker routes in the domain. The model domain is shown in Fig. 2(b).

Fig. 2 is to be inserted here

Since the area (Goa coastal region) of interest lies off the WCI and oil tanker routes, the southern boundary of the model is kept at Surathkal (13° N) and the northern boundary at Narpad (20° N). The basic input parameters required to simulate the hydrodynamics are bathymetry, tides and winds. The bathymetry data are generated from the combined data of MIKE-CMAP and modified ETOPO 5 (Sindhu et al., 2007). The domain extends to 1111 km and 777.7 km, respectively in the X and Y directions, covering the area bounded by the longitudes 65° to 75° E and latitudes 13° to 20° N. The waterlevels were predicted for open boundaries from Global Tidal Model (inbuilt in MIKE ZERO).

2.2.3. Tracking of tar ball transport

Tar ball transport is tracked using Particle Analysis (PA) module of MIKE 21. PA module is based on Lagrangian Random walk technique, and is used for the simulation of trajectory of tar ball; tar balls are considered as floating passive particles. The input parameters required to run the PA are winds and currents. In the present study, currents are obtained from the MIKE 21HD and winds from the WRF model. Using these inputs, we have run the Particle Analysis model for the period August 2010.

3. Results and discussion

The Meteorological and Oceanographic parameters that are responsible for the transport of tar balls to the shore have been discussed in Section 1.2. In the present study, WRF model is used to simulate the initial conditions required for running the hydrodynamic model. The initial conditions are zonal and meridional components of wind and sea level pressure at 10m height. The hydrodynamic model simulations are carried out for the periods August-September 2010 and 26 October-05 November 2011 with spatial resolution of 18 km and temporal resolution of 1 h. As the accuracy of hydrodynamic results depends on the modeled winds, the WRF model winds for the period August 2010 have been validated with Autonomous Weather Station (AWS) wind data. The accuracy of

AWS is 0.2 m/s for wind speeds in the range 0–60 m/s, 3° for wind direction in the range 0–360°The model winds are consistent with the measured data as shown in Fig. 3.

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Currents have been simulated for the selected domain with a spatial resolution of 5 km and temporal resolution of 30 minutes using hydrodynamic model. Since current data are not available for August 2010, we have simulated currents for the period 26 October to 05 November 2009 and validated the results with measured data of 26 October to 05 November 2009 (Fig. 4). Model results are in agreement with the observations. Subsequently, for the same domain with the same model set up we have run the hydrodynamic model for August 2010. These model results (winds from WRF model and currents from Hydrodynamic model) are further used to set up PA module for tracking the tar ball particles for August 2010.

Fig. 4. is to be inserted here

Tar balls primarily occur during pre-monsoon and SW monsoon seasons along the WCI (for example, deposition at several beaches of Goa on 18 April 2011, 20 May 2011 and 30 August 2010) (Fig. 5). The first deposition was observed at Colva beach (South Goa) on 30 August 2010, and continued for the next couple of days and the whole Goa coast was affected with the tar ball deposition. Field work was conducted during 01- 03 September 2010 off Goa coast. Each time approximately 500 m length of beach was surveyed. The average mass of deposits on the beaches during August 2010 are calculated as described in Section 2.1 and are given below: Candolim - 1206 g/m², Colva - 703 g/m², Benaulim - 680 g/m² and Calangute - 417.5 g/m². In the month of May 2011, tar balls were deposited along the stretch of Mandrem off Goa coast, and the average mass of deposit is 237.5 g/m².

Fig. 5 is to be inserted here

There were no reports of oil spill in the AS or the coastal belt of WCI prior to the tar ball deposit. We assume that some unknown spills or tanker wash along the international tanker routes (Fig. 2a) might be the cause for the formation of present tar balls. Our interest is to simulate possible trajectories of the tar balls from the source location (in the present case, the international tanker route) to the coast. August falls in southwest (SW) monsoon season. During SW monsoon season, surface currents in the AS are the sum of Ekman drift and geostrophic current. The geostrophic velocity is weak in comparison with Ekman velocity throughout the year, and directed eastward during SW monsoon

season and westward during northeast (NE) monsoon season. As a whole, the surface velocity fields in the AS are primarily due to wind driven Ekman flow (Hastenrath Greischar., 1981). The eastward surface flow in the central AS is fed by northeastward Somali current, which is very strong during SW monsoon period. During the transition periods between the monsoons (March–April and October), the geostrophic flow is strong along the Indian coast and dominates the circulation (Shankar et. al., 2002). During SW monsoon (June-September) season, the West India Coastal Current (WICC) flows equatorward, while NE monsoon season (November-February) it flows poleward.

In the present numerical experiment, particles weighing 5g were released randomly at probable locations (one particle at each location) in the AS (Fig. 6a) on 02 August 2010. Particles released at the locations Au1 (70.32° E, 16.29° N), Au2 (70.41° E, 16.20° N), Au3 (70.595° E, 16.01° N), Au4 (70.69° E, 15.92° N) and Au6 (69.50° E, 15.80° N) only reached the Goa coast as shown in Fig. 6d. It is interesting to note that the particles released at other points Au5 (69.5° E, 15.8° N), Au7 (71° E, 17° N) and Au8 (71° , 15° N) did not reach the Goa coast (Fig. 6d), and reached elsewhere (north and south of Goa coast). Among the eight particles which moved out from their initial release point, three particles (Au3, Au4 and Au6) reached the south Goa coast as shown in Fig 6b and the other two particles (Au1 and Au2) reached the north Goa coast as shown in Fig 6c.

Fig. 6. is to be inserted here

The transport pattern is in agreement with the observation. It may be noted that tar balls initially arrived along the south Goa beaches on 30 August 2010 (Anonymous, 2010), and subsequently moved to north Goa beaches. We have not compared the actual tar ball transport time (from initial movement to deposition) with the model-simulated time, because we do not know the actual transport time. Moreover, the properties (size, mass, volume) of released particles and the actual tar ball properties may differ considerably. However, we find that the model-simulated trajectories match very well with the circulation pattern of the AS. The trajectories of the particles in Fig. 6d are towards the southeast direction (clockwise direction). Earlier studies, based on 10-day averages of historical ship-drift data showed that the surface currents in the AS are clockwise during SW monsoon season (northeast in the western AS, east in the mid AS and southeast in the eastern AS), and they are counter-clockwise during northeast monsoon season (Cutler and Swallow 1984). The model-simulated trajectories are also in a clockwise direction and southeastward. But, close to the coast due to tidal influence, the particles changed their paths from southeastern to northeast direction and reached the Goa coast as shown in Fig. 6d. Thus, we find that it was wind driven circulation during southwest monsoon season together with tides that transported the tar balls towards the Goa

coast on 30 August 2010. It is also reasonable to assume that tanker derived oil spill along the International oil tanker route might be the source of these tar balls. However, this needs to be further verified with fine-tuned model scenarios and several case studies.

The middle-east countries to the northwest of the AS are rich in crude oil production. This oil is transported to the far eastern and far western countries across the AS. Therefore, there is a possibility for spills to occur due to heavy traffic. In addition, the oil tankers before entering the gulf countries for loading the oil, clean the tankers. Suneel et al. (2013) identified the source of the tar balls that are deposited along the Goa coast as tanker-wash (South East Asia Crude type). The resulting spilled oil spreads on the sea surface, and undergoes weathering processes. With the arrival of SW monsoon, all the slicks and emulsions that are floating on the surface of the AS, especially in the region of tanker routes (approximate width is 300-500 km, including the three lines) start moving towards WCI. During their journey, these residues form thick emulsion followed by tar balls and float in the water column; eventually they deposit on the nearby beaches in consistence with the circulation pattern.

4. Conclusions

It is known that deposition of tar balls is a serious concern in most places as they float on the sea surface and get transported to the coast under the influence of winds, currents, tides and waves. An attempt has been made to study the transporting mechanism of the tar balls deposited along the Goa beaches using the MIKE 21 Hydrodynamic and Particle Analysis modules. The model results reveal that the probable locations for the formation of these tar balls could be the corridor around the international oil tanker routes, and they get transported to the coast by the influence of prevailing winds, currents and tides. During the pre- and summer monsoon seasons, the circulation pattern in AS is such that it is conducive for the transport of tar balls towards the WCI.

Even though studies on tar balls started in the 1960s, there is still a gap in understanding the physics of tar ball formation and its transport to the coast. We observe deposition of tar balls along the beaches of Goa during pre- and SW monsoon seasons, more or less regularly. In the last couple of years, we started collecting samples for fingerprint analysis. As the longshore current is nearly parallel to the coast, the path of trajectories will not be affected by the longshore current till they reach the coastal region. However, the accuracy of trajectory prediction will certainly improve near the coast when longshore current is included.

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Figures

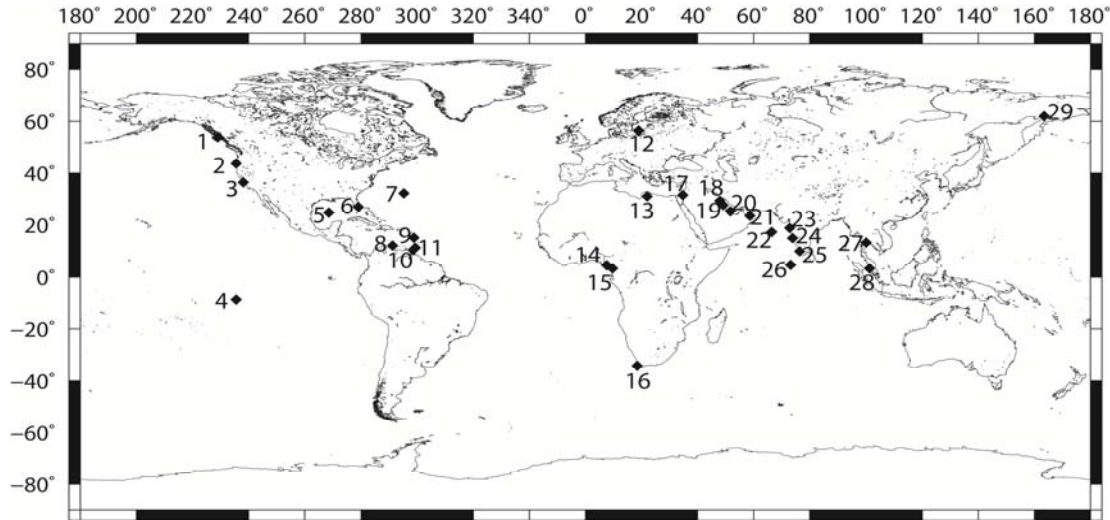


Fig. 1. Locations of observed tar balls are numbered as follows: 1. British Columbia, 2. Oregon, 3. California, 4. Pacific Ocean, 5. Gulf of Mexico, 6. Florida, 7. Bermuda, 8. Curacao, 9. Eastern Caribbean, 10. Trinidad, 11. Tobago, 12. Baltic Sea beaches, 13. Greece, 14. South-East Nigeria, 15. Cameroon, 16. Cape of Good Hope, 17. Israel, 18. Kuwait, 19. Saudi Arabia, 20. Qatar, 21. Muscat, 22. Arabian Sea, 23. Mumbai, 24. Goa, 25. Kochin, 26. Maldives, 27. Thailand, 28. Malaysia, 29. Alaska. These regions are known for tar balls accumulation.

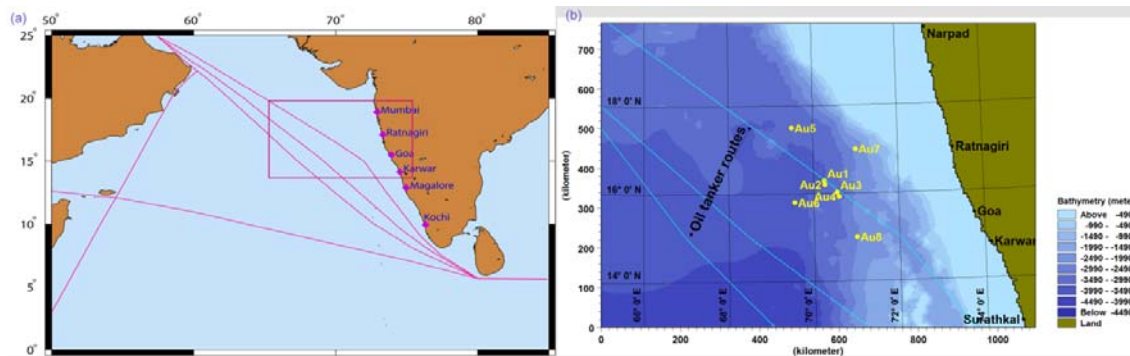


Fig. 2 (a) Oil tanker routes in the Arabian Sea reproduced from Sengupta and Kureishy(1981);(b) Model domain and bathymetry. The lines are the oil tanker routes passing through the domain. Au1, Au2, Au3, Au4, Au5, Au6, Au7, and Au8 are the origins of tar ball transport on 02 August 2010. Numerical experiments have been conducted by releasing particles at these locations.

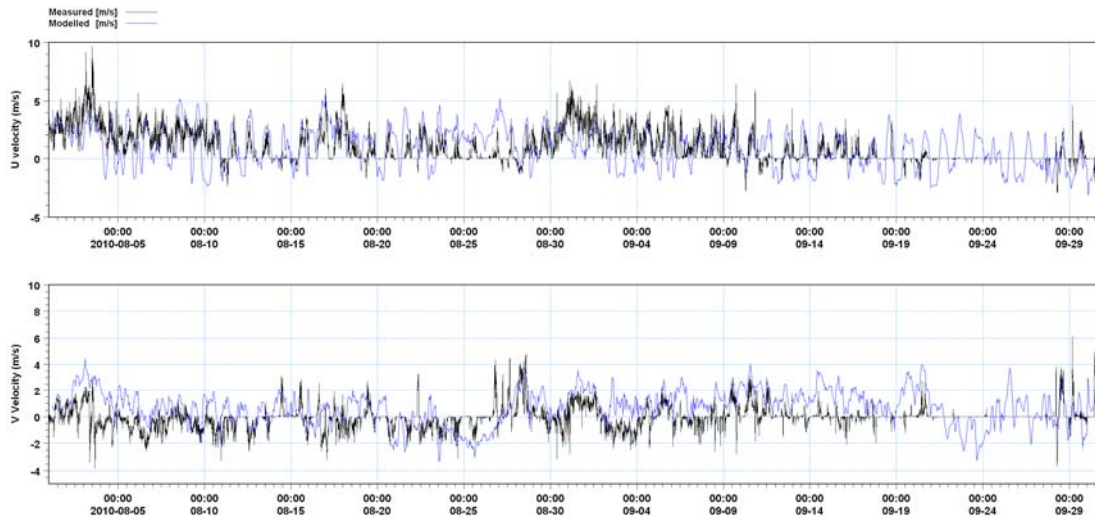


Fig. 3. Comparison between modeled (WRF) and measured (AWS) zonal (u) and meridional (v) winds (black line is measured and blue line is modeled).

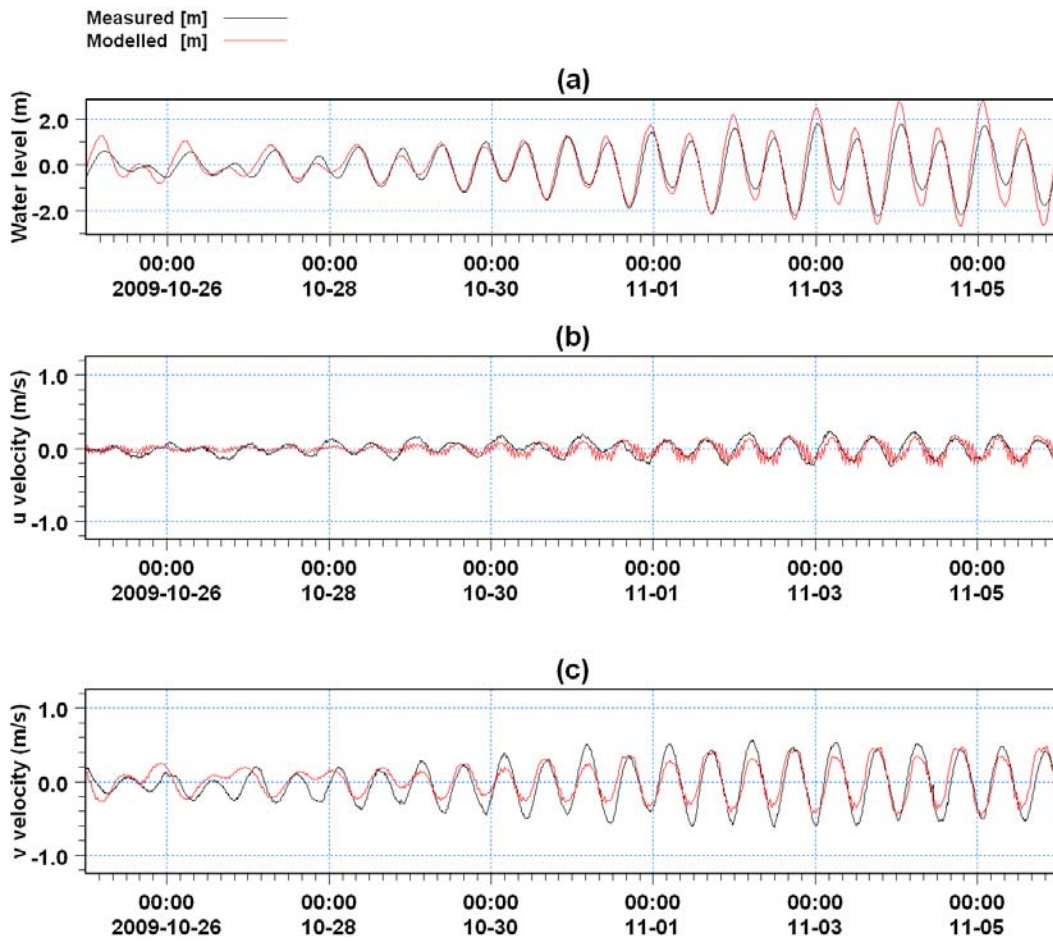


Fig. 4. Comparison between model simulated and measured (a) water level, (b) zonal component of currents and (c) meridional component of currents.



Fig. 5. Tar ball deposition on the beaches of (a) Candolim during 01 September 2010, (b) Colva during 31 August 2010 and (c) Mandrem during the 25 May 2011

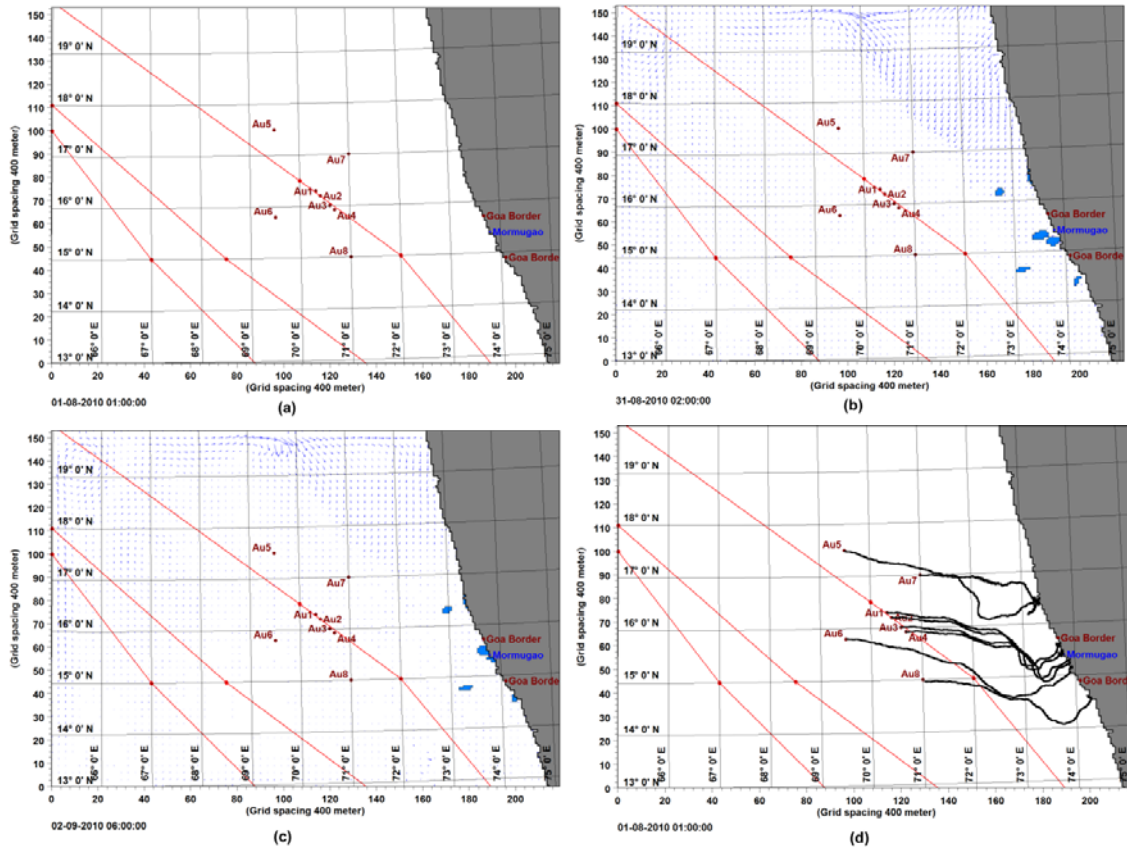


Fig. 6. Simulated tar ball trajectories during August 2010.