

A method for locating possible sources of oil pollution in the East Vietnam Sea

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Abstract: A method was proposed for locating possible sources of oil pollution in the East Vietnam Sea. The method includes two stages. The first stage is called the raw stage. In this stage, based on the history of oil pollution at the Vietnamese coast and oil pollution footprint detected by remote sensing technique, numerical computation of wind and flow field in the sea was carried out. With the obtained wind and flow fields, reversed analysis was carried out to have a raw determination of possible sources of oil pollution. The second stage is called the refined stage. In this stage, based on the results of the raw stage, the location of oil source was corrected by assuming different oil slick scenarios (locations of oil source, discharge amount and discharge time). Then, numerical computations were carried out again to determine the transport and weathering of oil after being discharged from the source. The oil slick scenario which best fit the history of oil pollution and oil slick footprint will be selected as the oil pollution source.

1. Introduction

Recently, oil pollution has become an increasing environmental problem for the Vietnamese coast and sea. The area with oil pollution is expanding while the degree of pollution is increasing. During recent ten years, there are more than ten oil pollution events which caused great environmental consequences to the estuarine and nearshore areas of Vietnam. Typical oil pollution events are listed bellows. On October 3, 1994, the Neptune Aries (Singapore) collided with pier at Cat Lai port, caused the slick of 1.700 tons of oil. On September 7, 2001, the Formosa One (Liberia) collided with other ship at Ganh Rai Bay, caused the slick of 900m³ of oil. On February 6, 2002, the Bach Dang Giang (Vietnam) collided with submerged rock in Hai Phong coastal water, caused the slick of 2.500m³ of oil. Recently, every year, during March to April, the oil pollution appears at the coastal areas of Central Vietnam. Especially, on January 29, 2007, oil began to polute Da Nang and Hoi An Beaches. After that, during the period from February 2007 to May 2007, the oil pollution affected the coastal areas of 17 cities, provinces of Vietnam, including Hai Phong, Ha Tiinh, Quang Binh, Quang Tri, Thua Thien - Hue, Đa Nang, Quang Ngai, Quang Nam, Binh Dinh, Phu Yen, Khanh Hoa, Vung Tau - Con Dao, Tien Giang, Ben Tre, Tra Vinh, Soc Trang and Ca Mau. The total collected oil from January 29, 2007 to April 18, 2007 is 1702 tons. Among it, 855 tons of polluted oil is collected at the Quang Nam beach. The impacts of the polluted oil on the environment, economic and society in the polluted coastal areas have not been fully understood.

Due to the seriousness of the oil pollution, the Government of Vietnam had assigned the Ministry of Natural Resources and Environment to carry out study to understand the processes of the transport and weathering of oil in the sea, and locate the possible sources of oil pollution. This article presents the results of the study carried out by the Vietnam Institute of Meteorology, Hydrology and Environment (IMHEN) for the above mentioned purpose.

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2 Methods

To study the processes of transport and weathering of oil in the sea, in this study, we used the numerical models in combination with remote sensing technique. The satellite images from the MODIS sensor (AQUA and TERRA), ENVISAT ASAR, ALOS PALSAR satellites were analyzed to determine the location of polluted areas in the sea. Then, a system of numerical models, including a numerical model for the computation of wind, air temperature and sea surface temperature fields. For the transport and weathering of oil in the marine environment, two numerical models are used. The first model is the MIKE31-PA/SA of Danish hydraulic. The second model is a system of models developed by a group of researchers at the IMHEN. In this system of models, a numerical model for the computation of wave field, numerical models for the computation of current field and a numerical model for the computation of the transport and weathering of oil in the sea were used to predict the transport of oil in the sea. Based on the past current and wind field and the present position of polluted oil, a reversed analysis technique was employed to locate the possible oil pollution.

2.1 Meteorological conditions

After being slicked into the marine environment, the polluted oil is transported under the combined actions of wind, waves and currents. The action of the wind on the transport of oil has three folds. At the first, the wind acts on the surface of the oil and transport the oil in the wind direction. It was estimated that (Stozenbach et al, 1977) that the drifted velocity of the surface oil layer due to the wind can be about 0.03 velocity of the wind. At the second, the wind generates the surface waves, which can advect the oil and intensify the oil weathering processes, leading to the dispersion of oil in the sea water. At the third, the wind drives currents, which can directly transport the polluted oil. Thus, in order to correctly predict the transport and weathering of the polluted oil, the wind must be correctly computed.

The AVN wind data with equal resolutions in both latitude and longitude directions of 1° are used for the computation of the wind field in the East Vietnam Sea. Since the resolution of 1° is too coarse for the current and oil transport computation, the MM5 model for numerical weather forecast is used to interpolate the wind to the $2'$ grid mesh resolution. The computed wind fields at the beginning of March are shown in Figures 1a-1f. Detailed computations (not shown) revealed that during February, 2007, the dominant wind in the entire Vietnamese sea and coastal areas have the north east direction. At the end of February until the beginning of March, the wind became very variable. As shown in Figs. 1a, from March 01 to March 05, 2007, the wind at the north of East Vietnam Sea was south east wind while the wind in the southern part was the north east wind. The wind speed was about 5-10m/s. During the period from 06 to 11 March, 2007 (Figure 1b), the continental high pressure became dominant over the Vietnamese land and sea, the dominant wind for the entire East Vietnam Sea was the north east with the wind velocity of 10m/s. The wind during the period from March 12 to March 16 was similar to that at the beginning of March (Figure 1c). A strong cold front influenced Vietnamese weather on land and sea from 17 to 20 March caused strong north east wind on the entire sea with the wind velocity of more than 10m/s (Figure 1d). At the beginning of April, the wind direction changed. On April 10, 2007, the wind on the sea was north east with with the speed of about 5-10m/s, and from 11 to 19 April, the wind at the north of the sea was south east to south while at the south of the sea, the wind was rather complex (Figure 1e).

2.2. Current conditions

The 3D POM (Princeton Ocean Model) model was used to compute the current field. Forcing on the current fields includes tide, wind and density current. The computational region was extended over whole East Vietnam Sea with the tidal forcing computed at the boundary of the computational region from the harmonic constants of 9 main tidal waves. The depth field used in the computation is ETOPO2. Sensitivity analysis showed that tidal current is strongly influenced by bottom friction. Then, the tidal flow was calibrated using the tidal data at main stations near Vietnamese coast. The calibration results shown in Figs. 2 (a-d) revealed that the numerical model could satisfactorily simulated the tidal current in the area.

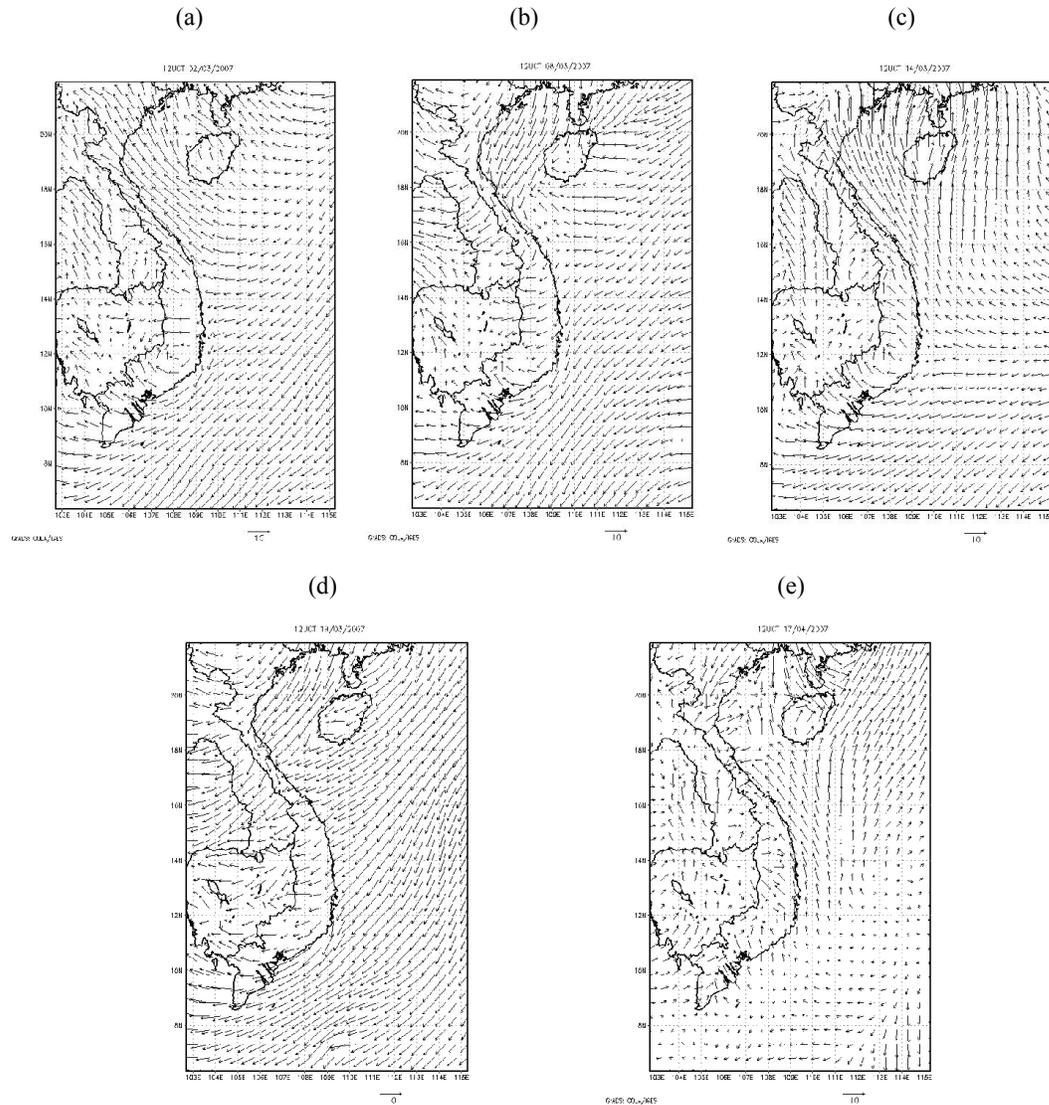


Figure 1. Wind field simulated by MM5 model

Computational results (not shown) revealed that the tidal current was rather strong nearshore, but not very strong offshore.

Examples of computed flow fields were presented on Figs. 3 (a,b,c,d). Figs. 3a,b respectively show the current fields on January 18 and January 30, 2007. As shown in the figure, during January, due to prevail north east wind, the current near Vietnamese shoreline have the south direction. This flow field together with the north east wind can transport the oil in the south direction. On the other hand, the flow fields on March 15 and April 14, 2007 are shown in Figs. 3 (c,d). It can be seen that in general, the flow fields near the Central Vietnam shore have the south direction. However, at the entrance of Bac Bo Gulf, the current have the north direction. This means that with the current together with south east wind can transport oil to pollute the coast of the Red River Delta.

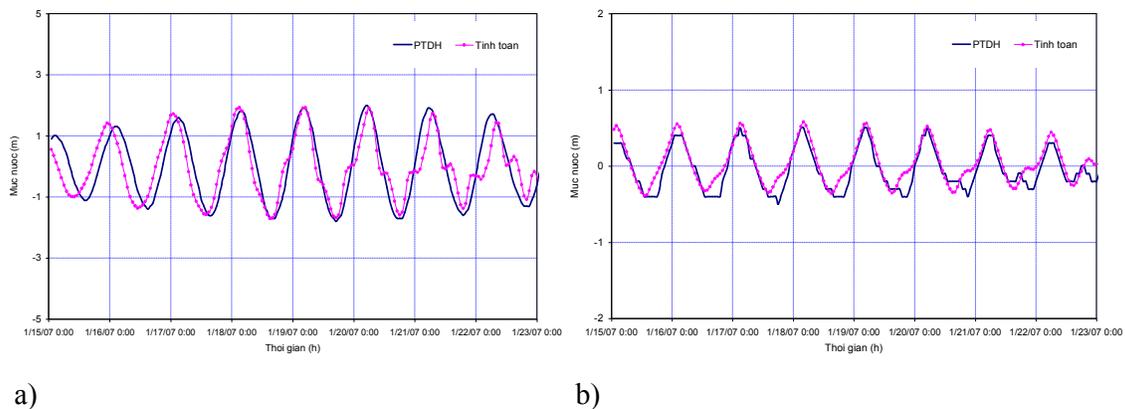
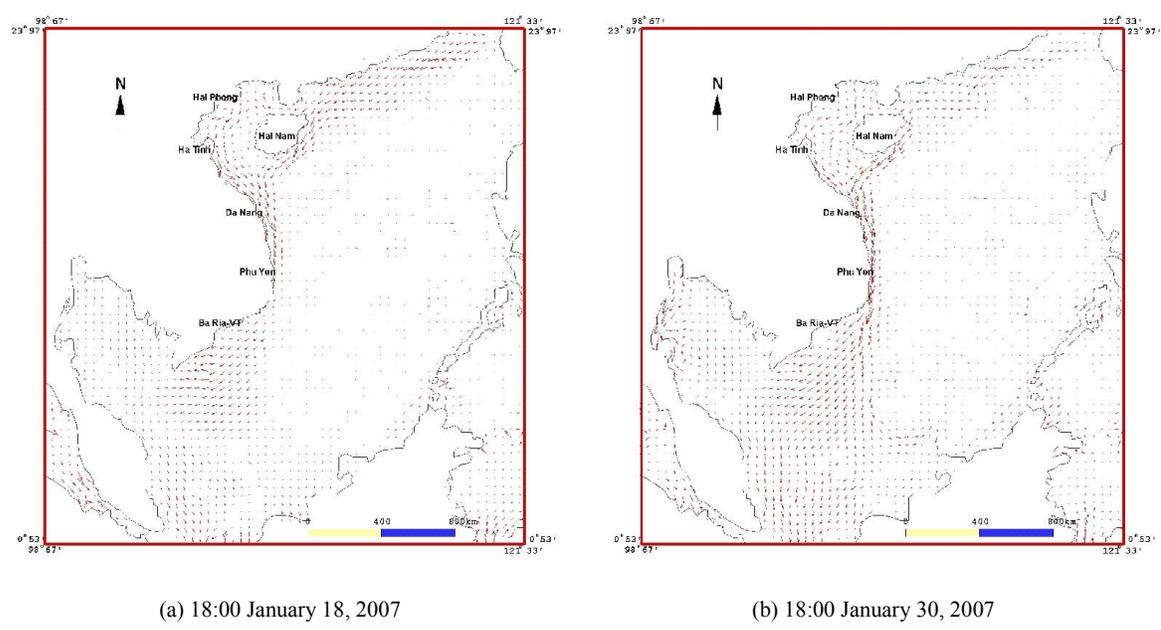
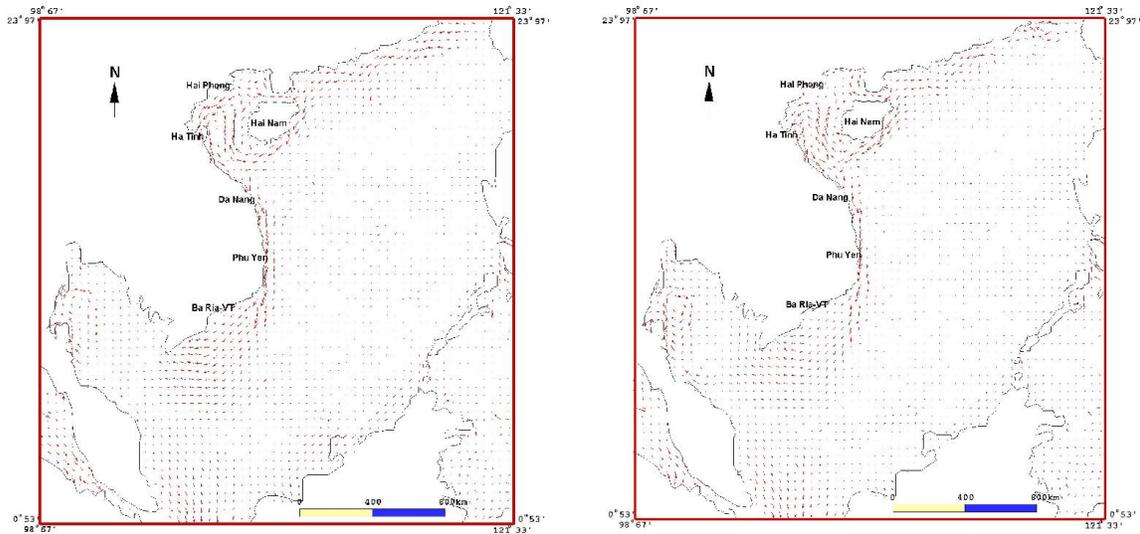


Figure 2. Comparison between computed and observed tidal water levels (a) at Hon Dau Station and (b) at Ha Tien Station

Since the East Vietnam Sea is a large sea, the general circulation in the sea due to wind can cause density abnormality, which drives the density density current. Then, the density current should be considered. However, due to time restriction on the sea water density distribution, in this computation, we still did not considered the effects of density stratification on the current field.





(c) 18:00 March 15, 2007

(d) 18:00 April 14, 2007

Figure 3 Computed flow fields

2.3 Numerical model for the transport and weathering of oil

A numerical model was developed at the Vietnam Institute of Meteorology, Hydrology and Environment for the computation of the transport and weathering processes of oil in the sea. The model considers all main processes happening when the oil slicked into the marine environment. When the oil is slicked into the marine environment, at first, it is transported on the water surface. Then, the oil undergoes weathering processes. Light components of the oil will be evaporated. The remained oil can undergo the emulsification processes, in which oil expands its volume due to water uptake. The emulsification processes will increase the possibility of oil dispersion into the water column in the form of oil droplets. A part of suspended oil droplets can interact with suspended sediment, increasing their density and sink to the sea bed. On the other hand, large submerged oil droplets can resurface to become the surface oil. A small fraction of oil can be dissolved into water. The contribution of dissolved oil into oil mass balance is negligible. Then, to study the oil transport in the marine environment, it is necessary to consider the transport of different phases of oil, including the transport of surface oil layer and suspended oil droplets in the water column under the surface, and the oil exchange between the different phases. As mentioned previously, the contribution of dissolved oil in the oil mass balance is negligible. Also, since this study aims at the study of the oil transport and weathering in a large area, the dissolved oil is neglected.

2.3.1 Equations governing the transport and dispersion of oil

In this study, we distinguish the surface oil layer and the under surface oil layer. With the assumption that the thickness of the surface oil layer is small compared with the water depth, the general equations governing the transport and dispersion of surface oil can be written as:

$$\frac{\partial C_s}{\partial t} + \frac{\partial}{\partial x}(u_s C_s) + \frac{\partial}{\partial y}(v_s C_s) = \frac{\partial}{\partial x} \left(K_x \frac{\partial C_s}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial C_s}{\partial y} \right) + \alpha v_b C_v - \gamma C_s - C_s S_e - C_s S_d - D_s(x, y) \quad (1)$$

here, x , y and t are respectively spatial and time variables; C_s is the density of oil on the sea surface (the mass of oil on a unit sea water surface); C_v is the volume density of suspended oil droplet in the water column; u_s and v_s are components of current velocities in x and y directions, respectively; α is a coefficient expresses the probability that a suspended oil droplet to resurface; νb is the rise velocity of oil droplet in the water column; γ is a coefficient, describing the rate of dispersion of surface oil into the water column; S_d and S_e respectively the degradation and evaporation of oil on a unit area of the oil surface; and D_s is the rate of oil deposition and reentranced at the shore line. The equation governing the transport and change of suspended oil in the water column can be written as:

$$\begin{aligned} \frac{\partial HC_v}{\partial t} + \frac{\partial (HuC_v)}{\partial x} + \frac{\partial (HvC_v)}{\partial y} + \frac{\partial (HwC_v)}{\partial z} = \frac{\partial}{\partial x} \left(HK_x \frac{\partial C_v}{\partial x} \right) + \frac{\partial}{\partial y} \left(HK_y \frac{\partial C_v}{\partial y} \right) \\ + \frac{\partial}{\partial z} \left(HK_z \frac{\partial C_v}{\partial z} \right) + \gamma C_s - \alpha V_b C_v - \beta C_v \end{aligned} \quad (2)$$

Here, C_v is the volume density of oil in the water; u , v and w are respectively the flow velocity in three directions x , y and z ; β is a coefficient used to determine the rate of deposition of suspended oil droplets into the sea bed.

2.3.2. The transport and degradation of oil

Besides being dispersed into the water column, the surface oil can be transported by the combined actions of wind, waves and surface current. The physical processes that govern the transport and weathering of oil can be written as.

a. Advection

The advection of oil on the water surface is due to combined action of surface current and wind. The drifted velocity of surface oil can be evaluated from the wind and surface current velocity as follows (Stozenbach et al, 1977)

$$V(u_s, v_s) = \alpha_w V_w + \alpha_c V_c \quad (3)$$

where, V_w is the wind velocity at 10m height above the water surface; V_c is the surface current velocity; α_w is the wind drifted velocity, equal to 0.03; and α_c is the water surface wind velocity, equal to 1 (Stolzenbach et al, 1977).

b. Vertical diffusion

The vertical diffusion coefficient is very important for the oil transport in the water column and the oil exchange between the water column and the surface oil layer. The vertical diffusion coefficient can be evaluated from the POM model, accounting also for the density stratification in the near surface layer

c. Mechanical oil spreading

In general, after being discharged into the marine environment, the oil on the sea surface undergoes mechanical spreading process. This process is governed by the balance between the gravity, the viscosity and the surface tension, and can be divided into four phases (Yapa, 1994). In the initial phase, the gravity and inertial forces plays leading roles. In the second phase, gravitational and viscous forces are main forces that govern the oil spreading. In the third phase, the surface tension and viscous forces are the main forces, and in the fourth phase, the spreading oil layer attains its balance.

In the first phase, the gravity and inertial forces plays leading roles, and the radius of the oil surface layer R can be calculated as:

$$R = 1.14(\Delta g V t^2)^{0.25} \quad (4)$$

In the second phase, gravity and viscosity play leading roles:

$$R = 0.98(\Delta g V^2 t^{1.5} / \nu^{0.5})^{0.167} \quad (5)$$

In the third phase, the surface tension and viscous force play leading roles, then:

$$R = 1.6(\sigma^2 t^3 / (\nu \rho_w^2))^{0.25} \quad (6)$$

And in the balance phase

$$R = (10^5 V^{0.75} / 3.14159)^{0.5} \quad (7)$$

with $\Delta = (\rho_w - \rho_o) / \rho_w$, relative density ratio; ρ_w is the density of water; ρ_o is the oil density; V is the volume of slicked oil, ν is the kinetic viscosity of oil; and σ is the surface tension of oil.

d. The deposition of oil at the shoreline

When the polluted oil reach the shoreline, it will deposit. After the deposition, the oil will be reentranced by waves, wind and current. Based on the half decayed period formula, the remaining fraction of oil at the shoreline can be evaluated as:

$$V_2 = V_1 e^{-k(t_2 - t_1)} \quad (8)$$

with V_1 and V_2 are respectively the volumes of oil remaing at the shoreline at t_1 and t_2 (days); $k = -\ln(1/2) / \lambda$ is the decayed coefficient, and λ is the half decayed period. The value of the half decayed period k changes from 0.001-0.01 at marshy land to 0.99 at rocky shoreline under light waves.

e. Evaporation

The evaporation is the main cause of oil loss, and can be evaluated according to MacKay et al (1980) as follows

$$F = \frac{1}{C} \left[\ln P_o + \ln \left(CK_e t + \frac{1}{P_o} \right) \right] \quad (9)$$

with $E = K_e t$ is the oil evaporation expose term, depending on time and environmental conditions; $K_e = K_m A V_m / R T V_o$ with $K_m = 0.0025 V_w^{0.78}$ is the mass exchange coefficient at the water surface, m/s; A is the area of the oil, m^2 ; V_m is the mole volume, m^3/mol ; R is the gas constant, $=82.06 \times 10^{-6}$ atm $m^3/(mol K)$; T is the absolute temperature of the oil, equal the sea water temperature; V_o is the initial oil slick volume, m^3 ; The initial vapor pressure P_o is calculated as atm at temperature T_e as follows

$$\ln P_o = 10.6(1 - T_o / T_e), \quad (10)$$

where T_o is the initial boiling temperature of the oil (Kelvin); For crude oil

$$C = 1158.9 API^{-1.1435} \quad (11)$$

$$T_o = 542.6 - 30.275 API + 1.565 API^2 - 0.03439 API^3 + 0.0002604 API^4 \quad (12)$$

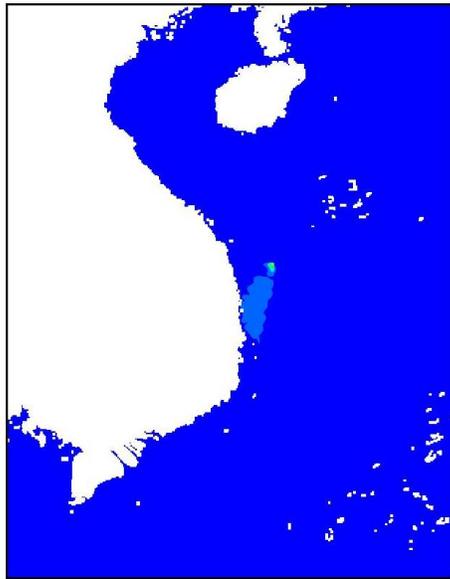
With API as the oil index, calculated from the oil density

$$\rho_o = 141.5 / (API + 131.5) \quad (13)$$

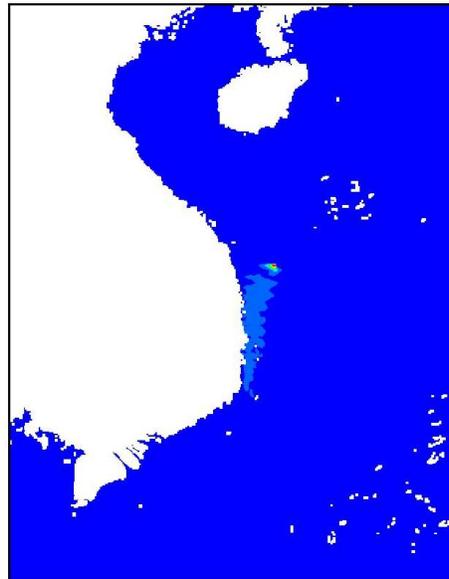
The mole volume of oil varies in the range from 150×10^{-6} to 600×10^{-6} m³/mol, depending on the oil components. For kerosel, this value is about 200×10^{-6} m³/mol.

f. The dissolution and deposition

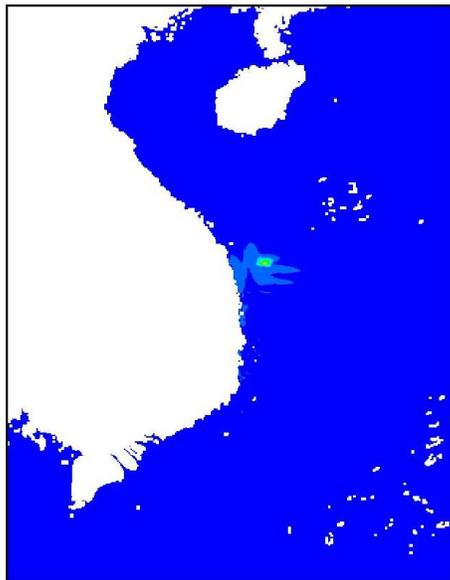
The dissolution of oil is neglected, while the deposition of oil is evaluated according to empirical formula. The dispersion of oil at the water surface to the water collum is calculated using the exchange coefficient between surface soil layer and the soil suspended in the water collum (Cohen et al, 1980).



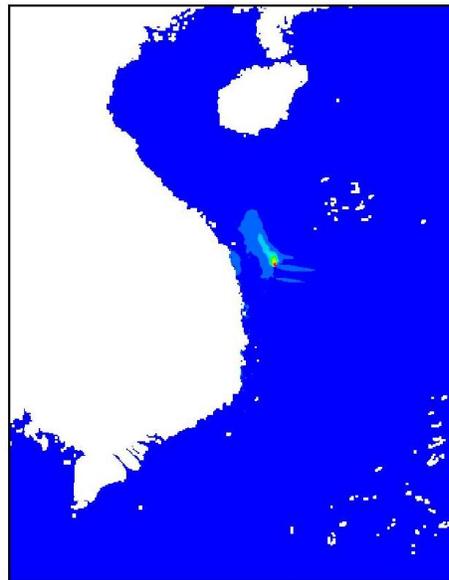
(a) 12:00 January 20, 2007



(b) 12:00 January 28, 2007



(c) 12:00 February 28, 2007



(d) 12:00 March 8, 2007

Figure 4. Computed oil pollution

g. Influence of waves to the soil dispersion

Waves strongly influence the oil emulsification and oil dispersion into the water column. The influence of waves on the above mentioned processes can be simulated based on the white capping fraction of waves.

3. Computational Results and Discussions

As shown by the computed current fields, if the oil pollution source is at the offshore of North Central Vietnam, the oil slick can be transported southwards to pollute the Central Vietnamese coast. At the same time, the oil can also be transported northwards to pollute the coast of North Vietnam. On the other hand, if the oil is slicked out of a oil field offshore of South Central Vietnam, then with the computed wind and current fields, it is not possible for the oil to be transported to pollute the coast of Central and North Vietnam. Figs. 4 (a,b,c,d) show examples of the oil pollution at different times, from 20 January to 8 March, 2007 with the source of oil pollution indicated in Figure 4a. It can be seen that with this source of oil pollution, the slicked oil can be transported to pollute all Vietnam coast, from the north to the south.

4. Conclusion

From the study results, it is possible to draw the following conclusions:

1. A method is developed to rapidly locate possible oil pollution source in the East Vietnam Sea. The method is not only applicable to the East Vietnam Sea, but every where;
2. Nowadays, with extensive oil drilling, oil transportation and other kind of transporation in the East Vietnam Sea, the risk of oil pollution to Vietnamese coast is rising, and it is neceasry to develop a decision support system for oil pollution events in Vietnam. The method we develop in this study can be used for developing such a system. The Vietnam Institute of Meteorology, Hydrology and Environment has the intention of developing such a system in the near future.

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