# Short-term regional wave and ice forecast for navigation assistance in the Arctic Ocean

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Akihisa Konno (Kogakuin U.),
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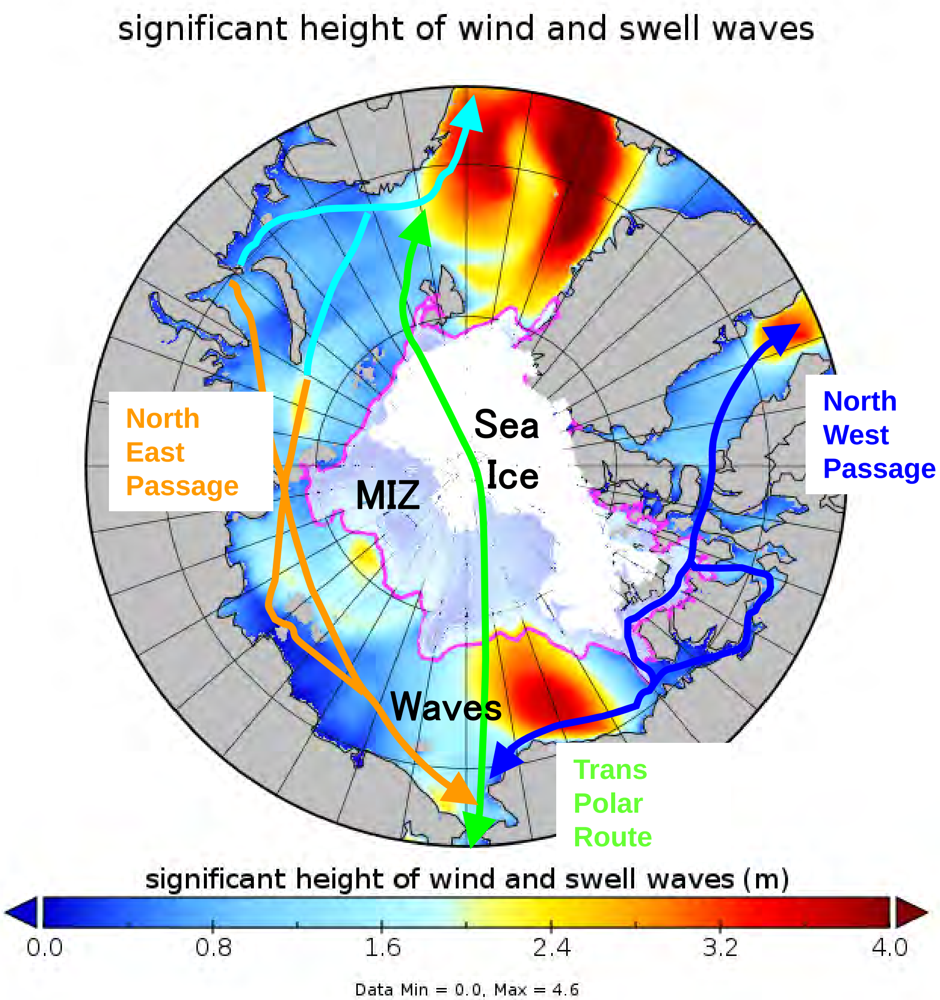
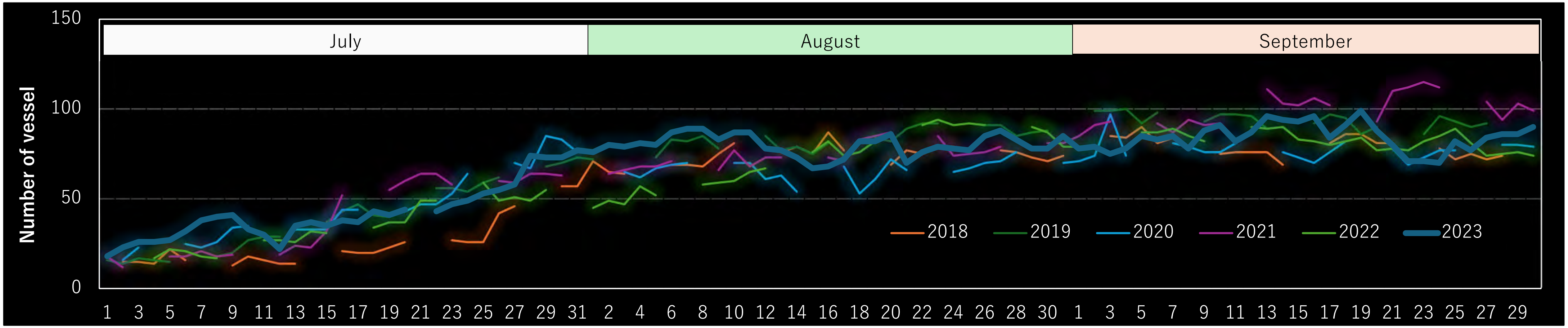
R/V Mirai cruise


APPLIED PHYSICAL OCEANOGRAPHY

Arctic Shipping Route

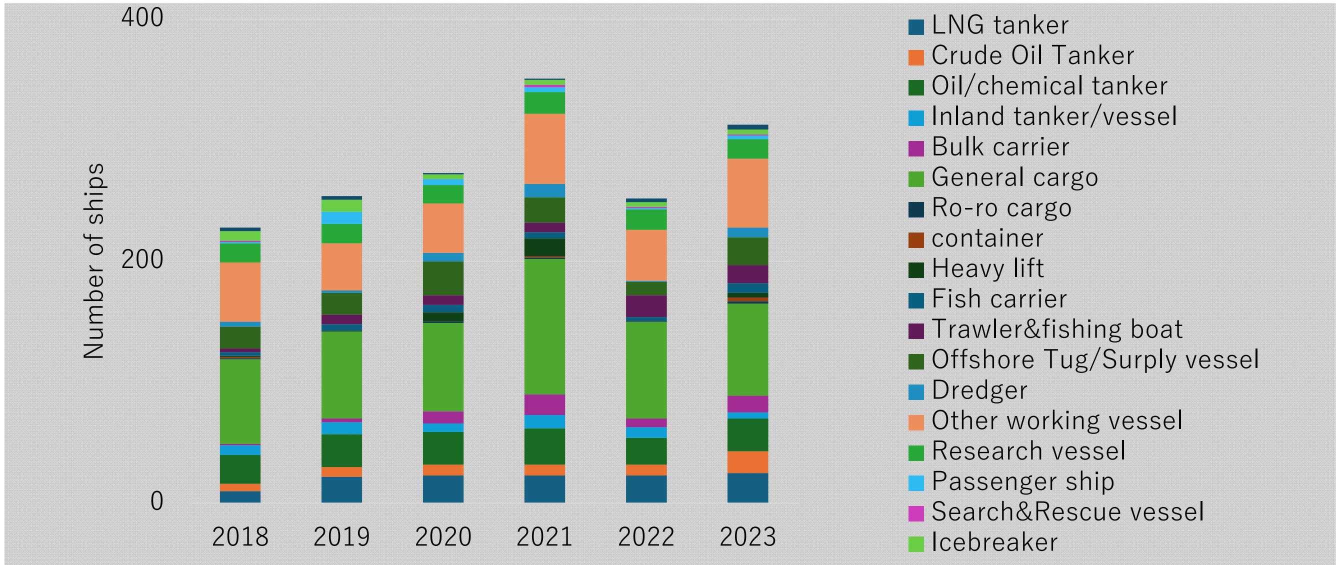


# Traffic in the Northern Sea Route




**Daily number of vessel that sailed the NSR （2018～2023, July ~ September）**

**Source: Northern Sea Route Administration and Rosatom**




Courtesy of Ohtsuka 2024

Number of ships sailed the NSR by ship type by Aug. and Sep.

Source: Northern Sea Route Administration

# Previous research – IcePOM

RESEARCH/REVIEW ARTICLE

**Ice–ocean coupled computations for sea-ice prediction to support ice navigation in Arctic sea routes**

Liyanarachchi Waruna Arampath De Silva,[1,2] Hajime Yamaguchi[2] & Jun Ono[3]

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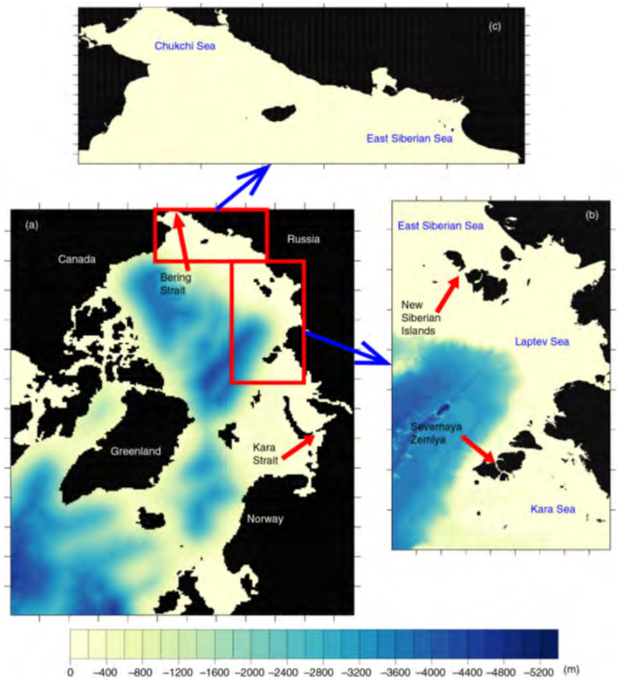


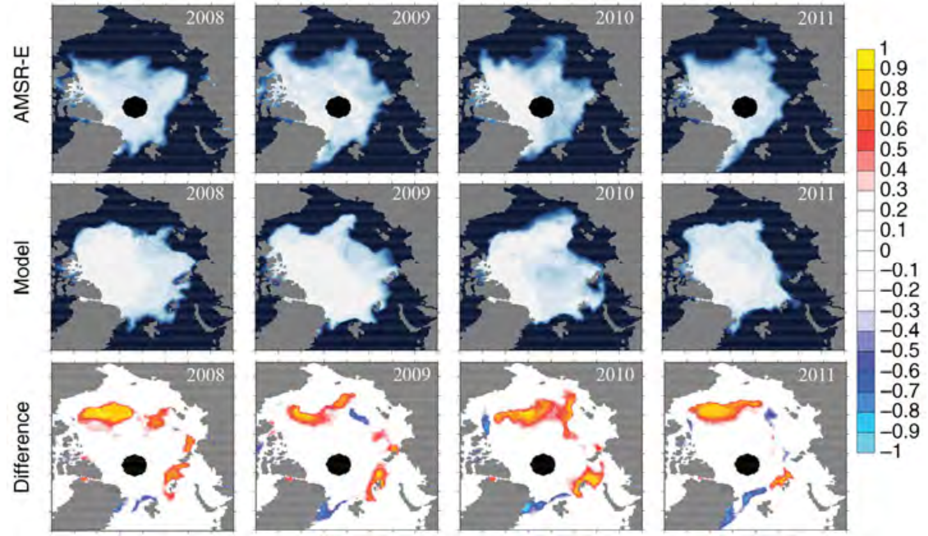

Polar Research 2015

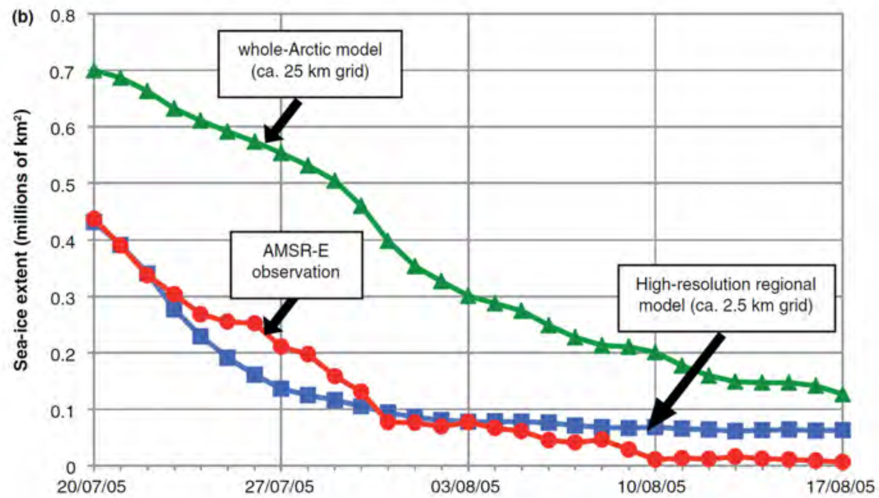
IcePOM

(e.g. Fujisaki et al. 2010 Okhotsk Sea)

- Princeton Ocean Model (POM; Mellor et al. 2002)
- 0-layer ice thermodynamics (Semtner 1976)
- Elastic-Viscous-Plastic rheology (Hunke & Dukowicz 1997, Hunke 2001)
  - *with ice-floe collision rheology (Sagawa & Yamaguchi 2006)*
- ETOPO1
- ERA-Interim
- Lateral boundary: PHC3.0 salinity and temperature, Bering Strait inflow (Woodgate et al. 2005, Watanabe & Hasumi 2009)

- **High resolution (2.5 km)** in Chukchi Sea, and East Siberian/Laptev/Kara Sea




Improvement with high-resolution (2.5km) @ Chukchi

High-resolution sea ice modeling is necessary

# Optimum routing in the Arctic Shipping Route

Arctic sea route path planning based on an uncertain ice prediction model

Minjoo Choi [a], Hyun Chung [a,*], Hajime Yamaguchi [b], Keisuke Nagakawa [b]

[a] Division of Ocean Systems Engineering, Korea Advanced Institute of Science and Technology, 373-1 Yuseong-gu, Daejon 305-701, South Korea
[b] Graduate School of Frontier Sciences, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8561, Japan

$$J = \text{distance} + \text{time} + \text{failure rate}$$

failure rate: ice thickness > ice breaking capability

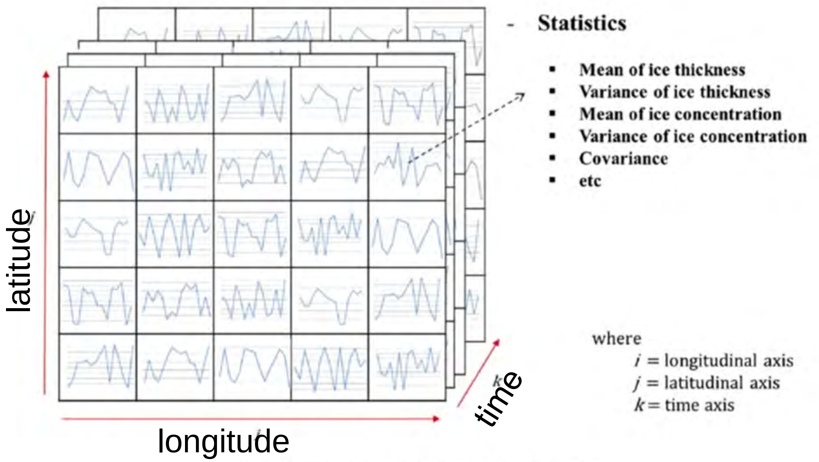



**Fig. 5.** Example of statistics from ensemble simulation.

Ensemble members providing mean and variances (covariances) of the relevant ice variables (ice thickness, ice concentration)

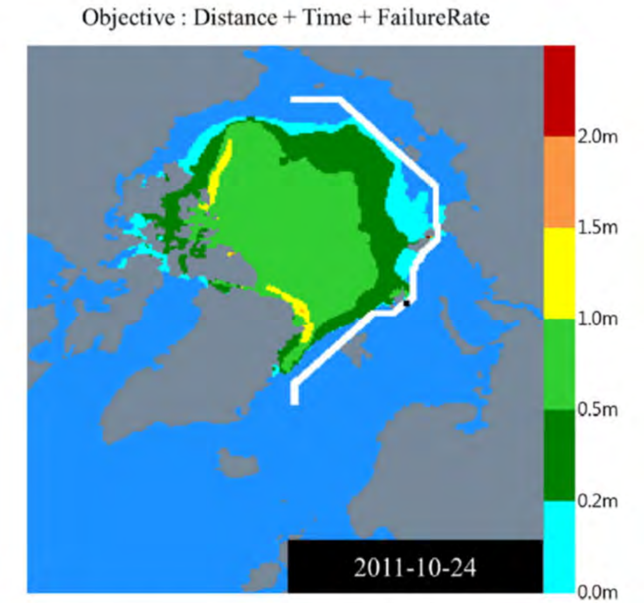



**Fig. 8.** An optimal Northern Sea Route considering distance, time and failure rate factors in mean ice thickness point of view.

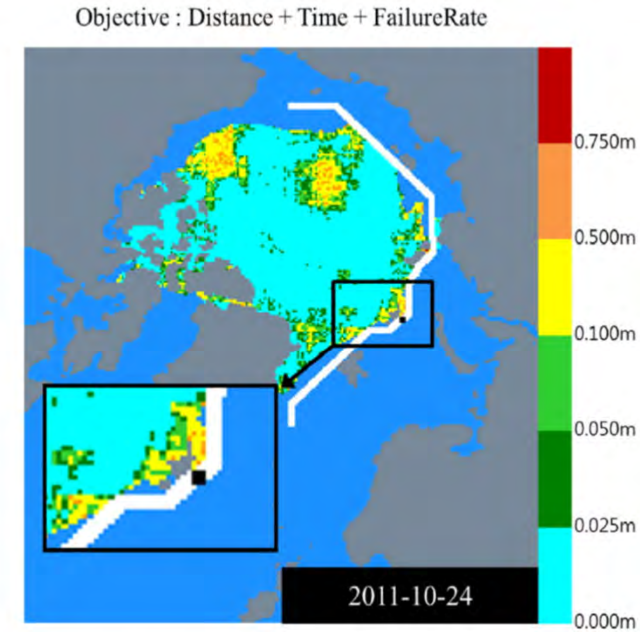



**Fig. 10.** An optimal Northern Sea Route considering distance, time and failure rate factors in STD ice thickness point of view.

Key factors
- Uncertainty of the sea ice variables
- Ice thickness variation due to ridging

Cold Regions Science and Technology 2015

# Floe Size Distribution (FSD) for Arctic Shipping Route

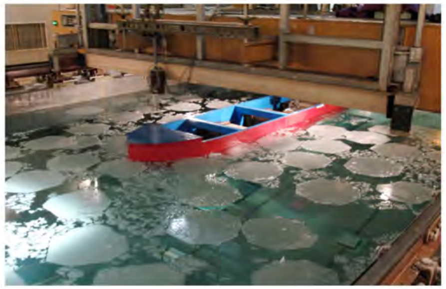
**Navigation in Pack Ice**
**Floe Size is correlated with ice resistance**
**→ FSD is a crucial factor for estimating ship speed and fuel consumption**

Courtesy of Matsuzawa

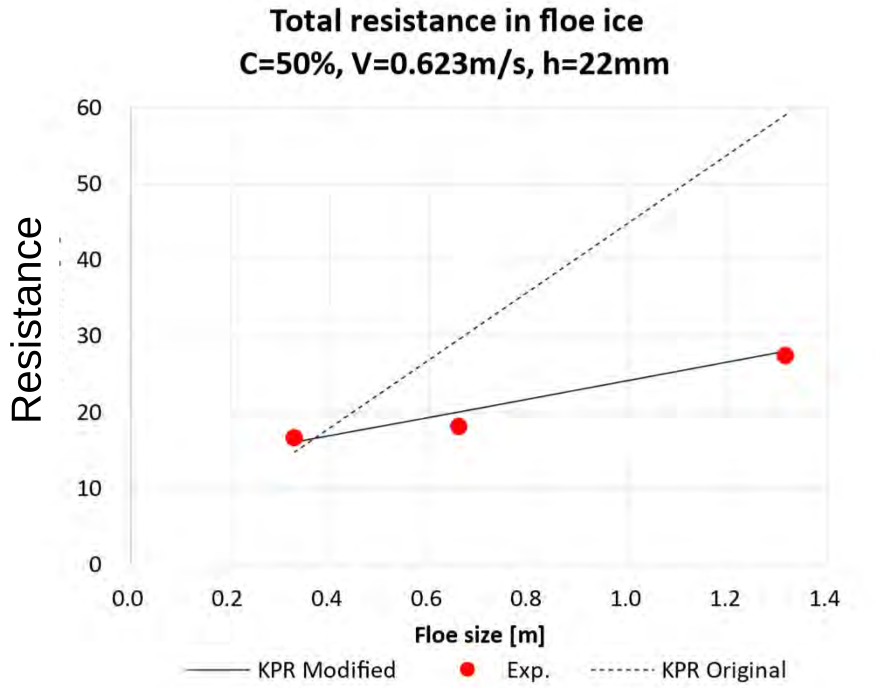
**対象船型**

82,000DWT Bulk Carrier

| Item | | Ship | Model |
|---|---|---|---|
| Length B.P. | m | 225.00 | 6.875 |
| Breadth molded | m | 32.26 | 0.986 |
| Draft | m | 12.2 | 0.373 |
| Trim | m | 0 | |
| Dead weight | $m^3$ | 76,361 | 2.179 |
| $C_B$ | - | 0.861 | |
| $C_P$ | - | 0.865 | |
| $C_W$ | - | 0.944 | |
| $C_M$ | - | 0.997 | |



Kashitelijan-Poznjok-Ryblin model considers momentum loss due to collision of ice floes and ship. Originally derived for a wide ship.

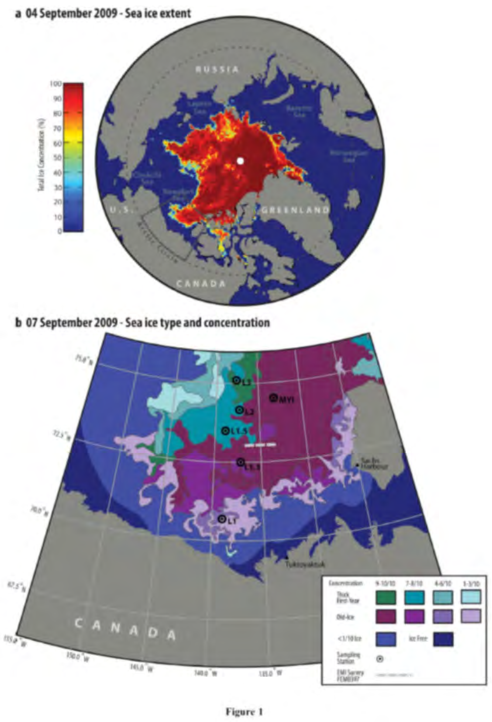



Total resistance vs. floe size from ice tank experiment
Solid line modified model.

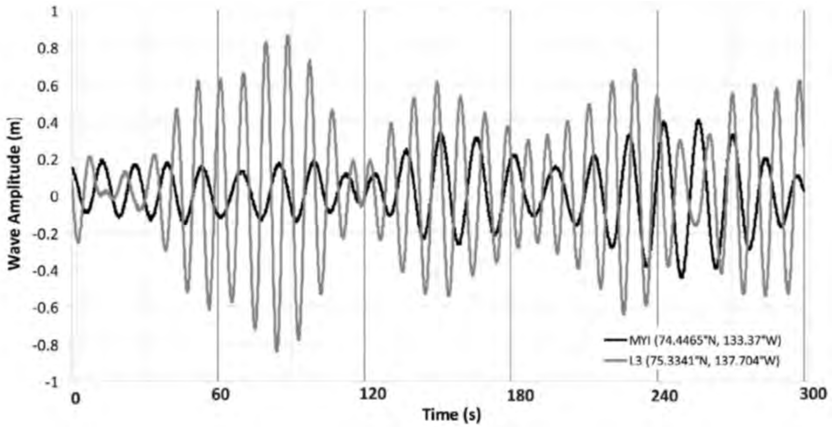
Matsuzawa et al. 2018

Key Factor: Floe Size Distribution

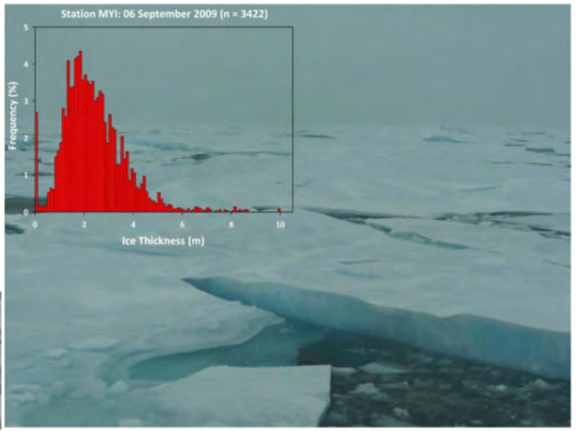
# Breakup of ice by waves – FSD in the MIZ

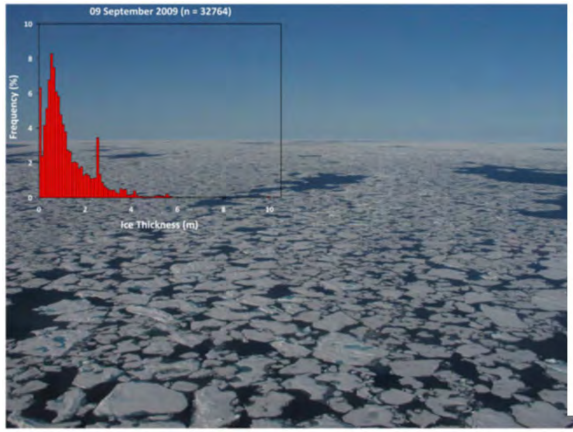



Swell propagation **250 km** from the ice edge




Asplin et al. 2012

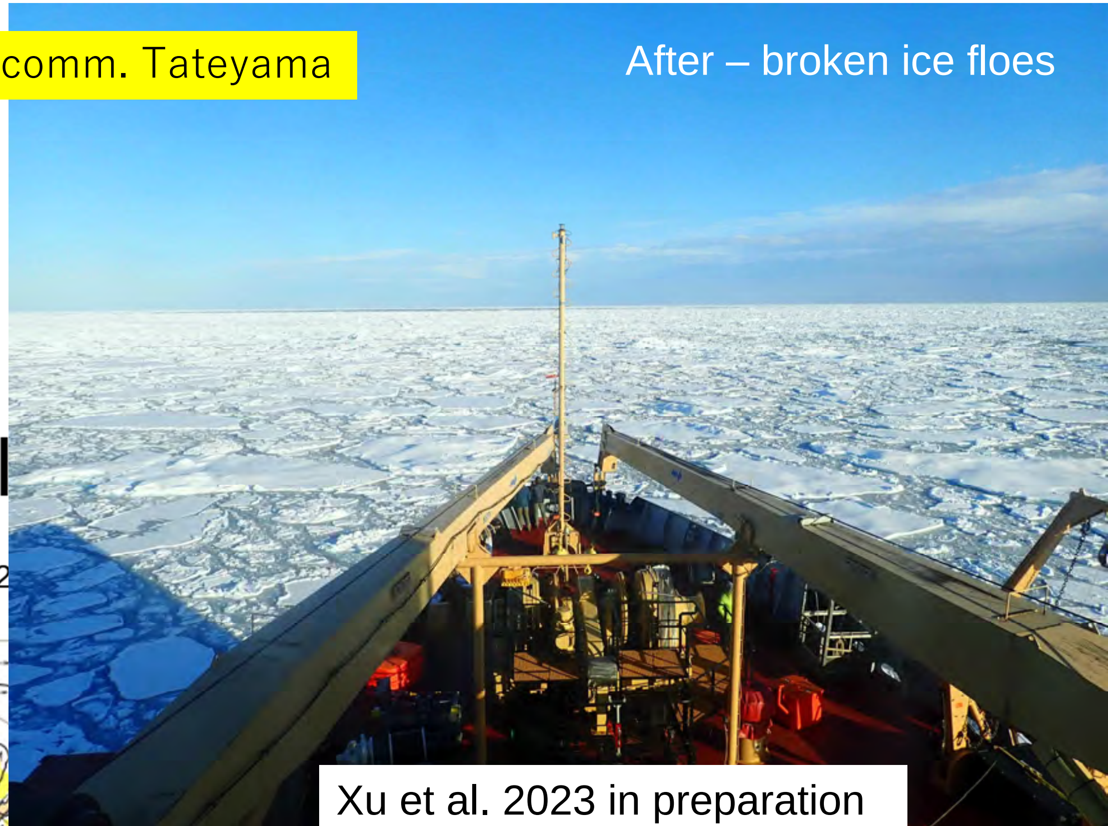


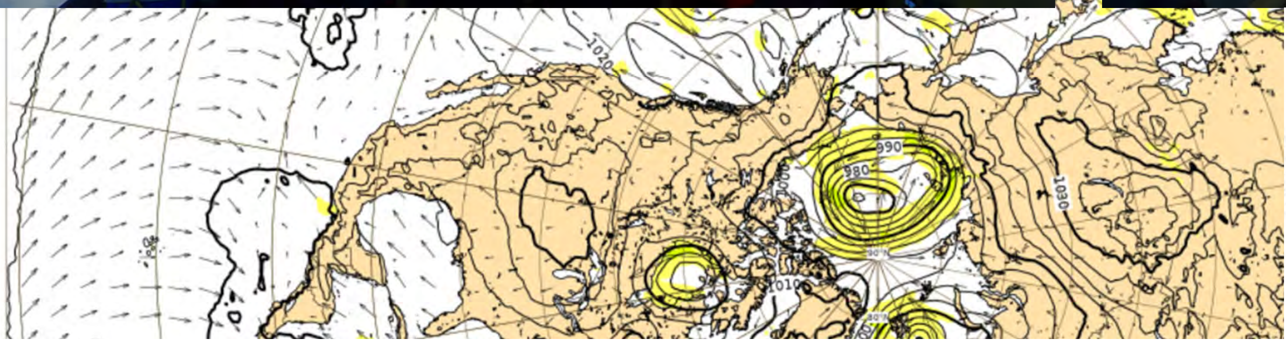

Floe Size Distribution dramatically changed after the swell propagation into ice

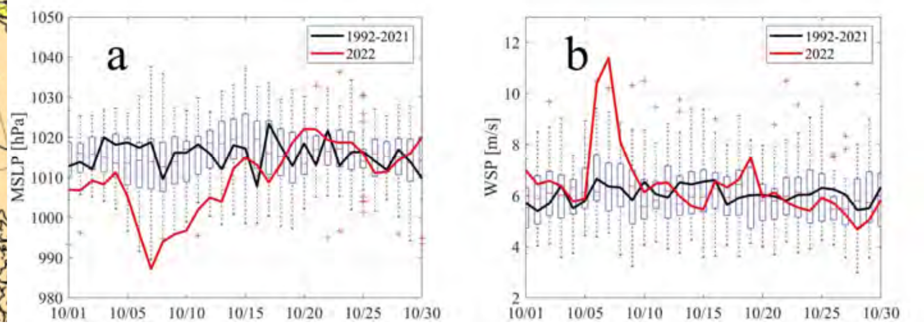
# Ice Breakup： 2022.10, strongest cyclone in record

JOIS 2022, person. comm. Tateyama


Xu et al. 2023 in preparation



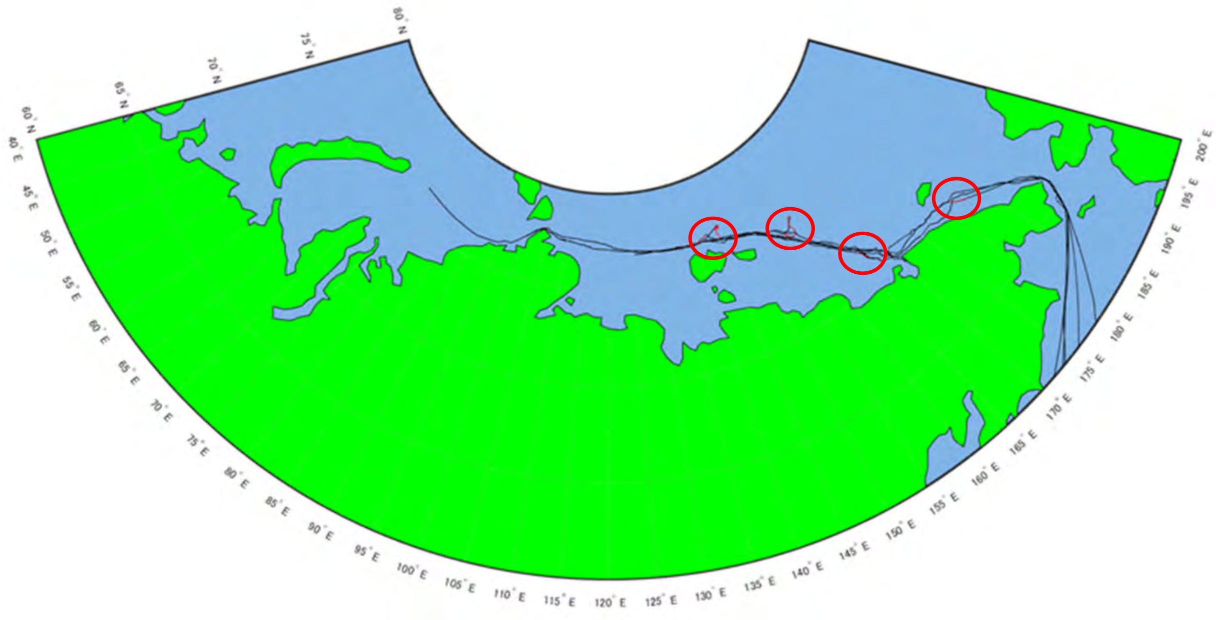



# Desired variable: Ice pressure

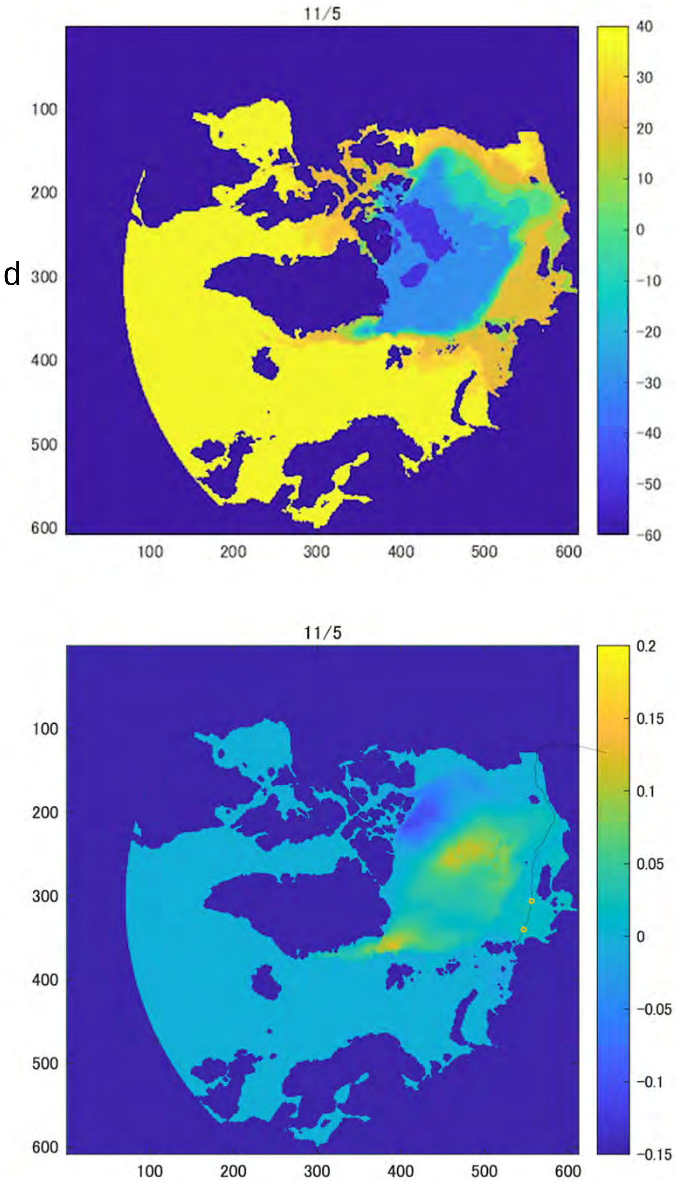
Risk Index : RIO = Σ(Cn × RIVn)

Cn: Ice Concentration of each ice type

RIVn: Parameter for each ice type defined by ice class. (IMO)



ship beset incident in Nov. 2021



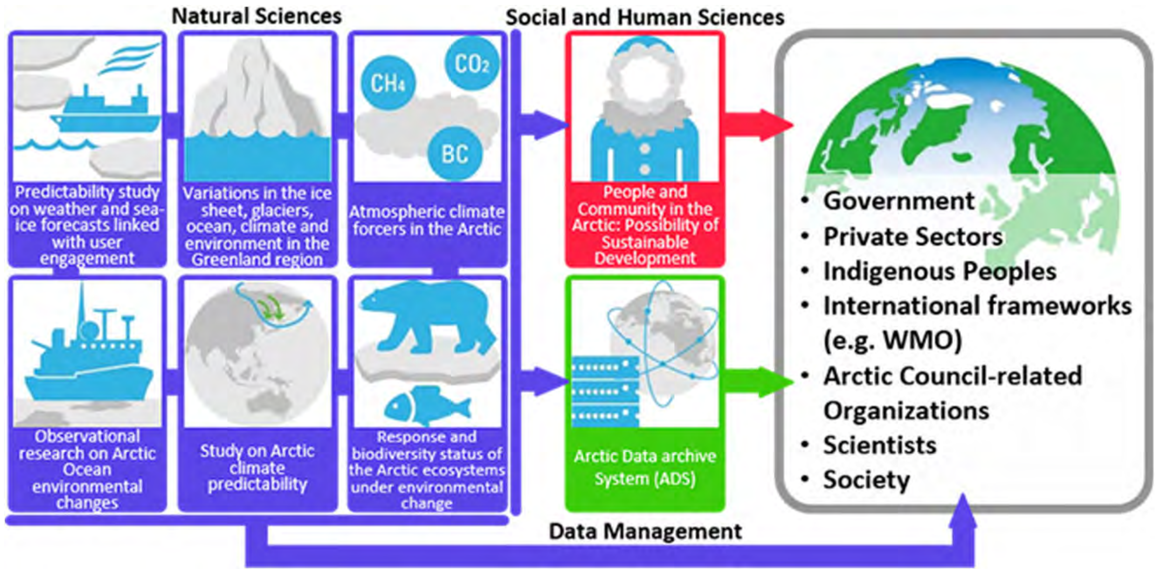

ice convergence (~ice pressure)

Courtesy of
Konno and Ohtsuka 2024

Arctic Challenge for Sustainability

2015-2020

- Theme1: Predictability study on weather and sea-ice forecasts linked with user engagement
- Theme2: Variations in the ice sheet, glaciers, ocean and environment in the Greenland region
- Theme3: Atmospheric climate forcers in the Arctic
- Theme4: Observational research on Arctic Ocean environmental changes
- Theme5: Study on Arctic climate predictability
- Theme6: Response and biodiversity status of the Arctic ecosystems under environmental change
- Theme7: People and Community in the Arctic: Possibility of Sustainable Development
- Theme8: Arctic Data archive System (ADS)



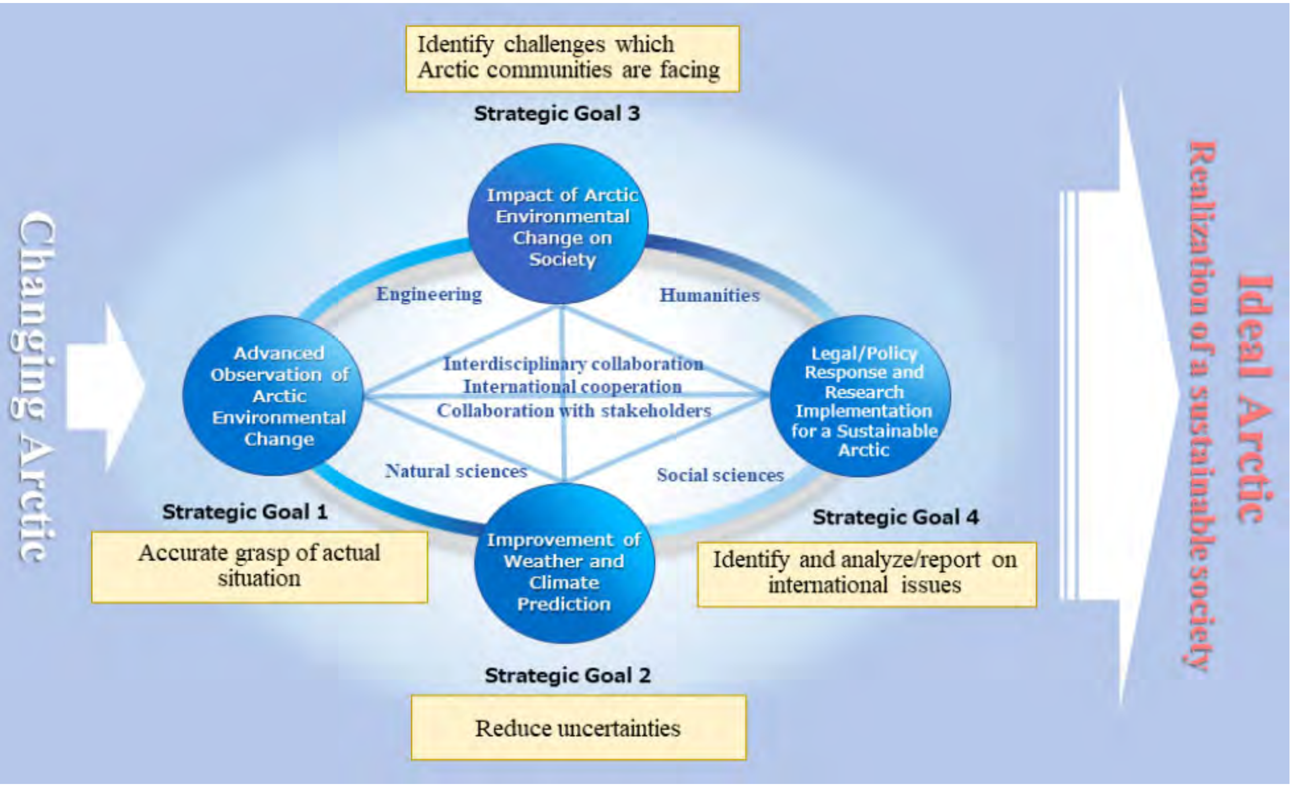

Theme 1: Predictability study on weather and sea-ice forecasts linked with user engagement

PI : Jun Inoue (NIPR)

(1) intensive Arctic observations and OSSE
(2) predictability studies on weather extremes associated with the Arctic mid-latitude climate linkages
(3) short-term sea-ice prediction & development of navigation support systems and a wave-ice interaction model for the Northern Sea Route.

Arctic Challenge for Sustainability II

2020-2025



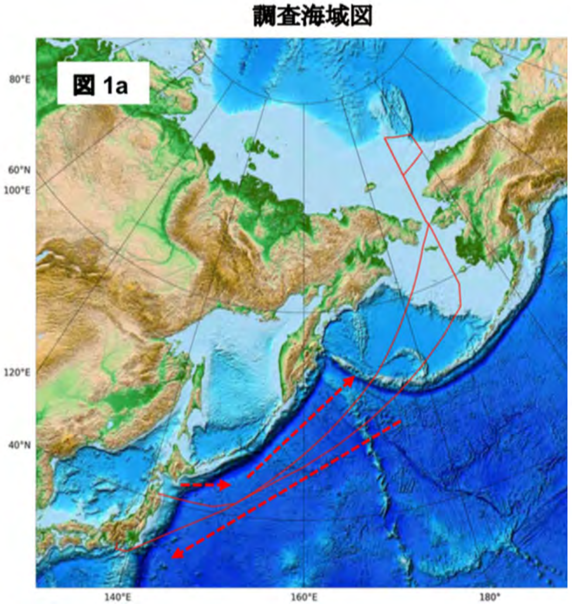

**Strategic Goal 1 (*Observation*)**
- Atmosphere
- **Ocean:** Research and Public Dataset Production on the Arctic Marine Environment
- Cryosphere
- Land

**Strategic Goal 2 (*Modeling*)**
- Teleconnection
- **Climate Prediction:** Weather and Climate Prediction and Its Technological Improvement

**Strategic Goal 3 (*Society/Engineering*)**
- Human Society
- **Arctic Sea Routes:** Sustainable Arctic Sea Routes in a Rapidly Changing Environment
- Coastal Environments

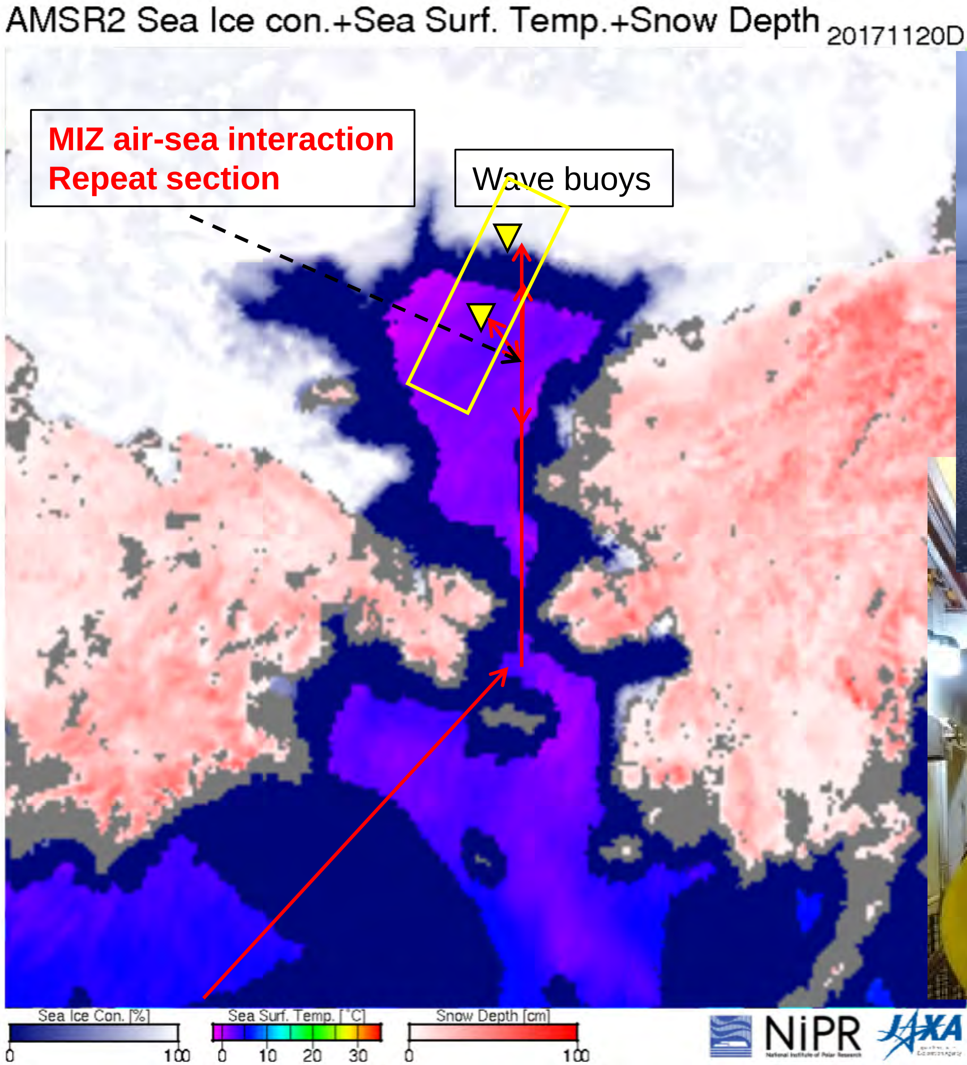
**Strategic Goal 4 (*Policy*)**
- International Law
- International Relations

# In support of R/V Mirai Cruise: *a rare November obs.* in 2018




2018 Oct. 23 – Dec.7

In the Arctic from ~Nov. 3





Takehiko Nose onboard

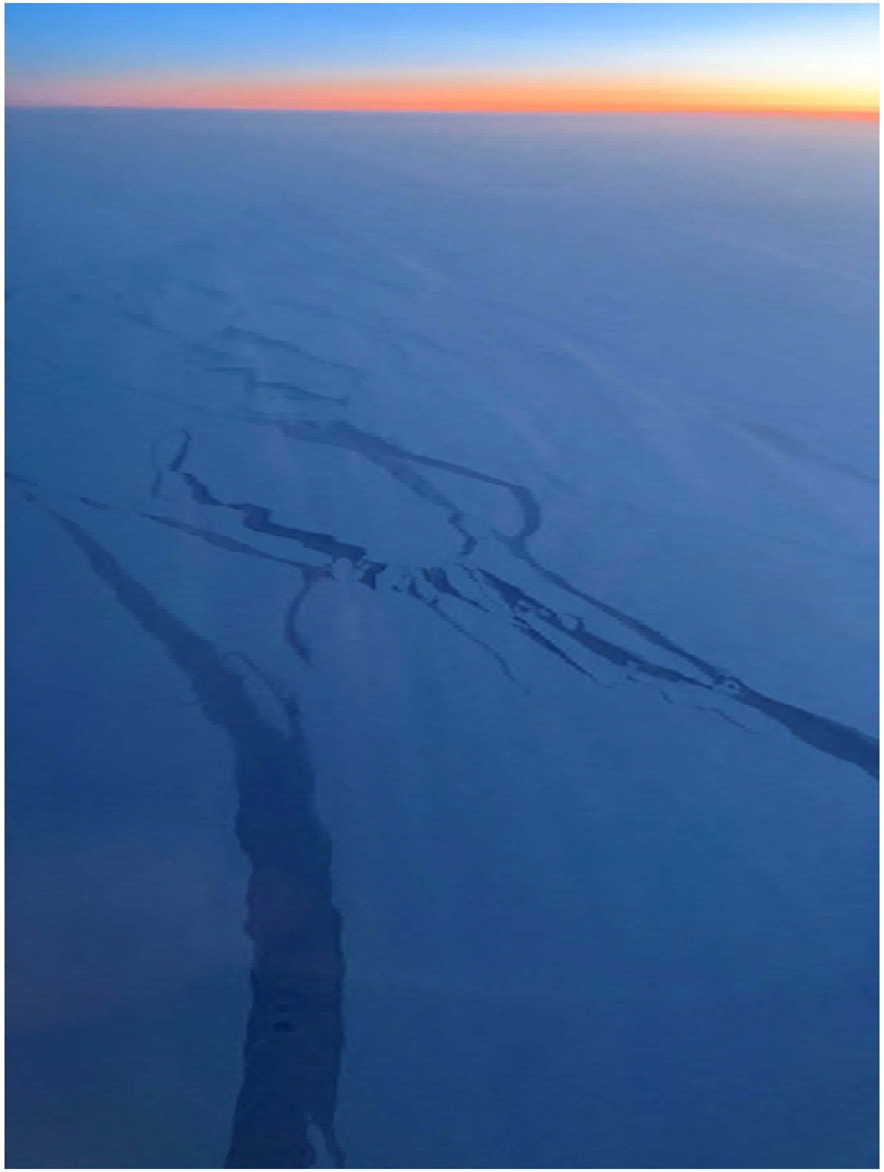
# Expedition support for R/V Mirai Arctic expeditions

| **R/V Mirai Cruises** | **Wave buoy deployment** | **Wave and Sea Ice forecasts (collaboration with Arctic Sea ice Information Center, ASIIC)** | |
|---|---|---|---|
| | | **Wave** | **Sea Ice** |
| MR16 *ArCS* | 2 x WII, open water, 2 months | N/A | N/A |
| MR18 *ArCS* | 2 x WII, MIZ, short lived | N/A | N/A |
| MR19 *ArCS* | 3 x Spotter, MIZ, 2 weeks | 3-day forecast, regional domain, Waseda Lab server | N/A |
| MR20 *ArCSII* | 5 x Spotter, MIZ, 2 weeks | 5-day forecast, nested pan-Arctic domain, Oakforest-PACS | 10-day forecast, nested pan-Arctic domain, Google Cloud Platform GCP |
| MR21 *ArCSII* | 2 x Spotter, near ice edge, 5 weeks | 3-day forecast, nested pan-Arctic domain, Google Cloud Platform GCP | 10-day forecast, nested pan-Arctic domain, GCP |
| MR22 *ArCSII* | 12 x FZ, 3 Spotter, near ice edge, 3 weeks | 5-day forecast, nested pan-Arctic domain, GCP | 10-day forecast, nested pan-Arctic domain, GCP |
| MR23 *ArCSII* | 16 x FZ, 2 Spotters, near ice edge, > 2 months | 5-day 5-member ensemble forecast, nested pan-Arctic domain, GCP | 10-day forecast, nested pan-Arctic domain, GCP |

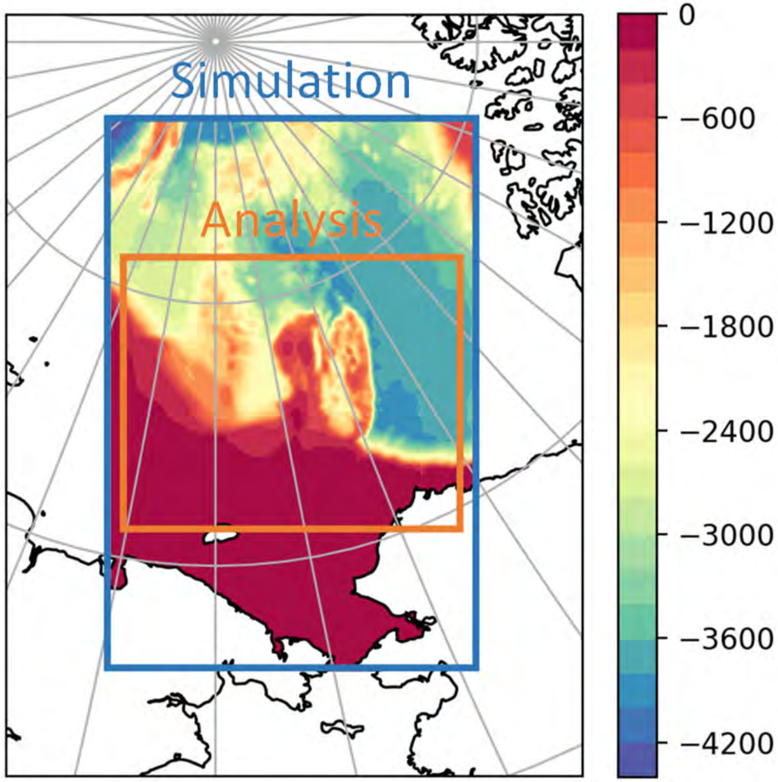
# Ocean-Ice coupling

## *do we really need a coupled regional model?*

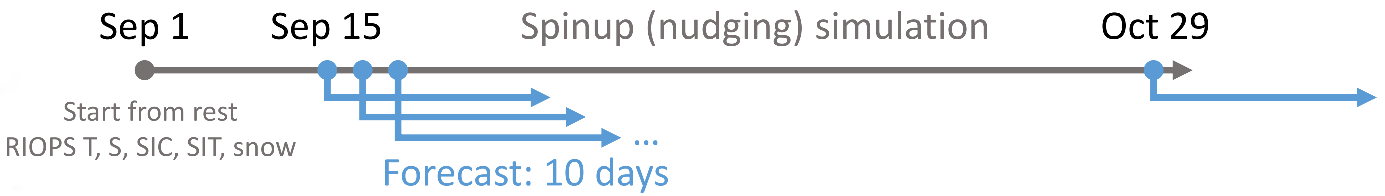
Contributions from Yasushi Fujiwara (ArCS2)



# Sea Ice model setup: modifying IcePOM for Mirai Cruise




Rotated lon-lat coordinate
560 x 840 x 33 grid points
Horizontal resolution ~ 2.5km
Minimum depth = 15 m




Spinup: nudge to RIOPS field
(Canadian ice/ocean analysis, issued every 12 hours)
ocean: T, S   ice: concentration, ice thickness, snow thickness

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \cdots - \chi(T - T_{\mathrm{RIOPS}})$$

**Surface BC**

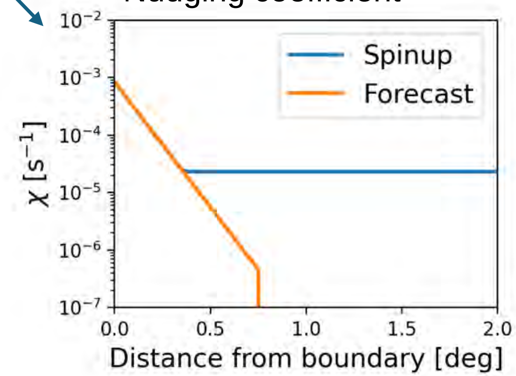
ECMWF 10-day forecast
p (surface), u, v (10m), T, $T_{dew}$ (2m),
total cloud coverage, precipitation

**Side BC**

Sponge layer with width ~ 75 km,
nudged to 1st day field of
RIOPS T, S, SIC, SIT, snow

Wall boundary condition for velocity

Nudging coefficient



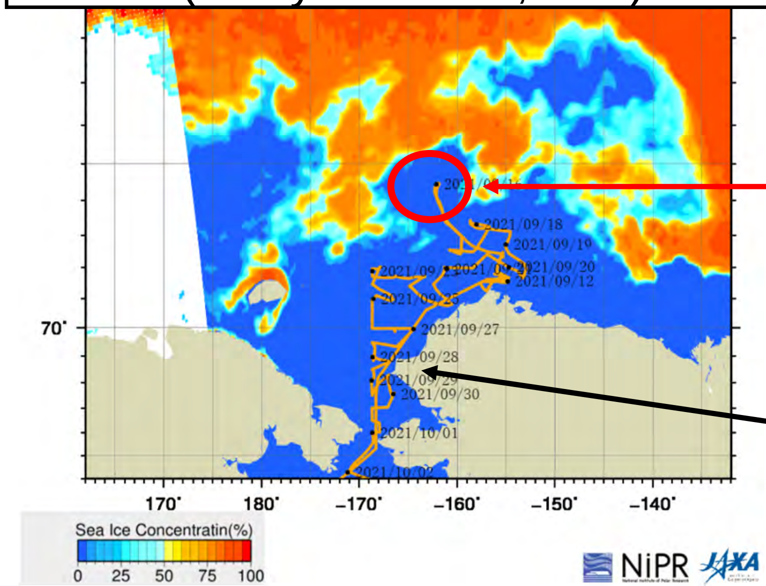
# Short-term sea ice forecast for observational support

Forecast was used to plan for the mooring retrieval operation with a 3~4-day lead time

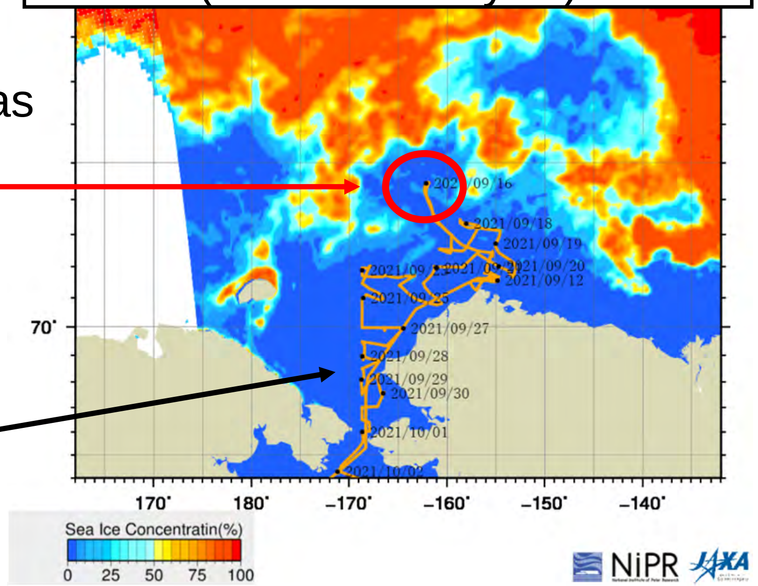
Operation: retrieve mooring system in area surrounded by sea ice.

Images were sent via satellite

Forecast 9/15 Sea Ice Concentration (4-day lead time, 9/11)




9/15 Sea Ice Concentration (IcePOM analysis)

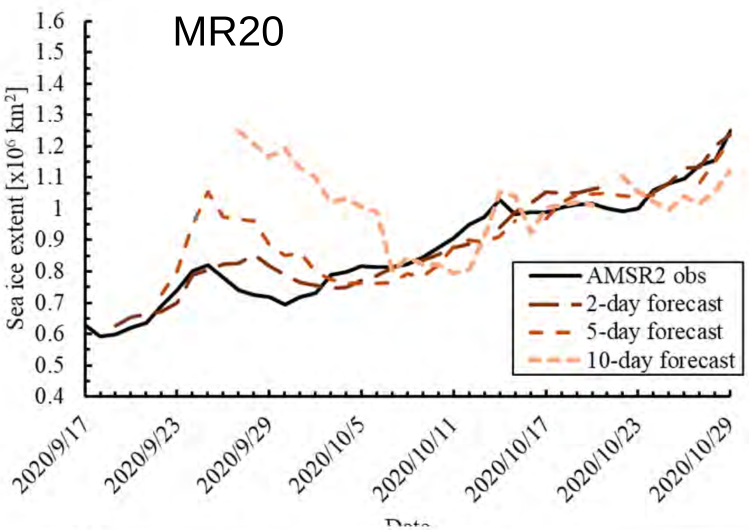


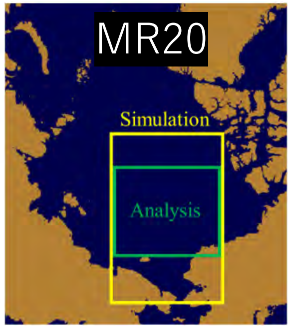

Mooring system was retrieved on 9/15

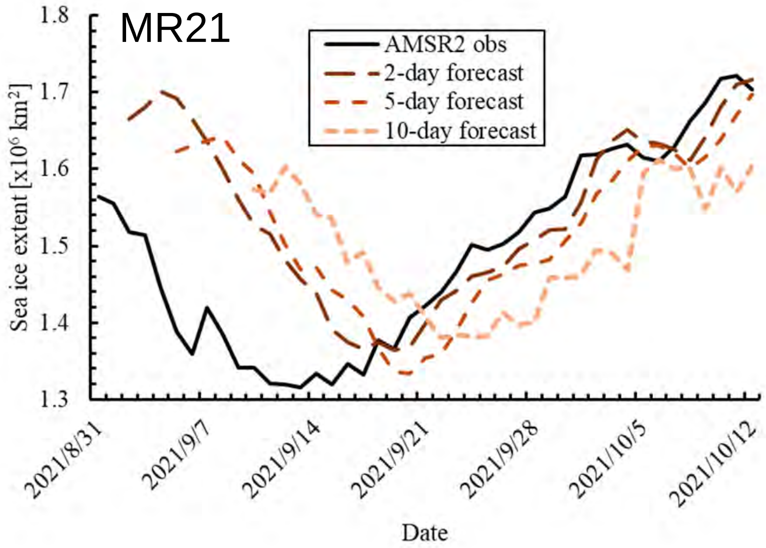
Ship route

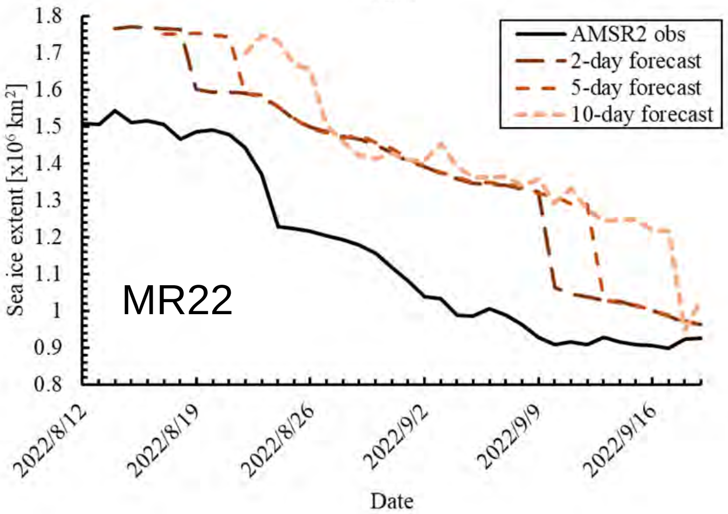
# Sea ice extent (SIC>0.15)
# Model vs. observation for the four R/V Mirai cruises

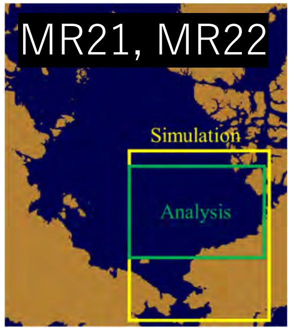
Large deviations – large uncertainty in the MIZ

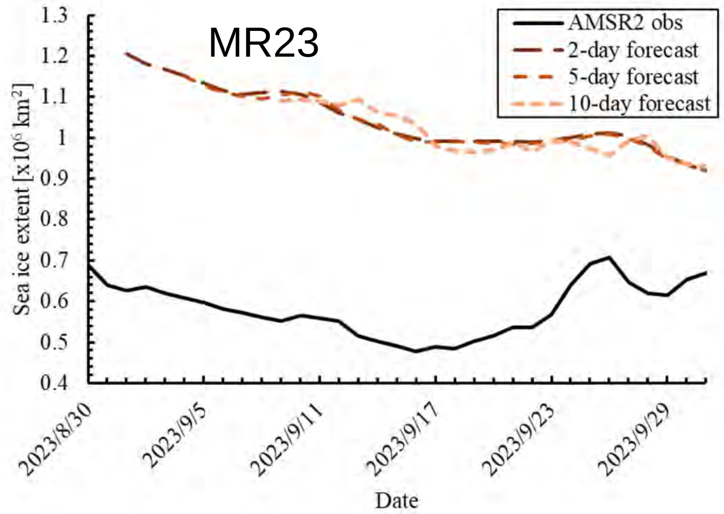


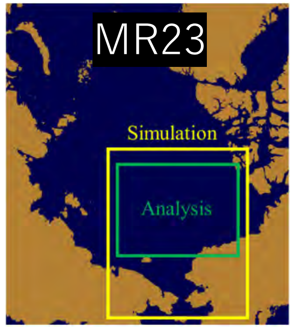



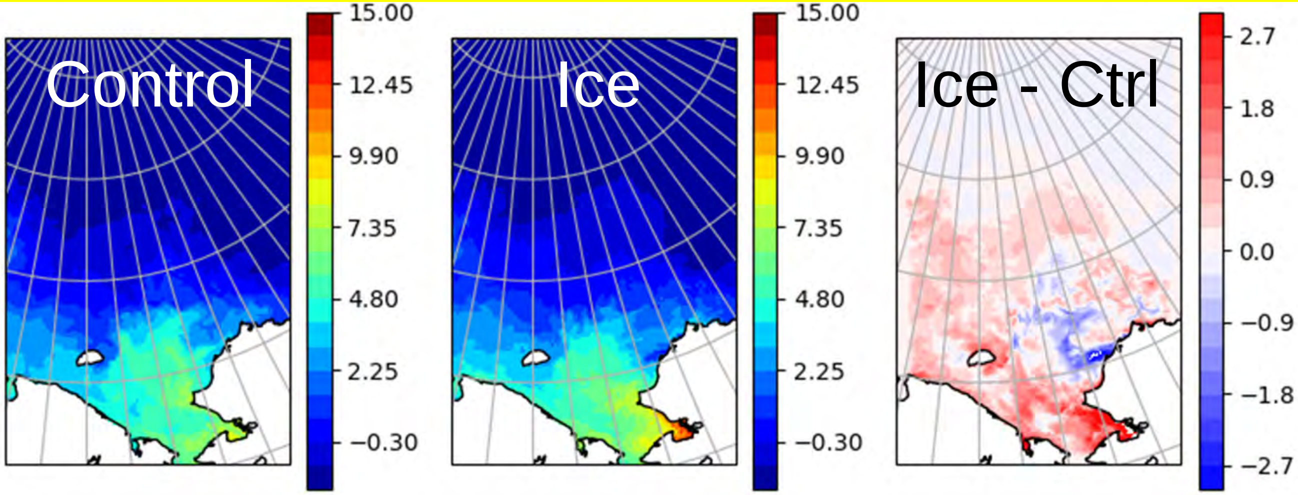
# Experiments with IcePOM

| **Series name** | **Spinup/nudging** | **Atmospheric forcing for forecast** |
|---|---|---|
| Control | RIOPS<br>Ice (SIC, SIT snow),Ocean (T, S) | ECMWF forecast product |
| Ice | RIOPS<br>Ice (SIC, SIT snow) only | ECMWF forecast product |
| ERA5-driven | RIOPS<br>Ice (SIC, SIT snow),Ocean (T, S) | ERA5 reanalysis |

ECMWF forecast product (SIC, SIT etc.) is also used for comparison
(note: RIOPS does not provide wind)

# Ocean is crucial for improved sea ice forecast

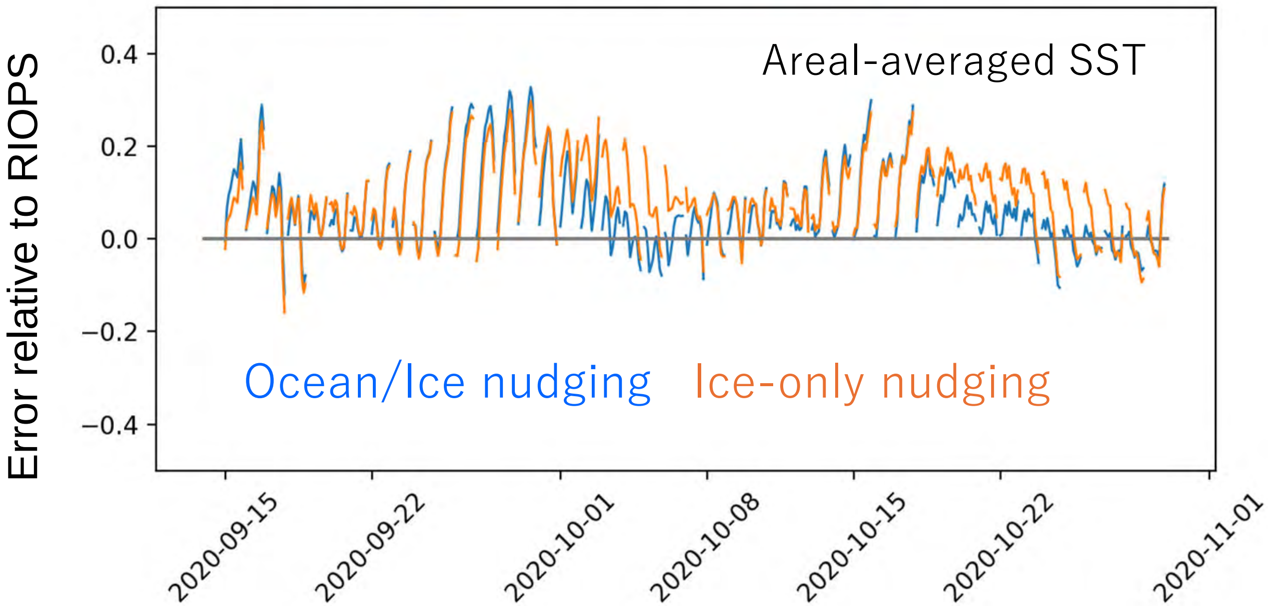
SST




Example of forecast initial temperature fields: 10/1

Control case is strongly nudged to RIOPS

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \boldsymbol{\nabla} T = \cdots - \chi(T - T_{\mathrm{RIOPS}})$$




SST field largely deviates from analysis if not assimilated

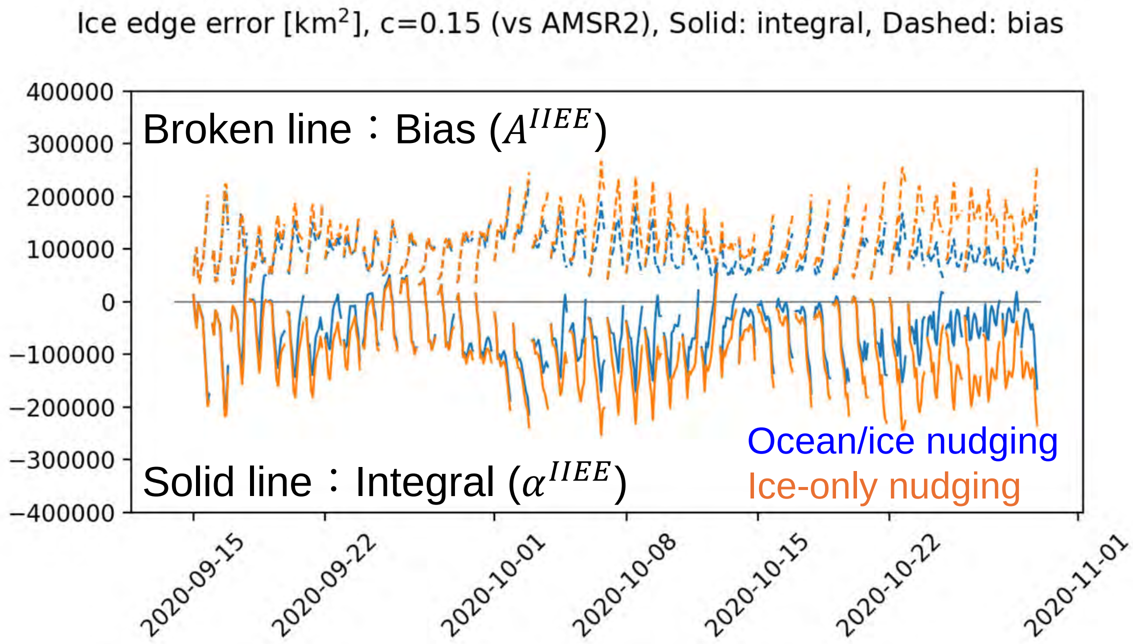
# Ocean interior

Overestimated and Underestimated areas are defined with $c_0 = 0.15$、 $c_{\text{ref}}$ as AMSR2.

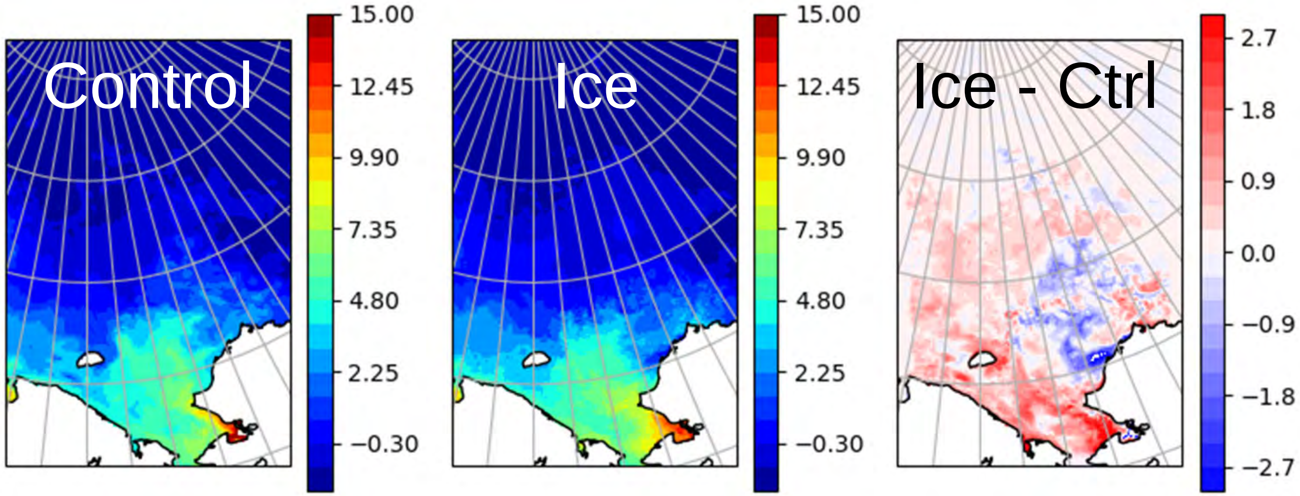
$$A^+ \equiv \int_{\substack{c>c_0 \text{ and} \\ c_{\text{ref}}<c_0}} dS\,, \qquad A^- \equiv \int_{\substack{c<c_0 \text{ and} \\ c_{\text{ref}}>c_0}} dS$$

Integral $A^{\text{IIEE}}$ and Bias $\alpha^{\text{IIEE}}$ scores are defined as

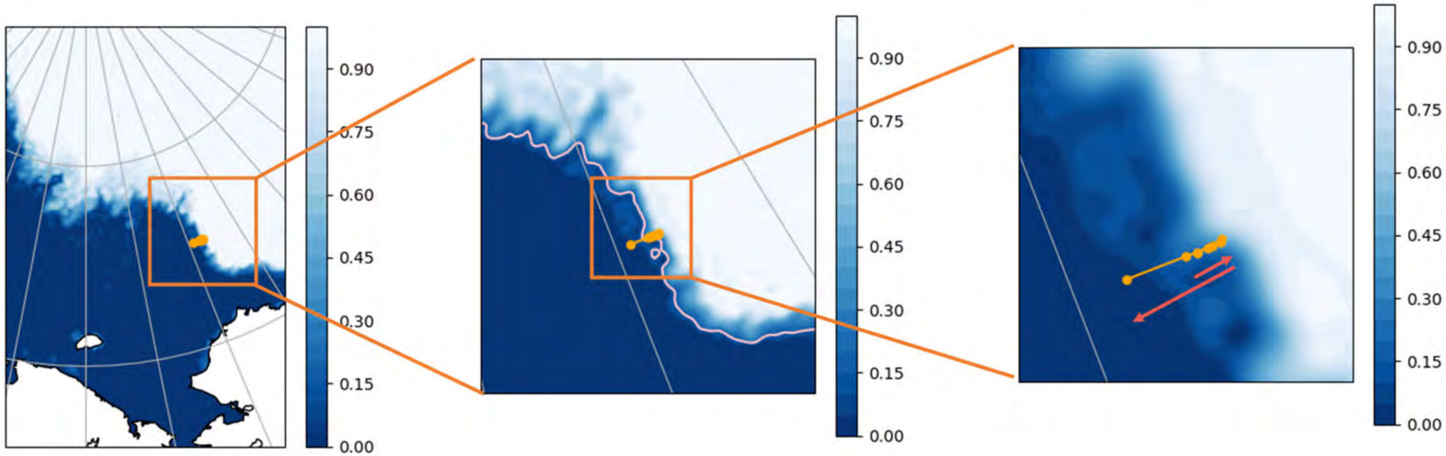
$$A^{IIEE} \equiv A^+ - A^-, \alpha^{IIEE} \equiv A^+ + A^-$$




T (10m)



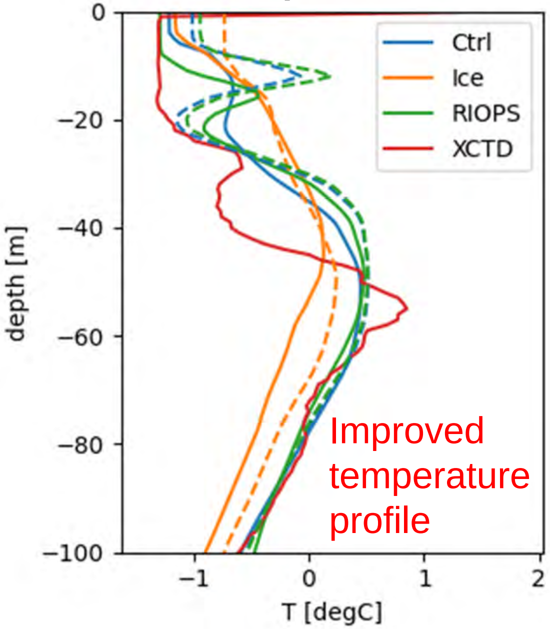
# Ocean Interior



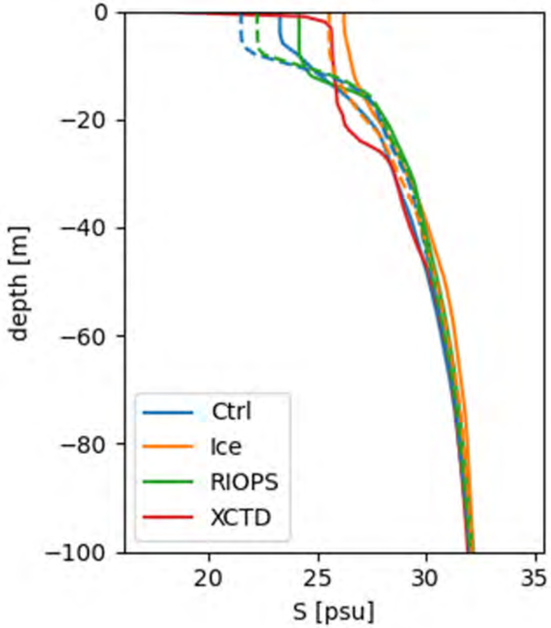

Mean profiles of 8 XCTD cast points on 10/12

MR20 T.Kodaira on board

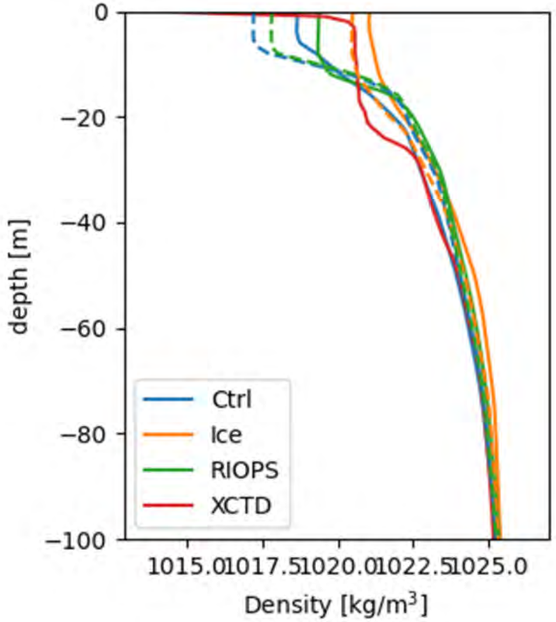
Temperature




Salinity




Density



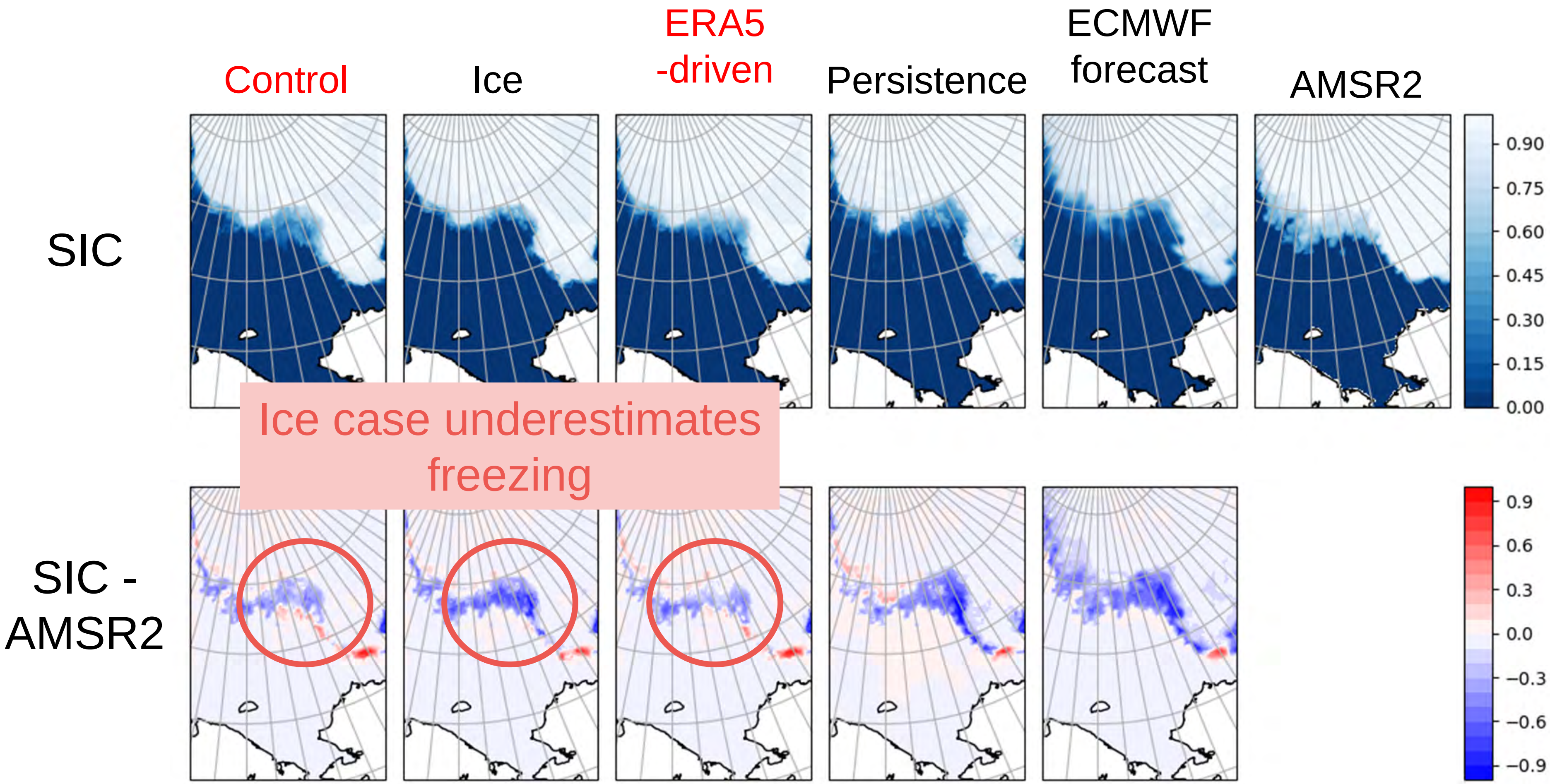

Subsurface still deviates from observation (nudged towards RIOPS)

High-resolution ocean modeling is necessary

Solid: 10/12 (Ctrl, Ice: forecast from 10/2), Dashed: 10/2

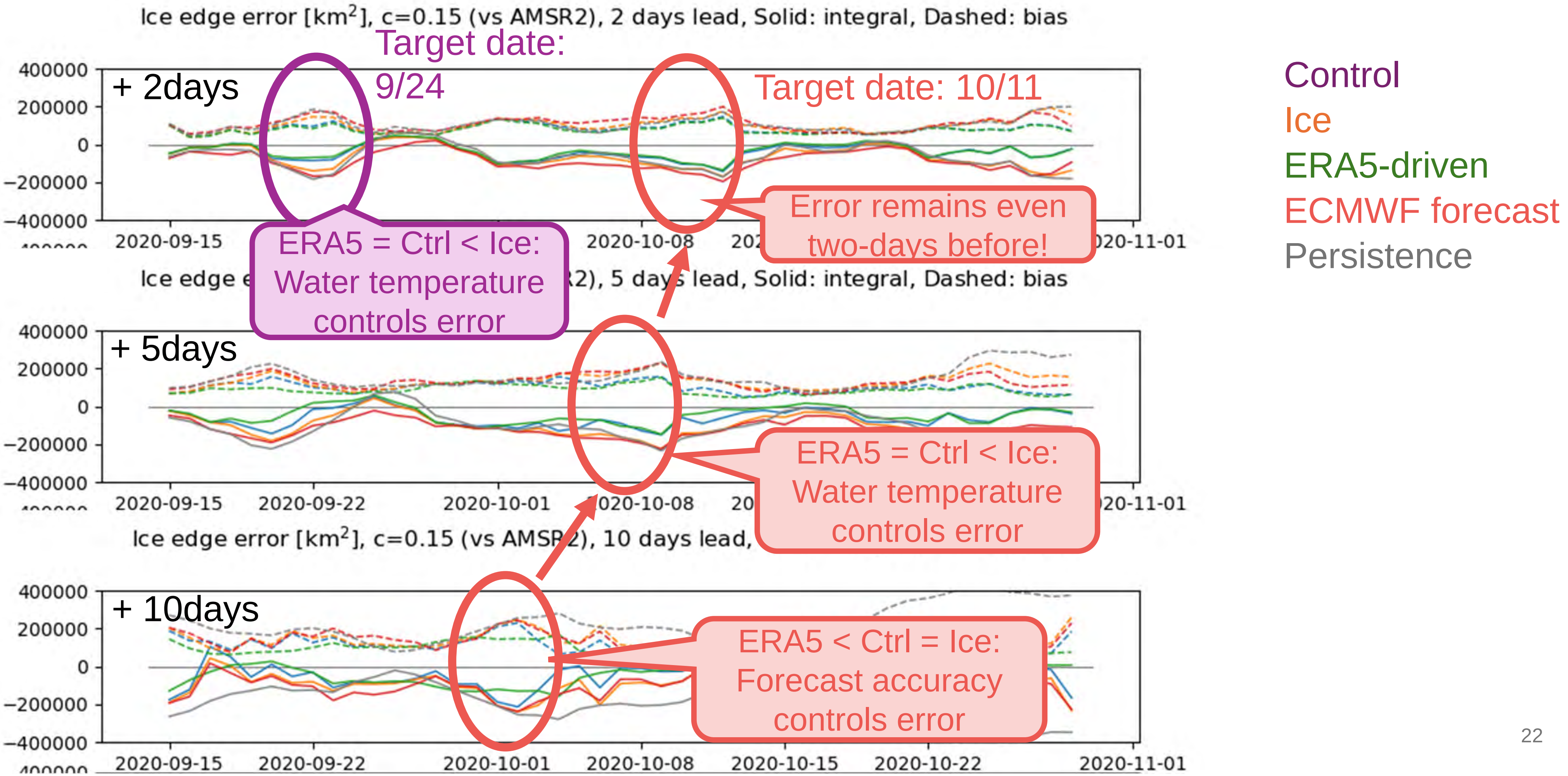
# Impact of atmospheric forcing

10/6 + 5 days SIC, vs AMSR2 (vs RIOPS was similar)



# Atmospheric forcing is also important

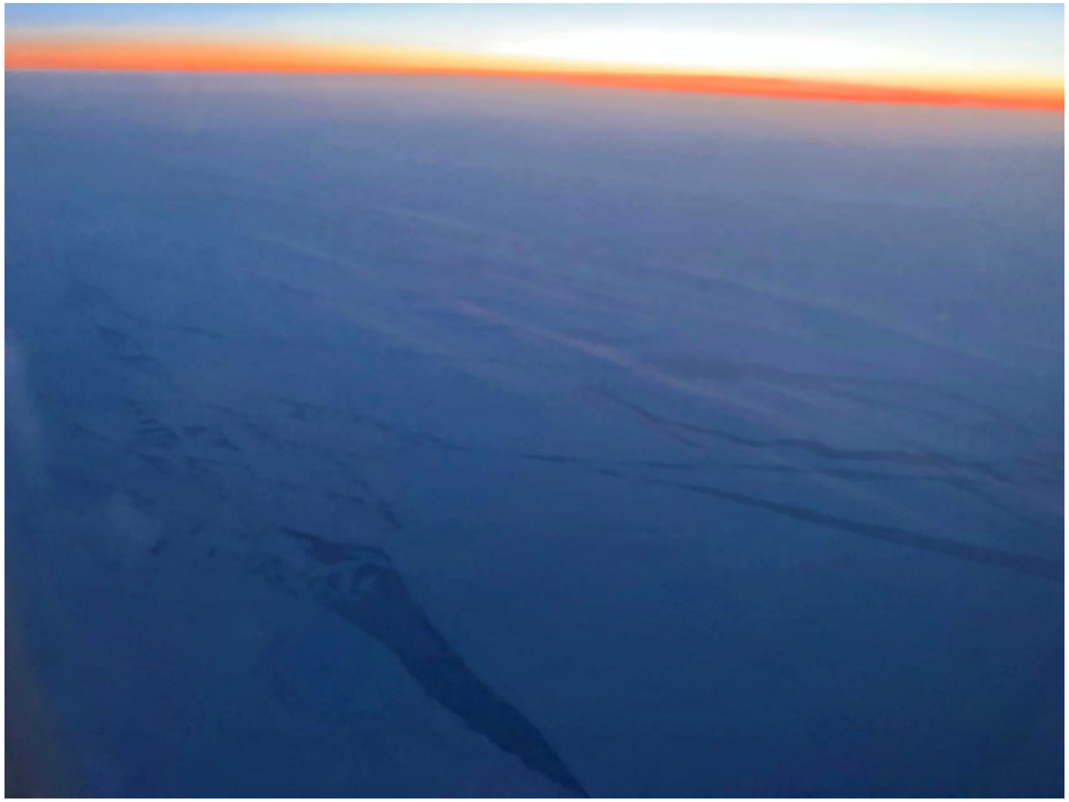
## Time series of IIEE, $c_0 = 0.15$, by lead time



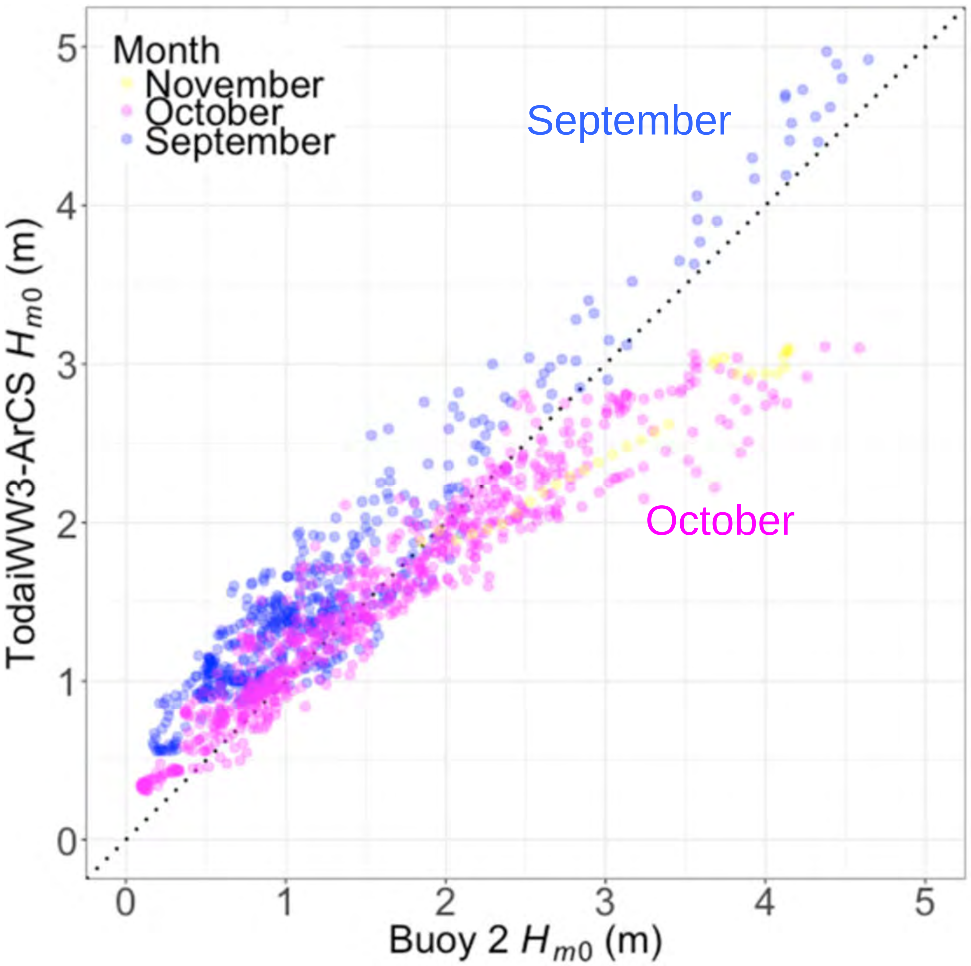
# Impact of uncertainty in wind

Wave forecast accuracy

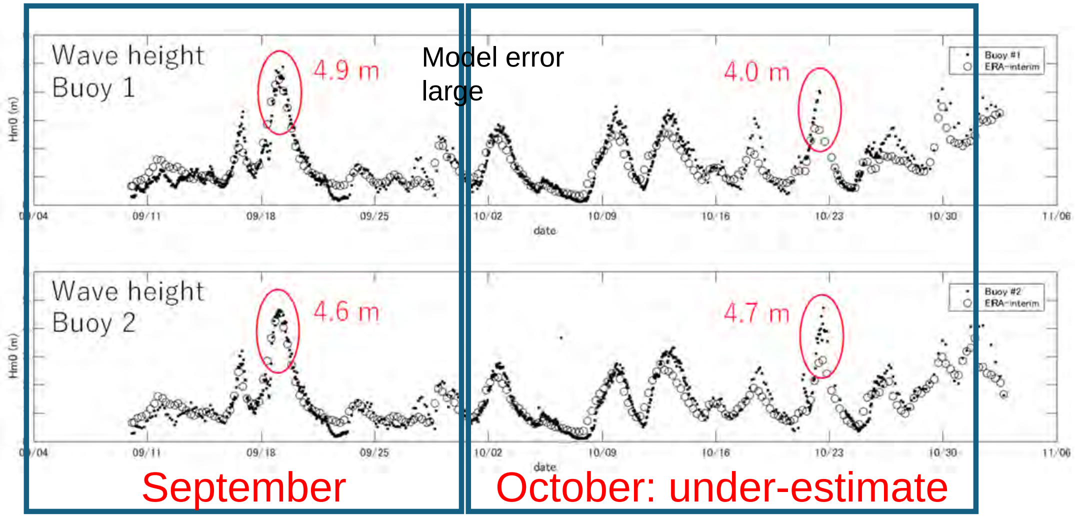
Nose et al. 2018

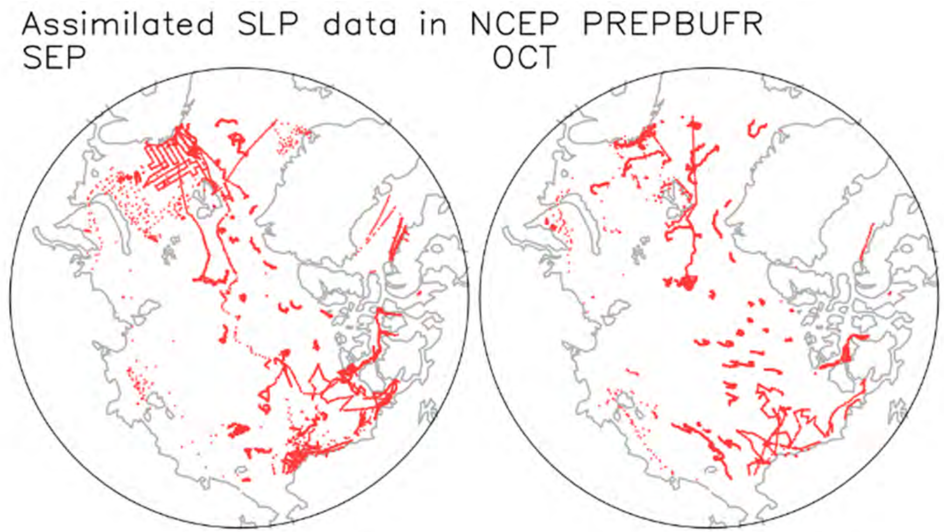


# Uncertainty due to inaccurate wind – when open water area expands

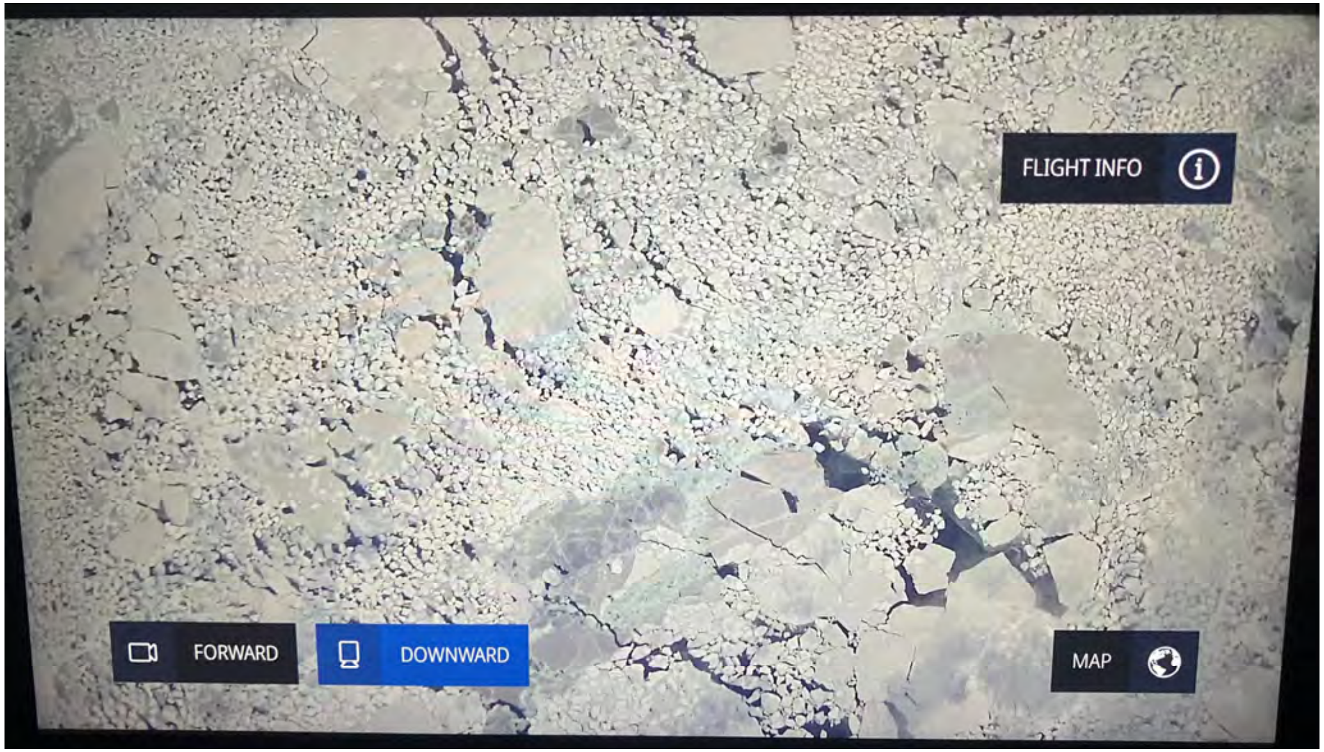



Nose et al. 2018 ODYN




Much less SLP observations in October




# Impact of uncertainty in sea ice

Wave forecast accuracy

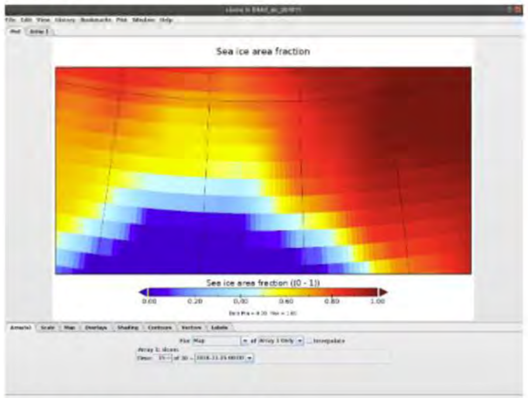
Nose et al. 2020

# Uncertainty due to inaccurate ice-edge location

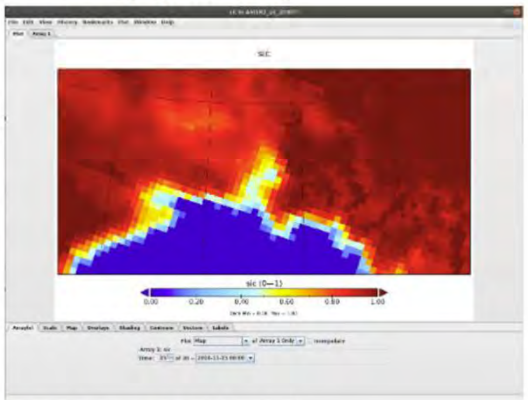
Variability of ice-edge
Depending on the satellite products.

Nov. 15, 2018 snapshots

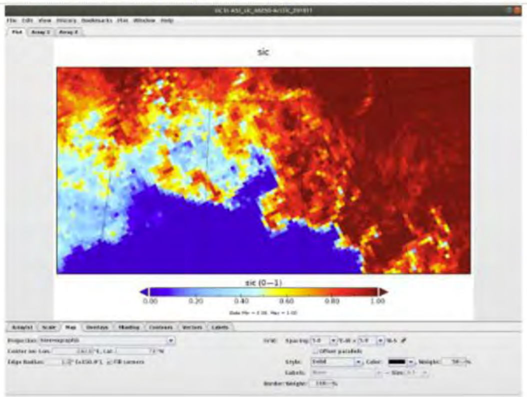
**ERA5**



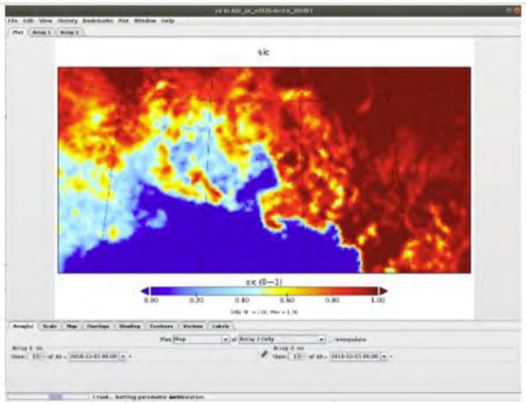

**Bootsrap (AMSR2)**

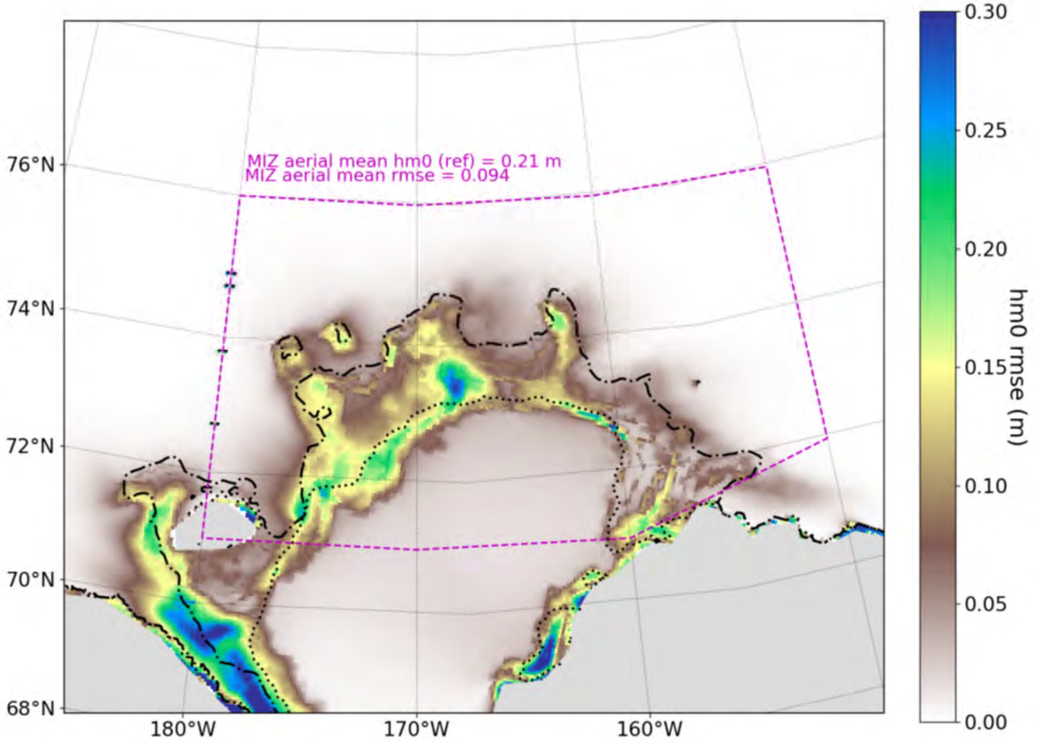



**ASI 6 km (AMSR2)**




**ASI 3 km (AMSR2)**

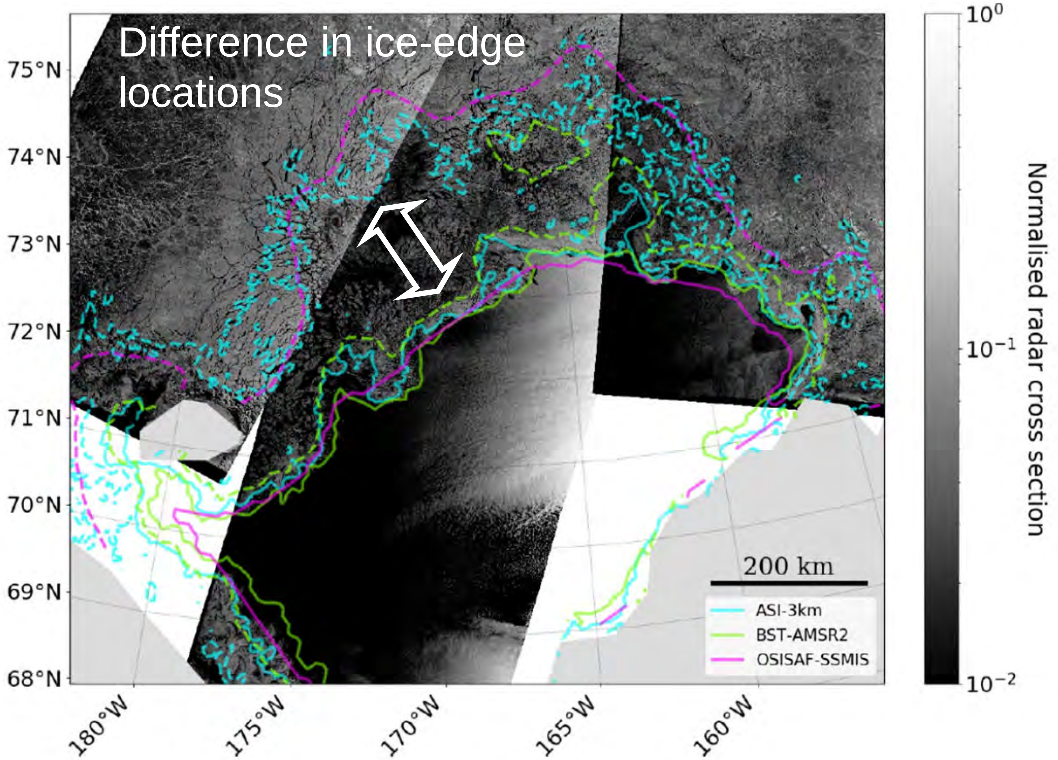



Wave field differs in the MIZ depending on the SIC used.

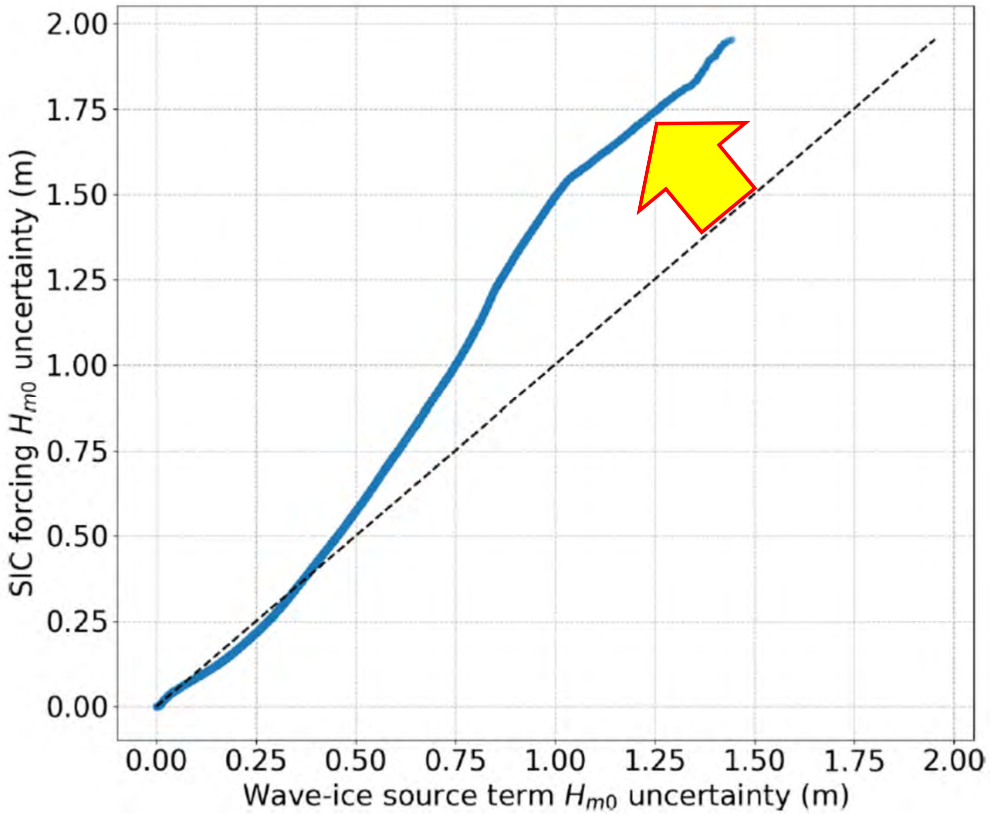
Nose et al. 2020 Cryosphere

# Comparing magnitudes of uncertainty – lateral boundary condition

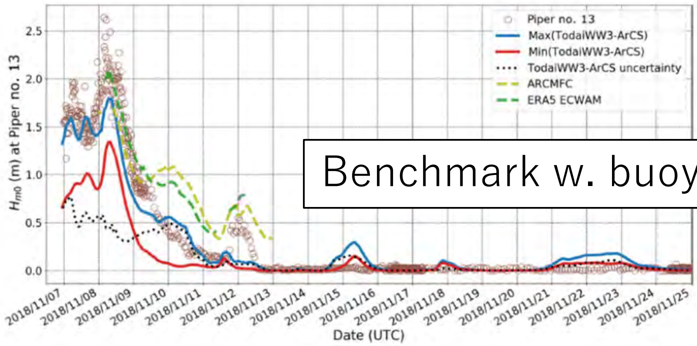



Uncertainty due to sic products

QQ-plot of uncertainties



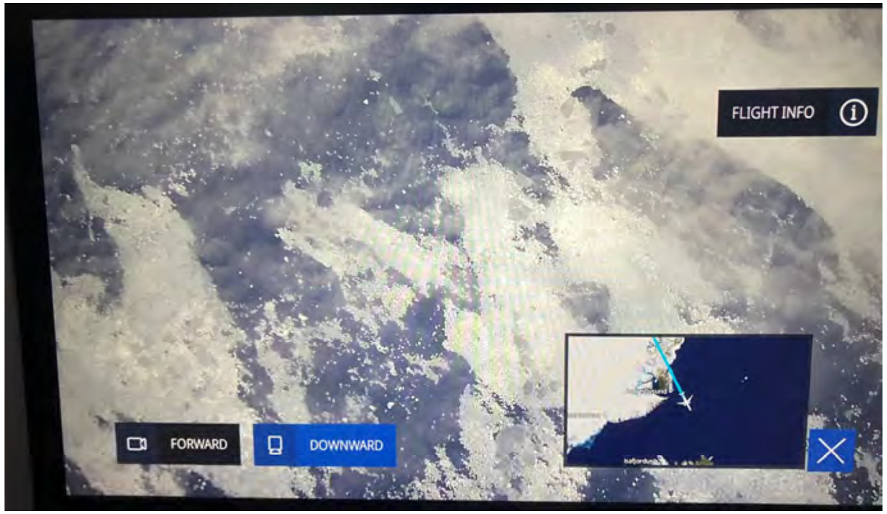

Uncertainty due to model physics

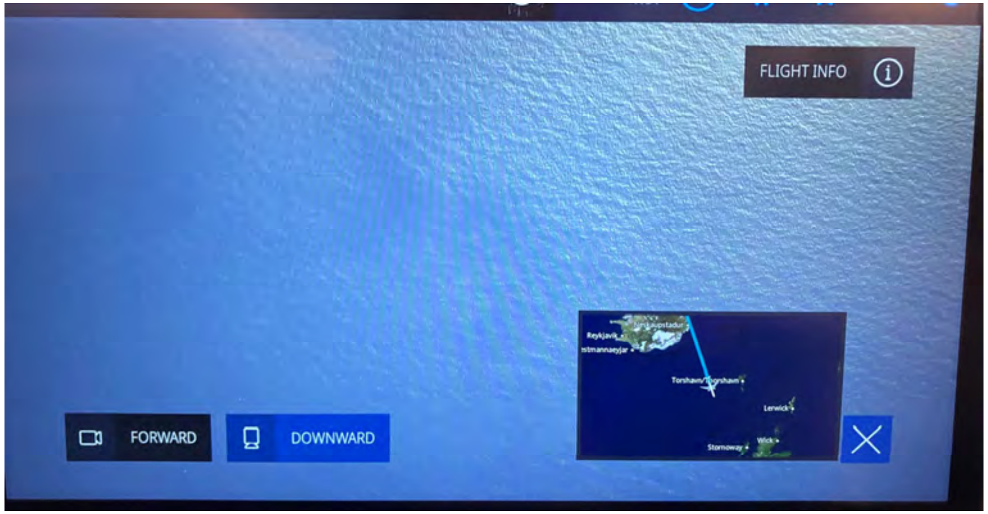



Benchmark w. buoy data

Uncertainty due to sic products

Nose et al. 2020 Cryosphere




# A step toward a wave-ice coupled model

Large uncertainty in the sea ice field

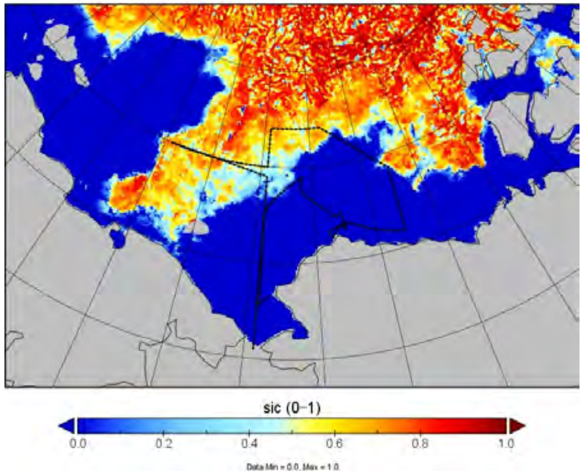
Ensemble wave forecast

Contributions from ArCS2 Takehiko Nose

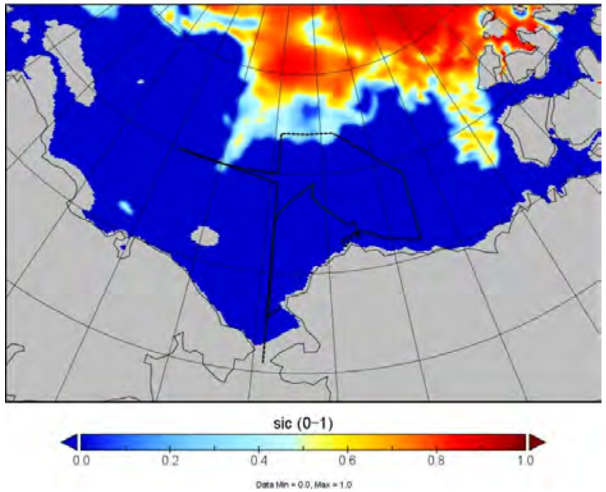
# MR23 modelled sea ice field 20230825 00:00 sea ice forecast

(black dotted line is the MR23 planned track)

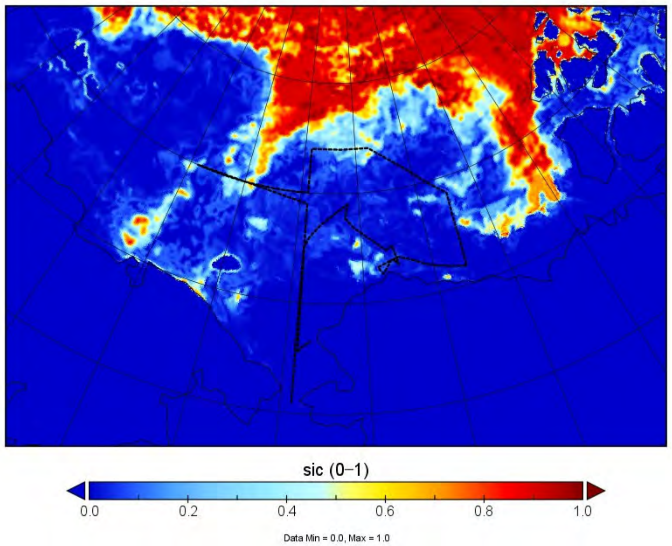
neXtSIM 3km sic



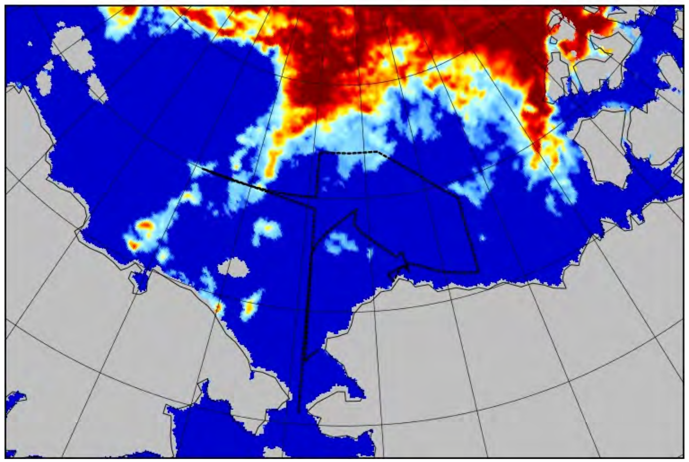

TOPAZ4 1/8 degree sic



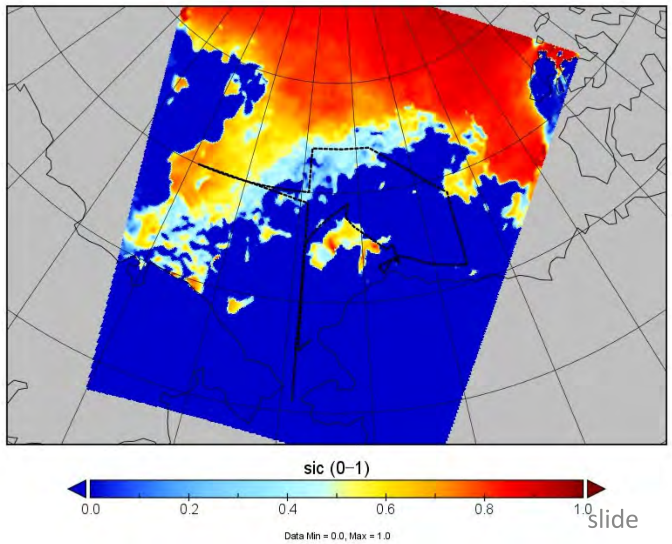

RIOPS 1/12 degree sic




AMSR2-JAXA 15km sic



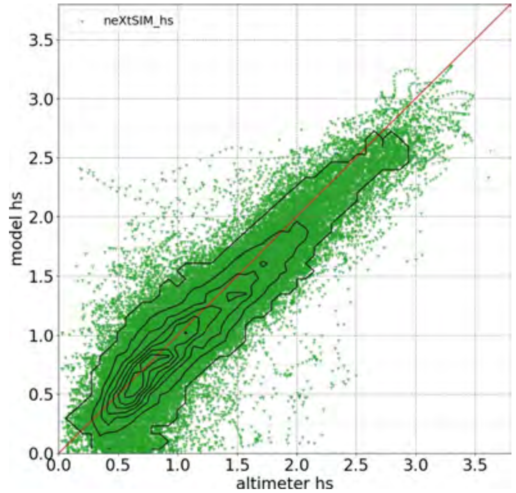
IcePOM 8Km sic



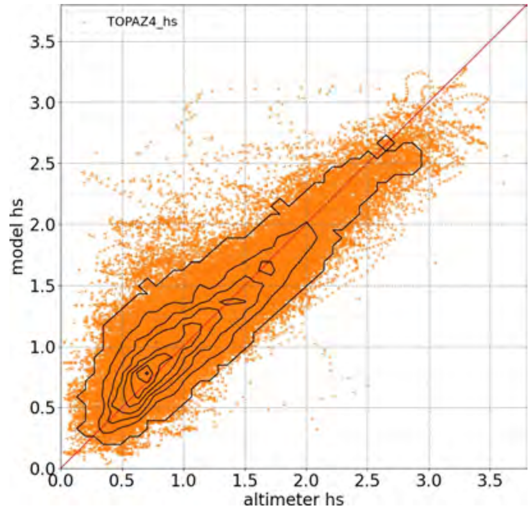
# Ensemble model evaluation

**Comparison of ensemble with the altimeters between 25 Aug and 25 Sep 2023**

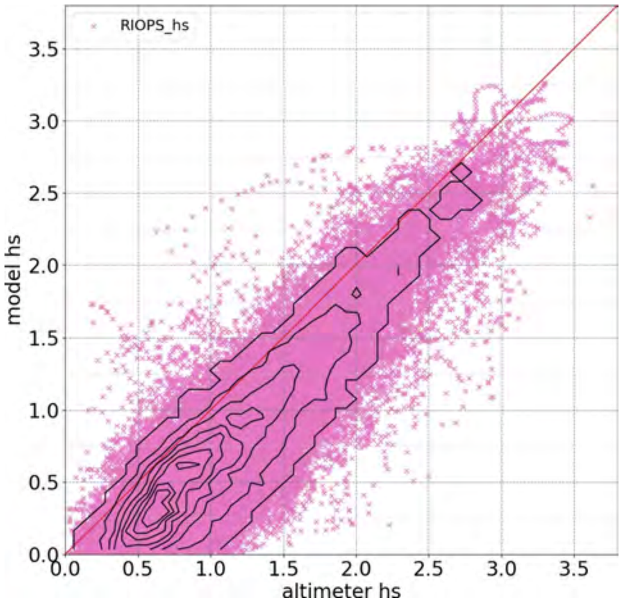
neXtSIM



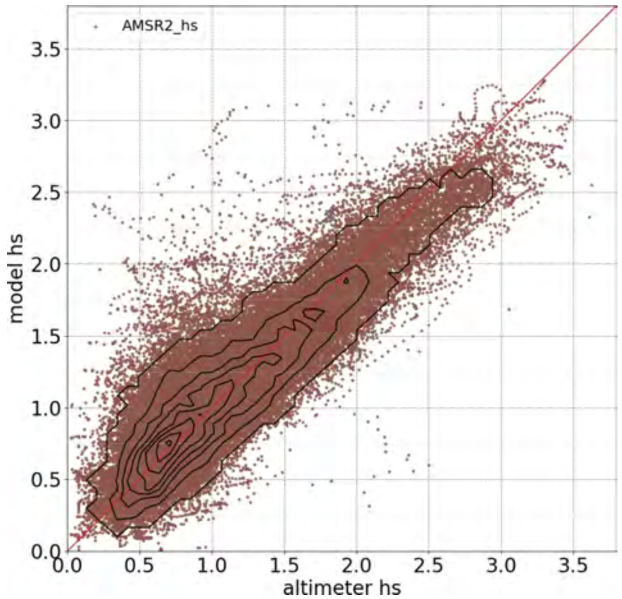

TOPAZ4



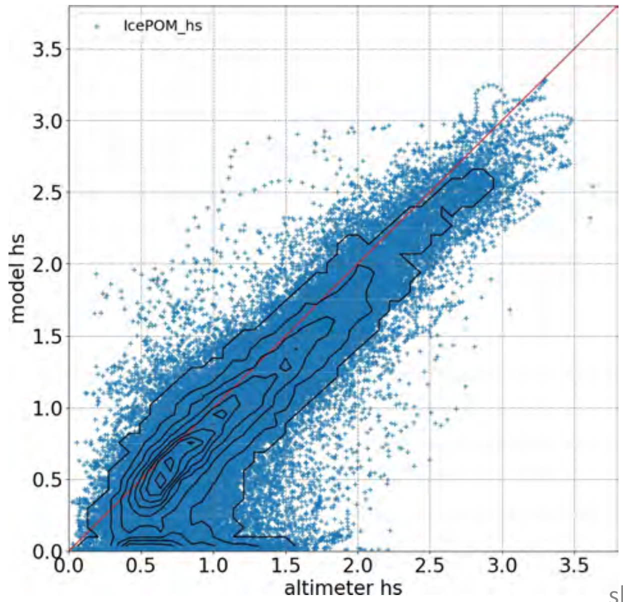

RIOPS




AMSR2-JAXA

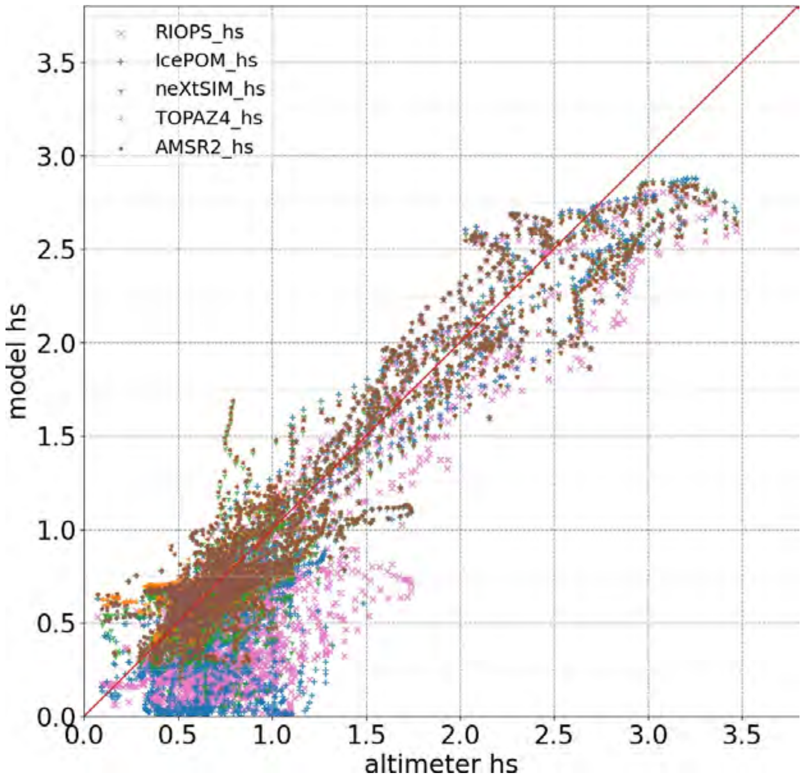


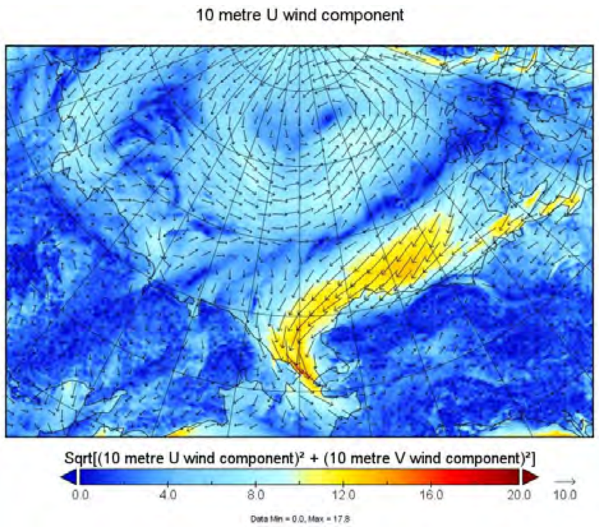

IcePOM

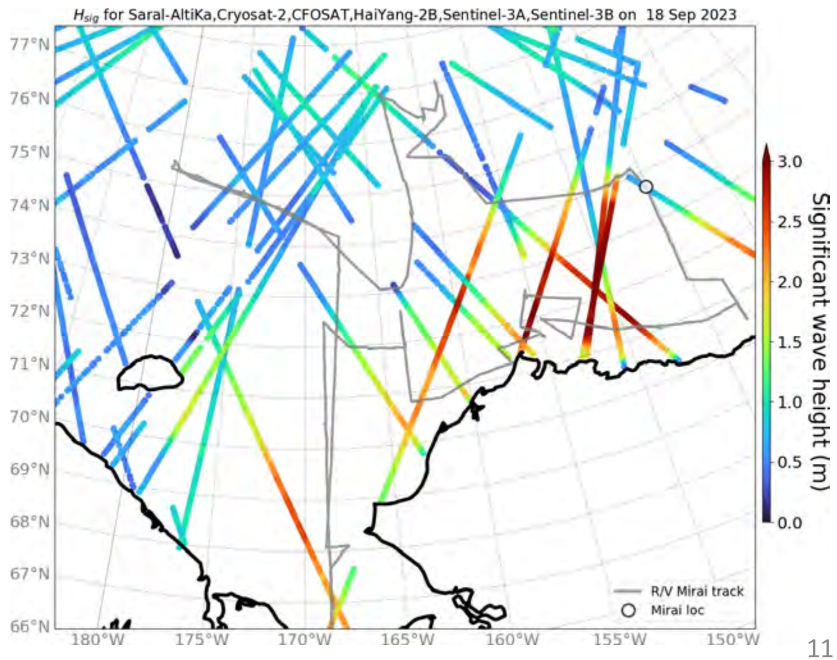


# Ensemble model evaluation

**The case of model Hs deviating from altimeter for high Hs**



# Summary – coupling among wave–ice–ocean–atmosphere

Engineering needs (Arctic Shipping Route)

- **a high-resolution model** is necessary. → regional model
- The desired outputs include, SIC, SIT, FSD and Ice Pressure with UNCERTAINTY

Ocean-ice coupling

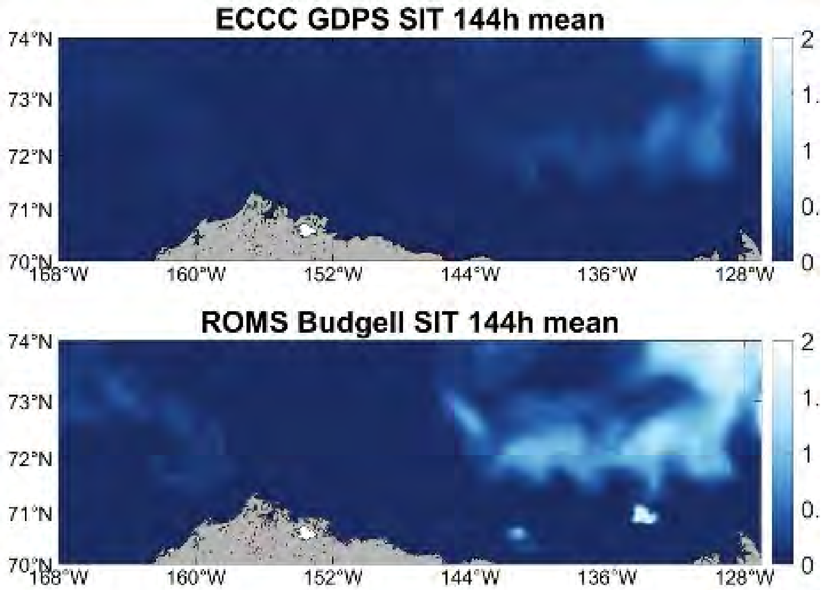
- The accuracy of sea ice forecast depends on the ocean (SST and interior). Constraining the regional model with coupled large scale model outputs improved the performance.
- Deficiency still exists: resolving sub-mesoscale ocean features, and sensitivity to wind forcing

Ice-Wave coupling

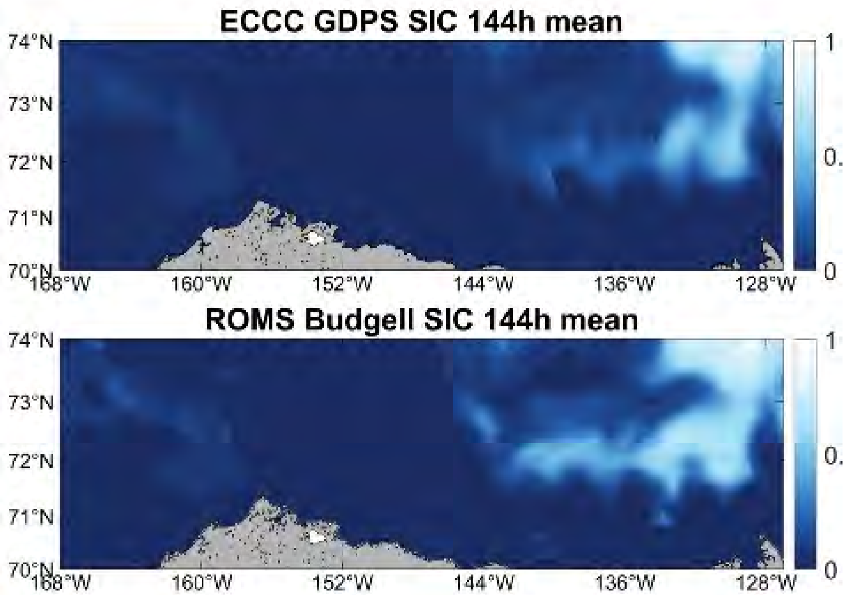
- sea ice uncertainty strongly affects the wave forecast in the open water
- uncertainty in wind affects wave forecast as well

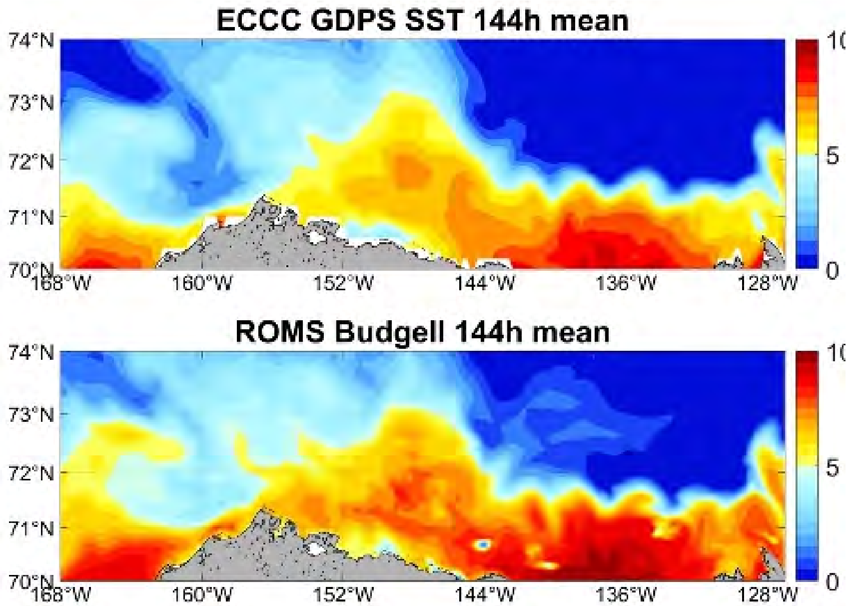
**A coupled regional high-resolution wave-ice-ocean-atmosphere model is necessary**
**- as a first step, ROMS-Budgell model is developed (nudged to GIOPS)**

# First step: Develop a regional ice-ocean model constrained by coupled large scale model (GIOPS), a preliminary result



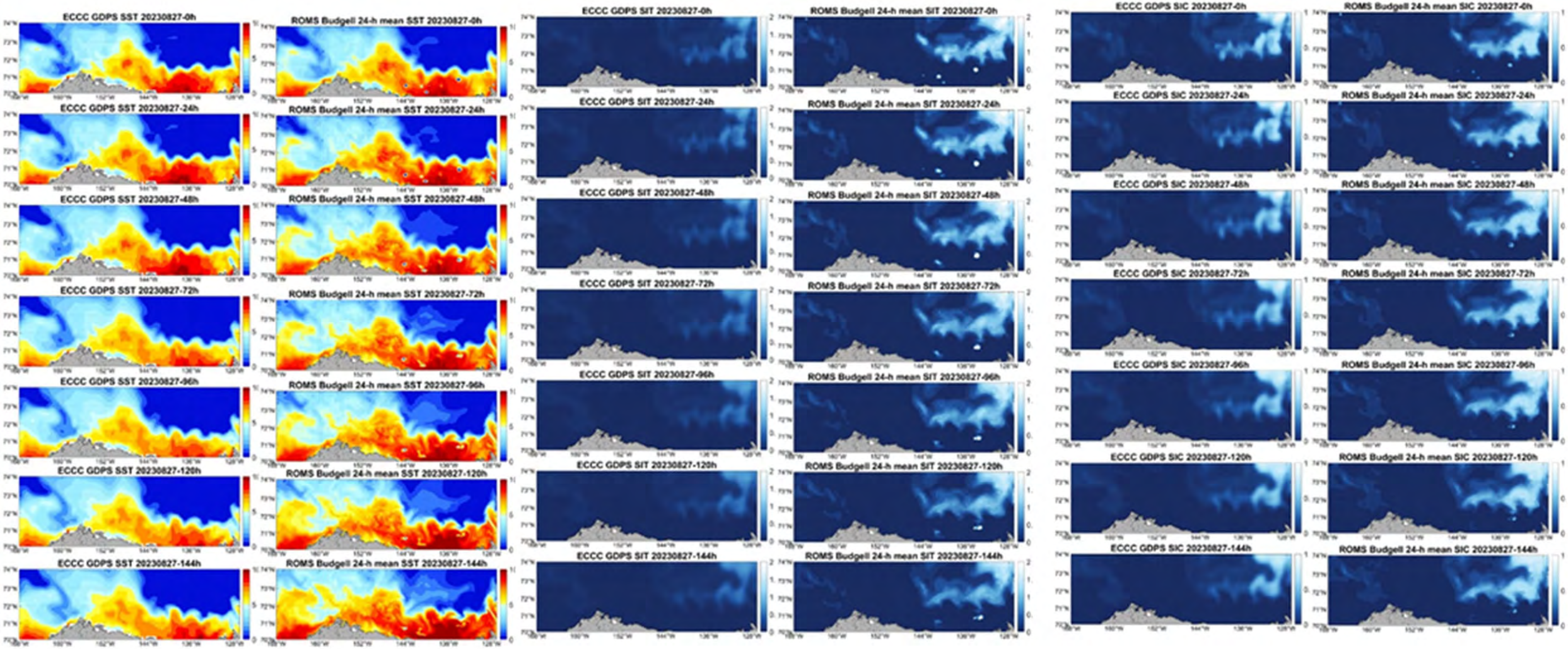

144-h averaged SIC, SIT, and SST:



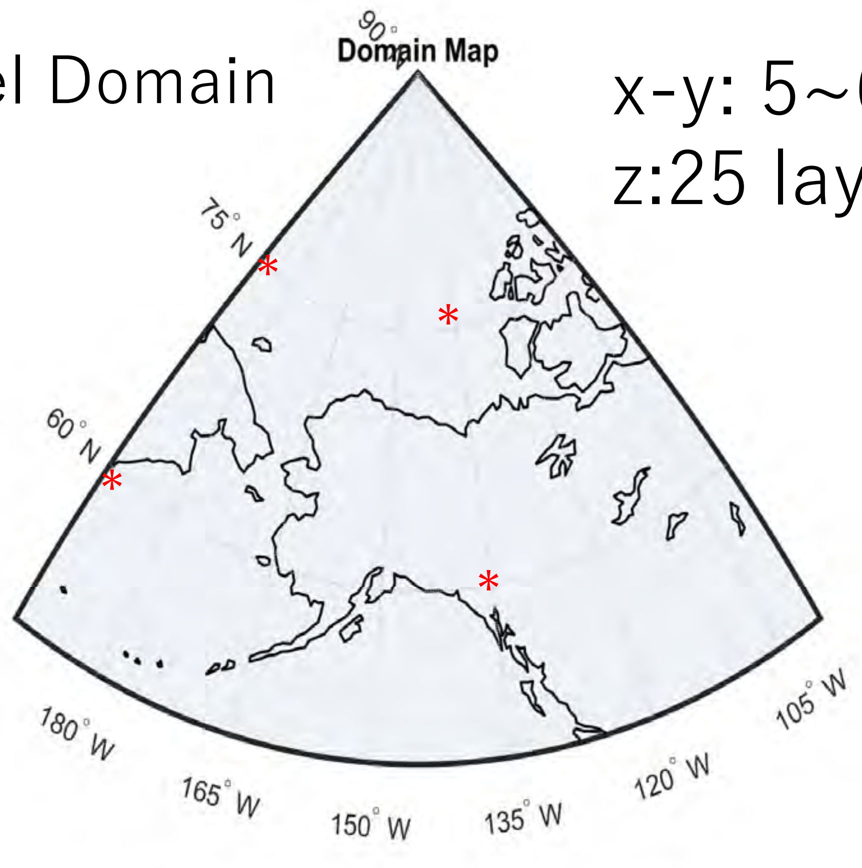
# 24-h averaged SIC, SIT, and SST

| SIC | | SIT | | SIC | |
|---|---|---|---|---|---|
| GIOPS | ROMS-Budgell | GIOPS | ROMS-Budgell | GIOPS | ROMS-Budgell |



# ROMS–Budgell: Hindcast

Model Domain




x-y: 5~6km
z:25 layers

ECMWF

| Forcing |
|---|
| TAIR |
| QAIR |
| PAIR |
| UWIND |
| VWIND |
| RAIN |
| SNOW |
| SW_DN |
| LW_DN |

\+

SMOS->Aice+Hice

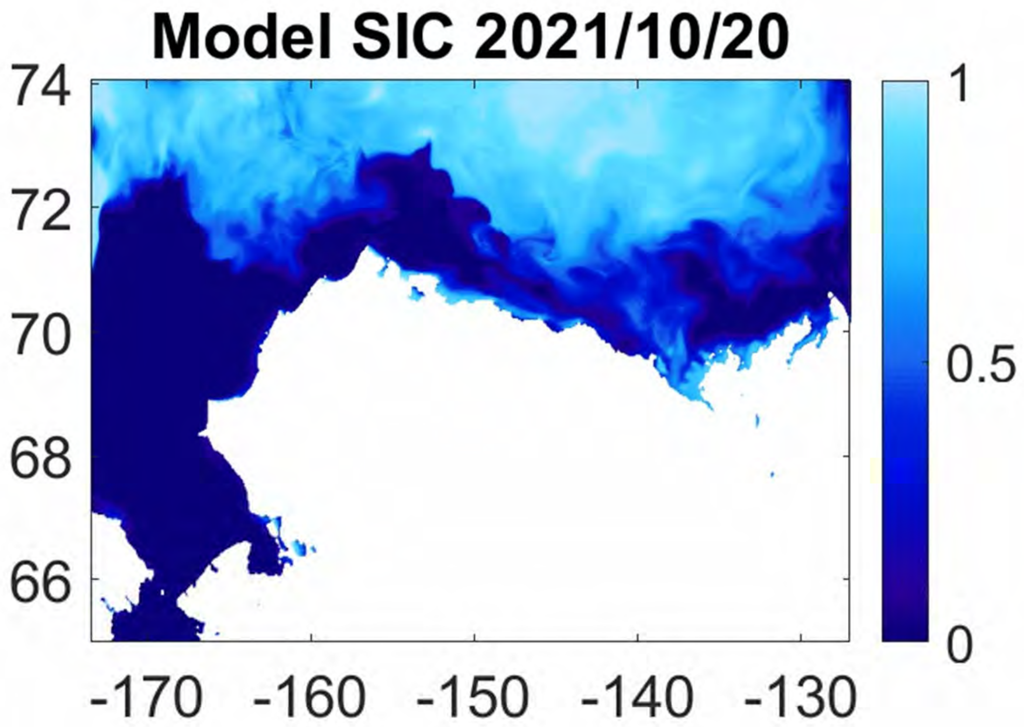
\+

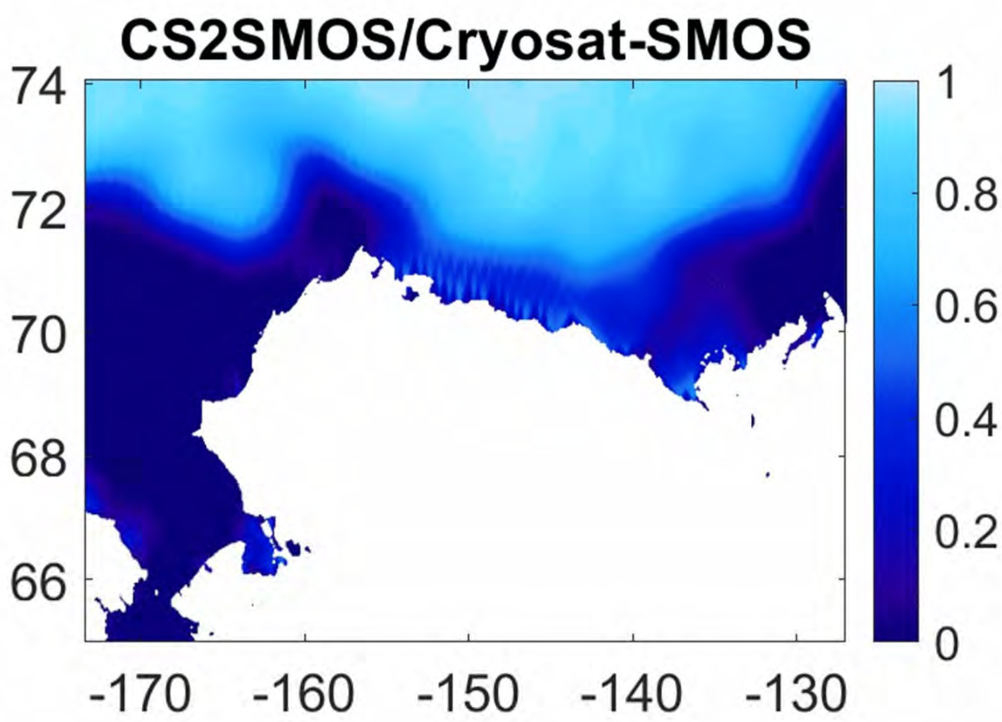
| ROMS |
|---|
| SST |
| SSS |
| u |
| v |
| SSH |

BRAN

Bluelink Ocean Forecasting

# ROMS-Budgell: Hindcast-SIC

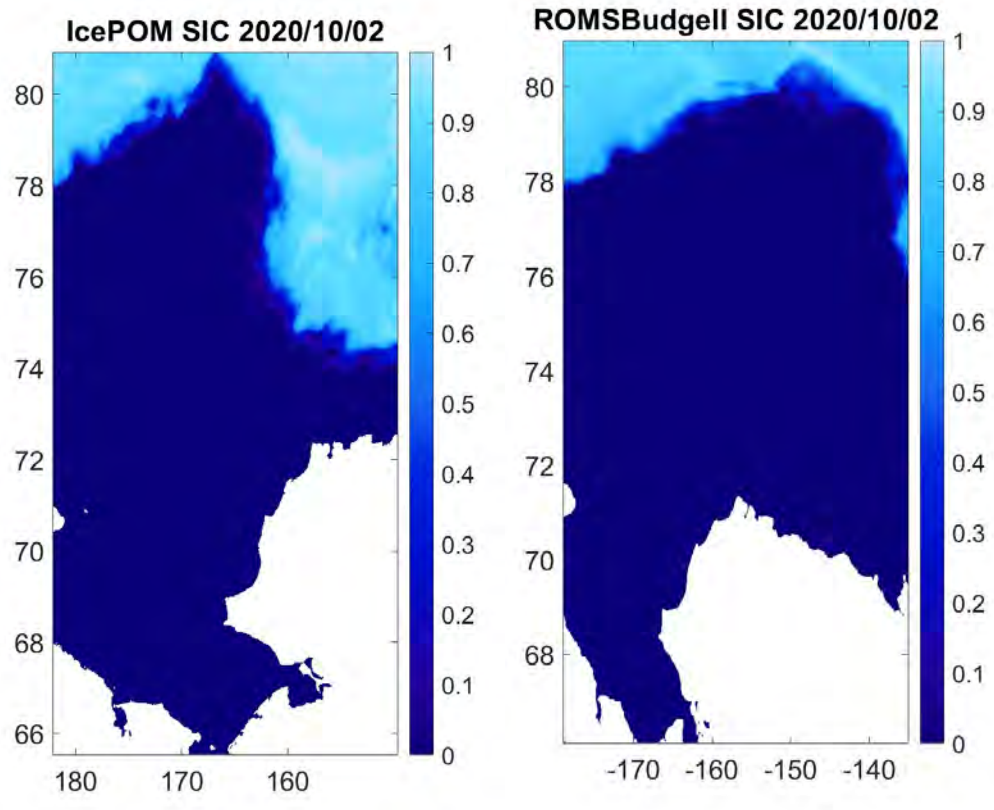


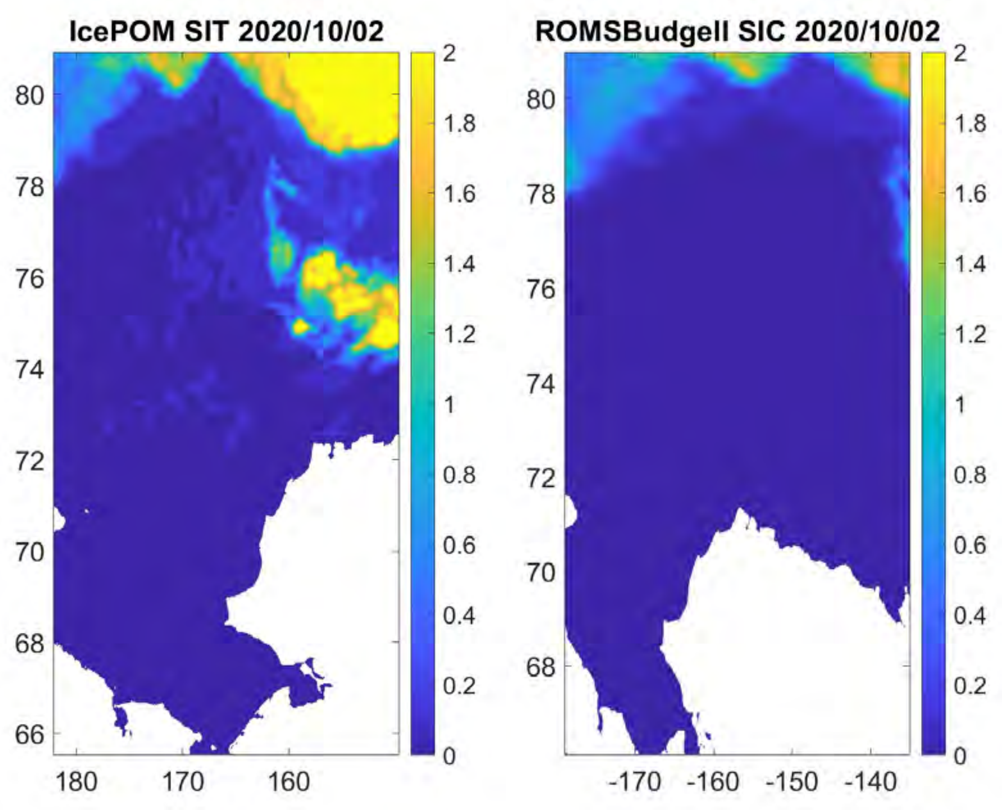

- Model vs Satellite SIC

# ROMS–Budgell vs IcePOM: Forecast

RIOPS+ECMWF




3 days average




3 days average