Wave forecasting for the Marginal Ice Zone

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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

Significant Wave Height (m) and mean wv. dir. | VT = 11-Oct-2015 00:00:00 UTC
Ice Concentration (contours) (0.25 0.50 0.75)
SQ time = 10-Oct-2015 16:00:00

colors: significant wave height (meters)
arrows (mean wave direction)
contours: ice concentration (25, 50, 75%)
magenta/white: ship track
circle: ship position

study area
October 11-14 “waves in pancake ice” event

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

Governing equation:
\[ \frac{\partial N}{\partial t} + \nabla \cdot \tilde{c}N = \frac{S}{\sigma} \]

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

- \( c \) = propagation speed
- \( k \) = wave number
- \( \sigma \) = relative radial wave frequency
- \( \theta \) = wave direction

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

\[ S = S(k, \theta, \bar{x}, t) \]  
[spectral description of source/sink terms]
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
3. Continuum theory

- Linear viscoelastic
- Consists of rheological parameters, incl. viscosity $\nu$ and shear modulus $G$

Ice physics options in WaveWatch3

Sept. 13 2017 Wave Hindcasting and Forecasting 8
Hₜ validation example

one of several models validated: parametric S_{ice}

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

Sept. 13 2017  Wave Hindcasting and Forecasting 9
**m₄ 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 (Tmₚ,₋₁,₀)**

also evaluated for this study, but omitted from presentation
Upper left: $m_4$ time series for entire cruise, model vs. obs
Lower left: $m_4$ scatter plot for entire cruise, model vs. obs
Upper right: $m_4$ time series for wave array #3 (WA3), model vs. “SWIFT buoy” obs
Lower right: $m_4$ scatter plot for WA3, model vs. “NIWA buoy” obs

$M_4$ validation

Further into ice

Nearer ice edge
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 $S_{\text{ice}}$, primarily)
- observation: a simple $S_{\text{ice}}$ 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

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

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

(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

ice concentration: CICE+DA

Ice conc (fraction) I VT = 09-Oct-2015 00:00:00 UTC
Ice Concentration (contours) ( 0.25 0.50 0.75 )

misses ice retreat October 12-14

Alaska

Ice conc (fraction) I VT = 09-Oct-2015 00:00:00 UTC
Ice Concentration (contours) ( 0.25 0.50 0.75 )

captures ice retreat October 12-14

Alaska

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Wave Hindcasting and Forecasting
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.

shown in next slide

**$H_s$ (m)**

**$H_m0$ (m)**

MM/DD in 2015
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 $S_{\text{ice}}$ formulations
- **required:** more info in gridded products re: ice type for use in $S_{\text{ice}}$ 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)
Nested grid system used for forecasting from R/V Sikuliaq and hindcasting

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

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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)
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

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

This implies a requirement for a numerical wave model.

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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
Ice physics options in WaveWatch3

- IC0: (pre-existing) ice as land or quasi-land, no $S_{\text{ice}}$
- IC1: simple $S_{\text{ice}}$ 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 $S_{\text{ice}}$
- IC5: another VE model (extended Fox and Squire)
- IS2: scattering (Meylan and Masson) (conservative)
case of obliquely off-ice winds

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

Significant variability between ice products: determines wave model skill for 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.
Regional Sea Ice Trends
1975-2015

Trend in Spring Retreat
(51 days earlier)

Trend in Autumn Advance
(44 days later)

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).

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.
The “Sea State” DRI field experiment: Fall 2015

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Wave Hindcasting and Forecasting