On Use of Internal Constraints in Recently Developed Physics for Wave Models

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On Use of Internal Constraints in Recently Developed Physics for Wave Models

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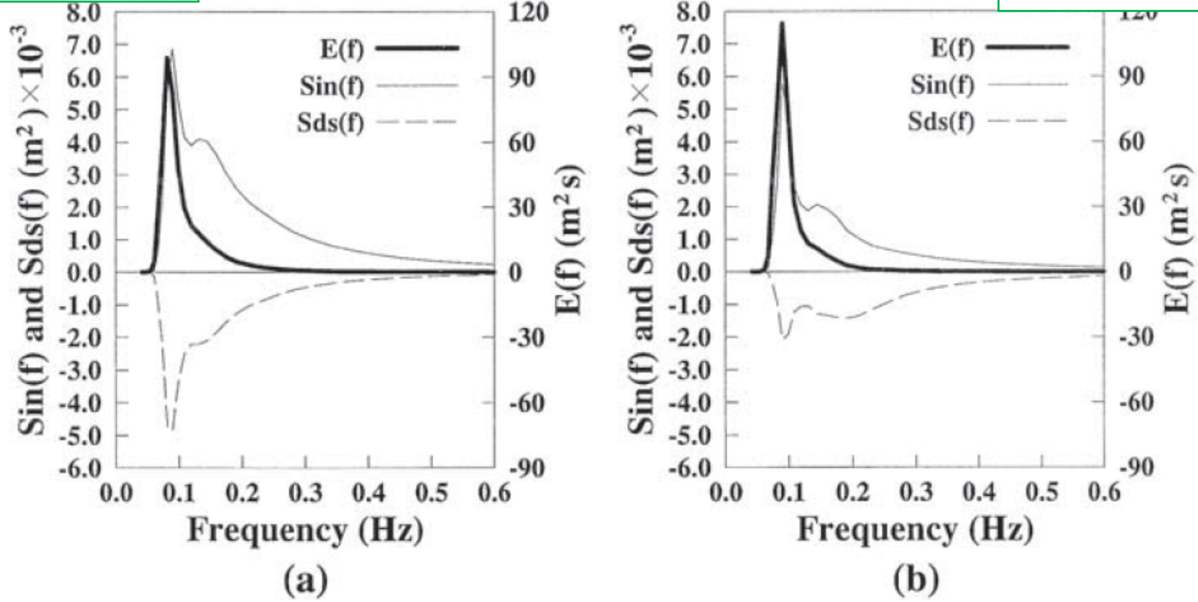
Contents

- Physical constraints in wave models
- WAVEWATCH III^{TM} development
  - Multi-grid modeling
  - Irregular-grid modeling
  - Modeling in the Arctic

Physical constraints on wind input and dissipation source functions

(a) : WAM Cycle 3 source terms

(b) : Tolman and Chalikov (JPO 1996) source terms



Observation and modeling of surface currents on the Grand Banks: A study of the wave effects on surface currents

C. L. Tang,[1] W. Perrie,[1] A. D. Jenkins,[2] B. M. DeTracey,[1] Y. Hu,[1] B. Toulany,[1] and P. C. Smith[1]

Physical constraints on wind input and dissipation source functions

From Tsagareli et al., Babanin et al. (JPO 2010)

- Constraint on wave-supported stress τ_{in}
  - $\tau_{atm} = \tau_{\nu} + \tau_{in}$
  - i.e. S_{in} cannot simply be anything we want
- Constraint on % energy retained
  - 1-R≡% energy retained
  - $R \equiv D_{tot}/I_{tot}$
  - $R=R(U/C_p)$ according to Donelan (1998)

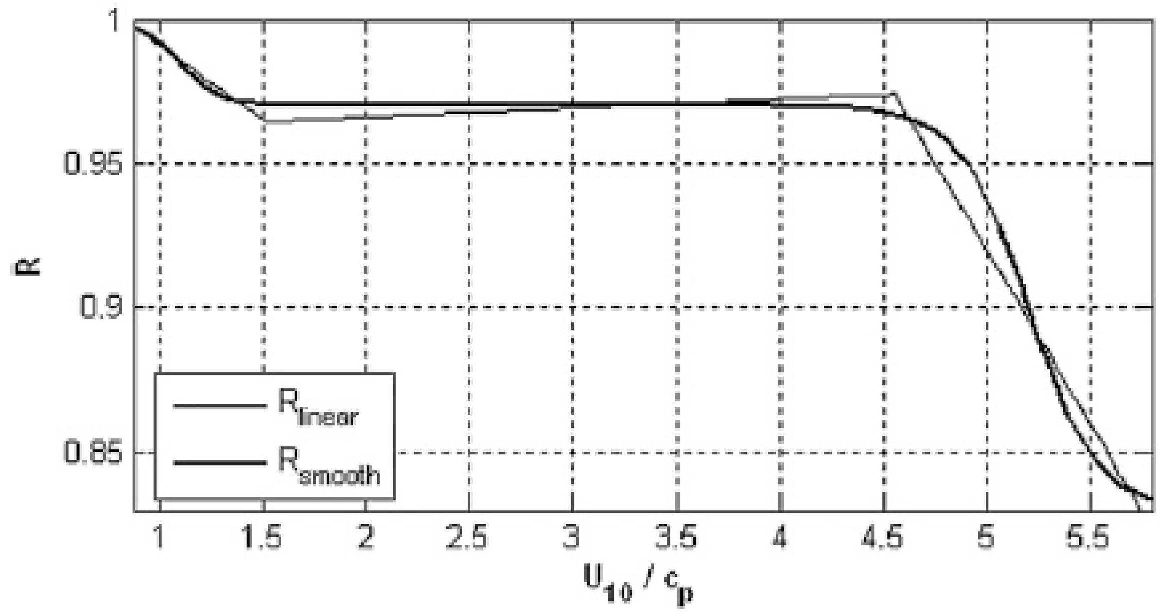
where

$$\vec{\tau}_{in} = \int \frac{S_{in}}{C}\frac{\vec{k}}{k}\,df\,d\theta$$

$$D_{tot} = -\int_0^{f_{\max}}\int_0^{2\pi} S_{ds}(f,\theta)\,df\,d\theta$$

$$I_{tot} = -\int_0^{f_{\max}}\int_0^{2\pi} S_{in}(f,\theta)\,df\,d\theta$$

Babanin et al. (JPO 2010)
Based on Donelan (1998) also follows from JONSWAP (1973)



$$R \equiv D_{tot} / I_{tot}$$

where $$D_{tot} = -\int_0^{f_{\max}} \int_0^{2\pi} S_{ds}(f,\theta) d f d\theta$$

$$I_{tot} = \int_0^{f_{\max}} \int_0^{2\pi} S_{in}(f,\theta) d f d\theta$$

$$R \equiv D_{tot} / I_{tot}$$

$$R \equiv D_{tot} / I_{tot}$$

$$\frac{\partial}{\partial t} E_{tot} = S_{tot} = I_{tot} - D_{tot}$$

where $$E_{tot} = \int_0^{f_{\max}} \int_0^{2\pi} E(f,\theta)\, df\, d\theta = \frac{1}{16} H_{m0}{}^2$$

$$R \equiv D_{tot} / I_{tot}$$

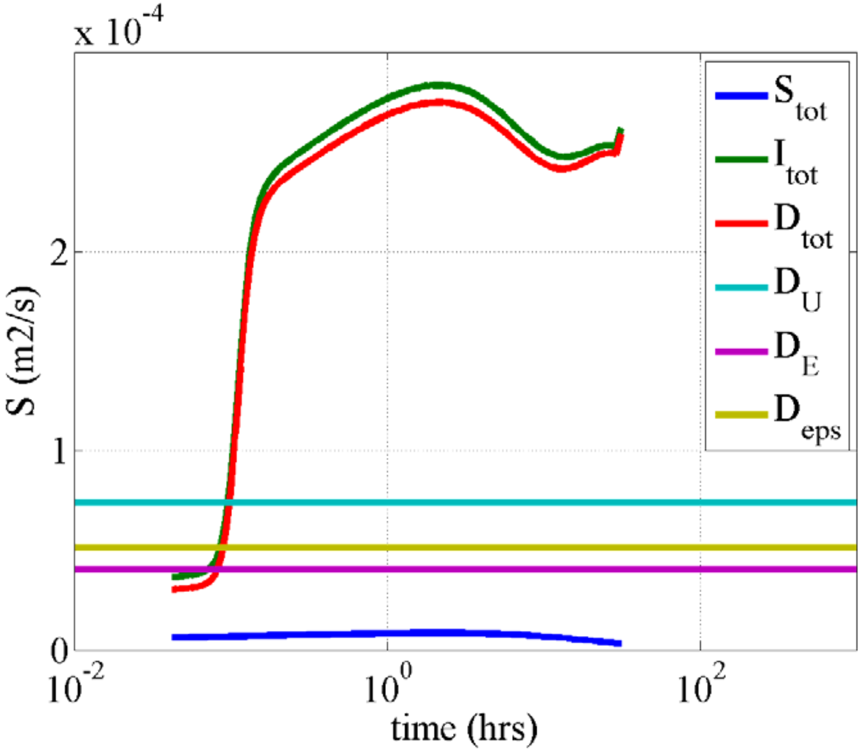
Expressions for $R=R(U/C_p)$ from Donelan (1998)

$$\frac{\partial}{\partial t} E_{tot} = S_{tot} = I_{tot} - D_{tot}$$

Expressions for $\partial E/\partial t$ from empirical growth curve (Young 1999)

$$D_{tot} = \frac{RS_{tot}}{(1-R)} \qquad I_{tot} = \frac{S_{tot}}{(1-R)}$$

D_{tot} and I_{tot} can be solved for

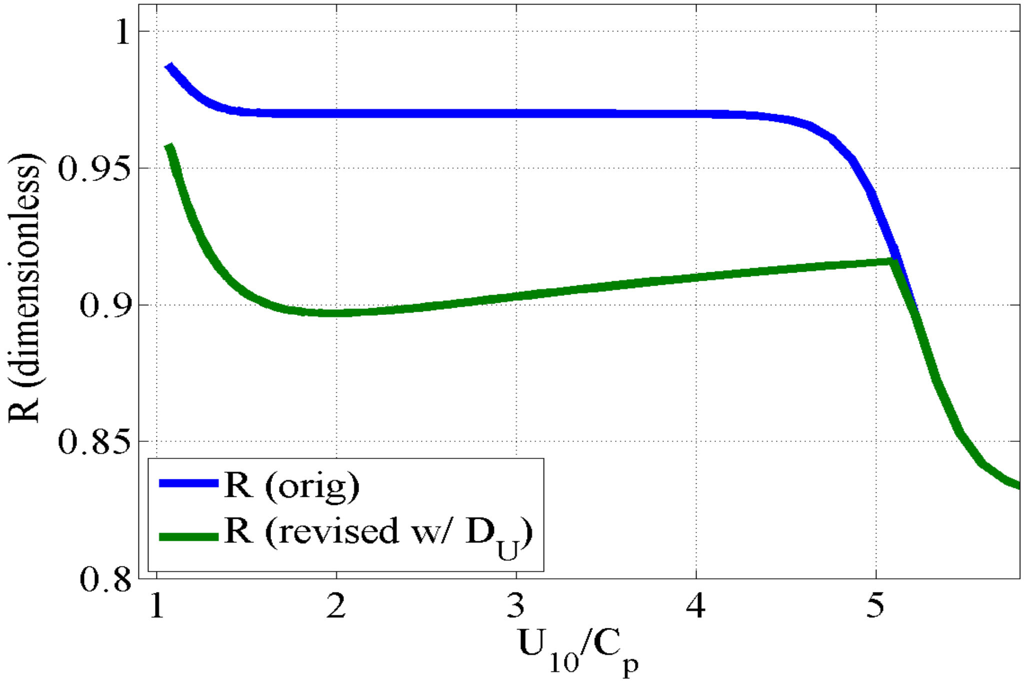


This result follows from assuming that the following are correct:

- Donelan (1998)
- empirical growth curves

Problem: Independent empirical estimates* of $D_{tot}(U_{10})$ suggest that our derived estimate for D_{tot} is too large by a factor of 3-6!

*Hwang and Sletten (JGR 2008) etc.



$$D_{tot} = \frac{RS_{tot}}{(1-R)}$$

$$I_{tot} = \frac{S_{tot}}{(1-R)}$$

This result follows from assuming that the following are correct:

- empirical estimates of $D_{tot}(U_{10})$ – Hwang and Sletten (JGR 2008)
- empirical growth curves

Taking $a = 5 \times 10^{-7}$, $b = -0.9$, and $C_d = 1.3 \times 10^{-3}$, $R = 15\%$ for $x = 0$ and goes to zero like $(xg/U_{10}^2)^{b-1}$.

The wave field becomes more "transparent" to the air–sea momentum flux as the waves get more developed because the momentum given to the waves is immediately lost to the current through whitecapping. This view of the air–sea momentum balance is consistent with Mitsuyasu's (1985) conclusions, who determined this ratio R as a function of the wave steepness. The values we find here are probably overestimated for short fetches (Donelan 1998 observed a maximum value R = 4%), essentially because we use a constant value for C_d. It is now firmly established that for a given wind speed C_d can increase by a factor 3 for very young windseas (i.e., short fetches).

R=0.85

R=0.96

Ardhuin et al. (JPO 2004)

Physical Constraints: Summary

- physical constraints must be critically evaluated before implementation
- relations presented here allow us (waves community) to revise estimates for
  - integral values of source terms

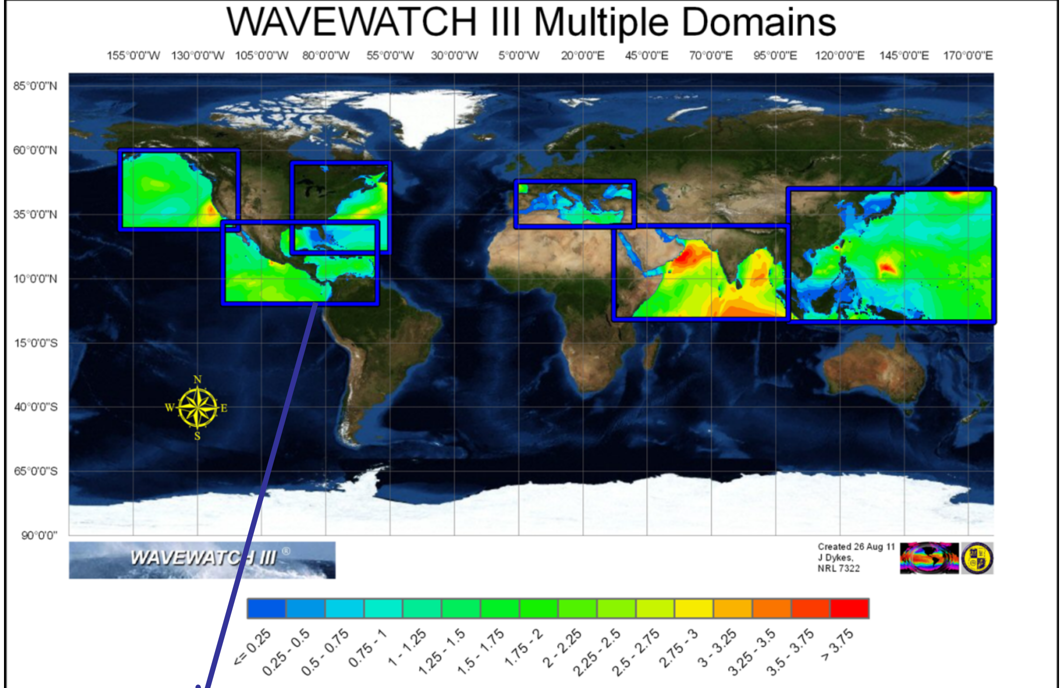
  OR

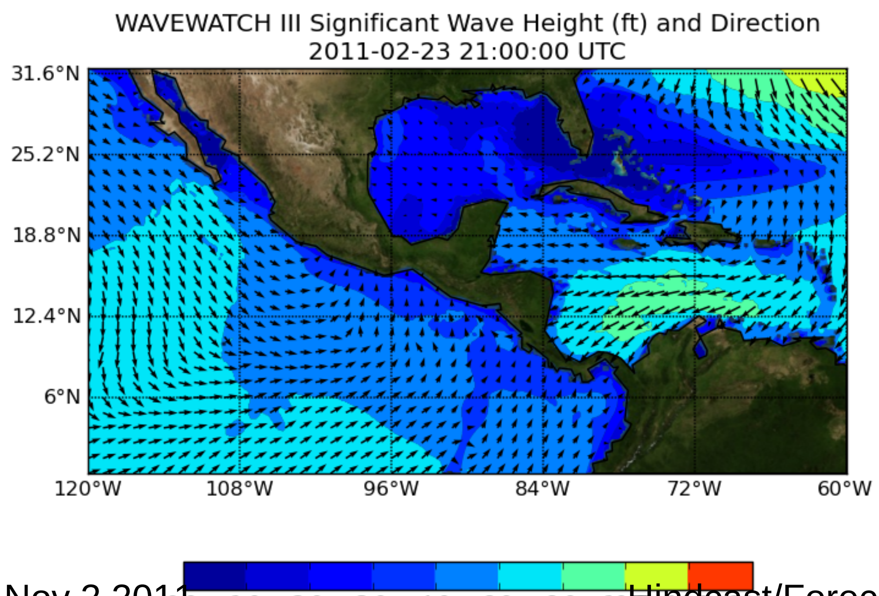
  - % energy retained by waves (much larger than proposed by Donelan (1998))

WAVEWATCH III^{TM} development

Multi-grid or “mosaic grid” feature in WAVEWATCH III

- Implemented in code in 2006 (Tolman Tech. Note 2007; OM 2008).
- Available in the last public release (v3.14)





Multi-grid or "mosaic" approach of WW3

Already operational at NCEP, being transitioned to NAVOCEANO now

Present NAVOCEANO setup shown:
Global WW3: 0.5°
(0.5° NOGAPS forcing)

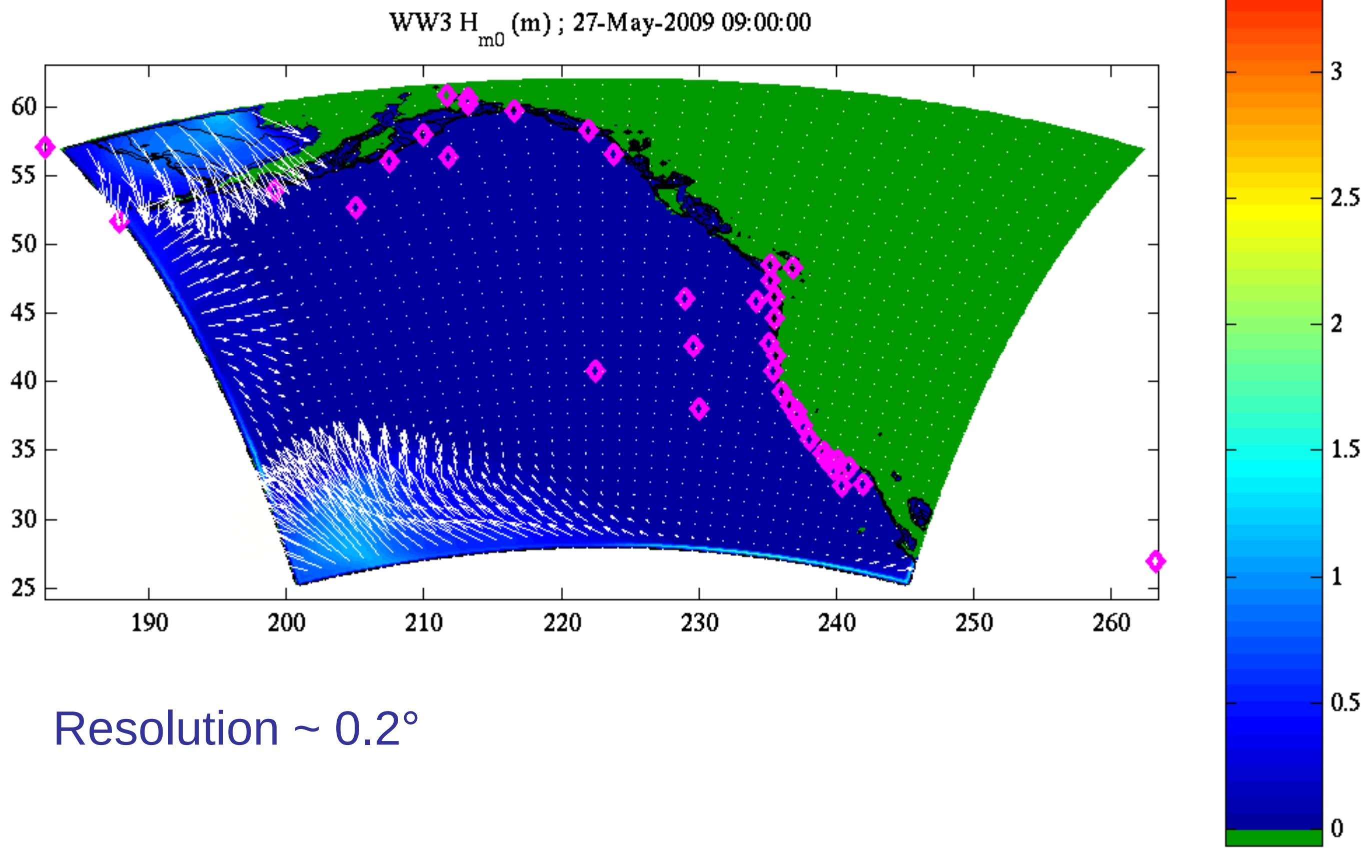
6 Regional WW3s: 0.2°
(0.2° COAMPS forcing)

Irregular-grid feature in WAVEWATCH III

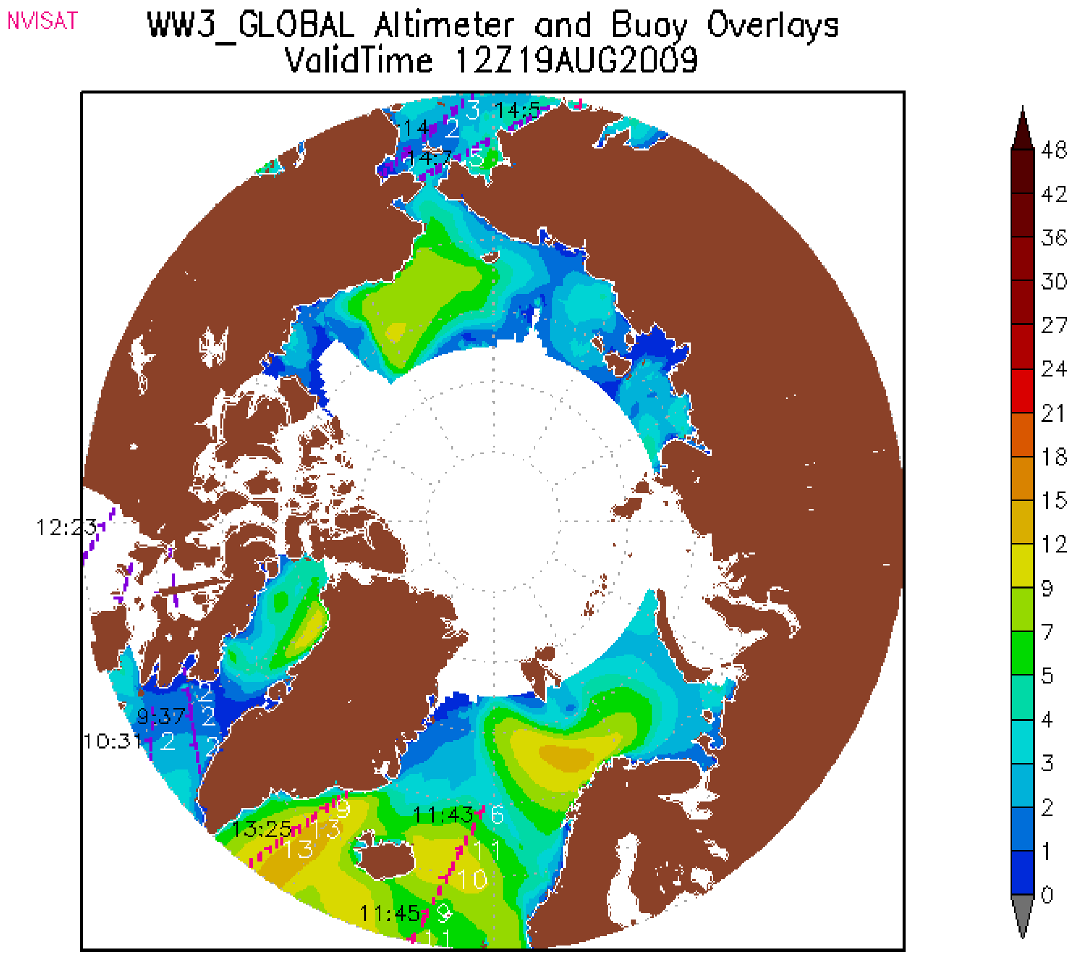
- Implemented in code in 2008 (Rogers and Campbell, NRL report 2009).
- Not included in the last public release (v3.14)
- Exists in NCEP WW3 development code
  - community model
  - trunk of WW3 in SVN repository
  - added in v4.01

WAVEWATCH III curvilinear EPAC grid: relevant files for one-way nesting provided to FNMOC

Animation: WW3 propagation (boundary forcing only) on Lambert Conformal EPAC grid. Waveheight in meters.

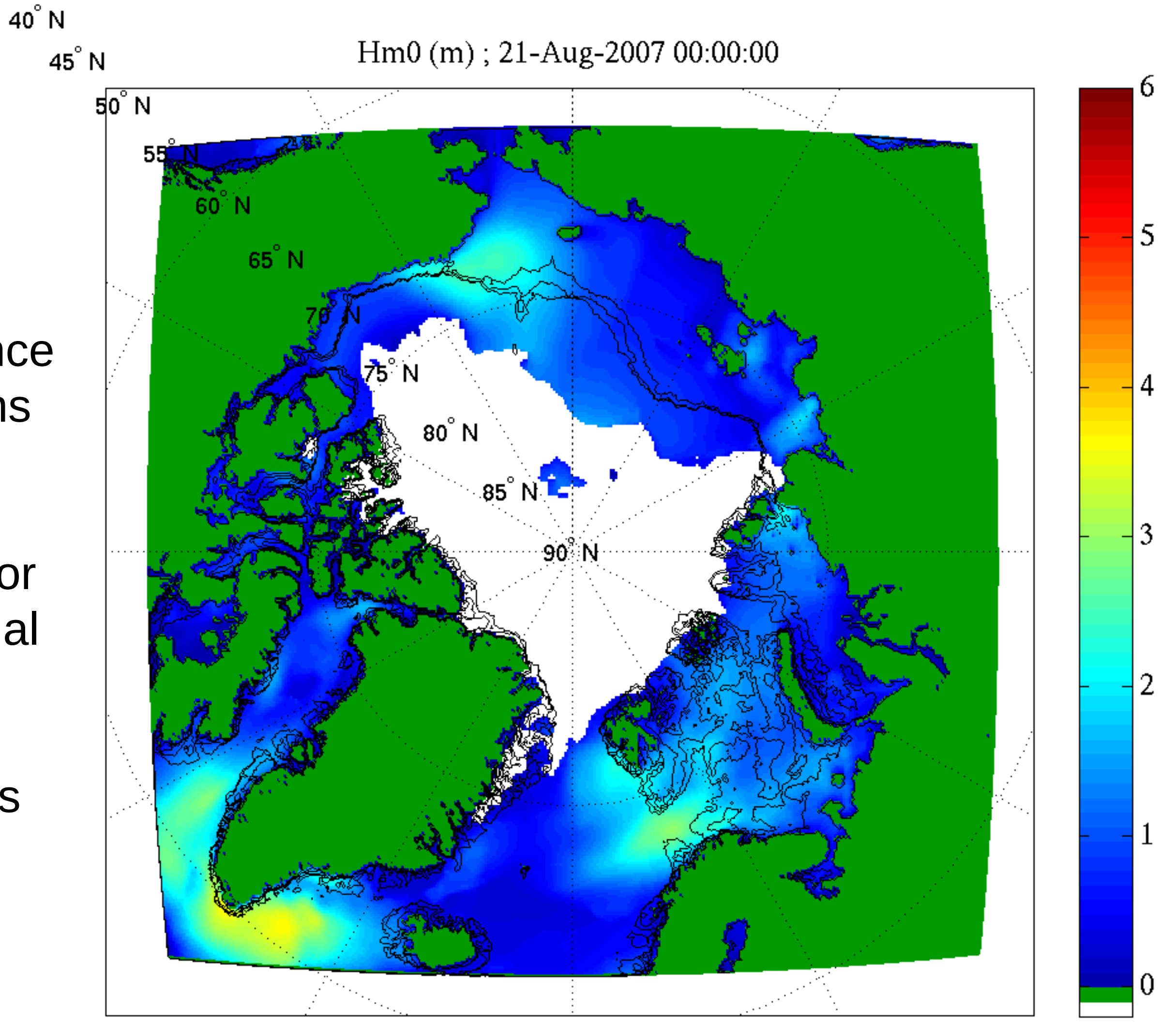


Resolution ~ 0.2°



The standard operational FNMOC global WW3 model, Arctic view. This model is on a regular 0.5 deg grid. The model stops at 78° N because the convergence of the meridians implies that resolution in real space becomes higher near the poles; due to the conditionally stable propagation scheme of WW3, extending the grid further north would require that the model use a smaller time step for the entire global grid (i.e. significant waste of computational resources).

WAVEWATCH III curvilinear Arctic grid, implemented on FNMOC "beta" queue (Wittmann)



Convergence of meridians leads to stability problems for conventional (regular) grids. No such issues here.

Rogers and Campbell (2009 report)

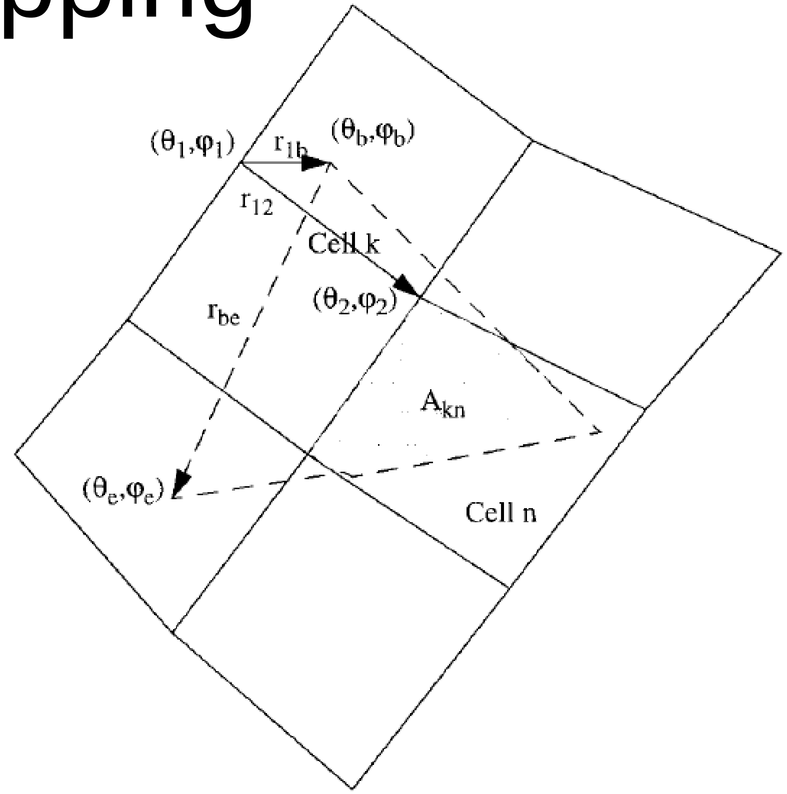
Animation: WW3 propagation and source term test on COAMPS Arctic grid. Waveheight in meters.

Summary: WW3 Status in 2010

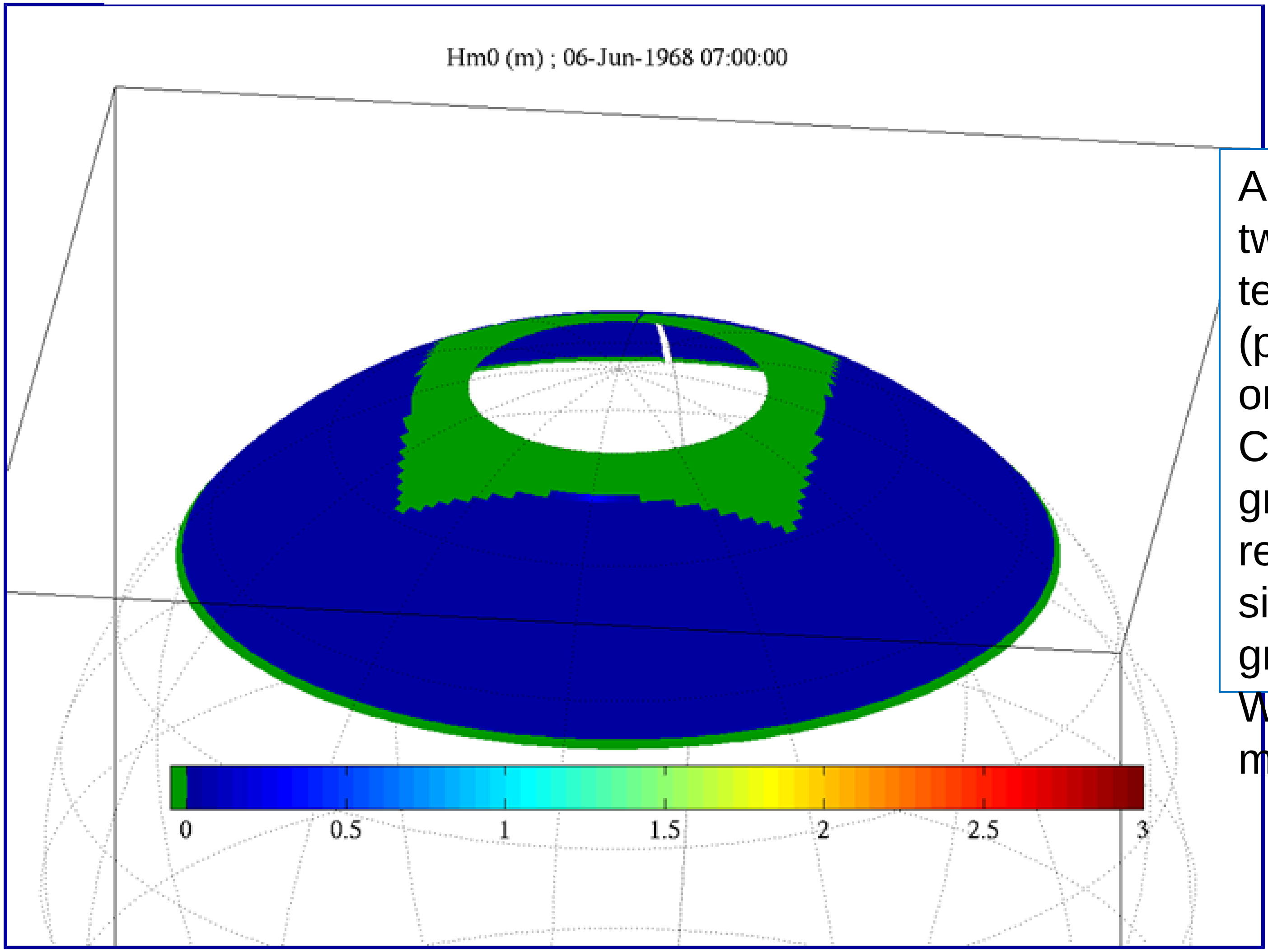
- Multi-grid WW3 working (v3.14), in transition to NAVOCEANO
- Irregular grid WW3 working (v4.01), transitioned to FNMOC
- These two features not working simultaneously

Primary challenge: conservative remapping

Jones (MWR 1999)

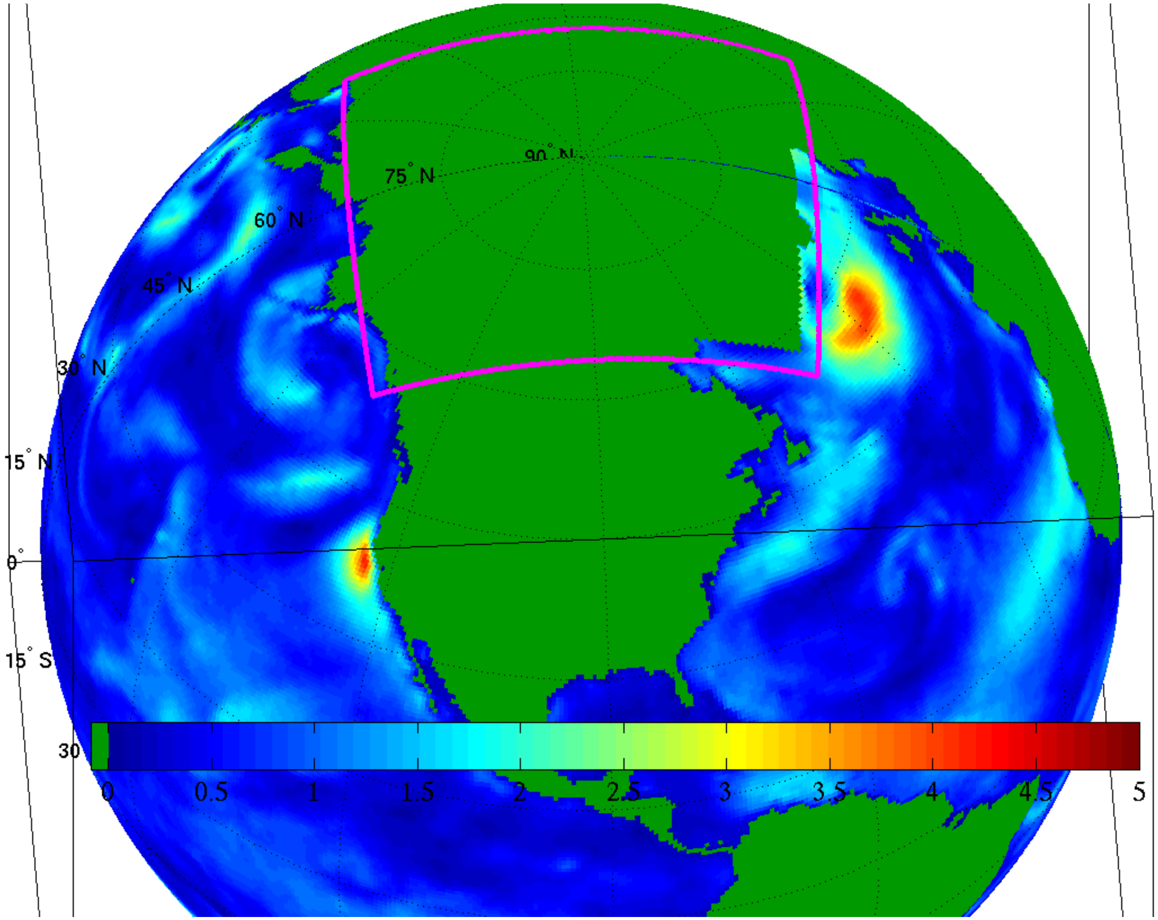


WAVEWATCH III: code adapted to allow use of curvilinear and multi-grid features simultaneously



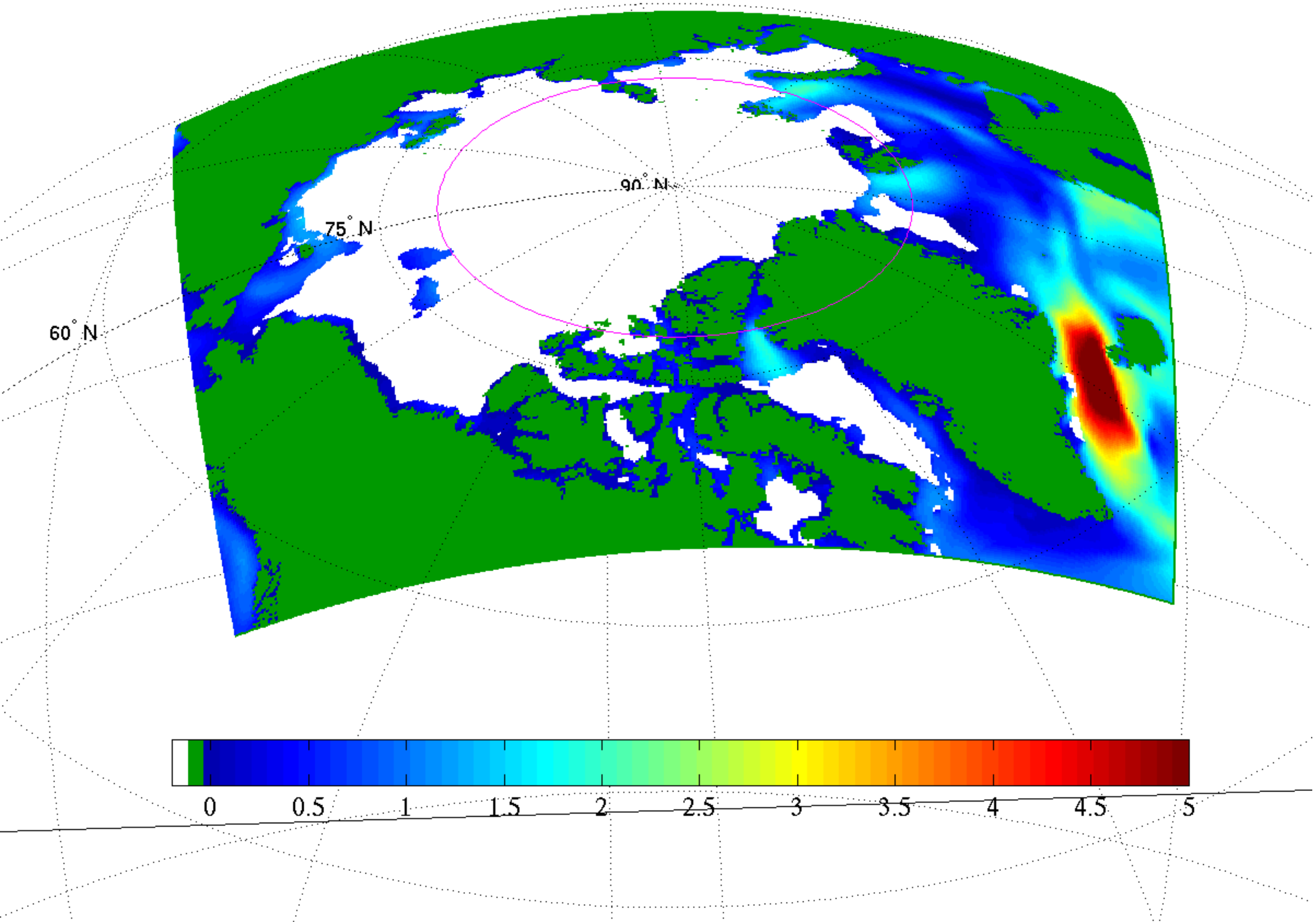
Animation: WW3 two-way nesting test (propagation only) with COAMPS Arctic grid (~16 km resolution) and a simplified global grid. Waveheight in meters.

WAVEWATCH III: code adapted to allow use of curvilinear and multi-grid features simultaneously



New system: WW3 two-way nesting test (propagation + wind + ice) with COAMPS Arctic grid (~16 km resolution) and full (0.5°) global grid. Waveheight in meters. The regular (global) grid is plotted. Masked areas are shown in green and include: land, ice, and areas covered by the curvilinear grid. Thus, the global model is not computing in areas covered by the Arctic grid (read: increased efficiency).

Result at May 25 2009 12Z, after a 12 hour simulation (from cold start). The boundary of the Arctic grid is shown with a magenta line. Ice is taken from PIPS and winds are taken from NOGAPS. Thus, this setup is very similar to what it would be for an operational model.



Results within the Arctic grid.

masked areas are denoted as either

- land (green)
- or ice with concentration of 0.75 or greater (white).

magenta line indicates 78 deg N, which is the upper limit of the operational global WW3 at FNMOC.

Wave energy propagates in both directions across the boundaries between the regional grid shown here and the global grid. The grids run simultaneously within the same machine executable.

Summary

- Old news:
  - Multi-grid WW3 working (2006)→v3.14
  - Irregular grid WW3 working (2008)→v4.01
- New news:
  - These two features working simultaneously* (2011)→v4.10

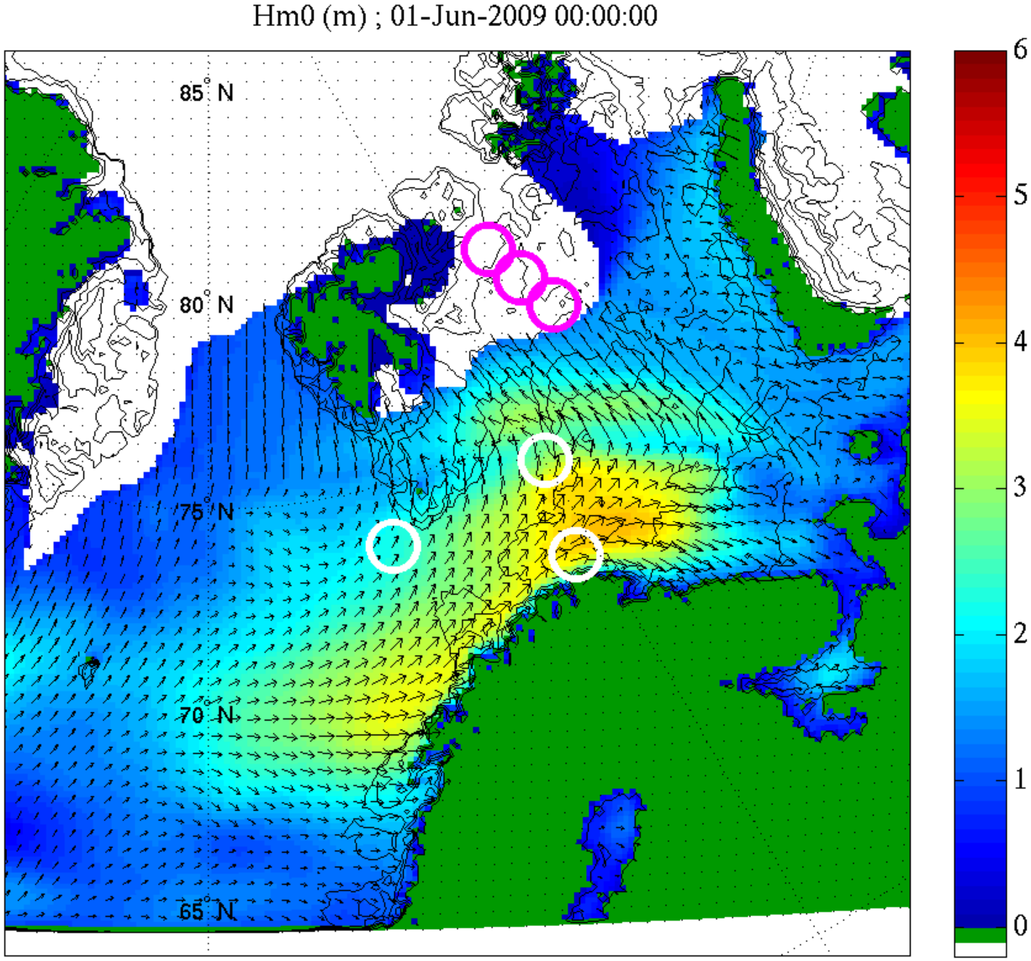
*communication between equal-rank grids still to be addressed

The End

So now we can run the wave model in the Arctic, but what do we do about the ice?

Inputs:
- PIPS
  - ice concentration
  - irregular grid
  - ~30 km
- NOGAPS
  - 10 m wind vectors
  - regular grid
  - 0.5°

Arctic grid resolution ~ 16 km



Rogers and Campbell (2009 report)

Animation: WW3 propagation and source term test on COAMPS Arctic grid (zoom on Barents Sea region). Waveheight in meters.

Representation of attenuation of waves by interaction with ice

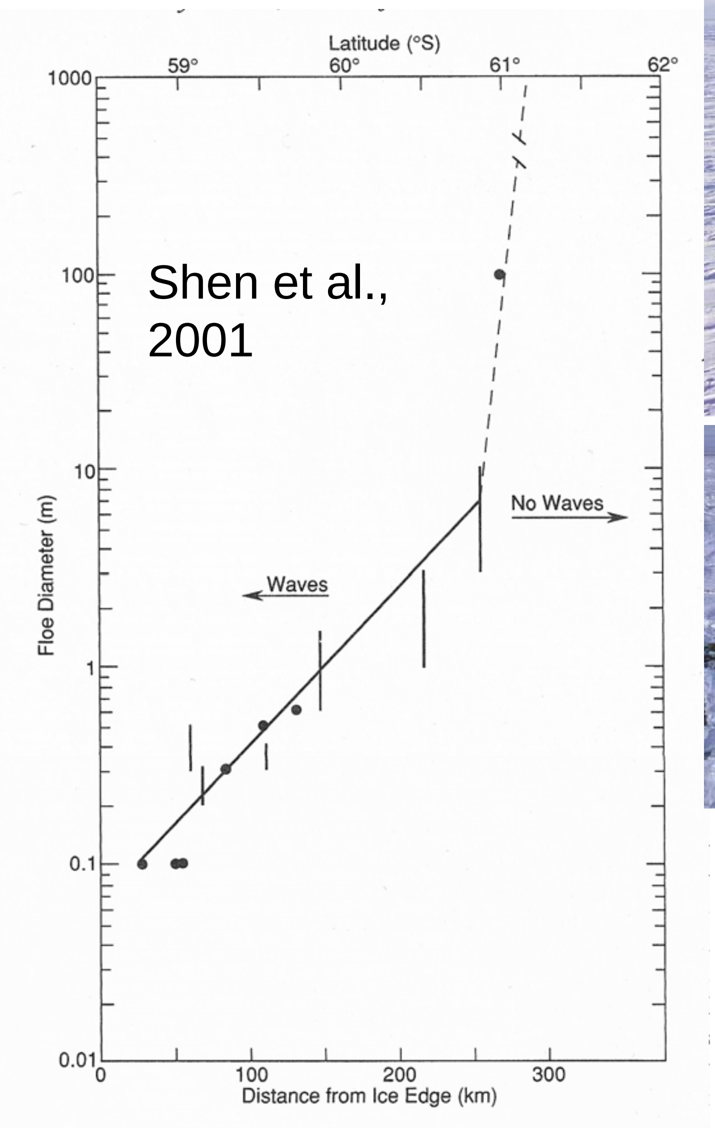
Model source terms: $S = S_{in} + S_{ds} + S_{nl}$

$$S_{ds} = S_{br} + S_{bot} + \underbrace{S_{ice}}_{\text{proposed}}$$

S_{ds} : dissipation (general)
S_{br} : steepness-limited breaking (whitecapping, surf)
S_{bot} : dissipation by interaction with seafloor (bedforms, mud, etc.)
S_{ice} : dissipation by interaction with ice, either
continuous ice or
ice floes (Marginal Ice Zone)

Secondary effect: Ice also affects wavenumber *k*

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



Slide provided by Dr. Ruixue Wang

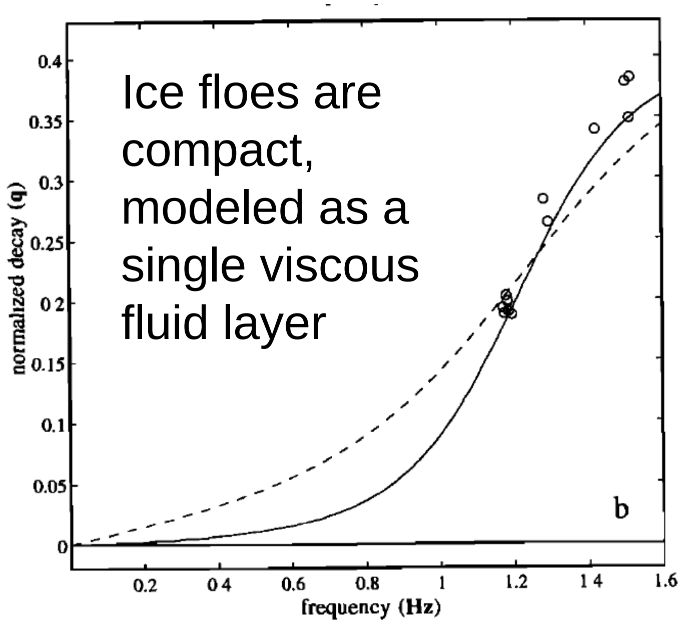


Figure 1. Comparison of laboratory to model predictions for experiment 1; see Table 1 for parameter description. On each panel the dashed curve shows the Stokes/Lamb one-layer model results for $\hat{\nu}_1 = 1.5\times10^4$; the solid curve shows the Keller two-layer results for $\hat{\nu}_2 = 2.5\times10^4$. The circles give our laboratory data; the vertical bars show the 95% confidence limits. (a) Normalized wavenumber $\hat{k}$ versus f, (b) normalized wave decay coefficient $\hat{q}$ versus f.

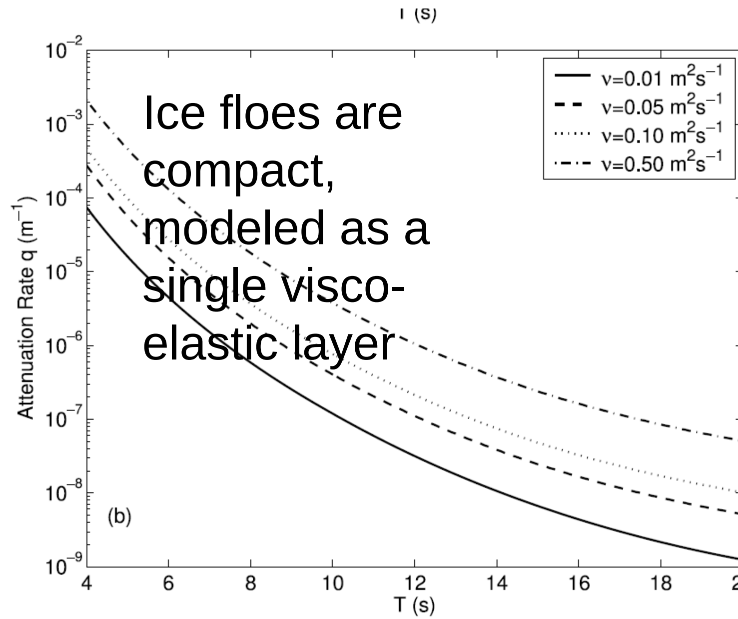


Figure 4. Viscous layer model for long waves. (a) Normalized wave number κ versus wave period $T(s)$ for the dominant wave mode and (b) attenuation rate $q(m^{-1})$ versus wave period $T(s)$ for the dominant wave mode. Parameters used are as follows: $h = 0.5\ m$, $H = 100\ m$, $G = 0$.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. C4, PAGES 7837–7840, APRIL 15, 1999

Comparison of laboratory data with a viscous two-layer model of wave propagation in grease ice

Karl Newyear[1] and Seelye Martin
School of Oceanography, University of Washington, Seattle

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, C06024, doi:10.1029/2009JC005591, 2010

Gravity waves propagating into an ice-covered ocean: A viscoelastic model

Ruixue Wang[1,2] and Hayley H. Shen[2]

Ice floes are compact, dissipation from turbulence at ice/water interface

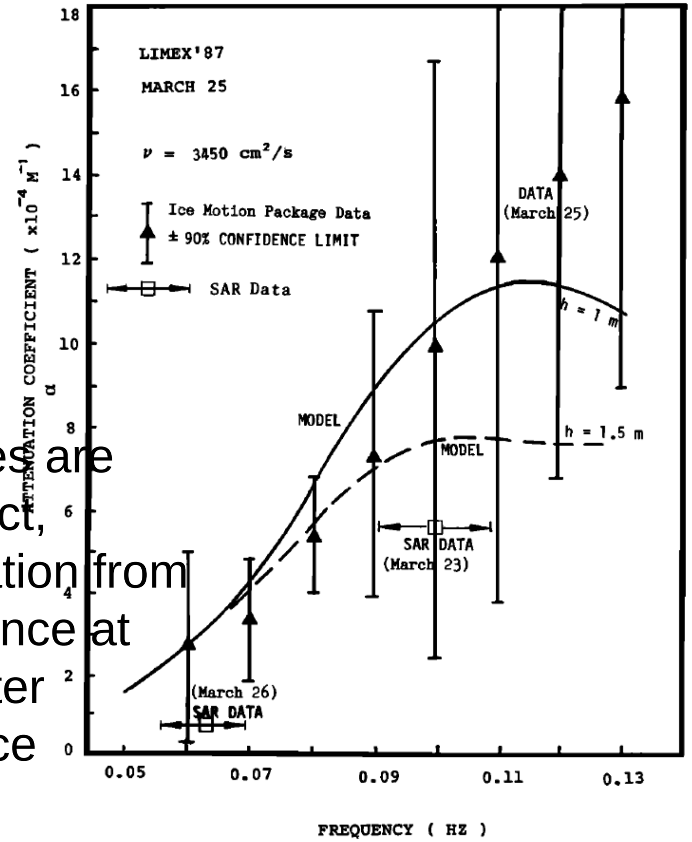


Fig. 11. Model-data comparisons for the wave attenuation coefficient as a function of wave frequency f

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. C3, PAGES 4605–4621, MARCH 15, 1991

Wave Propagation in the Marginal Ice Zone: Model Prediction and Comparisons With Buoy and Synthetic Aperture Radar Da

ANTONY K. LIU

Oceans and Ice Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland

BENJAMIN HOLT

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

PARIS W. VACHON

Canada Centre for Remote Sensing, Ottawa

Ice floes are not colliding, dissipation from scattering from floes

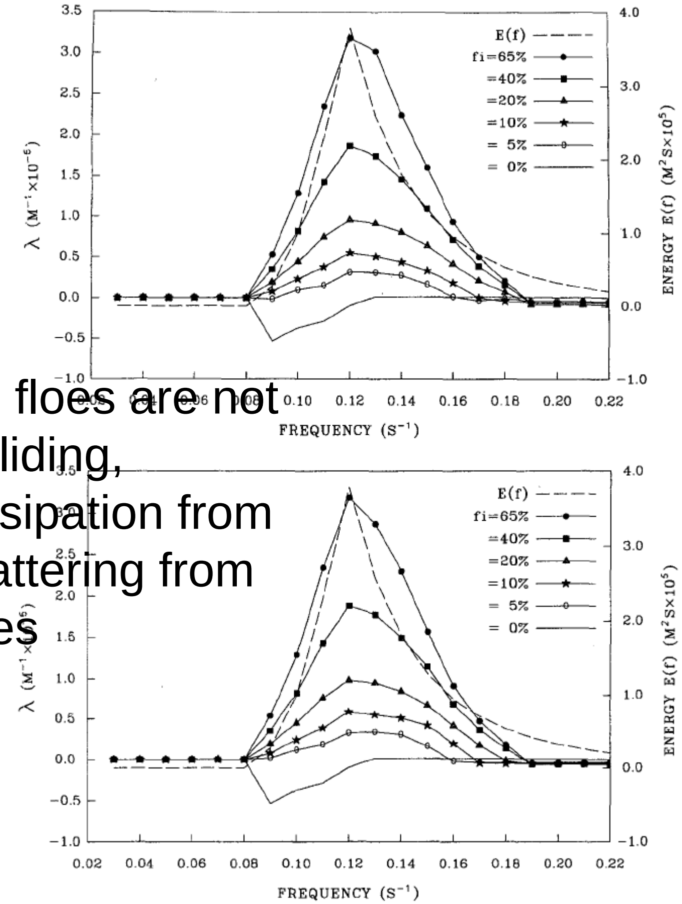


FIG. 3. Wave attenuation λ as a function of frequency f and ice cover concentration fi. The energy impinging on the MIZ is given by $E(f)$ assuming (a) 20-m floe diameter and 1.5-m floe thickness, (b) 20-m floe diameter and 3.0-m floe thickness and (c) 15-m floe diameter and 1.5-m thickness.

Air–Ice–Ocean Momentum Exchange. Part I: Energy Transfer between Waves and Ice Floes

W. PERRIE AND Y. HU

Physical and Chemical Sciences, Scotia–Fundy Region, Department of Fisheries and Oceans, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada

(Manuscript received 20 December 1994, in final form 18 October 1995)

Summary (Arctic)

- Numerical obstacles have been addressed
- Work on S_{ice} approved to start this FY
  - no shortage of theoretical models to use
  - challenge is to:
    - select appropriate model
    - provide necessary inputs

Backup slides

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

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

* (similar in SWAN)

In deep water, $S = S_{in} + S_{ds} + S_{nl4}$

c = propagation speed
k = wave number
σ = relative radian wave frequency
θ = wave direction

$$N = N(k, \theta, \vec{x}, t)$$

[spectral density, the variable that is being solved for]

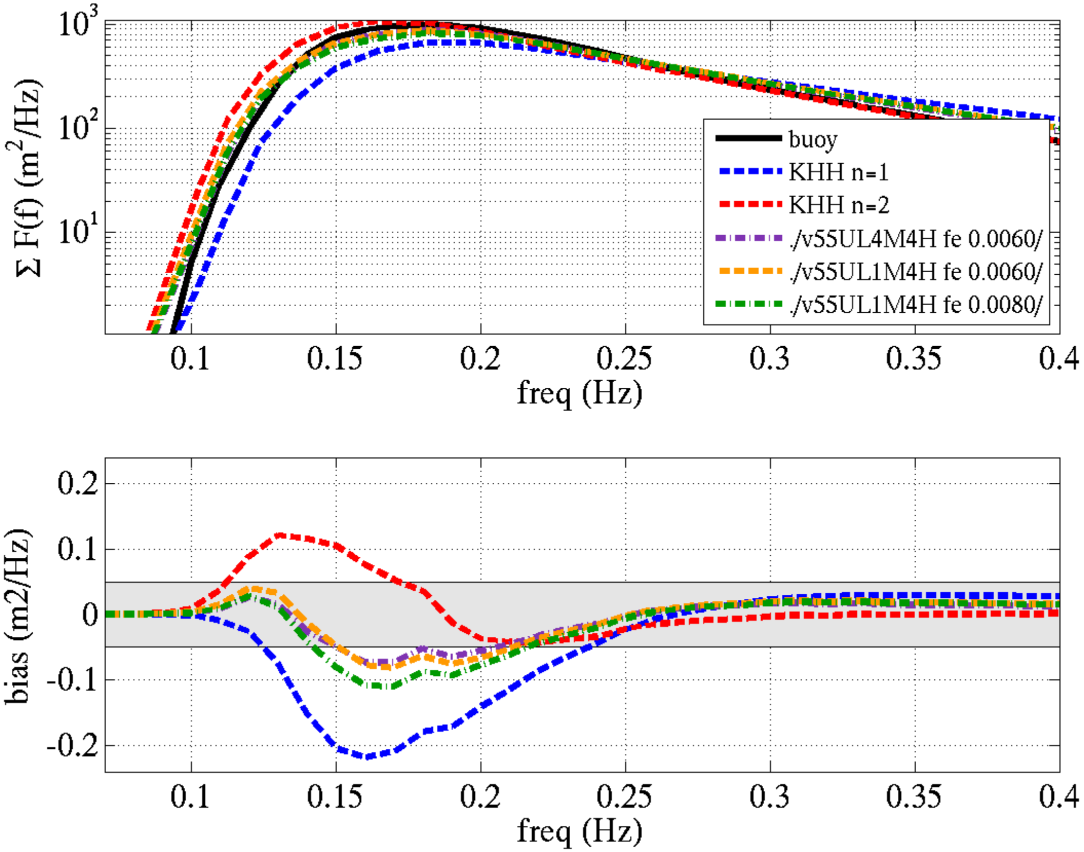
$$S = S(k, \theta, \vec{x}, t)$$

[spectral description of source/sink terms]

The implications of using the DIA for four-wave nonlinear interactions: separating myth from fact

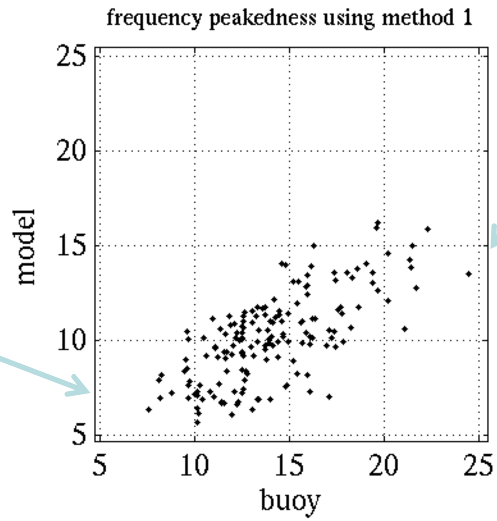
Lake Michigan (Fall 2002) simulation with several models

- Conclusion: models tend to be too broad in frequency space.
- But why?



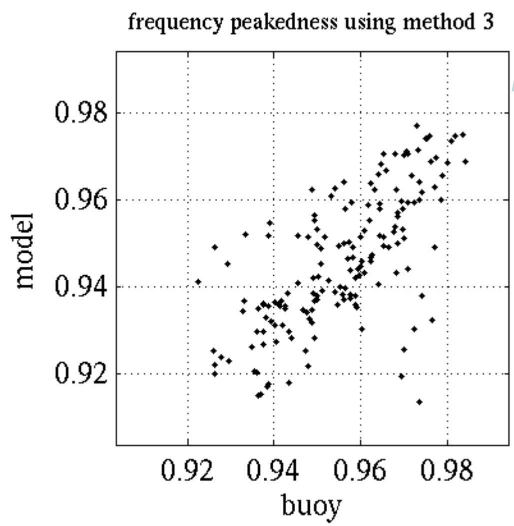
Metrics for quantifying frequency-narrowness for validation

Proposed method: Adapted from Babanin and Soloviev method for quantifying directional narrowness.

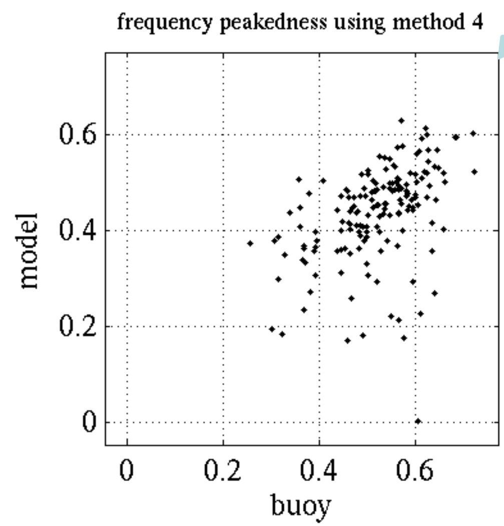


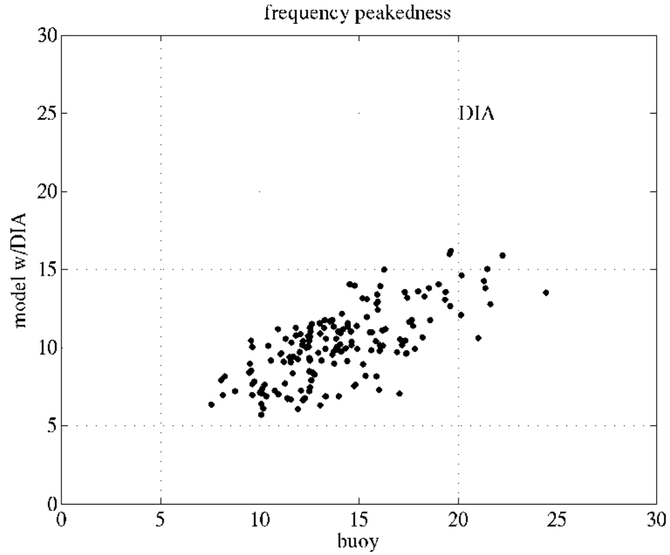
Proposed method, properly reflects the bias that is clearly seen in the E(f) comparisons (prior slide)

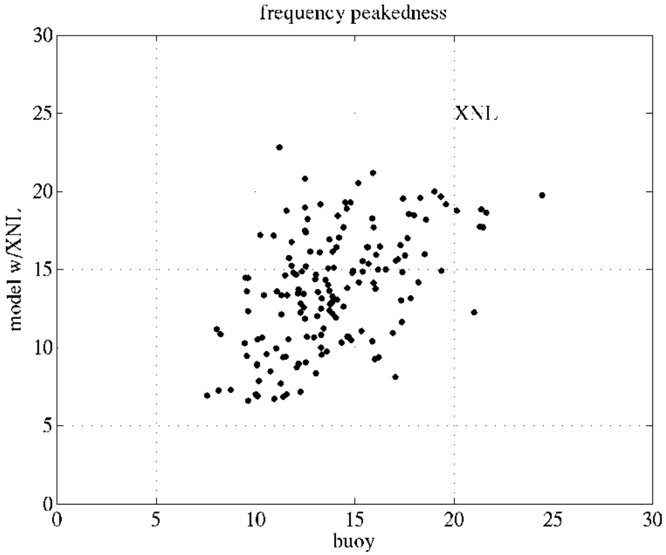
$T_{m0,1}/T_{m0,-1}$: indicates no bias

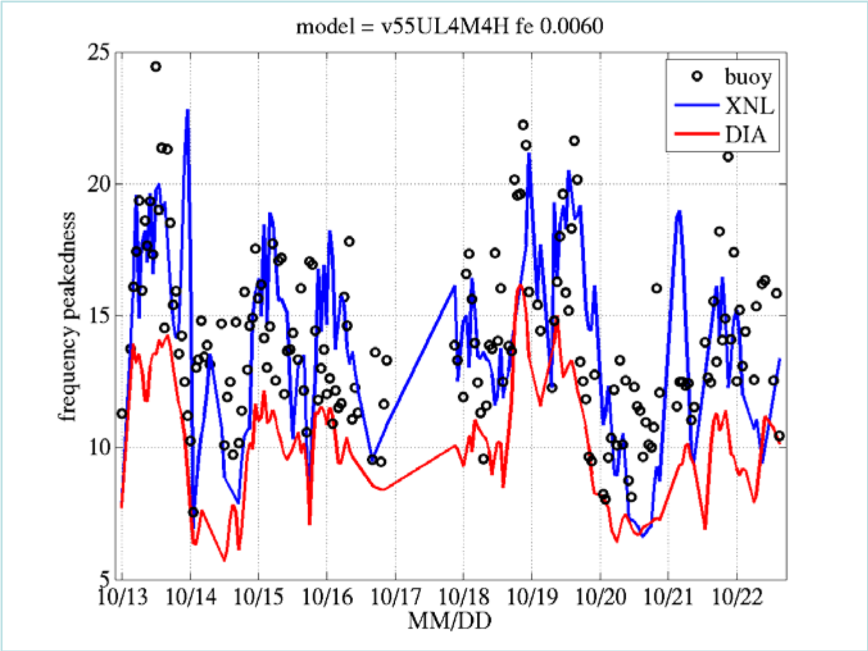


Traditional method, used by SWAN: indicates no bias!









Conclusions:

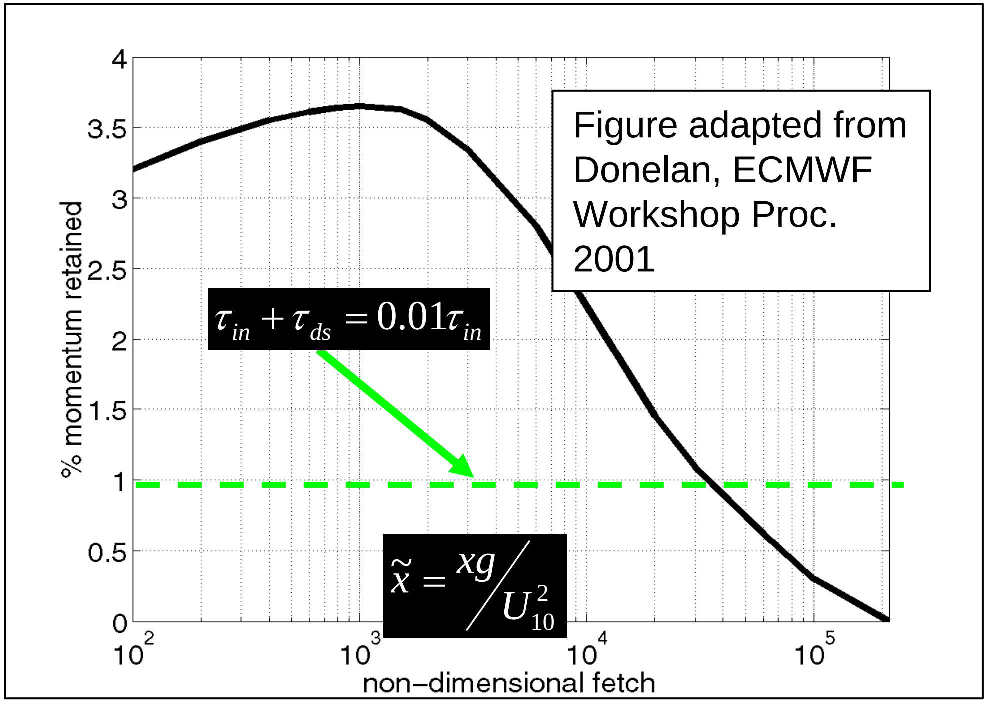
- bias in frequency peakedness is almost completely removed by using Exact-NL (Webb, Resio, Tracy as implemented by van Vledder)
- however random error actually increases (further investigation required)

Tang et al.:

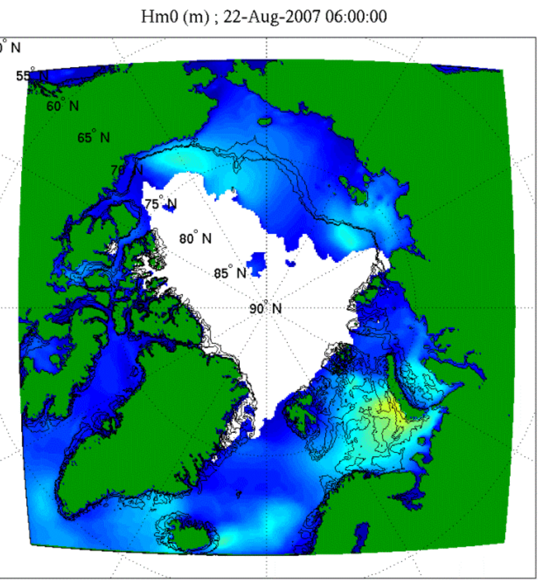
$(T_a/\rho_a)^{1/2}$, where ρ_a is the air density. According to (2), as the wave steepness approaches 0.07, the proportion of the applied wind stress transferred to the waves will approach 100%. Assuming that the wave directional energy distribution is proportional to $\cos 2\eta$ (η is the angle with respect to the wind direction), and using *Mitsuyasu*'s [1968] relation, $g^2 E/u_*^4 = 1.72 \times 10^{-4} (gx/u_*^2)\rho_o g$, for the fetch dependence of wave energy, *Mitsuyasu* [1985] found that in wind-generated waves,

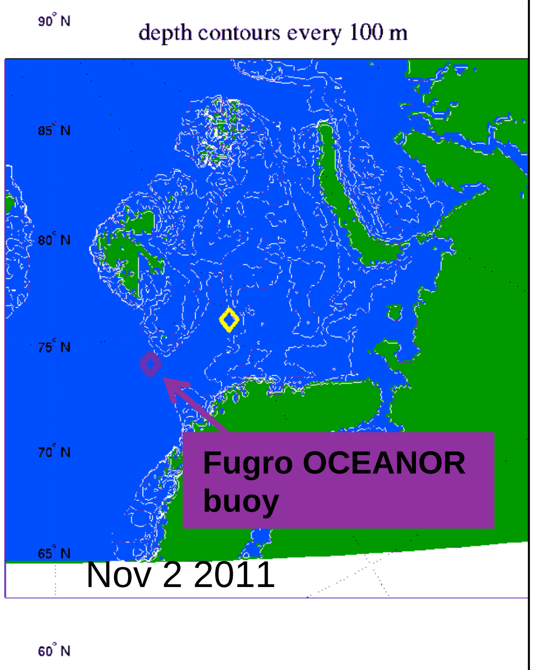
$$dS_{xx}/dx|_{total} \approx (3/8)dE/dx \approx 5.4 \times 10^{-2} T_a, \qquad (3)$$

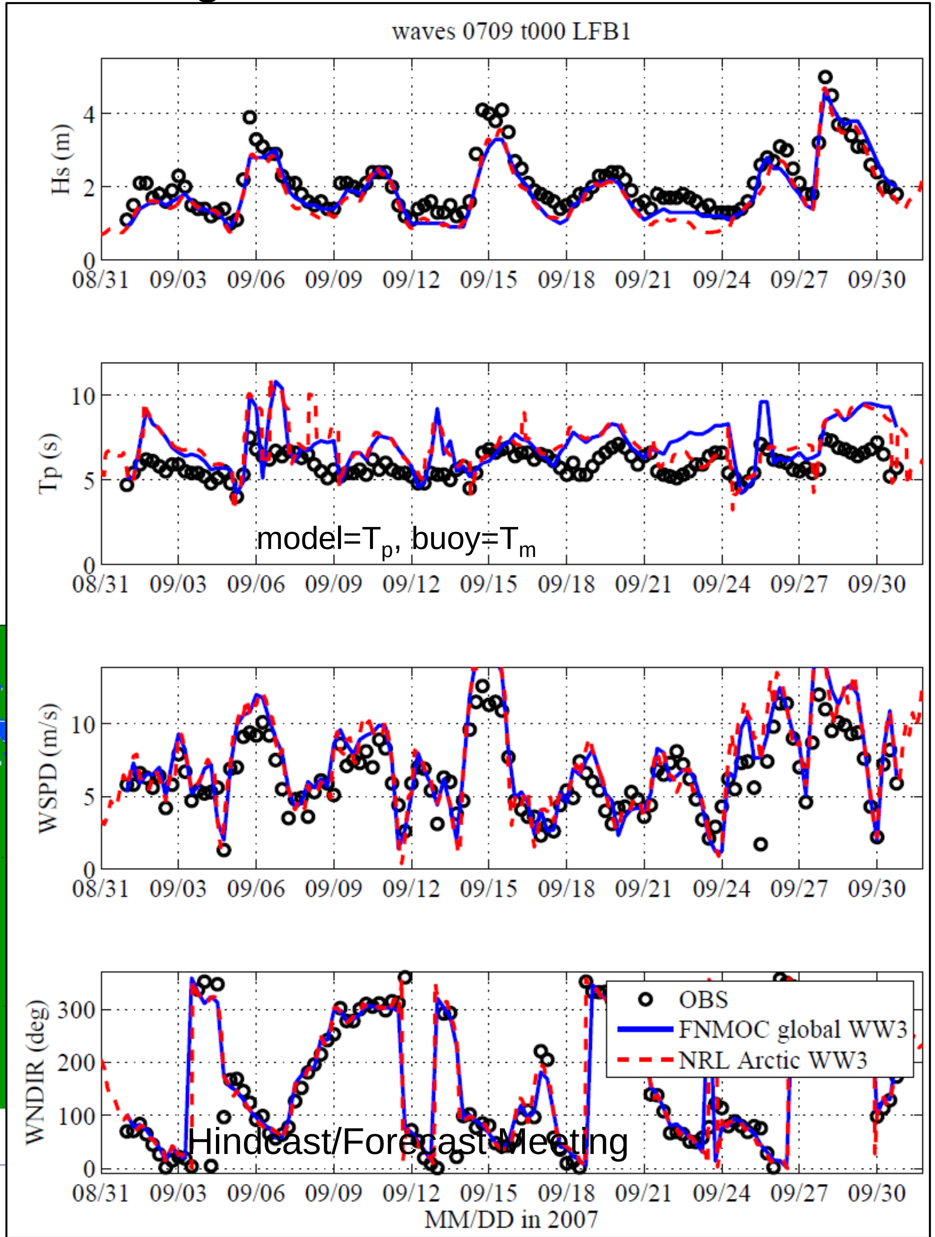
so that only about 5% of the applied wind stress is advected away by growing wind waves. Therefore, there should be a rough overall balance between the applied wind stress and the flux of momentum.



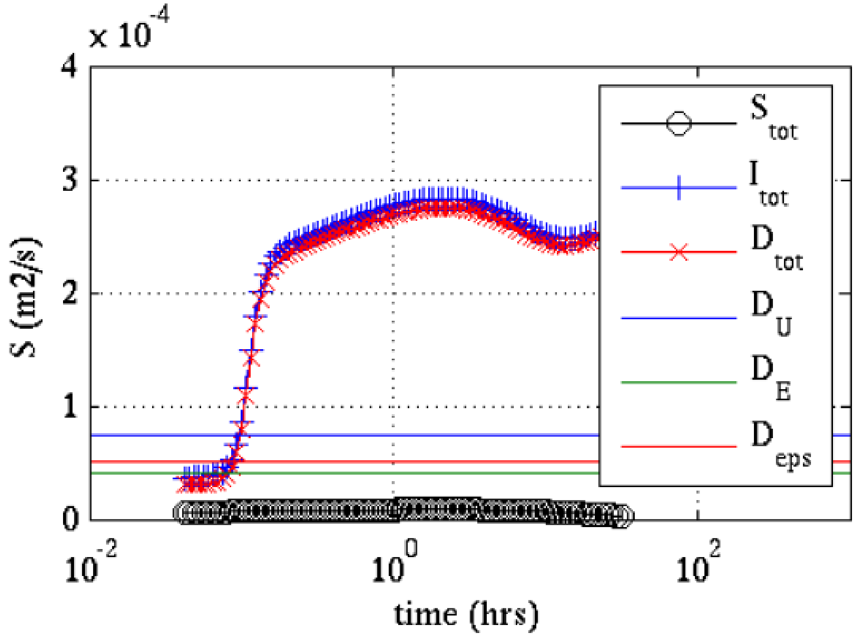
1498 Small Scale Ocean Modeling: Regional Wave Modeling with WAVEWATCH III Progress Demonstration







Shown: NRL model with wind speeds from NOGAPS and ice concentrations from PIPS vs. FNMOC global WW3 vs. buoy observations (Barents Sea)



This result follows from assuming that the following are correct:

- Donelan (1998)
- empirical growth curves

Problem: Independent empirical estimates of $D_{tot}(U_{10})$ suggest that our derived estimate for D_{tot} is too large by a factor of 3-6!

2.2 *Input to dissipation ratio, R*

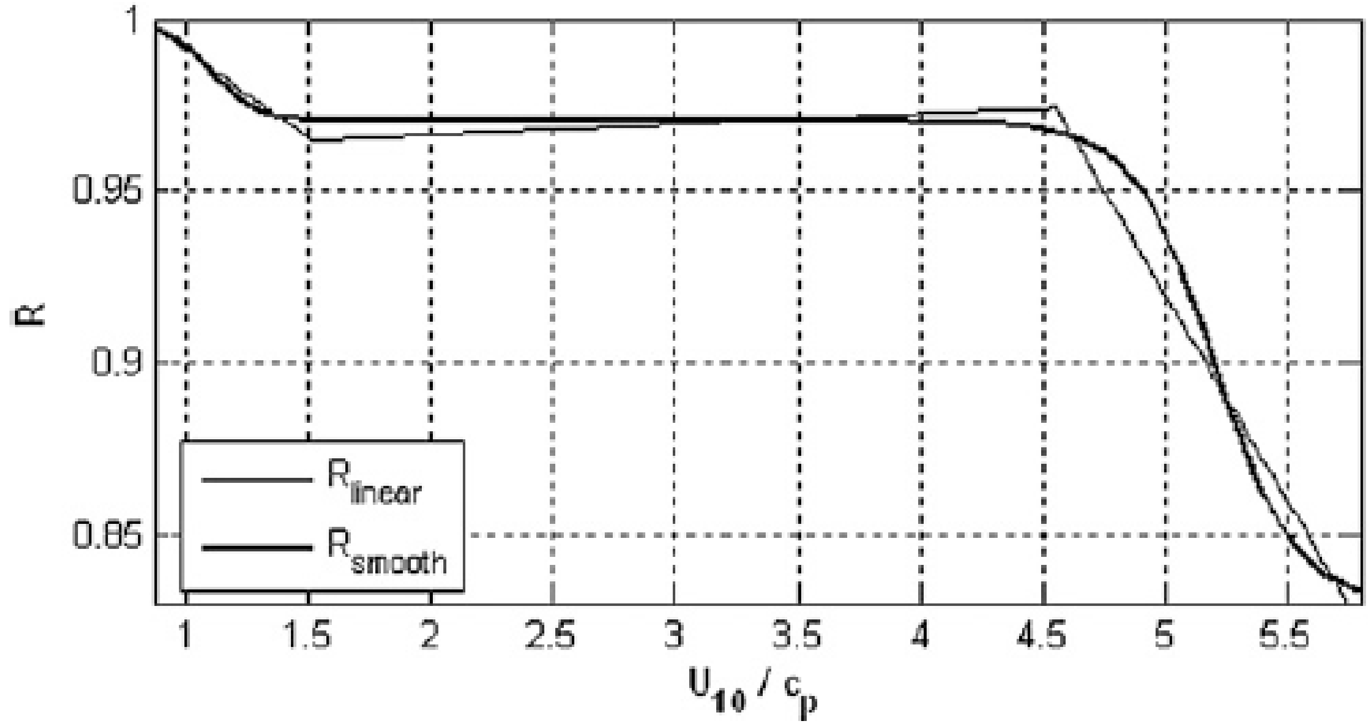
The ratio of dissipation to input $R \equiv D_{tot}/I_{tot}$ is used by Babanin et al. (JPO 2010) as a physical constraint in their numerical model. For this, they used an empirical form taken from Donelan (1998, book chapter):

$$R = R(U_{10}/C_p) \tag{7}$$

(see Babanin et al. 2010 equation 16) {We refer to this below as the "Donelan equation" or "Donelan expression", though Donelan (1998) provided only the figure, from which Babanin et al. (2010) created the actual equation.} This dataset and functional form yield a ratio R that is, for inverse wave age values between 1.5 and 4.5, approximately 0.97 (see their Figure 4). Donelan (1998) also points out consistency between his measurements and

[2] The commonality of ε and ν make it easy to convert between ς and χ numerically. Derivation of simple analytical methods of conversion is more troublesome.

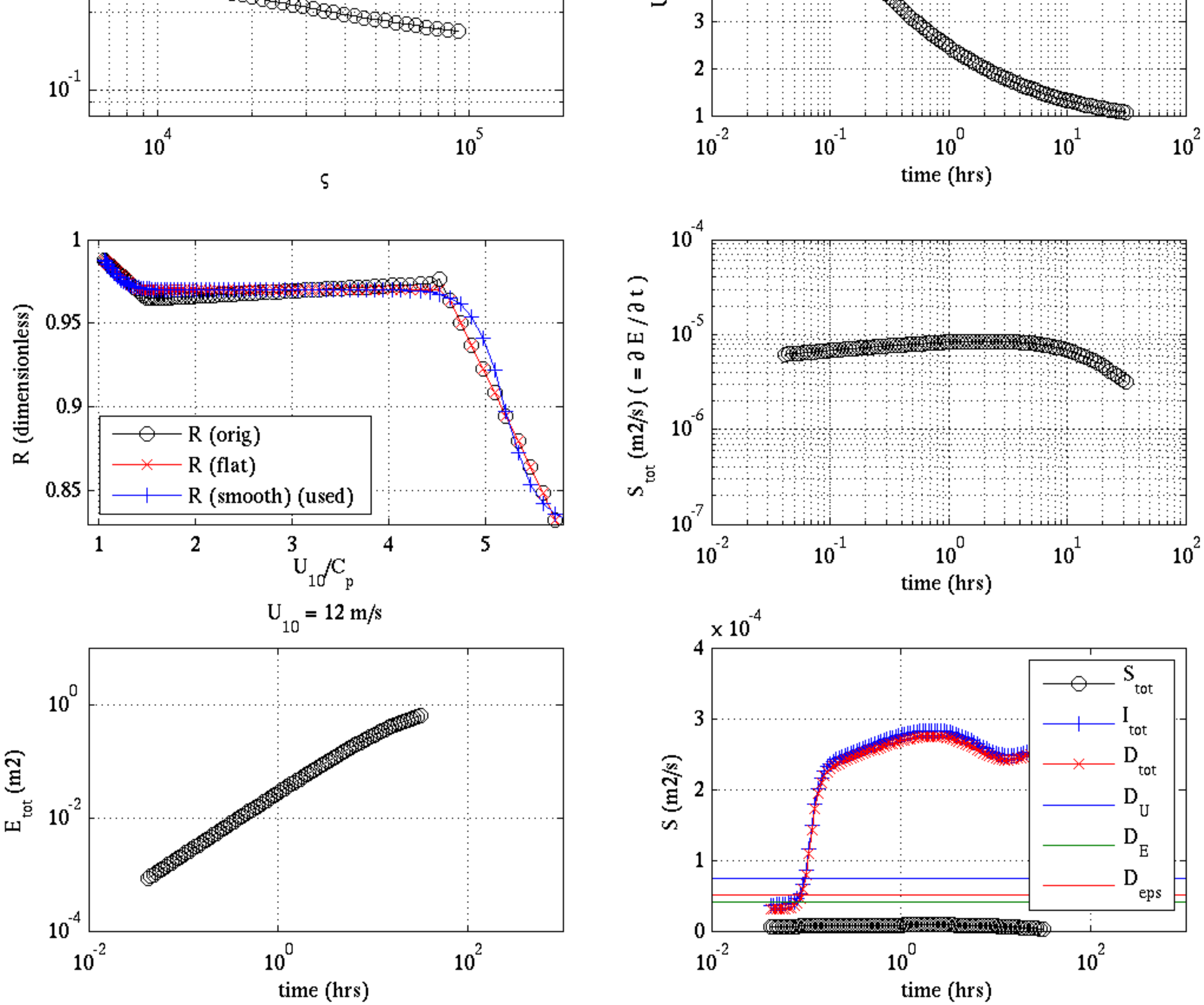
[3] The momentum analog to this would be $\tau_{rst} = 3/8\, \partial E/\partial x$. This simple formula assumes a $\cos^2(\theta)$ directional distribution (Hasselmann et al. JONSWAP 1973, Mitsuyasu 1985).



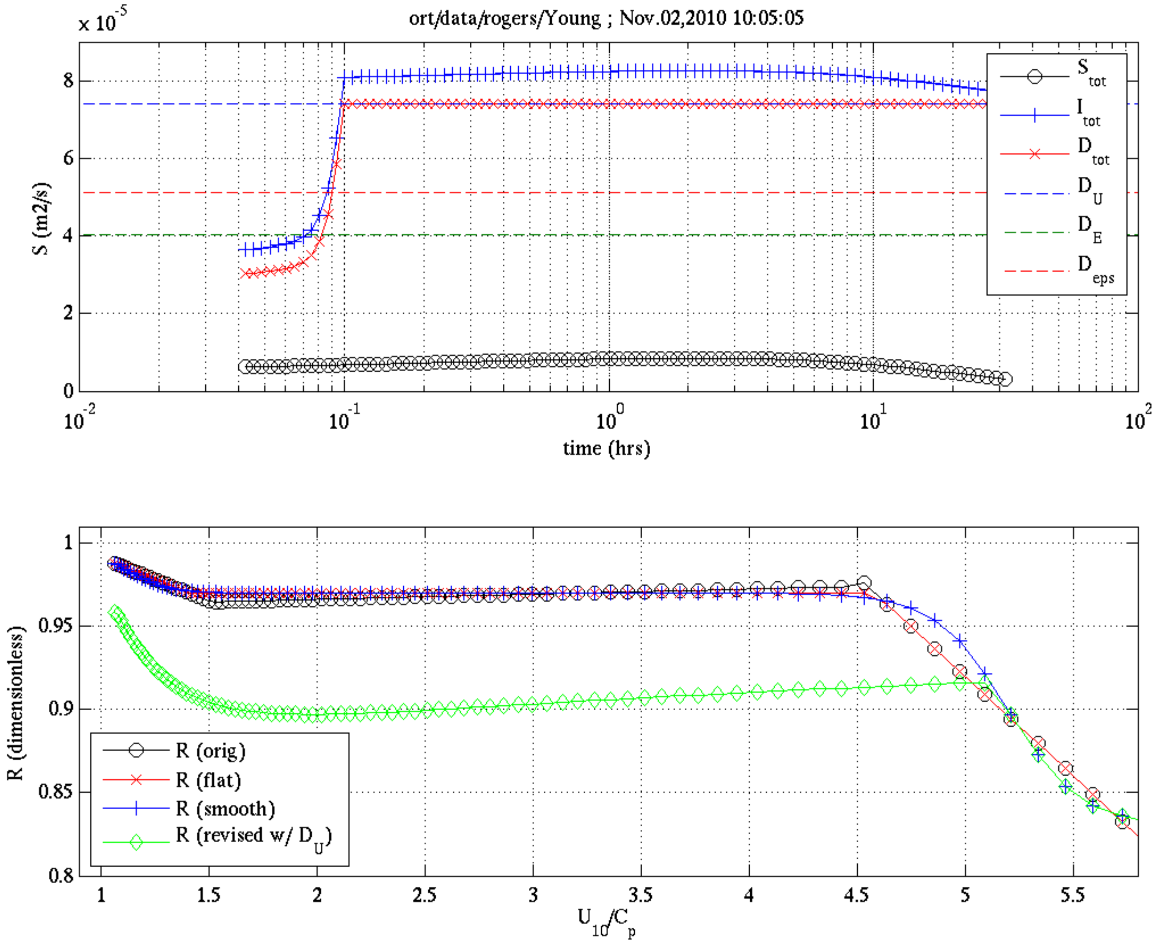
Babanin et al. (JPO 2010)

FIG. 4. Two parameterized forms of the dissipation ratio: R_{linear} [Eq. (14)] and R_{smooth} [Eq. (15)]. Computations were performed for the Combi spectra at the different stages of wave development U_{10}/c_p for wind speed $U_{10} = 10\ \text{m s}^{-1}$.

$$\int S_{\text{ds}}(f)\,df = R\int S_{\text{in}}(f)\,df. \qquad (17)$$



analytical models only



analytical models only

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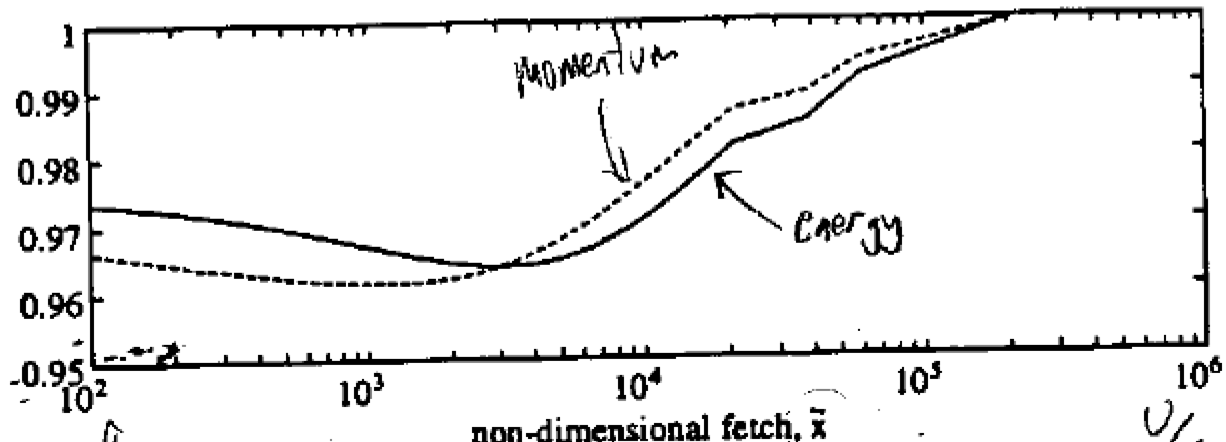
S_i = Large δ_r = small



$U/C_p = 4.5$ $U/C_p = 0.83$

Figure 6. The fraction of momentum (1 - $\underline{\tau}_r / \underline{\tau}_i$), (- -); and of energy (1 - $\underline{S}_r/\underline{S}_i$), (–) _ from the wind that is delivered locally to the surface waters. The non-dimensional fetch, $\bar{x}$ is related to the wind forcing parameter, U_{10}/C_p through Eq. (7). , not in reference