Better Operational Forecasting for the Contemporary Arctic via Ocean Wave Integration

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Outline

Motivation

Wave-ice interactions are a fundamental process currently overlooked in ice-ocean models (Nansen Centennial Symposium, Norway, June 1993) . . .

An unwise omission near the ice margins as ocean waves

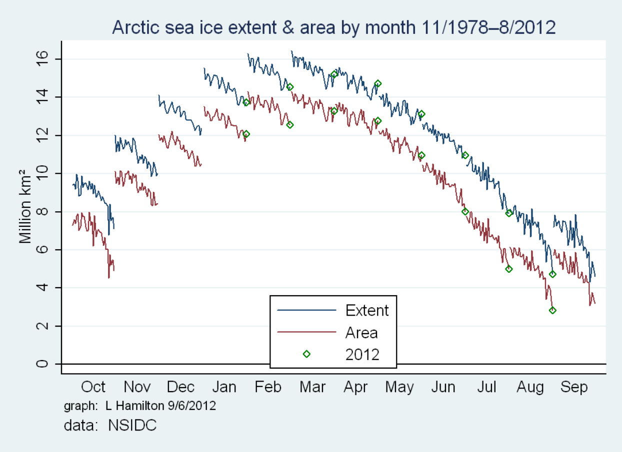
- penetrate the ice field and are attenuated by scattering, etc.
- break up floes that are too large, to create an FSD with floe sizes *increasing* from the ice edge
- can pummel the ice to a slurry when sufficiently fierce
- move the ice horizontally to cause patchy concentration
- assist melting, both directly and indirectly in summer.

Now a hot topic because, as its sea ice retreats, opens up and thins, the Arctic begins to look more like a MIZ, which permits

- ocean waves to enter and penetrate farther into the ice pack, with greater destructive payload
- wave generation within ice field because of longer wave fetches.

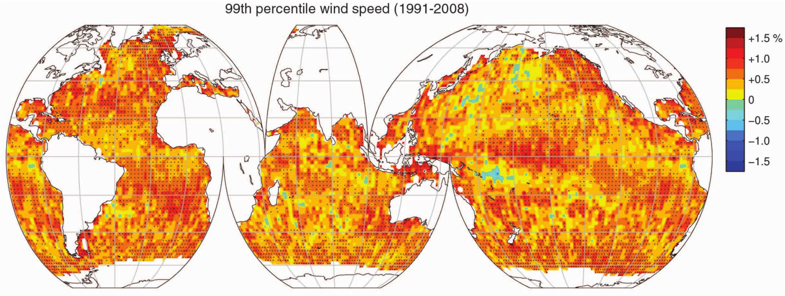
Modellers are now interested in the magnitude of this effect and how it might be parameterized in large-scale models.

Arctic sea ice change



But also . . .

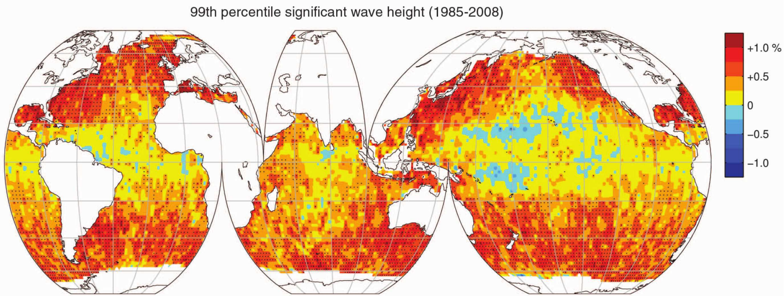
99th-percentile trend wind speed contours (% pa). Points that are statistically significant according to the Seasonal Kendall test are shown with dots. (After Young et al. 2012.)



Observations about wind speed

- There is a clear global increase in mean wind speed from 1985–2008, and at the 90th and 99th percentiles.
- The increase is largest (= 0.75%) for the 99th percentile, suggesting that the intensity of extreme events is increasing faster than the mean conditions.

Same for significant wave height (SWH)

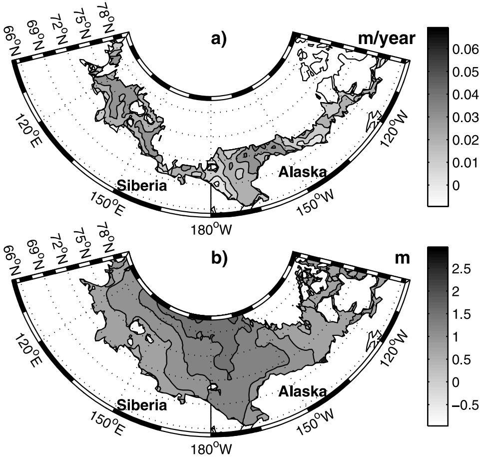


Observations about waves

- The 90th and 99th percentile SWH trends are progressively more positive with higher latitudes.
- SWH trend becomes more positive moving from the mean to the 99th percentile, i.e. moving to extreme conditions, where trend is 0.5%.
- For the 99th percentile SWH, the stronger positive trends at high latitude are statistically significant.
- For extreme conditions (99th percentile), waves tend to be generated by local storm events.

SWH

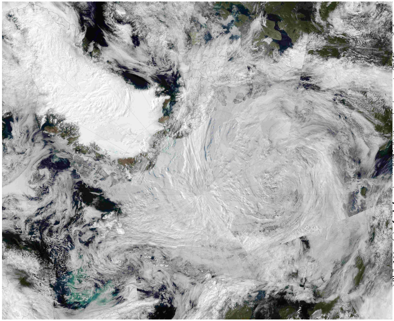
for Pacific-Arctic region during 1993–2010 showing (a) incremental change (metres/year) and, (b) mean value in metres. (After Francis et al. 2011.)

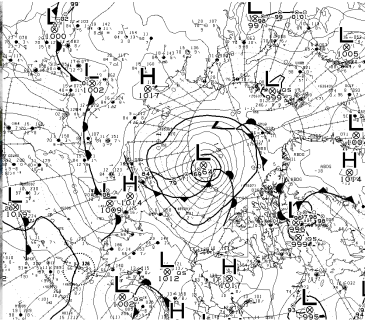


Mean annual SWH has increased significantly in almost every part of the Arctic Ocean. (a) The highest growth is near the northern Alaskan Coast, (b) 1993–2010 mean SWH is ∼ 1.5 m. SWH in region has doubled during the last two decades.

Arctic ice reduction is probably the primary cause of SWH changes, arising from increases in fetch allowing the growth of higher waves under the same winds, greater penetration, and a longer ice-free season.

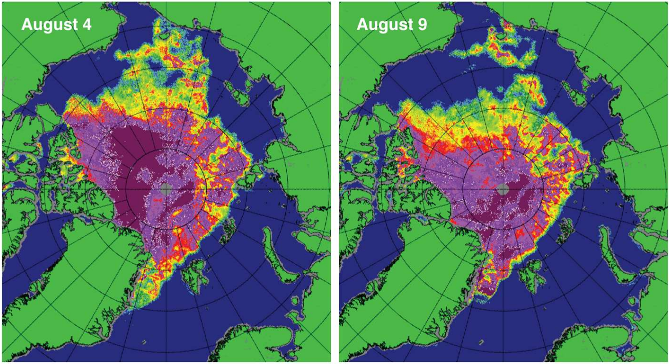
Arctic super storms





An unusually strong storm formed off the coast of Alaska on August 5, 2012, and tracked into the center of the Arctic Ocean, where it lingered for several days. The MODIS aboard the Aqua satellite captured this natural-colour image on August 7, 2012. The center of the storm was located in the middle of the Arctic Ocean at the time.

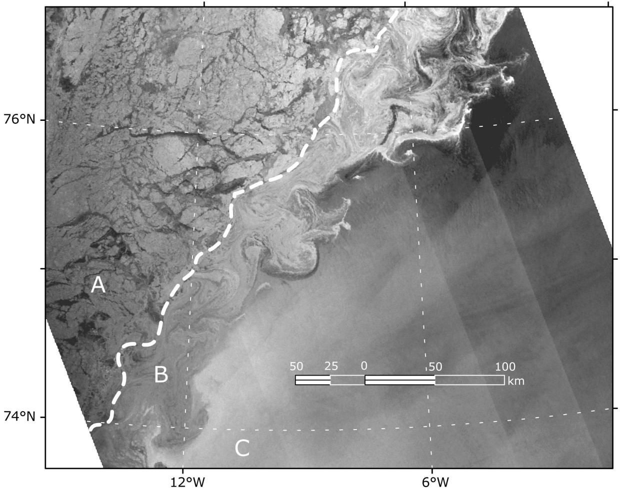
Special Sensor Microwave Imager/Sounder passive microwave sensor imagery



Maps of sea ice concentration from the SSMIS highlight the rapid loss of ice in the western Arctic (northwest of Alaska) during the strong Arctic storm. Magenta and purple colours indicate ice concentration near 100%; yellow, green, and pale blue indicate 60% to 20% ice concentration. On three consecutive days (August 7, 8, and 9), sea ice extent dropped by nearly 200,000 square kilometres (77,220 square miles). Image: National Snow and Ice Data Center, courtesy IUP Bremen.

The Marginal Ice Zone (MIZ)

Heterogeneous, mobile and primarily configured by ocean waves (width, FSD)

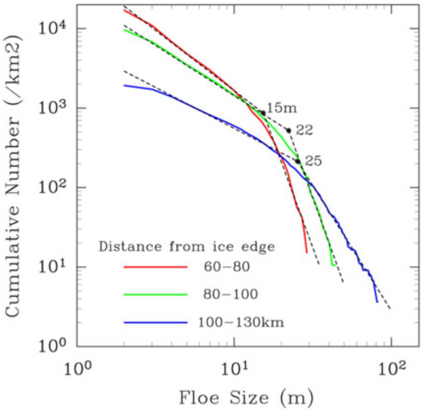


Sea ice

Some types of sea ice that must be modelled in relation to water waves

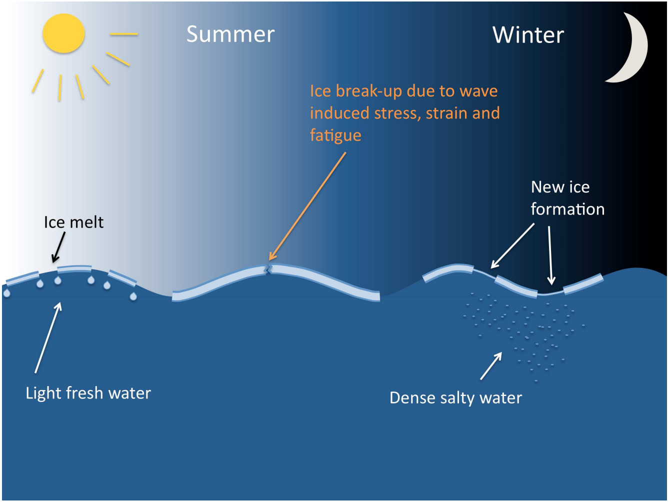
FSD observations

(After Toyota et al. 2011.)

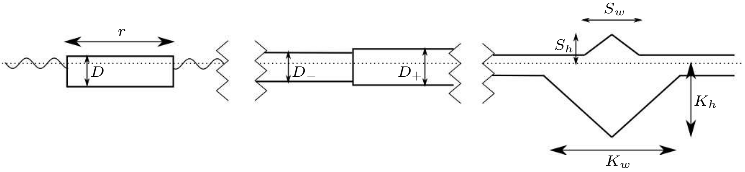


Bridge from small to large scales. FSD found to obey a (Pareto) power-law distribution, i.e. scale invariant. However, regime change between small/large floes noted by Toyota et al. (2006, 2011). Small floes mainly influenced by waves, large floes by wind/current stresses.

Why break up and the wave-induced rearrangement of ice floes is important



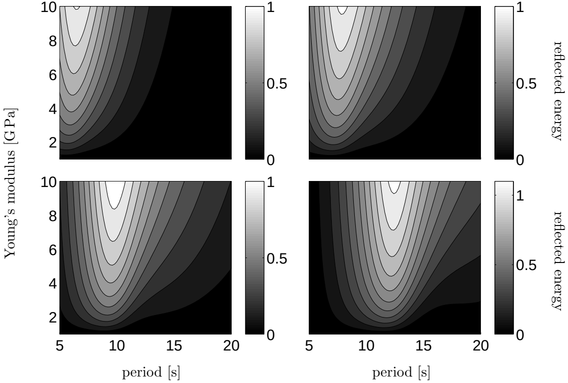
Sea ice features that affect wave propagation by reflecting energy back



Some ice features considered by Bennetts & Squire (2012), with notation. From left to right: a floe, a crack and a first-year pressure ridge with profile consistent with Timco & Burden (1997).

Wave energy reflected by a single ice edge

against wave period and the effective modulus

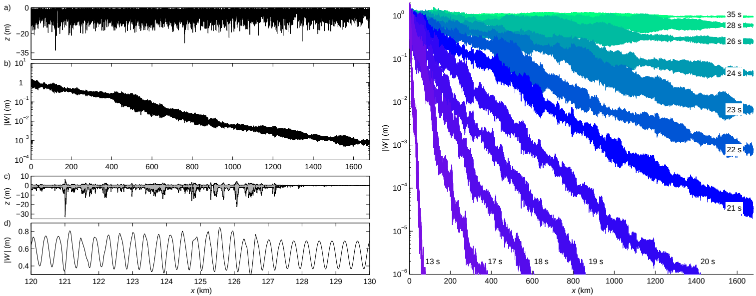


The contour values at each period are scaled by the values for the smallest modulus in the range considered, i.e. 1 G Pa, and are on a $\log_{10}$ scale. Ice thickness is 0.5 m (top-left panel), 1 m (top-right), 2 m (bottom-left) and 4 m (bottom-right).

Natural ice terrain

Quasi-continuous Arctic Basin ice. (After Squire et al. 2009.)

Heterogeneity is properly accommodated



Complete and partial transects with 22 s wave train and wave decay across a range of periods.

Attenuation

The ensemble average

A WSA[a] allows the ensemble average of the attenuation produced by any number of scatterers, i.e. the geometrically (logarithmically) averaged transmission, over all possible phases, to be found from the properties of the individual scatterers. Applied to a transect of M floes, the resulting expression is

$$e^{\langle\langle \log |T_{1,M}|^2\rangle\rangle} = e^{M\langle \log |T_0|^2\rangle}$$

so the corresponding nondimensional attenuation coefficient μ, with respect to the (large) number of scatterers, is given by

$$\mu = -\langle \log |T_0|^2\rangle$$

Applying a WSA to the floes themselves, the above expression is reduced to

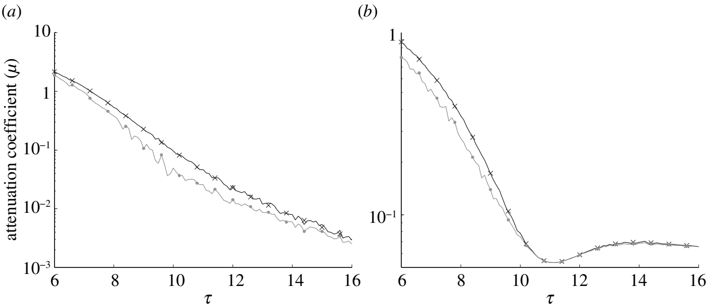
$$\mu = -2\log(1 - |R|^2)$$

This is an Anderson localization result. The dimensional attenuation coefficient u, defined with respect to distance into the ice cover, is given by $\mu = ul$ where l is the average distance between scatterers.

[a] wide spacing approximation

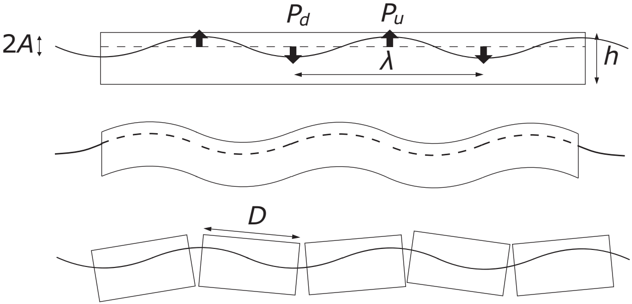
Attenuation coefficient

as a function of wave period τ



(a) A MIZ with identical floes of length 100 m and thickness 3 m. (b) Quasi-continuous ice of 3 m thickness containing cracks, where the primary wave number is given an imaginary component of magnitude 10^{-4} to include viscosity. In both cases the WSA is used to calculate the wave interactions between features and the distribution of their separations is uniform over half a wavelength. The solid curves show results calculated using ensembles with arithmetic (light grey, dotted) and geometric (i.e. logarithmic, black) averaging. The crosses are semi-analytic expressions.

Ice floe breakup
by wave-induced fracture



Flexural forces imposed on an ice plate by a passing wave. The upward force is the excess of buoyancy proportional to the density of the water while the downward force is the excess of weight proportional to the density of the sea ice. (After Dumont et al. 2011.)

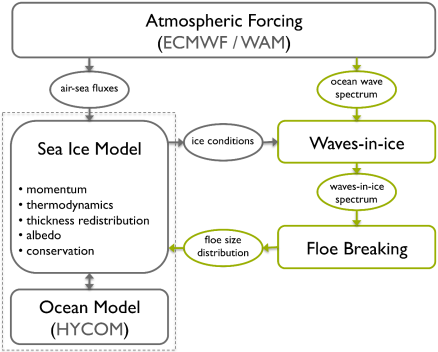
Ice floe breakup

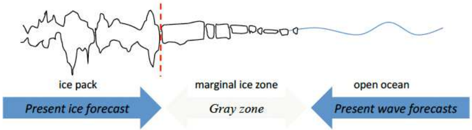
in the context of ice-ocean models

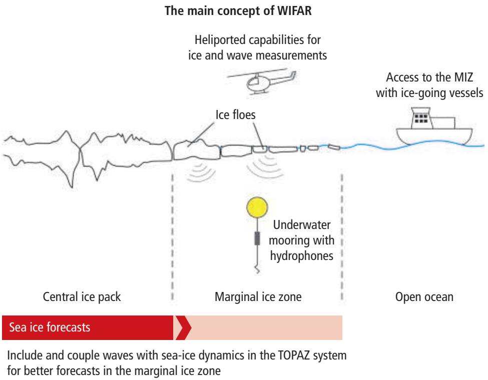
- Although it is well known that ocean waves break up ice floes in the MIZ, sometimes pummeling them to brash, few observations exist (Langhorne et al. 1998)
- The many observations of the flexural strength σ_c of sea ice suggest an empirical formula of the form $\sigma_c = 1.76\mathrm{e}^{-5.88\sqrt{\nu_b}}$ where ν_b denotes brine volume (Timco and Weeks 2010).
- This can be used along with further plausible arguments to create a breaking strain ϵ_c for ice floes that can exploit an expression for the strain per metre of wave amplitude, $\epsilon_A = gh\kappa_0^3/2\omega^2$, to give the spectral density function for the strain in the ice $S(\omega, \theta)\epsilon_A^2$, where all parameters are known.
- With a Rayleigh distribution assumed for the wave and strain amplitudes, A and E, respectively, the floes in an area will break when the probability $\mathbb{P}(E > \epsilon_c)$ exceeds a certain critical value (Vaughan and Squire 2011, Williams et al. 2012b).

Wave / ice interactions in an ice-ocean model

WIFAR (Waves-in-ice for Arctic operators) schematics







As well as modelling, WIFAR is also conducting field experiments in the MIZs of Fram Strait and the Barents Sea

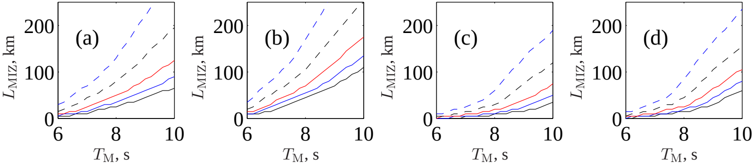
Operational details

- Recognize that due to computational limitations and satellite resolution, ice-ocean models are pixellated into cells within which sea ice descriptors are constant, i.e. heterogeneity at sub-cell scales is superfluous as only average thickness, floe size and concentration are known
- For every cell at each time step, there are four stages
  - advect the incoming open water spectral density function $S(\omega, \theta)$ into an intermediary unattenuated spectrum $\tilde{S}(\omega, \theta)$ at each point in the ice field
  - attenuate $\tilde{S}(\omega, \theta)$ to give the true $S(\omega, \theta)$ at those locations
  - determine which ice floes break up due to $S(\omega, \theta)$
  - modify the FSD and move to next time step.

  The use of satellite data products has the potential to improve predictions significantly
- The pixellated MIZ visualization will allow all identified key properties to be accommodated in a computationally efficient mathematical model, with randomness simulated at each level of the configuration.

Variation of MIZ width L_{MIZ} in Fram Strait

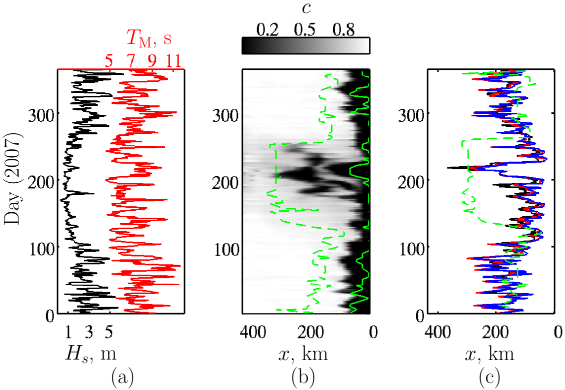
with peak spectral period T_{M} for different failure strains ϵ_c and significant wave heights H_s (after WIFAR)



In (a) and (b) $h = 2\,\mathrm{m}$; in (c) and (d) $h = 3\,\mathrm{m}$; in (a) and (c) $H_s = 1.5\,\mathrm{m}$; and in (b) and (d) $H_s = 2.5\,\mathrm{m}$. In all plots the concentration is uniformly 0.75 and $\epsilon_c = 5.5 \times 10^{-5}\eta$, where η takes the values of 0.2 (dashed blue curves), 0.5 (dashed black), 1 (red), 1.5 (solid blue) and 2 (solid black).

Model data and sample results

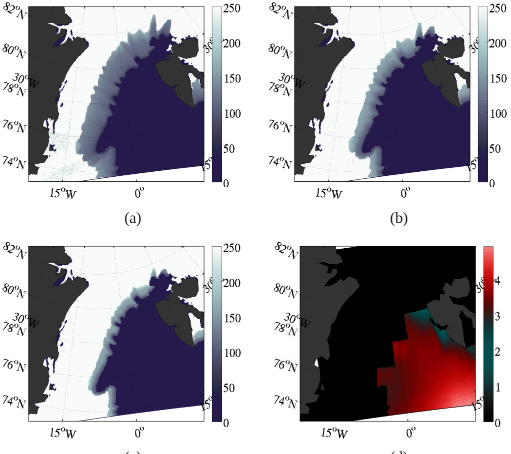
for a 1d 2007 Fram Strait simulation between the SE coast of Norske Øer (79°N, 17.7°W) and 79°N, 3°E (after WIFAR)



SWH and peak periods from WAM (a) are advected west through sea ice with TOPAZ concentrations and thicknesses. Interpolated concentrations are plotted in (b), with the ice edge (solid green) and MIZ limit (dashed green) from AMSR-E. (c) Resulting broken/unbroken ice delineation for model thicknesses h (black), $1.75 \times h$ (red), and $2.5 \times h$ (blue), with same AMSR-E dashed green line for MIZ interior boundary.

Maximum floe size in metres

for different thicknesses (a-c), significant wave height H_s (d) (after WIFAR)

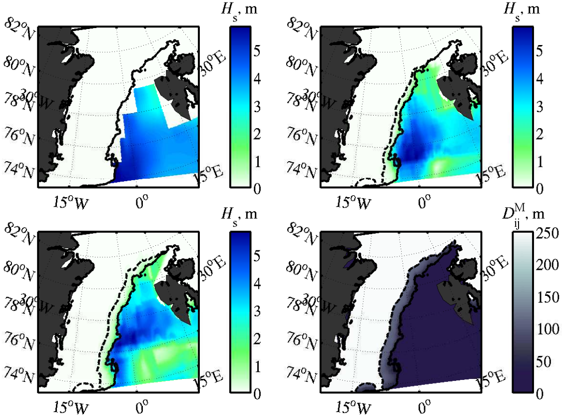


(a) (b) (c) (d)

Ice concentration is 0.8. Ice thickness is (a) 2 m, (b) 3 m and (c) 4 m.
Mean peak period is 10.5 s, mean wave direction is 187° with ten wave directions between −9° and 221° included at a resolution of 21.2°.

Advection and attenuation of ocean waves

as they travel into the ice and the resultant ice breaking (after WIFAR)



SWH and amount of breaking at $t = 0$, $t = 2.2$ and $t = 4.4$ hours. Bottom right shows maximum floe size after all waves have been attenuated. 10 wave directions ($N_\theta = 10$) are used, giving $L_{\mathrm{MIZ}} = 65$ km. Mean wave input parameters are $\langle H_s \rangle = 3.6$ m, $\langle T_{\mathrm{M}} \rangle = 9.4$ s and $\langle \theta \rangle = 119^\circ$. Mean ice parameters are $\langle h \rangle = 1.7$ m and $\langle c \rangle = 0.95$. Data are for 2 January 2007.

Advection and attenuation of ocean waves for $N_\theta = 5$: $L_{\mathrm{MIZ}} = 69\,\mathrm{km}$

Better Operational Forecasting in the Arctic

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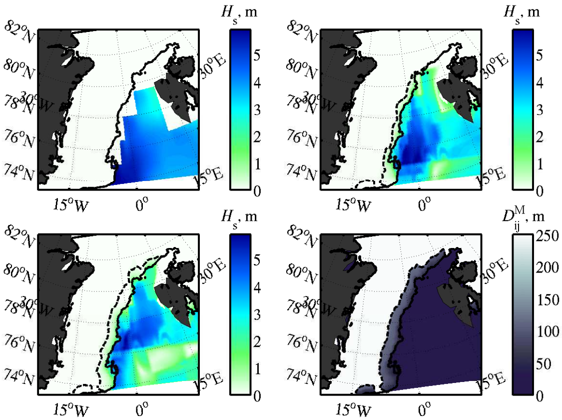
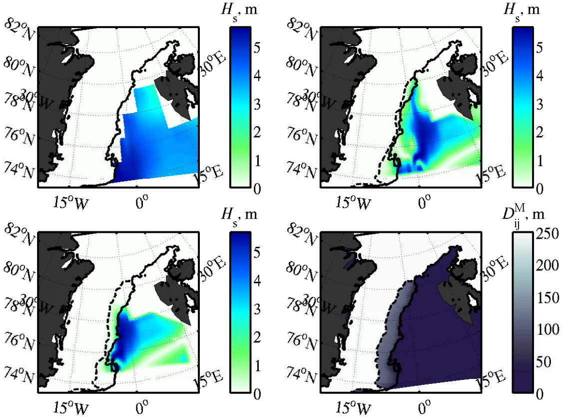
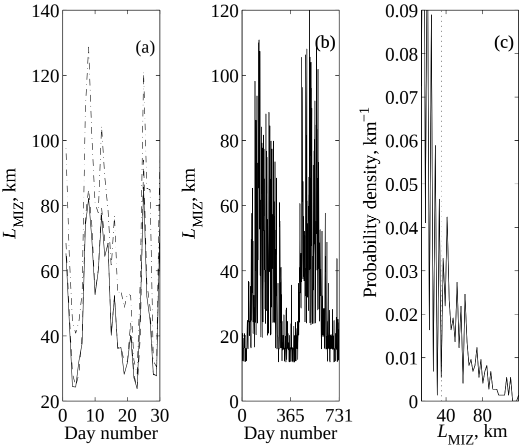


Advection and attenuation of ocean waves for $N_\theta = 1$: $L_{\mathrm{MIZ}} = 98\,\mathrm{km}$



How L_{MIZ} changes

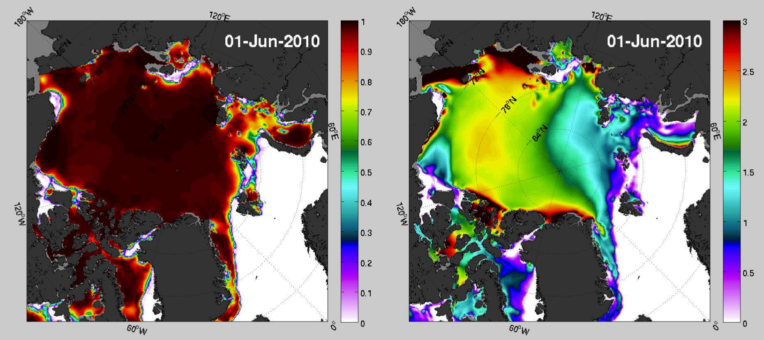
(a) $N_\theta = 1$ (−·), 5 (−−) and 10 (—); (b) $N_\theta = 8$; (c) L_{MIZ} probability density



(a) Day number 1 corresponds to 2 January 2007. (b) Day number 1 corresponds to 1 August 2006; (c) Probability density of over the 2-year simulation in (b). The mean value of L_{MIZ} is 35 km.

TOPAZ

Ice concentration and thickness



Aim is to embed waves in the TOPAZ Arctic model in a fully two-dimensional way, in the same way we have done during WIFAR for Fram Strait. This will include waves entering the Arctic from surrounding oceans and waves generated within the basin itself because of the larger percentage of open water that is now present due to climate change.

Questions

Acknowledgements. Research Council of Norway, Total E&P, University of Otago.

Thank you