FORECASTING BREAKING WAVES DURING STORMS

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BACKGROUND

>> occurrence and consequences of breaking waves have been a persistent concern for the maritime community, both in deep and coastal waters

BACKGROUND

MOTIVATION FOR THIS WORK includes:

>> upgrading present forecast capabilities to quantify probability of encountering dangerous breaking wave conditions

>> to include realistic modelling of wave breaking-induced effects such as:

• aerodynamic enhancement (air-flow separation) of sea surface drag coeff't

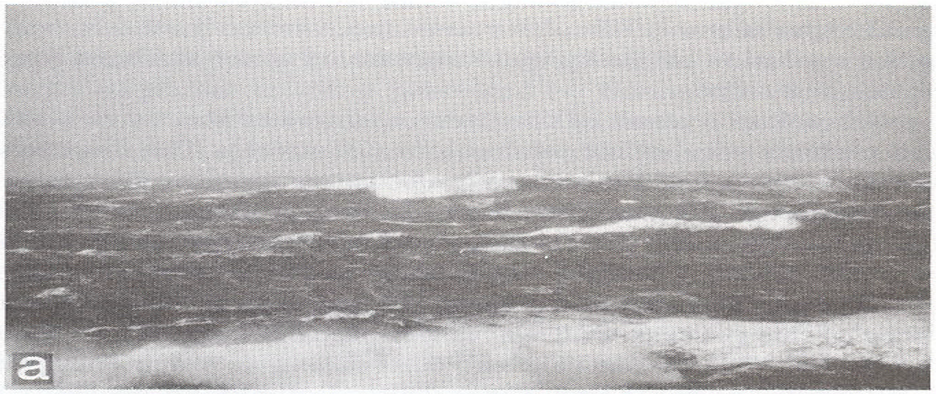
• increased upper ocean mixing and air-sea scalar fluxes – e.g. sea spray flux, believed to be crucial for tropical cyclone intensification

THIS TALK describes

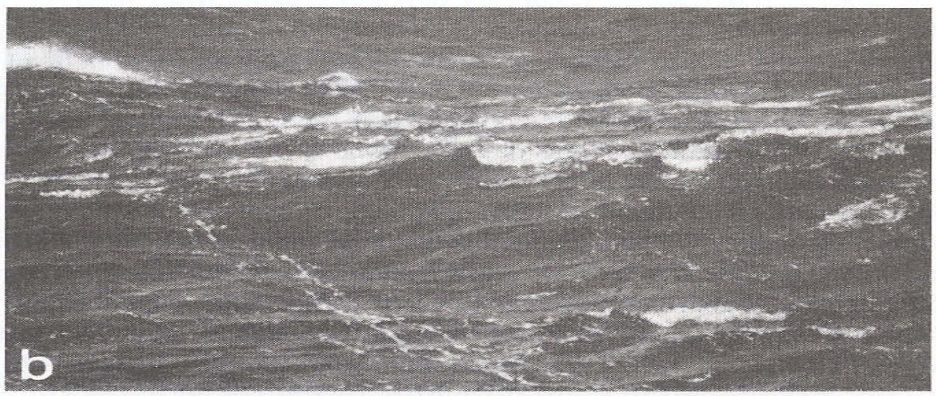
1. recent research progress on determining which environmental processes and variables appear to control the *relative occurrence rate* (probability) and *strength* of breaking waves.

2. recent progress towards improving the accuracy of wave forecasts, and to implement reliable forecasts of breaking waves.

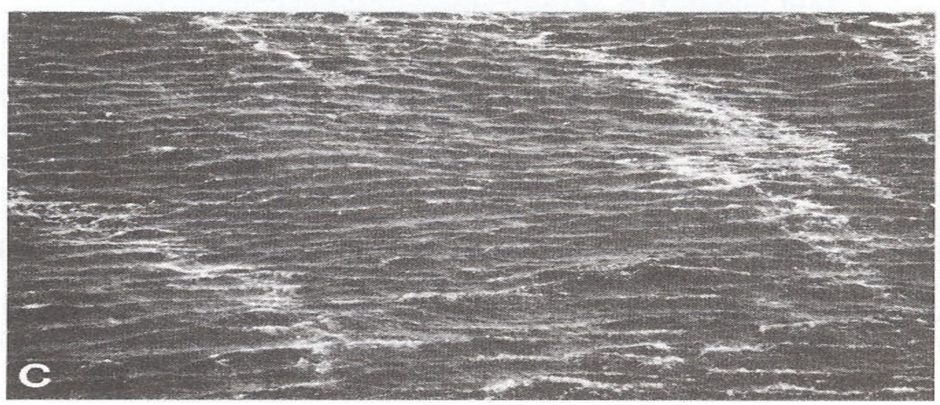
WAVE BREAKING ON DIFFERENT SCALES



DOMINANT SCALE



INTERMEDIATE SCALE



SMALL-SCALE

FIELD OBSERVATIONAL INSIGHT ON WAVE BREAKING IN OPEN OCEAN CONDITIONS

**e.g. Holthuijsen & Herbers (JPO,1986),
Gemmrich and Farmer (JPO, 1999)**

>> breaking waves cannot be easily identified by local wave steepness

>> breaking probability does not correlate strongly with wind speed

>> nor does it correlate strongly with wind forcing strength e.g. spectral peak inverse wave age U/c_p

IMPORTANCE OF WAVE GROUP STRUCTURE

- OPEN OCEAN BREAKING WAVE OBSERVATIONS

- First observed by Donelan, Longuet-Higgins and Turner (Nature, 1972)

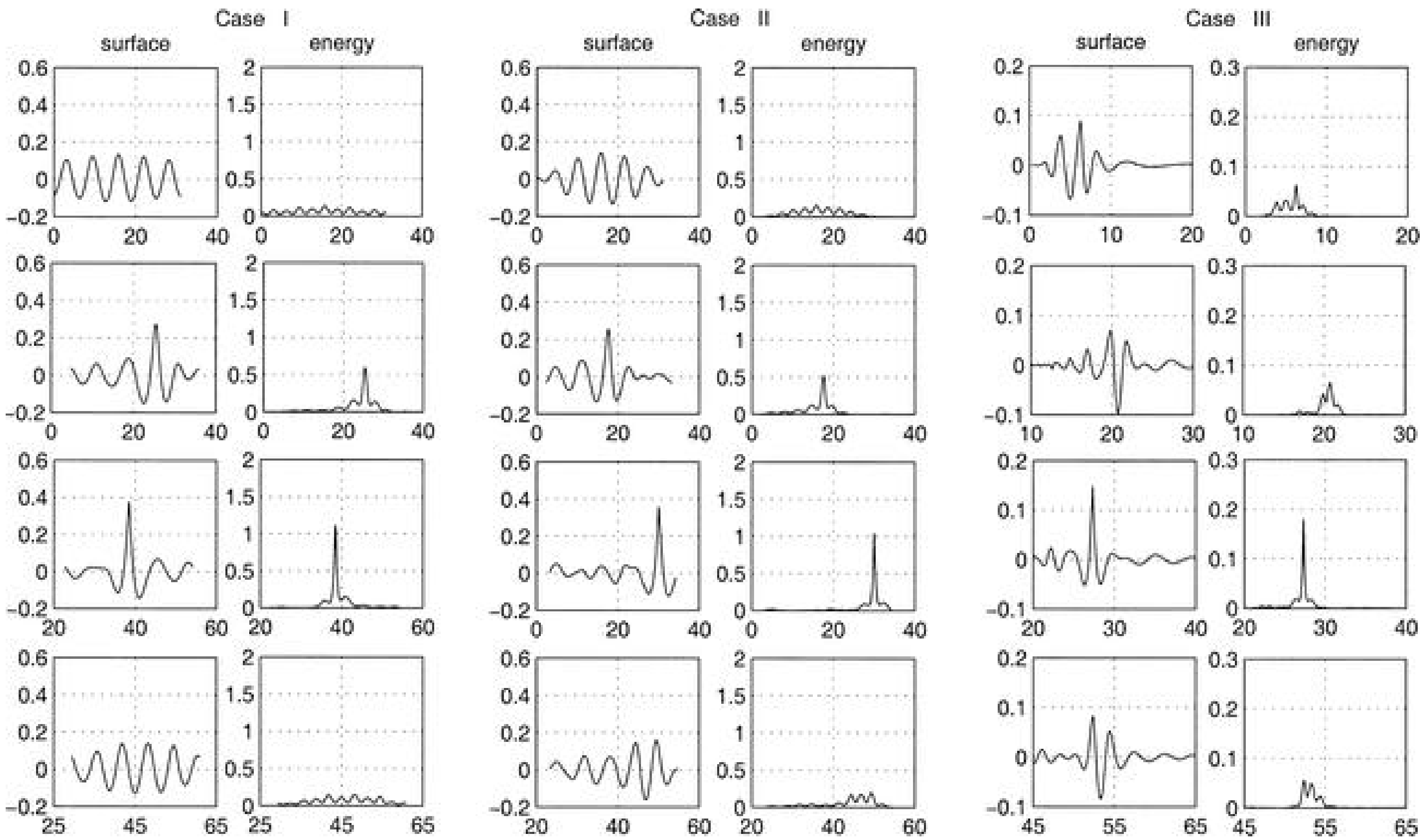
- Herbers and Holthuijsen (JPO, 1986) observed a large number (~ 1500) of wave groups in coastal and open ocean waters . The mean fraction of groups containing a breaking wave was 0.69.

- They also observed a remarkable correlation between the fraction of wave groups containing breakers and the group length – e.g. 70% of all 7-wave groups contained breaking waves!

>> These findings motivated a more global view rather than limiting to *local* breaking criteria, and looking more closely at ***group behaviour***

INSIGHT FROM MODELING OF 2-D NONLINEAR WAVETRAINS

• Results from 'exact' Euler equation boundary element codes (periodic domain and numerical wave tank models, Song & Banner, JPO, 2002)



TRACKING THE EVOLUTION OF WAVE GROUP MAXIMUM AND ITS ASSOCIATED ENERGY DENSITY

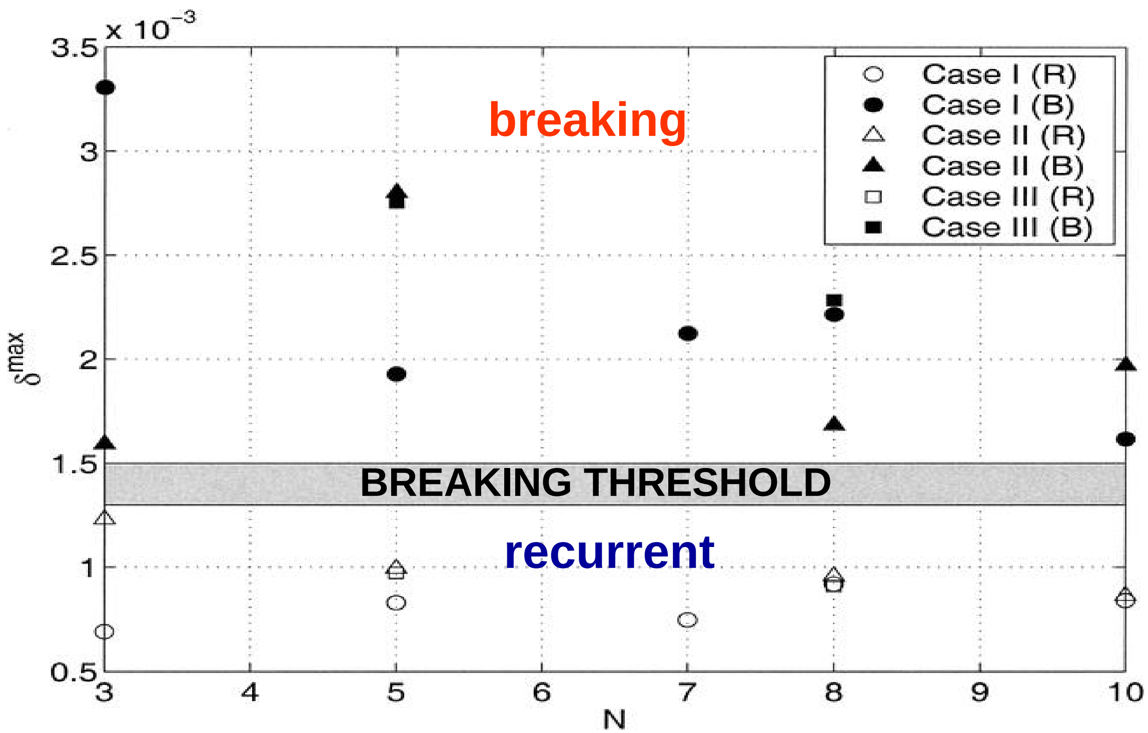
- **n**ote the convergence (flow) of energy towards the centre of the group, as one travels along with the group.

- we proposed that breaking onset is linked to a threshold in the mean convergence rate of wave energy at the envelope maximum (Song and Banner, JPO, 2002)

MODEL PREDICTIONS FOR BREAKING ONSET

• these calculations predict a ***threshold growth rate*** for a local non-dimensional energy density that can distinguish wave groups that evolve to break from those that relax without breaking, i.e. undergo ‘recurrence’. This growth rate reflects the **energy convergence rate at the envelope maximum**.

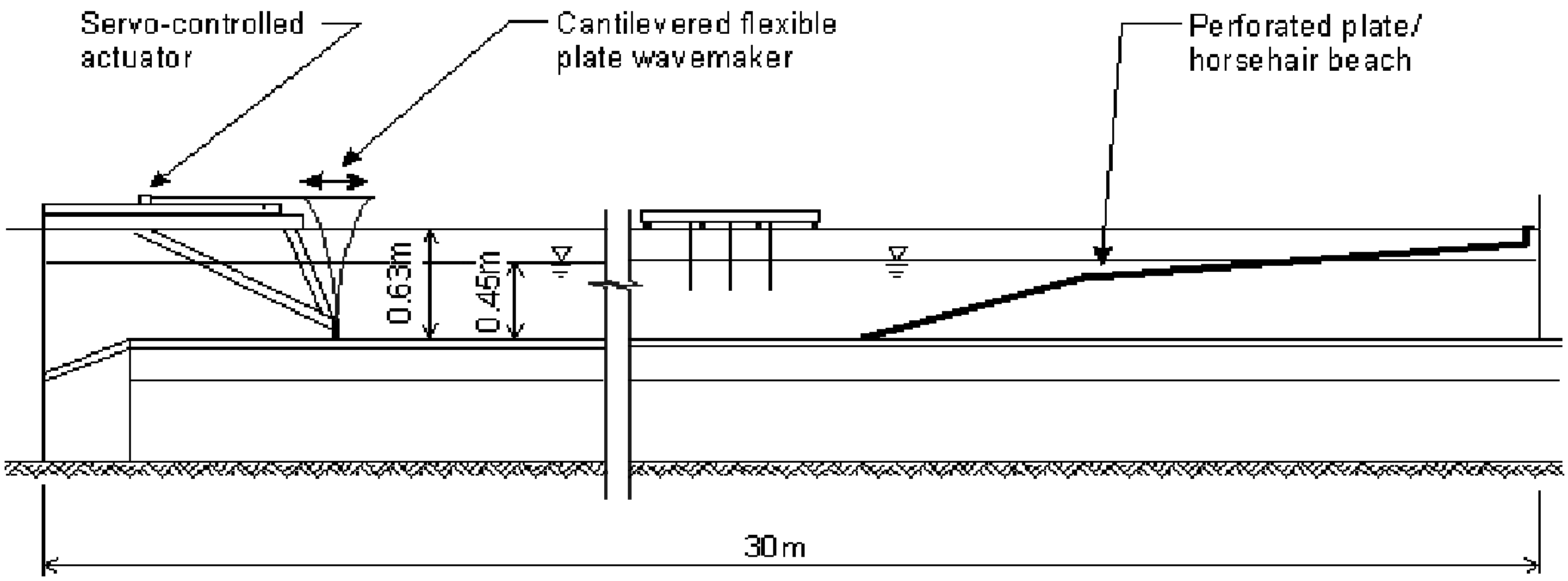
GROWTH MAX. RATE



NUMBER OF WAVES PER GROUP

OBSERVATIONAL VALIDATION STUDY IN A LABORATORY WAVE FLUME

WAVE TANK CONFIGURATION:

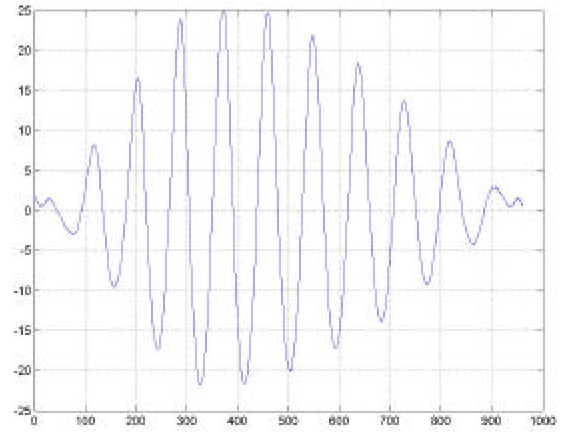


WAVE TANK ELEVATION
(approx. scale 1:50)

- *unforced 2D nonlinear wave groups with different initial structure:*

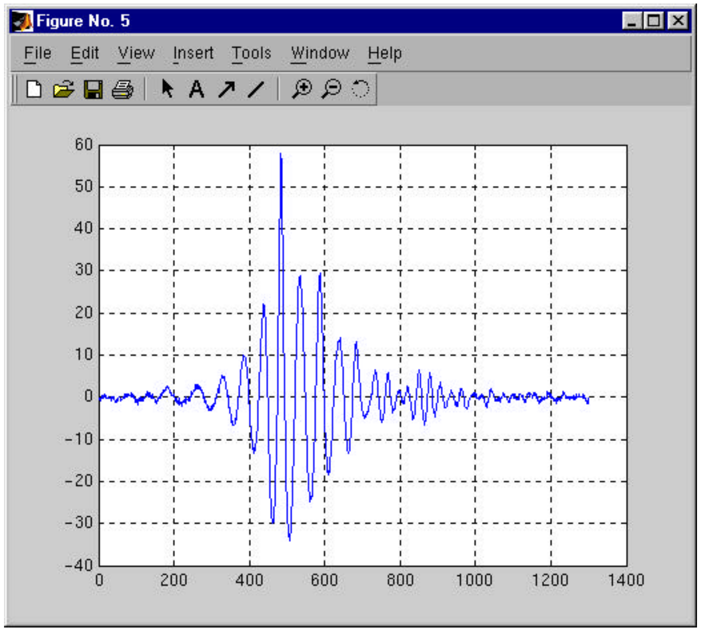
TYPICAL EVOLVING WAVE PACKETS

'Case II' wave groups: Initial weakly nonlinear bimodal spectrum

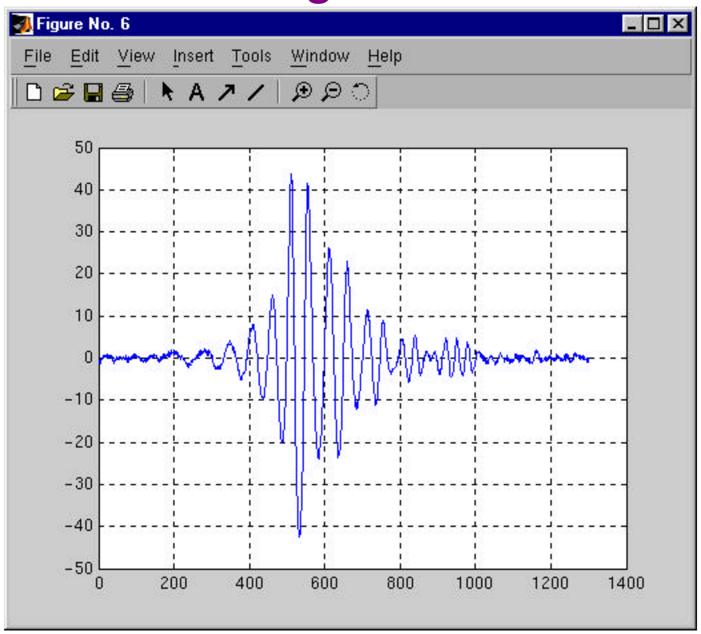


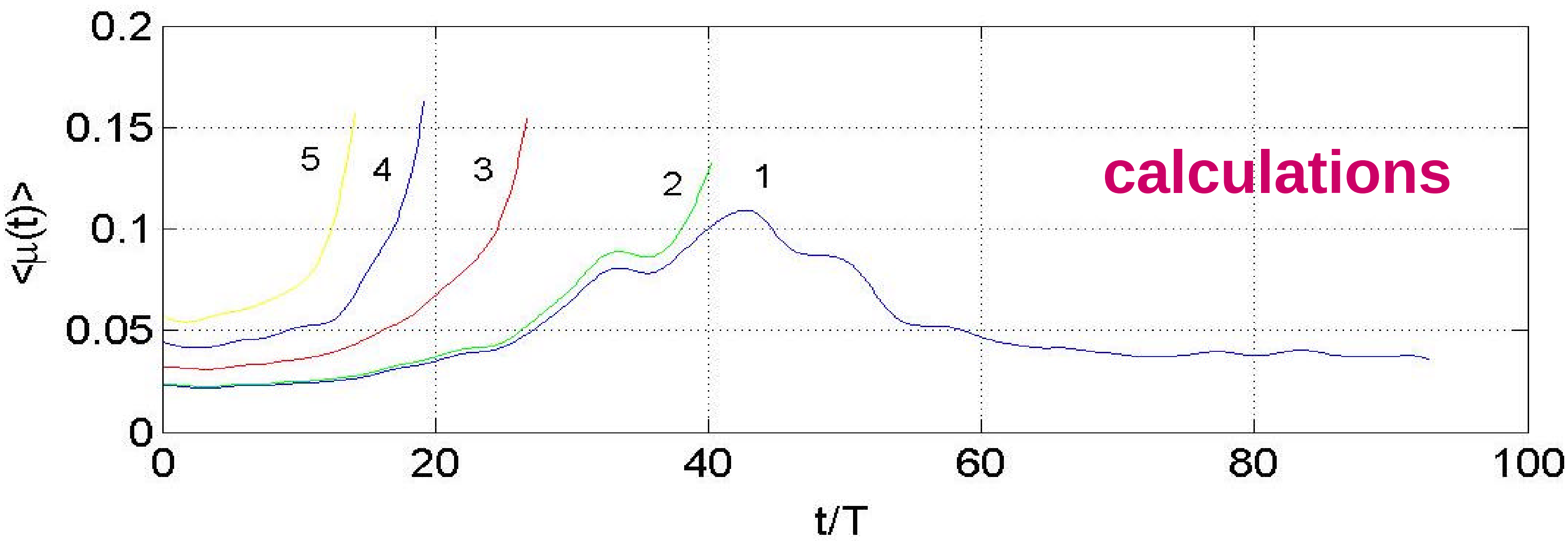
'Case III' groups: Initial chirped wave packet

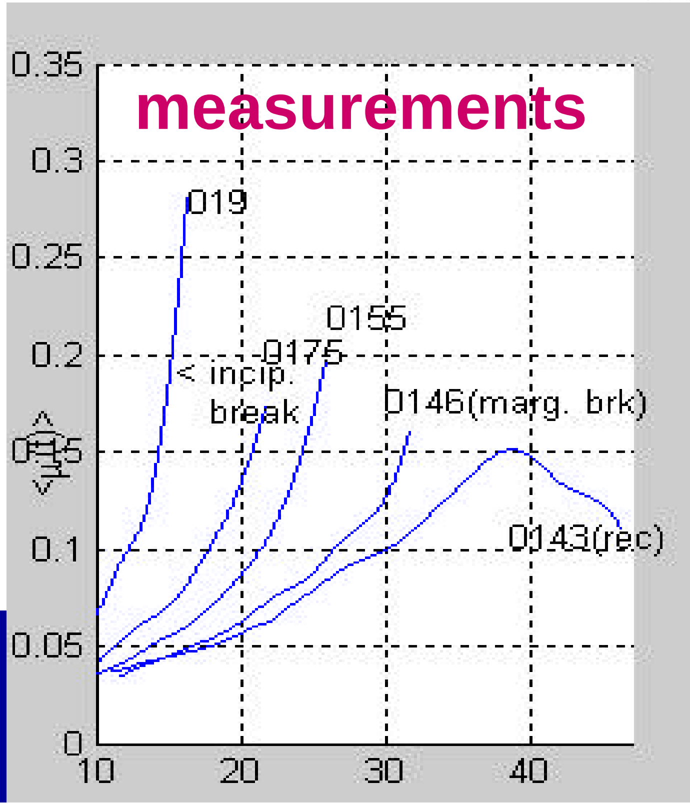
crest maximum



trough maximum

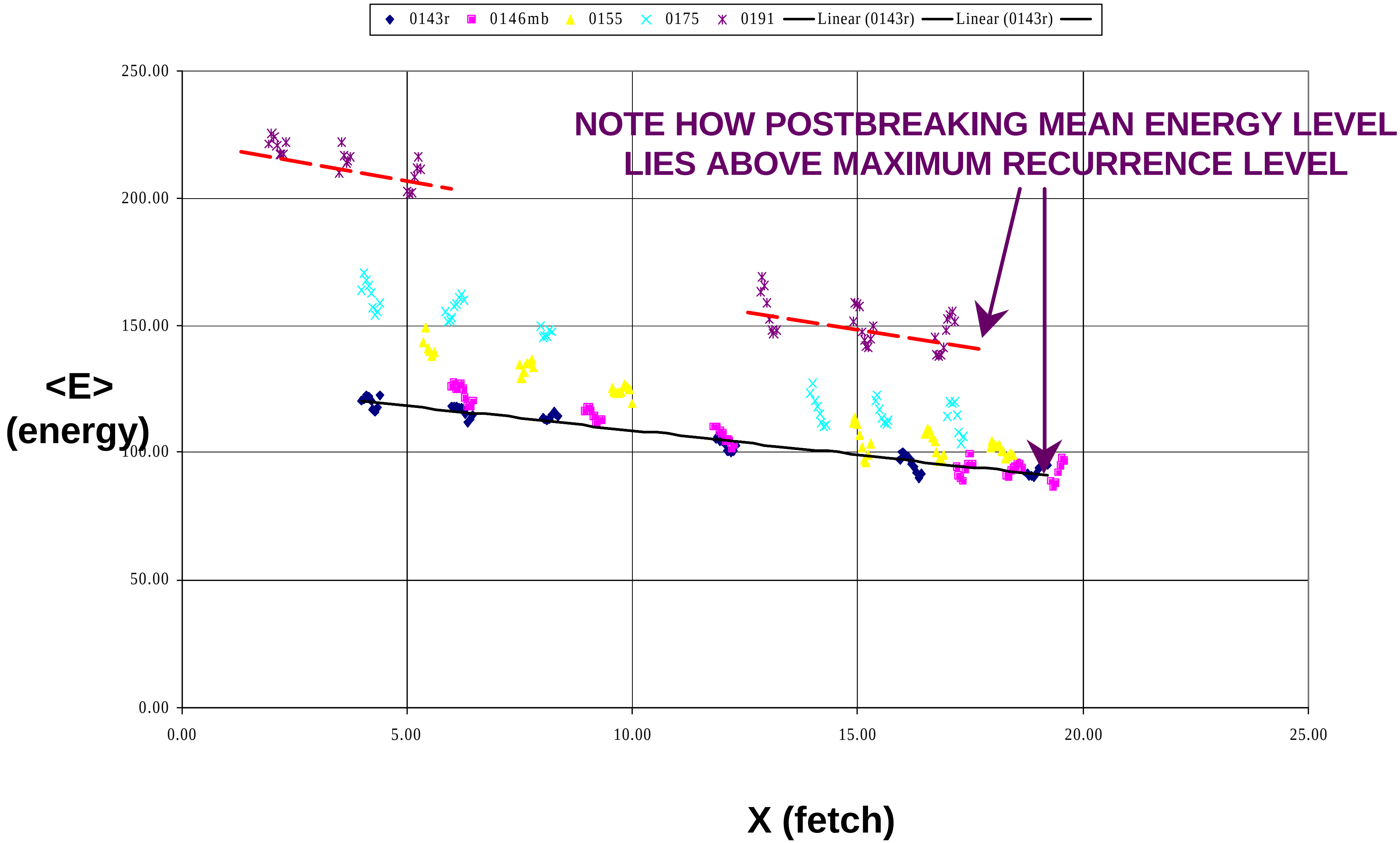






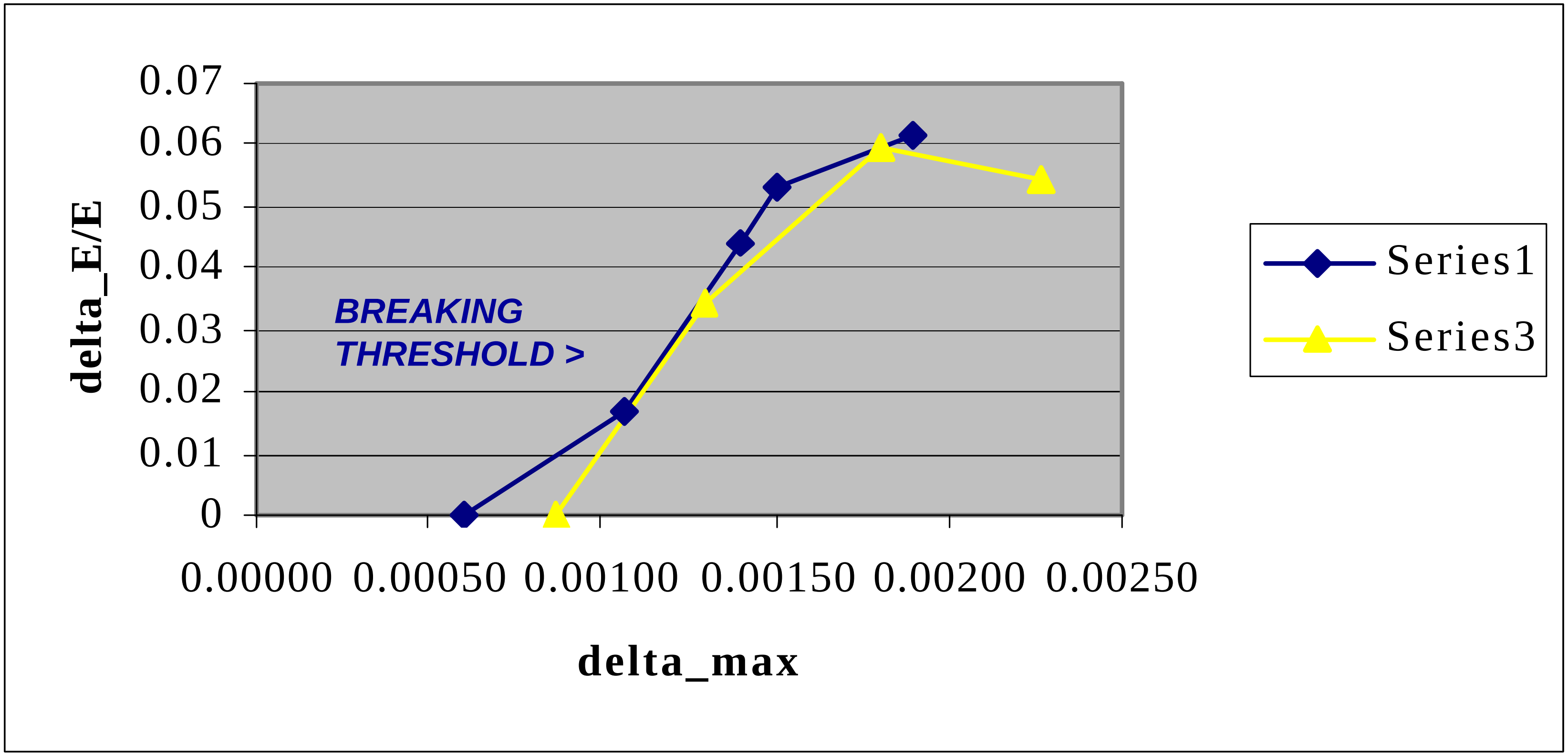
COMPARISON OF MEAN ENERGY GROWTH AT ENVELOPE MAXIMUM for 5-WAVE BIMODAL GROUPS

POST-BREAKING EVOLUTION AND ENERGY LOSS



RELATIVE ENERGY LOSS AS A FUNCTION OF MEAN ENERGY CONVERGENCE RATE AT GROUP MAXIMUM

- **BIMODAL SPECTRUM (Series 1)**
- **CHIRPED PACKET (Series 3)**



>> THIS RESULT PROVIDES A SIGNIFICANT ADVANCE IN OUR PRESENT UNDERSTANDING OF WAVE BREAKING

<u>PRESENT CONCLUSIONS FROM OUR LABORATORY STUDY</u>

• For both breaking and recurrence, the observed local energy density and its growth rate, following the maximum of the wave group, closely parallel the computational results [reported in Song & Banner (JPO, 2002)]

• The mean trend of the wave energy convergence towards (or away from) the maximum energy region within the wave group appears to determine the ultimate breaking or recurrence behaviour.

<u>In particular</u>:

• there is a <u>common breaking threshold</u> for the parametric convergence rate
• the post-breaking relative energy loss appears to be well-correlated with this convergence rate.

<u>Status of this work:</u>

• further cases are being investigated with different initial group structures

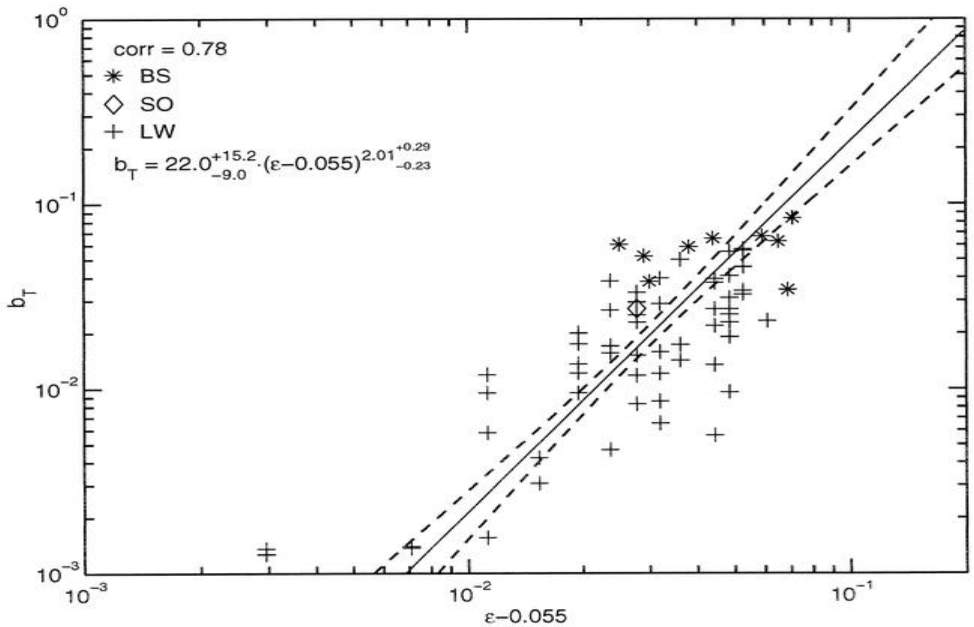
APPLICATION TO WAVES AT SEA

• Dominant sea waves occur routinely in wave groups, ***so are 2-D modelling results helpful ?*** E.g., is there a parametric threshold for wave field nonlinearity that correlates well with breaking onset of the *dominant* seas?

• Correlation of breaking probability* against ***significant mean steepness*** of the dominant waves revealed a ***threshold breaking behavior*** for a wide dynamic range of wave scales (Banner, Babanin and Young, JPO, 2000)

****defined as relative passage rate past a fixed point of breaking crests to total crests in spectral peak enhancement region***

breaking probability



mean steepness-threshold mean steepness

PRACTICAL IMPLICATIONS

THIS RESULT SUGGESTS THAT IF ONE CAN RELIABLY FORECAST

- **SIGNIFICANT WAVE HEIGHT H_s**
- **PEAK FREQUENCY f_p**

THEN ONE COULD PROVIDE A FORECAST FOR THE BREAKING PROBABILITY OF THE DOMINANT SEA WAVES.

>> OF COURSE, SUBJECT TO A SUITABLE FIELD VALIDATION, ESPECIALLY DURING STORM CONDITIONS

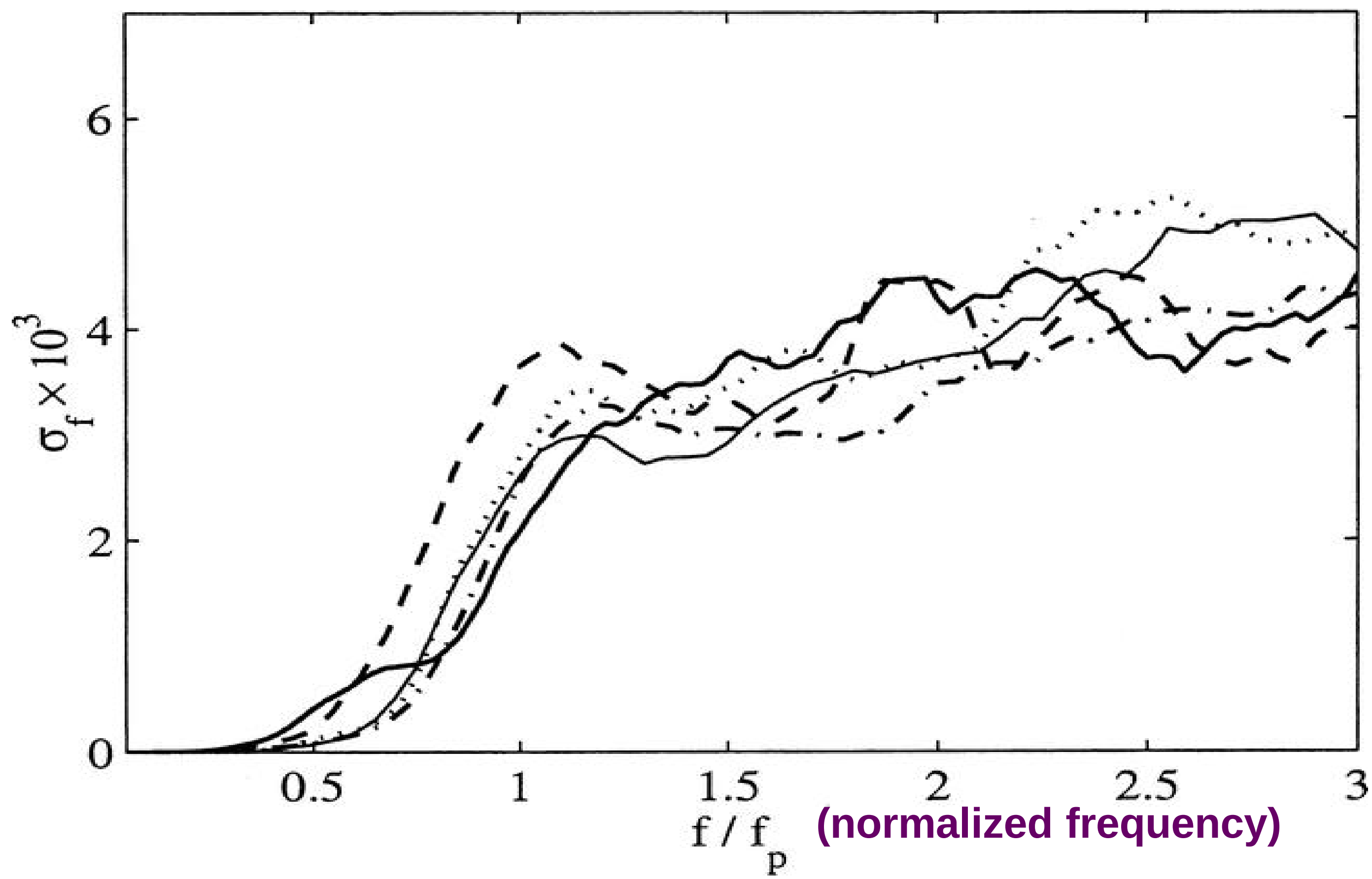
WHAT IF WE WANT BREAKING INFORMATION FOR SHORTER WAVE SCALES ABOVE THE SPECTRAL PEAK?

AZIMUTH INTEGRATED SPECTRAL SATURATION

This is a convenient non-dimensional measure of wave steepness at different spectral scales obtained from the frequency spectrum: <u>it is proportional to the fifth moment of F(*f*):</u> $s_{f}(\boldsymbol{k}) = (2\pi)^4 f^{\,5}\, \mathrm{F}(f)\, /\, 2g^2$ $[= k^4\, F(\boldsymbol{k})\,]$

e.g. N. Pacific Storm Wave Observations of GEMMRICH & FARMER (1999)

Azimuth integrated saturation

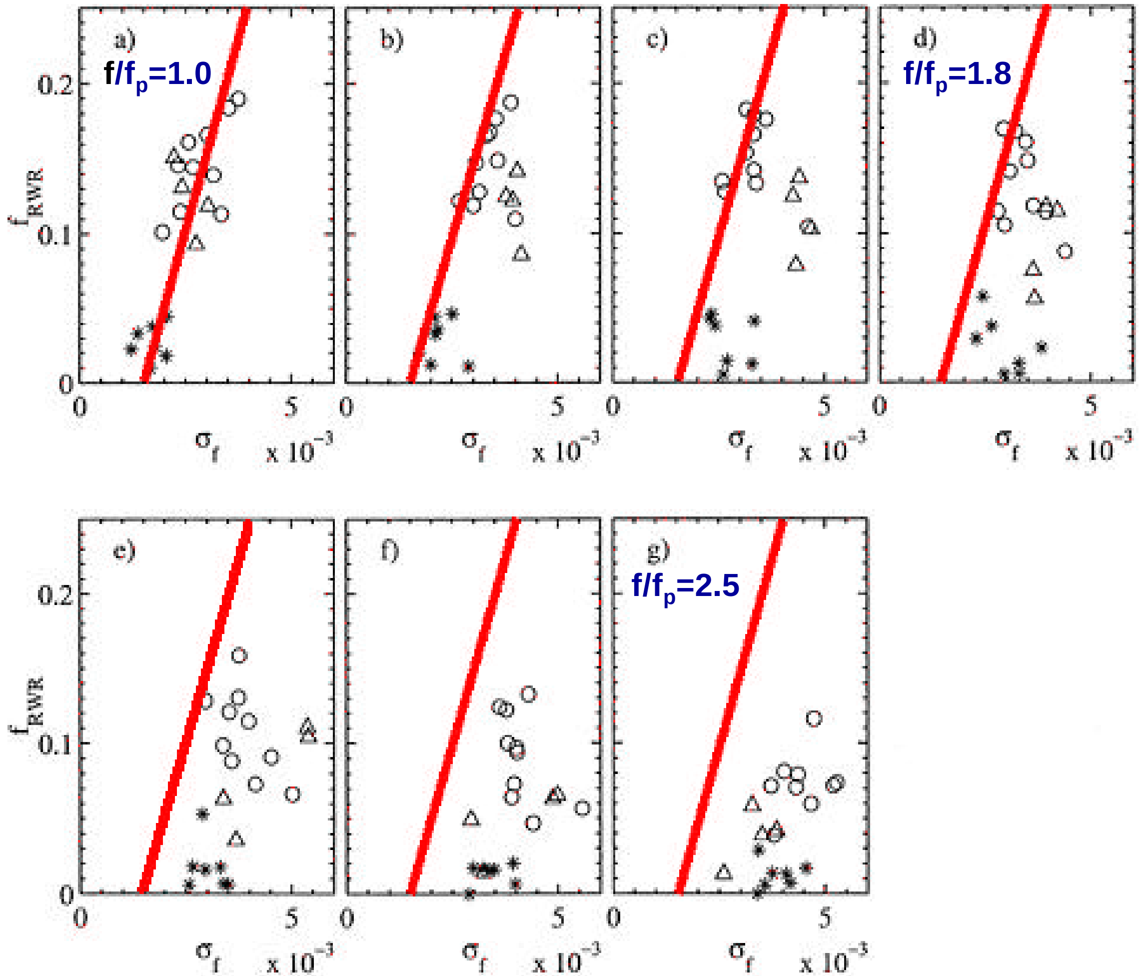


(normalized frequency)

BREAKING AT DIFFERENT WAVE SCALES

(Banner, Gemmrich and Farmer, JPO, 2002)

• using *spectral saturation* shows strong evidence of *threshold* behaviour at centre frequencies at the spectral peak and above.



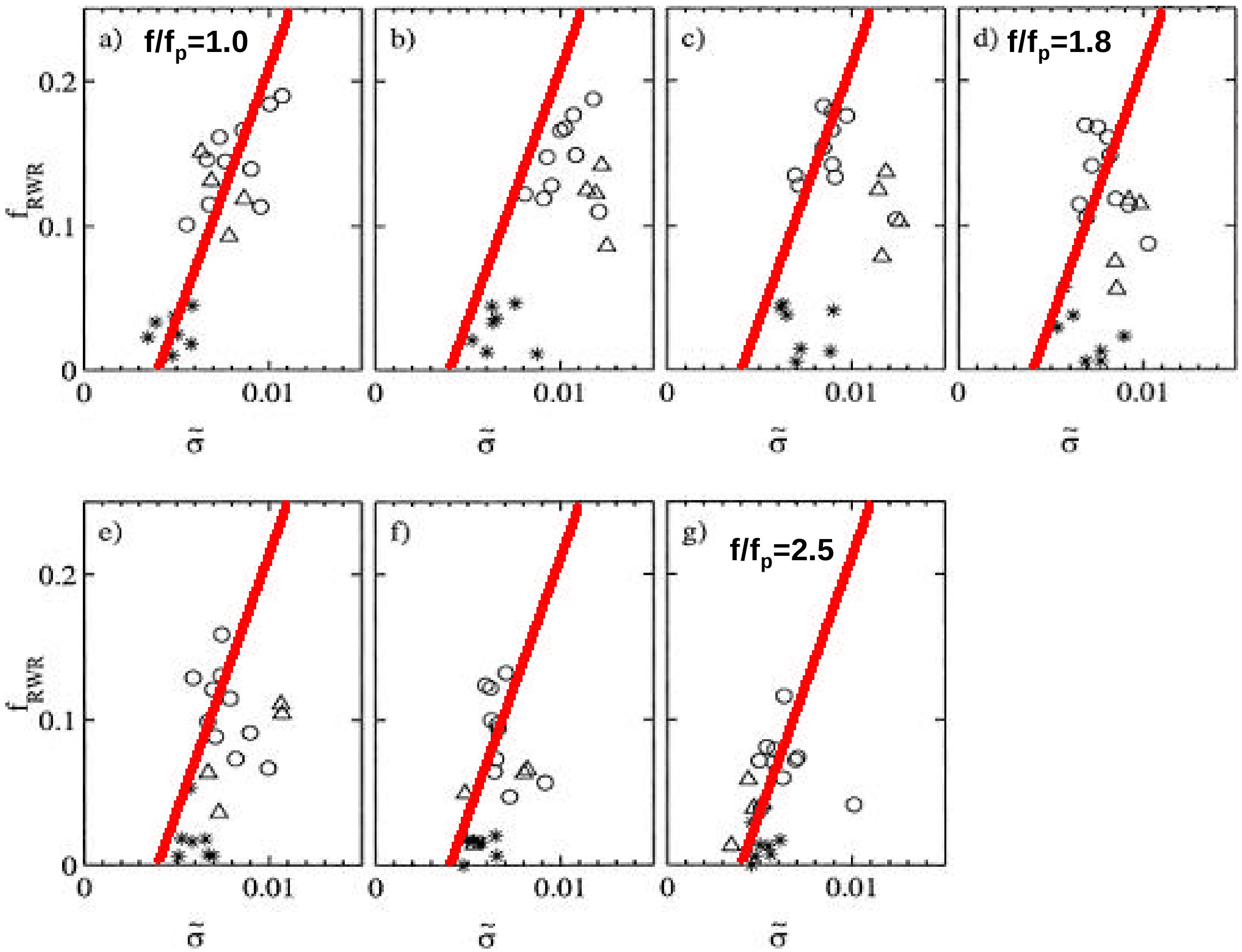
breaking probability

spectral saturation →

NB:* spectral saturation** s_f ***increases along with directional spreading width as f increases

NORMALIZATION

- dependences are complicated by the broader directional spreading with f/f_p but the same qualitative threshold behaviour is evident once the spectral saturation is <u>normalized to the directional spreading at the spectral peak</u>



breaking probability

directionally-normalized spectral saturation

PRACTICAL IMPLICATIONS

THIS RESULT SUGGESTS THAT IF ONE CAN RELIABLY MODEL THE WAVE SPECTRUM THEN THEN ONE COULD HOPE TO PROVIDE A FORECAST FOR THE BREAKING PROBABILITY OF THE DOMINANT SEA WAVES AND ALSO CENTER FREQUENCIES ABOVE THE SPECTRAL PEAK, SAY OUT TO 3f_p WHERE THE SPECTRAL SOURCE TERMS ARE BELIEVED TO BE VALID.

>> OF COURSE, SUBJECT TO A SUITABLE FIELD VALIDATION, ESPECIALLY DURING STORM CONDITIONS

WHAT IF WE ALSO WANT BREAKING INFORMATION FOR THE MUCH SHORTER WAVE SCALES WELL ABOVE THE SPECTRAL PEAK?

- **THIS IS AN ACTIVE RESEARCH TOPIC**
- **RECENT DEVELOPMENTS FOLLOW .....**

SPECTRAL WAVE MODELLING

***Radiative transfer equation* (deep water, no currents)**

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

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

←Total source term wind input, etc

where

- $F=F(k,q)$ 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 ***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*

SATURATION THRESHOLD-BASED S_{ds}

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

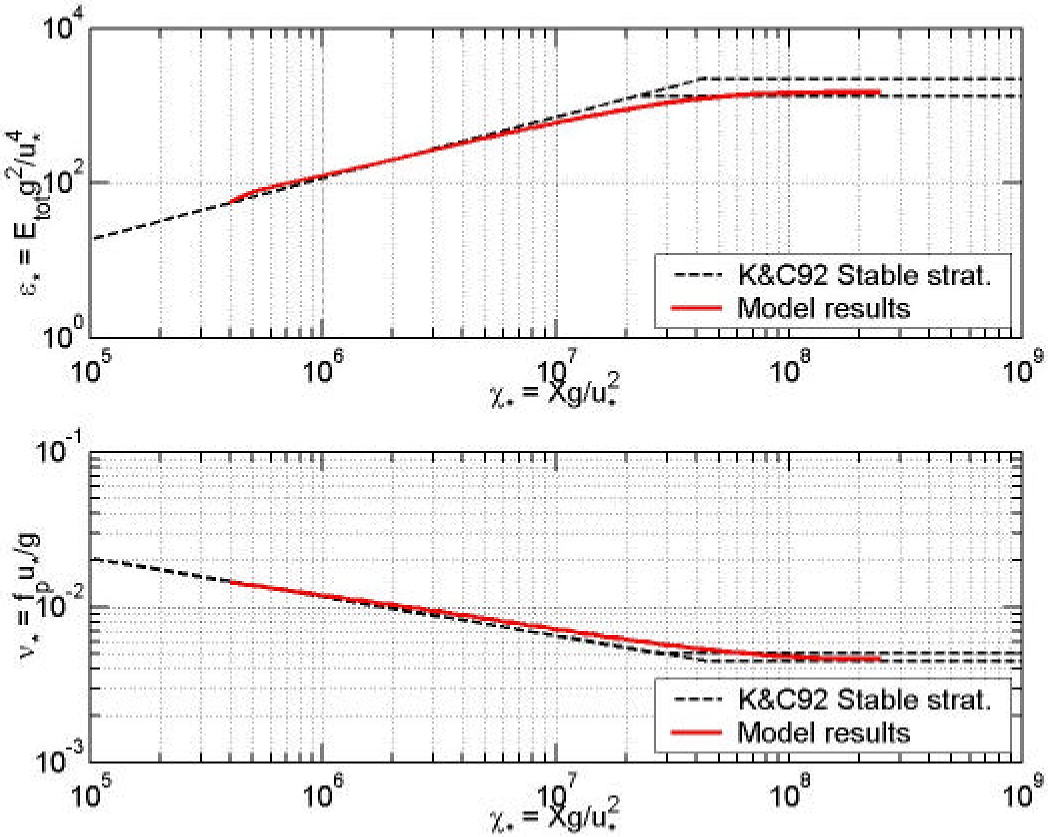
$$S_{ds}(k,q) = C\left[(s(k) - s_T)/s_T\right]^n G[s(k)]\, w\, F(k,q)$$

where

- s is the normalized azimuthally-integrated saturation $k^4F(\mathbf{k})$ over a constant relative wavenumber bandwidth at wavenumber $\mathbf{k}=(k,?)$
- **?** is the radian frequency
- s_T is the threshold normalised spectral saturation, determined observationally (Banner, Gemmrich and Farmer, JPO, 2002)
- To match dissipation to the observed thresholded and wind input behaviour, the exponent *n* was taken as 1 and G was taken as a power law function of [$\sigma/\sigma(k_m)$]
- The tuning constant *C* was chosen to provide the optimal match to observed fetch evolution of the spectral peak energy (Kahma and Calkoen, JPO, 1992)

RESEARCH IN PROGRESS

EXACT NL COMPUTATION OF FETCH-LIMITED WIND WAVE EVOLUTION

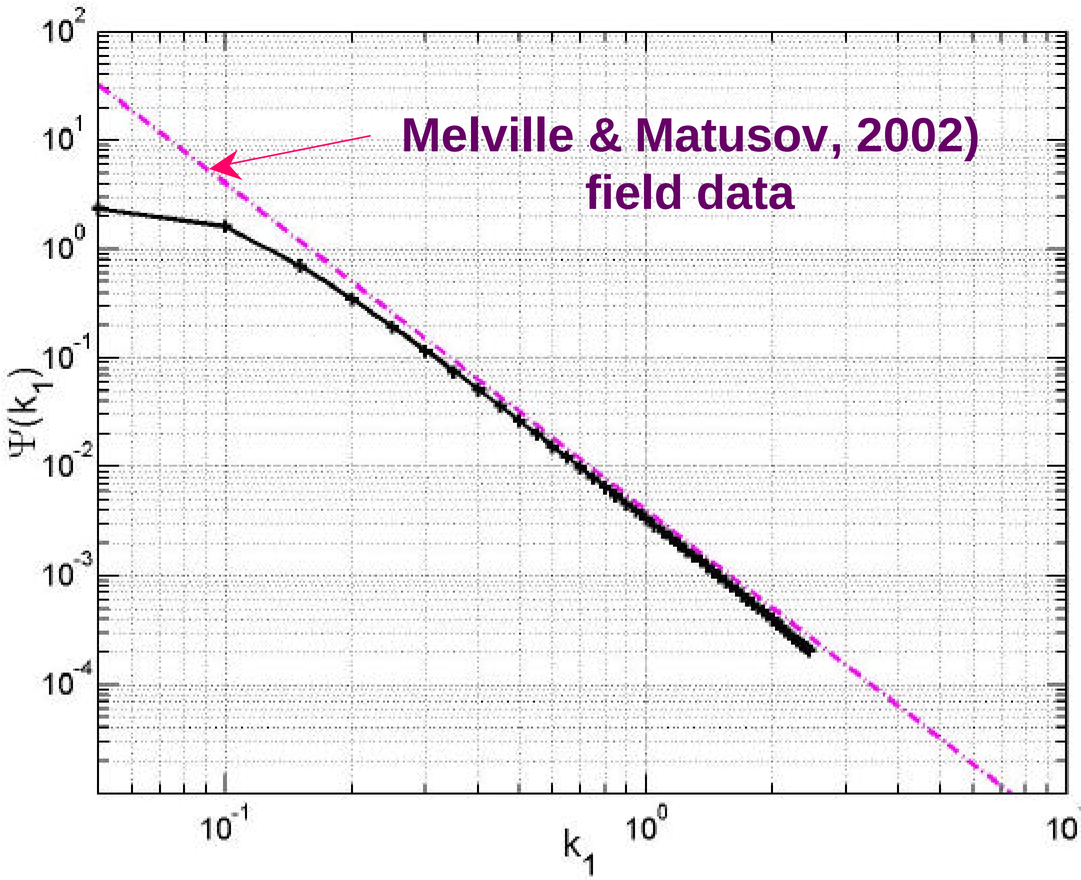


>> **whereas the quasi-linear (WAM) form of *S_{ds}* based on *integral steepness* is not sufficiently flexible over the range from young to old sea states, our new *S_{ds}* based on *local* saturation ratio addresses this shortcoming.**

1-D TRANSECT WAVENUMBER SPECTRA

<u>Computational vs. observed results</u> of Melville and Matusov (2002) for old wind seas at a wind speed of 10 m/s. Tail level and shape are very weakly sensitive to wind speed.

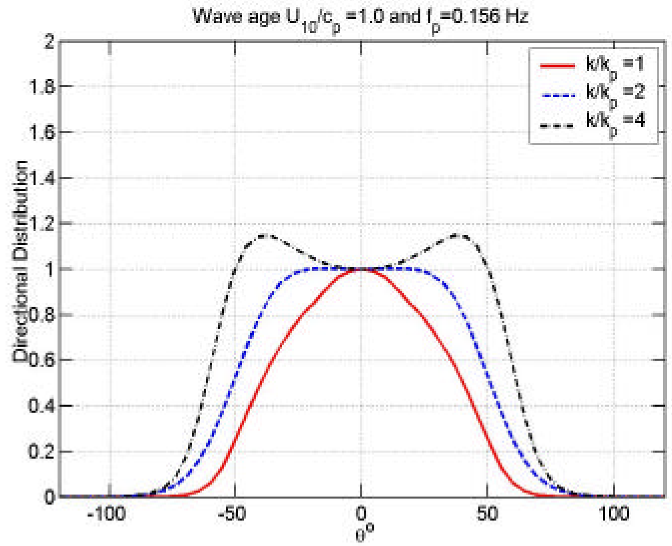
spectral density of wave energy



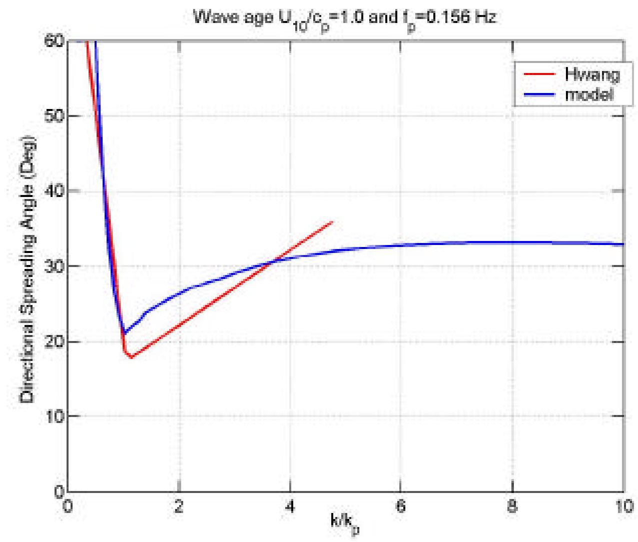
wave number

PROPERTIES OF THE SPECTRAL TAIL REGION

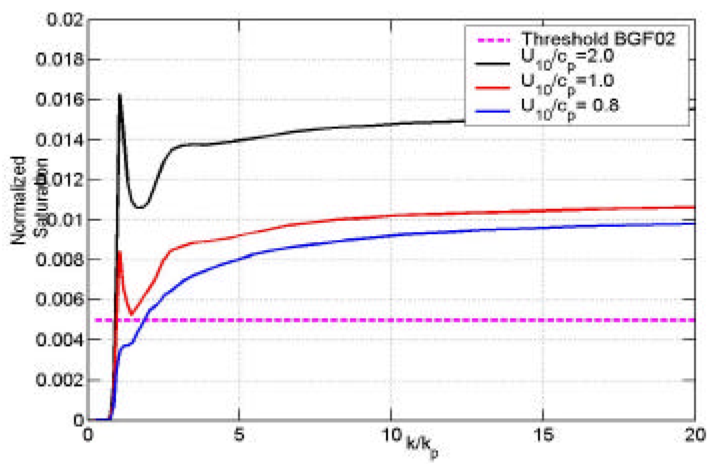
Directional spreading distribution



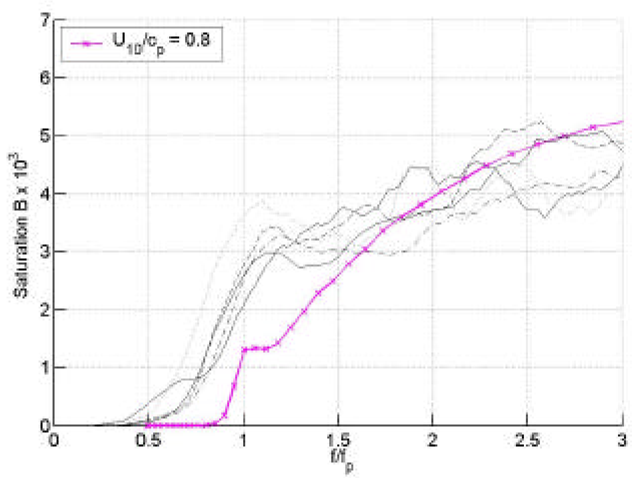
Mean directional spreading vs. k/k_p



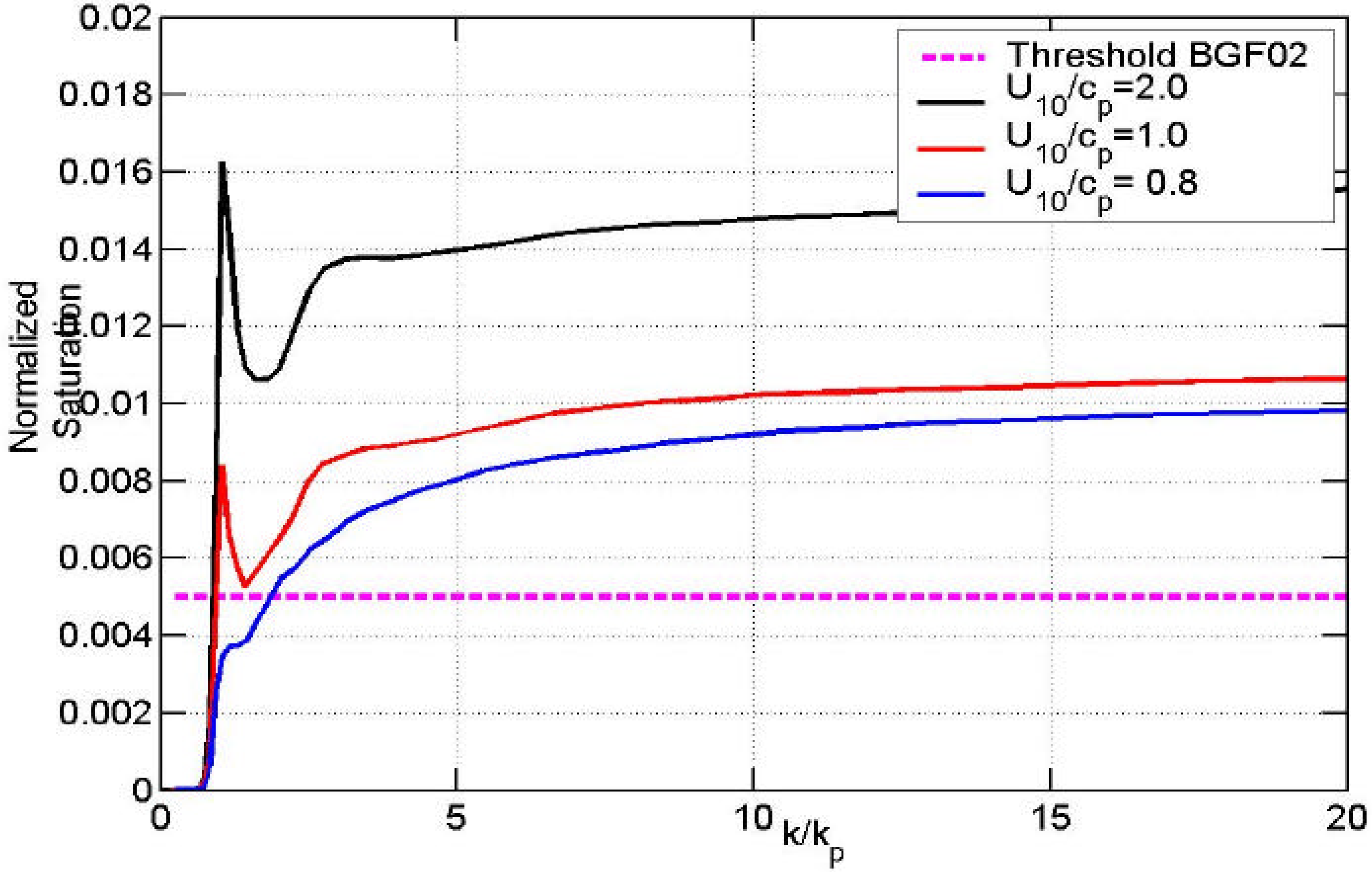
Integrated saturation with k/k_p vs. age



Integrated saturation with f/f_p vs. data



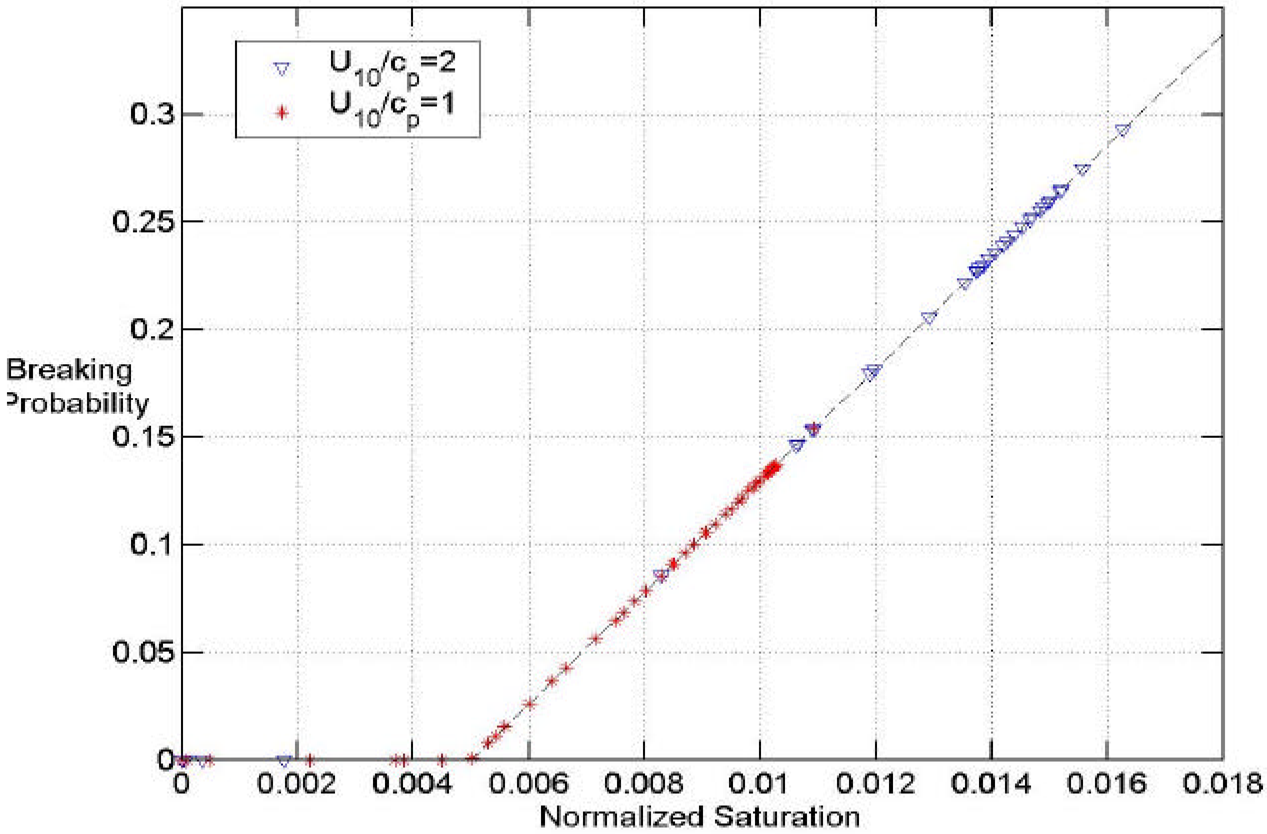
EVOLUTION OF NORMALIZED SPECTRAL SATURATION



Variation with distance (k/k_p) from the spectral peak wavenumber of the normalised spectral saturation as the wind sea develops. Note how the dominant wave (k/k_p=1) saturation decreases with wave age from 0.016 to below 0.004. <u>The predicted dominant wave breaking probability follows from the next figure.</u>

BREAKING PROBABILITIES

The observed threshold property for breaking probabilities provides a look-up table that can be added to a conventional wind wave forecast model to deliver timely warnings of large breaking waves occurrence rates in regional coastal waters.



THIS REQUIRES A SUITABLE FIELD VALIDATION. WE ARE WORKING TOWARDS THIS GOAL FROM A OIL/GAS PLATFORM OVER A YEAR OR MORE OF STORMS

$\mathbb{L}$(c) -- SPECTRAL DENSITY OF BREAKING CREST LENGTH /UNIT AREA TRAVELLING WITH SPEED c, c+dc

• this is a <u>different characterisation of wave breaking</u> in the spectrum, introduced by O.M. Phillips (JFM, 1985)

• it is measurable from data gathered by an aircraft-borne videocamera

• the belief is that the spectral dissipation rate of wave energy (very difficult to measure directly) can be related to the observed kinematic and geometric properties of whitecaps at different scales:

$$S_{ds}(c) = b\, c^5/g\, \mathbb{L}(c)$$

where the dimensionless coefficient 'b' connects the kinematics on the LHS to the energetics on the RHS. The form of 'b' is not yet known: the default is a constant value b~0.006 (Melville, JPO, 1996)

• while still very much in the research stage, our initial computational results provide a new perspective through a detailed comparison with recent observations of $\mathbb{L}$(c) reported by Melville and Matusov (2002).

SOME FURTHER BACKGROUND ISSUES

• IN DEEP WATER, BREAKING IS THE DOMINANT DISSIPATIVE PROCESS

• IT IS A **STRONG** PROCESS - MORE THAN 97% OF THE ENERGY FLUX FROM THE WIND ENDS UP AS TURBULENCE IN THE WATER COLUMN

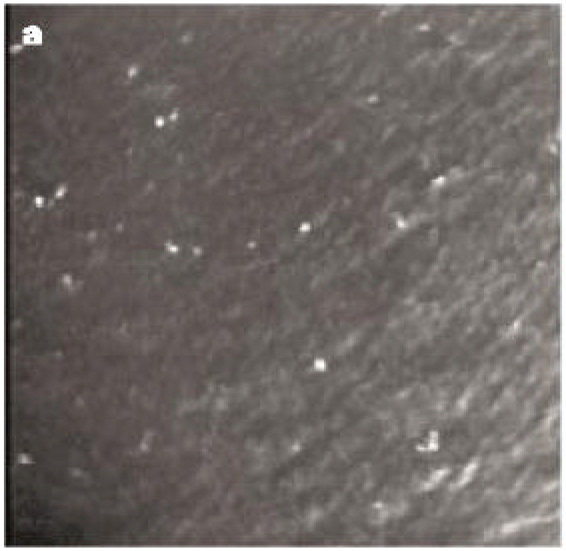
• YOUNG WIND SEAS HAVE UP TO O(20%) BREAKING DOMINANT WAVES

• BREAKING CREATES A WHITECAP-DRIVEN SHEAR STRESS THAT DOES WORK AGAINST THE ORBITAL MOTION OF THE WAVE UNDERGOING BREAKING

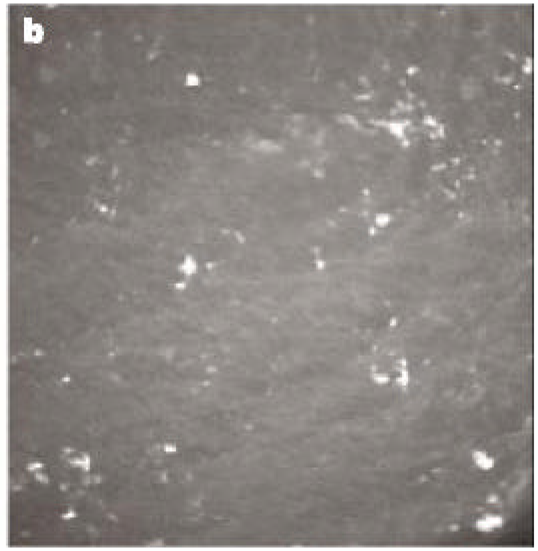
• A SIGNIFICANT **VORTEX** OF THE SCALE OF THE BREAKER IS GENERATED AND CAST OFF DURING THIS PROCESS (A LONG WAVE IS ALSO GENERATED, TOGETHER WITH OTHER SHORTER WAVES – THESE ALSO RADIATE AWAY PART OF THE EXCESS ENERGY FLUX)

AIRCRAFT BREAKING WAVE OBSERVATIONS

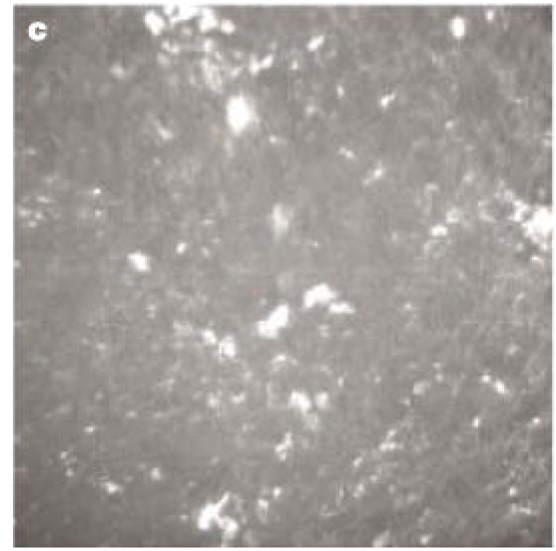
Melville and Matusov (2002)



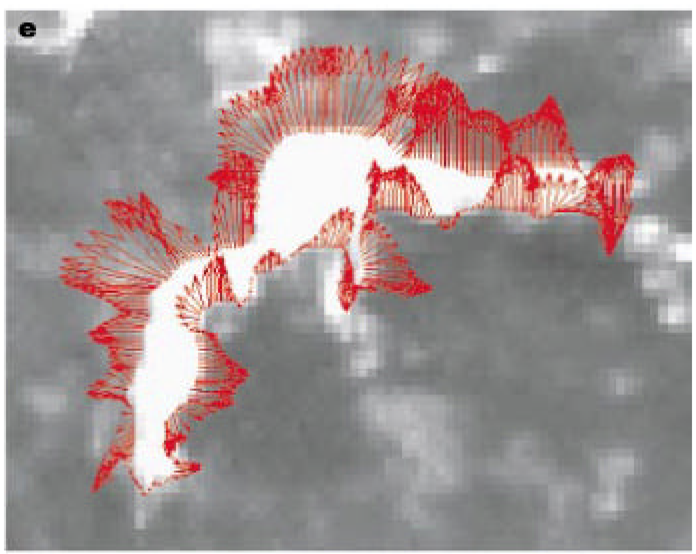
U=7.2 m/s



U=9.8 m/s



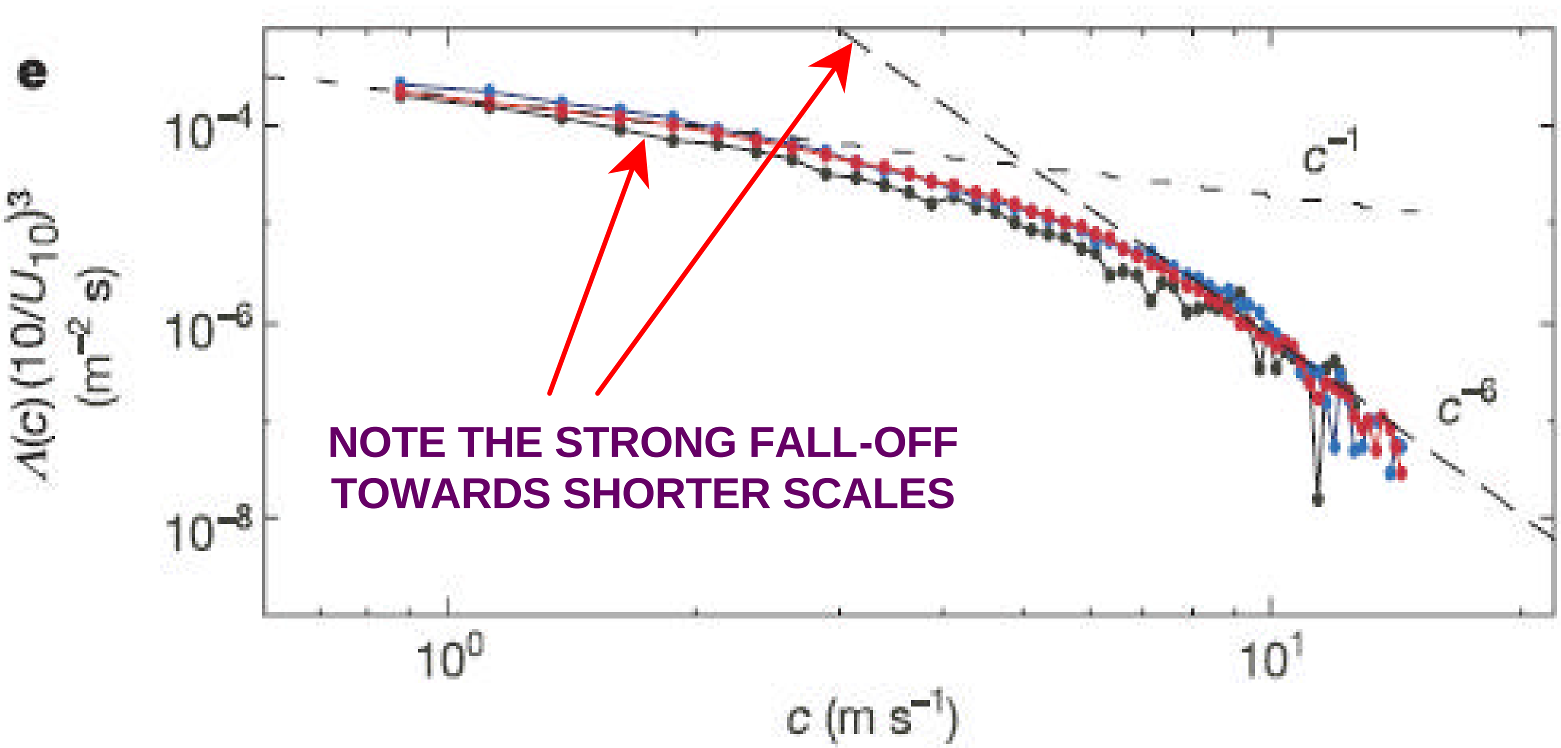
U=13.6 m/s



PIV analysis of whitecap

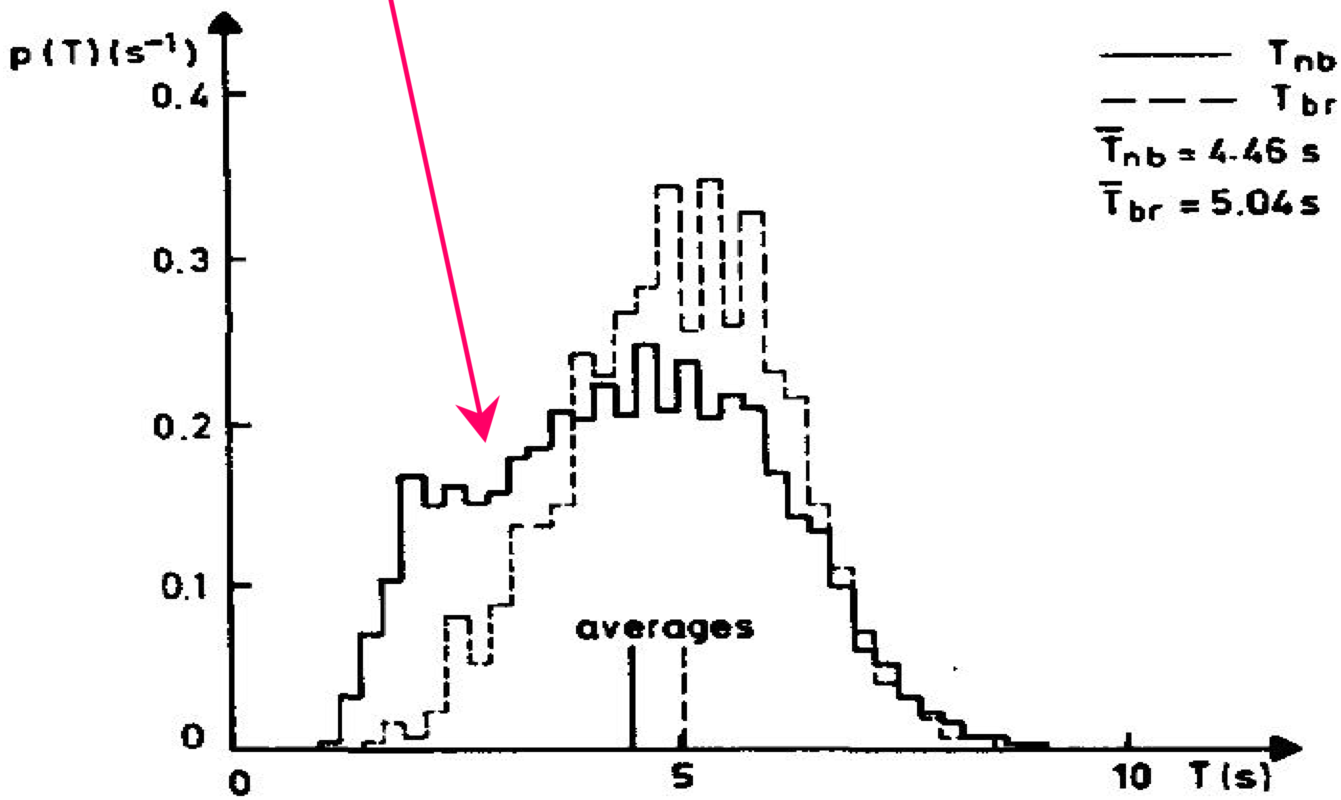
VERY STRONG UNEXPLAINED FALLOFF IN L(c) TOWARDS SHORTER SCALES

Ocean data of Melville and Matusov (2002)



Open ocean data of Herbers and Holthuijsen (JPO, 1986)--

<u>NOTE THE SHARP FALLOFF OF THE FRACTION OF BREAKING WAVES TOWARDS SHORTER (LOWER C) WAVES</u>



- <u>does not appear to support the concept of a concentration of breaking-related dissipation rate at the short wave end of the spectrum!!</u>

OUR COMPUTATIONS OF SPECTRAL BREAKING DISTRIBUTIONS –

WORK IN PROGRESS

COMPARISON OF OBSERVED AND COMPUTED L(c)

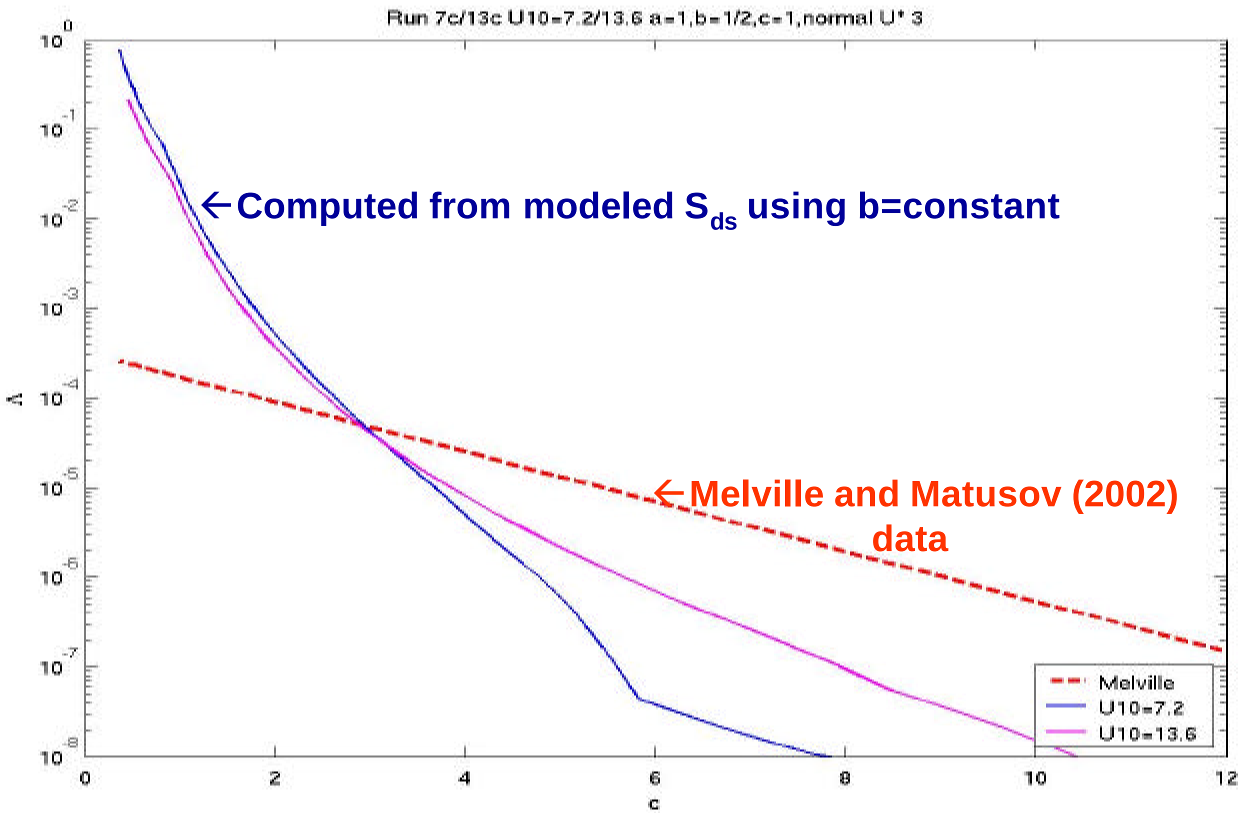
L(c) x $(10/U_{10})^3$

breaking crest

length/unit area

with speeds in

[c, c+dc]



wave speed c

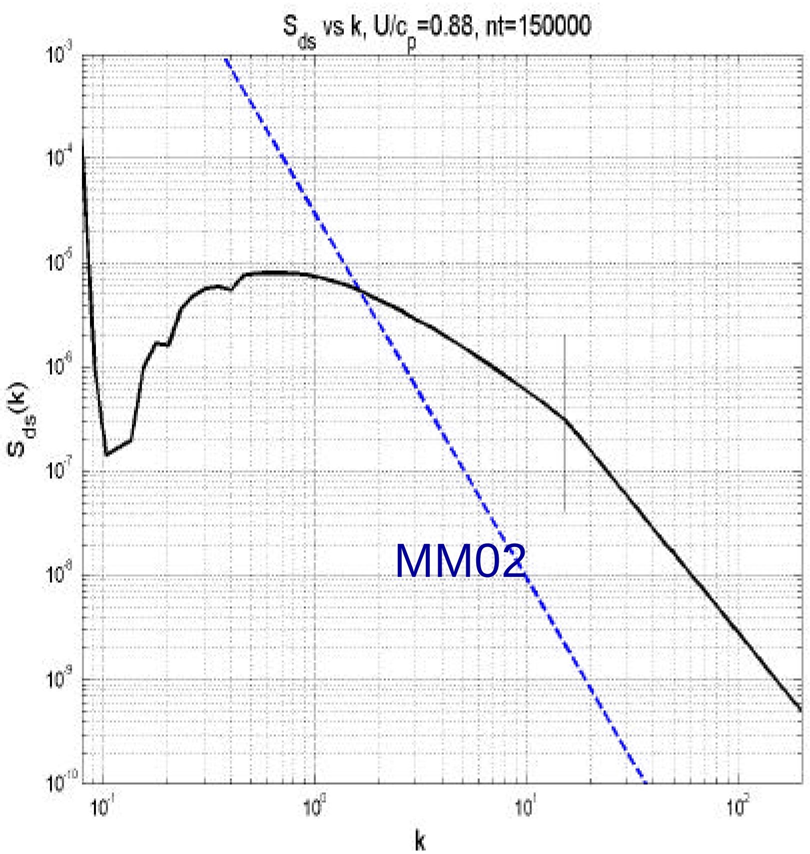
> <u>The model reproduces the cubic dependence on wind speed in the tail</u>

>> But…note how the <u>model seriously overpredicts</u> the observed distribution of L(c), based on assuming a constant value of the breaking strength coefficent b

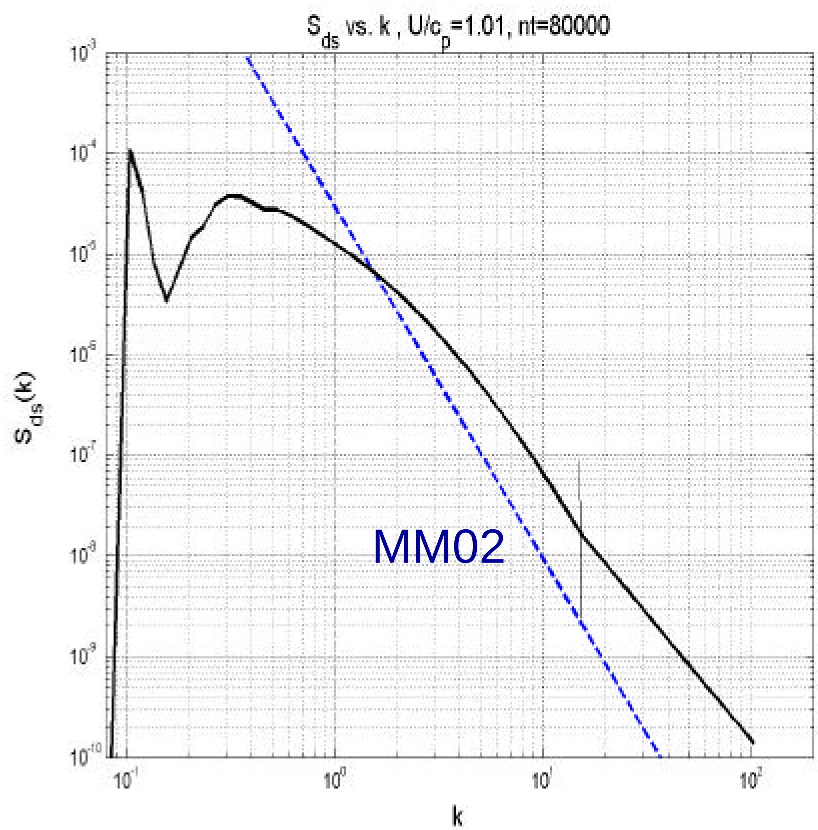
SPECTRAL DISSIPATION RATE SOURCE TERM S_{ds}

Behavior of modeled S_{ds} at ~10 m/s as a function of 0.5*Yan wind input source function - composite of 'Snyder' near peak transitioning to 'Plant' in <u>tail region.</u>

'Plant' form $(u_*/c)^2$ in tail region



'Plant' S_{in} attenuated by sech function

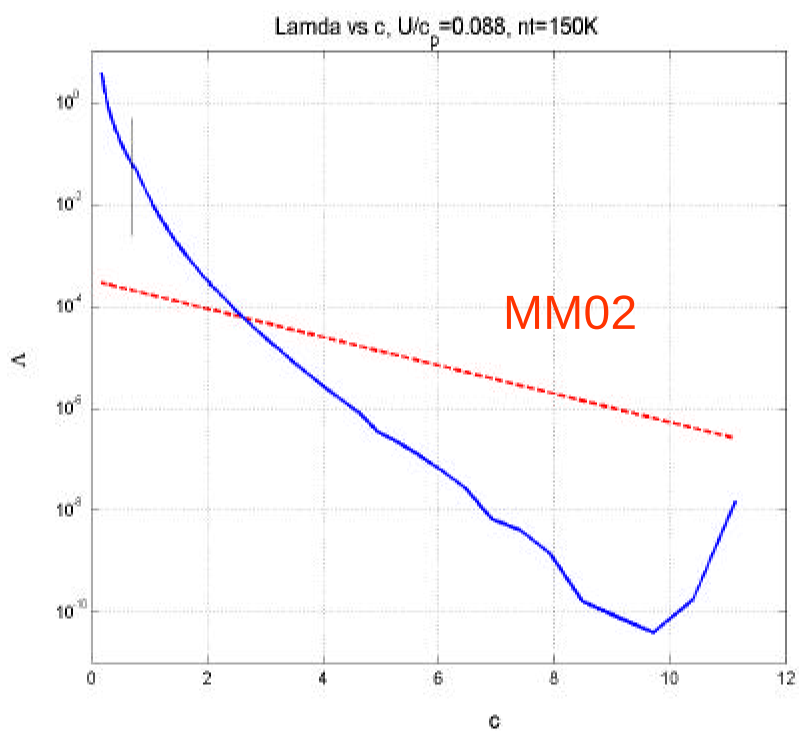


CORRESPONDING SPECTRAL DISTRIBUTION L(c) OF BREAKING CREST LENGTH IN (c, c+dc) P.U. AREA

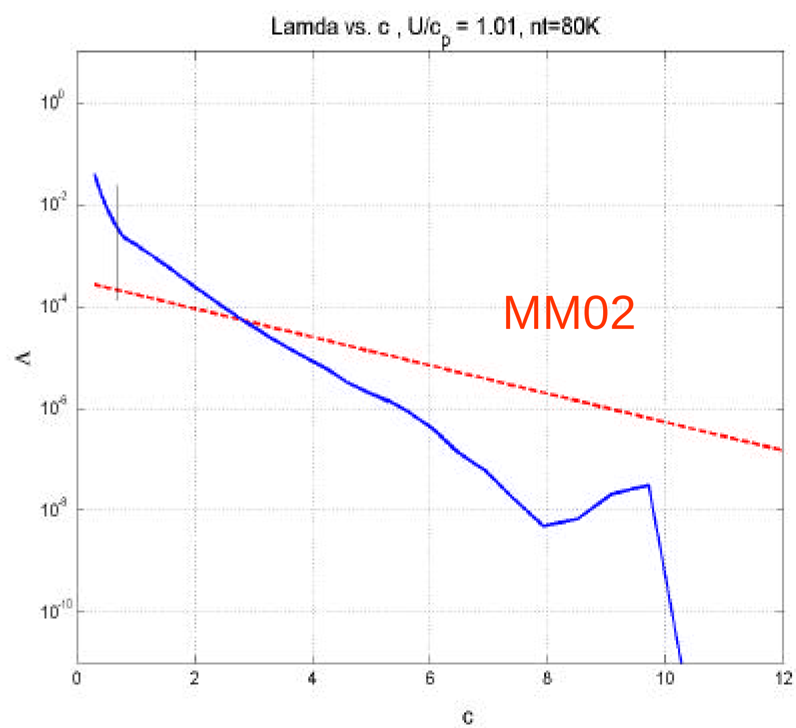
Transformation based on S_{ds}= b c^5/g L, using a ***constant* value for b** gives the following comparison for L.

NB: The actual dependence of b on k Is not yet known, but needs to be known in order to relate S_{ds} to L. It appears that 'b' is an increasing function of wave steepness, i.e. saturation, which would bring the curves below into alignment

'Plant' form $(u_*/c)^2$ in tail region



'Plant' S_{in} attenuated by sech function



ONGOING RESEARCH

We are presently exploring the possible impact of

an increasing breaking strength 'b' towards shorter scales, as warranted by a number of documented mechanisms, e.g. long wave damping of short waves

- **enhanced wind input to shorter breaking waves relative to hydrodynamic forcing**

and/or

- **enhanced background turbulence increasing the turbulent viscosity damping**

and/or

- **reduced wind input due to 'sheltering' mechanism(s), and hence a lower dissipation rate in the spectral tail and lower L (c) curves towards smaller c**

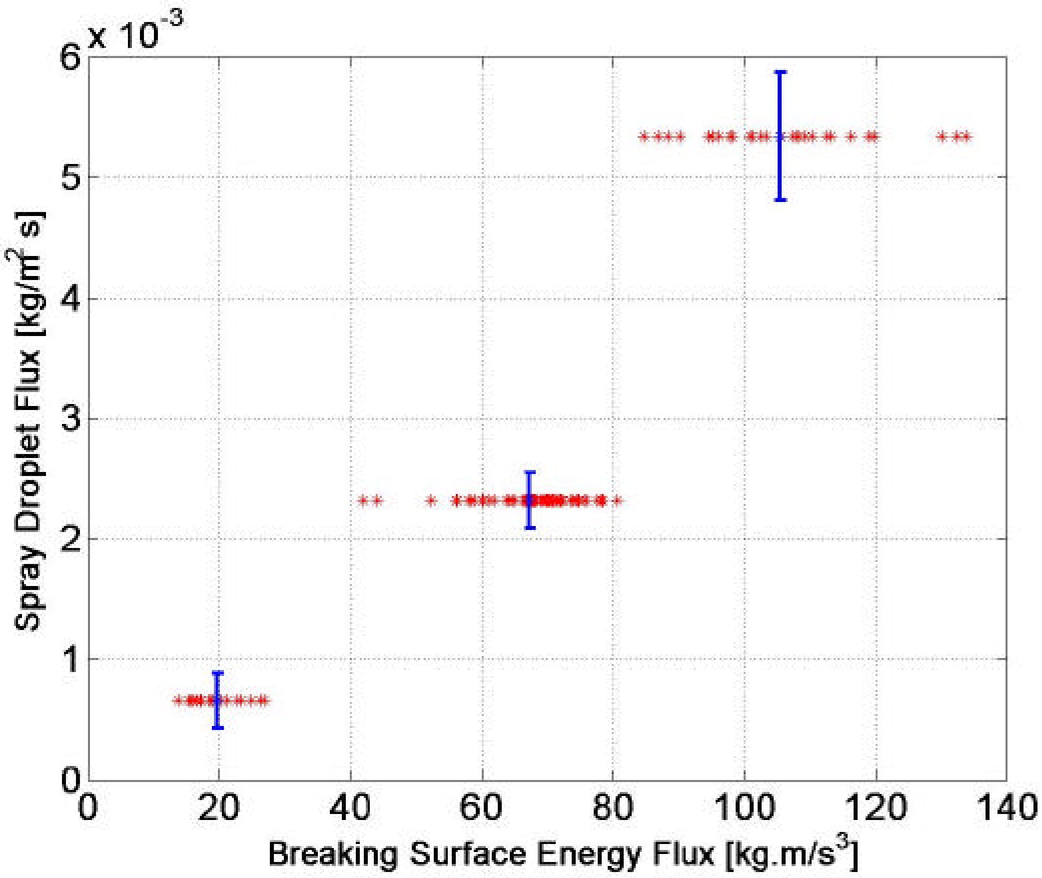
Once reconciled, this approach appears to offer the potential for adding several high wavenumber wave-breaking effects to operational models. These include sea spray production rates, additional breaking-induced wind drag, enhancement of CO_2 flux, bubble production rates, etc.

NEW BREAKING-WAVE BASED SPRAY FLUX

(Banner, Fairall, Asher and Peirson, 2004)

• ***this* will allow using <u>breaking wave properties</u> instead of <u>wind</u> to parameterize spray flux from breaking waves <u>(Newell & Zakharov, 1992)</u>**

<u>i.e. a near-linear dependence vs. some unknown high power of the wind speed</u>



CONCLUSIONS

• our approach is based on nonlinear wave group hydrodynamics as the *primary* mechanism involved in wave breaking. A threshold significant wave steepness relationship appears to be a good first approximation for correlating breaking probability for the dominant wind sea.

• for different spectral scales, a normalized spectral saturation appears to provide an effective measure of nonlinearity - breaking probability curves show self-similar threshold behavior for breaking onset at different scales

• **a** refined form for S_{ds} based on these observations performs well at the spectral peak (integral growth curves) and tail (level and angular spreading)

• predictions of the breaking crest length spectral density L are available from this model. Comparison of results from such calculations with recent field data requires refining our knowledge of the basic physics of shorter breaking waves.

• Extending the computations to severe sea state conditions is in progress.

• Implementation in an operational forecast model is straightforward once a systematic validation against breaking wave data has been completed.

• Initial tests show our new S_{ds} term delivers a significant improvement over present WAM model in operational wave height forecast applications.