Modeling Near-Inertial Wave Response in a Seasonally Ice-Free Arctic: Differences from a Mid-Latitude Wave Field

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James Morison and John Guthrie
Polar Science Center, APL-UW
1013 NE 40th St.
Seattle, WA 98105
phone: (206) 543 1394 fax: (206) 616 3142 email: morison@apl.washington.edu

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Major Goals

This grant grows out of our prior work investigating the decadal-scale changes in Arctic Ocean internal wave energy as part of the NSF-funded North Pole Environmental Observatory (NPEO) and the ONR Core-funded Seasonal Ice Zone Reconnaissance Surveys (SIZRS). By dropping eXpendable Current Profilers (XCP) to measure shear at hydrographic stations, NPEO has aimed to track the increase in internal wave energy and associated mixing as the sea ice cover has thinned and become less extensive. We have been surprised to find that Arctic Ocean internal wave energy and deep mixing are essentially the same now as they were 30 years ago [*Guthrie et al.*, 2013]. Moreover, the lowest internal wave energies continue to be found in the Canada Basin where declines in sea ice volume have arguably been the greatest. We think that this is because the strong near-surface stratification associated with the accumulation of freshwater enhances the dissipation of internal wave energy in the under ice boundary layer [*Morison et al.*, 1985]. It seems likely that as long as any ice is present, under-ice dissipation will work to keep internal wave energy low.

The extension of this idea is that we may see dramatically increased internal wave energy in the deep Arctic Ocean when the ice cover is completely gone, but results from SIZRS suggest even this isn't true. SIZRS gives the opportunity to compare ice-covered and ice-free internal wave energy by performing summertime monthly sections across the Seasonal Ice Zone (SIZ) of the Beaufort Sea using Aircraft eXpendable CTDs (AXCTD) and Aircraft eXpendable Current Profilers (AXCP) dropped from US Coast Guard C-130 airplanes. We have been conducting these surveys from 2012 to the present, typically from 72°N to 76-80°N along 150°W and 140°W. AXCP profiles made at southern stations late in the season when the ocean is ice-free show negligible increase in internal wave shear energy and mixing compared to stations made early in the season when ice cover is in place. These results, and others, suggest that there must be other factors besides ice cover limiting internal wave energy.

Our primary objective has been to understand the forcing of internal waves in the Arctic Ocean with the underlying aim of revealing why, even in spite of decreasing sea ice cover, Arctic Ocean internal wave energies and associated mixing are orders of magnitude lower than those in mid-latitude oceans. Rather than focus on the effect of sea ice on modulating the internal wave response in the Arctic Ocean, we have focused on hydrographic differences that could result in a substantially different internal wavefield when compared to the mid-latitudes. We have explored the role of β, the change in Coriolis parameter with latitude, in the Arctic Ocean. β is a critical parameter in causing the spatial variability in mixed layer inertial motion that produces vertical propagation of near-inertial wave energy downward from the surface. Another factor is strong near-surface stratification. Melting sea ice in summer results in extremely strong near-surface stratification and very shallow mixed layers, a factor that previous studies have shown to limit the wind forcing of internal waves. This is perhaps explained by the preferential distribution of energy into low modes for deeper mixed layers.

Experimental Framework

We have adapted a model of mid-latitude internal wave generation to explore the role of diminished β and shallow mixed layers in causing reduced generation of internal waves in the Arctic Ocean and compared the results to our ongoing SIZRS observations and the SODA observations of others. We have modeled near-inertial wave propagation through the stratified ocean by recreating the linear internal wave model developed by *Zervakis and Levine* [1995] that was previously used to accurately model the oceanic response in the ONR-sponsored Ocean Storms experiment.

Approach

With the model operational, a number of sensitivity studies were performed, to calculate the effects of β, depth, stratification, storm size, and direction of storm propagation on the internal wave field. These sensitivity tests were performed under idealized conditions, as this allowed a clearer interpretation of how important each parameter can be. Using a typical summer hydrographic profile from the Beaufort Sea, we can modify one important parameter at a time, disentangling their individual contribution to the wavefield. For identical hydrography, mixed layer depth and storm characteristics, we run the model for Beaufort Sea β versus other latitudes and see how the internal wave field is affected. Likewise, keeping β fixed allows us to examine the importance of mixed layer depth in the evolution of the internal wave field. The various contributions of individual parameters are then determined and quantified.

Accomplishments

Dr. Guthrie's and Dr. Morison's paper [*Guthrie and Morison*, 2021] captures the essential results of this grant. The work combines the SODA modeling with AXCP and AXCTD measurements from the ONR-funded SIZRS project. The SIZRS concurrent AXCTD and AXCP profiles from 2013-2018 are used to estimate internal wave energy and turbulent mixing from 50 – 300 m. We then separate them into ice-free (23) and ice-covered profiles (43) based on a 15% sea ice extent criterion. The main points of the paper are as follows:

- In the Canada Basin, internal wave energy and mixing from shear measurements are similar despite the presence or absence of sea ice

- Model results show that low values of Beta and shallow mixed layers result in a significant decrease in near-inertial internal wave energy
- Even in a future hypothetically ice-free Arctic Ocean, the effect of low Beta could inhibit near-inertial internal wave generation

Details of the model configuration are in the manuscript and available to the broader scientific community. Work is ongoing on a companion manuscript focusing on how regional stratification differences might affect near-inertial wave propagation in different basins of the Arctic Ocean. The role of temporal evolution in stratification at stations with long time series will also be explored.

Dr. Guthrie participated in the SODA Process Cruise onboard the R/V Sikuliaq in September 2018 and stemming from observations on the cruise is also one of the co-authors on an article in *Nature Communications* [*MacKinnon et al.*, 2021] titled "A warm jet in a cold ocean: subduction and heat storage in the new Arctic".

References

Guthrie, J. D., and J. H. Morison (2021), Not Just Sea Ice: Other Factors Important to Near-inertial Wave Generation in the Arctic Ocean, *Geophysical Research Letters*, *48*(3), e2020GL090508, doi:https://doi.org/10.1029/2020GL090508.

Guthrie, J. D., J. H. Morison, and I. Fer (2013), Revisiting internal waves and mixing in the Arctic Ocean, *Journal of Geophysical Research: Oceans*, *118*(8), 3966-3977, doi:10.1002/jgrc.20294.

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Zervakis, V., and M. D. Levine (1995), Near-Inertial Energy Propagation from the Mixed Layer: Theoretical Considerations, *Journal of Physical Oceanography*, *25*(11), 2872-2889, doi:10.1175/1520-0485(1995)025<2872:NIEPFT>2.0.CO;2.

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Our post-doc, John Guthrie, has carried out the bulk of this research. He has completed a paper [*Guthrie and Morison*, 2021] on the modeling work and working on a companion paper using the same modeling approach. He has also participated in the SODA process cruise and all the SODA meetings.

Results Dissemination:

Guthrie, J. D., and J. H. Morison (2021), Not Just Sea Ice: Other Factors Important to Near-inertial Wave Generation in the Arctic Ocean, *Geophysical Research Letters*, *48*(3), e2020GL090508, doi:https://doi.org/10.1029/2020GL090508.

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James Morison

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University of Washington – Applied Physics Laboratory
4333 Brooklyn Avenue NE
Seattle, WA 98105-6613

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14. ABSTRACT
The purpose of this grant has been to determine why internal wave energy, and by extension, the deep background mixing associated with it, are so low in the Arctic Ocean. Low internal wave energy has been thought to be solely due to the presence of the ice cover, which may both reduce forcing of waves and their dissipation. It has been speculated that as sea ice disappears we will see large increases in internal wave energy. However, analysis of Seasonal Ice Zone Reconnaissance Survey (SIZRS) Aircraft Expendable Current Profiler (AXCP) data for ice-covered and ice-free conditions shows this is not true. Rather our modeling study using an adaptation of a mid-latitude internal wave generation model indicates that internal wave energy in the Arctic Ocean is low largely because the low beta (change in Coriolis parameter with latitude) and high near-surface stratification there inhibit the vertical propagation of near-inertial internal wave energy. These effects can account for the majority of energy reduction compared to lower latitudes (Guthrie and Morison, 2021).

15. SUBJECT TERMS
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