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Predictability of waves near marginal ice zones during R/V Mirai observational campaign

Satellite retrieved sea ice concentration uncertainty and its effects on modelling wave evolution

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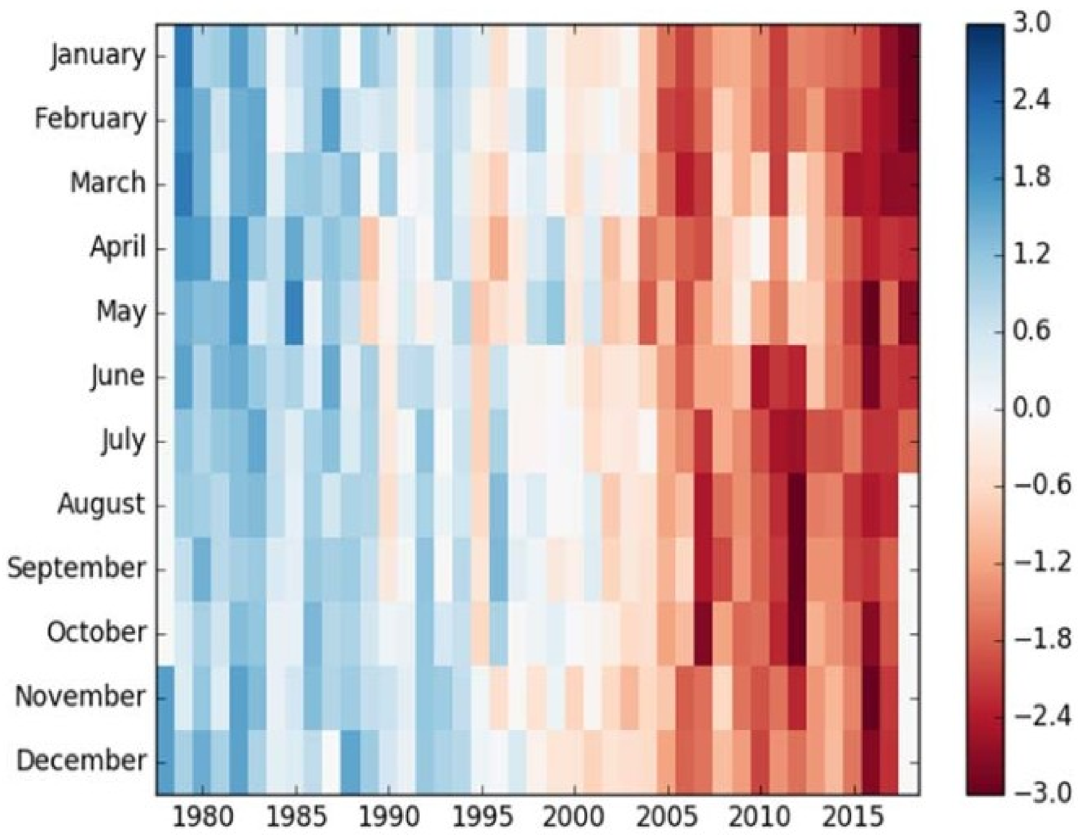
Introduction—the Arctic sea ice



Anomalies of monthly sea ice extent shown using σ of the 1981–2010 mean (Stroeve and Notz, 2018)

- The Arctic, with a decreasing sea ice extent, has the greatest regional warming on earth (AMAP, 2017) and conspicuously reflects the climate change effects.

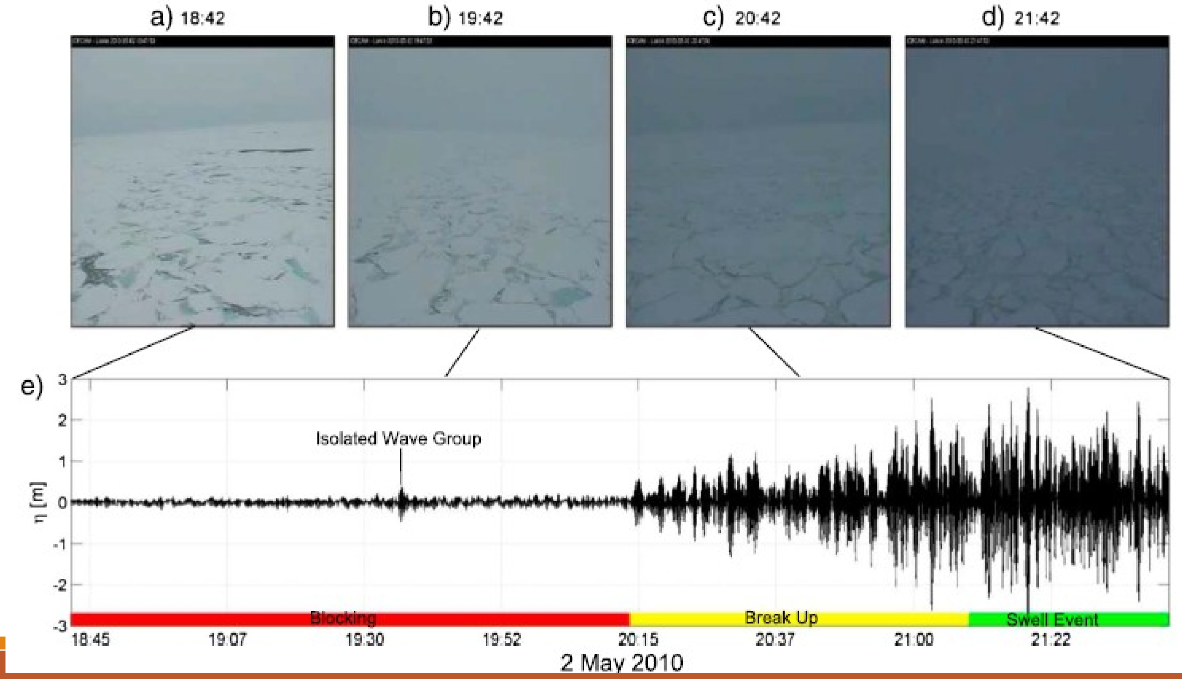
- Stroeve and Notz (2018) showed the record breaking 2012 Sep minimum extent was 3σ below the 1981–2010 long-term average.

- They also demonstrate downward trends in other months have been just as substantial:

    - May and November 2016 recorded ~4σ below long-term mean, which is the maximum deviation in the satellite era.
    - Between January 2016 and July 2018, all months had sea-ice coverage of more than 2σ below average, with the exception of May and September 2017, and July 2018.

Introduction—waves and sea ice

- Diminishing sea ice and increasing open water lead to more energetic wave climate.
- "New waves" in the Arctic Ocean lead to a completely new state of air-sea interactions with momentum, energy, heat, gas, and moisture fluxes being moderated or produced by waves, and affects upper-ocean mixing (Babanin et al., 2014, Khon et al., 2014).
- Waves can penetrate 100s of kilometres through sea ice (Kohout et al., 2016). Wave-ice interaction has attracted attention in the wave community for some time now, but the implementation of wave-ice physics in contemporary wave models remain a challenge.



Swell waves penetrating 100s of kilometres and evidence of ice sheet break up in the Antarctic (Kohout et al. 2016) (top) and a similar process on a smaller scale at the Barents Sea (Collins et al., 2016) (bottom).

Introduction—basis of spectral wave modelling in ice cover

- Numerical evolution of waves are simulated in physical and spectral coordinates as energy budgets following the action density balance equation (1).

$$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c}N = \frac{s_{\text{total}}}{\sigma} \qquad (1)$$

- The left hand side concerns the wave kinematics. Neglecting currents and in deep water, the primary source terms and default scaling in ice cover are as shown in (2) where the dissipation term is usually negative.

$$s_{\text{total}} = (1 - c_i)(s_{\text{wind}} + s_{\text{dissipation}}) + c_i s_{\text{ice}} + s_{\text{non-linear interactions}} \qquad (2)$$

- Wave evolution in ice cover is scaled by sea ice concentration (SIC), c_i. The wave-ice interaction source term is a negative source and further separates to scattering, basal friction, flexural dissipation, and visco-elastic dissipation.

- In WAVEWATCH III®, 3 physics-based parameterisation source terms are available: IC2, IC3, and IC5.

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$$(1 - c_i)(s_{\text{wind}} + s_{\text{dissipation}}) > c_i s_{\text{ice}}$$

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Introduction—passive microwave radiometry of SIC

- Passive microwave radiometry is the most effective tool to capture temporal and spatial coverage to characterise Earth sea ice cover (Comiso et al. 1997).

- SIC is an indirect measured quantity translated from brightness temperatures, T_b. Signal from different frequency channels can account for spatial and temporal changes in surface emissivity and physical temperatures.

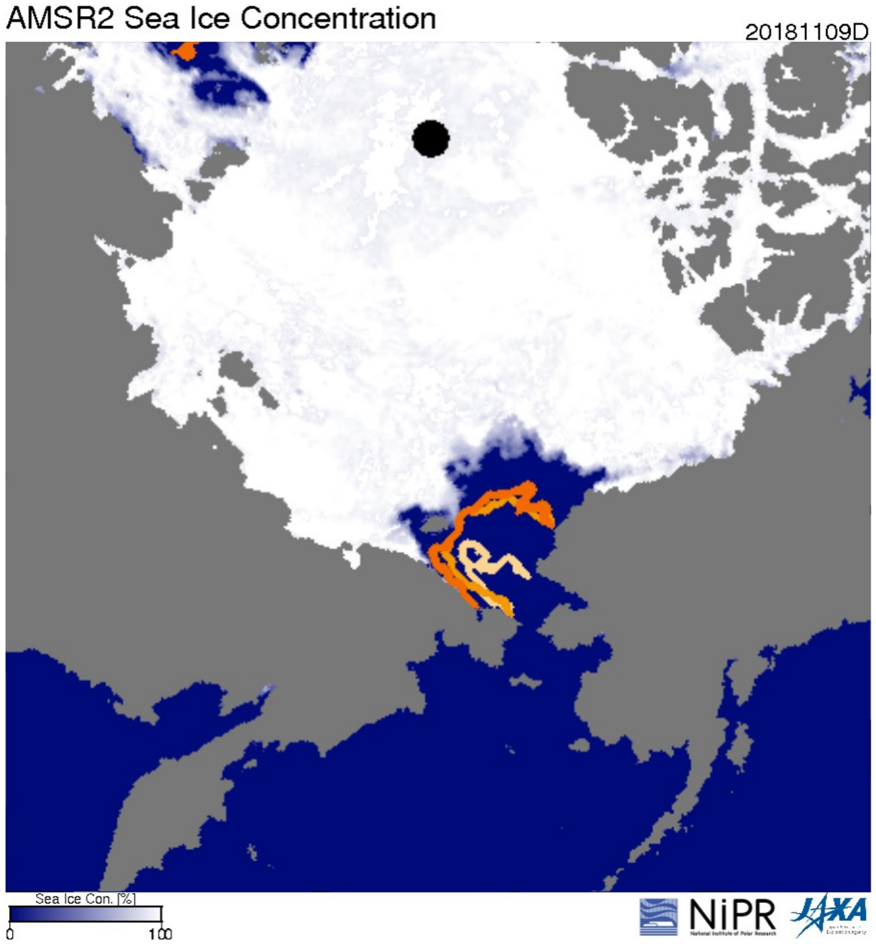
- SIC is derived given the ocean surface is binary, i.e., ice free (*o*) or ice covered (*i*). Then, SIC is calculated assuming that measured radiative flux, R, from a sensor is (3). Assuming linear EM radiation and surface temperature, SIC is expressed as (4) based on a set of tie points representing T_b at ice free and ice cover surface.

$$R = R_i c_i + R_o c_o \quad (3) \qquad c_i = \frac{T_b - T_o}{T_i - T_o} \quad (4)$$

- Low energy emissivity measured at the top of the atmosphere is sensitive to numerous factors like sea ice cover type, cloud cover, moisture contents, and surface roughening by wind. These effects introduce uncertainty in SIC estimates depending on algorithms used.

- Many intercomparison studies have been conducted, yet, there is no one SIC product that is superior (Ivanova et al., 2015; Comiso et al., 2017). The long-known SIC discrepancies imply there is uncertainty in the knowledge of true sea ice coverage (Notz, 2014).

R/V Mirai observational campaign



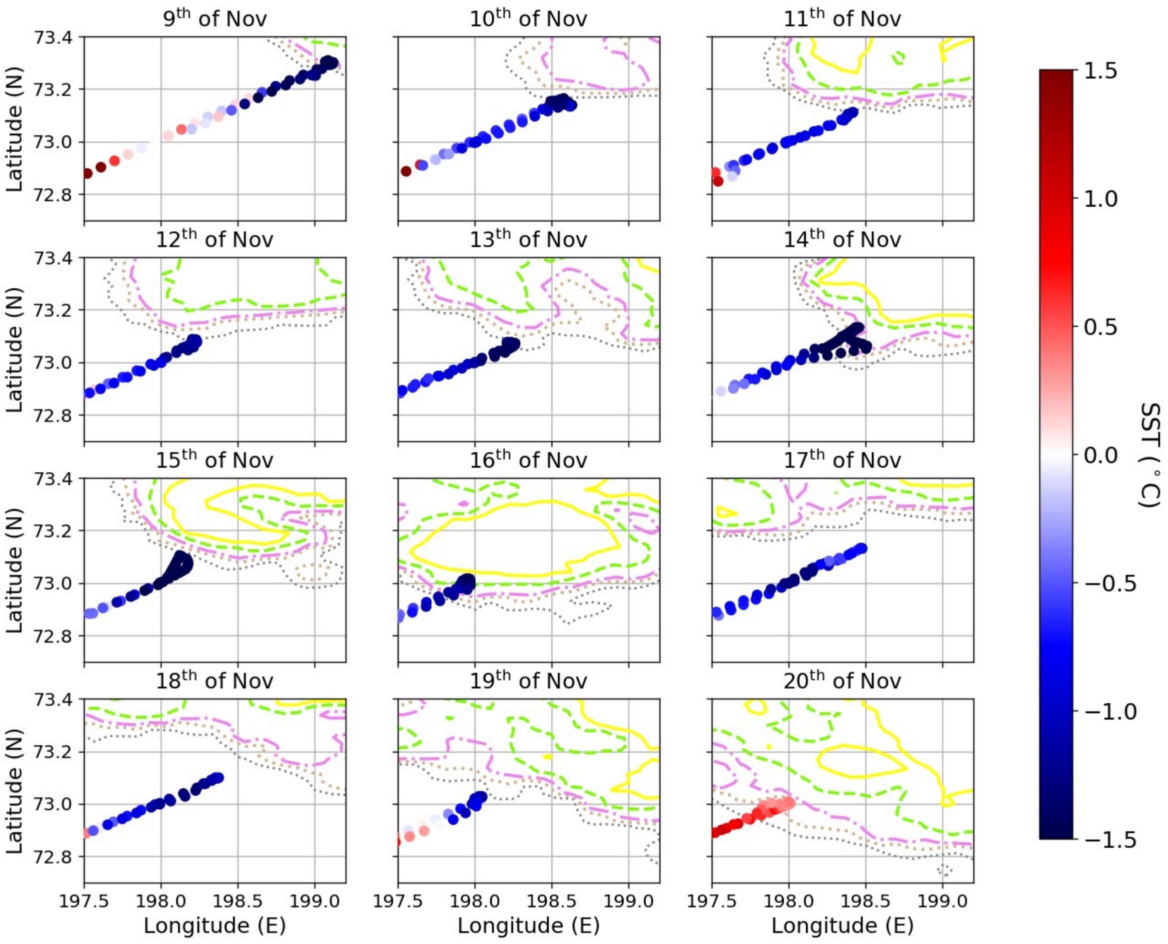
SIC on the first day of R/V Mirai repeat transect. 1980, 1990, and 2000’s mean contours shown in floral white, orange, and dark orange. (ADS-VISHOP)

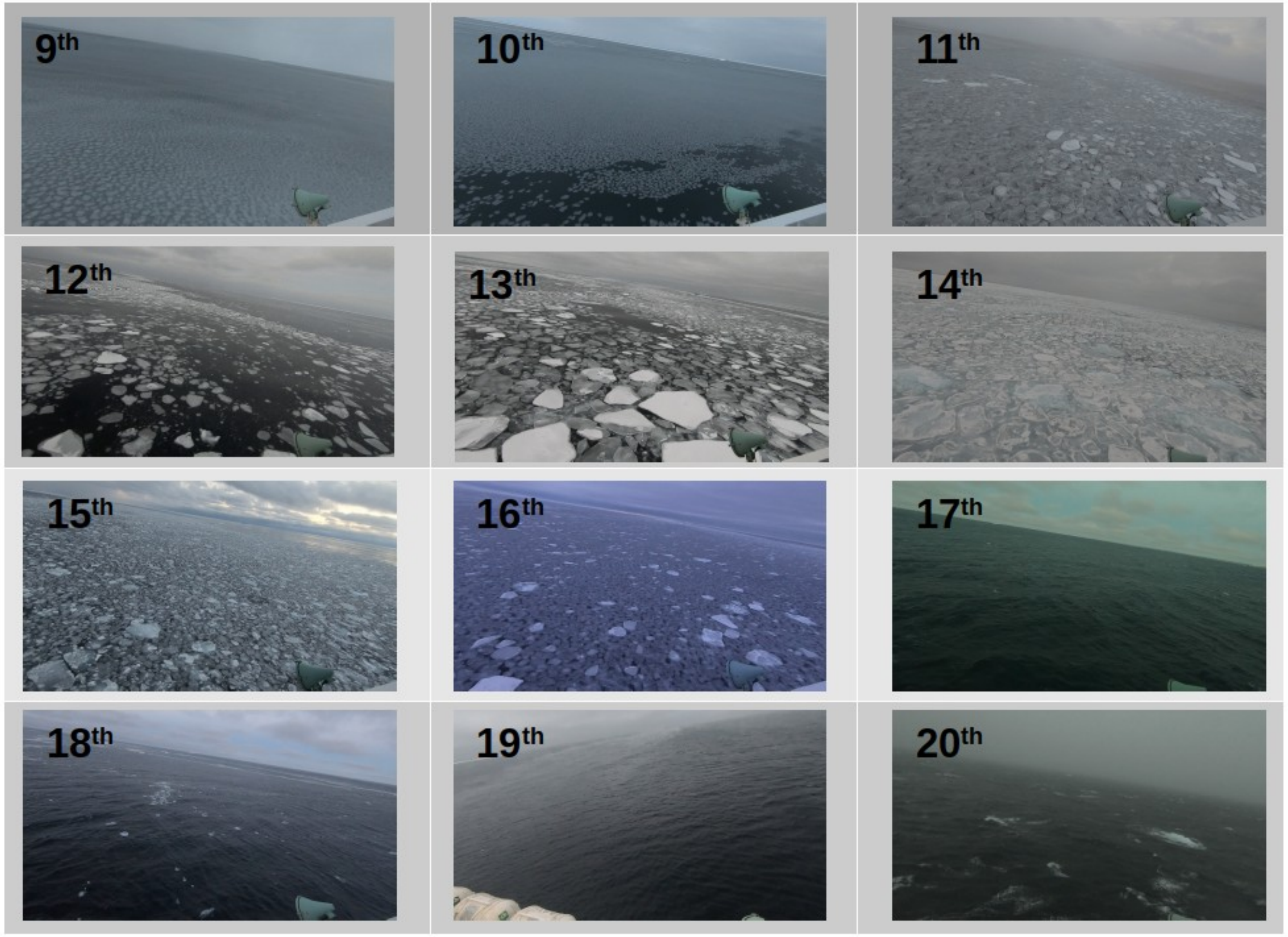
R/V Mirai sailed the Chukchi Sea to investigate why refreezing is delaying and encountered waves in sea ice.

vidLink

Video of waves in MIZs during R/V Mirai MR18-05C expedition (ADS-twitter, prepared by J. Inoue).

R/V Mirai transect observation—overview





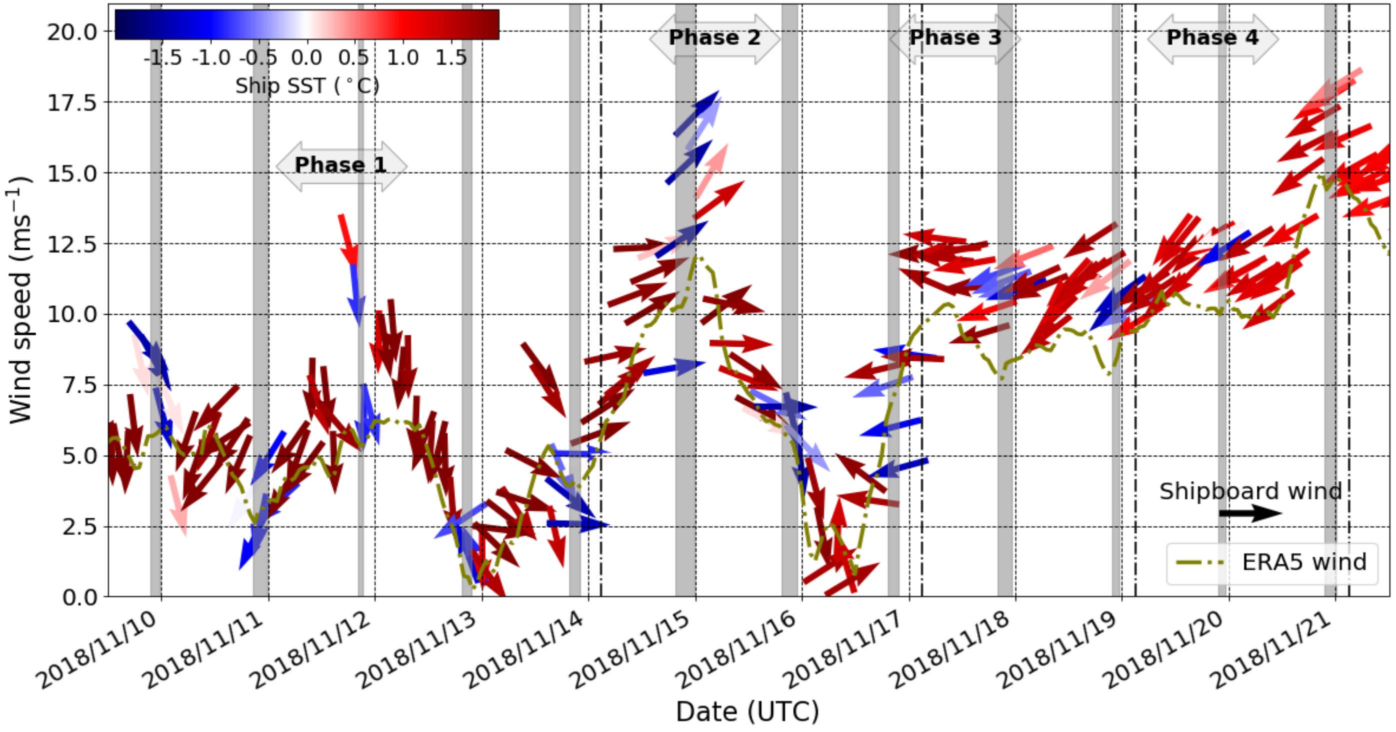
R/V Mirai track and SST with 0.05 (grey), 0.15 (tan), 0.25 (violet), 0.50 (lime green) and 0.75 (yellow) SIC contours from ASI-3 km.

Daily distinctive image from a fixed GoPro.

R/V Mirai transect observation—overview cont'd.

Daily sea-truth photographic data were taken at the same geographical locations for 12 days between the 9th and 20th of November, 2018 in the refreezing Chukchi Sea. The sea ice state is highly variable in time and space and distinctly responded to 4 meteorological conditions.

- **Phase 1: 9th–13th**
  Sea ice growth and formation under relatively calm wind and wave conditions.
- **Phase 2: 14th–16th**
  The on-ice wave event, sea ice break up, and subsequent sea ice advance.
- **Phase 3 & 4: 17th–20th**
  Rapid melt or advection and rising SST under moderate to strong cold off-ice wind.



Indicative wind (vectors) and SST (vector colour) at the R/V Mirai positions and bilinearly interpolated ERA5 reanalysis wind (dashed line). Grey highlighted times indicate when the ship was in ice cover based on the ice navigator's logs.

Compare R/V Mirai sea-truth images and satellite retrieved SIC

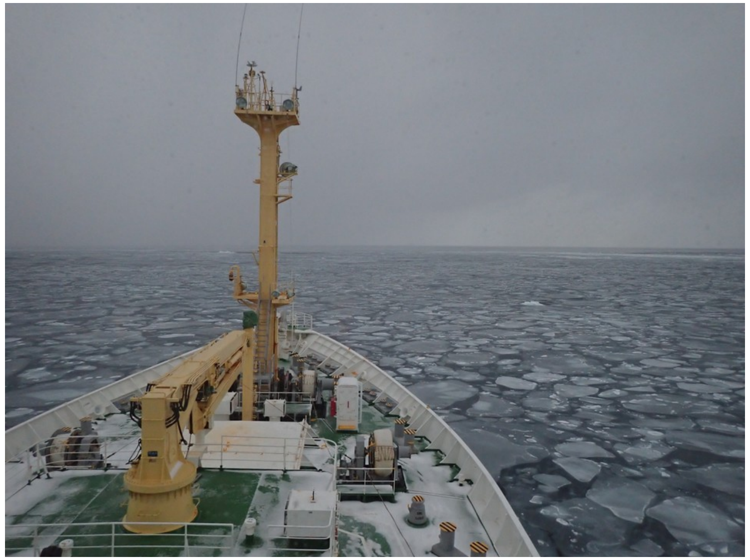
- From many sea ice products, 8 SIC products were analysed against the R/V Mirai sea-truth data.
- 4 leading algorithms NASA-Team, Bootstrap, OSISAF, and ARTIST-Sea-Ice applied to both AMSR2 and SSMIS sensors.

SIC products used for our study based on different retrieval algorithms and sensors.

Product name	Instruments	Abbreviation	Data reference (specified grid resolution)
NASA-Team (NT)	SSMIS	NT-SSMIS	Cavalieri et al. [1996] (25 km)
NASA-Team 2 (NT2)	AMSR2	NT2-AMSR2	Meier et al. [2018] (12.5 km)
Comiso-Bootstrap (BST)	SSMIS	BST-SSMIS	Comiso [2017] (25 km)
	AMSR2	BST-AMSR2	Hori et al. [2012] (10 km)
OSISAF	SSMIS	OSISAF-SSMIS	OSI-401-b: SIC product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (10 km)
	AMSR2	OSISAF-AMSR2	OSI-408: AMSR-2 SIC product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (10 km)
ARTIST-Sea-Ice (ASI)	AMSR2	ASI-6km	Spreen et al. [2008] (6.25 km Arctic grid)
	AMSR2	ASI-3km	Spreen et al. [2008] (3.125 km Chukchi-Beaufort grid)

R/V Mirai sea-truth compared with satellite SIC—Phase 2, on-ice wave event

2018/11/14 21:05



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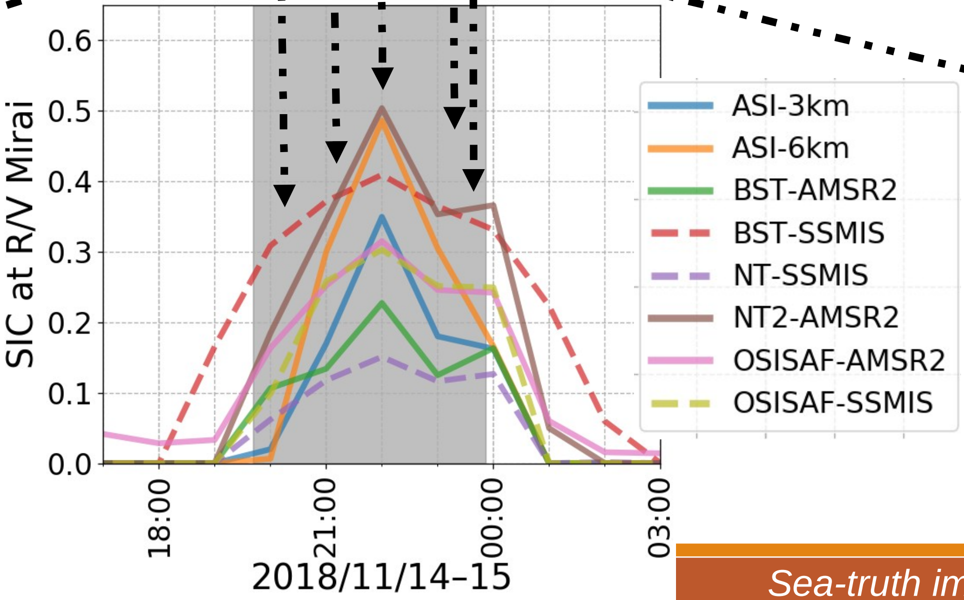


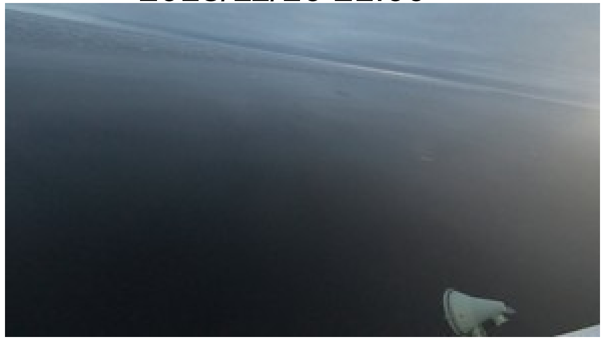
Sea-truth images during the on-ice wave event on the 14th of November in Phase 2.

R/V Mirai sea-truth compared with sat. SIC—Phase 2, on-ice wave aftermath

2018/11/15 22:35

2018/11/16 20:15

2018/11/16 21:00



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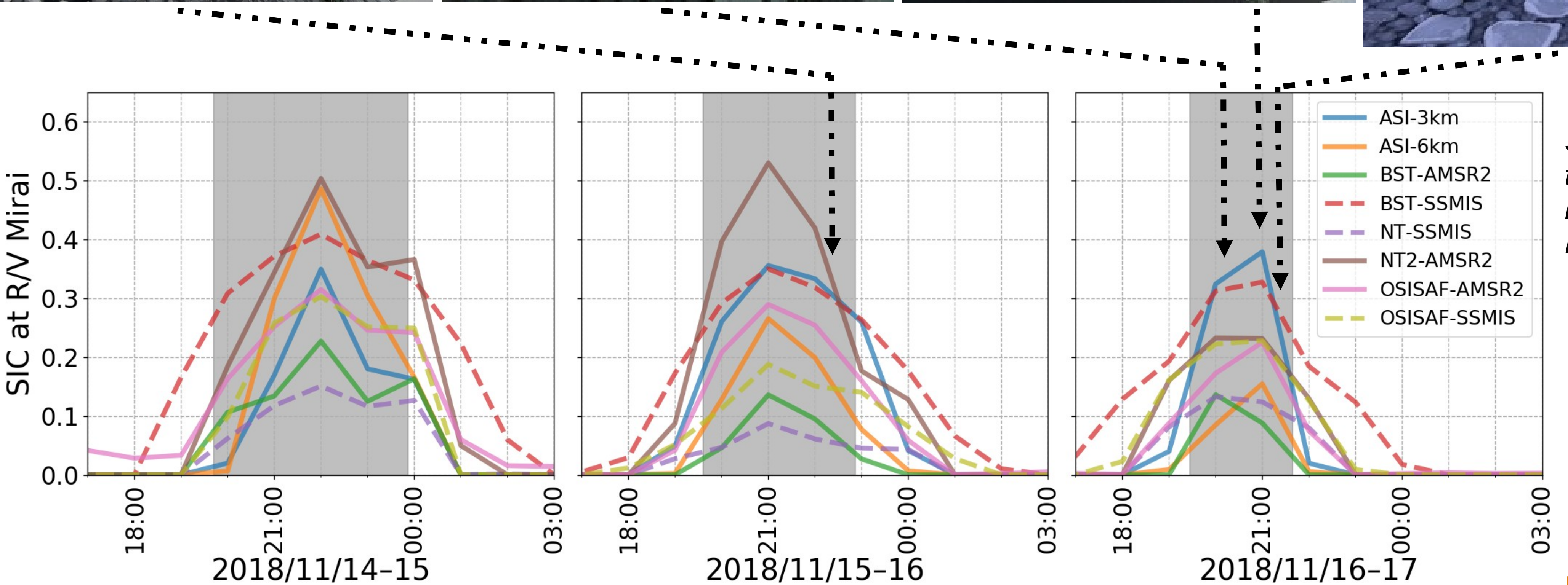
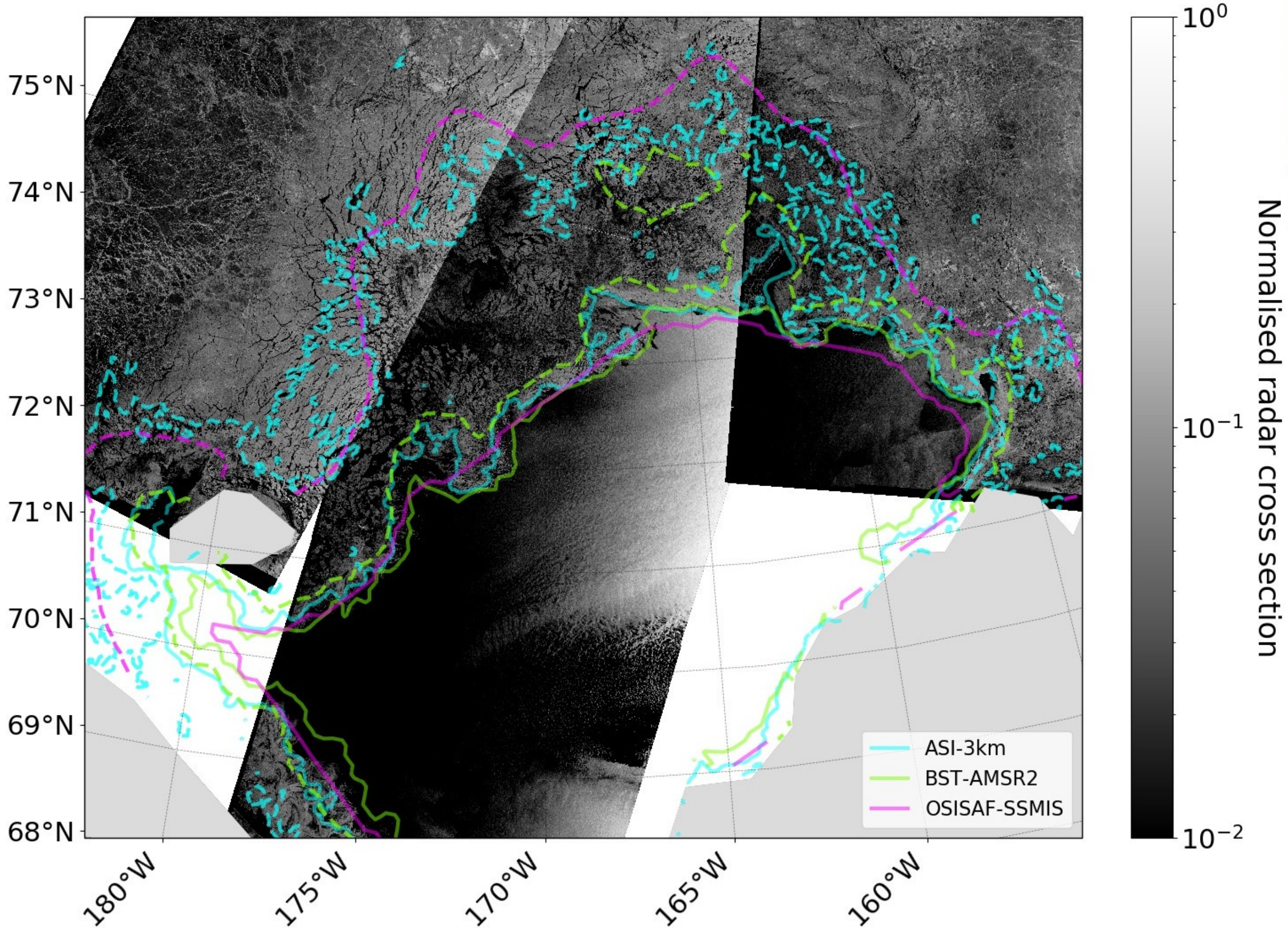
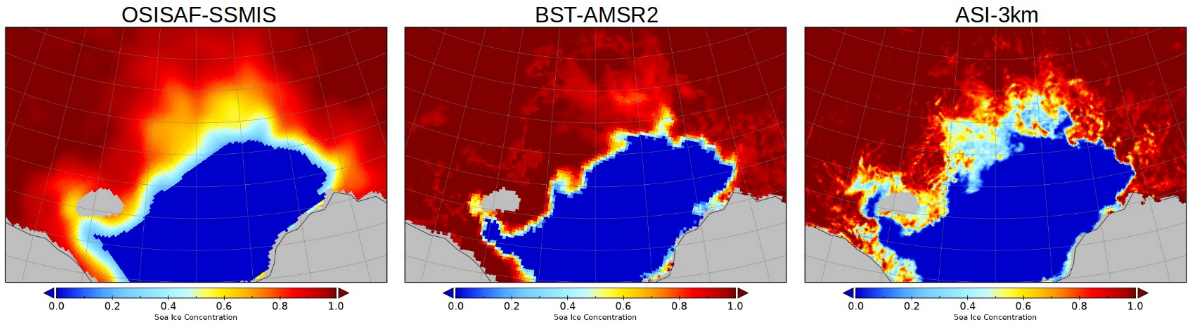


Sea-truth images during the most apparent sea ice advance on the 16th of November in Phase 2.

Spatial variability of sea ice field and uncertainty



Sentinel-1 NRCS (obtained from NOAA Coastalwatch) acquired on the 15th of November overlaid with 0.15 (solid) and 0.85 (dashed) SIC contours for ASI-3km (cyan), BST-AMSR2 (lime green), and OSISAF-SSMIS (magenta).



- Synthetic Aperture Radar image (of Normalised Radar Cross Section (NRCS)) is a useful medium to depict spatial variability of SIC among products.
- The NRCS shows that ice edges have wavy and highly irregular shape. AMSR2 products appear to better reproduce the irregular ice edges.
- BST-AMSR2 appears to have overestimated SIC on this date.
- OSISAF-SSMIS has monotonic function (at least a tendency) from open ocean to pack ice.
- ASI-3km qualitatively seems best equipped to represent the spatial variability of SIC fields as seen by NRCS.

Wave hindcast experiment using TodaiWW3-ArCS

- Wave hindcast experiment was conducted to study how SIC uncertainty used as model forcing translates to wave predictions in ice cover.

TodaiWW3-ArCS model setup

Details	TodaiWW3-ArCS
Base model	NOAA-WAVEWATCH III® (ver. 6.07)
Grid type	Curvilinear on a polar stereographic projection
Extent: Easting & northing	−1,800 km—1,512 km (E) & 520 km—2,904 km (N)
Sea grid cells	301,535
Spatial resolution	4 km
Spectral resolution	35 frequency and 36 directional bins
Bathymetry	IBCAO ver. 3.0 (polar stereographic, 500 m)
Shoreline	GSHHG ver. 2.3.4/5
Forcing: Wind	ECMWF's Reanalysis ERA5 (1 hour)
Forcing: Ice	6 SIC products
Forcing: Current	None
Output frequency	1 hour
Model physics	ST6 (Rogers et al, 2012; Zieger et al, 2015; Liu et al, 2019)
Wave-ice module	IC3 (Rogers et al, 2016; Cheng et al, 2017)
Simulation length	05–25/11/2018 (5 day spin up)

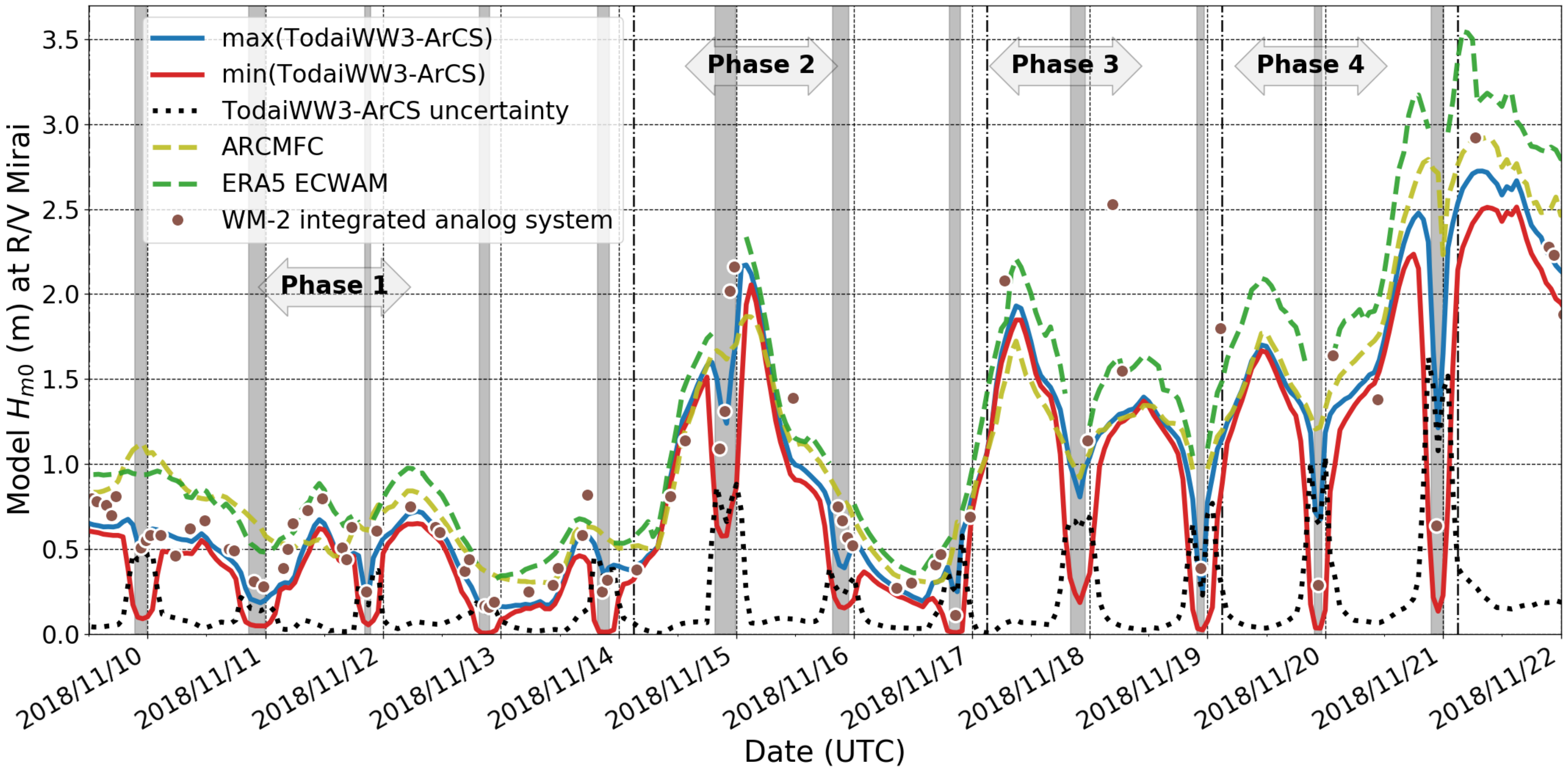
- Run a number of simulations with the same model setup, but with 6 different SIC forcing
  (2 SIC data discarded: ASI-3km with limited domain and OSISAF-AMSR2 with noise in open water).

- Uncertainty(H_{m0}) herein is defined as follows:

$$max(H_{m0\,sic1}, ..., H_{m0\,sic6}) - min(H_{m0\,sic1}, ..., H_{m0\,sic6})$$

- IC3 wave-ice source term (with default parameters) used because it has been developed with the refreezing Beaufort Sea data of Thomson et al. (2018). Our observation is similar pancake ice, so a homogeneous thickness of 10 cm used.

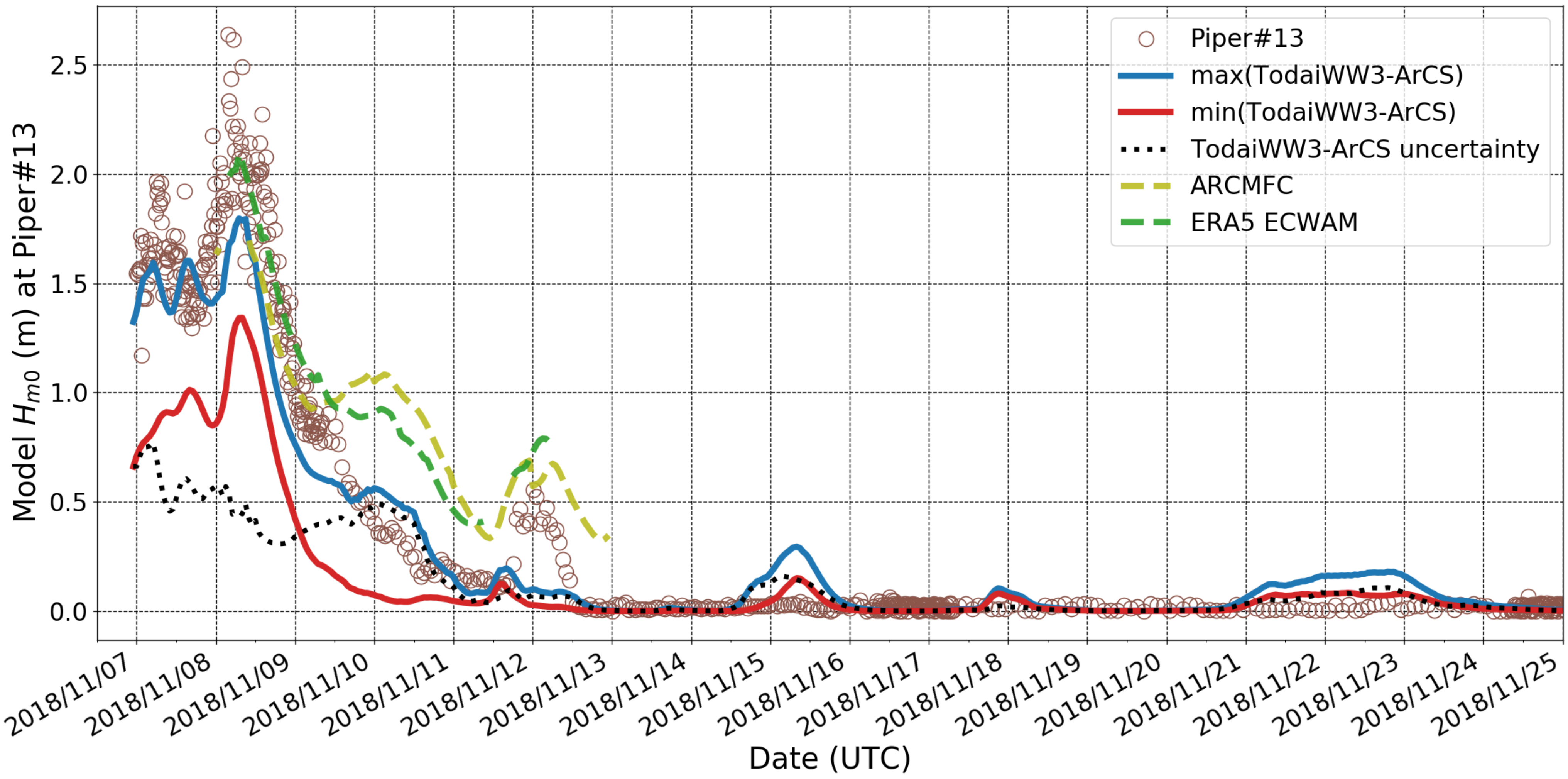
Modelled and indicative waves at R/V Mirai positions



Modelled wave heights from all TodaiWW3-ArCS simulations using 6 sea ice forcing, ERA5 ECWAM, and the ARCMFC wave model. Indicative WM-2 observations are shown as brown dots with white edges. Grey highlighted times indicate R/V Mirai in ice-covered seas according to ice pilot's log.

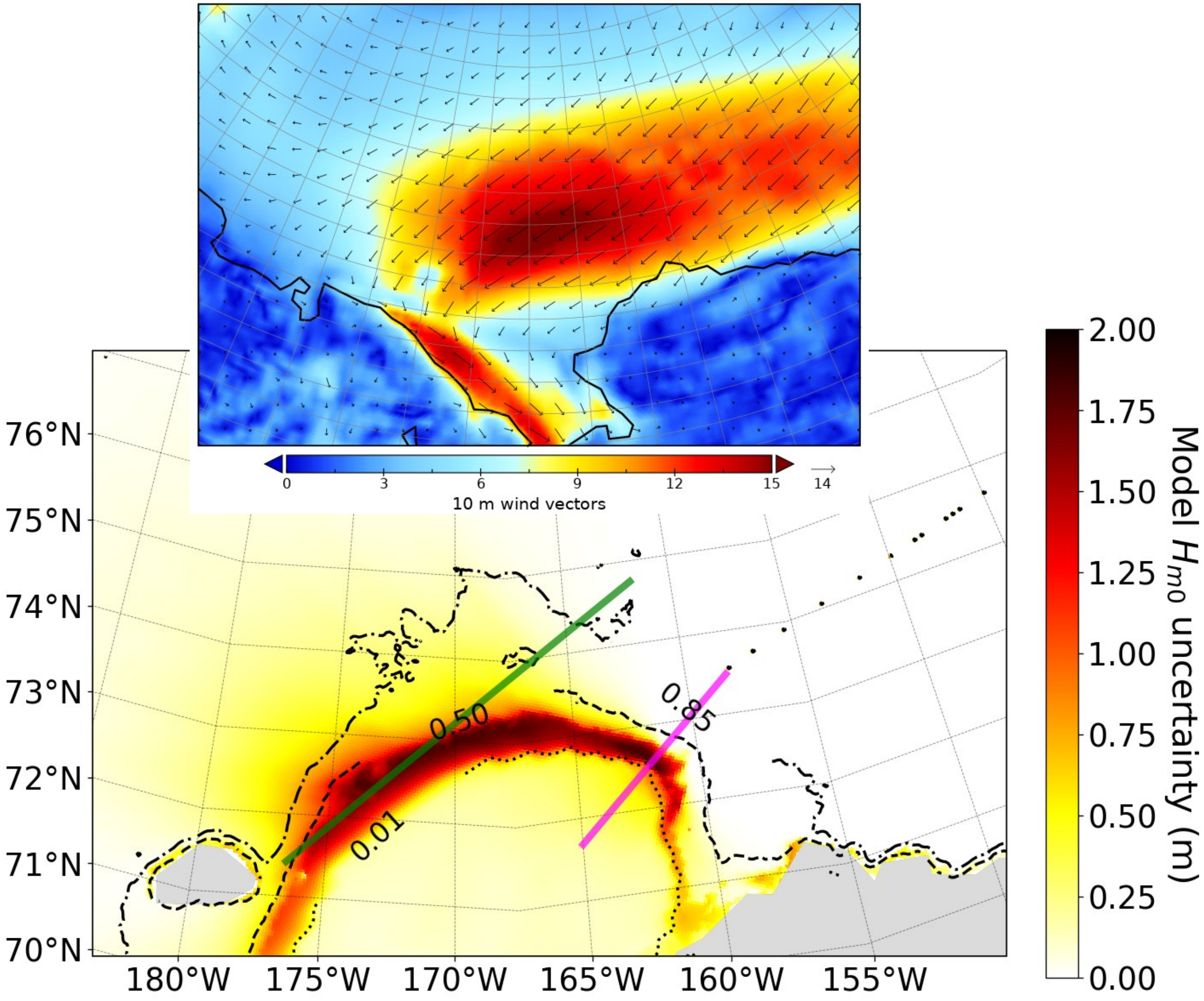
- TodaiWW3-ArCS simulations compared with indicative shipboard H_{m0}.
- 2 independent wave models in the Arctic Ocean, ERA5 ECWAM and ARCMFC, also compared.
- Wave decay apparent each time R/V Mirai entered ice cover with varying attenuation rates.
- Disparate model estimates apparent in open ocean as well.

Modelled compared with a drifting buoy



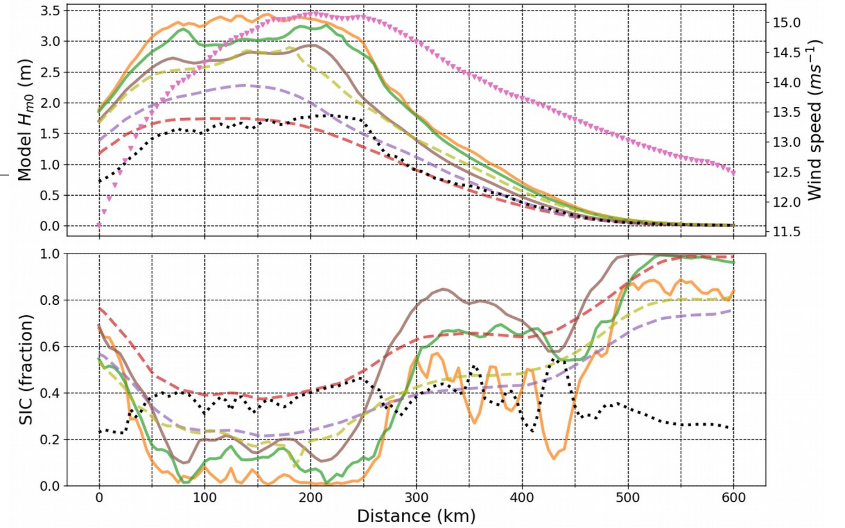
Modelled wave heights from all TodaiWW3-ArCS simulations using 6 sea ice forcing, ERA5 ECWAM, and the ARCMFC wave model. Indicative WM-2 observations are shown as brown dots with white edges.

Model H_{m0} and SIC forcing transects

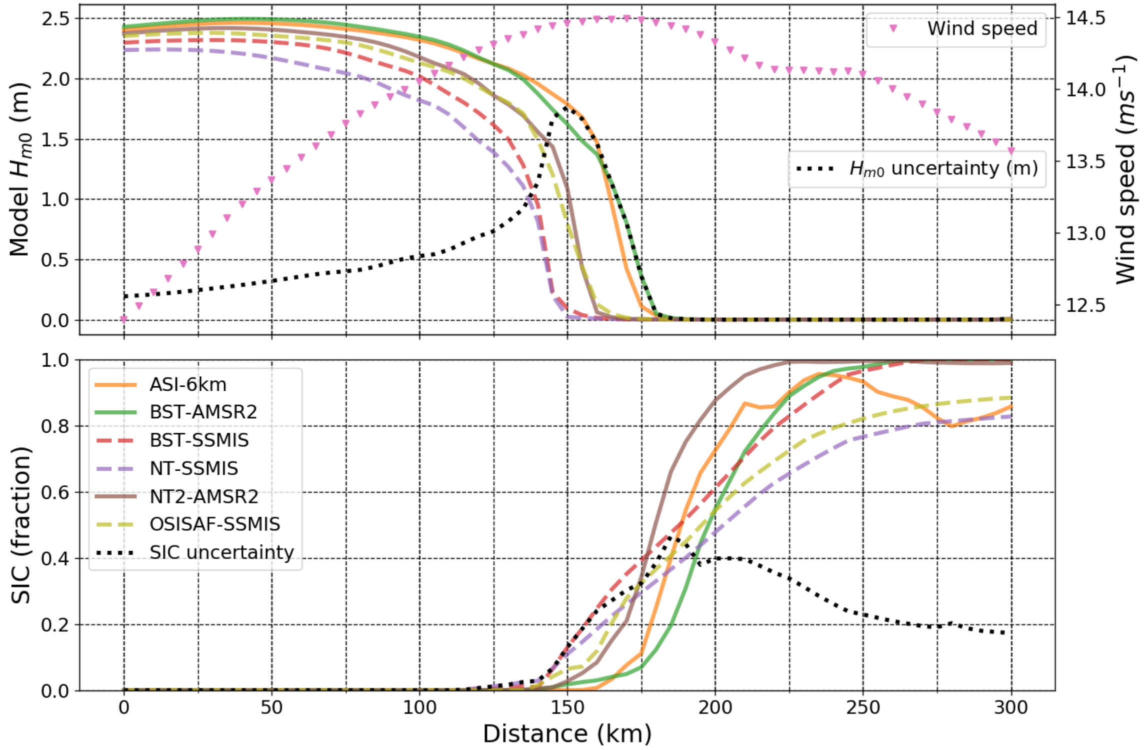


Above: TodaiWW3-ArCS wave height uncertainty at 18:00 on the 21st of November with mean 0.01, 0.50, and 0.85 SIC forcing contours.

Green transect



Magenta transect



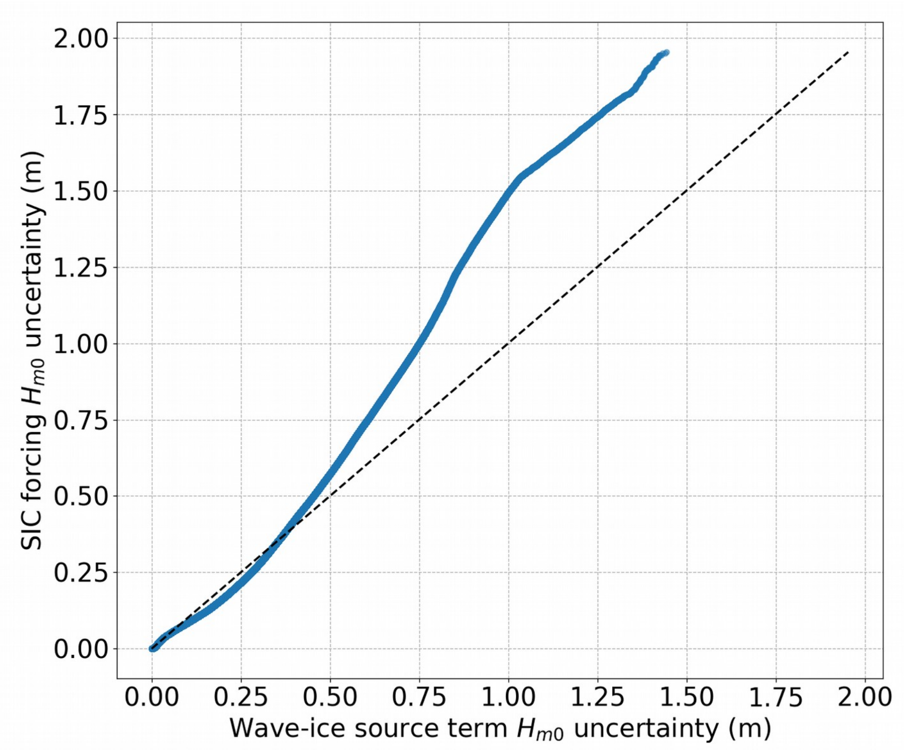
Right: Ice edge orientation (top) and off-ice (bottom) transects of modelled wave heights, wind speed, and SIC forcing.

Relevance to the big picture . . .

- We compared:

$$\text{SIC forcing } uncertainty(H_{m0}) = max(H_{m0\,sic1}, \ldots, H_{m0\,sic6}) - min(H_{m0\,sic1}, \ldots, H_{m0\,sic6})$$

$$\text{Wave-ice source term } uncertainty(H_{m0}) = max(H_{m0\,IC2}, H_{m0\,IC3}, H_{m0\,IC5}) - min(H_{m0\,IC2}, H_{m0\,IC3}, H_{m0\,IC5})$$



A Q-Q plot showing the bivariate uncertainty distributions for SIC forcing and wave-ice interaction source terms (which included 3 physics-based source terms, IC2, IC3, and IC5).

A list of wave-ice interaction studies (and the Arctic Ocean wave models shown before) and SIC forcing used.

Reference	Model (wave-ice interaction)	SIC data source
Rogers et al. (2016)	WW3 (IC3)	NASA-Team2 applied to SSMIS and Bootstrap applied to AMSR2 (assimilated in sea ice model)
Cheng et al. (2017)	WW3 (IC3)	NASA-Team2 applied to AMSR2
Gemmrich et al. (2018)	WW3 (IC4)	Bootstrap applied to AMSR2
Ardhuin et al. (2018)	WW3 (IC2 including IS2 scattering)	ARTIST-Sea-Ice applied AMSR2
Copernicus (2019)	ERA5 ECWAM (ice mask)	OSISAF applied to SSMIS (indirectly from OSTIA (Donlon et al., 2012))
ARCMFC (2019)	ARCMFC wave model (Sutherland et al., 2019)	OSISAF applied to SSMIS (assimilated in sea ice model)

Conclusion

- R/V Mirai sea-truth observation:
  - Sea ice in the refreezing Chukchi Sea is highly variable in time and space.
  - A comparison with satellite retrieved SIC reveals considerable uncertainty.

- SIC uncertainty affects wave predictability in MIZs when used as model forcing.
- Modelled H_{m0} uncertainties introduced from SIC forcing and wave-ice interaction source terms are both sizeable, but the more dominant error source is the accuracy of SIC forcing.
- The SIC uncertainty studied here warrants some attention for future wave-ice interaction studies/parameterisations
- Improving our understanding of wave-ice interactions from a physical view point may remain a challenge without the knowledge of true sea ice coverage of the ocean.