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Wave forecasting for the Marginal Ice Zone

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Acknowledgements: Jim Thomson (UW/APL), Hayley Shen (Clarkson U.), Pamela Posey (NRL-SSC), Dave Hebert (NRL-SSC), Li Li (NRL-DC), and ONR Sea State DRI Team

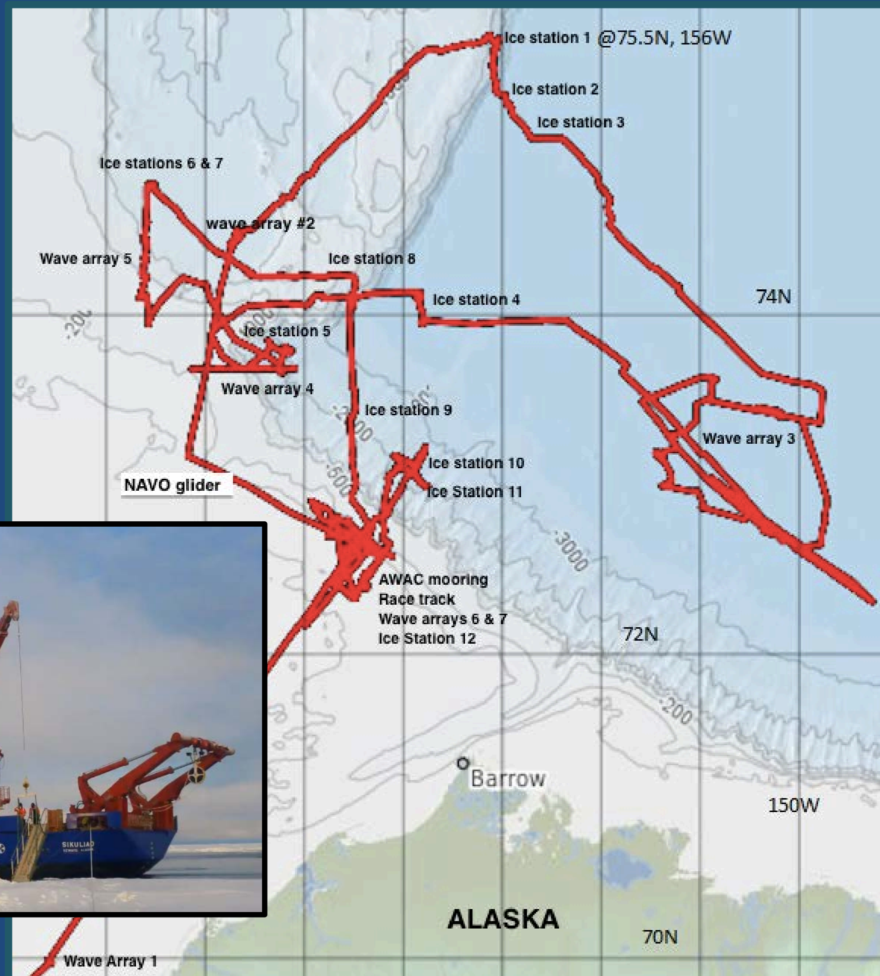
Preface

- This presentation is companion to…
  - WISE Spring 2016 presentation
  - "Dissipation of wind waves by pancake and frazil ice in the autumn Beaufort Sea" (Rogers, Thomson, Shen, et al.), *JGR-Oceans 2016*
- …but with more focus on hindcasting and forecasting, less on physics parameterizations

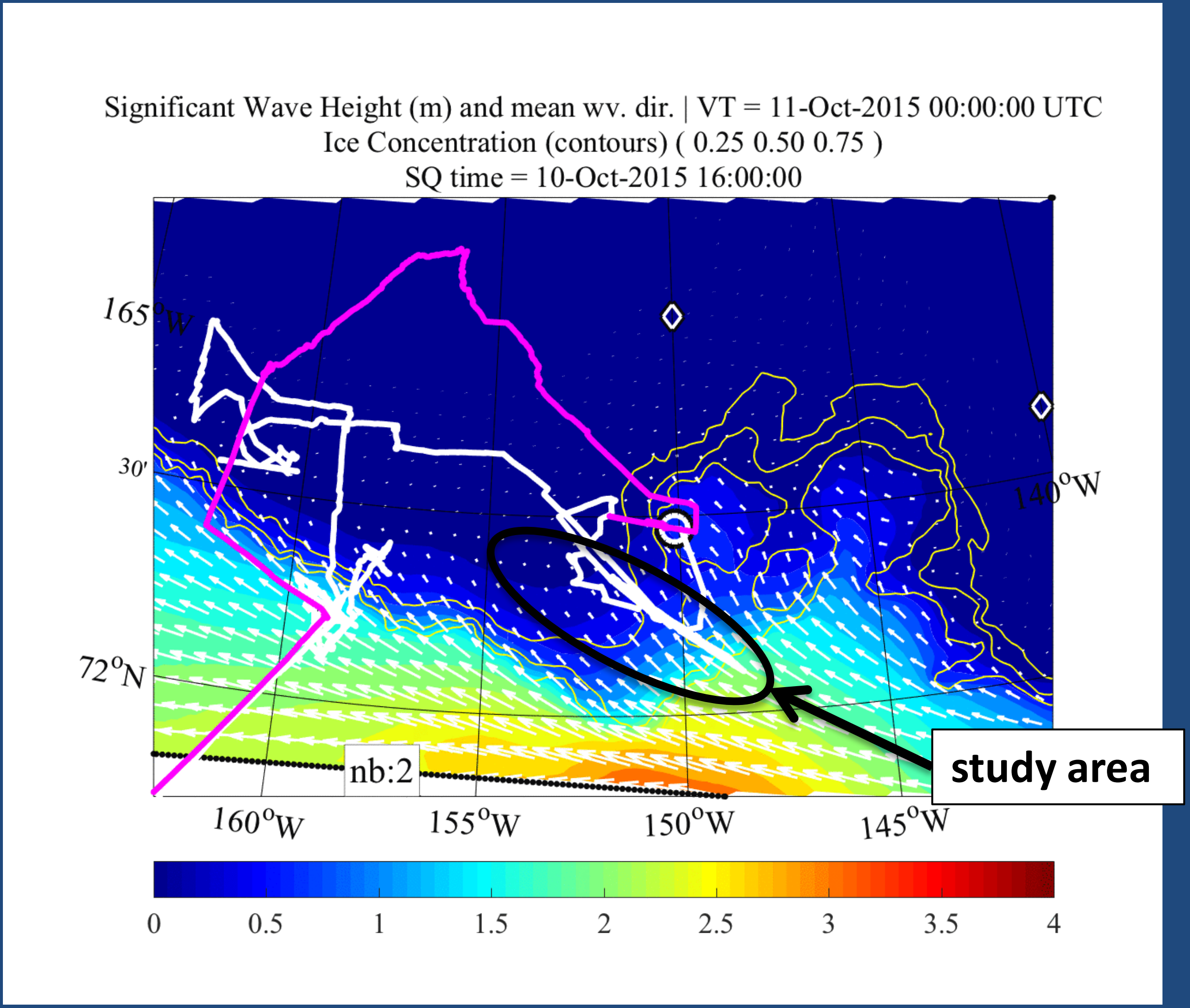
The “Sea State” DRI field experiment: Fall 2015

R/V Sikuliaq
- owned/operated by NSF, UNOLS, U. Alaska
- 261’
- First trials in 2014

6-week cruise (Sep 30 to Nov 10) with 13+ organizations in 26-person “science party”
- U. Washington
- U. Texas
- NPS
- WHOI
- U. Colorado
- Cambridge U.
- NRL-Stennis
- Clarkson U.
- JPL
- U. Miami
- NOAA (Boulder)



October 11-14 "waves in pancake ice" event



colors: significant wave height (meters)

arrows (mean wave direction)

contours: ice concentration (25, 50, 75%)

magenta/white: ship track

circle: ship position

October 11-14 “waves in pancake ice” event

Video made Oct 11, 1200 LT (2000Z) (wave experiment “WA3” covered in Rogers et al. 2016)

Spectral Description of Conservation of Energy used in WAVEWATCH-III® model

Governing equation: $$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c} N = \frac{S}{\sigma}$$

Primary source/sink terms in deep water: $$S = S_{in} + S_{ds} + S_{nl4}$$

c = propagation speed
k = wave number
σ = relative radial wave frequency
Θ = wave direction

$$S_{ds} = S_{br} + S_{bot} + \underbrace{S_{ice}}_{\text{new (relatively)}}$$

$$N = N(k, \theta, \vec{x}, t)$$ [spectral density of wave action, the variable that is being solved for]

$$S = S(k, \theta, \vec{x}, t)$$ [spectral description of source/sink terms]

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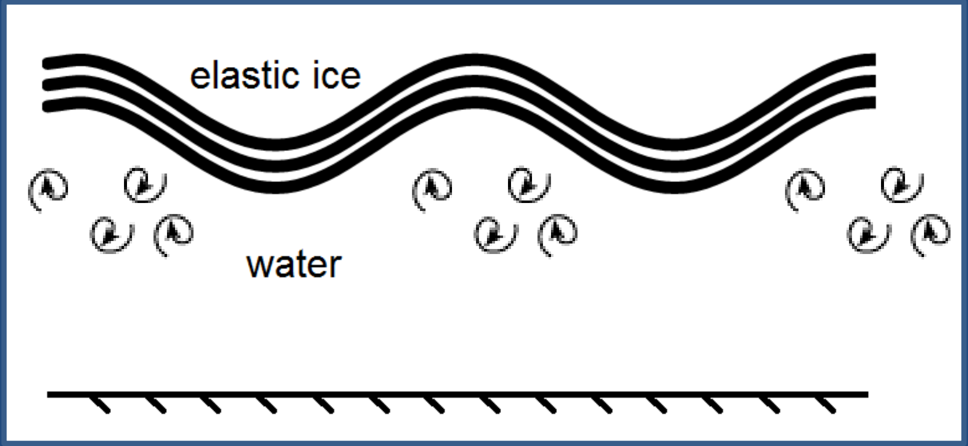
Ice physics options in WaveWatch3

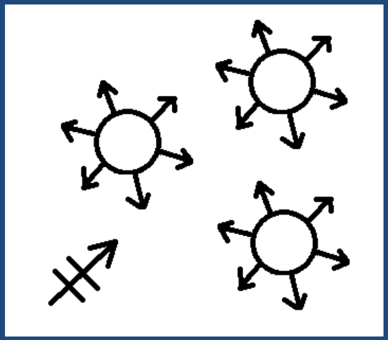
1. Turbulence-under ice theory

Elastic layer, dissipation caused by turbulence at ice-water interface



2. Discrete floe theory

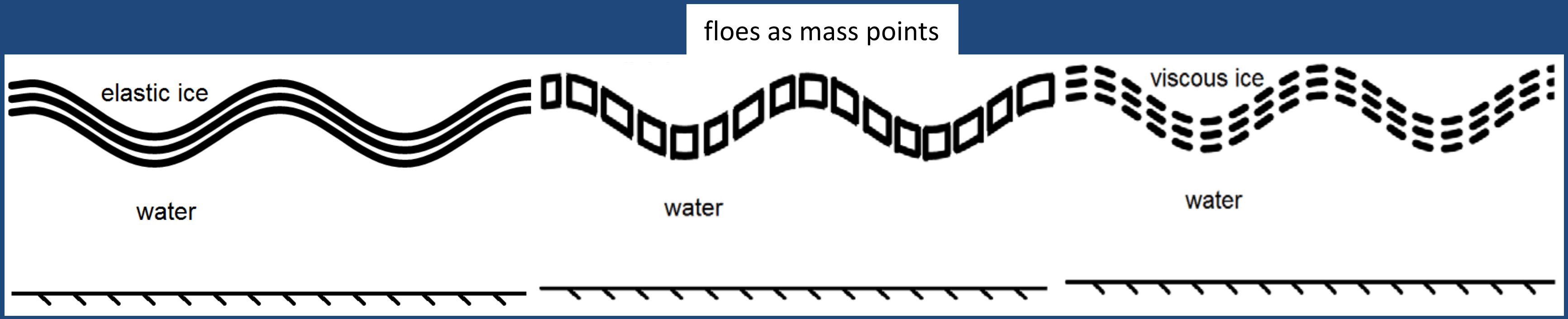
Each floe scatters wave to reduce the forward propagating energy



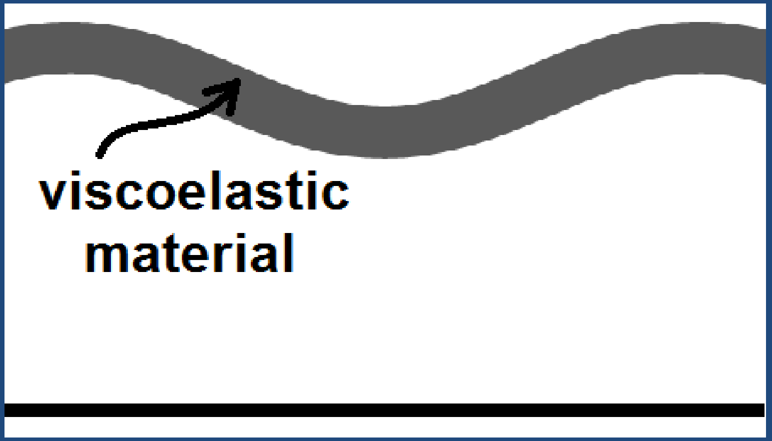
Ice physics options in WaveWatch3

3. Continuum theory

Thin elastic plate | Disjointed mass points | Viscous layer



- Linear viscoelastic
- Consists of rheological parameters, incl. viscosity ν and shear modulus G



H_s validation example

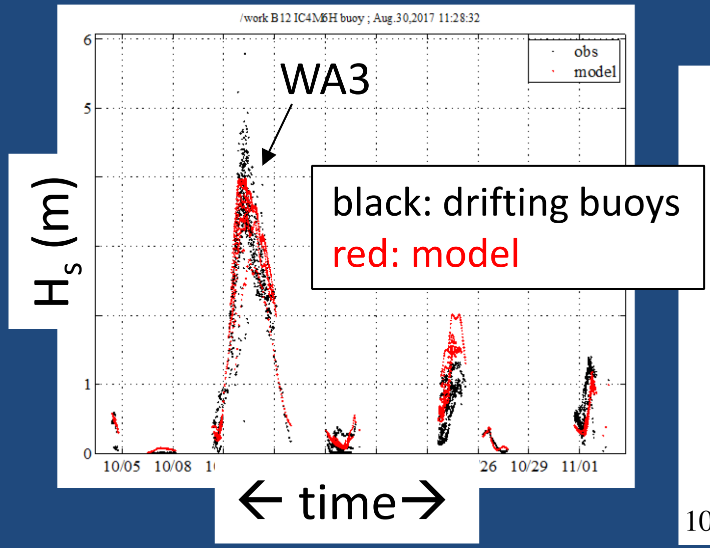
one of several models validated: parametric S_{ice}

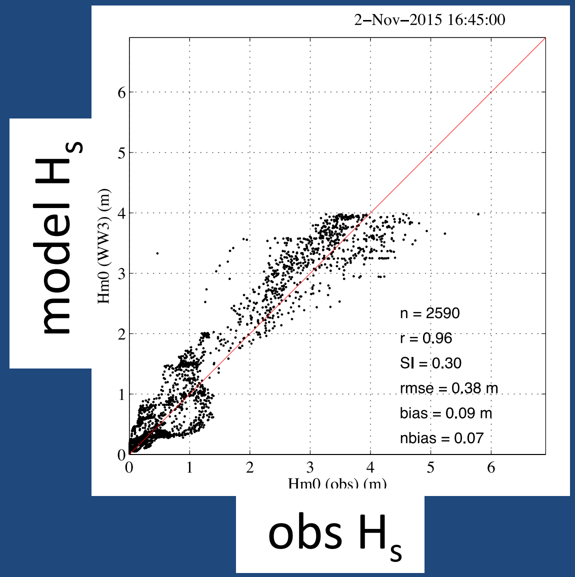
Upper left: H_s time series for entire cruise, model vs. obs

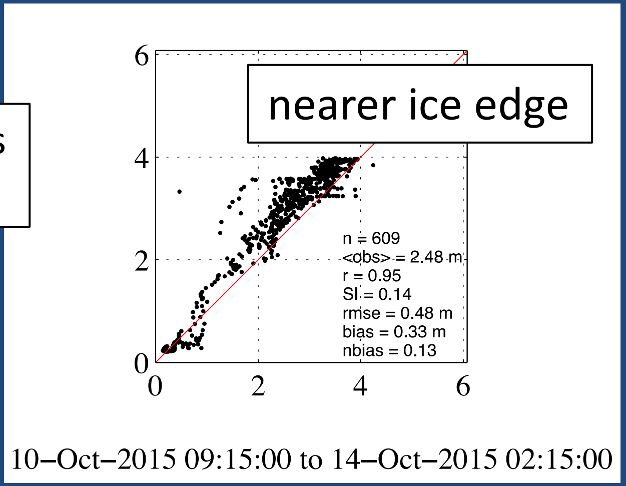
Lower left: H_s scatter plot for entire cruise, model vs. obs

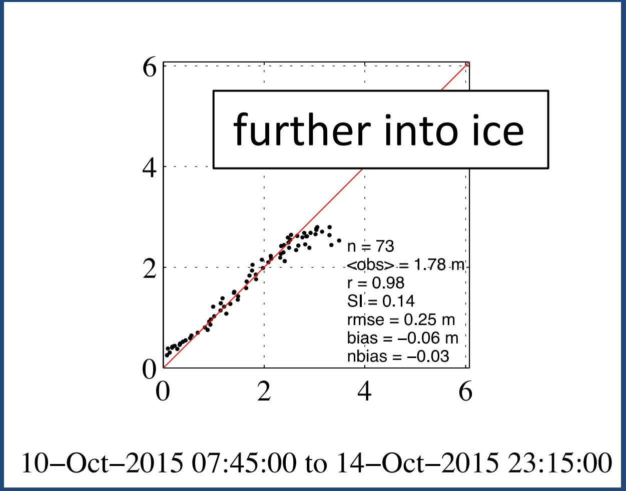
Upper right: H_s time series for wave array #3 (WA3), model vs. "SWIFT buoy" obs

Lower right: H_s scatter plot for WA3, model vs. "NIWA buoy" obs









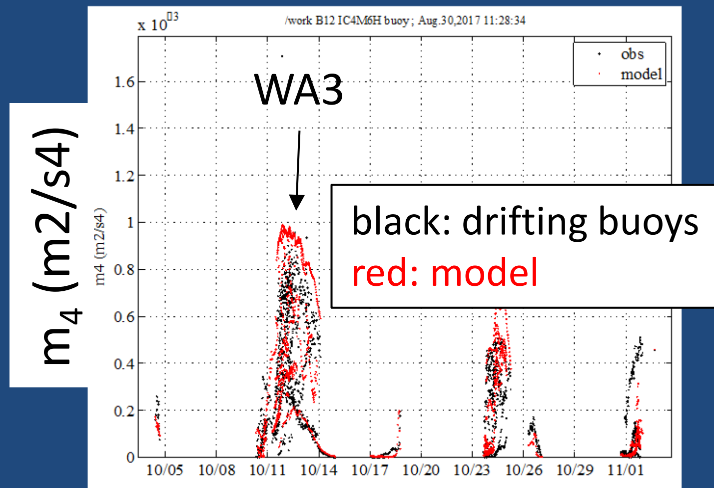
m_4 validation

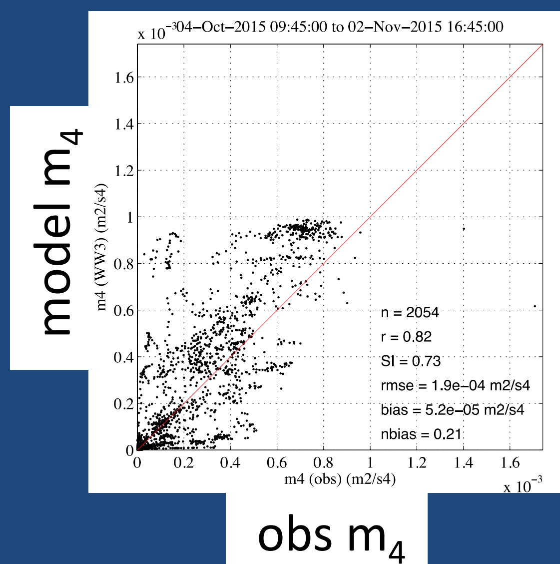
- m_4: 4th moment of 1d spectrum, E(f)
- ice strongly affects spectral tail
- m_4 is sensitive to changes in the spectral tail
- ergo: m_4 is a very useful parameter for wave model validation in ice

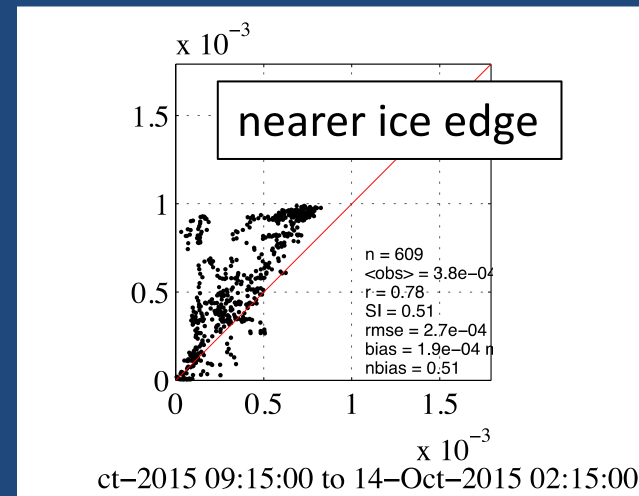
mean period (Tm,-1,0)
also evaluated for this study, but omitted from presentation

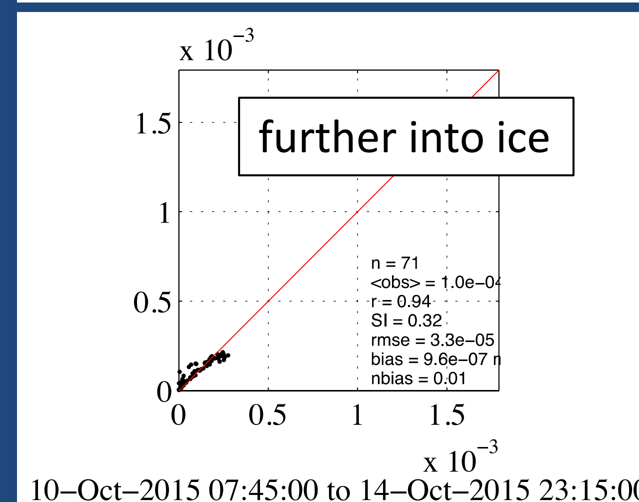
m_4 validation

<u>Upper left</u>: m_4 time series for entire cruise, model vs. obs
<u>Lower left</u>: m_4 scatter plot for entire cruise, model vs. obs
<u>Upper right</u>: m_4 time series for wave array #3 (WA3), model vs. ”SWIFT buoy” obs
<u>Lower right</u>: m_4 scatter plot for WA3, model vs. “NIWA buoy” obs









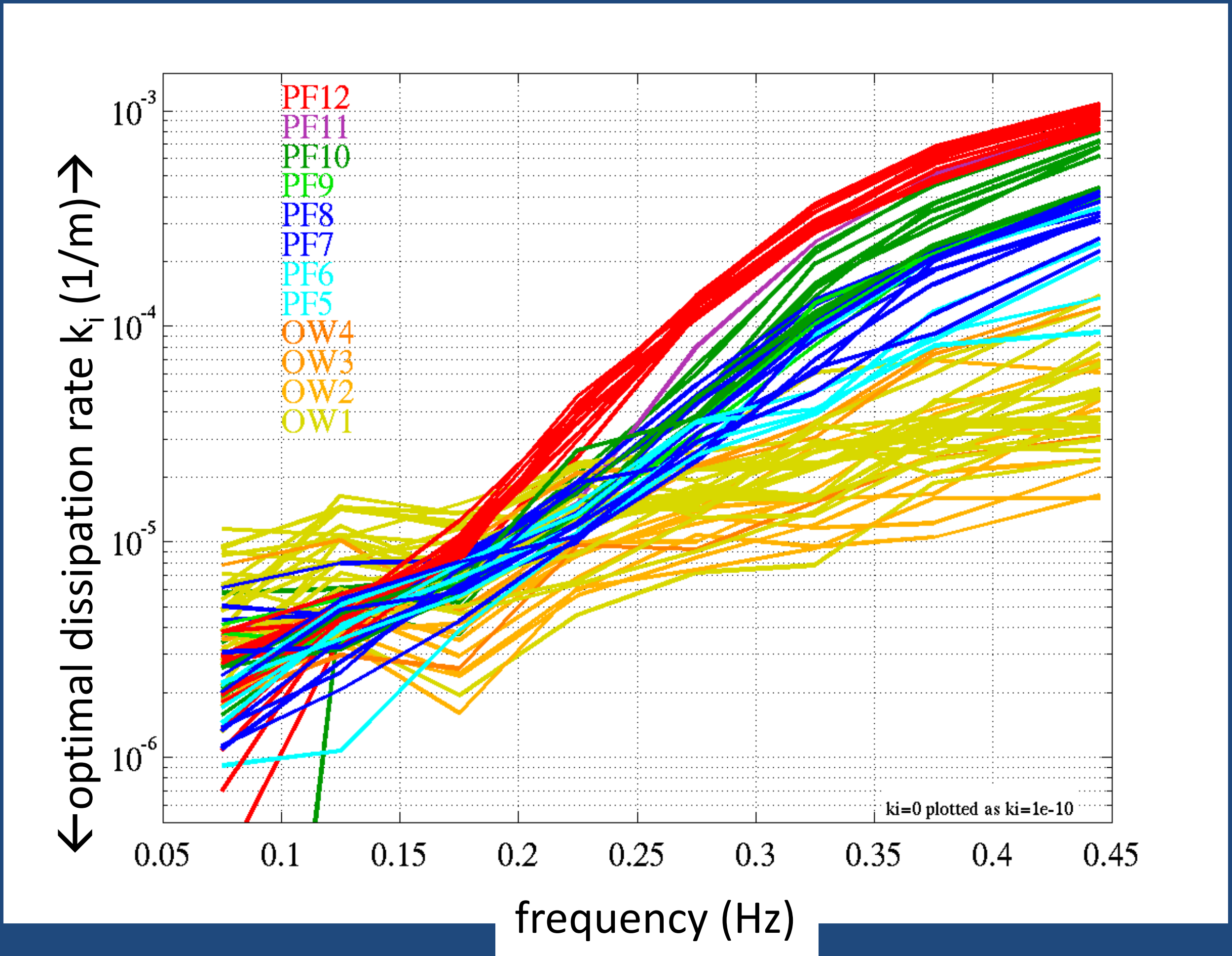
Validation summary

- H_s comparison: good skill, though not as good as one would expect in seas w/out ice
- m_4 comparison: bias is generally good, but skill is poor (credit and blame goes to S_{ice}, primarily)
- observation: a simple S_{ice} parameterization will typically be adequate for some ice types but not all (analog to bottom friction problem)
- conclusion: future effort should address variable ice type, even if empirical/parametric

WaveWatch3 / Buoy Photo / Buoy Spectra study

Dissipation of wave energy by sea ice

"Dissipation of wind waves by pancake and frazil ice in the autumn Beaufort Sea" (Rogers, Thomson, Shen, et al.), *JGR-Oceans 2016*

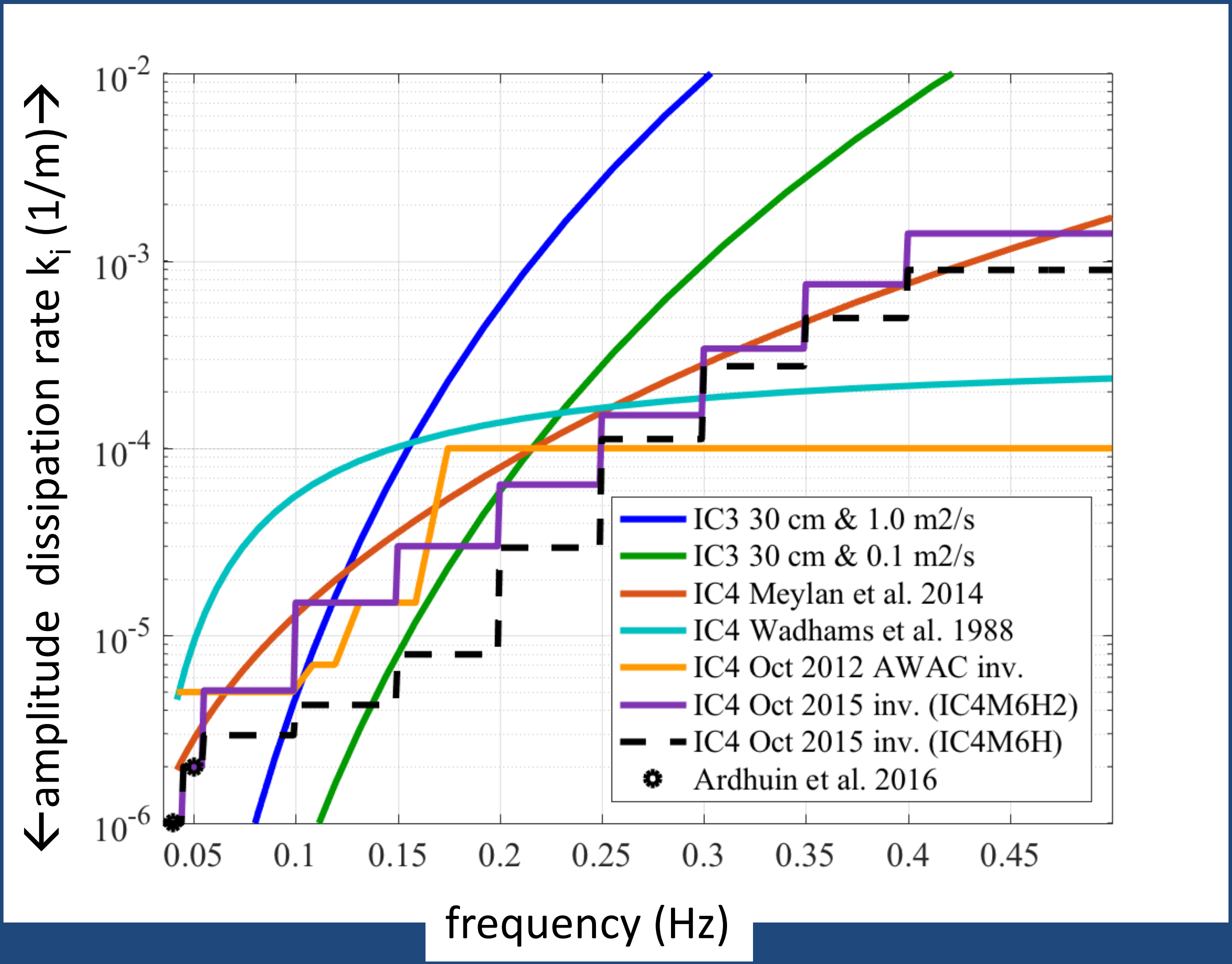


102 profiles, color coded by ice type as determined from APL buoy photos

Dissipation profiles correlate strongly with observed ice type.

These two metrics are derived by independent methods

Dissipation rate vs. frequency



Example profiles:

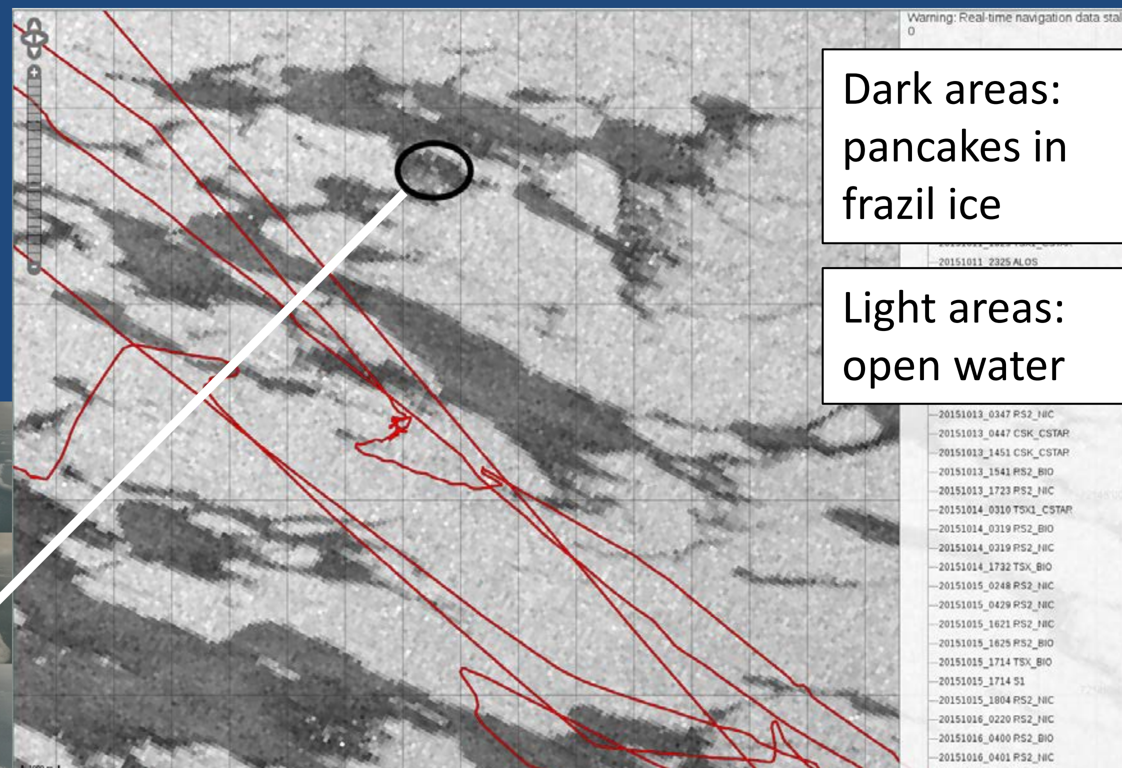
IC3: viscous model (VE model with elasticity set as zero)

IC4 & Ardhuin paper: parametric/empirical, or observed

Summary: viscosity model is not a good fit for dissipation from this experiment (purple and black lines), but strikingly good agreement with earlier observations, Meylan et al. (2014)

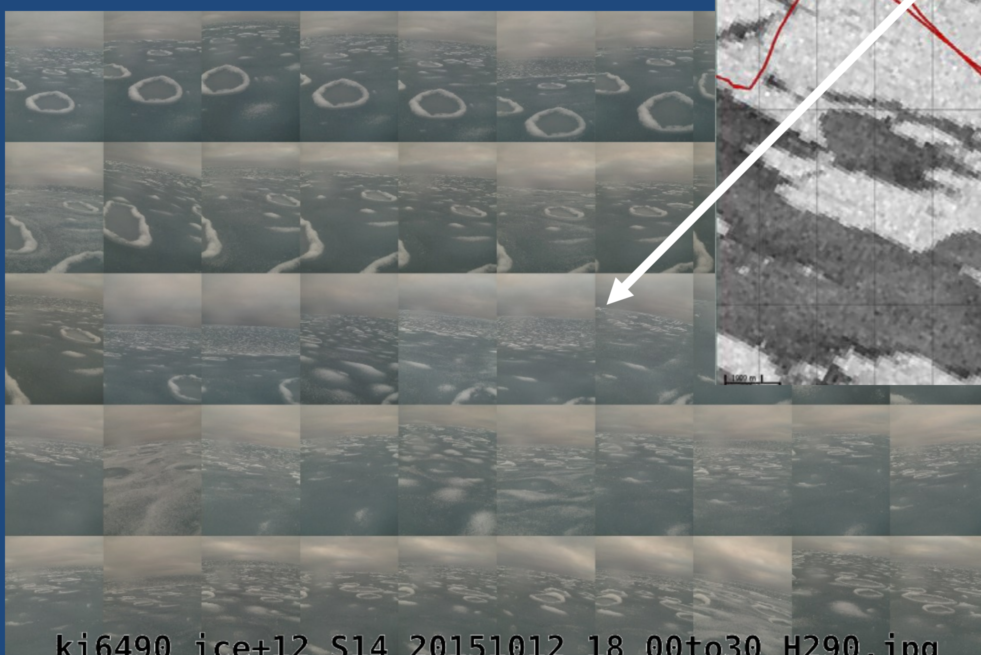
Buoy ice obs vs. SAR ice

SAR is good for determining presence of ice, but is not as useful for telling us the <u>type</u> of ice. In situ obs are best for this, obviously.



Dark areas: pancakes in frazil ice

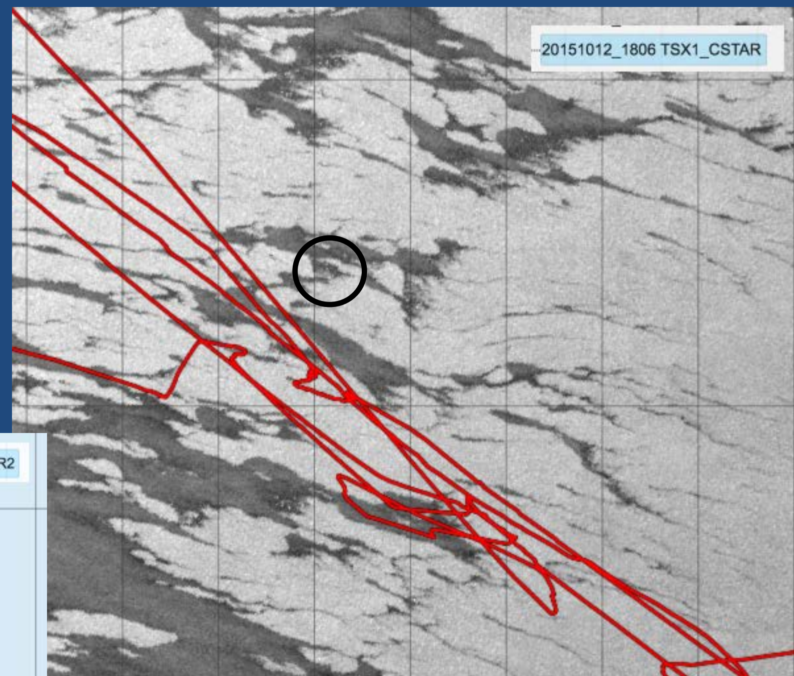
Light areas: open water



(Above SAR is from TerraSAR-X and CSTARS, one of several SAR products used during cruise)

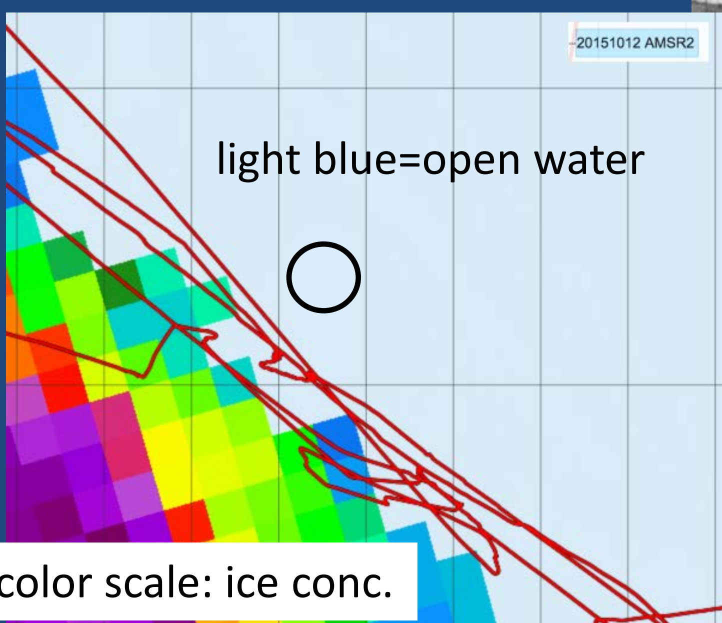
AMSR2 ice vs. SAR ice

AMSR2 (and other passive microwave) is better than SAR for providing regular coverage of entire Arctic, but it does not have the resolution of SAR, and can miss ice.



Dark areas: pancakes in frazil ice

Light areas: open water

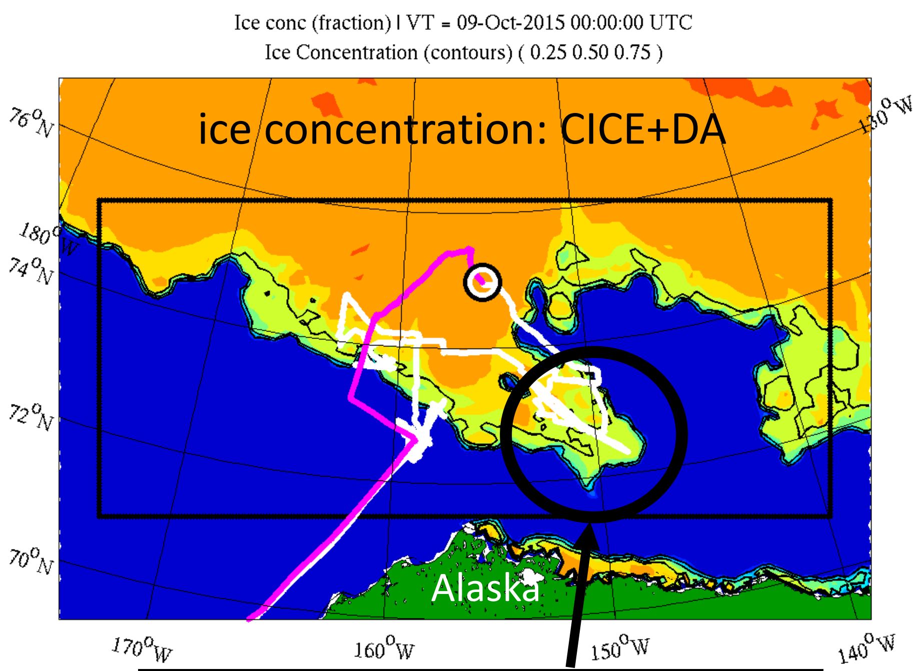


(Above SAR is from TerraSAR-X and CSTARS, one of several SAR products used during cruise)

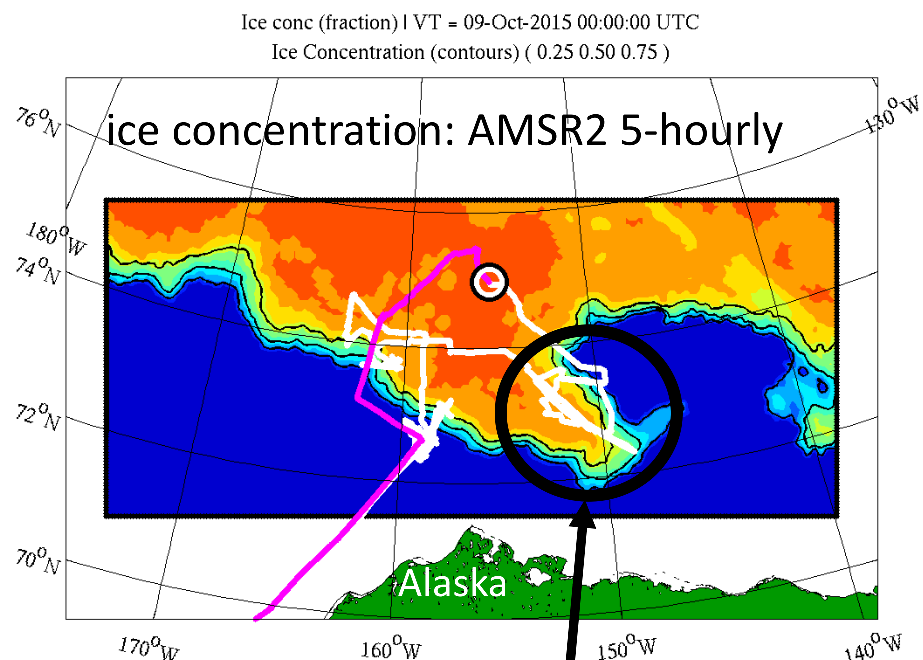
CICE+DA vs. AMSR2

CICE model is ingesting SAR info via DA, so should be superior: but fails due to assimilation of bad data (ice was not updated by ice analyst)

passive microwave, with high temporal resolution (5 hours, on average), tailored to requirements of regional wave model: derived from AMSR2 swath data



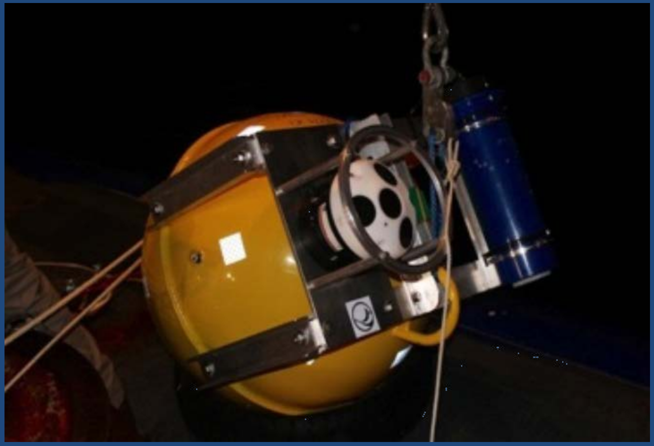
misses ice retreat October 12-14

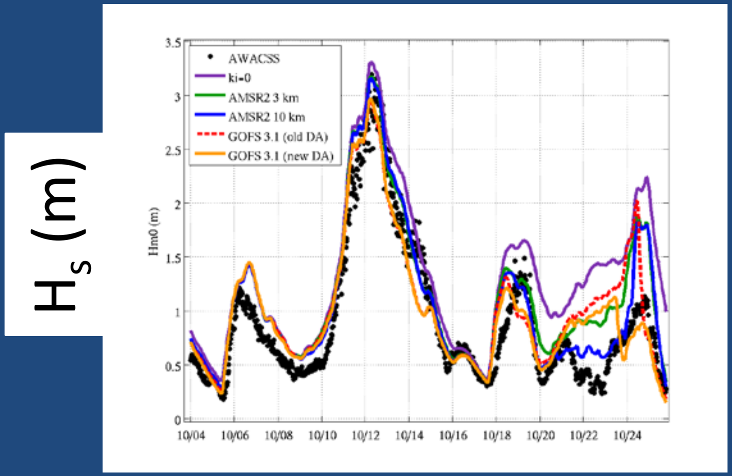


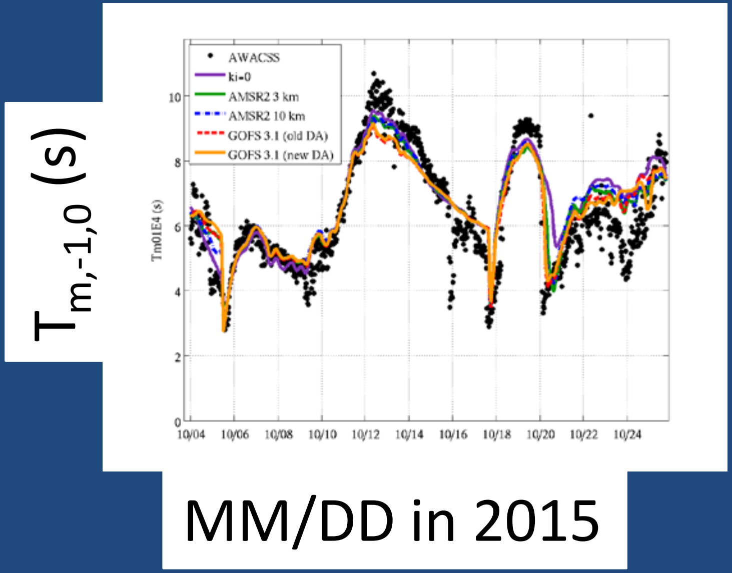
captures ice retreat October 12-14

Open-water validation: AWAC mooring

- Sub-surface buoy
- At 100 m isobath
- Open water for duration of deployment (Oct 3 to 26)
- Data processed by Madison Smith and Jim Thomson (APL/UW)

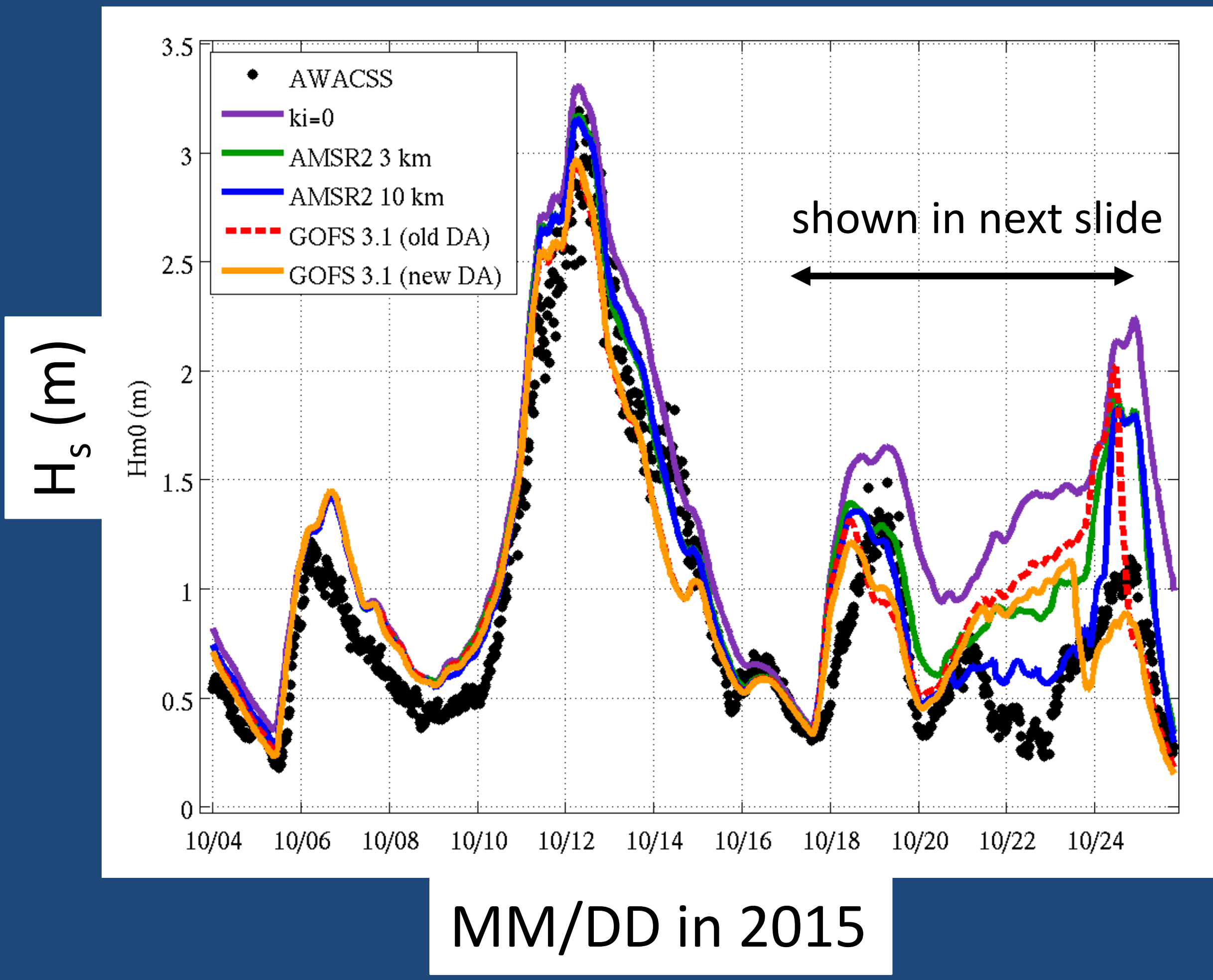






Open-water validation: AWAC mooring

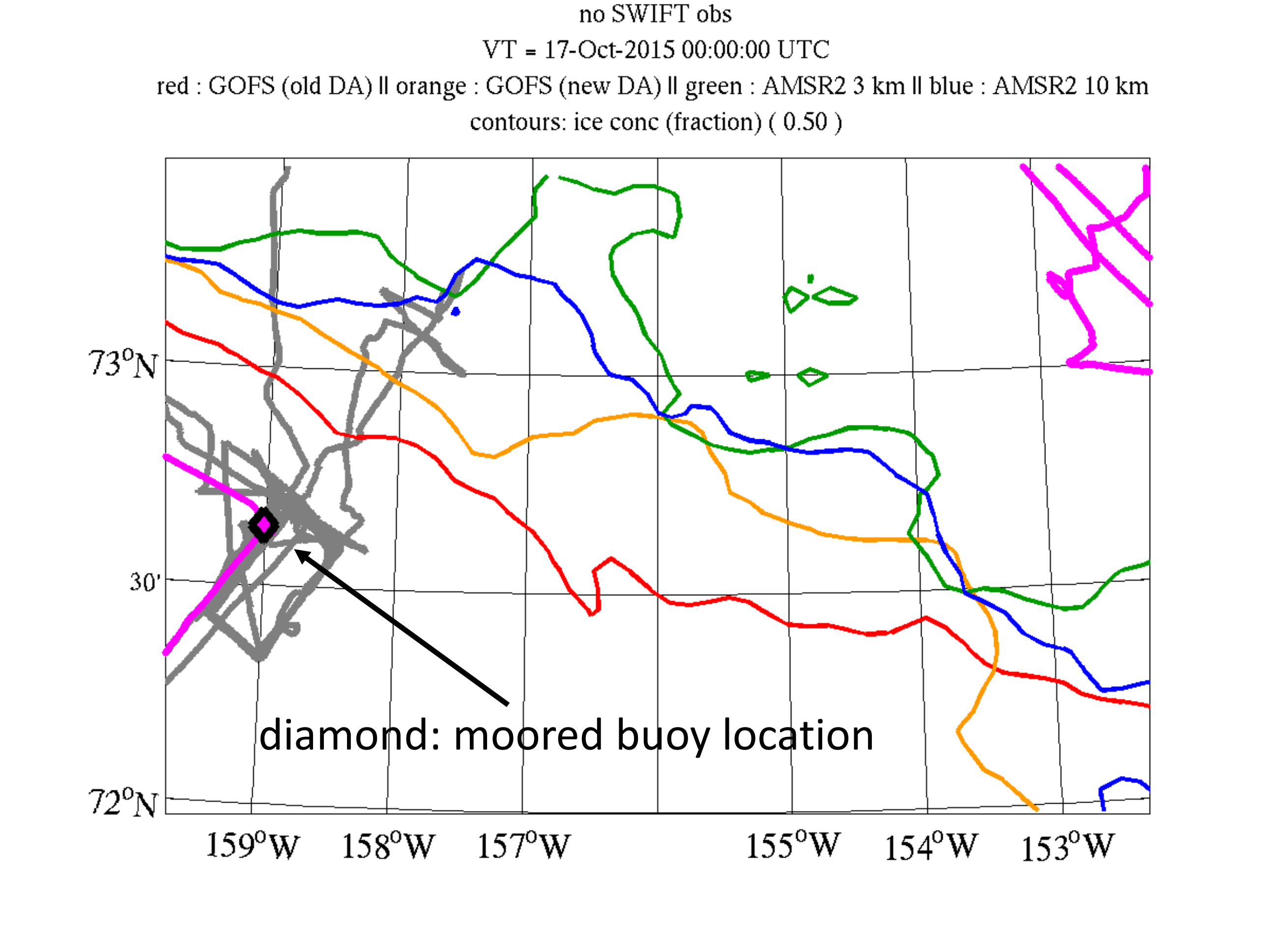
comparing WW3 with different forcing for ice concentration



- red: CICE nowcast
- orange: CICE analysis
- green: AMSR2 w/high spatial resolution
- blue: AMSR2 w/high temporal resolution

There is no ice at buoy. The ice forcing is still crucial, since it determines fetch available.

case of obliquely off-ice winds



- Black diamond: buoy location
- red contour: CICE nowcast
- orange contour: CICE analysis
- green contour: AMSR2 w/high spatial resolution
- blue contour: AMSR2 w/high temporal resolution

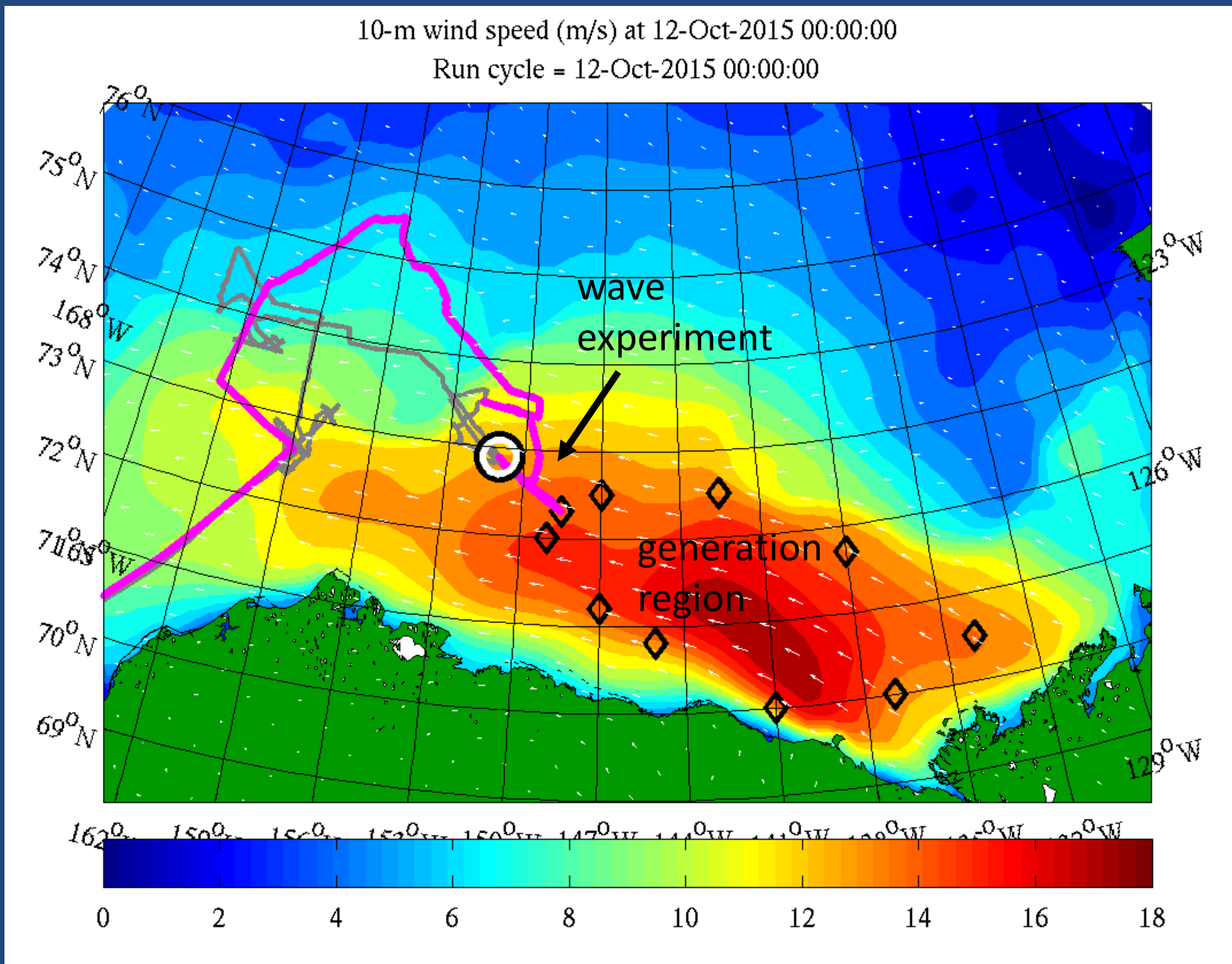
Significant variability between ice products: determines wave model skill for off-ice winds

Key points

- difficulty of forecast:
  - proximity to ice edge is most important
  - paradox: forecast for position outside ice (off-ice winds) can be more difficult than forecast for position inside ice (on-ice winds)
- accuracy of ice edge crucial (esp. if near edge)
- temporal resolution of ice product often crucial
- AMSR2 with high temporal resolution was overall best ice product for this cruise, though not 100% of the time
- recommendation: H_s and m_4 for primary evaluation of the dissipative S_{ice} formulations
- required: more info in gridded products re: ice type for use in S_{ice} parameterizations
  - but we need to take measures to limit impact of analyst error
- inferred dissipation vs. freq. profiles: excellent agreement with recent study in Antarctica (Meylan et al. 2014)

Extra slides

Evaluation of met. forcing: forecast skill

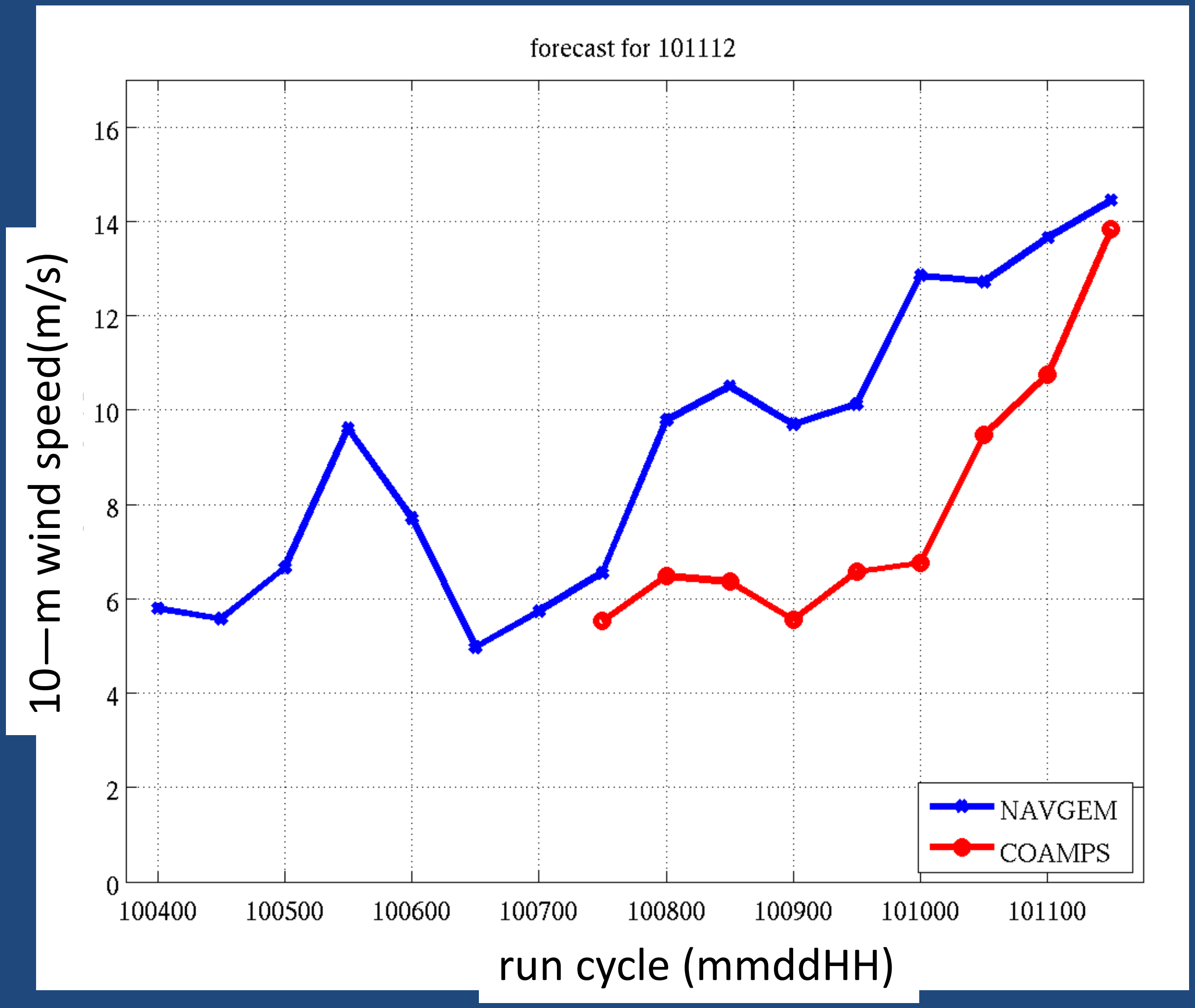


Colors and arrows: 10-m winds from nowcast/analysis

Black diamonds indicate generation region for Wave Array #3: polygon used for evaluation in next slide

gray/magenta: ship track
circle: ship location

Evaluation of met. forcing: forecast skill



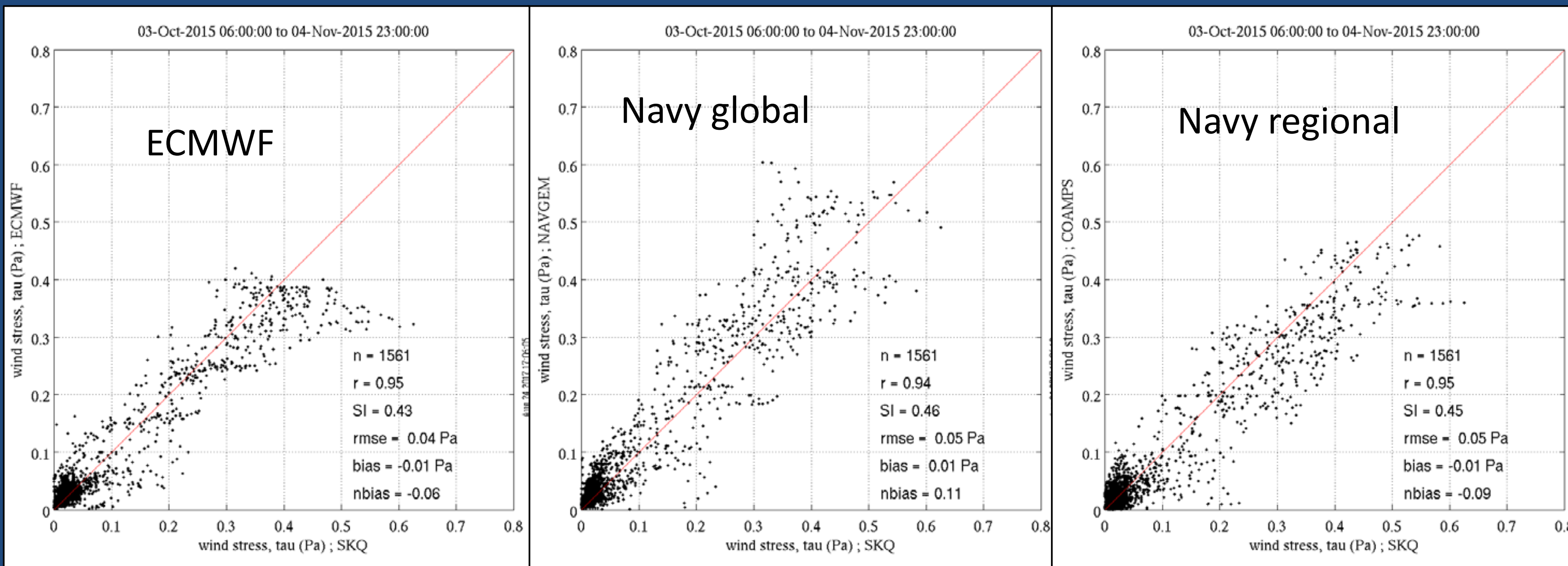
blue: Navy global met model

red: Navy regional met model

summary: the higher resolution product actually has less forecast skill

Not shown: ECMWF met model predicted wind event 1-2 days earlier than Navy model

Evaluation of met. forcing: nowcast skill



instead of U_{10}, approximate wind speed stress (via empirical formula) shown here to emphasize importance of higher winds, in context wave model

summary: Navy global model best captures highest winds in experiment area (ship location)

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Nested grid system used for forecasting from R/V Sikuliaq and hindcasting

ARCTIC SEA STATE 2015 · OFFICE OF NAVAL RESEARCH

Outer WW3 grid

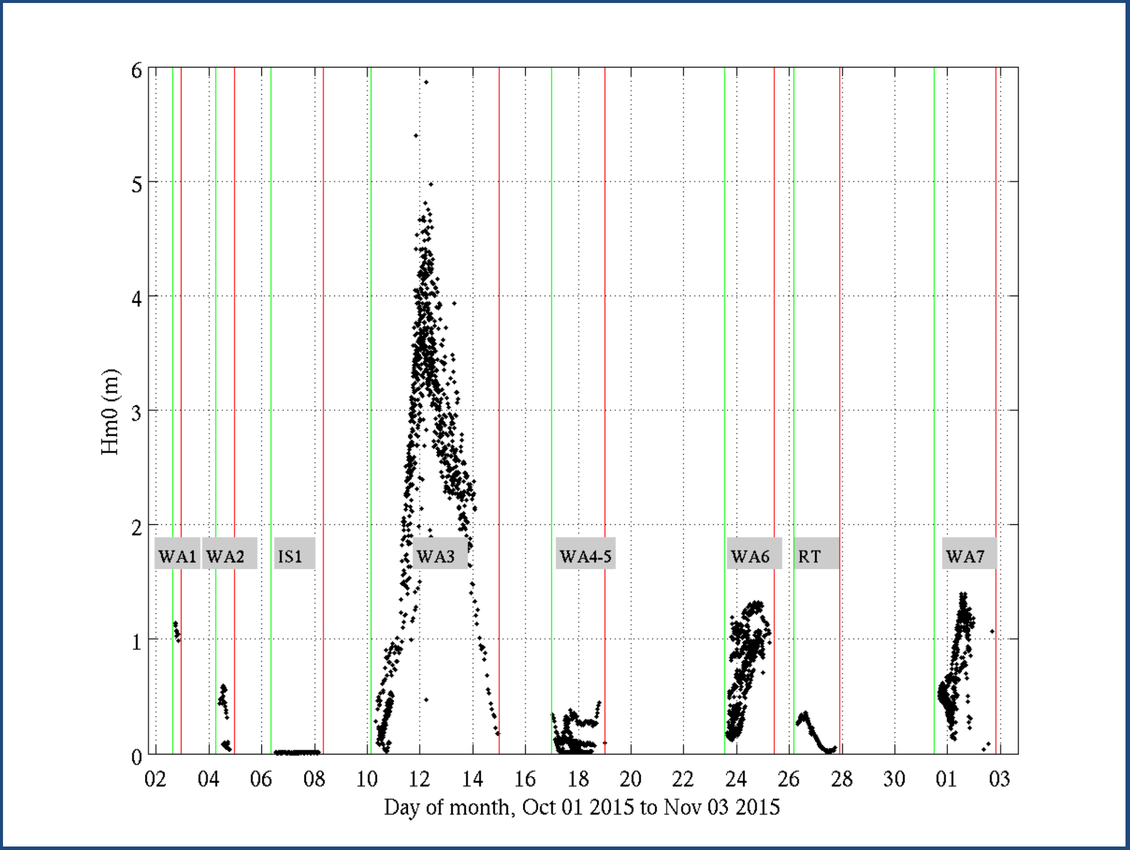
- 15 km Grid Resolution
  - 223x286x31x36
  - Polar Stereographic projection
- FNMOC forcing
  - 2/day. 12Z forcing ready ~noon SKQ time
  - Winds: NAVGEM (0.5 deg)
  - Ice concentration: SSMI analysis (0.5 deg)
- Crude ice physics
- 34 run cycles during cruise

Inner WW3 grid

- **10 km Grid Resolution**
  - **231x121x31x36**
  - **Irregular grid based on great circles**
- **Ice concentration, ice thickness: NRL 2 km CICE**
  - **1/day : 0Z file available ~0300 SKQ time**
- **New physics for wave damping by ice (visco-elastic model)**
- **Otherwise similar to outer grid**
- **24 run cycles during cruise**

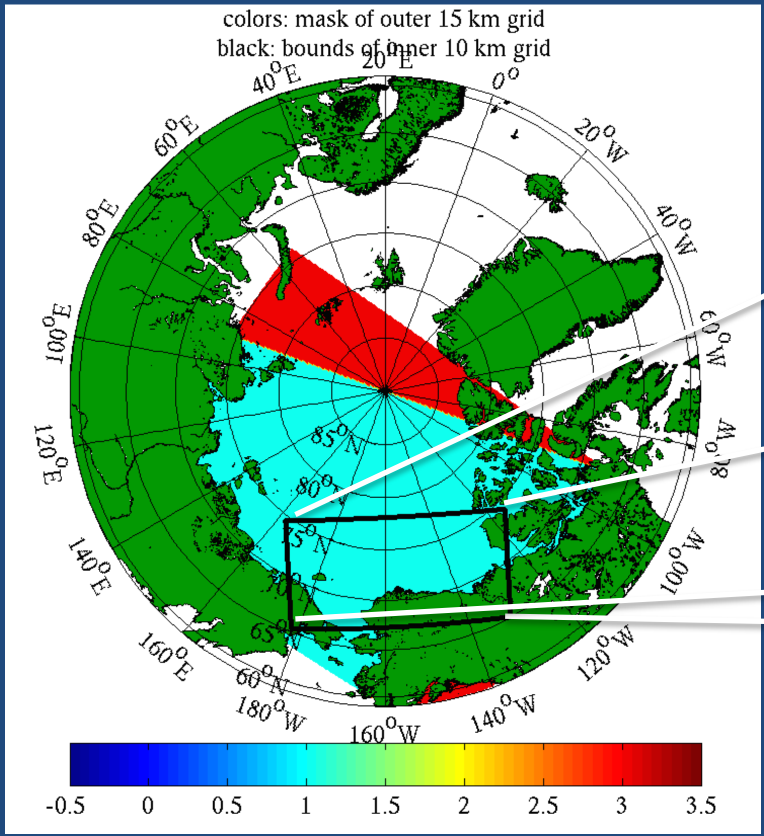
On-ship wave forecasting

- Laptop (late model Linux/MacOS): 4 cores
- 2 grids (15 km and 10 km, nested)
- 6 day forecast: ~ 45 minutes per grid
- Run 0 to 2 times daily (most often 1/day)
- Briefed at daily POD meetings, following Ola's weather brief
- Supplemented by shoreside wave forecasts
  - ECMWF (entire cruise)
  - NRL-Stennis 5 km WW3 (until Oct 10)

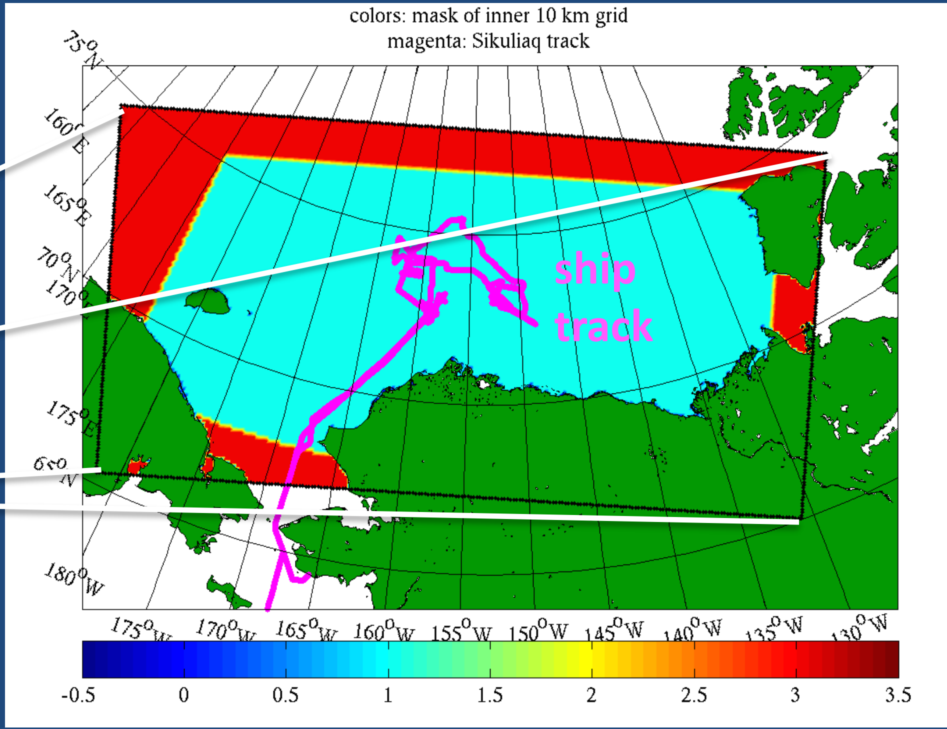

6
5
4
3
2
1
0
Hm0 (m)
WA1
WA2
IS1
WA3
WA4-5
WA6
RT
WA7
02 04 06 08 10 12 14 16 18 20 22 24 26 28 30 01 03
Day of month, Oct 01 2015 to Nov 03 2015

Nested grid system used for forecasting from R/V Sikuliaq and hindcasting

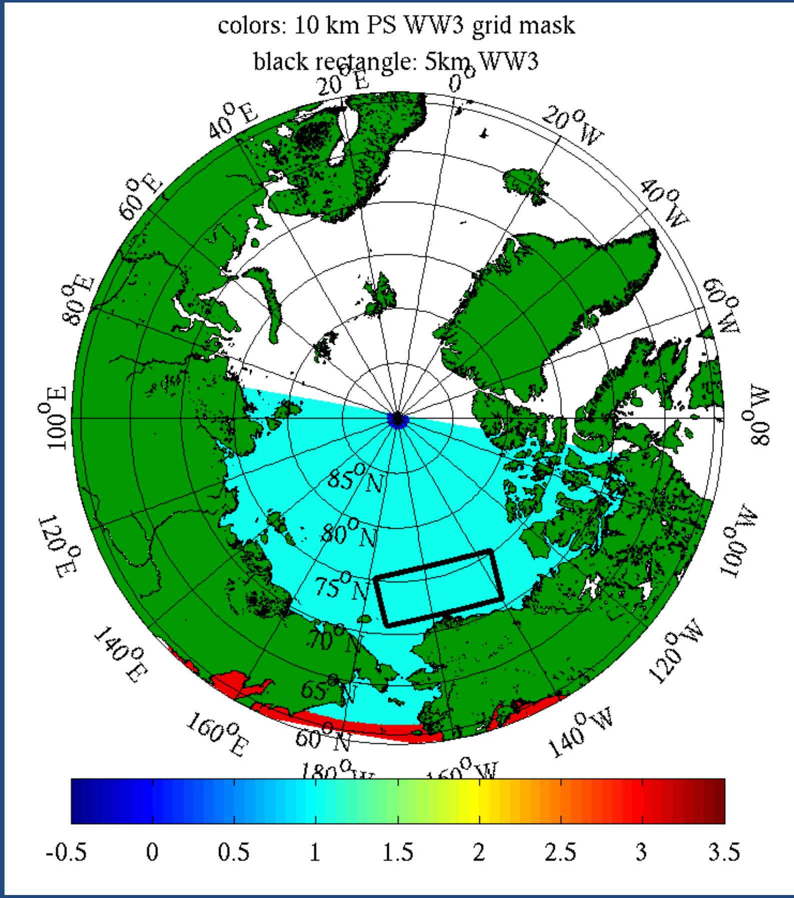
15 km outer grid



10 km inner grid using new ice physics and input from NRL 2 km CICE model



New nested grid system used for hindcasting on faster machines



10 km outer grid
forced with 24-hourly AMSR2 ice concentration

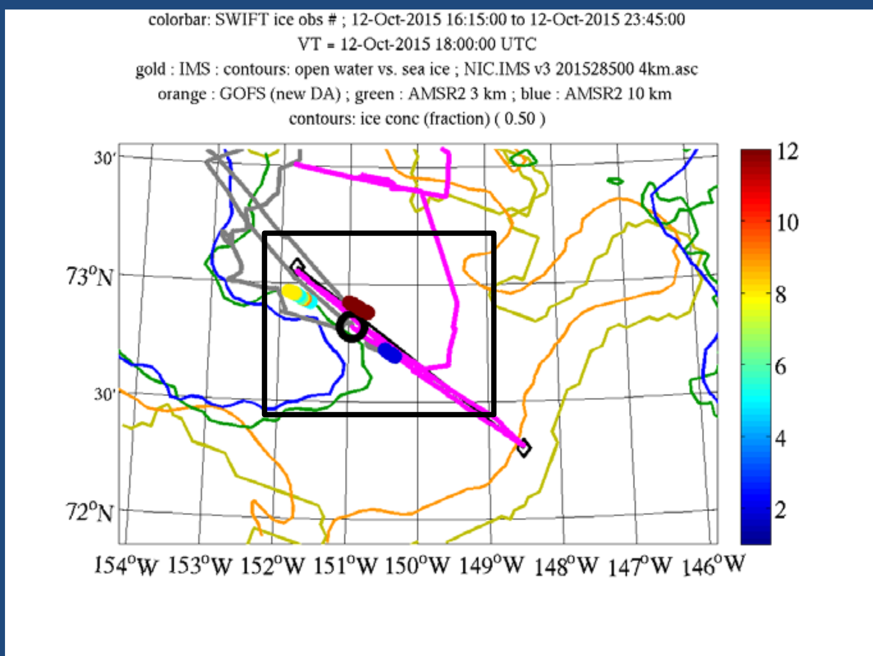
5 km inner grid
forced with ~5-hourly AMSR2 ice concentration

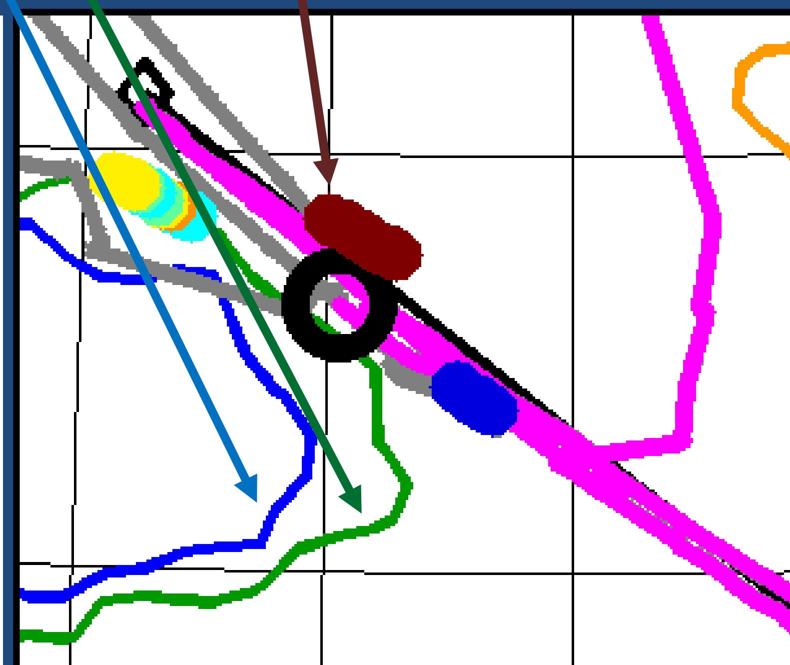
Buoy ice obs vs. AMRS2 ice

AMSR2 is provides regular coverage of entire Arctic, but it can miss ice, e.g. ice seen by buoy camera

AMSR2 contours

buoy track (garnet color indicates heavy ice)





accuracy of forcing

- scenario: ice edge in gridded products were not accurate enough for use in WW3, off-ice wind case)
- workaround: estimated fetch and wind speed and apply in parametric wave model

Applying fetch with parametric wave model

Hs predicted was within 10 cm of buoy obs!

~~NAVGEM 180 hrs = 7.5 days~~

$$X^* = \frac{gX}{U_*^2}$$

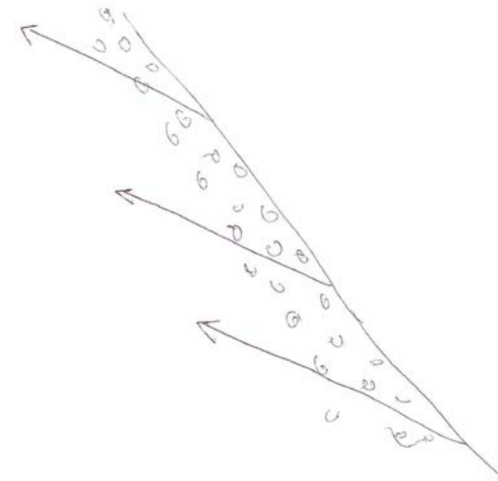
$$E^* = \frac{g^2 E}{U_*^4}$$

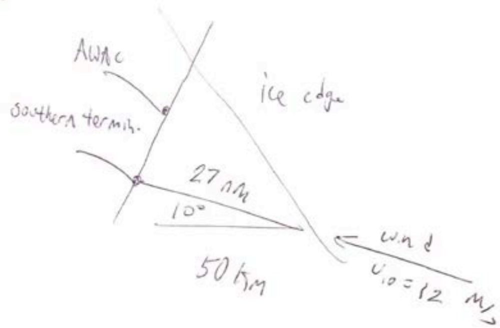
$$E^* = 6.5e^{-4} X_*^{0.9}$$

$$f_r^* = 3.08 X_*^{-.27}$$

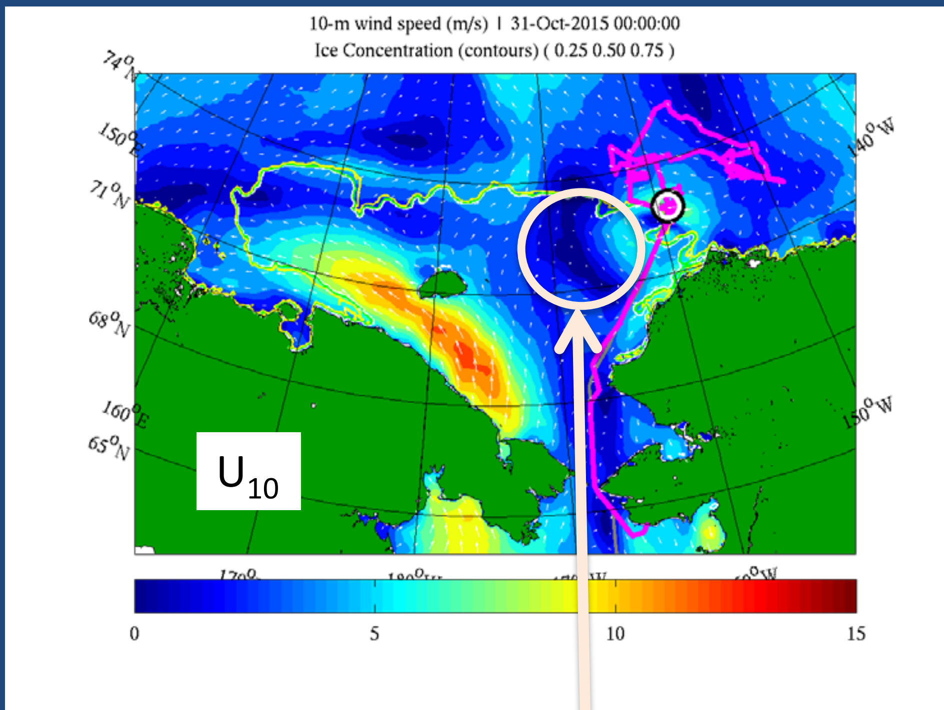
$H_{m0} = 1.76$ m

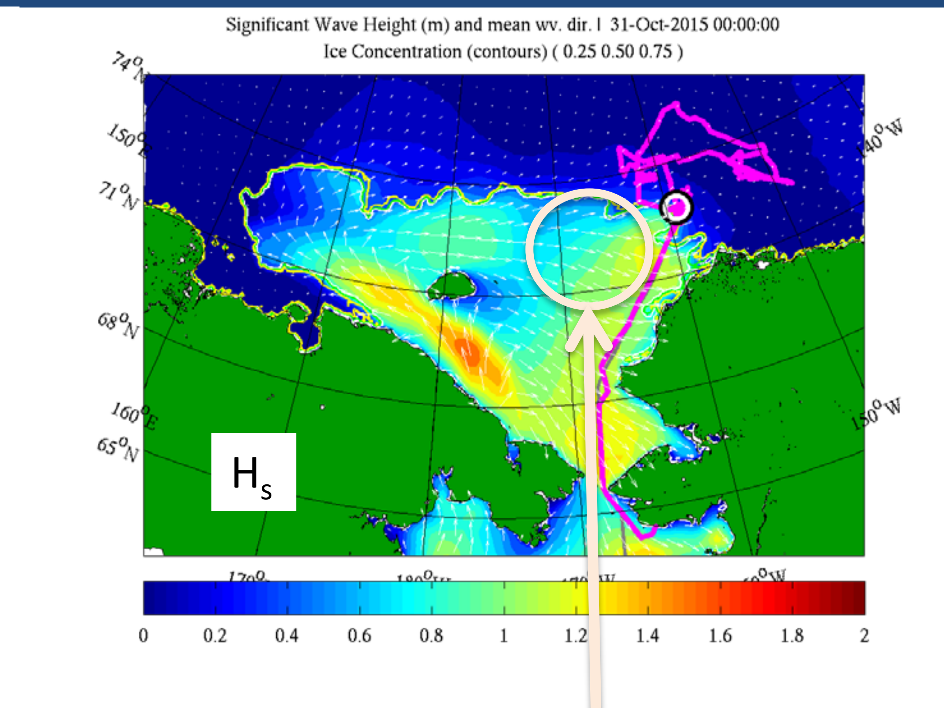
$T_p = 4.8$ s





Swells in small basins
(Chukchi/Beaufort/Western Arctic)



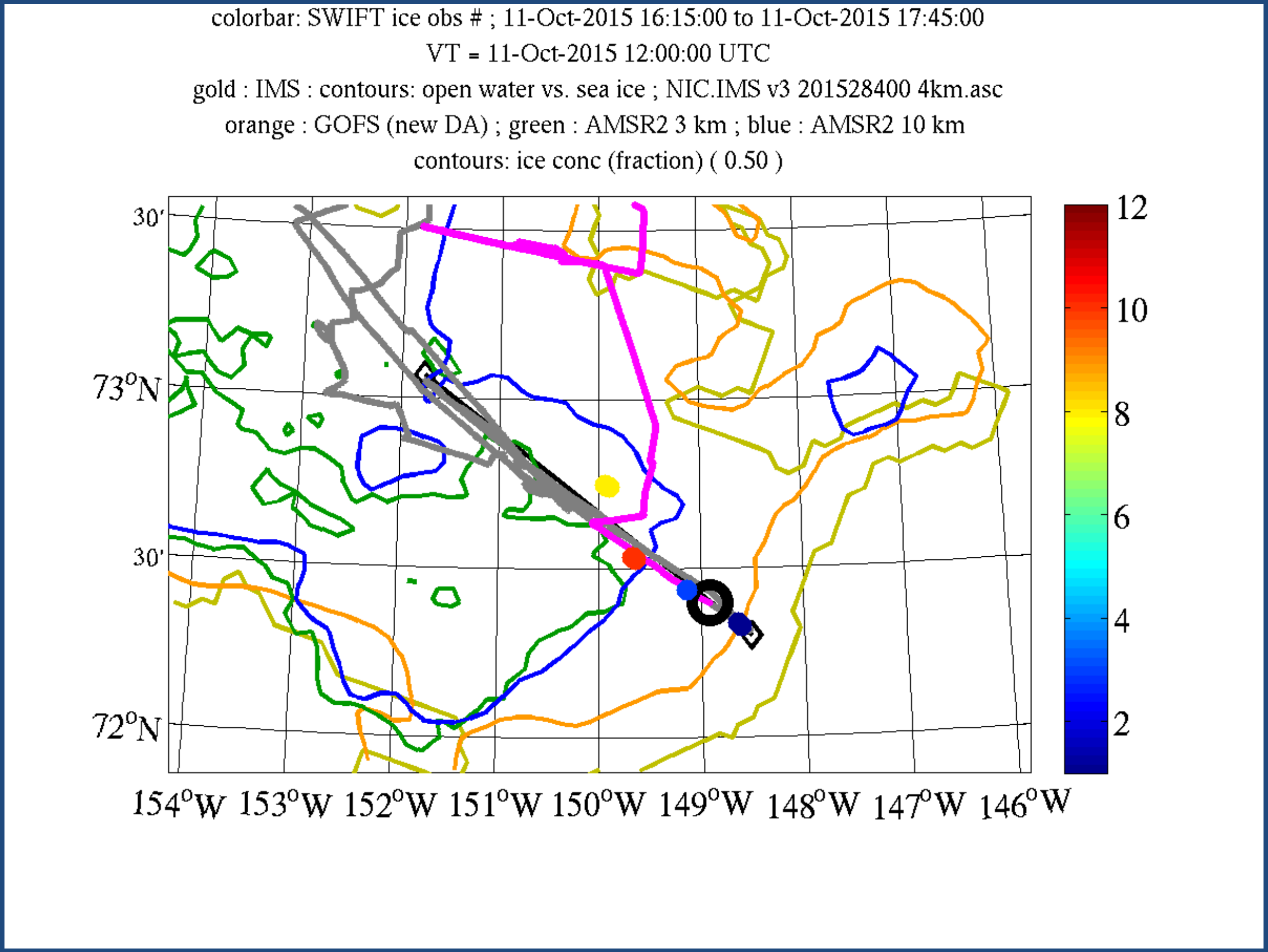


low winds

substantial waves

This implies a requirement for a numerical wave model.

ice concentration: corroboration from buoys



colored dots: buoy ice thickness (qualitative scale of 1 to 12)

- gold: DA input
- orange: CICE
- green: AMSR2 (high spatial resolution)
- blue: AMSR2 (high temporal resolution)

magenta: ship track

Assertion: high temporal resolution may be even more important than high spatial resolution

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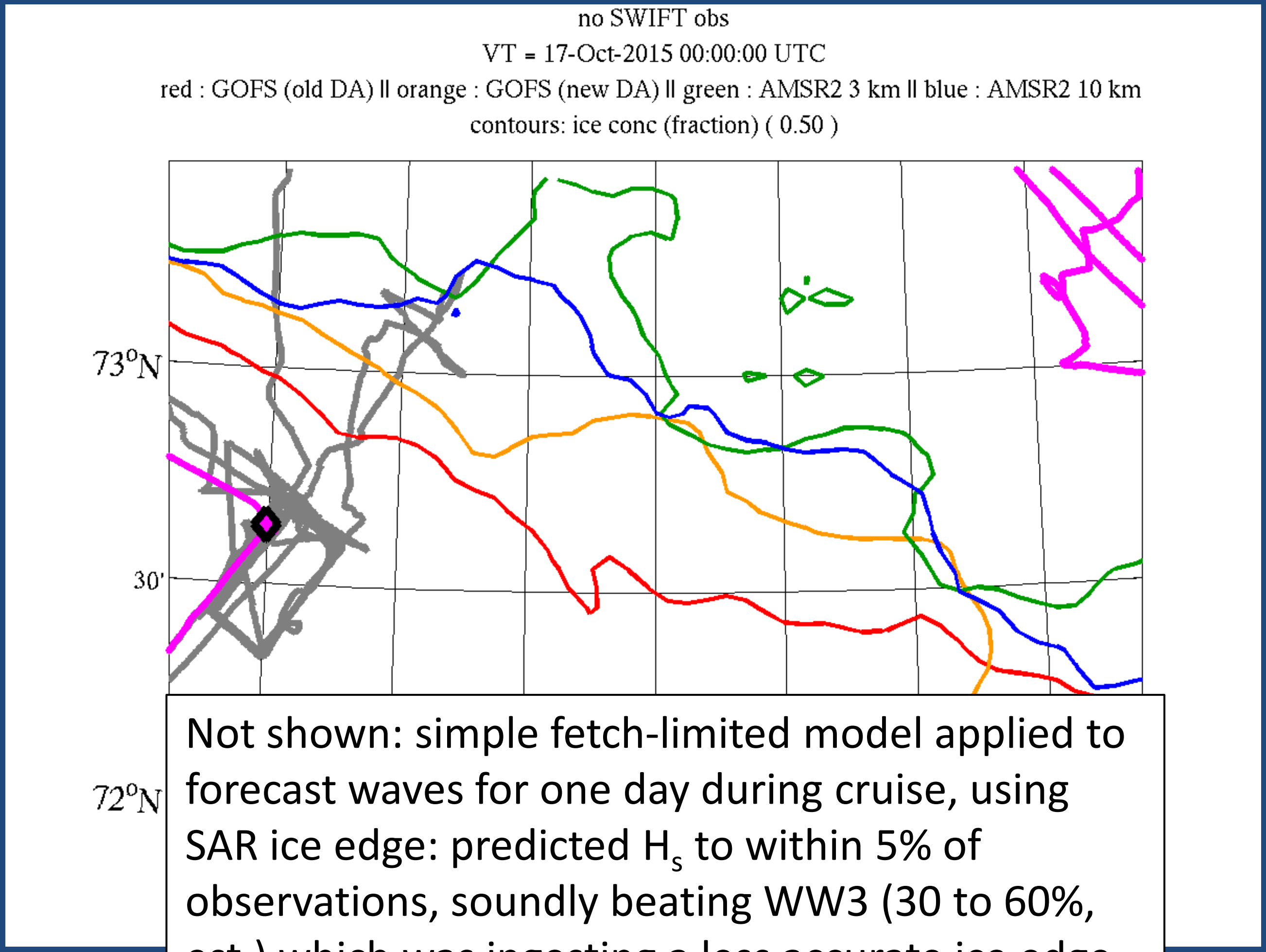
Ice physics options in WaveWatch3

- IC0: (pre-existing) ice as land or quasi-land, no S_{ice}
- IC1: simple S_{ice} dissipation, no variation with frequency
- IC2: thin elastic plate, with turbulence at ice-water interface
- IC3: visco-elastic (VE) layer (Wang and Shen)
- IC4: parametric and empirical S_{ice}
- IC5: another VE model (extended Fox and Squire)
- IS2: scattering (Meylan and Masson) (conservative)

case of obliquely off-ice winds



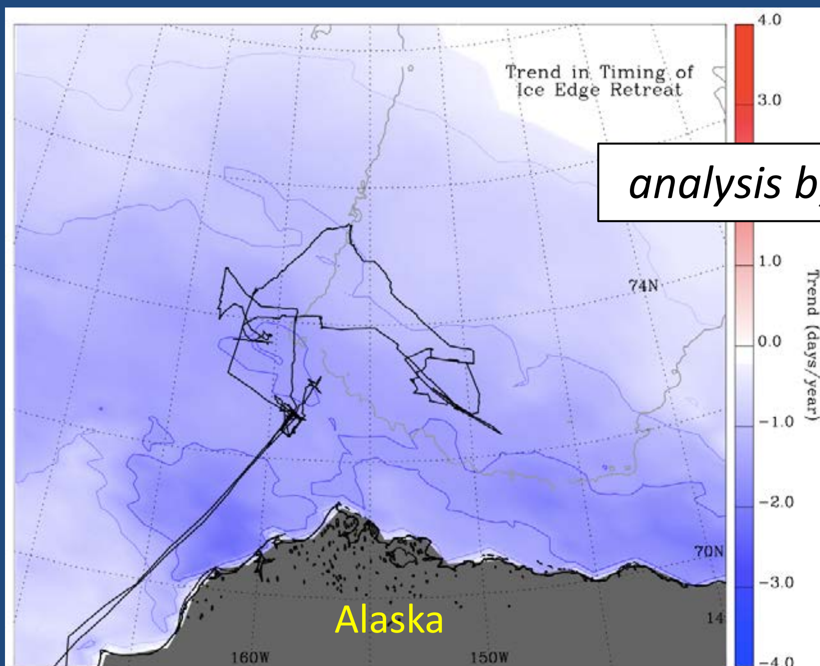
Not shown: simple fetch-limited model applied to forecast waves for one day during cruise, using SAR ice edge: predicted H_s to within 5% of observations, soundly beating WW3 (30 to 60%, est.) which was ingesting a less accurate ice edge

- Black diamond: buoy location
- red contour: CICE nowcast
- orange contour: CICE analysis
- green contour: AMSR2 w/high spatial resolution
- blue contour: AMSR2 w/high temporal resolution

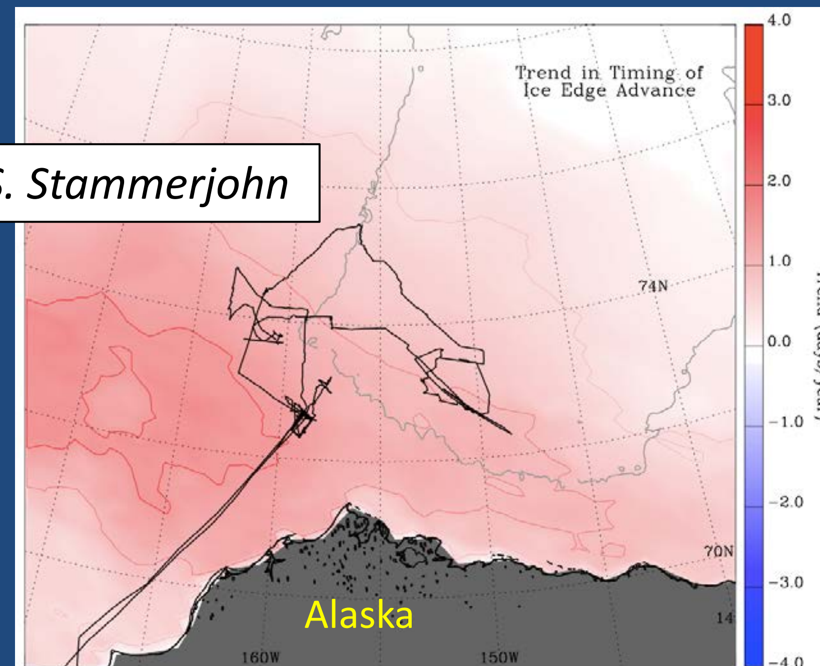
Significant variability between ice products: determines wave model skill for off-ice winds

Regional Sea Ice Trends 1975-2015

Trend in Spring Retreat (51 days earlier)



Trend in Autumn Advance (44 days later)



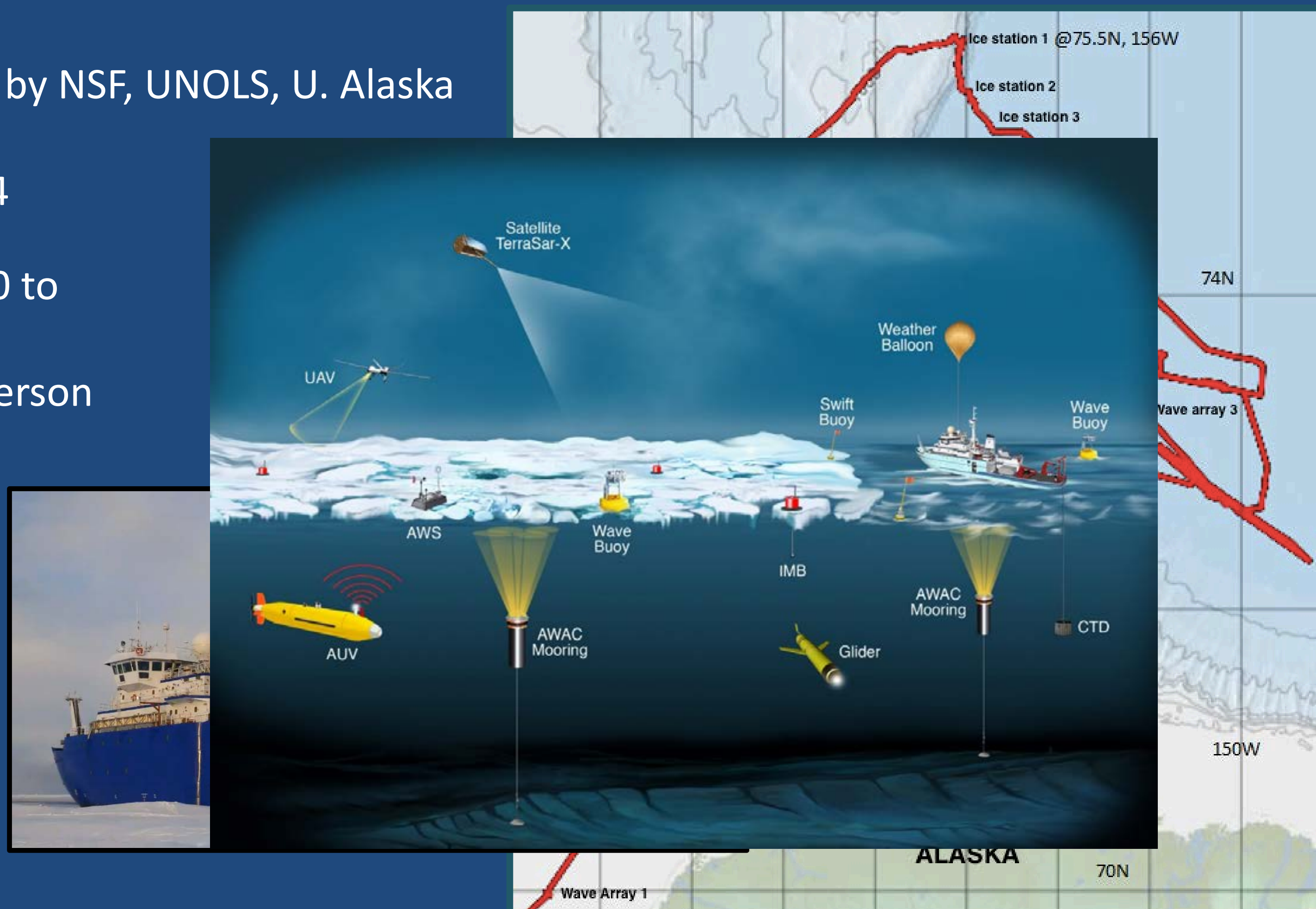
analysis by S. Stammerjohn

Figures showing *ONR Sea State DRI* study area.
The black line shows the Oct-Nov 2015 R/V Sikuliaq cruise track.
Colors indicate trend in days per year, 1975-2015.

In the eastern Siberian, Chukchi, and western Beaufort Seas, the ice season is shrinking at a rate of no less than 23 days every 10 years (Stammerjohn et al. 2012), and in the Chukchi and Beaufort Seas, the trend in delay of ice advance is 1.4 days per year (Thomson et al. 2016)

The “Sea State” DRI field experiment: Fall 2015

R/V Sikuliaq
- owned/operated by NSF, UNOLS, U. Alaska
- 261’
- First trials in 2014



6-week cruise (Sep 30 to Nov 10) with 13+ organizations in 26-person “science party”
- U. Washington
- U. Texas
- NPS
- WHOI
- U. Colorado
- Cambridge U.
- NRL-Stennis
- Clarkson U.
- JPL
- U. Miami
- NOAA (Boulder)