Nonlinear Waves on Collinear Currents with Horizontal Velocity Gradient

Alexander Babanin, Hwung-Hweng Hwung, Igor Shugan, Aron Roland, Andre van der Weshuysen, Arun Chawla, Caroline Gautier

Swinburne University of Technology, Australia
National Cheng Kung University, Taiwan
Darmstadt University, Germany
NOAA, USA
Deltares, The Netherlands

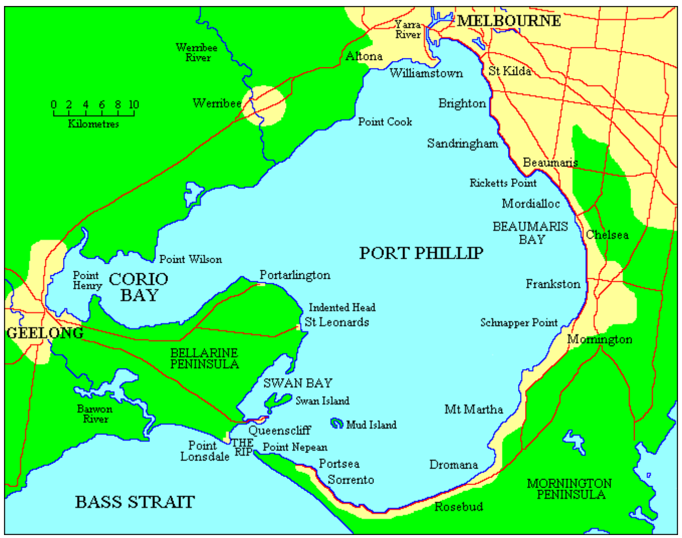
Wave Hindcast and Forecast Meeting
Big Island, Hawaii
November 2011

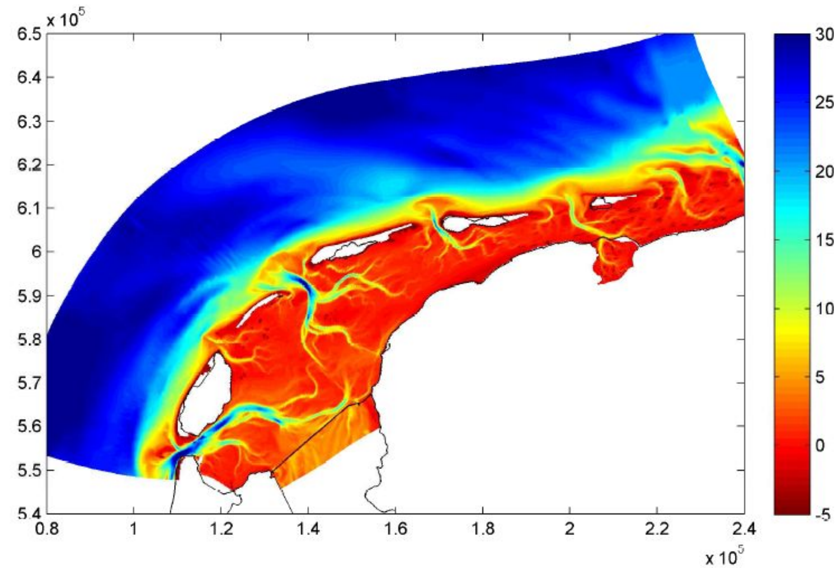
SWIN BUR NE SWINBURNE UNIVERSITY OF TECHNOLOGY

Motivation

Propagation of waves through spatially and temporally variable currents is a frequent occurrence in coastal areas

Port Phillip, Australia **Wadden Sea, Holland**





navigation **coastal defense**

Waves on currents is perhaps the last loose physics in wave forecast models

Conclusions

- Wave dynamics on currents with horizontal gradients:

nonlinear effects are very essential

- Stokes waves: realistic behaviour, theory predicts their steepening to the Stokes limit, i.e. to breaking, rather than singularity
- Measurements of currents: fully nonlinear effects mostly dominate
- Adverse current

  - irreversible downshifting,

  - if the gradients are strong, downshifting is fast and goes beyond the lower sideband

  - waves can penetrate the blocking currents
- Following currents:

  - linear steepening is observed (important for modelling the dissipation)

  - downshifting happens if the waves are steep enough
- Spectral models: physics needs updating

What is in the models?

- Interpretation of the waves on currents is mostly concentrated on the linear and quasi-linear Doppler-shift related or refraction/reflection related effects
- Nonlinear effects are typically limited to Stokes corrections
- Even then a large portion of attention has been paid to waves travelling on adverse currents and specifically to the conditions of wave-energy blocking
- Relative wind speed with respect to current

The WISE Group (Progr. Oceanogr., 2007):
There is still little validation of wave propagation over horizontally varying currents

What is available?

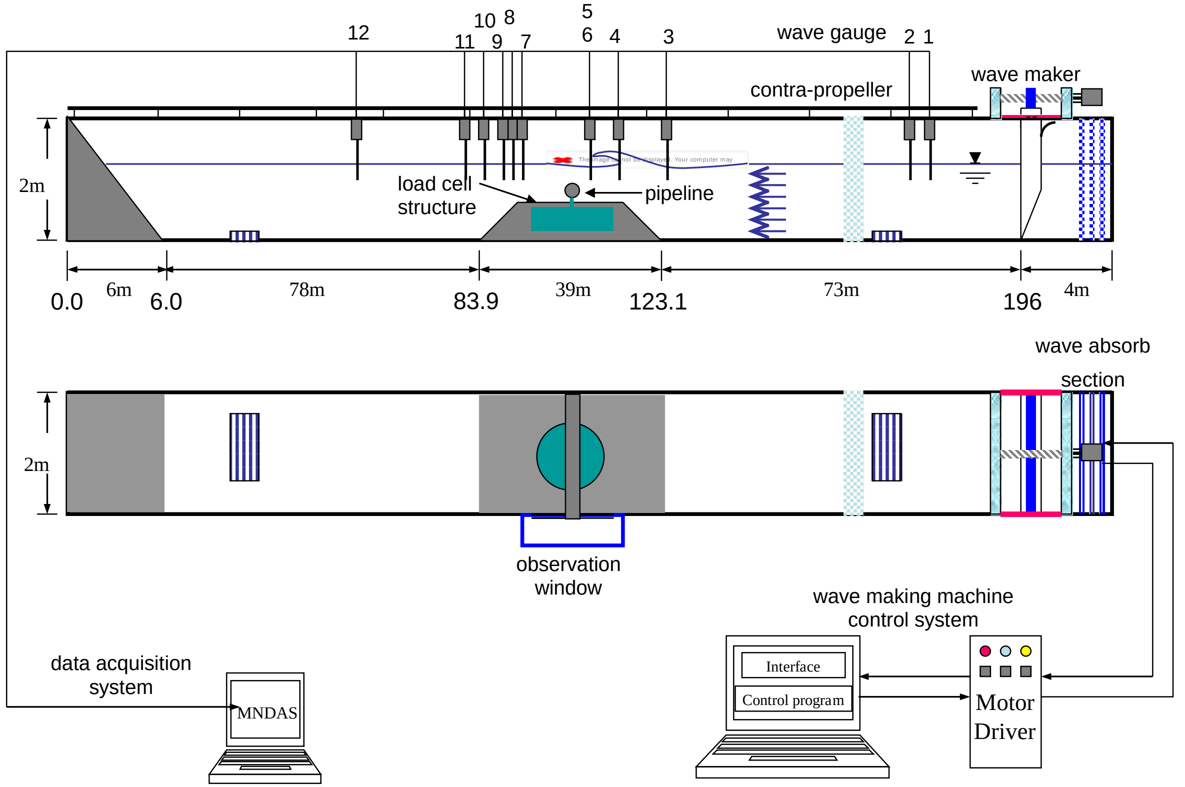
- If the waves get steeper (adverse accelerating currents, following decelerating currents), breaking rates and dissipation should increase, and vice versa
- Van der Westhuysen (CE, submitted) proposes to scale the degree of whitecapping dissipation with the incremental shortening/steepening of the waves due to negative current gradients, which is related to the relative Doppler shifting rate c_σ/σ:

$$S_{ds}\left(\sigma,\theta\right) = -C_{ds}\max\left[\frac{c_\sigma(\sigma,\theta)}{\sigma},0\right]\left[\frac{B(k)}{B_r}\right]^{\frac{p}{2}} E(\sigma,\theta)$$

- fully nonlinear effects

- Janssen and Herbers (JPO, 2009): linear directional focusing triggers modulational instability
- Onorato et al. (PRL, 2011): MI is enhanced by presence of adverse currents
- nonlinear wave-current interactions (not available actually)

Experimental setup



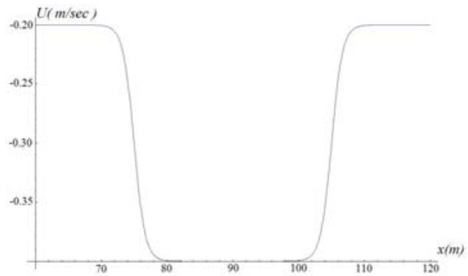
NCKU, Taiwan

200m long wave tank, mechanically-generated waves

Variable depth, adverse and following currents

Stokes waves on non-uniform current

Igor Shugan following Hwung et al. (JFM, 2009)



- dispersion relation for nonlinear surface waves on deep water:

$$\sigma^2 = gk + k^4\phi_0^2 + (\phi_{0tt} + 2U\phi_{0xt} + U^2\phi_{0xx})/\phi_0 \;,$$

- wave action conservation law in the presence of current:

$$[\phi_0^2\sigma]_t + [(U + \frac{g}{2\sigma})\phi_0^2\sigma]_x = 0\,,$$

- condition of wave phase compatibility:

$$k_t + (\sigma + kU)_x = 0 \;,$$

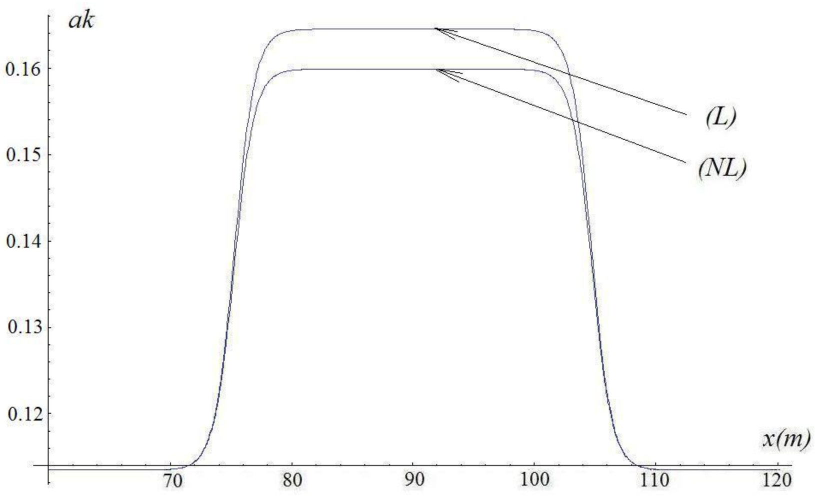
wavenumber and intrinsic frequency (k,σ); ϕ_0 is amplitude of the velocity potential,

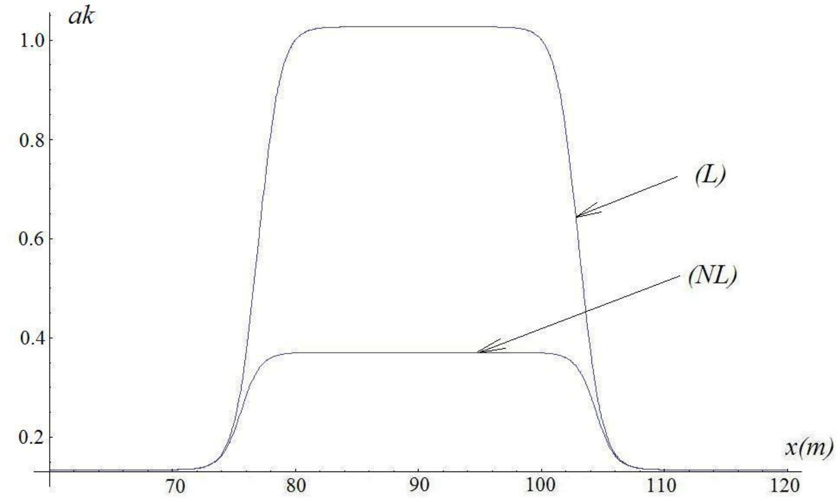
wave action flux A_0

$$\frac{1}{U^2}\left(\frac{A_0}{\phi_0^2}\right)^2 = \frac{g(g+4\Omega_0 U)}{4U^2} + \left(\left(\frac{g}{2} - \frac{A_0}{\phi_0^2}\right)\frac{1}{U^2} + \frac{\Omega_0}{U}\right)^4 \phi_0^2 + U^2\phi_{0xx}/\phi_0 \;.$$

The last two terms are higher-order nonlinear amplitude Stokes correction and the effect of amplitude dispersion, respectively

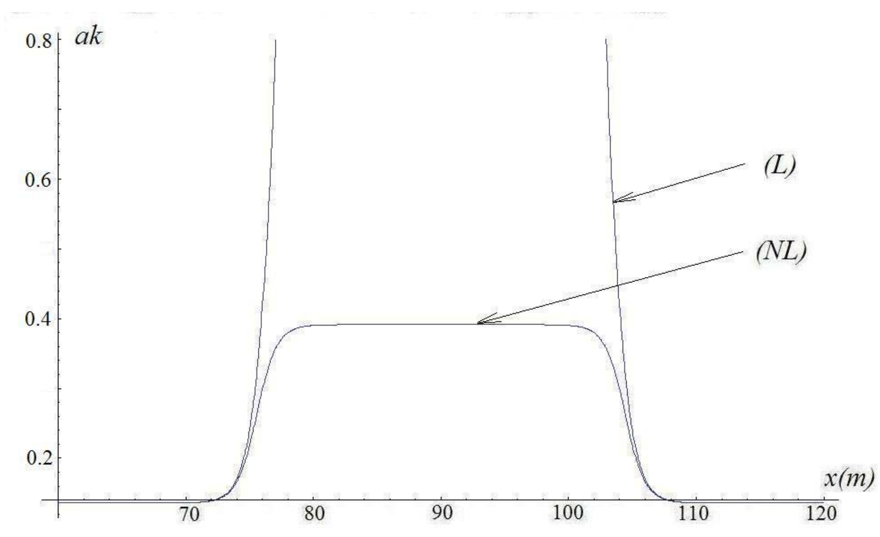
Stokes waves on non-uniform current





U=-20cm/s

U=-39cm/s



U=-40cm/s

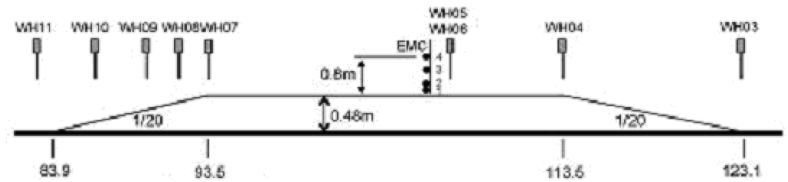
Blocking for waves with T=1sec

Steepness close to Stokes limit

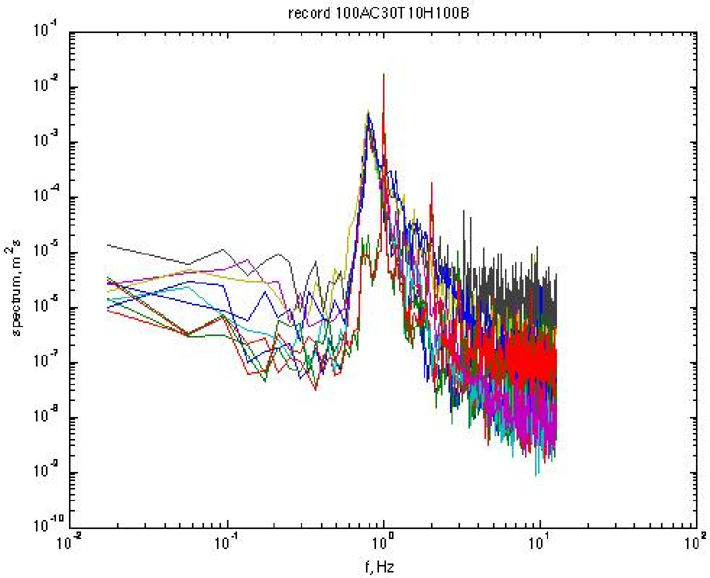
Breaking rather than singularity

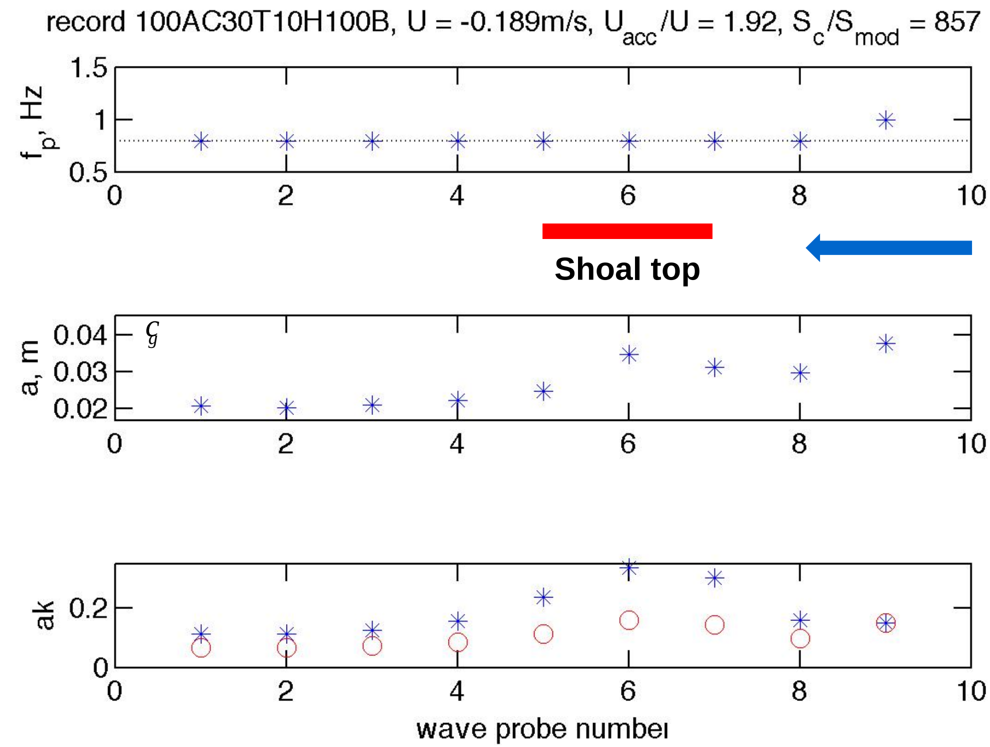
Measurements, adverse currents

low velocity gradients, less than c_g<1/4



downshift to lower sideband





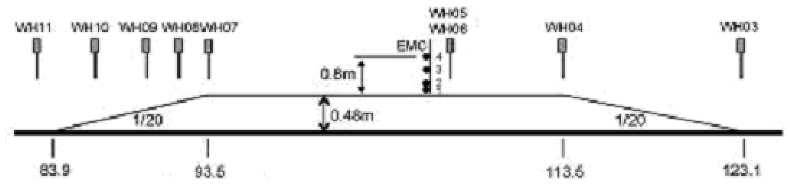
- waves propagate from right to left
- circles signify downshifting observed, dashed line the sideband
- probes 7-5 are over the bottom elevation

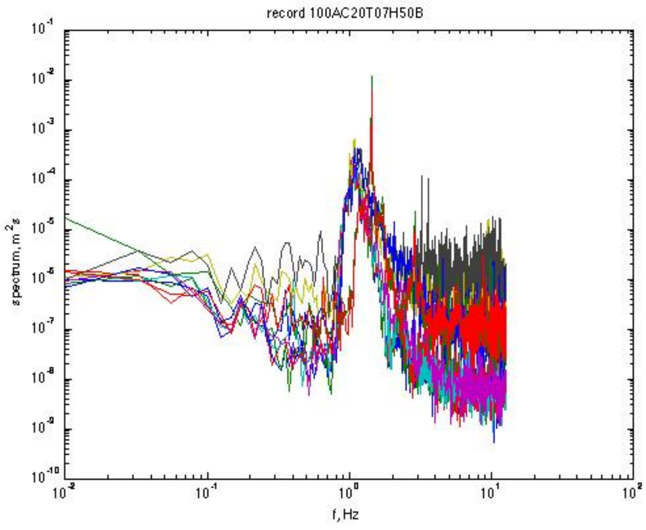
Measurements, adverse currents

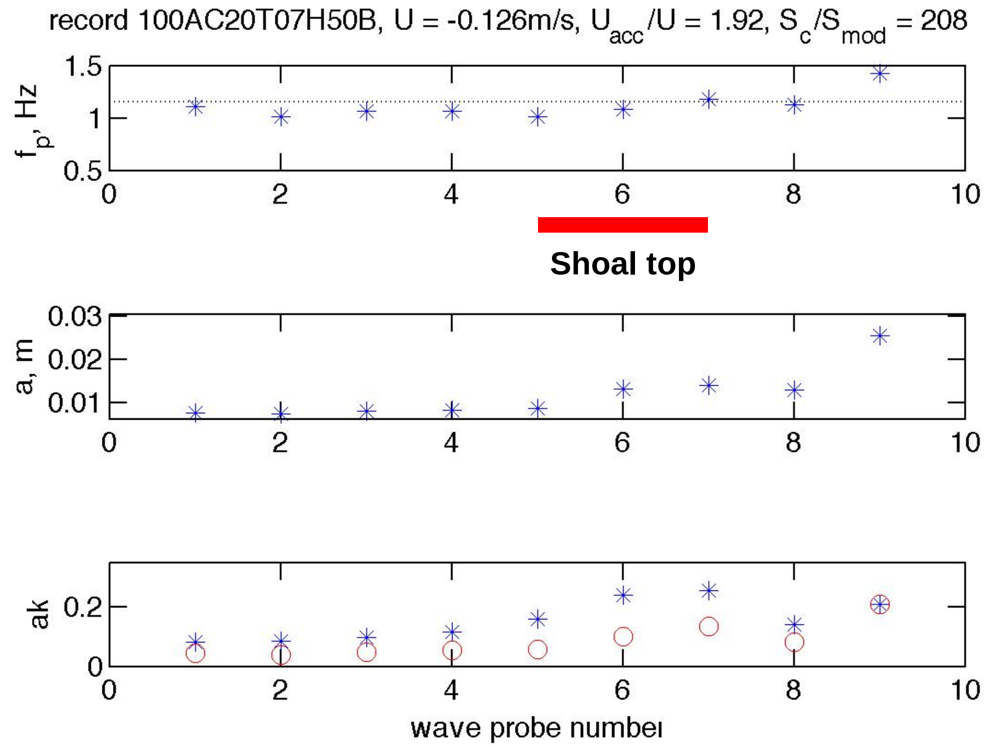
stronger velocity gradients, $c_g>1/4$

gradual irreversible downshift

beyond lower sideband

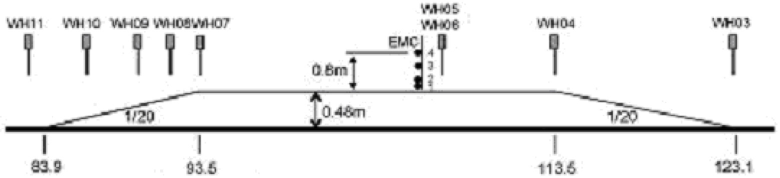






- waves propagate from right to left
- circles signify downshifting observed, dashed line the sideband
- probes 7-5 are over the bottom elevation

Measurements, adverse currents

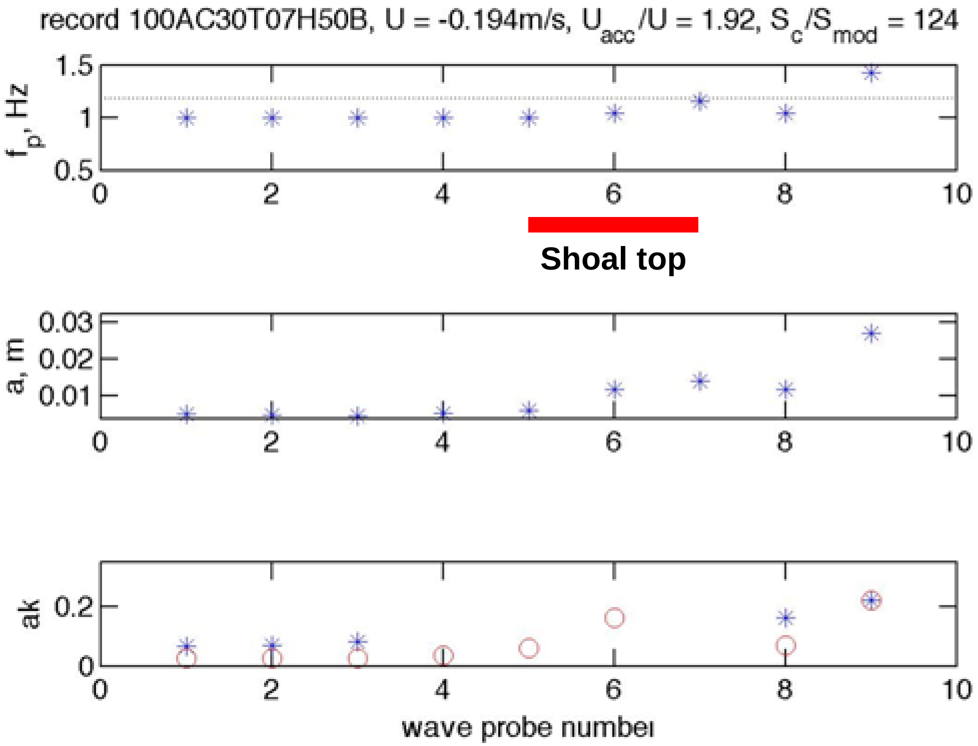


blocking conditions

fast irreversible downshift beyond the lower sideband

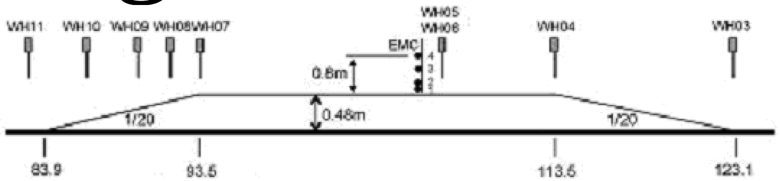
low-frequency waves penetrate the blocking point without breaking

different scenario to the Stokes wave theory



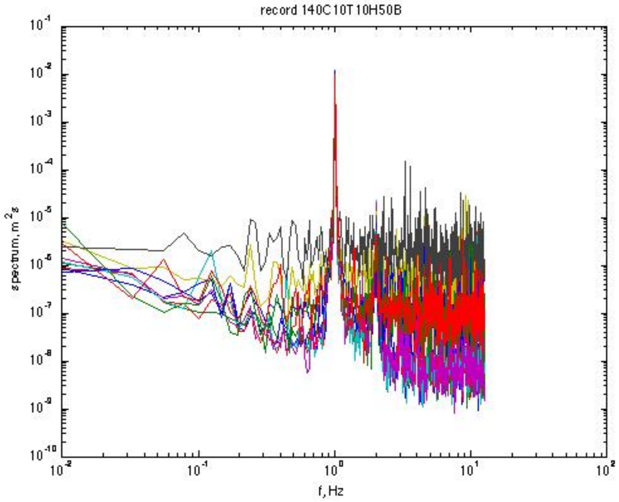
- waves propagate from right to left
- circles signify downshifting observed, dashed line the sideband
- probes 7-5 are over the bottom elevation

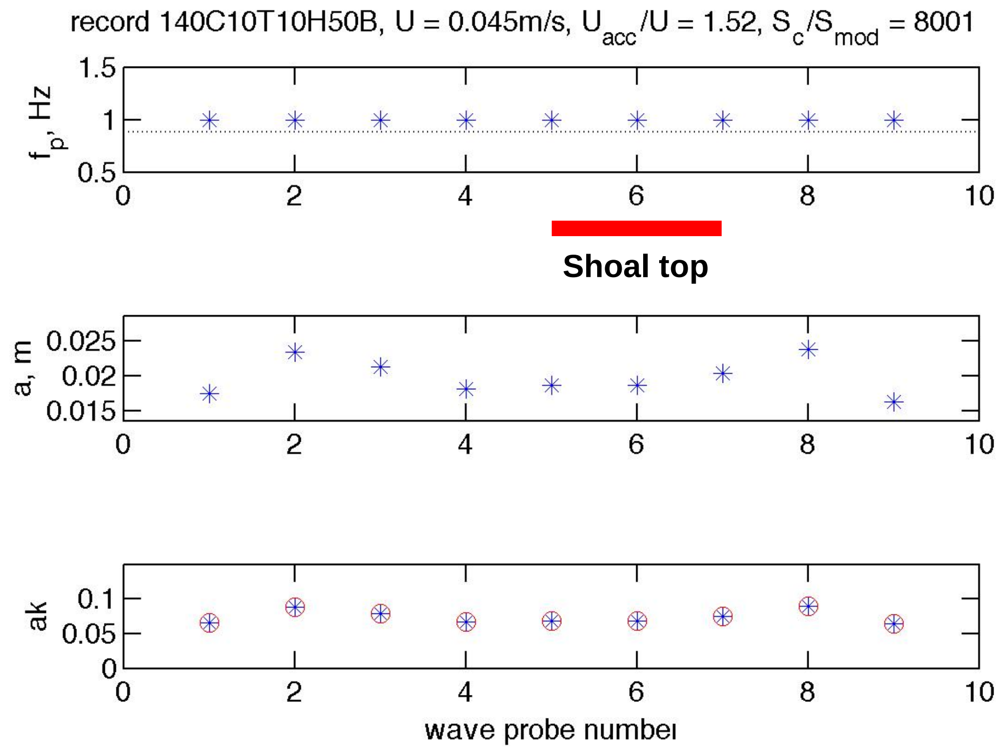
Measurements, following currents



low steepness waves

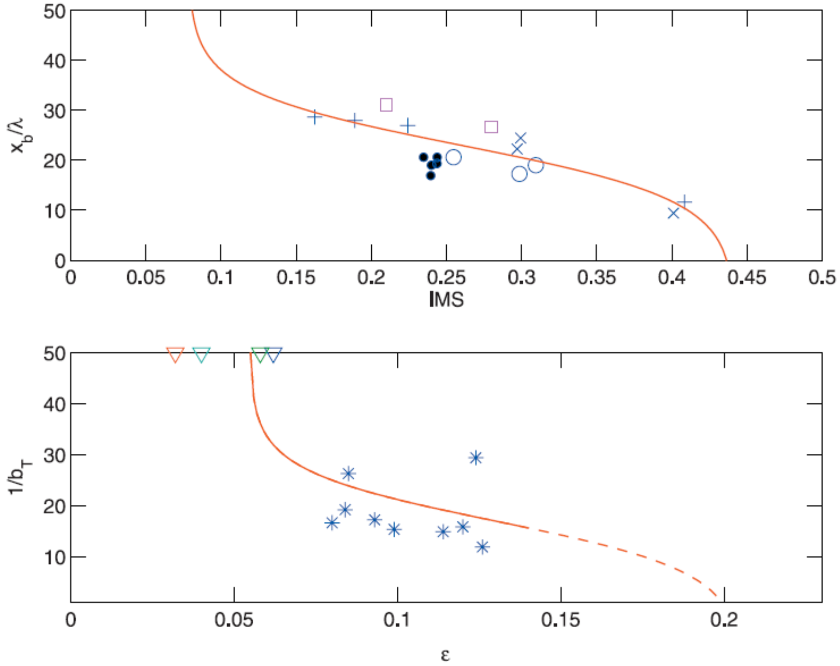
linear theory scenario

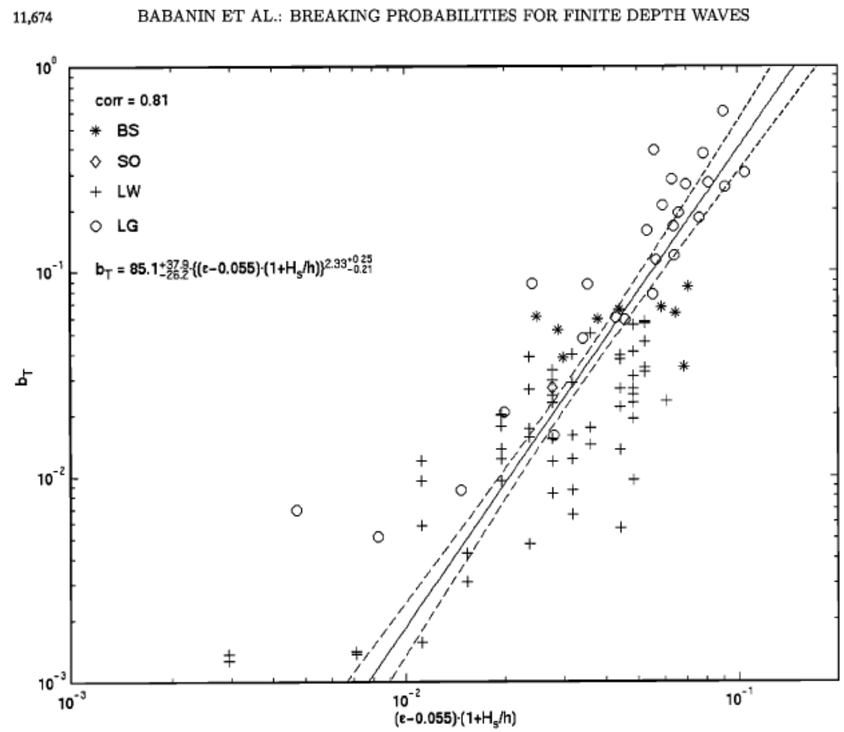




- waves propagate from right to left
- circles signify downshifting, dashed line the sideband
- probes 7-5 are over the bottom elevation

Dominant Breaking in Field Conditions Threshold





Laboratory and numerical simulations

Babanin, Chalikov, Young, Savelyev, 2007, GRL

Field measurements (also in the bottom left)

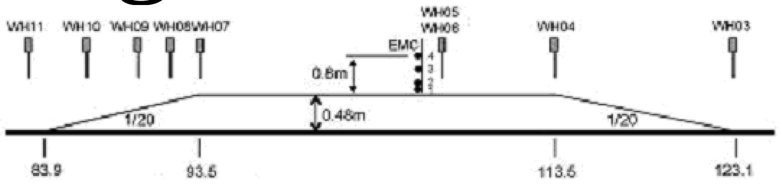
Babanin, Young, Banner, 2001, JGR

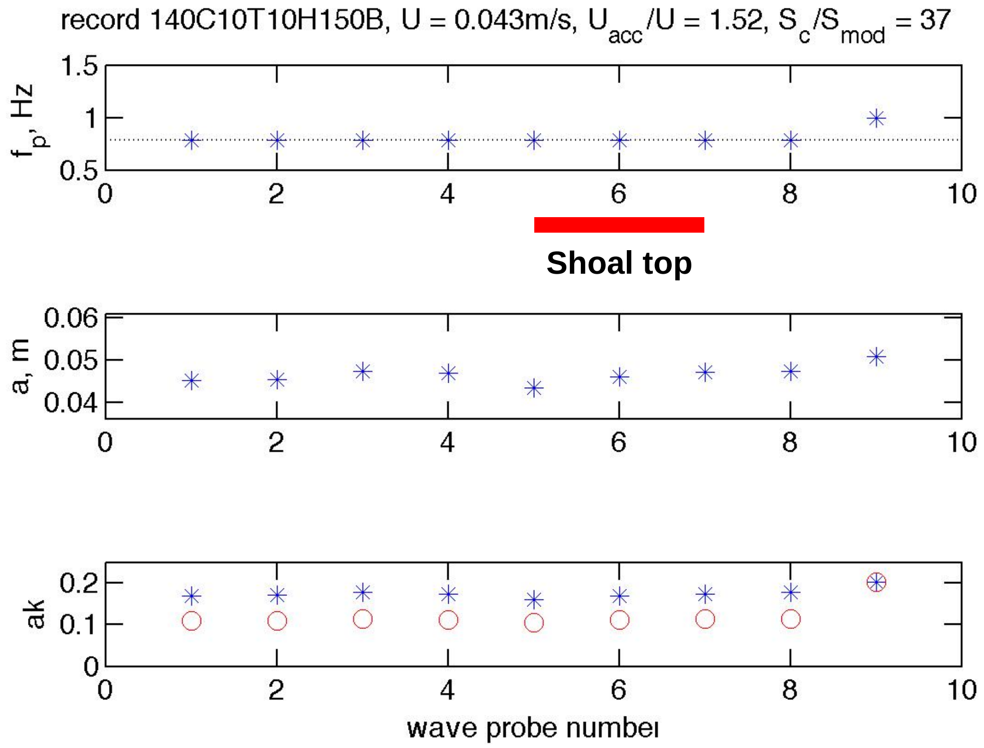
Measurements, following currents

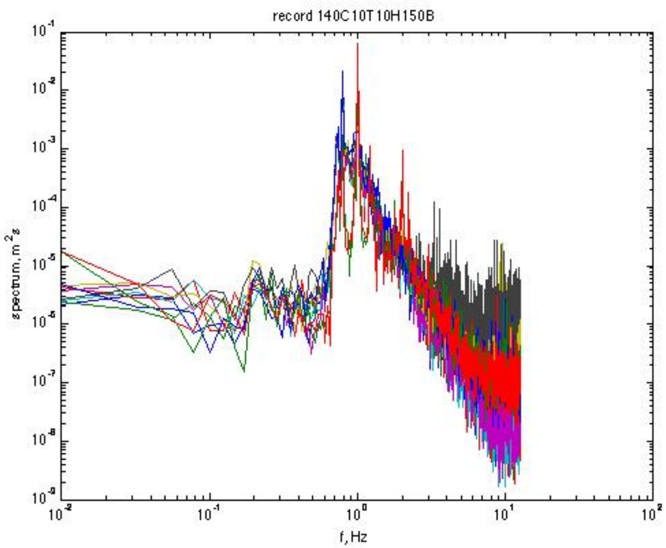
much steeper waves

nonlinear scenario

downshifting and sharp growth of the secondary peak







- waves propagate from right to left
- circles signify downshifting, dashed line the sideband
- probes 7-5 are over the bottom elevation

Conclusions

- Wave dynamics on currents with horizontal gradients:

nonlinear effects are very essential

- Stokes waves: realistic behaviour, theory predicts their steepening to the Stokes limit, i.e. to breaking, rather than singularity
- Measurements on currents: fully nonlinear effects mostly dominate
- Adverse current

  - irreversible downshifting,

  - if the gradients are strong, downshifting is fast and goes beyond the lower sideband

  - waves can penetrate the blocking currents
- Following currents:

  - linear steepening is observed (important for modelling the dissipation)

  - downshifting happens if the waves are steep enough
- Spectral models: physics needs updating