MSE:
Transforming the Future of Engineering & IT

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New Generation of Wave Forecast Models, Made in Australia

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In collaboration with Ian Young, Erick Rogers, Mark Donelan, Stefan Zieger, Qingxiang Liu and many many others,

1996 - now

Forum for Operational Oceanography
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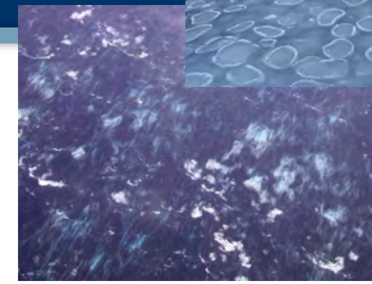
Motivation



- physics (parameterisations of the source terms) was cursory
- was not based on observations
- bulk calibration

Requirements for the modern-date models:

- more accurate forecast/hindcast
- being used in the whole range of conditions, from swell to hurricanes, from finite depths to the ice
- coupling with weather, ocean circulation and climate models

Radiative Transfer Equation is used in spectral models for wave forecast

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

- **Describes temporal and spatial evolution of the wave energy spectrum E(k,f,θ,t,x)**

S_{tot} – all physical processes which affect the energy transfer

S_{in} – energy input from the wind

S_{ds} – dissipation

S_{nl} – nonlinear interaction between spectral components

S_{bf} – dissipation due to interaction with the bottom

$$S_{ds} = S_{breaking} + S_{adverse\_wind} + S_{swell} + \dots$$

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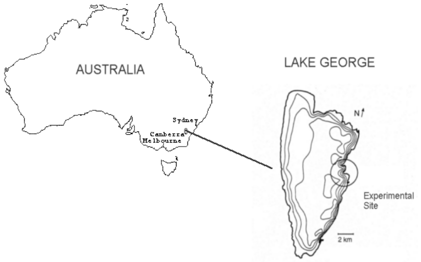
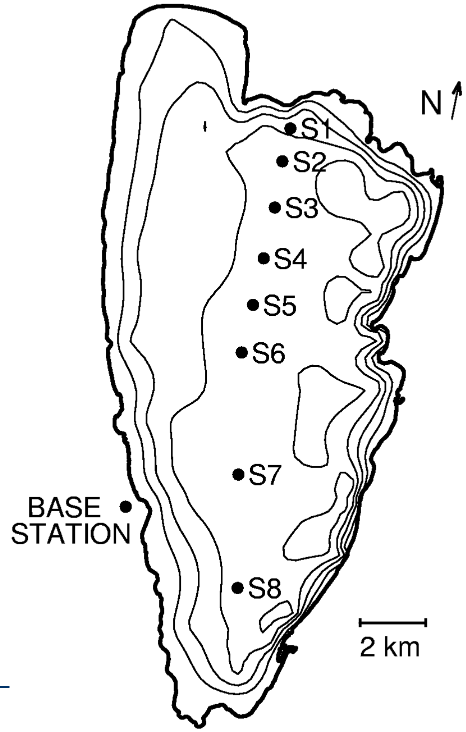
$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

Lake George field experiment

20 km x 10km

- uniform finite water depth (0.3m - 2.2m)
- steep waves $f_p > 0.3$ Hz
- strongly forced waves $1 < U/c_p < 8$





How do we directly measure the wind input?

$$S_{in}(\omega) = \rho_a \omega g \gamma(\omega) E(\omega)$$

- pressure in quadrature with the water surface results in an energy flux from the wind to the waves

$$\frac{\partial E(\omega)}{\partial t} = \frac{1}{\rho_w g} I(\omega) = \frac{1}{\rho_w g}\left\langle p\frac{\partial \eta}{\partial t}\right\rangle = \frac{1}{\rho_w g}\left\langle p\frac{\partial \eta}{\partial x}\right\rangle c(\omega)$$

- non-dimensional growth rate is the quantity of interest

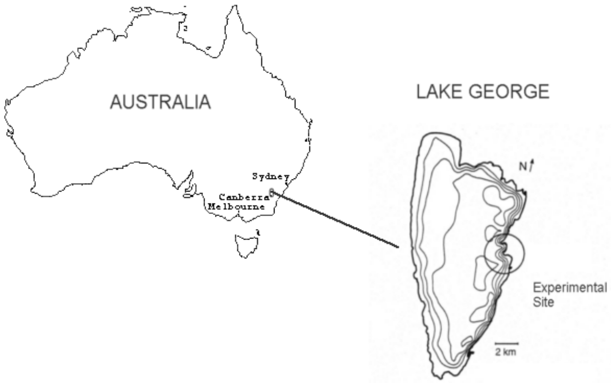
$$\gamma(\omega) = \frac{\rho_w}{\rho_a}\frac{1}{\omega E(\omega)}\frac{\partial E(\omega)}{\partial t}$$

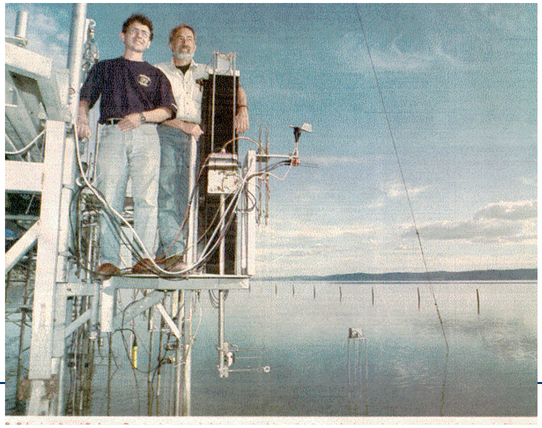
- the fractional energy increase in terms of quadrature spectrum

$$\gamma(\omega) = \frac{Q(\omega)}{\rho_a g E(\omega)}$$

Wind Input following the waves

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

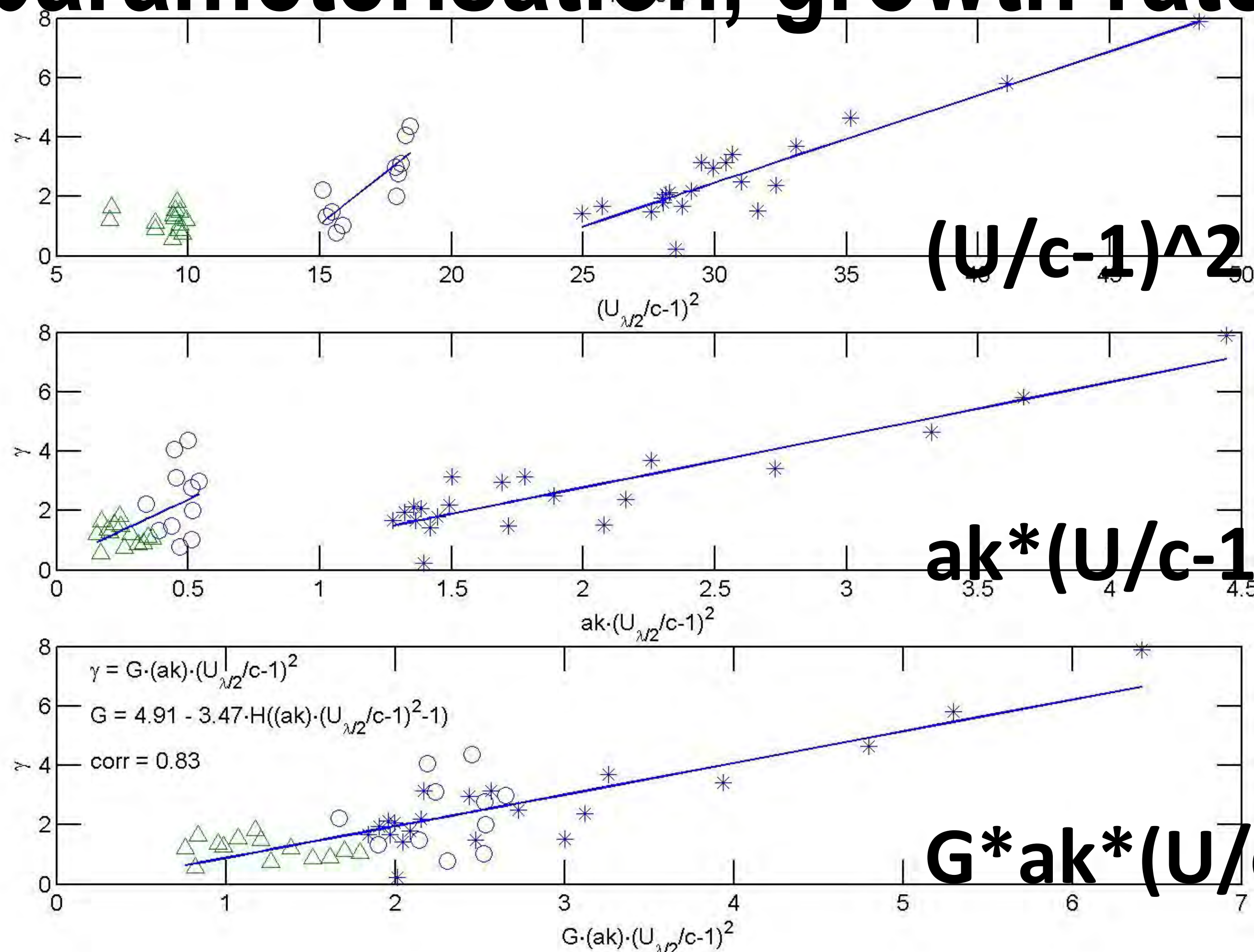




Young et al., JAOT, 2005, Donelan et al., JAOT, 2005, JPO, 2006, Babanin et al., JPO, 2007

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

The parameterisation, growth rate γ



(U/c-1)^2

ak*(U/c-1)^2

G*ak*(U/c-1)^2

$$S_{in}(\omega) = \rho_a \omega g \gamma(\omega) E(\omega)$$

Wind Input – S_{in}

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

- a new parameterisation of the wind input function, based on field measurements, is obtained
- the parameterisation includes very strongly forced and steep wave conditions, the wind input for which has never before been directly measured in field conditions
- new physical features of air-sea exchange have been found:

  - full separation of the air flow at strong wind over steep waves

  - leads to the sea drag saturation

  - the exchange mechanism is non-linear and depends on the wave steepness

  - enhancement of the wind input over breaking waves

$$S_{in}(\omega) = \rho_a \omega g \gamma(\omega) E(\omega)$$

Breaking Dissipation S_{ds}

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

two passive acoustic methods to study spectral dissipation
- segmenting a record into breaking and non-breaking segments
- using acoustic signatures of individual bubble-formation events

Babanin et al. (2001, 2007, 2010), Babanin & Young (2005), Manasseh et al. (2006), Young & Babanin (2006), Babanin & van der Westhuyusen (2008), Babanin (2011)

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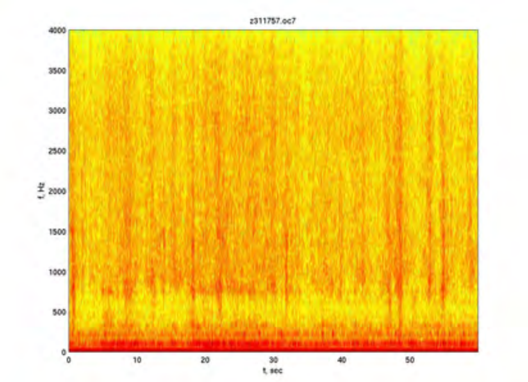
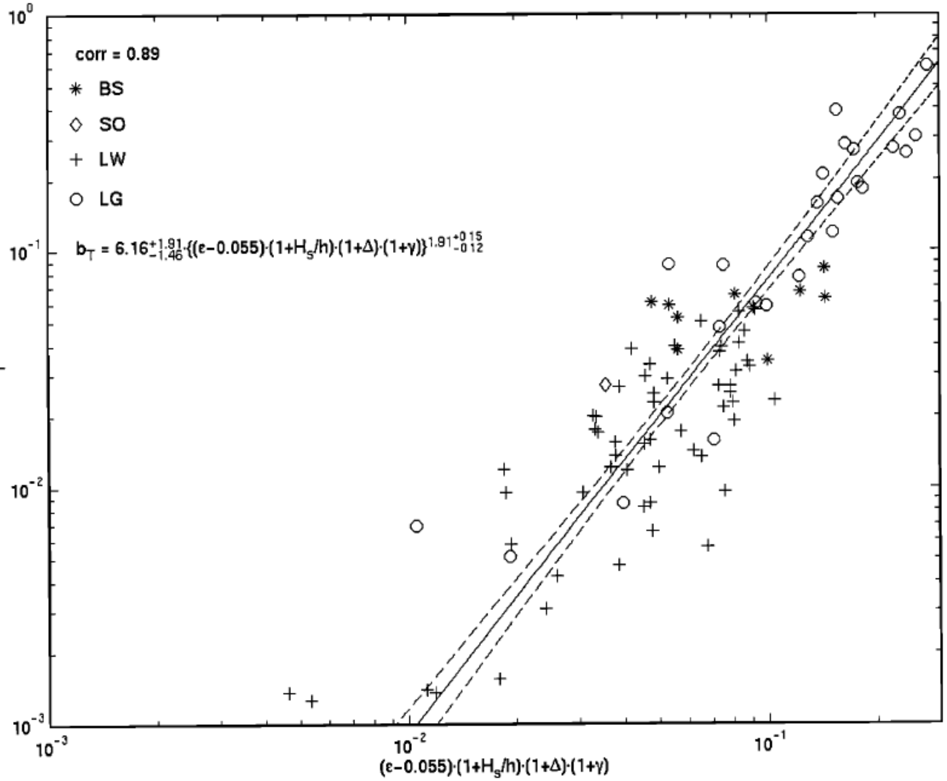
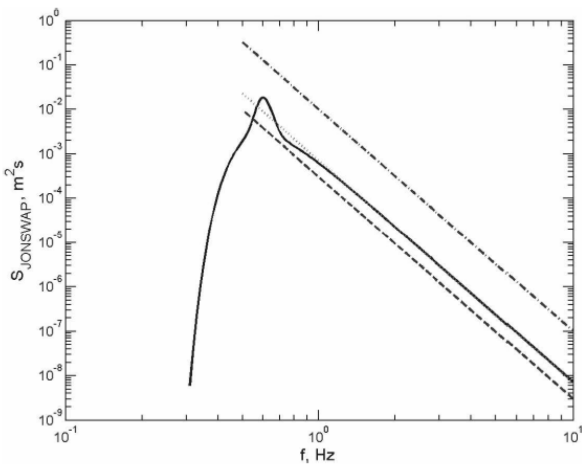
Breaking probability dominant waves



b_T





$$\varepsilon - 0.055$$

$$S_{ds}(\omega) = -\rho_a \omega g \gamma_{ds}(\omega) E(\omega)$$?

$$S_{in}(\omega) = \rho_a \omega g \gamma(\omega) E(\omega)$$

Whitecapping Dissipation S_{ds}

• spectral dissipation was approached by two independent means based on passive acoustic methods

• if the wave energy dissipation at each frequency were due to whitecapping only, it should be a function of the excess of the spectral density above a dimensionless ***threshold spectral level***, below which no breaking occurs at this frequency. This was found to be the case around the wave spectral peak. ***dominant breaking***

• dissipation at a particular frequency above the peak demonstrates a ***cumulative effect***, depending on the rates of spectral dissipation at lower frequencies

$$S_{ds}(f) = a \cdot f(F(f) - F_{thr}(f))A(f) + b\int_{f_p}^{f}(F(g) - F_{thr}(g))A(g)dg$$

• dimensionless saturation threshold value of $\sqrt{\sigma_{thr}(f)} \approx 0.035$

should be used to obtain the dimensional spectral threshold $F_{thr}(f)$ at each frequency *f*

• dependence on the wind at strong wind forcing

$S_{in}(\omega) = \rho_a \omega g \gamma(\omega) E(\omega)$

swell

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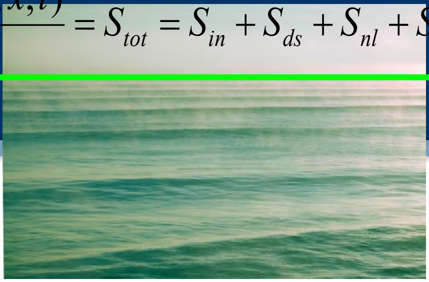
Wave-turbulence interaction

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$



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

Dissipation

- volumetric

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

- per unit of surface

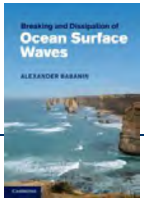
$$D_a = b_1 k \int_0^\infty u(z)^3 dz = b_1 k u_0 \int_0^\infty \exp(-3kz) dz = \frac{b_1}{3} u_0^3.$$

- per unit of propagation distance

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

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

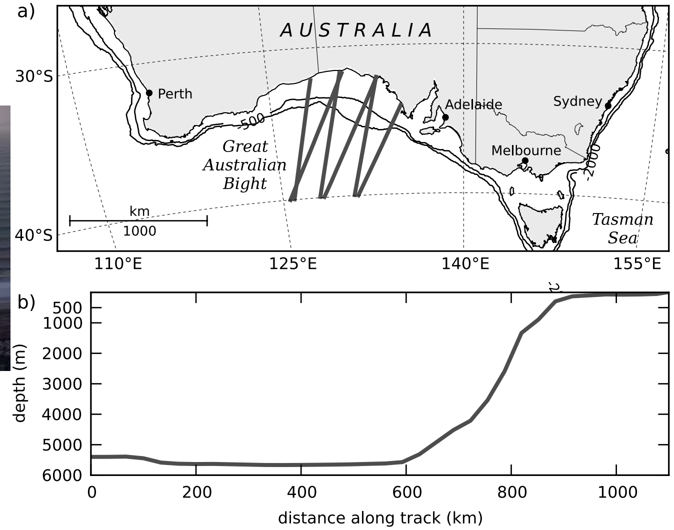
$$a_0(x)^2 = \frac{4}{B^2} x^{-2} = \frac{9}{4 \cdot b_1^2 k^4} x^{-2} = \frac{9}{64} 10^6 k^{-4} x^{-2}.$$

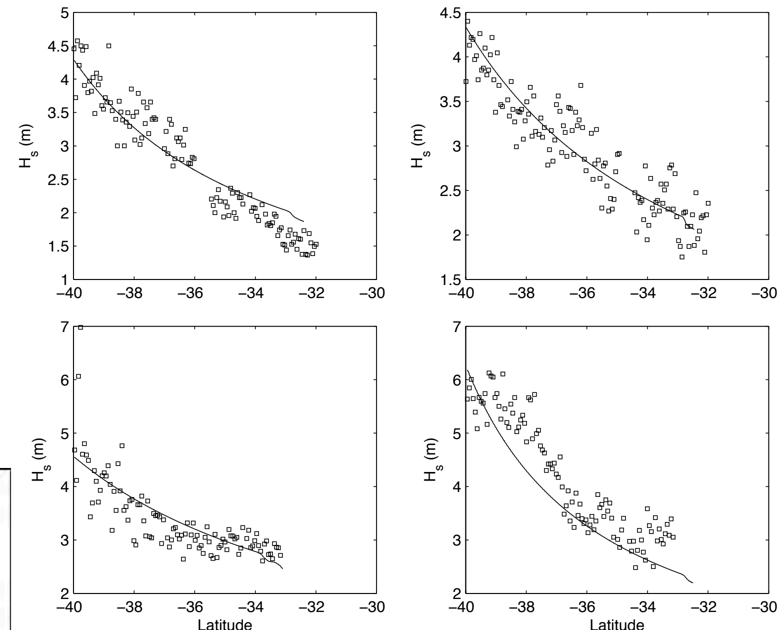


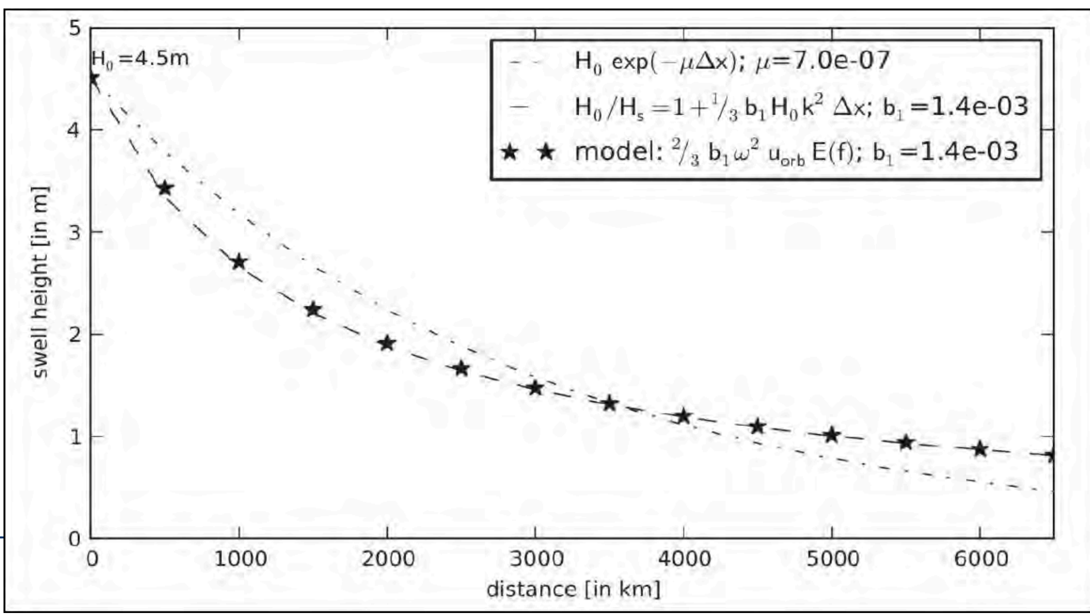
Babanin, CUP, 2011

Swell Dissipation S_{swell}

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

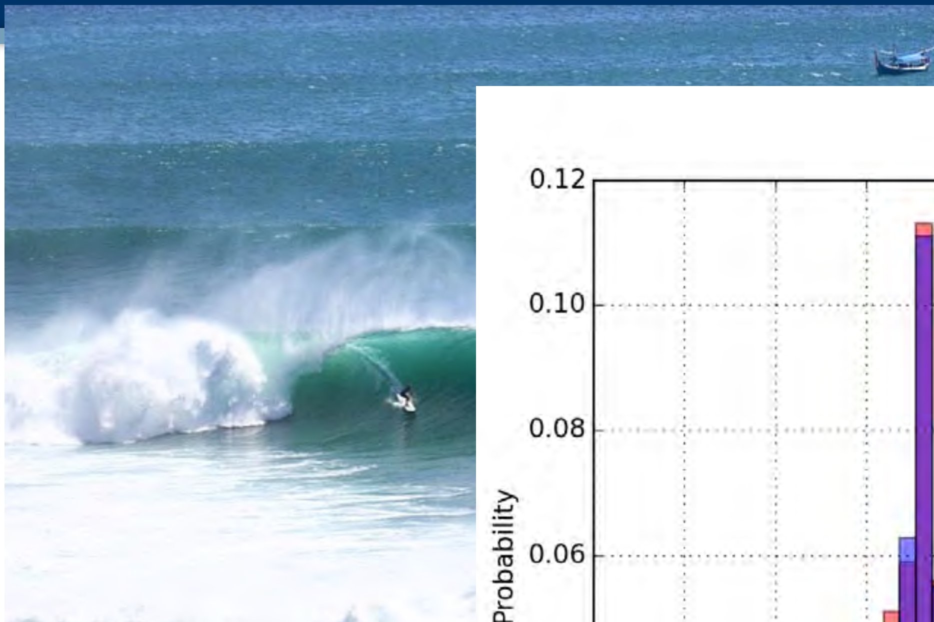


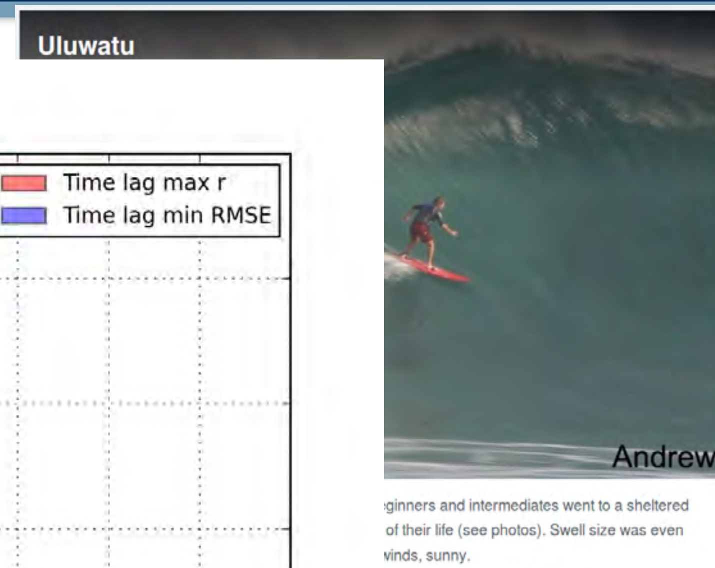


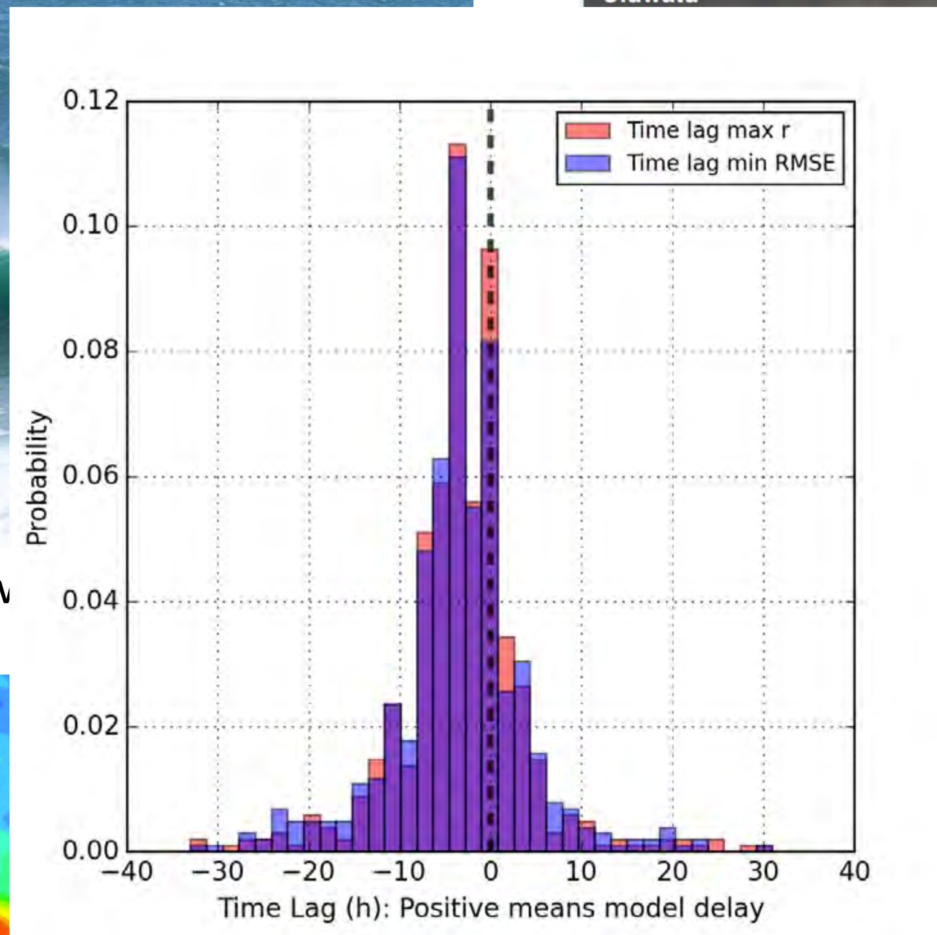


Babanin, 2011, *OMAE*, 2012
Young, Babanin, Zieger, *JPO*, 2013
Jiang, Babanin, Chen, *JPO*, 2016
Babanin & Jiang, *OMAE*, 2017

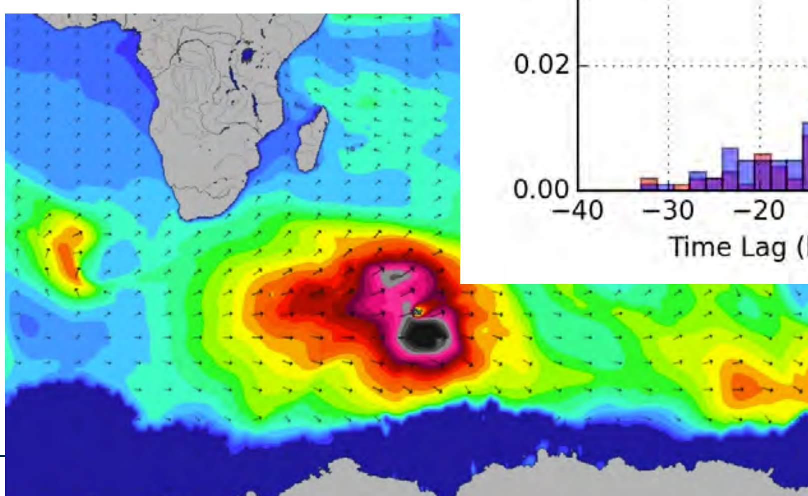
Swell arrival (anecdotal and objective evidence)

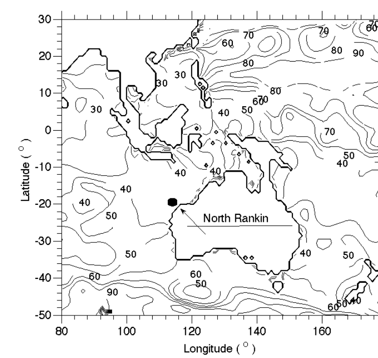






Surfers in Indonesia: sv … to the forecast





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

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The approach

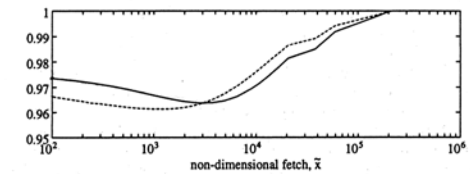
$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

- Traditional approach (ie. Komen et al. (1984)): reproduce known growth curves – i.e. model the balance of the source functions rather than the functions themselves
- Main constraint: integral wind momentum input must be equal to the total stress less viscous stress:

$$\int_0^{f_\infty} S_{in}^m(f)df = \int_0^{f_\infty} \frac{k}{\omega} S_{in}(f)df = \tau_w$$

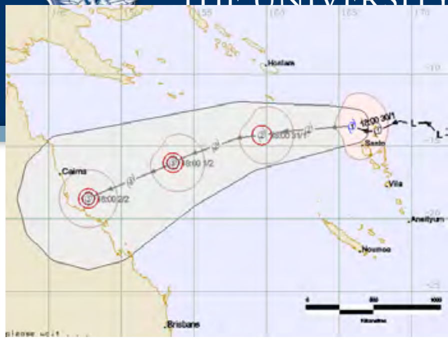
- experimental dependences for total stress and viscous stress are used
- experimental dependences for ratio ot total input and total dissipation are used

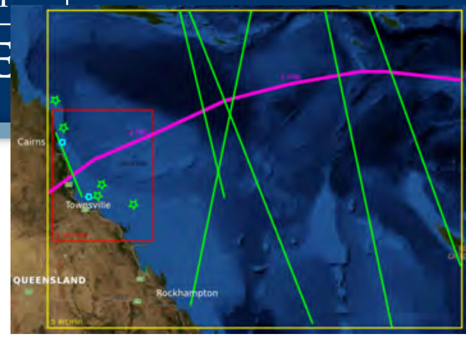
$$\int_0^{f_\infty} S_{ds}(f)df \le \int_0^{f_\infty} S_{in}(f)df$$



Babanin et al., *JPO*, 2010, Tsagareli et al., *JPO*, 2010

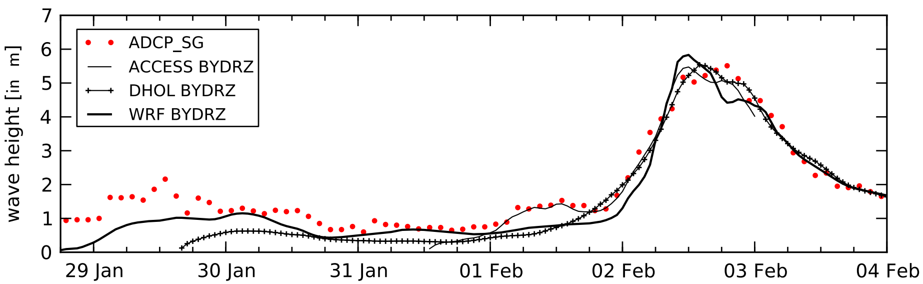
TESTING, CALIBRATION, VALIDATIONS

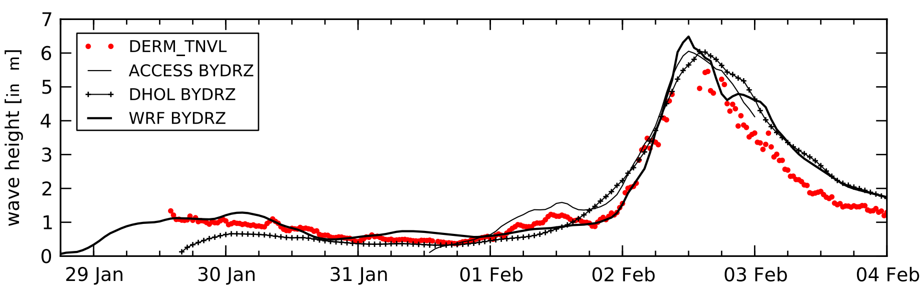


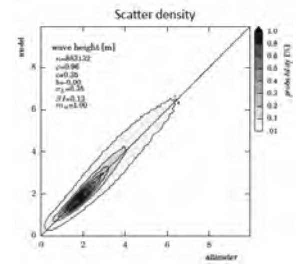


cyclone modelling, sponsored by Woodside

observed waves next to Townsville (ADCP) and Cape Cleveland (buoy) for three wind fields

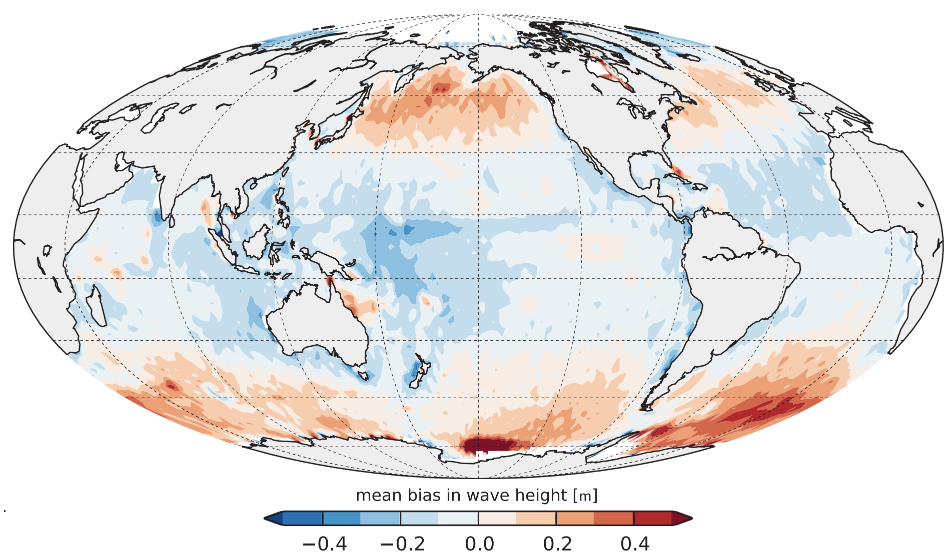






global hindcast, sponsored by ONR

WAVEWATCH-III versus altimeter 2006 (full year), wave height scatter plot (above), bias (below)

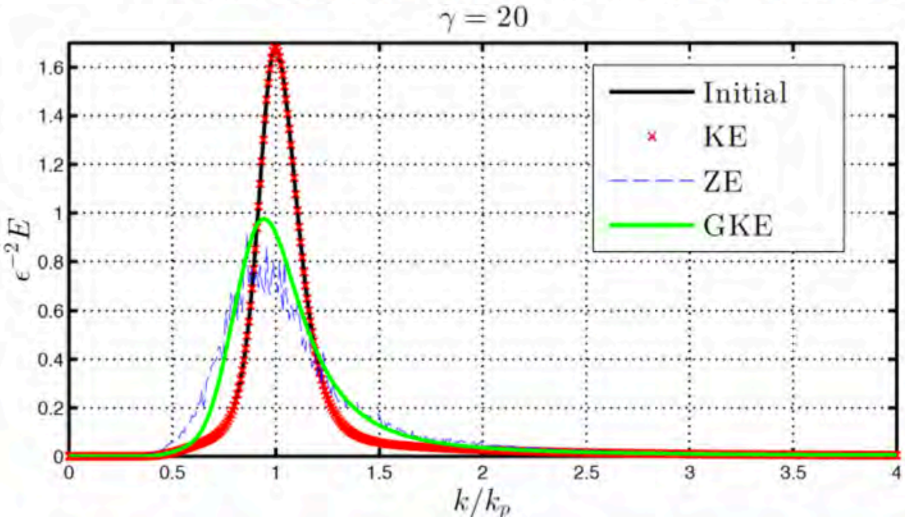


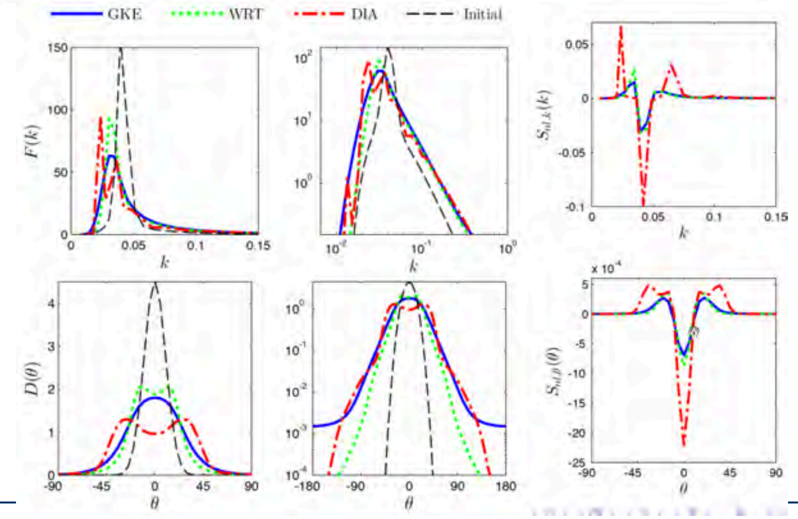
Further developments

Nonlinear Term S_{nl}

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

- The GKE (Annenkov & Shrira, 2006; Gramstad & Stiassnie, 2013) is implemented as a source term in WAVEWATCH.
- From a theoretical point of view the GKE is better (more general) than the KE. The GKE can incorporate effects of phase mixing.
- The advantage of the GKE over the KE, which is clear in 1D, is less clear for realistic 2D spectra. However, some differences are observed and should be investigated further.

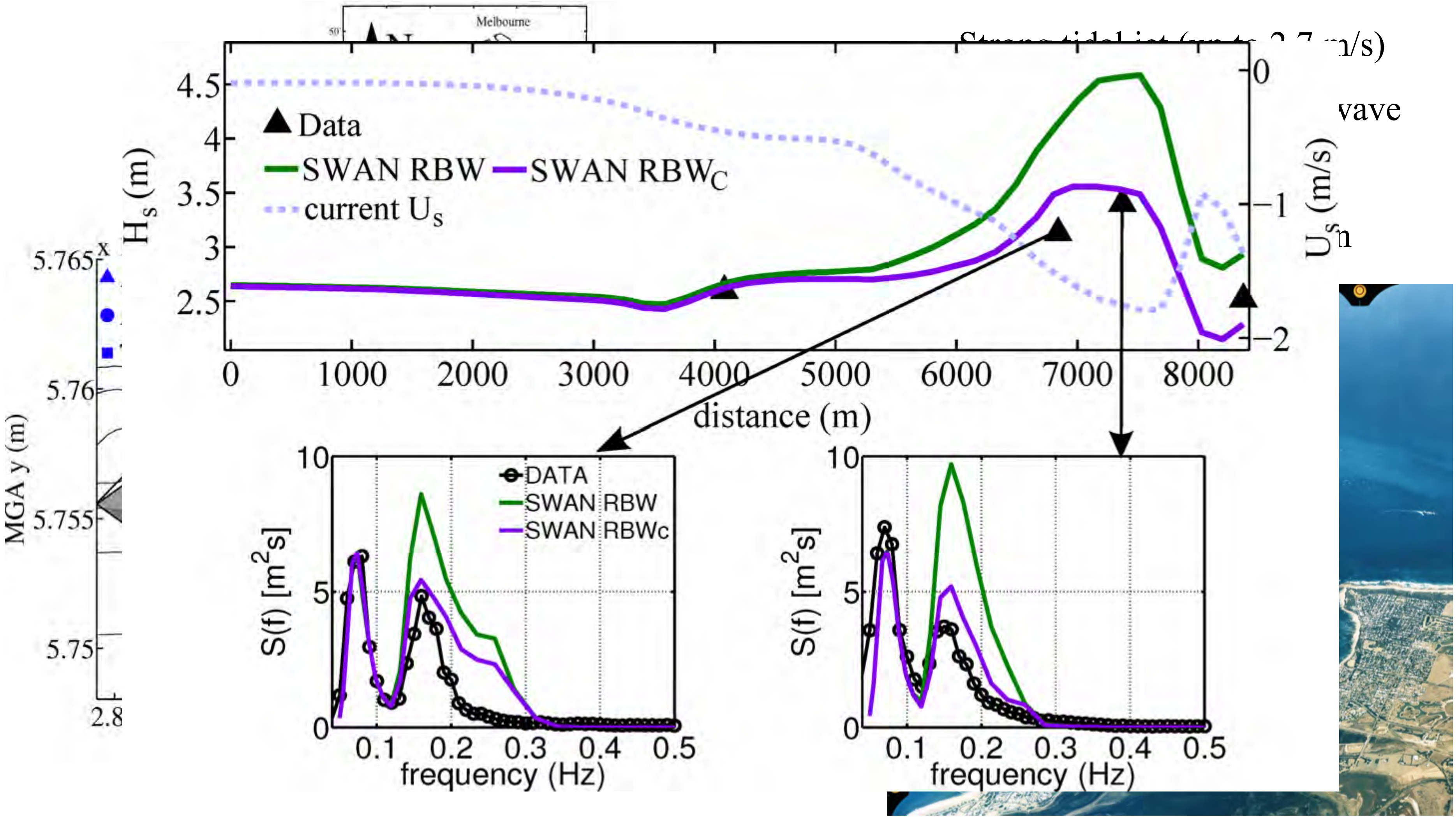




Gramstad & Babanin, *OMAE*, 2014, *O.Dyn.*, 2016

Current-induced dissipation – Port Phillip Heads

Strong wave dissipation on the tidal jet



Source: Port of Melbourne Corporation

Rapizo et al., *JGR*, 2017

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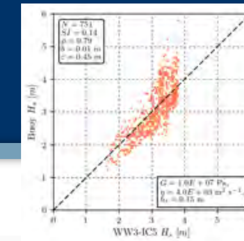
S_{ice}: ice-induced wave decay (IC5 in WW3, v6.07

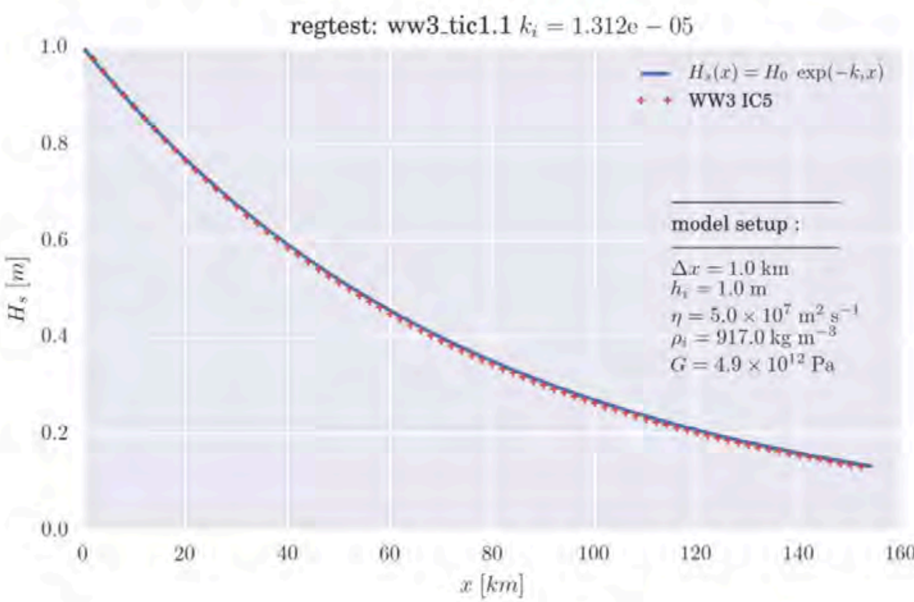


- Dispersion relation of IC5

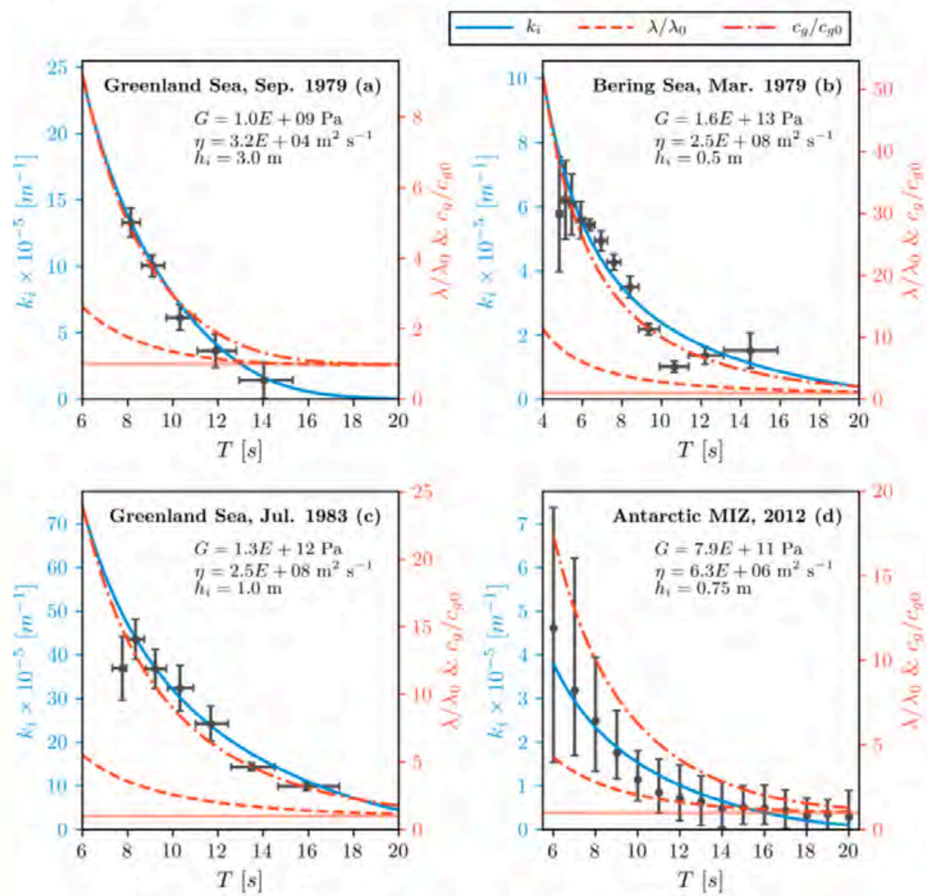
$$Qg\kappa\tanh(\kappa d) - \sigma^2 = 0,$$

$$Q = \frac{G_\eta h_i^3}{6\rho_w g}(1+\nu)\kappa^4 - \frac{\rho_i h_i \sigma^2}{\rho_w g} + 1,$$

1D Academic test of IC5 in WW3



Fit IC5 to field observations



Data from Wadhams et al. (1988) and Meylan et al. (2014)

Observation-based physics 100% made in Australia

$$\frac{dE(k,f,\theta,x,t)}{dt} = S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bf}$$

- replaced previous physics
- implemented in official releases of WAVEWATCH-III (US NOAA wave-forecast model, 2014, 2016, 2019), SWAN (European coastal engineering model, 2018), WWM (German 3rd generation model, 2019)
- new source terms: wind input, whitecapping dissipation, swell dissipation, wave-bottom interaction, interaction with adverse winds
- quantitatively: based on measurements
- qualitatively: new physical features, previously unknown
- in progress: nonlinear wave-current interactions, nonlinear wave-wave interactions, coupling with phase-resolving models, wave-ice modules, infragravity waves, directional source functions