Complications of robotic delineation of oil spills at sea

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ABSTRACT

Disasters at sea often run the risk of producing oil spillage. The level of spill depends on the type of vessel, the severity of damage, the weather conditions and nature of the disaster. Rapid response is crucial, yet an effective response depends on knowledge of the extent of the spill through the water column. Autonomous underwater vehicles are attractive to delineate a spill due to their capability of rapid deployment and ability to sense in three-dimensional space. This paper describes the assessment of oil sensors for their effectiveness on AUVs as rapid response instruments for delineation of an oil spillage at sea. Three sensors were tested to sense marine diesel oil in regular and breaking wave conditions. The outcomes implied that the robotic mission algorithms must account for oil in water that forms patches and clouds of droplets of various sizes and distribution at varied depths using appropriate sensors.

1. INTRODUCTION

1.1. BACKGROUND

An oil spill can have devastating consequences for the marine environment and living organisms. Humans, soil and even air qualities can be affected due to a variety of toxic chemical substances released into the environment during a spill. After being released to ocean and coastal waters, the oil continuously spreads due to the action of wind and waves [1].

The pollution risk in the Antarctic Ocean is on the increase because of the gradually growing scientific interest, tourism and both legal and illegal fishing [2]. Continuous growth of marine traffic resulted in 19 vessel accidents reported between 2001 and 2011, which have released or that had the potential to release oil near Antarctica and sub-Antarctica [3].

1.2. ISSUES OF OIL SPILL RESPONSE IN THE ANTARCTIC OCEAN

Spills in the Antarctic Ocean are infrequent; their environmental impact in such a pristine area is much more severe than in other parts of the ocean [4]. Low temperature significantly slows the biodegradation mechanism down by years when it may only take weeks or months in temperate areas [5]. Polar marine organisms consequently have longer exposure to pollutants.

Once an oil spill takes place, rapid response in its early stages is crucial to restrict the spread and minimise the effect of the spill. It inevitably requires immediate ship arrangements along with crews and survey instruments. One obvious challenge in the event of oil spills in the Antarctic Ocean, a particular focus of this paper is that the extreme remoteness and weather conditions hinder the access of professional personnel for response, ships and necessary equipment. This is even more so during winter months. Another issue is the long-term spreading of the spilled oil due to the presence of seasonal sea ice. While the closely packed floes are apt to trap the oil, reducing the spreading rate and evaporation [6], oil beneath young ice may be encapsulated by new ice within 12 – 24 hours [7] . The adhesive effect of snow and ice encapsulation may detain the oil initially yet spread it over a larger area at the onset of next warm season [8].

1.3. AUV APPLICATIONS IN OIL SPILLS

Autonomous Underwater Vehicles (AUVs) are untethered and unmanned robots that have proven to be effective and efficient in performing given tasks in dangerous, distant and dynamic ocean environments through many missions [9]. On account of a growing maximum range, increased battery life and payload sensor advancement, their application has been widely expanded [10].

The *Deepwater Horizon* offshore rig explosion in 2010 resulted in the largest oil spill incident in history. About 800 million litres of crude oil in total were spilled during the incident. The use of subsurface dispersant injection resulted in plumes of oil being trapped at around 1,000 metres depth of water, and therefore the true horizontal extent and vertical distribution of the spill could not be determined from the surface. So, AUVs were sent to the presumed water depth. The *Sentry* AUV of Woods Hole Oceanographic Institution (WHOI) equipped with a mass spectrometer was deployed to detect the underwater oil plume [11]. The *Dorado* AUV of Monterey Bay Aquarium Research Institute (MBARI) with gulper samplers returned with ten 1.8 litre oil-and-water samples and confirmed the presence of the oil plume [10].

Responding to an oil spill in polar conditions is more challenging than that in extremely deep water. There is limited bathymetry data. Many parts of both the ocean bottom and polar regions are little known or mapped. Moreover, it is very difficult to rely on guidance by human operators except when the AUV approaches the surface. When the release location of the source is unclear, an AUV must be able to adaptively track the oil down from the surface as oil does not necessarily rise vertically due to ambient currents and the nature of dispersion [12]. Therefore, a high-level of autonomy and complex behaviours by the robot are essential. The vehicle must be able to readily access the region where human and ship access is denied and prohibited. It needs to keep making decisions while conducting tasks and adaptively respond to unanticipated situations in the dynamic environment. In that sense, an AUV is the most ideal platform, provided that it has high resolution sensors that enable itself to perceive changes in its surroundings and a reliable in-situ analysis system that allows prompt reactions.

2. WAVE TANK EXPERIMENT

Fuels are complex mixtures of hydrocarbons composed of hundreds of thousands of organic and inorganic compounds [13]. They may fall into the same classes of compounds, yet have different physical properties depending on different amounts of chemical components [3]. For an AUV to correctly distinguish oil in water from other organic matter in the ocean, it is important to use appropriate sensors that are guaranteed to detect oil compounds under the conditions similar to those in the natural environment.

2.1. WAVE TANK FACILITY AND TESTING CONDITIONS

Experiments were carried out in November 2018 in the wave tank facility operated by the Centre for Offshore Oil, Gas and Energy Research (COOGER) at the Bedford Institute of Oceanography (BIO). Marine diesel oil (MDO) was selected as the subject target oil because its properties are the most analogous to Special Antarctic Blend (SAB) diesel, one of the most commonly used fuels in the Antarctic [3]. A set of experimental varied wave conditions was triplicated (six tests in total).

The experiments were conducted in a rectangular wave tank. The dimension of the tank is 32m long, 0.6m width and 2m high with an average water level of 1.5m as shown in Figure 1. A series of manifolds equip the tank to allow a uniform current flow to pass through the tank. Both regular non-breaking and plunging breaking waves could be generated by a computer-controlled flap-type paddle located 2.8m from the fore end of the tank. The tank accommodated a total volume of 28,000 litres of filtered seawater.

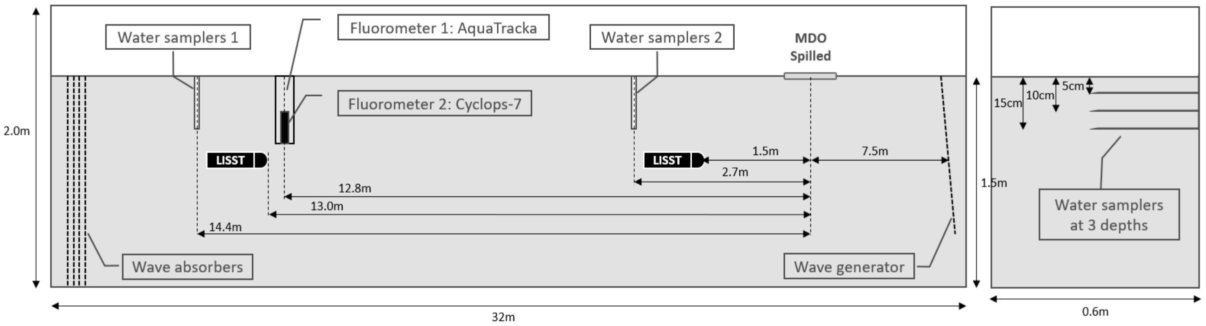

Figure 1. A schematic of the wave tank (not to scale, all values are in meters).

Inside the tank, two fluorometers, a *Cyclops-7* (*Turners Design*) and a *UV AquaTracka* (*Chelsea*) were mounted and submerged 12.8m downstream from the spilled location. Two Laser In-situ Scattering and Transmissometry (LISST) 200X particle size analysers (*Sequoia Scientific*) were installed at 1.5m and 13.0 m downstream, respectively. The frequency of both fluorometers was 10Hz. The LISST sampled every 1.5 second (0.667Hz) over a measurement range of 1.0 to 500 μm. Water samplers were installed at two locations in the tank at three depths (5cm, 10cm and 15cm).

2.2. METHODOLOGY

A fixed amount of oil (approximately 240 – 245mL) was added to the tank by pouring it into a 34cm diameter containment ring located 7.5m downstream on the surface from the wave generator. A uniform current was applied in every test at a flow rate of 230L/min, allowing the average current speed of 0.0042m/s. Having the type of waves selected, the wave generator was switched on, while the containment ring was lifted up right before the arrival of the first wave. The current and wave conditions were maintained for 60 minutes in each test. By the generated current, waves and natural wind force, the spilled oil was subjected to transport processes (spreading and dispersion) as well as evaporation. Wave reflection was minimised by the porous screens installed at the end of the tank away from the wave maker.

Water temperature (°C) and salinity (ppt) were measured at the beginning of each test. Water samples were extracted for chemical analysis at every 5, 15, 30, 45 and 60 minutes. The tank was drained thoroughly and cleaned with absorbing pads and seawater at the completion of each test to remove oil. The specification of the test conditions is shown in Table 1.

Table 1. The wave tank experiment specification.

Testing fuel	*Marine Diesel Oil*
Testing time	60 minutes
In-situ submersible sensor	*Cyclops-7 (Refined), AquaTracka (Refined), LISST-200X*
Waves	Regular waves, Breaking waves
Current speed	0.0042m/s
Chemical analysis	Benzene, Toluene, Ethylbenzene and Xylene (BTEX) Total Petroleum Hydrocarbon (TPH) Gas Chromatography-Mass Spectrometry (GC-MS)

3. RESULTS AND DISCUSSION

3.1. SUBMERSIBLE FLUOROMETER ANALYSIS

While the *UV AquaTracka* sensed MDO in water, the measurements collected by the *Cyclops* remained at a constant level of concentration without having the high peaks sensed during all tests implying that the oil was not detected by this sensor. The following parameters must fit within the correct range to ensure successful detection of the subject oil: minimum detection limit (MDL), a maximum fluorescence wavelength and fluorescence spectral width. The peak of the spectral distribution of the marine diesel oil is at about 400nm [14], which is outside the excitation (290nm) and emission (350nm) intensity wavelength of the *Cyclops*. The MDL of the *AquaTracka* and the *Cyclops* are 0.001ppb and 400 ppb, respectively.

The test results using the *UV AquaTracka* with breaking waves and regular waves are shown in Figure 2. The peaking curves mean higher fluorescent concentration indicating the amount of oil in water that the sensor captured. Breaking waves had a significant impact on the vertical distribution of the plume. They caused the oil to break up into various sized droplets which were distributed at depth in the water column. In contrast, the spilled oil was slowly carried downstream horizontally by the regular waves, yet it stayed mostly on the surface. A dissolved fraction of the oil contributed to an increase in the average oil concentration level.

The average of the current speed in Antarctica is 5 – 10 cm/s varying from 5cm/s further offshore to 25cm/s near the coast [15]-[16]. So, the relative speed between the sensor and a plume would be faster in a real-life situation using a sensor on an AUV. Namely, there are potential risks of losing the plume when travelling at a cruising speed of 1m/s. Therefore, an AUV will need to adaptively adjust its forward speed when detecting an oil plume.

Several variations have been observed between tests with the same experimental conditions. Firstly, the extent of vertical dispersion and persistence varied amongst the three breaking wave tests. That of Set #2 was notably noisier. The background level in Set #3 was initially 33% higher than the other tests. Marginal conditions, such as the intensity and direction of wind, may have developed such variations. Since one oil spill does not involve identical environmental conditions with any other oil spill, each gets to evolve in a different way.

From visual observation, the spilled MDO formed multiple surface slicks which kept adhering and detaching from one another. This will add confusion for an AUV to determine whether it is still inside the plume or just in between patches.

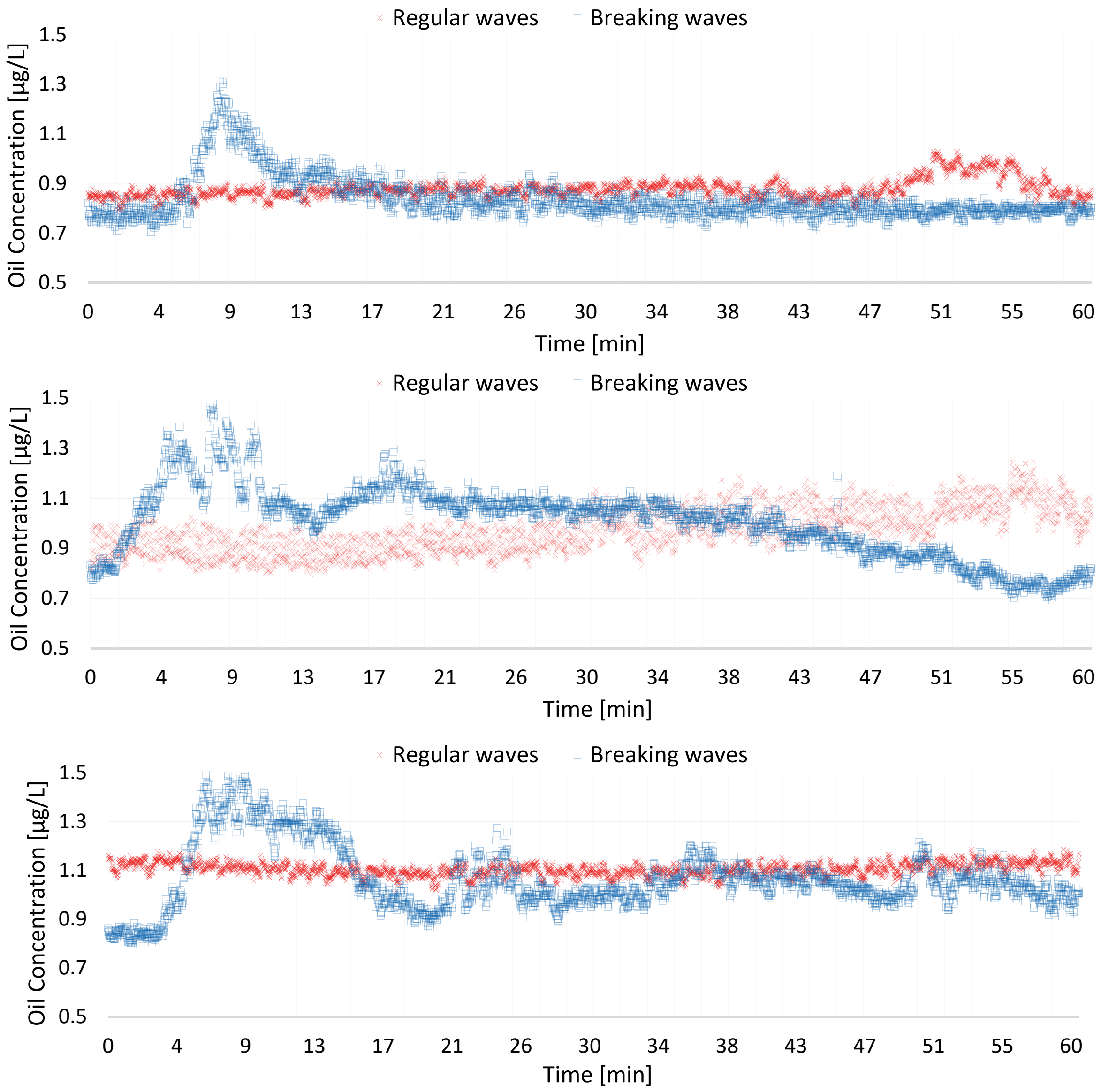

Figure 2. MDO release test sets of two wave conditions; breaking waves and regular waves.

3.2. PARTICLE SIZE ANALYSIS

Two LISST particle size analysers were deployed in the wave tank to monitor the droplet sizes of dispersed MDO during the wave tank experiments. Plots showing the distribution of droplets during breaking and regular wave experiments are shown in Figure 3. It can be seen that both wave types produced subsurface patchy plumes of dispersed oil droplets that moved down the length of the wave tank over the course of the experiment. Plume concentrations peaked 5-10 minutes post oil release, and then droplet concentrations declined, but stayed in patches over the remainder of the experiment as the water returned to pre-oil release conditions.

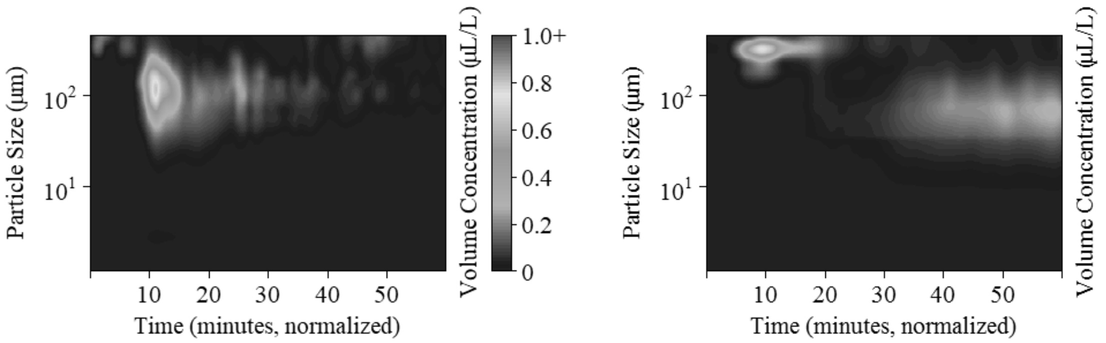

Figure 3. Contour plots showing the volume concentration of MDO droplets in the water column over time as detected by the LISST particle size analyser during breaking wave (left panel) and regular wave (right panel) experiments.

A difference in the droplet breakup was observed between the two wave energies used in the experiments. Droplet size distributions for regular and breaking wave experiments are shown in Figure 4. The higher energy breaking waves produced smaller droplets with a sauter mean diameter of 93 μm at the peak of the plume, while the lower energy regular waves had larger droplets with a sauter mean diameter of 131 μm. Droplet size has implications for the long-term fate and behaviour of MDO spilled in marine environments. Smaller droplets will remain in the water column for a longer period of time and would be more available for weathering processes and biodegradation. The greater surface area to volume ratio of the smaller droplets will also allow for more dissolution of water-soluble hydrocarbons into the water column, which would influence the response of in-situ sensors such as the fluorometers used in this study [17].

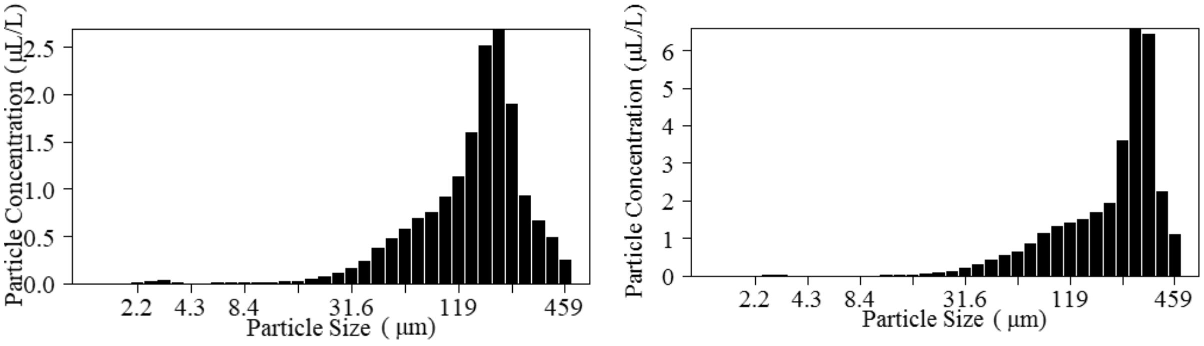

Figure 4. Oil droplet size distribution for breaking wave (*left*) and regular wave (*right*) experiments.

4. CONCLUSION

The risk of oil spills in the Antarctic remains high due to increasing volumes of marine traffic. Utilising an AUV in oil spill response is still at its early stages. Constraints in responding to such a devastating disaster in the Antarctic highlight the advantages of an AUV as an effective means to delineate a three-dimensional oil plume. The results from the fuel spill in experimental study indicated that fluorometers for the AUV must be carefully selected considering the oil type, minimum detection limit and the light intensity range. The potential for a patchy distribution of the dispersed plume also suggested that the AUV adaptive sampling algorithm must account for the discontinuous form of an oil plume.

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