ON MODELING SPECTRAL DISSIPATION DUE TO WAVE BREAKING FOR OCEAN WIND WAVES

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THIS TALK…..

- Part A reviews key observational aspects associated with wave breaking

Part B describes our recent progress on spectral wave modeling:

The overall focus of this talk is how the availability of new breaking wave data has allowed us to:

- ***refine the dissipation and wind input source terms***
- ***provide reliable directional wave spectra forecasts***
- ***validate our breaking wave forecasts***

A. OBSERVATIONAL BACKGROUND

MOTIVATION includes extending present coastal and open ocean forecast model capabilities to include wave breaking and breaking-induced effects including *greatly enhanced air-sea fluxes* (wind stress, sea spray, gas flux,..) and *upper ocean mixing*.

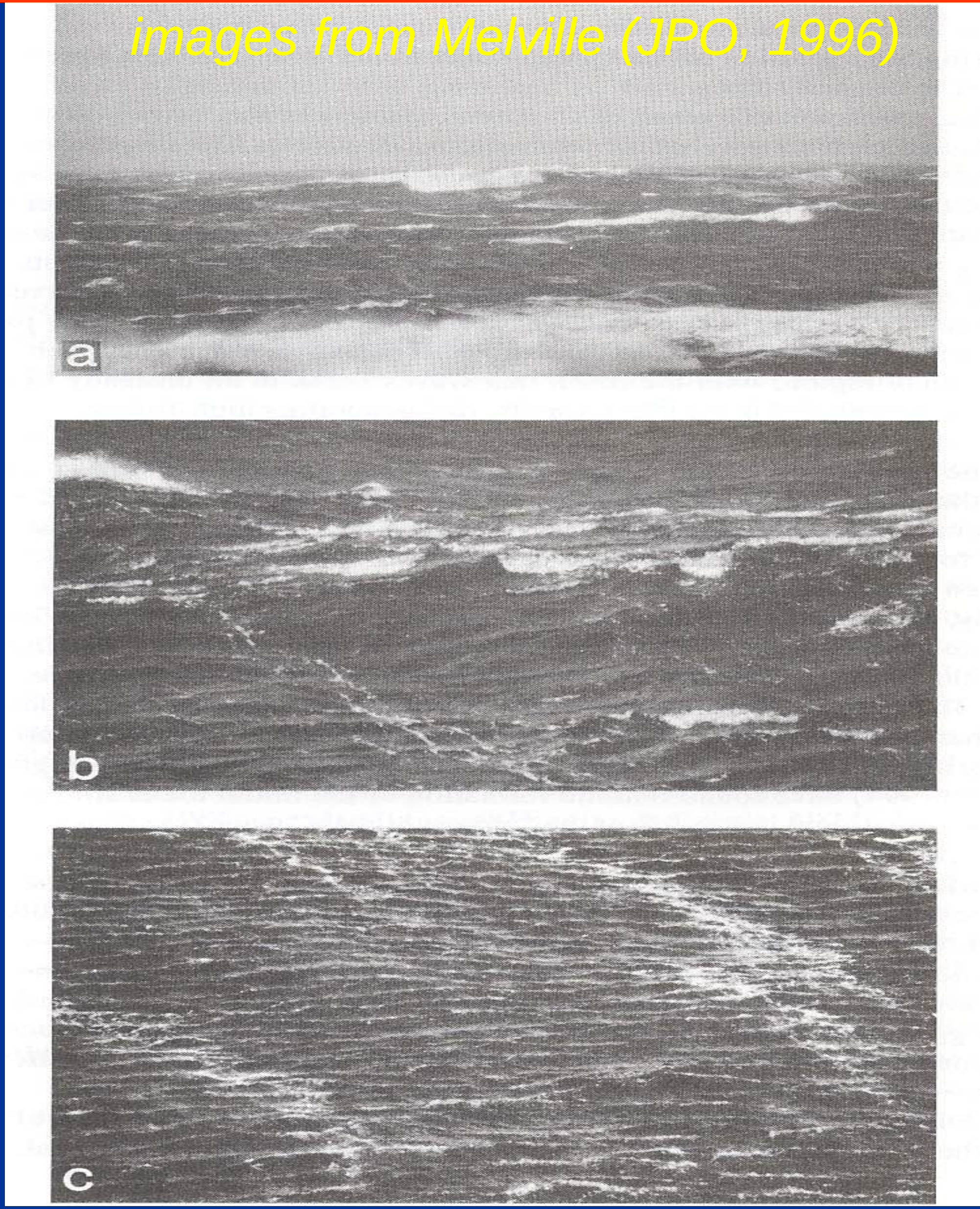
MODELING ISSUES

PHYSICAL DOMAIN: breaking is a complex interfacial process - it is associated with wave energy focusing. In deep water, *nonlinear wave group modulation* plays an important role. This is not described in current 3G spectral models.

SPECTRAL DOMAIN: its representation is even more challenging and a physically based representation is explored here.

WAVE BREAKING OCCURS ON DIFFERENT SCALES DEPENDING ON WAVE AGE c_p/U_{10}

images from Melville (JPO, 1996)



DOMINANT SCALE

INTERMEDIATE SCALE

SMALL-SCALE

OVERALL CONSTRAINTS ON ENERGY AND MOMENTUM FLUXES FROM THE WIND TO THE OCEAN

Donelan (1998)

- almost all of the wind momentum and energy fluxes are transferred locally to the water column. Above wind speeds ~10 m/s, this occurs primarily via wave breaking

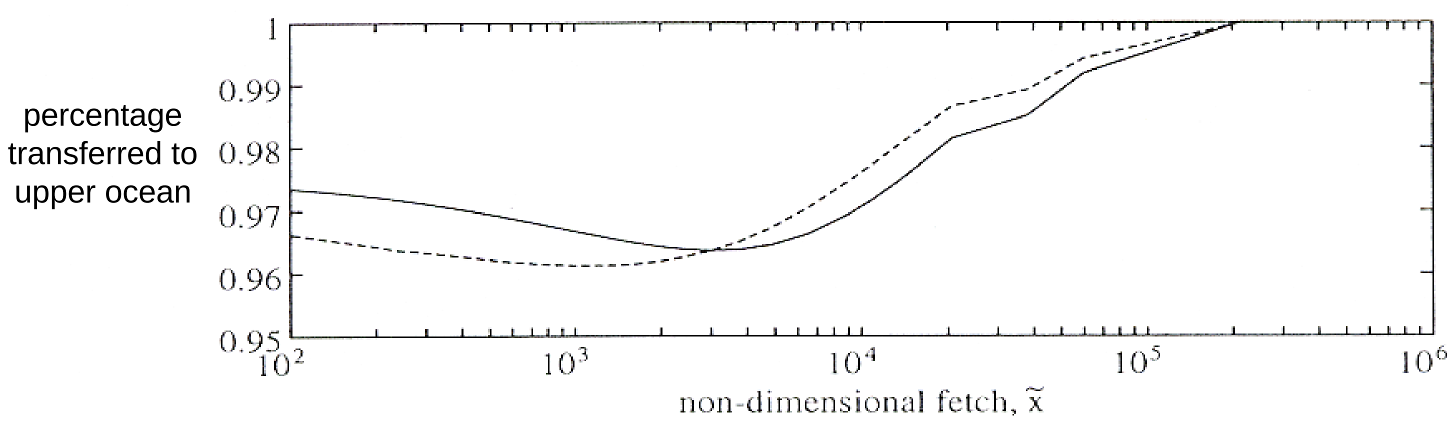
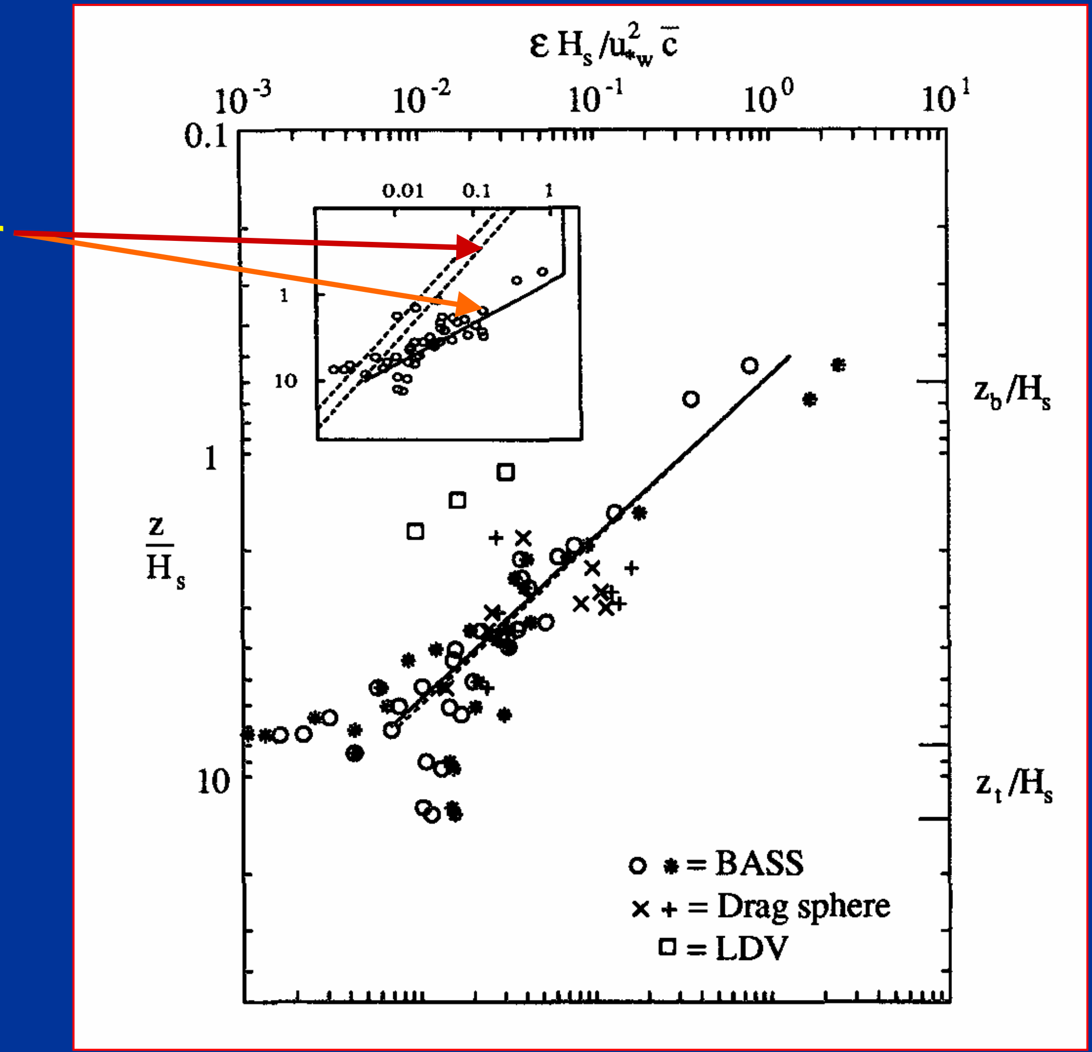


Figure 6. The fraction of momentum $(1 - \tau_r/\tau)$, (- -); and of energy $(1 - S_r/S_i)$, (—) from the wind that is delivered locally to the surface waters. The non-dimensional fetch, $\tilde{x}$ is related to the wind forcing parameter, U_{10}/C_p through Eq. [7].

ENHANCED ENERGY DISSIPATION RATE IN WAVE BOUNDARY LAYER e.g. Terray et al, 1996

- wave breaking is an *active source of TKE flux* at the ASI

Note very strong enhancement over rough wall level



MORE RECENTLY

Gemmrich and Farmer, JPO, 2004 report an authoritative observational program linking wave breaking and upper ocean dissipation rates. It was part of the FAIRS (2000) experiment from FLIP with U10 ranging up to ~12 m/s

A TOPICAL QUESTION:

how large is S_{diss} compared with S_{nl} at different stages of wave evolution?

Field data for evolving wind seas (unique data set):

• included developing wind seas from the FAIRS (2000) experiment for which the total S_{ds} was measured in the water

• unique breaking wave dataset analyzed by Gemmrich (2005)

(discussed in greater detail in the talk following this one).

EVOLVING SEA STATE CONDITIONS IN FAIRS EXPT (2000)

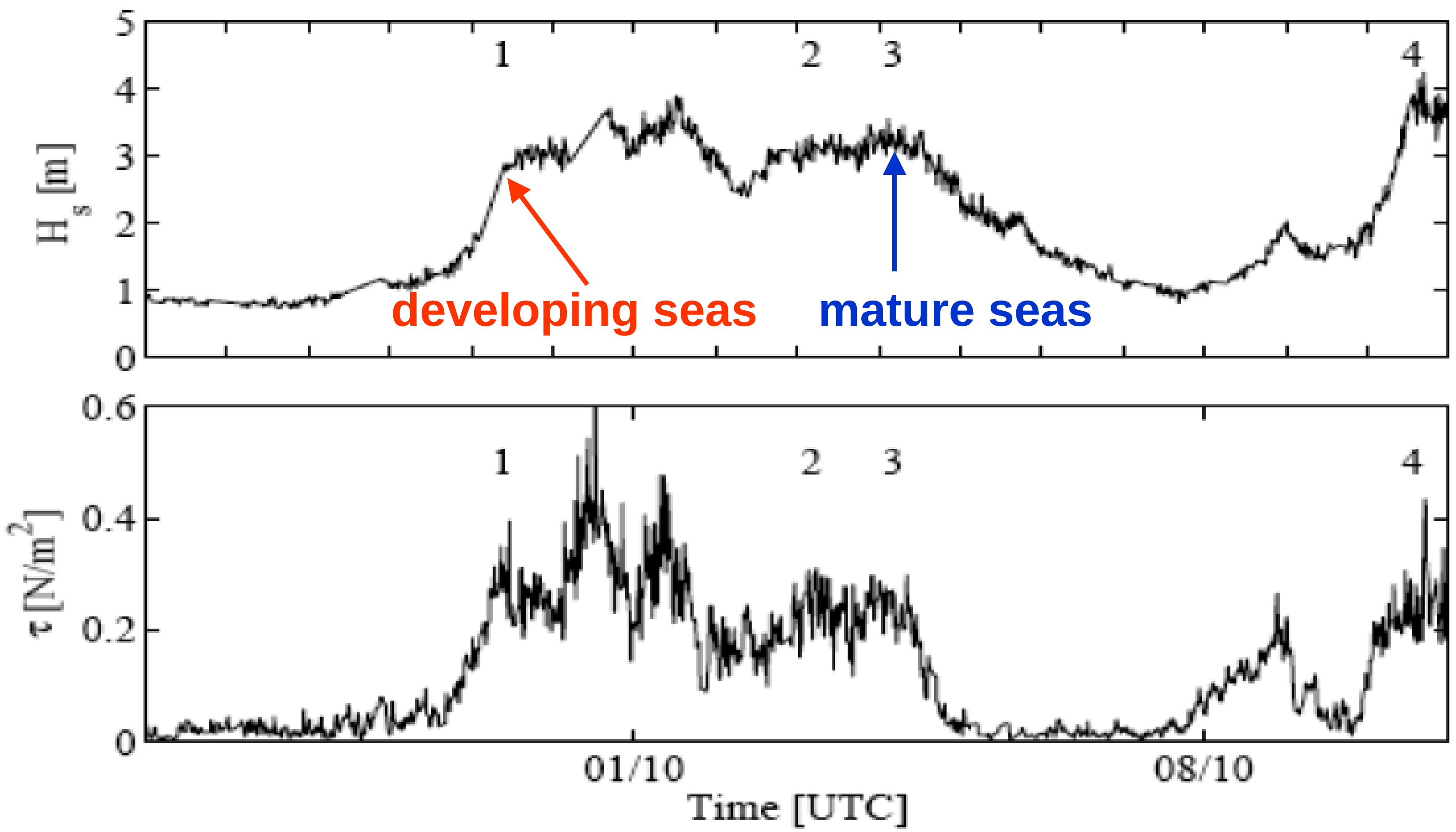


Figure 1. Significant wave height (H_s) and wind stress (τ) during the FAIRS experiment. The wind direction was around 300° for most of the observational period. Periods 1 (growing seas) and 3 (mature seas) are of particular interest in this study, during which the mean wind was measured to be 12 m/s.

BREAKING WAVE PROBABILITY DISTRIBUTIONS

period 1 – **growing** seas period 3 – **mature** seas

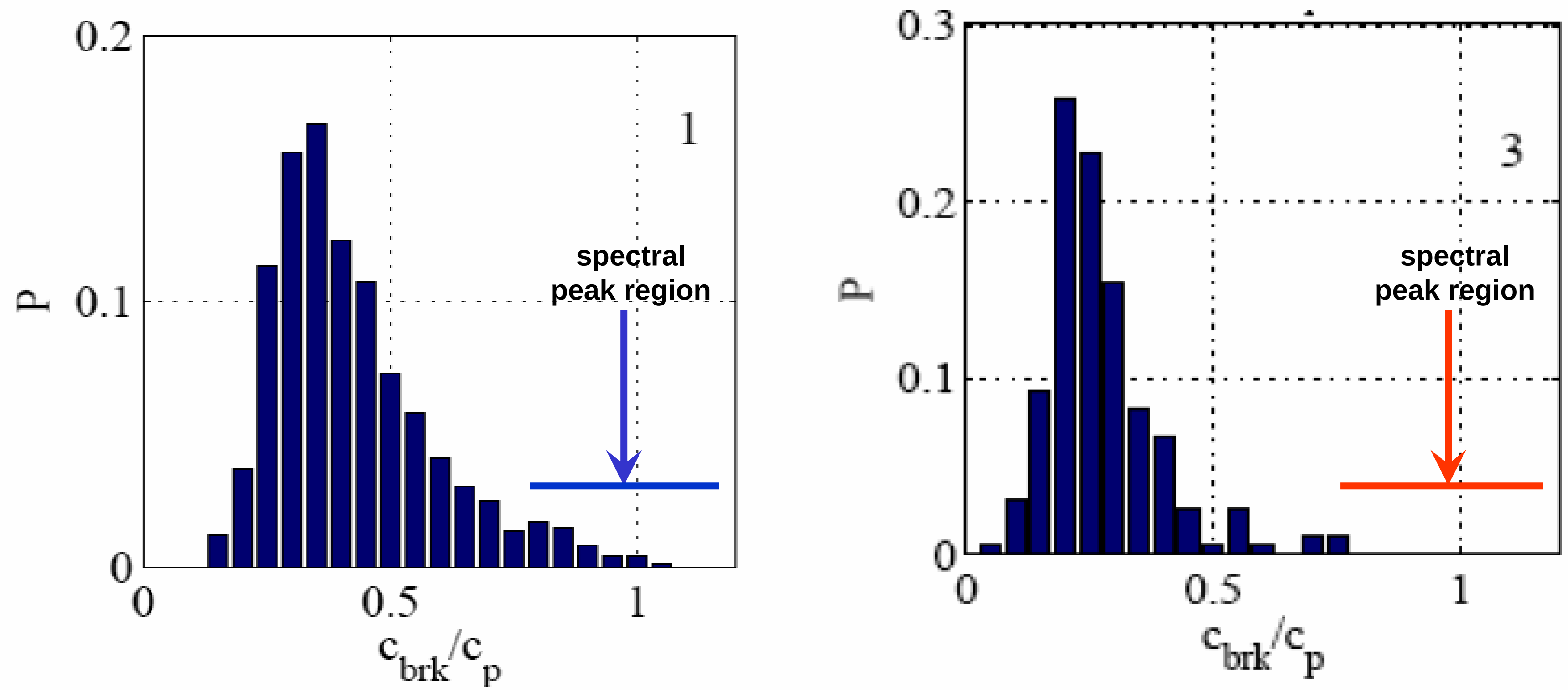
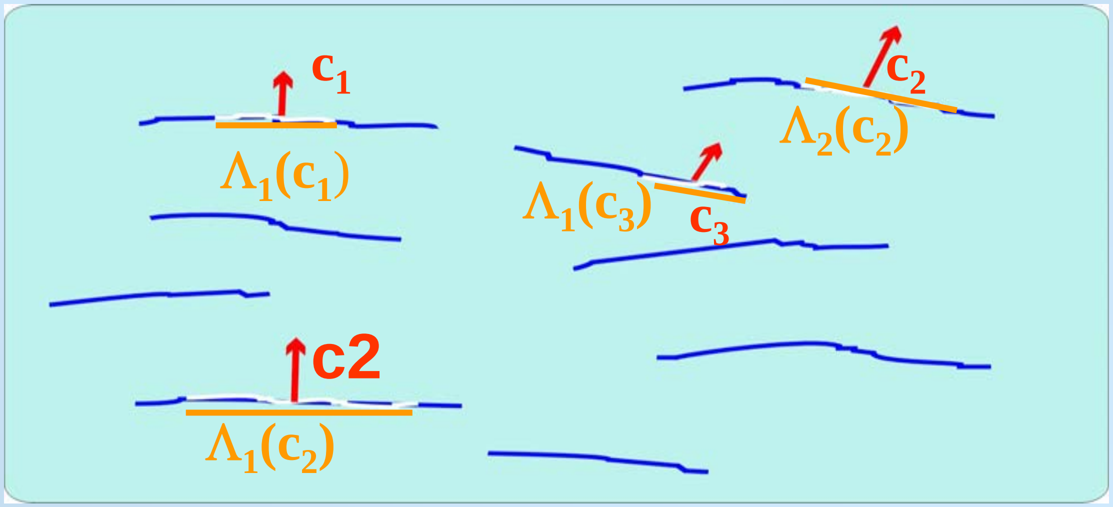


Figure 2. Probability distribution of breaking waves as a function of wave speed relative to the spectral peak, for period 1 (growing seas) and 3 (mature seas). Note that breaking events occur at the spectral peak ($0.8<c_{brk}/c_p<1.2$) for period 1, but not for period 3.

MULTI-SCALE BREAKING RATE – $\Lambda(c)$ [Phillips, '85]

Λ(c): spectral density of *breaking wave crest length* per unit area with velocities in the range (c, c+dc)



$$b \frac{\rho}{g} c^5 \Lambda(c)\, dc$$

wave energy dissipation rate at scale c

$$b \frac{\rho}{g} c^4 \Lambda(c)\, dc$$

momentum flux from waves of scale c to currents

MEASURED $\Lambda(c)$ DISTRIBUTIONS FOR DEVELOPING AND MATURE SEAS

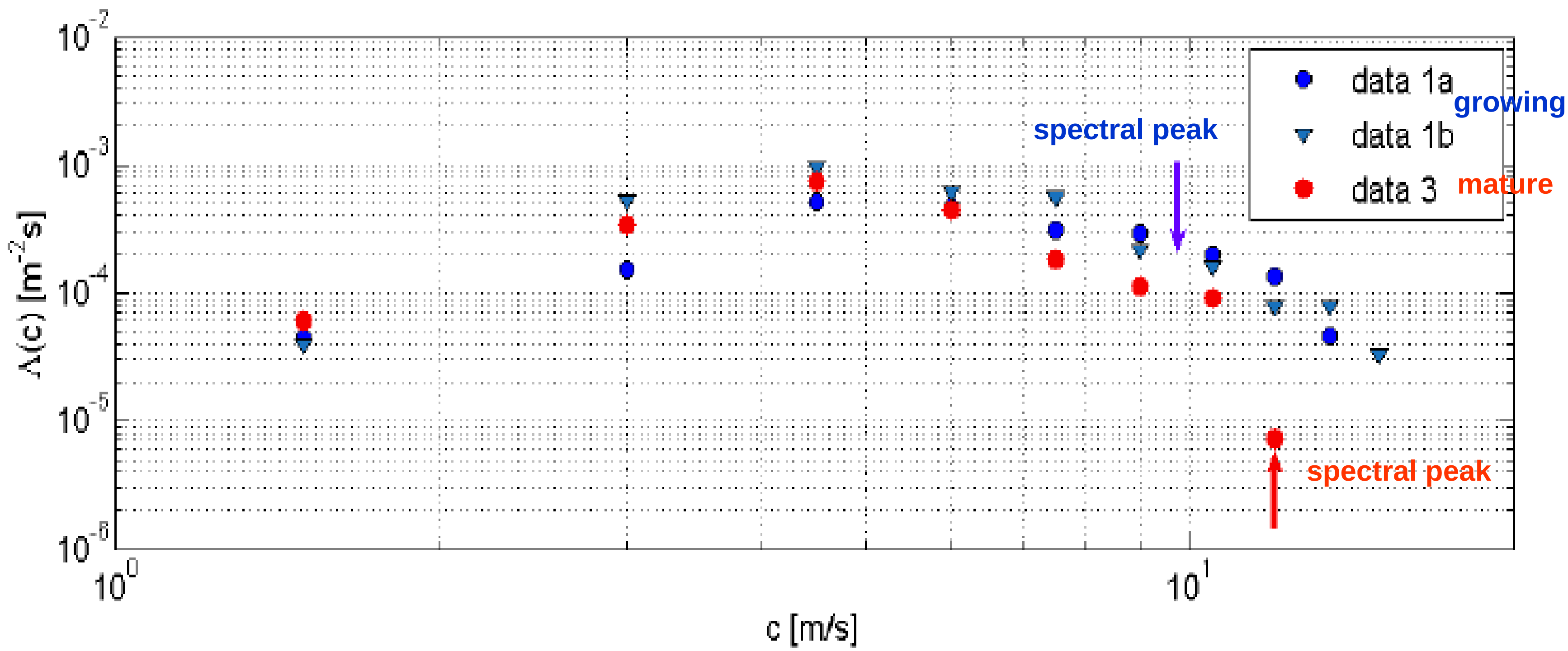


Figure 10. Measured breaking wave crest length spectral density $\Lambda(c)$ for period 1 (blue circles and triangles) and period 3 (red circles) during the evolution for U_{10}=12 m/sec. The red and blue arrows indicate the spectral peaks corresponding to the wave age conditions during periods 1 and 3, where the spectral peak speeds were 10 m/sec and 12.5 m/sec respectively.

B. __MODELING WAVE BREAKING__ –
Recent Progress

Radiative transfer equation (deep water, no currents)

The radiative transfer equation for describing the evolution of the wave height spectrum *F(**k**)* is given by:

$$\frac{\partial F}{\partial t} + \boldsymbol{c}_g \cdot \nabla F = S_{tot}$$

where

- *F=F(k,θ)* is the directional wave spectrum
- c_g is the group velocity
- $S_{tot} = S_{in} + S_{nl} + S_{ds}$ is the total source term.
- S_{in} is the ***atmospheric input*** *spectral source term*
- S_{nl} is the ***__'exact'__ nonlinear spectral transfer*** *source term representing nonlinear wave-wave interactions within the spectrum*
- S_{ds} is the spectral ***dissipation rate*** *due primarily to wave breaking*

OVERVIEW OF OUR MODELING EFFORT TO DATE

Conceptual Wave Model Refinements:

- wind input source function S_{in}
- compatible dissipation source function S_{ds}

Key Validations:

- growth of integrated wave energy and peak period
- spectral tail shape and level
- directional spreading
- dissipation rate approximately cubic in wind speed
- plausible wind stress level
- match spectral breaking wave data (Gemmrich, 2006)

WIND INPUT SOURCE FUNCTIONS S_{in}

There are many variants in use, based on either observations and/or theory. *These have fundamental differences*, *which have not been reconciled*. Examples are:

Janssen (1991) (basis of ECMWF wave forecast model) :

- based on Miles critical layer theory
- tuned to agree with Snyder and Plant empirical observations
- turns out to have a viable spectral distribution during tests for U_{10} ranging from 7-60 m/s

Other proposed S_{in} forms include:

Hsaio-Shemdin (1983), Yan (1987), Tolman-Chalikov (1996, used in WWIII), amongst several others.

➢ these forms for S_{in} have significantly different impacts when used to force a spectral wave model – we'll look at this presently

PLOT SHOWING DIFFERENT WIND INPUT GROWTH RATES

NB. Log scale

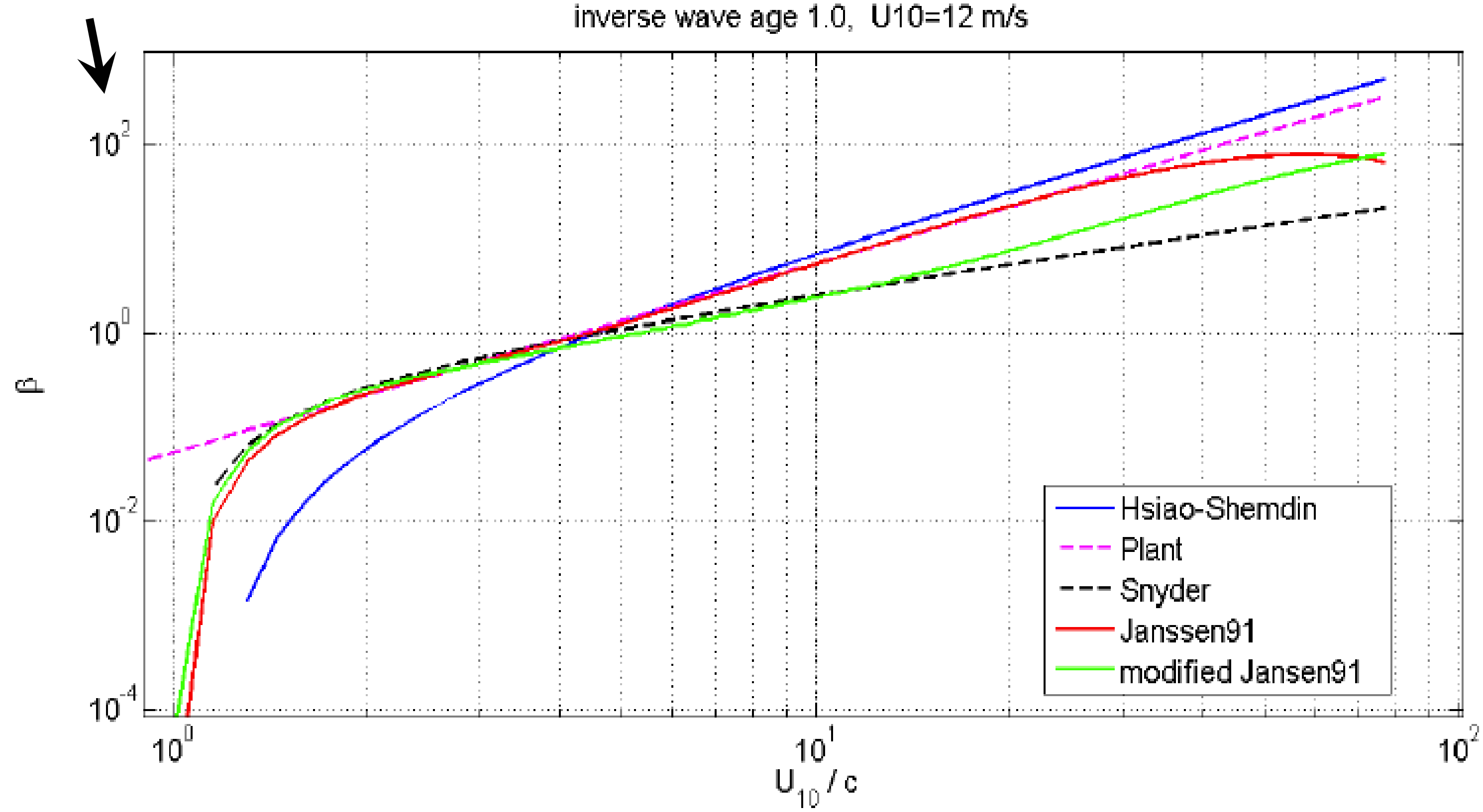


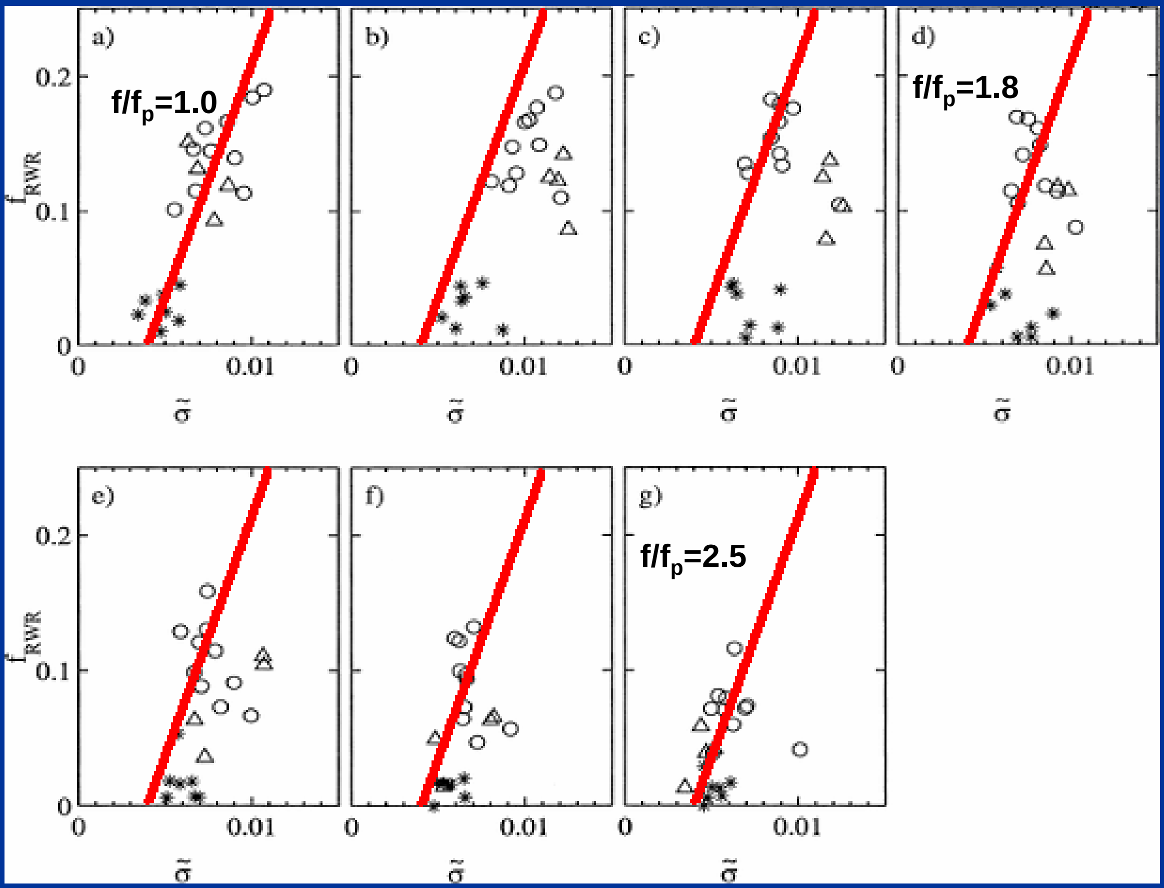
Figure 3. Plot showing the considerable differences between the spectral growth rate β of selected commonly implemented forms of S_{in} for maturing seas (U_{10}/c_p~1.0). The modified Janssen91 curve shows the extent of sheltering introduced for the slower moving, shorter wave components. This is sufficient to align the computed windstress with observed levels.

BREAKING PROBABILITY IN THE WAVE SPECTRUM

(Banner, Gemmrich and Farmer, JPO, 2002)

•using spectral saturation normalized to the directional spreading at the spectral peak shows strong evidence of *common threshold behaviour* for the dissipation rate at different frequencies above the spectral peak.

breaking probability



normalized saturation

SATURATION THRESHOLD-BASED S_{ds}

- based on treating spectral bands as nonlinear wave groups. Uses a low power of the spectral saturation ratio (~steepness ratio) to simulate observed threshold behaviour *[extension of Alves & Banner (JPO, 2003)]*

$$S_{ds}(k,\theta) = C\,[(\tilde{\sigma} - \tilde{\sigma}_T)/\tilde{\sigma}_T)^a\,\tilde{\sigma}^b + \varepsilon_{res}]\,(\sigma/\sigma_m)^c\,\omega F(k,\theta)$$

where

- σ is the normalized azimuthally-integrated saturation:

$$\sigma(k) = (k^4 F(\mathbf{k}))/\theta(k) = [(2\pi)^4 f^5 F(f) / 2g^2]$$

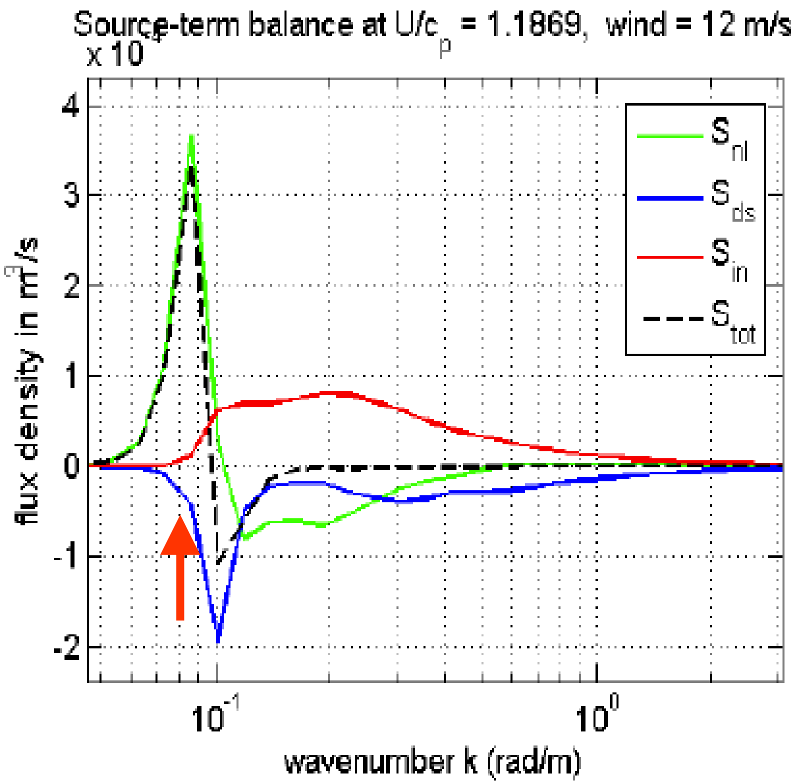
over a constant relative wavenumber bandwidth at wavenumber $\mathbf{k}=(k,\theta)$

- σ_bar = $\sigma(k)/\theta(k)$, where $\theta(k)$ = mean spreading width at wavenumber k
- ω is the radian frequency
- σ_T_bar is the threshold normalized spectral saturation, determined observationally (Banner, Gemmrich and Farmer, JPO, 2002)
- To match dissipation to input behaviour, various forms for the tail attenuation index c were investigated
- ε_{res} is a background dissipation rate (agrees with observed swell dissipation rates)
- The tuning constant C is chosen to provide the optimal match to observed duration-limited evolution of the spectral peak energy (Young, 1999)

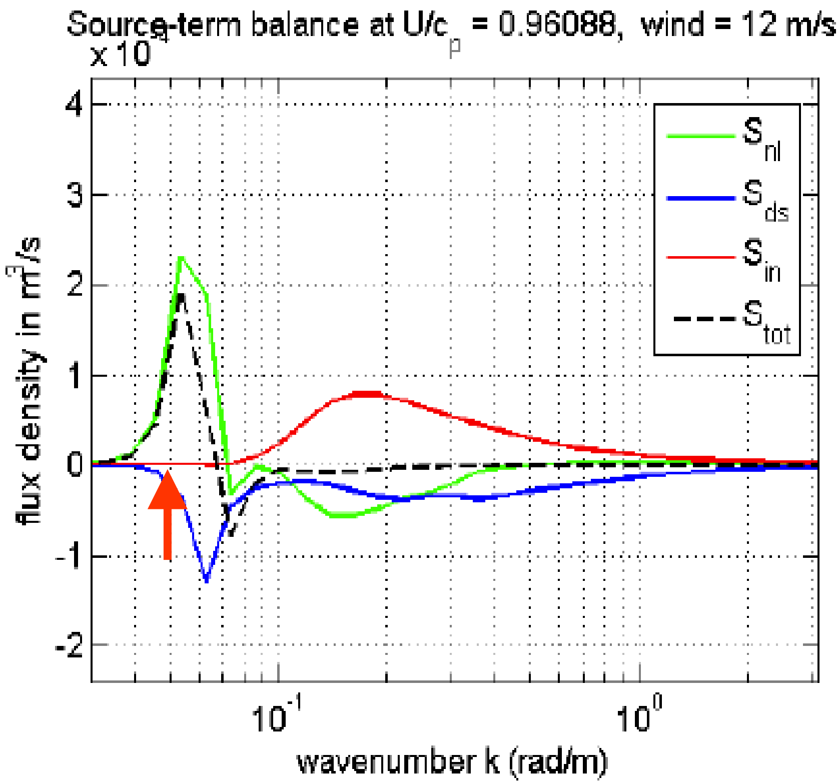
AZIMUTH-INTEGRATED SOURCE TERM BALANCE

U_{10} = 12 m/s simulation

developing wind sea



mature wind sea

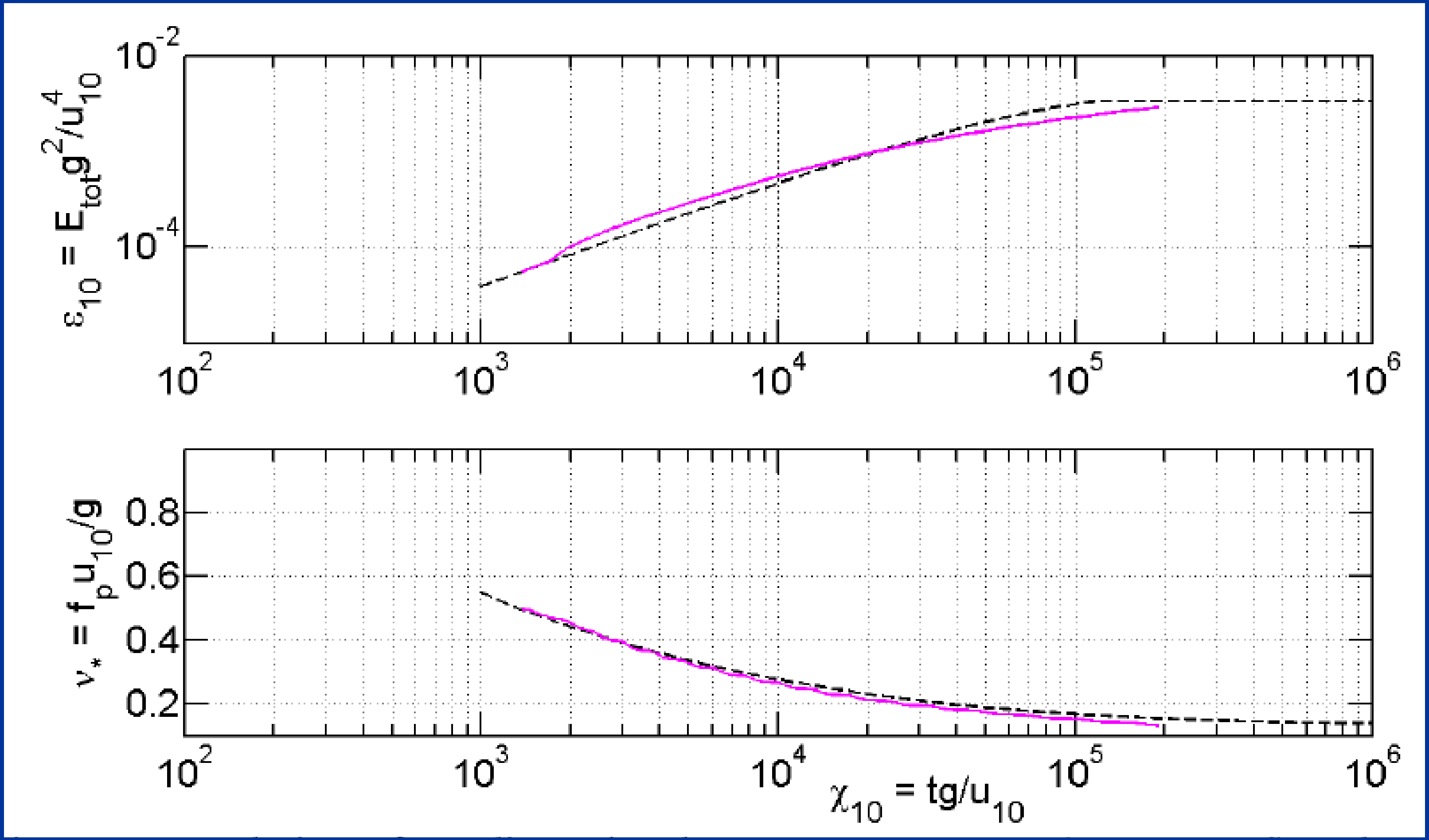


Near spectral peak [↑], note how the dissipation offsets the nonlinear transfer, NOT the wind input. This is consistent with breaking due to nonlinear wave group modulation effects [Song and Banner (2002).

RESULTS

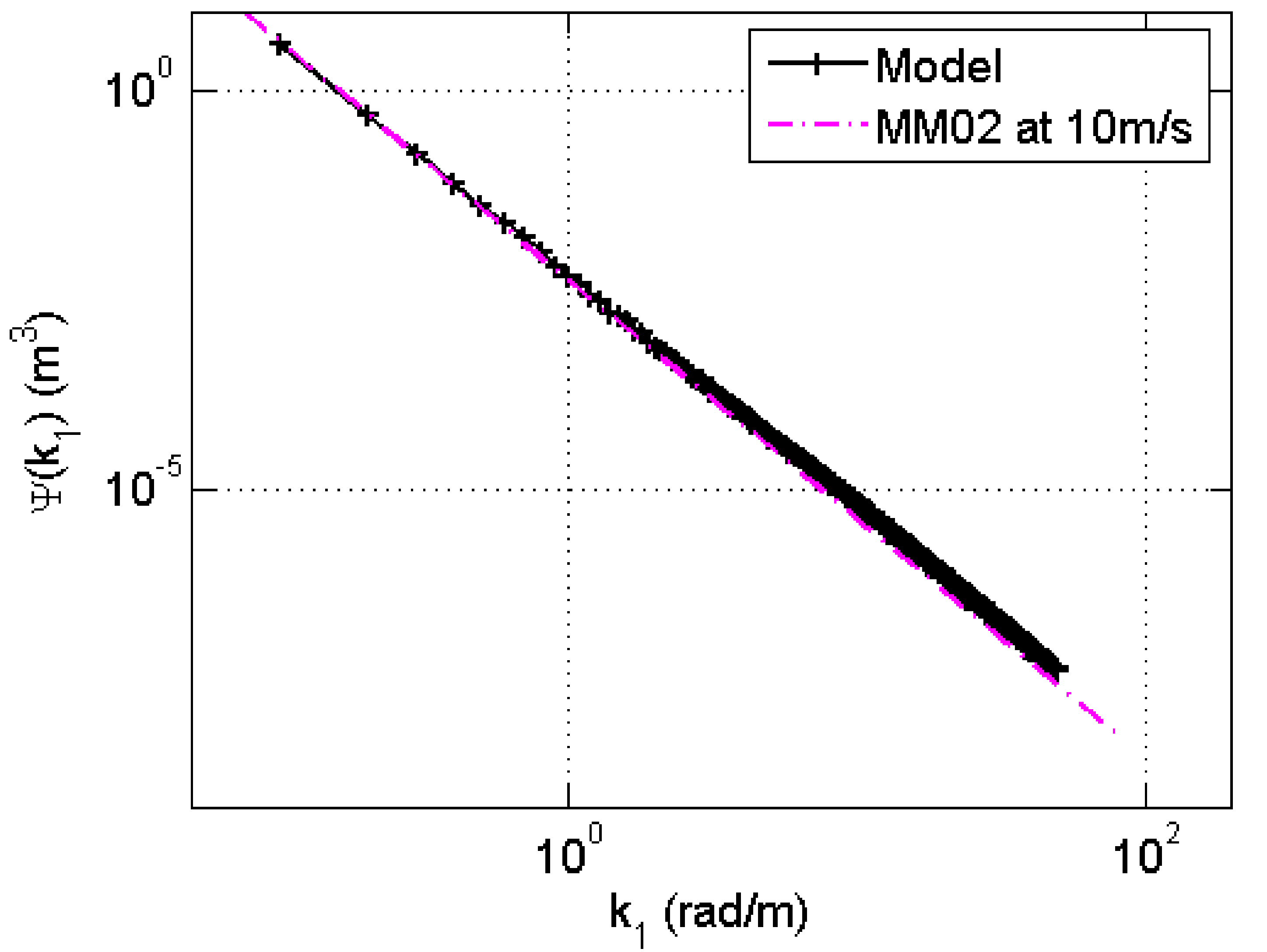
EXACT NL COMPUTATION OF DURATION-LIMITED EVOLUTION

Janssen (1991) input source term, with high wavenumber sheltering



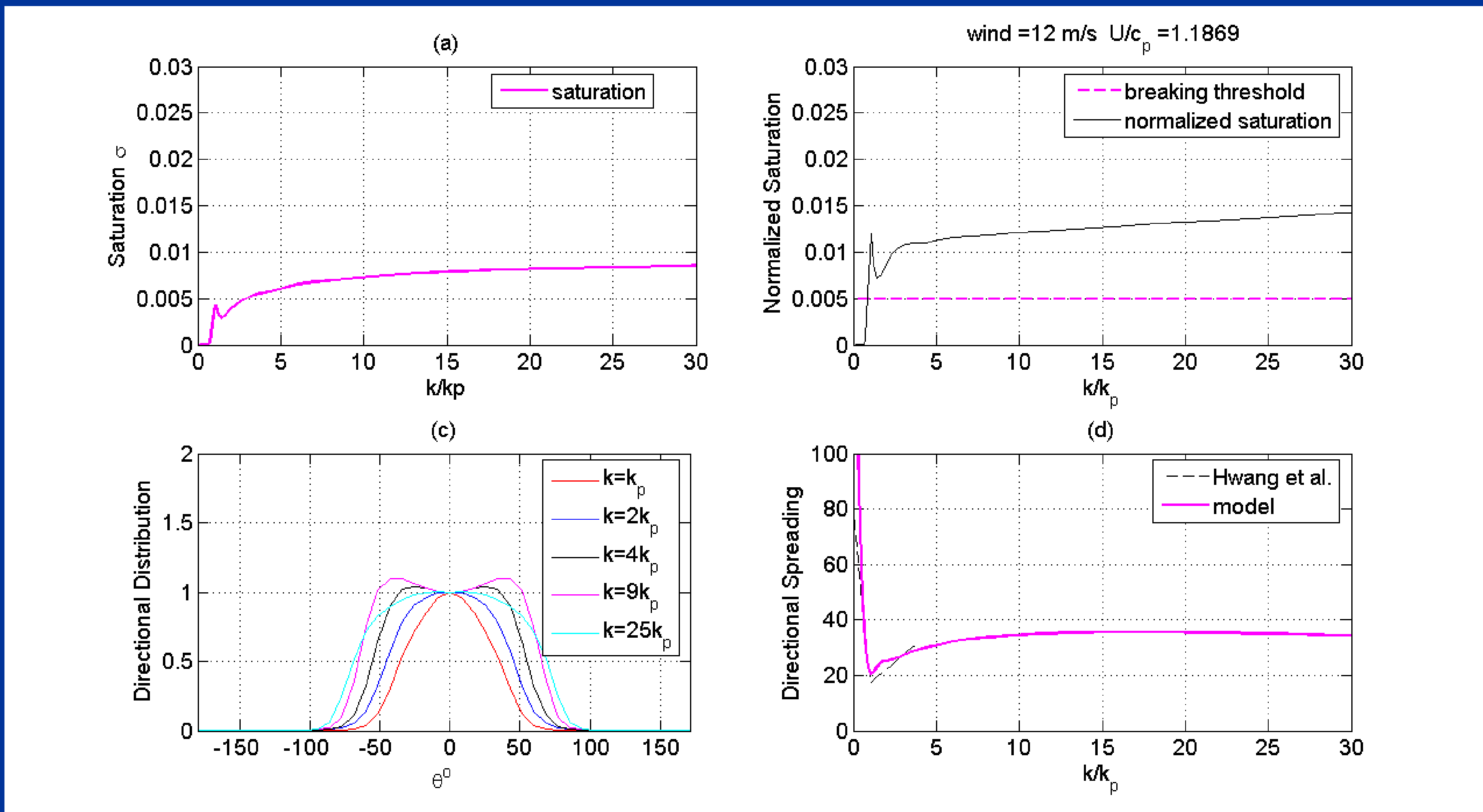
Note: our S_{ds} based on *local saturation ratio* has more flexibility than the quasi-linear (WAM) form of S_{ds} based on *integral steepness*

1D TRANSECT WAVENUMBER SPECTRUM



PROPERTIES OF THE SPECTRAL TAIL REGION

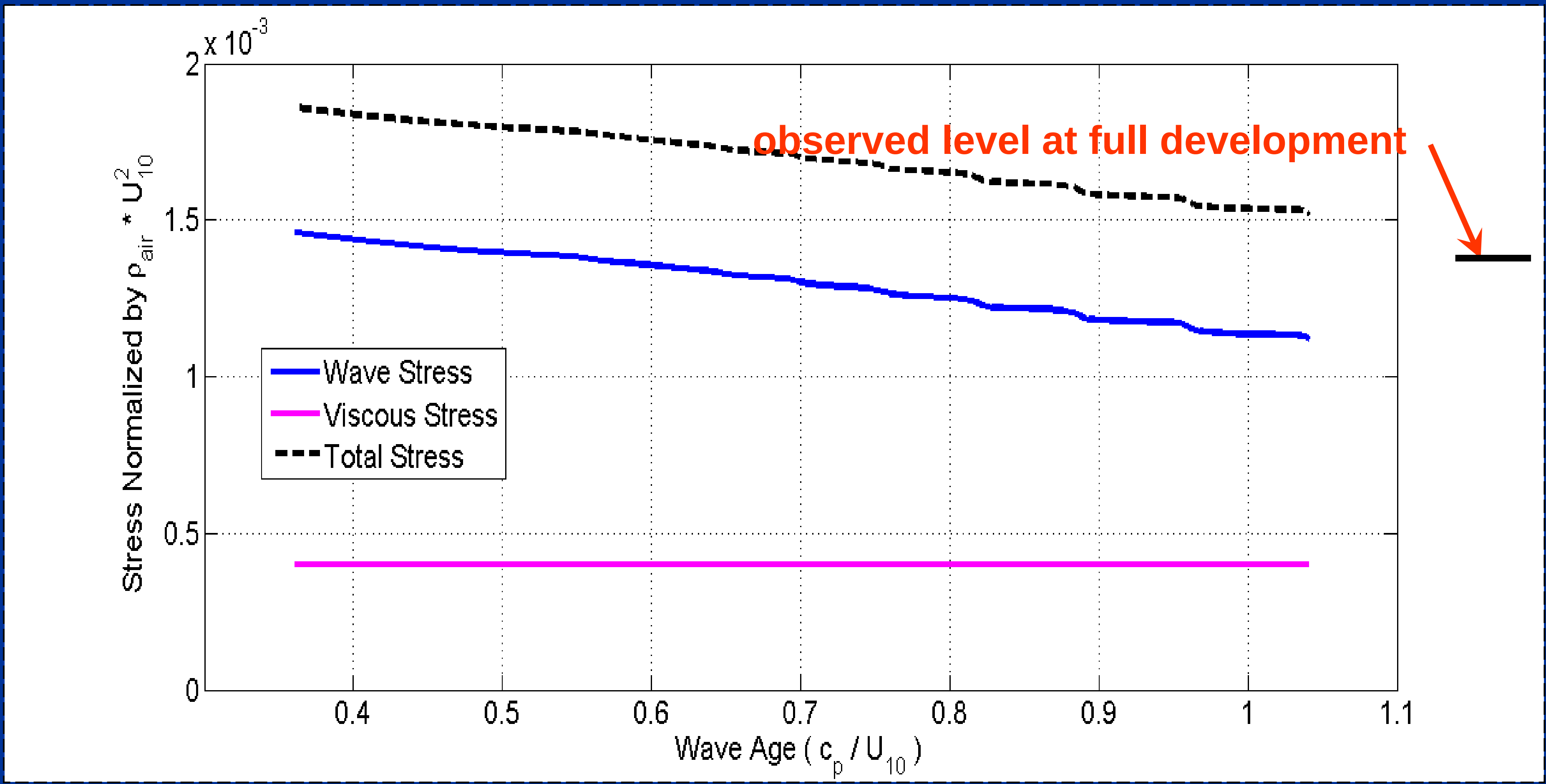
Integrated saturation with k/k_p **Normalized saturation with k/k_p**



Directional spreading distribution **Mean directional spreading vs. k/k_p**

COMPUTED WIND STRESS AND ITS COMPONENTS

U_{10}=12 m/s



CALCULATING SPECTRAL PROPERTIES OF THE BREAKING WAVES

We now seek to use the computed S_{ds} to infer the spectral breaking wave crest length distribution at different wave ages.

We followed Phillips (1985) framework for relating $\Lambda(c)$ to S_{ds}:

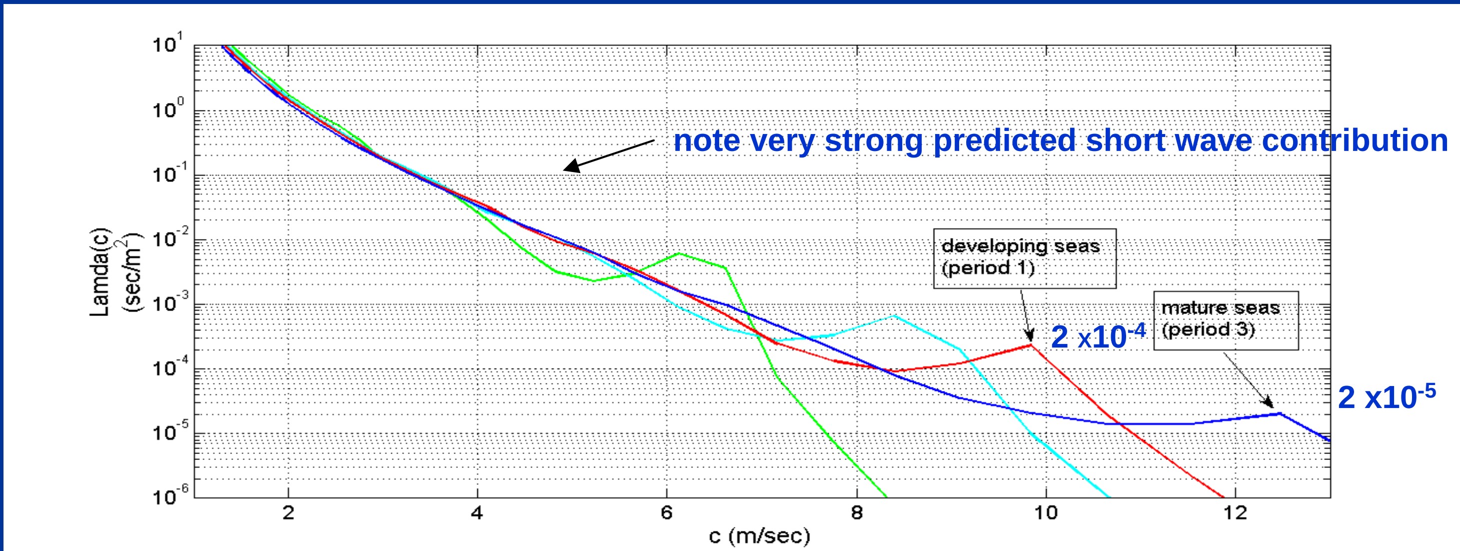
$$S_{ds}(c)\,dc = b\,g^{-1}c^{5}\Lambda(c)\,dc$$

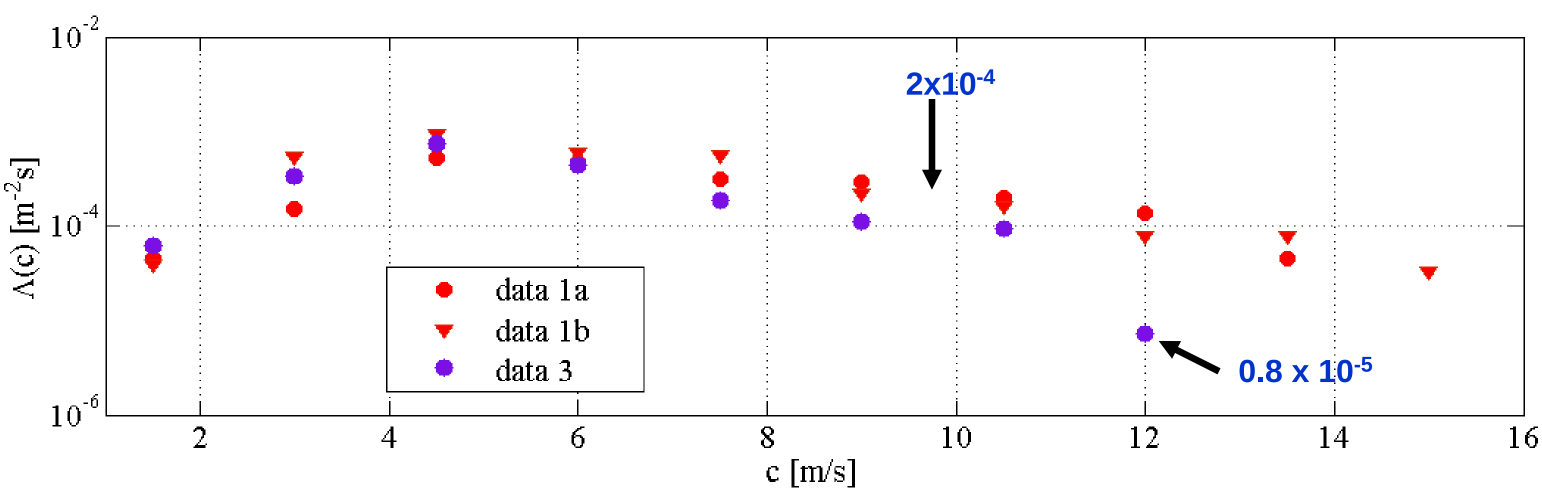
- this assumes breaking at scale c dominates $S_{ds}(c)$

- this assumption is likely to be best for the dominant waves

- we used a value of $b \sim 3 \times 10^{-5}$ as measured by Gemmrich (next talk)

COMPARING MODELED and OBSERVED $\Lambda(c)$





WIND INPUT SOURCE TERM SENSITIVITY TESTS

➢ we also investigated using a wind input source term S_{in} due to Hsaio and Shemdin (1983)

➢ relative to Janssen (1991), its spectral levels have less input to faster longer waves, more input to the slower shorter waves

➢ we were not able to match both total energy and wave breaking levels at the spectral peak through an evolution to mature seas

➢ tuning S_{ds} to give the standard energy and peak frequency evolution curves gave S_{ds} levels far too low at the spectral peak to match available observations. The corresponding breaking wave properties were too low by a wide margin.

We expect that the Tolman-Chalikov form would have the same difficulties.

IMPLICATIONS:

- we have investigated a spectral wave modeling approach using

(i) a saturation threshold S_{diss} formulation

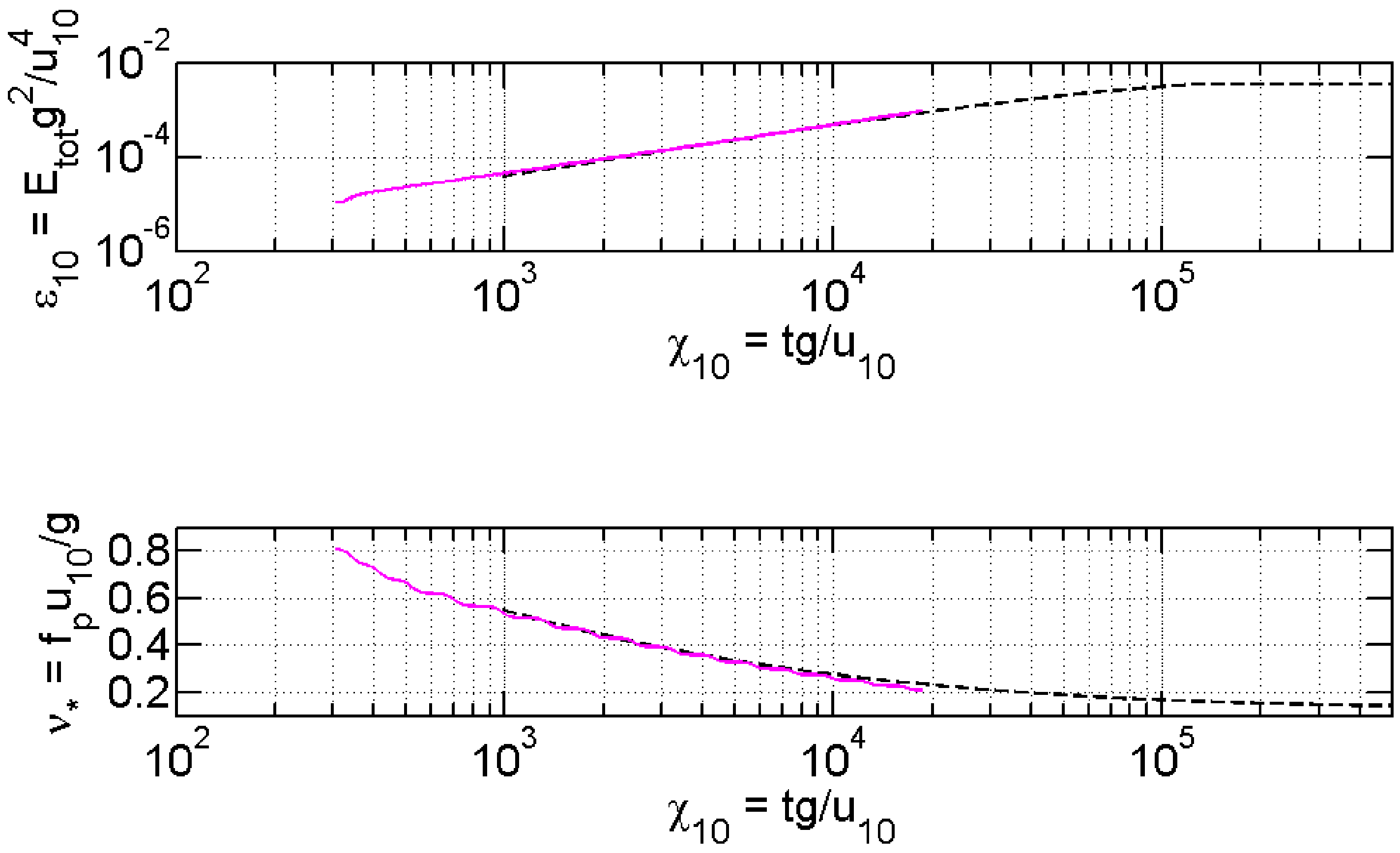
(ii) a wind input term S_{in} with levels consistent with Janssen (1991)

- this combination, with '*Exact*' S_{nl}, appears capable of representing wave observations closely, even out into the spectral tail region
- the computed wind stress is consistent with observations
- the calculated breaking crest length spectral density reproduces levels from the (few) available observations
- the total dissipation rate is close to estimated levels from observations
- our preliminary studies for hurricane applications are showing that the *same model settings* appear to provide stable, plausible results out to 60 m/s wind speeds. eg.

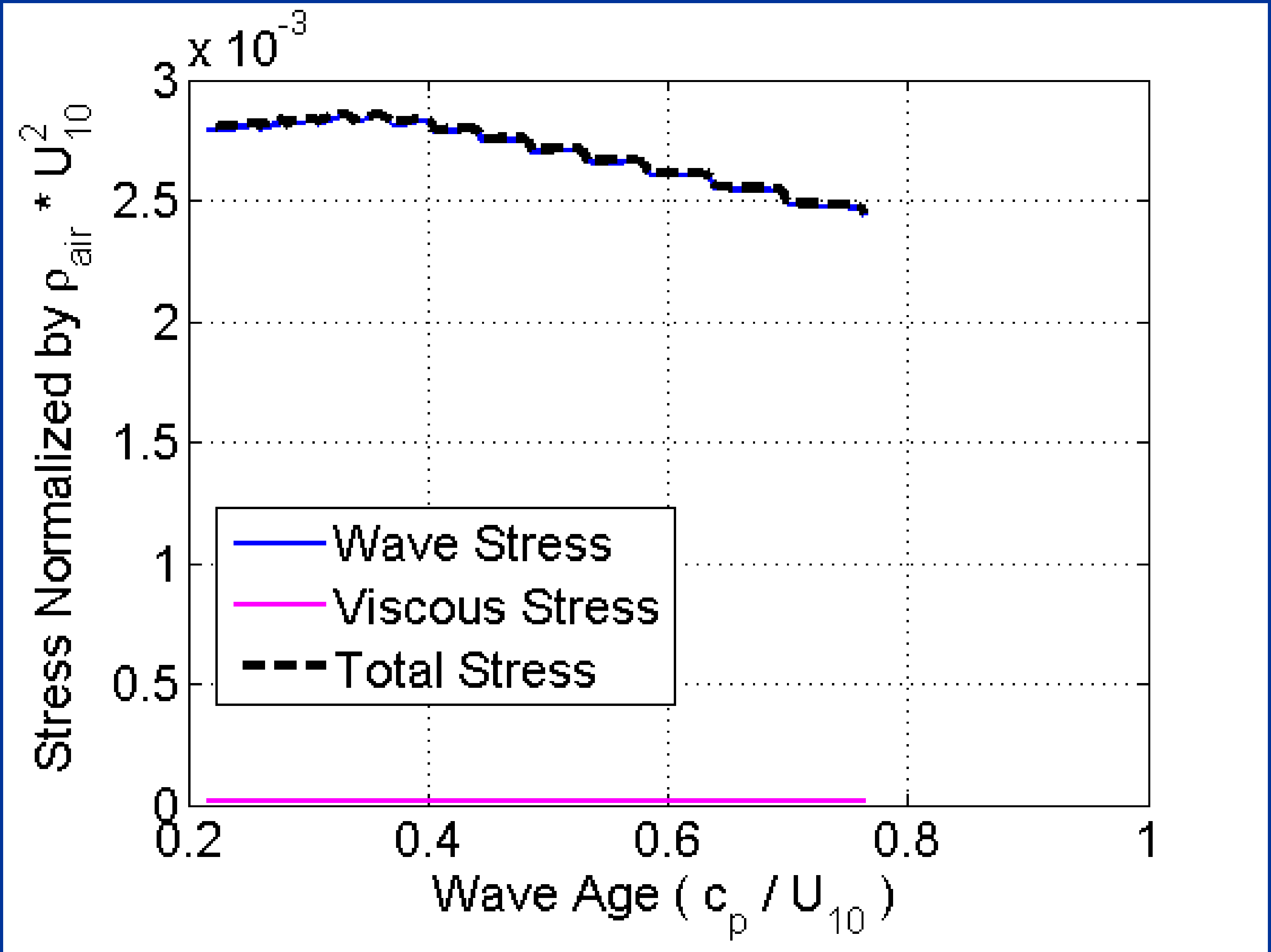
HURRICANE WIND SPEED EVOLUTION

U_{10}=45 m/s

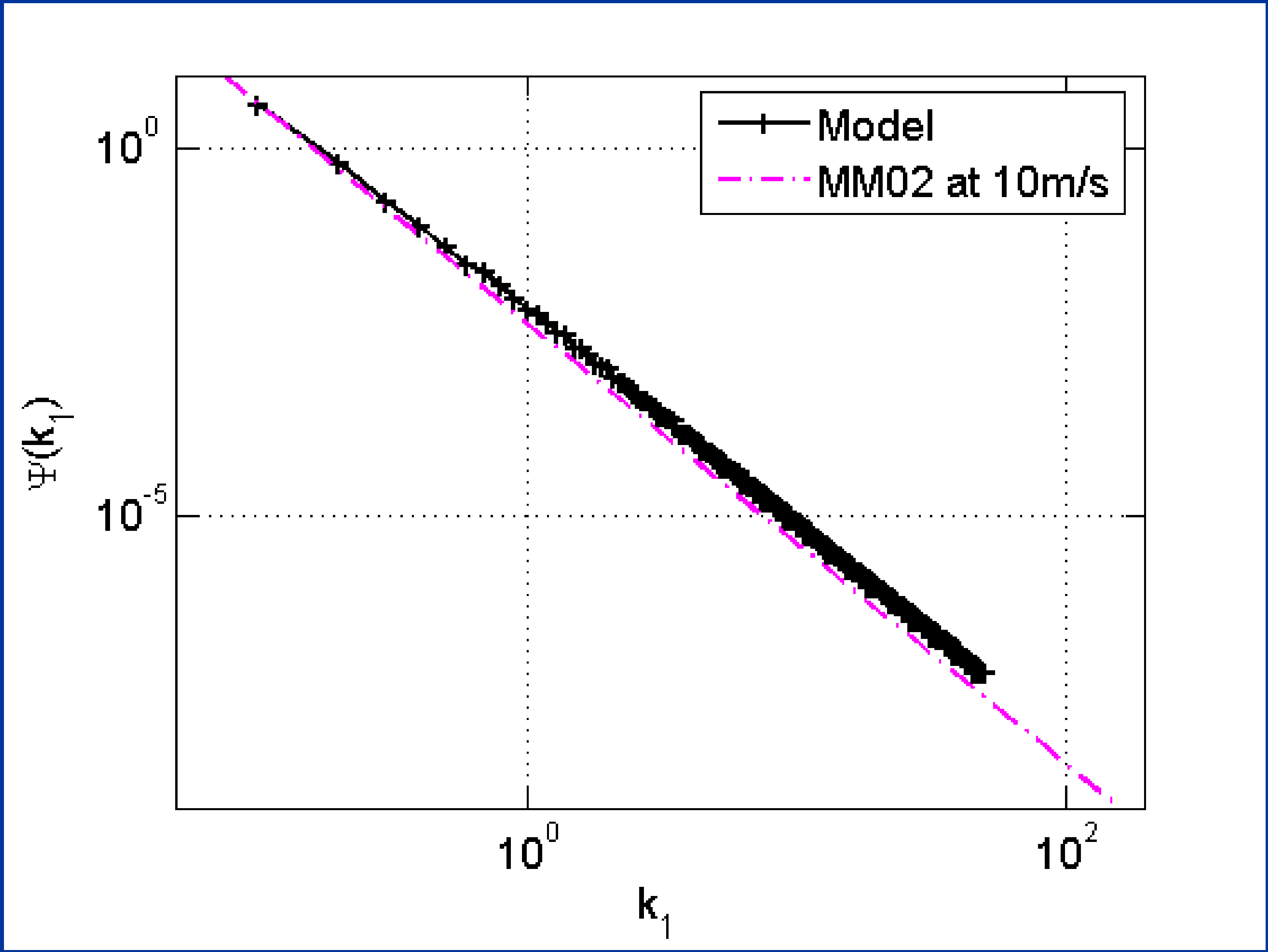
wave energy and peak frequency



computed wind stress and its components



1D transect wavenumber spectrum



SUMMARY/CONCLUSIONS

• wave breaking has been integrated into our wind-wave model. This model provides wave and wind stress forecasts, including estimates of the wind stress components due to waves and skin friction.

• wave breaking forecasts appear to be realistic near the spectral peak. Further validation against higher wind sea data is in progress

• availability of breaking data allows refining wind input source term

• for shorter scales, fundamental issues have been identified that remain to be resolved between data sets, and also with the model

e.g. rollover of $\Lambda(c)$ at short scales needs to be better understood - is it real, or just the transition to breaking without air entrainment?

• ongoing work includes validation for hurricane conditions in deep water and its extension for shallow water conditions.