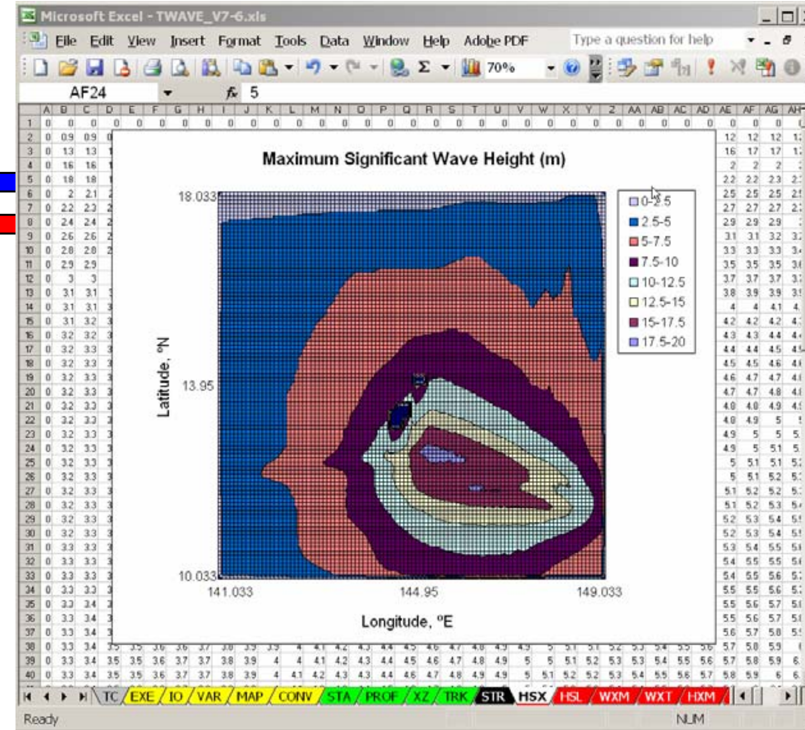
Combined Wind and Waves over a Fringing Reef

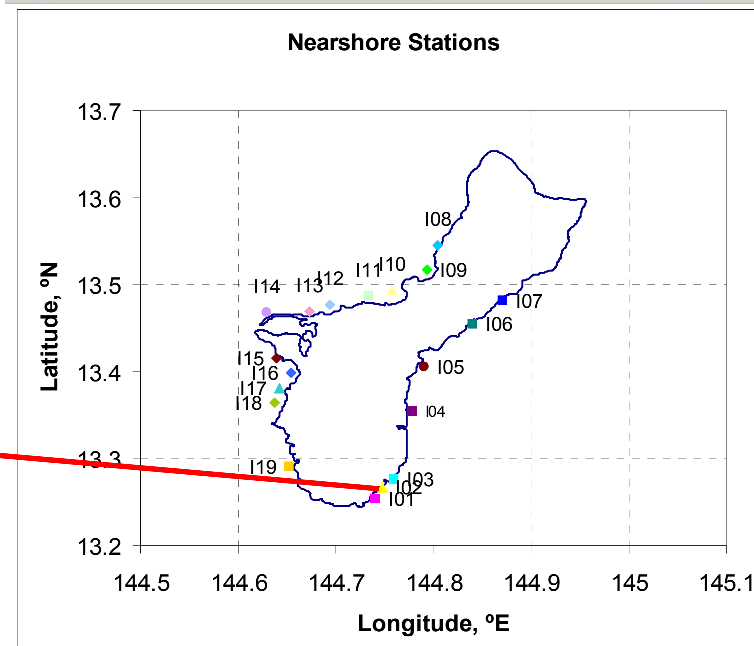
Alejandro Sánchez
Jane McKee Smith, Zeki Demirbilek, and Stan Boc
Coastal Hydraulics Laboratory
U.S. Army Corps of Engineers, Vicksburg MS

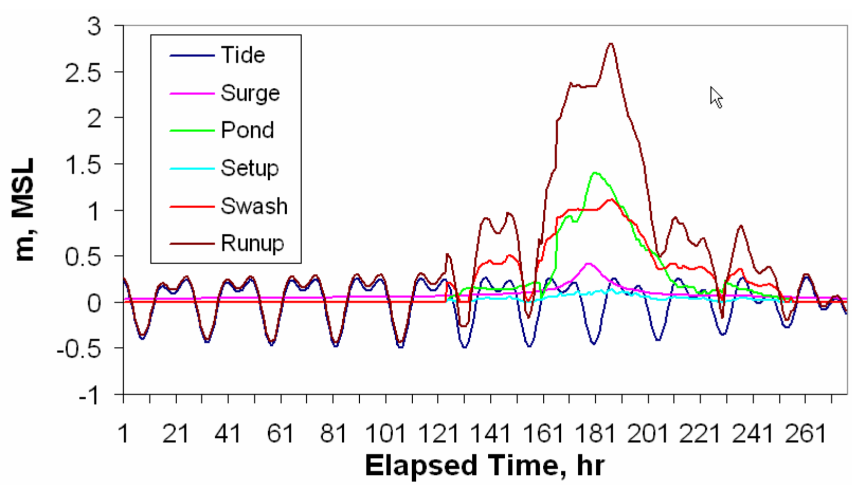
10th International Workshop on Wave Hindcasting and Forecasting & Coastal Hazard Assessment
November 16, 2007

Introduction

- Surge and Wave Island Modeling Studies (SWIMS), USACE
  - Coastal modeling package: TWAVE
- Targeted for U.S. Civil Defense agencies and district offices
- PC-based, user-friendly, comprehensive package
- Multi-level: Quick answers with large uncertainty, and slow answers with small uncertainty







Objective

- To test the applicability of various models to simulate wave transformation and setup over fringing coral reefs

Summary and Conclusion

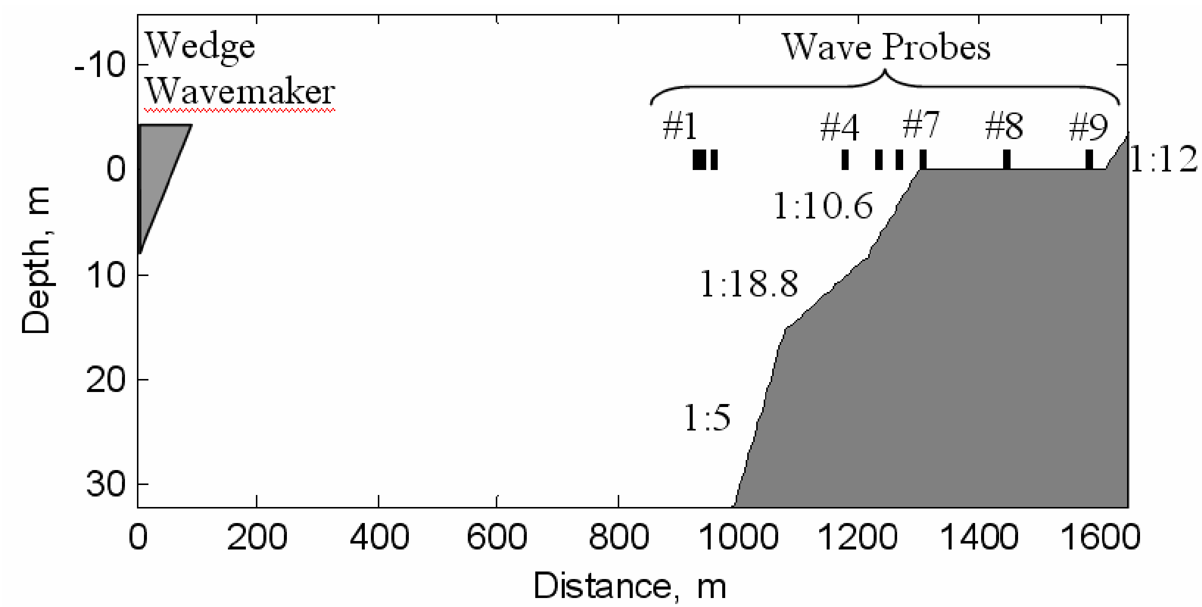
- Setup generated by strong winds is a significant contribution to water levels over fringing coral reefs
- Wind also causes increased wave breaking intensity causing the waves to break further offshore and reducing the setup
- STWAVE and ADCIRC are agreed relatively well with laboratory measurements of wave heights and water levels over a fringing reef
- 1-D wave energy balance models are robust, fast and are suitable for engineering applications, feasibility studies, etc.

Outline

- Laboratory Datasets
- Numerical Models
- Results
  - Waves only
  - Wind and waves
- Discussion
- Summary and Conclusion
- Future Work

Laboratory Dataset

- University of Michigan Laboratory Study
  - 83 Tests
  - 1:64 scale Guam-type reef
  - Wind and irregular waves
  - Gauges 1-6 on reef slope and gauges 7-9 on reef top



STWAVE and ADCIRC (STAD)

- STeady-state spectral WAVE model
  - Solves the wave action balance equation by finite-differences on a cartesian grid
  - **Wave breaking** modified to use **Battjes and Janssen (1978)**

$$D_b = \frac{1}{4}\rho g B \bar{f} H_b^2 Q_b \qquad H_{rms}^2 \ln Q_b = H_b^2 (1 - Q_b) \qquad H_b = 0.88 \tanh(kd)/k$$

  - 5-m grid resolution
  - No bottom friction
  - No wind generation (1-km fetch, simplicity)
- ADvanced CIRCulation model
  - Finite-element, nonlinear, depth-averaged flow model
  - 10- to 30-m grid resolution
- Coupling
  - Wave radiation stress gradients from STWAVE to ADCIRC
  - Water levels from ADCIRC to STWAVE
  - No wave-current interaction
  - At least 3 simulations of STWAVE and 2 of ADCIRC

One-dimensional Models

- Wave energy balance equation

$$\frac{\partial}{\partial x}(EC_g \cos\theta) + D_b + D_f = 0$$

  – Wave Breaking

    - Dally et al. 1985 (DDD85)

$$D_b = \frac{\kappa}{d}\left[EC_g - \min(E, E_s)C_g\right],$$

$$E_s = \frac{1}{8}\rho g(\Gamma d)^2$$

    - Janssen and Battjes 2007 (ABJB07)

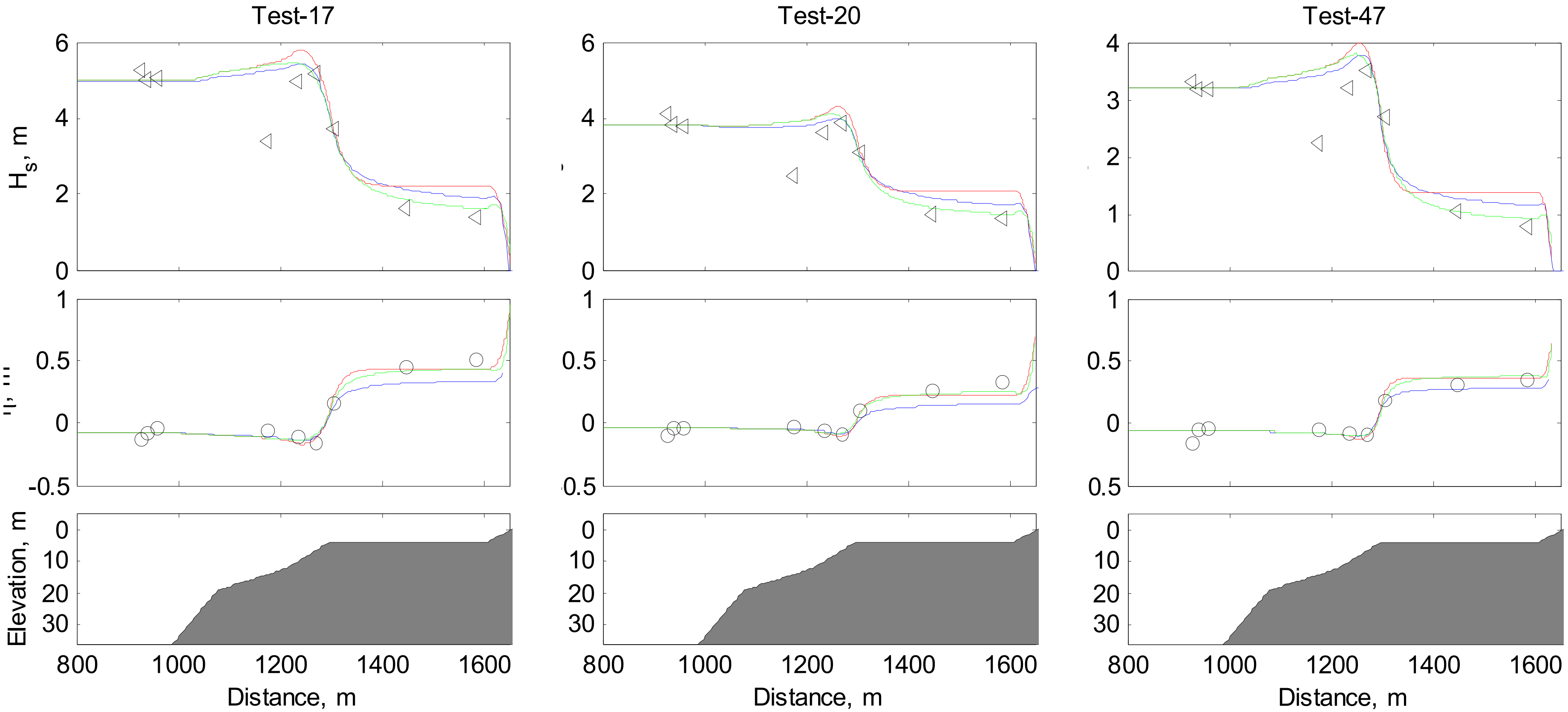
$$D_b = \frac{3\sqrt{\pi}}{16}\rho g B \bar{f} \frac{H_{rms}^3}{d} Q_b,$$

$$Q_b = 1 + \frac{4}{3\sqrt{\pi}}\left(R^3 + \frac{3}{2}R\right)\exp\left(-R^2\right) - \mathrm{erf}(R), \qquad R = H_b / H_{rms}$$

- Momentum balance

$$\rho g(h+\eta)\frac{\partial \eta}{\partial x} + \frac{\partial S_{xx}}{\partial x} = \tau_{wx},$$

UM Dataset, Waves Only



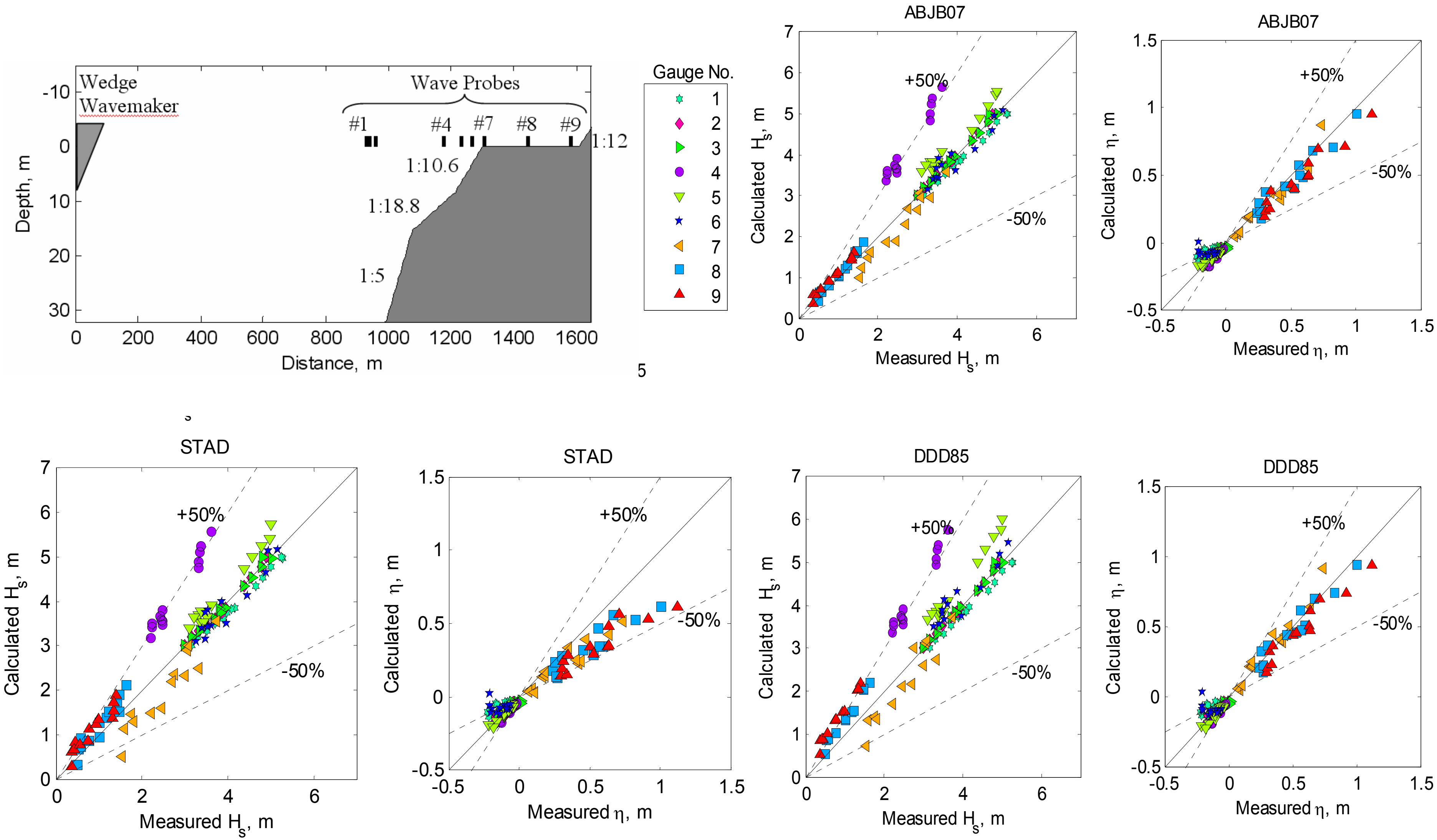
$H_o = 4.99$ m $T_p = 12.0$ sec
$h_r = 3.26$ m $U = 0.5$ m/sec

$H_o = 3.84$ m $T_p = 10.0$ sec
$h_r = 3.26$ m $U = 0.4$ m/sec

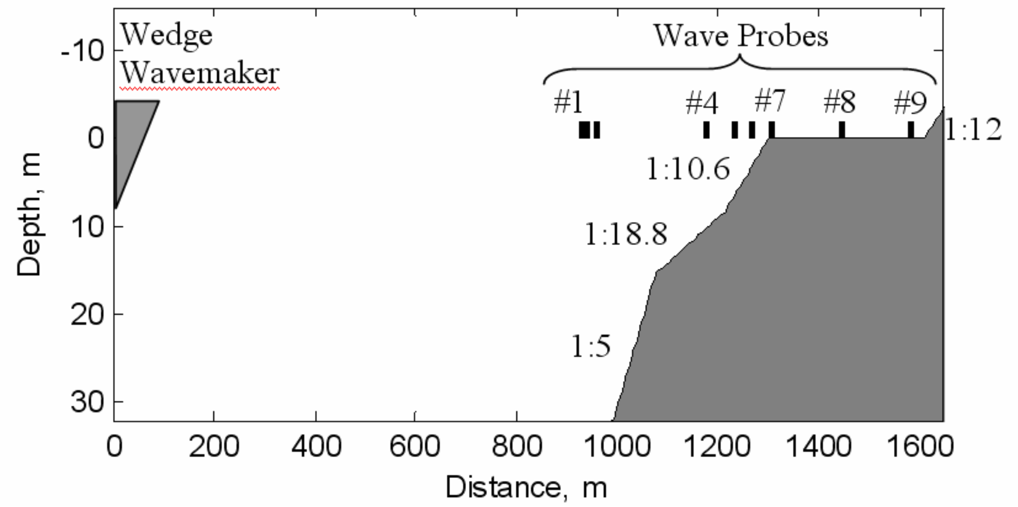
$H_o = 3.20$ m $T_p = 12.0$ sec
$h_r = 1.92$ m $U = 0.7$ m/sec

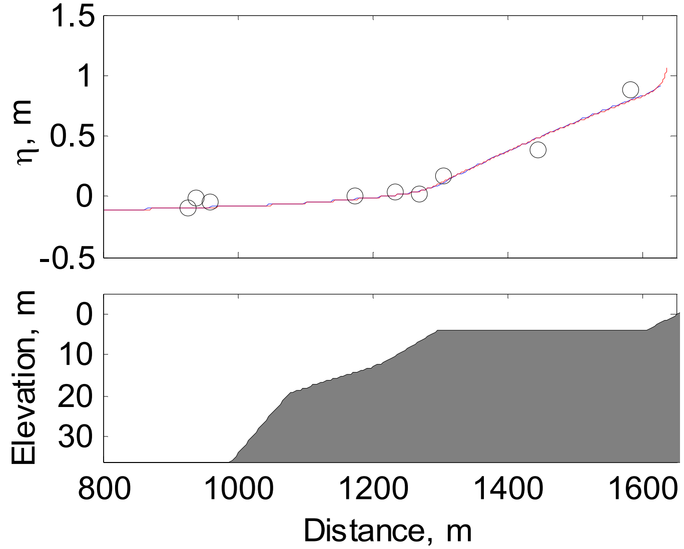
— ABJB07, — DDD85, — STAD

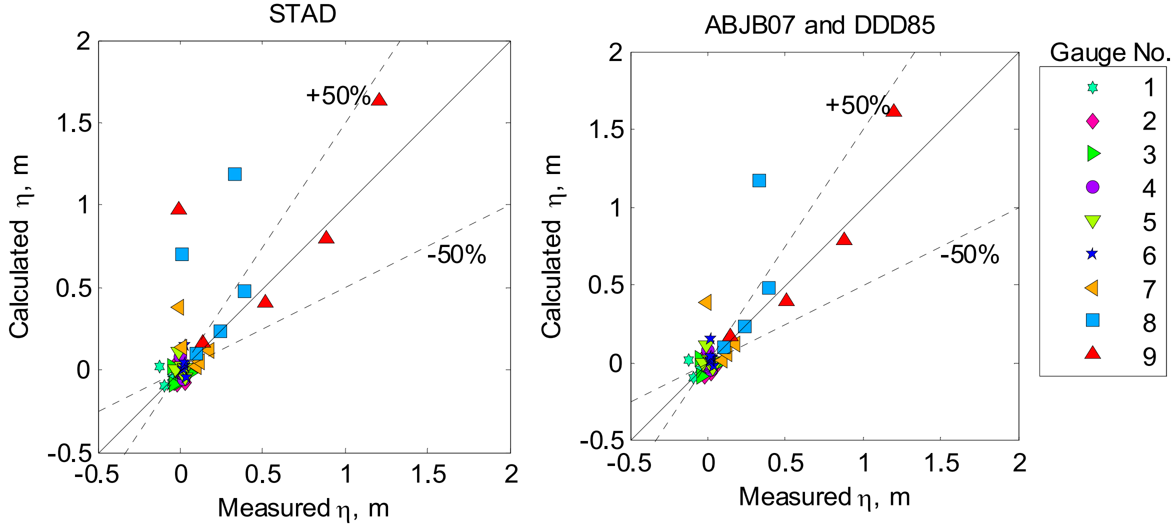
UM Dataset, Waves Only



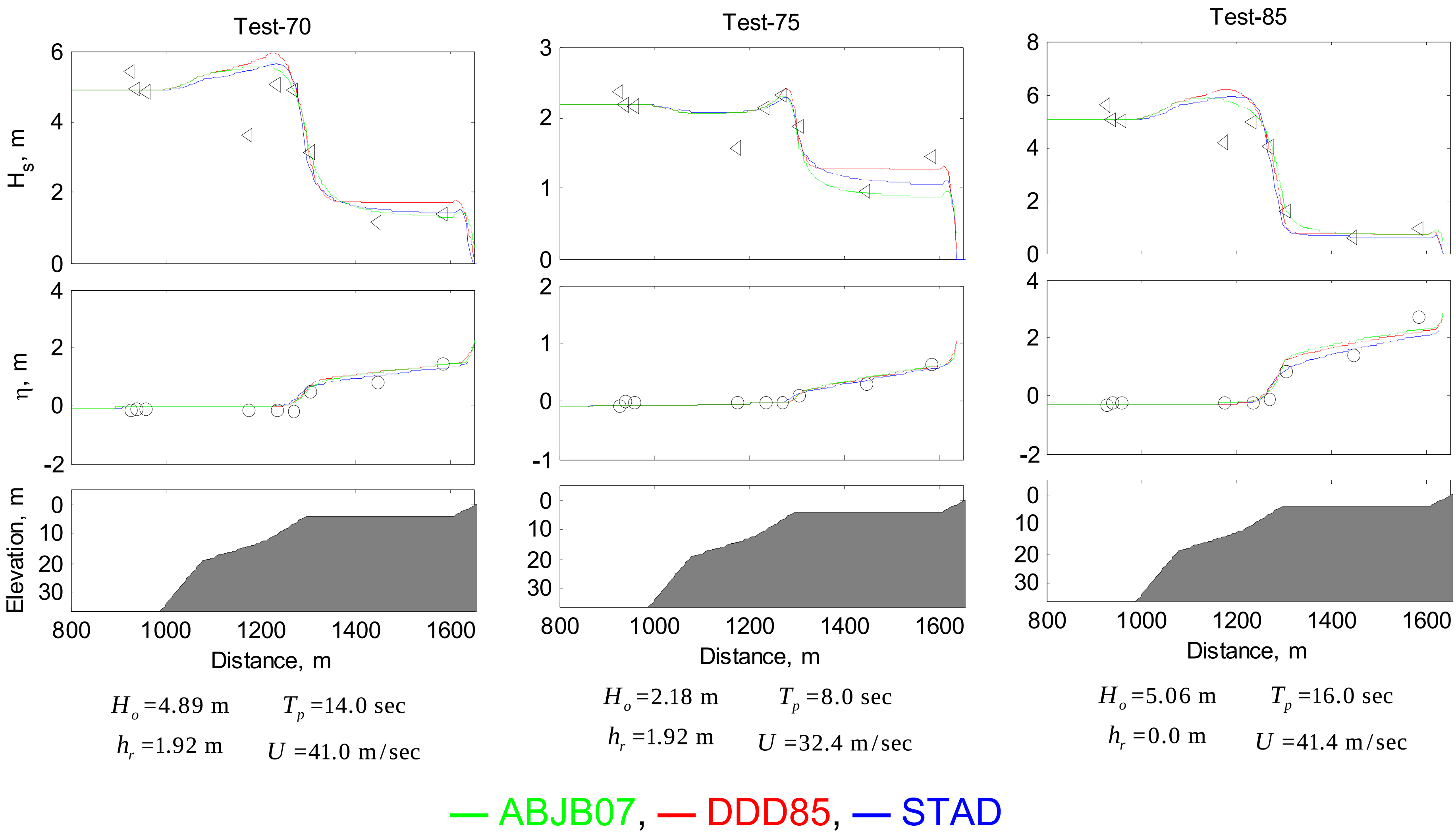
UM Dataset, Wind Only



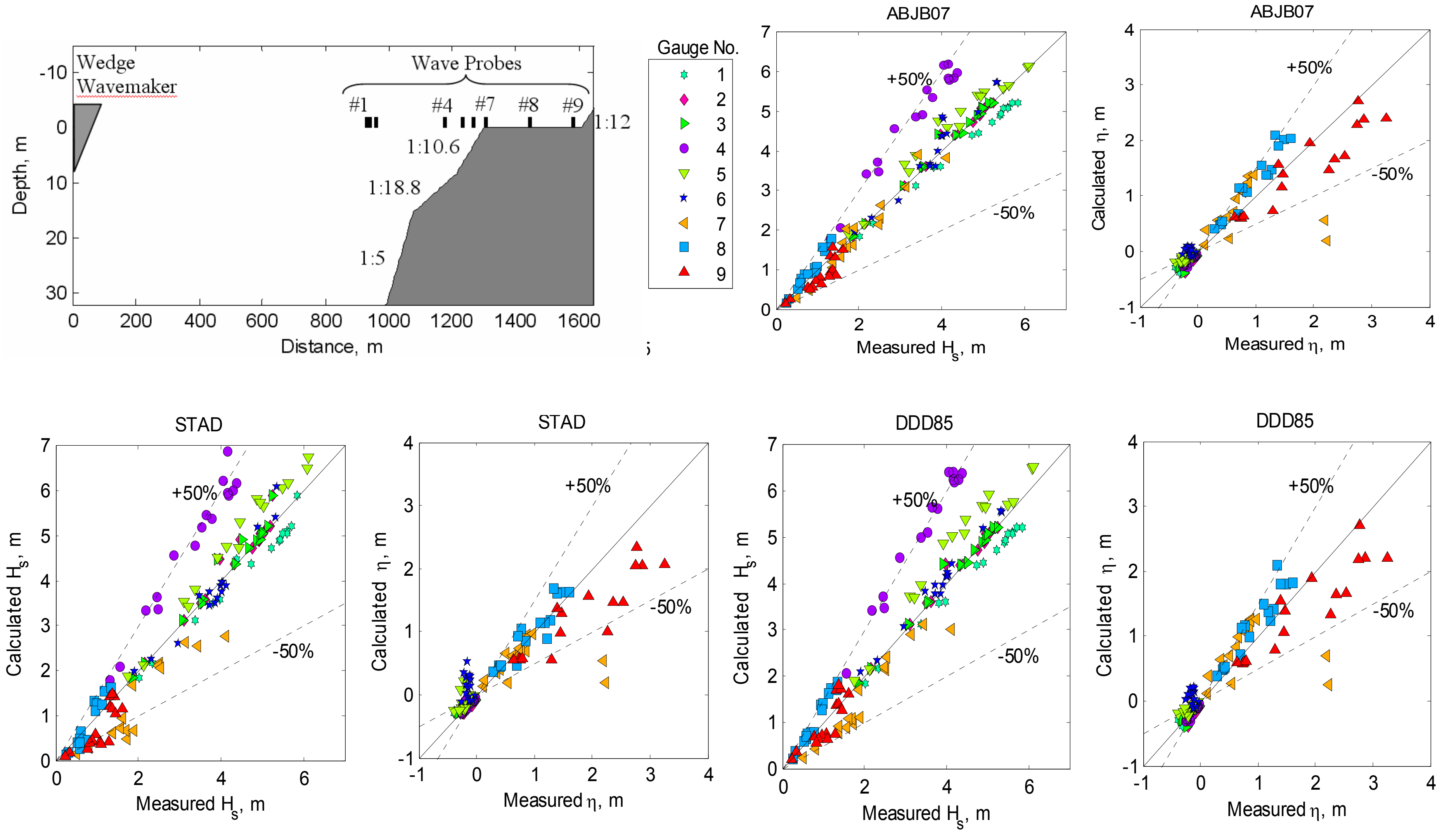




UM Dataset, Wind and Waves

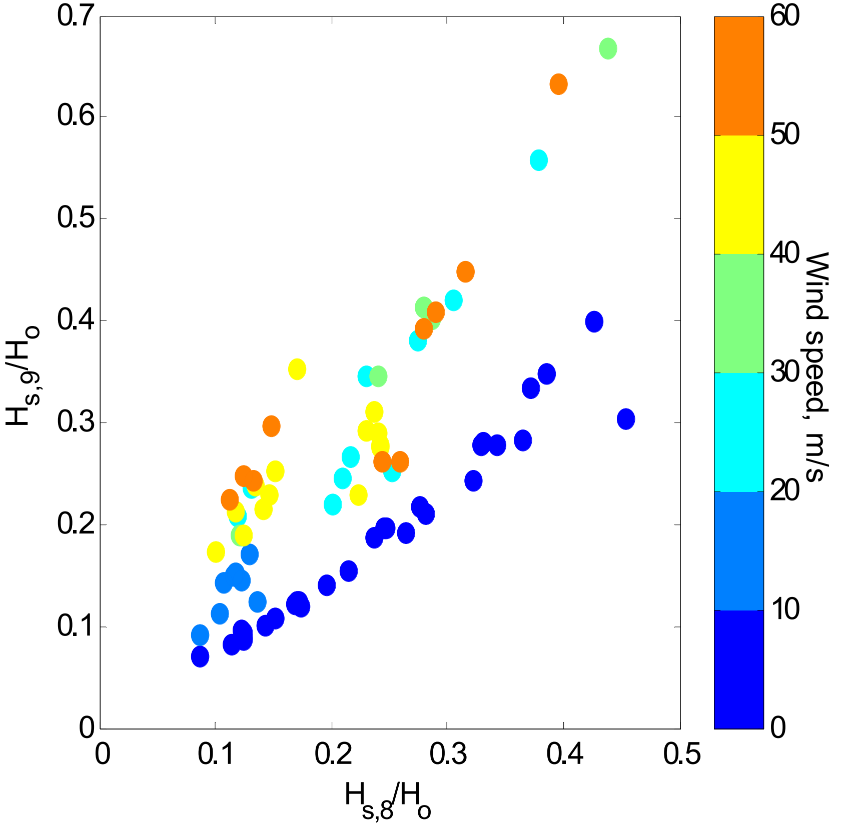


UM Dataset, Wind and Waves



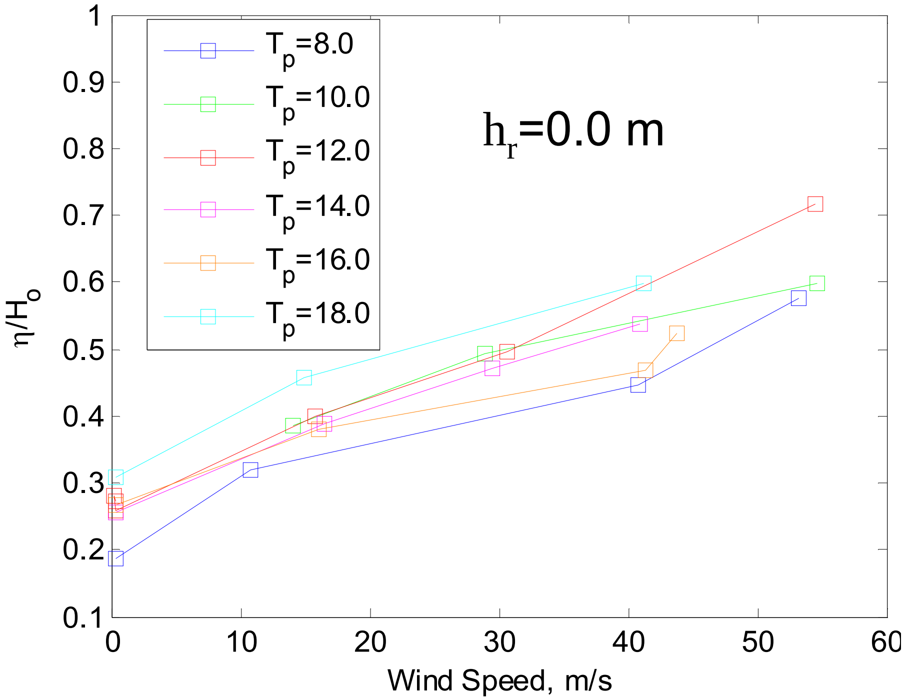
Wave Height Over Reef-top

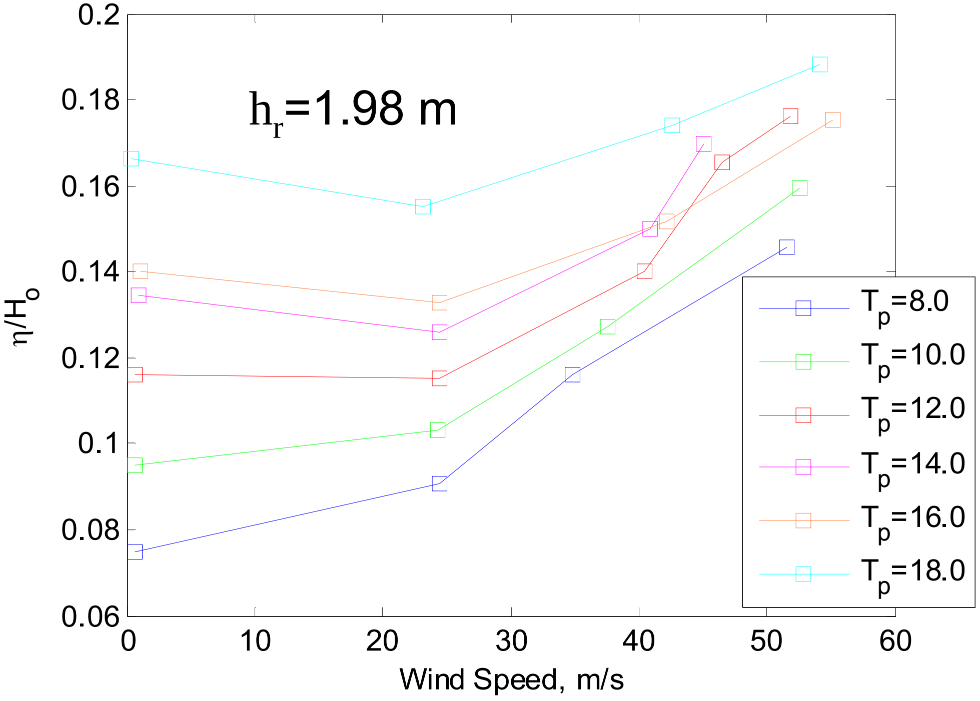
- Wave height increase not related to wind speed?



Wind setup

- Wind setup important for strong winds or shallow depths



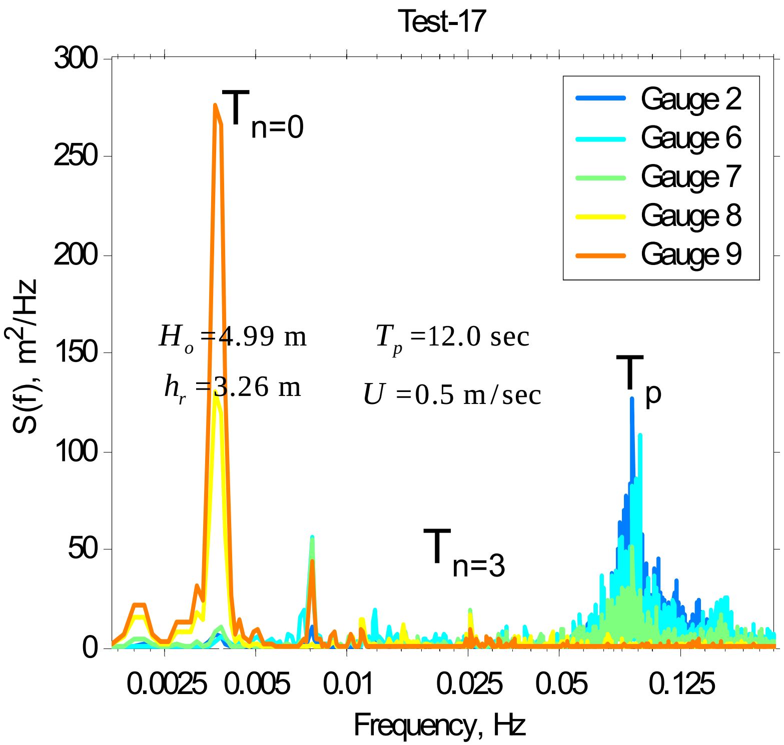


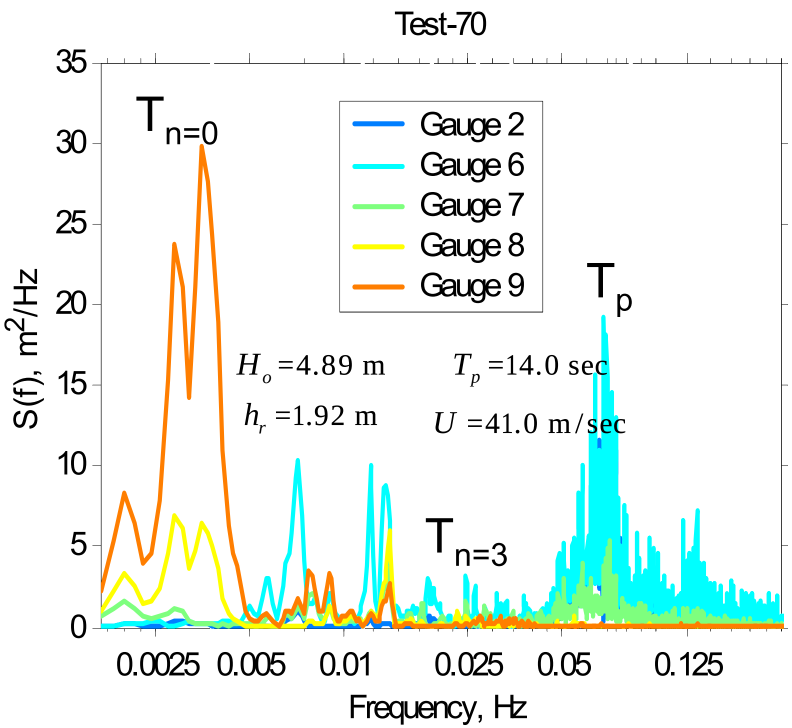
Spectral Wave Transformation

- Natural periods of oscillation for an open basin

$$T_n = \frac{4l_r}{(1+2n)\sqrt{gd_r}}$$

- Infragravity wave energy >> gravity wave energy
- First and forth modes



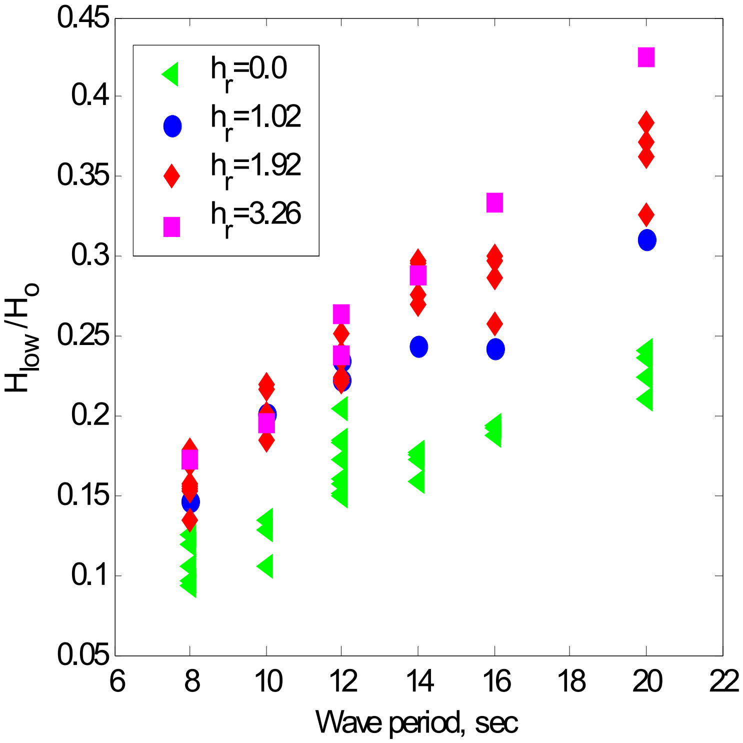


Infragravity Wave Energy

$$H_{low} = 4\sqrt{m_o}$$

$$m_o = \int_0^{f_c} S(f)df \quad \text{where} \quad f_c = 0.02\,\text{Hz}$$

- Infragravity energy
  - < 0.02 Hz
  - Increases with increasing incident wave period
  - Increases with water depth

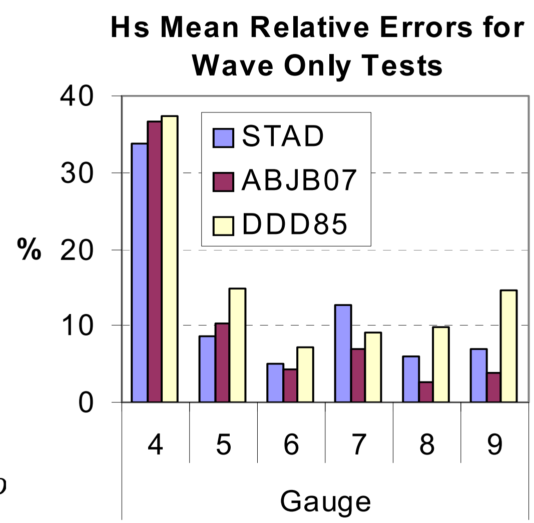


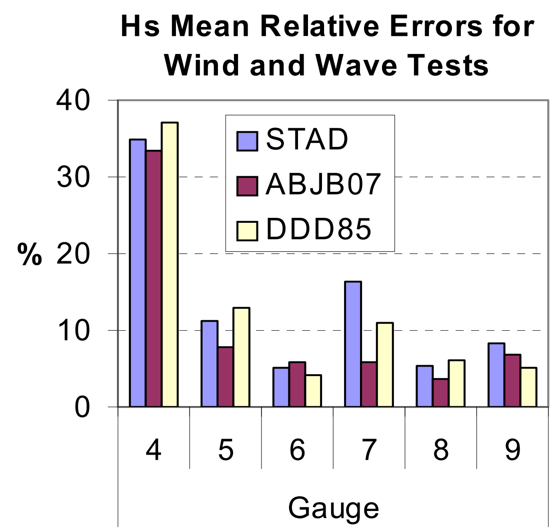
Wave Height Error Analysis

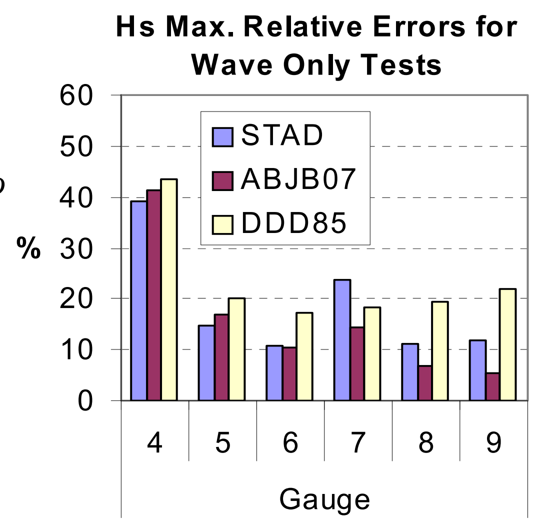
- Relative error (%)

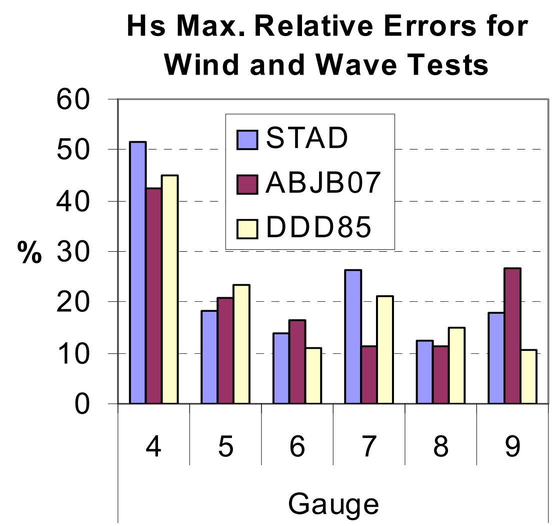
$$\varepsilon = \frac{100}{NH_o}\sum_{i=1}^{N}\left|H_{s,\mathrm{meas}}^{\,i} - H_{s,\mathrm{comp}}^{\,i}\right|$$

- Waves only
  - Average errors <0.15H_o
  - Max errors <0.25H_o
- Waves and Wind
  - Average errors <0.15H_o
  - Max errors <0.25H_o
- ABJB07 – Best results







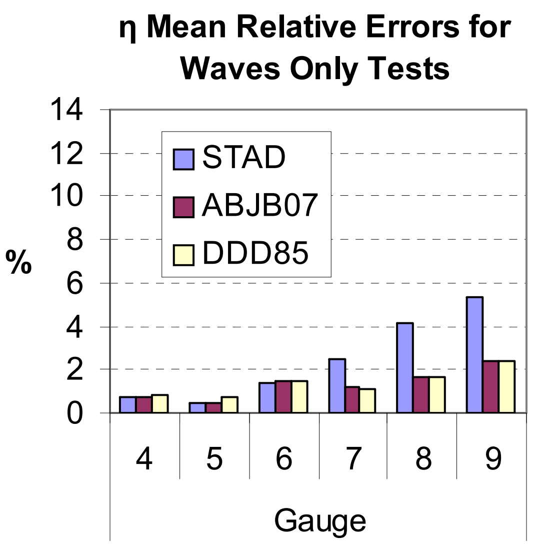


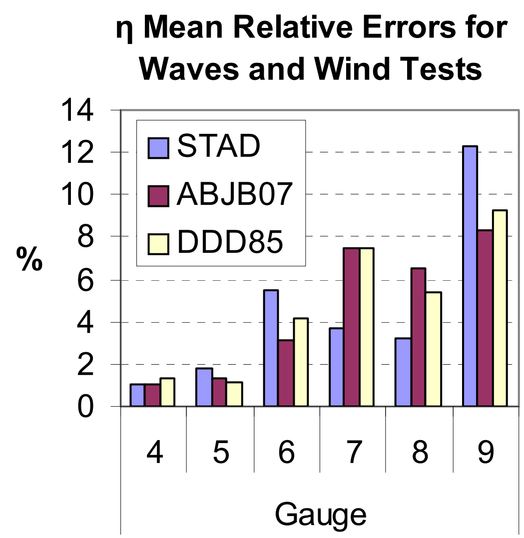
Setup Error Analysis

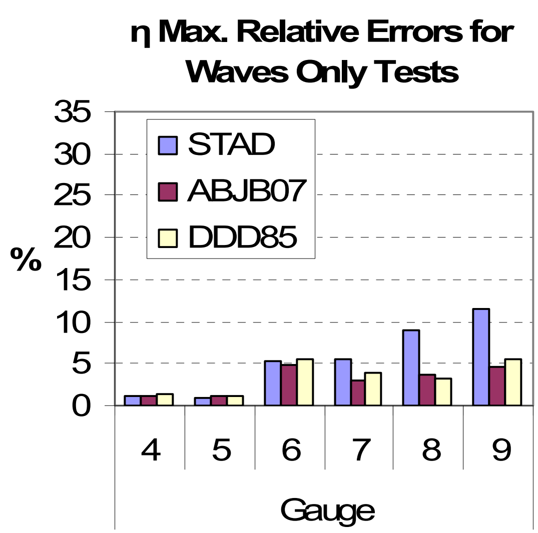
- Relative error (%)

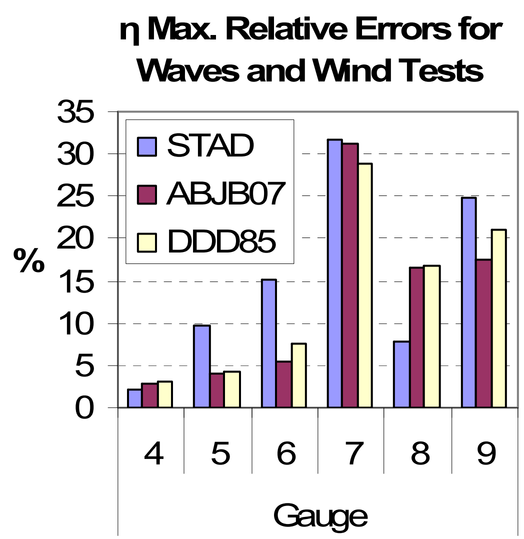
$$\varepsilon = \frac{100}{NH_o}\sum_{i=1}^{N}\left|\eta^i_{meas} - \eta^i_{comp}\right|$$

- Waves only
  - Average errors $<0.05H_o$
  - Max errors $<0.12H_o$
- Waves and Wind
  - Average errors $<0.15H_o$
  - Max errors $<0.35H_o$
- Excellent results for cases with no wind
- Ok results with wind
- ABJB07 – Best results







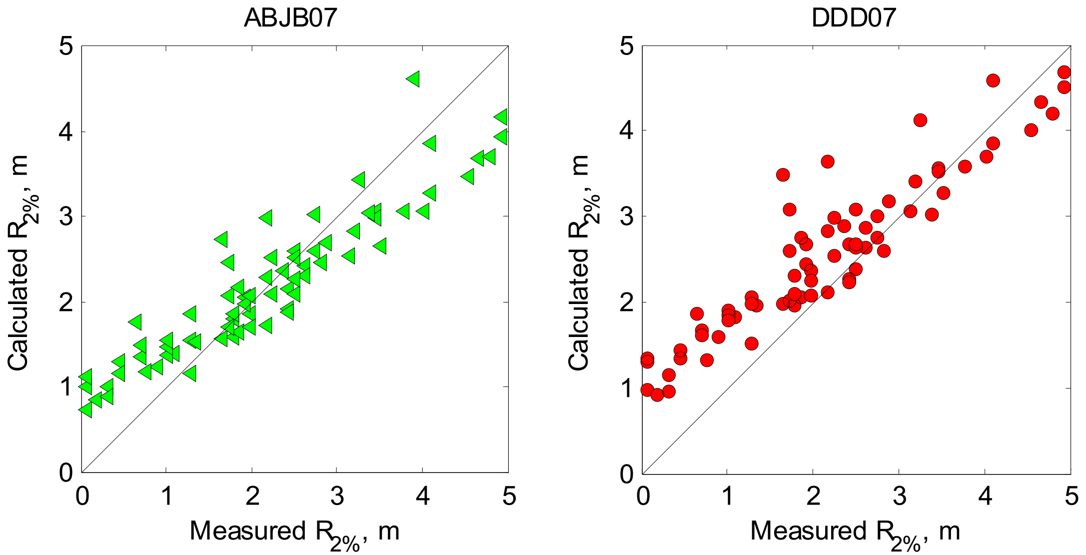


Runup, UM Dataset

- $R_{2\%}$ = Runup exceeded 2% of the time
- Runup with respect to still-water level
- Slope 1:12
- Mase (1989)

$$R_{2\%} = 1.86\xi^{0.71}$$

$$\xi = \tan\theta / \sqrt{H_r / L_o}$$



Discussion

- Although the 1-D models performed slightly better than the STWAVE/ADCIRC, their applicability is limited, and STWAVE and ADCIRC have a lot more physics such as wave-current interaction, wave growth terms, 2-D effects etc.
- Empirical coefficients likely difference than for sandy beaches and need to be estimated based on breaker types, wind, roughness etc.
- More work needed on the sensitivity of ADCIRC to grid resolution
- Despite the presence of long period infragravity motions, the models are able to predict reasonably well wave heights and average water levels

Summary and Conclusion

- Setup generated by strong winds is a significant contribution to water levels over fringing coral reefs
- Wind also causes increased wave breaking intensity causing the waves to break further offshore and reducing the setup
- STWAVE and ADCIRC are agreed relatively well with laboratory measurements of wave heights and water levels over a fringing reef
- 1-D wave energy balance models are robust, fast and are suitable for engineering applications, feasibility studies, etc.

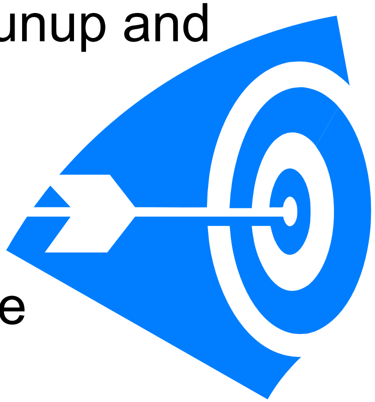
Future Work

- Include the formulation for wave breaking dissipation of Janssen and Battjes (2007) in STWAVE
- Incorporate a formulation for wave setup in STWAVE which would decreases the number of iterations between STWAVE and ADCIRC
- Develop and incorporate an empirical formulation for wave runup in STWAVE

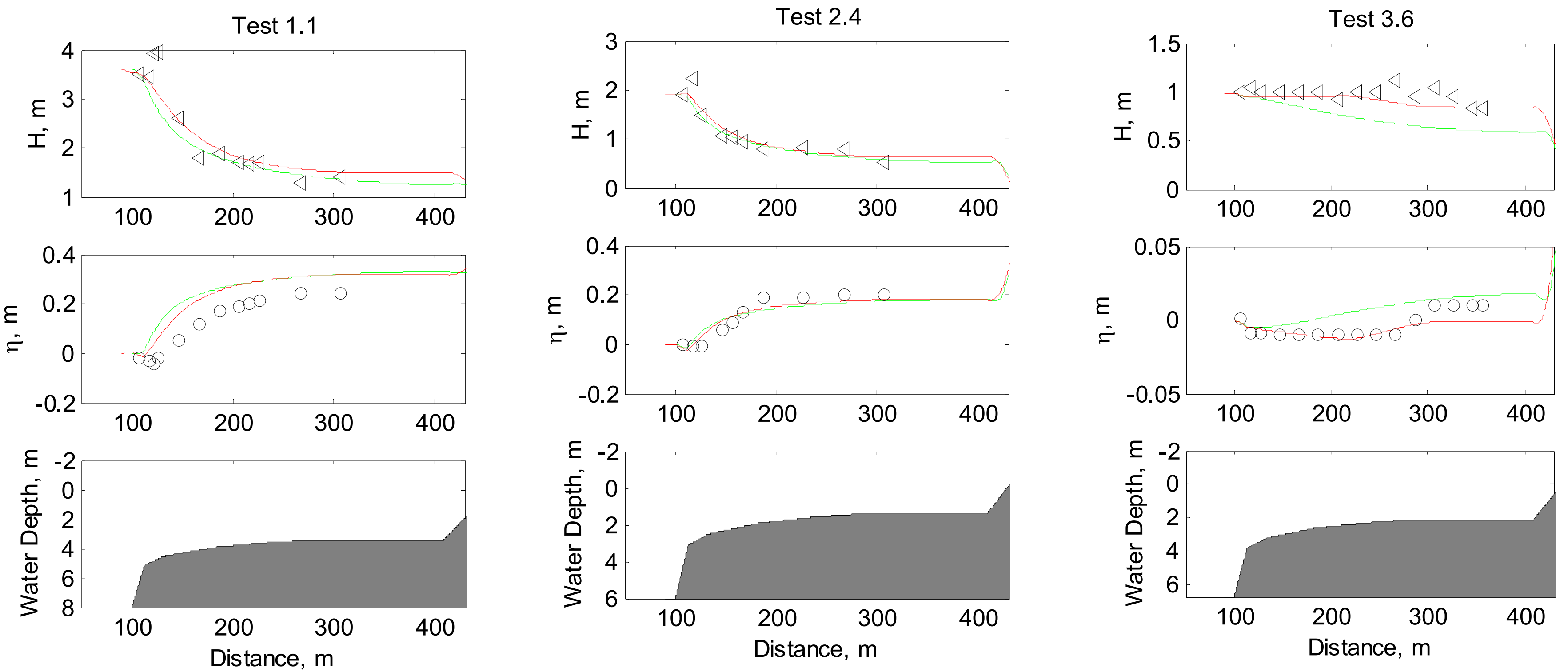
Thank you.
Questions?

Motivation

- Forecast
  - 36-hr forecast at 6-hr intervals – interpolated to 1-hr intervals
  - Unfeasible to simulate whole time history using complex nonlinear models such as Boussinesq-type models
  - Need to identify worst case conditions for potential runup and inundation for nonlinear models
  - Backup model
- Hindcast
  - Not enough data on hurricane events to merit the use nonlinear models
- Hypothetical events
  - Only need to be realistic
- Engineering Applications
  - Sometimes you just don’t need so much accuracy



Hayman Island Dataset

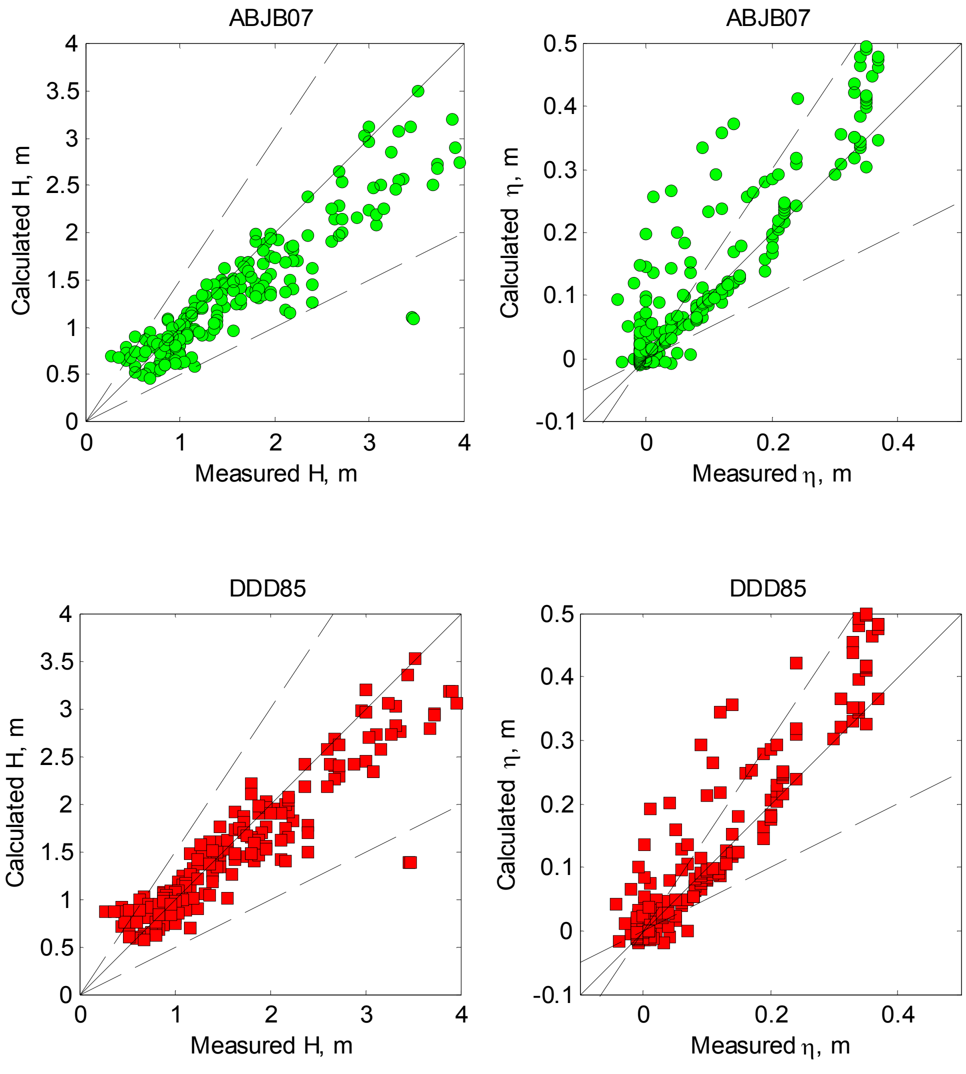


H_i =3.44 m T =6.8 sec h_r =3.4 m

H_i =1.90 m T =5.4 sec h_r =1.4 m

H_i =0.99 m T =3.8 sec h_r =2.1 m

Hayman Island Dataset



Setup: Review of Empirical Relations

- Seelig (1983)

$$\Delta\eta = \begin{cases} -0.92 + 0.77\log_{10}\left(H_o^2 T\right) & \text{for } h_r = 0 \text{ m} \\ -1.25 + 0.73\log_{10}\left(H_o^2 T\right) & \text{for } h_r = 2 \text{ m} \end{cases}$$

- Gourlay (1996)

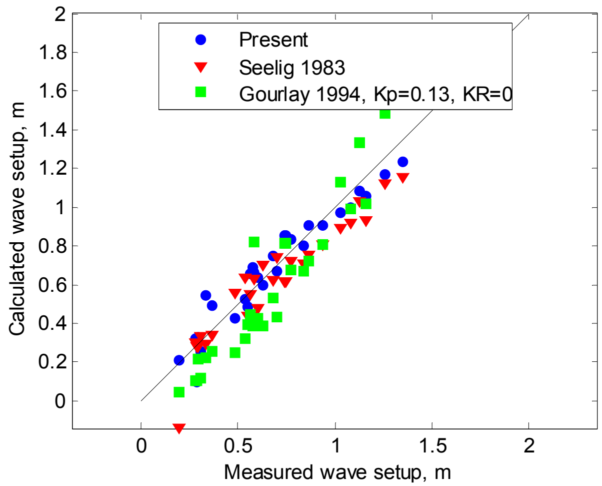
$$\Delta\eta_r = \frac{3}{64\pi} K_p \frac{g^{1/2} H_o^2 T}{\left(h_r + \eta_r\right)^{3/2}} \left[1 - K_R^2 - 4\pi K_r^2 \frac{1}{T}\sqrt{\frac{h_r + \eta_r}{g}}\right]$$

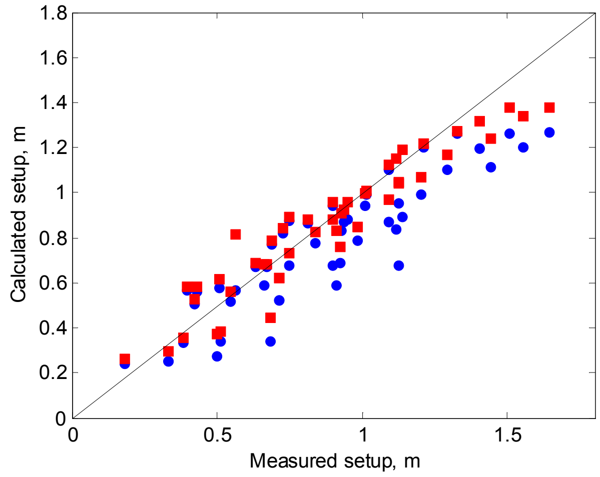
- Proposed

$$\Delta\eta_{total} = \Delta\eta_{wave} + \Delta\eta_{wind}$$

$$\Delta\eta_{wave} = -0.18h_r + 0.48\log_{10}\left(H_o^2 T\right) - 5.53H_o / T^2$$

$$\Delta\eta_{wind} = \frac{WC_d U^2}{10^5 (h_r + \Delta\eta_{wave})}$$

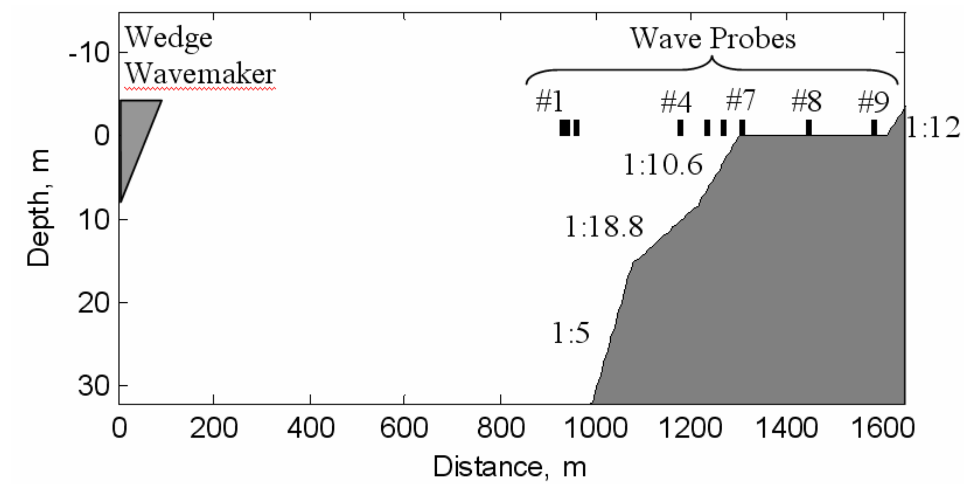


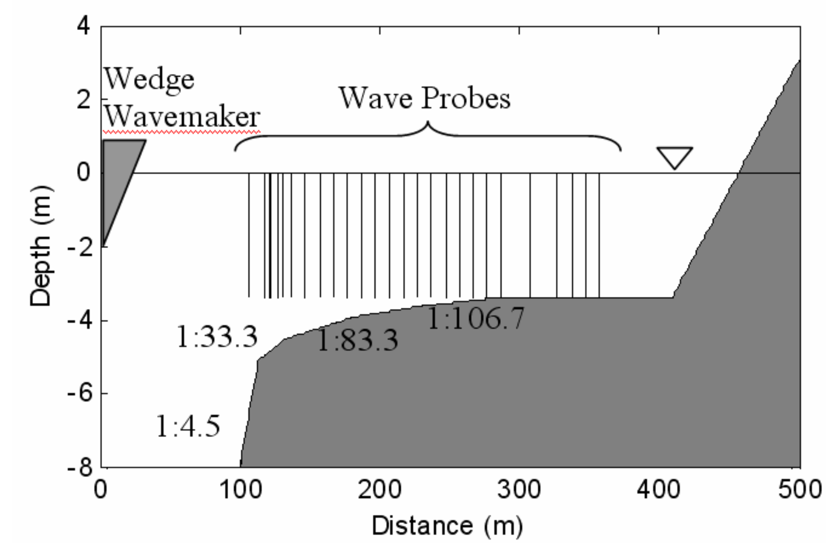


● Only wave setup, ▪ Wind and Wave setup

Laboratory Dataset

- University of Michigan Laboratory Study
  - 83 Tests
  - 1:64 scale Guam-type reef
  - Irregular waves
  - Wind and waves
- Hayman Island Fringing Reef Study (Gourlay, 1994, Coast. Eng. Vol. 23)
  - 18 Tests
  - 1:20 scale, Australian reef
  - Regular Waves
  - No wind





One-dimensional Models

- Wave energy balance equation

$$\frac{\partial}{\partial x}(EC_g \cos\theta) + D_b + D_f = 0 \qquad E = \frac{1}{8}\rho g H_{rms}^2 \qquad C_g = nC \qquad n = \frac{1}{2} + \frac{kd}{\sinh 2kd}$$

  - Wave Breaking
    - Dally et al. 1985 (DDD85)

$$D_b = \frac{\kappa}{d}\left[EC_g - \min(E, E_s)C_g\right],$$

$$E_s = \frac{1}{8}\rho g(\Gamma d)^2$$

    - Janssen and Battjes 2007 (ABJB07)

$$D_b = \frac{3\sqrt{\pi}}{16}\rho g B \bar{f}\frac{H_{rms}^3}{d}Q_b,$$

$$Q_b = 1 + \frac{4}{3\sqrt{\pi}}\left(R^3 + \frac{3}{2}R\right)\exp\left(-R^2\right) - \operatorname{erf}(R), \qquad R = H_b / H_{rms}$$

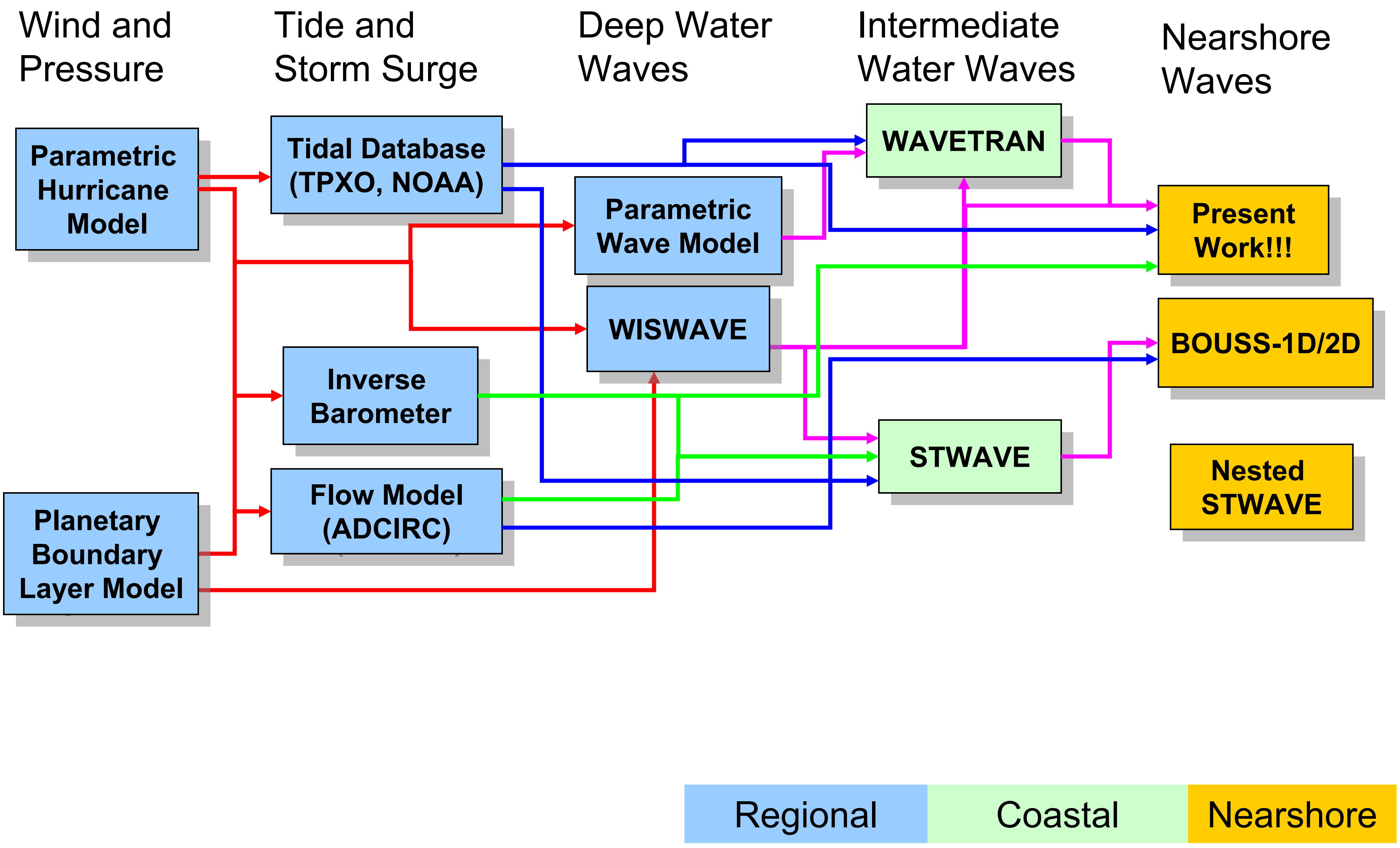
$$H_b = 0.88\tanh(\gamma kd / 0.88)/k \qquad \gamma = H_b / d = 0.5 + 0.4\tanh(33H_o / L_o)$$

- Momentum balance

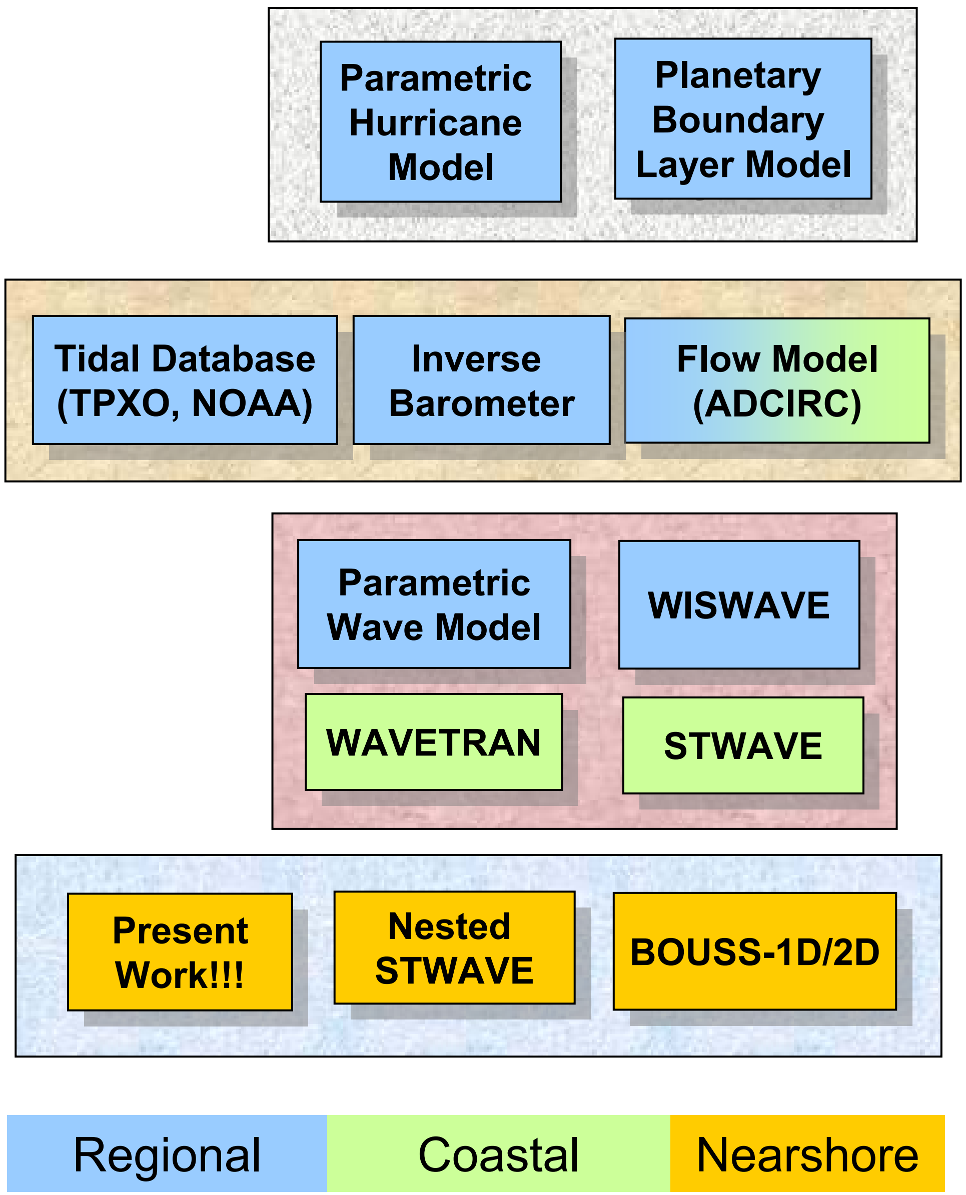
$$\rho g(h+\eta)\frac{\partial \eta}{\partial x} + \frac{\partial S_{xx}}{\partial x} = \tau_{wx}, \qquad \tau_{wx} = C_d \rho_a U\left|U\right|, \qquad S_{xx} = E\left(n(\cos^2\theta + 1) - \frac{1}{2}\right),$$

$$H_s = 4\sqrt{m_o} \qquad m_o = \int_{f_c}^{f_{ny}} S(f)df \ \text{ where } f_c = 0.02\,\text{Hz}, f_{ny} = \text{Nyquist Freq.}$$

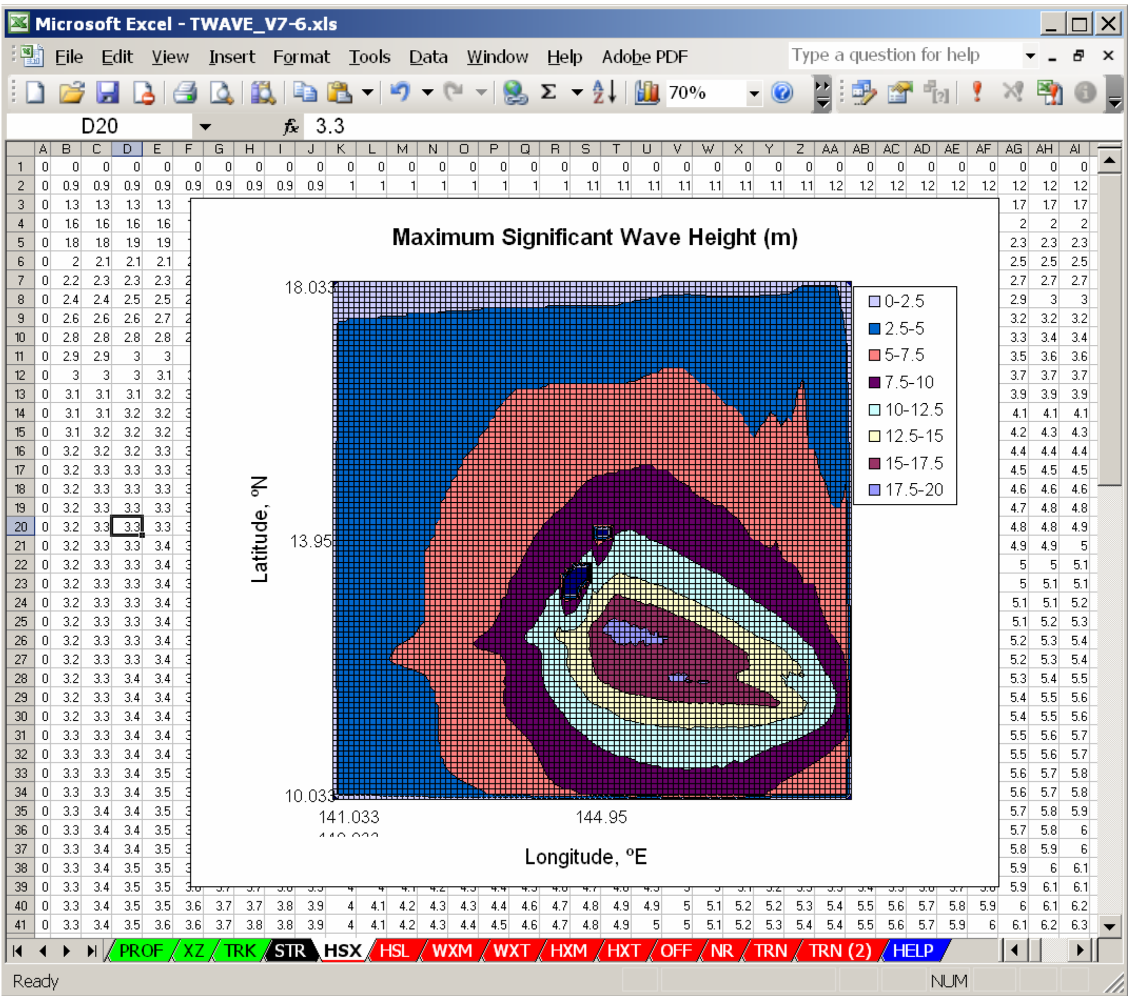
Coastal Modeling Package: TWAVE

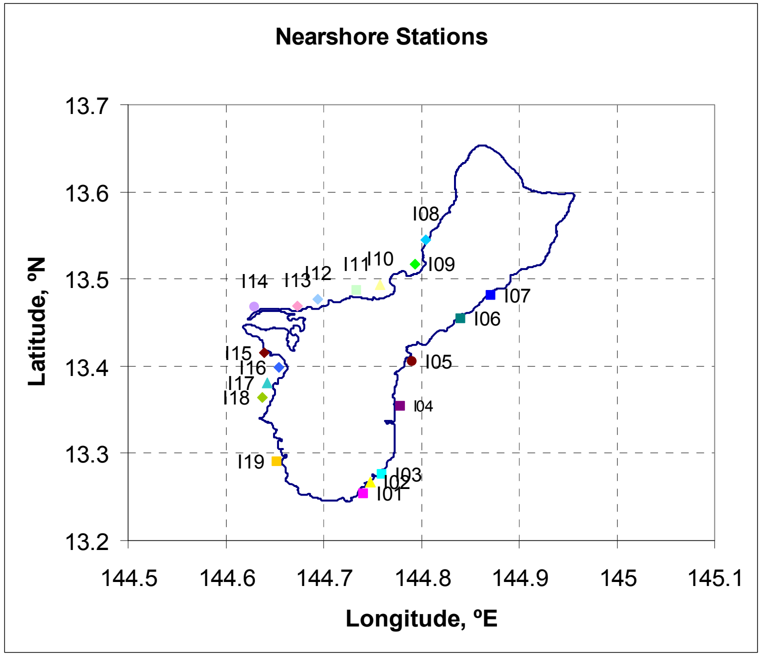


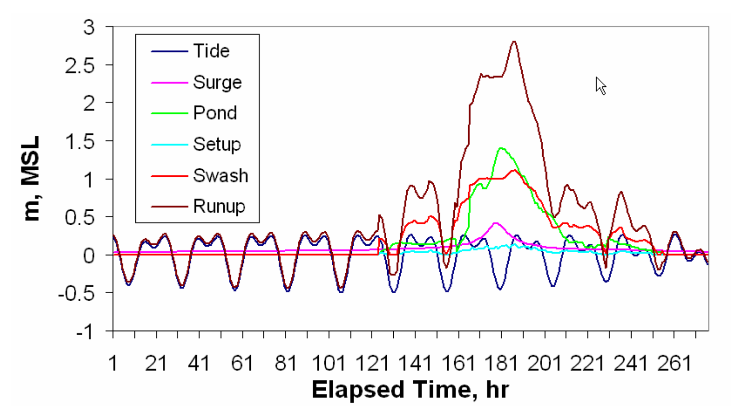
• Sy


Parametric Hurricane Model
Planetary Boundary Layer Model
Tidal Database (TPXO, NOAA)
Inverse Barometer
Flow Model (ADCIRC)
Parametric Wave Model
WISWAVE
WAVETRAN
STWAVE
Present Work!!!
Nested STWAVE
BOUSS-1D/2D
Regional
Coastal
Nearshore

TWAVE: Example

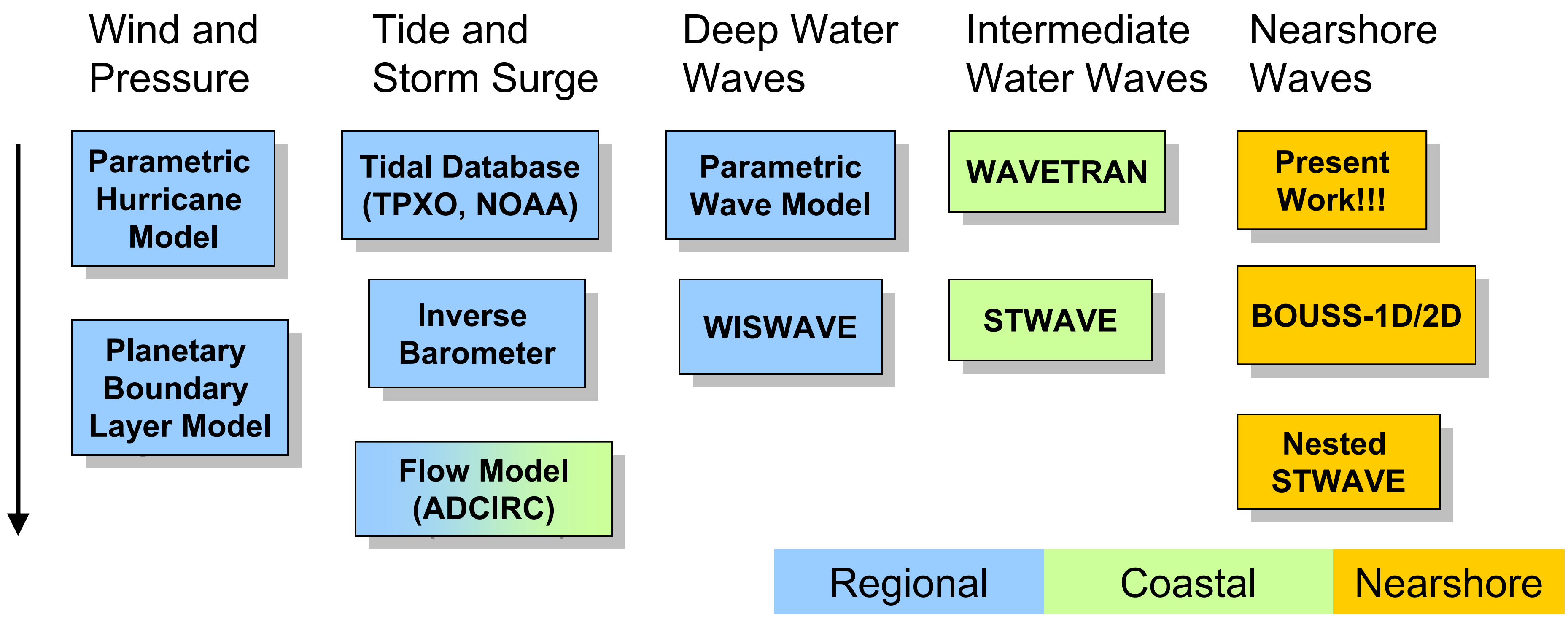






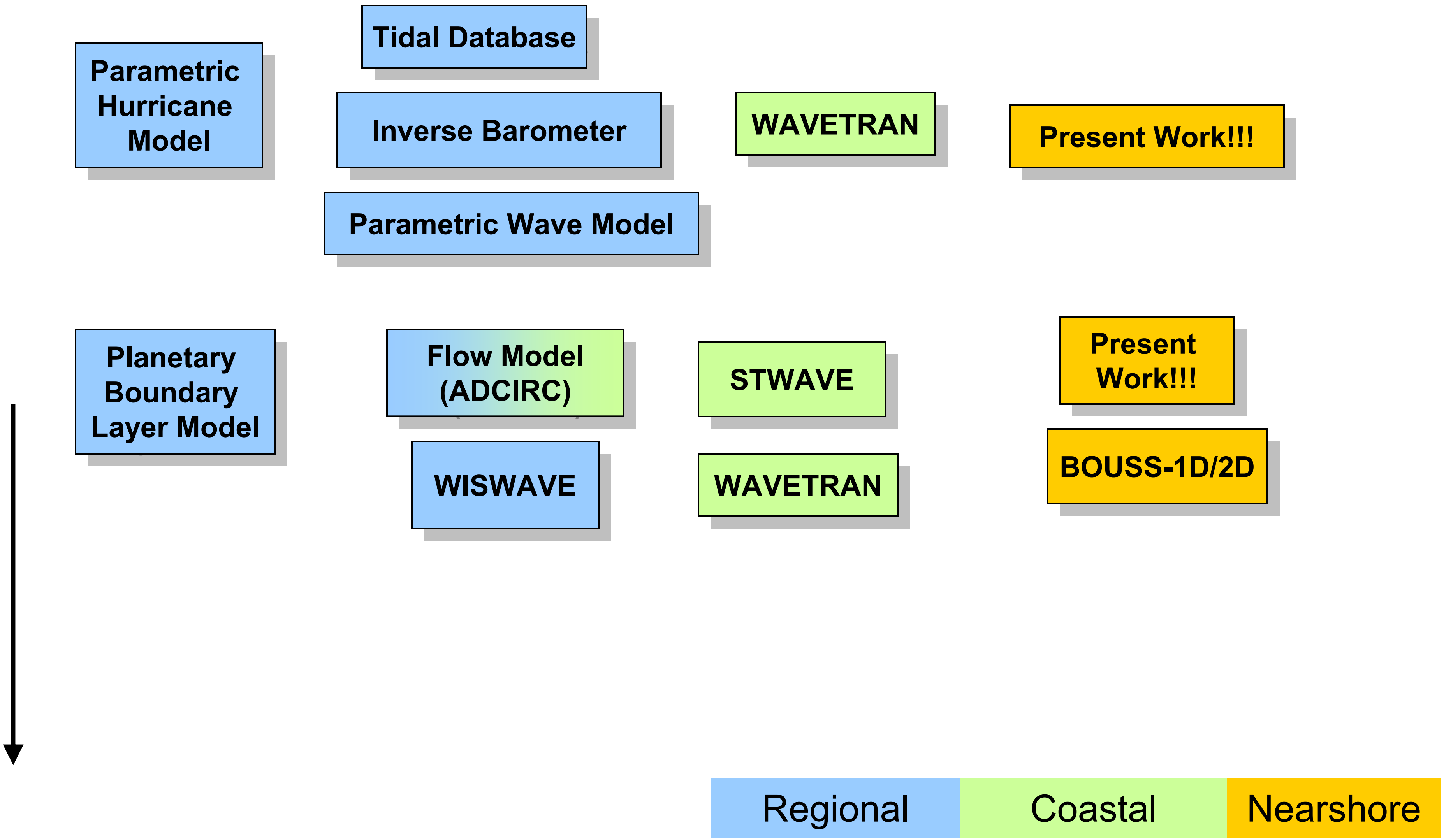
Coastal Modeling Package: TWAVE

- Background
  - Coastal Modeling Package developed Surge and Wave Island Modeling Studies (SWIMS) by the U.S. Army Corps of Eng. (USACE)
- TWAVE Coastal Modeling Package
  - Multi-level, user-friendly, comprehensive

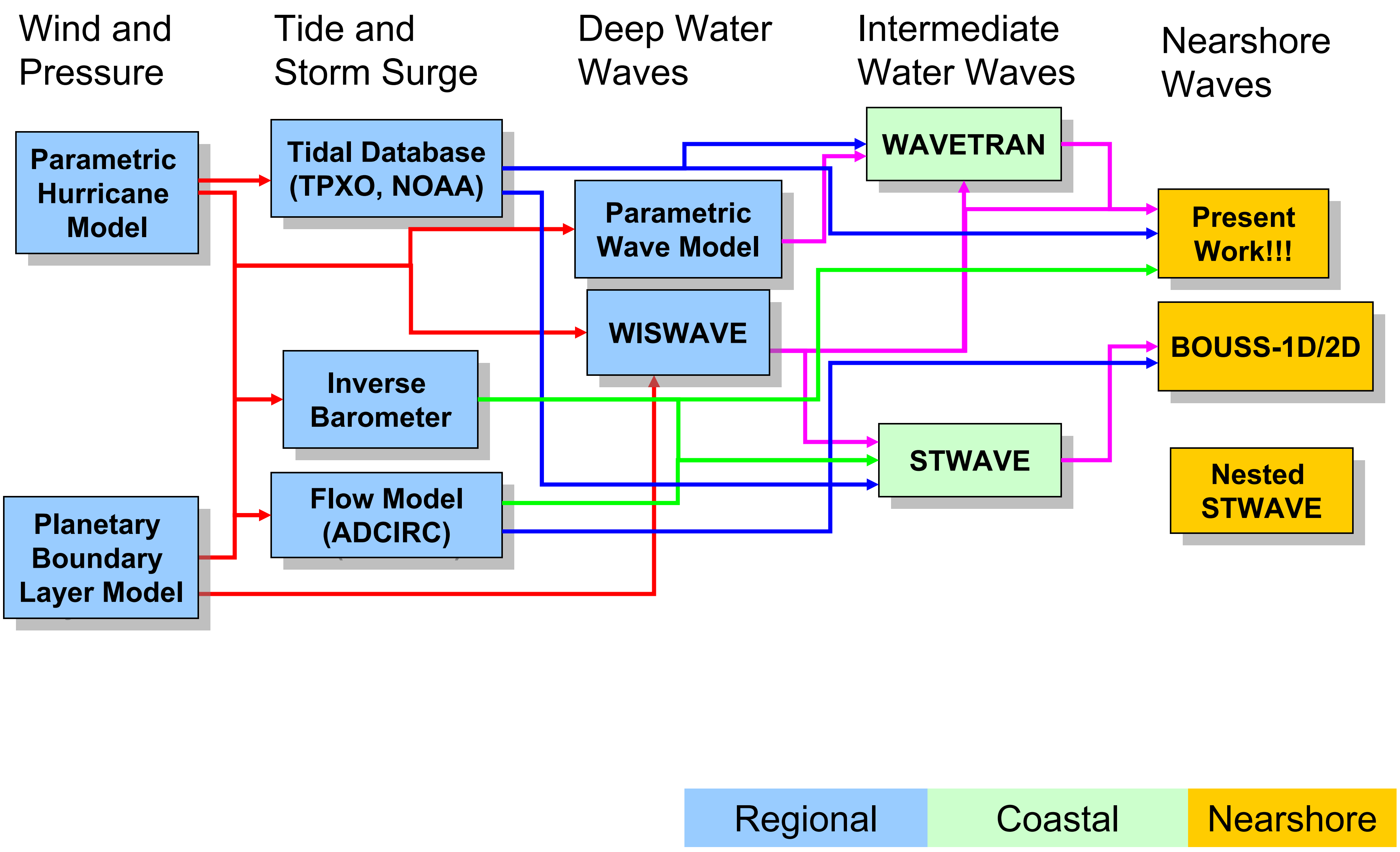


Multi-level Approach

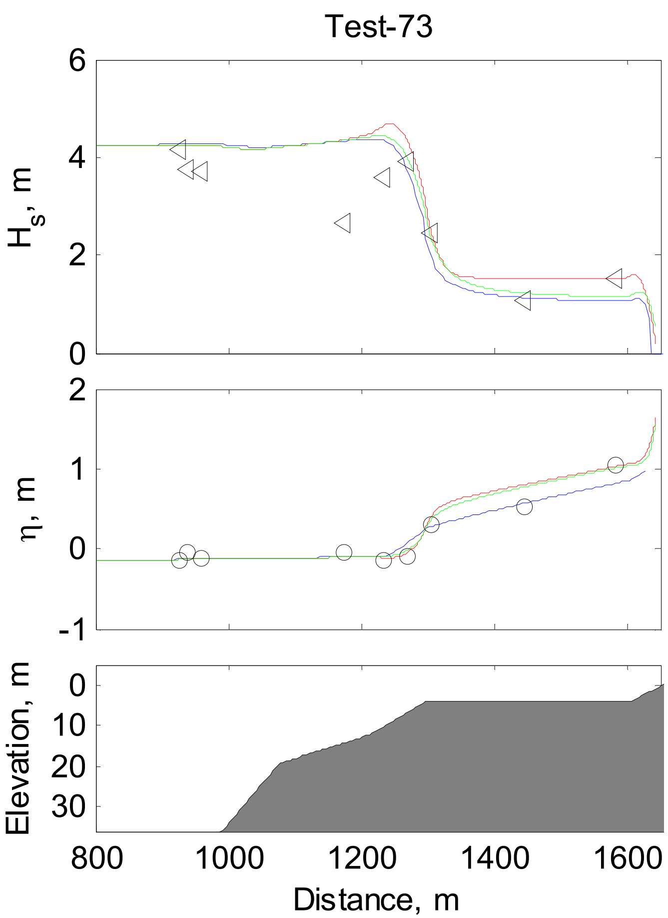
Coastal Modeling Package



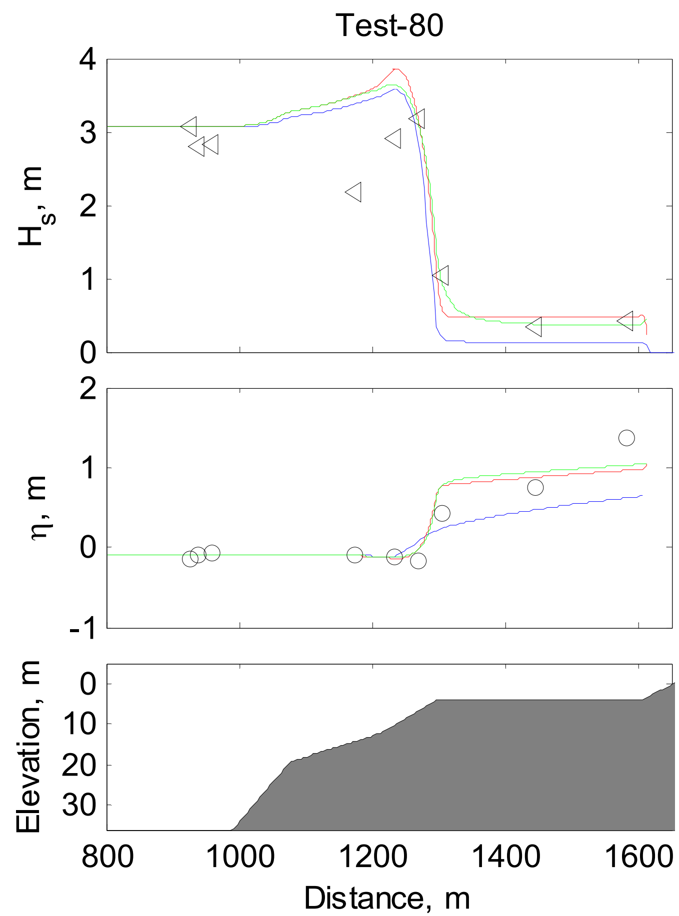
Coastal Modeling Package: TWAVE



UM Dataset, Wind and Waves



H_o = 4.22 m, T_p = 10.0 sec, h_r = 1.92 m, U = 37.5 m/s

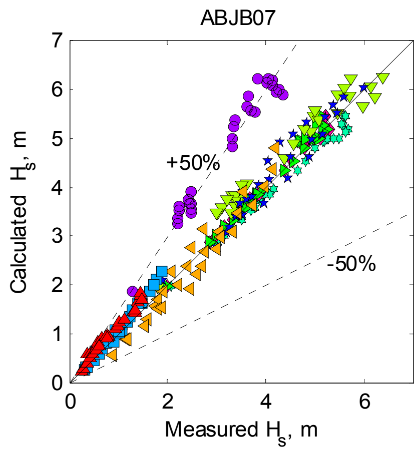


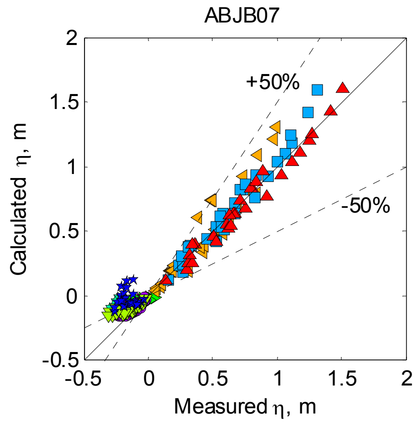
H_o = 3.07 m, T_p =12.0 sec, h_r =0.0 m, U =13.8 m/s

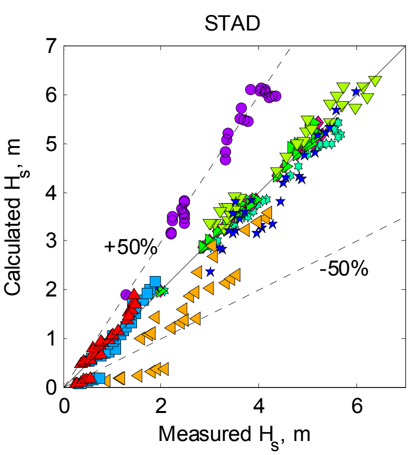
— ABJB07, — DDD85, — STAD

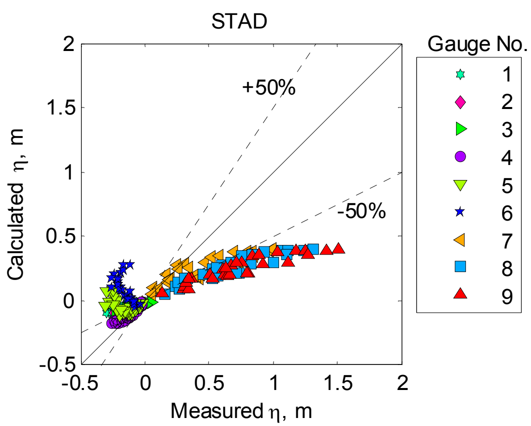
UM Dataset, Waves Only

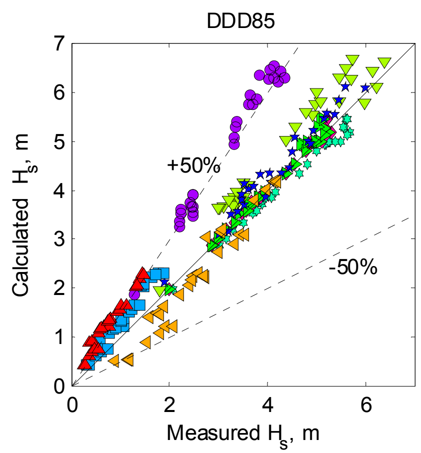
- Hayman Island

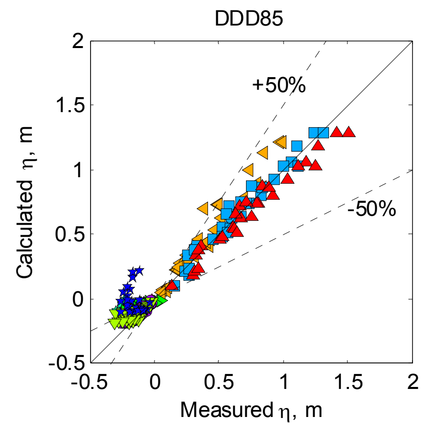












UM Dataset, Wind and Waves

- Hayman Island