

HYDRODYNAMIC AND TRAJECTORY MODELING OF THE AUGUST 11, 2006 M/T SOLAR 1 OIL SPILL IN GUIMARAS, CENTRAL PHILIPPINES WITH VALIDATION USING ENVISAT ASAR DATA

Jojene R. Santillan and Enrico C. Paringit

Research Laboratory for Applied Geodesy and Space Technology, Training Center for Applied Geodesy and Photogrammetry & Department of Geodetic Engineering, University of the Philippines, Diliman, Quezon City, Philippines; Tel: +63-2-9818500 ext. 3147; E-mail: jrsantillan@up.edu.ph; paringit@gmail.com

KEY WORDS: Oil spill modeling, Envisat ASAR, M/T Solar 1, Guimaras, Philippines.

ABSTRACT: Oil spill patterns detected from Envisat ASAR images were integrated with hydrodynamic and oil spill trajectory models for the purposes of understanding the August 11, 2006 M/T Solar 1 oil spill, and to evaluate the accuracy of the oil spill patterns simulated by an oil trajectory model. The oil spill incident event that occurred a few kilometers southwest of Guimaras Island in Panay Gulf and Iloilo Guimaras Strait (PG-IGS), Central Philippines, is considered to be the worst oil-related environmental disaster the Philippines has experienced. A three-dimensional, wind- and tide-driven hydrodynamic model of the PG-IGS coastal zone was developed using the Environmental Fluid Dynamics Code (EFDC) to ascertain water circulation patterns. The simulated currents by the EFDC model were used as inputs to an oil spill trajectory model based on the General NOAA Operational Modeling Environment (GNOME) that provided continuous simulation of the transport of spilled oil from its source to the nearby coastal communities. The oil trajectories simulated by the GNOME model were validated by comparing it to oil spill patterns detected from Envisat Advanced Synthetic Aperture Radar (ASAR) images of the oil spill incident. The use of sea surface currents simulated by the EFDC-based hydrodynamic model was vital in explaining the trend, shape, and direction of the observed oil slicks from the Envisat ASAR images. Conversely, the use of Envisat ASAR images for oil spill pattern validation provides an easier and direct assessment of the GNOME-based oil trajectory model's performance. The comparison between model-simulated oil spill patterns and the patterns mapped from Envisat ASAR images showed that in general, the simulated slick patterns differ in location, shape and extent to those detected from the SAR images. It appears from the results of actual-versus-simulated oil spill patterns that improvement is needed in the EFDC and GNOME models, most especially in their data inputs. While the oil spill patterns simulated by the GNOME model differs at some aspects from the actual patterns, the results highlighted the usefulness of the model for oil spill trajectory analysis and its use for oil spill response in the future once improvements to the model have been considered.

1. INTRODUCTION

During the stormy afternoon of August 11, 2006, a marine tanker M/T Solar 1, chartered to transport 2.4 million liters of bunker fuel oil sank in Panay Gulf, at a location that is a few kilometers southwest of Guimaras, an island province in the Visayas (Figure 1). About 200,000 liters of oil leaked from the sunken tanker affected some 184 kilometers of coastline, about 1,141 hectares of mangrove ecosystem, about 88 hectares of sea grass beds in Guimaras Province, and about 4.5 kilometers of coastline and about 38 hectares of mangroves in Iloilo (Silliman University

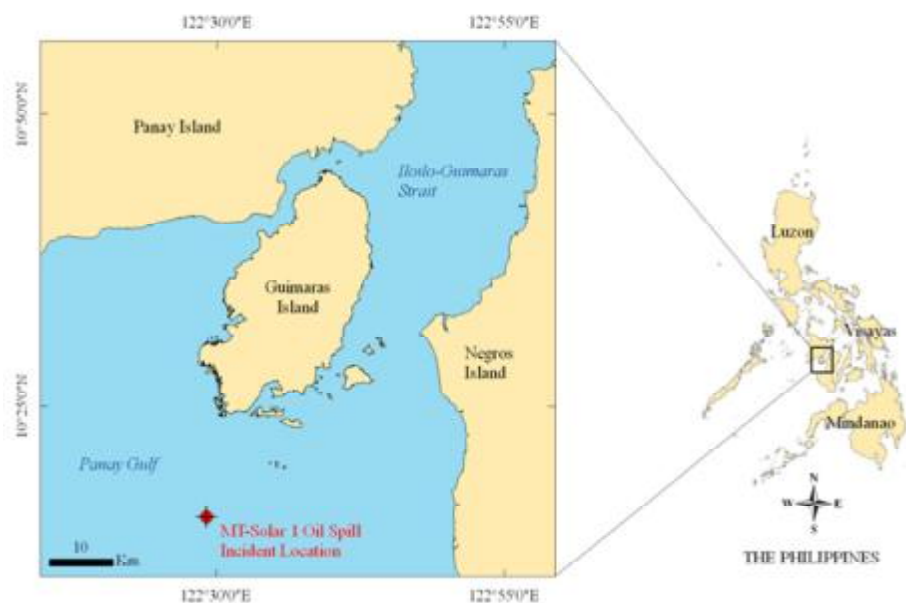


Figure 1. Map showing location of the August 11, 2006 MT-Solar 1 oil spill incident in Panay Gulf, near Guimaras Island, Visayas, Philippines.

Marine Laboratory, 2006). The M/T Solar 1 oil spill incident is considered to be the worst oil-related environmental disaster the Philippines has experienced.

Space-borne synthetic aperture radar (SAR) sensors have been extensively used for the detection of oil spills in the marine environment (Topouzelis, 2008). While SAR imageries and related manipulation techniques provide multi-temporal information on the location of oil spills, other information may need to be integrated to better understand and assess the degree of contamination in coastal resource and nearby environments such as hydrodynamic characteristics and water circulation patterns. Hydrodynamic and oil spill trajectory models are often used for this purpose wherein mathematical formulations or algorithms are linked to represent oil transport and fate processes (ASCE Task Committee on Modeling of Oil Spills, 1996). A large number of oil spill models have been developed and in use, ranging in capability from simple trajectory, or particle-tracking models, to three-dimensional trajectory and fate models that include simulation of response actions and estimation of biological effects (Reed et al., 1999).

In this paper, we integrated oil spill patterns detected from Envisat ASAR images with hydrodynamic and oil spill trajectory models to understand the August 11, 2006 M/T Solar 1 oil spill. The oil spill incident is reconstructed by coupling the hydrodynamic model with an oil trajectory model. This oil spill modeling effort not only aims to reconstruct the M/T Solar 1 oil spill incident but also to develop a computational model for forecasting oil spill should a similar incident happen in the PG-IGS or other coastal waters in the Philippines in the future.

One of the issues in oil spill modeling, however, is determining how accurate the models are in predicting the fate and transport of spilled oil. In this study, the accuracy of the oil trajectory model was evaluated by comparing the simulated oil spill patterns with the actual oil spill patterns derived from the analysis of a time series of Envisat ASAR images.

2. METHODS

Figure 2 shows the general steps involved in the development of the PG-IGS hydrodynamic and oil trajectory models, including the latter's validation using oil spill patterns extracted from Envisat ASAR images. Each step is discussed in the following sections.

2.1 The PG-IGS Hydrodynamic Model

Hydrodynamic modeling of PG-IGS was implemented using the Environmental Fluid Dynamics Code or EFDC (Hamrick, 1992). The physics of the EFDC model and many aspects of the computational scheme are equivalent to the widely used Blumberg-Mellor model (Blumberg & Mellor, 1987). EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid.

EFDC model development, parameterization and result visualizations were implemented using EFDC_Explorer version 5 (EE). EE is a Microsoft Windows™ based pre-processor and post-processor of EFDC (Craig, 2009). The model was configured on sigma vertical and orthogonal horizontal coordinate systems. For faster computation time, the model domain (PG-IGS) was subdivided into a 72x63 square grid, each cell having a resolution of 2x2 km (Figure 3). Land areas were not included in the model, resulting to 1,808 active water cells only. Ten sigma vertical layers were used in order to accurately capture sea surface currents. Bathymetry/bottom elevations referenced at Mean Lower Low Water (MLLW) were obtained from existing nautical charts and topographic maps published by the Philippines' National Mapping and Resource Information Authority. Spot depths and depth curves were digitized from the maps and subjected to kriging interpolation to derive a 2x2 km bathymetric map. This bathymetric grid was then used as input to the EE to assign bottom elevations to 1,808 grid cells. A uniform bed roughness of 0.04 was also assigned to each cell.

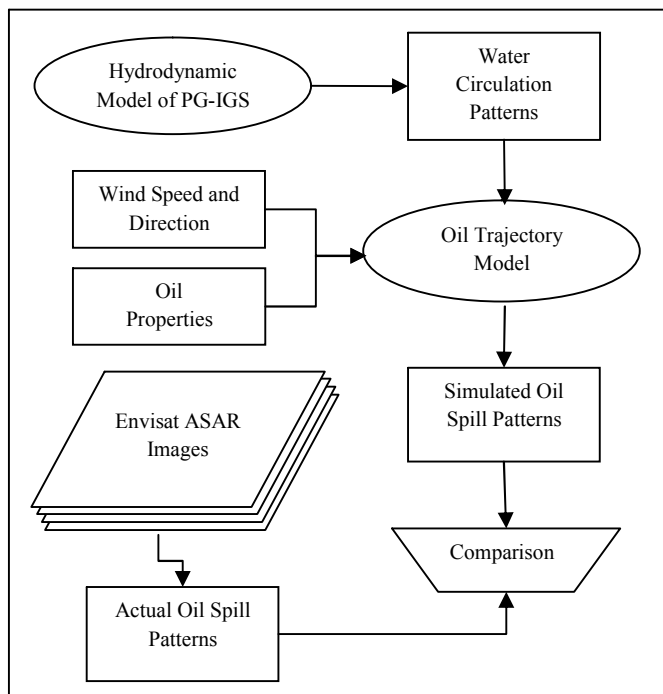


Figure 2. Flowchart showing the general steps involved in developing the PG-IGS Oil Spill Model and its validation using Envisat ASAR images.

The model is forced by tidal changes in sea surface elevations at the east and west open boundaries, and by a time-varying wind forcing across the model domain. For the East and West open boundaries (OC), time series of tidal heights (August 1-September 3, 2006) for each boundary cell were obtained from the China Seas Regional Barotropic Ocean Tide Model (CSRBOTM; Egbert & Erofeeva, 2002). Tidal heights (z) at 5-min interval for each of the OC cells were extracted from CSRBOTM using the Tidal Model Driver, a MATLAB toolbox (http://www.esr.org/polar_tide_models/Model_AOTI_M5.html). For the wind forcing, 3-hourly wind speed and direction data recorded by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) - Iloilo City Station was used.

The PG-IGS EFDC hydrodynamic model was run for the following periods: model warm-up (to stabilize the model): July 31 – August 9, 2006; Actual simulation: August 10 – Sept. 3, 2006. The time step was set at 30 seconds in accordance with the Courant-Friedrich-Levy criterion. Model simulated sea surface currents for each cell where outputted at 30-minute interval. The simulated currents were used (i.) to explain the oil spill patterns detected from Envisat ASAR images (see Section 2.3), and (ii.) as input to the PG-IGS oil trajectory model.

2.2 The PG-IGS Oil Trajectory Model

To simulate the release of oil particles from the sunken M/T Solar 1, an oil trajectory based on the National Oceanographic and Atmospheric Administration (NOAA)' General NOAA Operational Modeling Environment (GNOME; Beegle-Krause, 2001) was prepared. GNOME is a publicly available oil spill trajectory model that simulates oil movement due to winds, currents, tides, and spreading. In general, GNOME can (1) estimate the trajectory of spills by processing information on wind and weather conditions, circulation patterns, river flow, and the oil spill(s) that are to be simulated, (2) predict the trajectories that can result from the inexactness (uncertainty) in current and wind observations and forecasts, and (3) use weathering algorithms to make simple predictions about the changes the oil will undergo while it is exposed to the environment. GNOME is a mixed Eulerian/ Lagrangian trajectory model that uses lagrangian elements or particles to represent spills of oil within Eulerian currents and wind. Oil particle movements are modeled to be statistically independent of each other. Horizontal particle movement is tracked across the surface of the water, up to and including their point of stranding on the shore. The surface current grid in GNOME provides the advection component of simulated particle trajectories and incorporates generalized, average current conditions. Horizontal diffusion is treated as a random-walk process, calculated from a uniform distribution.

The time series of water surface velocities (at 2x2 km resolution) computed by the EFDC model and spatially-constant but time-varying wind speed and direction data were used as "particle movers". A horizontal diffusion coefficient of $8,000 \text{ cm}^2/\text{s}$ was set to introduce randomness in the spilled oil particles.

After all the external model parameters have been set, parameters related to the amount and type of oil and information on the spill incident (start and end time of oil spill) were set next (Table 1). The end release time of the spill was set through analysis of Radarsat images available from Ligas Guimaras (2006) (Figure 4). Based on these images, oil is continuously leaking from the sunken vessel on September 15, 2012. Hence end time of oil release could be days from the start of spill. As of Sept. 15, 2006, oil is still leaking from the vessel as shown by a RADARSAT image. As of Sept. 17, 2006, Radarsat image shows no indication of presence of oil. The end of spill might be between Sept. 16 and 17, 2006. In this modeling exercise, the end release date and time was set as 12:00 AM of September 17, 2006.

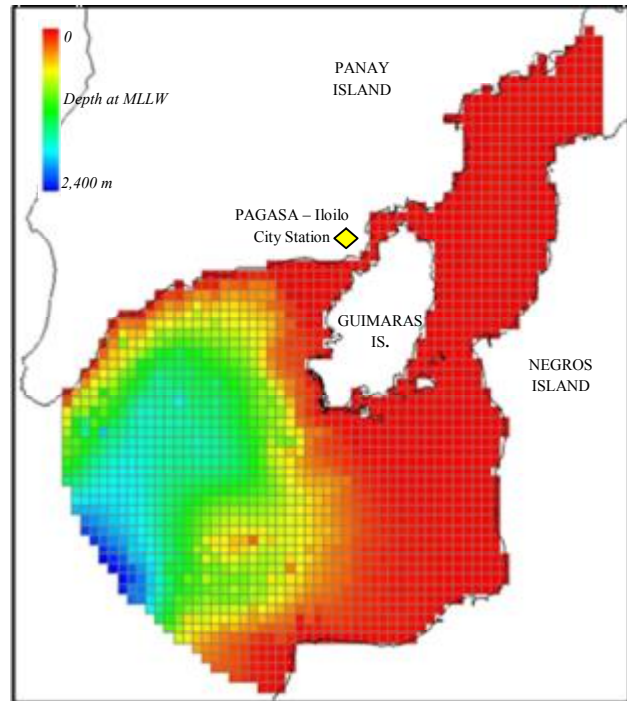


Figure 3. The PG-IGS Model Domain. Each cell is 2km x 2km.

Table 1. Oil-spill related GNOME oil trajectory model parameters.

Date and time of spill (or oil release)	August 11, 2006, 11:00 PM
Geographic location of the spill:	Latitude = 10.255560 Longitude = 122.48611 (based on UNOSAT.org maps)
Type of oil:	Bunker fuel oil (Fuel oil no. 6)
Amount of spillable oil (total cargo) in the tanker	2.19 Million liters (2,064 metric tons)
Approx. date and time of end of spill:	September 17, 12:00 AM

After setting up all the parameters, the model was then run for the period of 11:30 PM, August 11 - 1:30 AM September 1, 2006. The simulated oil spill patterns for August 24, 25 and 28, 2006 were compared with oil spill patterns derived from the Envisat ASAR images of the same dates to evaluate the accuracy of the simulation.

2.3 Oil Spill Detection and Mapping using Time Series of Envisat ASAR images

2.3.1 Image Pre-processing

Three (3) Level 1P SAR images used in oil spill detection and mapping included archived ENVISAT ASAR images (Figure 5) obtained from the European Space Agency (ESA). The images were acquired on the following date and local time: (i.) August 24, 2006, 9:44 AM; (ii.) August 25, 2006, 9:53 PM; and (iii.) August 28, 2006, 9:56 PM. The images were already ground-range and slant-range corrected as provided by ESA.

Using the Basic Envisat SAR Toolbox (BEST) version 4.2.2 software, standard radar image pre-processing procedures were applied to the SAR images prior to the oil spill detection and mapping. This included radiometric calibration to generate a backscatter (" β ") image, and geometric correction. The images were then exported to Environment for Visualizing Images (ENVI) software version 4.3 for further analysis. Here, the images were "de-speckled" using a 3x3 Enhanced Lee filter to remove the noisy pixels while preserving texture information.

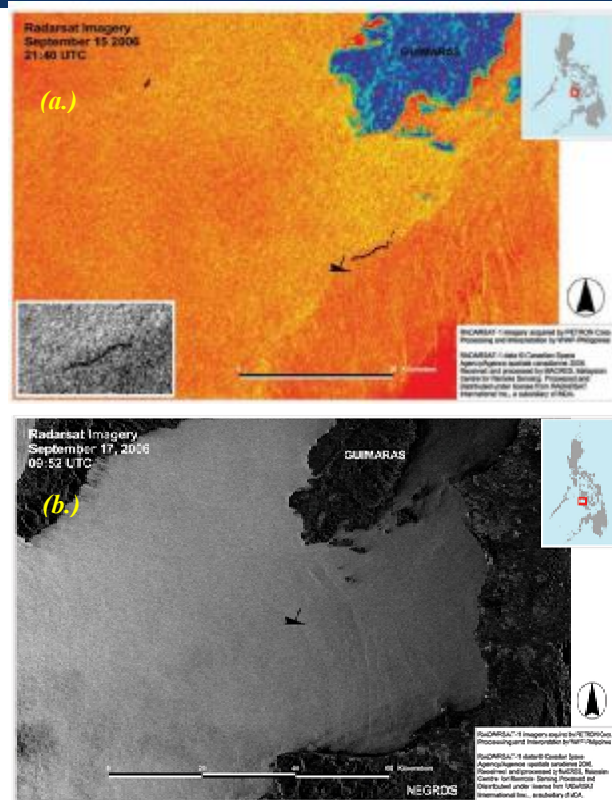


Figure 4. Radarsat images obtained from Ligtas Guimaras (2006) showing oil still leaking from the sunken vessel on September 15, 2006 (a). Two days after, no more oil slicks were observed (b).

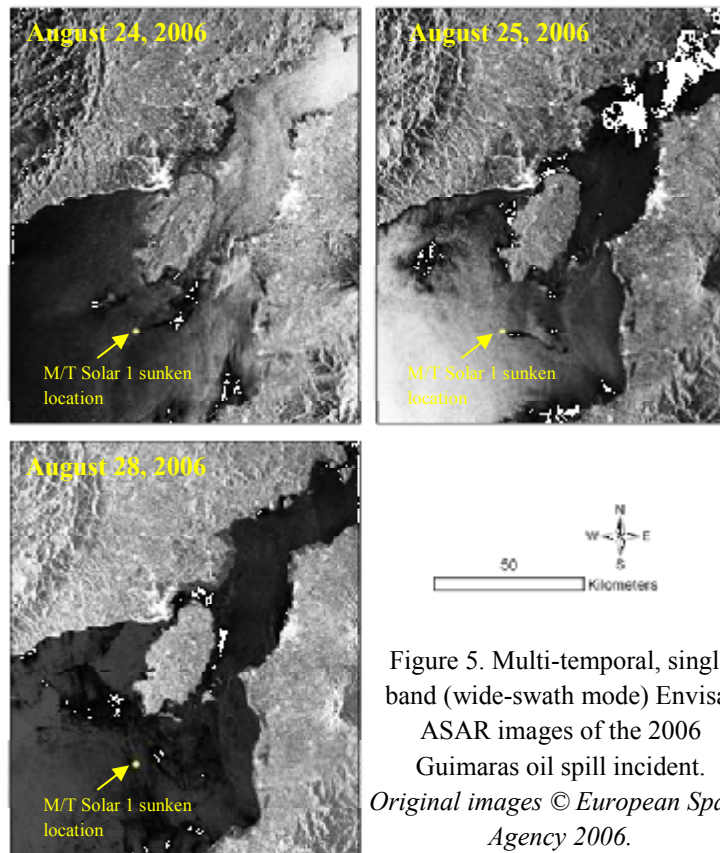


Figure 5. Multi-temporal, single band (wide-swath mode) Envisat ASAR images of the 2006 Guimaras oil spill incident. Original images © European Space Agency 2006.

2.3.2 Oil Spill Detection

Oil spill mapping using the pre-processed Envisat ASAR images was done by first implementing a dark formation detection and segmentation using histogram analysis and radar backscatter thresholding to detect suspicious oil slicks. Details of this procedure are reported in Santillan & Paringit (2011). The segmented dark formations were then manually analyzed to differentiate actual oil slicks from look-alikes. Oil spill maps published by UNOSAT (2006) and Ligtas Guimaras (2006), and field reports by the Silliman University Marine Laboratory (2006) were used as references in this manual classification.

3. RESULTS

3.1 Hydrodynamic characteristics of PG-IGS at the time of the oil spill incident

Figure 6 shows the current patterns simulated by the PG-IGS hydrodynamic model during the time that M/T Solar 1 was reported to have sunk in the PG. The current patterns simulated by the model indicate northeasterly movement of water from PG towards IGS. But at IGS, there is an incoming wave of water and it seems to oppose the movement of water from the PG. Given that the time of release of spill from the sunken vessel is at the same time M/T Solar 1 sank, it can be speculated that the movement of spilled oil particles will most likely toward the southwestern coast of Guimaras Island, in northward-northeastward directions.

3.2 Oil Spill Maps from Envisat ASAR images

Figure 7 shows the oil spill maps derived from the analysis of the Envisat ASAR images. The most striking features of the oil spill maps are the variation in sizes of the oil slicks and their lateral dispersion through time.

The August 24, 2006 map showed a very large slick (approx. 30 km in length and 10 km width) originating from the location of the sunken vessel. This total surface area of this slick is approx. 120 km² and is seen to have contaminated the coastal areas of Southern Guimaras. Some slicks are found to be already traversing towards Iloilo-Guimaras Strait. The general direction of the slicks is heading east-northeast at the time of image acquisition. It can be noticed that in very deep areas (>100 m.) near the source of the spill, the oil slicks are elongated while in shallow areas (<100 m.), the elongation is also present but the relative width of the slick have significantly increased.

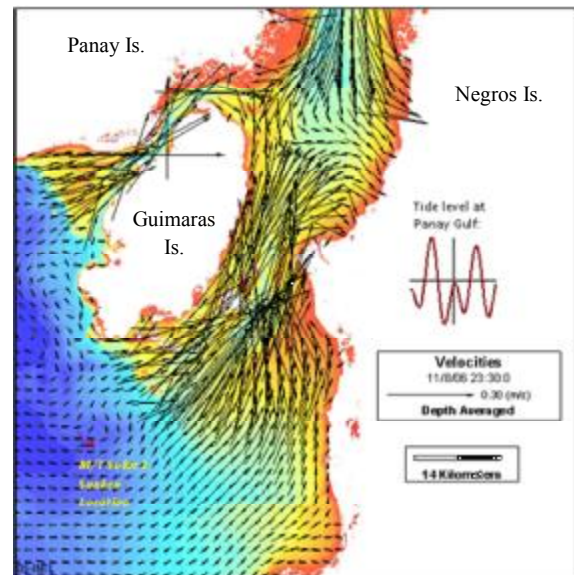


Figure 6. Model simulated current patterns during the day and time (11:30 PM, August 11, 2006) that M/T Solar 1 was reported to have sunk in the Panay Gulf.

It is very apparent from August 24, 2006 map that most of the still-floating oil slick will be stranded to the south, southeast and southwest portions of Guimaras Island. This is confirmed in the August 25, 2006 map where majority of the spill have already contaminated these coastal areas. Noticeable in this map is the change in the pattern of the slicks near the source. Oil spill pattern for August 28, 2006 could be results of strong tidal currents and calm wind conditions. The overall extent of the dispersion of the oil slicks is circular which may be due to gyrations before or during the time of image acquisition. The estimated surface area of the oil slicks is 153 km². Some of these slicks may have come from the slicks dispersed since August 24, 2006 that have not yet stranded in the nearby shores. It is very unfortunate that oil slicks can no longer be detected in the coastal areas due to low spatial resolution of the image. Nevertheless, this lack of actual sea truth information can be supplemented using the observed oil spill patterns on August 25, 2006. Without these historical record, and to rely only on the August 28, 2006 oil spill map would provide erroneous conclusions as to where are the areas contaminated by the spilled oil.

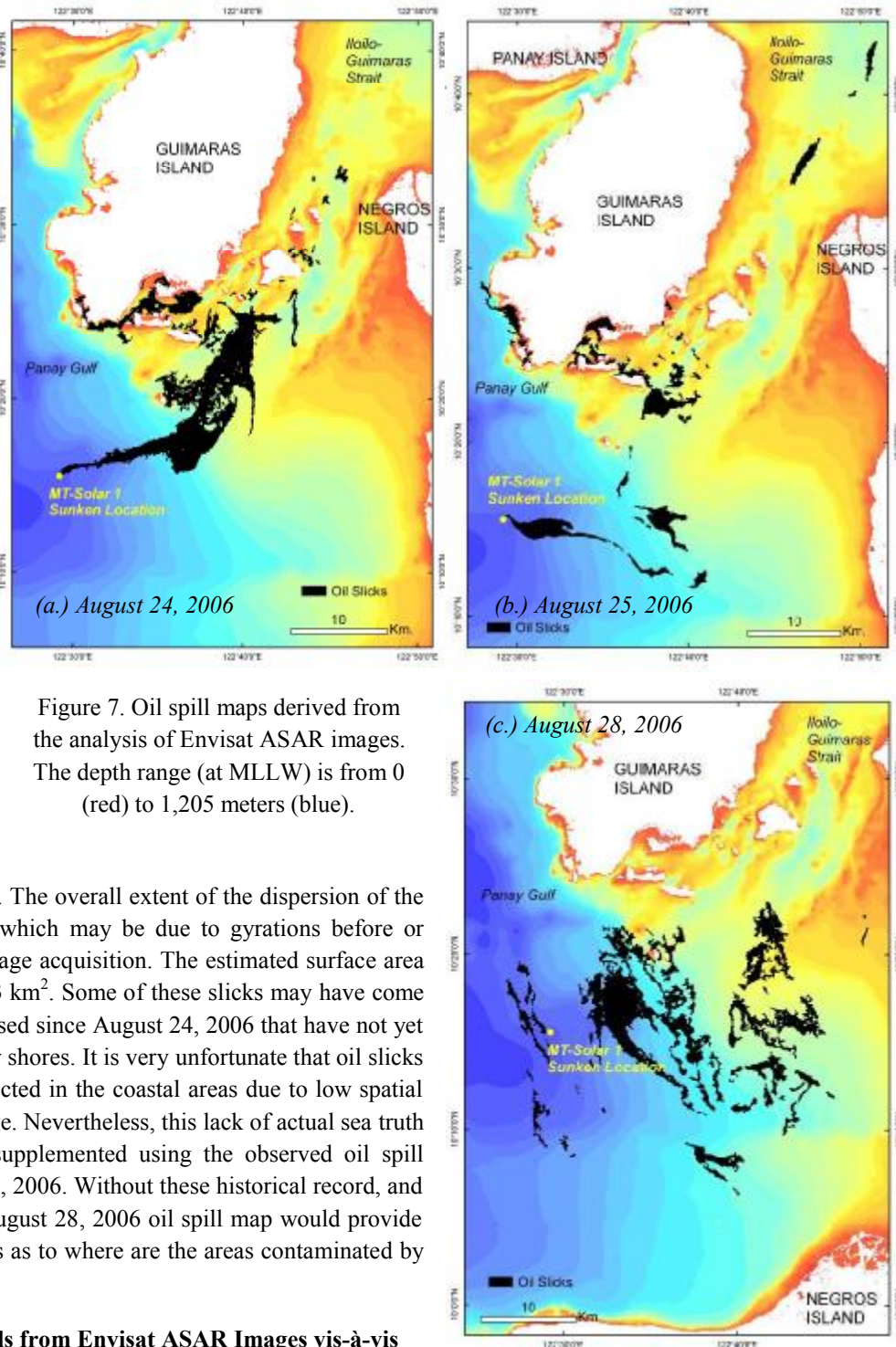


Figure 7. Oil spill maps derived from the analysis of Envisat ASAR images. The depth range (at MLLW) is from 0 (red) to 1,205 meters (blue).

3.3 Detected Oil Spills from Envisat ASAR Images vis-à-vis Simulated Sea Surface Currents

Shown in Figure 8 are the detected oil spill patterns from the August 24, 2006 Envisat ASAR images overlaid with simulated sea surface current patterns approximately 3 hours before and during the time when the image were acquired. The detected oil spill patterns are explained according to the simulated sea surface currents by the EFDC hydrodynamic model as a way to understand the transport of spilled oil from the sunken vessel.

The August 24, 2006 result shows a consistent northeasterly movement of surface water from PG towards IGS three hours before and during the time when the observed oil spill pattern was detected by the Envisat ASAR sensor. There is high association between the simulated current patterns and the spatial pattern of the oil slicks. First, the general direction of the oil spread is similar to the prevailing current patterns and even 3 hours before it. This means that oil coming from the sunken vessel was continuously transported by sea surface currents (with lateral spreading

by wind) in a northeasterly direction. The strong currents in the relatively shallower areas between Guimaras and Negros Islands greatly affected the emerging oil spill pattern, “pulling” the oil slicks towards IGS. The elongation of the oil slicks near the source seems to have been due also to this, with additional effect by easterly currents from PG (specifically in the area north of the source) pushing the oil slicks towards IGS approximately 3 hours before.

The results of the hydrodynamic characterization of PG-IGS in relation to the oil spill, using the August 24, 2006 as example, provided very relevant information in explaining the trend, shape and direction of the observed oil slicks from the Envisat ASAR images. The simulated current patterns seem to agree with the detected patterns of the oil spill.

3.4 Reconstructed Guimaras oil spill using the PG-IGS oil trajectory model and its validation using Envisat ASAR images

The simulated oil spill patterns by the PG-IGS Oil Trajectory model and its validation with actual oil spill patterns detected from the August 24, 25 and 28, 2006 Envisat ASAR images are shown in Figures 9 to 11. The simulated trajectories include the best estimated location of the oil particles and the “minimum regrets”. The “Best Estimate,” or Forecast, trajectory assumes that all of the information that is loaded into the model (winds and currents) is exactly correct. The model then calculates a “Best Estimate” trajectory based on this information alone. The “Minimum Regret” or Uncertainty trajectory shows where spills could go if the model inputs were incorrect. The “Minimum Regret” is useful in actual application of the oil spill trajectory model as tool for oil spill response. Responders could use the “Minimum Regret” trajectory to pinpoint other possible oil spill trajectories that could have serious consequences (NOAA, 2002). They could then decide how to allocate resources, taking into account less likely but highly costly possibilities.

Based on oil spill patterns detected from the Envisat ASAR images, the PG-IGS oil trajectory model performed unsatisfactorily in simulating the M/T Solar 1 oil spill. Model simulated slick patterns are very different in location, shape and extent to those detected from the SAR images. It is worth noting, however, that at least for each oil spill image there are portions that both datasets have common results.

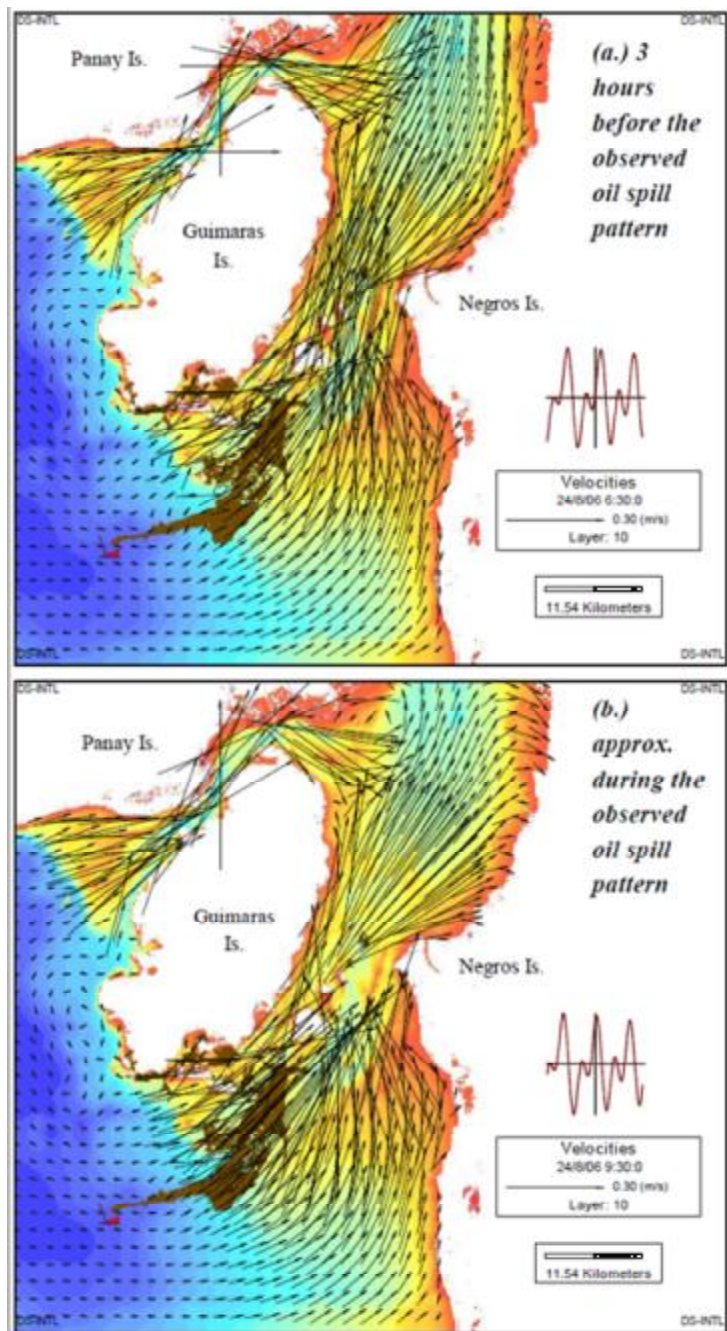


Figure 8. Simulated sea surface current approx. 3 hours before and during the time when the oil spill pattern was detected from the August 24, 2006 Envisat ASAR image. Oil slicks are shown in dark brown color. Also shown are the tidal levels at Panay Gulf.

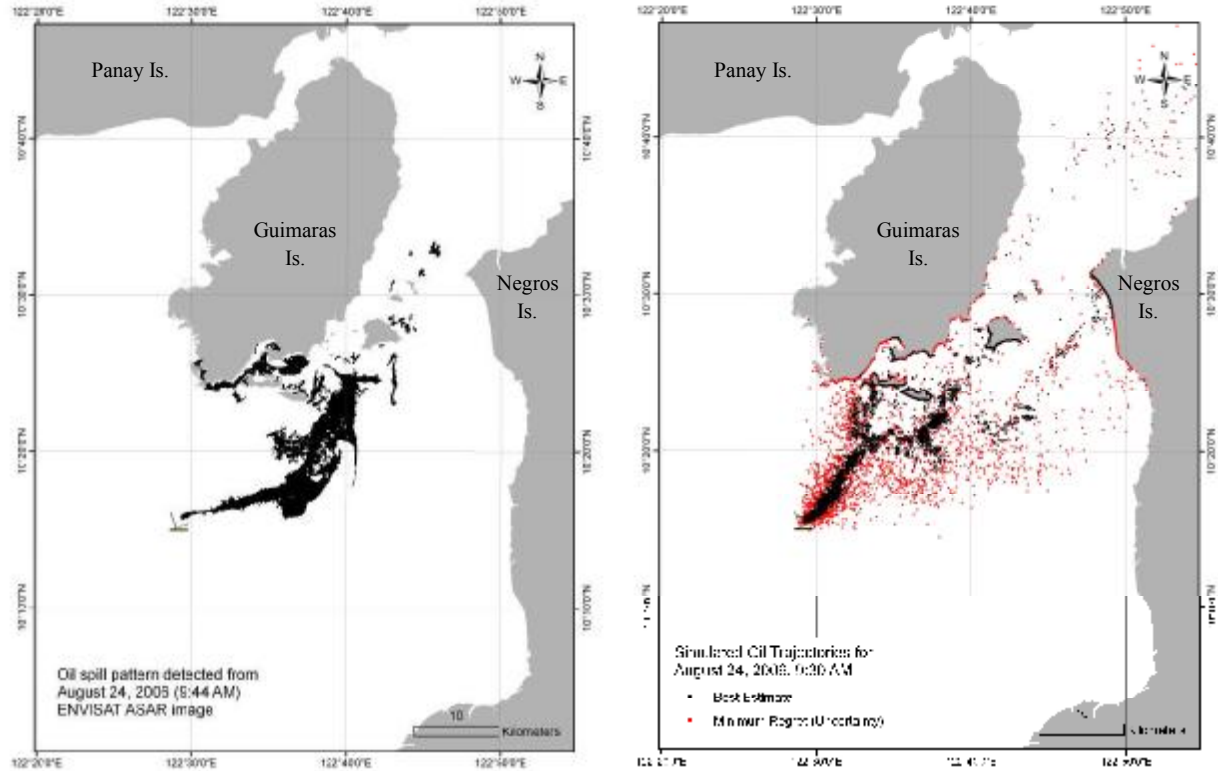


Figure 9. Comparison between Envisat ASAR-detected and model simulated oil trajectories for August 24, 2006.

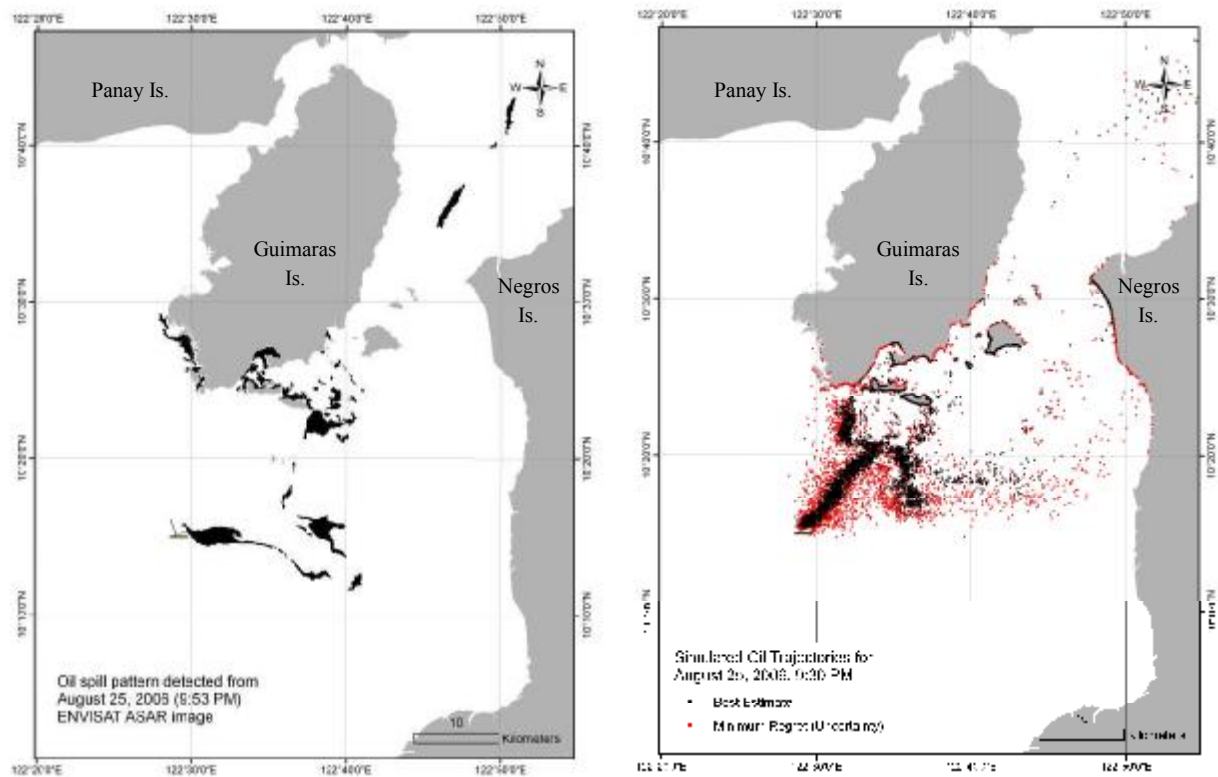


Figure 10. Comparison between Envisat ASAR-detected and model simulated oil trajectories for August 25, 2006.

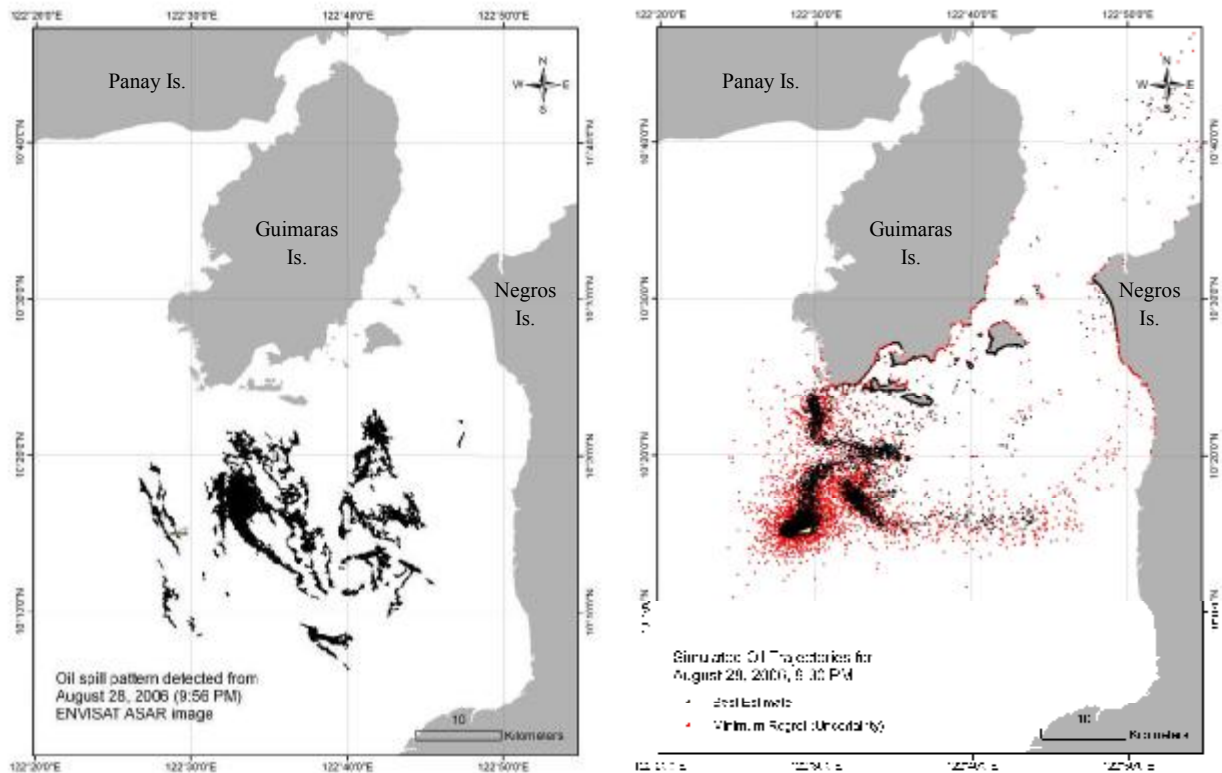


Figure 11. Comparison between Envisat ASAR-detected and model simulated oil trajectories for August 28, 2006.

4. DISCUSSIONS

The Envisat ASAR-based oil spill maps derived in this study provided spatial patterns that are suggestive of the degree of contamination that the oil spill caused to nearby coastal communities in the PG-IGS. It is an accepted limitation that not all oil slicks can be detected from SAR imagery even if daily images of the spill are available. This is very true in cases when the spill has already interacted with coastal habitats such as mangroves, sea grass beds and coral reefs. This scenario of undifferentiated oil slicks could be due to the coarseness of image's spatial resolution and the existing wind and tide conditions. Obtaining an historical record of oil spill contamination using time series of SAR images is very important in identifying which areas have been contaminated (historically) by oil.

Hydrodynamic modeling of the PG-IGS using EFDC presents a good approach in understanding the M/T Solar 1 oil spill. Although no information is available to validate the sea surface currents simulated by the EFDC model, the results of the hydrodynamic characterization of PG-IGS in relation to the oil spill provided very relevant information in explaining the trend, shape, and direction of the observed oil slicks from the Envisat ASAR images. The simulated current patterns seem to agree with the detected patterns of the oil spill. This has significance in analyzing the impacts of oil spills, as the degree of impact is often dictated by how oil slicks are being transported from its source towards the coastal zones.

The GNOME-based PG-IGS oil trajectory model developed in this study showed poor performance. The direct comparison between the model simulated and the actual oil spill patterns detected from Envisat ASAR images provides indication that the model needs improvement. Coarseness of the wind data could be the major reason for the unsatisfactory model performance. The wind data used in this study is 3-hourly and was recorded at Iloilo City-PAGASA Station, approximately 40 km from the study site. As modeling results suggest, this data may have not captured actual wind patterns in the PG-IGS. The poor performance could be due also to the coarseness of the surface currents used in the simulation. At a 2km x 2 km spatial resolution, the trajectory results showed that oil particles cannot be "moved" by the given surface currents in areas near the coast. Another factor could be the uncertainties associated with the actual volume of the spilled oil and the actual start and end of the oil spill. In this study, the dates and times of the start and end of spill were all based on secondary reports, if not assumed. These information needs to be as accurate as possible in order to obtain reliable simulations of oil trajectories.

5. CONCLUSIONS

In this paper, we presented an approach wherein we integrated oil spill patterns detected from Envisat ASAR images with hydrodynamic and oil spill trajectory models for the purposes of understanding the transport of spilled oil from the sunken vessels, and to evaluate the accuracy of the oil spill patterns simulated by the oil trajectory model. The use of simulated sea surface currents from the EFDC-based hydrodynamic model was vital in explaining the trend, shape, and direction of the observed oil slicks from the Envisat ASAR images. Conversely, the use of Envisat ASAR images for oil spill pattern validation provides an easier and direct assessment of the GNOME-based oil trajectory model's performance. It appears from the results of actual-versus-simulated oil spill patterns that improvement is needed in the EFDC-based hydrodynamic model and GNOME-based oil trajectory model, most especially in their data inputs. While the oil spill patterns simulated by the GNOME model differs at some aspects from the actual patterns, the results highlighted the usefulness of the model for oil spill trajectory analysis and how it for oil spill response in the future. However, the usefulness of the model could be maximized if provided with accurate atmospheric and hydrodynamic data. This can be done by coupling a much finer resolution hydrodynamic model to the GNOME model so that surface currents used for "moving" the oil particles could provide trajectory estimates in a manner close to reality. For oil spill response, the improved model could be useful in predicting where the spilled oil will go as long as there are available wind forecasts (or even best estimates of it) and surface currents from hydrodynamic modeling.

ACKNOWLEDGEMENTS

The Envisat ASAR images were provided by the European Space Agency (ESA) through Cat1 5988. This work was part of a Grant-In-Aid project, "Development of Geospatial Techniques to Analyze Impacts of Oil Spills on Coastal Resource and Environment", funded by the Philippine Council for Advanced Science and Technology Research and Development (PCASTRD) of the Department of Science and Technology (DOST).

REFERENCES

- ASCE Task Committee on Modeling of Oil Spills of the Water Resources Engineering Division, 1996. State-of-the-art review of modeling transport and fate of oil spills. *Journal of Hydraulic Engineering*, 122(11), pp. 594-609.
- Beegle-Krause, C.J., 2001. General NOAA oil modeling environment (GNOME): a new spill trajectory model. In: *Proceedings of the 2001 International Oil Spill Conference*. Mira Digital Publishing, Inc., St. Louis, Missouri, pp. 865-871.
- Blumberg, A.F. & Mellor, G.L., 1987. A description of a three-dimensional coastal ocean circulation model. In: N. S. Heaps, ed. *Three-Dimensional Coastal Ocean Models*, Coastal and Estuarine Science. American Geophysical Union, pp. 1-19.
- Craig, P.M., 2009. User's Manual for EFDC_Explorer: A Pre/Post Processor for the Environmental Fluid Dynamics Code (Rev 00), Dynamic Solutions, LLC.
- Egbert, G.D. & Erofeeva, S.Y., 2002. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology*, 19(2), pp. 183-204.
- Hamrick, J.M., 1992. A three-dimensional environmental fluid dynamics computer code: Theoretical and computational aspects, Gloucester Point, Virginia: Virginia Institute of Marine Science, School of Marine Science, College of William and Mary.
- Ligtas Guimaras, 2006. Satellite images and maps of the MT-Solar 1 oil spill. Retrieved from <http://www.ligtasguimaras.com.ph/satelliteimages.asp>
- NOAA, 2002. General NOAA Oil Modeling Environment (GNOME) User's Manual, Seattle, Washington.: National Oceanic and Atmospheric Administration.
- Reed, M. et al., 1999. Oil spill modeling towards the close of the 20th century: overview of the state of the art. *Spill Science and Technology Bulletin*, 5(1), pp. 3-16.
- Santillan, J.R., Paringit, E.C., 2011. Oil spill detection in Envisat ASAR images using radar backscatter thresholding and logistic regression analysis. In: *Proceedings of the 32nd Asian Conference on Remote Sensing*, October 3-6, 2011, Taipei, Taiwan.
- Silliman University Marine Laboratory, 2006. Final Report: M/V Solar 1 Oil Spill Rapid Assessment, August 25-30, 2006. http://web.kssp.upd.edu.ph/oil_spills/oil%20spills%20fora.html. Date accessed: 28 April 2008.
- Topouzelis, K. N., 2008. Oil spill detection by SAR images: dark formation detection, feature extraction and classification algorithms. *Sensors*, 8(10), pp. 6642-6659.
- UNOSAT, 2006. Satellite identification of major oil spill off the coast of Guimaras Island, Philippines. Retrieved from <http://www.unitar.org/unosat/node/44/771>.