Wave-ice feedbacks in polar oceans

Peter Sutherland (*LOPS – IFREMER*)

Key collaborators: Justin Stopa (UH), Dany Dumont (UQAR), Fabrice Ardhuin (LOPS), John Brozena (NRL ret.).

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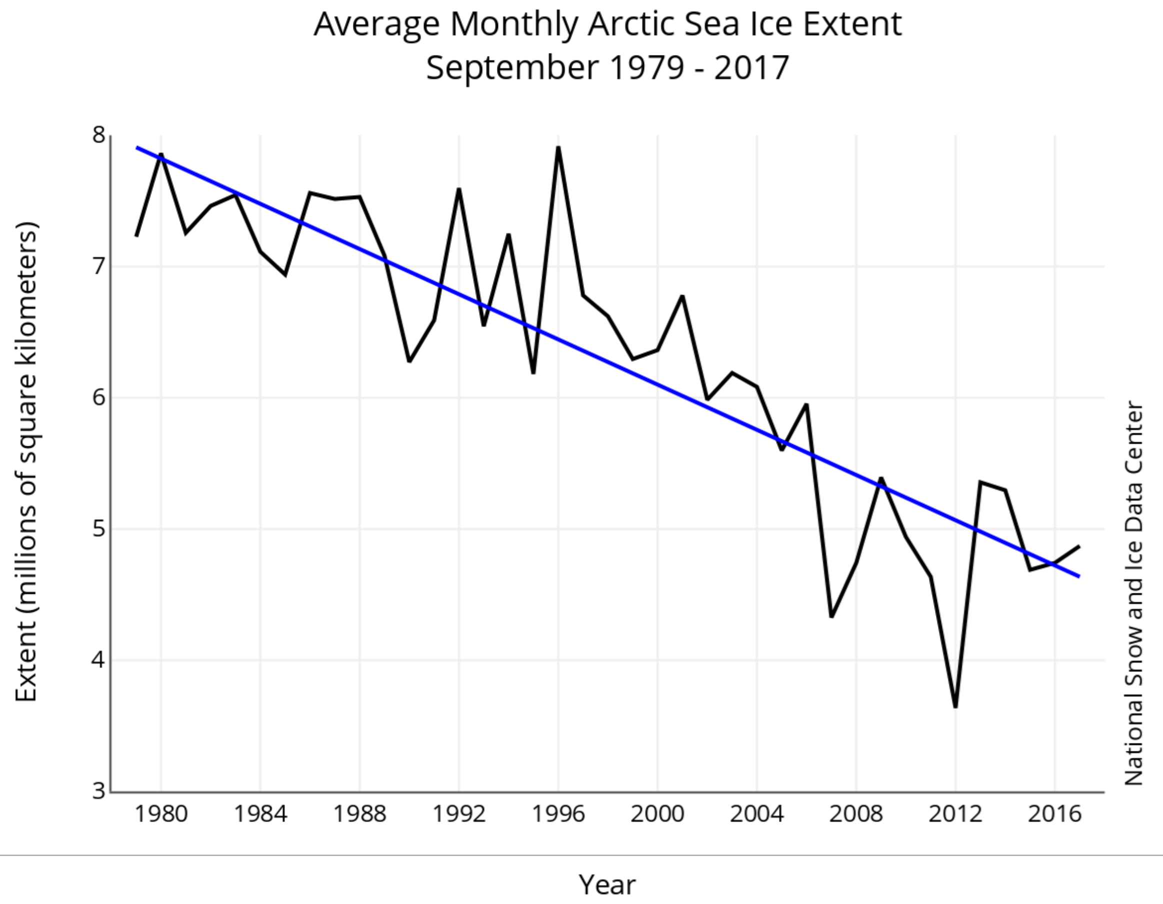
Ifremer

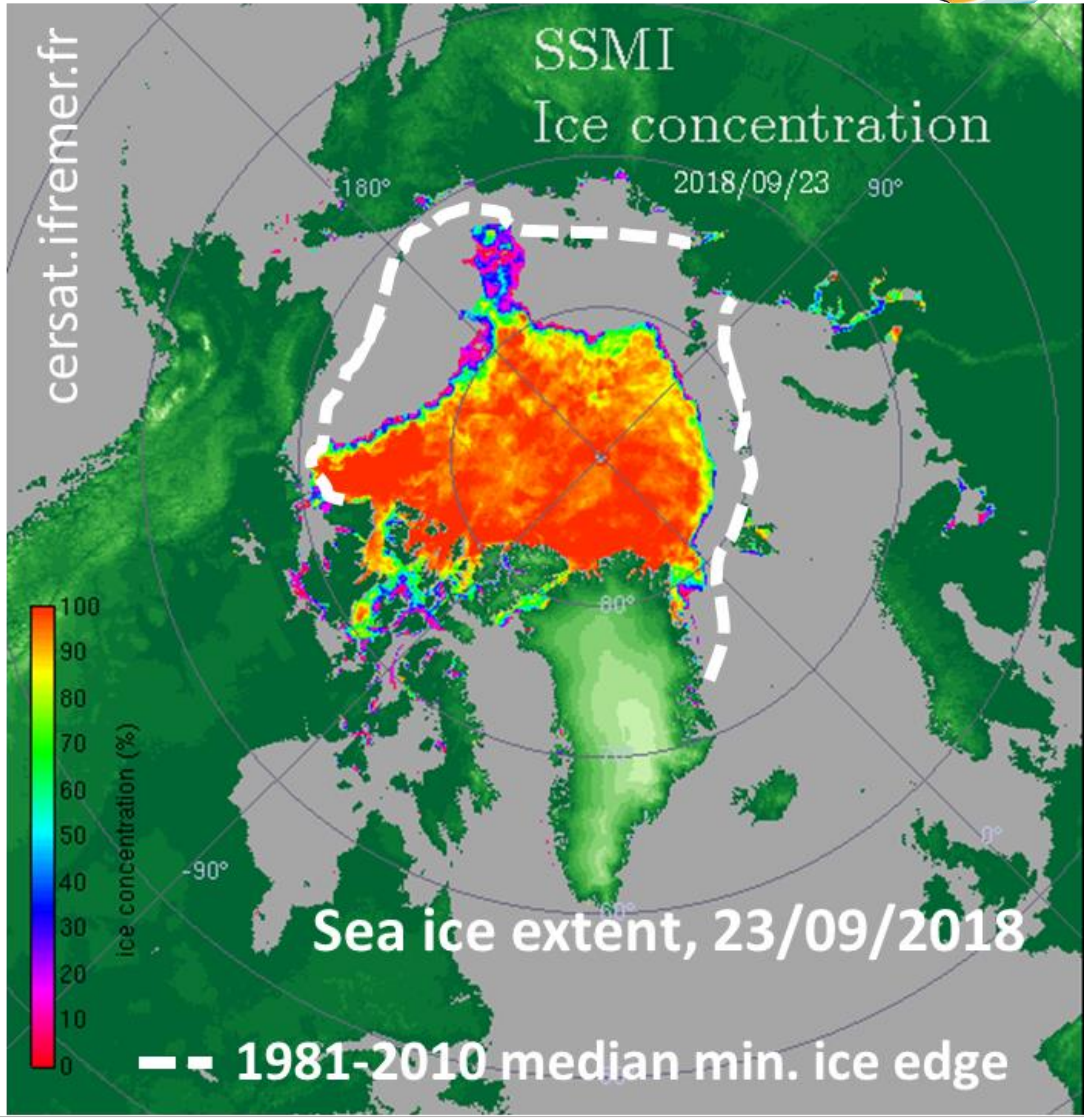
LOPS

The Arctic is changing

Teleconnections with lower latitudes mean that Arctic sea ice:

- **Is an <u>indicator</u> of GLOBAL climate change.**
- **<u>Modulates</u> GLOBAL climate change.**

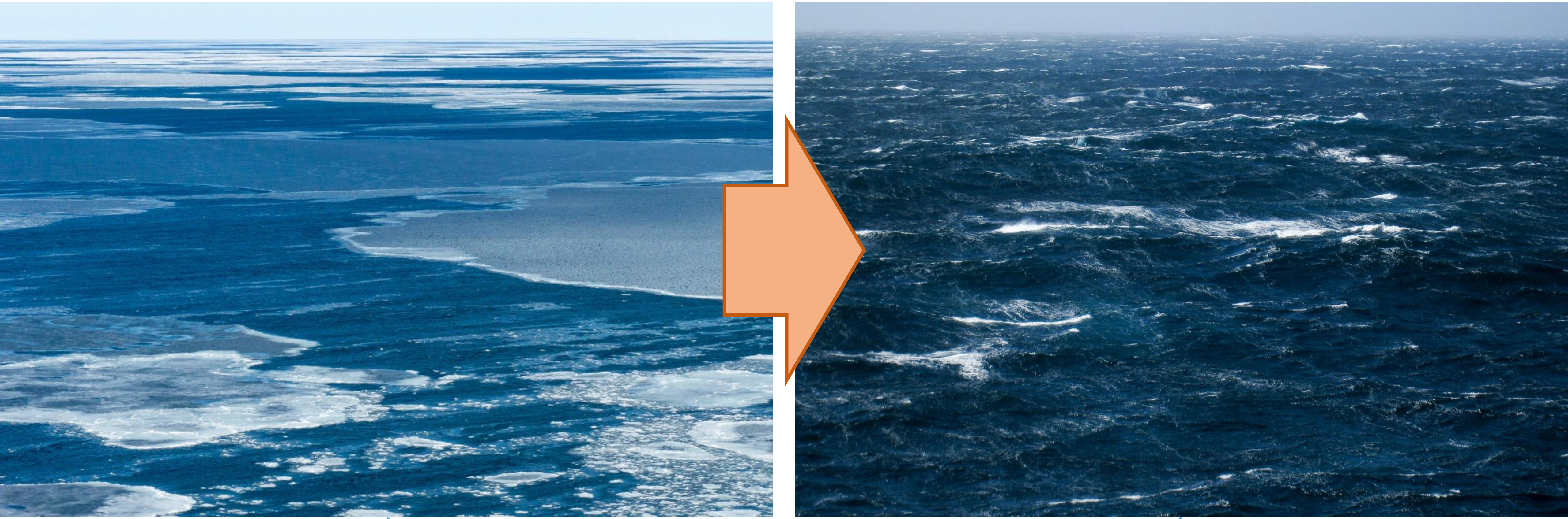




Transition to a seasonally wave-driven upper-ocean

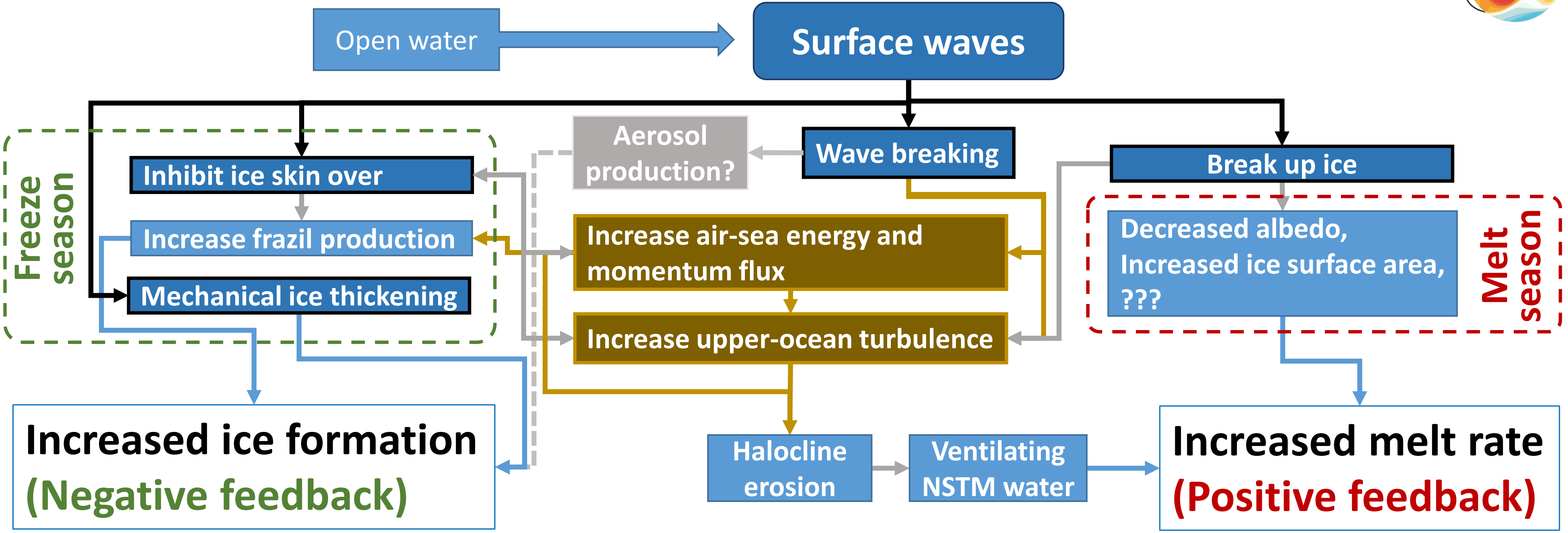
- Less ice → more open water→ larger fetch for wave development

  → More energetic wave climate



Same wind speed (17 m/s)… very different boundary layers

Emerging feedback mechanisms (first-order uncertainties)



Need to **quantify these feedbacks** in order **to make accurate Arctic (and global) predictions.**

Emerging feedback mechanisms (first-order uncertainties)

Freeze season

In

In

M

Melt season

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?**

Increas ... **t rate**

(Negativ ... **back)**

Need to ... **ctic (and global) predictions.**

Wave effects in the MIZ – Ice formation

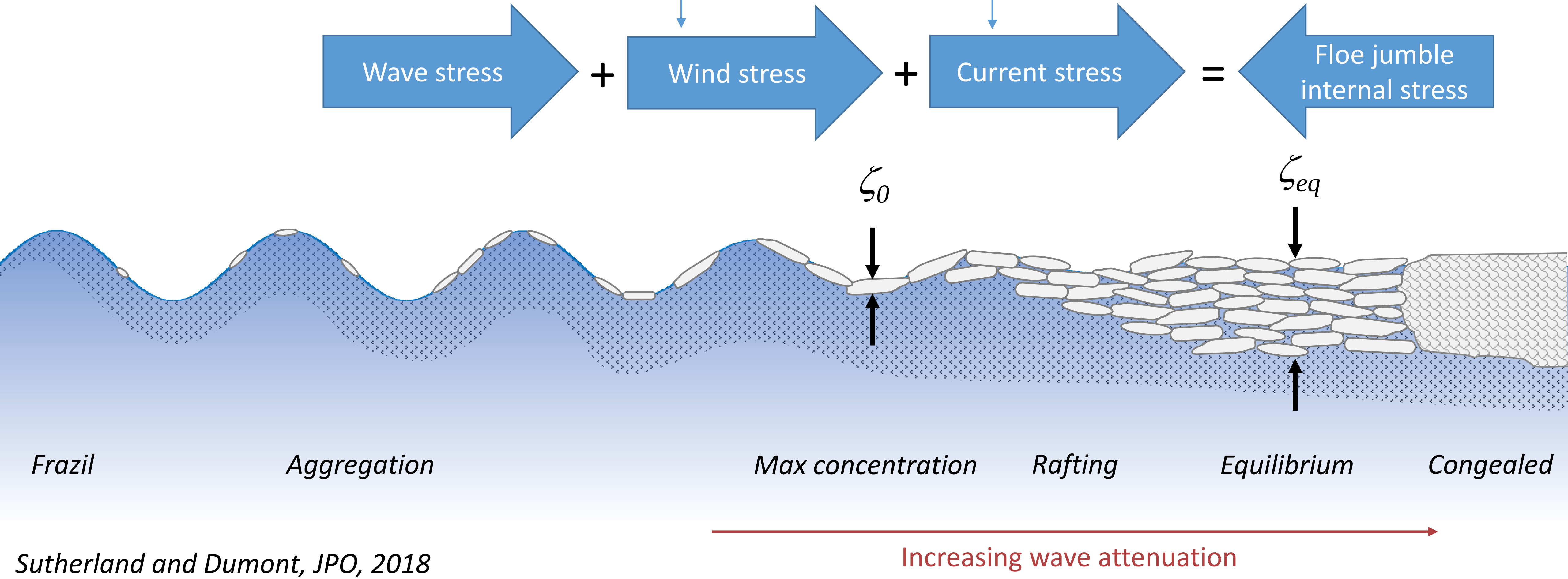
- In calm conditions, a thin surface skin of ice quickly forms.
- All additional growth is thermally controlled
- Wave motions and associated turbulence inhibit this skin formation.

The wave-affected ice formation process

Ice-edge normal stresses:

$$\boldsymbol{\tau}_{air} = \rho_a C_a \left|\boldsymbol{U}_{10} - \boldsymbol{u}_I\right| (\boldsymbol{U}_{10} - \boldsymbol{u}_I)$$

$$\boldsymbol{\tau}_{water} = \rho_w C_w \left|\boldsymbol{U}_w - \boldsymbol{u}_I\right| (\boldsymbol{U}_w - \boldsymbol{u}_I)$$



Sutherland and Dumont, JPO, 2018

External stress acting on MIZ : Wave radiation stress

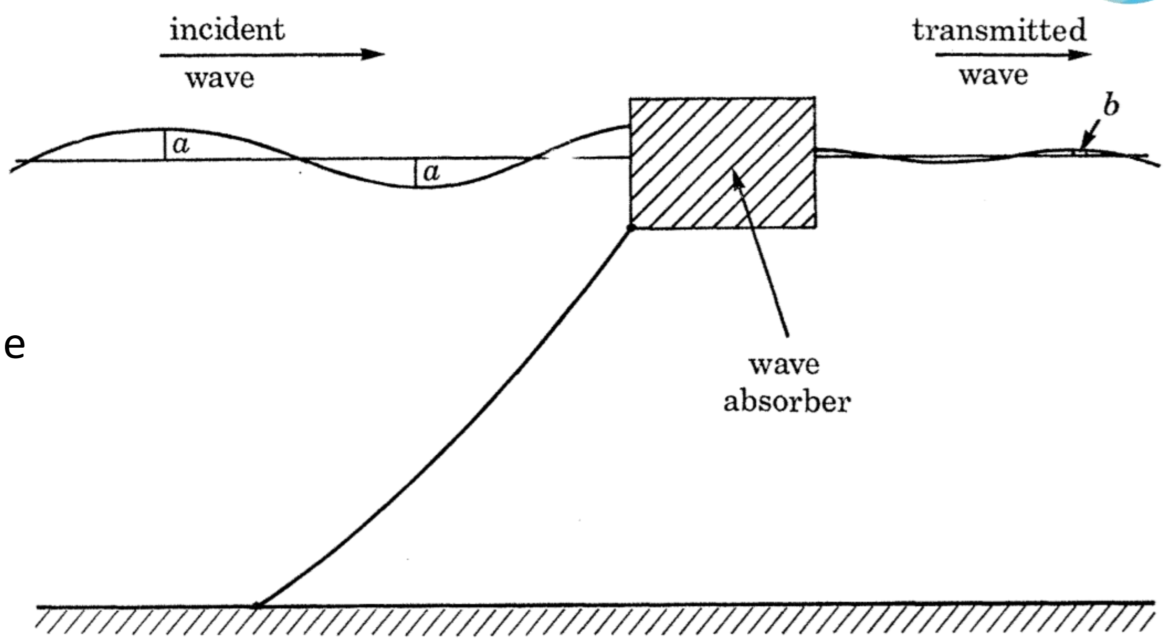
Excess flow of momentum due to waves.
Proportional to wave energy, *E*.

The **stress applied to the ice is**:

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

(deep water plane waves in the *x*-direction)

Gradient of wave energy



Longuet-Higgins 1977

→ **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:**

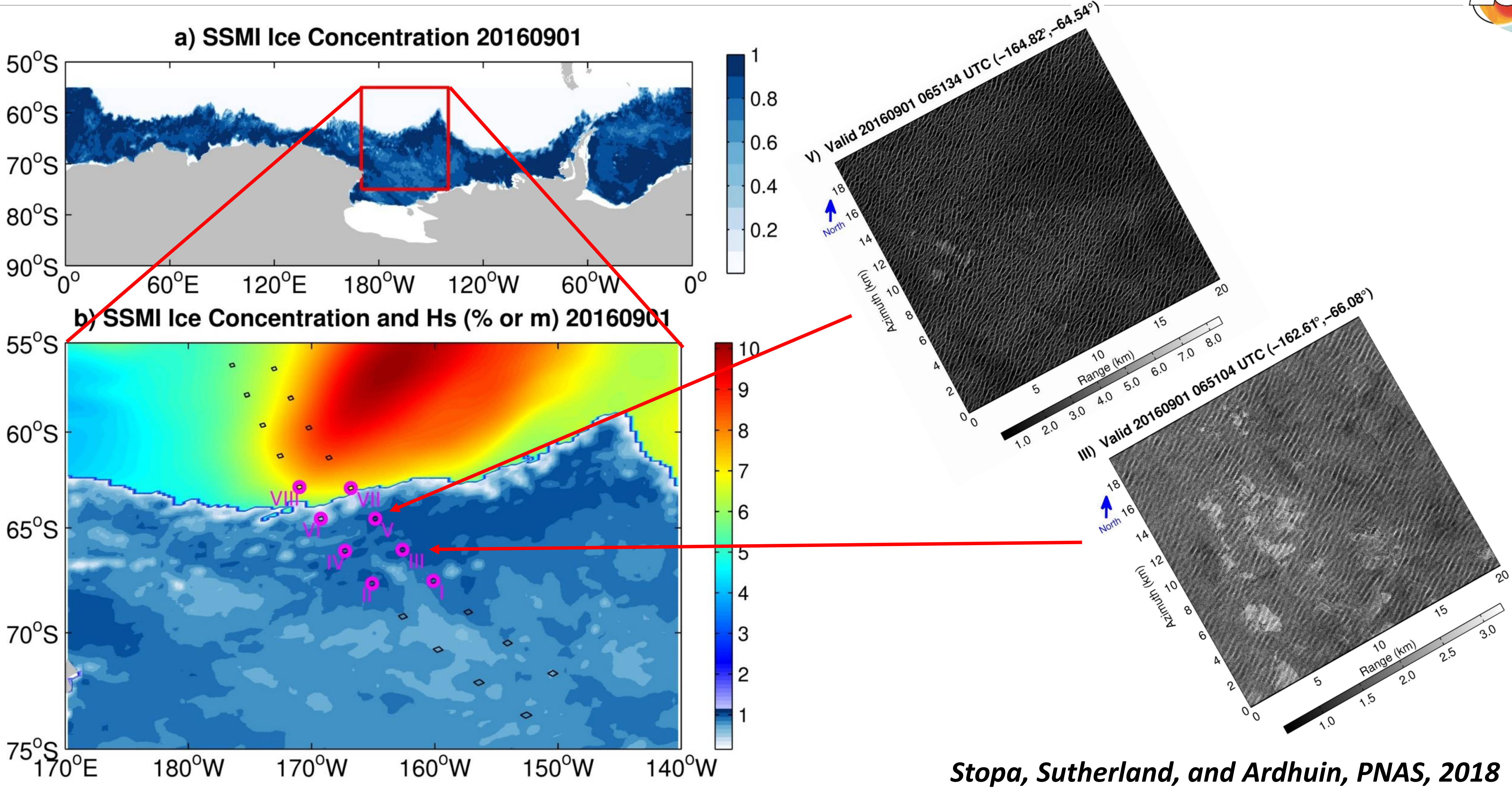
Integrated wind stress = $G_{air} = \int_0^{X_{MIZ}} \tau_{air} dx = \rho_a C_D U_{10}^2 X_{MIZ}$

Total wave radiation stress = $G_{wv0} = \int_0^{\infty} \tau_{wv} dx = \frac{\rho g}{2} E_0$

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

Sutherland and Dumont, JPO, 2018

The large scale picture – Waves in the Antarctic MIZ

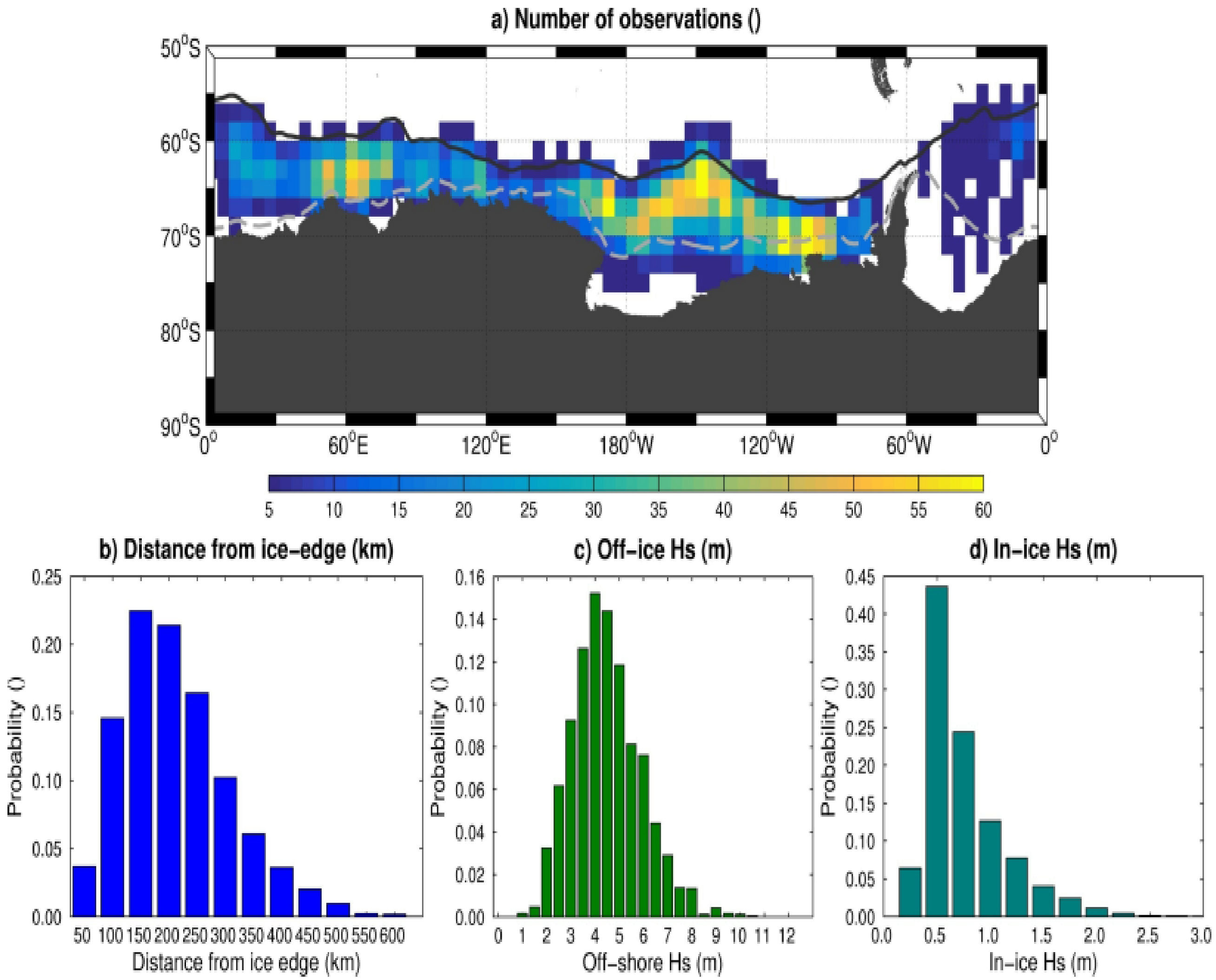


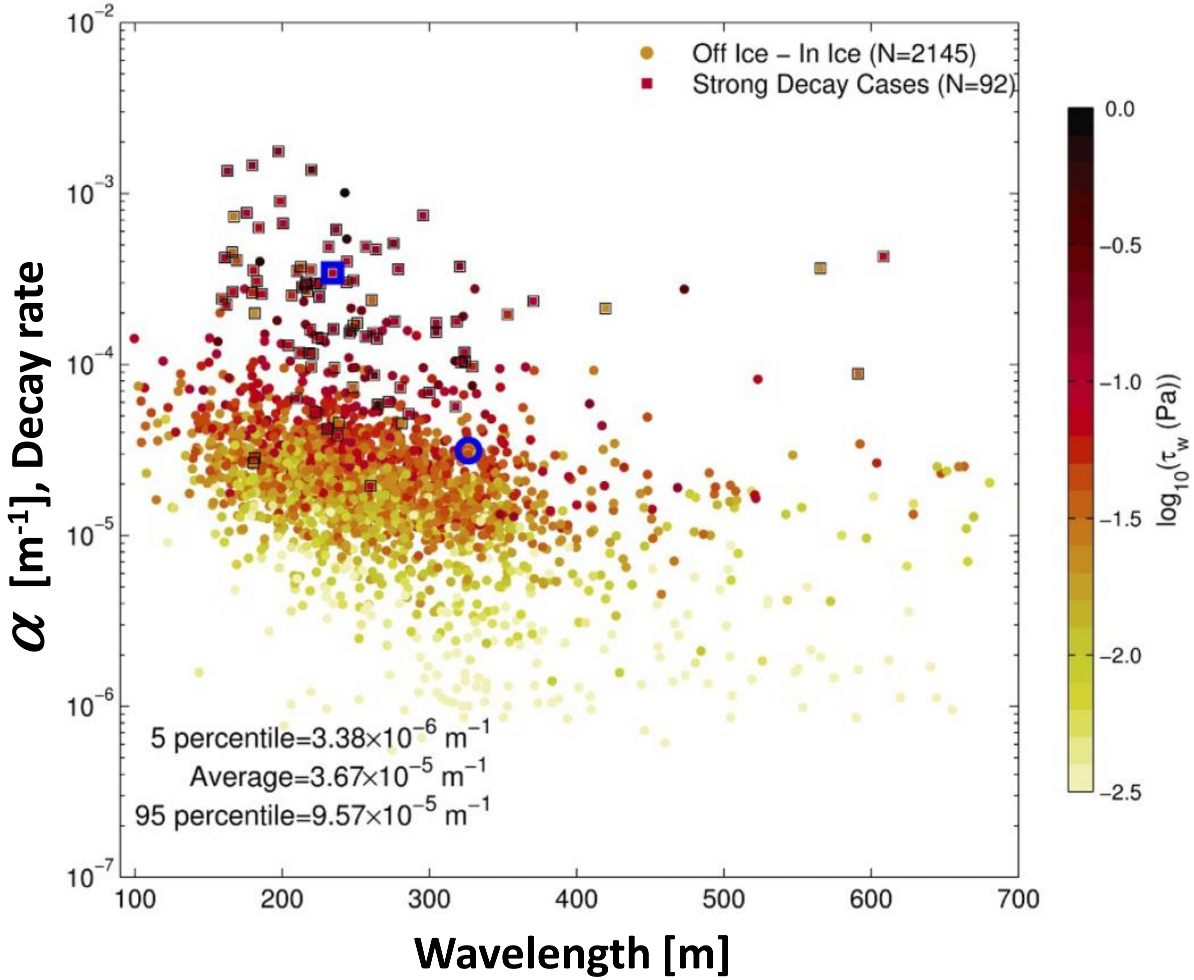
Stopa, Sutherland, and Ardhuin, PNAS, 2018

The large scale picture – wave attenuation in the MIZ

Largest-ever dataset of measurements of wave spectra in sea ice; covering the entire Antarctic MIZ in all seasons over multiple years.

$$E(x_{ice}) = E_0 e^{-\alpha x_{ice}}$$

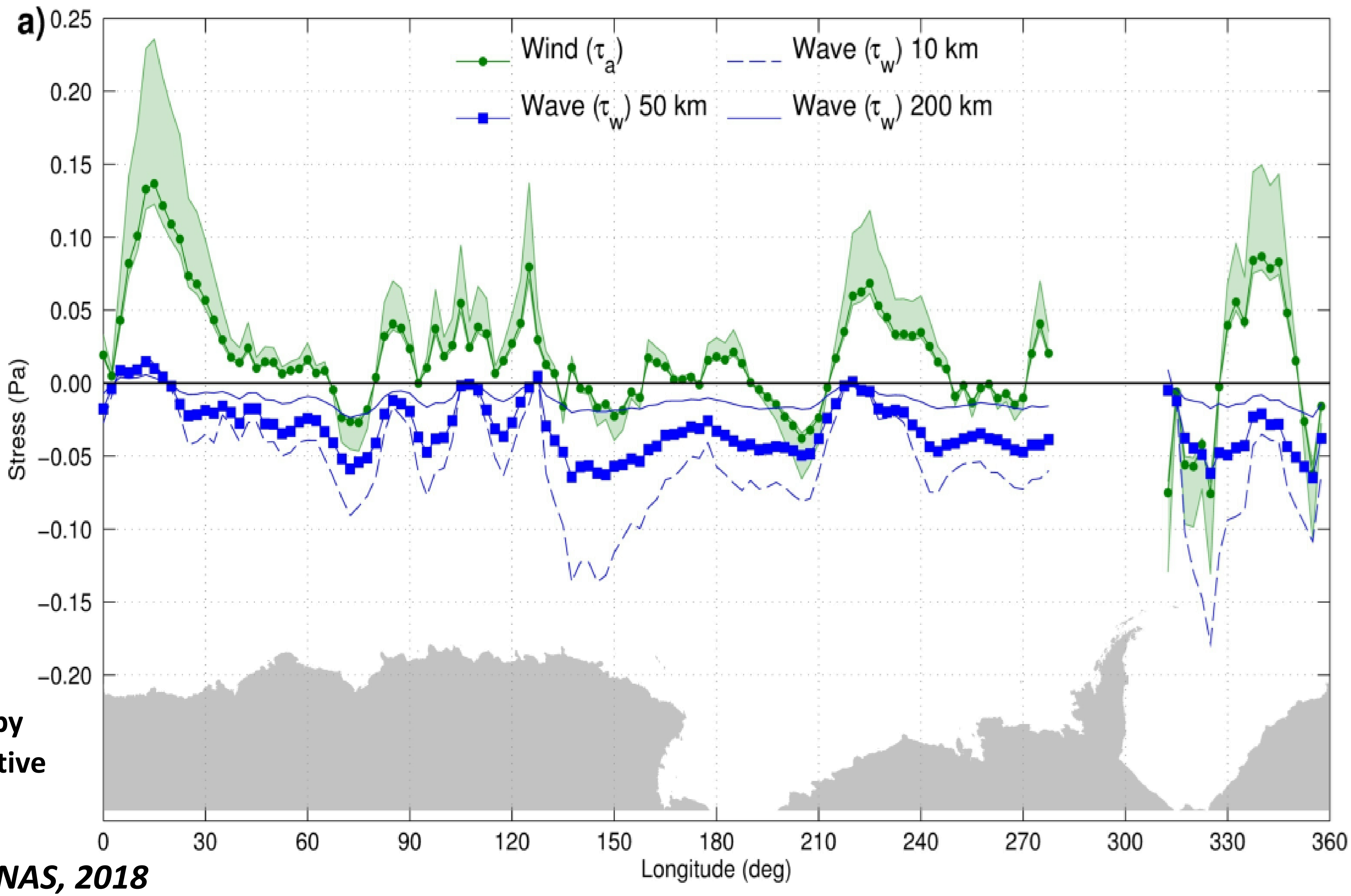




Stopa, Sutherland, and Ardhuin, PNAS, 2018

Wave radiation stress forcing at larger scales

- **On average, waves dominate over wind forcing for the first X_{MIZ}~40 km**
- **Wave attenuation is highly spatially and temporally inhomogeneous.**
- **Waves provide a stabilizing mean on-ice forcing in the MIZ.**



→ 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, σ_x, of Mohr-Coulomb granular material is related to vertical stress, σ_z:

$$\sigma_x = [(1+\sin\phi)/(1-\sin\phi)]\sigma_z$$

Depends upon ϕ = Internal friction angle (TBD)

Ice jams literature: Uzuner and Kennedy, 1976

Photo: Wyoming Department of Homeland Security (USA)

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

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

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

n = porosity (0.4)
ρ_i = Ice density (900 kg/m^3)
ρ_w = Water density (1035 kg/m^3)

Solving for ζ_{eq} gives the maximum ice thickness for a given incoming wave field

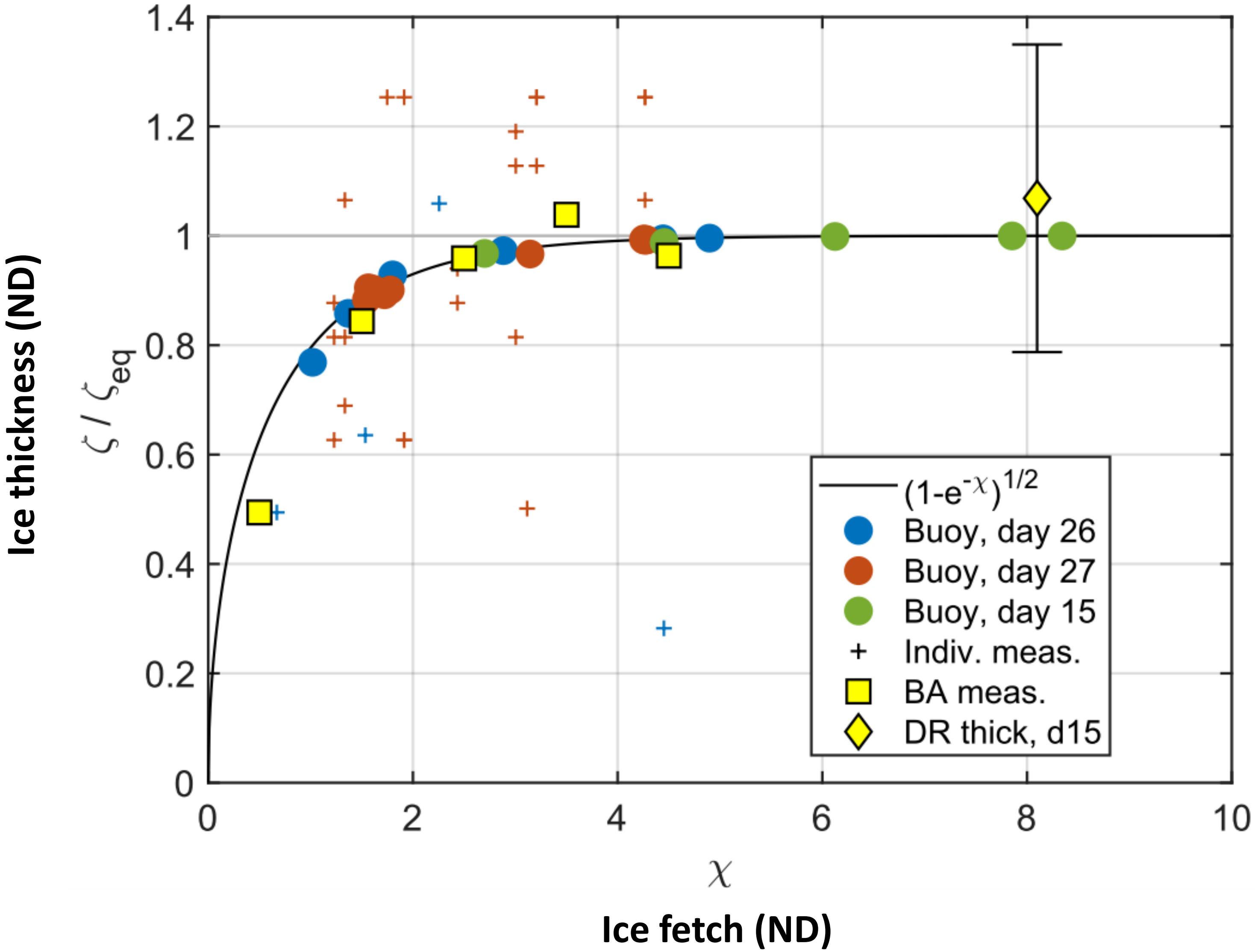
MC-radiation stress model applied to in situ data (LSLE)

Thickness normalised by equilibrium thickness

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

Ice fetch normalised as

$$\chi = \alpha(x_{\text{ice}} - x_c)$$



Sutherland and Dumont 2018 JPO

Wave modification of ice: Perspectives

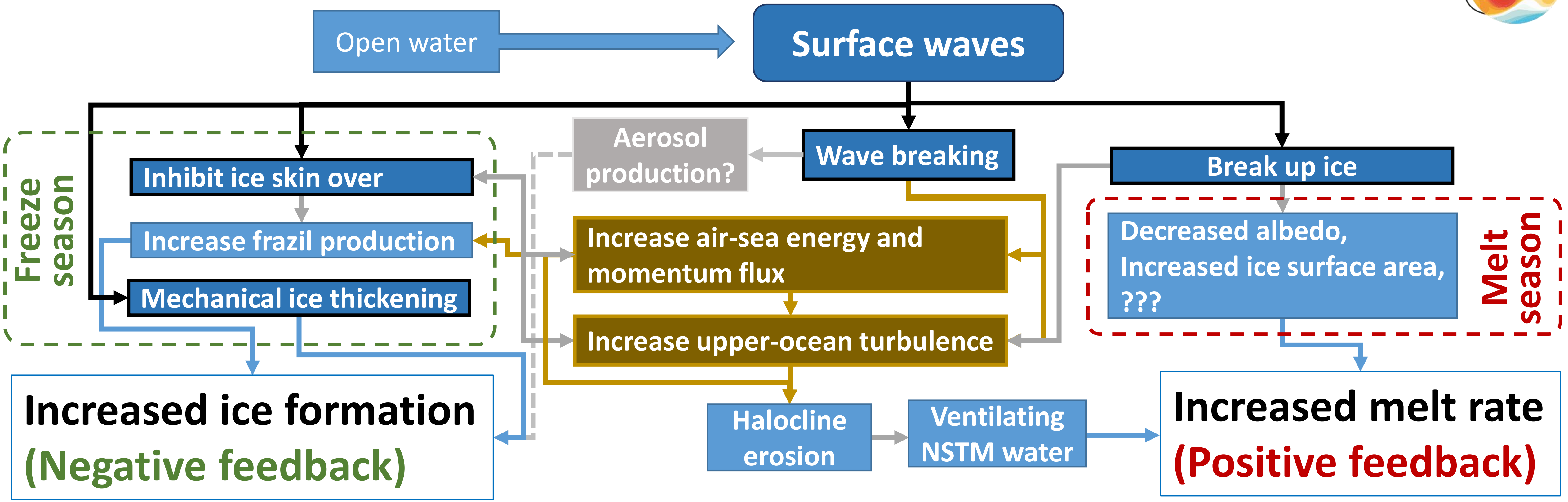
Progress:

- 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)



Need to **quantify these feedbacks** in order **to make accurate Arctic (and global) predictions.**

WAAXT → 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?

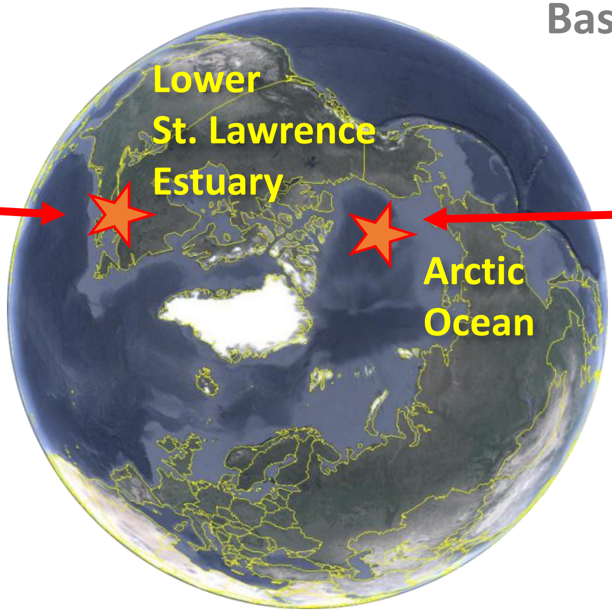
2) Modify open water stratification in the Arctic Ocean?

3) Break up and help melt sea ice?

WAAXT Methodology – Increasingly ambitious process studies

Theory, laboratory experiments

Basin-scale remote sensing, modelling

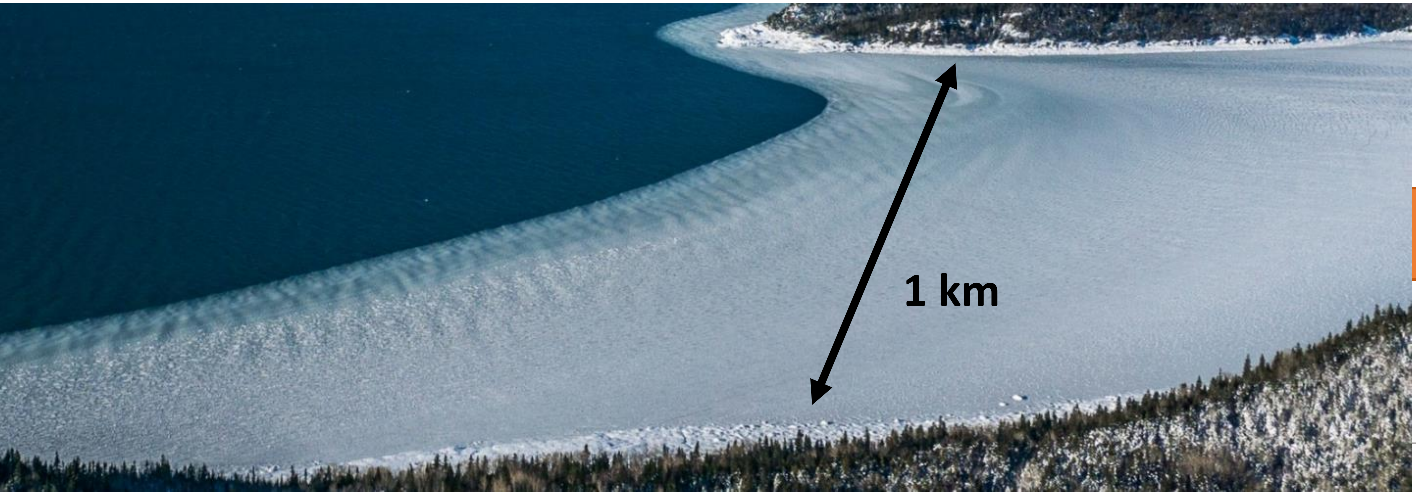


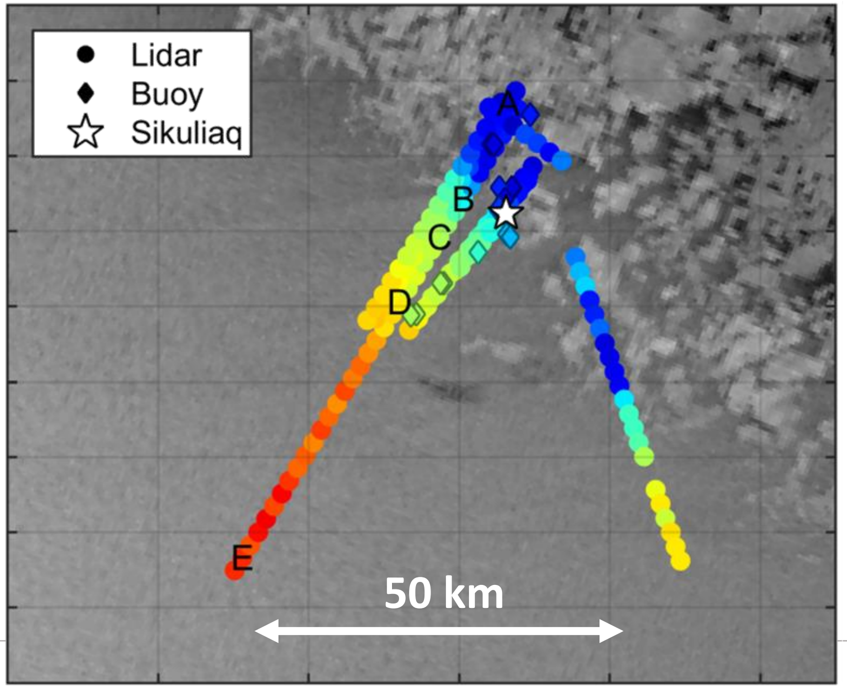
LSLE Natural laboratory (2+ Experiments)
Simplified access to relevant physical processes on a reduced scale:

- **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**



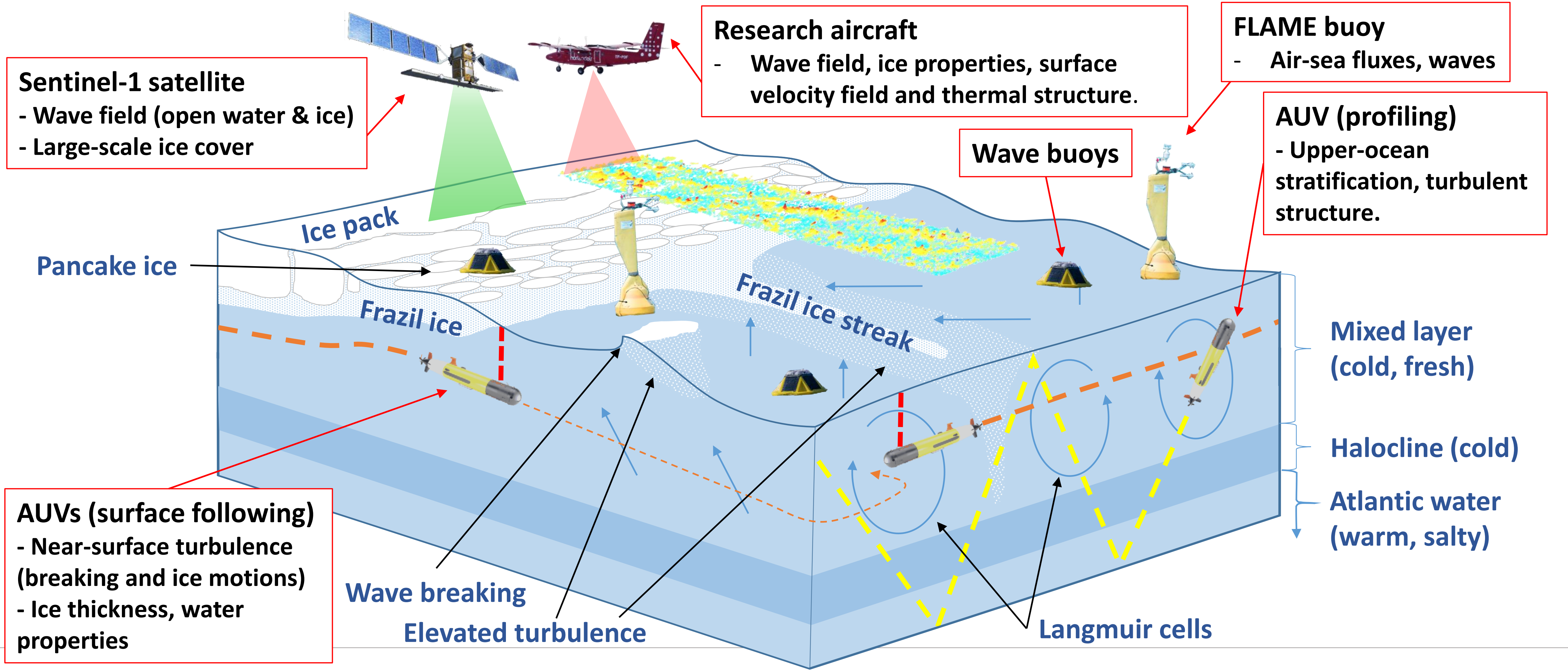


Sutherland et al. 2018 JGR

WAAXT measurement approach

→ **Capture spatial and temporal intermittency**

→ **Measure small processes and their bulk effects;** close energy and momentum budgets.



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.**