
Ocean Waves Workshop

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Deficiencies in the Physics of Existing Operational Wave and Surge Models

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DEFICIENCIES IN THE PHYSICS OF EXISTING OPERATIONAL WAVE AND SURGE MODELS

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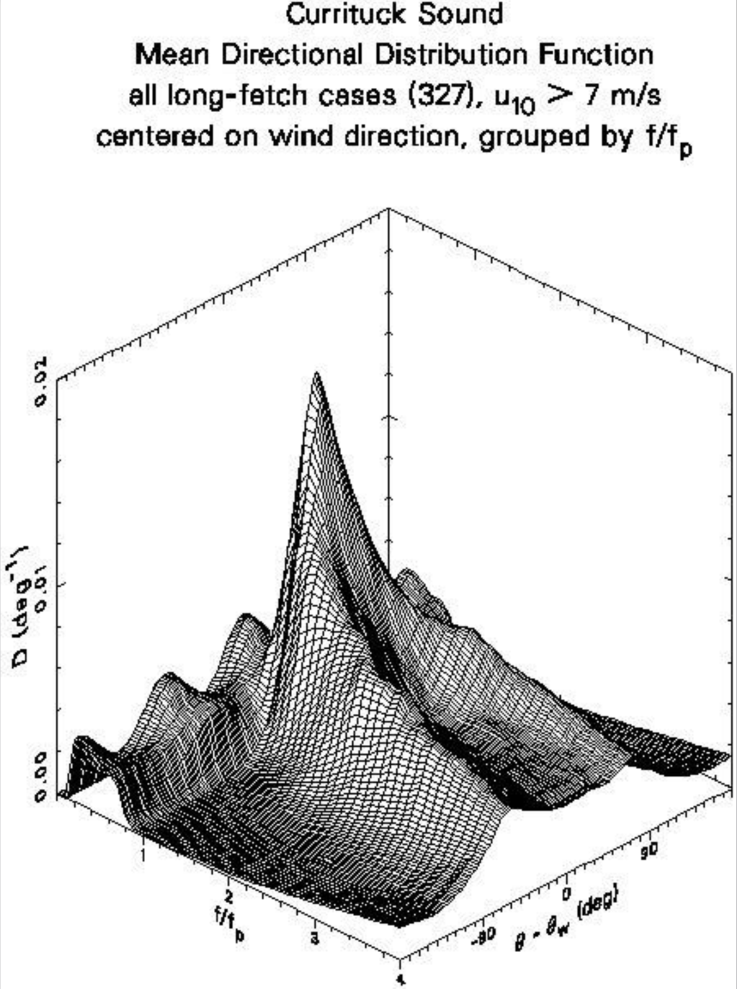


Introduction

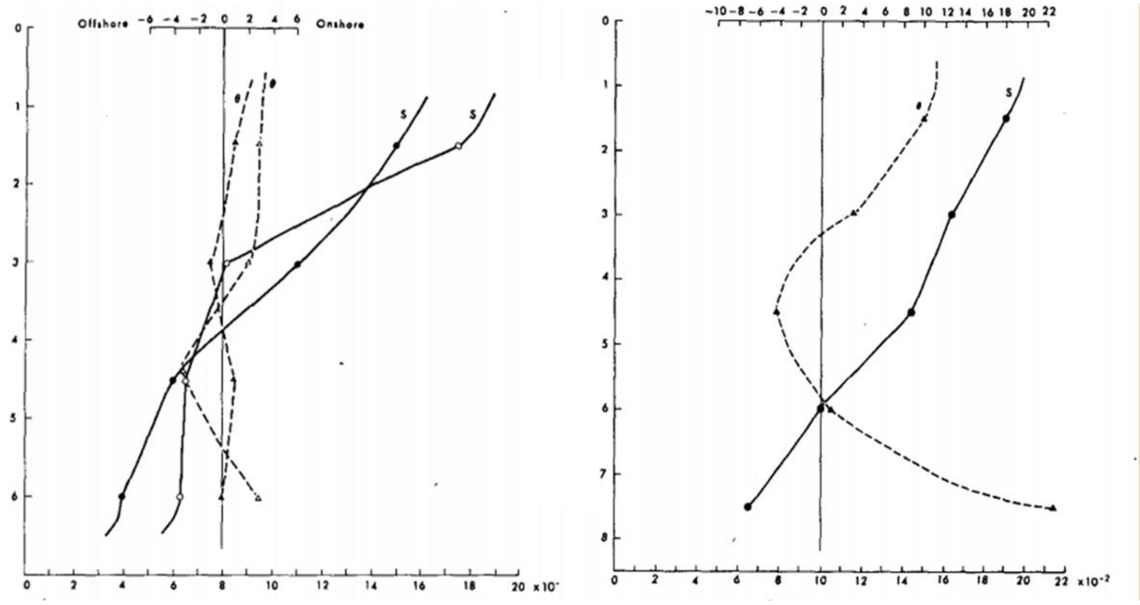
- The need for accurate ocean and coastal models continues to increase
  - Coastal resilience
  - Emergency/Military Operations
  - Weather prediction

- A very significant problem exists with respect to the number of “tuning knobs” that must be used to optimize the performance of surge and wave models

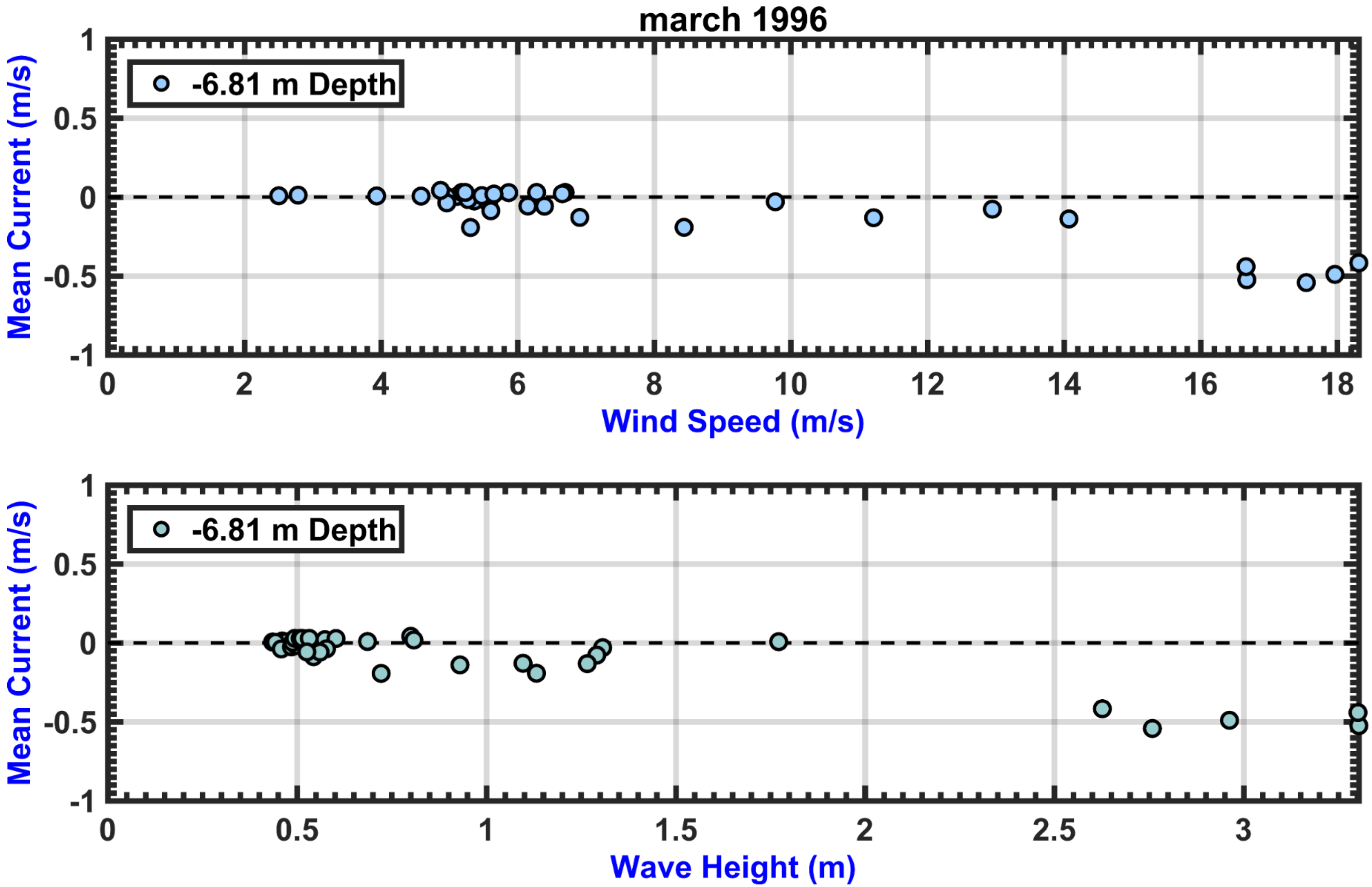
Existing Work

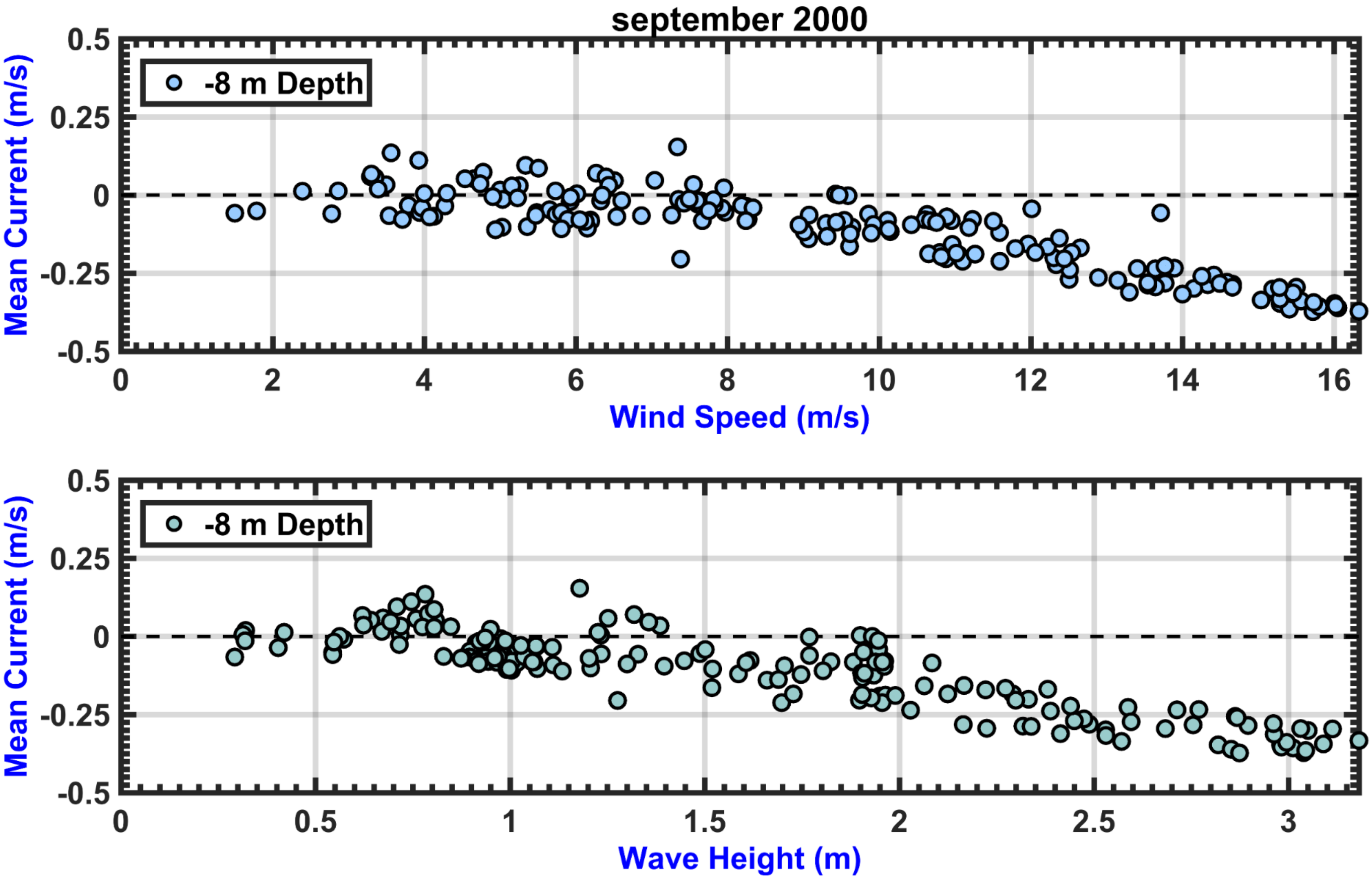
- The beginning of storm surge prediction started with observational data, and empirical models.
- With the arrival of computers in the 60’s, computational models became common
- Due to computational speed and processing power limitations, two dimensional depth integrated (2DDI) are typically the computational model most often used for forecasting and hindcasting storm events.
  - Westerink, J. J., et al., 2008, Dawson, C. et al. 2011, Mastenbroek, C. G., et al. 1993, and others
- These models all used depth averaged velocities (i.e. speed and direction of current averaged over the water column to have one mean value for each)

Observational studies have shown this is not the case…



Speed and Direction (positive from shoreline) from Drogue Experiment at Florida Gulf Coast study site (Murray, 1975), winds on average around 4m/s.


march 1996
-6.81 m Depth
Mean Current (m/s)
1
0.5
0
-0.5
-1
0
2
4
6
8
10
12
14
16
18
Wind Speed (m/s)
-6.81 m Depth
Mean Current (m/s)
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
Wave Height (m)


september 2000
-8 m Depth
Mean Current (m/s)
0.5
0.25
0
-0.25
-0.5
0
2
4
6
8
10
12
14
16
Wind Speed (m/s)
-8 m Depth
Mean Current (m/s)
0.5
0.25
0
-0.25
-0.5
0
0.5
1
1.5
2
2.5
3
Wave Height (m)

Objectives
Amanda Tritinger's PhD

1. Develop a three dimensional model that captures the velocity profiles throughout the water column
    - In cross- shore and along-shore directions
    - For varying wind speed/direction and at multiple depths with varying slopes
2. Find the relaxation time needed for given depths and stress forcing
    - To help understand trends throughout the water column
    - Ultimately used to project the 3D physical functions onto a 2DDI code (parameterized)
3. Investigate currents in open coastal areas
    - By examining the difference between 2D and 3D observed flows

Approach

- The primary driver of coastal surge is transfer of momentum transmitted to the water column in situ by winds and momentum produced by waves traveling over a given distance (Resio & Westerink, 2008).
  - $\tau_s = C_d \rho_a W^2$
- The following were developed to represent momentum balance (Murray, 1975);
  - $\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + fv + K\frac{\partial^2 u}{\partial z^2}$
  - $\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial y} - fu + K\frac{\partial^2 v}{\partial z^2}$
    - For the approximation done is her dissertations, it was assumed that the pressure gradient was initially zero.
    - dt was half a second
    - dz was dependent on the depth (i.e. depth was broken up into 40 segments, dz was the height of each)
    - K is 0.4, the von Kármán constant

Approach

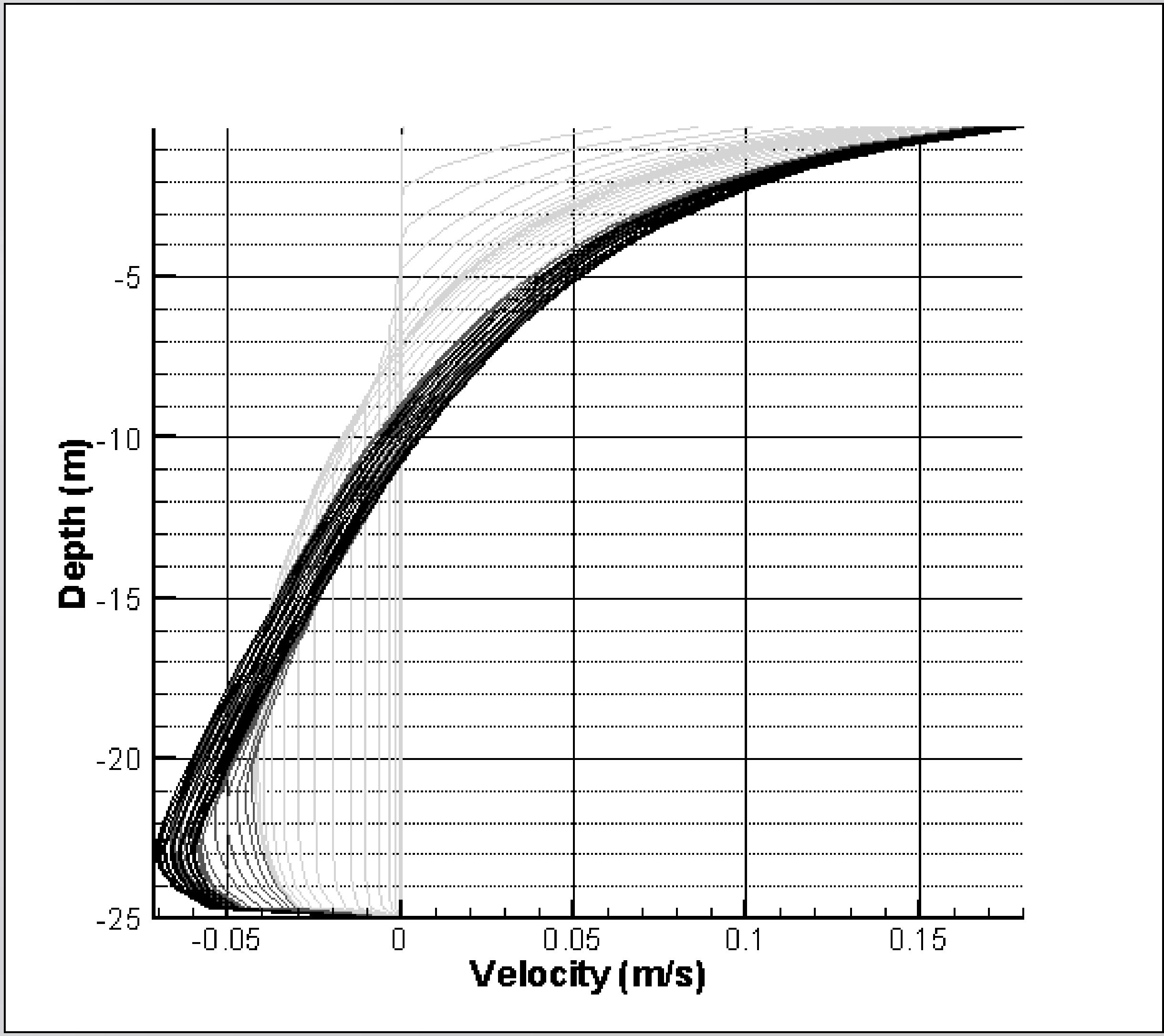
- After the addition of both wind stresses and bottom friction equations 4 and 5 were derived;
  - $U^{n+1} = U^n + \left[fV^n - g\frac{dh}{dx} + \left(\frac{\frac{\rho a}{\rho w} C_d U_w^2}{H} cos\theta \right) - \frac{C_b \overline{U}^2}{H} \right] dt$
  - $V^{n+1} = V^n + \left[-fU^n - g\frac{dh}{dy} + \left(\frac{\frac{\rho a}{\rho w} C_d U_w^2}{H} sin\theta \right) - \frac{C_b \overline{V}^2}{H} \right] dt$

Results

Velocity Profiles in the Cross-Shore Direction for Selected Runs.

Bottom friction is directed back toward the coast and is not ZERO.

Surges are underpredicted but tuning can adjust the results



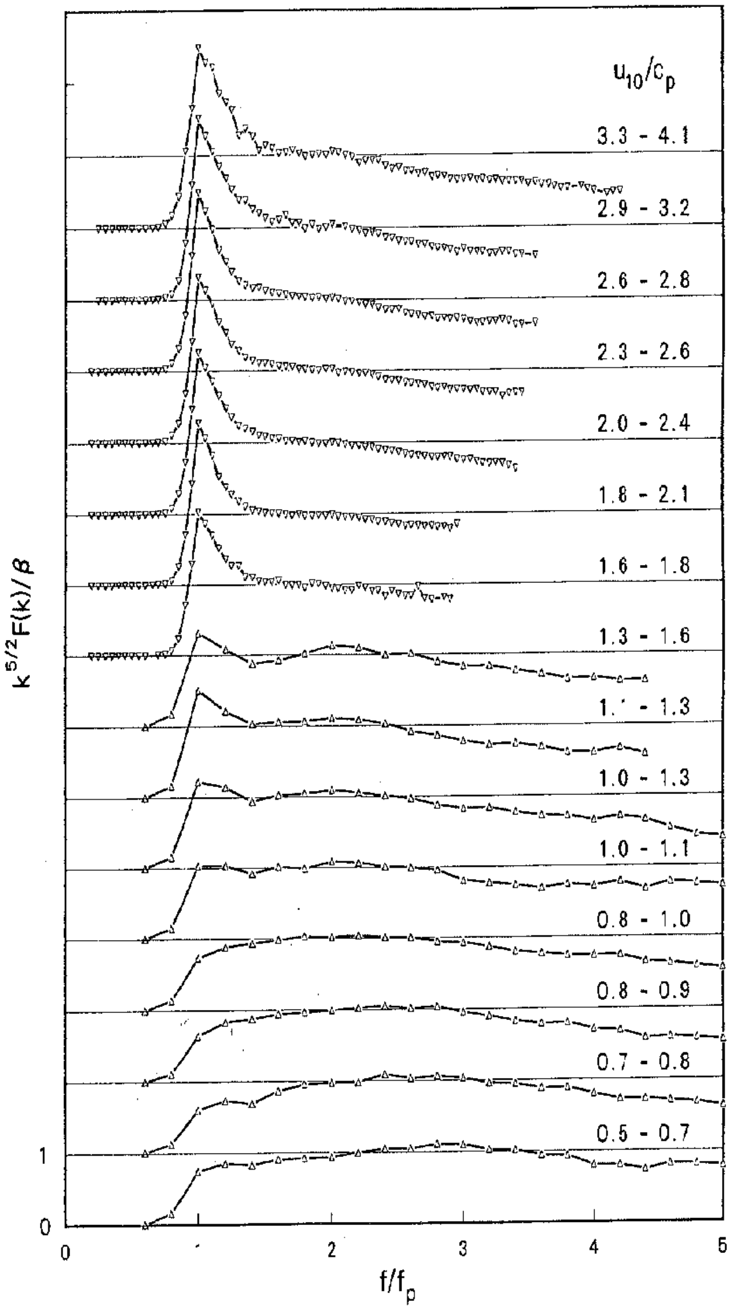
WAVES

Motivation

- Operational wave modeling has made great strides over that last decade or so
- Skill scores continue to improve in terms of their ability to predict integrated wave parameters such as wave height and mean period

However:

- There are many terms in the operational models which are optimized empirically to match the integrated parameters but not for spectral shape
- Spectral shape continues to elude the model in terms of 1) spectral peakedness, 2) angular distributions, and 3) energy levels and shape of equilibrium range



Problems?

Coastal waves still live in a fundamentally monochromatic, unidirectional world

All three source terms are fundamentally parametric with N degrees of freedom (actual problem is NxN).

Wind input, breaking and nonlinear interactions have been shown to be incorrect in recent publications

Long-distance propagation neglects diffraction

MOTIVATION

- The initiation of 3G wave modeling was predicated on the need for an improved “detailed-balance” form for source terms
- 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.”
- 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 in model source terms in a 3G context

Methodology

1. Quick review of spectral shapes
2. Problems with existing source terms?
3. Potential new source terms
    - Snl
    - Wind input
    - Dissipation
4. Some test results
5. Conclusions

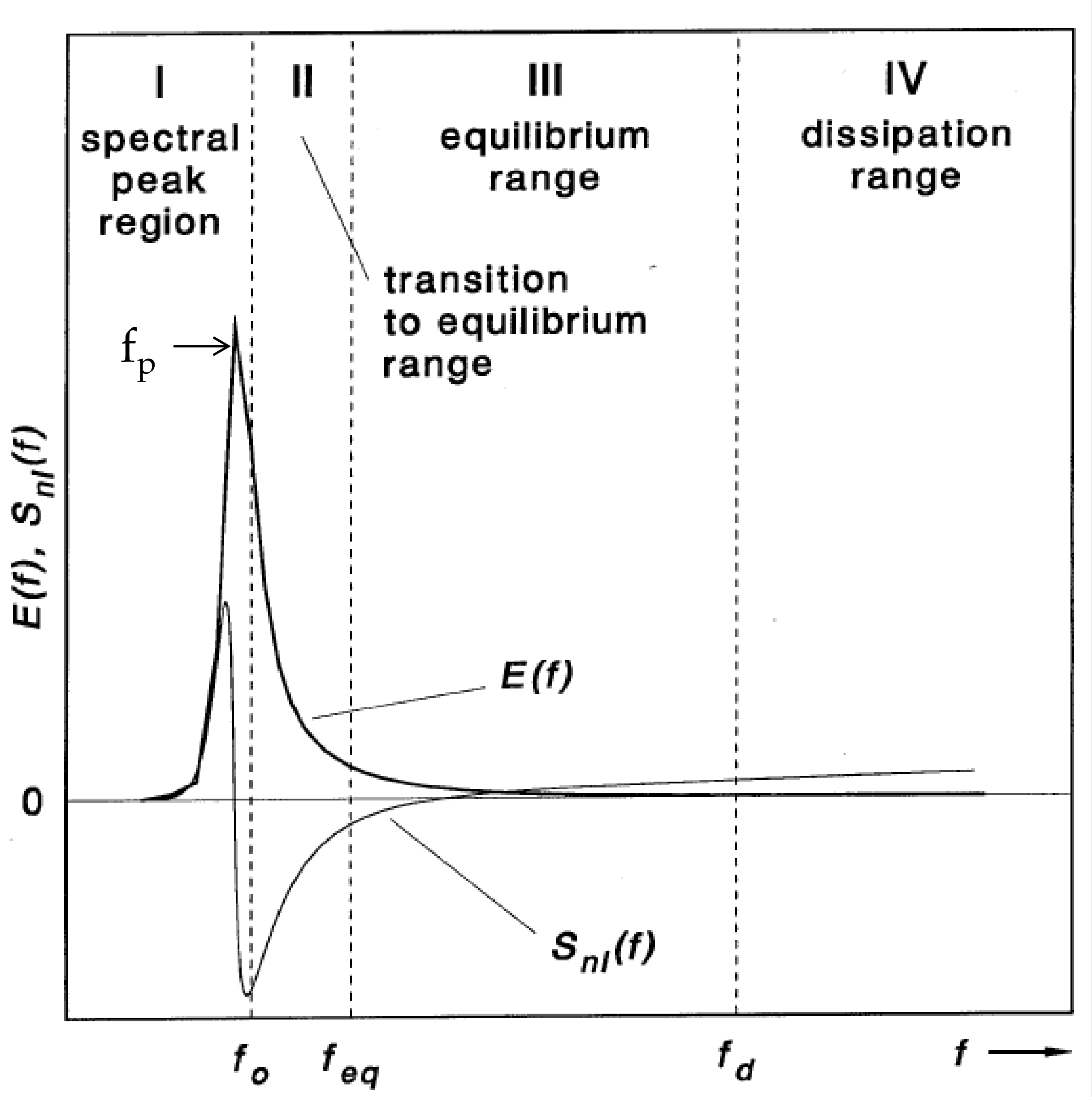
Spectral Shape

Four frequencies:

f_p peak frequency

f_0 "0-flux" frequency

f_d high-frequency region dominated by dissipation



Wave breaking with α = universal constant, JONSWAP: $\alpha=\alpha(gx/u^2)$

Phillips, 1958 $E(f) \sim \alpha_5 g^2 f^{-5}$

Wind input with α_4 = universal constant x energy flux from atmosphere

Toba, 1974 $E(f) \sim \alpha_4 u g f^{-4}$

where

α_4 is the equilibrium range coefficient and

u is term with units of velocity.

Wind input with α_4 = universal constant x momentum flux from atmosphere

Resio, Long, & Vincent 2004 $E(f) \square \alpha_4 (u^2 c_p)^{1/3} f^{-4}$

Where
C_p = phase velocity of spectral peak

Wave breaking (or something) changes the source balance at some transition frequency (f_t) above the spectral peak

Forristall, 1981 $E(f) \sim \alpha_4 u g f^{-4} \quad \rightarrow \quad \sim \alpha_5 g^2 f^{-5}$

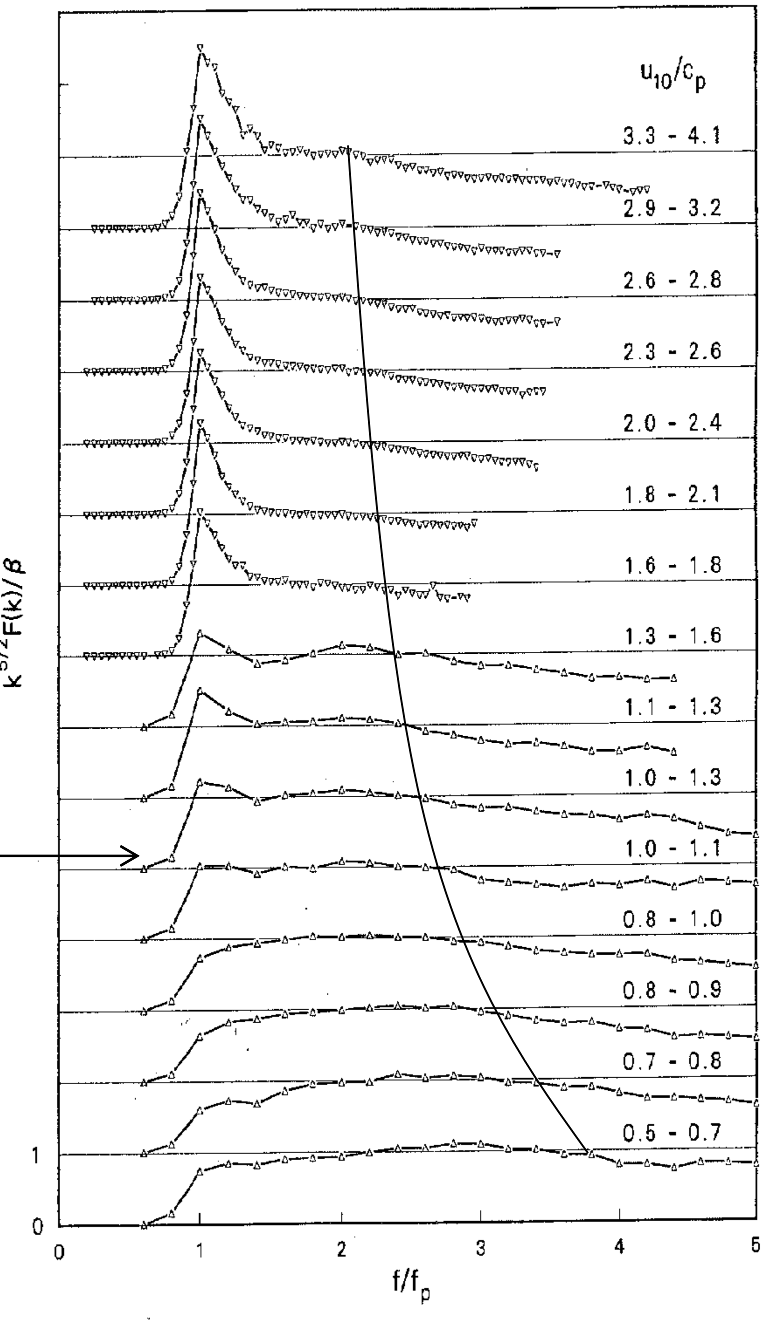
for $\hat{f}\ (= u f g^{-1}) > const.$

Many spectra from around the world are shown here, is what is termed a compensated spectral form.

In deep water this is an f^{-4} form with its energy level scaled by momentum flux

FULLY-DEVELOPED FORM ? ⟶

Note that the “fully developed” form fits nicely into this pattern but is not an “end-point” to it.



Source Terms

- **Nonlinear wave-wave interactions**

  (4-wave, resonant)

- **Wind input**

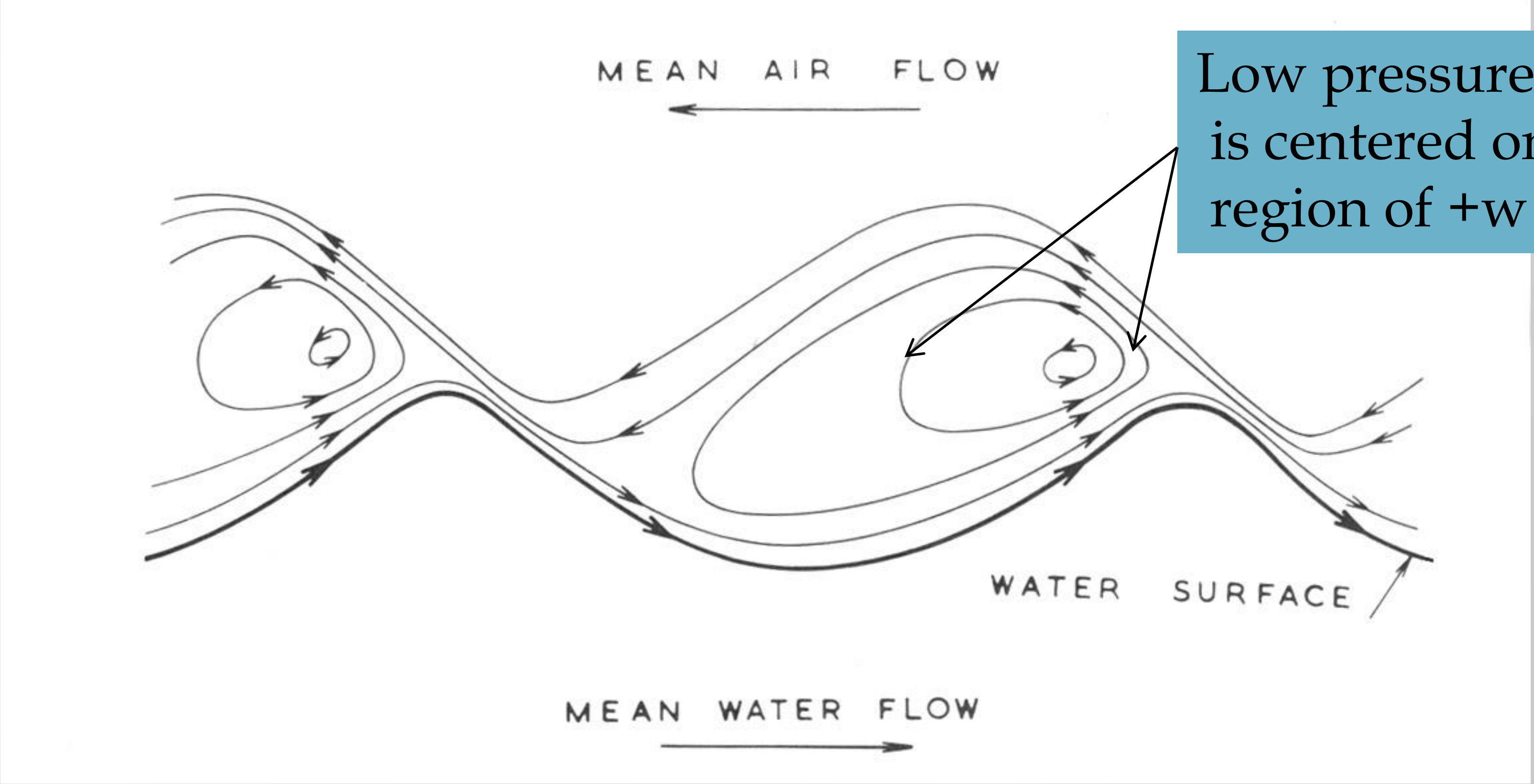
- **Wave dissipation (breaking)**

Wind Input

Miles postulated a mechanism by which momentum from a shear flow can transfer momentum from the atmosphere into the irrotational flow in the wave field for a *monochromatic unidirectional* wave

Basic concept is that δp and w must be correlated (where p is pressure and w is the vertical water motion)

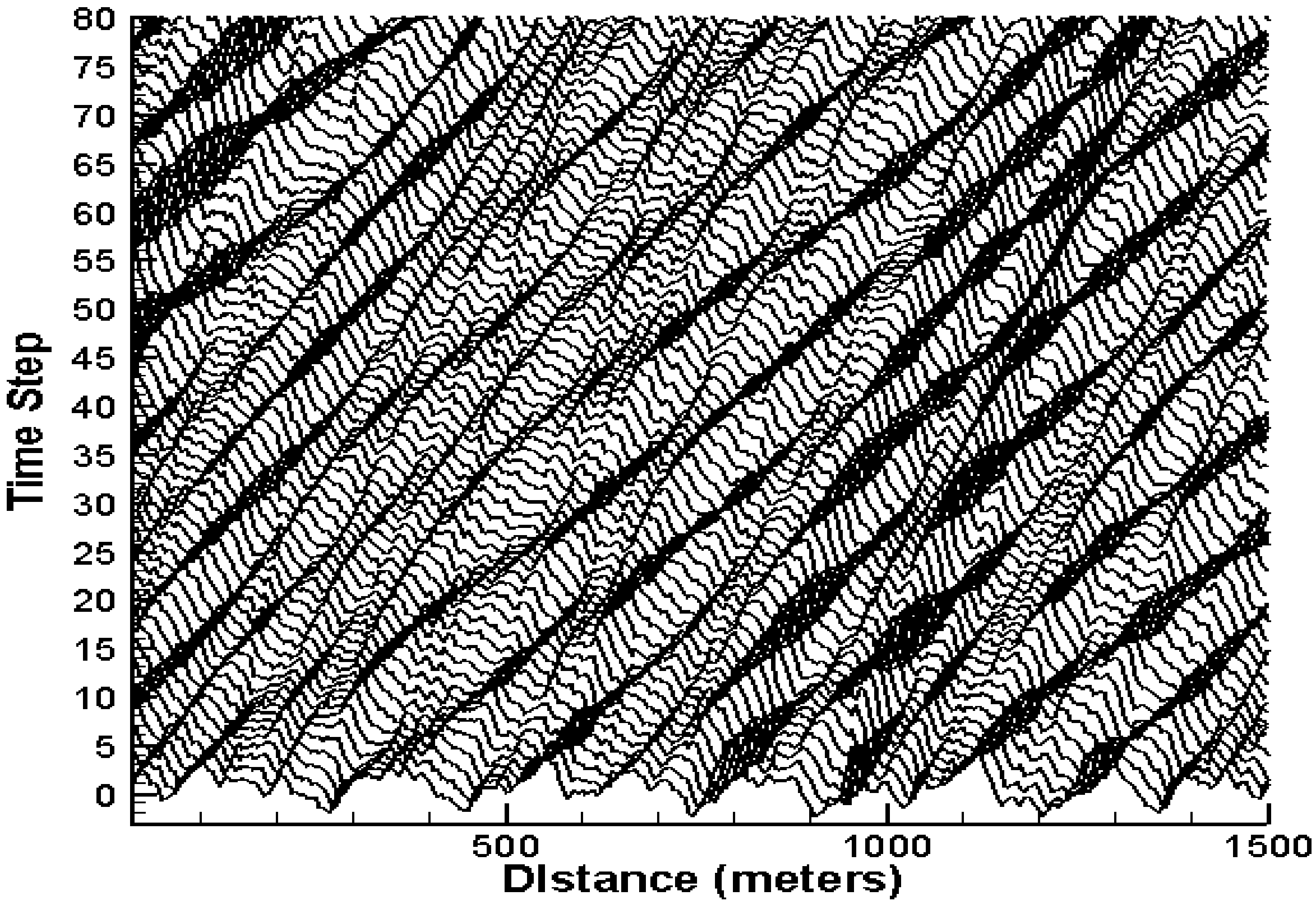
Extension to spectrum was linear superposition – but this assumes that pressure perturbations don’t see the real water surface



Low pressure is is centered on the region of +w

Flow field in air passing over waves "visualized" from smoke injected into a laboratory flume. Frame of reference is moving with the phase speed of the spectral peak. Note that the "cats eyes" are shifted with respect to the wave crests.

We have formulated a new wind input term which operates on the water surface not individual spectral components



Our new source term estimates the pressure perturbations over moving water surfaces, which varies in time and space. Pressure perturbations are created by the superposition of spectral components not individual components

Wind Input

Monte Carlo simulations of water surface create moving pressure perturbations which are linked primarily to the large waves and travel with these waves for some number of wave periods

Using the moving pressure patterns created by the surface, the covariance of δp and w is calculated for the random phase spectra which create the water surface.

The resulting covariance structure is strongly positive in the vicinity of the spectral peak and concentrated near the direction of the wind

To convert to a wind input we normalize on expected momentum flux (only 1 free parameter – the percentage of total momentum entering the wave field which can be deduced from fetch growth measurements)

Wave Breaking: A new/old approach

- Irisov and others:
- Monte-Carlo simulations of dynamics of 2D, potential, and random surface gravity waves indicate that the dominant physical mechanism causing wave breaking appears to be the "concertina" effect (using the terminology introduced by Longuet-Higgins)

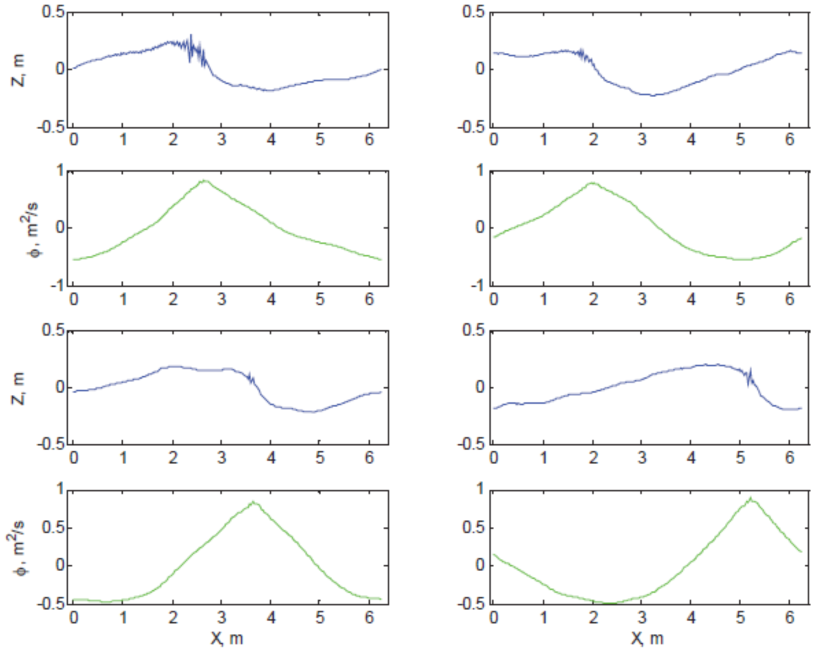


Figure 1. A few examples of the surface profile (blue) and velocity potential (green) at the of instability development.

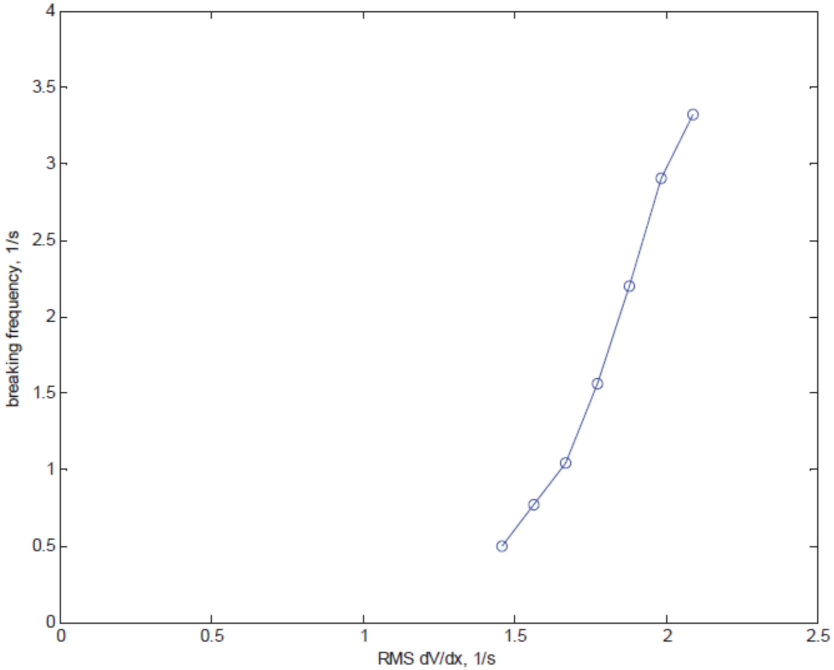
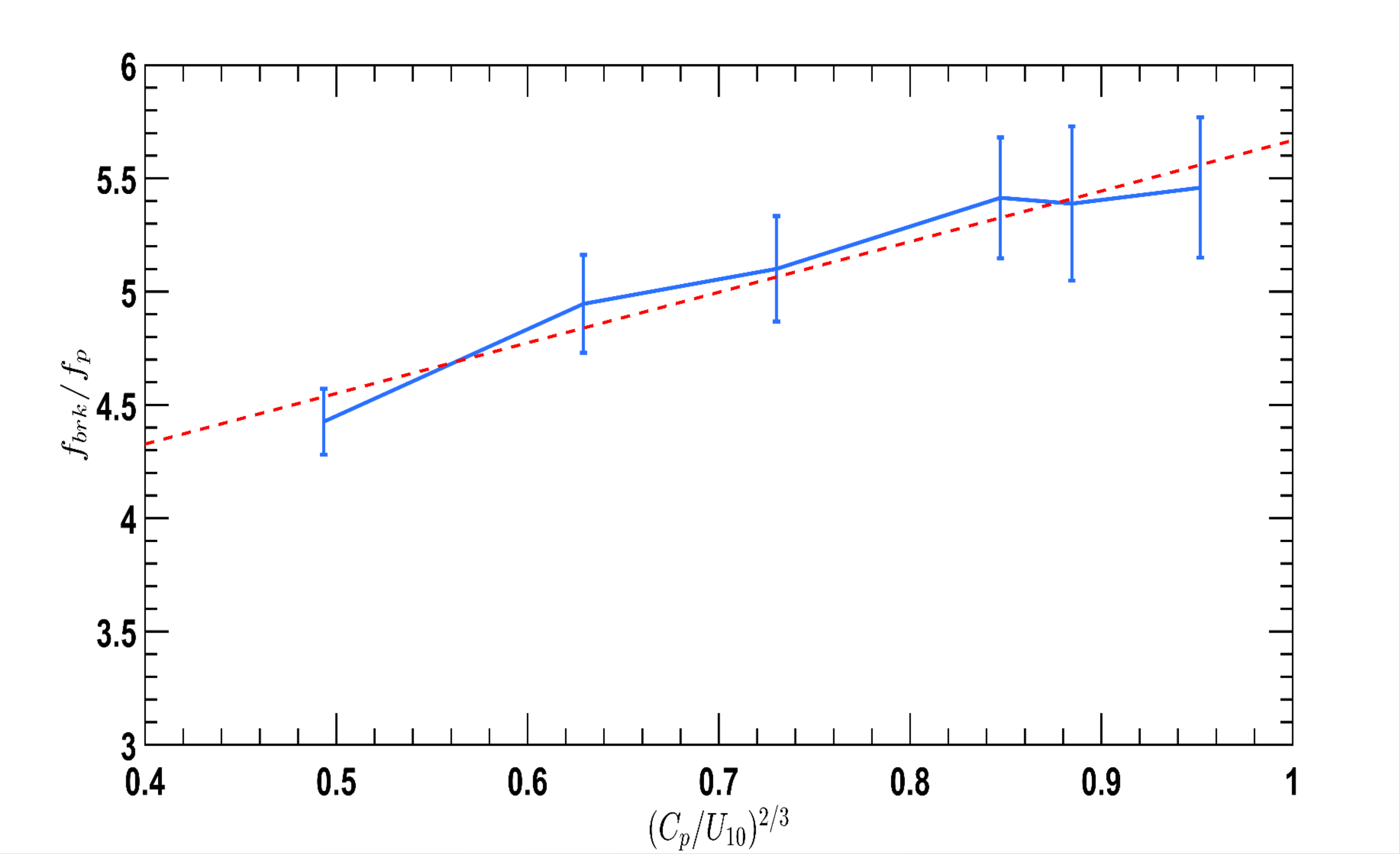


Figure 3. The dependence of the averaged breaking frequency on mean surfac current (negative) gradient.

Comparison of Transition Point Location



Conclusions:

- **To obtained more accurate spectral shapes in models, they must be built on an accurate detailed-balance Snl form**
- **Momentum, energy and action fluxes should be constant for modeled spectral shape in the equilibrium range**
- **Existing source terms do not accomplish this**
- **New wind input & dissipation terms postulated here appear to provide reasonable agreement with observations – dissipation paper in review**
- **The stationary, fully-developed sea appear may be a bad paradigm for source term balance: particularly for low-frequency wave energy in the ocean**

QUESTIONS??