Early Student Support for the Study of Inertial Motions in the Arctic Ocean

Luc Rainville
Applied Physics Laboratory
1013 NE 40th Street
Seattle, WA 98105
phone: (206) 685-4058, fax: (206) 543-6785
Email address: rainville@apl.washington.edu

Grant Number: N00014-11-1-0454

LONG-TERM GOALS

The decreasing trend in minimum Arctic Ocean sea-ice extent has been a topic of concern with far reaching effects. At least seasonally, there are good reasons to believe that the Arctic Ocean will become more dynamically active, with larger surface waves, stronger lateral fronts, and more intense internal wave activity. Particularly in the marginal ice zone, the processes controlling the response of the ocean to wind forcing span a wide range of spatial and temporal scales. In this project, we use a combination of data from existing instruments and simple theoretical models to study the internal wave field in the Western Arctic Ocean; to determine spatial and temporal variations in wave energy and investigate feedback processes between propagating internal waves and ocean stratification.

OBJECTIVES

This project supported Hayley Dosser, who completed her PhD in Oceanography at the University of Washington in September 2015. Her work involved a combination of analysis of existing observational data from drifting Ice-Tethered Profiler instruments and numerical modeling based on internal wave theory. The focus of her project was to quantify internal wave energy in the Western Arctic Ocean over the last decade, and determine how internal wave propagation affected the ultimate fate of this energy. The relationships between the internal wave field and the atmospheric forcing, the sea-ice cover, and the ocean stratification were investigated.

Near-inertial internal waves, which carry most of the energy in the internal wave field, are associated with vertical isopycnal displacements and vertical shear, and, as at low latitudes, can break and significantly mix the water column. The first goal of this work was to use the Ice-Tethered Profiler dataset to quantify a seasonal cycle and interannual trend in near-inertial wave energy, investigate spatial patterns in the Canada Basin, and connect observed variations to changes in sea-ice properties.

As near-inertial waves propagate downward in the Canada Basin, transporting energy through the water column, they encounter strong stratification in the upper halocline (50-200m), and a thermohaline staircase at the top of the Atlantic Water (200-400 m). The second goal of this work was to investigate interactions between the waves and this complex stratification, which has the potential to cause wave instability and mixing. Spatial and temporal variability of the near-inertial wave field are expected to cause an inhomogeneous distribution of vertical diffusivity. This directly impacts how temperature, salinity, and other properties (tracers, nutrients, etc.) evolve in the upper Arctic Ocean (Rainville et al. 2011).

APPROACH

Dr. Dosser's project focused primarily on analyzing salinity and temperature profiles from 27 Ice-Tethered Profilers (ITPs) drifting in the Beaufort Gyre region during the years 2005 to 2014 to quantify the near-inertial internal wave field. Previous observations of internal waves in the Arctic, typically from ships or ice camps, have been spatially and temporally limited, lacking year-round or multi-year time series. The ITPs have collected year-round time series for the last decade, providing an excellent record of the spatial and temporal evolution of internal waves in the region in the upper 750 m of the water column. Information about the near-inertial wave field in the upper 200m was further used to constrain the parameter space investigated with the numerical model, providing theoretical predictions for the propagation and stability of waves within the observed stratification profiles.

WORK COMPLETED

The Ice-Tethered Profiler dataset provides the first decade-long record, with broad spatial coverage, for the near-inertial internal wave field in the Arctic Ocean. The data used were collected by 27 ITPs that drifted in the Canada Basin between Fall 2005 and Fall 2014, completing a total of just over 30,000 (profiles (Figure 1).

Due to poor time resolution and irregular sampling, near-inertial frequency signals are only marginally resolved by ITPs. The initial part of this project demonstrates that by using careful fitting of ideal sinusoidal waves to the measured isopycnal displacements, estimates of the slowly varying amplitude of the near-inertial waves can be obtained (Figure 2). Importantly, an error analysis was carried out to estimate the associated uncertainty in this technique, including the impacts of instrument sampling and possible aliasing of the internal wave continuum. More details on the technique and initial results can be found in Dosser et al. (2014) and Dosser and Rainville (2015).

As an example, internal wave amplitudes estimated from ITP6 for an entire year (2006-2007) are shown in Figure 3. There is significant wave activity at all depths, but particularly just below the Atlantic Water maximum (near 400m) and very near the surface. Periods of high amplitude waves are observed every few weeks, and are distributed fairly evenly over all latitudes and longitudes traversed by the ITP (not shown). There is a significant seasonal cycle associated with the scaled vertical displacement amplitude of the waves at all depths.

RESULTS

This work demonstrated that it is possible to use the Ice-Tethered Profiler dataset and the complex demodulation technique to quantify the near-inertial internal wave field at all depths, including in regions of complex stratification such as the double-diffusive staircase. This allowed for an assessment of the near-inertial wave field spanning nearly 10 years in the Canada Basin (Figure 4a) - the first record of such length for internal waves in the Arctic Ocean.

As a result of the drift of the sea ice in which the ITPs are anchored, measurements of the near-inertial internal wave field capture variations in both time and space. If the entire data record is viewed as a spatial map (Figure 4b), bearing in mind that every measurement corresponds to a different time, possibly separated by years, then large-scale spatial patterns in the near-inertial wave field can be investigated across a large fraction of the Canada Basin. If the entire data record is treated as a time series, both seasonal and interannual variations in the wave field can be quantified and compared to changes in wind forcing and sea-ice characteristics.

Variability in near-inertial internal wave field is linked to seasonal and interannual variations in sea-ice cover. The spatial pattern in the wave field is dominated by a roughly linear decrease in wave amplitude to the north, which is partially explained by spatial variations in sea ice, including thicker, older ice cover in the north-east of the Canada Basin. There is a seasonal cycle in the near-inertial wave field, with waves that are 16% larger on average during summer (June to November), compared to winter (December to May). Waves are most energetic in September, during sea-ice retreat, with a second peak in early winter during a period with strong winter storms and wind speeds frequently exceeding 10m/s.

There is an interannual trend in near-inertial wave energy in the upper ocean during both summer and winter, mirroring the pronounced sea-ice decline over the last decade. Average wave amplitude has increased by 5% over the course of the 9-year record, and the variance in the wave amplitude distribution has doubled, indicating a significant increase in highly energetic near-inertial waves in recent years. Variations in wave energy on seasonal and interannual timescales match those in the `wind factor', which connects sea-ice drift speed to wind speed, suggesting a crucial dependence of near-inertial wave energy on sea-ice characteristics that determine how readily the ice responds to wind forcing (Figure 5).

While mixing due to breaking internal waves in the Arctic Ocean has historically been at least an order of magnitude below that in other oceans, the impact of an increasingly energetic internal wave field on mixing is unknown. One of the largest uncertainties is the behavior of internal waves as they propagate through the unique double-diffusive staircase stratification within the relatively warm Atlantic Water layer (Figure 6). Using an analytical numerical model (Ghaemsaidi et al., 2015), the impact of rapid variations in stratification on internal wave amplitude and stability with depth is investigated. Typical Western Arctic Ocean stratification profiles and a realistic parameter space for the internal wave field were defined using results from high-resolution CTD measurements and the near-inertial wave amplitude distribution determined from the ITP dataset.

The impact of the double-diffusive staircase on wave energy was found to vary with vertical wavenumber and wave frequency (Figure 7). For internal waves with vertical wavelengths between 1m and 100m - a representative range for the Arctic Ocean - the staircase often causes significant reflection of wave energy back into the upper ocean. For a typical wind-generated near-inertial wave, reflection of between 50-100% of the incoming wave energy is predicted. Partially reflected internal waves can also constructively interfere within the double-diffusive staircase, amplifying wave energy at those depths by a factor of 2 to 3. This is consistent with observed peaks in wave amplitude within the staircase.

An assessment of internal wave shear instability suggests that, based on the observed changes in internal wave amplitudes in the Arctic Ocean, episodic mixing due to highly energetic near-inertial waves may be increasing over the depths of the warm Atlantic Water, which has the potential to weaken the stratification and increase vertical heat flux towards the surface. Such waves now comprise about 15% of the observed near-inertial wave field, up from only 5% a decade ago. A manuscript describing these results, detailed in Chapter 4 of Dosser (2015), is in preparation for publication (Dosser et al.*, in preparation*). This represents a significant shift in the internal wave field in the Arctic Ocean, likely to continue into the future as sea ice declines, with implications for the vertical transport of heat and nutrients in the upper ocean.

IMPACT/APPLICATIONS

The analysis of all ITPs deployed in the Canada Basin have resulted in a multi-year, regional climatology of the near-inertial internal wave field. Since all ITPs are anchored in multi-year ice floes, the near-inertial wave field is that of an (at least marginally) ice-covered ocean. The dominant focus of this work is to undertand the seasonal and interannual variations of the internal wave field and associated mixing, and the coupling between the atmosphere, sea-ice, and ocean. Such knolwedge is critical to accurately model the upper Arctic Ocean and to predict changes in response to the increased Arctic seasonality and sea-ice decline in recent years.

RELATED PROJECTS

The work conducted by Dr. Dosser as part of this award is closely related to the ONR Arctic DRI on the Emerging Dynamics of the Marginal Ice Zone. As part of the MIZ DRI, Craig Lee and Luc Rainville deployed 4 Seagliders in the Arctic in summer 2014, extensively sampling the region between the full ice cover and open water. The glider observations will allow us to compare and constrast the internal wave field across a range of ice conditions, and understand how (and when) the ITP data - always under ice and tethered to an ice floe, by design - are representative of the dynamics in the entire basin.

REFERENCES

Krishfield, R., K. Doherty, D. Frye, T. Hammar, J. Kemp, D. Peters, A. Proshutinsky, J. Toole, and K. von der Heydt, Design and Operation of Automated Ice-Tethered Profilers for Real-time Seawater Observations in the Polar Oceans, WHOI-2006-11, 79 pp., 2006.

Rainville, L., C.M. Lee, and R.A. Woodgate, 2011. Impact of Wind-Driven Mixing in the Arctic Ocean, *Oceanography Magazine,* 24(3):136–145.

PUBLICATIONS

Dosser, H. V., L. Rainville, and J. M. Toole. 2014. Near-inertial internal wave field in the Canada Basin from Ice-Tethered Profilers. *J. Phys. Oceanogr.*, **44**, 413–426. doi: http://dx.doi.org/10.1175/JPO-D-13-0117.1

Dosser, H. V., L. Rainville, 2015. Dynamics of the changing near-inertial internal wave field in the Arctic Ocean. In revision at *J. Phys. Oceanogr.*

Dosser, H. V., 2015. Internal Waves in the Western Arctic Ocean. *PhD Dissertation*, University of Washington, Seattle, WA.

Dosser, Hayley V., Sasan J. Ghaemsaidi, Thomas Peacock, and Luc Rainville, xxxx. Internal Wave

Propagation and Stability in the Western Arctic Ocean. In preparation for *J. Phys. Oceanogr.*

Ghaemsaidi, Sasan J., Hayley V. Dosser, Luc Rainville, and Thomas Peacock, 2015. The impact of multiple layering on internal wave transmission, in revision at *J. Fluid Mech.*

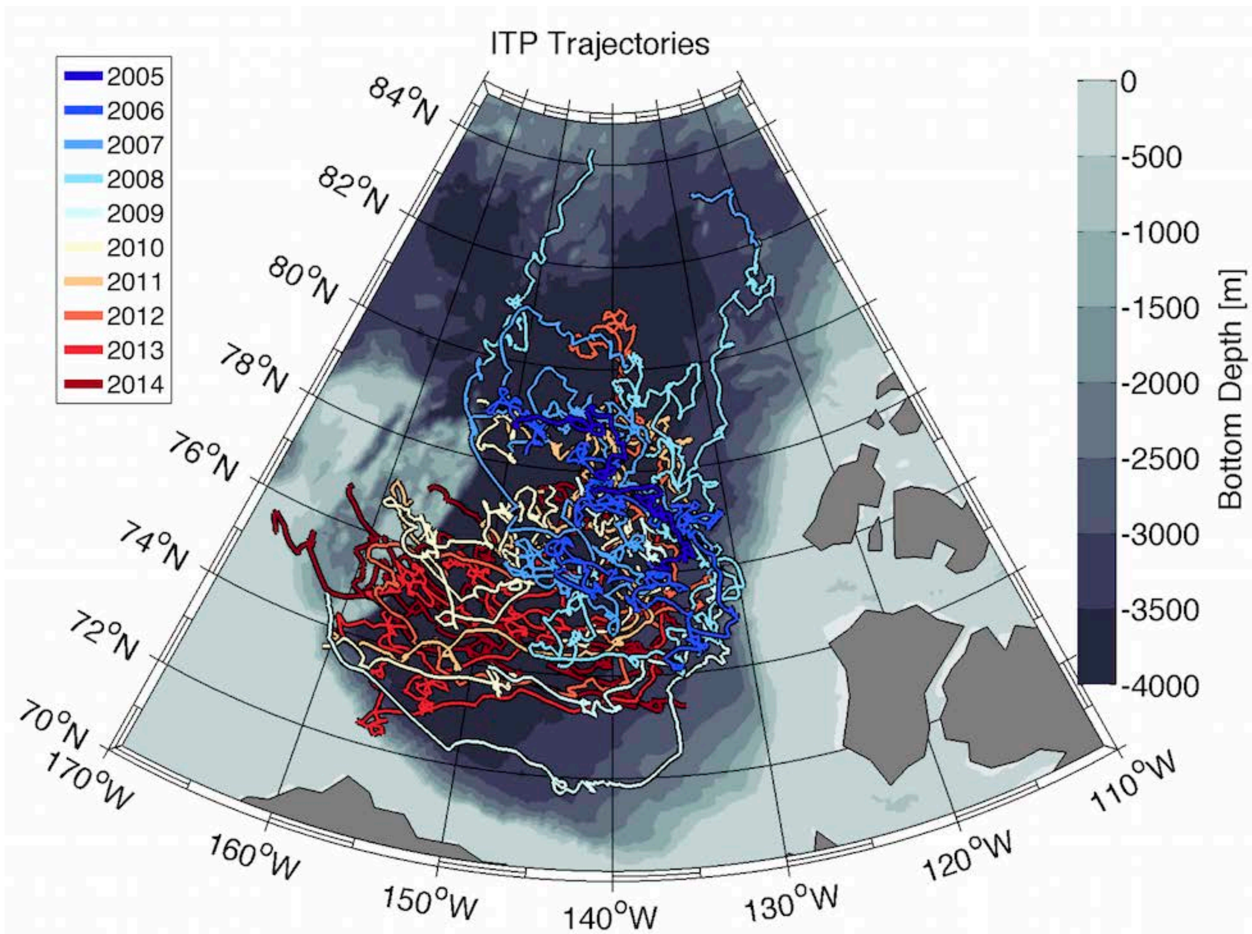

Figure 1: Trajectories 27 ITPs with processed data available from Fall 2005 to Fall 2014 in the Beaufort Gyre region of the Canada Basin. Colours correspond to different years. Gray contours show bathymetry.

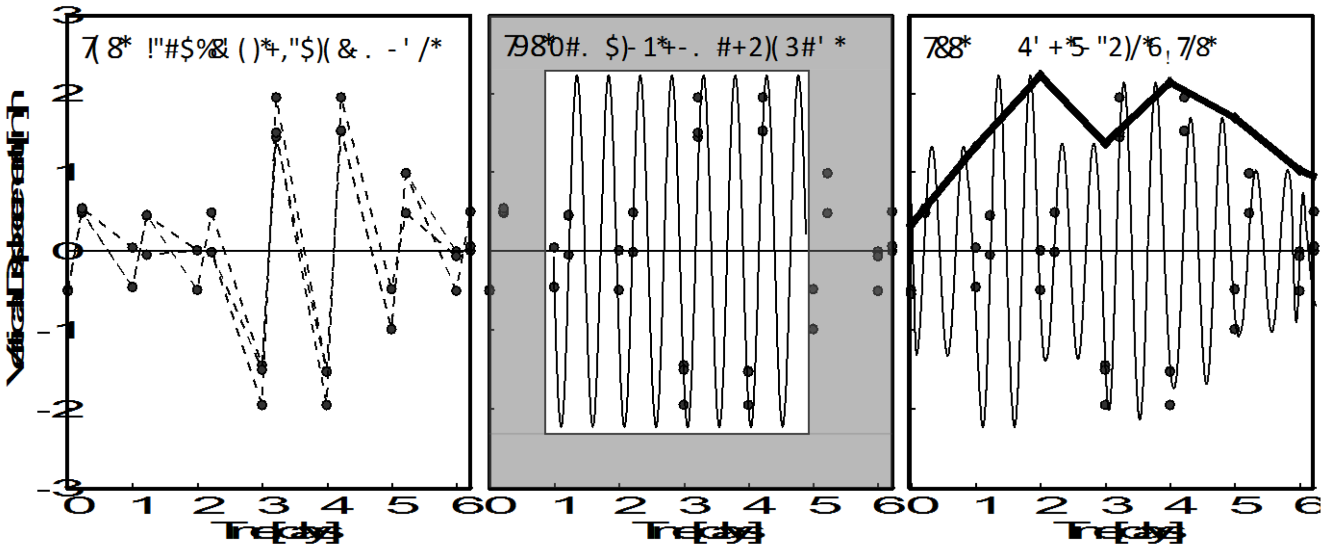

Figure 2: (a) Data: Vertical displacements for 3 isopycnals within a 6-m depth range, with the low-frequency signal removed. (b) Method: A harmonic least-squares fit to each window of data gives the amplitude and phase of the ideal cosine (thin black line) that best explains the near-inertial variance in the data. (c) Result: The `complex demodulation' procedure produces a slowly varying wave amplitude (thick black line) and phase (not shown) corresponding to a near-inertial wave consistent with the observed vertical displacements (thin black line).

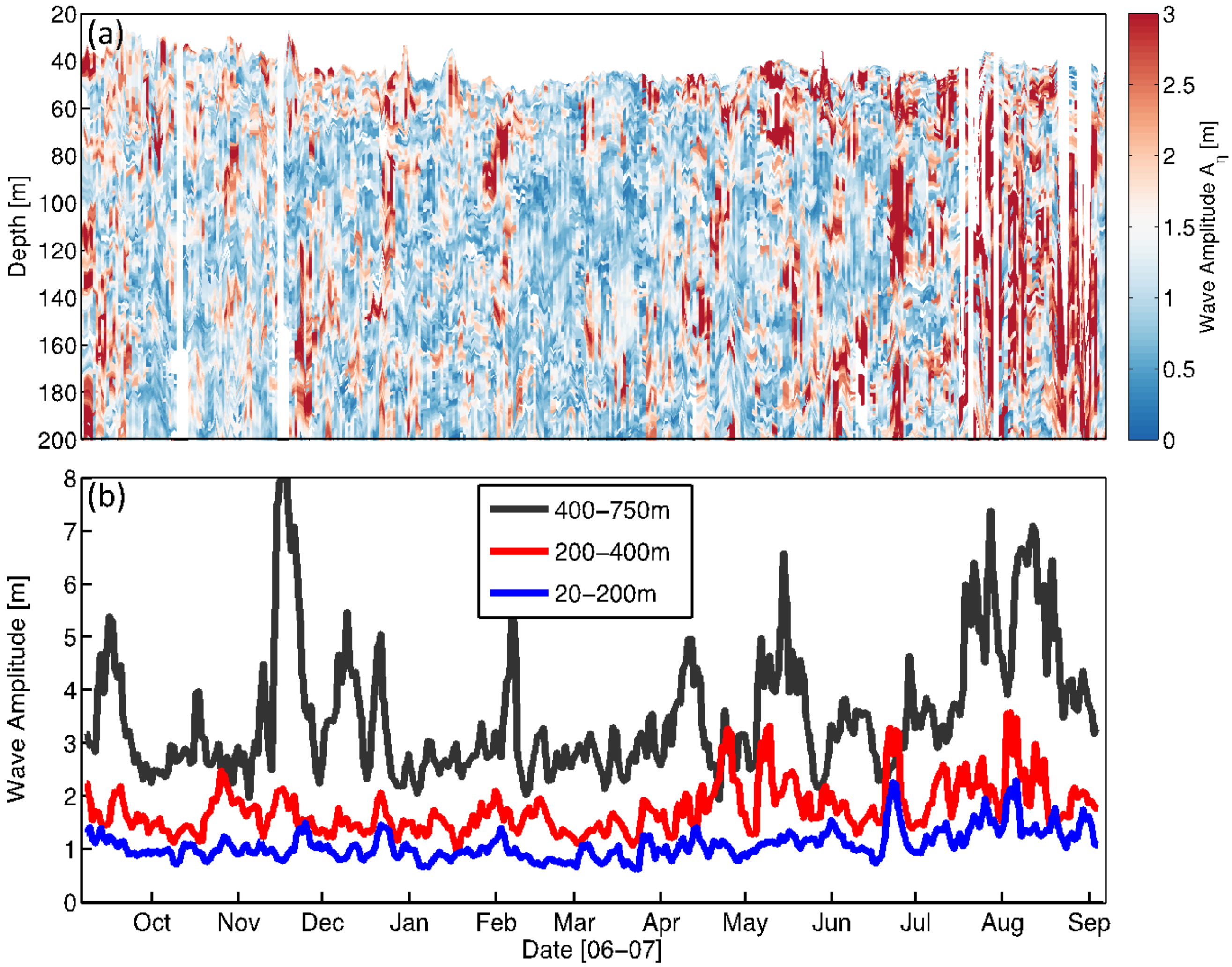

Figure 3: (a) Vertical displacement wave amplitude field for one full year of data from ITP 6, over the top 200 m of the water column. Waves with larger vertical displacements are red. Gaps are regions without data or flagged as estimated with low confidence. (b) Depth-averaged vertical displacement wave amplitude for the top 200 m (blue line), the double-diffusive staircase region from 200-400 m (red line), and the lower water column from 400-750 m (grey line).

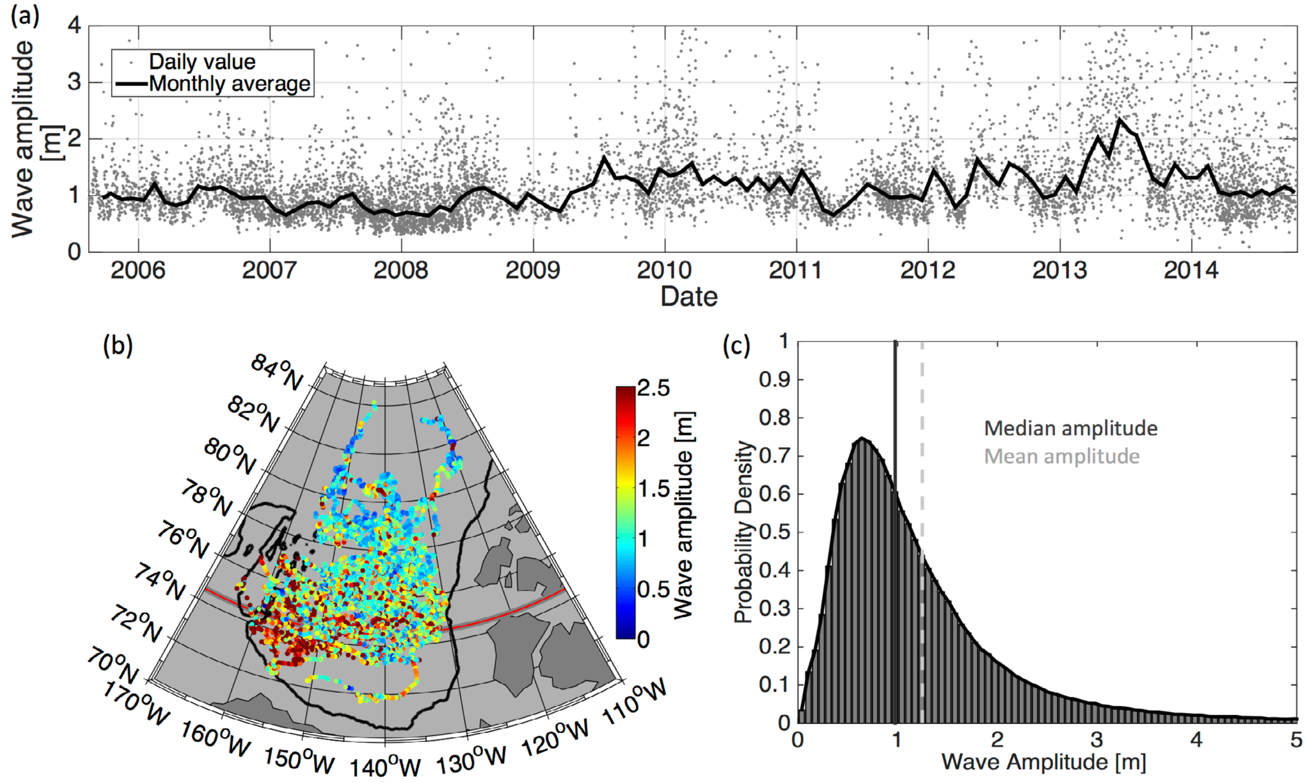

Figure 4: (a) Time series of individual measurements (grey dots) and monthly averages (black line) of depth-averaged vertical displacement near-inertial wave amplitude from Fall 2005 to Fall 2014. Labels mark the 1st of Jan of each year. (b) Spatial map of depth-averaged wave amplitude following the ITP tracks from 2005 to 2014. Black line: 1000m isobath. Red line: critical latitude for the M2 semi-diurnal tide at 74.5°N. (c) Probability density distribution of calculated near-inertial wave amplitude estimates from all ITP data considered. Dark and light grey lines indicate the median and mean amplitude for the distribution, respectively.

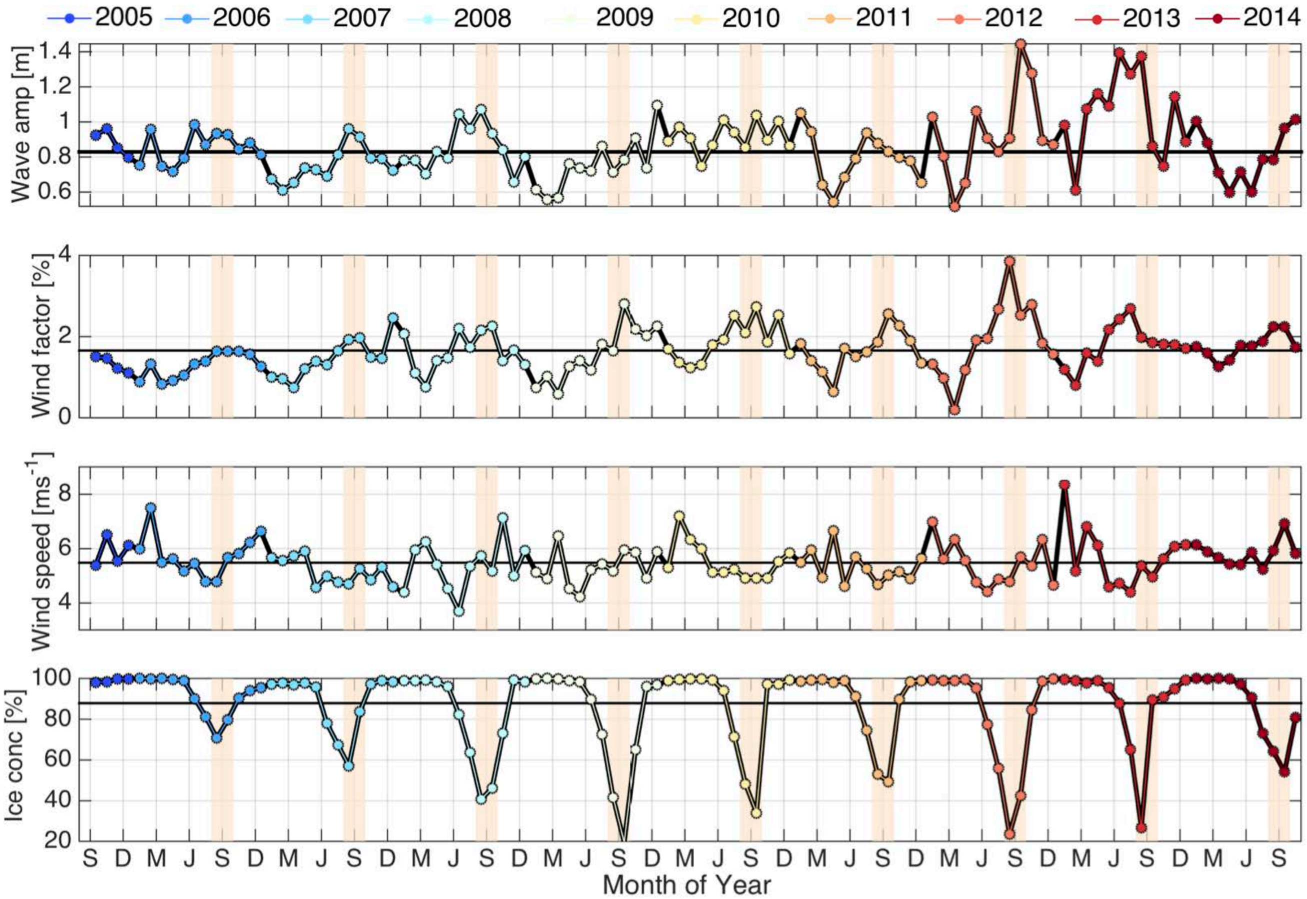

Figure 5: Interannual variations from Fall 2005 to Fall 2014. Data is binned by month and colored by calendar year. From top to bottom, fields are: near-inertial wave vertical displacement amplitude, wind factor, wind speed, and sea-ice concentration. Tan vertical bars indicate the summer sea-ice melt from Aug 1st to Oct 1st. Horizontal black lines give overall time series average for each field.

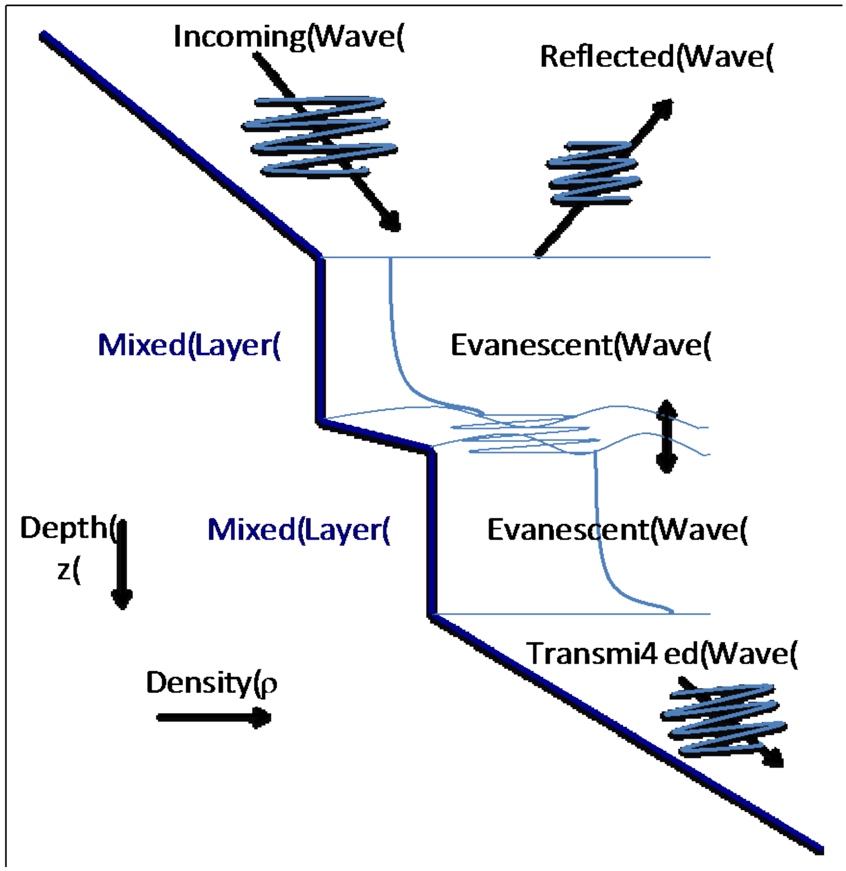

Figure 6: Cartoon showing an internal wave incident on a series of mixed layers separated by thin, stratified interfaces, representative of the double-diffusive staircase with the Atlantic Water layer in the Western Arctic Ocean. The waves are oscillatory above and below the mixed layers and within the interfaces, and evanescent within the mixed layers. Resonance occurs when internal waves within the stratified interfaces are in phase and constructively interfere, causing amplification of wave energy and/or transmission through the staircase.

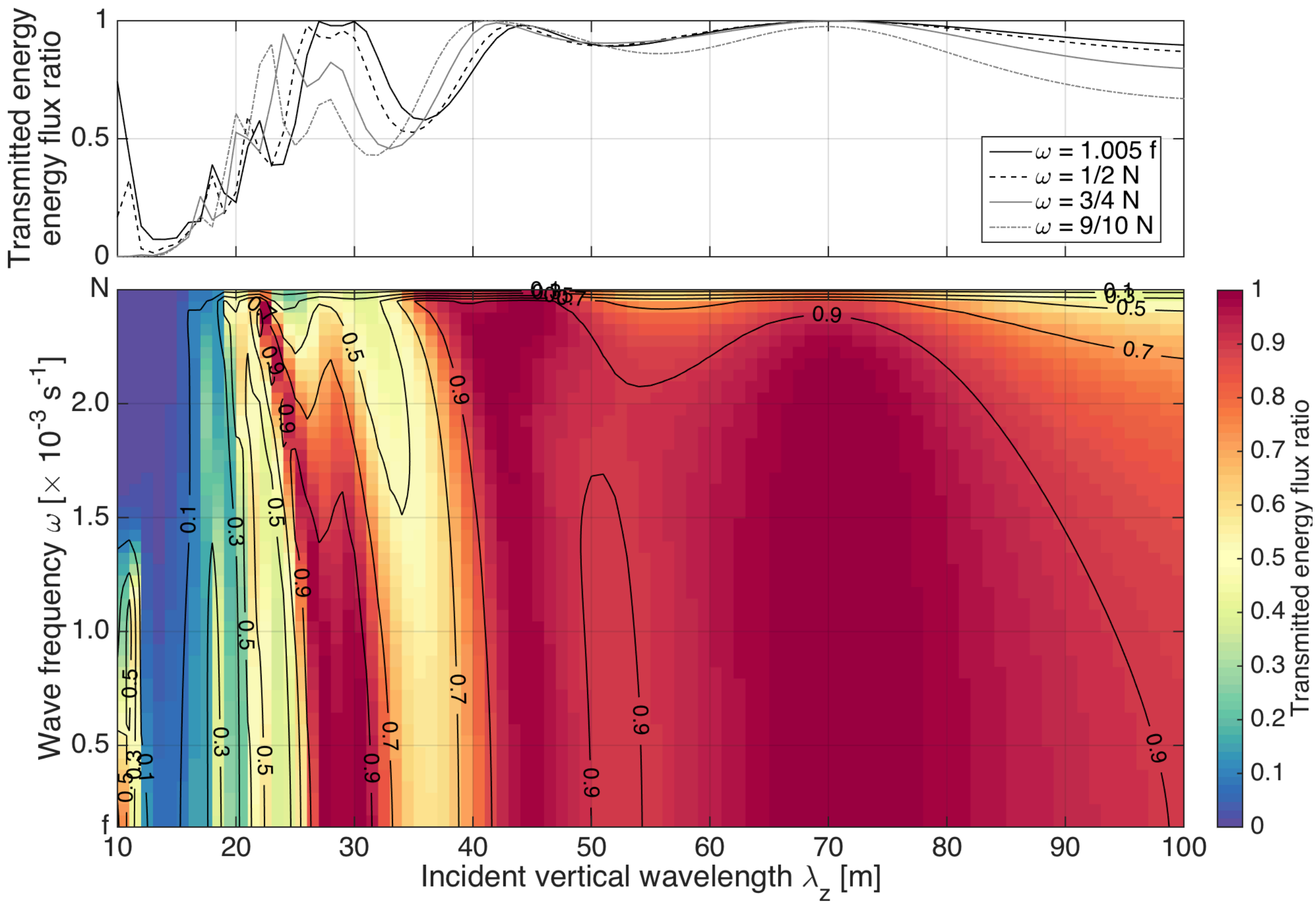

Figure 7: Transmitted vertical energy flux for internal waves of given frequency ω and incident vertical wavelength λ_z propagating through the double-diffusive staircase in the Canada Basin as determined from a high-resolution CTD profile. A value of `0' indicates complete reflection of wave energy, while a value of `1' indicates complete transmission. The top panel shows wave energy transmitted to the deep ocean for select internal wave frequencies. Near-inertial waves (thin black line) with vertical wavelengths of roughly 20-40m (typical of observations in the Canada Basin) are predicted to be significantly reflected back into the upper ocean.