Measurement of Wave-induced Signals on the Ross Ice Shelf

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Ocean Forcing
Swell
Infragravity Waves
Determine spatial and seasonal variability of elastic and mechanical properties of the Ross Ice Shelf from passive broadband seismometer observations of gravity wave-induced vibrations.
Motivation: Nascent Iceberg Seismometer

MacAyeal et al., GRL, 2006
Cathles et al., JGR, 2009

Vertical bands -> local to regional
Southern Ocean wave activity

Slanted bands indicate dispersion
=> non-local distant wave generation
Nascent Iceberg Seismometer

Swell damping by sea ice

Some structure in spectral levels < 0.01 Hz
Nascent Iceberg Seismometer

Swell

Infragravity waves

Difference spectra: removing the median
Nascent Iceberg Seismometer

Swell

Infragravity waves

Very long period North Pacific swell

Cathles et al. 2009
Bromirski et al. 2010
Slopes of dispersion trends and forward modeling using the gravity wave dispersion relation confirm North Pacific infragravity wave and swell source locations.
• The spectral peak centered near 0.5 Hz persists when swell is significantly damped, suggesting a possible relationship to a resonance/eigen frequency of the RIS front.

• If this spectral peak results from crustal structure, its amplitude could vary with forcing amplitude, but the bandwidth should not, suggesting complicated shelf motions (or tilt effects).
• The spectral peak centered near 0.5 Hz persists when swell is significantly damped, suggesting a possible relationship to a resonance/eigen frequency of the RIS.

• If this spectral peak results from crustal structure, its amplitude could vary with forcing amplitude, but the bandwidth should not, suggesting complicated shelf motions (or tilt effects).

IG levels in April are similar to those in February. This suggests that IG waves are not appreciably damped by sea ice, impacting the RIS throughout the year.

RIS Seismic Arrays

PASSCAL Instrumentation:
3-component broadband post-hole self-leveling seismometers – 240s +

Elevations: BEDMAP2

Wiens et al. (red stars)
Three ice-front stations to measure reference forcing and front g-w response variability

Orthogonal linear array roughly tracks a seafloor channel
Transverse and Orthogonal Transects

Mean ice shelf thickness over the orthogonal array ~ 350m

Shelf front
Ice thickness: ~200 m
Water depth: ~700 m
Ice Flow-velocity

ROSS Area Sites with BEDMAP2 Ice Velocities

Velocities (meters per year)
The orthogonal linear array roughly tracks a zone of fast-moving ice as well as the seafloor channel.
Gravity Wave Pressure Decay with Depth

Water Depth Considerations:
Gravity Wave energy in the Sub-Shelf Water Cavity

100 s IG shows little decay with depth, in contrast to Swell

Ice thickness: ~200 m
Water depth: ~700 m
Wave-induced Vibration Propagation Paths

How far can ice-front gravity-wave “impact” signals be detected \( \rightarrow \) ice properties
Wave-induced Vibration Propagation Paths

Velocities: Elastic (~3700 m/s) >> IG (~80 m/s) or Swell (~40 m/s)

Gravimeter data indicate IG-wave signals can be detected near 80S [Williams and Robinson, 1979]
Array Processing

Goal: Determine spatial variability of ice shelf properties

• Beamforming to estimate dominant source direction
• Cross-correlation between station pairs to estimate energy propagation group velocity
• Estimate phase velocity
  -> giving estimates of elastic moduli
  -> used in seismic (TDFD) and mechanical modeling
Wave Model Hindcast: 2006 1 27 15

Amery Ice Shelf
Source Directionality

Array beamforming to obtain dominant signal direction

Beam power

Bassis, Fricker et al. 2007
Multiple propagation paths “sampling” different portions of RIS

Idealized swell direction and signal propagation
Complicated wavefronts through the ice-water-sediment-crust system

TDFD modeling indicates resonance peak frequency depends on ice thickness and properties

Summary and Objectives: Expected Signal Observations

Measure the dynamic response of the Ross Ice Shelf to gravity wave impacts from broadband seismometer observations to estimate:

• Spatial variability of its elastic and mechanical behavior
• Response to IG-waves and Swell: Along and orthogonal to the shelf front
• Icequakes: Distribution and variability along the RIS front and interior
• Array processing to determine spatial variability of signal and propagation characteristics
• Model the spatial response to estimate elastic structural parameters that affect signal propagation.
Underlying Question:

What role, if any, do gravity wave - ice shelf interactions play in reducing ice shelf integrity or triggering collapse?
Seasonal Variability

Summer (Jan–Feb) vs Winter (Aug-Sep)

- Ice shelf specific non-gravity wave spectral peaks, with the 0.5 Hz peak most prominent
- Other peaks near 1.0Hz and 2 Hz, ice shelf resonances?

- The absence of IG wave band signals at VNDA in the Dry Valleys suggests that observed signals at RIS2 and SBA are not seismic “hum” (Bromirski and Gerstoft, 2009). They are likely related to the response characteristics of the ice shelf/sub-ice-shelf water cavity system.

- IG wave band levels at SBA are similar throughout the year, suggesting that:
  - North Pacific IG wave forcing persists throughout the year
  - Sea ice does not significantly damp ocean IG waves
Transoceanic Infragravity (IG) Waves and Swell Impacting Antarctic Ice Shelves

Slopes of dispersion trends and forward modeling using the gravity wave dispersion relation confirm North Pacific infragravity wave and swell source locations.

Higher amplitude possibly due to incidence angle (impacting more of the shelf front simultaneously), OR swell energy penetrating the sub-shelf cavity.
Gravity-wave Pressure decay with Depth

![Graph showing the decay of gravity-wave pressure with depth. The graph plots P/P₀ (dB) against wave period, with different lines representing different water depths (200, 500, 700, 900 m). The graph indicates a decrease in pressure with increasing depth and wave period.]

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IG
Nascent Iceberg Seismometer

Swell

Difference spectra: removing the median
Organization

- **Background**  Previous RIS observations: gravity wave signatures

- **The Experiment**  Broadband seismic array geometry and related broad-scale RIS structure

- **What we hope to measure**  Preliminary analysis, implications
Nascent Conclusions

• Gravity wave source locations and spectral characteristics can be determined from near-front seismic stations

• Ice shelf / gravity wave interactions produce vibrations of the RIS that can be used to investigate the spatial variability of RIS elastic and mechanical properties

• RIS response characteristics (resonances) give insights into RIS structure

NASA: Ross Ice Shelf
Questions that will be answered

- How does the RIS response vary along the front?
- Was the MacAyeal RIS seismometer site location exceptional?
- How does the RIS response vary with distance from the front?
Diagnostic Implications

• Much IG likely penetrates the sub-shelf cavity, potentially continuously generating signals along the base of the RIS

• Much greater elastic wave speed compared to gravity waves may allow separation/identification of signals generated at the front or at the basal surface

• Although proportionately much less Swell energy penetrates the sub-shelf cavity, it may be significant

• Does the basement rise near 81.5S significantly enhance IG-wave basal-induced RIS response?
Nascent Seismic Observations Raise a Host of Questions

- IG wave amplitudes at the ice shelf edge?
- IG wave -> shelf displacement transfer function?
- Ross Sea ice shelf destabilization?

Observation plan:
- Seismometer array on the RIS
North Pacific - Antarctic Connections

Oct. 21, 2005

Cracking events (Okal and MacAyeal, SRL, 2006)

(MacAyeal et al., GRL, 2006)

(Cathles et al., JGR, 2009)
North Pacific – Antarctic Connections

Ross Ice Shelf, Antarctica Seismometer Observations

Slope of dispersion trends indicates distance from the ocean wave source (North Pacific circled)

Vertical bands => local storms

Sea ice damping of swell

<--- Infragravity waves

MacAyeal et al., GRL, 2006
Cathles et al., JGR, 2009
Spectral Amplitude Temporal Variability

In general, RIS > SBA (Ross Island)

December 2004 – April 2005
Spectral Amplitude Temporal Variability

In general, RIS > SBA (Ross Island) > VNDA (Dry Valley)

Spectral bands at RIS and B15A are at slightly different frequencies – due to different structure or less constrained motions of B15A, or tilt.
Slopes of dispersion trends and forward modeling using the gravity wave dispersion relation confirm North Pacific infragravity wave source locations.

**Climate connection**: IG waves impacting ice shelves may produce or expand fractures and also trigger collapse events.
Comparison of Ice-Shelf Observations with Land Stations at Scott Base and Palmer Station, Antarctica

Mean Spectra (EQ noise excluded)

Ross
Scott Base
Palmer Station

Difference Spectra (re: Jan. mean)

February (summer)

August (winter)

The much higher mean amplitudes on the Ross Ice Shelf illustrate the much larger response of the ice shelf to infragravity wave forcing.

IG waves are not significantly damped by sea ice and impact the ice shelves throughout the year.
Significance: IG Waves as Possible Triggers of Ice Shelf Collapse

Infragravity waves from transformed swell along the Patagonia coast may have played a role in triggering the catastrophic 2008 collapse of the Wilkins Ice Shelf.
Nascent Iceberg Seismometer

Vertical bands -> local to regional Southern Ocean wave activity
Slanted bands indicate dispersion – non-local distant wave generation
Nascent Iceberg Seismometer

Swell

Infragravity waves
Gravity wave dispersion relation propagation over great circle paths (infinite depth)
Gravity wave dispersion relation propagation over great circle paths (infinite depth)

Dispersion trends and the associated IG wave lag are consistent with coastal generation from the same storm waves
North Pacific Mid-ocean and Coastal Source Regions

Nascent Seismometer

4 hr average

NOAA Buoy: CA Coast

NOAA WWIII Wave Model

(http://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.html)