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Modelling acoustic propagation beneath Antarctic sea ice using measured environmental parameters

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ABSTRACT

Autonomous underwater vehicles are improving and expanding in situ observations of sea ice for the validation of satellite remote sensing and climate models. Missions under sea ice, particularly over large distances (up to 100 km) away from the immediate vicinity of a ship or base, require accurate acoustic communication for monitoring, emergency response and some navigation systems. We investigate the propagation of acoustic signals in the Antarctic seasonal ice zone using the BELLHOP model, examining the influence of ocean and sea ice properties. We processed available observations from around Antarctica to generate input variables such as sound speed, surface reflection coefficient (R) and roughness parameters. The results show that changes in the sound speed profile make the most significant difference to the propagation of the direct path signal. The inclusion of the surface reflected signals from a flat ice surface was found to greatly decrease the transmission loss with range. When ice roughness was added, the transmission loss increased with roughness, in a manner similar to the direct path transmission loss results. The conclusions of this work are that: (1) the accuracy of acoustic modelling in this environment is greatly increased by using realistic sound speed data; (2) a risk averse ranging model would use only the direct path signal transmission; and (3) in a flat ice scenario, much greater ranges can be achieved if the surface reflected transmission paths are included. As autonomous missions under sea ice increase in scale and complexity, it will be increasingly important for operational procedures to include effective modelling of acoustic propagation with representative environmental data.

1. Introduction

Sea ice is a key component of the global climate system that controls ocean-atmosphere exchange, driving the meridional overturning circulation and influencing Southern Ocean marine ecosystems (Wadhams, 2009; Massom and Stammerjohn, 2010). Despite its local and global importance, the collection of in situ sea ice data has been restricted by its remote location and harsh environmental conditions, limiting the validation of climate models and remote sensing products. As global political emphasis remains on determining the appropriate response to changes in climate, the need to understand these key polar areas of the world's oceans increases. While satellite technology has allowed remote sensing of Antarctic sea ice extents (Comiso and Nishio, 2008) and is advancing capability in volumetric measurements (Kurtz and Markus, 2012), Antarctic sea-ice thickness remains greatly undersampled (Lemke et al., 2007; Williams et al., 2014). For satellite and aircraft-based measurement techniques to be used reliably, there needs to be greater in situ observations for calibration and validation.

One method for estimating ice thickness for calibration/validation efforts is to create a map of the ice draft, which can be combined with surface measurements to calculate volume (Williams et al., 2013). The best sensor to make these maps is an upward looking multibeam sonar. An under ice capable Autonomous Underwater Vehicle (AUV) is the safest and most repeatable way to deploy this instrument, with geo-referenced coordinates, under the Antarctic ice. However, AUV missions in polar environments are challenging, in particular over the 10–100 km ranges desired for effective comparison with satellite data and model grid sizes. The inability of the AUV to surface during under ice missions means there is a greater reliance upon the underwater acoustic

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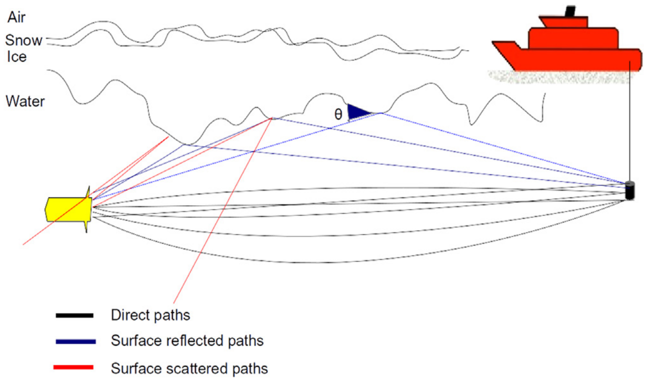

Fig. 1. Schematic of AUV operation under ice, showing sea ice, AUV, ship, acoustic receiver, and propagation paths. The grazing angle (θ) is shown.

communication link between the operator and AUV (Kukulya et al., 2010; Lewis et al., 2012) than in equivalent open water operations. The variability of effective communication due to environmental conditions is often unknown, creating uncertainty in the reliability of acoustic systems. For an AUV to be deployed with confidence over long distances, it is necessary to obtain a comprehensive understanding of the underwater acoustic environment in order to predict the effectiveness of the proposed acoustic equipment.

There are several ways in which acoustic signals can propagate under sea ice is depicted in Fig. 1. The 'direct path' is made up of the combination of any signals that propagate between the source and receiver without interacting with the surface or bottom. Modelling that uses a completely unreflective surface and bottom produces results that isolate these direct path signals. Hereinafter, when the surface reflected signals are also included in propagation modelling, the term 'multipath' is used. When an acoustic signal interacts with a surface it can undergo changes in magnitude, phase, and propagation direction. Primarily this is through the reflection of the signal back into the water. This reflection can occur both at the interface of a surface with the water column or within different structures within the surface itself. For example, upon interaction with an ice surface, some of the acoustic signal may reflect straight back into the water and part of the signal may propagate through the ice and then reflect back on interaction with the ice-air interface. The reflection coefficient (R) is a descriptor for modelling the magnitude and phase change of a signal with a given approach angle as it interacts with a surface. The surface described by R can be a complex multi-layered structure and hence takes into account both primary and secondary transmission and reflection. Here we present a realistic Antarctic acoustic environment model and examine how sound propagates through it. This paper examines the factors that affect under ice acoustic propagation and the subsequent development of a model to predict signal detection reliability. This was achieved through identification and analysis of the core physical elements of the Antarctic sea ice environment (Data and Methods) and propagation simulations based on their variation (Results). Modelling was undertaken using the BELLHOP (Porter, 2011) program, a Fortran acoustic beam code that is part of the Acoustics Toolbox (Duncan, 2006).

2. Data and methods

2.1. Physical oceanography of the Antarctic seasonal ice zone

The primary defining characteristic of the Southern Ocean is the Antarctic Circumpolar Current (ACC), as described in Orsi (1995) and references therein. Its major water mass is Circumpolar Deep Water (CDW), whose origin is North Atlantic Deep Water from the northern hemisphere. The centre of the ACC, where cold Antarctic surface waters meets warmer waters from north, is known as the Polar Front, or Antarctic Convergence, and the latitude of this boundary changes seasonally. Our study region is focused on the upper layer of the ocean south of the Polar Front over the Antarctic Continental Slope as described in Williams et al. (2008), Williams et al. (2011). Vertically, the two key water masses in the upper layer of this region are Antarctic Surface Water (AASW) and CDW. The region in which there is a change in density between two water masses is called a pycnocline and this is driven by a combination of gradients in salinity and temperature, independently called haloclines and thermoclines, respectively. Beginning in winter, the AASW is comprised of a Winter Mixed Layer (WML) that results from convection driven by atmospheric cooling and the input of salt rejected once the surface freezes to form sea ice. The boundary between the AASW (which in wintertime is essentially the WML), and the underlying CDW, is the Permanent Pycnoline (PP). The WML/PP gets deeper when moving from offshore into the coastal regions where sea ice production is strongest, across a region over the continental slope referred to as the Antarctic Slope Front.

In summer, a new Seasonal Pycnocline (SP), sitting above the PP, results as a summer mixed layer (SML) forms in the upper part of the AASW, over the remnant WML (also called Winter Water or the Tmin layer). In contrast to the WML, the SML forms due to the freshening and warming at the surface in the sea ice melt season. The depth of both pyncoclines, and the average water mass properties of the respective winter and summer mixed layer above them, is seasonally and spatially variable in relation to the patterns of sea ice growth and melt.

2.2. Acoustic modelling

The aim of this simulation is to establish the impacts of large-scale variability in water and ice parameters on acoustic signal propagation. The BELLHOP model is used to provide transmission loss estimates with range and depth for a given set of environmental conditions. To model acoustic propagation in Antarctic sea ice covered waters, the key environmental conditions considered were the water properties and the reflective and roughness features of the underside of the sea ice. BELLHOP was selected for use as it provides a well-tested and stable code base for acoustic beam modelling that enables fast simulation at high frequency and multi-kilometre ranges. The Bounce program, also a part of the Acoustics Toolbox, was used to calculate the reflection coefficient with angle, based on sets of acoustic media properties determined from ice cores. For input to BELLHOP, the water properties needed to be represented as sound speed, a combination of salinity, pressure and temperature. The reflective properties of the ice surface were input to BELLHOP as a generalised reflection coefficient. This coefficient can be calculated from the salinity, density, and temperature profiles returned from the ice core data. When examining surface roughness, BELLHOP was only designed to consider a specific surface realisation. The challenge with representing the sea-ice surface was then to create a method for statistically generalising the surface roughness based on measured results, such that a Monte Carlo simulation could be run for a set of generated profiles.

Table 1 shows the data flow between environmental variables and the processed output, indicating the section of this paper or external reference where the methods for each transformation can be found. The physical location of field data used is shown in Fig. 2.