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Assessment and Modeling of Oil Spill Dispersion in Mediterranean Sea on the North East Coast of Egypt and the Arabian Gulf

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Abstract This paper aims assessing the environmental impact of oil spills which are caused by hypothetical oil tankers and offshore nuclear power plants accidents; where the effect of the changes in wind and water current on the oil spill movement and fate is studied. In case (a), multiple oil spills which are caused by a tanker accident near to the north coast of Egypt in the Mediterranean Sea are simulated by MEDSLIK[1] software. In this case, variable wind data is documented every 24 hours for 10 days[5] of simulation and non-uniform current input[4] were used. In case (b), the "best guess"[2] of oil spill trajectory and the associated uncertainty of an oil spill occurred on the Iranian coastline in the Arabian Gulf after an accident in Bushehr Nuclear Power Plant, which is caused by an earthquake, are calculated by using GNOME[2] software. In this case, wind forecast data from Bushehr Airport meteorological station[3] and three current patterns[2] are used to simulate the oil spill dispersion. These cases give decision-makers critical guidance in predicting the behavior of oil spills in the studied regions. Moreover, they show the effect.

Keywords MEDSLIK, GNOME and Trajectory Analysis

1. Introduction

Accidental and illegal marine pollution in the Sea water constitutes a major threat to the marine environment. Previous incidents in the Mediterranean Sea and the Arabian Gulf have resulted in environmental and economic damages to fisheries, to the tourist industry and to coastal marine ecosystems. Oil-pollution discharges from ships and offshore power plants in the Mediterranean and Arabian Gulf have been described as significant and are a cause of environmental degradation in the seas of the Middle East region. To prevent the major impact of accidental oil spills, local and regional preparedness and response plans recommend the use of computer-aided support systems based on operational oceanography and real-time ocean forecasts and real-time ocean forecasts coupled with satellites images and oil spill models.

2. Materials and Methods

Table (1-a). Input data

Type of accident	**A tanker accident**	
Type of pollutant	Basrah medium	
Position of accident	1st spill	Latitude : 31°38.17 (N) Longitude : 31°49.95 (E)
	2nd spill	Latitude : 31°28.15 (N) Longitude : 32°9.06 (E)
	3rd spill	Latitude : 31°21.71 (N) Longitude : 32°17.63 (E)
Date	9, January, 2012	
Time of spill	1st spill	9 AM
	2nd spill	13 PM
	3rd spill	15 PM
Duration of spill	0.0 hrs (instantaneous spills)	
Rate of spillage	0.0 tons per hr (immediate leakage assumed)	
Volume of spill	1st spill	2000 tons
	2nd spill	1500 tons
	3rd spill	3000 tons
Wind	In this case variable wind data each 24 hrs for 10 days of simulation used.[5]	
Water current	In this case a non-uniform current input used from National Institute of Oceanography and Fishers (NIOF) study, shows the current patterns of the Egyptian Mediterranean coasts in winter.[4]	
Sea surface temp. (SST)	17.4°C	
Interval for output	2 hrs	

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Figure (1-a). Levantine Basin map by MEDSLIK

a) MEDSLIK incorporates the use of forecasts developed under MFS (Mediterranean forecasting system) program for the whole Mediterranean Sea and its sub-regions such as Levantine Basin (figure (1-a)). This program was used to simulate a multiple oil spills occurred by a tanker near to the north coast of Egyptian. MEDSLIK uses a modified version of Mackay's fate algorithms for evaporation and emulsification and the dispersion algorithm of Buist and Mackay[1]. The following is the typical data and information required as inputs for MEDSLIK:

Table (2-a). Wind data for MEDSLIK

	Date	hour	Speed (m/s)	Direction (°)
1	9/1/2007	9 AM	2	70
2	10/1/2007	1 PM	3	240
3	11/1/2007	1 PM	2	120
4	12/1/2007	1 PM	3	150
5	13/1/2007	1 PM	4	70
6	14/1/2007	1 PM	2	40
7	15/1/2007	1 PM	5	240
8	16/1/2007	1 PM	4	180
9	17/1/2007	1 PM	4	260
10	18/1/2007	1 PM	4	180
11	19/1/2007	1 PM	3	180
12	20/1/2007	1 PM	4	70

b) GNOME (General NOAA Oil Modeling Environment) was developed by the Hazardous Materials Response Division (HAZMAT) of the National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA OR&R)[2]. The program was used to simulate an oil spill occurs on the Iranian coastline on the Arabian Gulf after an accident in Bushehr Nuclear Power Plant after an earthquake occurred. The following are input data:

Table (3-b). GNOME input data

Type of accident	**A nuclear power plant accident; an explosion in fuel tanks used to feed the emergency diesel generators after an earthquake struck the region.(Bushehr Station)**
Type of pollutant	Diesel
Volume	10,000 tons
Position of accident	Latitude : 28°49'48.13" (N) Longitude : 50°53'9.77" (E)
Date	9, April, 2013
Time of spill	16:22
Release end date and time	10, April, 2013 at 22 PM
Wind	Wind forecast data from Bushehr Airport meteorological station[3]
Water current	Three current patterns are used to simulate the circulation in the inner Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area. These include a reverse estuarine flow, river flow, and a wind-driven circulation derived with NNW winds. Tidal flows are not simulated in the Location File because it is concerned with a large scale (>10 km) region and long (> 1 day) timescale simulations[2].
Model run duration	72 hrs. (3 days)

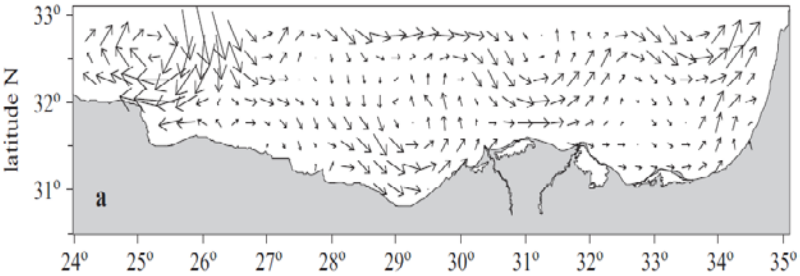


Figure (2-a). Distribution of currents at 30 m depth off the Egyptian coast in winter

Figure (3-a). Locations of three oil spills and the tanker path in north eastern direction of egyptian coasts

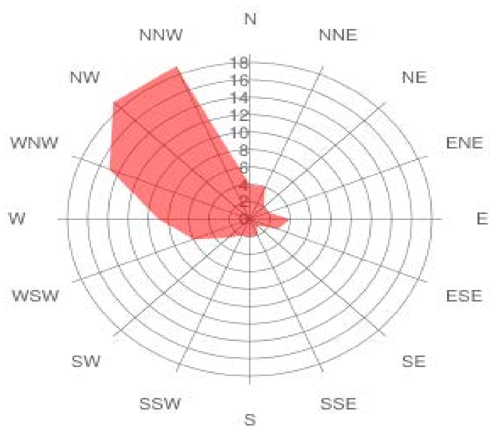


Figure (4-b). Wind direction distribution for April, 2013

Month of year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sep 09	Oct 10	Nov 11	Dec 12	SUM 1-12
Dominant Wind dir.	nnw	nnw	nnw	nw	nnw	nnw	nnw	nw	nw	nnw	nnw	nnw	**nnw**
Wind probability >= 4 Beaufort (%)	23	32	36	20	28	24	21	16	16	17	15	17	**22**
Average Wind speed (m/s)	4	5	5	5	5	5	5	4	4	4	4	4	**4**
Average air temp. (°C)	17	18	21	26	33	34	35	37	34	30	24	19	**27**
Select month (Help)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year

Figure (5-b). Average wind speed and dominant wind distribution in 2013

Local date	9, April, 2013								10, April, 2013							
Local time	01h	04h	07h	10h	13h	16h	19h	22h	01h	04h	07h	10h	13h	16h	19h	22h
Wind direction	nnw	n	n	nw	w	w	wnw	nw	n	nw	nne	wsw	wsw	wsw	w	sw
Wind speed (m/s)	3	3	1	3	6	6	4	2	1	1	1	2	5	7	4	3
Wind gusts (m/s)	4	4	2	3	6	6	4	2	1	2	1	2	5	7	4	3
Cloud cover																
Precipitation (mm/3h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air pressure (hPa)	1011	1010	1009	1010	1010	1008	1009	1010	1010	1008	1009	1010	1010	1008	1008	1010
Air temperature (°C)	24	23	23	28	31	30	28	26	26	24	25	30	33	32	29	27

Local date	11,April,2013								12,April,2013							
Local time	01h	04h	07h	10h	13h	16h	19h	22h	01h	04h	07h	10h	13h	16h	19h	22h
Wind direction	e	nne	n	nw	w	wsw	ssw	sse	se	s	s	sw	sw	sw	wsw	wnw
Wind speed (m/s)	2	1	2	3	6	9	4	4	1	1	2	3	6	6	2	1
Wind gusts (m/s)	2	1	2	3	6	9	5	5	1	1	2	3	6	6	2	1
Cloud cover																
Precipitation (mm/3h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
Air pressure (hPa)	1008	1007	1008	1008	1007	1007	1008	1009	1007	1007	1008	1009	1008	1006	1007	1008
Air temperature (°C)	27	26	27	31	33	31	28	27	27	26	27	30	33	31	29	27

Figure (6-b). Wind data by the meteorological Station in Bushehr Airport on 9th, 10th, 11th and 12th of April, 2013

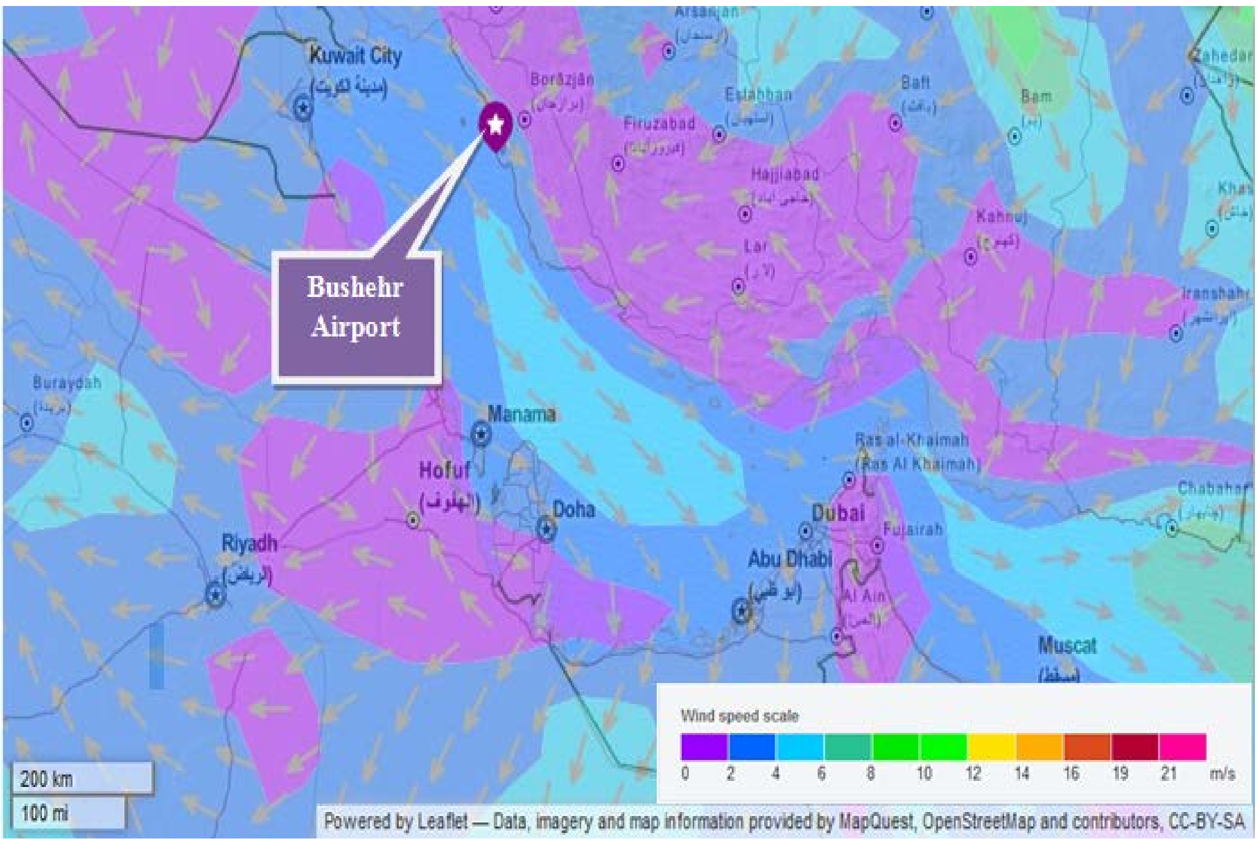


Figure (7-b). Wind map on 9th April, 2013 for Arabian Gulf region

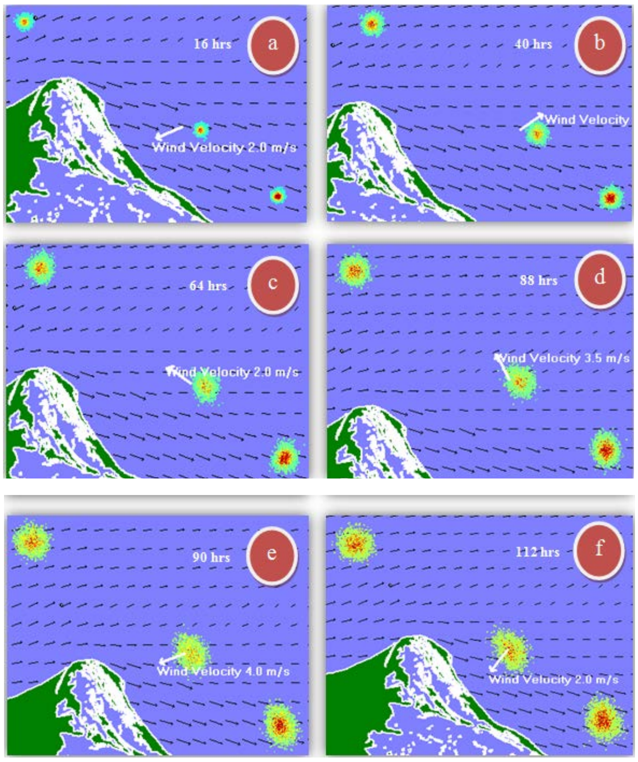
Figure (8-b). Location of Bushehr Nuclear Power Plant in Iran

Figure (9-b). Bushehr nuclear power plant

3. Results and Discussions

All the above data are inputted to MEDSLIK (tanker accident on the north east coast of Egypt) and GNOME (Bushehr nuclear power plant accident on the Arabian Gulf) and the outputs are presented and summarized as follows:

a) The output of MEDSLIK(tanker accident on north east coast of Egypt):



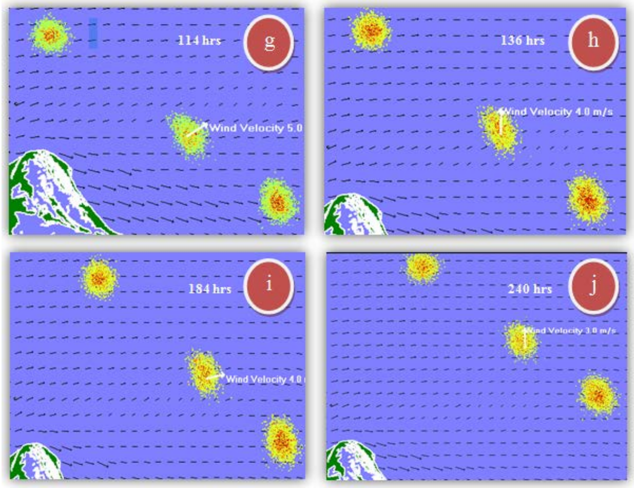
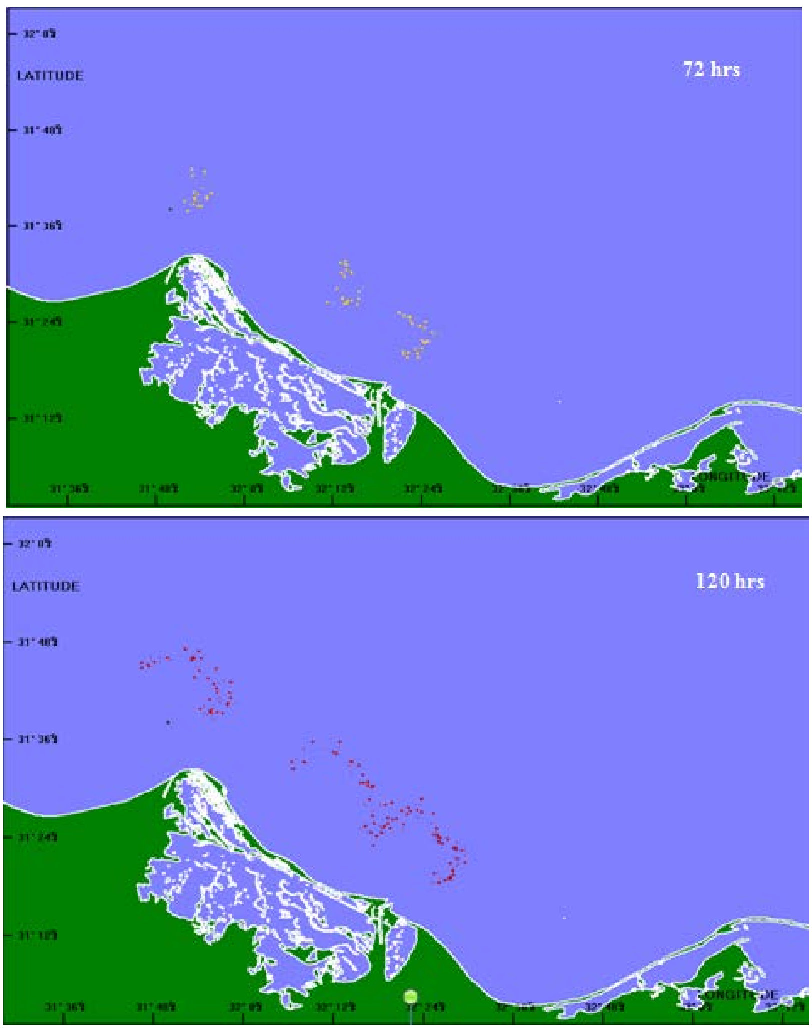


Figure (10-a). Surface oil by MEDSLIK

Figure (11-a) (Dispersed oil after three, five and ten days) shows that the dispersed oil propagates in the north direction away from the coastline and there's no coast impact. We used daily wind forecast data for eleven days (table (2-a)) covering the timeline of the accident simulation period (10 day), this may provide more accurate output. Figure (9-a) shows the surface oil for 10 days (240 hrs.) as wind changes as following:



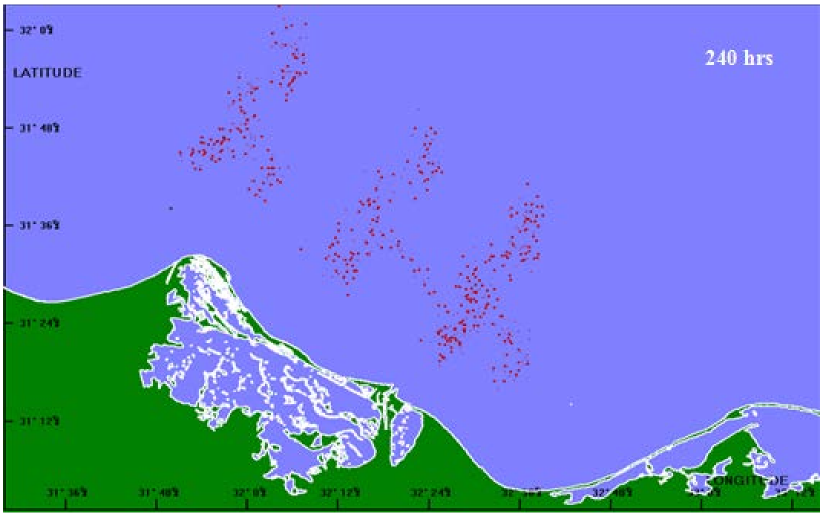


Figure (11-a). Dispersed oil by MEDSLIK

Table (4-a). Changes in the propagation direction of the surface oil for 240 hrs

Time range (hrs.)	Surface oil propagation direction
8 to 16	SW
18 to 40	NE
42 to 64	NW
66 to 88	NNW
90 to 112	WSW
114 to 136	SW
138 to 160	NE
162 to 184	N
186 to 208	ENE
210 to 240	N

Figure (12-a) oil fate parameters after 10 days (240 hrs.):

a. Percentage of oil on the sea surface:
o (0 to 28 hrs.), decreases sharply.
o (28 hrs. to 240 hrs.), decreases slowly.
b. Percentage of oil evaporated:
o (0 to 32 hrs.), increases.
o (32 to 240 hrs.), constant = 33.68%.
c. Percentage of oil dispersed in water column:
o (0 to 240 hrs.), slightly increase to become 3.4427% after 240 hrs.
d. Total percentage of oil on the coast:
o Constant = 0.0%.
e. Percentage of oil on the coast but potentially releasable:
o Constant = 0/0%.

Figure (13-a) oil viscosity after 10 days (240 hrs.):

a. Viscosity of the oil-water mousse from the oil first released (maximum viscosity):
o (0 to 110 hrs.), increases.
o (110 to 240 hrs.), constant = 3111.71 kg/(s·m).
b. Viscosity of the oil-water mousse from the oil last released (minimum viscosity):
o (0 to 114 hrs.), increases.
o (114 to 240 hrs.), constant = 3111.71 kg/(s·m).
c. Oil viscosity of the oil first released (maximum viscosity):
o (0 to 26 hrs.), increases.
o (26 to 240 hrs.), constant = 100.45 kg/(s·m).
d. Oil viscosity of the oil last released (minimum viscosity):
o (O to 32 hrs.), increases.
o (32 to 240 hrs.), constant = 100.45 kg/(s·m).

Figure (14-a) oil density after 10 days (240 hrs.):

a. Density of first oil released as percentage of density of sea water (maximum density ratio):
o (0 to 68 hrs.), increases.
o (0 to 240 hrs.), constant = 96.9%.
b. Density of last oil released as percentage of density of sea water (minimum density ratio):
o (0 to 84 hrs.), increases.
o (84 to 240 hrs.), constant = 96.9%.
c. Percentage of water emulsified in the oil-water mousse of first oil released (maximum water fraction):
o (0 to 68 hrs.), increases.
o (68 to 240 hrs.), constant = 72.5%.
d. Percentage of water emulsified in the oil-water mousse of last oil released (minimum water fraction):
o (0 to 71 hrs.), increases.
o (71 to 240 hrs.), constant = 72.5%.

Figure (15-a) slick volume after 10 days (240 hrs.):

a. Volume of oil released in:
o (0 to 4 hrs.), constant = 2000 tons (first spill).
o (At 5^{th} hrs.), step change to 3500 tons (second spill).
o (5 to 6 hrs.), constant = 3500 tons
o (At 7^{th} hrs.), step change to 6500 tons (third spill).
o (7 to 240 hrs.), constant = 6500 tons.
b. Total volume of emulsified oil in surface slick in:
o (0 to 4 hrs.), almost constant ≈ 2000 tons, but slightly increase (first spill).
o (At 5^{th} hrs.), step change to 3500 tons (second spill).
o (5 to 6 hrs.), almost constant =3500 tons, but slightly increases.
o (At 7^{th} hrs.), step change to 65000 tons (third spill).
o (7 to 77 hrs.), increases.
o (77 to 240 hrs.), decreases.

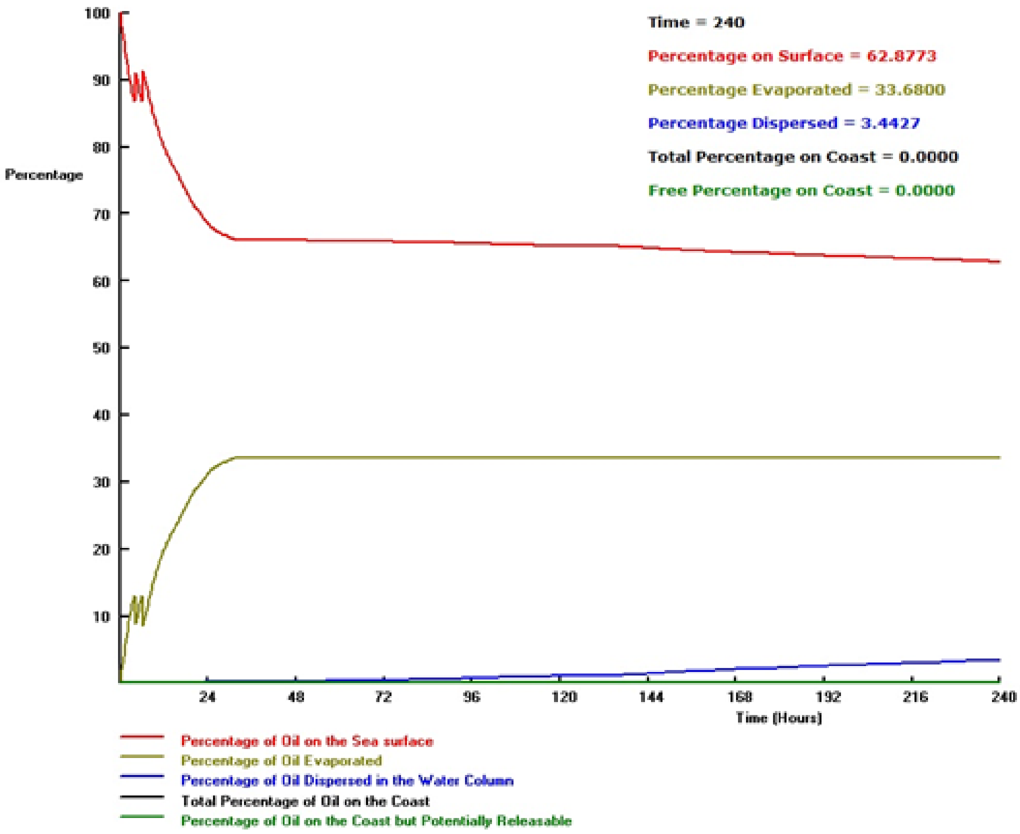


Figure (12-a). Oil fate parameters

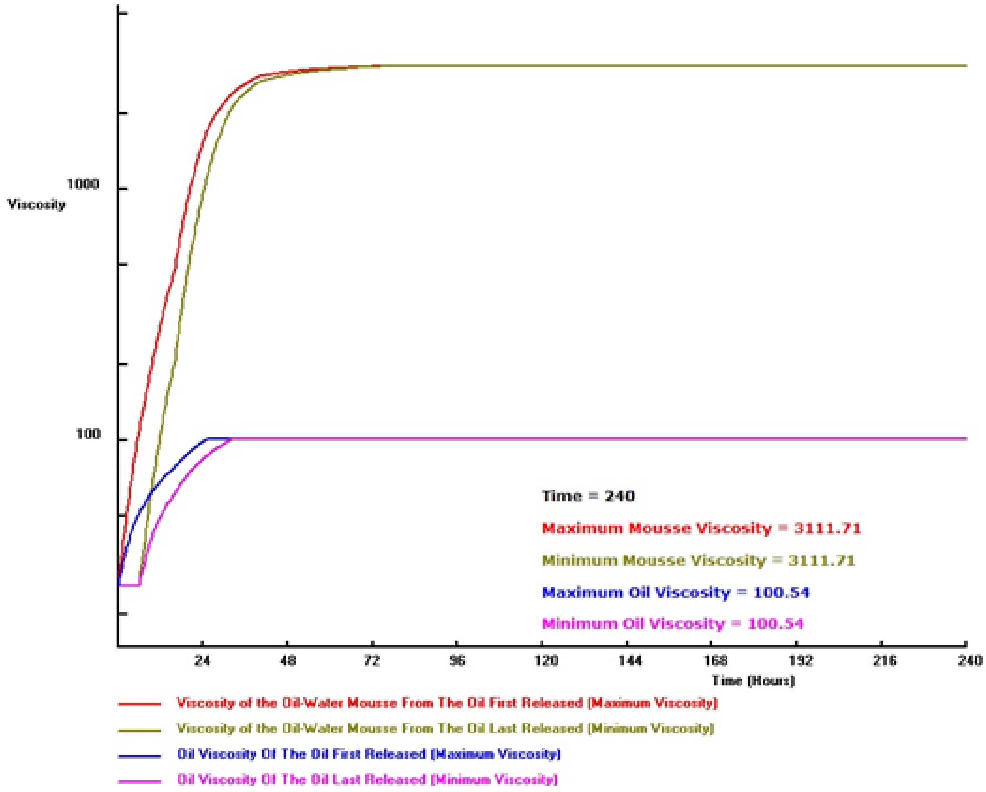


Figure (13-a). Oil viscosity

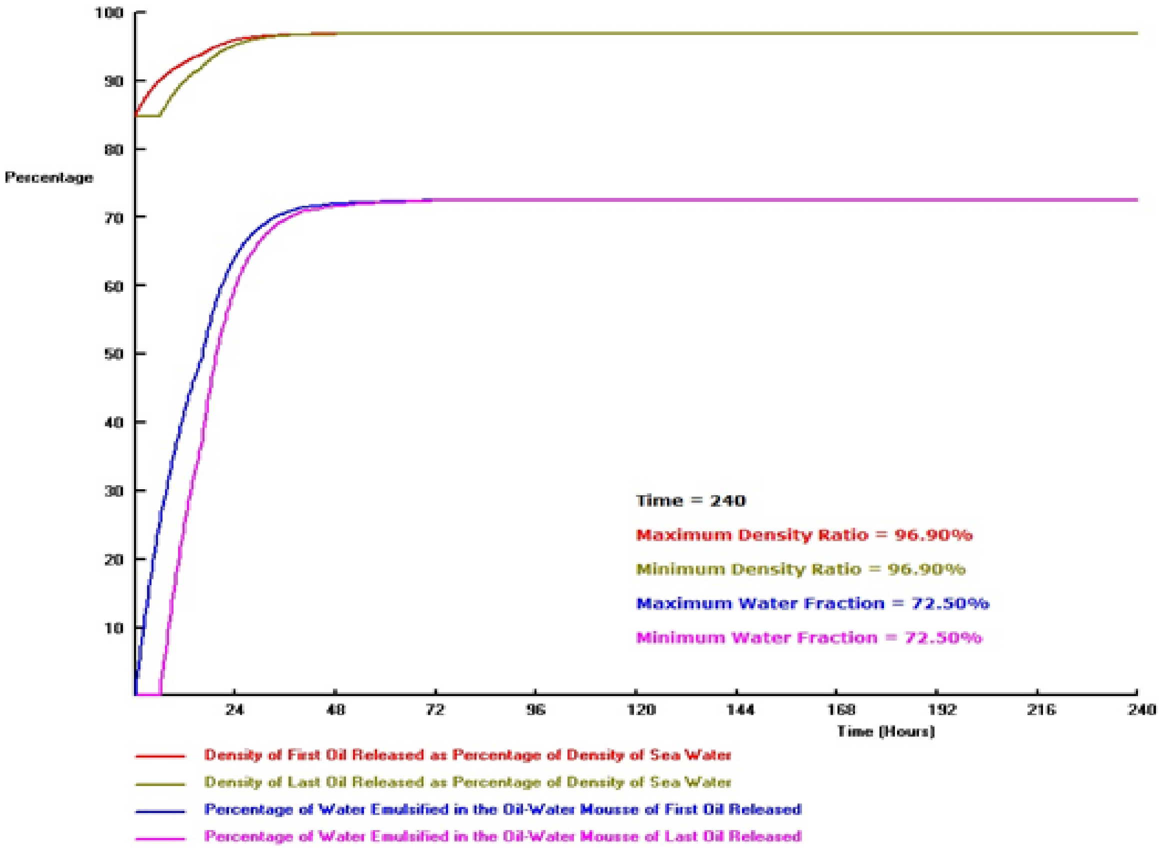


Figure (14-a). Oil density

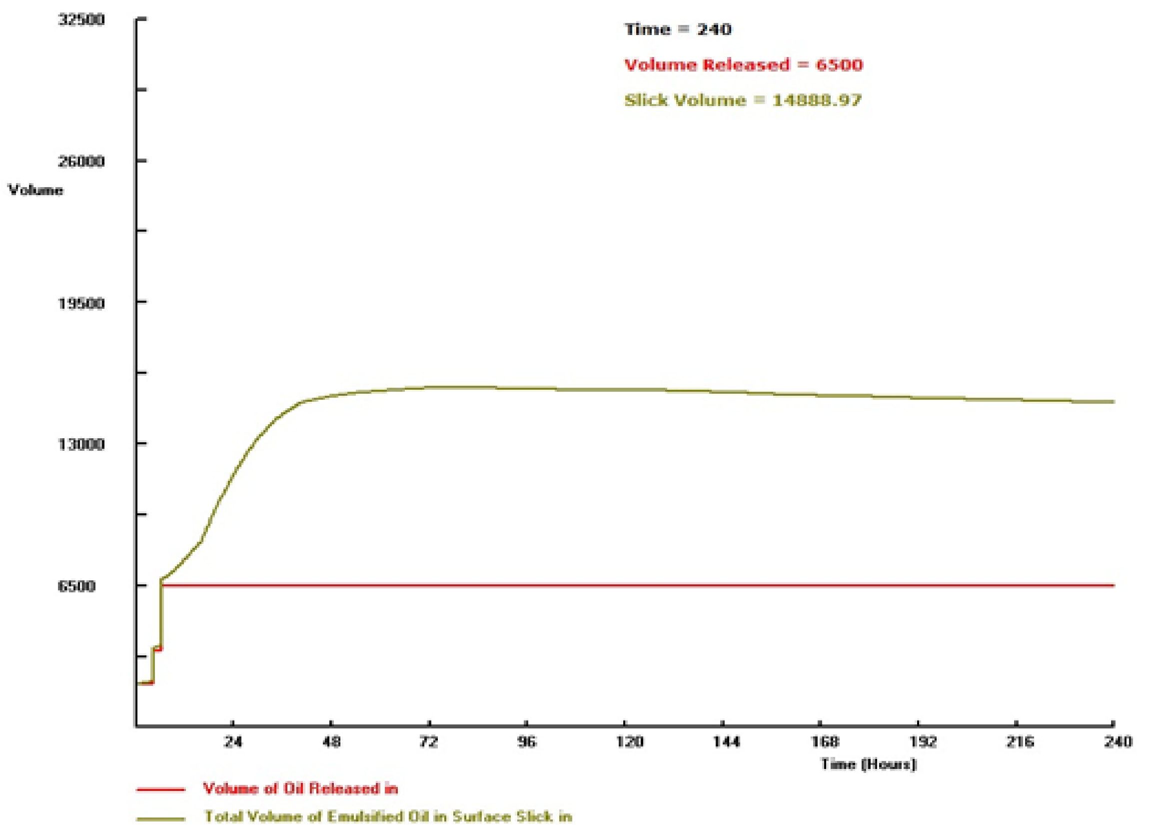


Figure (15-a). Slick volume

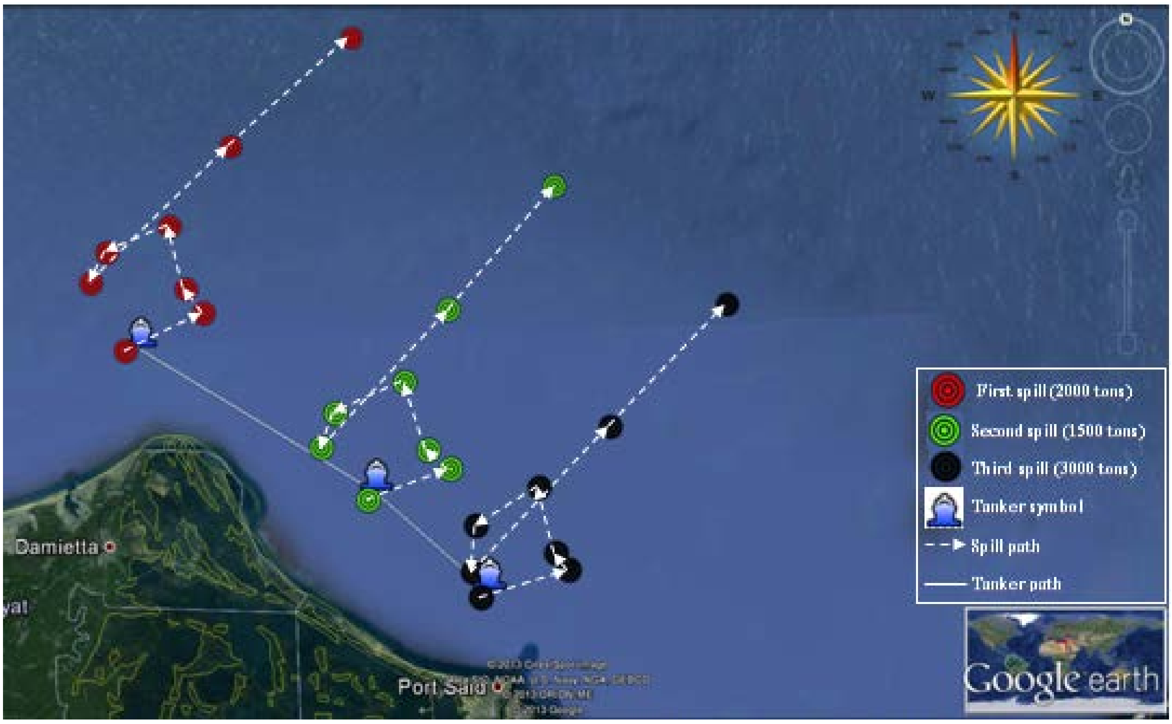


Figure (16-a). The three spills paths for 10 days (240 hrs.)

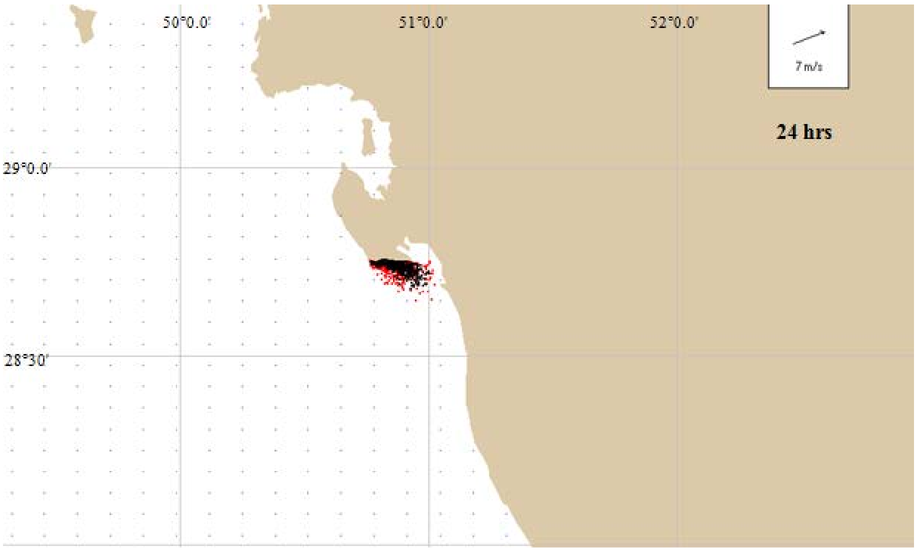
a) The output of GNOME (Bushehr nuclear power plant accident on the Arabian Gulf:

The oil spill's propagation direction during the first day is mostly south-east (figure (17-b)) and there is a large coastal impact on the coasts of Bushehr facility region. The wind directions in day 9, April, 2013 at 16 PM, 19 PM and 22 PM were W, WNW and W respectively. The directions during 10th of April are N, NW and NNE at 1AM, 4AM and 7AM respectively. It remained in WSW direction from 10 AM to 16 PM. (figure (6-b)). Later in the day, the response team is able to conduct an over flight of the spill area to visually locate slicks and sheens of oil on the water. They made aerial observations from a helicopter to spot oil on the water. One large area of black oil and three smaller areas of brown oil were spotted with silver-to-rainbow sheens trailing them to the East (figure (18-b) and figure (19-b)).

The **black splots** (figure (17-b) and figure (19-b)) represent **best guess** trajectory estimate of the oil spilled from the tanker. To make this best guess, we assume that:

a. The data input on the wind file accurately represent the wind directions in the timeline of the simulation for the next 3 days after the accident which is measured every 3 hours provided by the meteorological station in the Bushehr Airport (figure (3-b)).

b. The data in the Location File accurately represent the current patterns during the time of the spill.



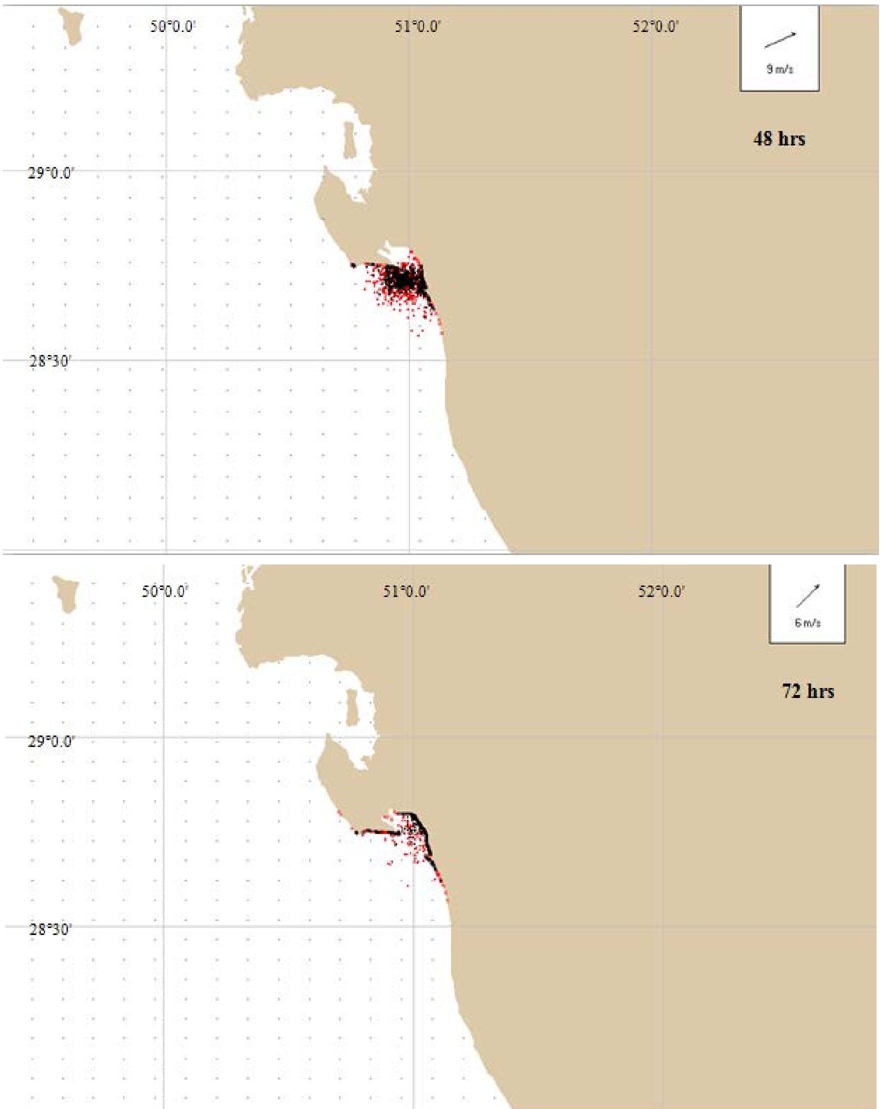


Figure (17-b). Oil spill by GNOME after 1, 2 and 3 days

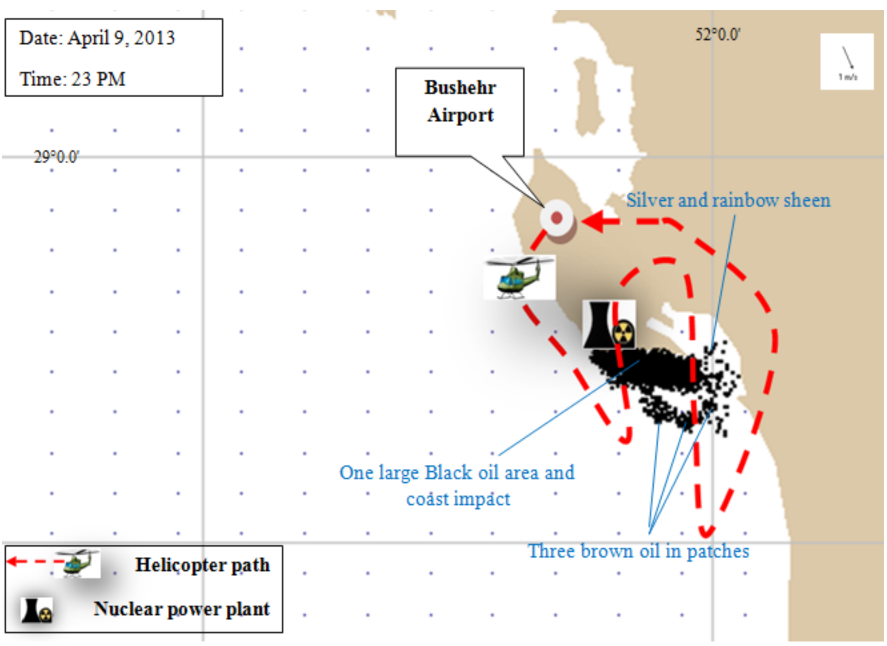


Figure (18-b). Overflight map by GNOME

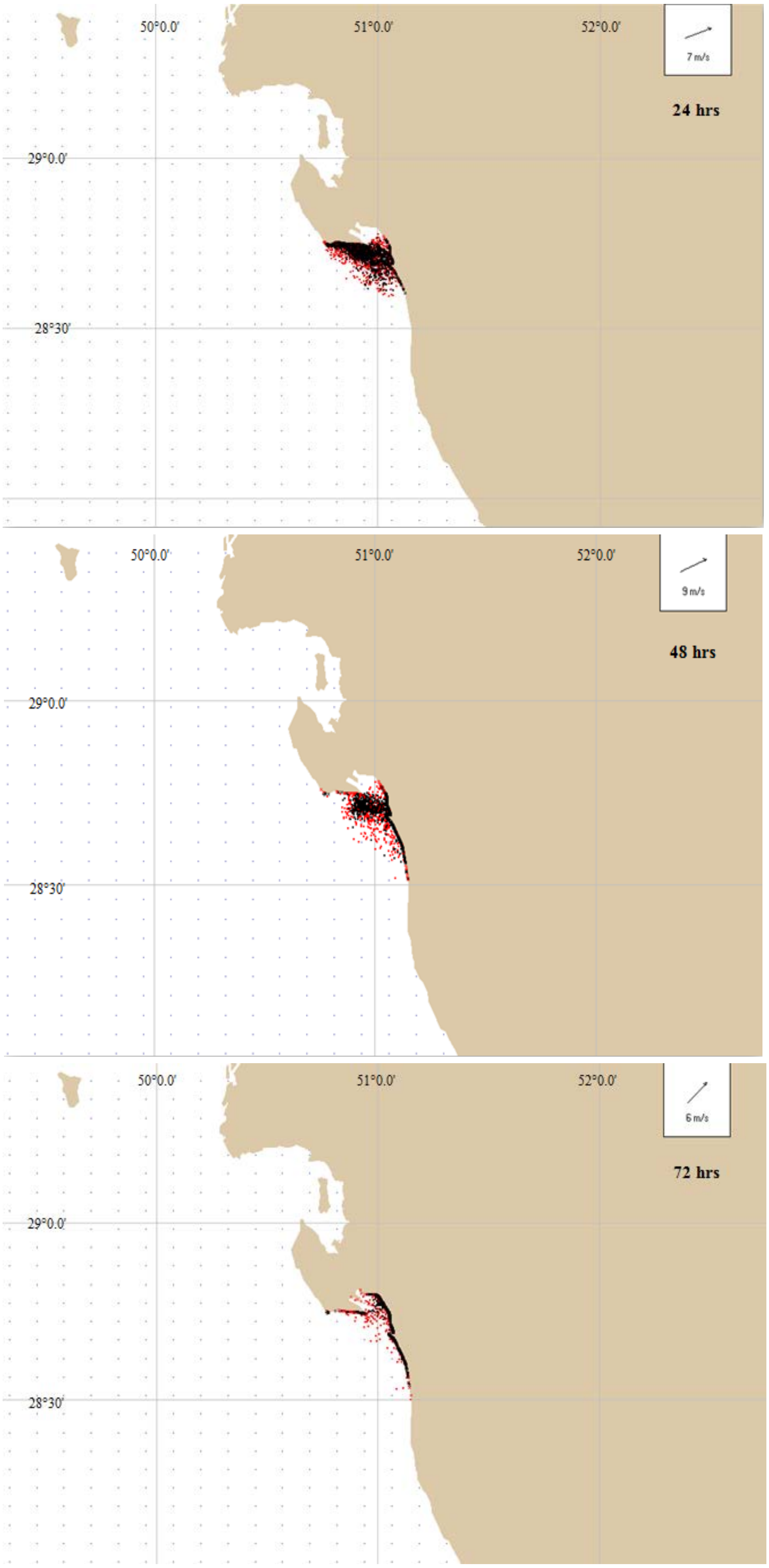


Figure (19-b). Oil spill by GNOME after 1, 2 and 3 days after conducting an overflight

The **red splots** (figure (17-b) and figure (19-b)) represent the model's larger **minimum regret** trajectory estimate for the same spill. To predict this trajectory, the model accounts for uncertainty in the wind and current information that we entered. As a very rough rule of thumb—assuming a "typical" degree of uncertainty in the wind and current information, we use in modeling a spill scenario the chance that the spilled oil will remain within the area covered by the **red** splots is on the order of 90%. It is impossible to assign a more precise probability, because little is yet known about uncertainties in wind and current forecasts.

The assumed accident scenario as follows: Immediately after the earthquake, the Bushehr reactors shut down automatically and emergency generators came online to power electronics and coolant systems. However, the earthquake had caused deformations in the earth's crust in Bushehr station region which caused seawater to flood the low-laying rooms in which the emergency generators were housed. The flooded generators failed, cutting power to the critical pumps that must continuously circulate coolant water through a nuclear reactor for several days in order to keep it from melting down after being shut down. As the pumps stopped, the reactors overheated due to the normal high radioactive decay heat produced in the first few minutes after nuclear reactor shutdown. In the high heat and pressure of the reactors, a reaction between the nuclear fuel metal cladding, and the water surrounding them, produced explosive hydrogen gas. The pool overheated, sparking fires in the building over the next hours. These massive explosions and fires reached the diesel tanks used to feed the emergency diesel generators which causes a huge leakage of oil to the sea water. About 10,000 tons of diesel was released to the sea, which caused a large oil spill in the Arabian Gulf.

On April 9, 2013,anearthquake struck the Iranian province of Bushehr, near the city of Khvormuj and the towns of Kaki and Shonbeh. Seismologists said the quake struck at 16:22 (11:52 GMT) at a depth of 10 km (6.2 miles) near the town of Kaki, south of Bushehr - a Gulf port city that is home to Iran's first and only nuclear power plant (figure (20-b)).

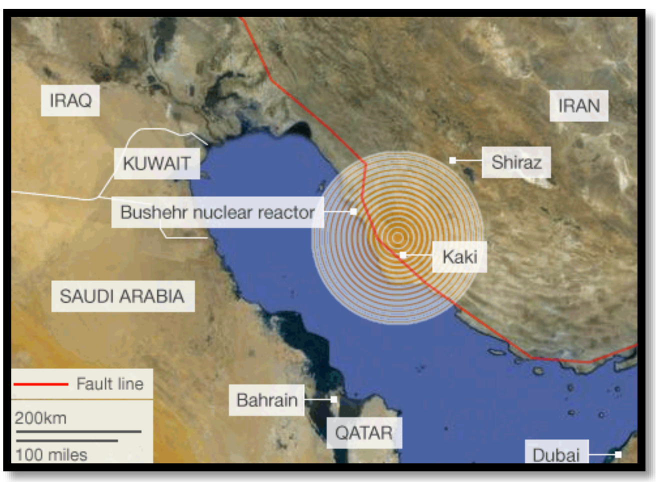


Figure (20-b). Epicenter of the earthquake and the seismic activity fault line

After about 2 days (48 hrs) there is coast impact on the coasts of Delvar (fig.(17-b) and fig.(19-b)) which is a city and the capital of Delvar District, in Tangestan County, Bushehr Province, Iran. Delvar is located near the coast. At the 2006 census, its population was 3,201, in 723 families. The oil spill also starts to propagate in the northern direction of Delvar (figure (21-b)) causing coast impact.

Figure (21-b). Coast impact on Delvar city shoreline after about 2 days (48 hrs)

4. Conclusions

1. Accidental and illegal marine pollution in the Mediterranean Sea and the Arabian Gulf constitutes a major threat to the marine environment**.** Previous incidents in the Mediterranean Sea and the Arabian Gulf have resulted in environmental and economic damages to fisheries, to the tourist industry and to coastal marine ecosystems**.**

2. To prevent the major impact of accidental oil spills, local and regional preparedness and response plans recommend the use of computer-aided support systems based on operational oceanography and real-time ocean forecasts and real-time ocean forecasts coupled with satellites images and oil-spill models.

3. Knowing the trajectory of the spill gives decision-makers critical guidance in deciding how best to protect resources and direct cleanup. However, it is often very difficult to predict accurately the movement and behavior of an oil spill. This is due, in part, to the interaction of many different physical processes about which information is often incomplete at the start of a response.

4. The modeler must thus continuously update pre-dictions with new data and explore the consequences and likelihood of other possible trajectories, a procedure called "trajectory analysis." The end product of trajectory analysis is often a map showing the forecast and probable uncertainty bounds of the slick movement.

5. Forecasting the movement of an oil spill is often hampered by insufficient input data, particularly in the first few hours of the release. Detailed spill data (location, volume lost, product type) are often sketchy and

environmental data (wind and current observations and forecasts) are often sparse or unavailable. Nonetheless, the modeler must examine the data and attempt to understand the physics and chemistry that will likely affect the oil movement and fate of the particular spill.

6. As the spill unfolds, the forecast of oil movement and fate improves because the quality and quantity of the on-scene observational data improves (while initial spill data becomes relatively less important).

7. Trajectory analysis should include not only the "best guess" of the oil movement and fate but also some representation of the uncertainty in the spill and environmental data used to make the forecast. The uncertainty in a trajectory forecast depends on the length and time-scale of the spill.

5. Appendix

5.1. Advection and Diffusion of the Slick

It is assumed that the surface oil is transported at a speed that is a certain fraction α of the wind speed and at a certain angle β to the right of the wind direction.

In MEDSLIK, the oil spill is modeled using a Monte Carlo method. The pollutant is divided into a large number of Lagrangian parcels of equal size. At each time step, each parcel is given a convective and a diffusive displacement as follows. Let (X_i, Yi, Z_i) be the position of the i^{th} parcel at the beginning of a particular step, Z being measured vertically upwards from the bottom. Then at the end of the time step of length τ the parcel is displaced to the point

Where $u(x, y, z)$ and $v(x, y, z)$ are the water velocity components in the x and y directions,

Wx and Wy the components of wind velocity and $\Delta X_i^{(d)}$,$\Delta Y_i^{(d)}$,$\Delta Z_i^{(d)}$ are the diffusiveDisplacements in the three directions. The vertical velocity w is not included in the model since it is generally very small.

$$X_i' = X_i + \left\{u\left(X_i, Y_i, Z_i + a\left(W_x \cos\beta + W_y \sin\beta\right)\right)\right\}\tau + \Delta X_i^{(d)} \quad (1)$$

$$Y_i' = Y_i + \left\{v\left(X_i, Y_i, Z_i + a\left(-W_x \sin\beta + W_y \cos\beta\right)\right)\right\}\tau + \Delta Y_i^{(d)} \quad (2)$$

$$Z_i' = Z_i + +\Delta Z_i^{(d)} \quad (3)$$

The diffusive displacements are given by:

$$\Delta X_i^{(d)} = [2rand(0,1) - 1]\sqrt{6K_h\tau} \quad (4)$$

$$\Delta Y_i^{(d)} = [2rand(0,1) - 1]\sqrt{6K_h\tau} \quad (5)$$

$$\Delta Z_i^{(d)} = [2rand(0,1) - 1]\sqrt{6K_v\tau} \quad (6)$$

Where K_h and K_v are the horizontal and vertical diffusivities and rand (0, 1) is a uniform random number lying between 0 and 1.

$$r.m.s.\left\{\Delta X^{(d)}, \Delta Y^{(d)}, \Delta Z^{(d)}\right\} = \left\{\sqrt{2K_h}\tau, \sqrt{2K_h}\tau, \sqrt{2K_v}\tau\right\} \quad (7)$$

K_h and K_v are the horizontal and vertical diffusion coefficients.

Probability of washing back on each time step τ is given by:

$$Probability\ of\ release = 1 - 0.5^{\tau/\tau_w}$$

T_w is the half-life for oil to remain on the beach before washing off again. The random number generator is called and the parcel is released back into the water if

Rand (0, 1) < Probability of release

T_w is assigned to each coastal segment depending on the coastal type. On each time step it is assumed that the fraction of a beached parcel seeping is

$$Fraction\ seeping = 1 - 2^{-\tau/T_s}$$

T_s is a half-life for seepage or other mode of permanent attachment.

$$Fraction\ seeping = \left[1 - 2^{-\tau/\tau_s}\right]\exp(-d/d_0)$$

Where d is the existing density of oil on the segment (bbl /km) and $d0$ is a parameter. The half-life Ts for heavy oils:

$$T_s = T_{s0}\left[1 + C_H(30 - API)\right] for API > 30 \quad (8)$$

Where T_{s0} is the default half-life

5.2. Technical Description of the Fate Models

For any sub-spill at any time step, let V_{tk} and V_{tn} be the volumes of oil remaining respectively in the thick and the thin slicks, A_{tk} and A_{tn}t heir two surface areas and T_{tk} and T_{tn} their thicknesses. It is assumed that the thickness T_{tn} of the thin slick is constant equal to 10 microns, which is a typical observed value for the final thickness of the sheen. On any time step, the two volumes are updated as

$$V_{tk}' = V_{tk} - \Delta V_{tk}^{(e)} - \Delta V_{tk}^{(d)} - \Delta V_{tn}^{(s)} \quad (9)$$

$$V_{tn}' = V_{tn} - \Delta V_{tn}^{(e)} - \Delta V_{tn}^{(d)} - \Delta V_{tn}^{(s)} \quad (10)$$

Where $\Delta V_{tk}^{(e)}$, $\Delta V_{tn}^{(e)}$ are the volumes lost by evaporation, $\Delta V_{tk}^{(d)}$, $\Delta V_{tn}^{(d)}$ are the volumes lost by dispersion and $\Delta V_{tn}^{(s)}$ is the amount flowing from the thick to the thin parts of the slick. These transfers of oil are illustrated in Figure 21.

Having updated the volumes of the two parts of the slick, their areas are also updated on each step using semi-empirical spreading formulas (see below). Then the new thickness of the thick slick is computed:

$$T_{tk} = V_{tk} / A_{tk} \quad (11)$$

In the following sections, expressions based on MacKay's algorithms will be developed for all the volume and area increments.

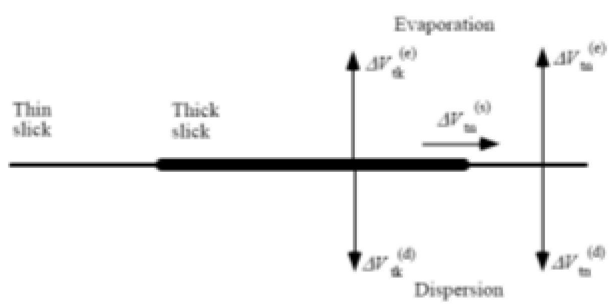


Figure 20. Volume transfers from the thick and thin slicks

5.2.1. Evaporation

First, for the oil in the thin slick, it is supposed that the light component evaporates immediately. The volume evaporating on each time step from the thin slick equals the total content of light component in the thin slick:

$$\Delta V_{tn}^{(e)} = V_{tn} \left(f_{max} - f_{tn}\right)/(1 - f_{tn}) \quad (12)$$

Where f_{tn} is the fraction of the oil in the thin slick that has already evaporated at the beginning of the step and f_{max} is the initial fraction of evaporative component, which represents the maximum value that f_{tn} can attain.

For the thick slick, the increment in the fraction f_{tk} of the oil that has evaporated is expressed as a product of the vapor pressure, P_{oil}, and the change in an evaporative exposure, ΔE_{tk}

$$\Delta f_{tk} = P_{oil}\, \Delta E_{tk} \quad (13)$$

The vapor pressure is expressed in the form

$$P_{oil} = P_0\, exp(-c f_{tk}) \quad (14)$$

P_0 is the initial vapor pressure and c a constant that measures the rate of decrease of vapor pressure with fraction already evaporated. The increment in exposure is expressed as a product of a mass transfer coefficient Km, the time step τ, the slick area A_{tk} and the molar volume of the oil V_{mol}, divided by the gas constant R, the temperature T in °K and the initial volume of the sub-spill, V (0):

$$\Delta E_{tk} = \frac{K_m V_{mol} A_{tk} \tau}{RTV^{(0)}} = \frac{k_m V_{mol} A_{tk} (1 - f_{tk})\tau}{RT V_{tk}} \quad (15)$$

Where V_{tk} is the current volume of oil in the thick slick, equal to $V_{(0)}$ $(1 - f_{tk})$ in the program, the various quantities are given the values V_{mol}= 0.0002, R = 0.000082 and

$$K_m = C^{(e)}\left(W_{kph}\right)^{y} \quad (16)$$

Where W_{kph} is the wind speed in kilometers per hour and $C_{(e)}$ and γ are coefficients with default values 0.00067 and 0.78 respectively.

Then the volume loss by evaporation per time step is equal to the increment in the fraction evaporated multiplied by the original volume:

$$\Delta V_{tk}^{(e)} = \Delta f_{tk}\, V^{(0)} = \Delta f_{tk}\, V_{tk}/(1 - f_{tk}) \quad (17)$$

Although the evaporative component in the thin slick has been assumed to disappear immediately, the thin slick is fed by oil from the thick slick that has not in general fully evaporated. Thus the fraction f_{tn} of oil in the thin slick that has evaporated must be reduced from the maximum value f_{max}. Equating the oil content of the thin slick before and after the inflow, we have

$$V_{tn}'(1 - f_{tn}) = \left(V_{tn}' - \Delta V_{tn}^{(s)}\right)(1 - f_{max}) + \Delta V_{tn}^{(s)}(1 - f_{tk}) \quad (18)$$

Where V_{tn}' is the updated volume, this leads to the formula

$$\left(f_{tn} = f_{max} - \Delta V_{tn}^{(s)}(f_{max} - f_{tk})\right)/V_{tn}' \quad (19)$$

Having updated the volumes evaporated from the thick and thin slicks, the total fraction of the oil that has been lost by evaporation can be computed. This lost fraction is assumed to apply to all the parcels in the particular sub-spill and their fraction of light component is adjusted accordingly. Evaporation is stopped when the fraction evaporated reaches the fraction f_{max} of light component in the original oil. Evaporation leads to an increase in the viscosity of the oil, and the formula used for this is

$$\eta_{oil} = \eta_0 exp\left(K^{(e)} f_{tk}\right) \quad (20)$$

Where η_0 is the initial viscosity and $K_{(e)}$ a constant that determines the increase of viscosity with evaporation (default value 4.0)

5.2.2. Emulsifications

Emulsification refers to the process by which water becomes mixed with the oil in the slick. Let f_w be the fraction of water in the oil-water mousse. Then Mackay's model for the change in this fraction per time step is[16]

$$\Delta f_w = C_2^{(m)}\left(1 - C_3^{(m)} f_w\right)\tau \quad (21)$$

Where $C_2^{(m)}$ *and* $C_3^{(m)}$ are constants. This model is based on assuming mousse formation is a first-order process with the water-in-oil fraction having an upper limit of ${C_3^{(m)}}^{-1}$ (default value taken as 75% for light oils but decreasing with API number for heavy oils).

The principal effect of emulsification is to create a mousse with greatly increased viscosity. It is supposed that the viscosity η_{em} of the mousse is given by

$$\eta_{em} = \eta_{oil}\, exp\left\{2.5 f_w/\left(1 - C_1^{(m)} f_w\right)\right\} \quad (22)$$

Where $C_1^{(m)}$ *is* a constant that determines the increase of viscosity with emulsification

5.2.3. Dispersion

The model of dispersion of oil into the water column is based on the work of Buist[17] and Mackay et al[16]. The process is illustrated in Figure 22. Wave action drives oil into the water, forming a cloud of droplets beneath the spill. The droplets are classified as either large droplets that rapidly rise and coalesce again with the spill, or small droplets that rise more slowly, and may be immersed long enough to diffuse into the lower layers of the water column. In the latter case they are lost from the surface spill and considered to be permanently dispersed. The criterion that distinguishes the small droplets is that their rising velocity under buoyancy forces is comparable to their diffusive velocity, while for large droplets the rising velocity is much larger.

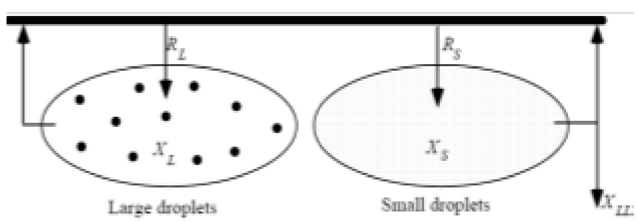


Figure 22. The dispersion model

Consider first the thick slick. At a given instant, let R_L and R_S be the downward volume fluxes of oil per unit area of the slick entering the water as large and small droplets respectively. Let the corresponding concentrations be c_L and c_S. If the rising velocities of the large and small droplets are v_L

and v_s, then for a quasi-steady state we can equate the downward and upward fluxes:

$$R_L = c_L v_L R_s = \frac{1}{2} c_s\left(v_s + C_1^{(d)}\right) \quad (23)$$

Where $C_1^{(d)}$(>>v_s) is the (upward) diffusive velocity of the small droplets. Thus,

$$c_L = R_L / v_L \frac{1}{2} c_s = R_s / \left(v_s + C_1^{(d)}\right) \quad (24)$$

The total volumes of oil beneath the thick slick in the form of large and small droplets are then given by

$$X_L = c_L u_m A_{tk} \quad (25)$$

$$X_s = c_s u_m A_{tk} = 2 R_s u_m A_{tk} / \left(C_1^{(d)} + v_s\right) \quad (26)$$

Where u_m is the vertical thickness of the droplet cloud. On each time step, a fraction of the small droplets is assumed to be lost by diffusion to the lower layers of the water column. The total volume lost on each step is taken as

$$\Delta X_{LL} = \frac{1}{2} c_s\left(C_1^{(d)} - v_s\right) A_{tk}\tau = \frac{R_s A_{tk}\tau\left(C_1^{(d)} - v_s\right)}{\left(C_1^{(d)} + v_s\right)} \quad (27)$$

Where again $C_1^{(d)}$ is the diffusive velocity of the small droplets. The total volume ofdispersed oil beneath the thick slick is then incremented according to

$$\Delta V_{tk}^{(d)} = \Delta X_{LL} + (X_s' - X_s) \quad (28)$$

Where the last term represents the change in the small droplet cloud during the time step due to changing conditions (The large droplets are not regarded as dispersed since they eventually re-coalesce with the slick.)

To complete this part of the model, expressions are required for the downward fluxes, R_L and R_S. For this, the fraction of the oil in either the thick or the thin slick that is dispersed each time step is taken as

$$\Delta f_d = C_3^{(d)}\left(W_{m/s} + 1\right)^2 \tau \quad (29)$$

Where $W_{m/s}$ is wind speed in m/s. For the thick slick, the fraction of this that consists of small droplets is taken as

$$f_s = \left\{1 + C_4^{(d)}(\eta_{em}/10)^{1/2}(T_{tk}/0.001)(\sigma/24)\right\}^{-11} \quad (30)$$

Where σ is the interfacial surface tension between the oil and sea water, the downward fluxes per unit area of slick per time step are then given by

$$R_s = f_s(\Delta f_d/\tau) \quad (31)$$

$$R_L = (1 - f_s)(\Delta f_d/\tau) \quad (32)$$

For the thin slick, the following simpler expression is used for the fraction of small droplets:

$$f_s = \left\{1 + C_5^{(d)}(\sigma/24)\right\}^{-1} \quad (33)$$

And it is assumed that all the small droplets below the thin slick are permanently dispersed. Thus the volume loss is given by

$$\Delta V_{tn}^{(d)} = f_s \Delta f_d V_{tn}^{(d)} \quad (34)$$

The total volume of oil dispersed from both thick and thin slicks, $V_{(d)}$ is then incremented according to

$$\Delta V^{(d)} = \Delta V_{tk}^{(d)} + \Delta V_{tn}^{(d)} \quad (35)$$

This gives a probability of any particular Lagrangian parcel being dispersed into the water column on the given time step equal to

$$p^{(d)} = \Delta V^{(d)} / V^{(0)} \quad (36)$$

For each parcel the random number generator is called, and the parcel is dispersed if

$$rand\,(0,1) < p^{(d)}$$

Dispersion is assumed to stop when the viscosity η_{em} of the mousse reaches a value η_{max}.

5.2.4. Spreading

To complete the algorithms we need models for the changes in areas of the thick and thin slicks and the rate of flow of oil from the one into the other[18, 19]. For the thick slick, spreading consists of two parts, one a loss of area due to oil flowing from the thick to the thin slicks and a second corresponding to Fay's gravity-viscous phase of the spreading[9]. Thus the change of area of the thick slick per time step is

$$\Delta A_{tk}^{(s)} = -\frac{\Delta V_{tn}^{(s)}}{T_{tk}} + C_2^{(s)} A_{tk}^{1/3} T_{tk}^{4/3} \tau \quad (37)$$

Where $C_2^{(s)}$ is a constant and $V_{tn}^{(s)}$ is the volume increment flowing from thick to thinslick. This volume is related to the increment in area of the thin slick:

$$\Delta V_{tn}^{(s)} = \Delta A_{tn}^{(s)} T_{tn} \quad (38)$$

Thus, once we have a value for $\Delta A_{tn}^{(s)}$, we can update the area, $\Delta A_{tk}^{(s)}$ of the thick slick.

Mackay approximates the increment in area of the thin slick by a formula similar to the Fay formula: proportional to the cube root of the area times the time step times an exponential function of the thickness of the thick slick that reflects the tendency of the slicks to stop spreading when they become very thin:

$$\Delta A_{tn}^{(s)} = C_1^{(s)} A_{tn}^{1/3} \tau exp\left(-C_3^{(s)} \Big/ (T_{tk} + 0.00001)\right) \quad (39)$$

Mechanical spreading is considered to occur for an initial period of 48 hours after the release of each sub-spill or until the thickness of the thick part of the slick becomes equal to that of the thin slick if this occurs first.

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