Annex D

Discharge Modelling Report

55 Village Square Drive
South Kingstown, RI 02879
Phone: +1 401 789-6224
Fax: +1 401 789-1932
www.asascience.com

FINAL REPORT

Oil Spill, Produced Water, Drilling Mud and Drill Cuttings Discharge Modeling, Ghana

AUTHOR(S):

Christin Reynolds , Yong H. Kim, Tatsu Isaji, Kathy Jayko, Eric Comerma

Project Manager – Reviewer: Eoin Howlett

PROJECT NUMBER:

ASA 09-051

VERSION: FINAL-2

DATE: 24 July 2009

CLIENT:

Mark Irvine, ERM – UK

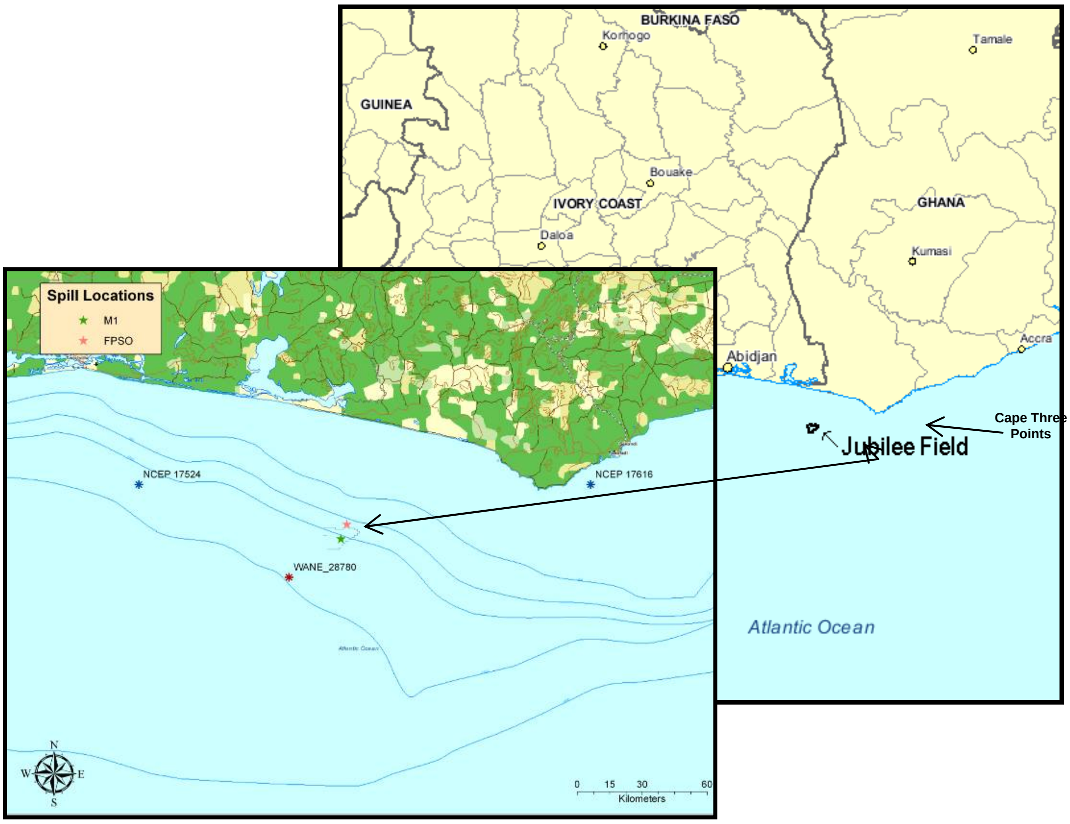


Table of Contents

List of Figures

List of Tables

Executive Summary

ERM contracted with Applied Science Associates, Inc. (ASA) to assess potential marine gasoil and crude oil spills, produced water discharges, and drilling mud (drilling fluid) and cuttings discharges from the Jubilee Field within the Deep Water Tano and West Cape Three Points Blocks off the coast of Ghana.

Wind data based on wind hindcast models were obtained for the Ghana offshore region from NOAA's NCEP atmospheric model reanalysis, and WANE (**W**est **A**frica (Met-Ocean) **N**ormals and **E**xtremes) predicted winds. Both datasets exhibit the same predominant southwestern wind direction, with very little variation over the course of the year. Regional currents were assessed from ADCP (Acoustic Doppler Current Profiler) collected data and WANE predicted currents.

OILMAP's stochastic model was applied to eleven potential surface spill scenarios using WANE winds and currents. Spills were assumed to originate at the FPSO or Well Mahogany 1. For all scenarios the predominant transport of spilled oil is to the east. The footprint for the area of potential impact varies with spill size, with the maximum length of the footprint ranging from 40 km for a marine gasoil spill of 10 Tonnes to more than 600 km for crude oil spills of 1000 Tonnes or more. Spilled oil could reach the Ghana shoreline in a minimum time of 1-1.25 days although the average time to reach shore is 2.5-4.5 days. Roughly 200-300 km of shoreline is at risk for oiling with the larger spill sizes having the potential for more shoreline impact. The shoreline with the highest probability of being oiled is the 100 km west of Cape Three Points. East of Cape Three Points a longer reach of shoreline could potentially be oiled, but the probability of oiling is generally less than 10 percent.

A trajectory/fate simulation was done for the ten spill scenarios with shoreline impacts, using the same simulation start date for each. The simulation start time was selected to encompass a period of winds and currents that resulted in a greater transport of oil to shore than most other time periods. For these scenarios, the results showed that the first oil reached shore 45 hours after the spill began. The extent of shoreline oiling was directly related to the duration of the oil release. An instantaneous or 2-hour duration spill resulted in 10-12 km of shoreline impacted. Longer duration spills contribute to wider spreading of the surface oil due to variations in the wind direction. For the 48-hour release 75 km of shoreline were impacted, for the 168-hour release 125 km were oiled. The mass balance indicated 20-30% of the crude oil and approximately 60% of the marine gasoil evaporated before reaching shore.

Produced water discharges were simulated using ADCP current data as input to ASA's MUDMAP modeling system. Westward and eastward flow conditions were considered for maximum possible (80 MSTB/D), and maximum (18.4 MSTB/D) and average (6 MSTB/D) predicted discharge rates. Based on a continuous surface discharge for 30 days, elevated hydrocarbon concentrations were found to be confined within a fairly short distance of the release location for the maximum and average predicted discharges. The maximum distance from the

discharge point to the 0.005 ppm contour is 2000-2200 m for the maximum possible discharge, 600-700 m for the maximum predicted discharge rate, and 300-400 m for the average predicted discharge rate. The vertical extent of the effluent remains within 5 m of the surface for the predicted discharge rates, and within 7-8 m of the surface for the maximum possible discharge.

The results of the mud/cuttings discharge simulations show that water column concentrations are primarily due to mud solids, while seabed deposition is primarily due to cutting discharges. The majority of deposition occurs close to the discharge site due to the relatively low current velocity at depths greater than 50 m. The maximum horizontal extent of the discharge plume with a concentration greater than 0.5 mg/l is approximately 0.015 km^2 and extends 100-200 m from the well depending on the current direction. The larger size particles of the cutting discharges are deposited in the immediate vicinity of the well site, slightly oriented towards the north and east. The maximum deposition thickness is 73-79 mm within 25 m of the drilling site; the area covered by deposits more than 1 mm thick is approximately 0.053 km^2.

1. Introduction and Scope of Work

ERM contracted with Applied Science Associates, Inc. (ASA) to perform the impact assessment of several operational and potential pollutants from the Jubilee Field in the Seep Water Tano and the West Cape Three Points Blocks off the coast of Ghana.

ASA was requested to undertake the following numerical model simulations:

- Dispersion of potential surface crude and marine gasoil spills from the FPSO and Well Mahogany 1 (M1).
- Dispersion of the produced water from the FPSO
- Dispersion of the drilling discharges from Well M1, in order to estimate the actual seabed deposition of the bulk material and maximum water column concentration.

Several modeling scenarios were defined to represent different wind and current conditions encountered in the study area, as well as to consider different discharge conditions.

Meteorological and oceanographic descriptions of the area of interest were provided by Tullow Ghana Ltd. for use as model input. In addition, ASA performed the following tasks prior to performing the requested simulations:

- A climatologic analysis of the meteorological and oceanographic conditions
- A characterization of the mud and cuttings discharges (volume, size distribution)

The following models were applied:

- ASA's MUDMAP modeling system (Appendix A) to simulate the dispersion of produced water, and mud and drill cuttings discharges, and
- ASA's OILMAP (Appendix B) to simulate potential surface crude and marine gasoil spill from the FPSO and Well M1 locations.

Input data for the models is described in Section 2, including the study location, and the characterization of modeling scenarios. The results of the simulations are described in Sections 3, 4 and 5. Conclusions are in Section 6, and References in Section 7. The appendices include brief descriptions of the models used, and additional details on the oil spill scenarios.

2. Location and Model Setup

2.1. Study Location

The study area is located in the Jubilee Field in the Deep Water Tano and West Cape Three Points Blocks approximately 60 km south of Ghana, West Africa.

This modeling study addresses different operational discharges and potential pollutant spills from Well M1 and FPSO locations, as shown in Figure 1 and Table 1. The well site is located in water approximately 1200 m deep.

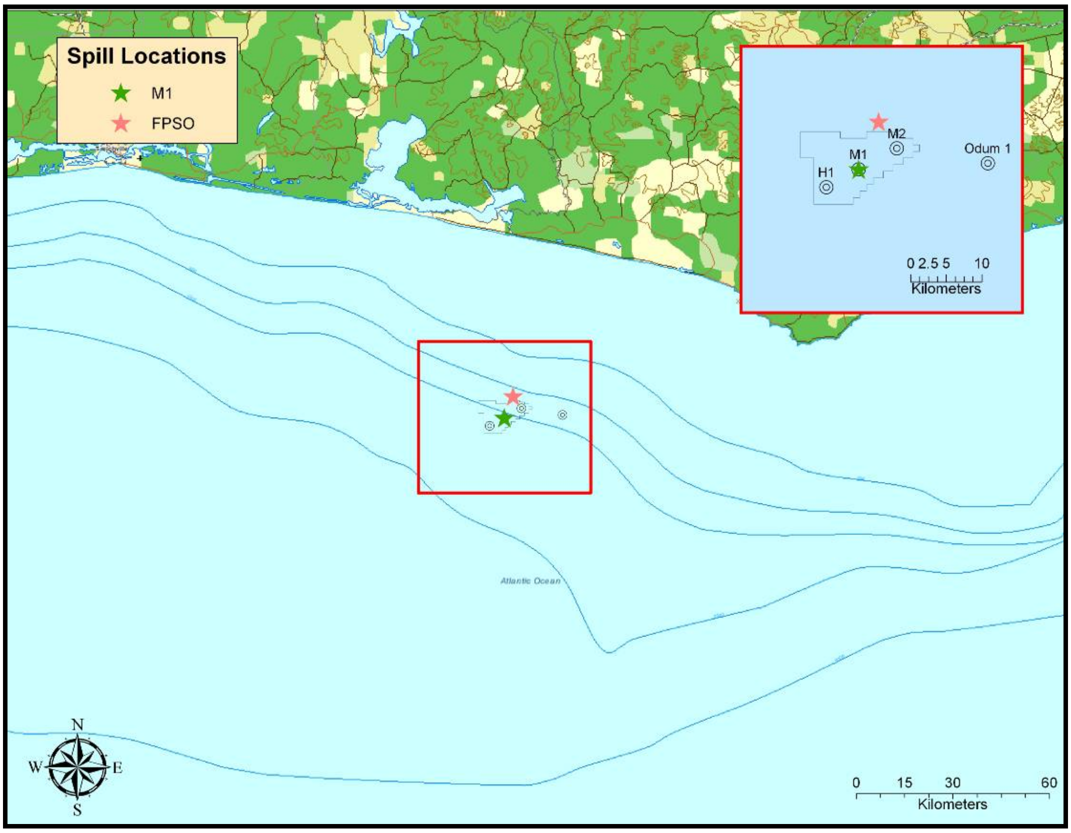


Figure 1. Area of study, showing Well M1, FPSO, bathymetric contours, and local geographic points of reference offshore Ghana.

Table 1. Spill locations

Location	Latitude	Longitude	Datum
FPSO	4.595927° N	2.884601° W	WGS 84
Well M1	4.535758° N	2.909648° W	WGS 84

2.2. General Overview of the Main Dynamics in the Area

Ghana is located within the Inter-tropical Convergence Zone (ITCZ). The ITCZ is a zone of low pressure that migrates from south to north and back again over the course of the year; this shift affects the seasonal patterns. During November-

April the ITCZ is in its southern position when dry winds blow in from the Sahara. During May-October the ITCZ is in its northern position; during this time the year-round southwest trade winds gain a more southeasterly direction due to the Coriolis force.

The wind direction and speed is fairly consistent all year. Winds are primarily from the southwest quadrant with maximum non-squall observed wind speed of 10 m/s. Squall events, caused by thunderstorm cells, generate extreme wind conditions. There are approximately 15-30 events per year. The squall events have a short duration and therefore generate weak currents and low wave heights.

2.3. Wind Data Input

Wind data at a 10 m height were obtained for the Ghana offshore region from NOAA's NCEP atmospheric model reanalysis. Two stations (NCEP point 17524 and NCEP point 17616) are located in the general study area and provide winds for the time period of 1985 to 2009. In addition the WANE (**W**est **A**frica (Met-Ocean) **N**ormals and **E**xtremes) wind file (WANE 28780) was assessed. These three data locations are displayed in Figure 2.

For each data set average monthly wind roses were generated (Figure 3 - Figure 5). All three datasets show the same predominant southwestern wind direction, with average wind speeds of 3.7-4.0 m/s and maximum winds speeds of 8.8-10.8 m/s. There is very little difference in wind speeds and directions over the course of the year. Both data sources (WANE and NCEP) are based on wind hindcast models; such data typically under-represents actual extreme values (i.e., squalls).

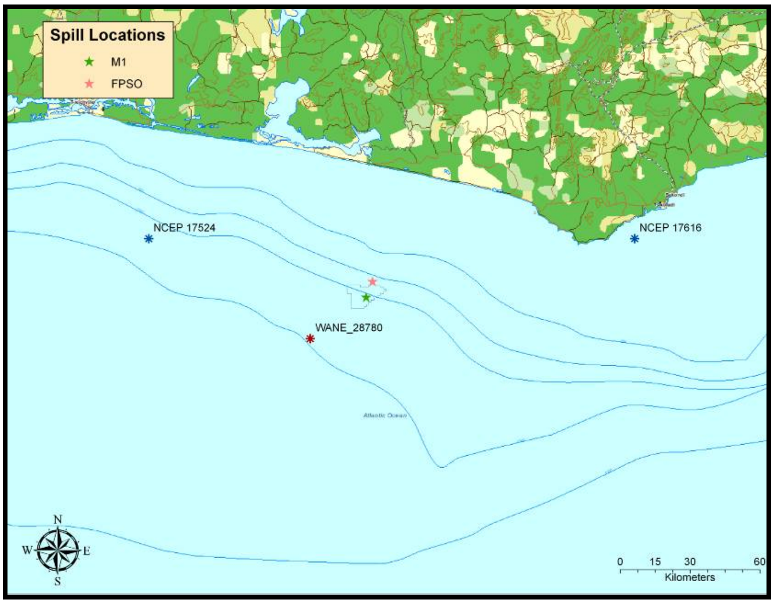


Figure 2. Locations of wind data stations: NCEP 17524, NCEP 17616 and WANE 28780

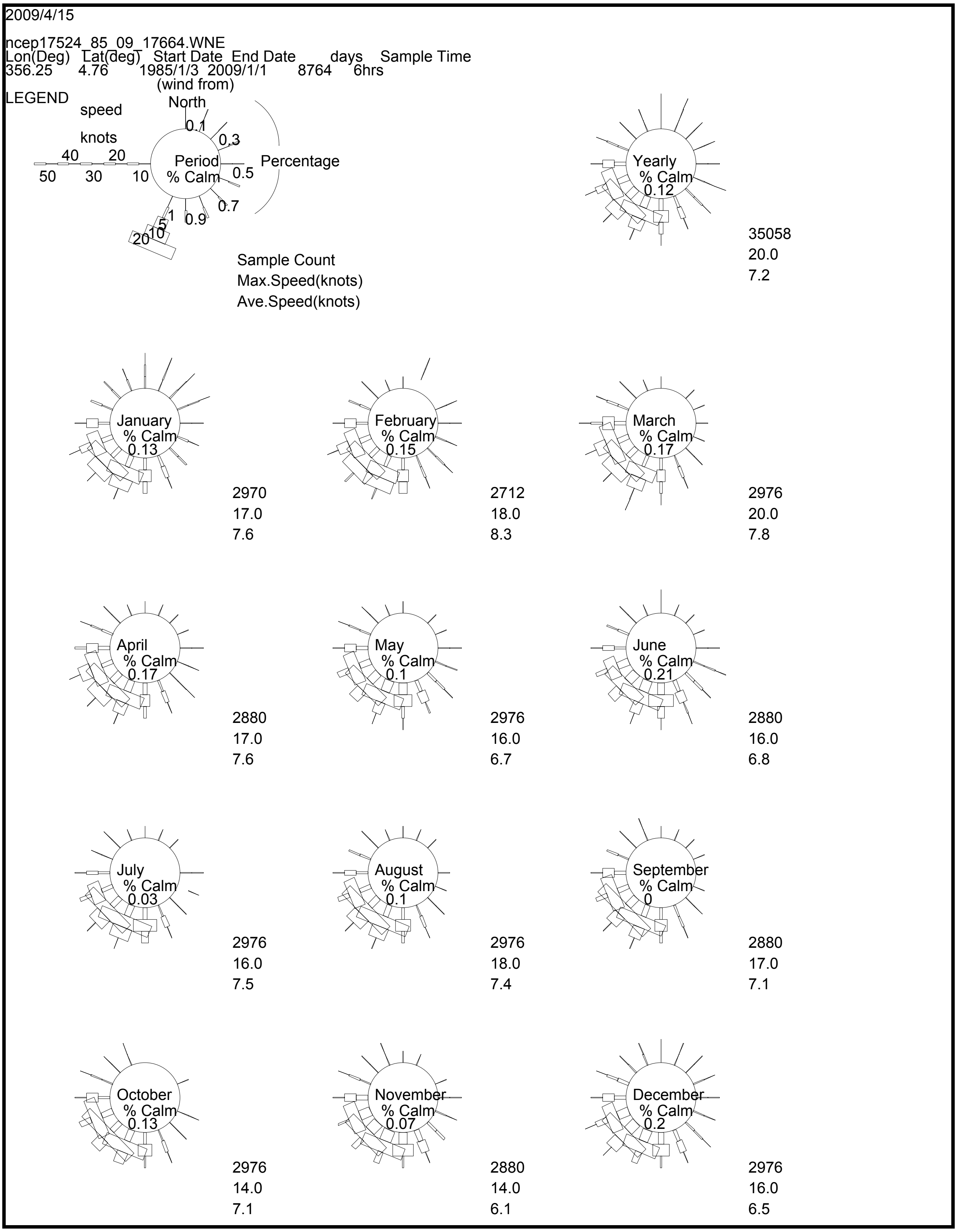


Figure 3. Wind rose of monthly averaged NCEP wind data offshore Ghana, NCEP 17524

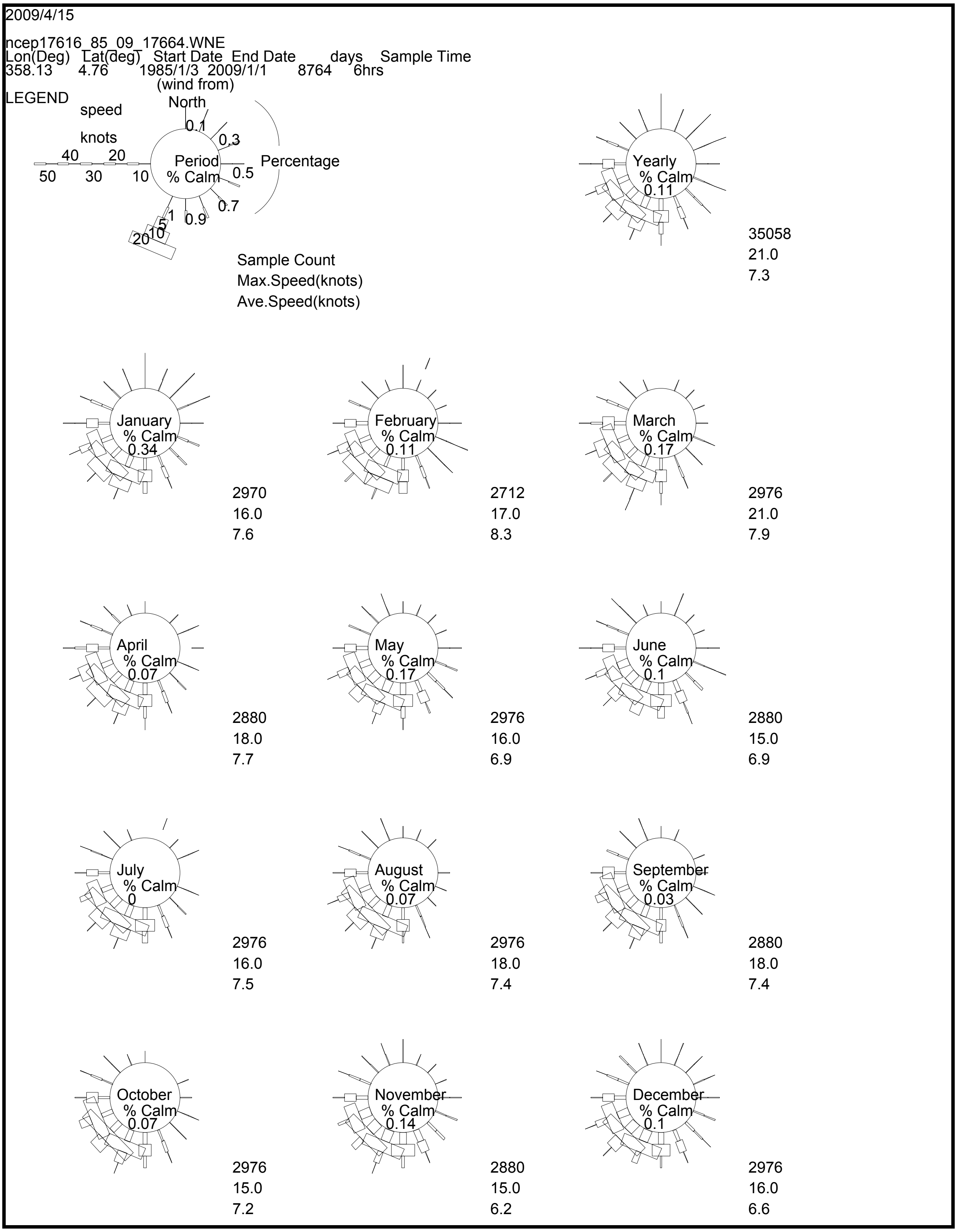


Figure 4. Wind rose of monthly averaged NCEP wind data offshore Ghana, NCEP 17616

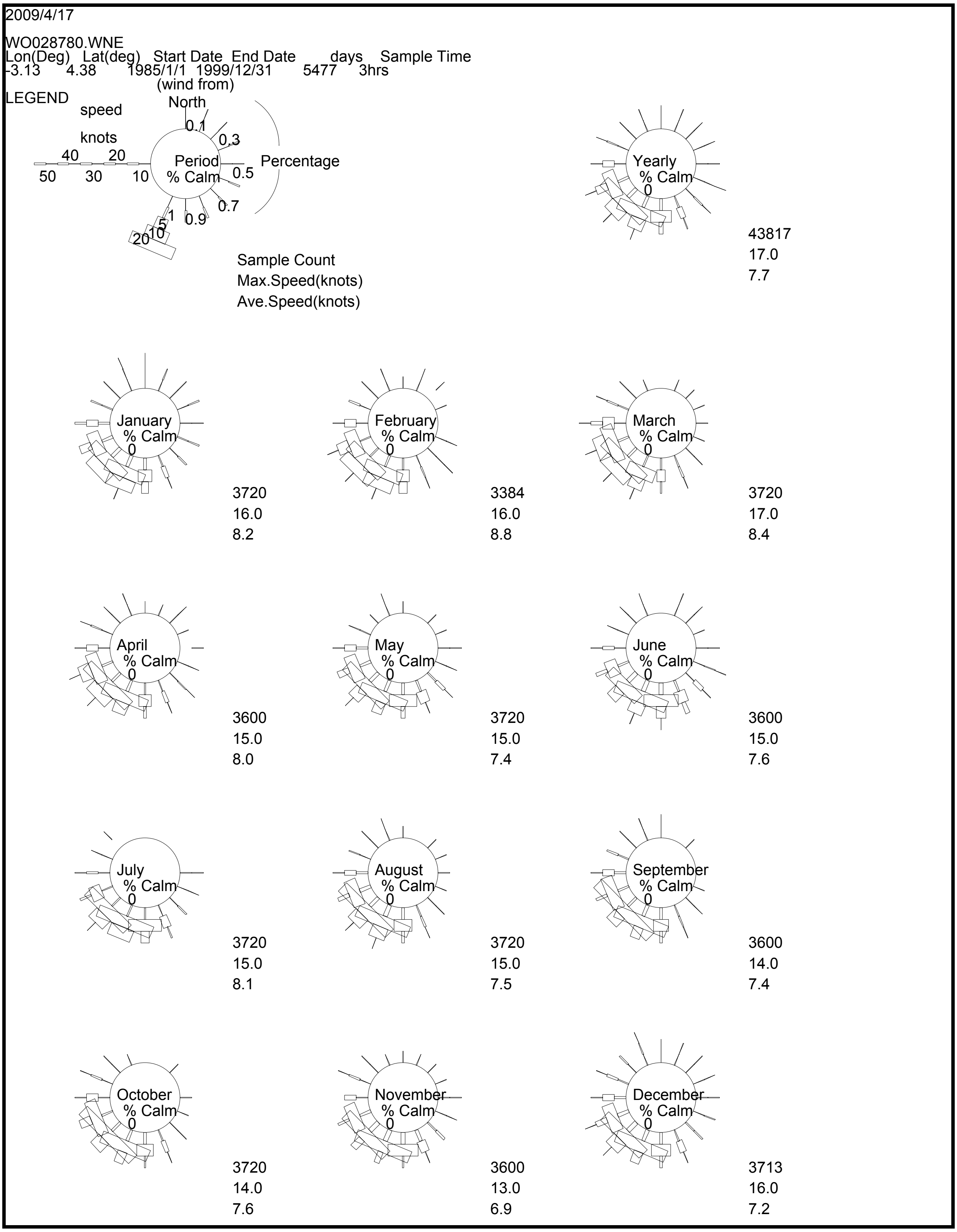


Figure 5. Wind rose of monthly averaged WANE wind data offshore Ghana, WANE 28780

2.4. Current Data Input

Regional currents were assessed from ADCP (Acoustic Doppler Current Profiler) collected data and WANE (**W**est **A**frica (Met-Ocean) **N**ormals and **E**xtremes) predicted currents. Figure 6 shows the location of the current data stations in relation to the Jubilee Field.

ADCP files

Current data was collected at two moorings (M1 and M2, labeled E&H M1 and E&H M2, respectively, in Figure 6). The data files (Evans-Hamilton, Inc., 2008, 2009) are organized in two deployment periods, covering one continuous time span of approximately six months from September 2008 to March 2009. At each mooring, multiple instruments sampled at ~2 m intervals. For use in this study, the data were compiled and sub-sampled at standard NODC depths in the vertical and at hourly time intervals. Figures 7 and 8 present stick vectors representing the currents at standard NODC depths over the deployment period for moorings M1 and M2, respectively.

Observations near the surface are only available for mooring M1. For the first half of the observation period (September – November), surface currents exhibit a strong westward component. Beginning in December the surface currents become generally weaker and have a more eastward orientation. Currents at depths greater than 50 m are weaker than surface currents and do not display any consistent directional trends. The exception to this is the strong NNE-SSW orientation of currents near the bottom, particularly noticeable at mooring M1. These anomalous observations may be related to tidal signals in the deep waters (900, 1000, and 1100 m at M1 and 1200 m at M2).

Based on the directional trends of the surface currents at mooring M1, the ADCP currents are considered to represent periods of eastward or westward flow for the produced water and drill cuttings and mud discharge simulations discussed in Sections 4 and 5, respectively.

WANE product files

Data for three WANE current locations (labeled wc_1114, wc_1148 and wc_1149 in Figure 6) were provided by Tullow Ghana Ltd. Two of the stations are located in waters deeper than the potential well site. The triangle symbols in Figure 6 indicate additional WANE current locations (the original distribution) for which data could potentially be obtained if necessary.

WANE currents cover the period from 1985 to 1999. A representative time series of currents at location wc_1149 is shown in Figure 9. For comparison, Figure 10 displays the ADCP data at the same depths as the WANE data in Figure 9. The two figures cover the same months but in different years since the time periods covered by the two data sets do not overlap. The WANE currents exhibit a strong easterly component near the surface and do not show the westward trend in the surface currents noted in the ADCP data. Similar to the ADCP currents, the WANE currents also show decreasing speed with depth. However, the WANE data exhibits more coherent/consistent directional patterns at greater depths, reflecting its source as model-generated data.

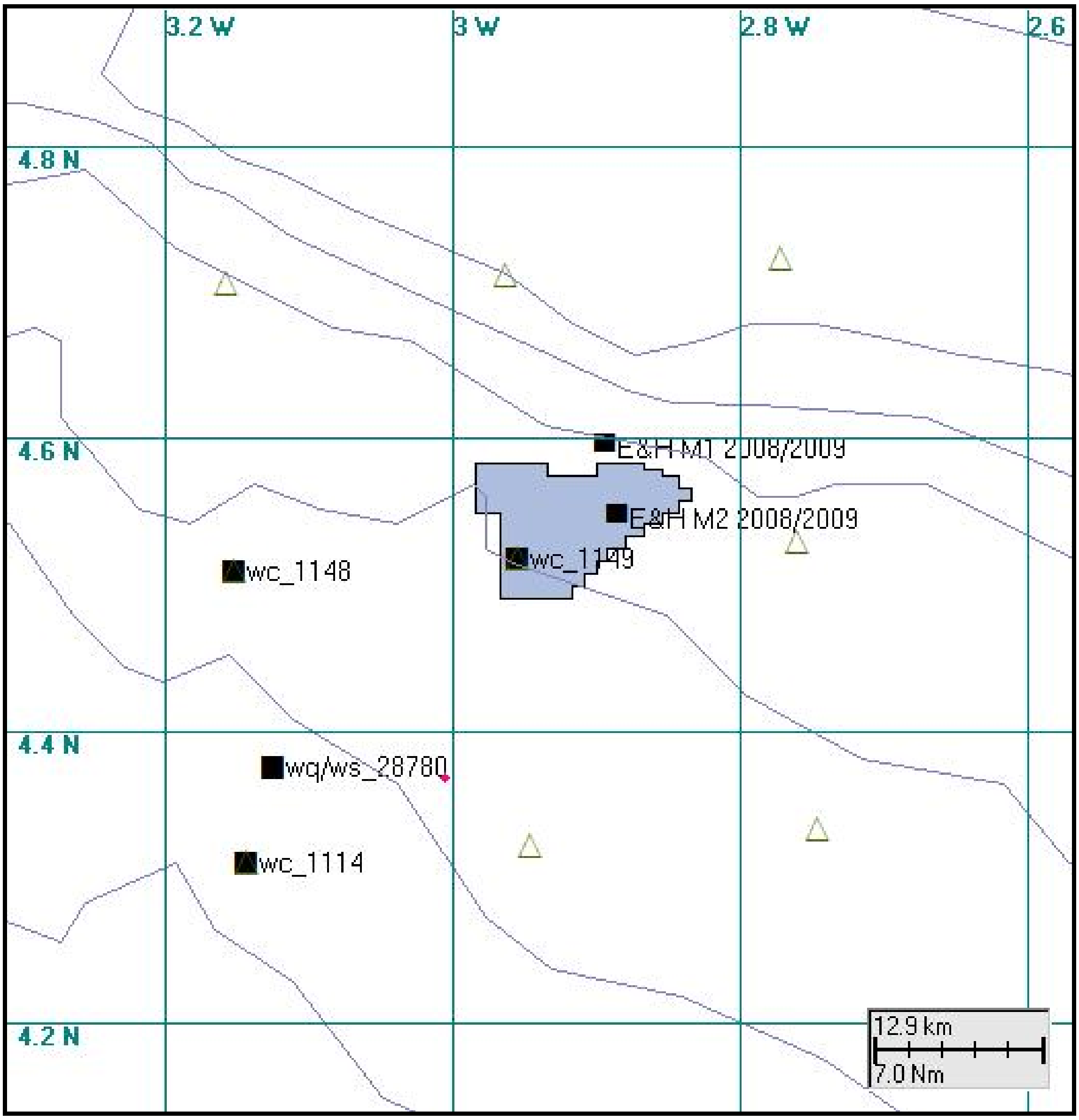


Figure 6. Location of current data

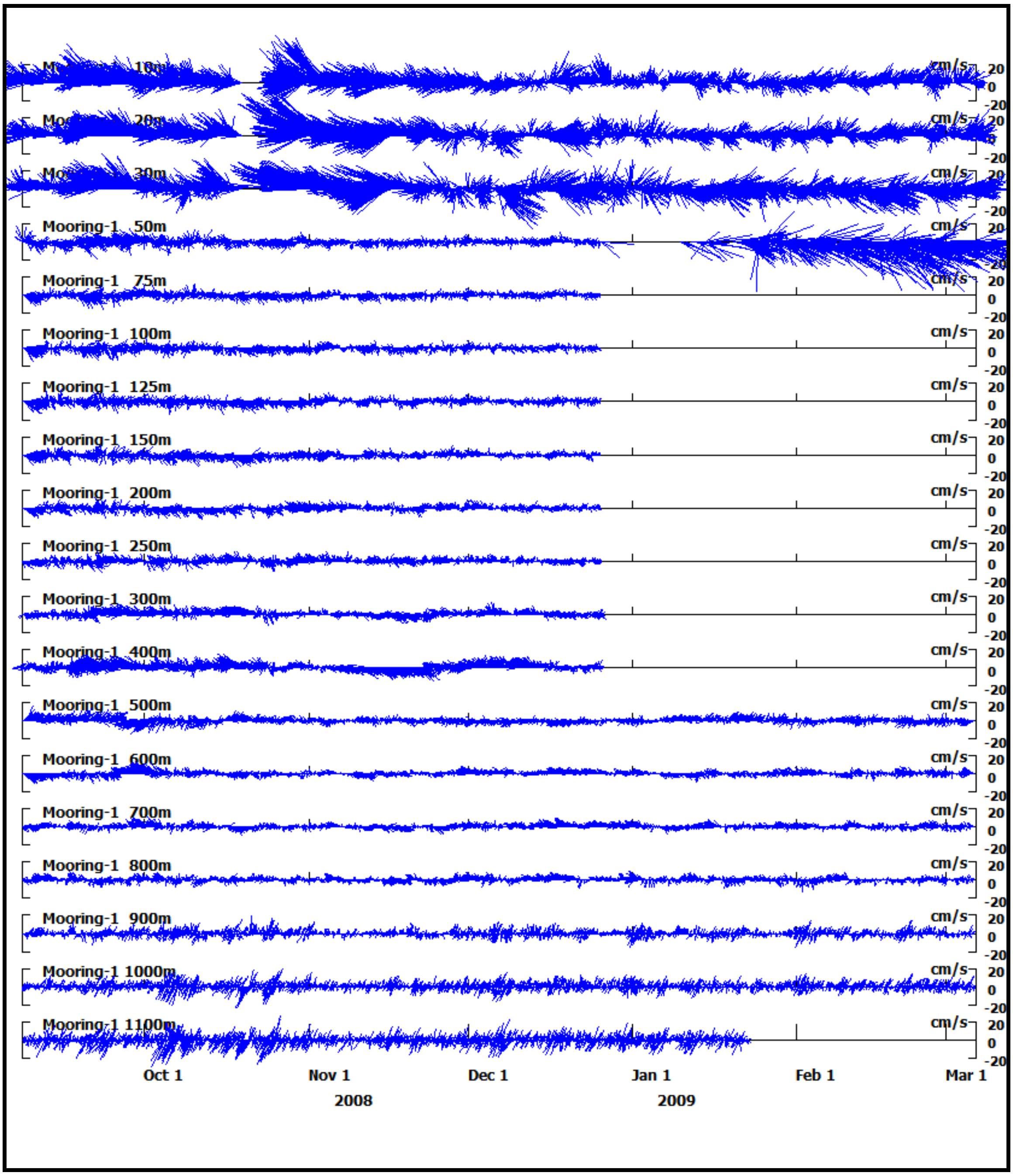


Figure 7. Current vectors at selected depths for Evans-Hamilton ADCP Mooring 1

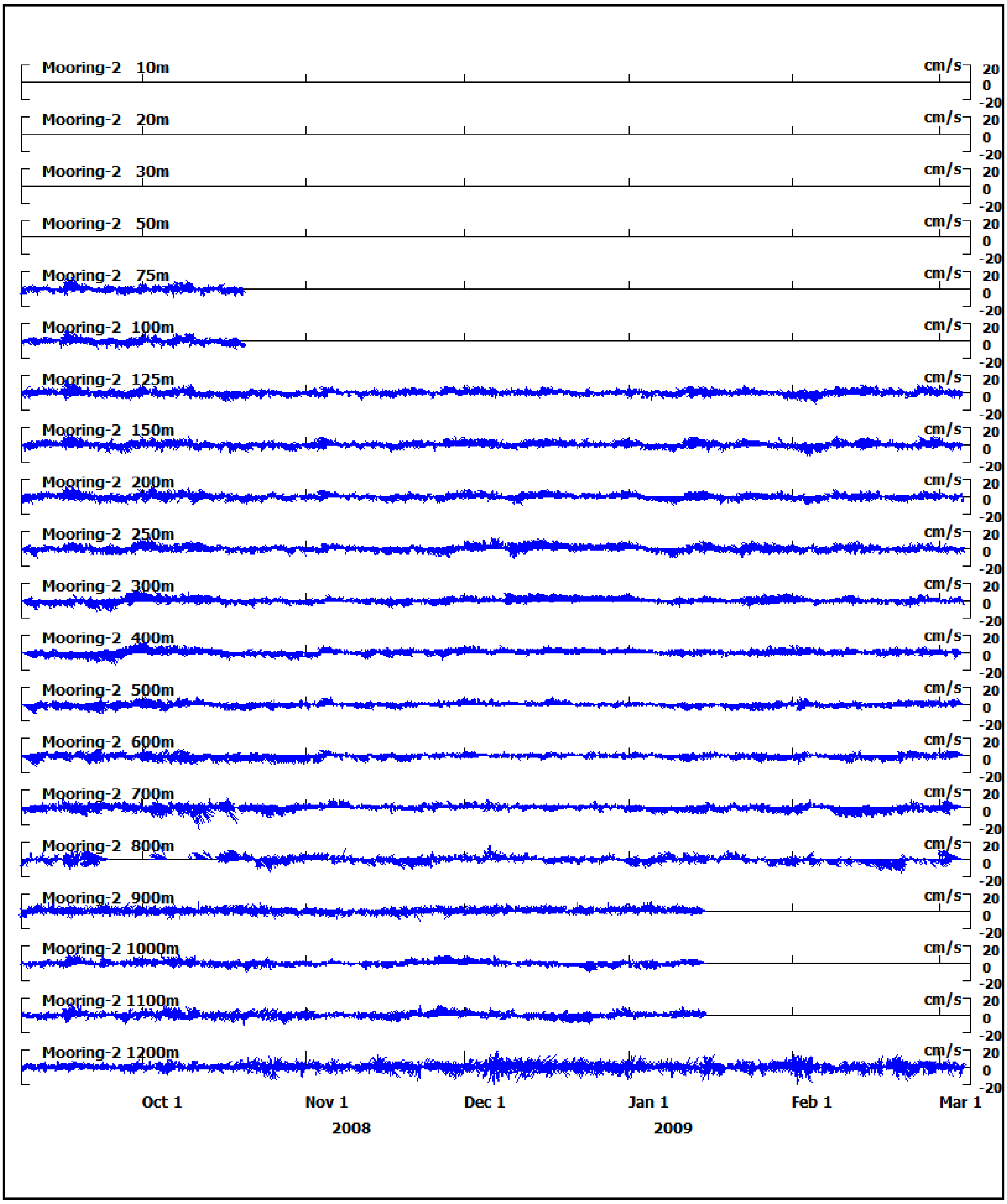


Figure 8. Current vectors at selected depths for Evans-Hamilton ADCP Mooring 2

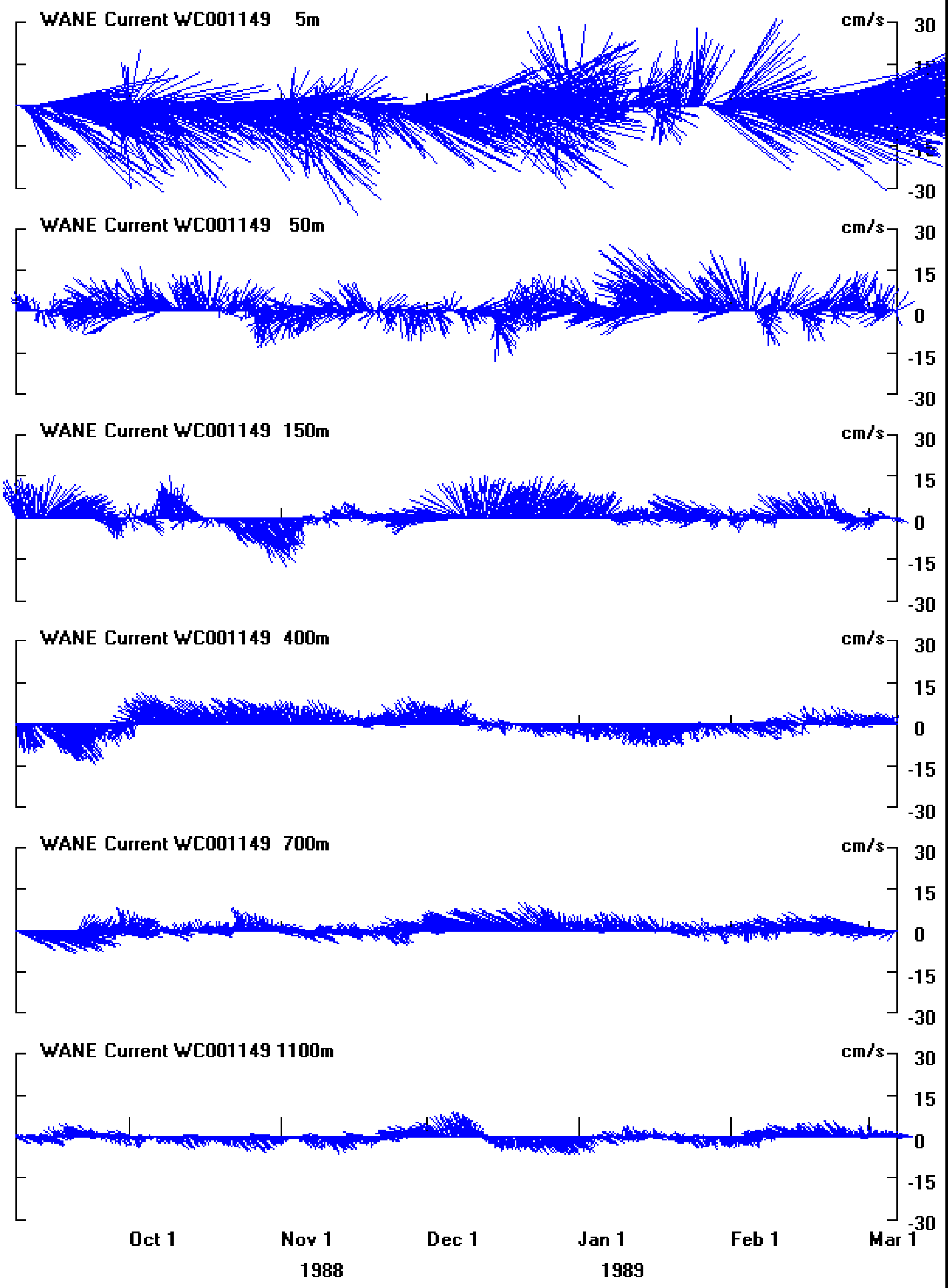


Figure 9. Current vectors at selected depths for WANE data location wc_1149

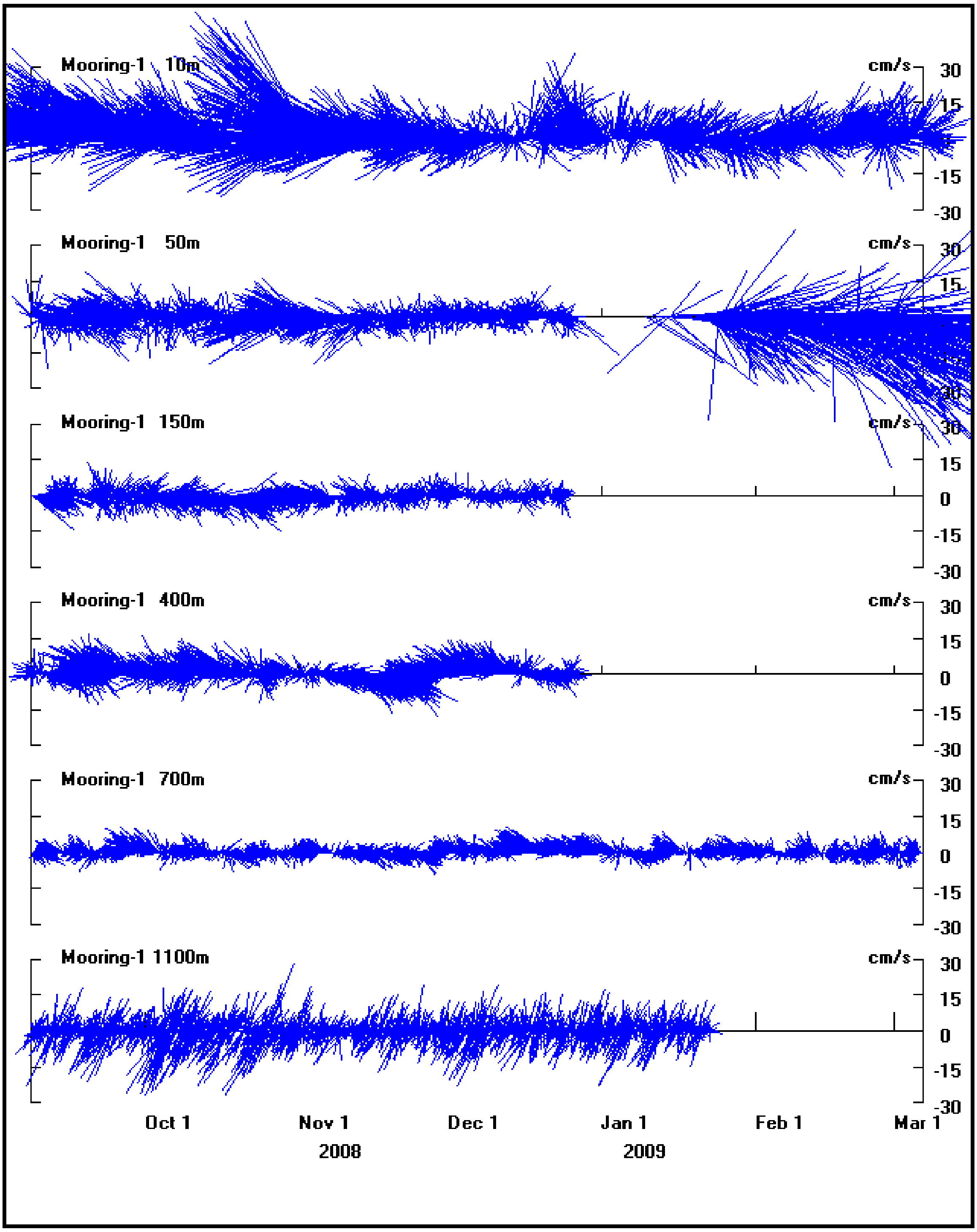


Figure 10. Current vectors for Evans-Hamilton ADCP Mooring 1, at the same water depths as WANE currents in Figure 9.

3. Surface Oil Spill Simulations

3.1. Surface Release Scenarios

Eleven spill scenarios (Table 2) were simulated to represent potential spill consequences. The full list of selected spill scenarios and the representative surface spill modeling scenarios are given in Appendix C. All spill scenarios assumed a surface release and were simulated for 14 days.

Table 2. Surface spill modeling scenarios

Scenario	Location	Oil Type	Release Duration (hours)	Spill Volume (tonnes)
1	Well M1	Crude	Instantaneous	10
2	FPSO	Marine Gasoil	Instantaneous	10
3	Well M1	Crude	Instantaneous	100
3a	FPSO	Crude	Instantaneous	100
4	FPSO	Marine Gasoil	Instantaneous	100
5	Well M1	Crude	48	1000
5a	FPSO	Crude	2	1000
6	Well M1	Crude	48	5000
7	Well M1	Crude	168	20000
8	Well M1	Crude	48	28000
8a	FPSO	Crude	2	28000

3.2. Oil Characterization

The characteristics of the oils used in the simulations are given in Table 3. Evaporation characteristics were assumed based on representative oils with similar density and viscosity.

Table 3. Oil characterization summary

Oil Type	Density @ 15°C (gm/cm^3)	Viscosity @ 25°C (cP)
Marine Gasoil	0.8564	4.8
Crude	0.8783	33

3.3. Stochastic Model Predictions

The OILMAP stochastic model was applied to predict sea surface probabilities of oiling due to potential oil spills during drilling, production and transfer from Jubilee Field Well M1 and FPSO locations. The stochastic simulations provide insight into the probable behavior of potential oil spills under the met-ocean conditions expected to occur in the study area. Two types of statistics are generated: 1) sea surface areas that might be oiled and the associated probability of oiling, and 2) the shortest time required for oil to reach any point in the areas predicted to be oiled. The stochastic analysis is based on a large number of individual simulations, each with a different start time within the selected season.

OILMAP's stochastic model was applied to the eleven potential surface spill scenarios. WANE winds and currents were used as input to the oil spill simulations due to their long data record. Since wind conditions remain very consistent year-round, only one "season" was considered for selecting the start times of individual simulations. Five hundred simulations were run to generate the stochastic statistics for each scenario.

The following figures (Figure 11-21) depict water surface probabilities of oiling, and travel time contours. The plots define the area in which sea surface oiling may be expected and the probability of oil reaching the area, based on the ensemble of trajectories from the 500 independent simulations run for each scenario. They do not imply that the entire colored surface presented would be covered with oil in the event of a spill. The plots do not provide any information on the quantity of oil in a given area (water surface or shoreline); they only show the probability that some oil reaches the area.

All simulations show the predominant transport of spilled oil is to the east. This transport is due to the influence of consistent winds from the southwest quadrant and the WANE currents with a strong easterly component. The footprint for the area of potential impact varies with spill size, with the maximum length of the footprint ranging from 40 km for a marine gasoil spill of 10 Tonnes to more than 600 km for crude oil spills of 1000 Tonnes or more. Shoreline oiling is possible for all scenarios except the marine gasoil spill of 10 Tonnes.

The simulations show that the minimum time in which spilled oil could reach the Ghana shoreline is 1-1.25 days although the average time to reach shore is 2.5-4.5 days. Roughly 200-300 km of shoreline is at risk for oiling with the larger spill sizes having the potential for more shoreline impact. The shoreline with the highest probability of being oiled is the 100 km west of Cape Three Points. East of Cape Three Points a longer reach of shoreline could potentially be oiled, but the probability of oiling is generally less than 10 percent. The shoreline east of Cape Three Points has the highest probability of oiling due to a 168-hour release of 20,000 Tonnes of crude oil from Well M1. For this scenario some areas have up to a 15 percent probability of being oiled.

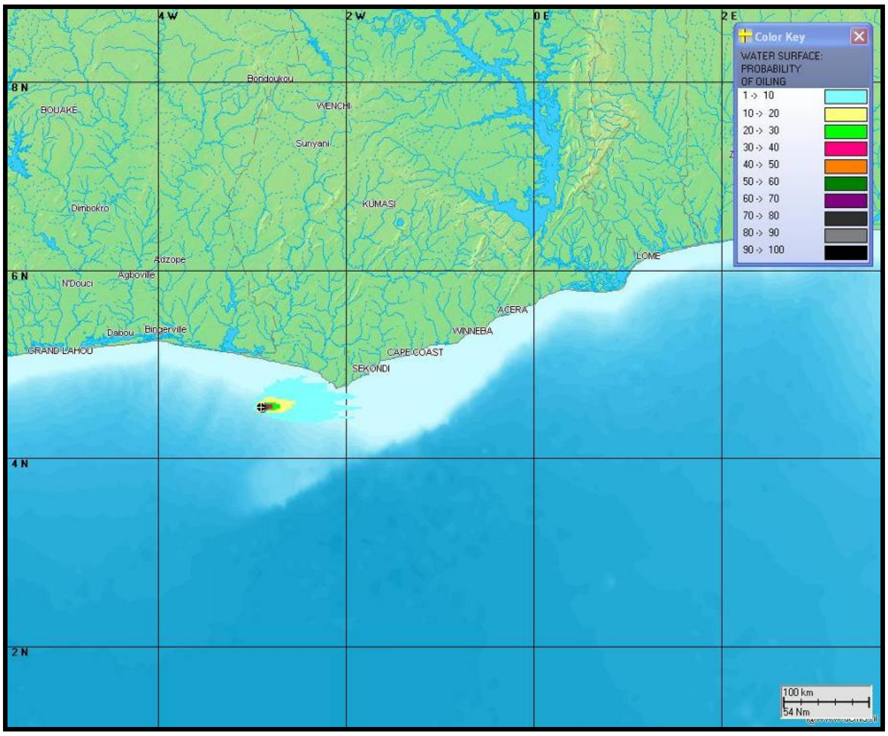
Table 4 summarizes the results of the eleven stochastic scenarios in terms of shoreline impacts. The table shows that 45-82 percent of the 500 simulations run for each scenario resulted in oil reaching shore by the end of the simulation. For those simulations with oil reaching shore, the table also indicates the minimum and average time for oil to reach shore, the maximum and average mass of oil that reaches shore, and the length of shoreline that has greater than a 10 percent probability of being oiled.

It should be noted that the stochastic simulations use winds and currents generated by model hindcasts. Such data is valuable for providing long time series of environmental conditions and is accurate in a statistical sense. However model-generated data may not replicate the very short-term or anomalous behavior that is often seen in observations. This is evident in the comparison of WANE (modeled) and ADCP (observed) currents (Section 2.4); the WANE data does not reproduce the westward flowing surface currents measured by the ADCP. By using modeled environmental data, the stochastic model predictions do not reflect anomalous wind or current patterns. Such anomalous conditions represent a very low probability of occurrence and may not be reflected in the oil spill results.

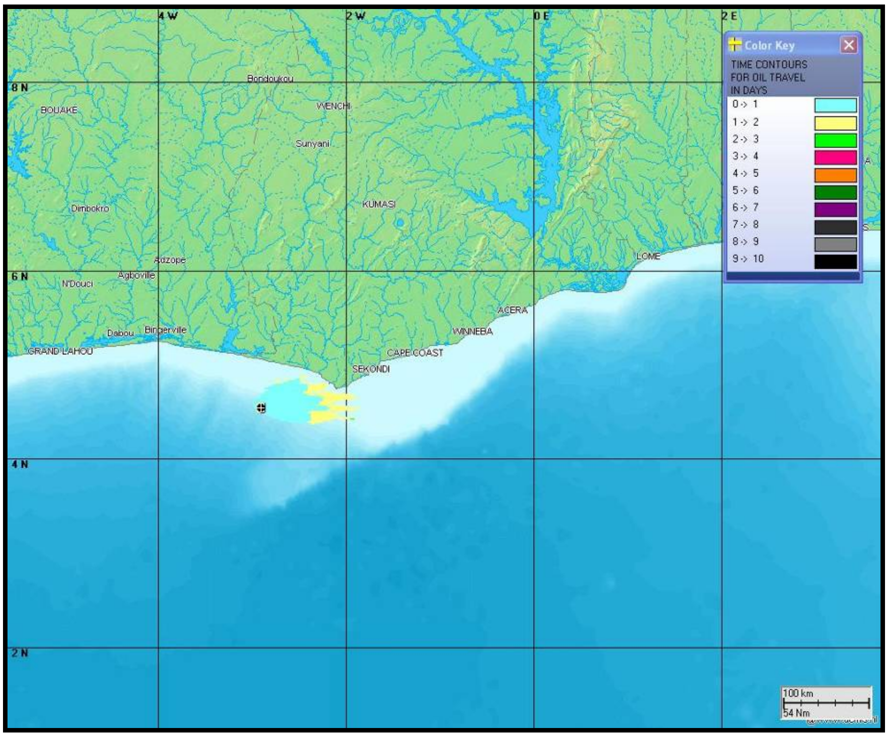
Table 4. Summary of shoreline statistics for stochastic simulations

Scenario	Volume (Tonnes)	Spill Duration	Oil Type	Spill Location	Percent of Simulations Reaching Shore	Minimum Time to Reach Shore (Hours)	Average Time to Reach Shore (Hours)	Maximum Amount of Oil Ashore (Tonnes)	Average Amount of Oil Ashore (Tonnes)	Length of Shoreline with Greater than 10% Probability of Oiling (km)
1	**10**	**Instantaneous**	**Crude**	**Well M1**	45	31	73	7	6	40
2	**10**	**Instantaneous**	**Marine Gasoil**	**FPSO**	NA*	NA	NA	NA	NA	NA
3	**100**	**Instantaneous**	**Crude**	**Well M1**	64	28	96	66	60	60
3a	**100**	**Instantaneous**	**Crude**	**FPSO**	69	24	90	66	60	65
4	**100**	**Instantaneous**	**Marine Gasoil**	**FPSO**	72	25	85	64	58	55
5	**1000**	**48 hours**	**Crude**	**Well M1**	66	31	102	684	559	115
5a	**1000**	**2 hours**	**Crude**	**FPSO**	73	22	84	689	583	70
6	**5000**	**48 hours**	**Crude**	**Well M1**	74	28	97	3,530	2,746	110
7	**20,000**	**168 hours**	**Crude**	**Well M1**	82	29	109	14,817	9,341	170
8	**28,000**	**48 hours**	**Crude**	**Well M1**	72	27	99	21,053	16,372	100
8a	**28,000**	**2 hours**	**Crude**	**FPSO**	70	21	88	21,193	18,849	55

*NA – Not Applicable.

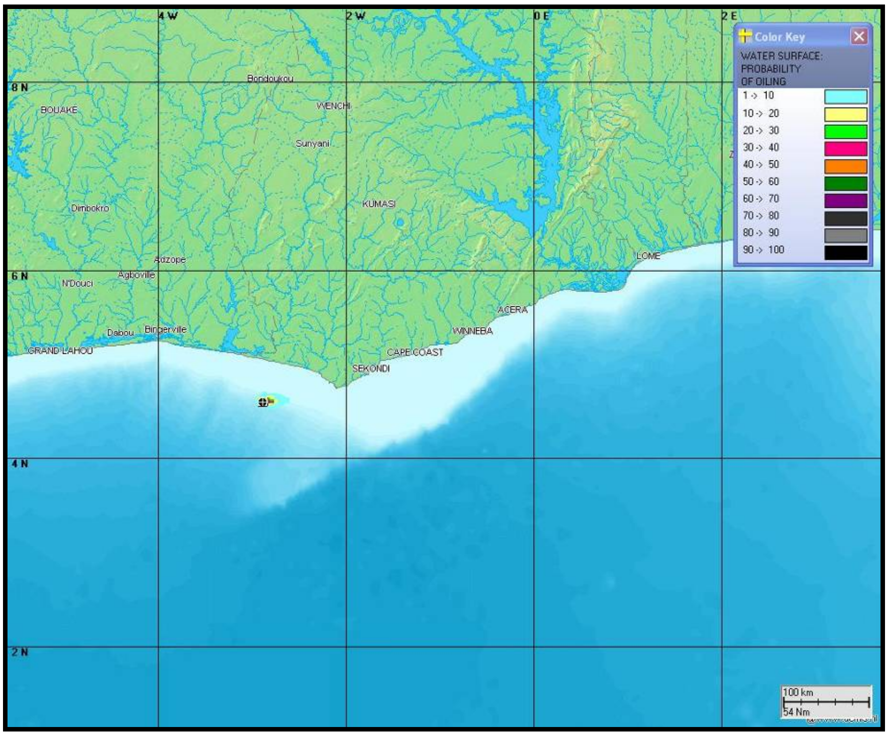


a)

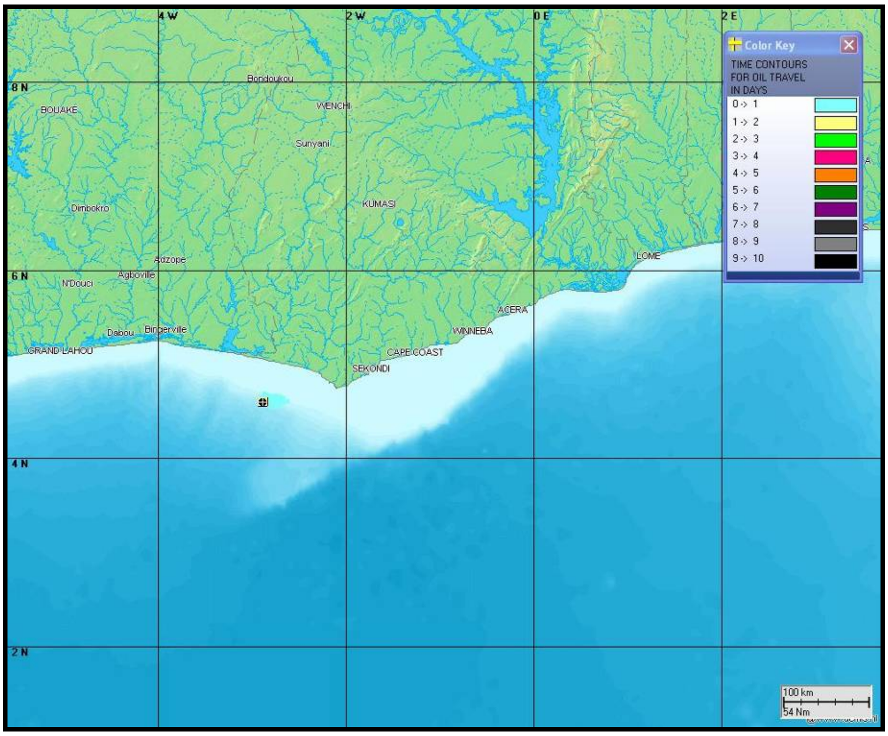


b)

Figure 11. Crude spill of 10 Tonnes at Well M1, a) water surface probabilities of oiling; b) travel time contours.

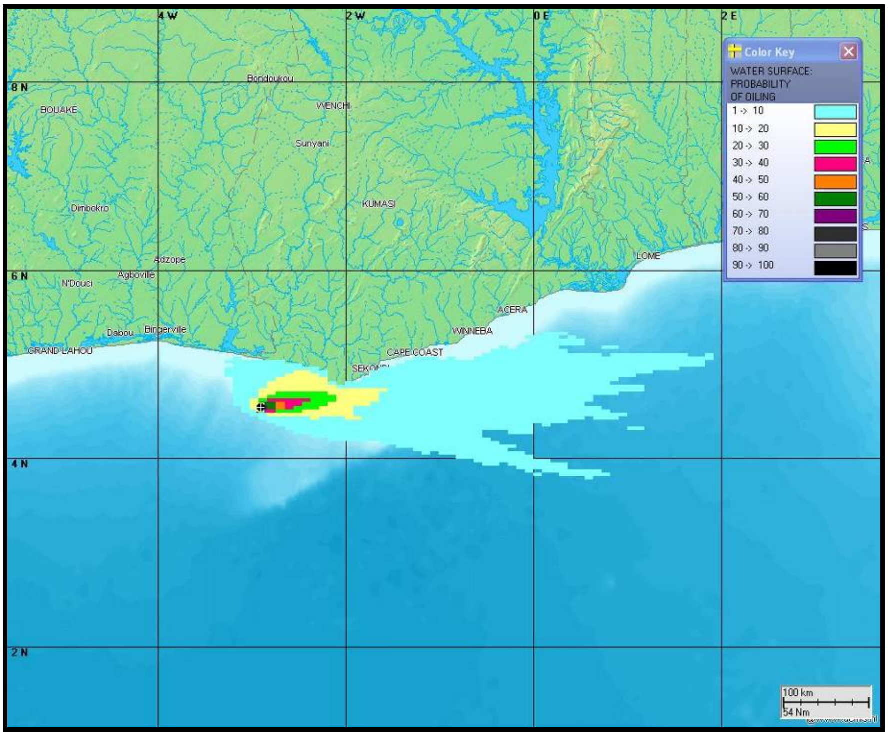


a)

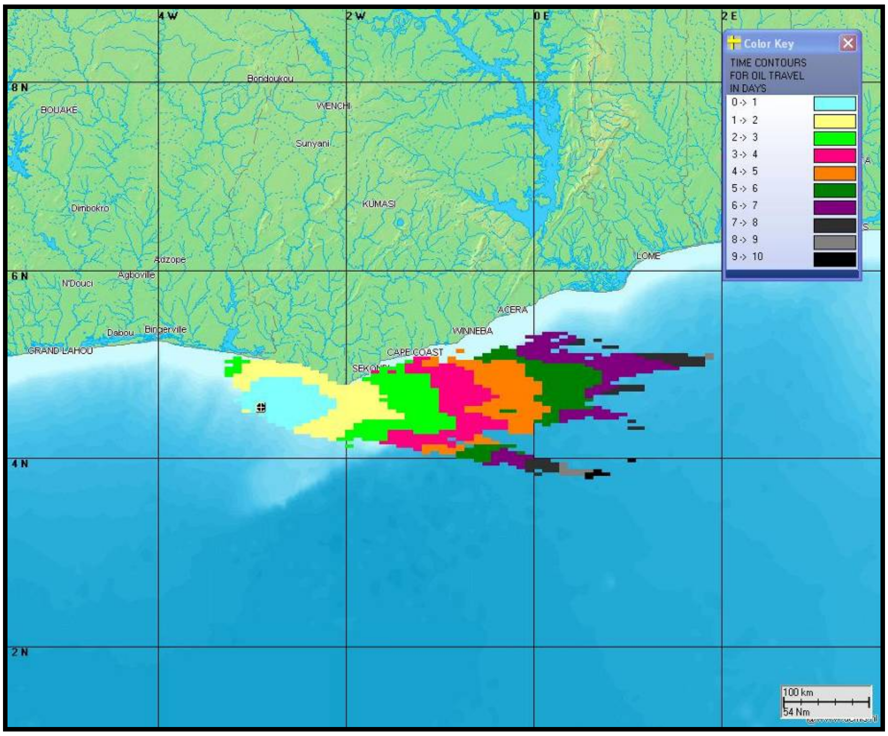


b)

Figure 12. Marine gasoil spill of 10 Tonnes at the FPSO, a) water surface probabilities of oiling; b) travel time contours.

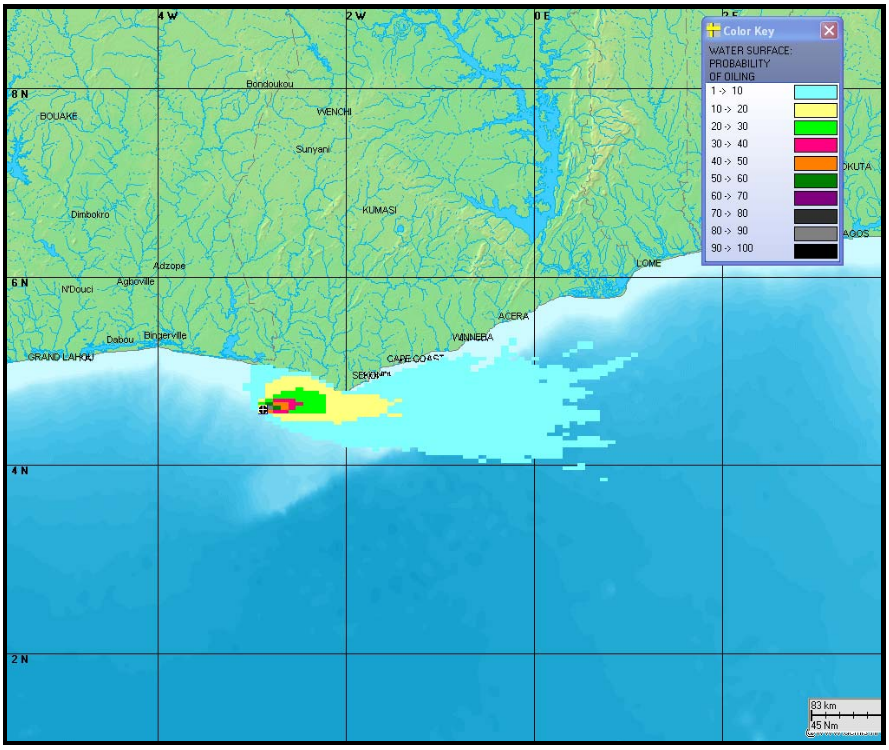


a)

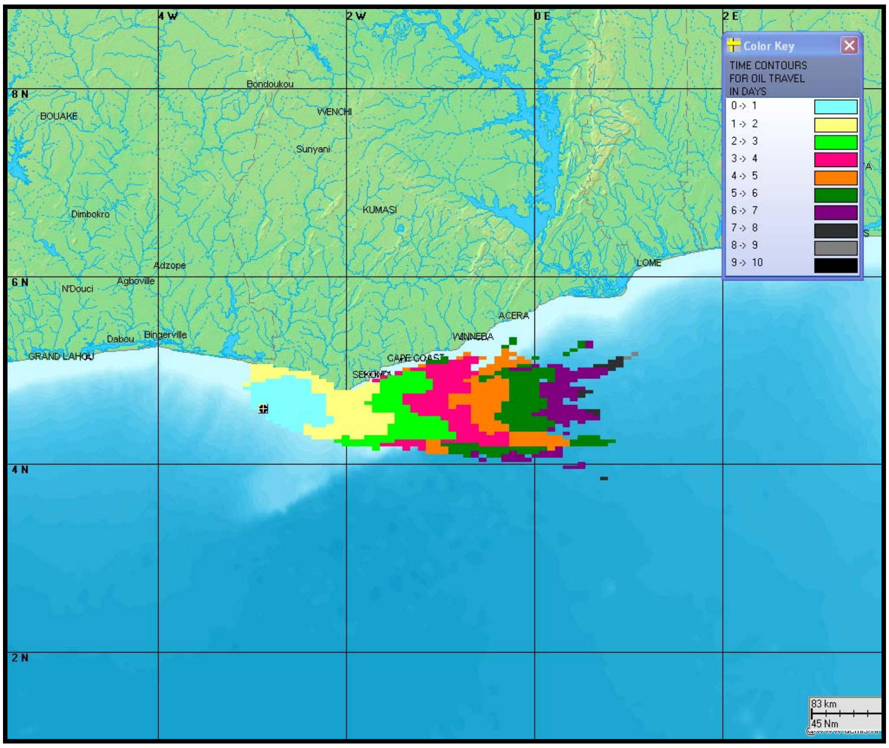


b)

Figure 13. Crude spill of 100 Tonnes at Well M1, a) water surface probabilities of oiling; b) travel time contours.



a)



b)

Figure 14. Crude spill of 100 Tonnes at the FPSO, a) water surface probabilities of oiling; b) travel time contours.