Wave-ice feedbacks in polar oceans

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The Arctic is changing

Teleconnections with lower latitudes mean that Arctic sea ice:
- Is an indicator of GLOBAL climate change.
- Modulates GLOBAL climate change.
Transition to a seasonally wave-driven upper-ocean

- Less ice $\rightarrow$ more open water $\rightarrow$ larger fetch for wave development
  $\rightarrow$ More energetic wave climate

Same wind speed (17 m/s)... very different boundary layers
Emerging feedback mechanisms (first-order uncertainties)

Freeze season

- Inhibit ice skin over
- Increase frazil production
- Mechanical ice thickening

Increased ice formation (Negative feedback)

Melt season

- Open water
- Surface waves
  - Wave breaking
  - Aerosol production?
    - Increase air-sea energy and momentum flux
    - Increase upper-ocean turbulence
  - Wave breaking
    - Break up ice
      - Decreased albedo, Increased ice surface area, ???
  - Halocline erosion
  - Ventilating NSTM water

Increased melt rate (Positive feedback)

Need to **quantify these feedbacks** in order to make accurate Arctic (and global) predictions.
Emerging feedback mechanisms (first-order uncertainties)

Key questions:
1. How does ice affect waves? Energy attenuation, spectral evolution, etc.
2. How do waves affect ice?
   a. Breakup and melting of sea ice.
   b. Wave forcing in the MIZ
   c. Modification of the ice formation process.
3. How does wave-driven turbulence affect the upper-ocean heat content / stratification in the Arctic?

Need to quantify these feedbacks in order to make accurate Arctic (and global) predictions.
Wave effects in the MIZ – Ice formation

• In calm conditions, a thin surface skin of ice quickly forms.

• All additional growth is thermally controlled

• Wave motions and associated turbulence inhibit this skin formation.
The wave-affected ice formation process

Ice-edge normal stresses:

\[ \tau_{air} = \rho_a C_a |U_{10} - u_I| (U_{10} - u_I) \]

\[ \tau_{water} = \rho_w C_w |U_w - u_I| (U_w - u_I) \]

Wave stress + Wind stress + Current stress = Floe jumble internal stress

Frazil, Aggregation, Max concentration, Rafting, Equilibrium, Congealed

Sutherland and Dumont, JPO, 2018
External stress acting on MIZ: Wave radiation stress

Excess flow of momentum due to waves. Proportional to wave energy, $E$.

The stress applied to the ice is:

$$\tau_{wv} = -\rho g \frac{1}{2} \frac{\partial E}{\partial x} \hat{e}_x$$

(gradient of wave energy)

Well known force acting on floating bodies (Longuet-Higgins 1977, etc.)

Used to model ice motion (Perrie and Hu, 1996, 1997)

Also used to describe ice banding (Wadhams 1983)
Defining the marginal ice zone

“Area at the ice edge over which open-water processes are important”

• Set distance at which integrated wind stress is equal to the total wave radiation stress forcing:

 Integrated wind stress = \[ G_{air} = \int_{0}^{X_{MIZ}} \tau_{air} \, dx = \rho_a C_D U_{10}^2 X_{MIZ} \]

 Total wave radiation stress = \[ G_{wv0} = \int_{0}^{\infty} \tau_{wv} \, dx = \frac{\rho g}{2} E_0 \]

 \[ X_{MIZ} = \frac{\rho_w g}{32 \rho_a C_D} \left( \frac{H_s}{U_{10}} \right)^2 \]

Sutherland and Dumont, JPO, 2018
The large scale picture – Waves in the Antarctic MIZ

Stopa, Sutherland, and Ardhuin, PNAS, 2018
Largest-ever dataset of measurements of wave spectra in sea ice; covering the entire Antarctic MIZ in all seasons over multiple years.

\[ E(x_{\text{ice}}) = E_0 e^{-\alpha x_{\text{ice}}} \]

Stopa, Sutherland, and Ardhuin, PNAS, 2018
Wave radiation stress forcing at larger scales

- On average, waves dominate over wind forcing for the first $X_{MIZ} \sim 40$ km

- Wave attenuation is highly spatially and temporally inhomogeneous.

- Waves provide a stabilizing mean on-ice forcing in the MIZ.

$\rightarrow$ Zonal dependence of MIZ forcing by wind (green) and waves (blue). Negative values are in the on-ice direction.

Stopa, Sutherland, and Ardhuin, PNAS, 2018
Mohr-Coulomb materials

Horizontal failure stress, $\sigma_x$, of Mohr-Coulomb granular material is related to vertical stress, $\sigma_z$:

$$\sigma_x = \left[ \frac{(1 + \sin \phi)}{(1 - \sin \phi)} \right] \sigma_z$$

Depends upon $\phi = \text{Internal friction angle (TBD)}$

1D deep water plane waves, neglecting wind and current stress:

$$K_r \zeta_{eq}^2 = \frac{\rho g}{2} E_0$$

where

$$K_r = \frac{1}{2} \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right) (1 - n) \rho_i g \left( 1 - \frac{\rho_i}{\rho_w} \right)$$

$n = \text{porosity (0.4)}$

$\rho_i = \text{Ice density (900 kg/m}^3\text{)}$

$\rho_w = \text{Water density (1035 kg/m}^3\text{)}$

Solving for $\zeta_{eq}$ gives the maximum ice thickness for a given incoming wave field
MC-radiation stress model applied to in situ data (LSLE)

Thickness normalised by equilibrium thickness

$$\zeta_{eq} = \left( \frac{\rho g}{2K_r} E_0 \right)^{1/2}$$

Ice fetch normalised as

$$\chi = \alpha \left( x_{ice} - x_c \right)$$
Wave modification of ice: Perspectives

Progress:
• Developed the largest-ever dataset of wave attenuation in sea ice using SAR.
• Waves dominate over wind forcing over outer 40 km of Antarctic MIZ.
• Wave stress is a stabilizing forcing on the Antarctic MIZ.

Questions:
• Global applicability of MC model; under what conditions does it actually work? Is it useful on a large scale?
• How does ice transition from pancake jumbles to solid ice? In individual forcing events or more gradually?
• Ice breakup by waves (not covered here): What is the real-world FSD? What sets it? How does wave attenuation change when ice is broken?
• Needed: Broad parameter space ...measurements of ice thickness, type, wave spectra, and air water temperature and heat flux. Large-scale, before, during, and after events.
Wave-modulated Arctic Air-sea eXchanges and Turbulence (WAAXT)

Open water → Surface waves → Wave breaking → Break up ice

- Inhibit ice skin over
- Increase frazil production
- Mechanical ice thickening

Aerosol production? → Increased air-sea energy and momentum flux → Increased upper-ocean turbulence → Halocline erosion → Ventilating NSTM water → Increased melt rate (Positive feedback)

Decreased albedo, Increased ice surface area, ???

Melt season

Freeze season

- Increased ice formation (Negative feedback)

Need to quantify these feedbacks in order to make accurate Arctic (and global) predictions. WAAXT \(\rightarrow\) Provide a better understanding of the governing small-scale physics.

Use novel, integrated measurements to answer, “How do waves:”

1) Affect the ice formation process? 
2) Modify open water stratification in the Arctic Ocean? 
3) Break up and help melt sea ice?
WAAXT Methodology – Increasingly ambitious process studies

LSLE Natural laboratory (2+ Experiments)
Simplified access to relevant physical processes on a reduced scale:
- **MIZ process studies** – Focus on **wave effects on ice formation and breakup** in a dynamic and adaptable environment before extending them to global scales.
- **Instrument development** – Allows inexpensive and rapid iterations of instrumentation and measurement techniques.

Arctic Marginal Ice Zone (1+ Experiment)
Full scale experiment
- Extend LSLE results to **larger parameter space** ( Longer more energetic waves, thicker ice, etc.)
- Focus on interactions with **Arctic stratification**

Theory, laboratory experiments

Basin-scale remote sensing, modelling

![Image showing laboratory and Arctic region](image-url)
WAAXT measurement approach

→ Capture spatial and temporal intermittency
→ Measure small processes and their bulk effects; close energy and momentum budgets.

Sentinel-1 satellite
- Wave field (open water & ice)
- Large-scale ice cover

Research aircraft
- Wave field, ice properties, surface velocity field and thermal structure.

FLAME buoy
- Air-sea fluxes, waves

AUV (profiling)
- Upper-ocean stratification, turbulent structure.

AUVs (surface following)
- Near-surface turbulence (breaking and ice motions)
- Ice thickness, water properties

Wave breaking
Elevated turbulence

Mixed layer (cold, fresh)
Halocline (cold)
Atlantic water (warm, salty)
Summary: An emerging wave climate =

**First-order unknowns**
- Do these feedbacks exist? Do they matter?

**Affects a wide range of stakeholders**
- Operational users, modelling community, and pure science.

**Rich scientific problem**
- Intersection of fluid mechanics, solid mechanics, thermodynamics, chemistry, ...and biology?

**Timely**
- Arctic ocean is undergoing rapid changes – we need to understand what is happening.
- New remote sensing and measurement techniques are finally making this possible.