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Emerging Formulations for Revised Wave Physics

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Why did modeling technology evolve into the Third-Generation Paradigm?

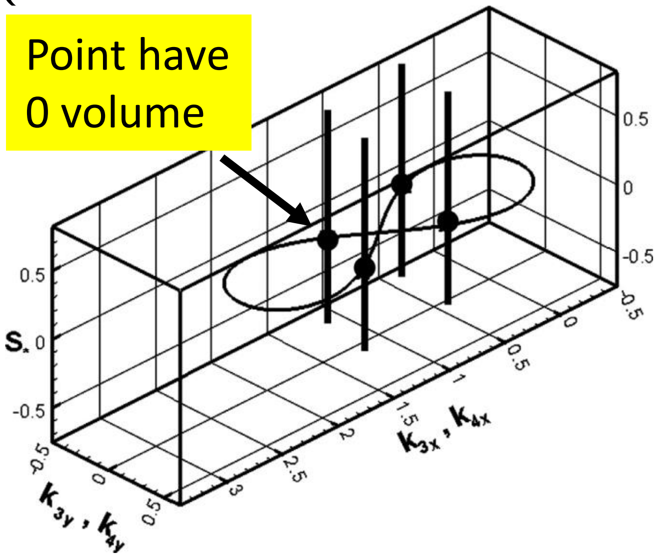
The initiation of 3G wave modeling was predicated on the need for an improved "detailed-balance" form for source terms, arguments included:

- **WAMDIG (1988): "in order to treat all of the complexity of the wave-generation process in critical applications, it is important to examine the detailed balance of energy within each frequency-direction component of the spectrum individually." This was to allow spectral shape to evolve properly.**
- **2G models would require too much tuning to perform this task in different basins.**
- **Spectra should evolve into correct shape since there would be no parametric constraints on shape.**
- **Thus, spectral shape provides a critical basis for the examining the correctness of the detailed-balance performance in model source terms in a 3G context**
- **How far have we come toward reaching this goal????**

How well do 3G models perform in terms of reproducing accurate spectral shapes??

- Sufficiently poorly that comparisons are quantified in terms of parameters of spectra rather than the spectra themselves
- Resio, Vincent and Ardag showed that
  - If one integrated around the entire locus of the Phillips 3-wave interaction locus, the actual result is ZERO, since that integral cannot transfer energy, action and momentum (due to its reduced dimensionality)

The DIA's form is the central first of two central problems that preclude existing 3G models from attaining the goal for which they were developed.



1. The DIA lacks the number of degrees of freedom needed to represent the dimensions of the full integral:
$(N_{ang} \times M_{freq})^2$ vs $N_{ang} \times M_{freq}$

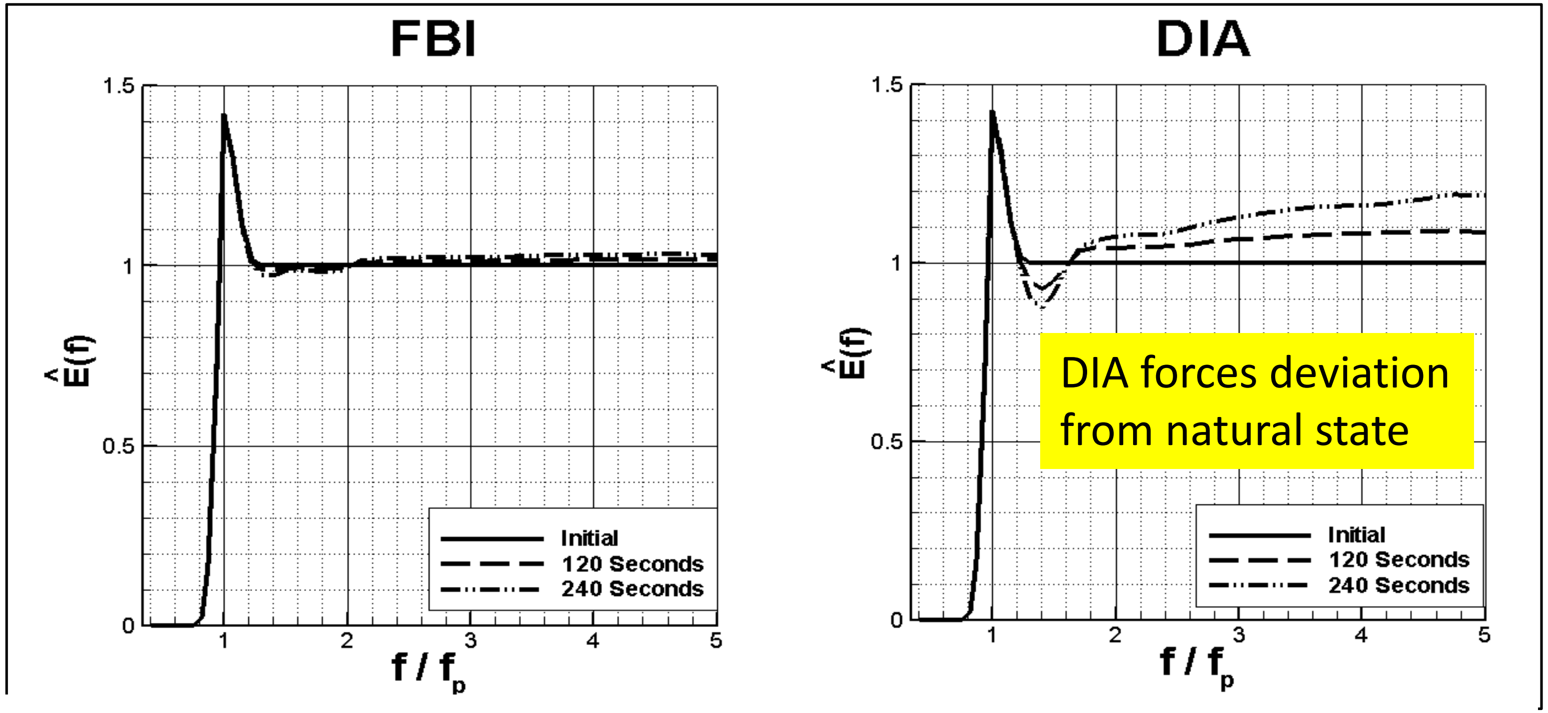
Outline of Presentation

- **After 34 years, has the 3G goal been achieved?**
  - Nonlinear interactions
  - Wind input
  - Wave breaking
- **Implications for a new wave modeling paradigm**

Results from Ardag and Resio (2019a)

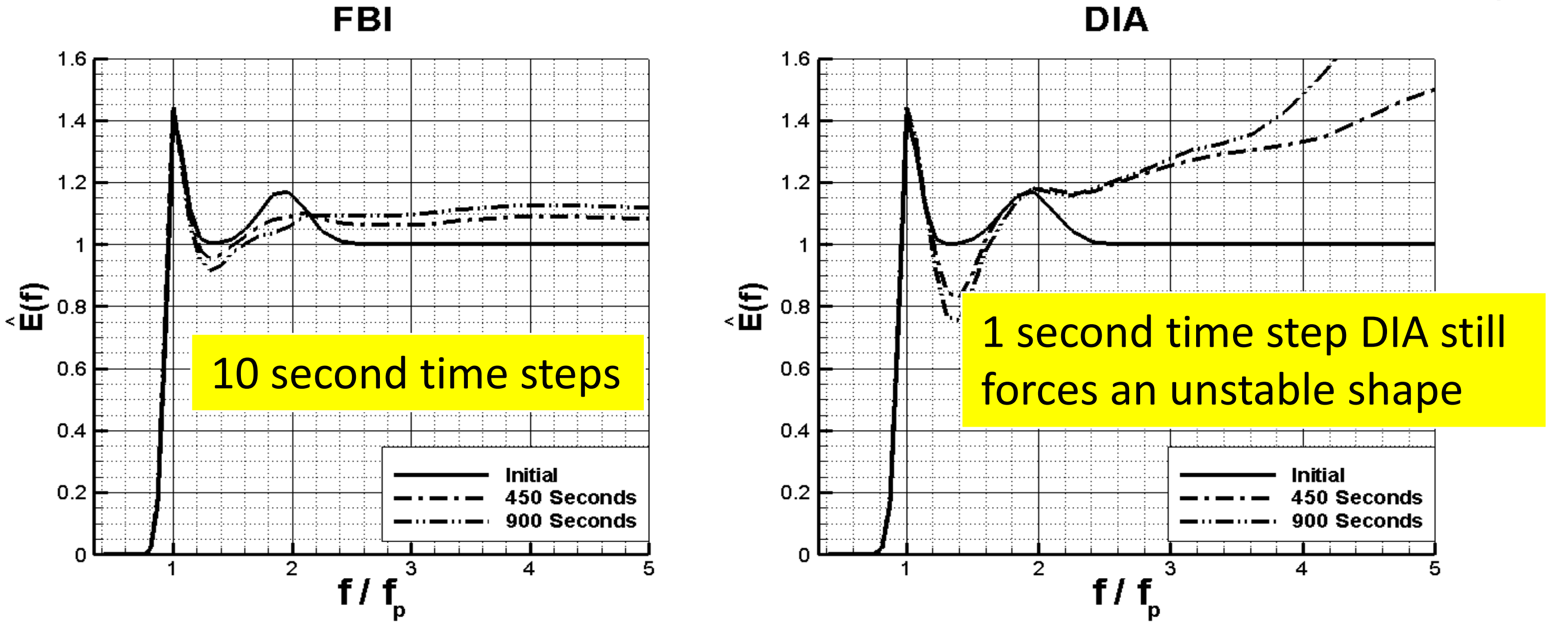
- The derivation of the method for converting the 3-wave integral used in the DIA to a 4-wave integral assumed that the spectral dimension could be properly scaled using a JONSWAP spectrum
  - Unfortunately, the basic form for 4-wave interactions is fundamentally coupled to an f^{-4} form rather than an f^{-5} form of the JONSWAP/Pierson-Moskowitz type. This meant that the other dimensions related to geometric factors in the Boltzmann integral were distorted and **cannot maintain self-similar behavior.**
  - Ardag and Resio examined the ability of the DIA to 1) maintain an equilibrium range in its proper form and 2) return an equilibrium range to the proper form following a perturbation
  - As noted previously, both of these criteria were the motivating reasons for moving to a 3G modeling paradigm for "better physics"

Tests of 240 second spectral evolution for a compensated spectrum using 10 second time steps



No Perturbation

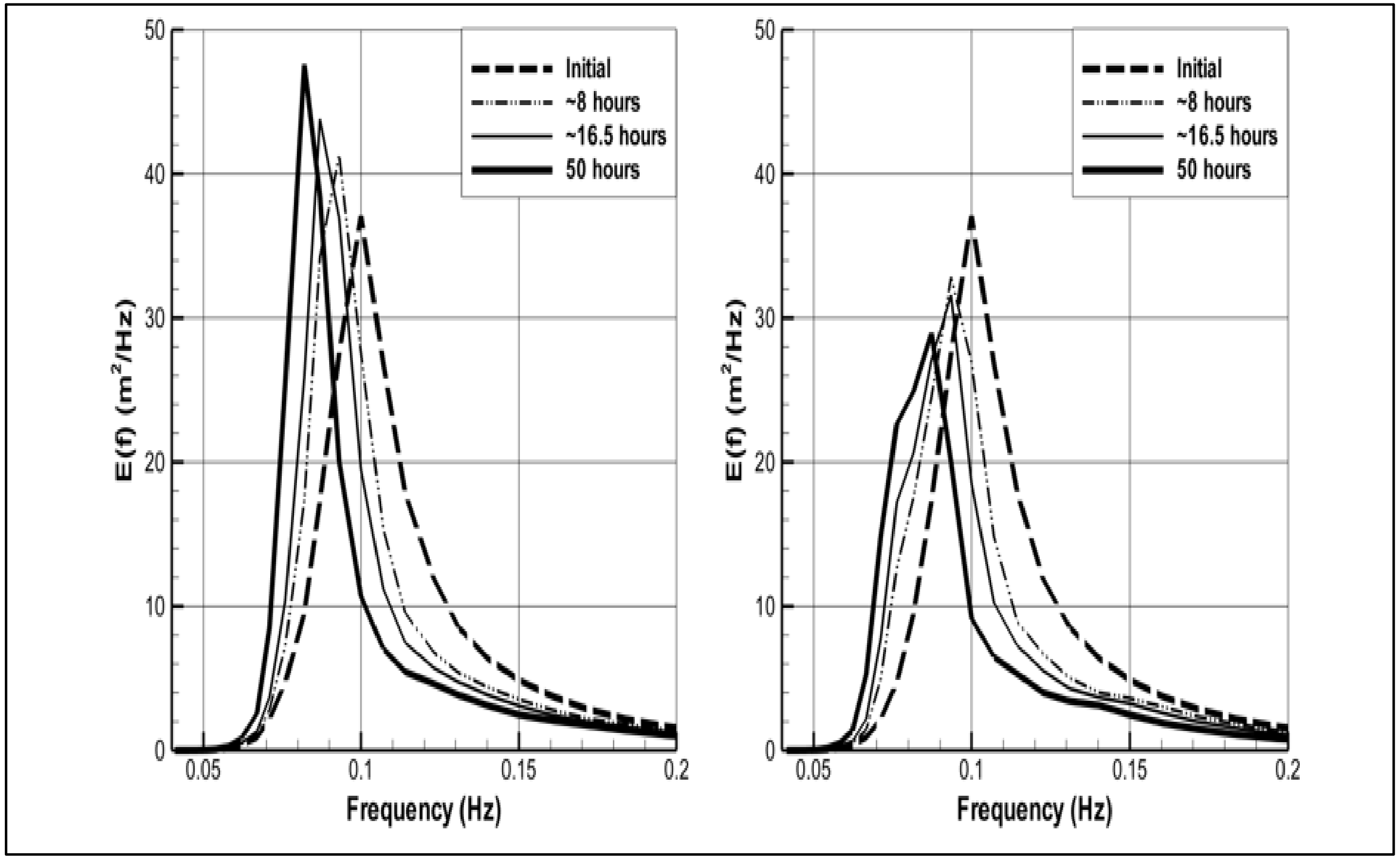
Both cases f_p =0.3hz
Compensated spectrum is $E(f)xf^4$



Perturbation at 0.34 Hz

This Distortion Affects Long-Term Evolution

- Long-term performance of spectral peak shifting deviates from spectral shape, peak period (affecting swell arrival time) and total energy.



Some Practical Consequences of the DIA

- Needs Limiters in operational models and much reduced time steps

- Swell Evolution deviates significantly from full integral behavior

- Thus, Spectral Shape Does not Evolve into Correct Shape even in Simple Cases

- Other source terms have to compensate for discrepncies in the DIA with forms that are not representative of their natural forms

New Work on Wind Input Source Term

- The concept that all spectral components retain an atmospheric perturbation coupled to a monochromatic-unidirectional spectral component, while it is superposed with many, many other components, has been shown to be unrealistic
- Miles theoretical basis assumes that resonant behavior is necessary to exchange energy between atmosphere and sea
- The leads to a behavior of the form:

$$\frac{\partial E(f)}{\partial t} \rightarrow E(f)f \quad \text{for directionally integrated spectra or with directionality}$$

$$\frac{\partial E(f,\theta)}{\partial t} \rightarrow E(f,\theta)f\cos(\theta)$$

Highly Resolved Numerical Studies Disagree

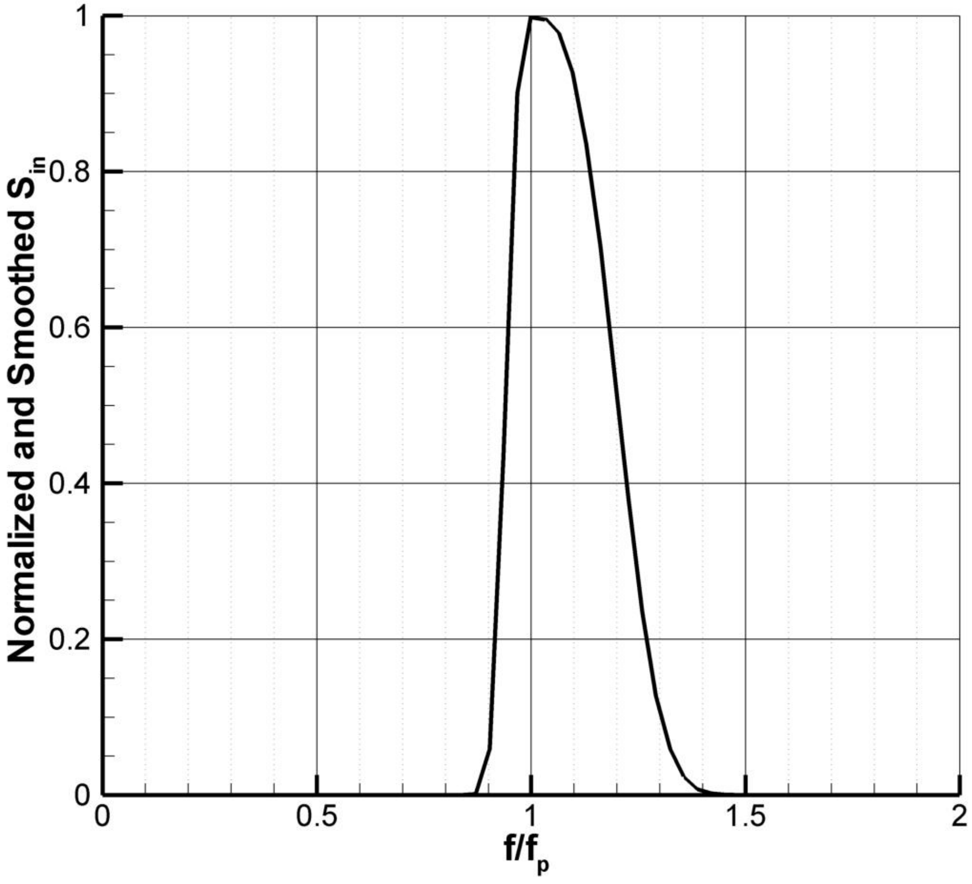
- Hao and Shen (2019), in a highly refined LES-HOS model show that the atmosphere responds to the sum of all of the upward velocities relatively rapidly
- As expected statistically from this, the combination of upward velocities, similar to the distribution of zero-crossing wave heights, produces a very peaked distribution of wind input into the spectrum at f_p and in the vicinity of the central angle around the peak sea angle within some distance of the wind direction
- Migration of the spectral peak is very dependent on S_{nl}, not dominated by wind input
- "**Shows good agreement with Russian model": Badulin, ZRP, etc."**

Comparison of Miles and New Source Term (Smoothed and Normalized)

Normalized and smoothed $S_{in}(f)$ from data generated by Hao and Shen (2019).

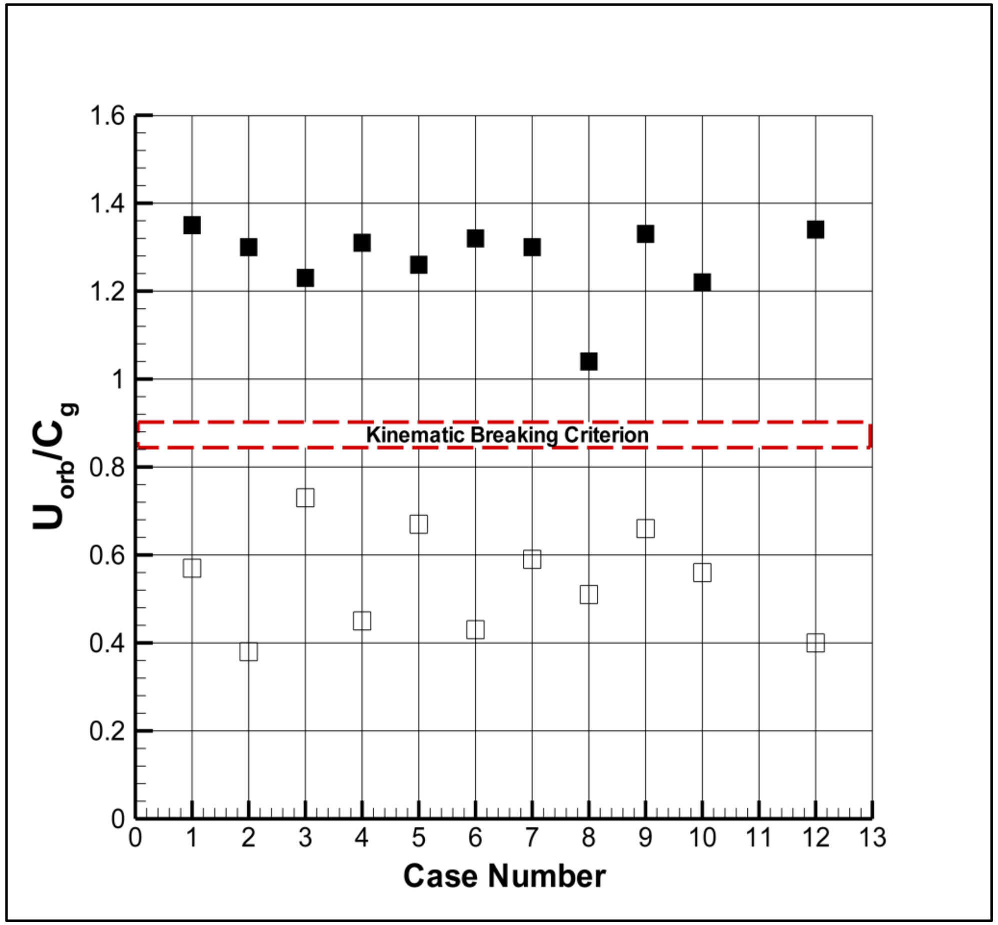
Angular pattern is similarly "tight" around the central angle

This shows why Hao and Shen did not think that S_{in} played a significant role in shifting the spectral peak in their simulations



The Wave Breaking Source Term

- Several independent groups of researchers have found that a single kinematic breaking criterion appears to hold in many different situations:
- See references included on the last slide
- Ardag and Resio (2019b) have recently shown that this can be extended into a spectral criterion for probabilistic spectral breaking that provides a consistent relationship to nonlinear fluxes and narrow-banded wind input



Energy Lost Per Breaking Event and the Lowest Frequency at which Breaking is Initiated

$$(1)\ f_b = \psi \frac{g}{(4\pi U_{orb})}$$

Defines the lowest frequency surpassing the breaking frequency per individual wave

$$(2)\ \Delta E_{brk_m} = \int_{f_{brk_m}}^{\infty} \alpha_5 g^2 f^{-5} df = \frac{\alpha_5 g^2 f_{brk}^{-4}}{4}$$

Defines the amount of energy lost in a single breaking event

$$(3)\ \frac{\Delta E_b}{\Delta t} = \frac{1}{t_{tot}} \left\langle \Delta E_{b_m} \right\rangle \approx \bar{f}_b \alpha_5 g^2 \frac{\sum_{m=1}^{N_{tot}} \bar{f}_{b_m}^{-4}}{4N_{tot}} = \Gamma_E^+$$

Defines the rate of breaking waves that at equilibrium it must equal the flux past this frequency f_b in this new paradigm

$$(4)\ \left(\frac{\Delta E_b}{\Delta t} \right)_{f_{ti}} = \Gamma_E^+$$

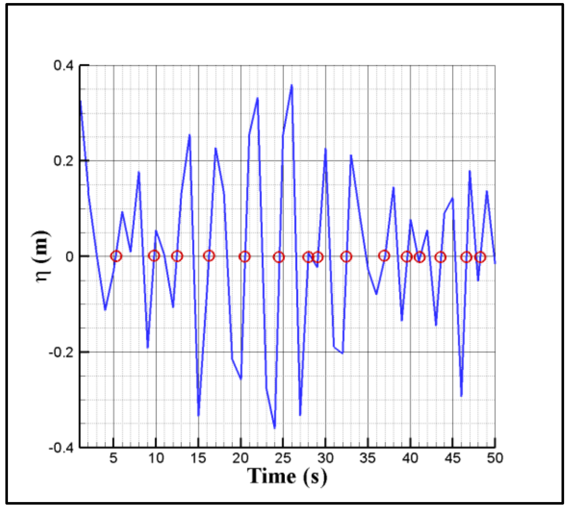
Closure is obtained from balance with nonlinear fluxes

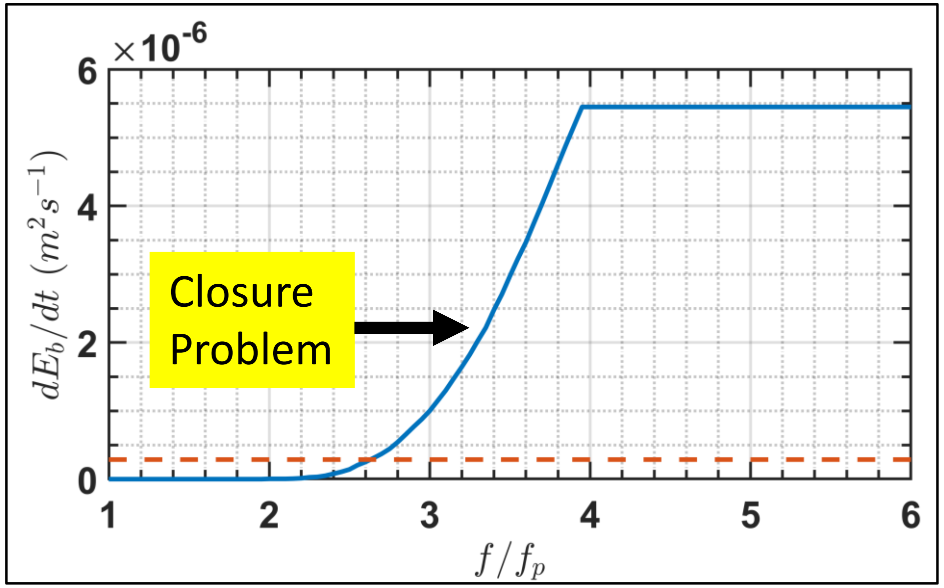
Methodology

- Probabilistic breaking is obtained by Monte-Carlo simulations to determine max horizontal velocities for individual up-crossing waves
- This is integrated step-wise in frequency to obtain a relationship between the number of waves breaking from the integral up to a given frequency

$$U_{orb}(f_{ifrq},t)=\sum_{i=1}^{ifrq}\sum_{j=1}^{N_{ang}} a_{i,j}\omega_{i,j}\cos(\varphi_{i,j}+k_i x_{i,j}-\omega_{i,j}t)\ \cos(\theta_0-\theta_j)\delta\omega\delta\theta$$

- Produces a cumulative rate of breaking as a function of frequency (whitecapping)





An Interesting Relationship Is Developed

$$(5)\ \Gamma(f_{fti}) = \alpha_4 \beta g f_{ti}^{-4} = \alpha_5 g^2 f_{ti}^{-5} = \frac{\langle \Delta E_{brk} \rangle}{\Delta t}$$

Note that this produces a balance between a fundamentally f^{-4} and f^{-5} spectral forms

$$(6)\ \frac{\lambda \beta^3}{g} = \frac{\alpha_5}{4} g^2 \bar{f}_b^{-3}$$

Using the form for fluxes and combining it with the breaking relationship using equation 4 from the previous slide yields

$$(7)\ \lambda \beta^2 = \frac{\alpha_4}{4} g^2 \bar{f}_b^{-2}$$

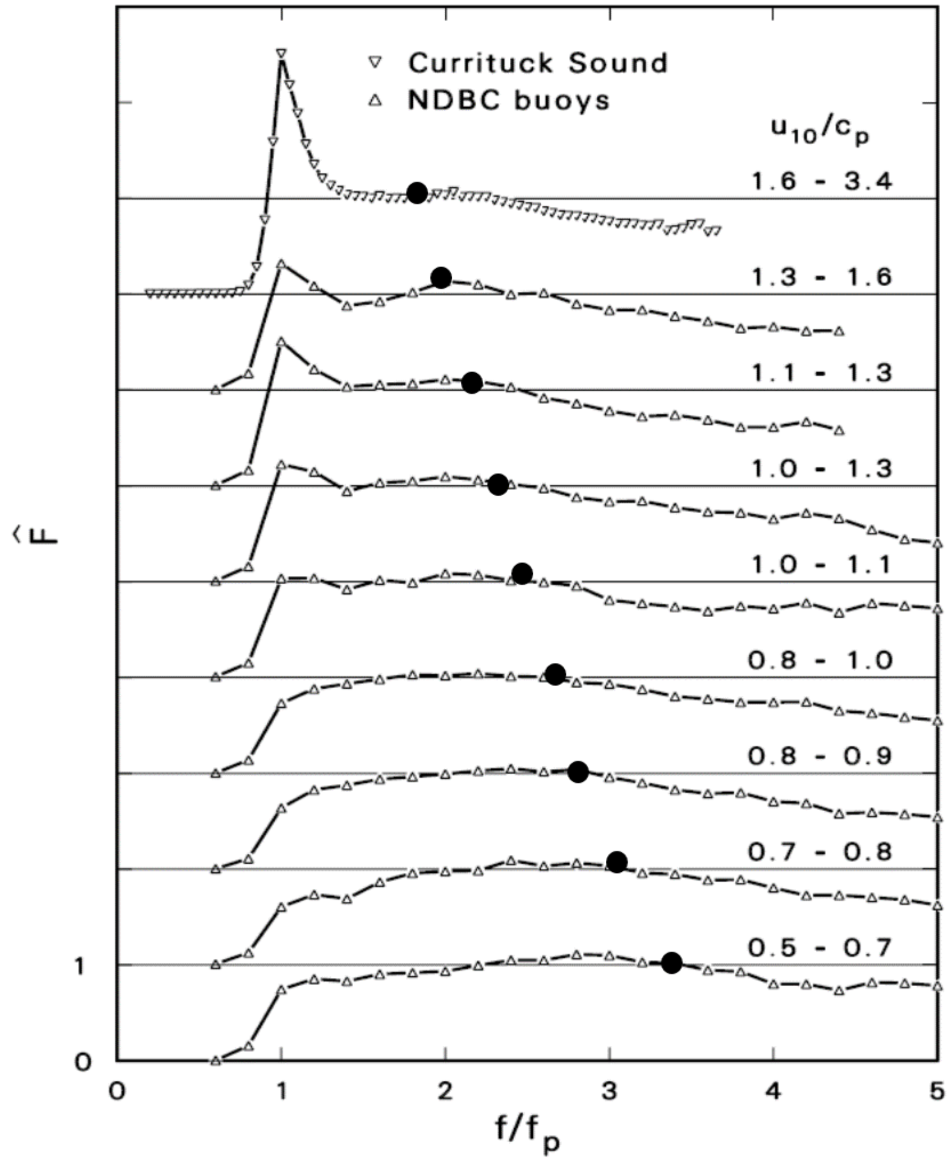
Combining these yields

$$\chi \beta = \frac{g}{\bar{f}_{brk}}$$

Which can be reduced to the form shown here, where χ contains empirical factors that relate β to wind speed and phase velocity

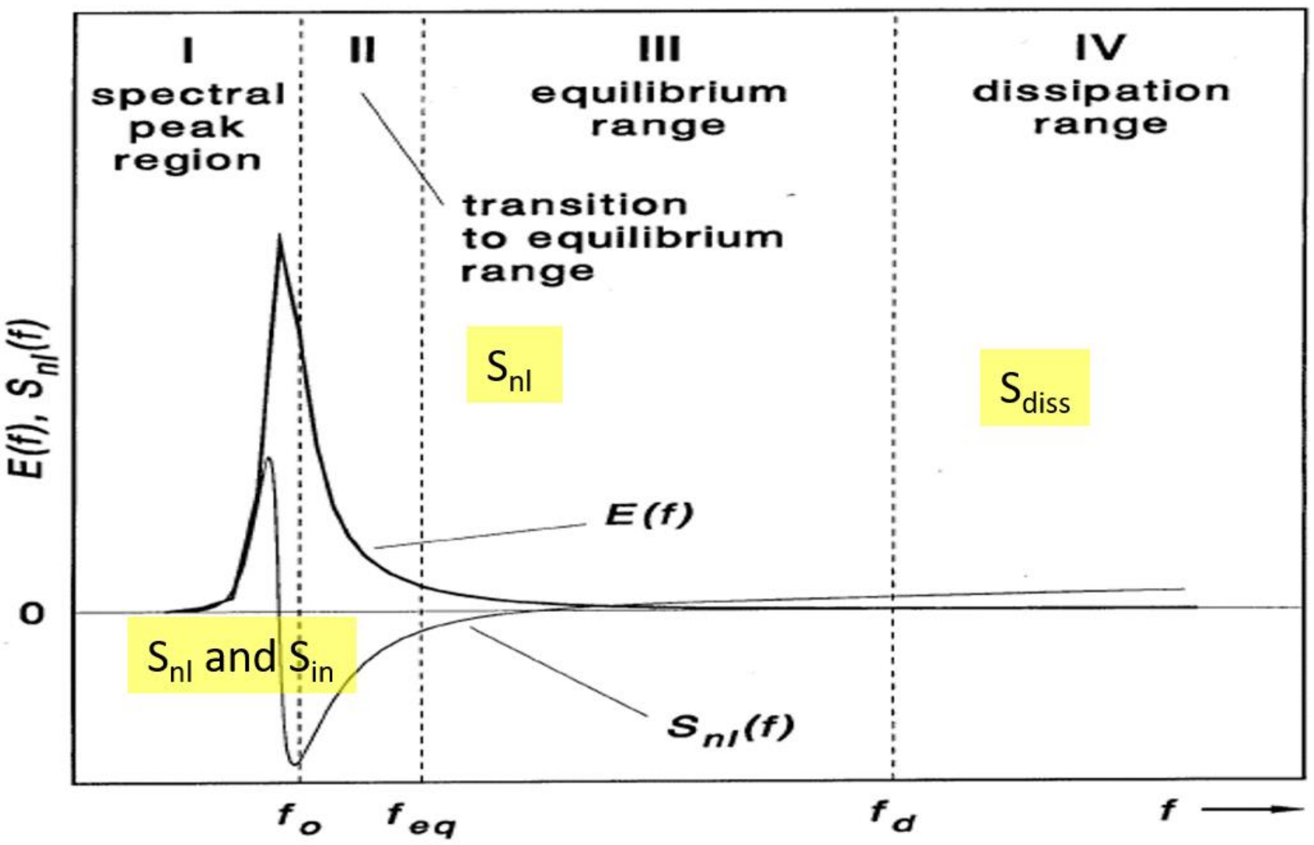
Does it agree with observations?

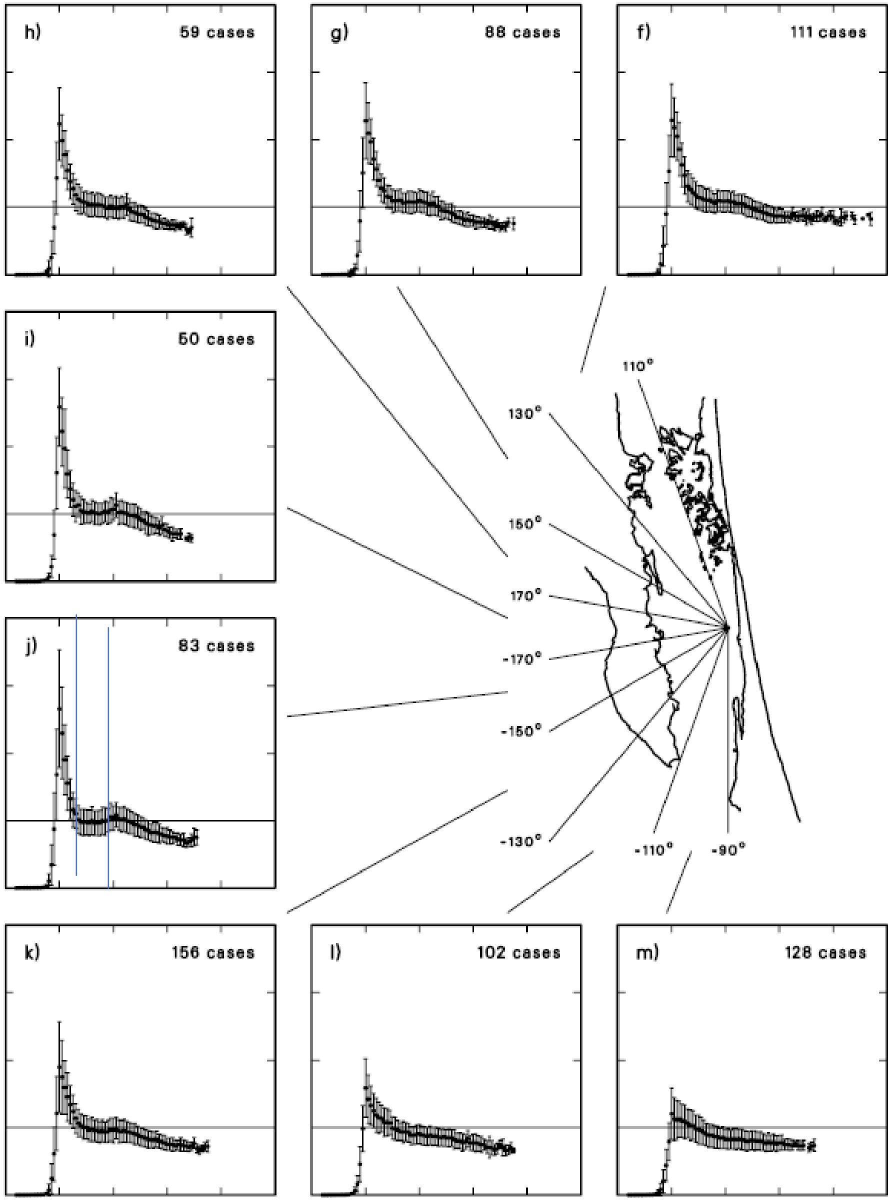
- Dots show location of transition frequency (from f^{-4} form to f^{-5} form at higher frequencies, using data from Long and Resio (2007) and the estimated flux constant from Resio et al. (2004)



Two depictions of emerging concepts for wave generation

Typical Spectral Perspective





Compensated Spectral Perspective

Conclusions

- It is time to move past the DIA and 3G modeling, since it does not produce the spectral shapes observed in nature and forces the need for distorted wind and breaking source terms
- Choices: 1) fix the nonlinear term and the other terms that are now compensating for erroneous flux divergence or 2) keep adding tuning knobs to 3G models with computer optimization of the wrong physics, 3) return to 2G physics since it is much, much faster and actually produces better spectral shapes
- The developing wave-generation physics is producing more and more evidence that options 1 and 3 are probably more fruitful than option 2. I prefer option 1.

References

- Ardag, D. and D.T. Resio, 2019a. Inconsistent Spectral Evolution in Operational Wave Models due to Inaccurate specifaction of Nonlinear Interactions. J. Phys. Oceonogr., 49, pp 705-722.
- Ardag, D. and D.T. Resio, 2019b. A New Approach for Modeling Dissipation Due to Breaking in Wind Wave Spectra, J.Phys. Oceanogr., in press.
- Barthelemy, X., M. L. Banner, W. L. Peirson, F. Fedele, M. Allis, and F. Dias, 2018: On a unified breaking onset threshold for gravity waves in deep and intermediate depth water. J. Fluid Mech., 841, 463–488, https://doi.org/10.1017/jfm.2018.93.
- Derakti, M., M. L. Banner, and J. T. Kirby, 2018: Predicting the breaking strength of gravity water waves in deep and intermediate depth. J. Fluid M, ech., 848, R2, https://doi.org/10.1017/jfm.2018.352.
- Hao, X., and L. Shen, 2019. Wind-wave coupling study using LWSS of wind and phase-resolved simulation of nonlinear waves, J. Fluid Mech.874, 391-425.
- Irisov, V., and A. Voronovich, 2011: Numerical Simulation of Wave Breaking. J. Phys. Oceanogr., 41, 346–364, https://doi.org/10.1175/2010JPO4442.1.
- Itay, U., and D. Liberzon, 2017: Lagrangian Kinematic Criterion for the Breaking of Shoaling Waves. J. Phys. Oceanogr., 47, 827–833, https://doi.org/10.1175/JPO-D-16-0289.1.
- Long, C. E., and D. T. Resio, 2007: Wind wave spectral observations in Currituck Sound, North Carolina. J. Geophys. Res. Ocean., 112, C05001, https://doi.org/10.1029/2006JC003835.
- Resio, D. T. , C. E. Long, and L. C. Vincent, 2004: Equilibrium-range constant in wind-generated wave spectra. J. Geophys. Res., 109, C01018, https://doi.org/10.1029/2003JC001788.
- Resio D.T., Vincent,C. L. and D. Ardag, 2016. Characteristics of directional wave spectra and implication for detailed-balance modeling, Ocean Modelling, 103, 38-52.
- WAMDI Group, 1988. The WAM model, A third-generation ocean wave prediction model, J. Phys Oceanogr., 18, 1775-1810.
- Waseda, T., and Coauthors, 2014: Deep water observations of extreme waves with moored and free GPS buoys. Ocean Dyn., 64, 1269–1280, https://doi.org/10.1007/s10236-014-0751-4.
- Zakharov, V., Resio, D., and A. Pushkarev, 2017: Balanced source terms for wave generation within the Hasselmann equation. *Nonlinear Process Geophys*., 581–597, doi:doi.org/10.5194/npg-24-581-2017

Questions???

PS: It’s the winds, stupid…..