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Detection and quantification of oil under sea ice: The view from below

J.P. Wilkinson [a,*], T. Boyd [b,1], B. Hagen [b], T. Maksym [c], S. Pegau [d], C. Roman [e], H. Singh [c], L. Zabilansky [f]

[a] British Antarctic Survey, UK
[b] Scottish Association for Marine Science, UK
[c] Woods Hole Oceanographic Institution, USA
[d] Oil Spill Recovery Institute, USA
[e] University of Rhode Island, USA
[f] Cold Region Research Laboratory, USA

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ABSTRACT

Traditional measures for detecting oil spills in the open-ocean are both difficult to apply and less effective in ice-covered seas. In view of the increasing levels of commercial activity in the Arctic, there is a growing gap between the potential need to respond to an oil spill in Arctic ice-covered waters and the capability to do so. In particular, there is no robust operational capability to remotely locate oil spilt under or encapsulated within sea ice. To date, most research approaches the problem from on or above the sea ice, and thus they suffer from the need to 'see' through the ice and overlying snow. Here we present results from a large-scale tank experiment which demonstrate the detection of oil beneath sea ice, and the quantification of the oil layer thickness is achievable through the combined use of an upward-looking camera and sonar deployed in the water column below a covering of sea ice. This approach using acoustic and visible measurements from below is simple and effective, and potentially transformative with respect to the operational response to oil spills in the Arctic marine environment. These results open up a new direction of research into oil detection in ice-covered seas, as well as describing a new and important role for underwater vehicles as platforms for oil-detecting sensors under Arctic sea ice.

1. Introduction

The nexus of the reduction of Arctic sea ice, large untapped reserves of oil and gas within the Arctic basin, increasingly competitive Arctic shipping routes, and increasing demand for tourism have increased the need to develop improved techniques to combat potential oil spills in ice-covered waters. This is particularly important in regions subjected to a combination of enhanced sea ice retreat and human activity, such as the Alaskan outer continental shelf where current methods of oil spill response would face increased logistical and technical barriers (National Research Council, 2014). Of specific concern is the possibility of an oil spill occurring within the sea ice cover, with oil trapped beneath, or possibly encapsulated within, the ice. Despite decades of research by governmental organisations, academia and industry, the remote detection of oil under sea ice remains a challenge (Holland-Bartels and Pierce, 2011; National Research Council, 2014, PEW, 2010). Most currently applied sensing methods are deployed from on, or above, the ice surface, and thus there is a requirement that the sensor must 'see' through the sea ice and any overlying snow cover to infer the presence or absence of oil. Furthermore, most surface-based systems are impractical for deployment on young ice, deformed ice, or in the discontinuous ice conditions found within the marginal ice zone (MIZ).

In contrast, oil detection using upward-looking instrumentation from below the sea ice (mounted on underwater vehicles) avoids many of the difficulties of surface-based and airborne techniques. Unmanned underwater vehicles (UUVs) are now capable of routine under ice operation (e.g. Wadhams et al., 2004; Wadhams et al., 2006; Sohn et al., 2008; Jenkins et al., 2010; Williams et al., 2013). With appropriate sensors mounted on an UUV, mapping of oil spilt beneath the ice is now feasible. Advantages of this approach include:

(a) *Independence from weather and sea ice conditions*: UUVs have the potential to operate largely independent of ice thickness, roughness, and other physical properties in a generally quiescent ocean environment free of the effects of weather that may impede an on ice or airborne survey.
(b) *Unimpeded view of the oil:* Most importantly, for oil located below the ice, there is a direct view of the oil from the vehicle. This not only makes detection simpler for many sensors, but it also allows the use of some sensors that cannot be used from above the ice.

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* Corresponding author at: British Antarctic Survey, High Cross Madingley Road, CAMBRIDGE, CB3 0ET, United Kingdom. Tel.: +44 (0)1223 221400; Fax: +44 (0)1223 362616.

E-mail address: jpw28@bas.ac.uk (J.P. Wilkinson).

[1] We dedicate this manuscript to the memory of Tim Boyd who tragically died during its preparation.

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Previous experimental releases of oil underneath sea ice revealed that oil is highly mobile and spreads along the bottom of an ice sheet as a gravity current, preferentially flowing towards regions of thinner ice and accumulating in interconnected depressions under the ice as it spreads (Fingas and Hollebone, 2003; Izumiyama et al., 2002; Wadhams, 1980; Yapa and Weerasuriya, 1997). A numerical model incorporating a regional distribution of ice-bottom morphology (i.e. the heterogeneous, natural distribution of ice thickness) revealed that the oil distribution in contaminated areas will be heterogeneous; some areas will have a light covering of oil whilst others (e.g. hollows) will experience ponding (Wilkinson et al., 2007). An oil detection system should then be able to both determine the presence of oil under sea ice, as well as the thickness of the oil.

Due to high contrast between oil (black) and the ice bottom (white) digital imaging is potentially a simple and highly effective method for mapping the extent of oil located under ice. It has the advantage of being a well-established technology for underwater surveys with a wide variety of systems and image processing and classification software available. It's two-dimensional data allows straightforward delineation of the extent of a spill, although the high data volume may limit real-time data transmission. In most instances, it easy for a human operator to interpret, although variable light levels and turbid water may complicate discrimination of oil from bare ice.

Active acoustics offers the possibility of detecting not only the oil, but also its thickness. Sea ice is a relatively strong reflector of sound because of the acoustic impedance contrast between seawater and the ice bottom. The effectiveness of the ice/water interface in reflecting incoming acoustic energy has enabled the use of sonars to detect and map the underside of sea ice (Wadhams et al., 2006), and has contributed to early awareness of the changing climate of Arctic sea ice (Rothrock et al., 1999). The somewhat weaker scattering from oil due to the smaller acoustic impedance contrast between oil and seawater may be exploited to detect the presence or absence of oil under sea ice.

When the oil is pooled beneath the ice, it forms a multilayer system of seawater, oil, and ice. By detecting discrete reflections from each interface, the thickness of the oil layer may be determined, which when the extent is also mapped (e.g. by sonar or digital imagery), the volume of oil can also be determined.

In this paper we present results from a sea ice tank experiment to evaluate the potential for upward-looking optical and acoustic sensors suitable for deployment on an UUV to detect the presence and thickness of oil spilled under sea ice.

2. Methods

Oil spill experiments under sea ice were carried out at the US Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. Sea ice was grown in the outdoor Geophysical Research Facility tank (18.25 m long, 6.7 m wide, and 2 m deep) over the 2011–12 winter period leading up to experiments on January, 18–20, 2012. Hollows of dimensions of about 2.4 m by 1.2 m (in the along- and across-tank directions, respectively) were produced in the underside of the ice by placing insulating boards over the upper surface of the growing ice so that these areas were slightly thinner than the surrounding ice. Alaska North Slope (ANS) crude oil was injected into these pockets, where it pooled. A sensor suite including cameras, sonars, and a laser system was mounted on a trolley travelling on rails along the tank bottom (Fig. 1).

The results presented here are from observations of a sequence of two oil injections into a single ice hollow using the sonar and camera systems. The experimental sequence was as follows:

(1) The ice underside was mapped (via sonar) to clearly distinguish between the hollows and flat regions,
(2) The trolley was parked under the central region of the hollow,
(3) Oil was injected into the hollow and its spread was observed, and
(4) A second measure of oil was injected into the same hollow.

Additional observations were made to map the spill by moving the trolley beneath the hollow. These observations are qualitatively similar to the stationary measurements but of lower quality as jittering of the trolley as it moved along the rails affected the sonar signal, and are thus not presented here. The characteristics of the experiment are summarised in Table 1.

2.1. Delivery of oil

The oil was delivered from a 20 litre pressurised canister-based system mounted on the surface of the ice (Fig. 2). An air compressor forced oil from the canister through a hose that ran through a PVC pipe frozen into the ice at the edge of the hollow and then to the base of the ice in the hollow. This allowed accurate determination of the volume of oil released whilst ensuring stable delivery of the oil to the ice underside and preventing spread of the oil beyond the edge of the hollow of flow back out of the hole and onto the ice. Details of the experimental setup are given in Table 1.

2.2. Instrumentation

2.2.1. Camera system

Two upward-looking Prosilica high dynamic range cameras (one colour, and one black and white) were mounted on the sensor trolley to provide overlapping views of the ice bottom. These cameras are designed for extremely low-contrast applications typical of underwater (and under ice) applications. These colour-calibrated cameras have a 12-bit dynamic range with a resolution of 1380 × 1024 pixels and a field of view (FOV) of 39.5° horizontally and 30.5° vertically.

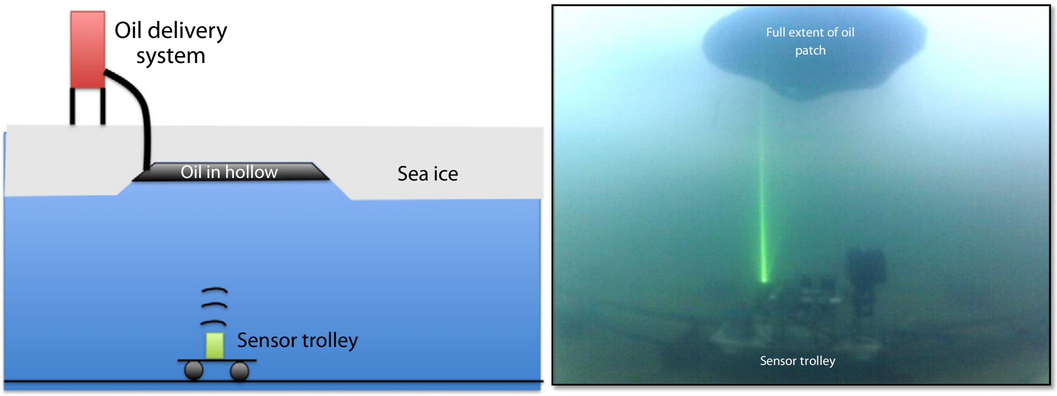

Fig. 1. Left: Cartoon showing the experimental layout. The sensor trolley was located on tracks at the tank bottom. All sensors looked up towards the oil that was located just over a metre above. Right: Under sea ice oil slick and sensor trolley as viewed from the side using an underwater, wide angle "Go-Pro" camera. The green light is from a sheet laser system that accompanied the sonar and cameras on the trolley.