Predicting the Wave Breaking Probability in Deep to Finite-Depth Waters

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Wave breaking: why do we care?

DYNAMICS OF WIND-GENERATED WAVES, OCEAN ENGINEERING, COASTAL ENGINEERING, AIR-SEA INTERACTIONS, OCEAN TURBULENCE, OCEAN DYNAMICS, CLIMATE, REMOTE SENSING

- **wave energy dissipation**
- **wind input (sea drag)**
- **nonlinear interactions (strong and weak)**
- **extreme waves (wave height limiter)**
- **wave impacts on structures, fixed and floating**
- **navigation**
- **wave-bottom interactions**
- **sediment suspension and transport**
- **coastal erosion**
- **air-sea gas exchange**
- **air-sea moisture exchange**
- **ocean turbulence**
- **ocean mixing**
- **ocean dynamics**
- **extreme oceanic conditions**
- **aerosol production**
- **ocean remote sensing (both useful and unwanted signal)**

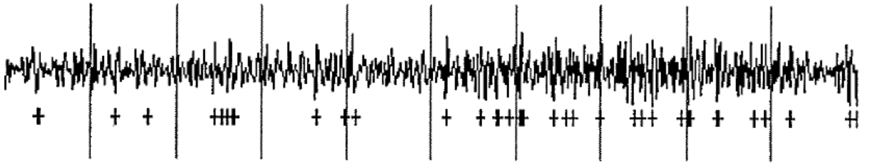


Figure 1. Example of acceleration wave series put together with breaking marks. Subdivisions correspond to 10 minute period

Introduction. 20 years ago

Breaking probability, Black Sea

Fig. 1. Locations of the research platforms in the Black Sea.

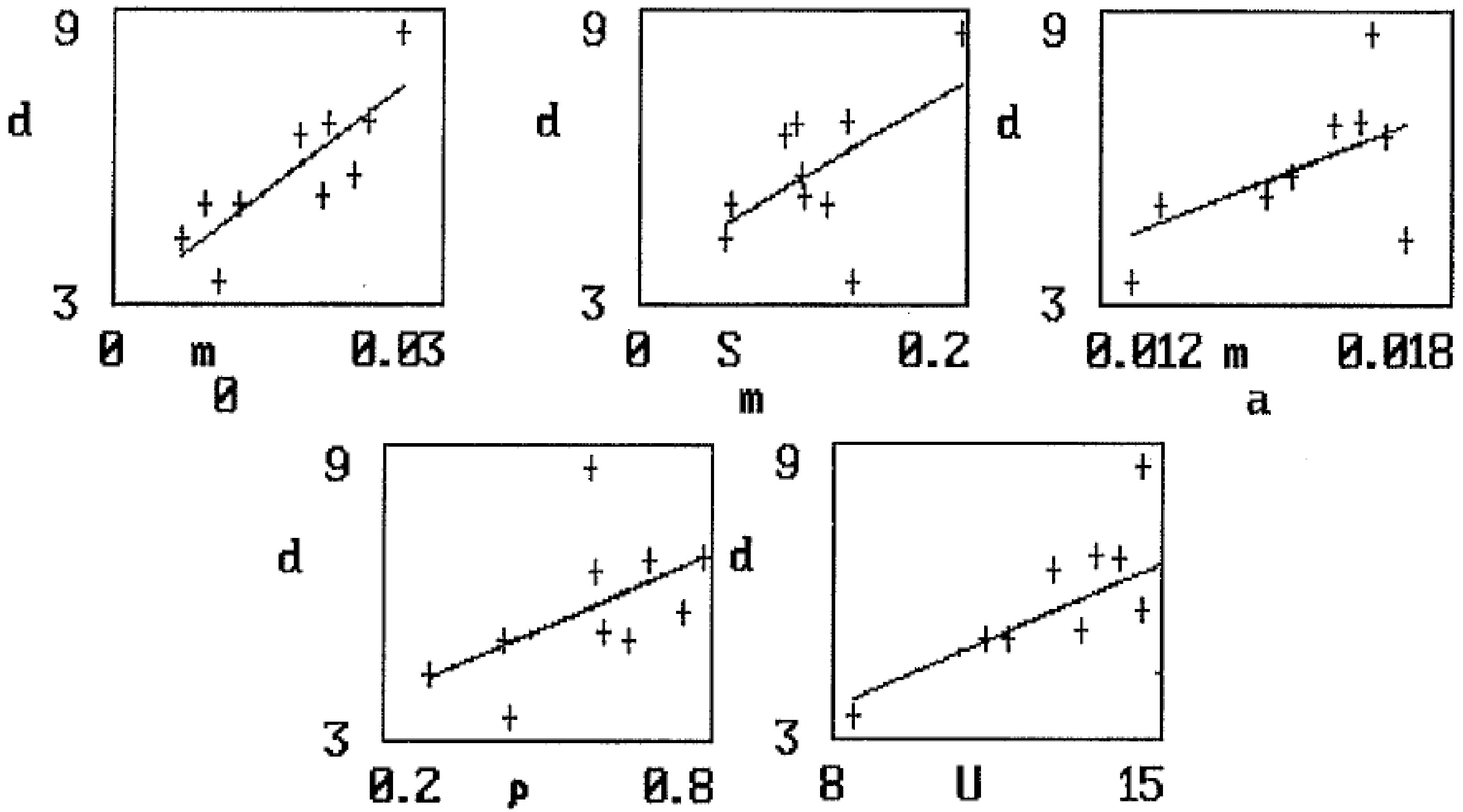


Figure 2. Breaking frequency d (number/minute) versus the wind wave spectrum parameters m_0 (m^2), S_m (m^2 s), ρ, m_a (m^2/s^4) and local wind speed U (m/s)

Babanin, 1995, Proc. Int. Conf. Med. Coast. Env.

Breaking probability & threshold, lab data

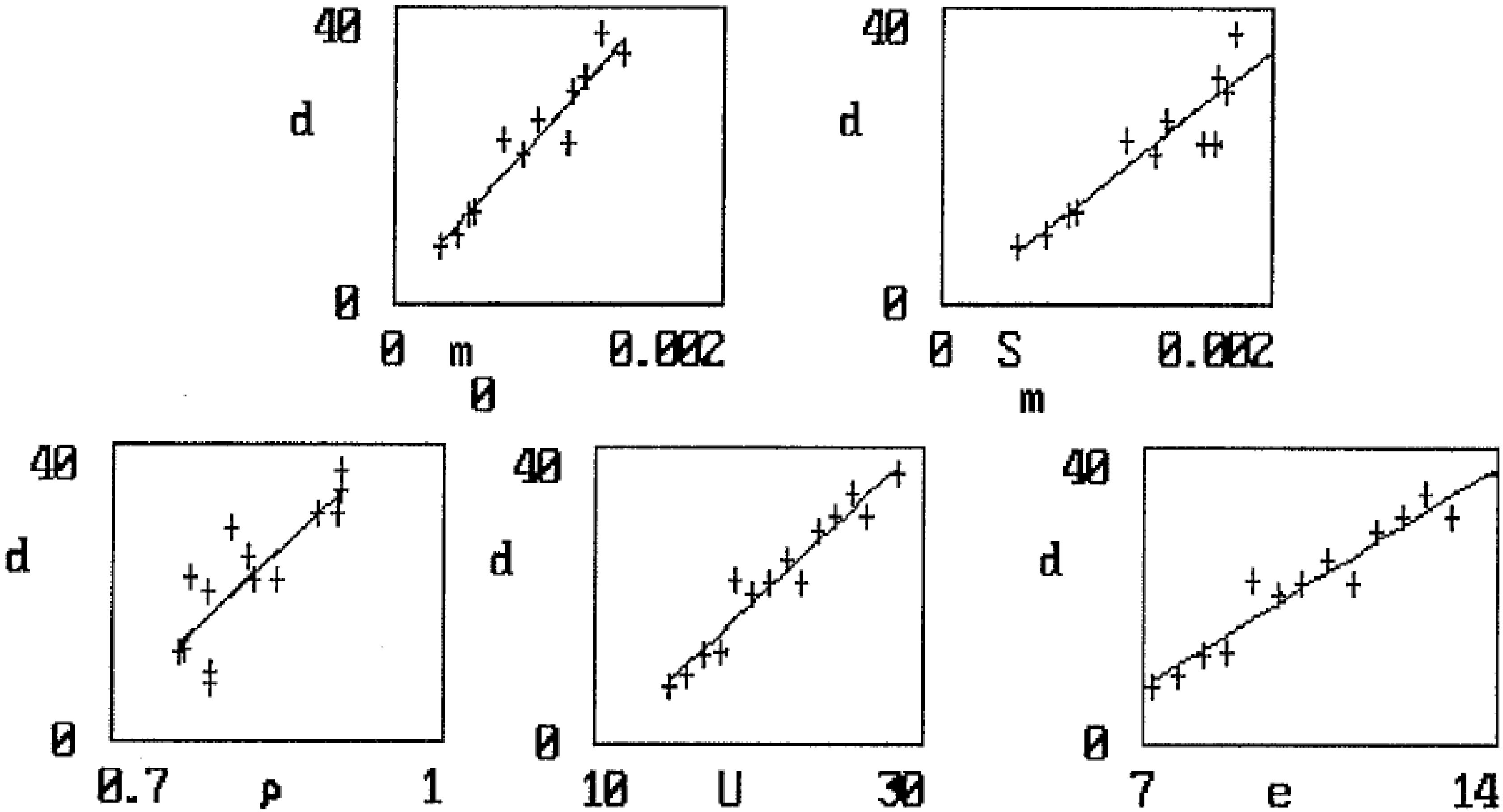


Figure 3. Breaking frequency d (number/minute) versus the wind wave spectrum parameters m_0 (m^2), S_m (m^2 s), ρ, local wind speed U (m/s) and wave development stage parameter e.

Babanin, 1995, Proc. Int. Conf. Med. Coast. Env.

Breaking probability, wind dependence

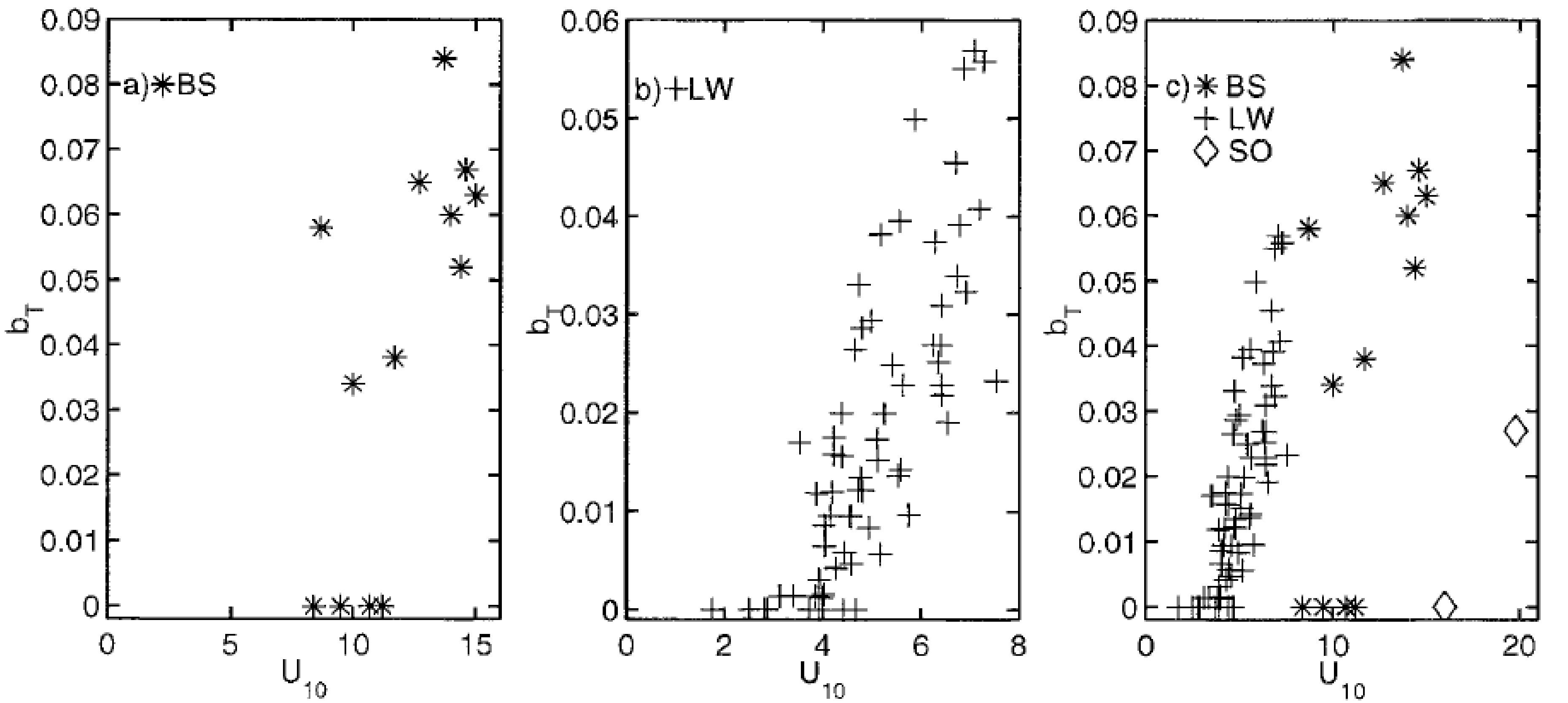
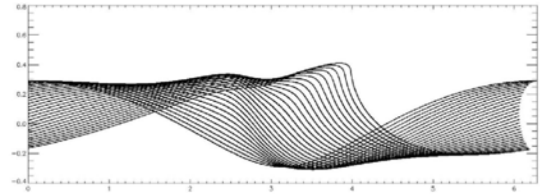


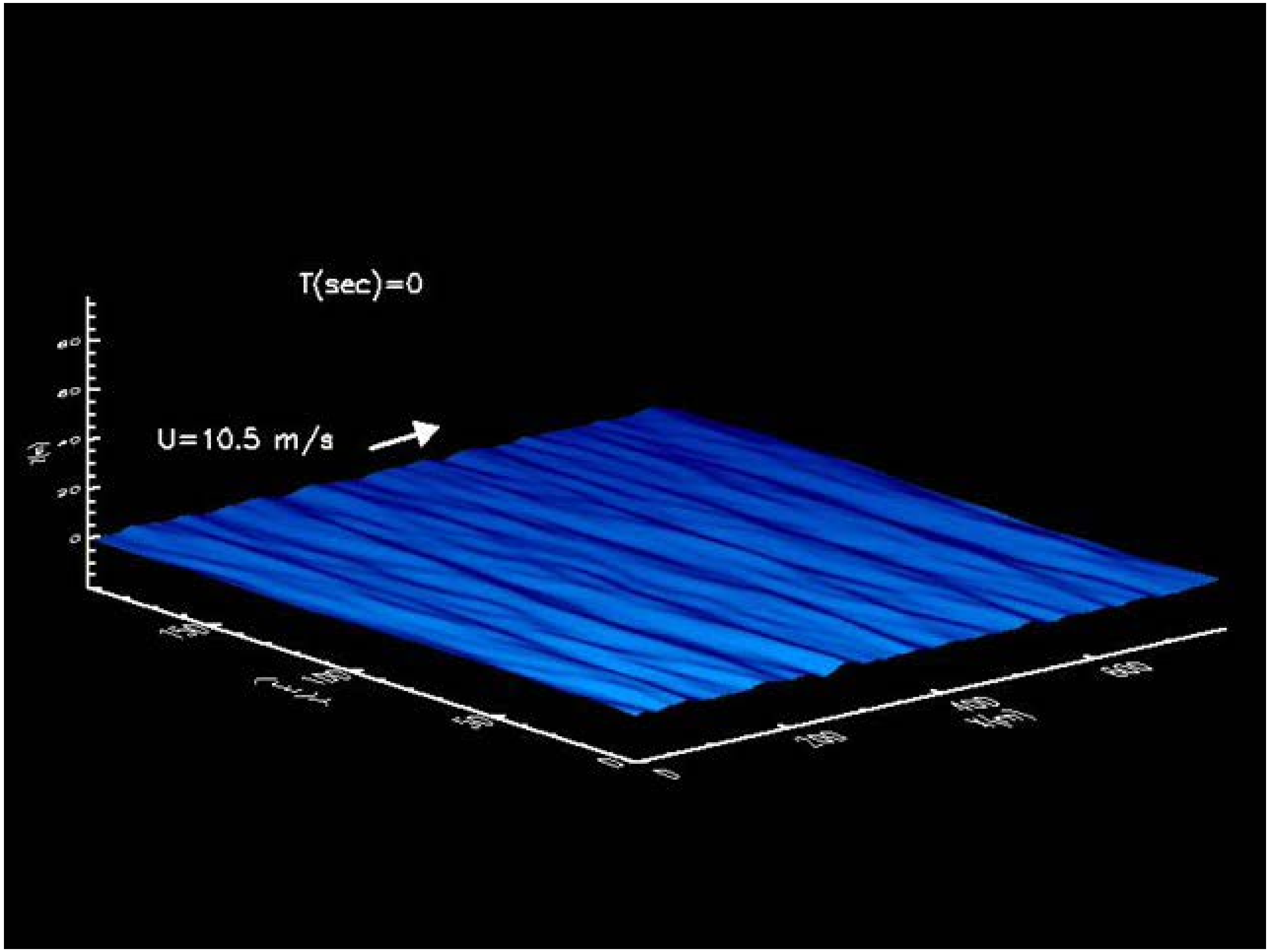
FIG. 1. Plot of observed dominant wave breaking probability b_T vs 10-m wind speed U_{10} for three diverse field sites: (a) Black Sea data (*), (b) Lake Washington data (+), and (c) composite of Southern Ocean data (◇) with (a) and (b).

Banner, Babanin, Young, 2000, JPO

physics of the wave breaking

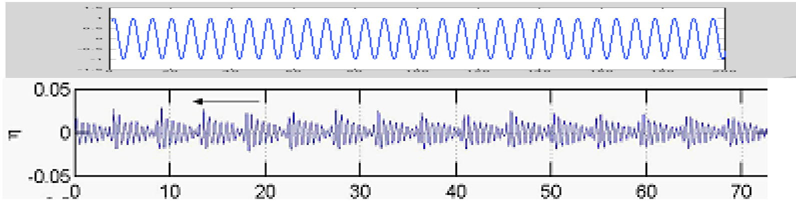
Fully nonlinear 3D potential wave model



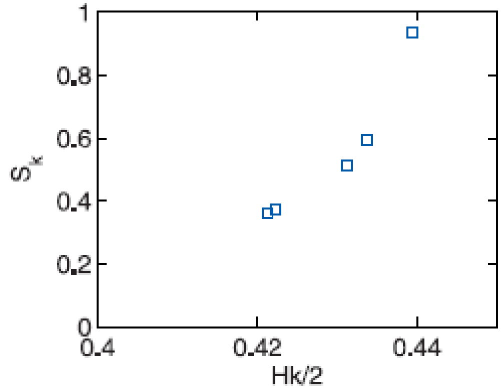


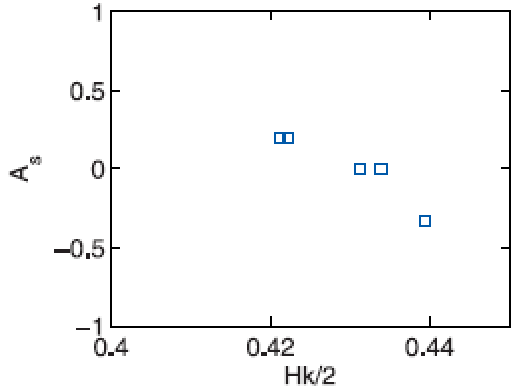
Chalikov & Babanin, OMAE 2013

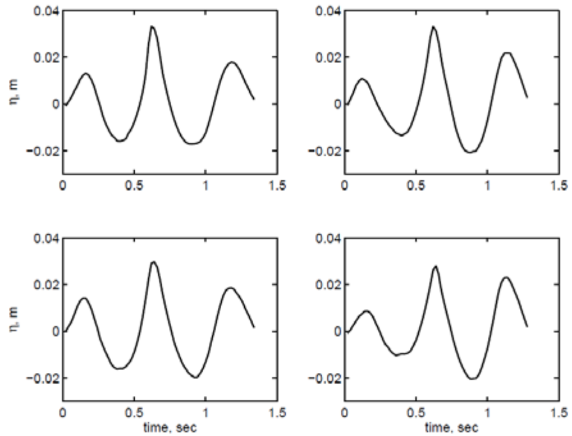
Incipient breaking, lab measurements



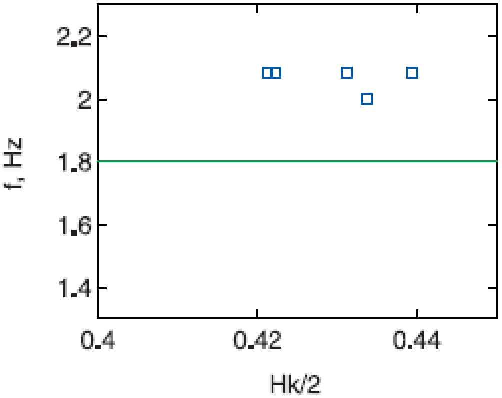
Following *Babanin, Chalikov, Young, Savelyev, 2010, JFM*







$$S_k = \frac{a_1}{a_2} - 1$$



asymptotic limit

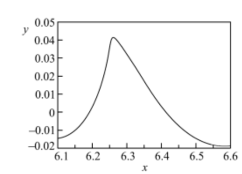
kH/2≈0.44

S_k*≈1*

Dyachenko & Zakharov (2005)

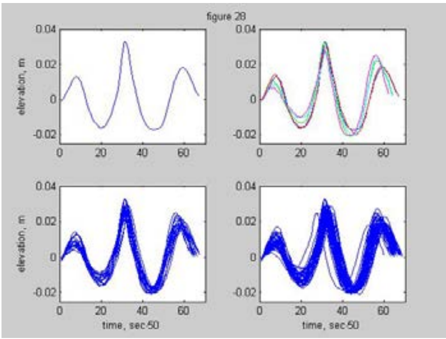
Fully non-linear model

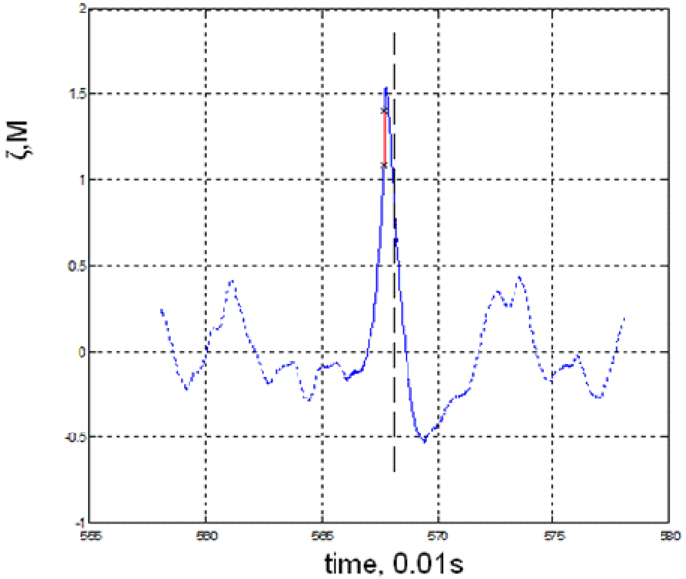
kH/2 = 0.44



Shape is different from the Stokes shape

Dominant breaking in field conditions



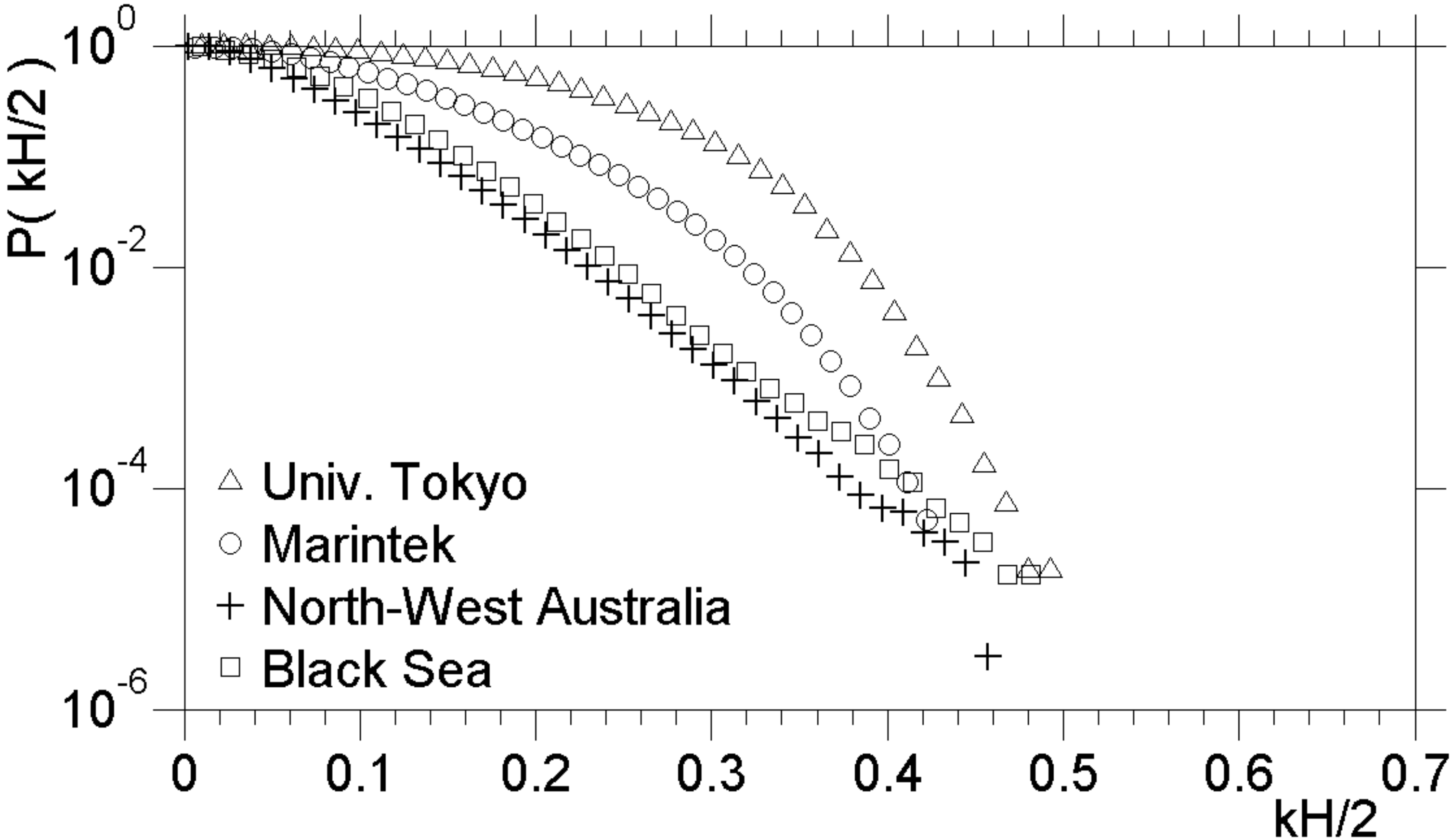


- measuring breaking onset in a field is a challenge
- if measured, limiting steepness, skewness and other features appear similar to those due to 2D modulational instability

Vladimir Dulov, personal communication

breaking onset, Black Sea, *kH~0.9*

Probability density function of wave steepness



Toffoli, Babanin, Waseda, Onorato, 2010, GRL

Wave-breaking onset

Message

- *Evidences are that the wave breaking limiting steepness is* kH/2~0.44
- *This is regardless whether this is due to instability, superposition, in presence/absence of the wind, in 2D/3D circumstances*
- *Breaking onset due to modulational instability is accompanied by reduction of wave length/speed*

What can make waves reach the limiting steepness

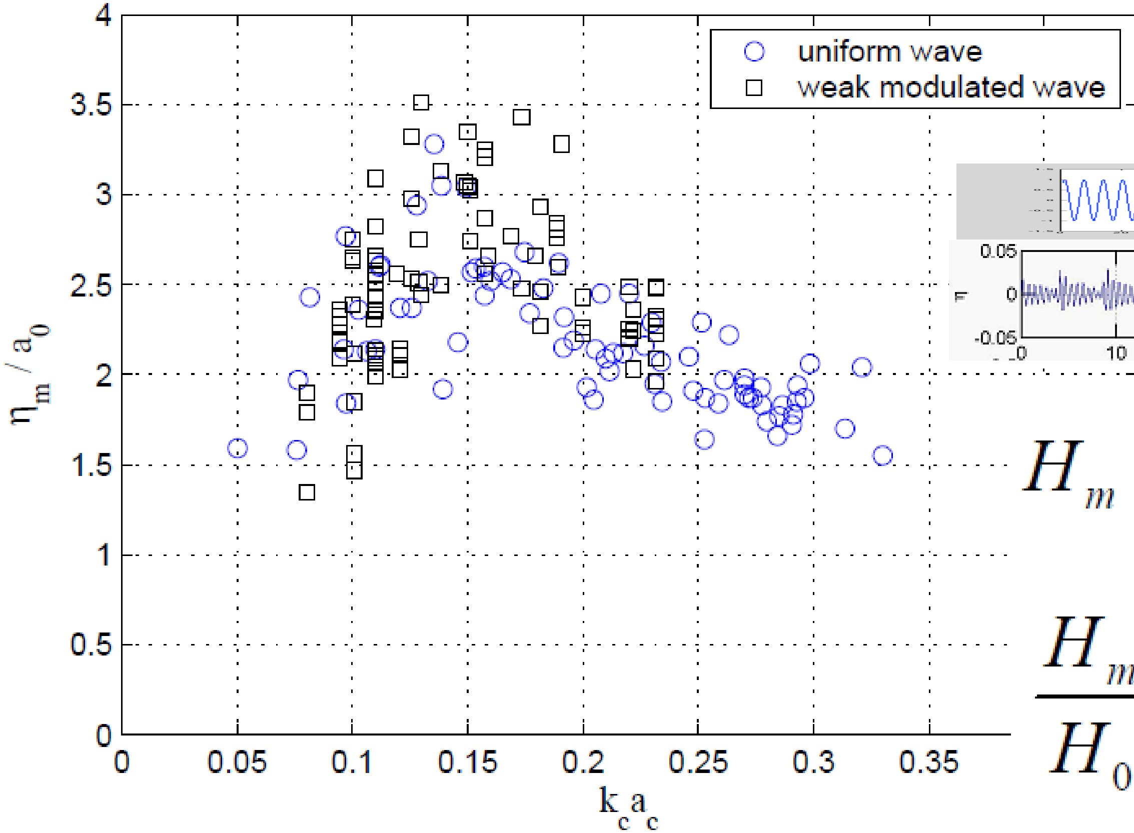
- ***Modulational instability***: two types of instability
- ***Focusing***:

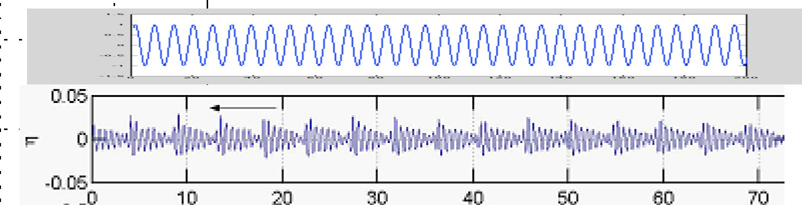
  - frequency focusing

  - amplitude focusing

  - directional focusing
- Wind (if the wave grows within one-two periods)
- Current
- Bottom proximity
- Modulation by longer waves

Maximal possible H_{max}/H_{mean} in unstable wave trains





$$H_m = a_{cr_m} + a_{tr_m} = \frac{3}{2}\eta_m .$$

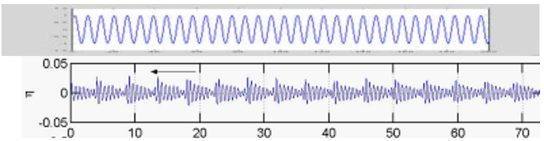
$$\frac{H_m}{H_0} = \frac{(3/2)\eta_m}{2a_0} \approx 2.6 .$$

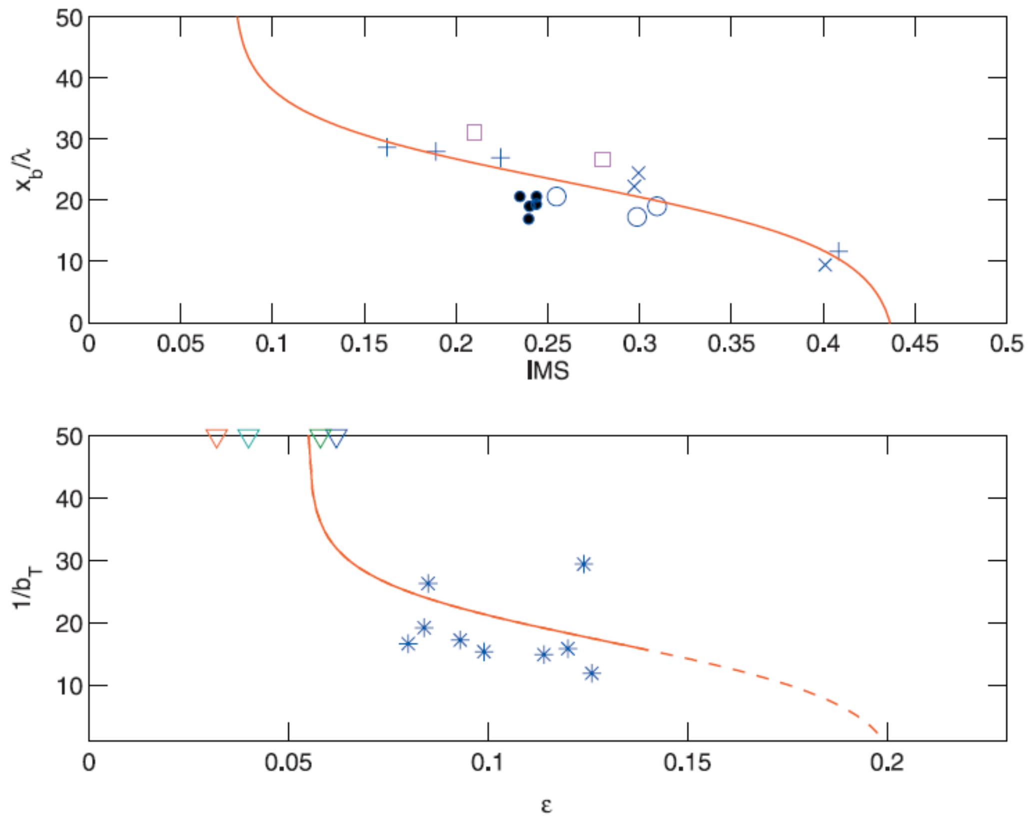
Fig. 2.2.6.13 Normalized maximum crest elevation versus initial wave steepness.

for high mean wind steepness, probability of high waves goes down because of wave breaking

Babanin, Waseda, Shugan, Hwang, 2011, OMAE

Number of wave lengths to the breaking versus mean steepness





$$N = -11\,\mathrm{atanh}\left[5.5\left(IMS - 0.26\right) + 23\right]$$

- spectral measure of steepness:

$$\varepsilon = H_p k_p / 2$$

$$H_p = 4\left\{\int_{0.7 f_p}^{1.3 f_p} F(f)\,df\right\}$$

- No wind forcing, except filled green circles
- Red squares derived from Melville (1982)
- *IMS* > 0.44, break immediately
- *IMS* < 0.08, never break in the absence of wind forcing

Laboratory (top), Black Sea (bottom)

Babanin, Chalikov, Young, Savelyev, 2007, GRL

Breaking and instability in wave fields with full spectrum

Chalikov & Babanin, 2012, JPO

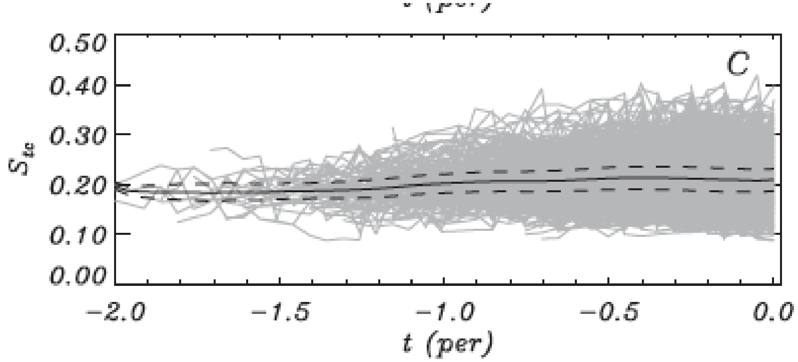


FIG. 8. (a) Evolution of trough-to-crest wave height H_{tc} normalized by H_s prior to breaking as function of time t. (b) Evolution of ratio of actual wavelength L_m to spectral wavelength of peak wave L_p. (c) Evolution of overall steepness S_{tc}. The styles of curves are as in Fig. 6.

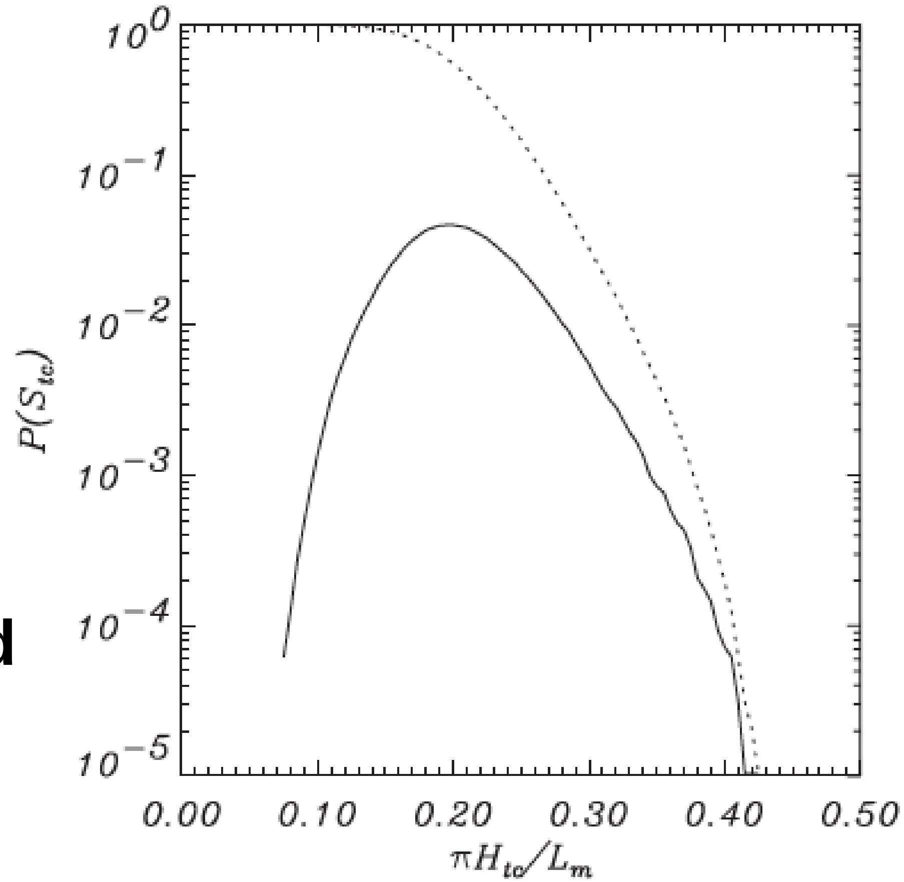
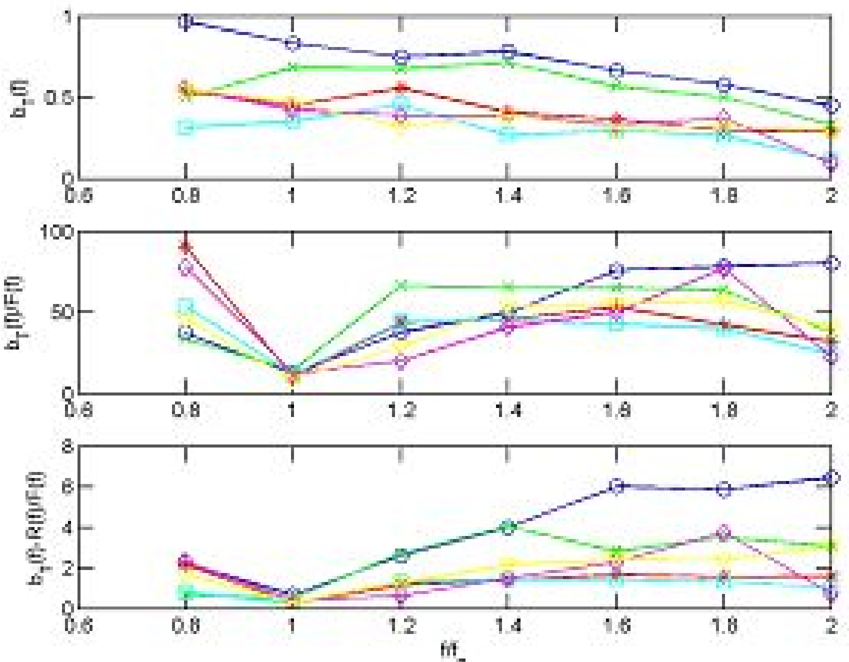


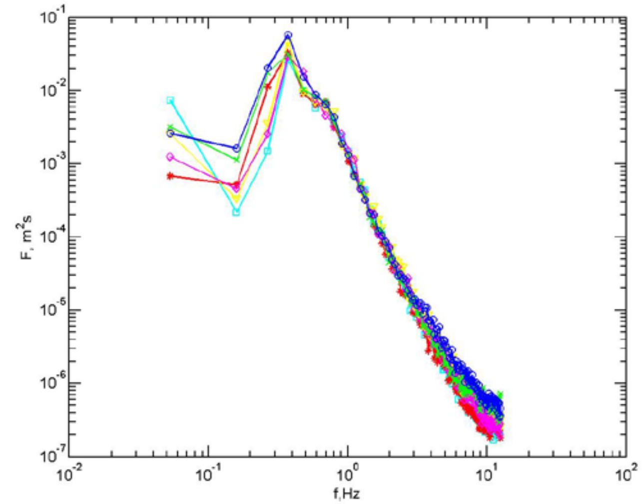
FIG. 9. Probability distribution for criterion overall steepness S_{tc}.

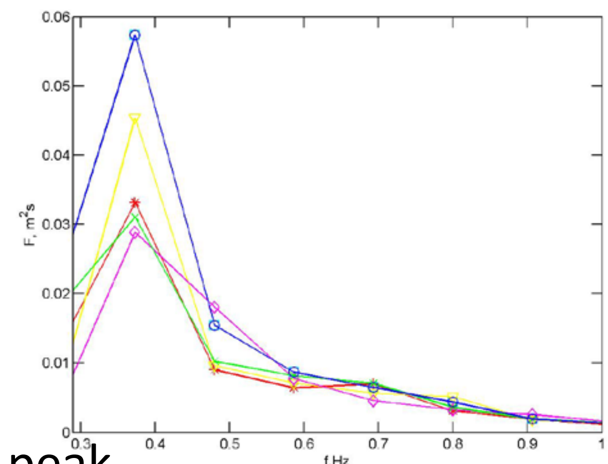
- **The *ak*~0.42 limiting steepness criterion is valid**
- **Most of waves, however, break at lower steepness**
- **This is due to short waves causing local instability**

Breaking probability across the spectrum

Cumulative effect
Dependence on the wind



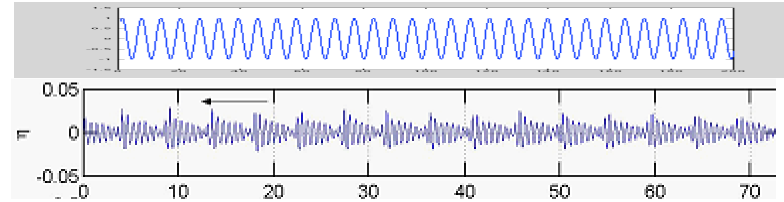




- ➢ two-phase behaviour of breaking probability:
- linear dependence of S_{ds} on the spectrum at the peak
- cumulative effect at smaller scales
- ➢ b_T depends on the wind for $U_{10} > 14$ m/s

Manasseh et al., 2006, JTec

Incipient breaking, with and without wind



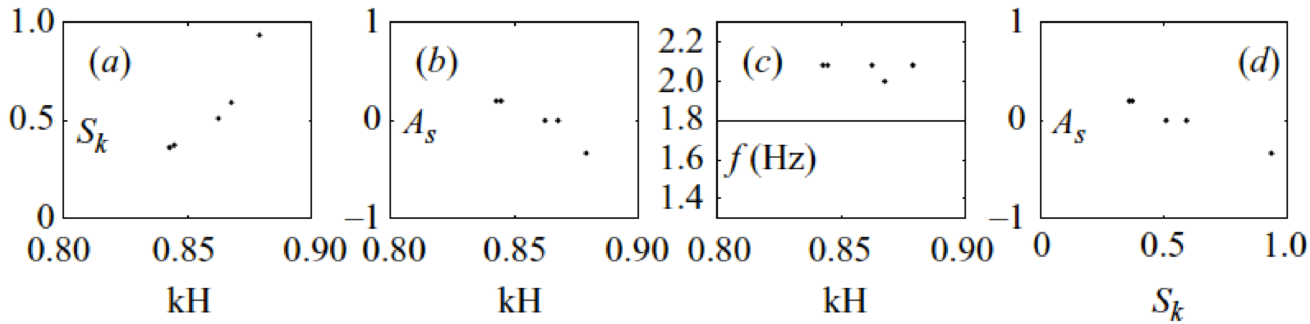


FIGURE 11. As the top four subplots in figure 10, for five steepest breakers.

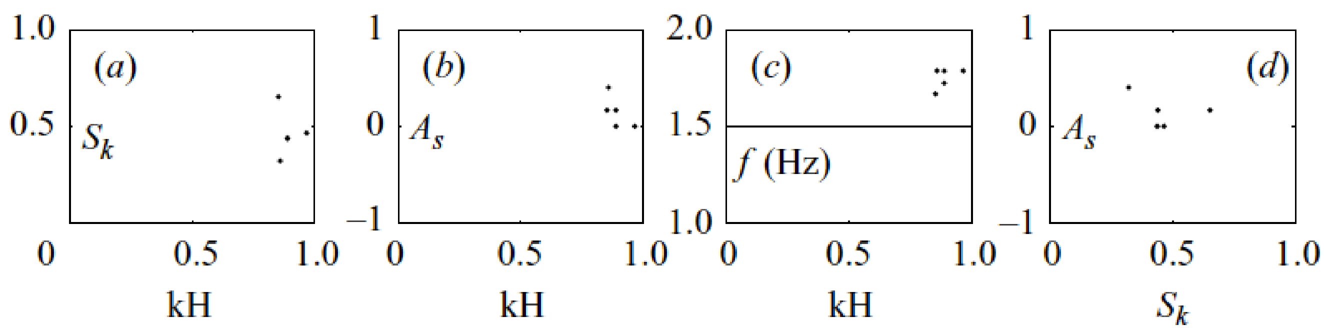


FIGURE 15. As figure 11, with wind forcing: $IMF = 1.5$ Hz, $IMS = 0.30$, $U/c = 3.9$. Laboratory statistics for five steepest incipient breakers.

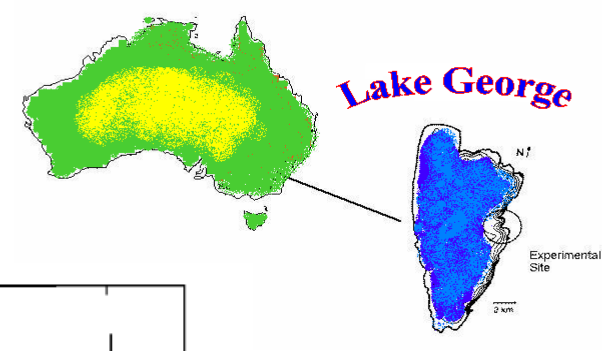
Babanin, Chalikov, Young, Savelyev, 2010, JFM

Everything changes at extreme conditions

- at wind speeds *U>32m/s,* dynamics of the atmospheric boundary layer, of the ocean wave surface and of the upper ocean layer – all change
- sea drag saturates at $U_{10}=32\text{-}33m/s$ above the surface
- cross-interface gas fluxes still grow, but at a slow rate if $U_{10} > 35m/s$, additional mechanisms become active below the surface
- at the surface, wave assymmetry saturates at $U_{10}{\sim}34m/s$. This indicates change of the wave breaking mechanism to the direct wind forcing
- wave breaking probability would no longer be controlled by nonlinear processes

Babanin, 2011, Proc. Coasts and Ports

Breaking in finite depths



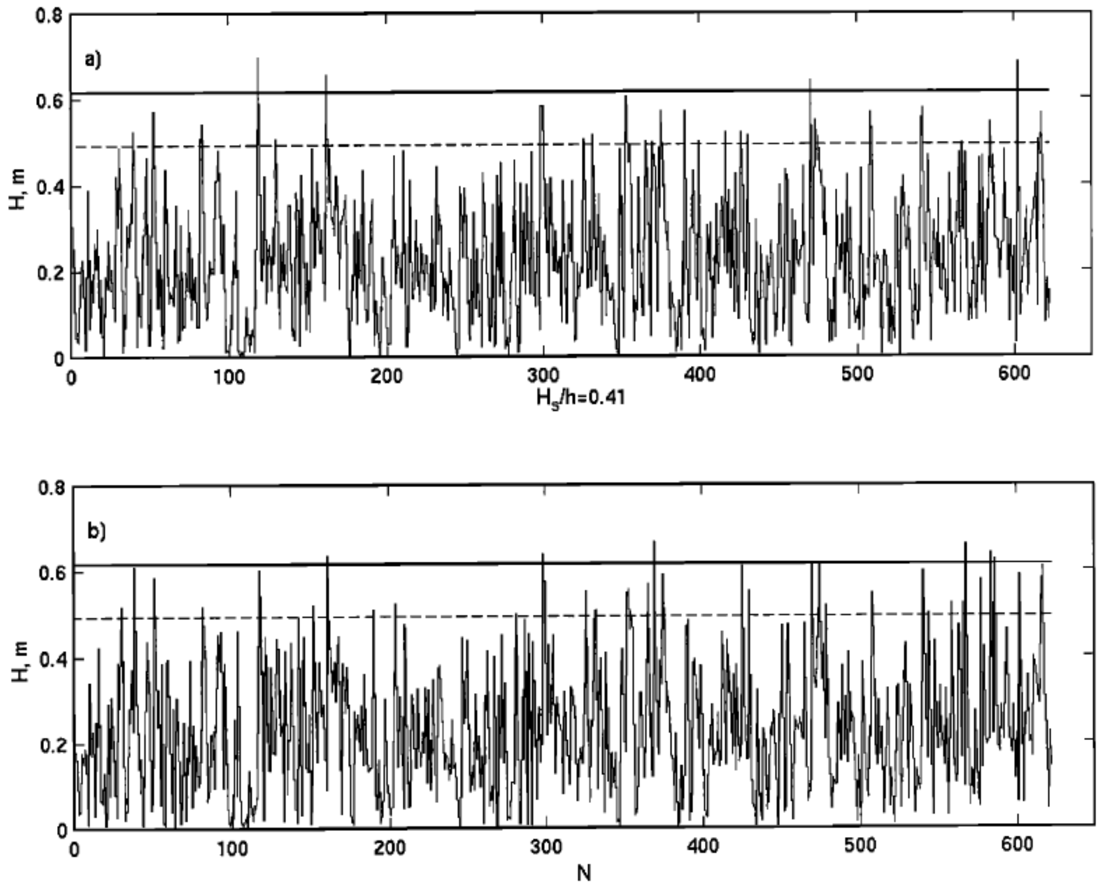
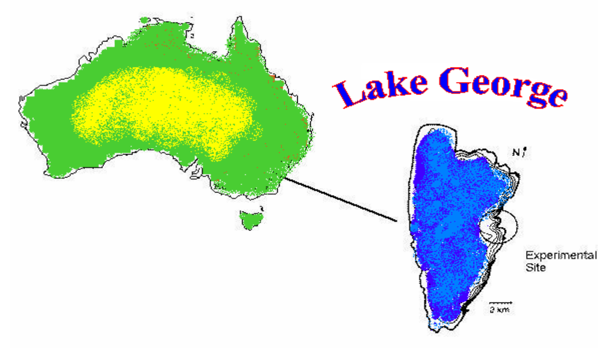


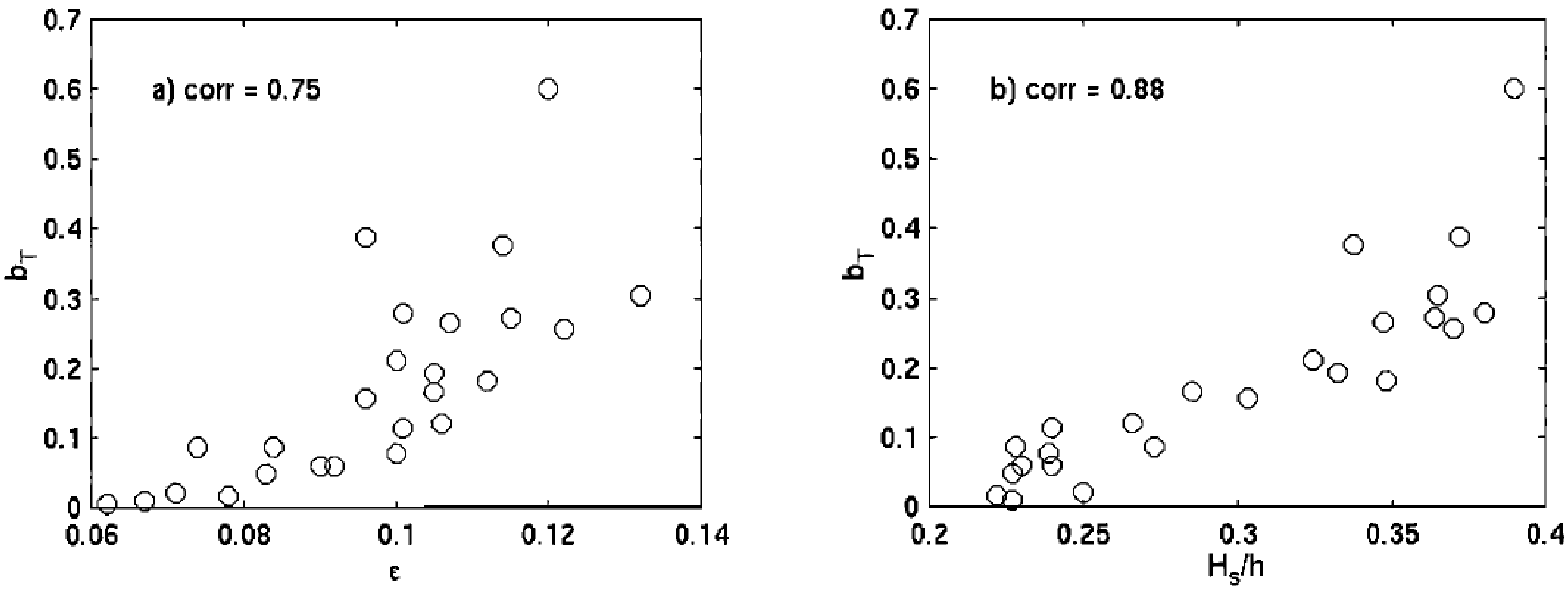
Figure 6. Consecutive (a) down-crossing and (b) up-crossing wave heights of record 5 (Table 1). The horizontal lines indicates the $0.55h$ limit (solid lines) and the $0.44h$ limit (dashed lines). The legend shows the H_s/h ratio.

Babanin, Young, Banner, 2001, JGR

Breaking in finite depths

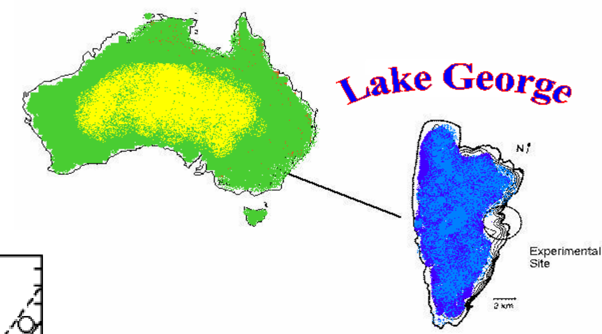


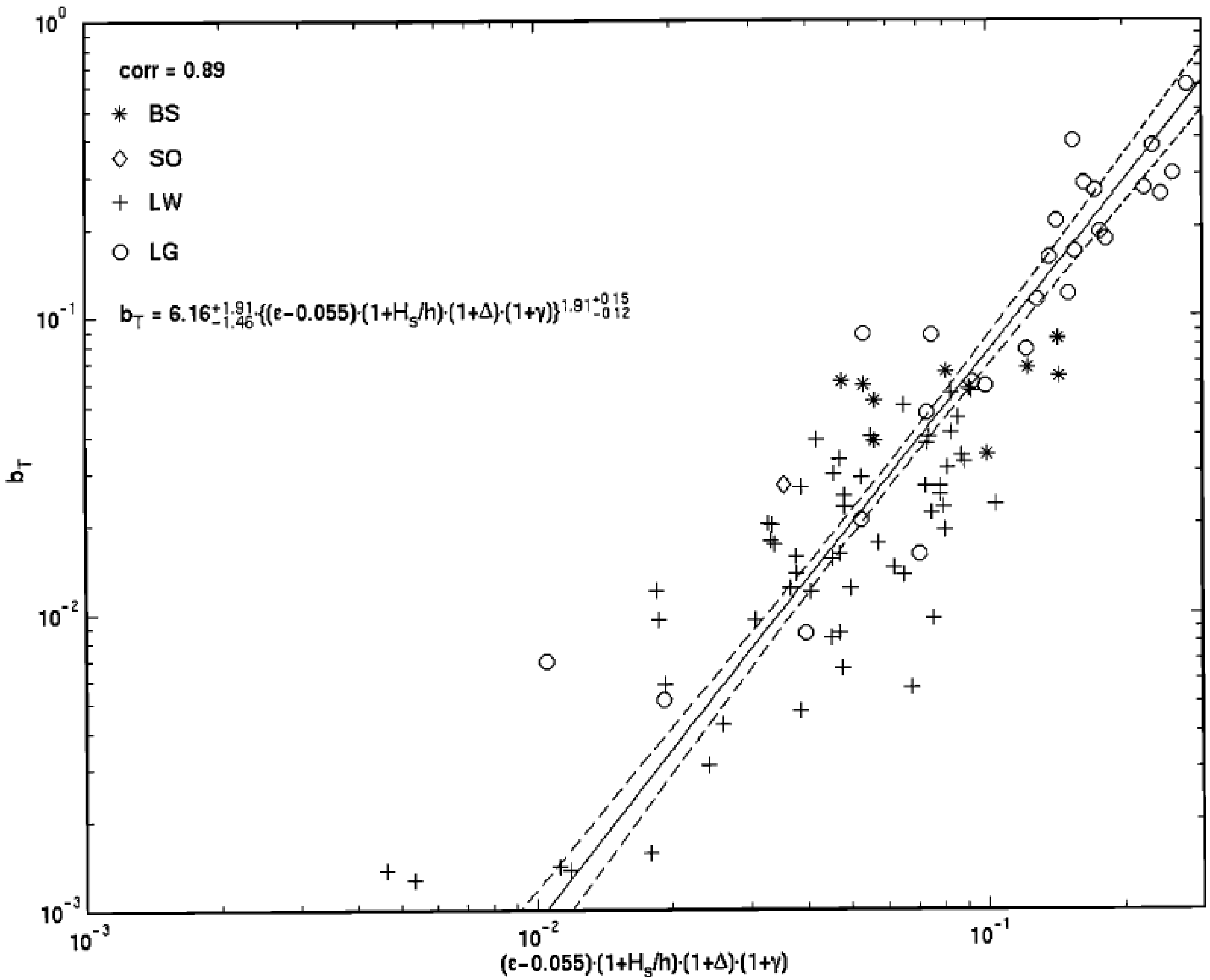
BABANIN ET AL.: BREAKING PROBABILITIES FOR FINITE DEPTH WAVES 11,671



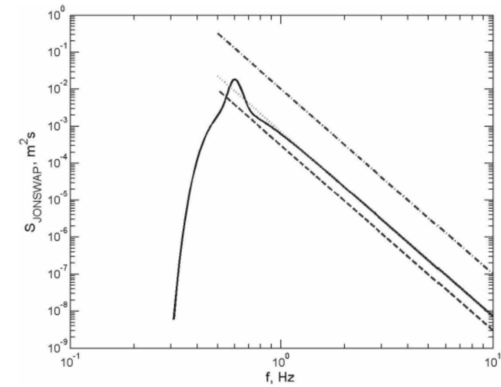
Babanin, Young, Banner, 2001, JGR

Breaking in finite depths





Babanin, Young, Banner, 2001, JGR



Babanin & van der Westhuysen, 2008, JPO

Conclusions

- Breaking probability parameterisation is described for the dominant waves
- Primary parameter is the mean peak wave steepness
- There is a breaking threshold in terms of the mean steepness (no breaking below the threshold)
- There is a limit in terms of individual wave steepness
- Secondary parameter is dimensionless water depth
- There is a limit in terms of wave height with respect to the water depth
- Third influence is due to the wind
- Probability of wave breaking away from the peak is cumulative

Chalikov-Sheinin Model

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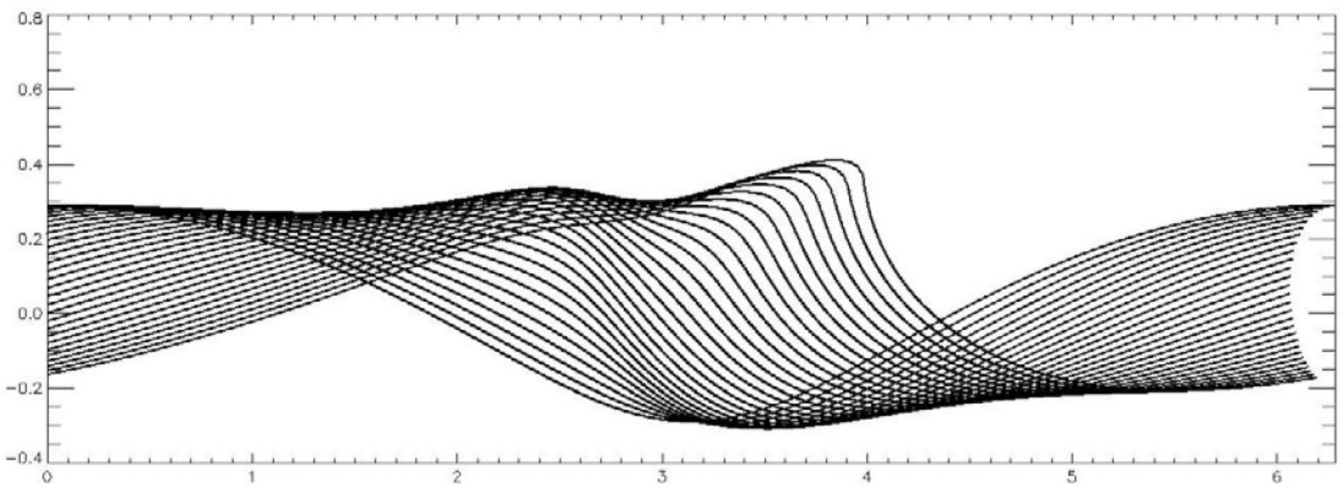
Modeling extreme waves based on equations of potential flow with a free surface

Dmitry Chalikov [a,*], Dmitry Sheinin [b]

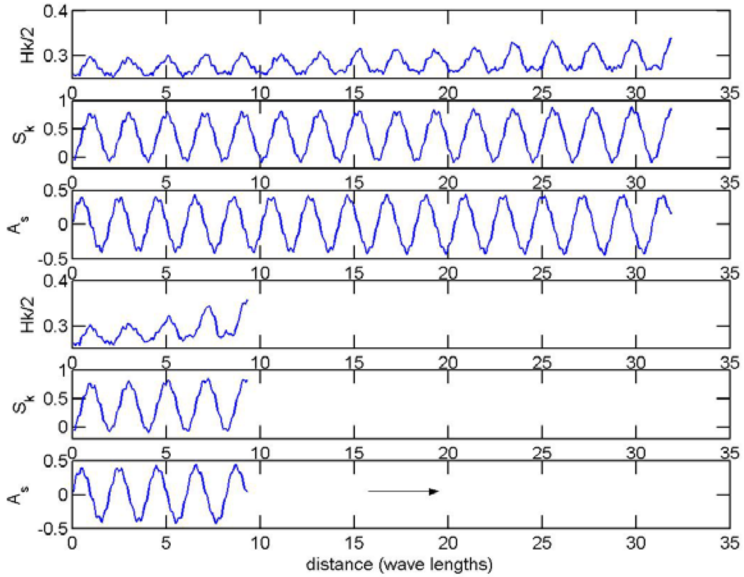
- fully non-linear
- very high precision
- stable for hundreds of periods
- coupled with atmosphere

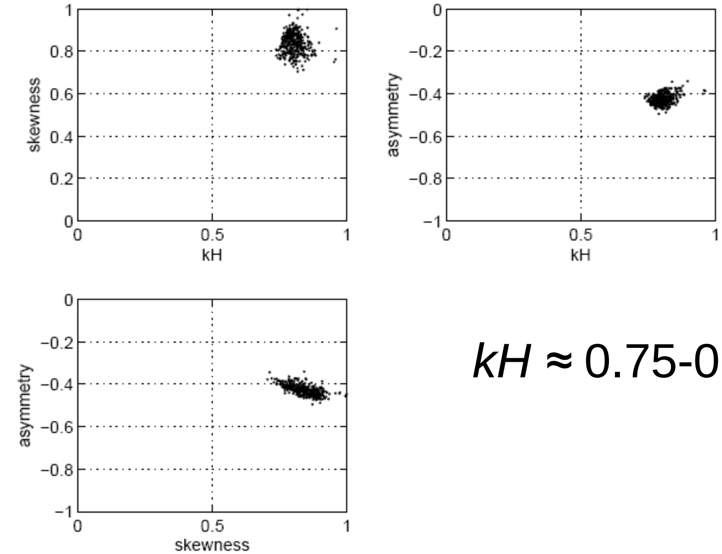


CSM: steep wave developing asymmetry

Numerical Simulations of Wave Evolution

Following *Babanin, Chalikov, Young, Savelyev, 2010, JFM*





$kH \approx 0.75\text{-}0.85$

Individual waves, from start to breaking

IMS = 0.26, U/c = 2.5, U/c = 5.0

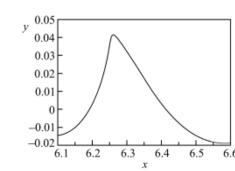
Initial skewness and asymmetry are zero

S_k and A_s oscillate

Wind doubles, distance to breaking reduces 4 times

Dyachenko & Zakharov (2005)

Fully non-linear model

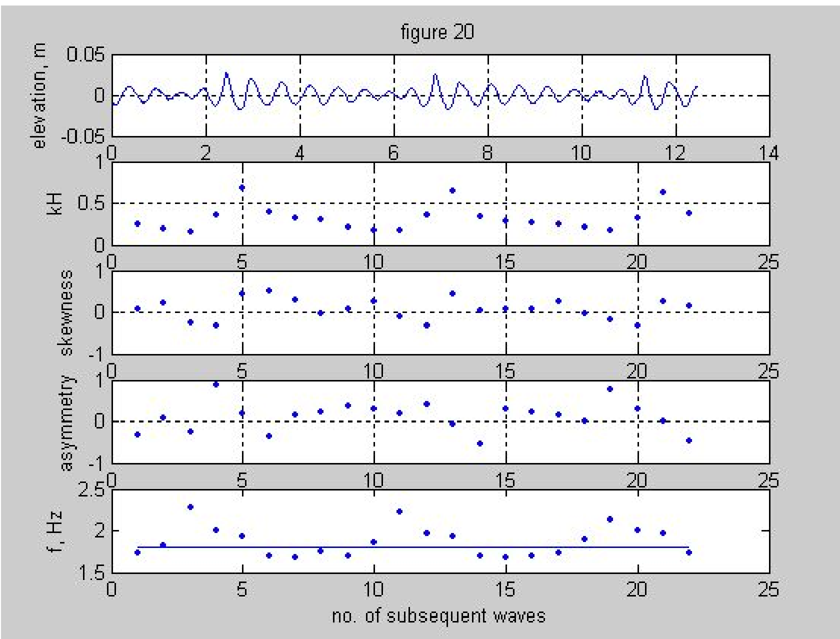


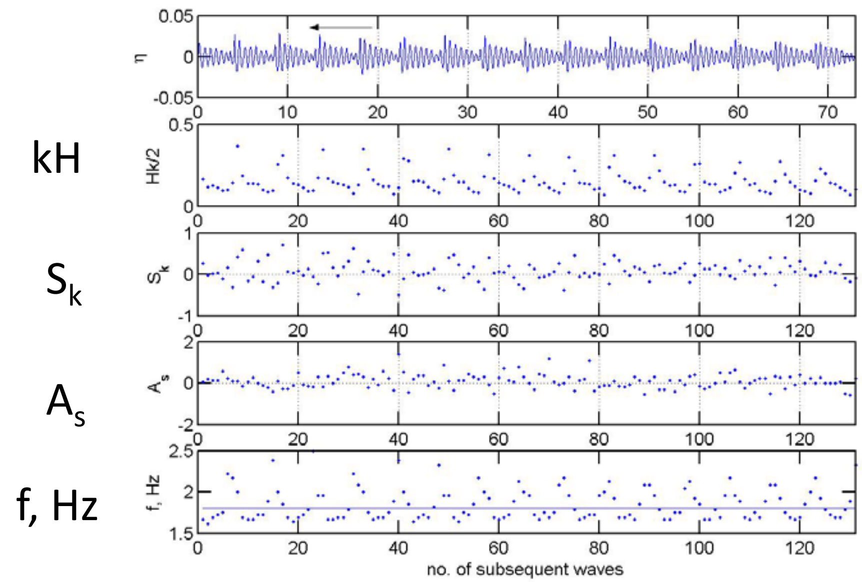
kH/2 = 0.44

Shape is different from the Stokes shape

Experiment. Time Series Analysis

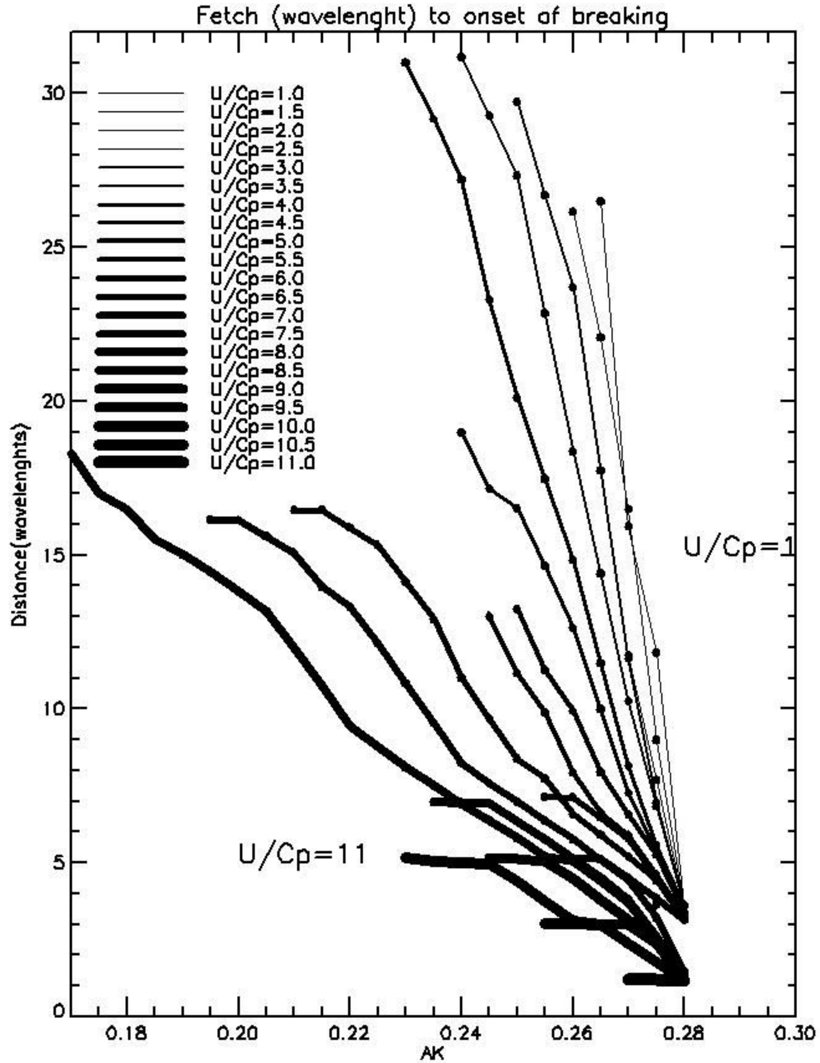
- *IMF* = 1.8Hz, *IMS* = 0.30, U/c = 0, breaking immediately after the 10.73 m probe
- major features seen in the numerical model are confirmed





- incipient breaking waves are the steepest waves in the wave train
- steepness, skewness and asymmetry oscillate. Asymmetry is shifted
- at the point of breaking S_k is maximal, A_s is small, frequency is increased

Numerical Simulations. Distance to Breaking



IMS

If *IMS* > 0.3, waves will break immediately

If *IMS* < 0.1, waves with no wind forcing will never break

Between the limits, dimensionless distance to breaking decreases if *IMS* increases

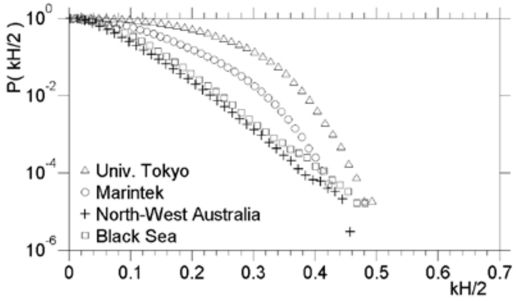
Wind:

-Accelerates wave steepness growth

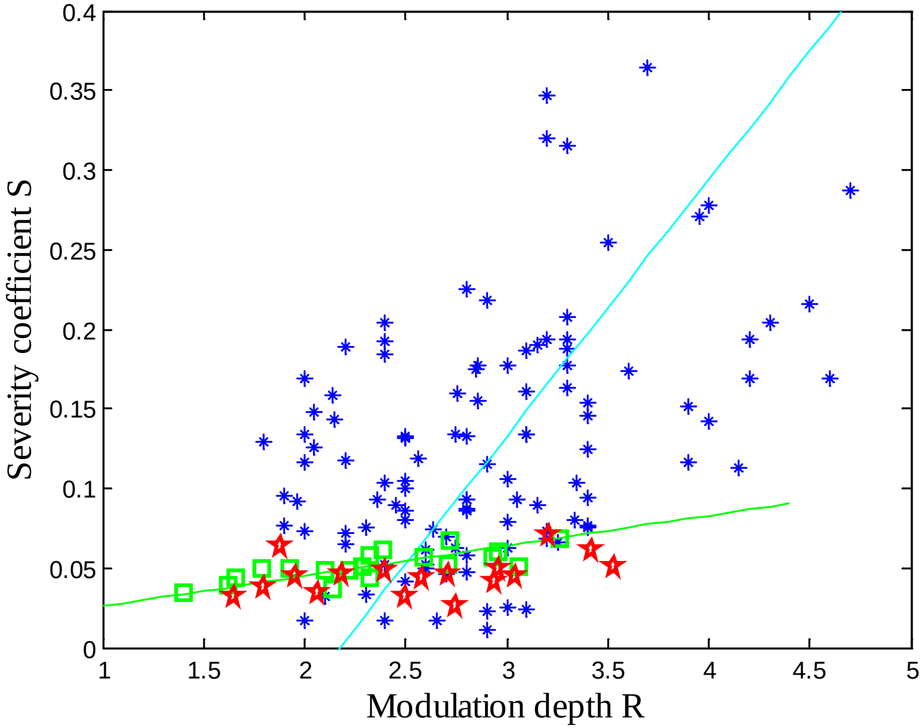
-Can reduce the critical steepness if strong (*U/c* >10)

Chalikov, personal communication

modulational instability is affected by the wind



breaking severity depends on the instability growth rates



$$S = \frac{E_{bb} - E_{ab}}{E_{bb}}$$

Breaking severity per wave group

Ranges from 2% to 35%

$$S = (0.16 \pm 0.03)R - (0.35 \pm 0.06)$$

Galchenko, Babanin, Chalikov, Young, Haus, 2012, JPO

no wind – blue asterisks, *U/c*=2 – green squares, *U/c*=3.8 – red stars

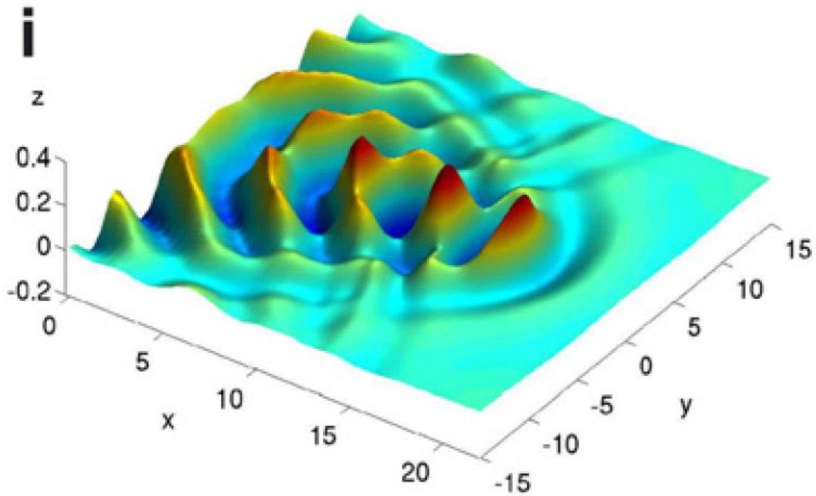
Modulational Instability or Focusing?

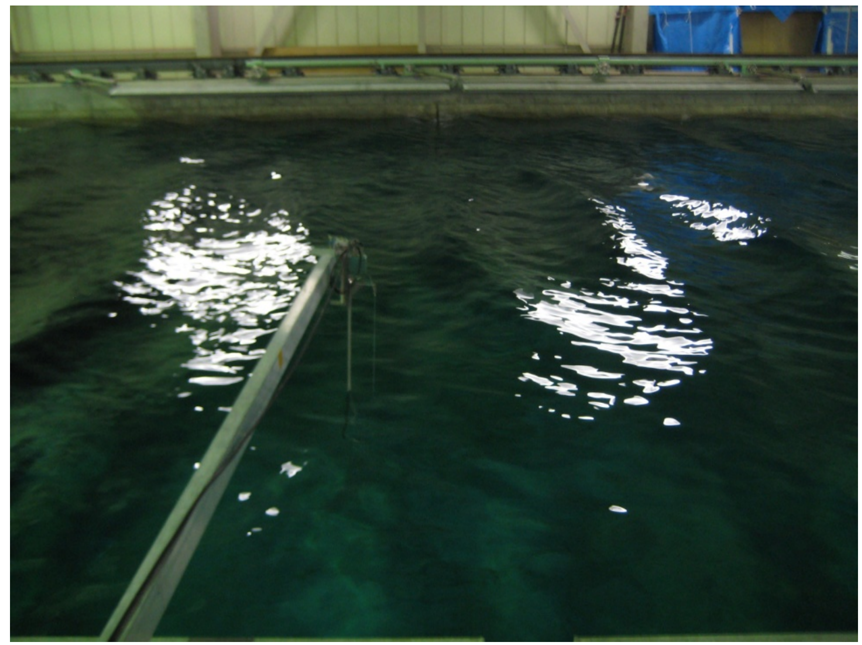
Features of modulational instability/ Observations in the field

- Threshold in terms of average steepness/ *Babanin et al., 2001, JGR*
- Upshifting of the spectral energy prior to breaking/ *Liu and Babanin, 2004, Ann. Geoph.*
- Oscillations of asymmetry and skewness/ *Agnon et al., 2005, GRL*
- Energy is lost from the carrier wave/ *Young and Babanin, 2006, JPO*

Modulational instability or directional focusing in 3D fields?

Forchesato et al., 2007





University of Tokyo, directional wave tank

Following *Babanin, Waseda, Kinoshita, Toffoli, 2011, JPO*

The separation!