Abstract
This paper describes the ongoing project on autonomous spilled oil and gas tracking buoy system and application to marine disaster prevention system for 5 years since FY2011. Objectives of this project are as (1) autonomous tracking and monitoring of spilled plumes of oil and gas from subsea production facilities by an underwater buoy robot, (2) autonomous tracking of spilled oil on the sea surface and transmission of useful data to a land station through satellites in real time by multiple floating buoy robots, (3) improvement of the accuracy of simulations for predicting diffusion and drifting of spilled oil and gas by incorporating the real-time data from these robots.

To realize (1) and (2) objectives, we have developed an autonomous underwater robot named SOTAB-I, and an autonomous surface vehicle named SOTAB-II. To realize (3) objective, Data fusion methods in the simulation models incorporating real-time measured data not only from a SOTAB-I for gas and oil blowouts, but also from multiple SOTAB-IIs for spilled oil drifting on sea surface were developed.

1. Introduction
There have been many major sea oil spills in recent years. These spills damage not only the ocean environment but also regional economies. Once spilled oil washes ashore, it is difficult to recover it effectively. This results in a high residual amount of spilled oil and long-term damage to the environment as well as to marine and human life.

Explosion of offshore oil rig at Gulf of Mexico in 2010 has roused our attention to danger of a large amount of oil spill from subsea oil production systems. On the other hand, once gas blows out from seabed by an accident of subsea oil production system or by a seismic activity and subsea landslide in the area of ample reserves of methane hydrate in the sea, it seriously damages not only ships and airplanes, but also natural environment.

To prevent oil and gas spills from spreading and causing further damage over time and space, early detection and monitoring systems should be deployed around the offshore oil and gas production system. In addition, oceanographic data should be collected in order to grasp the environmental changes around the accident. Based on the collected data, oil and gas drifting simulation must be performed to predict where the spilled oil will wash ashore and to adequately deploy oil recovery machines before this occurs.

The objectives of this study are as follows;
(1) Autonomous tracking and monitoring of spilled plumes of oil and gas from subsea production facilities by an underwater buoy robot,
(2) Autonomous tracking of spilled oil on the sea surface and transmission of useful data to a land station through satellites in real time by multiple floating buoy robots,
(3) Improvement of the accuracy of simulations for predicting diffusion and drifting of spilled oil and gas by incorporating the real-time data from these robots.

This research project adopts the following methods to realize these objectives:
(1) An autonomous underwater robot equipped with a buoyancy control device and two pairs of rotational fins for guidance and control, and sensors to detect dissolved gas and oil has been developed. It has been tested in several sea areas, including the Gulf of Mexico and Toyama Bay in Japan.
(2) An autonomous sea surface vehicle equipped with a sail—the orientation and size of which are adjustable—and sensors to detect oil slicks on the sea surface has been developed. It has been tested in Japan using artificial targets on the sea surface.
(3) A data fusion method incorporating real-time measured data from buoy robots in simulation models for not only gas and oil blowouts, but also spilled oil drifting on the sea surface have been developed.

The system described above can be applied to regular environmental monitoring around subsea production facilities, the collection of spilled oil drifting on the sea surface, and the deployment of oil-recovery devices (see Fig.1) [1].

Fig.1 Autonomous tracking and monitoring system of spilled plumes of oil and gas from seabed

2. Autonomous tracking and monitoring of spilled plumes of oil and gas from seabed by an autonomous underwater robot

2.1 Autonomous Underwater Robot for Automatic Tracking and Monitoring of Spilled Plumes of Oil and Gas from Seabed (SOTAB-I)
There have been two types of underwater robots autonomously monitoring marine environments in 3-D space from sea surface to seabed over the long term. One is Argo Float[2] and the other is underwater glider[3][4]. Argo Float floats vertically and repeats descending and ascending in the vertical direction. However, it does not have a function of active movement in the horizontal direction. Underwater glider has a streamlined body with fixed wings. It can descend and ascend by using a buoyancy control device, while it moves in the horizontal plane like a glider for long distance. However, the ratio of vertical movement distance to horizontal movement distance is small.

2.2 Outline of SOTAB-I
An overview of SOTAB-I is shown in Fig. 1 and its main mechanical characteristics are shown in Table 1.

SOTAB-I can be submerged in water as deep as 2,000 meters. It can descend and ascend by adjusting its buoyancy using a buoyancy control device while changing its orientation through two pairs of movable wings. At the bottom side of the robot, four fixed wings are attached. SOTAB-I can also move in the horizontal and vertical directions through two couples of horizontal and vertical thrusters.

Table 1 Principal particulars of SOTAB-I

<table>
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<tr>
<th>Feature</th>
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<tr>
<td>Total Length</td>
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<tr>
<td>Diameter</td>
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<tr>
<td>Weight in Air</td>
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<tr>
<td>Weight in Water</td>
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<table>
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<th>Movable Wing</th>
<th>Chord [mm]</th>
<th>Span [mm]</th>
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<td>Chord</td>
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<td>400</td>
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<table>
<thead>
<tr>
<th>Fixed Wing</th>
<th>Chord [mm]</th>
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<tr>
<td>Chord</td>
<td>200</td>
<td>400</td>
</tr>
</tbody>
</table>

SOTAB-I installs an underwater mass spectrometer(UMS) that can measure dissolved gas and volatile organic compounds in situ up to the mass ratio of 200 with the detection limit of 20 nmol/L, CTD sensor(resolution: 0.0001 °C for temperature, 0.00005 S/m for conductivity, 0.002% for full scale pressure), ADCP(frequency : 1.200kHz, 4 beams, 10 layers with 0.5 m width) for oceanographic data sampling. It also installs GPS, doppler velocity log(DVL) and ultra-short baseline underwater positioning system(USBL) for navigation, and acoustic modem for communication between SOTAB-I and the computer on mother ship and Iridium modem for communication between SOTAB-I floating on sea surface and the computer on mother ship through Iridium satellite.

2.3 Operational Modes
SOTAB-I adopted some operational modes for its guidance and control. The first is “Rough Guidance mode” for finding plumes of oil and gas using UMS. In this mode, SOTAB-I descends and ascends along the surface of a cylinder which surrounding the plumes. Using movable wings and buoyancy control device, it can move horizontally and vertically. While moving, it gathers the data of underwater currents, temperature, salinity, and dissolved gas and oil. Furthermore, it gets the position of the plumes roughly. The second mode is called “Precise Guidance mode” to survey the detailed characteristics of the plumes by repeating descending and ascending within the plumes. The third is “Measurement Mode of Vertical Distribution of 3-D Ocean Current (VDOC Mode)” using the data from USBL and ADCP. This has the purpose to comprehend the ocean current distribution in vertical direction. And the fourth is “Photograph mode” for observation of blowout of plumes of oil and gas. SOTAB-I records the condition of oil well with an installed camera by moving horizontally 1-meter above the seabed. Additional modes are called “Manual mode” for the preliminary experiment and “Emergency mode” to make SOTAB-I ascend urgently with the maximum buoyant force in emergent situations.

2.4 Travelling performance in vertical and horizontal planes
SOTAB-I can move horizontally and vertically using movable wings and buoyancy control device.

Figure 2 shows the traveling performance in vertical and horizontal planes using movable wings and buoyancy control device for the set depth of 100 m. The left figures show the time variations of depth, set buoyancy ratio(100% is equivalent to 74.48N), and actual buoyancy ratio. The right figures show the trajectories in horizontal plane during descending and ascending. We can see that the ratio of traveling distance in horizontal plane to ascending distance in vertical plane reaches about 1.3, which means that the inclination angle from the vertical axis reaches 52.4°. SOTAB-I can travel within this angle during ascending.

Fig.1 Picture of SOTAB-I during launching
Fig.2 Movement of SOTAB-I in vertical plane and horizontal plane with the wing angles of 0° for two pairs of wings (upper) and that with the wing angles of 30° for one pair of wings during ascending(lower).
2.5 Physical and chemical data sampling performance

(a) Physical data sampling

SOTAB-I uses CTD, ADCP, DVL and USBL for physical data sampling. DVL outputs 3-D velocity components of SOTAB-I against the seabed in body-fixed coordinate within the altitude of 30 m from seabed, which are transformed in earth-fixed coordinate. ADCP outputs 3-D relative velocity components of water currents in body-fixed coordinate, which are transformed in earth-fixed coordinate.

Within the altitude of 30 m from seabed, water current velocity components in earth-fixed coordinate are obtained by summing up the velocity components of SOTAB-I measured by DVL and relative velocity components of water currents measured by ADCP.

Over the altitude of 30 m from seabed, water current velocity components in earth-fixed coordinate are obtained by summing up the velocity components of SOTAB-I calculated by differentiating the horizontal position data from USBL and the depth data from CTD with time, and relative velocity components of water currents measured by ADCP.

(b) Chemical data sampling

Experiments were performed from 6th to 15th December 2013 in the Gulf of Mexico in the USA (Fig. 5), near where Deepwater Horizon Oil Spill Accident in 2010 and Hercules 265 oil rig blowout in 2013 leading to release of methane gas. The aim of the exploration was the evaluation of performances of SOTAB-I surveying abilities. Due to the strong wind and severe weather conditions, experiments were carried out in shallow water and in particular, in the mouth of the Mississippi River where UMS data were measured. The area is characterized by its prevalent abandoned oil rigs and natural seepage of hydrocarbons [6].

Figure 6 shows the change of concentration of (a) methane, (b) oxygen and (c) carbon dioxide along the water column. The concentration of methane in the upper water layers is negligible down to a depth of 30 m, and that it starts to increase steadily down to a water depth of 44.6 m. The oxygen concentration moderately decreases from water depth of 0 m to that of 10 m, followed by slower rate of decline from of 10m to 27m water depth. Then, oxygen concentration declines considerably from water depth of 27m to that of 44m. Three zones can be distinguished based on the change in carbon dioxide concentration: In water depth between 0
m and 10m, carbon dioxide concentration decreases gradually. From 10 m to 27m water depth, it keeps decreasing but at a slower rate. Below 30m, carbon dioxide concentration increases down to water depth of 44m. From this point of view, we can say that SOTAB-I succeeded to measure dissolved substances variation along the vertical water column. On the other hand, other alkanes and BTX were below the sensory threshold and had no significant concentration.

3. Autonomous Surface Vehicle Tracking Spilled Oil Slick Drifting on Sea Surface (SOTAB-II)

The mission of the tracking spilled oil slick on sea surface is that multiple autonomous surface vehicles follows the drifting oil slick automatically and sends the positioning data and hydrographic phenomena to the operation base continuously. We can watch the oil slicks drifting in real-time and predict their precise destinations using the monitoring data from the SOTAB-IIs. (Fig.7).

![Fig.7 Concept of operation of SOTAB-II system](image)

The existing equipment cannot provide such useful data in real-time and in the long term. Plane flies over the sea and watches the oil slicks by visual recognition. In the night, however, the oil slicks are not visible on the seawater. Fluorescence lidar[7] is a compact imaging lidar system detecting the fluorescence of substances excited using CCD camera. This equipment is mounted on a helicopter and can provide images of spreading spilled oil and its classification even in the night. However, the plane cannot track the spilled oil continuously because of limit of its endurance. Drifting buoys[8] are used to track spilled oil. However, they have no device to track it again, when they get apart once from the spilled oil. The method of the X-band radar detection[9] is used under condition that the vessels can track the oil slicks. It is rare case that the vessels can track the spilled oil continuously because weather of the sea is not always fine. The satellite remote sensing[10] is not carried out more frequently than the plane method. However, SOTAB-II has another important function which is to move large distance by using the auxiliary propulsion mechanism. If the drag force on SOTAB-II is so big, the auxiliary propulsion mechanism uses large electricity to bring SOTAB-II to a certain location. Therefore, we design a new model of SOTAB-II with a yacht shape to reduce the drag coefficient in water[12].

By utilizing an autonomous surface vehicle (ASV) equipped with oil detection sensor system, oil spill spread and drift can be monitored in real-time. As ASV uses wind energy for its propulsion, it can take long range mission, and can be used for sampling and surveillance for vast ocean. ASV gives independence of space requirements for batteries, motors, data acquisition and control electronics due to its broader beam and larger displacement[13]. ASV has been exploited due to their several advantages for sampling, surveillance and oceanography of the vast ocean. It also provides better spatial and temporal resolution of the oceanographic data compared to the fixed oceanographic monitoring buoy and other remote sensing technique such as satellite. Proposed ASV (SOTAB-II) uses optical fluorescence sensor for oil detection (slick sleuth s300). One of the best attractive feature of this technique is that it can be done in both day and night condition. It can detect oil on a variety of sea states, and uniquely among remote technique it can discriminate among various oil type.

The hull of SOTAB-II has a yacht shape shown in Fig.8. Hull form of sailing yacht "KIT34" designed by Kanazawa Institute of Technology was selected for the new SOTAB-II hull design. SOTAB-II hull is scaled down version of KIT34. The hull dimension is 1/4 of the original hull dimension. Main hull dimensions are shown in the Table.1

![Fig.8 Configuration of SOTAB-II](image)

<table>
<thead>
<tr>
<th>Total Length (LOA)</th>
<th>2.64m</th>
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</thead>
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<tr>
<td>Maximum Width (Beam)</td>
<td>0.76m</td>
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<tr>
<td>Draft</td>
<td>0.61m</td>
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<tr>
<td>Mast Height</td>
<td>1.64m</td>
</tr>
<tr>
<td>Displacement</td>
<td>150Kg</td>
</tr>
<tr>
<td>Keel Position From Hull Bottom</td>
<td>0.40m</td>
</tr>
<tr>
<td>Keel Weight</td>
<td>30 Kg</td>
</tr>
</tbody>
</table>
Different from the basic type of SOTAB-II, the new SOTAB-II drifts along with oil slick by controlling its sail size and rudder. In this research, CFD software “Fluent” of ANSYS was used in order to simulate the effects of sail and brake board. The idea is to make SOTAB-II a wind propelled system rather than using onboard thruster for tracking oil spill so that less of battery power is consumed for propelling it. New SOTAB-II sail shape was modified to square for using maximum advantage of wind power. Hence the size was chosen as .75m both in width and height which is also equal to the maximum hull width. For achieving the drift velocity of the oil slick the SOTAB-II should drift with 2-5% of wind speed, as the resistance force of the bare hull is smaller than the drift forces acting on the hull. This could speed up SOTAB-II leading to lose the tracking of spilled oil. Hence to increase the drag force of SOTAB-II a rectangular board called as brake board measuring 300mm in height and 500mm in width is used. A single rudder system was selected for SOTAB-II to make sure to have sufficient steering effect in every sailing situation. Assembled inside the hull, the rudder actuators are well sealed and protected against water. In order to achieve higher stability and preventing the robot from capsizing in rough weather conditions, SOTAB-II keel with a draft of .4m consist of thin slim fin with a 30Kg ballast bulb.

3.2 Speed control and heading control

![Flow chart of SOTAB-II system](image)

Figure 9 shows the decision making process for target heading(TD) and target speed(TV) in various conditions.

3.3 Field experiments

Field experiments were carried out at Osaka University pond as shown in Fig.11 to validate the capability of SOTAB-II, to autonomously track oil spill as well as, guidance and navigation capability of SOTAB-II based on its onboard sensor input and control logic to derive target heading and target direction. For this experiment neoprene sheet served as an oil, due to the legal issues. Experiments to study drifting behavior of oil on sea surface, were carried out using pseudo oil made with sponge rubber. For SOTAB-II experiment, neoprene sponge rubber of thickness 10mm was used. In addition, white fabric sheet was pasted on neoprene sponge rubber, because the oil sensor outputs a similar signal to actual oil when it is focused on white fabric. To carry out the experiments, a floating fence of 4 ×4m was used to fix the position of SOTAB-II at the center of the floating fence. Neoprene sheet of dimension 35 ×35 cm was used as artificial oil with total area of 16 m. After fixing SOTAB-II temporarily with the floating fence, neoprene sheets were spread around SOTAB-II. After releasing the floating fence, the experiment was started.

![Experimental setup of rubber sheets and SOTAB-II](image)

Figure 9 shows the flow chart of SOTAB-II system. Slick Sleuth (S300) is an optical based oil sensor which captures fluorescence property of oil for oil detection. The ultraviolet beam fired from the sensor transmitter, is in form of cone with the cone angle of 14deg. The oil sensor shaft is rotated for 360 degrees to cover the area around SOTAB-II. Circular target area of radius 1.6m around SOTAB-II, was selected as oil sensor target area. The circular zone was divided into 12 sectors of 30°. To be fully aware of present position of SOTAB-II relative to oil slick, oil sensor is made to take one complete rotation. It takes two seconds for mast to rotate by 30° and one second for the sensor to acquire data. As the mast rotates from −180° to +180° it takes 12 steps, hence for oil sensor data an array of 13 elements is assigned as $s_j$ where, $j = 0,1,2,3, ....,12$ for each step. As the value of $j$ is derived from mast current angular position, $j$ is unique for each angular position of mast ($\varphi$), while mast is rotating back from +180° to −180° or moving to a new position instead of updating the full array $s_j$ only array element pointed by $j$ is updated.

$$P_l = \{s_1,s_2,\ldots,\ldots,s_{12}\} \quad \text{Where } s_j = 1 \text{ or } 0$$

![Target heading and target speed using oil sensor data point](image)
Figure 12 shows the time variations of the summed up values of $s_j$ ($j=1,...,12$) at each time and the longest distance of the part where the value of 1 continues in $s_j$ ($j=1,...,12$). We can see that SOTAB-II almost loses the target between 40 s and 60 s, and that it detects the target again after that. Figure 13 shows the time variations of speed of SOTAB-II and the hypothetical and specific value, 3.0%, of wind velocity at a 10m height from the water surface. We can see that the speed of SOTAB-II follows fairly well the change of 3.0% of wind velocity at a 10m height from the water surface.

4. Assimilation Analyses of Environmental Simulation and Measured Data by SOTAB-I and SOTAB-II

A data fusion method incorporating real time measured data from buoy robots in the simulation models for not only gas and oil blowouts, but also spilled oil drifting on sea surface has been developed. Precision of prediction of oil and gas behavior using simulation models will be improved by incorporating real time measured data from buoy robots SOTAB-I and SOTAB-II.

4.1 Numerical simulation of methane seeping from deep water seabed in the Japan Sea

Section 2 shows the development of an autonomous underwater robot SOTAB-I. The final goal of SOTAB-I is to predict spilled region of oil and gas in real time, while the measured field data and the simulation system are communicated on site. SOTAB-I has a function to measure the vertical profiles of water currents, water temperature, water salinity around spilled region, these data are precious for the simulation of oil and gas distributions. On the other hand, SOTAB-I has the other function to measure the vertical profiles of dissolved gas and volatile organic compounds in real time while it repeats zigzag diving around the spilled region, the simulated oil and gas distributions are valuable information to save the power of the robot maneuvering. From this viewpoint, as a fundamental development of the hybrid system with robot measurement and simulation, we developed a numerical simulation code to predict the methane seep phenomena in the Japan Sea by utilizing the field measurements by Matsumoto et al. [14].

4.1.1 Numerical model

The present numerical model is mainly based on the method proposed by Yapa [15-18]. Their model is intended to oil and gas spills in deep water, however, the formulations of the associated physical and chemical processes are applicable to the methane seeping in the present study.

Seeped methane gas is treated as an individual particle bubble because the gas ejection of small amount does not form a cluster of bubbles such as massive blowout. Ejected gas particles from the seabed are tracked by the standard Lagrangian tracking method.

(a) Motion of each particle

Motion of each particle is divided into the components of horizontal and vertical directions. Horizontal velocity $u$ is described as follow:

\[ u = u_w + u_r \]  

where $u_w$ is the horizontal component of ambient water velocity and $u_r$ is the horizontal diffusive velocity. The horizontal velocity of ambient water $u_w$ is given by the interpolation of field observation data at any points or reanalysis data by ocean model. On the other hand, $u_r$ is calculated by the random walk model, that is,

\[ u_r = \gamma \frac{2D}{\Delta t} \]  

where $D$ is horizontal diffusivity of gas particle motion and $\gamma$ is random number from -1 to 1 and $\Delta t$ is time increment for the temporal integration of simulation. Vertical velocity $w$ depends on the shape of gas bubble and is defined in three regimes of bubble diameter, spherical shape, ellipsoidal shape and spherical-cap.

(b) Formation of methane hydrate

Since the condition of deep water is low-temperature and high-pressure, seeped methane gas forms hydrate in deep level and
the phase of methane must be considered in the simulation. Figure 14 shows the equilibrium curve of methane in seawater and the temperature profile at the Joetsu offing. In this figure, methane exists at the hydrate phase under the equilibrium curve, and at gas phase over the curve. The level of crossover point between the equilibrium curve and the seawater temperature is about -300 m, and it is the critical depth of methane hydrate. To model hydrate formation at each particle, the following assumptions were used:

(i) Methane hydrate forms a spherical shell, including gas inside.

The shell has a porous structure, and methane gas diffuses through the porous shell and react at the interface between the hydrate shell and ambient fluid.

(ii) The temperature of hydrate shell is equal to that of the hydrate-fluid interface. Therefore, the heat of hydration transfers into the ambient fluid.

(iii) The mass and heat transfer in each particle is quasi-steady at each time step of simulation, because the gas-hydrate boundary moves and changes slowly during rising.

(iv) The pressure of gas inside the hydrate shell is equal to that of the ambient fluid because the shell is porous.

(v) The hydrate shell over gas is of a uniform thickness and the detachment of hydrate flake is neglected.

Under these assumptions, the growth rate of methane hydrates at each particle is calculated by

\[ \frac{dn}{dt} = K_f \cdot 4\pi r_e^2 (f_{gas} - f_{eq}) \]  

where \( n \) is the mole weight of methane, \( K_f \) the coefficient of reaction rate, \( r_e \) the radius of particle, \( f_{gas} \) and \( f_{eq} \) are the fugacities of gas phase and three-phase equilibrium state, respectively. The coefficient of reaction rate \( K_f \) is calculated by the Ranz-Marshall equation[19]. The decomposition of methane hydrates, gas dissolution and hydrate dissolution were also included in the model.

4.1.2 Field conditions

At the Joetsu offing in the Japan Sea, there is the Umitaka spur in the north-south direction. Along the Umitaka spur, the investigation of methane hydrates in the seabed was carried out by the research group of Matsumoto, and the hydrated methane in bedrock and the seeping of methane gas from the seabed were observed at some points[14]. In the present study, we selected the seeping point at latitude 37.436 North and longitude 128.005 East corresponding to the piston coring point of methane hydrate investigation by Matsumoto et al.[14]. Matsumoto et al. observed directly methane seeping at this point by using ROV monitoring and collected pure methane hydrate rising from the seabed. Figure 14 shows the phase equilibrium curve of methane and a standard temperature profile at the Joetsu offing. In this figure, methane exists at about -100 m depth, and the critical depth depended only on the thermophysical properties of methane. The terminal level of methane gas was -120 m, and it was also independent from the ambient flow conditions. This simulation shows that the phase change to hydrate has been completed within 4 m rising from the seabed. This result agrees with the in-situ observation at the Joetsu offing by Matsumoto et al. [14]. We then conclude that the present numerical model provides accurate predictions for hydrate formation, and it can be used to simulate actual field observations.

4.2 Assimilation of Weather Research and Forecasting(WRF) in the Model of Drifting of Spilled Oil on Sea Surface

For the prediction of drifting of spilled oil on sea surface, a combination of Princeton Ocean Model(POM) for ocean modeling and Weather Research Forecasting Model(WRF) has been used in this study. To raise the accuracy of prediction of drifting of spilled oil on sea surface, this study adopted variational data assimilation method for WRF Model and POM using data from SOTAB-II and others. As a case study, a simulation of the drifting of spilled oil after the incident of the Russian tanker Nakhodka in the Sea of Japan in January 1997 was performed to evaluate the effectiveness of data assimilation method. We reported that this system can estimate spilled oil behavior and DA scheme using real observations are effective to improve its accuracy[21].

We try here to use the data from the buoy robot SOTAB-II. But SOTAB-II is under development. Therefore, numerical experiments are conducted to verify its validity and efficacy by providing
pseudobservations as the data from the buoy robots SOTAB-IIs to the numerical simulation of Nakhodka oil spill accident.

### 4.2.1 Numerical method

The velocity of drifting oil on the sea surface is expressed using the current velocity due to the wind, the tidal current velocity and the current velocity on sea surface. The velocity is also under the effect of the velocity of oil diffusion and of oil spreading. The bulk method was applied to express wind effect in this study.

These velocities are computed by the atmospheric model WRF, the ocean model ROMS, and an oil spreading model. A data assimilation scheme is applied for atmospheric model. So-called three dimensional variational (3DVAR) DA scheme implemented in WRFDA (WRF Data Assimilation) and cv of 5 option were selected as the DA scheme and the background error covariance based on the numerical experiment carried out. The oil spreading model is based on the Lagrangian particle method considering the change of oil property such as evaporation, emulsification, and spreading by the sea water and characteristics of itself. In this simulation, 1 kiloliter of oil is treated as a particle for Lagrangian particle. The simulation domains of this computation for WRF and ROMS are shown in Fig.16.

![Simulation domains for ROMS and WRF](image)

Fig. 16 Simulation domains for ROMS and WRF

As the initial condition of ROMS, the computational result of SODA by University of Maryland and Texas A&M University (https://climatedataguide.ucar.edu/climate-data/soda-simple-ocean-data-assimilation) was interpolated and used. As the boundary condition, the monthly mean flow rate, salinity and seawater temperature are given at open boundary by interpolating the data of JCOPE2 by JAMSTEC, Japan (http://www.jamstec.go.jp/frcge/jcope/htdocs/distribution/index.htm). For WRF, “NCEP/NCAR Global reanalysis Products” were used as the boundary condition. The wind stress calculated by WRF was given at sea surface as external forces of ROMS.

The number of SOTAB-IIs to be deployed corresponds to the heavy oil spilled from the sunken hull part and the drifted bow part of Nakhodka in the accident. To track spilled oil effectively, SOTAB-IIs should track not only spilled oil from drifting bow part, but also that from sunken main hull.

When we use the data from SOTAB-IIs, we set two cases. Firstly, SOTAB-IIs track both spilled oil from the drifted bow part and that from the sunken hull part, and secondly, SOTAB-IIs track the spilled oil from the sunken hull part only. Hereafter, the computation for the first case is expressed as “SOTAB-II DB(drifted bow)” and the second case as “SOTAB-II SH (sunken hull)”. In the first case, we set 16 of 20 SOTAB-IIs to track the bow part of Nakhodka, and 4 SOTAB-IIs to track the spilled oil from the sunken hull part. Data from SOTAB-II were estimated by interpolating the atmospheric data computed with high precision instead of real observations. We supposed that SOTAB-IIs can send environmental data every 6 hours in the computation of DA.

### 4.2.2 Computational results

The simulation results are shown in table 3. In this table, Obs, w/o DA and DA real obs denote the ratio of amount of collected oil ashore in each prefecture to total amount of collected oil ashore in 6 prefectures, computational drifted oil particles ashore without DA and the computational result with DA using real observations, respectively.

To discuss the efficiency of the numerical methods for total area, the root mean square error (RMSE) was obtained for each simulation method with respect to the ratio of amount of collected oil ashore in each prefecture to total amount of collected oil ashore in 6 prefectures. The definition of RMSE is as follows:

\[
RMSE = \sqrt{\frac{1}{6} \sum_{i=1}^{6} (x_i - x*)^2}
\]

here \(x_i\) is amount of collected oil ashore in each prefecture to total amount of collected oil ashore in 6 prefectures, and \(x*\) is the ratio of drifted oil particles ashore in each prefecture to total amount of drifted oil particles ashore in 6 prefectures with regard to a simulation method.

The calculated value of RMSE on each simulation method is shown in final column of table 3. We can see that data assimilation is effective and that the assimilation simulation method of SOTAB-II DB is the most effective. It shows that if SOTAB-IIs are arranged properly, it is so effective to improve numerical accuracy by applying DA using the data from SOTAB-IIs.

<table>
<thead>
<tr>
<th>Prefecture</th>
<th>Obs</th>
<th>w/o DA</th>
<th>DA real obs</th>
<th>SOTAB-II SH</th>
<th>SOTAB-II DB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tottori</td>
<td>0.14</td>
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<td>0.0</td>
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<td>Hyogo</td>
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### 5. Conclusions

To realize autonomous tracking and monitoring of spilled plumes of oil and gas from seabed as well as autonomous tracking of
spilled oil slick drifting on sea surface, we have developed an autonomous underwater robot named SOTAB-I, and an autonomous surface vehicle named SOTAB-II. Data fusion methods in the simulation models incorporating real time measured data not only from a SOTAB-I for gas and oil blowouts, but also from multiple SOTAB-IIs for spilled oil drifting on sea surface were developed.

Sea experiment using SOTAB-I will be carried out off Niigata to explore methane gas seeping from seabed in August, 2015. Sea experiment using SOTAB-II will also be carried out to verify its performance of autonomous tracking of artificial oil in Japan.

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Reference

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