Measurement of Wave-induced Signals on the Ross Ice Shelf

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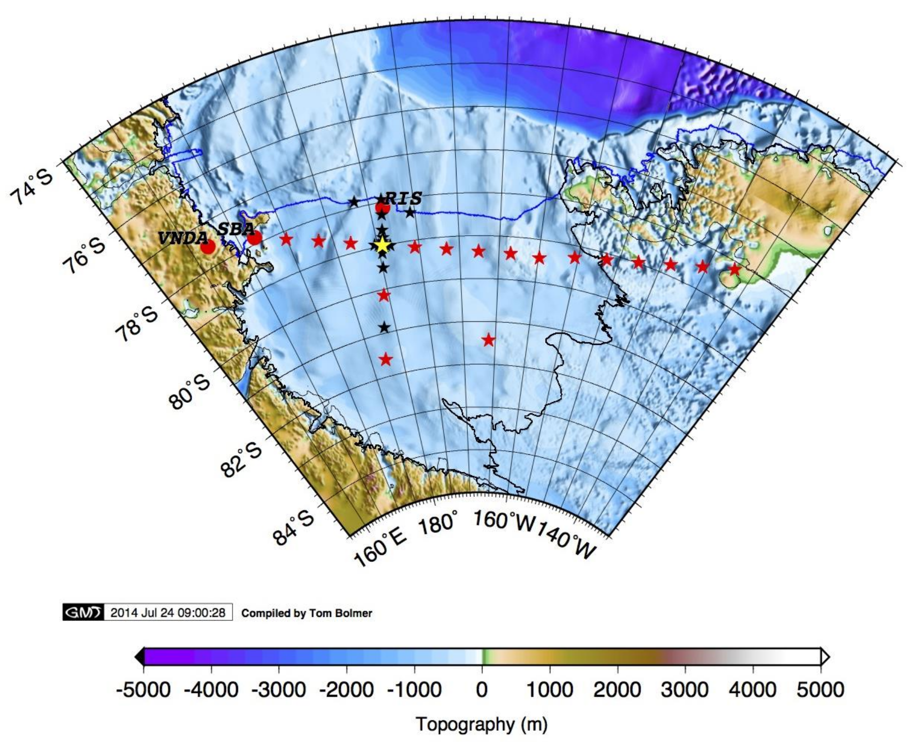
Support from NSF Glaciology Polar Programs, Julie Palais Program Manager

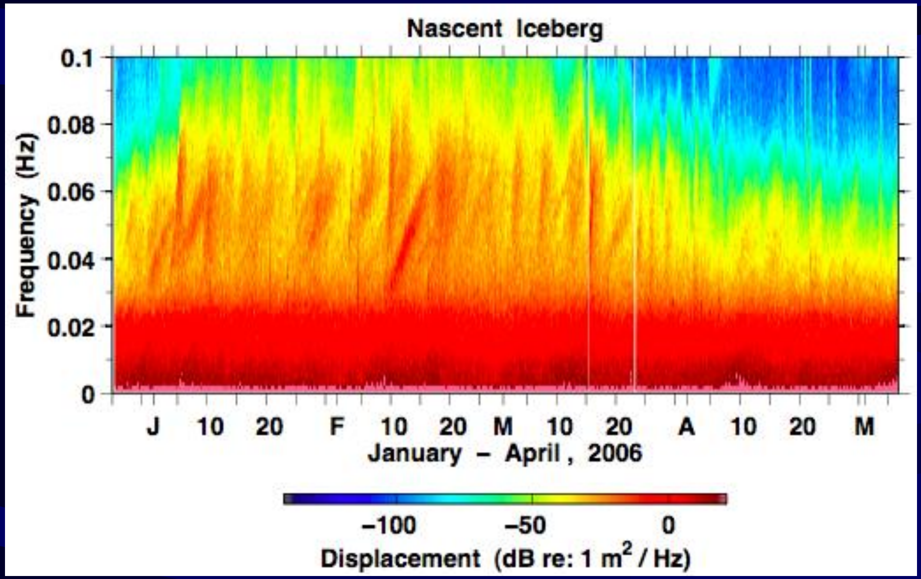
Ocean Forcing

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



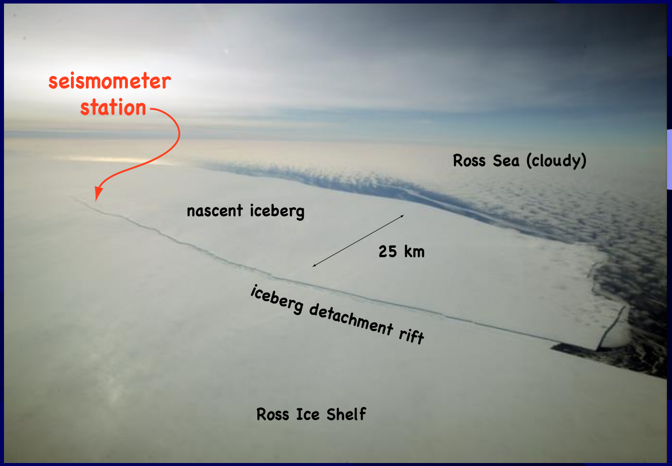
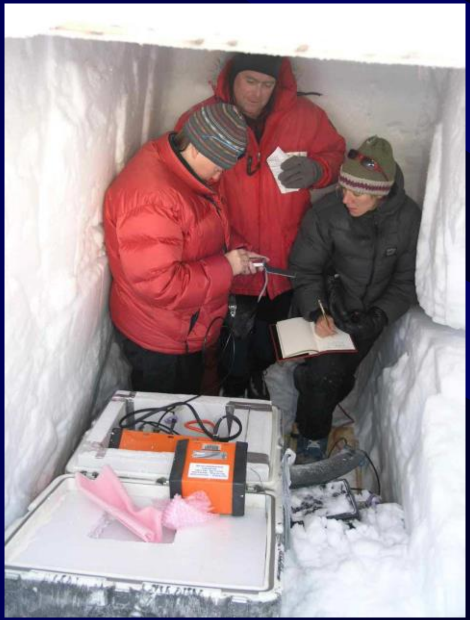


Image: Joe Harrigan
Olga Sergienko

MacAyeal et al., GRL, 2006

Cathles et al., JGR, 2009

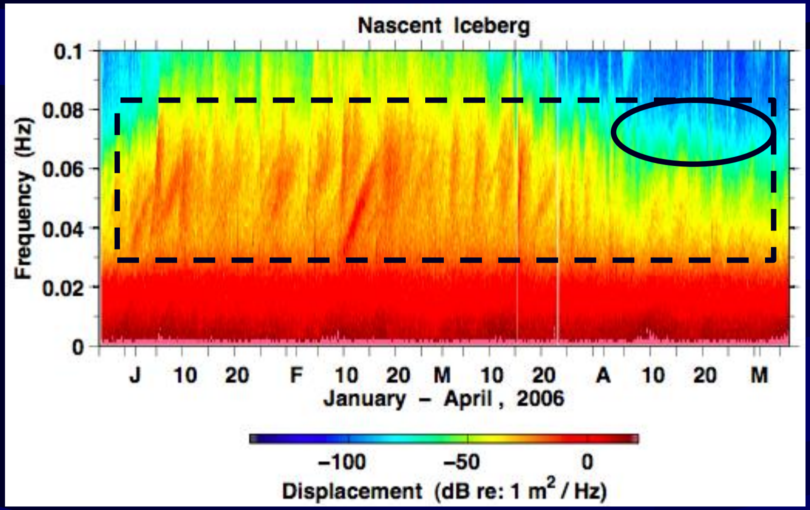
Doug in Vault



Vertical bands -> local to regional Southern Ocean wave activity

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

Nascent Iceberg Seismometer



Swell

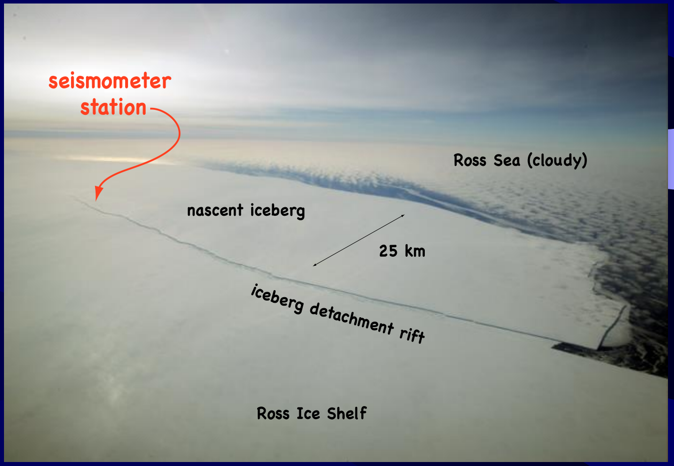
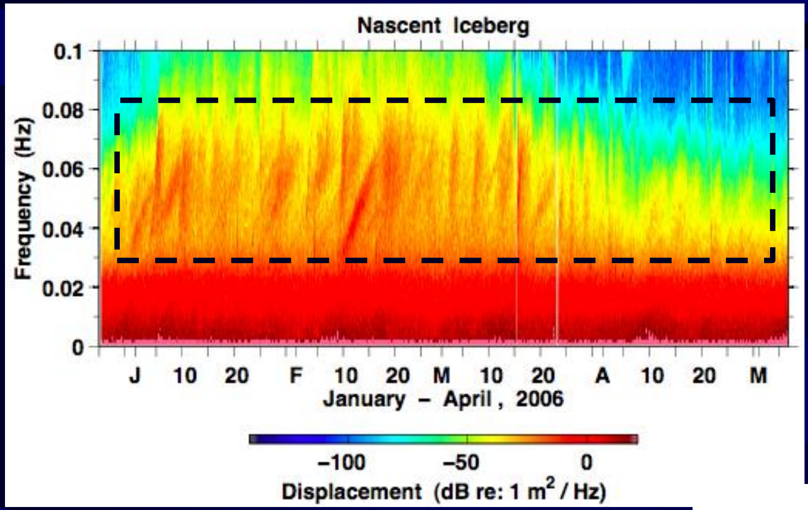


Image: Joe Harrigan
Olga Sergienko

Swell damping by sea ice

Some structure in spectral levels < 0.01 Hz

Nascent Iceberg Seismometer



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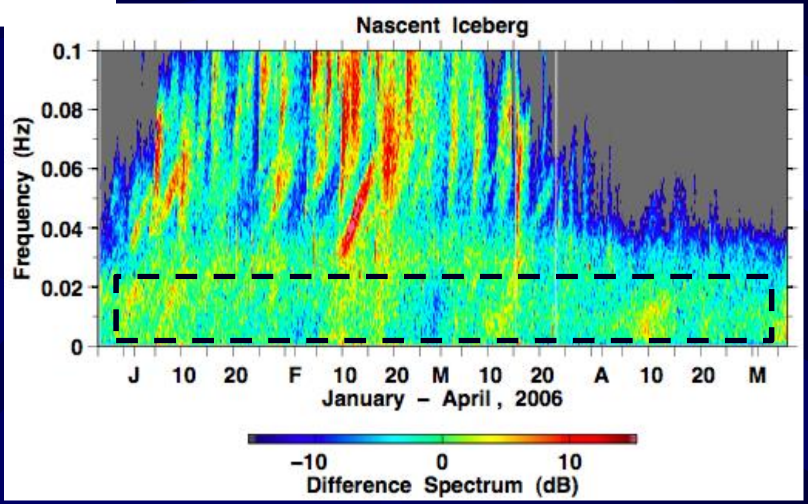
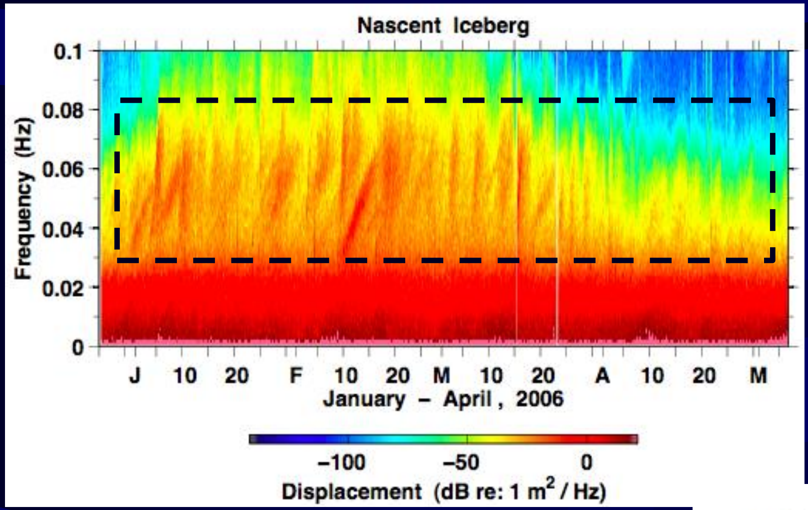


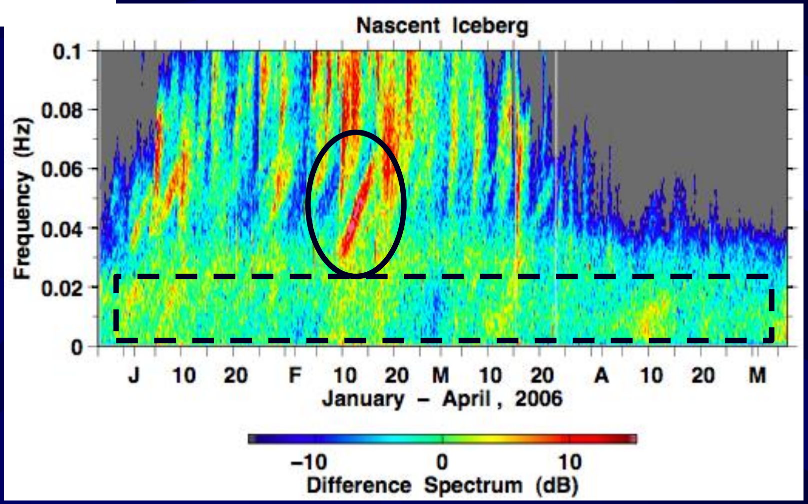
Infragravity waves

Difference spectra: removing the median

Nascent Iceberg Seismometer



Swell

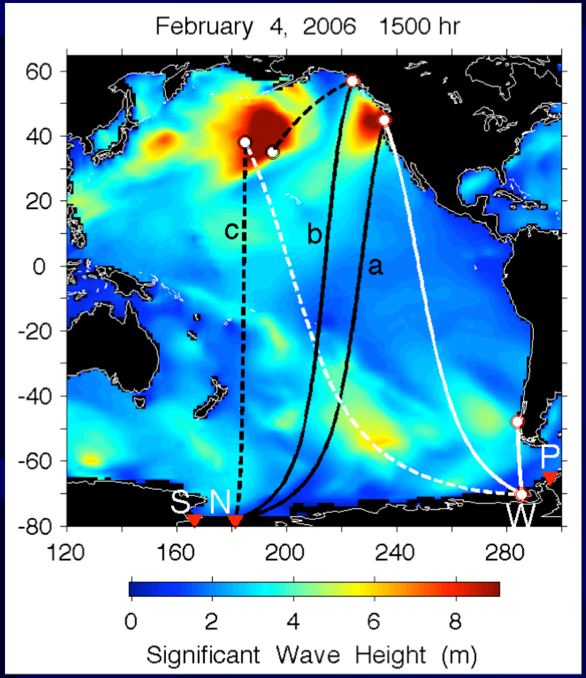


Infragravity waves

Very long period North Pacific swell

Cathles et al. 2009
Bromirski et al. 2010

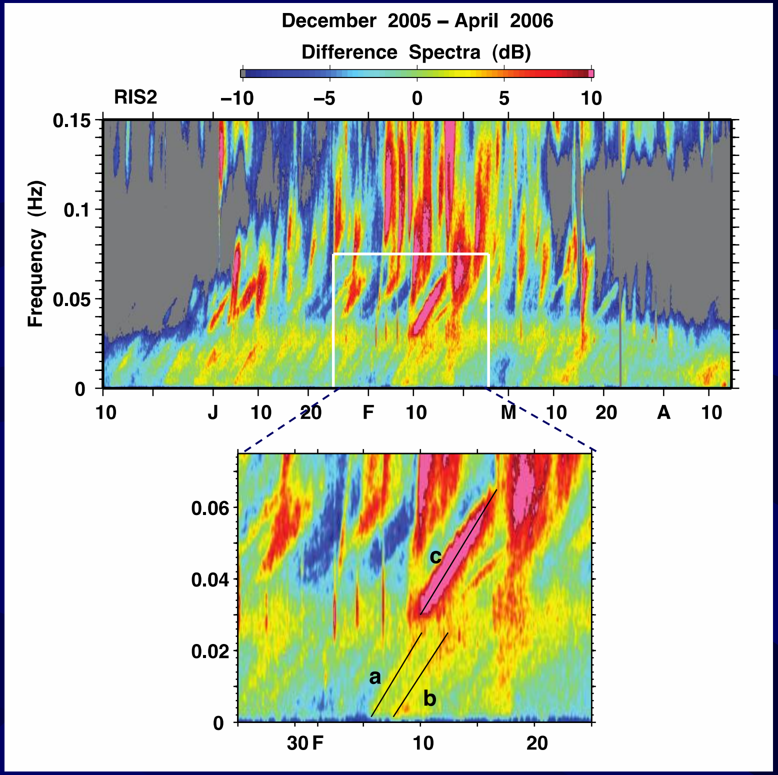
Transoceanic Infragravity (IG) Waves and Swell Impacting Antarctic Ice Shelves



Model wave height Feb 2006

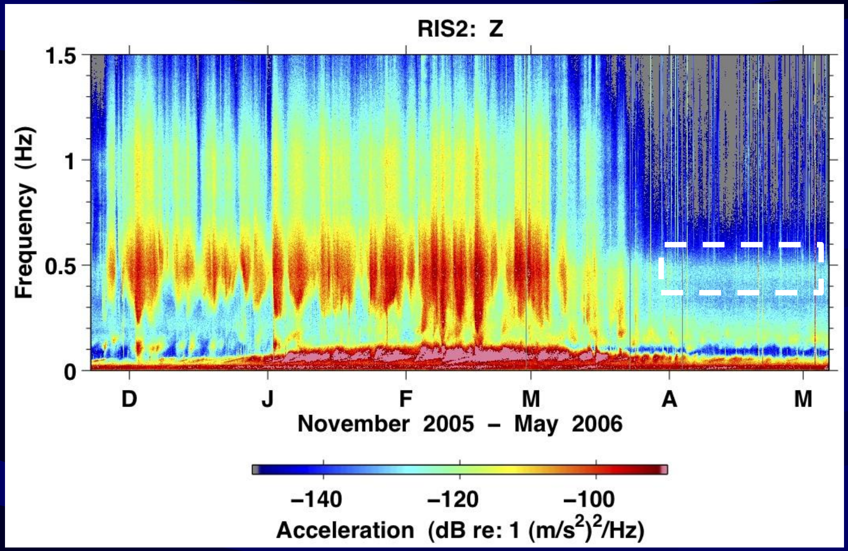
Bromirski et al. 2010

Difference Spectra



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

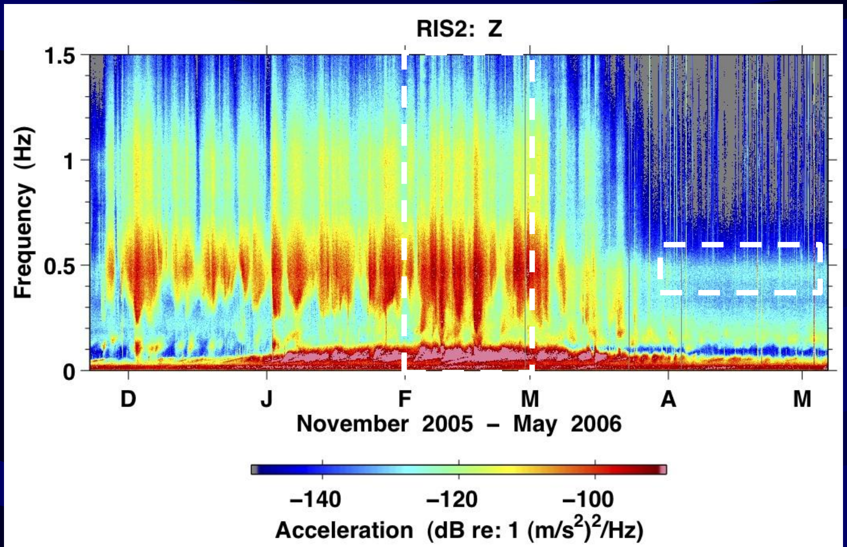
Swell-Forced RIS Resonance

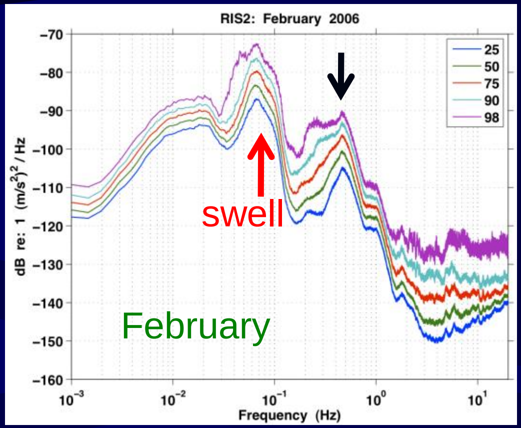


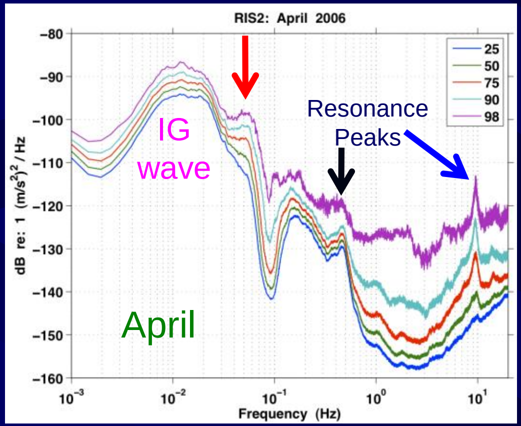
• The spectral peak centered near 0.5 Hz persists when swell is significantly damped, suggesting a possible relationship to a resonance/eigen frequency of the RIS front.

• 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).

Swell-forced Higher-frequency RIS Resonance







Swell levels drop about 30 dB

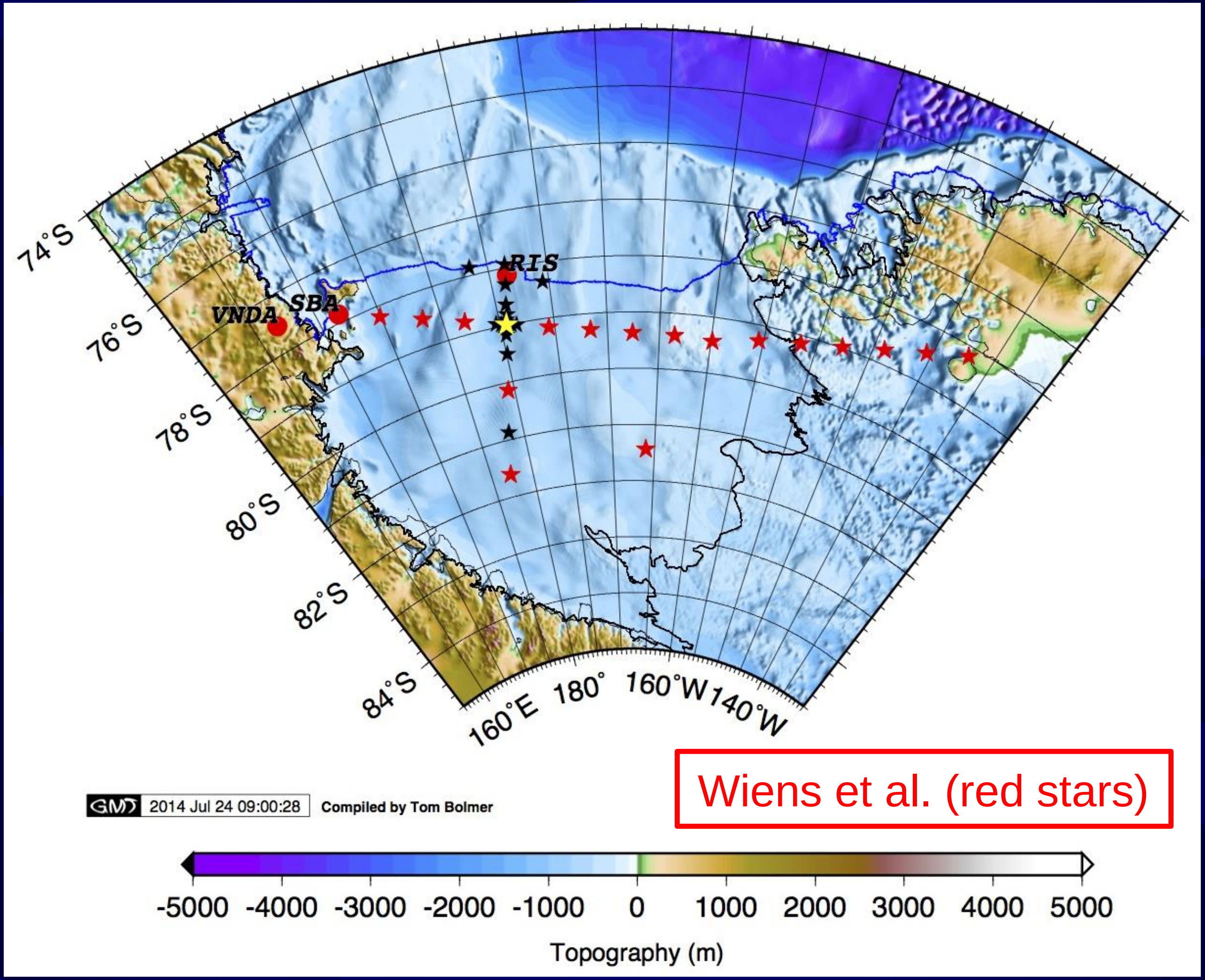
• The spectral peak centered near 0.5 Hz persists when swell is significantly damped, suggesting a possible relationship to a resonance/eigen frequency of the RIS.

• 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.

Bromirski and Stephen, *Ann. Glaciol.*, 2012

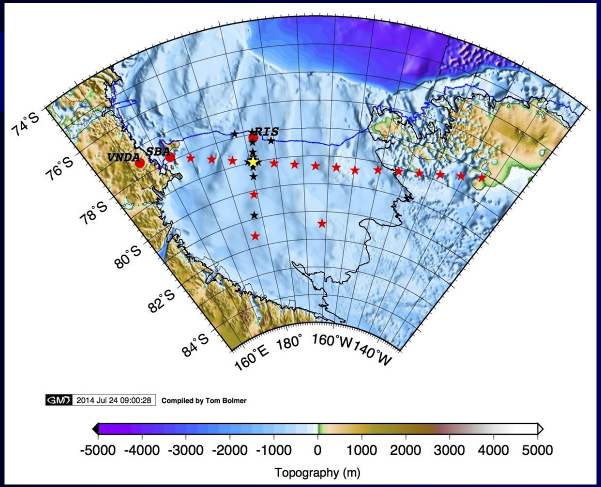
RIS Seismic Arrays



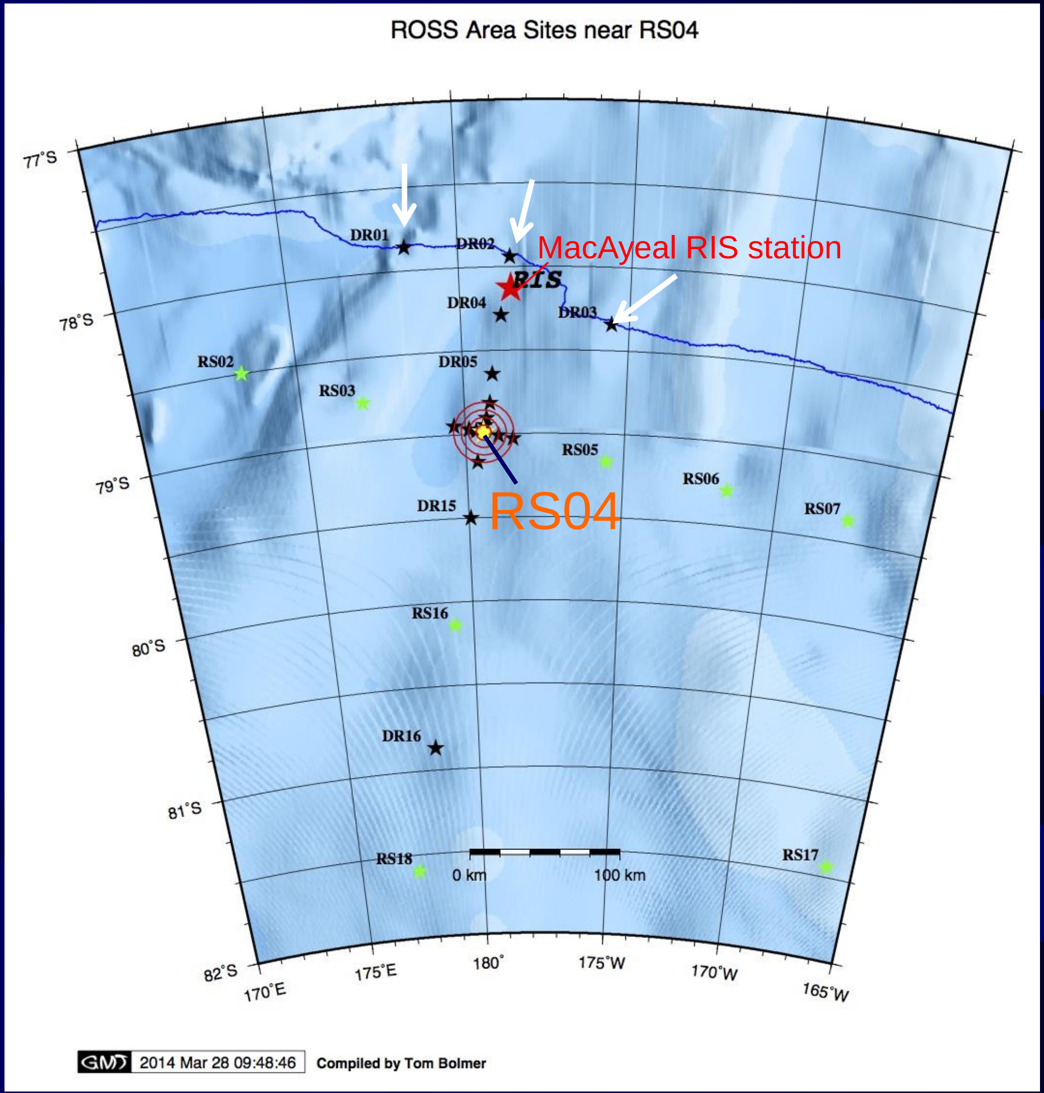
Elevations: BEDMAP2

PASSCAL Instrumentation:

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

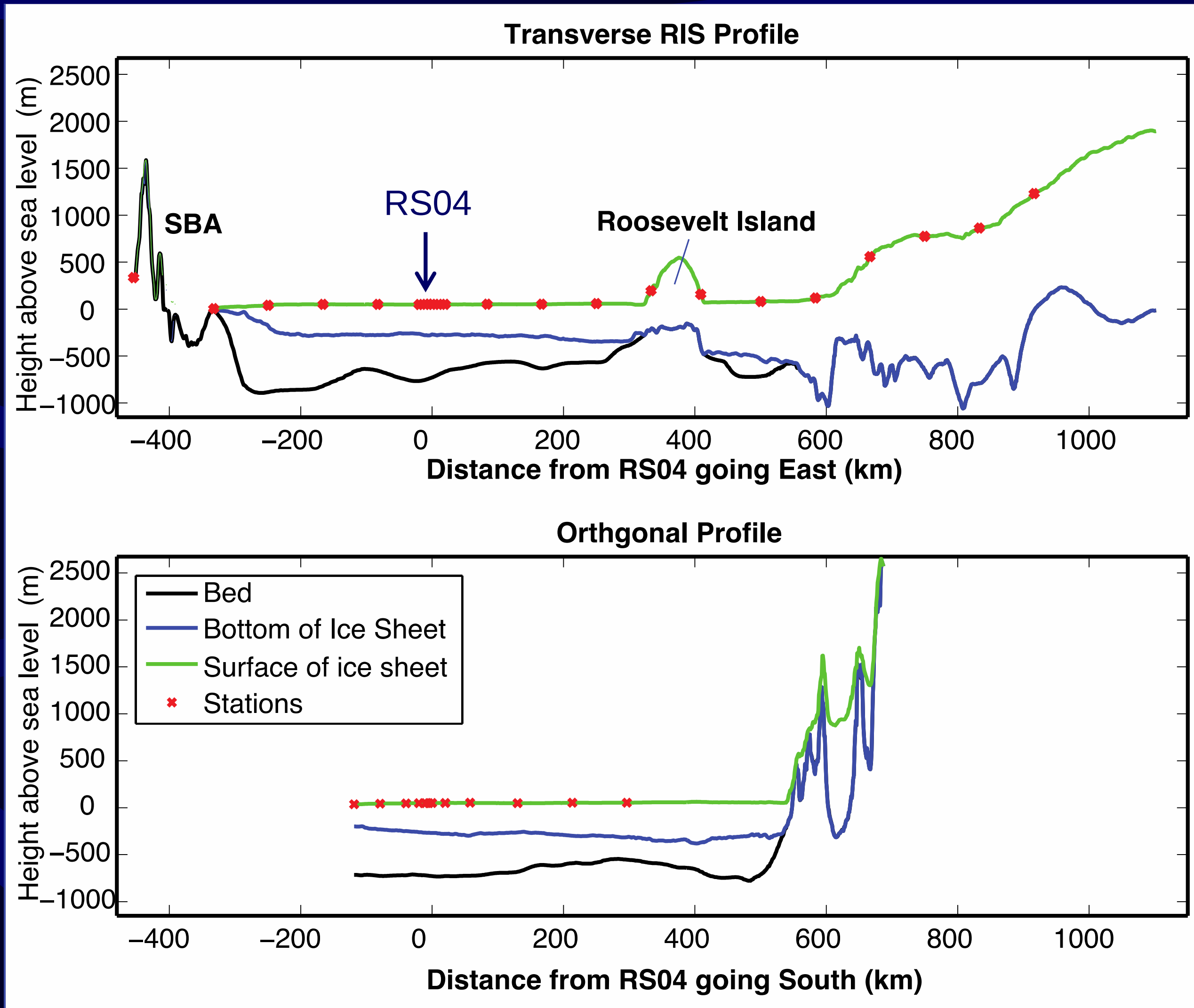


Three ice-front stations to measure reference forcing and front g-w response variability



Orthogonal linear array roughly tracks a seafloor channel

Transverse and Orthogonal Transects

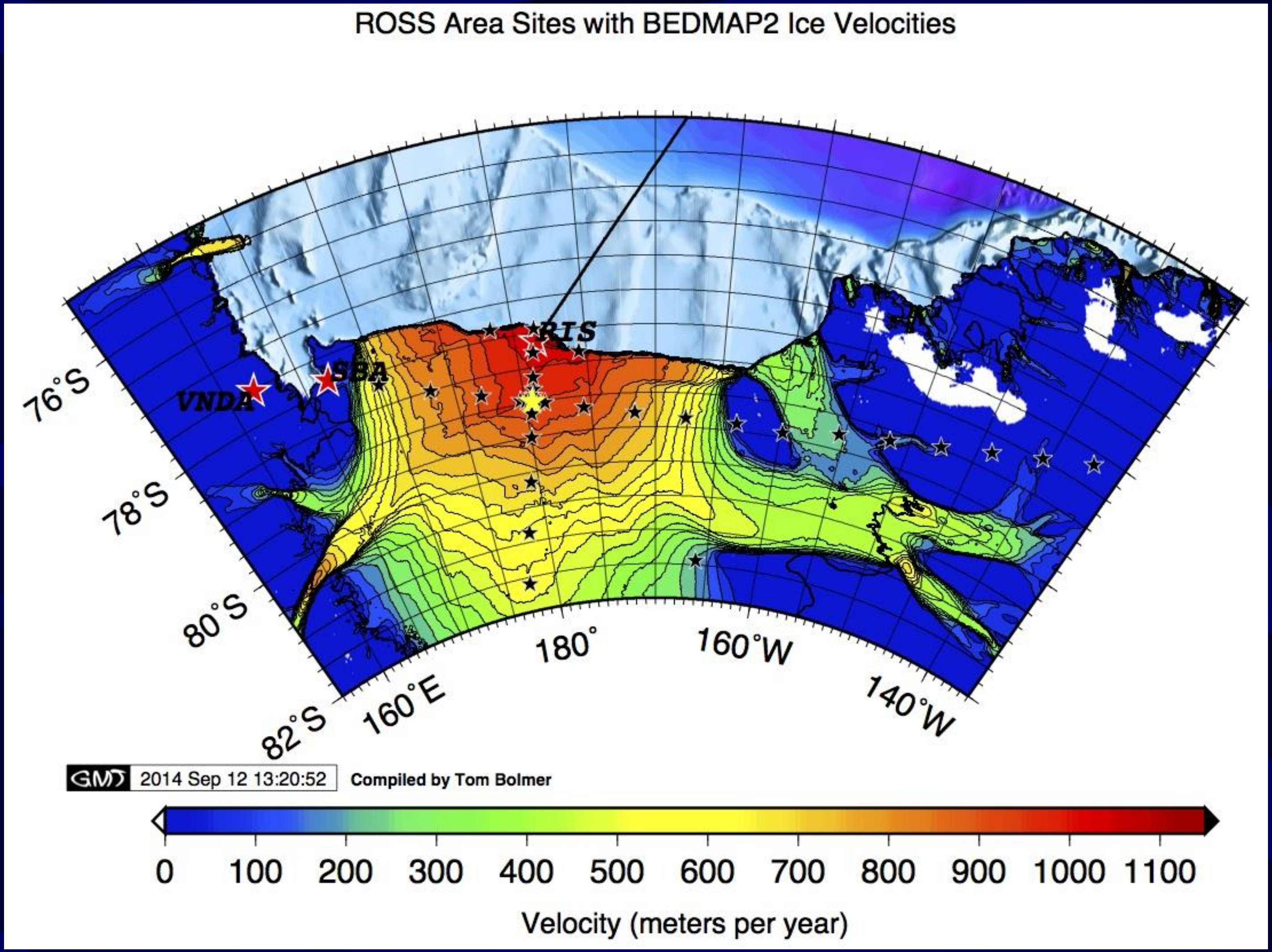


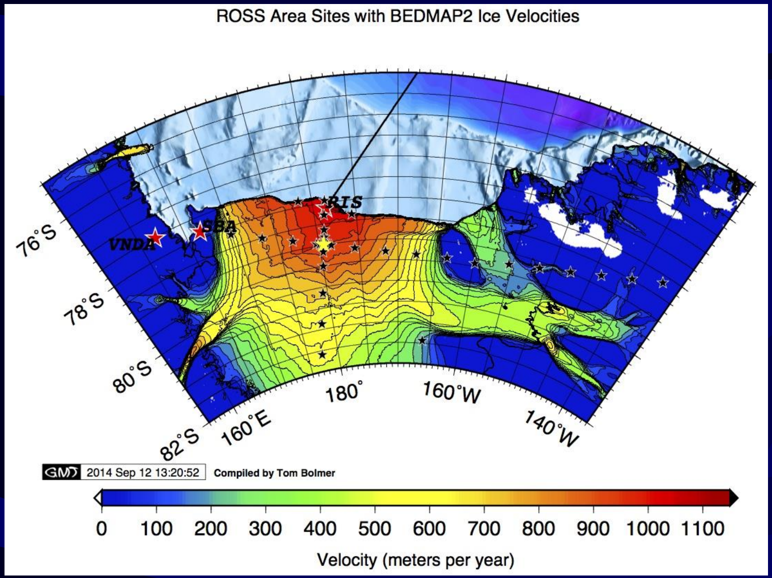
Shelf front

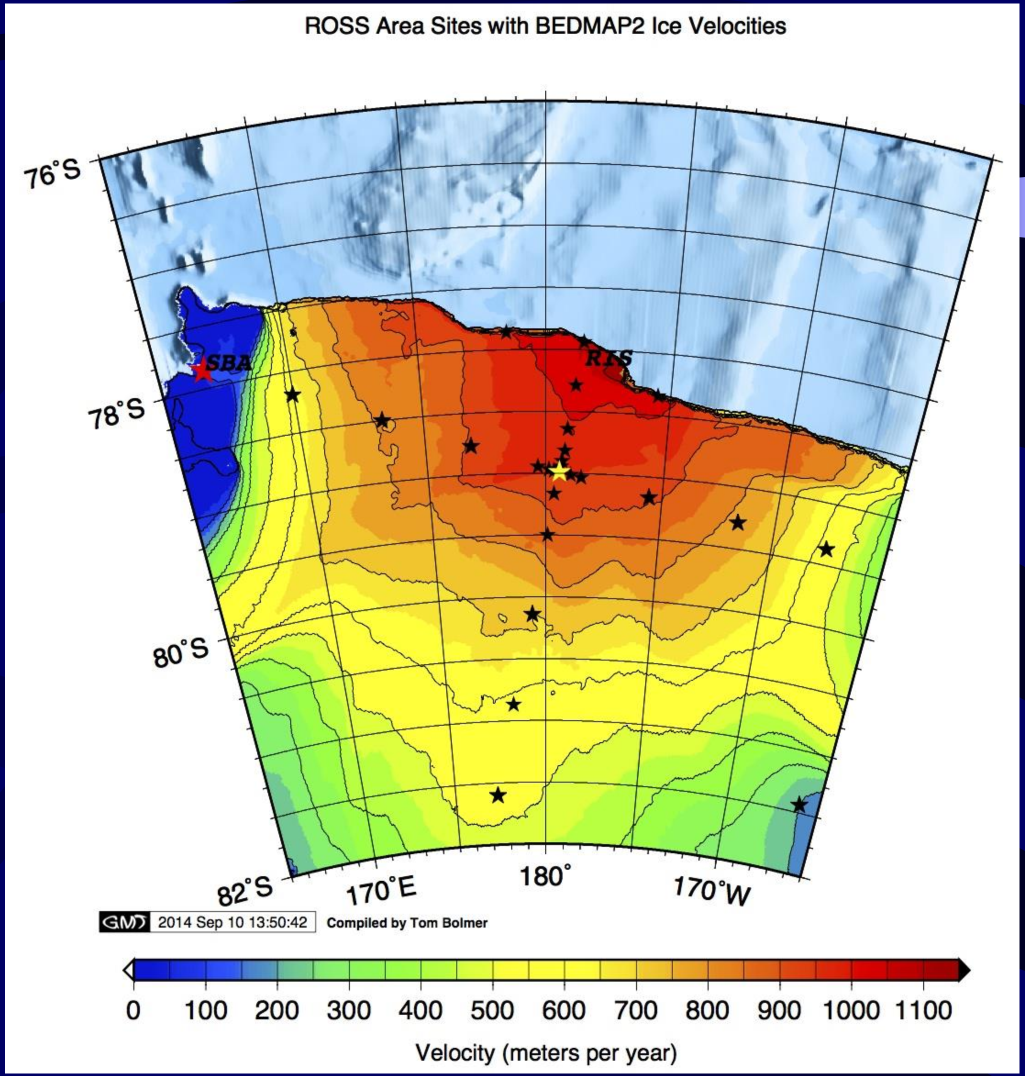
Ice thickness: ~200 m
Water depth: ~700 m

Mean ice shelf thickness over the orthogonal array ~ 350m

Ice Flow-velocity





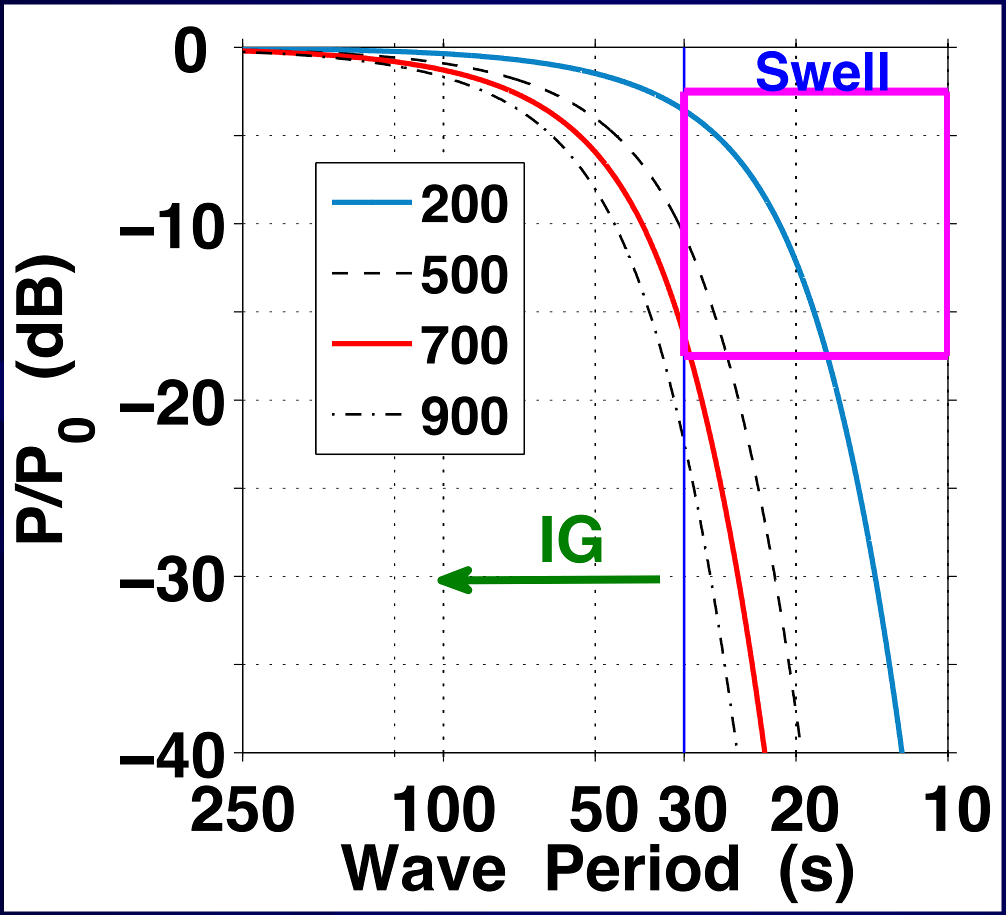


The orthogonal linear array roughly tracks a zone of fast-moving ice

as well as the seafloor channel

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

Gravity-wave Pressure Decay with Depth

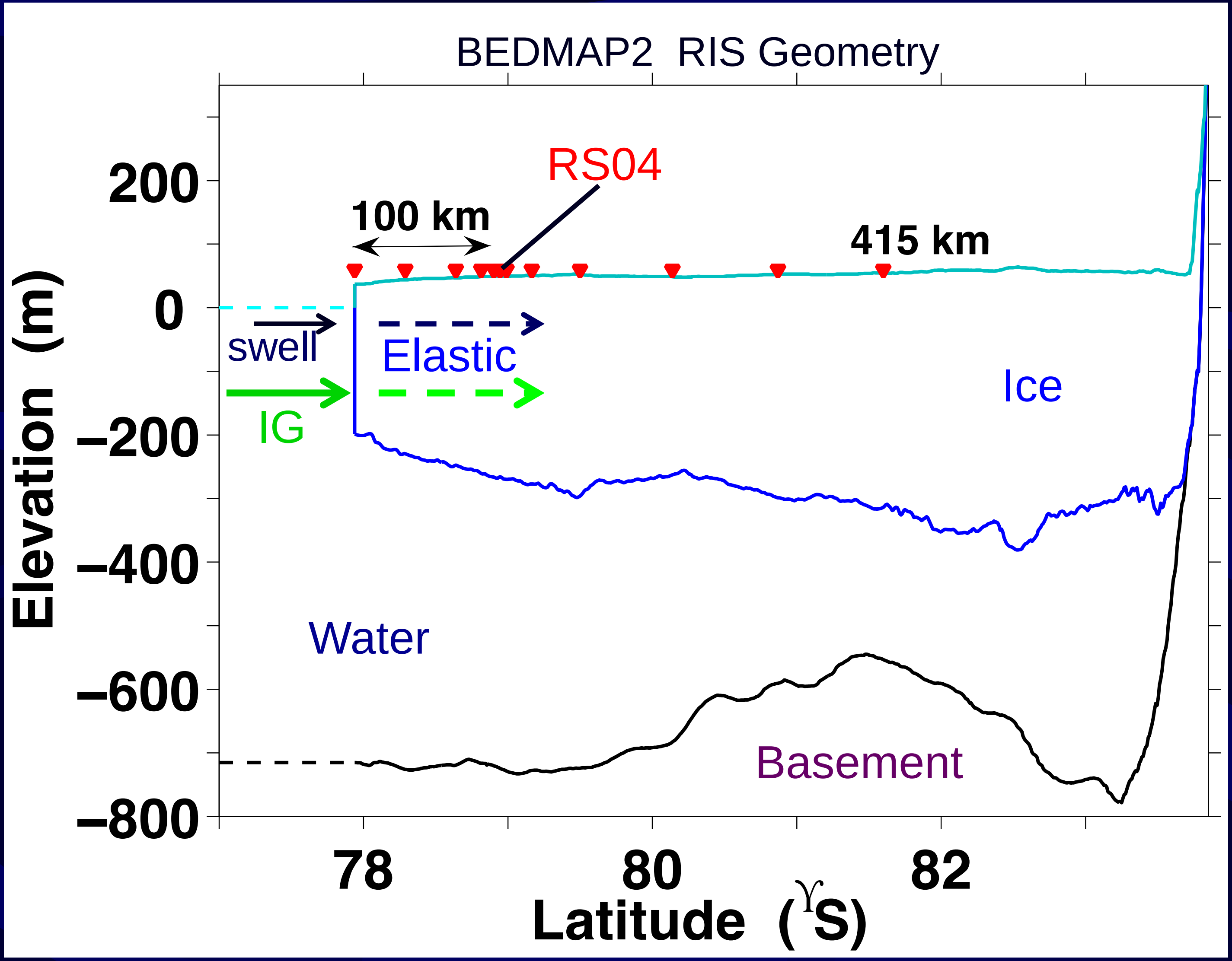


Shelf front

Ice thickness: ~200 m
Water depth: ~700 m

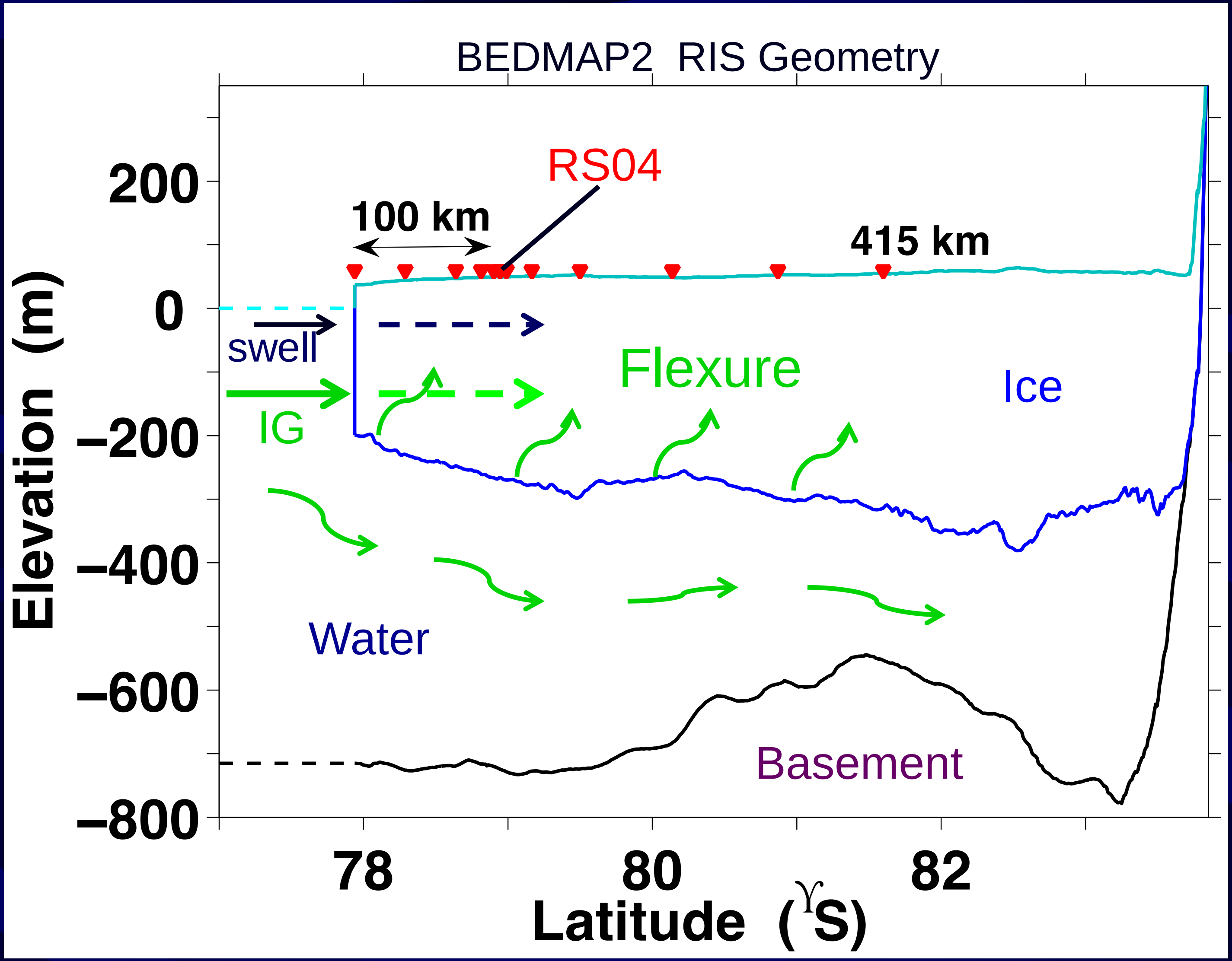
100 s IG shows little decay with depth, in contrast to Swell

Wave-induced Vibration Propagation Paths



How far can ice-front gravity-wave “impact” signals be detected → 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

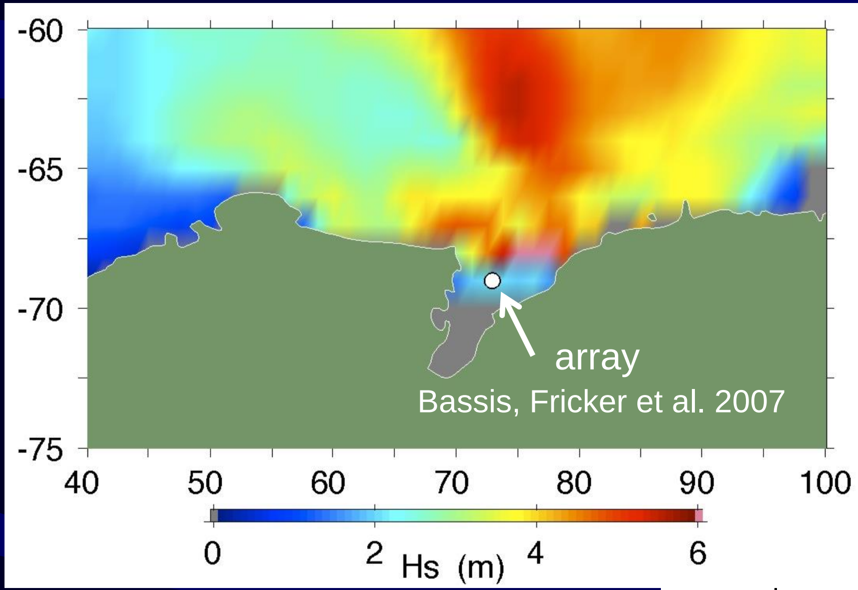
Goal: Determine spatial variability of ice shelf properties

- Beamforming to estimate dominant source direction

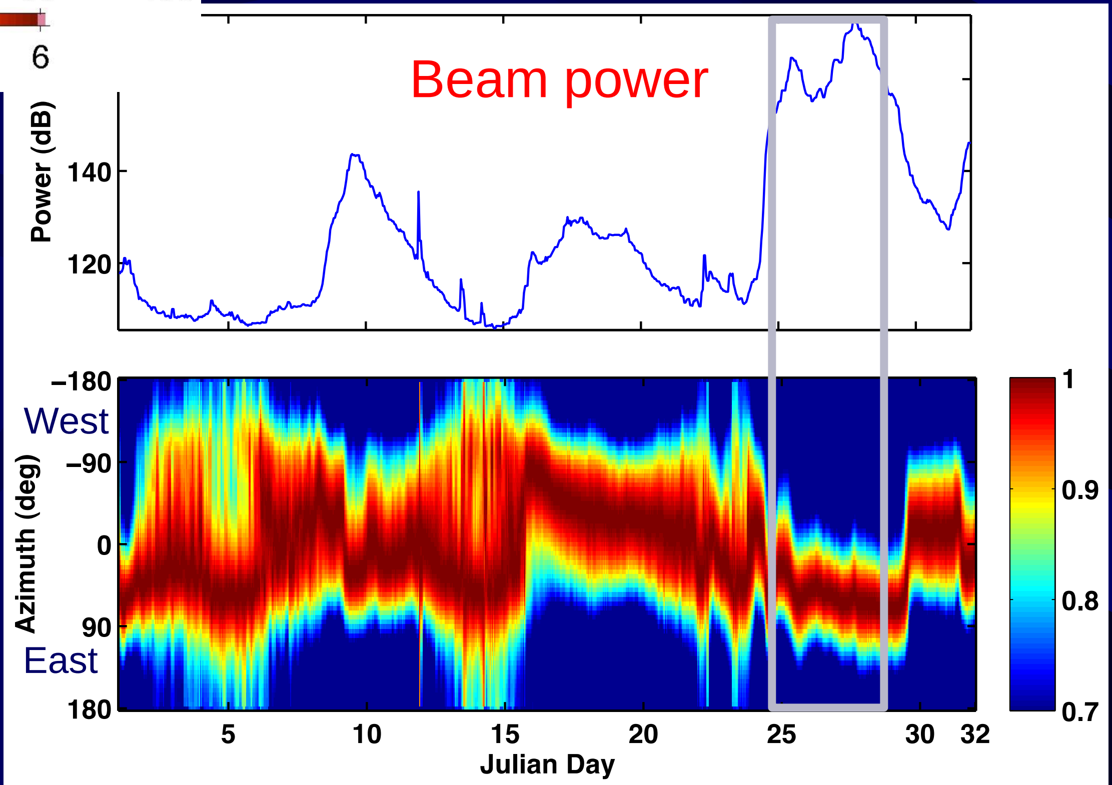
- Cross-correlation between station pairs to estimate energy propagation group velocity

- Estimate phase velocity
  -> giving estimates of elastic moduli
  -> used in seismic (TDFD) and mechanical modeling

Wave Model Hindcast: 2006 1 27 15

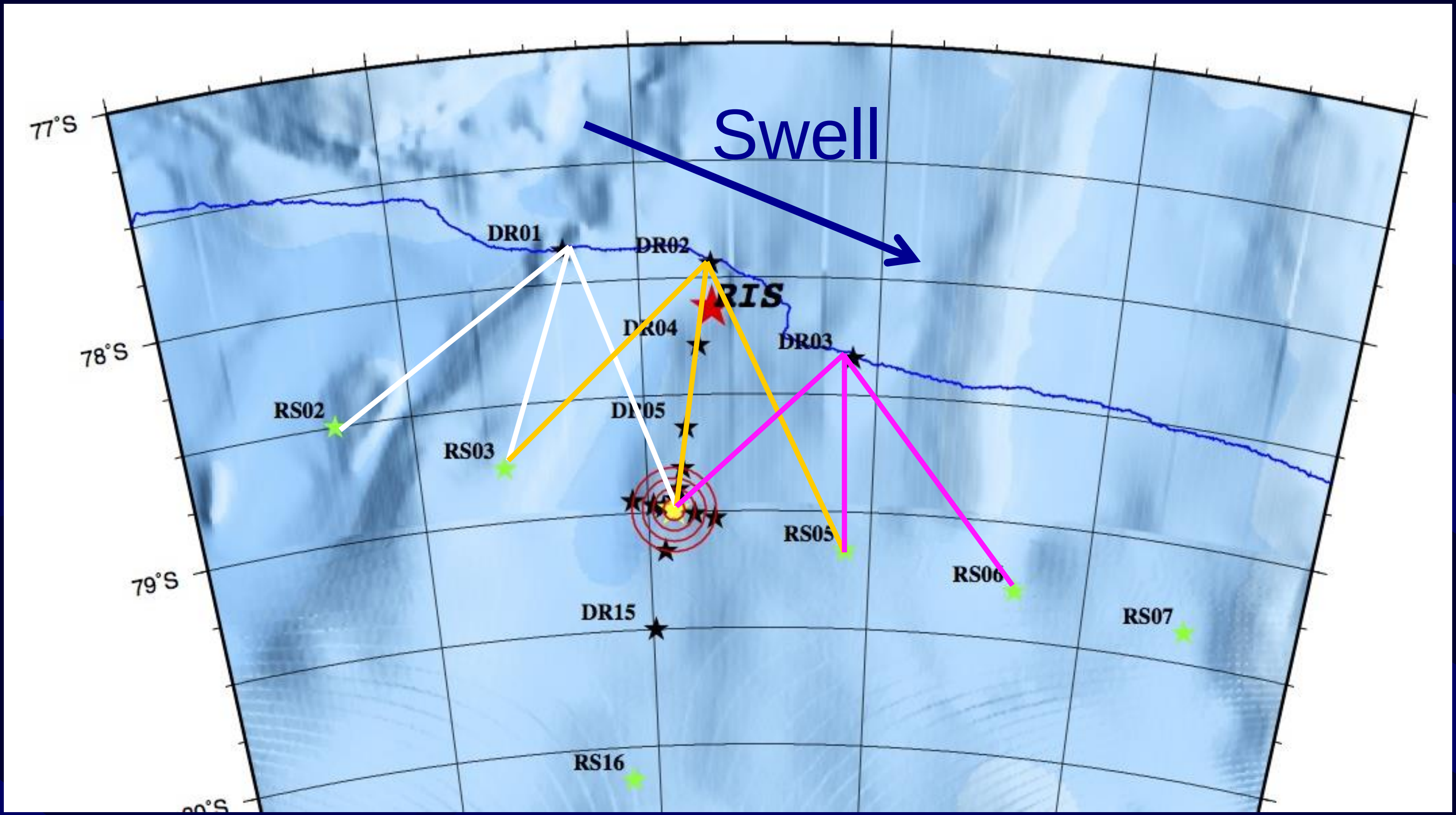


Amery Ice Shelf Source Directionality



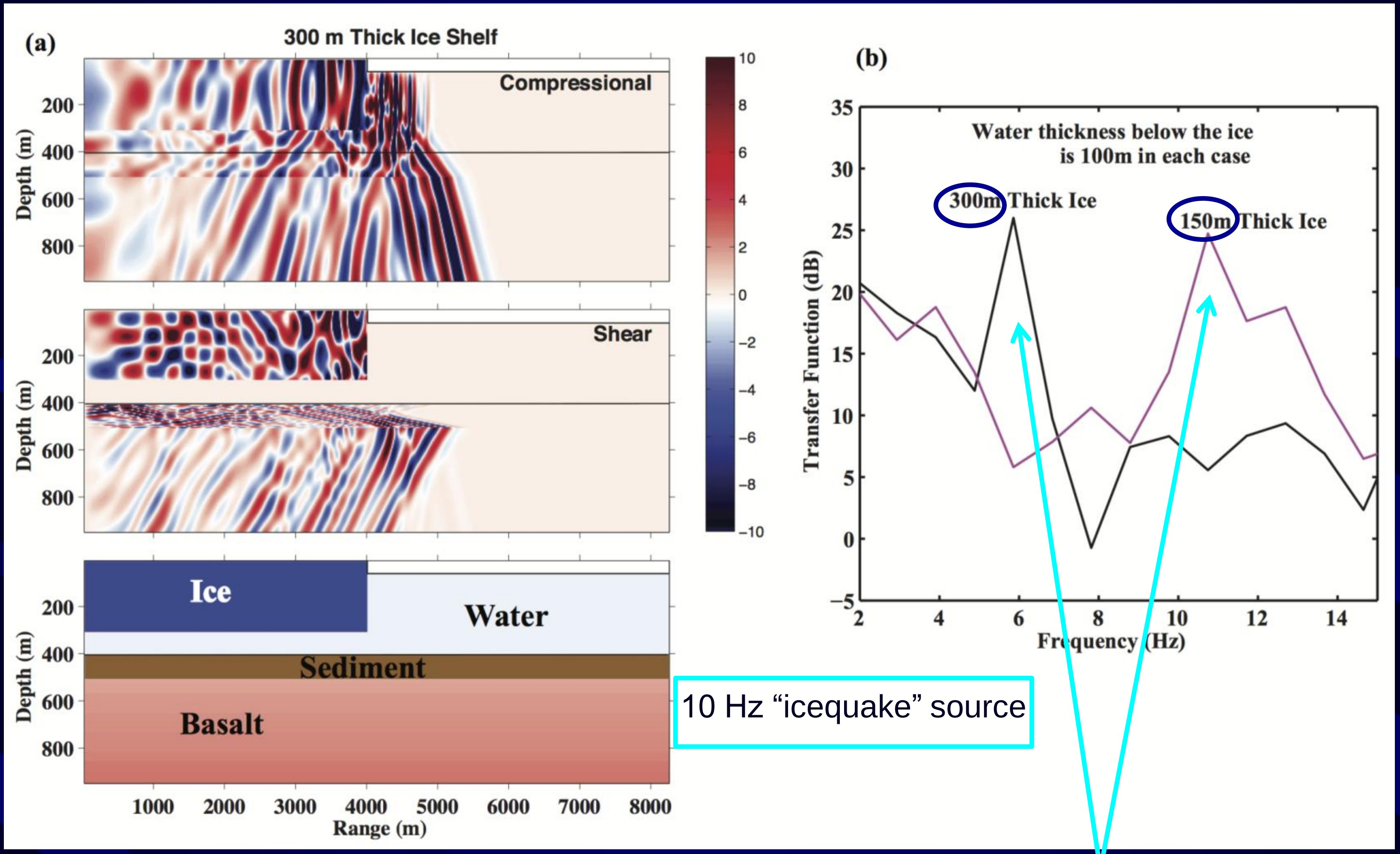
Array beamforming to obtain dominant signal direction

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

Bromirski and Stephen, *Ann. Glaciol.*, 2012

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

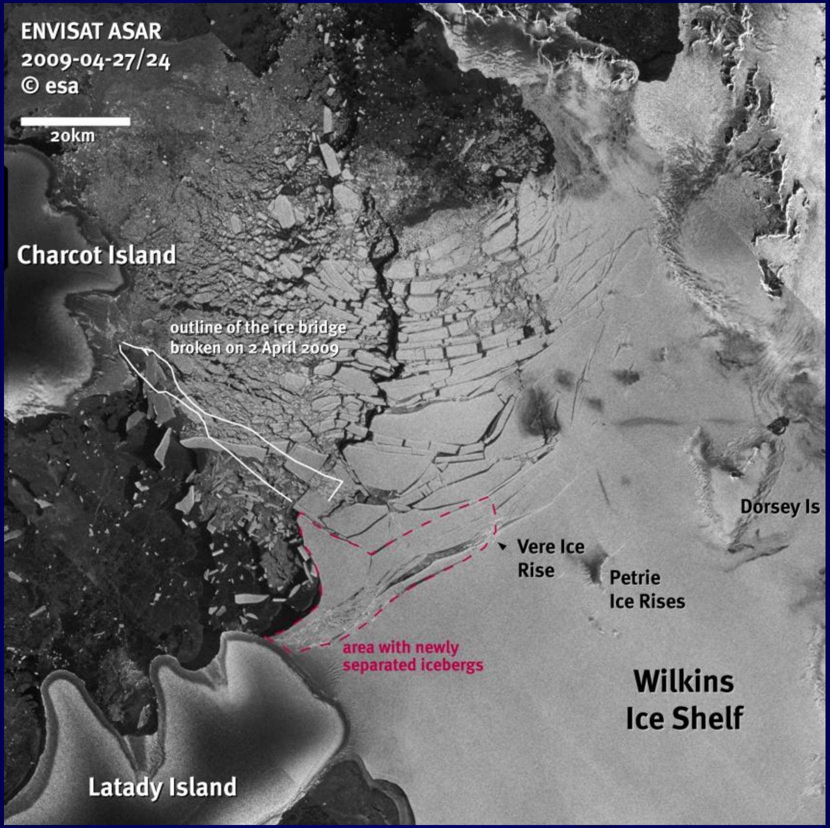
•Icequakes: Distribution and variability along the RIS front and interior

•Array processing to determine spatial variability of signal and propagation characteristics

•Model the spatial response to estimate elastic structural parameters that affect signal propagation.

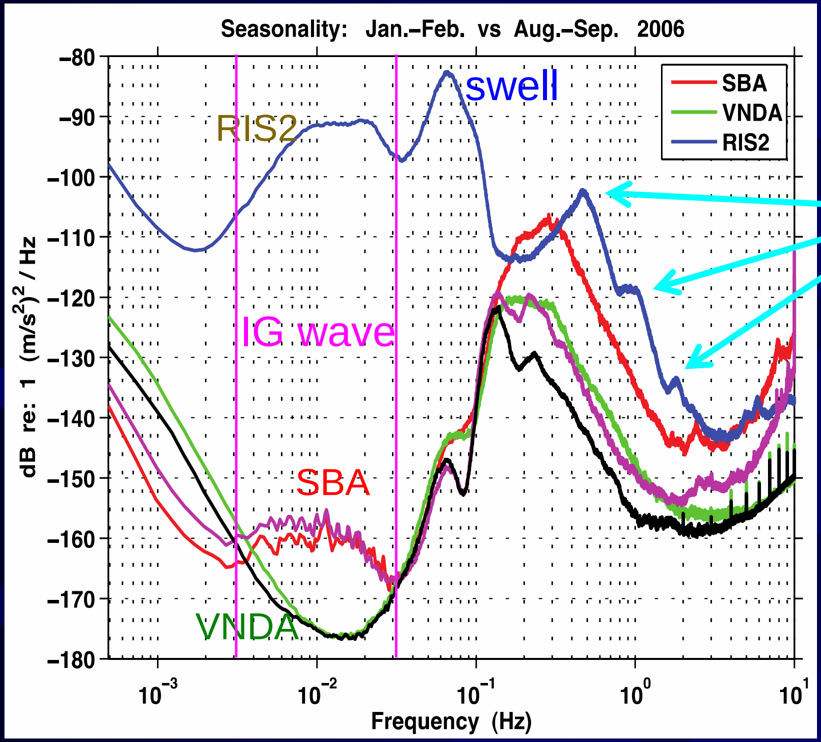
Underlying Question:

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)



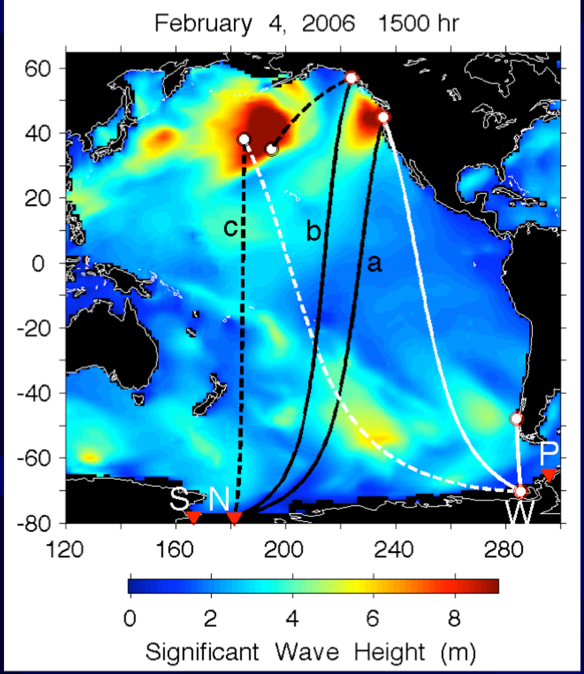
Ice shelf specific non-gravity wave spectral peaks, with the 0.5 Hz peak most prominent

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

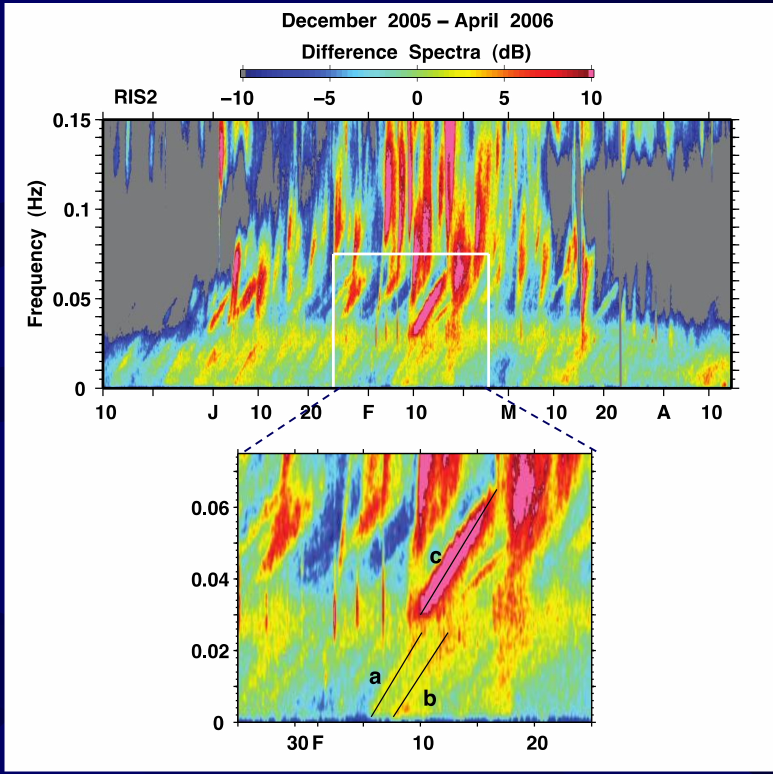
Transoceanic Infragravity (IG) Waves and Swell Impacting Antarctic Ice Shelves



Model wave height Feb 2006

Bromirski et al. 2010

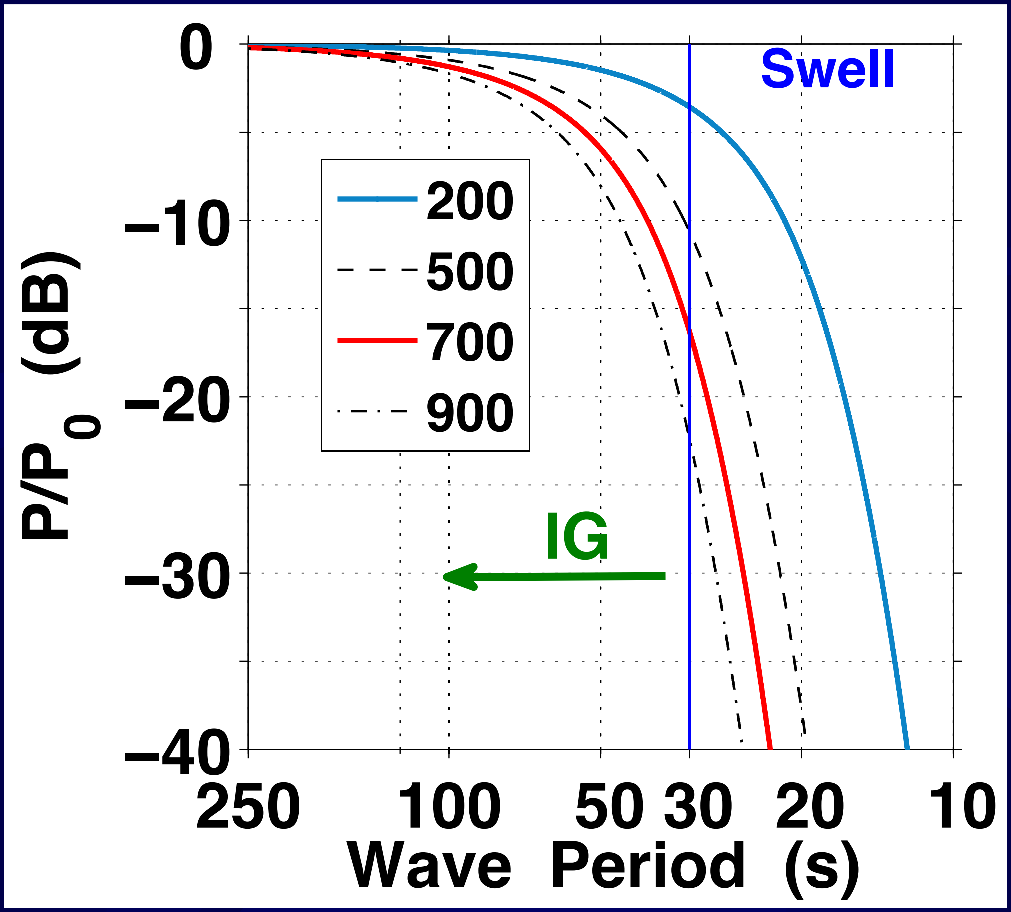
Difference Spectra

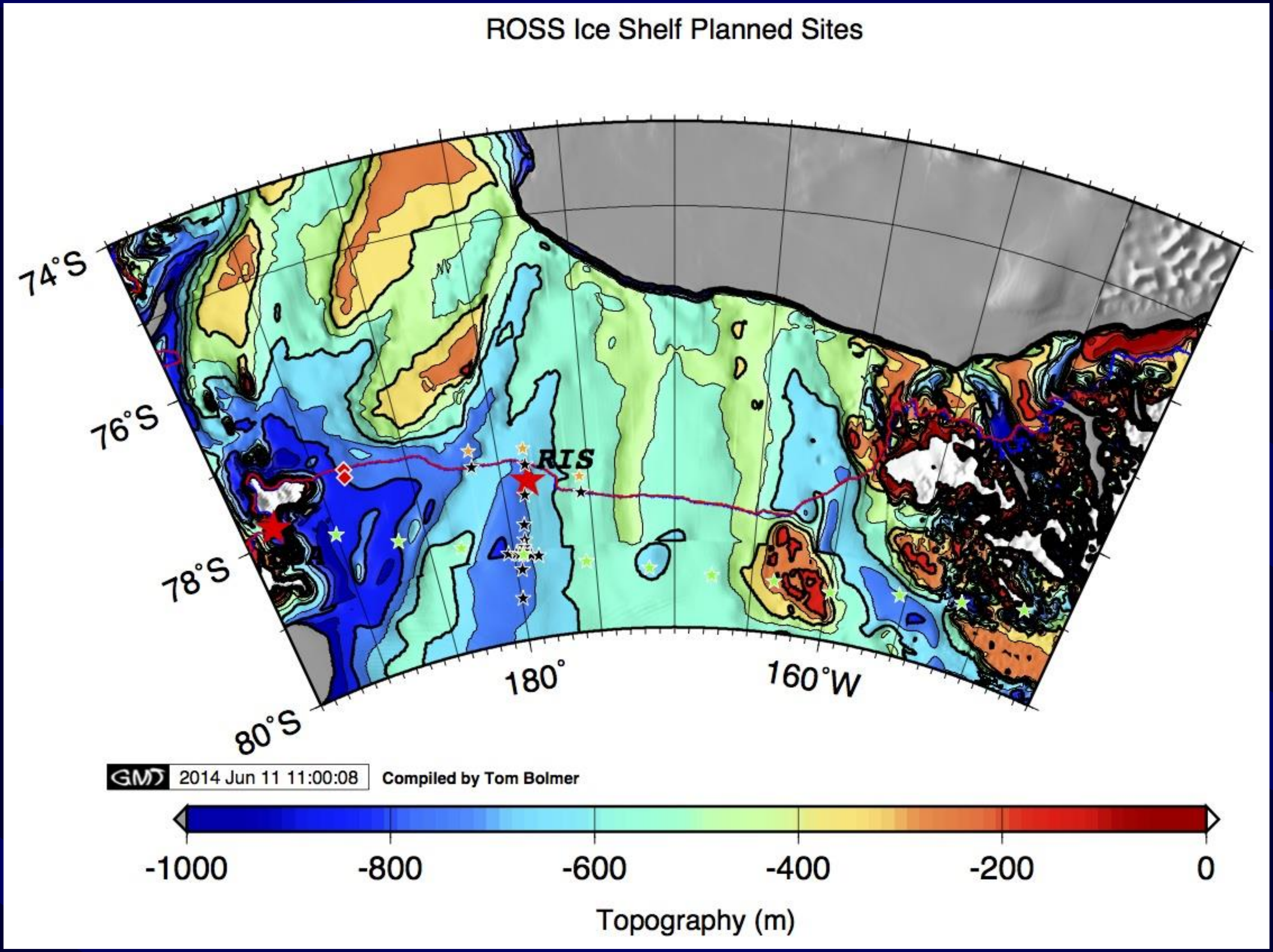


Slopes of dispersion trends and forward modeling using the gravity wave dispersion relation confirm North Pacific infragravity wave and swell source locations

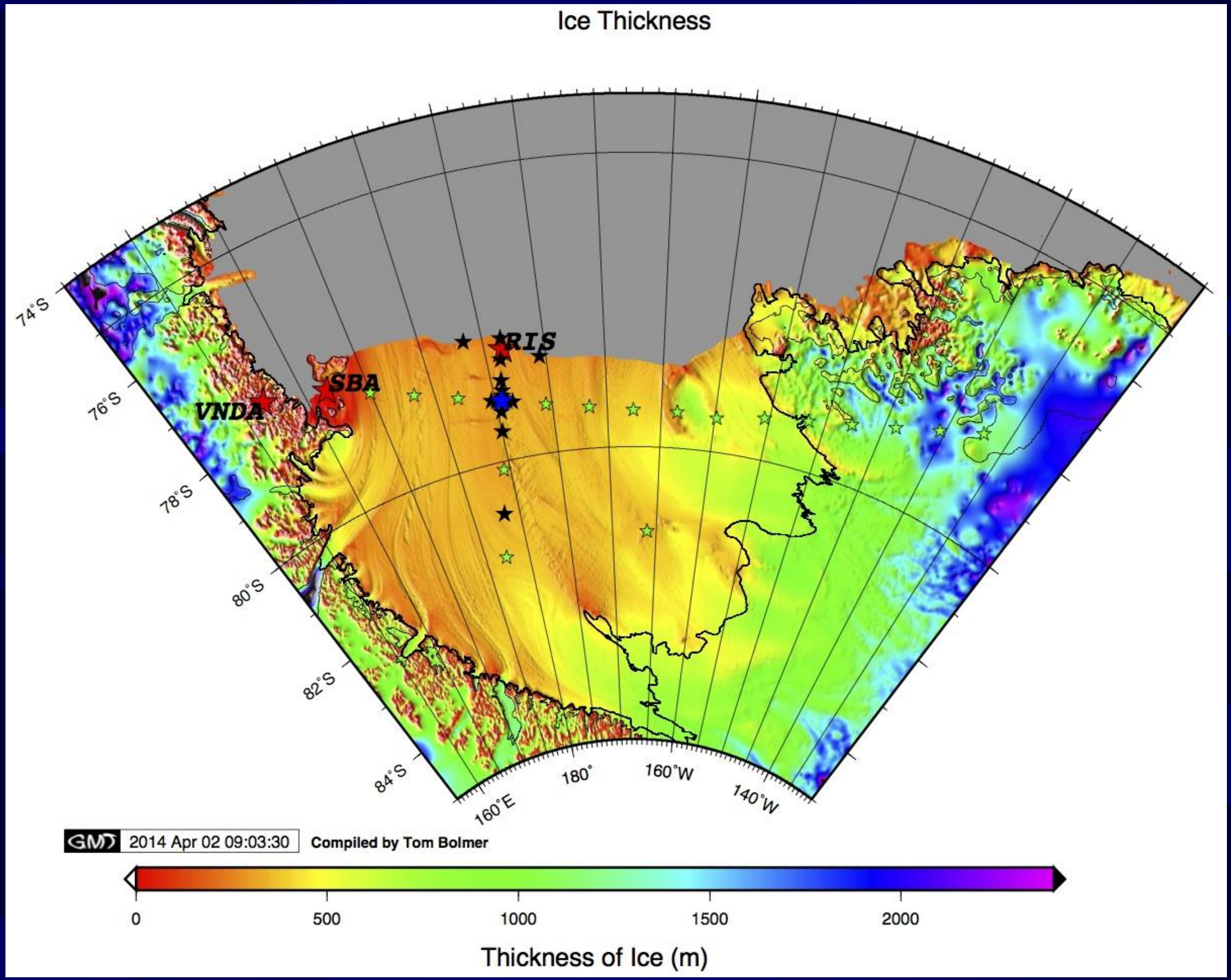
Higher amplitude possibly due to incidence angle (impacting more of the shelf front simultaneously) , OR swell energy penetrating the sub-shelf cavity

Gravity-wave Pressure decay with Depth



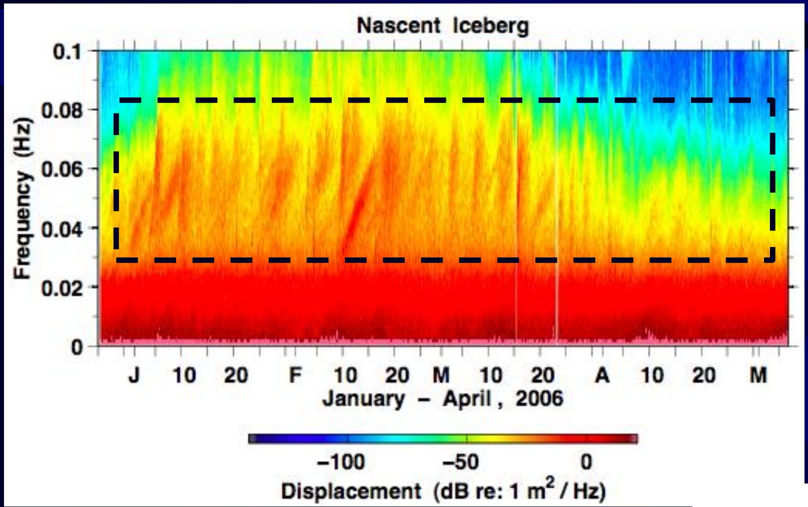


ROSS Ice Shelf Planned Sites
74°S
76°S
78°S
80°S
180°
160°W
RIS
2014 Jun 11 11:00:08
Compiled by Tom Bolmer
-1000
-800
-600
-400
-200
0
Topography (m)

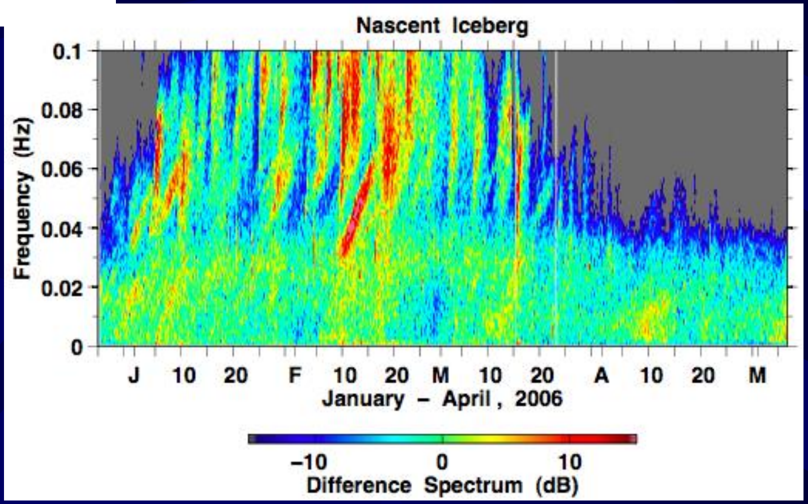


Ice Thickness
RIS
SBA
VNDA
74°S
76°S
78°S
80°S
82°S
84°S
160°E
180°
160°W
140°W
2014 Apr 02 09:03:30
Compiled by Tom Bolmer
0
500
1000
1500
2000
Thickness of Ice (m)

Nascent Iceberg Seismometer



Swell

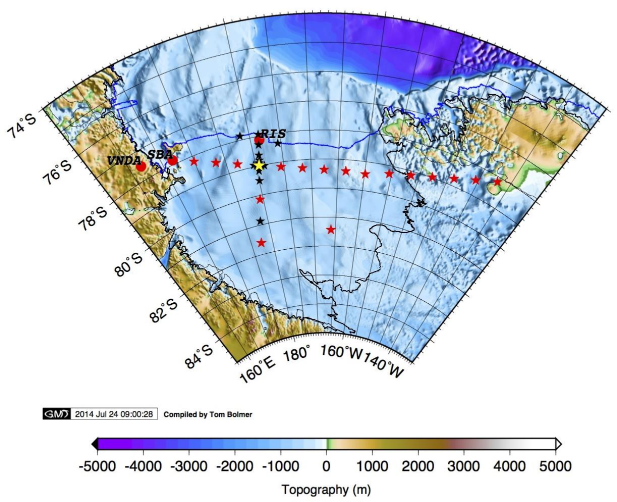


Difference spectra: removing the median

Organization

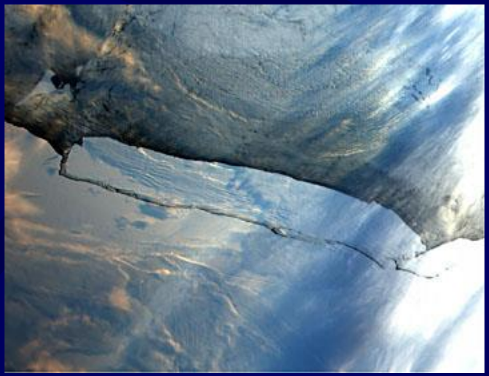
Doug in Vault

- 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

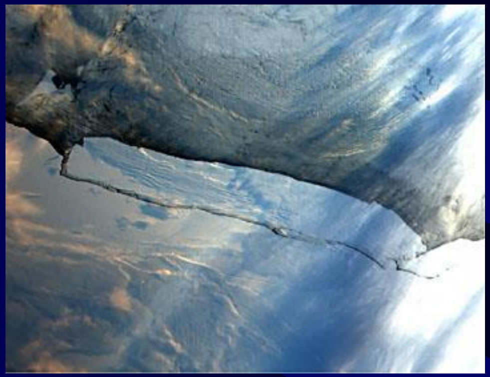
- Much greater elastic wave speed compared to gravity waves may allow separation/identification of signals generated at the front or at the basal surface

- 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?



NASA: Ross Ice Shelf

Observation plan:

- Seismometer array on the RIS

North Pacific - Antarctic Connections

Oct. 21, 2005

(MacAyeal et al., GRL, 2006)

Cracking events (Okal and MacAyeal, SRL, 2006)

(Cathles et al., JGR, 2009)

North Pacific – Antarctic Connections

Ross Ice Shelf, Antarctica Seismometer Observations

Sea ice damping of swell

<--- Infragravity waves

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

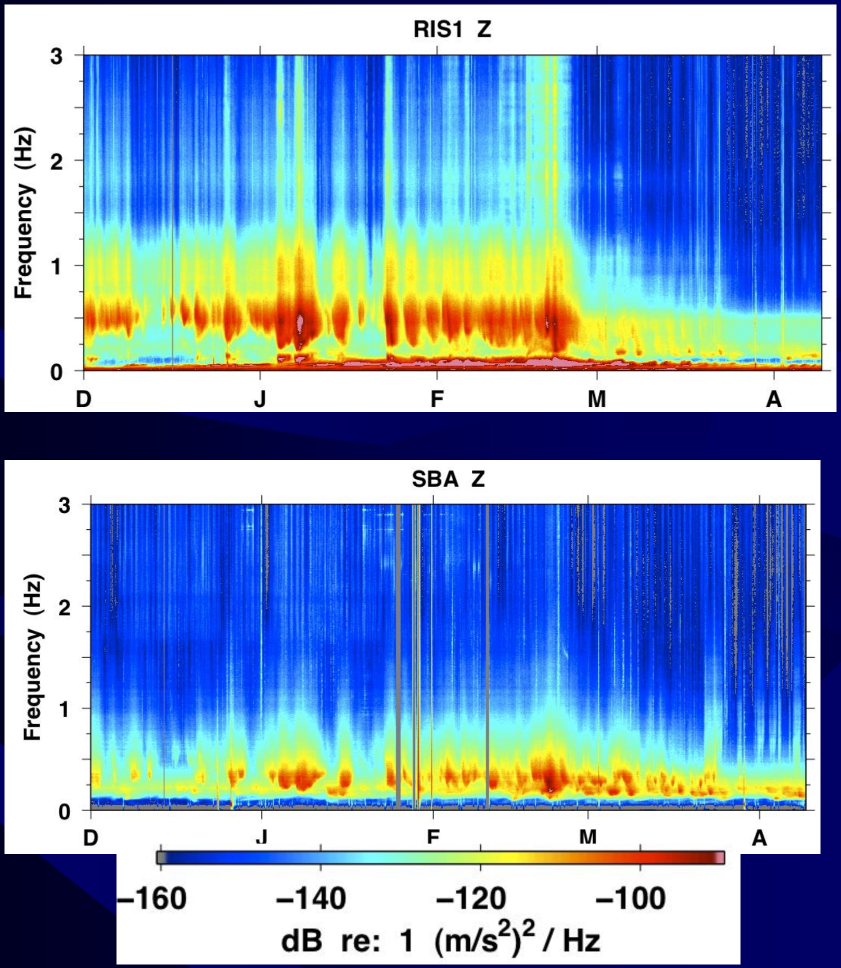
Vertical bands => local storms

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

Transocean Infragravity (IG) Waves Impacting Antarctic Ice Shelves

Difference Spectra

Model wave height Feb 2006

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

(Bromirski et al., GRL, 2010)

Comparison of Ice-Shelf Observations with Land Stations at Scott Base and Palmer Station, Antarctica

Difference Spectra (re: Jan. mean)

February (summer)

Ross

Mean Spectra (EQ noise excluded)

Scott Base

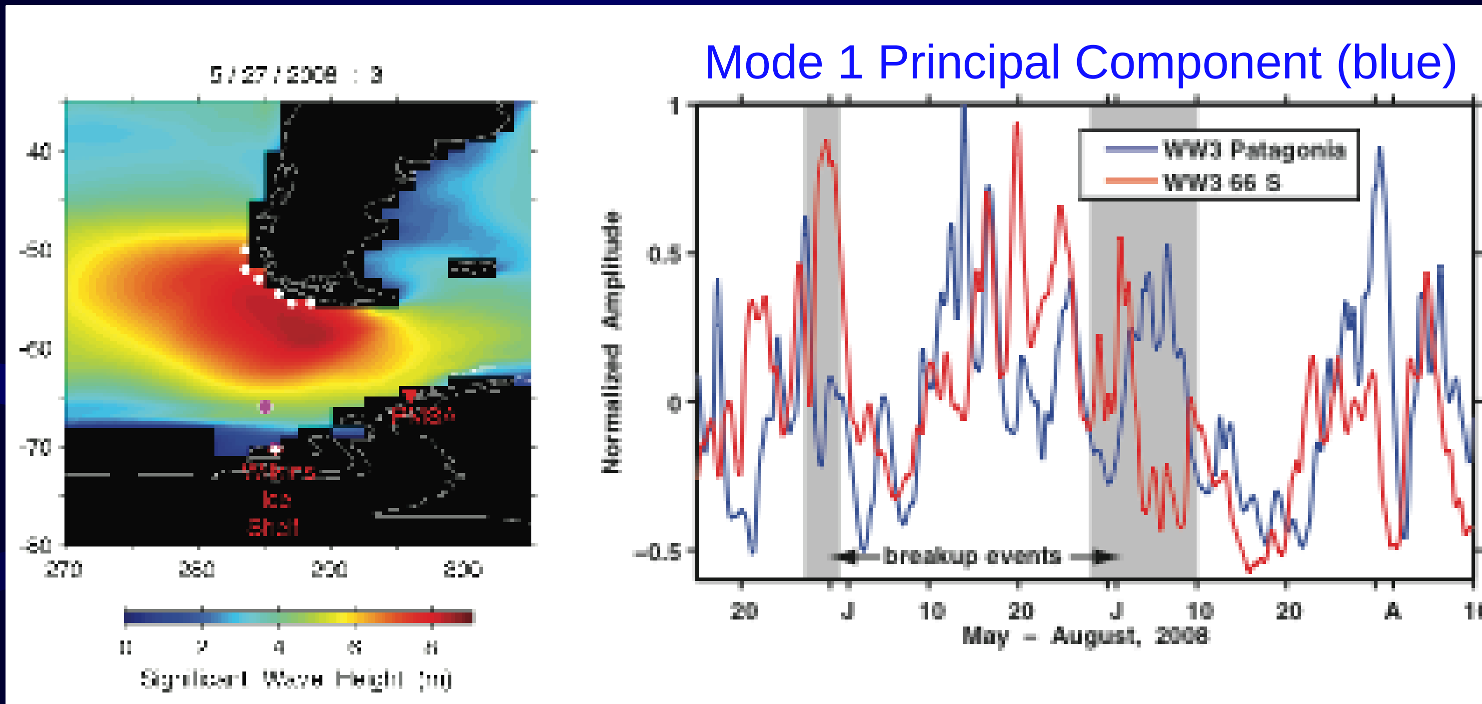
August (winter)

Palmer Station

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

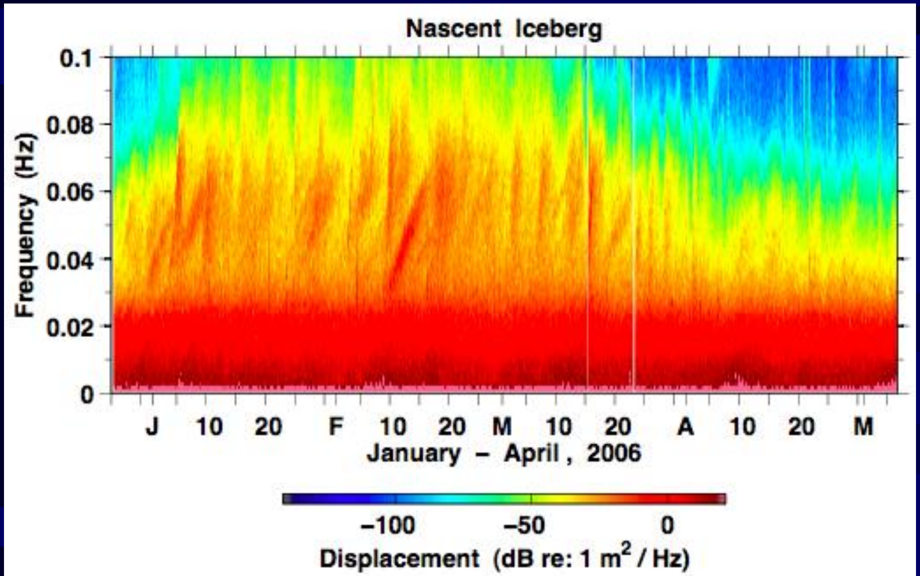


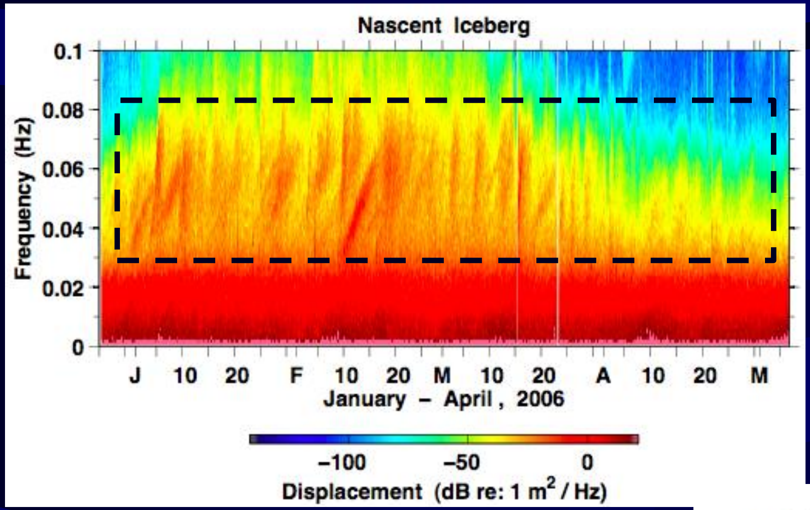
Image: Joe Harrigan
Olga Sergienko

MacAyeal et al., GRL, 2006

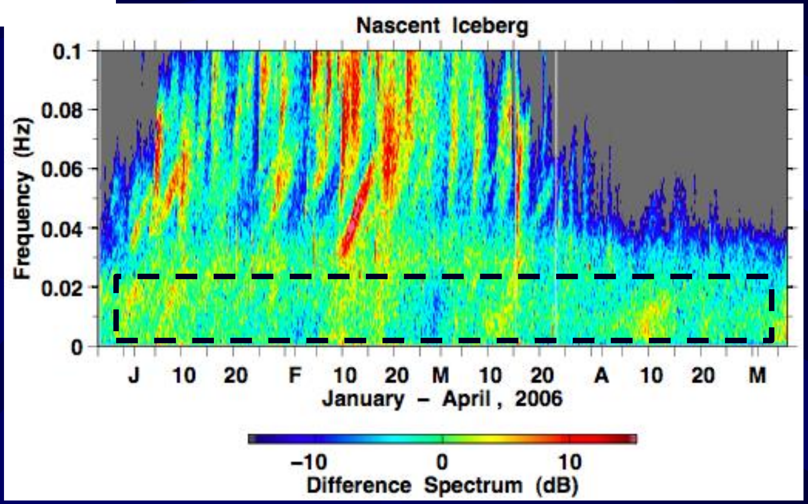
Cathles et al., JGR, 2009

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

Nascent Iceberg Seismometer

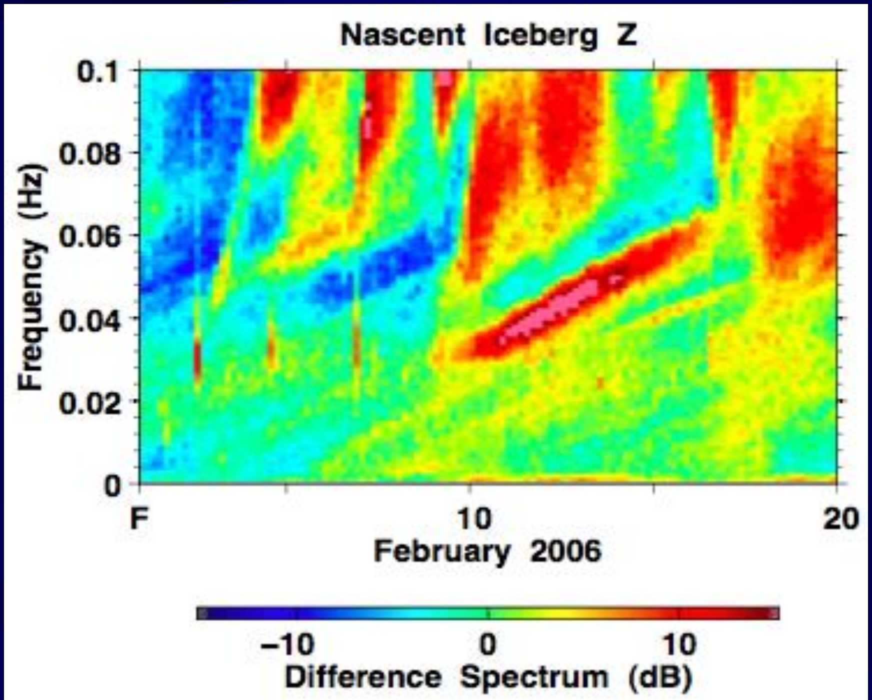


Swell



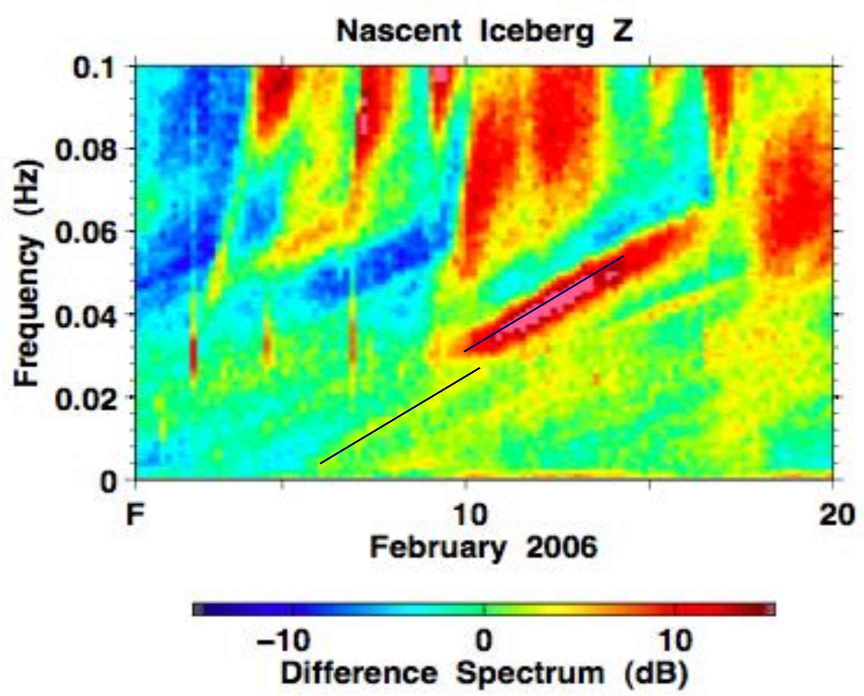
Infragravity waves

Dispersion Trends



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

Dispersion Trends



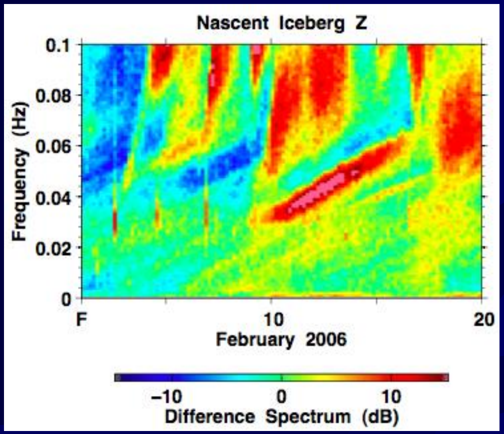
Gravity wave dispersion relation propagation over great circle paths (infinite depth)

Dispersion trends and the associated IG wave lag are consistent with coastal generation from the same storm waves

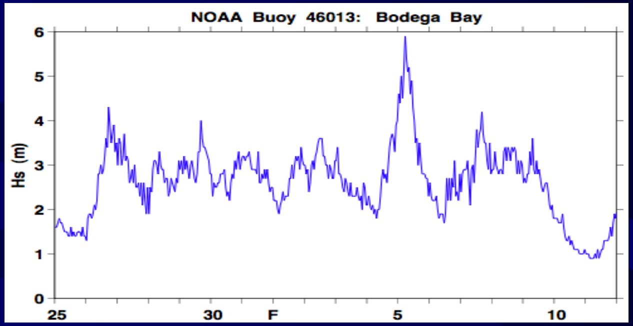
North Pacific Mid-ocean and Coastal Source Regions

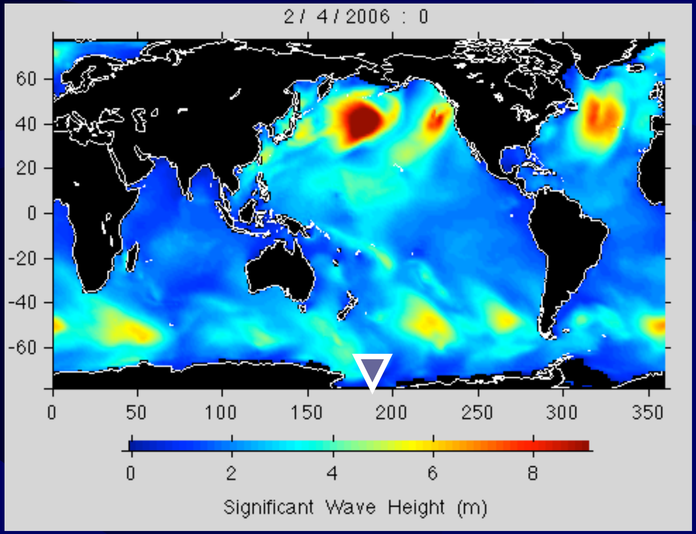
Nascent Seismometer

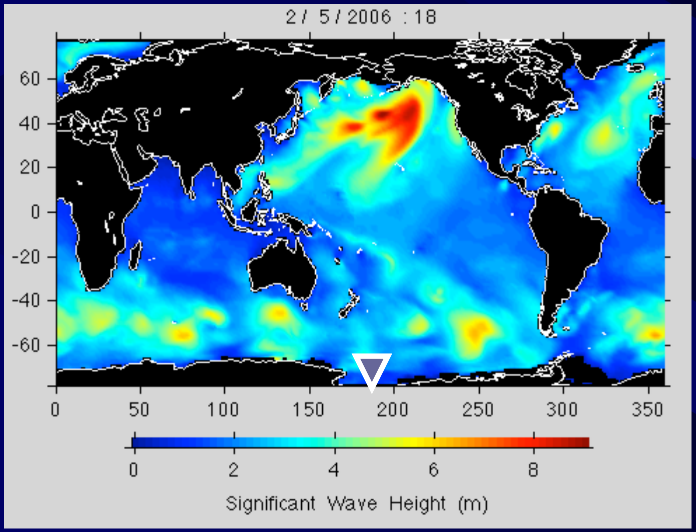
4 hr average



NOAA Buoy: CA Coast







NOAA WWIII Wave Model

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