The evolution of wave directional properties in the marginal ice zone

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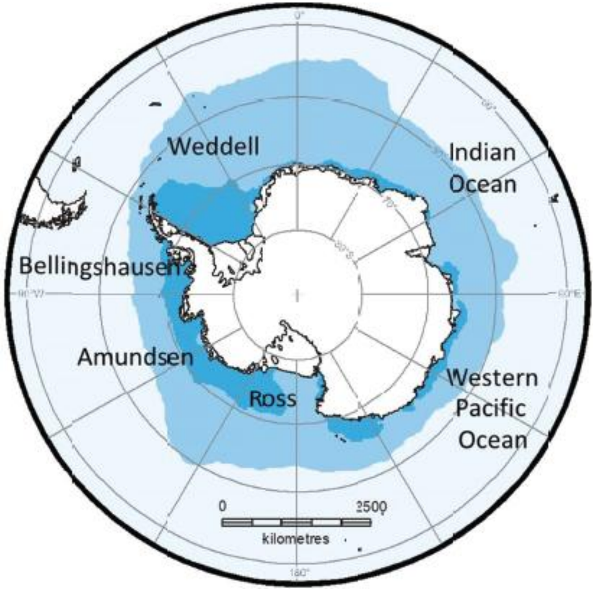
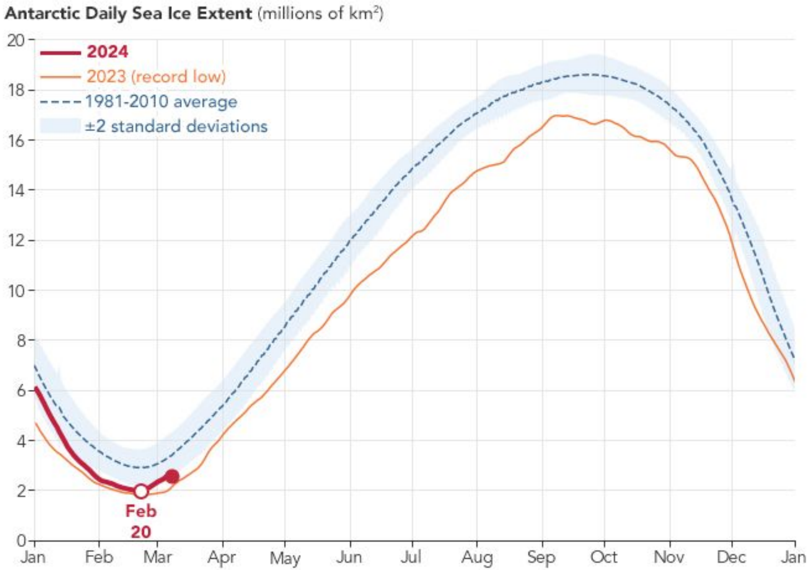
with
E. Parau, Q. Liu and F De Santi

#5thWSwaves @ECMWF

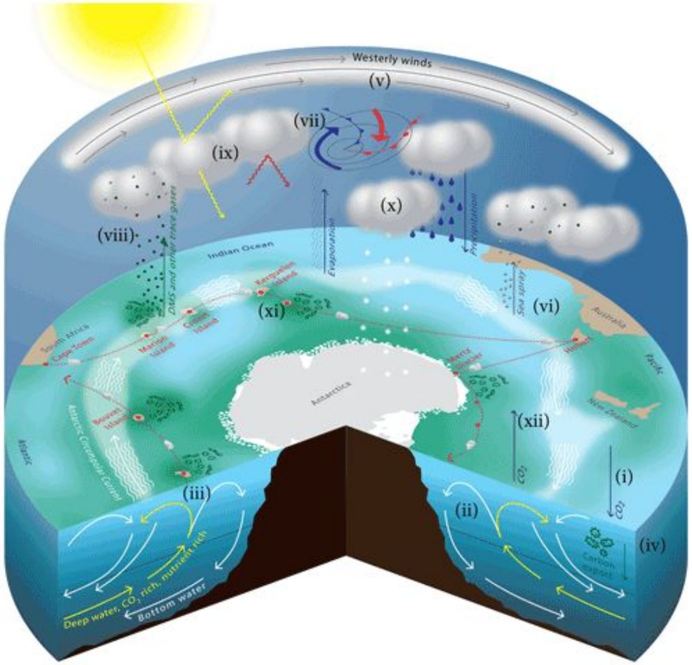
Antarctic sea ice





Undergoes the largest seasonal cycle on Earth, but is changing rapidly.
In August 2023 ~1.5 million sq km less than 2022 (5x UK).

SO, sea ice and the climate system



Key component of Earth's climate system

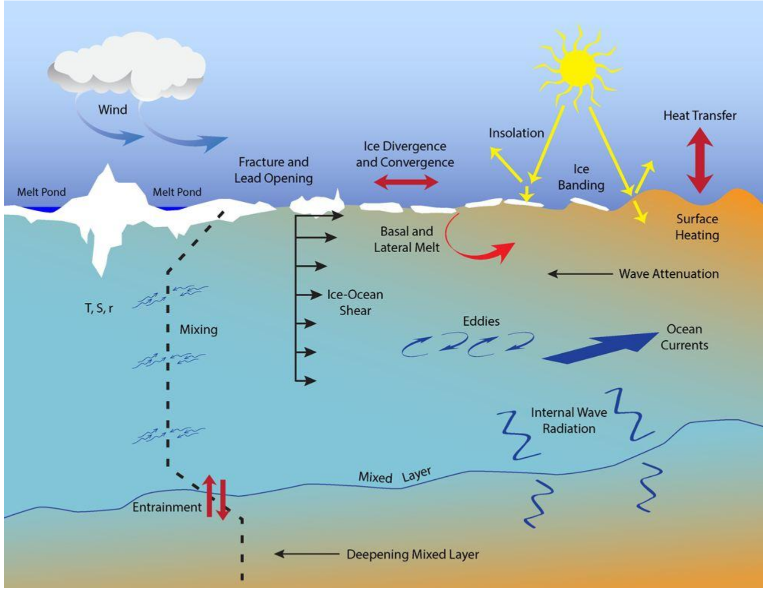
(ocean circulation, water cycle and freshwater fluxes, biological composition and productivity, trace gases, microbial components, ...)

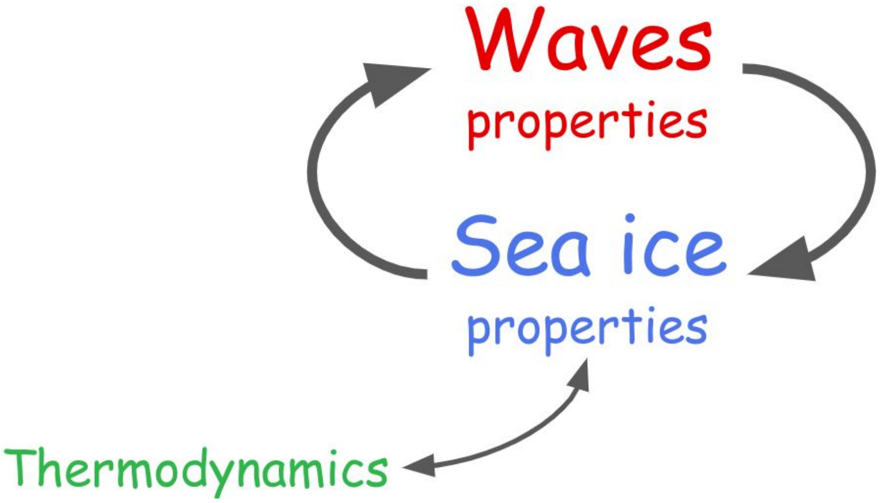
OCEAN WAVES modulate:

- ocean mixing
- sea spray emission
- biological production
- sea ice dynamics

Landwehr, [Alberello] et al., 2021, Earth Syst Dynam

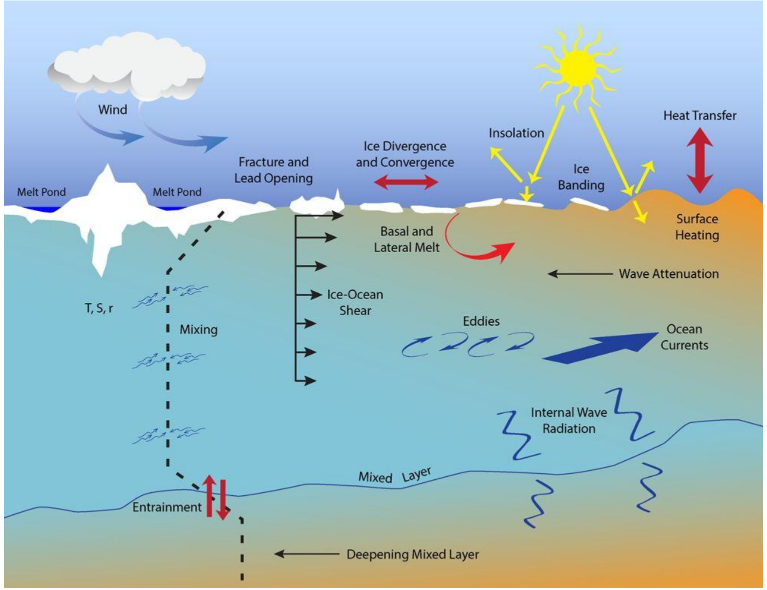
Marginal Ice Zone (MIZ)

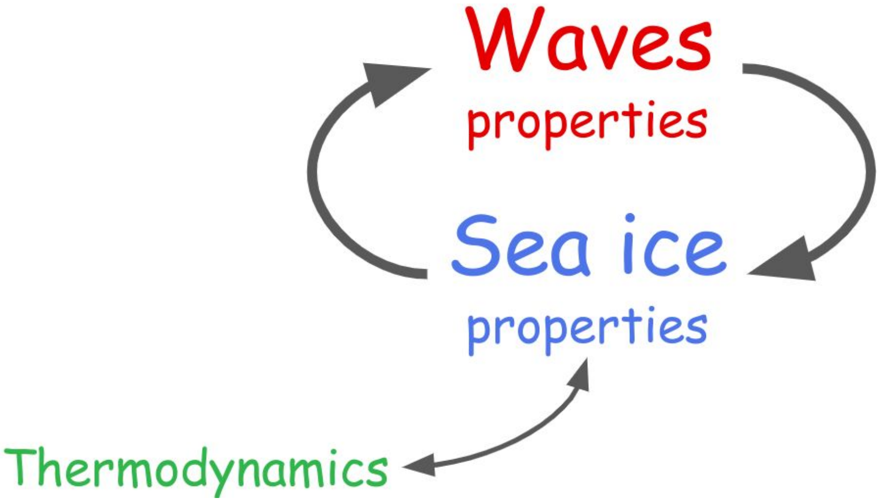




MIZ: sea ice exposed to open ocean (**waves**; Wadhams, 2000).

Marginal Ice Zone (MIZ)

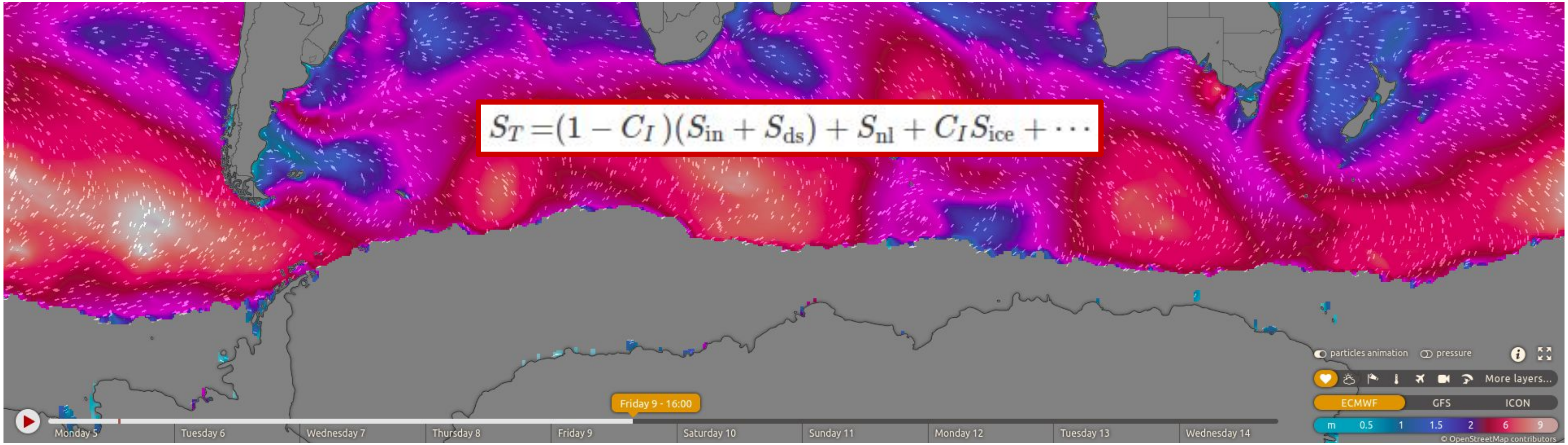




MIZ: sea ice exposed to open ocean (**waves**; Wadhams, 2000).

Often defined based on 15%<SIC<80%

Wave modelling in the MIZ



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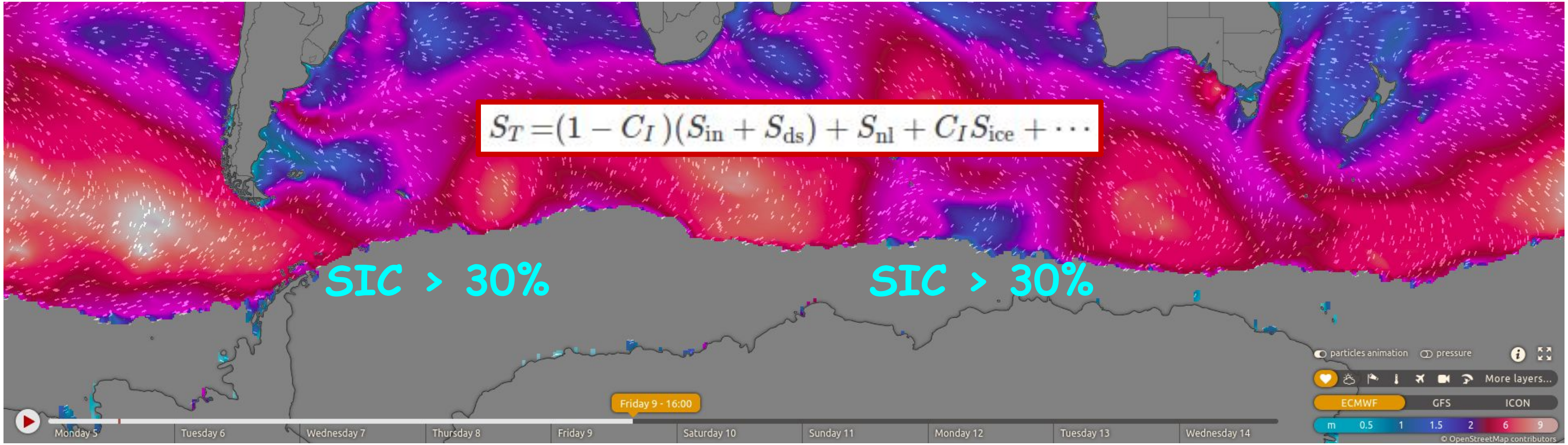

Waves in the MIZ

SA Agulhas II, 24 July 2022, Southern Ocean (59 South, 1 East)
https://www.youtube.com/watch?v=I3_ZCF9J6q4

Waves in the MIZ

SIC > 30%

and satellites
SIC > 80%

SA Agulhas II, 24 July 2022, Southern Ocean (59 South, 1 East)
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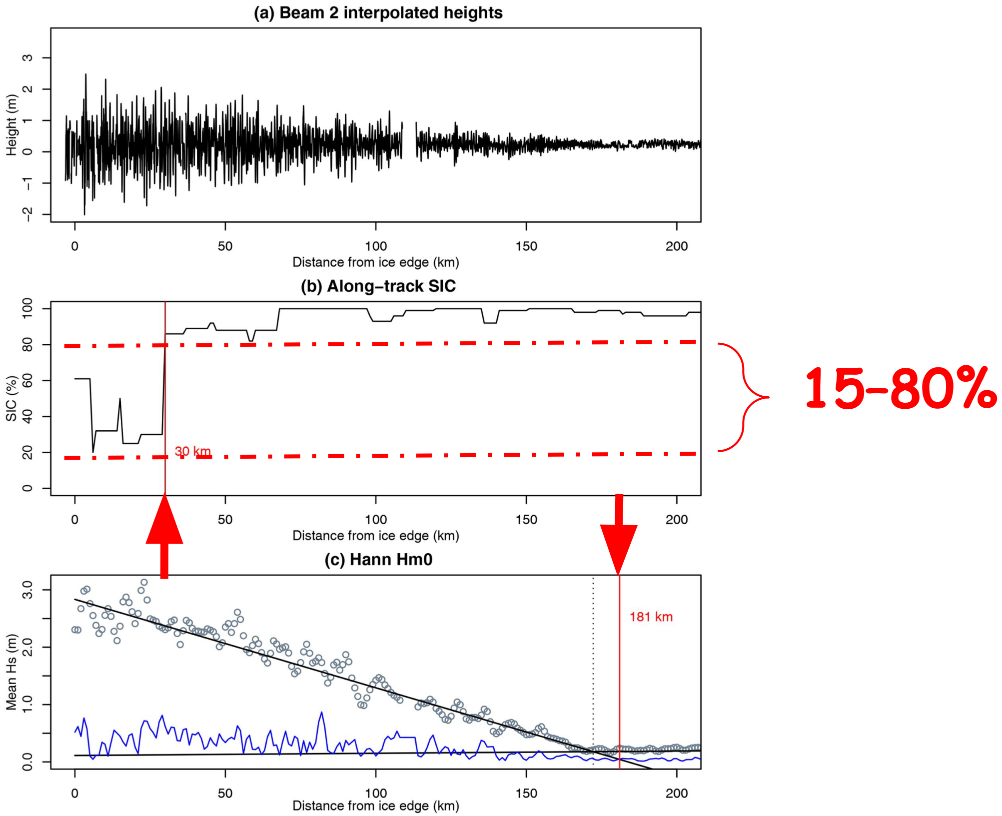
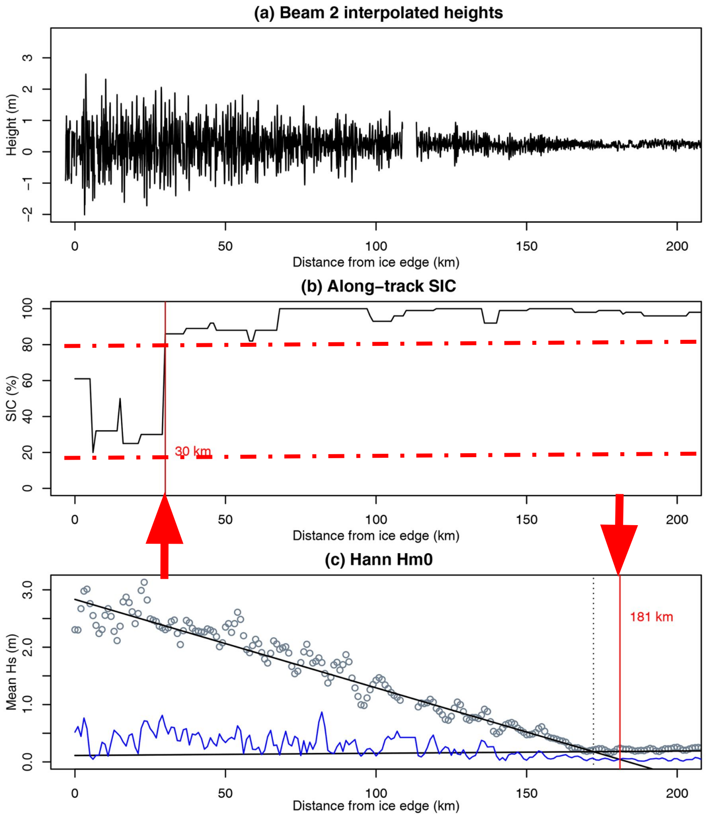
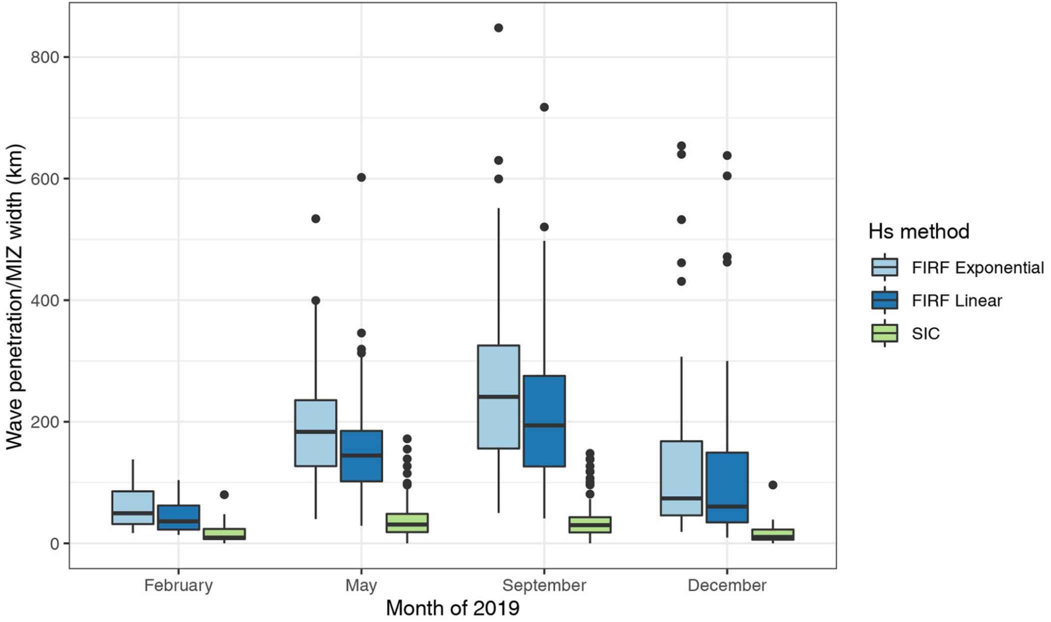
MIZ from ICESat-2



Brouwer, [Alberello] et al, 2022, The Cryosphere

MIZ from ICESat-2





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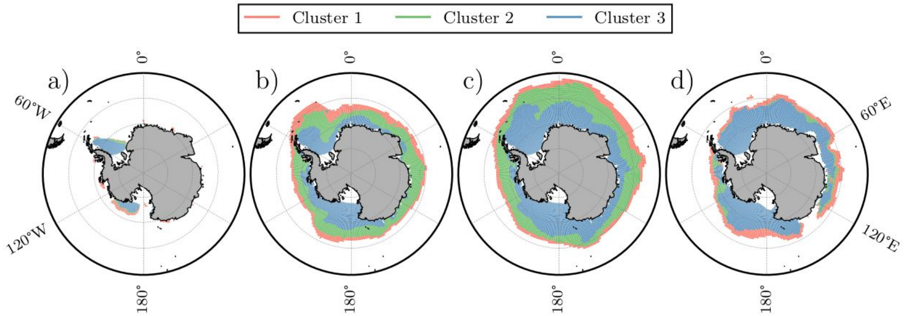
MIZ from CICE with WIM simulations

The wave-in-ice module enables wave induced breakup and pancake ice formation.



Day, [Alberello] et al, Submitted

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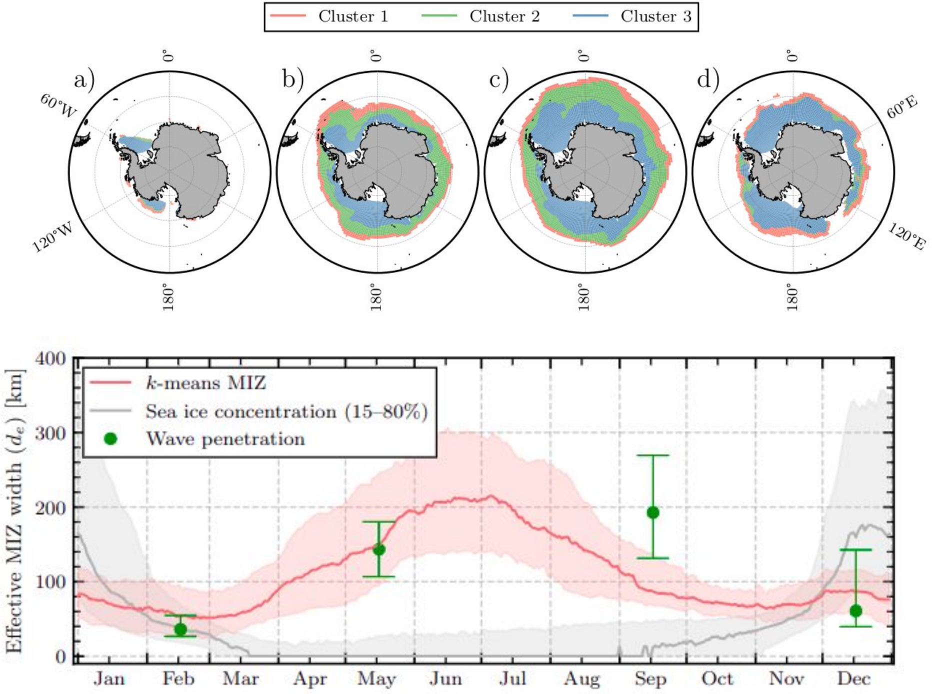


Day, [Alberello] et al, Submitted

Day
k-means

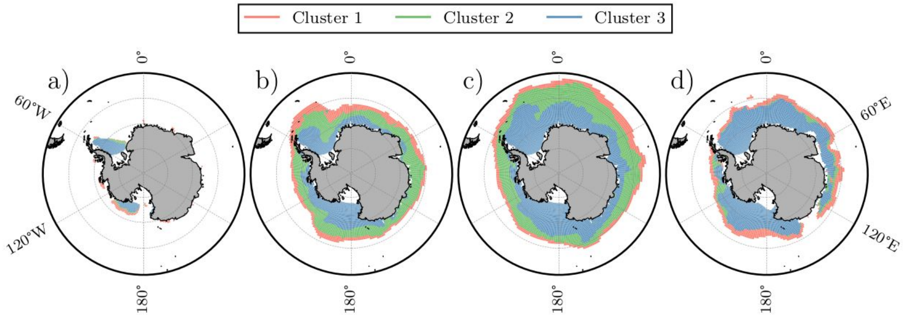
Brouwer
ICESat-2

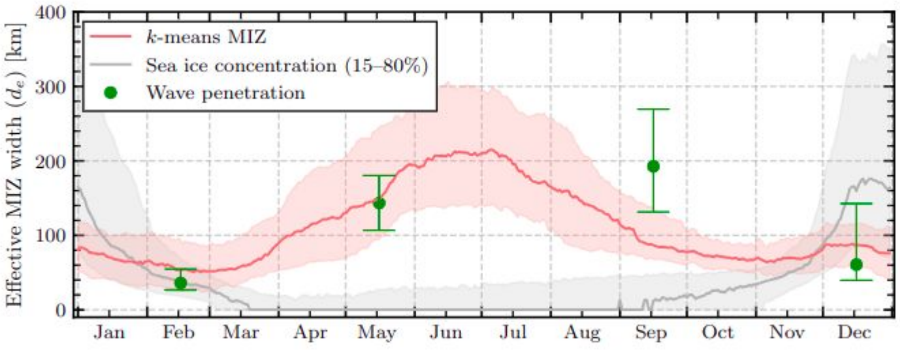
Traditional
concentration

MIZ from CICE with WIM simulations

The wave-in-ice module enables wave induced breakup and pancake ice formation.

Small, thin and young floes, generally in low concentration





Day, [Alberello] et al, Submitted

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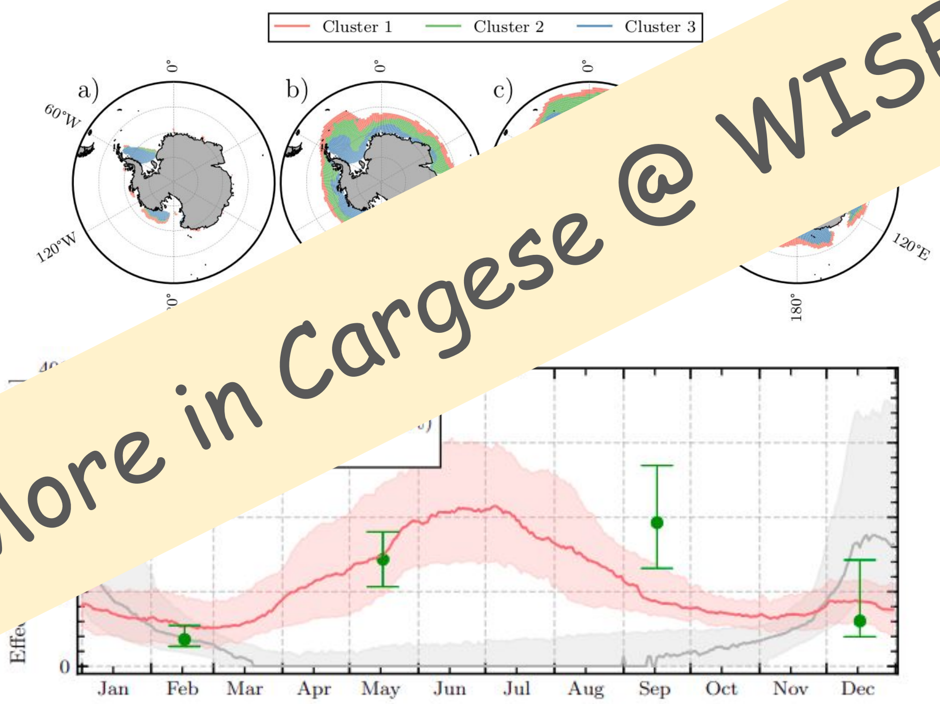

Day, [Alberello] et al, Submitted

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k-means

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Traditional
concentration

Wave dissipation in the MIZ

SCATTERING vs **VISCOUS**

SCATTERING

Floes > wavelength

Directional Broadening

vs

VISCOUS

Floes < wavelength

Directional Narrowing

Wave dissipation in the MIZ

~~SCATTERING~~

~~Floes > wavelength~~

~~Directional Broadening~~

vs

VISCOUS

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Directional Narrowing

Wave directionality in the lit

Squire & Moore (1980): narrowing [wave buoys]
Wadhams et al (1986): isotropy [wave buoys]
Meylan et al (1997): isotropy [wave buoys]
Sutherland & Gascard (2016): increase directionality at high frequency, unchanged at the peak [LiDAR]
Arduhin et al (2020): narrowing (particularly at low frequency) [SAR]
Alberello et al (2020): narrowing [stereo cameras]
Montiel et al (2018): narrowing [wave buoys]

SCATTERING

VISCOUS

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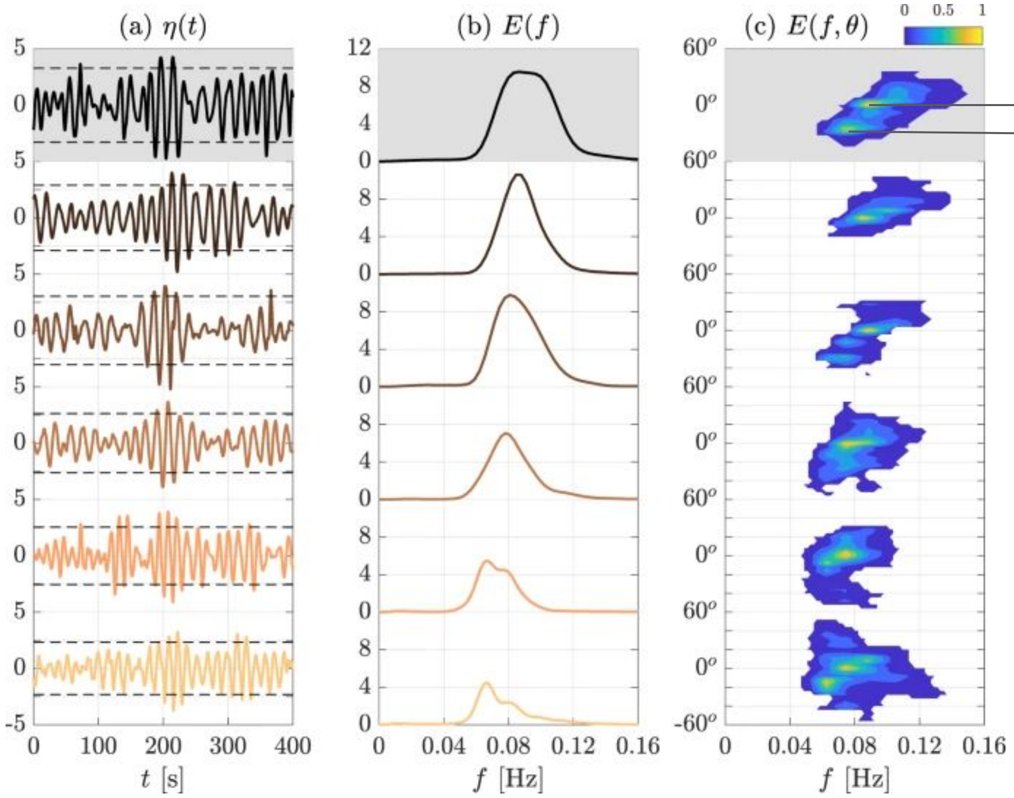
WAVE BUOYS have been the workhorse of measurements in the MIZ, but often only transmit integrated directional properties

SCATTERING **VISCOUS**

Wave properties in the MIZ



Wind sea

Swell

$$a_1 = \int_0^\infty \int_{-\pi/2}^{\pi/2} \cos\theta S(f,\theta) d\theta df,$$

$$b_1 = \int_0^\infty \int_{-\pi/2}^{\pi/2} \sin\theta S(f,\theta) d\theta df.$$

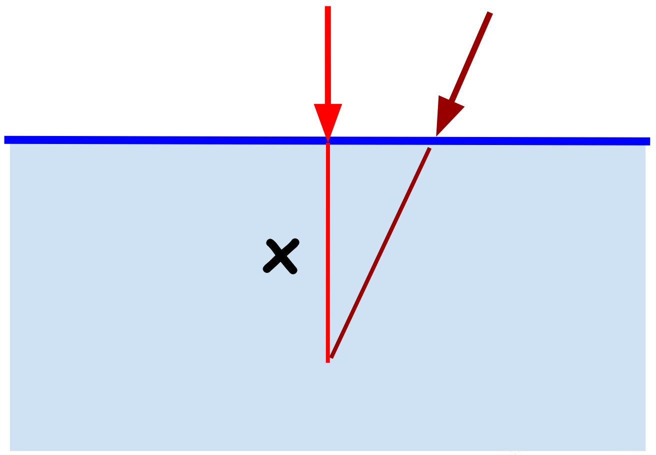
$$\sigma_1 = \sqrt{2\left(1 - \sqrt{a_1^2 + b_1^2}\right)}$$

Alberello et al, 2022, Nat Comms

Wave properties in a **VISCOUS** MIZ

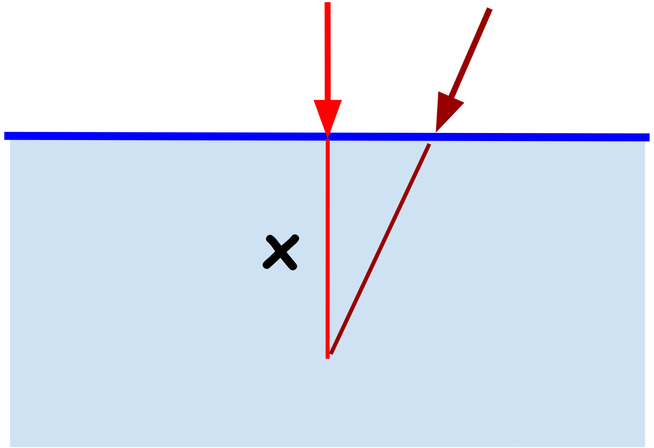
Few simplifying hypothesis

Wave properties in a VISCOUS MIZ



$$S(f,\theta;x) = S(f,\theta;0)\exp\left(\frac{-\alpha(f)x}{cos\theta}\right)$$

Wave properties in a VISCOUS MIZ

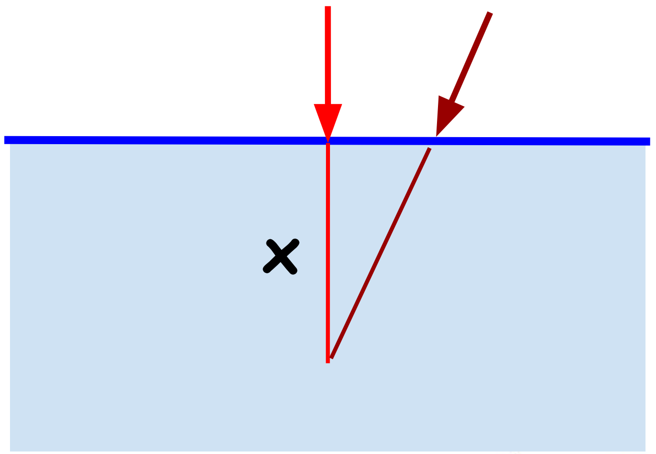


$$S(f,\theta;x) = S(f,\theta;0)\exp\left(\frac{-\alpha(f)x}{cos\theta}\right)$$

$$\alpha(f) = Af^2 + Bf^4$$

Meylan et al, 2014, JGR

Wave properties in a VISCOUS MIZ



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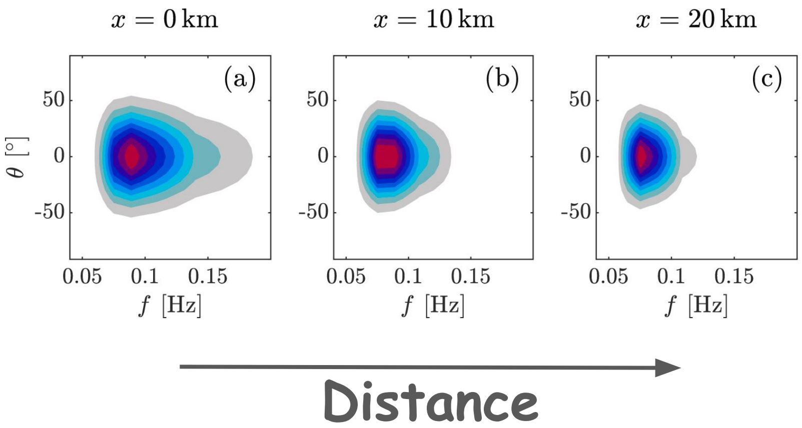
$$\alpha(f) = Af^2 + Bf^4$$

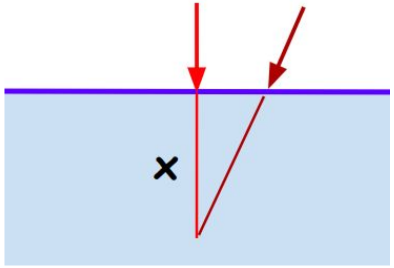
Meylan et al, 2014, JGR

No changes in dispersion relation,

All changes attributed to frequency dependent attenuation and path-length effect

Wave spectrum 2d





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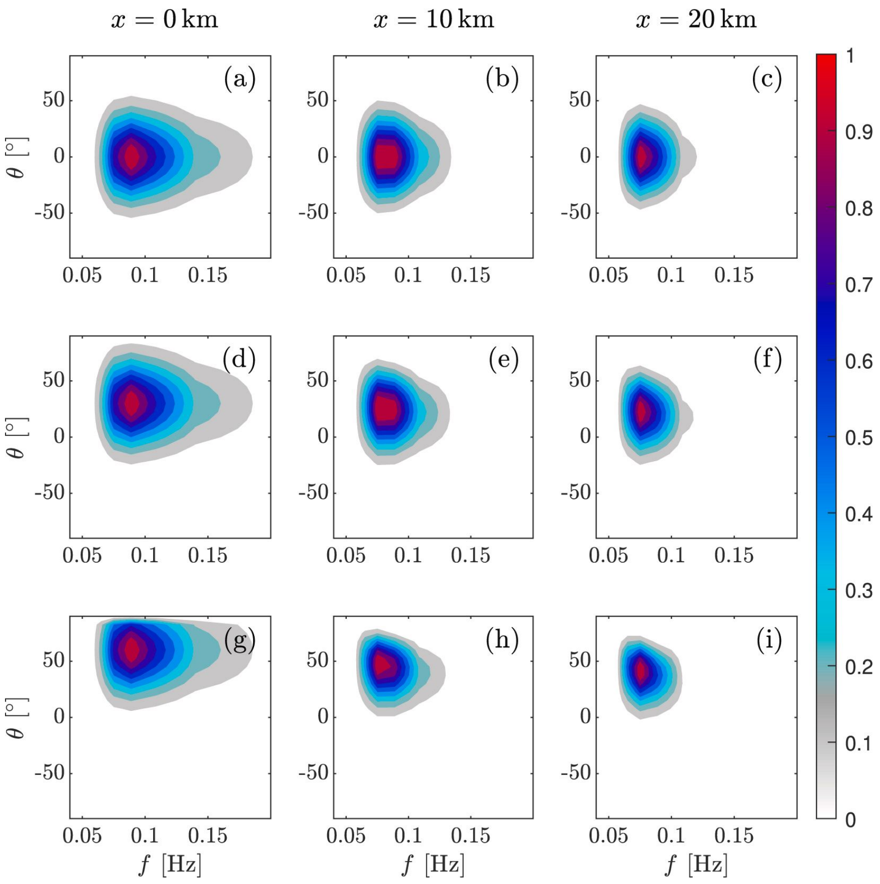

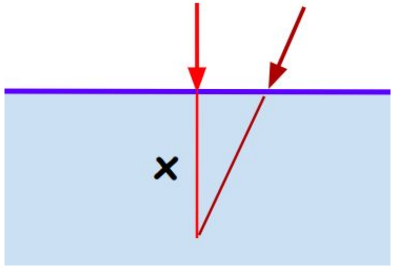

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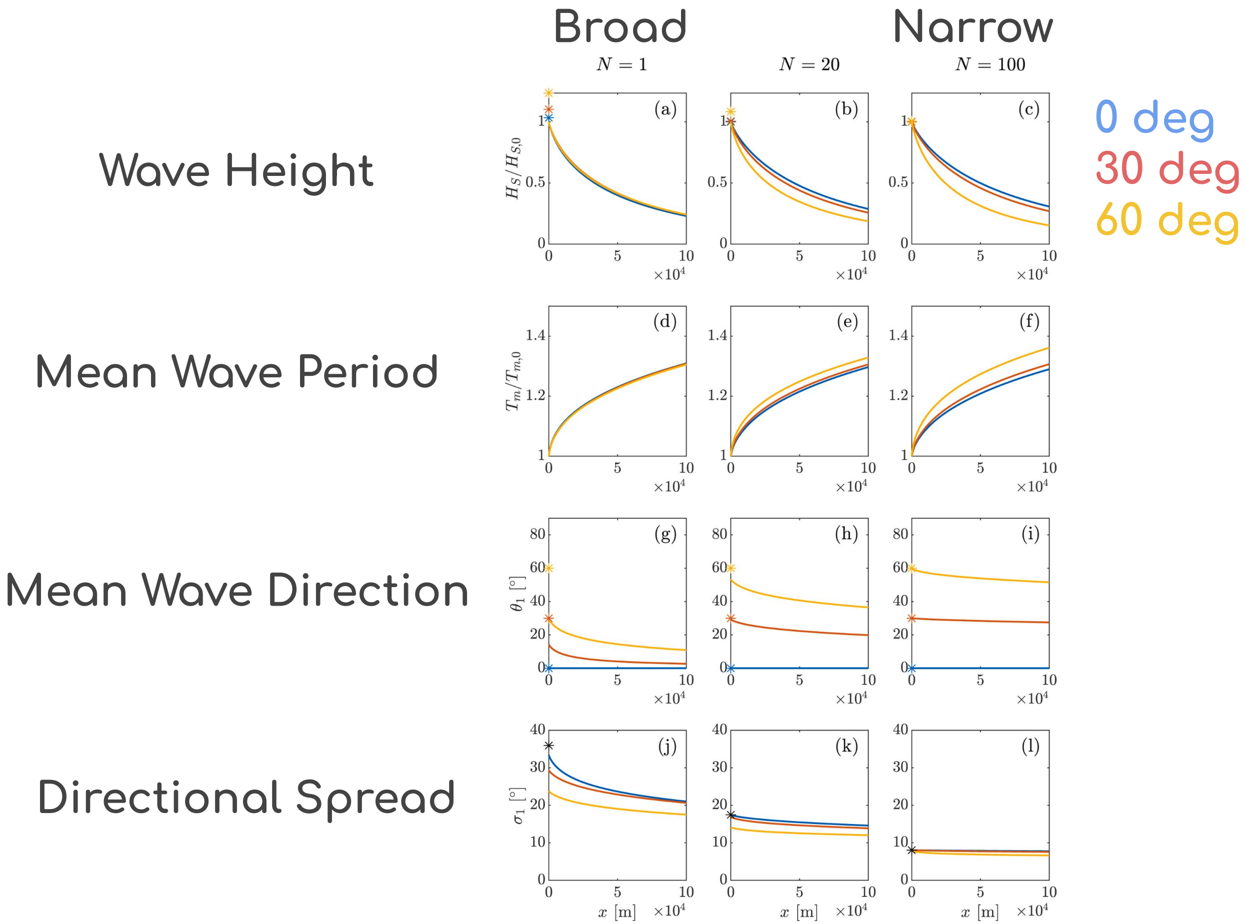
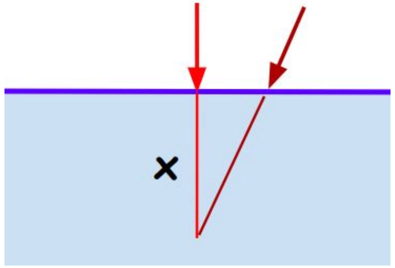




Wave spectrum 2d

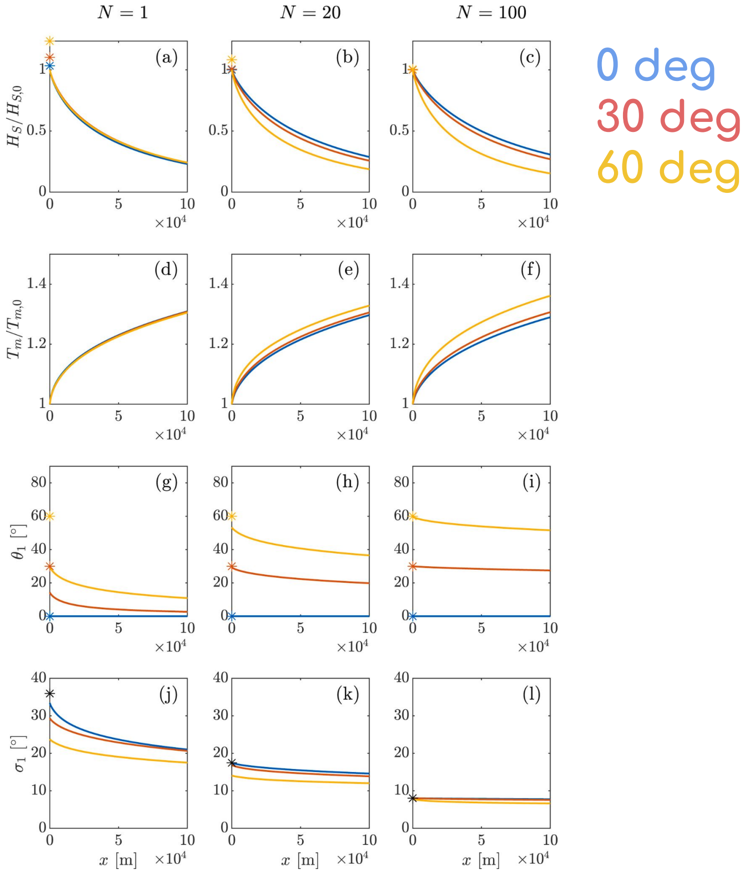
In BROAD seas the incidence angle is less important

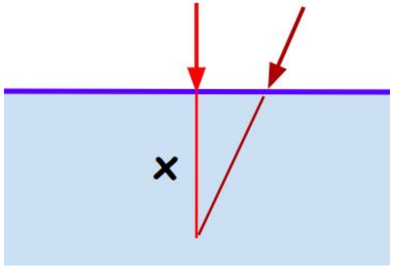
In BROAD seas the dominant component is the one with the shortest path

$$S(f,\theta;x) = S(f,\theta;0)\exp\left(\frac{-\alpha(f)x}{\cos\theta}\right)$$

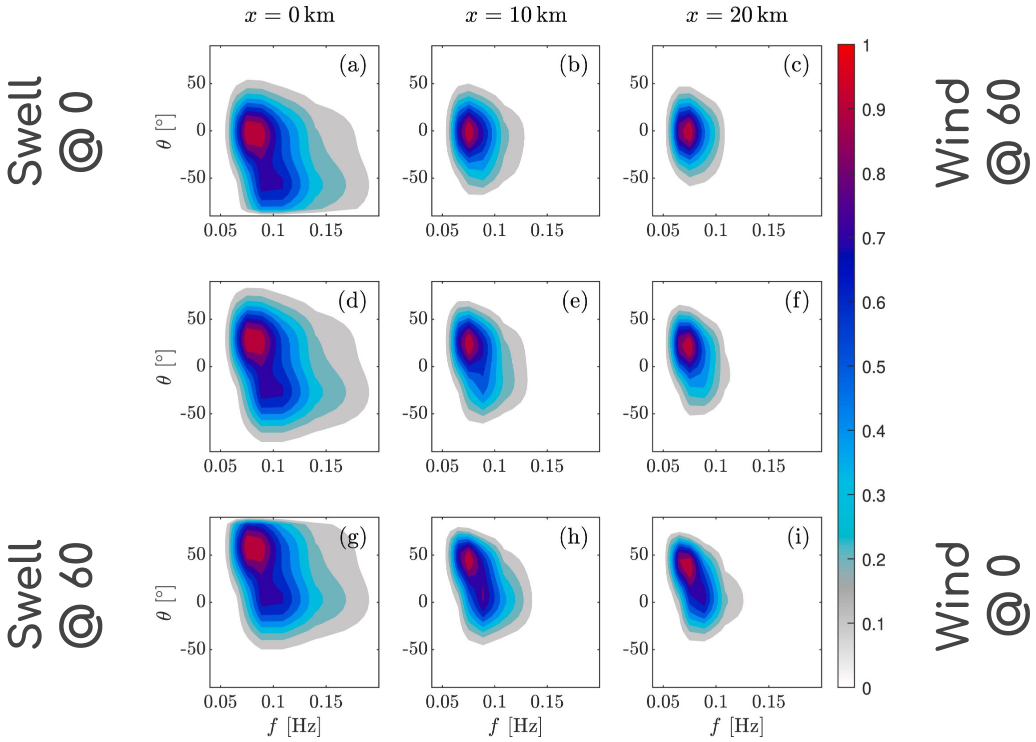
Broad

Narrow

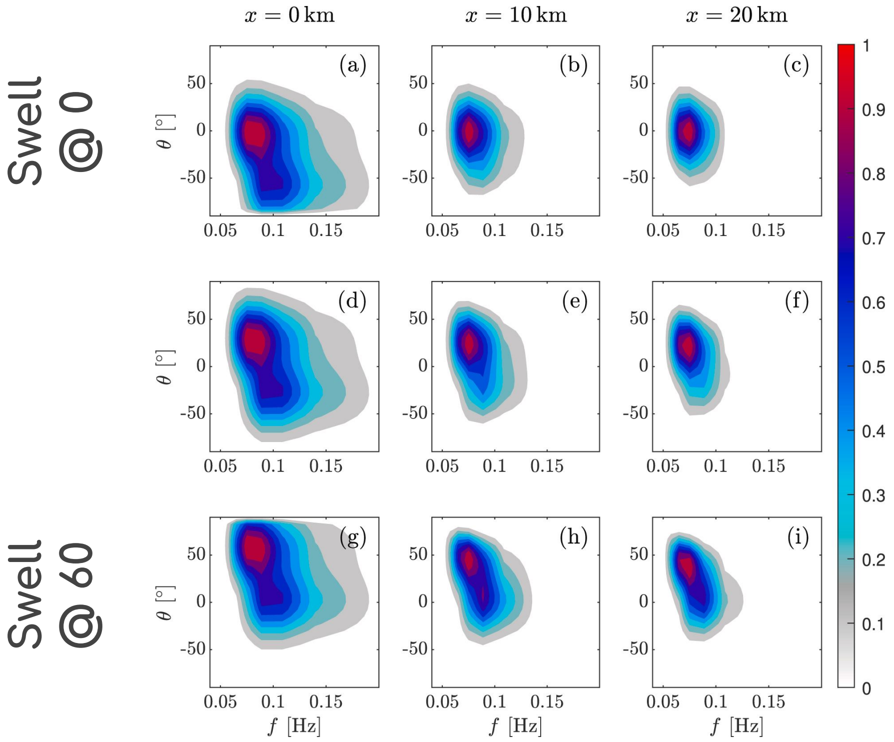




Bi-modal wave spectrum



Bi-modal wave spectrum



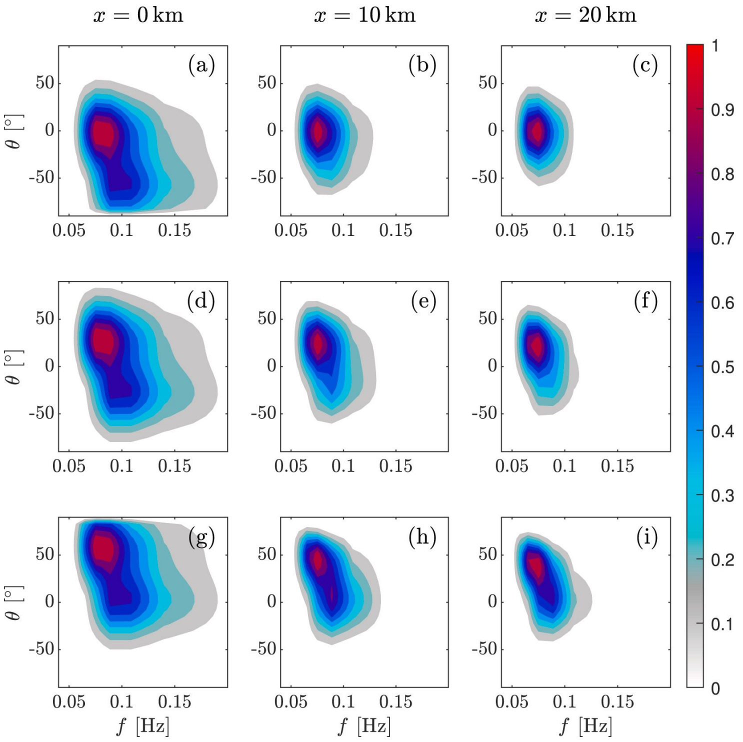
Similar to SWELL only

Dominated by SWELL but strong asymmetry in original WIND

Bi-modal wave spectrum

Narrow

Swell @ 0



Similar to SWELL only

Dominated by SWELL but strong asymmetry in original WIND

The shortest distance of wind sea counterbalance the higher dissipation

Bi-modal wave spectrum

Swell @ 0

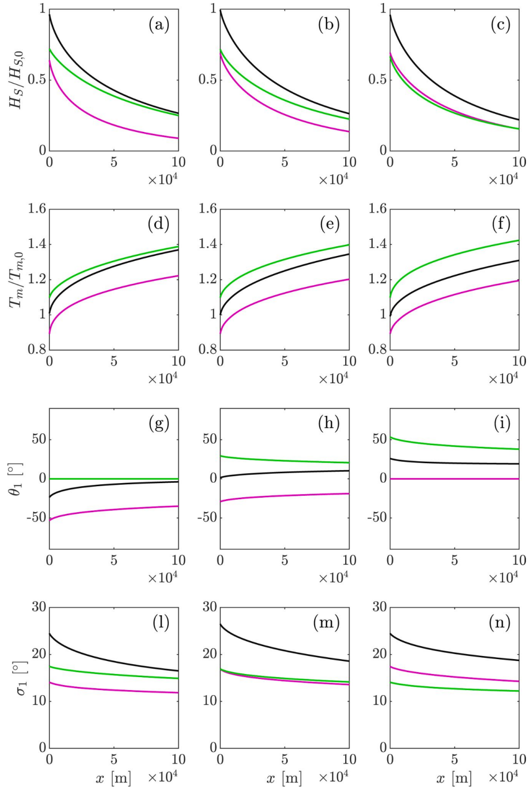
Wind @ 0

Wave Height

Mean Wave Period

Mean Wave Direction

Directional Spread



Bi-modal wave spectrum

Swell @ 0

Wind @ 0

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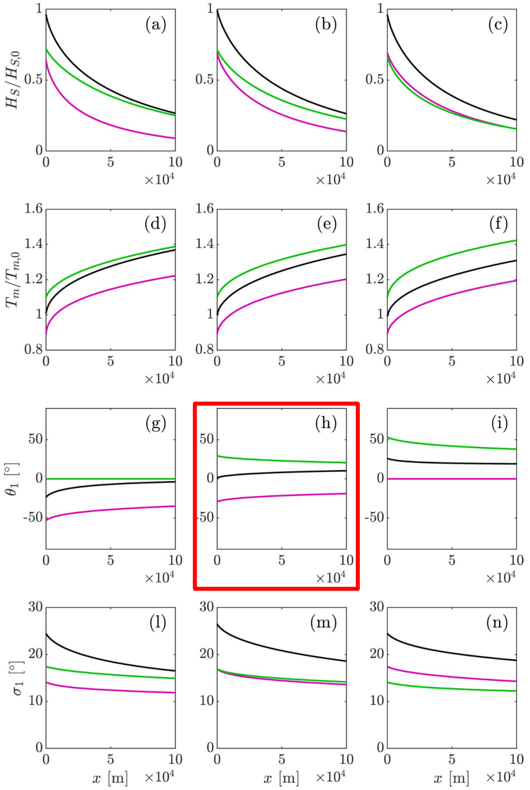
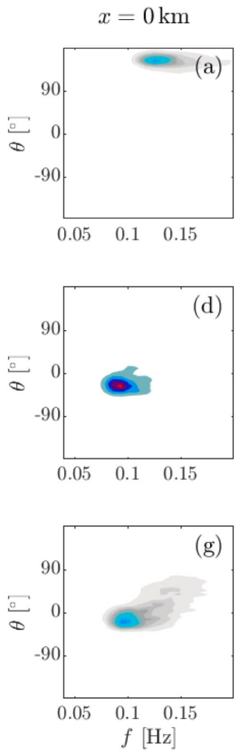
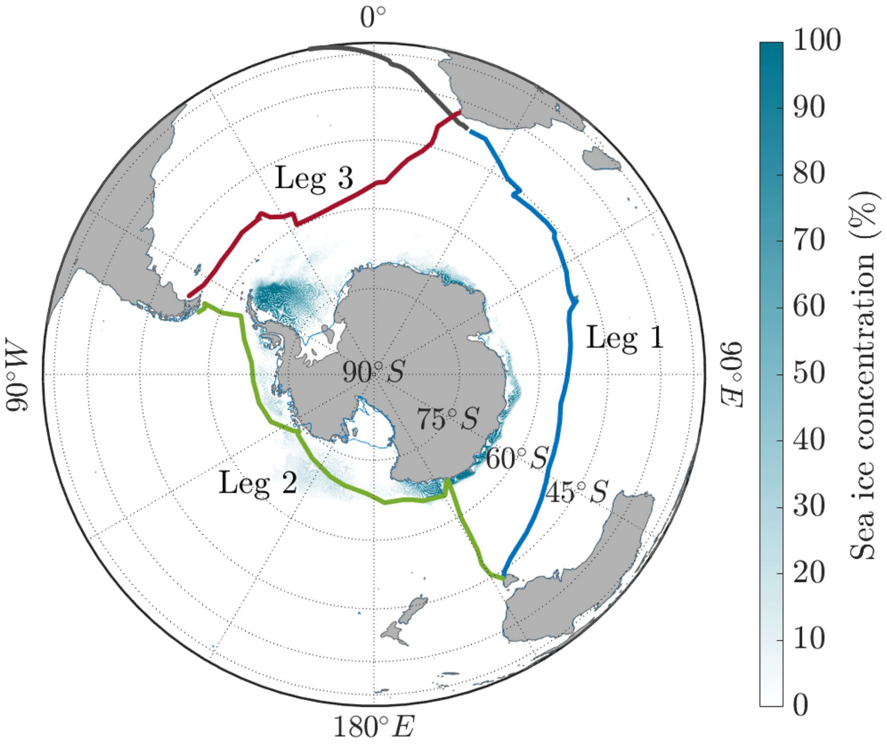


The total deviated away from 0 (tends to SWELL)

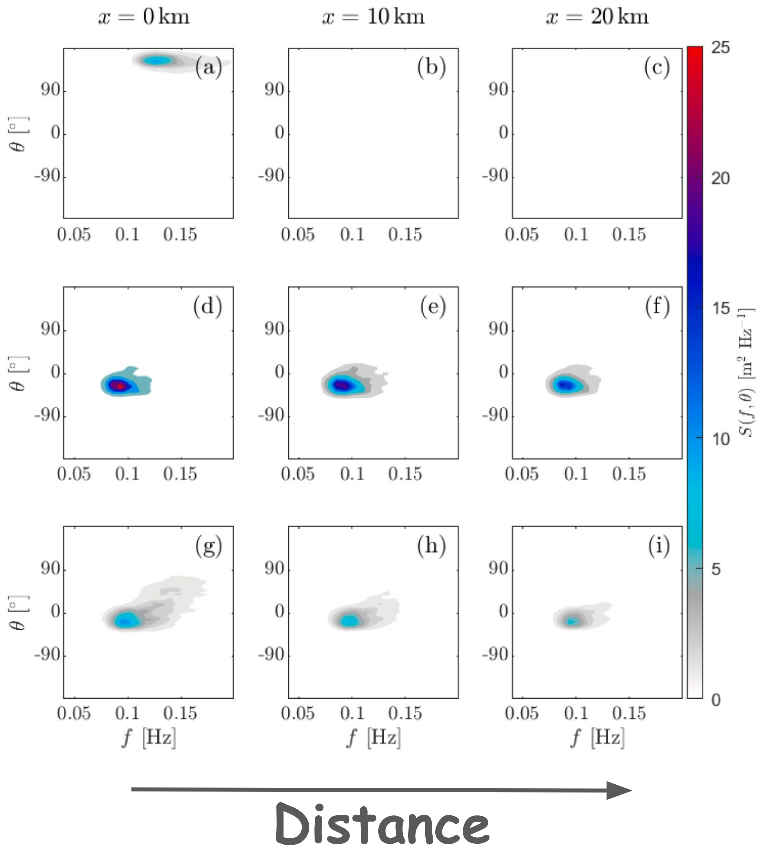
Wave spectra during ACE (WaMoS-II)



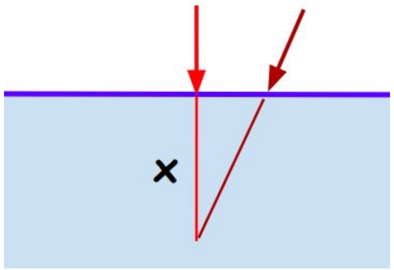


Derkani et al, 2021, ESSD

Wave spectra during ACE



Wave moving away from ice (North)



$$S(f,\theta;x) = S(f,\theta;0)\exp\left(\frac{-\alpha(f)x}{cos\theta}\right)$$

Similar to unimodal

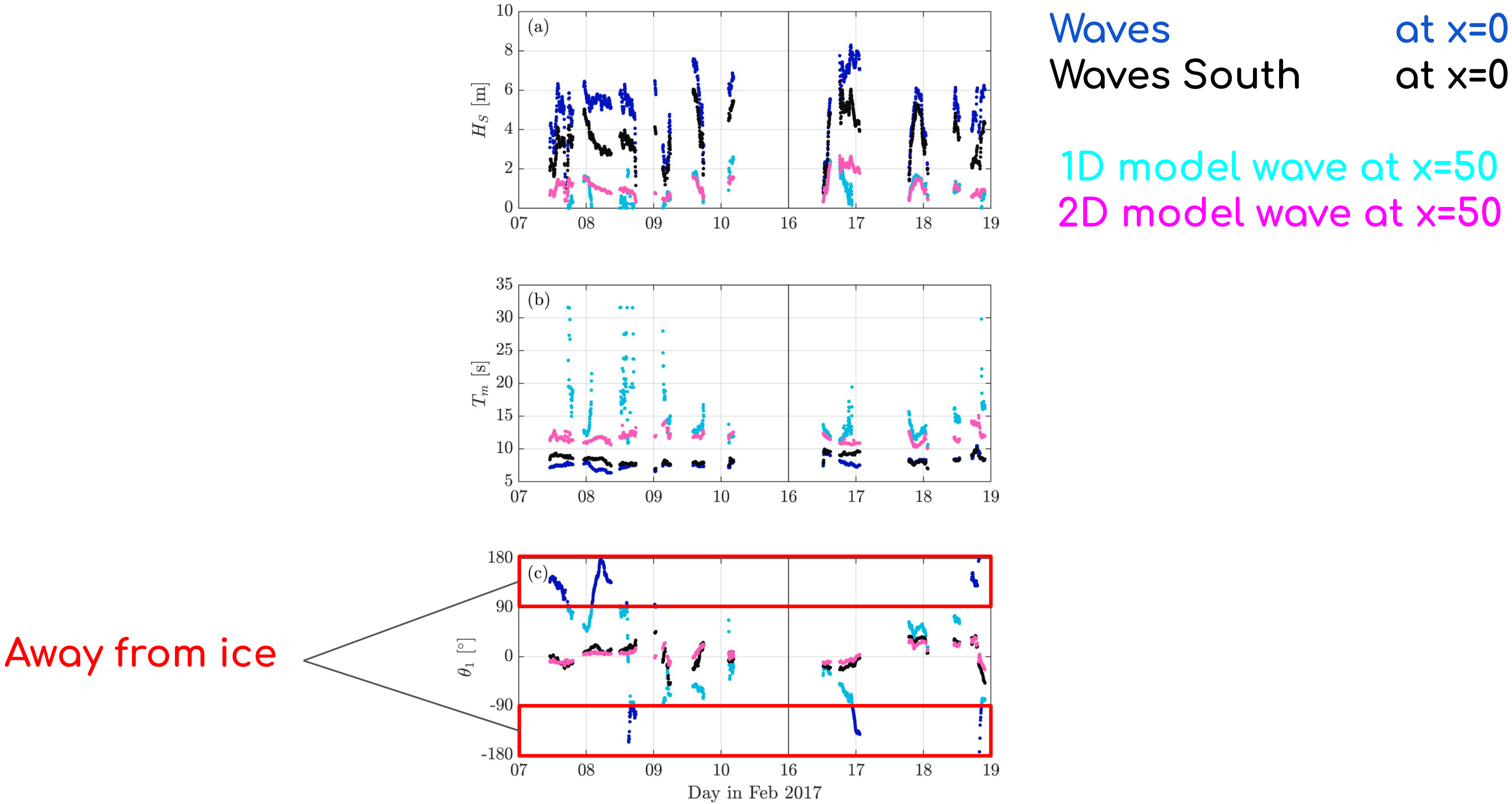
Similar to Wind Sea+Swell

Wave spectra during ACE

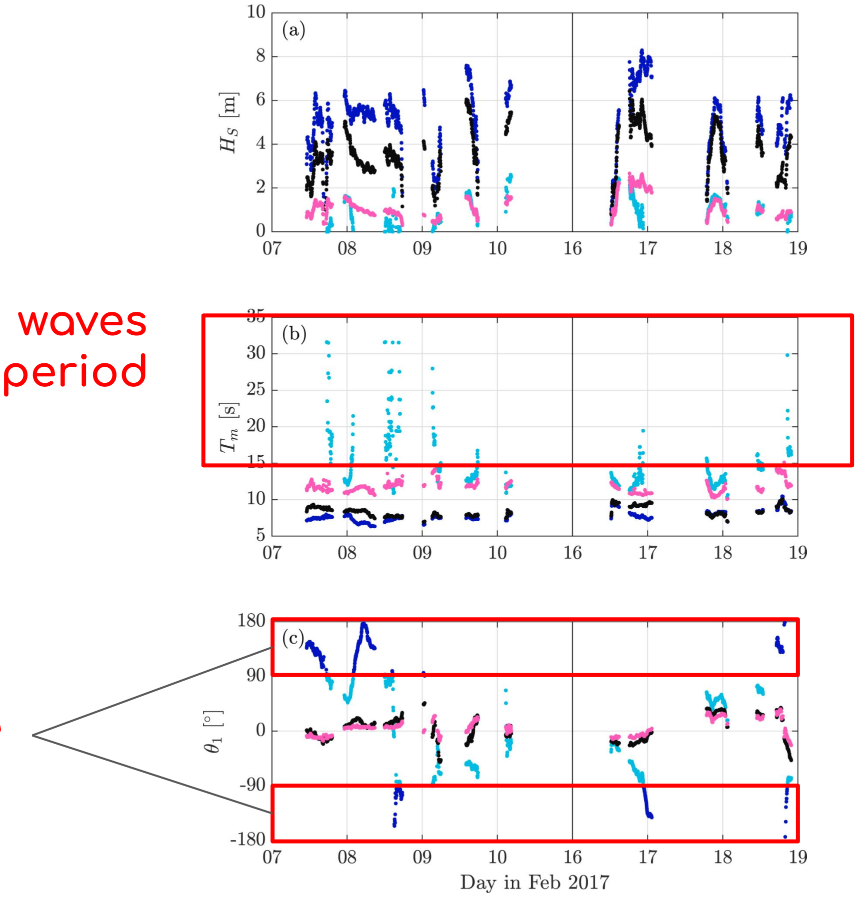
Waves at x=0
Waves South at x=0

1D model wave at x=50
2D model wave at x=50

Wave spectra during ACE



Wave spectra during ACE



Waves at x=0

Waves South at x=0

1D model wave at x=50

2D model wave at x=50

1D model predicts waves with mean wave period >15s, cf 2D model

Away from ice

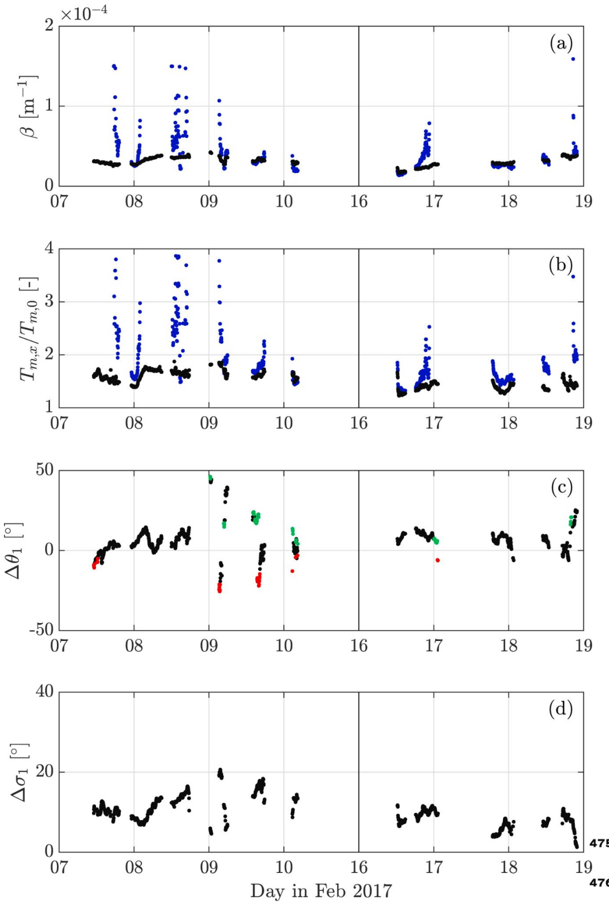
Wave spectra during ACE

Attenuation

Downshift

Rotation

Narrowing



1D model
2D model

475

476

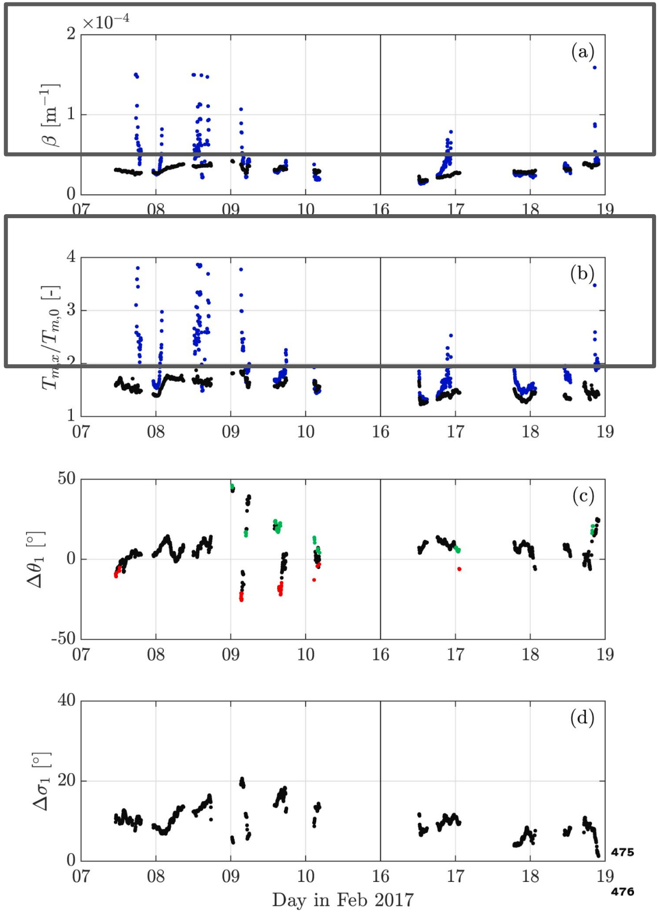
Wave spectra during ACE

Attenuation

Downshift

Rotation

Narrowing



1D model
2D model

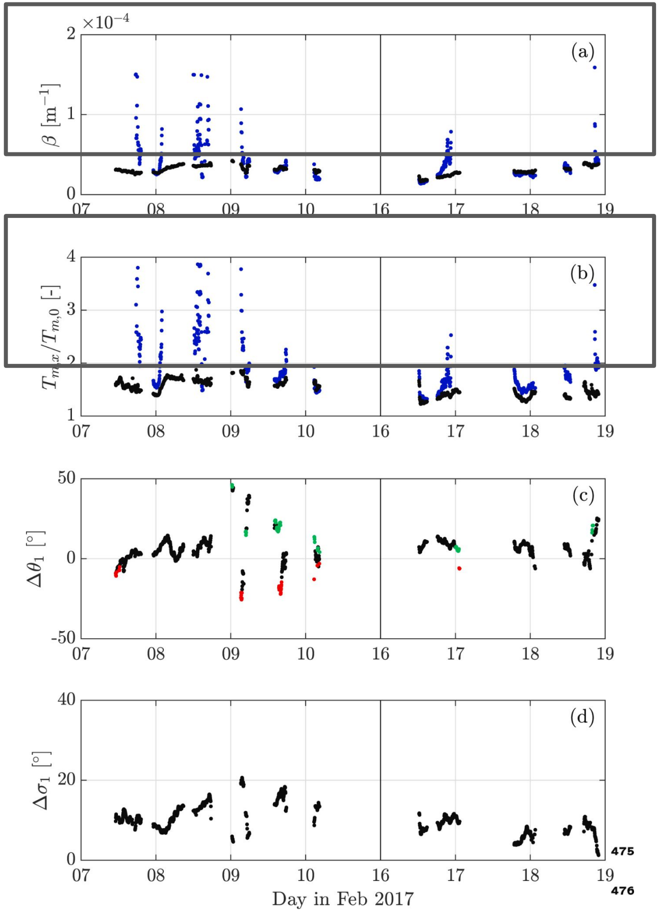
Wave spectra during ACE

Attenuation

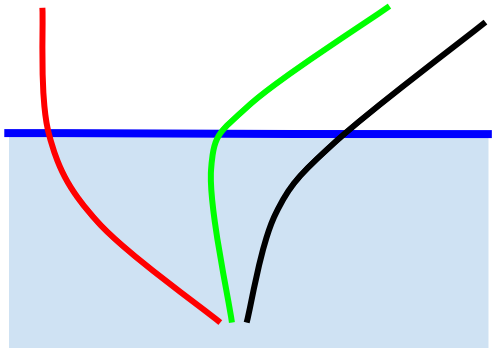
Downshift

Rotation

Narrowing



1D model
2D model



Bimodal seas

Wave and wave-coupled processes

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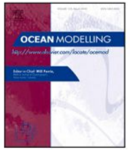

Check for updates

Evolution of wave directional properties in sea ice

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[b] *Frontier Science Center for Deep Ocean Multispheres and Earth System (FDOMES) & Physical Oceanography Laboratory, Ocean University of China, Qingdao, China*
[c] *Department of Infrastructure Engineering, The University of Melbourne, Melbourne, 3010, Australia*
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A R T I C L E I N F O

Keywords:
Marginal ice zone
Waves
Directionality
Sea ice

A B S T R A C T

Ocean waves and sea ice properties are intimately linked in the marginal ice zone (MIZ), nevertheless a definitive modelling paradigm for the wave attenuation in the MIZ is missing. The evolution of wave directional properties in the MIZ is a proxy for the main attenuation mechanism but paucity of measurements and disagreement between them contributed to current uncertainty. Here we provide an analytical evidence that viscous attenuation tilts the mean wave direction orthogonal to the sea ice edge and the narrows directionality. Departure from this behaviour are attributed to bimodality of the spectrum. We also highlight the need for high quality directional measurements to reduce uncertainty in the definition of the attenuation rate.

Summary

Waves are directionally spread, also in the MIZ, and can be bimodal

but directionality is poorly captured by integrated parameters

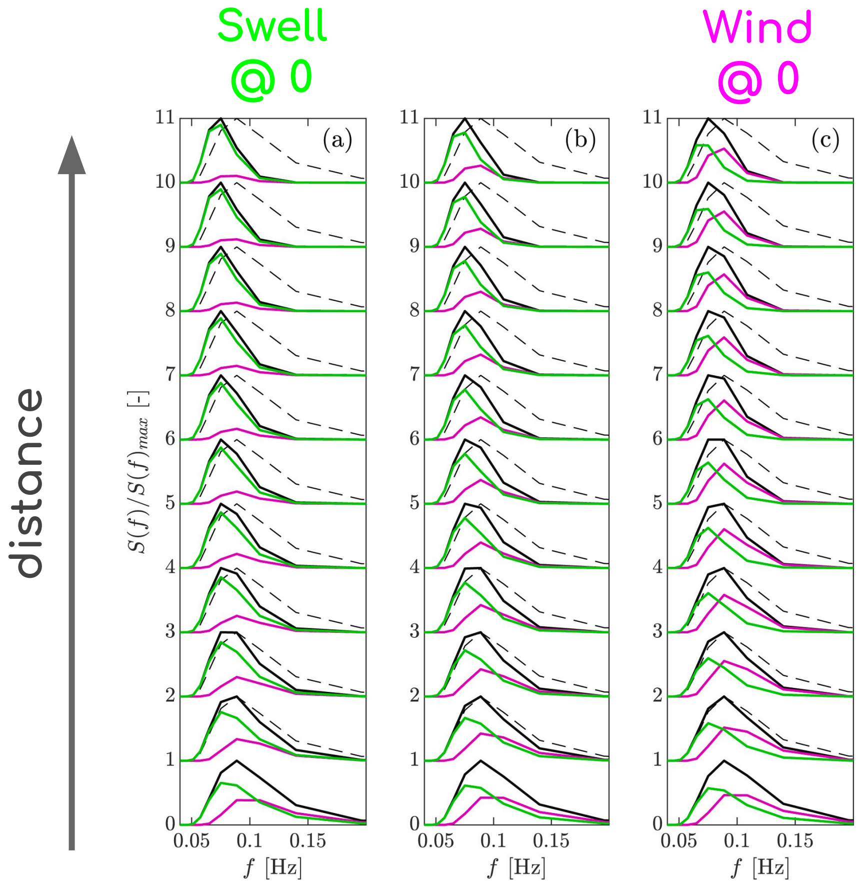
and misrepresentation of directional properties can affect estimation of attenuation rate and downshift

In the MIZ (viscous-like dissipation) wave spectrum becomes narrower and normal to sea ice edge

but deviation away are possible in bimodal seas

In summary, more measurements with directional properties are needed

Bi-modal wave spectrum



When WIND @0 the shortest distance counterbalance the higher dissipation

$$S(f,\theta;x) = S(f,\theta;0)\exp\left(\frac{-\alpha(f)x}{cos\theta}\right)$$

Bi-modal wave spectrum