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Ocean Swell, how much do we know

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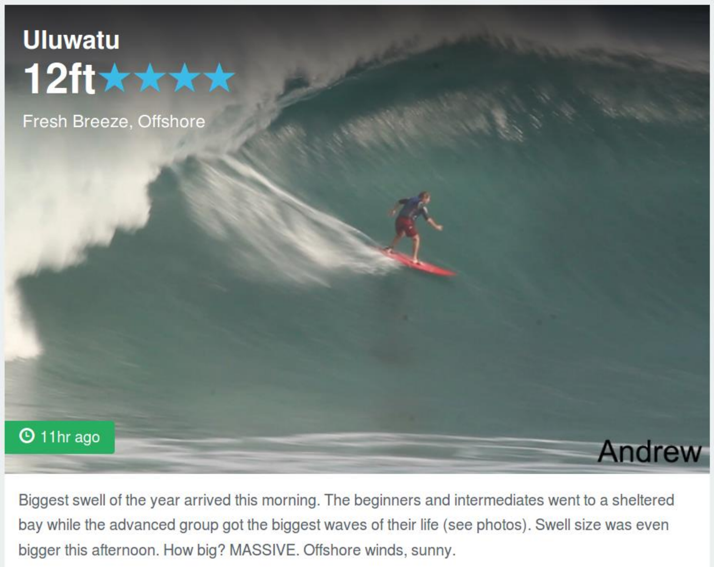
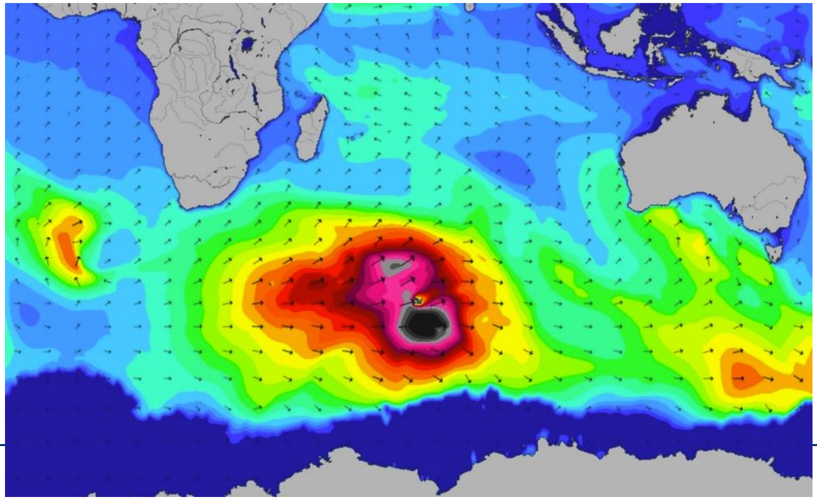
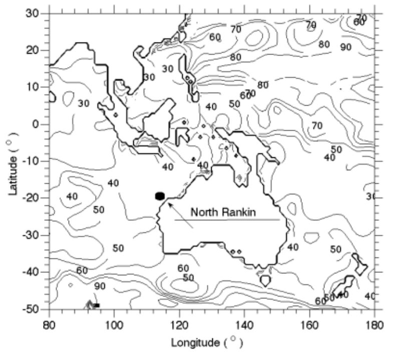
17th Int. Workshop on Wave Hindcasting and Forecasting
University of Notre Dame, Indiana, USA
5 October 2023

Motivation



Surfers in Indonesia: swells are normally delayed by a day with respect to the forecast

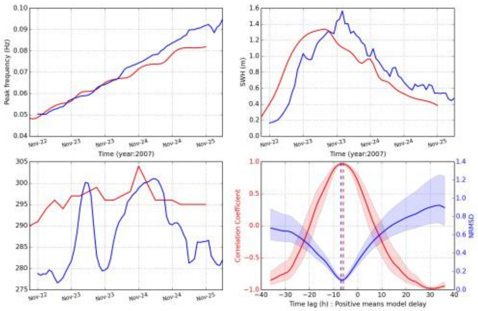




Industry at North-Western shelf: swells are always early with respect to the forecast

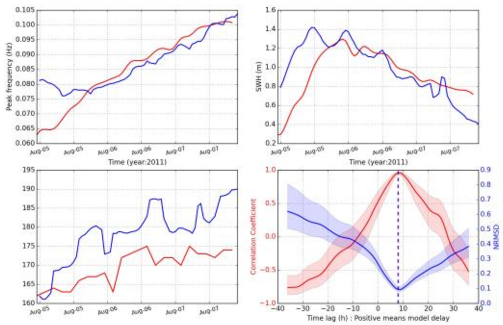
Swell arrival (relative to models)

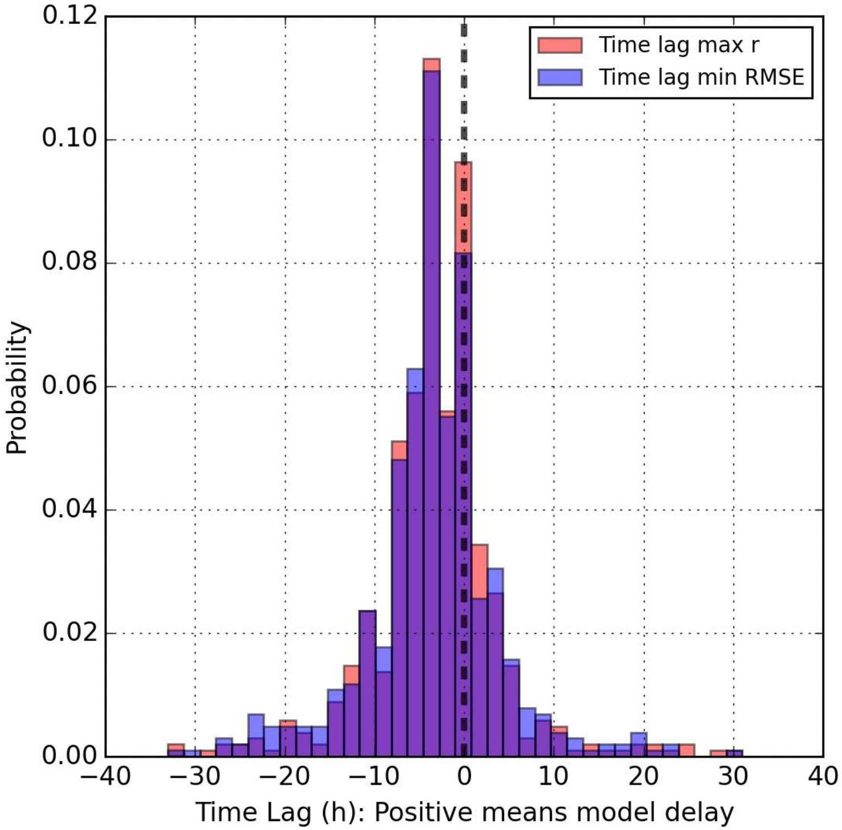
- North West Australia: early
- Indonesia: very late
- Hawaii: on time?



Model early

Model late





Jiang, Babanin, Chen, JPO, 2016

Definitions

- Long-crested (uni-directional)
- Disconnected from local wind
  - outrunning the win
  - perpendicular to the wind
  - against the wind

Wind-forced swell outrunning the wind

Long fetches
Slowing winds
Arctic Ocean

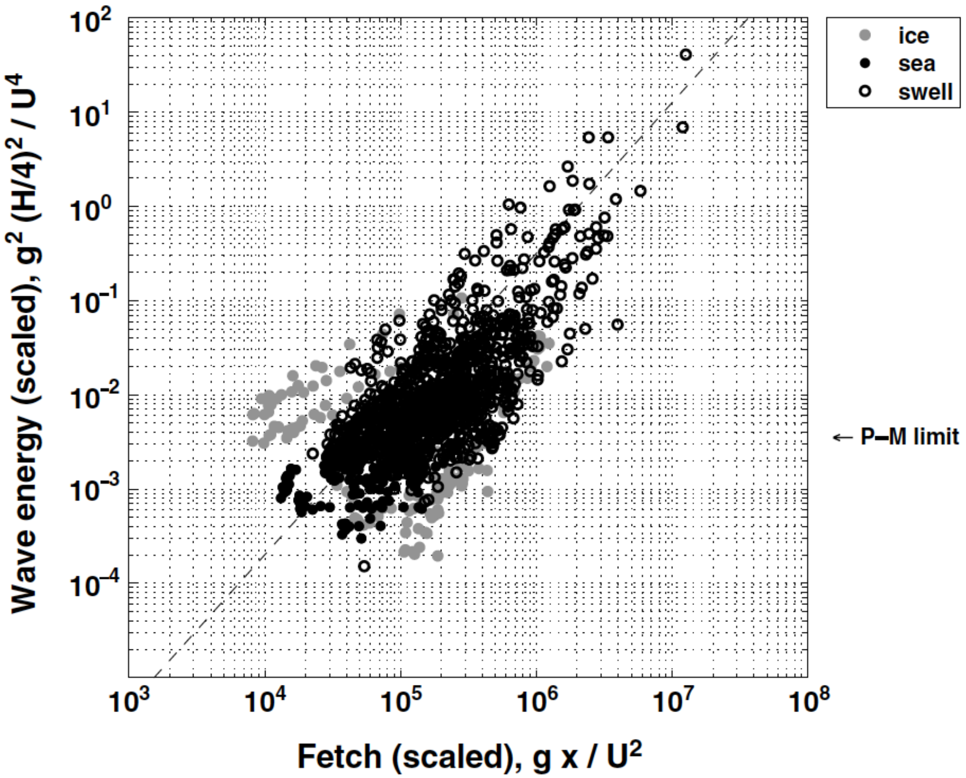


Figure 3. Scaling of waves in the Arctic Ocean, using nondimensional wave energy versus nondimensional fetch. There are 1880 points (each corresponding to an hourly observation from the in situ mooring at 75°N, 150°W). Symbols as in Figure 2. The dashed line is a regression with a logarithmic slope of 1.6. The Pierson–Moskowitz limit for pure wind seas is shown at $\mathcal{E} = 3.64 \times 10^{-3}$.

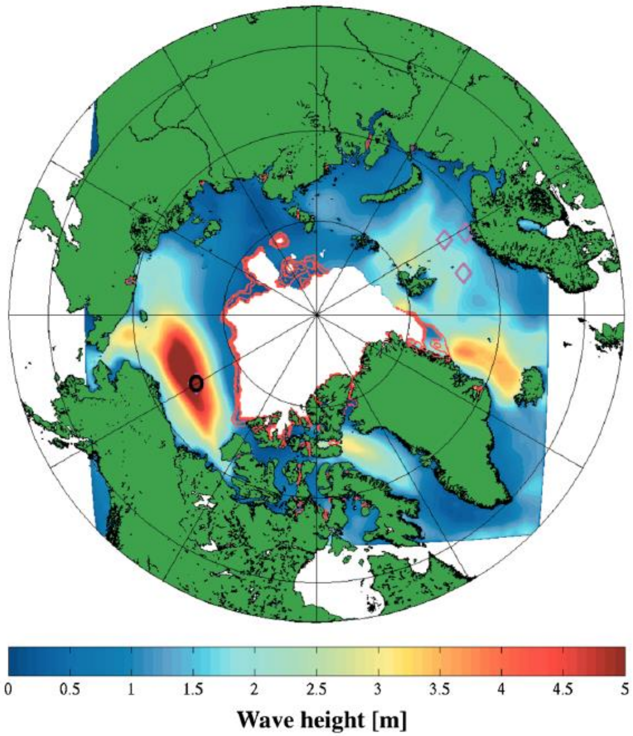
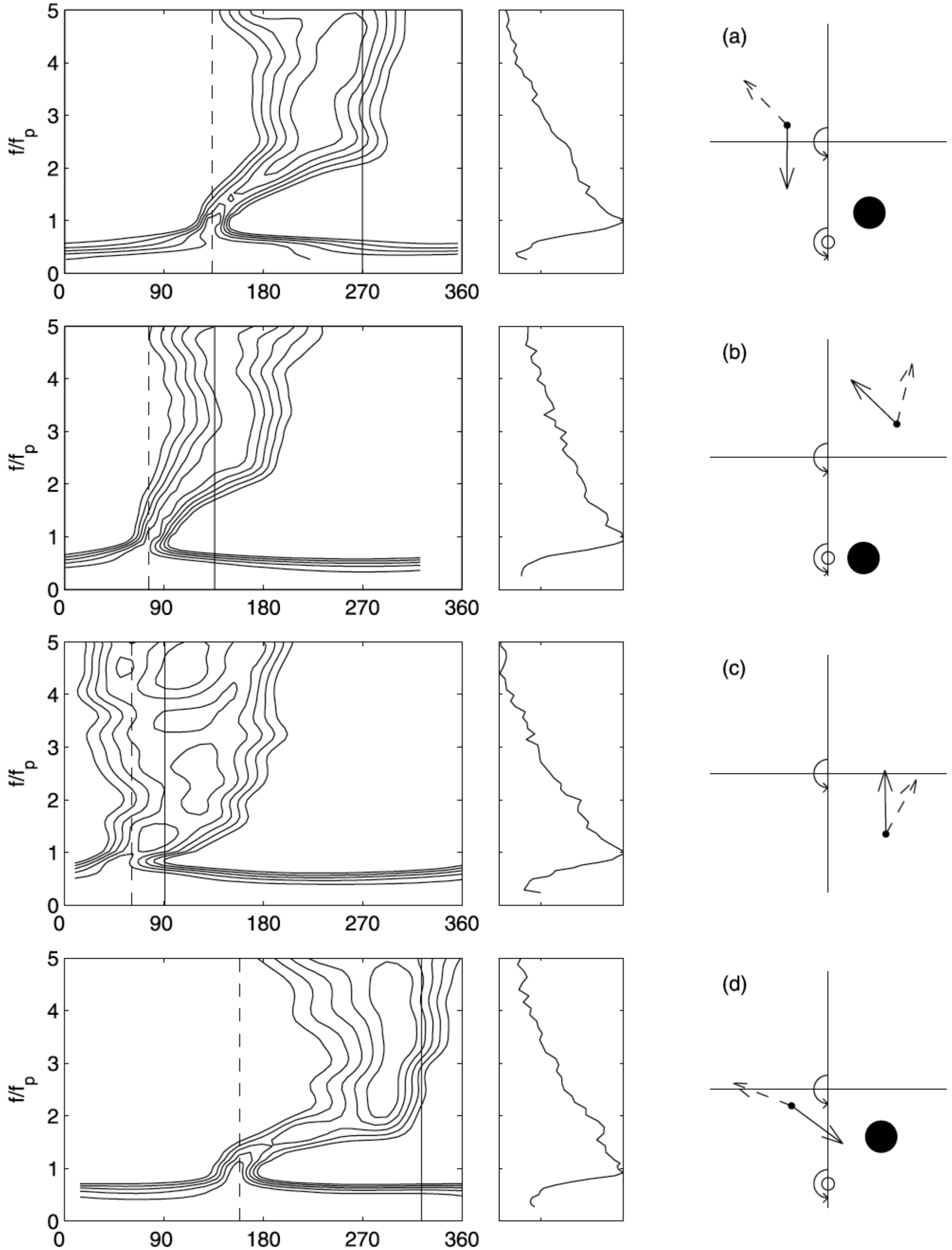


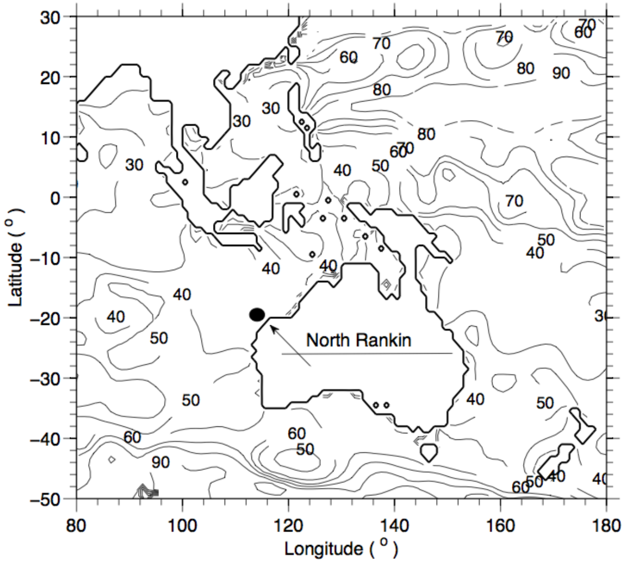
Figure 1. Example wave model hindcast during September 2012 storm. The map is centered on the North Pole, and the mooring location is indicated by the black circle north of Alaska. The color scale indicates significant wave height from 0 to 5 m.

Thomson & Rogers, JPO, 2014

Wind-forced swell 90 and 180 degrees



Tropical cyclones
Indian Ocean



Young, JPO, 2006

Model performance

Wind waves / swells

Wave height

- Well predicted (<10% globally)/

  / poor (factor of 2 is not uncommon)

Wave period (arrival time)

- Reasonable (metrics is uncertain)/ very poor (large under- and over-predictions)

Direction

- Depends on situation (eg. presence of currents) / unknown

Swell Height

Swell attenuation

Attenuation and dissipation are not the same

- dispersion/spreading
- energy is conserved (spread forward/obliquely)
- dissipation/exchange with air-water
- energy is lost from the wave system
- lateral energy diffraction
- energy is conserved (spreads laterally)

Interaction with local winds/waves can lead to swell growth

- energy is gained by swell

Dispersion/ Spreading

- Attenuation along the great circles
- Point source (> 4000 km)
- *Can be evaluated analytically*
- Complicated closer to the storm

$$\frac{\mathrm{d}E_s}{E_s \mathrm{d}x} = I_{fd} + I_{as}$$

$$I_{fd} \approx -1/(\alpha R) = -1/x$$

$$I_{as} \approx -cot(\alpha)/R = -cot(x/R)/R$$

Collard et al., JGR, 2009

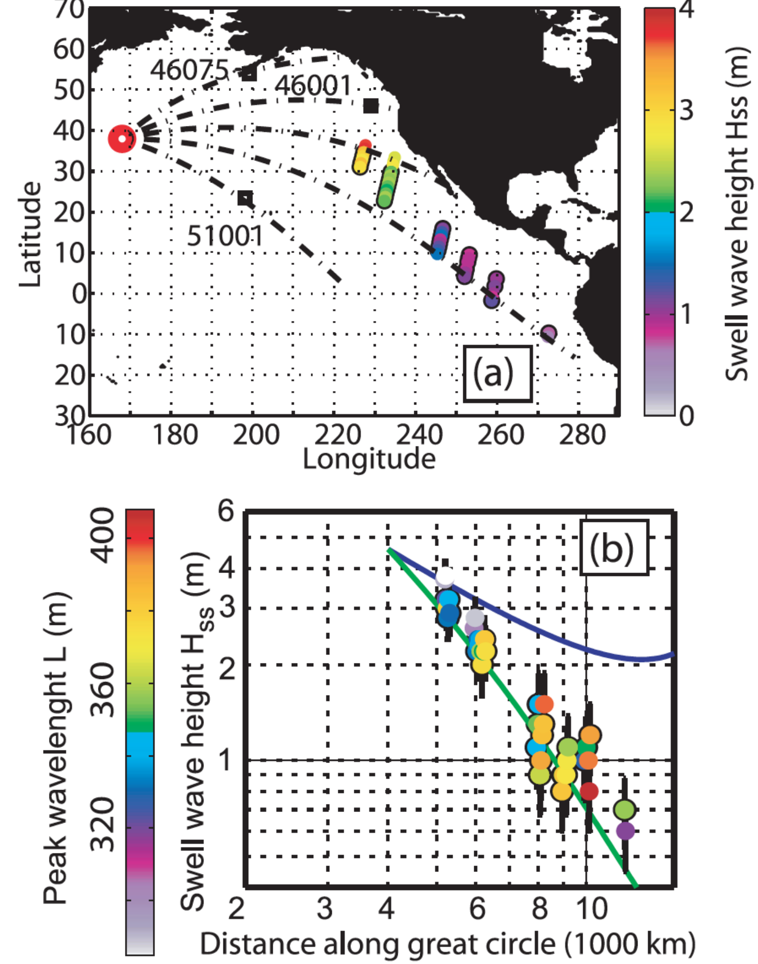


Figure 8. (a) Location of SAR observations with a 15 s peak period swell system corresponding to the 12 February source, with outgoing directions of 74 to 90°. The same swell was also observed at all buoys from 46075 off western Alaska to 51001 in Hawaii. The dash-dotted line represents great circles leaving the storm source with directions 42, 59, 74, 90 and 106°. (b) Observed swell wave height as a function of distance. The solid lines represent theoretical decays using no dissipation (blue) or the fitted linear dissipation (green) for swells observed in February 2007. Outlined dots are the observations used in the fitting procedure. Error bars show one standard deviation of the expected error on each SAR measurement.

Dissipation
wave-induced turbulence

Swell dissipation

$$\varepsilon = 300 \cdot a^{3.0\pm1.0} \quad b = b_1 k\omega^3 = 30. \quad b_1 = 0.004$$

$$\epsilon_{dis} = b_1 k\omega^3 a_0^3 = 0.004 k u_{orb}^3.$$

$$D_a = b_1 k \int_0^\infty u(z)^3 dz = b_1 k u_0 \int_0^\infty \exp(-3kz) dz = \frac{b_1}{3} u_0^3.$$

$$D_x = \frac{1}{c_g} D_a = \frac{b_1}{3} 2 \frac{k}{\omega} u_0^3 = \frac{2}{3} b_1 k\omega^2 a_0^3 = \frac{2}{3} b_1 g k^2 a_0^3.$$

$$\frac{g}{2} \frac{\partial (a_0(x)^2)}{\partial x} = \frac{2}{3} b_1 g k^2 a_0(x)^3,$$

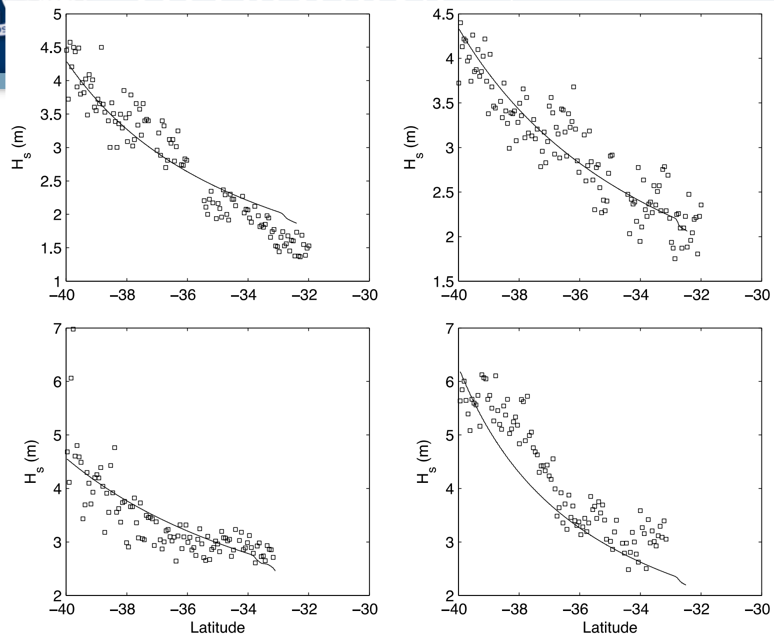
$$a_0(x)^2 = \frac{4}{B^2} x^{-2} = \frac{9}{4 \cdot b_1^2 k^4} x^{-2} = \frac{9}{64} 10^6 k^{-4} x^{-2}.$$

Dissipation

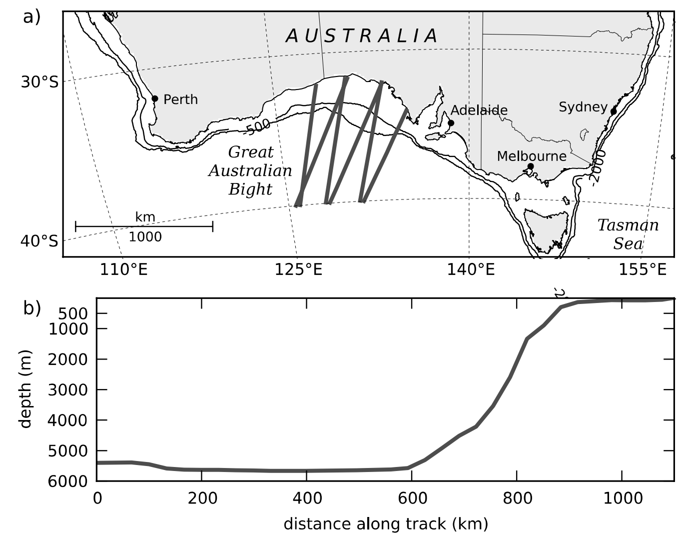
- volumetric
- per unit of surface
- per unit of propagation distance

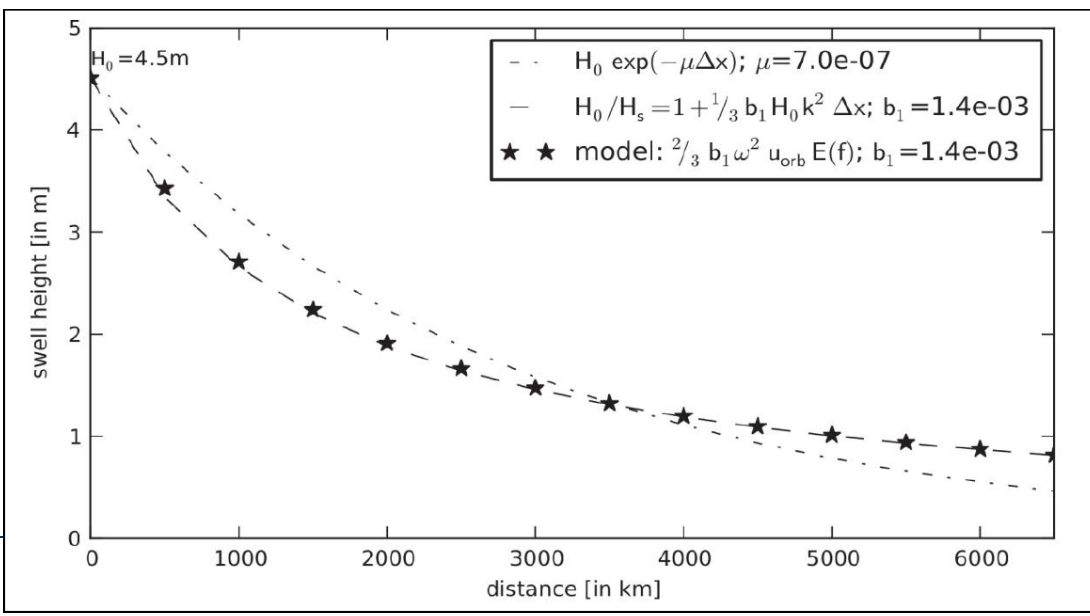
Babanin, CUP, 2011, OMAE, 2012

Swell dissipation



Altimeter measurements Southern Ocean





Young, Babanin, Zieger, JPO, 2013

Interaction with Adverse Wind/ negative input

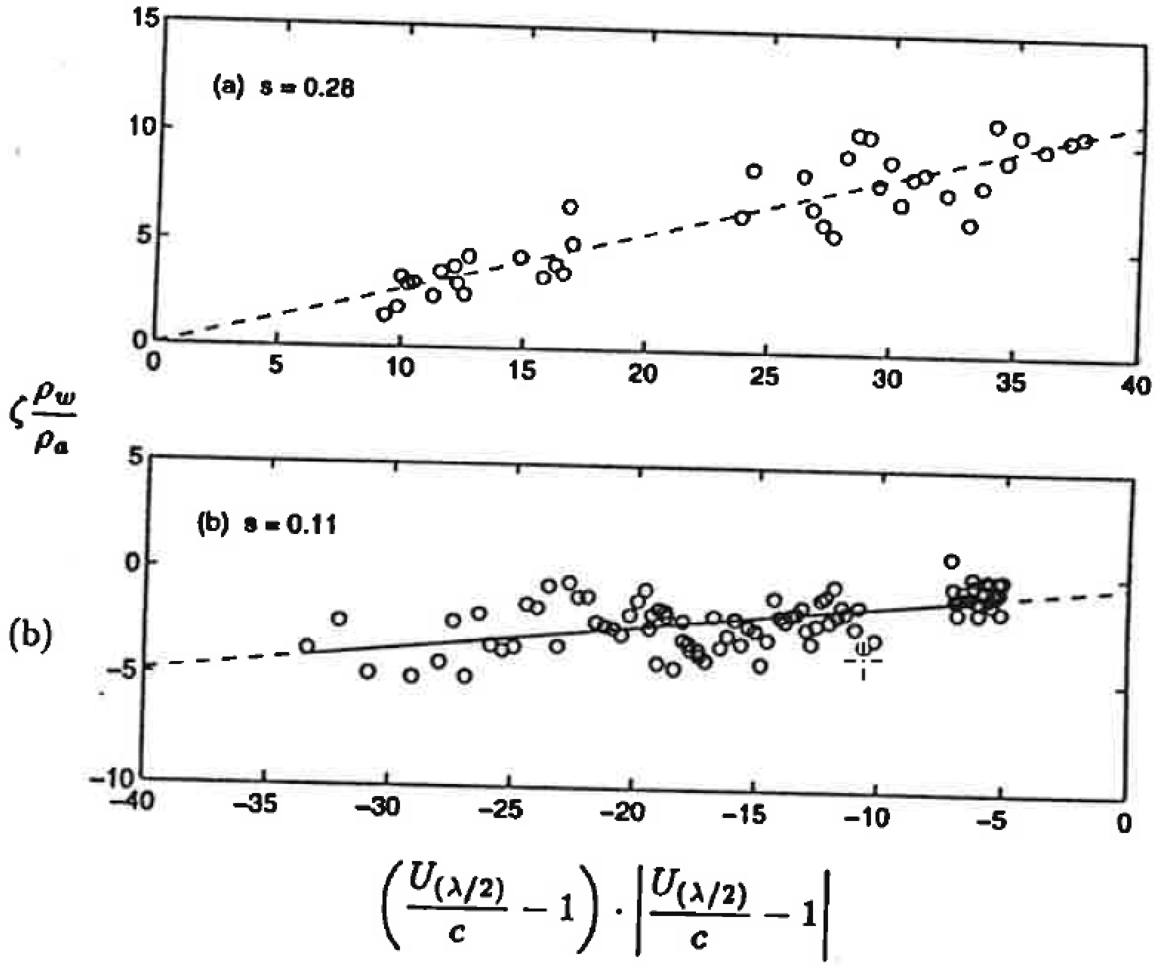


Figure 4. The magnitude of the fractional energy change per radian × the density ratio, (a) growth rates for the wind-sea, and (b) attenuation rates for the paddle-generated waves travelling against the wind. The regression lines to the data are shown and the corresponding sheltering coefficients (line slopes) are indicated on the figure

Donelan, ECMWF, 1999

Attenuation summary

- Three attenuation mechanisms were discussed:
  - dispersion/ spreading
  - interaction with turbulence in the water
  - energy/momentum exchange with adverse wind

Diffraction (lateral spread of wave energy)

following Babanin & Waseda, OMAE, 2015

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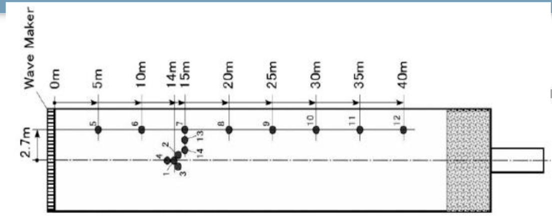
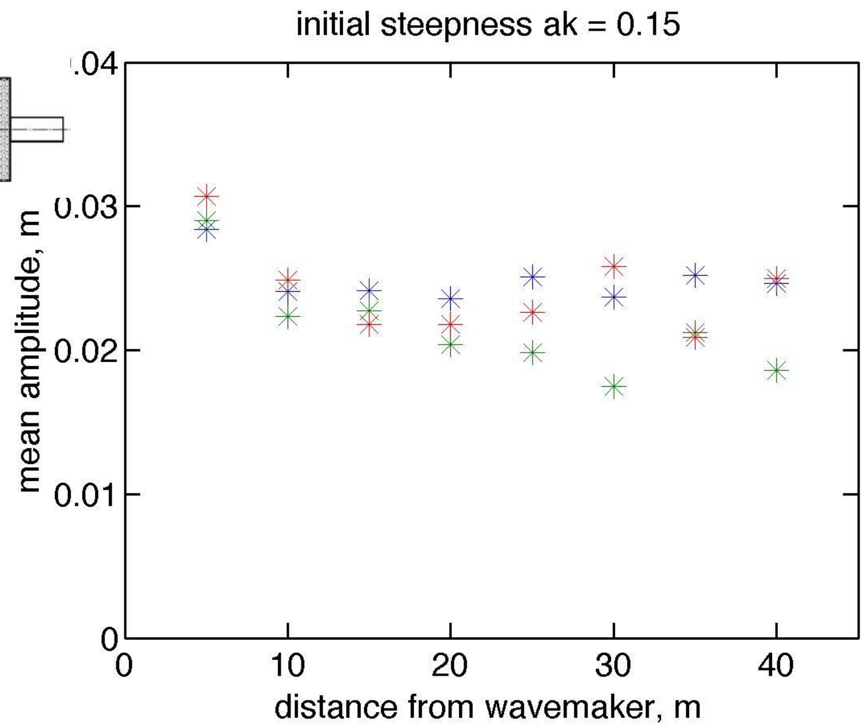
Coherent quasi-1D wave trains

Chabchoub et al., 2018

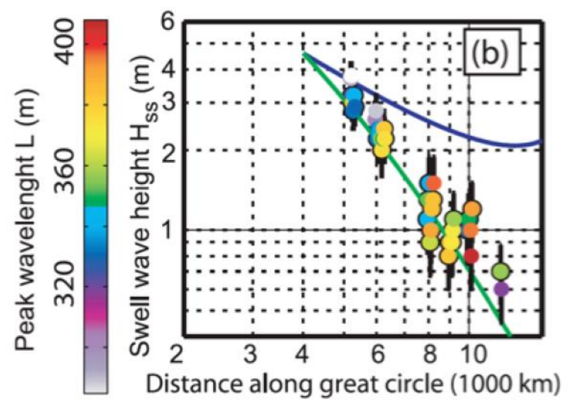




- crests 10m (blue), 5m (green), 5m/5m with 180-degree phase shift (red)
- ***no diffraction if each half-tank has the waves***
- visually, coherent wave trains do not mix

Babanin & Waseda, OMAE, 2015

Interaction of Swell with Background Waves and Winds



- When the swells enter storm area, will be ***NO diffraction***
- In *Ardhuin et al. (2009), Collard et al. (2009)* ***swells can be growing***
- possible reasons:

- forcing by concurrent wind
- nonlinear interactions with background wind-generated waves

CONCLUSIONS

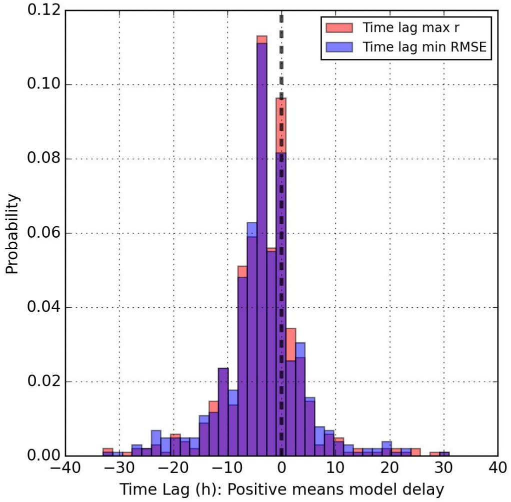
- Swell is a difficult problem
- Attenuation: dispersion, dissipation, diffraction – all important
- Can (perhaps) grow due to reconnection with local winds or waves
- Arrival: can decelerate or accelerate – variety of possible physical mechanisms, as well as numerical reasons
- Experiments (high-resolution satellite observations) of swell propagation are needed
- Problem needs a dedicated effort

Motivation

- Important for the ocean engineering
- Observations have become available
- Wave-forecast models have large biases in regions dominated by swells, such as tropical areas
- This is because physics of spectral models is based on the physics of wind-generated waves:

$$\frac{dF(w,k,q,x,t)}{dt} = S_{input} + S_{nonlinear} + S_{dissipation} + \ldots$$

- Swell physics, however, is absolutely different from the wind-wave physics
- The only relevant term is the energy sink, and this sink is not due to wave breaking

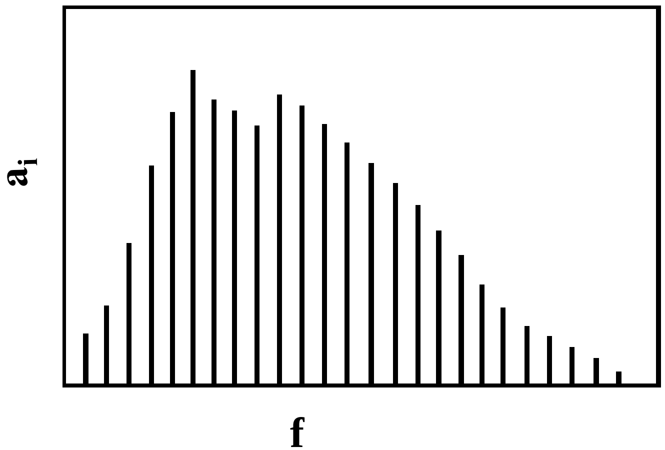


Swell Arrival

can arrive on time, be late or be early

Linear propagation

- Final resolution of peak frequency
  - would explain the scatter
- Different decay rate of different frequencies
  - would explain early arrival
- Note that swells can be propagating for days



Young, Elsevier, 1999

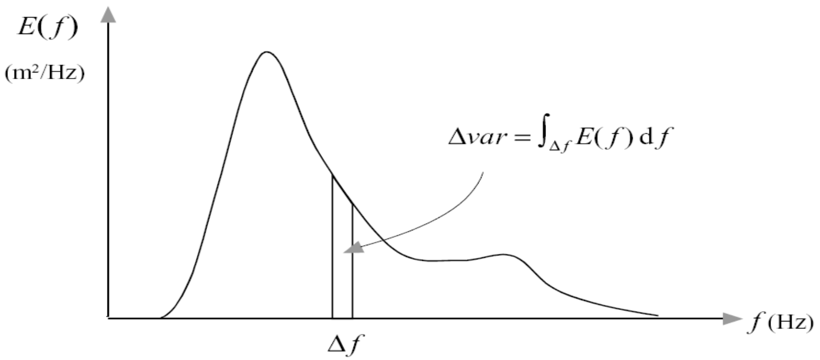
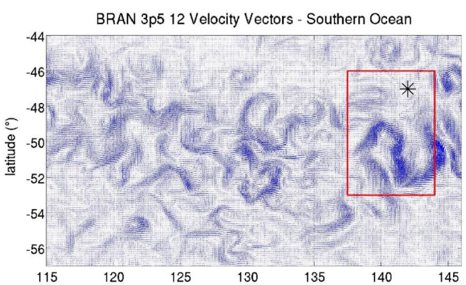


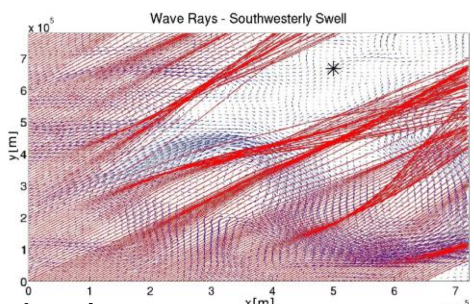
Figure 3.8 The interpretation of the variance density spectrum as the distribution of the total variance of the sea-surface elevation over frequencies.

Holthuijsen, CUP, 2007

Refraction

- Currents/ large-scale eddies can extend the fetch
- Can extend the time of swell to go through shallow areas
- Swell will decellerate



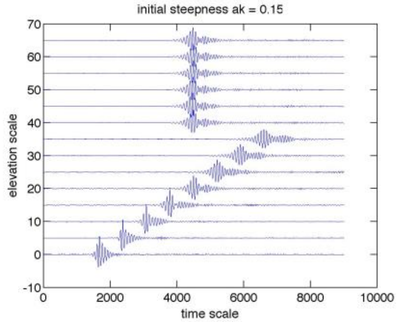


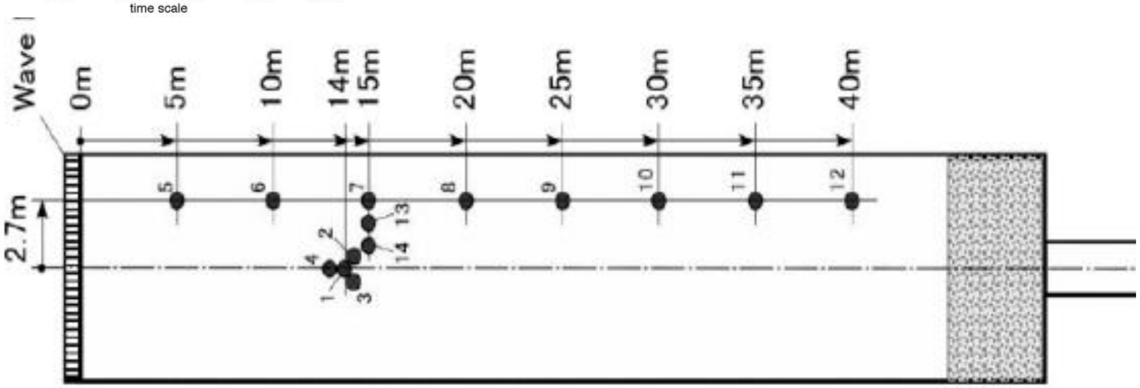
Rapizo, Babanin, Gramstad, Ghantous, AFMC, 2014

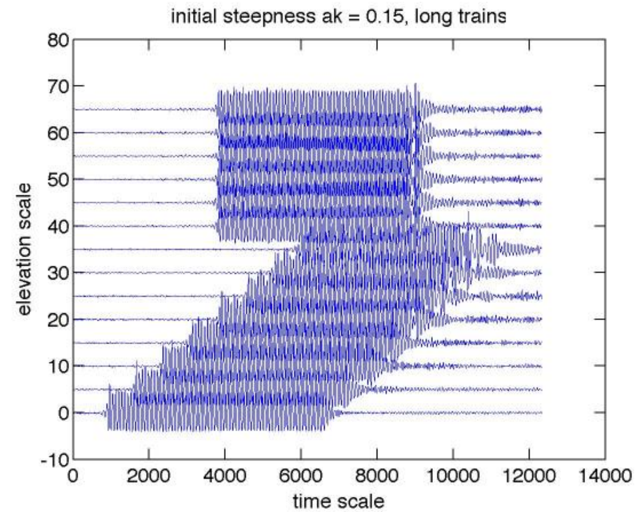
Nonlinear effects

- Modulational instability causes downshifting (Raman effect)
- Adverse currents with horizontal gradients cause downshifting (e.g. *Babanin et al., Hindcast/Forecast, 2011*)
- *Swell will accelerate*
- Interaction with wind/waves can affect

The Experiment





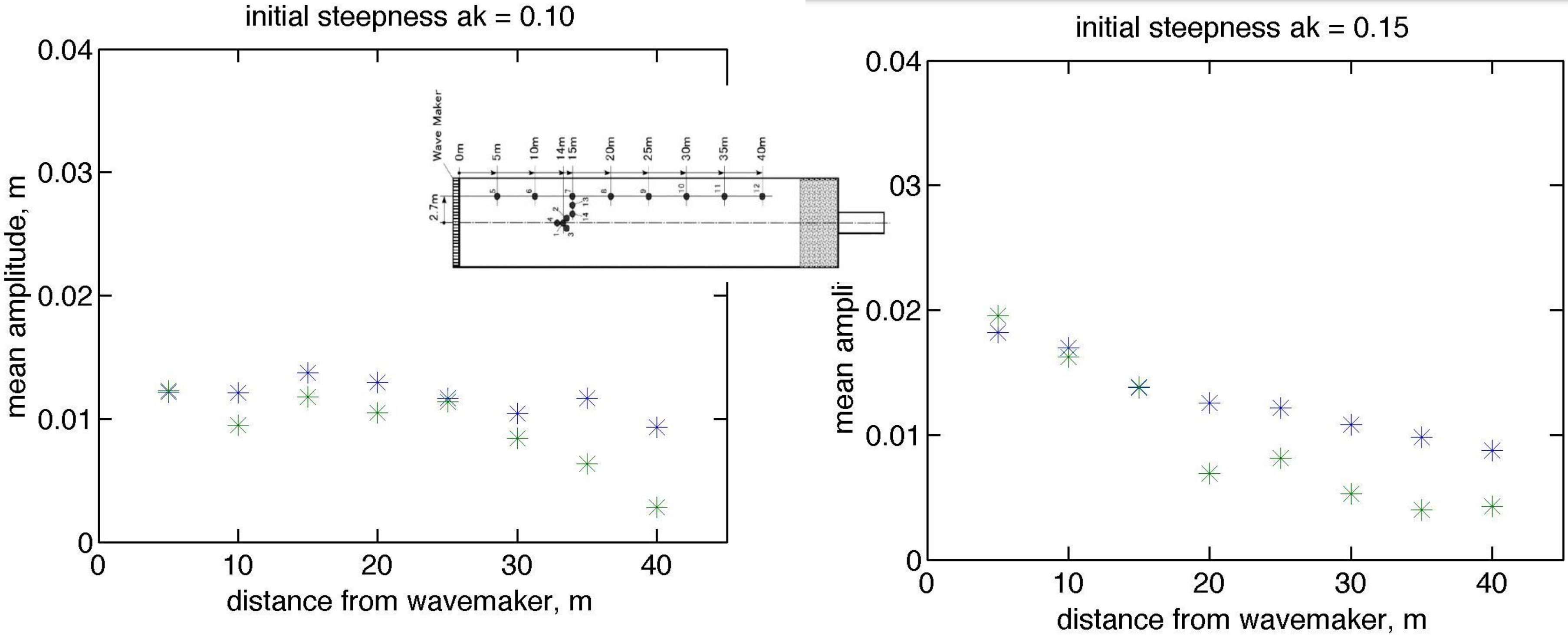


Ocean Engineering Basin, University of Tokyo

- 50m x 10m x 5m
- Wavemaker: 32 programmable plungers
- 1D wave array of 8 probes (2.3m from the wall)
- Directional wave array in the centre
- Single wave groups or wave trains (40 groups)

Babanin & Waseda, OMAE, 2015

Nonlinear diffraction of short-crested waves



- Single groups; crests 10m (blue), 5m (green)

$$v_e = \frac{2.7m}{40s} = 0.0675\frac{m}{s} = 0.11c_g \text{ » } e \times c_g$$

$$v_d = \frac{5m}{64.5s} = 0.078\frac{m}{s} = 0.12c_g \text{ » } e \times c_g$$

$$v_e = \frac{2.7m}{24s} = 0.113\frac{m}{s} = 0.18c_g \text{ » } e \times c_g$$

$$v_d = \frac{5m}{48s} = 0.104\frac{m}{s} = 0.17c_g \text{ » } e \times c_g$$

Babanin & Waseda, OMAE, 2015

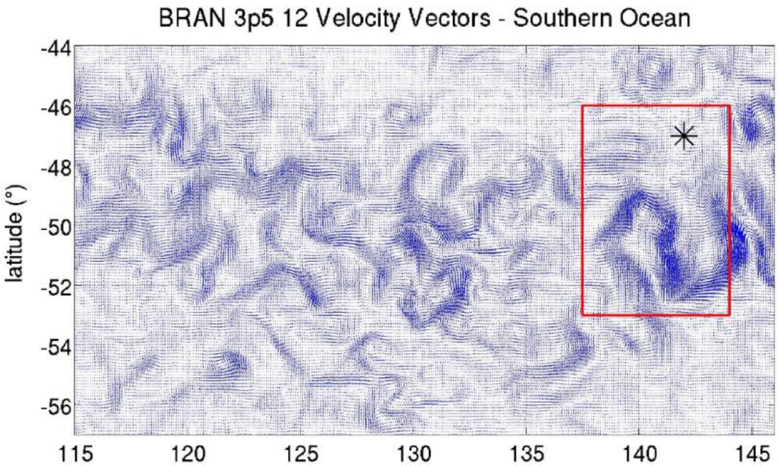
Nonlinear diffraction of short-crested waves

$v \approx \varepsilon \cdot c_g$ $\qquad\qquad$ $v = 14.3\varepsilon^{2.6} c_g + 0.08$

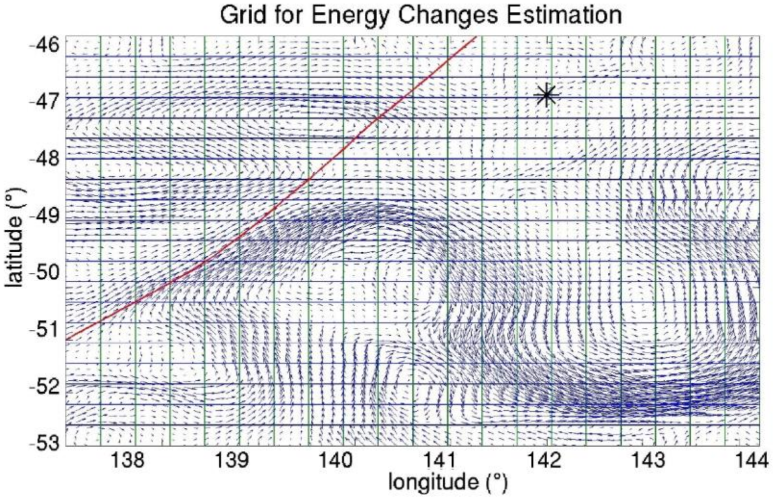
- Such diffraction is too fast for the ocean
- 100 m wave/crest length swell, with 0.01 steepness would double its crest length within 10 to 19 minutes
- This is unrealistic
- The dynamics must be more complicated
- Question of the lateral diffraction of swell remains open
- If wave energy already present in the areas, there will be no diffraction

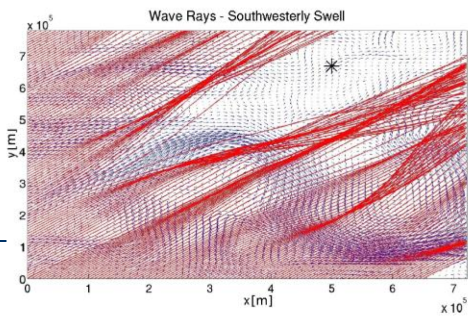
Babanin & Waseda, OMAE, 2015

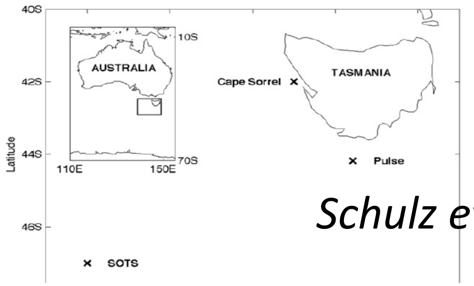
Swell direction



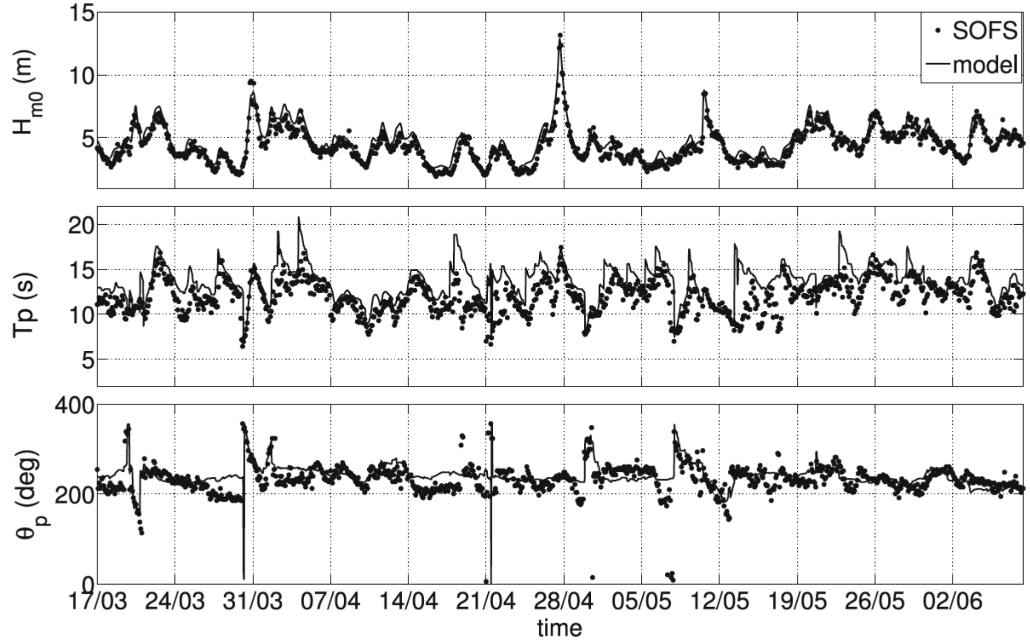
Wave refraction

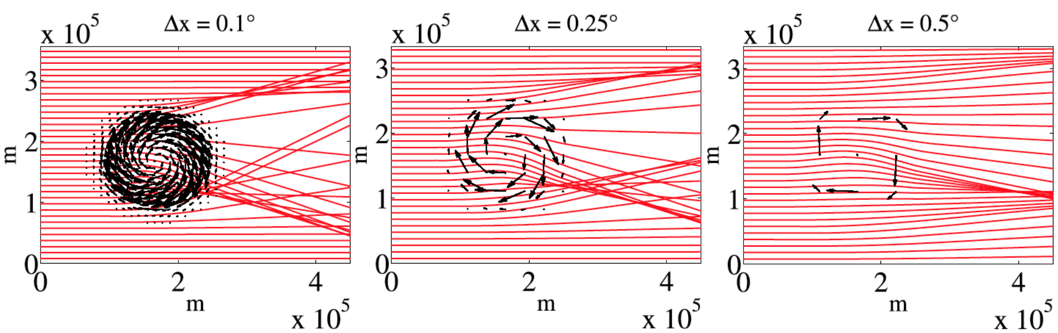






Schulz et al., JTec, 2011





Rapizo et al., AFMC, 2014, Ocean Dyn., 2016, 2018

Swell attenuation

Attenuation and dissipation are not the same

- frequency dispersion
- directional spreading
- viscous dissipation (negligible)
- interaction with air turbulence (Ardhuin et al. 2009)
- interaction with water turbulence (Babanin 2006, 2011)
- interaction with adverse wind (Donelan 1999)
- nonlinear interactions with currents (hypothetical)
- lateral energy diffraction (Babanin & Waseda, 2015)

Interaction with local winds/waves can potentially lead to swell growth