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THE INCREASING PREVALENCE OF HIGH FREQUENCY INTERNAL WAVES IN AN ARCTIC OCEAN WITH DECLINING SEA ICE COVER

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ABSTRACT

Receding seasonal sea ice extent over the Arctic Ocean is increasing access to what was a largely inaccessible region. At lower latitudes the complex vertical current structure associated with large amplitude, high frequency non-linear internal waves, sometimes referred to as solitons, present a significant challenge to the safe engineering design and operation of offshore infrastructure. In this paper we examine the prevalence this type of internal wave in the Arctic Ocean. To do so we will draw on both *in situ* and remotely sensed oceanographic data. This will be combined with state-of-the-art numerical modelling to demonstrate a link between the geographical occurrence of these waves and the tide. Whilst the link implies that these features are geographically limited, it is also likely that the geographical limits will change with declining sea ice cover. These results will then be used to provide a road map towards a methodology for forecasting the prevalence of these phenomena in a future Arctic Ocean.

Keywords: Arctic Ocean, solitary waves, internal tide.

INTRODUCTION

The Arctic Ocean differs from other oceans globally in a number of respects, the most conspicuous of which is the presence of sea ice over large areas of its surface. However, the decline in seasonal sea ice extent and volume in recent years is well documented, with more recent evidence for decline in winter sea ice extent. These changes are facilitating the development of sea routes and the possibility of offshore infrastructure. The changes are partly driven by the increasing geographical influence of North Atlantic water entering the Arctic Ocean to the north of Norway and Svalbard. This influence includes a major regime shift in winter sea ice coverage in the Barents Sea [1] and changes in water column stratification which are impacting on local sea ice coverage in the eastern Eurasian basin of the Arctic Ocean [2].

The declining sea ice extent has also facilitated an expansion in both the availability and geographical extent of both *in situ* and remotely sensed oceanographic data from the region. In this paper we will focus on evidence of the existence of high frequency, large amplitude non-linear internal waves (NIW) of relevance to offshore engineering in this region. The complex, rapidly varying vertical current profiles associated with NIWs must be accounted for in a wide range of offshore engineering applications [3].

Stratification is widespread across the Arctic including the main continental shelf regions. Whilst in much of the global ocean the strength of stratification is dominated by changes in temperature with depth, in the Arctic stratification is dominated by changes in salinity which are sufficiently large to support inverted temperature structures. Typically, colder and fresher water is found overlying warmer saltier water of Atlantic origin. Furthermore stratification is found throughout the year.

Conventional oceanographic measurements of sufficient resolution to resolve NIWs in the Arctic are extremely rare, both spatially and temporally. Here we examine evidence derived from remote sensing, which we demonstrate to be consistent with recent advances in our understanding of the generation mechanisms of NIWs in the Arctic Ocean. The applicability of

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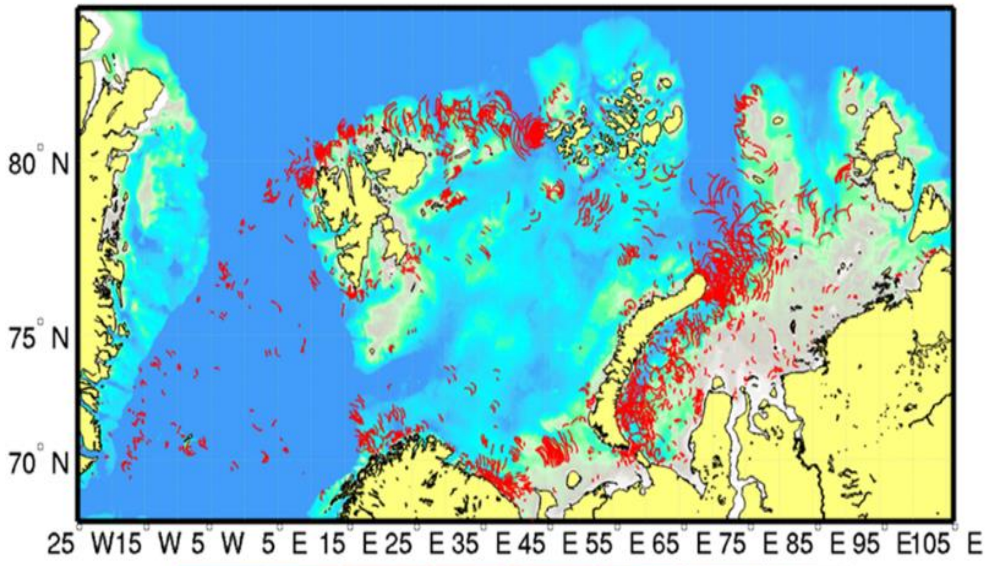

Figure 1: Map showing the Eastern Arctic Ocean, together with Svalbard and the northern section of the Fram Strait. Water depth (m) is contoured with dark blue indicating depths > 500m, and lighter blues, continental shelf regions. The spatial distribution of NIWs over the eastern Arctic Ocean is shown as a series of wave fronts (red lines). It is derived from spaceborne Envisat Advanced SAR images acquired between June and September 2007.

the body force calculation approach to the calculation of baroclinic tidal energy conversion (eg. [4]), and hence the estimation of the risk of NIWs, is considered. The results will then be used to assess the likely present day geographic extent of NIWs in the region and to map-out a methodology for the prediction of NIWs in a future Arctic Ocean.

1.1 Evidence from space

High-resolution spaceborne synthetic aperture radar (SAR) images acquired by Envisat Advanced SAR in June-September 2007 are used to map NIW over the Eastern Arctic Ocean. The summer of 2007 is noted for the unusually low levels of sea ice recorded in the region of interest. SAR observations have been recently proved to be effective for inferring the detailed 2-D structure and kinematics of tidally-generated NIWs over the various Arctic Ocean regions [5,6]. The data are available from the European Space Agency rolling archive. SAR images were taken in Wide Swath Mode and Image Mode Precise with spatial resolution of 150 and 30 m, respectively. Pre-processing of SAR images and identification of surface signatures of NIWs was performed using the MATLAB-based code INTERWAVE to calibrate and de-trend the SAR data, and extract NIW parameters and background wind conditions. The methodology of NIWs identification is described and applied in [7, 8]. Analysis of about 1400 ENVISAT Advanced SAR images helped to identify 2788 NIWs packets over the study region. The leading fronts of all detected NIWs trains over the analysis period are shown in figure 1 for the eastern Arctic Ocean.

Figure 1 shows the primary regions of NIW occurrence over the area of interest. They are predominantly found close to the shelf break region, and over the narrow continental shelf, to the north of Svalbard. The shelf break region to the west of Franz-Josef Land is also found to be an area of significant NIW activity. There is also evidence over the shelf break and outer shelf region to the north of Norway, with further hot spots near the Kola peninsula in the southern Barents Sea. Further to the East they are found in the Kara Sea, in the vicinity of Cape Zhelaniya, over the Novaya Zemlya Trough and in the Kara Gates Strait, a known region for observing high-amplitude internal tidal waves [9].

1.2 The role of the tide

NIW are widely reported across much of the tropical and temperate ocean [10] and are a result from the interaction of the stratified flow with steep topography [11]. However, much of the Arctic Ocean lies poleward of the critical latitude for the principle semi-diurnal tide. This essentially means that the radiation pathway of tidal energy to dissipation, via internal waves, is significantly different at polar latitudes from that identified equatorward of the critical latitude. Specifically, a recent study has identified the formation of high-frequency non-linear wave trains (NIW) as the key mechanism for the conversion and dissipation of tidal energy poleward of the critical latitude [12]. This result implies that regions of significant dissipation of tidal energy (away from shallow regions where the dissipation due to the bottom boundary turbulence is likely to dominate) will have a high probability of the presence of NIW. As such we propose that a first order estimate of the geographical distribution of NIWs can be obtained by mapping the tidal dissipation based on satellite altimetry data.

The dissipation of tidal energy, D, was calculated from tidal elevations and transports from TPXO8 [13] following [14]:

$$D=W-\nabla\cdot P \qquad (1)$$

Here, W is the work done by the tide-generating force and P is the energy flux vector, respectively given by

$$W=g\rho\langle U\cdot\nabla(\eta_{EQ}+\eta_{SAL})\rangle \qquad (2)$$

and

$$P= g\rho\langle U\eta\rangle \qquad (3),$$

where the angled brackets indicate time-averages over a tidal period; g is gravity; ρ is sea-water density; U is the tidal transport vector; η is the tidal amplitude; and η_{EQ} and η_{SAL} are the equilibrium tide and self-attraction respectively.

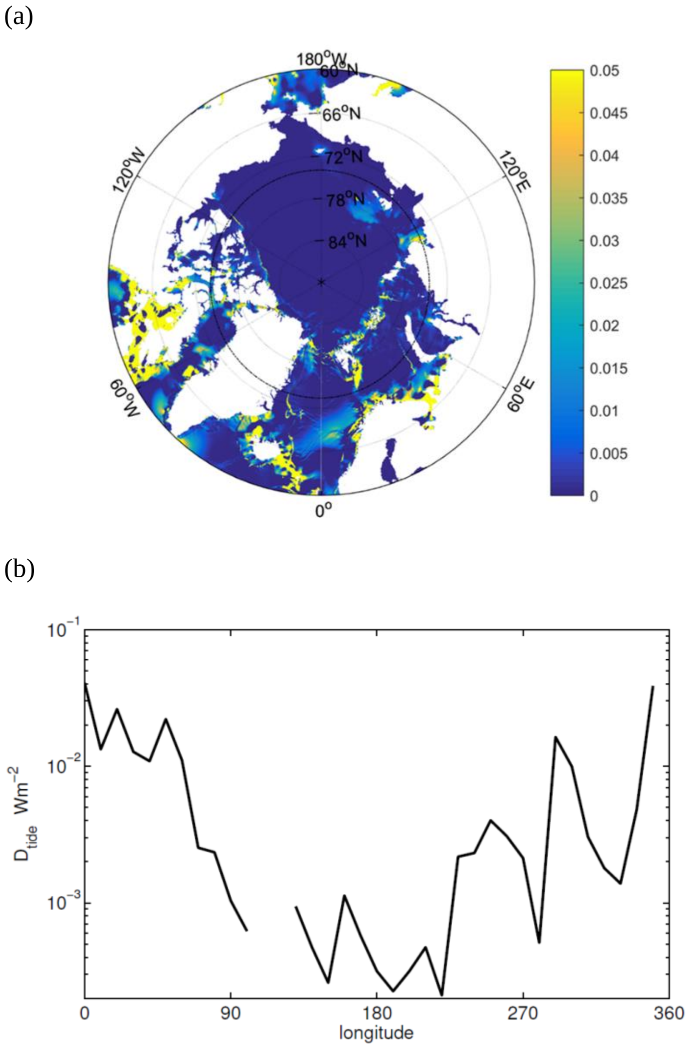

Figure 2: The geographical distribution of the dissipation of tidal energy across the Arctic Ocean. (a) A map of the Arctic on which the dissipation of tidal energy is contoured. (b) The average dissipation of tidal energy over the continental shelf break moving anti-clockwise around the Arctic Ocean.

Figure 2 shows the geographical distribution (a), together with the shelf break integrated values (b), of the rate of conversion of tidal energy. The estimates of the dissipation of tidal energy have previously been shown to be consistent with independent measurements of turbulent dissipation [15]. It shows significant levels of tidal energy dissipation in the vicinity of the Svalbard, Franz Joseph Land and the Kara Sea, consistent with the identification of the presence of significant NIWs as evident in figure 1. It also implies significant NIW activity along the shelf break to the north of the Canadian Archipelago.

Limited measurements of water column structure and flow reveal the vertical structure of the NIWs evident in the fig 1 and implied by the enhanced dissipation rates shown in figure 2. Kurkina & Talipova [17] show NIWs of amplitude 10 – 20 m and period about 20 mins over the Spitsbergen Bank to the south of Svalbard. They observe these NIW to be coincide with current speeds reaching 50 cms^{-1} and maximum vertical current shears of the thermocline of $4x10^{-4}$ s^{-1}. Morozov & Pisarev [16] report measurements further to the north (80 – 81°N), in the Franz-Victoria Trough to the east of Svalbard, which show tidally modulated NIWs with amplitudes of up to 40 m and wavelengths of 4 to 6 km. They find these NIWs within a depth range of 200-500m with the NIWs propagating from the slope and the amplitudes decreasing significantly as they move over a flatter sea bed. Kurkina & Talipova [17] report NIWs of 50m in this region. Vlasenko et al [18] present data from a location near Bear Island, close to the critical latitude, which show NIWs of amplitude 40m and significant velocity shear. This limited evidence suggests that they have characteristics very similar to those observed elsewhere globally.

SUMMARY AND DISCUSSION

We have presented remote sensing evidence of significant NIW activity across continental shelf break regions of the eastern Arctic Ocean. These NIWs are consistent with observed estimates of the rate of conversion of tidal energy, implying that they are of tidal origin. However much of the Arctic Ocean is poleward of the critical latitude at which the period of the semidiurnal tide matches the local inertial period and so the generation of freely propagating linear internal tides is not permitted. As such a standard method for the assessment of the likelihood of NIWs applied equatorward of the critical latitude, the body force calculation for baroclinic tidal energy conversion (which is based on linear theory, eg. [4]), is not valid for much of the Arctic Ocean.

The results presented here suggest that a first order risk assessment of the probability of NIWs in particular shelf break regions can be obtained from basin wide estimates of the rate of conversion of barotropic tidal energy based on altimeter measurements (e.g. figure 2). [12] and [18] show that the characteristics of the NIW are dependent on the steepness of the local topography, the strength of the tide and the local stratification.

The location of much of the Arctic Ocean poleward of the critical latitude, for the semidiurnal tide, implies a subtly different tidal energy pathway to internal waves and dissipation and hence probability of the generation of, when compared with regions equatorward of the critical latitude. An outstanding question which therefore remains to be answered is whether that pathway poleward of the critical latitude increases the probability of the generation of large NIWs, when compared to identical conditions equatorward of the critical latitude. The subsequent fate of the NIWs is likely similar to those equatorward of the critical latitude. For those waves travelling over shoaling topography there are a number of different scenarios which are determined by the wave amplitude and the bottom inclination [18]. These involve the local breaking and disintegration of large amplitude NIWs, although smaller amplitude NIWs can penetrate some distance onto the continental shelf.

In recent years there is evidence of the increasing influence of the (warmer) inflowing water from the Atlantic Ocean on stratification and sea ice cover [1]. This influence has now extended as far as the eastern Eurasian Basin of the Arctic Ocean [2]. A second outstanding question thus concerns the impact of the changing stratification on the geographic extent of the NIW generation zones.

Whilst much of the Arctic Ocean remains logistically challenging for the type of oceanographic measurements required to fully characterize the risk associated with NIWs we propose that the combination of remote sensing coupled with inverse tidal modelling, as outlined here, together with targeted field observations coupled with a non-hydrostatic model sensitivity study, of the type reported by [12], would be sufficient to provide a robust first order map of the risk of NIW in the Arctic Ocean.

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