WaveWatch III
Applications from global to coastal scales

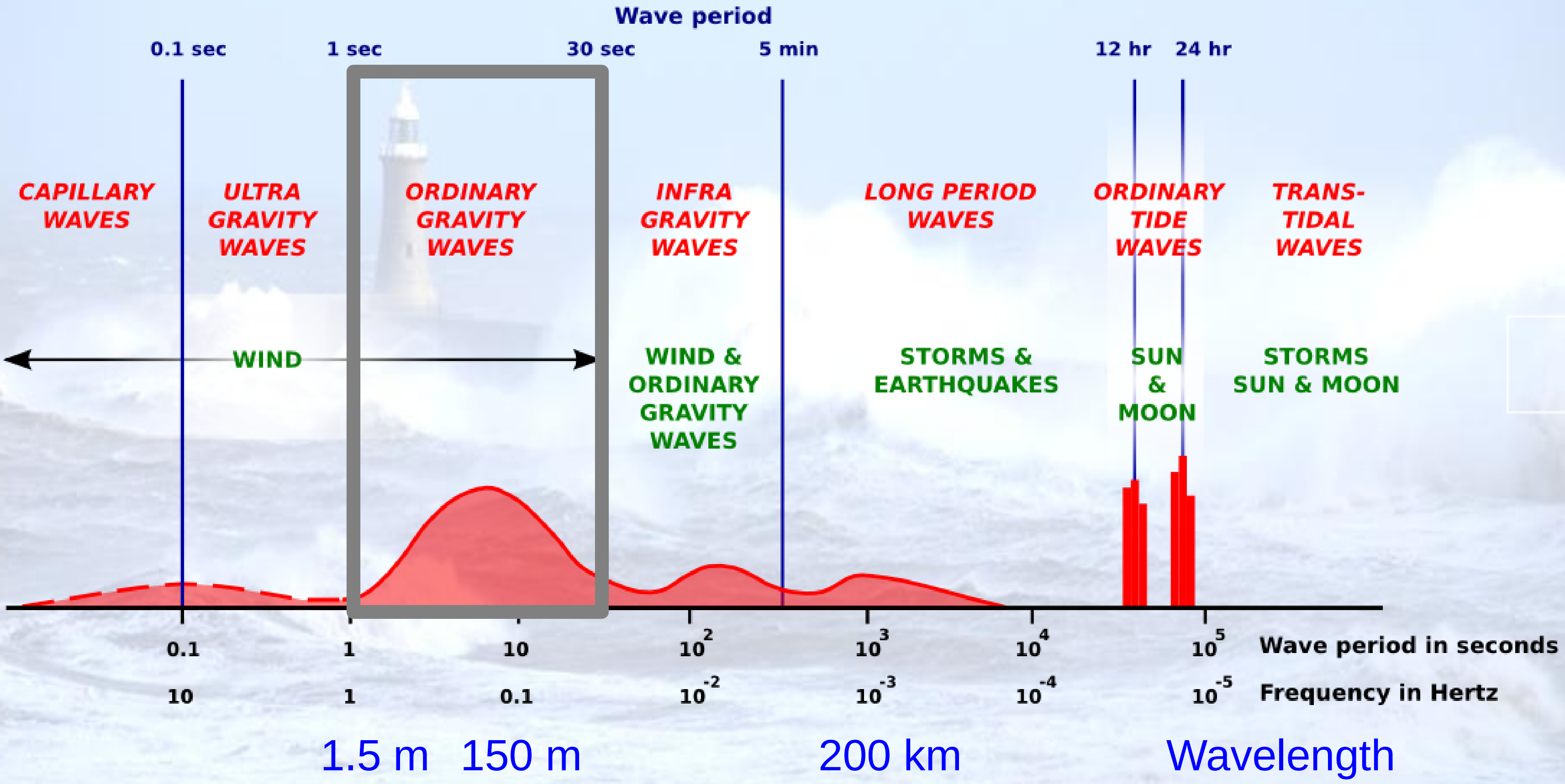
Justin E. Stopa, Fabrice Ardhuin, Mickael Accensi

Ifremer, Plouzane, France 13/03/2015

Outline

1. Introduction
2. WaveWatch III
    1. Governing Equation
    2. Physics – Source Term Balance
    3. Other features
3. Applications
    1. Wave Energy
    2. Seismic Noise
    3. Nearshore IG waves

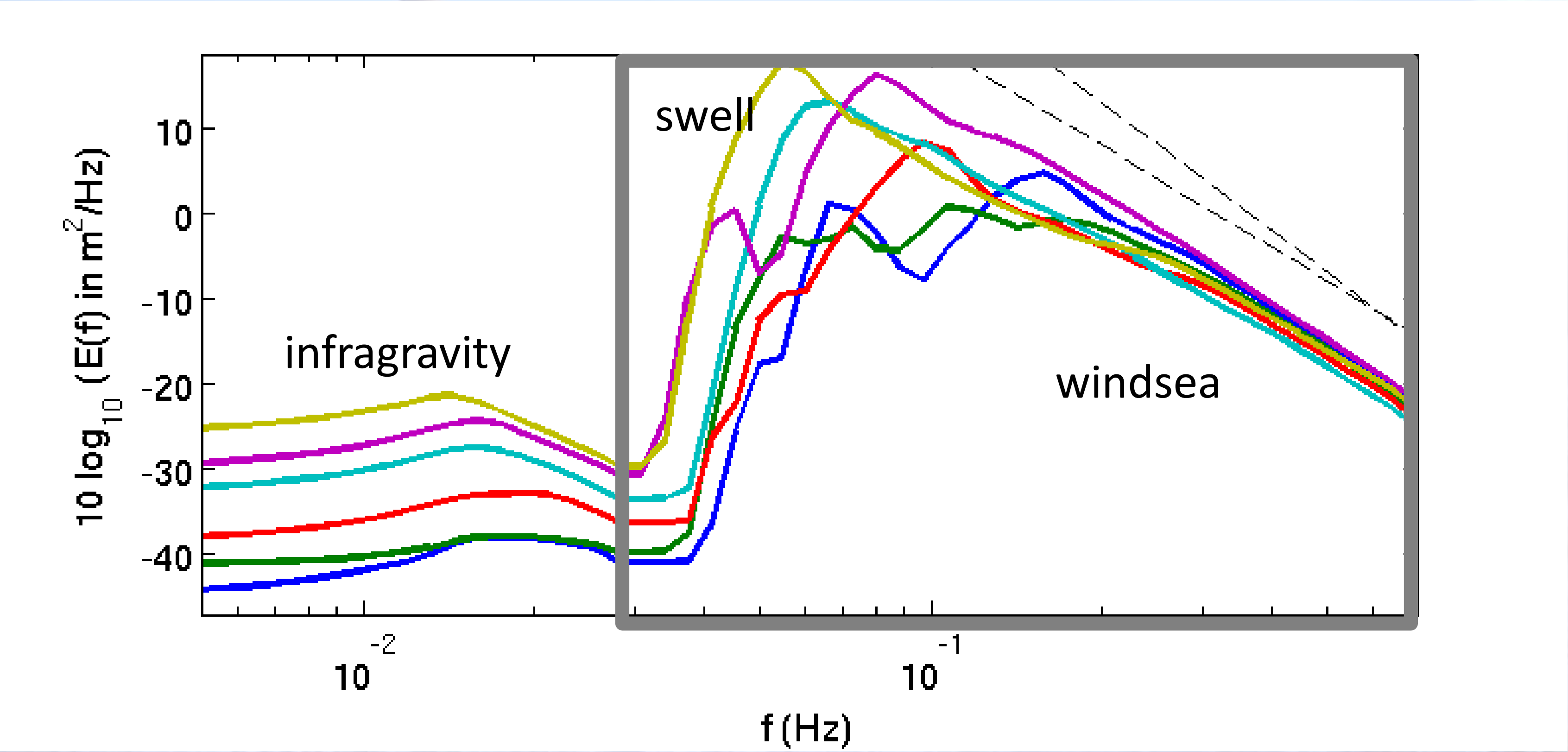
1.) Introduction: Wave Time Scales



- For typical basin and regional wave modeling applications wave periods of 1-30 s are sufficient

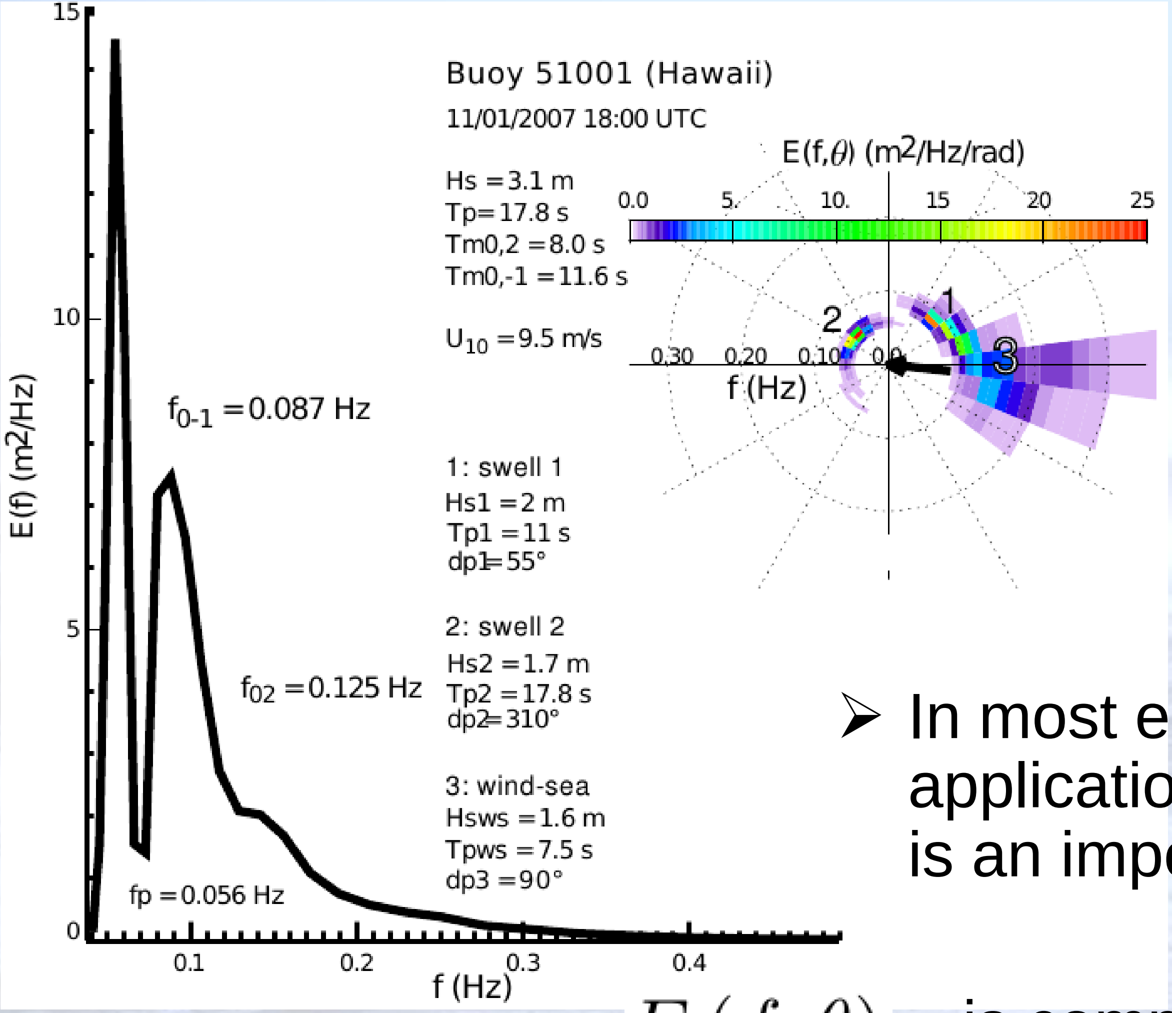
Example Frequency Spectra

- Sufficiently long time series of surface elevation
- Power spectra *E*(*f*) – excellent way to describe waves



- Grey box – typical wave regime important for most applications

Waves are directional: $E(f, \theta)$



datawell buoy

- In most engineering applications the wave direction is an important quantity

$E(f, \theta)$ ~ is computed in WaveWatch III

2.) WaveWatch III

- History - originally developed by Hendrik Tolman
  - WaveWatch I at Delft (Tolman, 1989, 1991)
  - WaveWatch II at NASA Goddard (Tolman 1992)
  - WaveWatch III at NCEP (Tolman et al., 2002)
- Now it is a community model through the NOAA partnership program – dedicated for source development

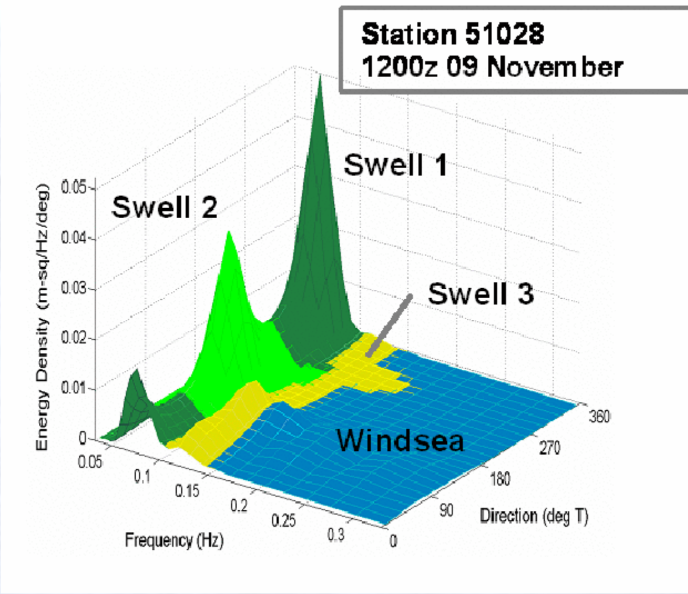
➢ WaveWatch solves the action balance equation
  - Assumes that properties of the medium (like water depth, currents) and the wave energy vary on scales much larger than a single wave.

Governing Equation

- WaveWatch evolves the action density ***N*** for a range of wavenumbers ***k*** and directions θ

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\dot{x}N + \frac{\partial}{\partial y}\dot{y}N + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial \theta}\dot{\theta}N = \frac{S}{\sigma}$$

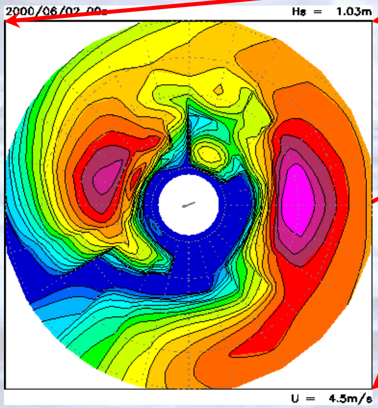
- where *t* denotes time, *k* is wave number, $\sigma = 2\pi f$ is intrinsic angular frequency, the over-dot represents the rate of change, and *S* denotes the source terms

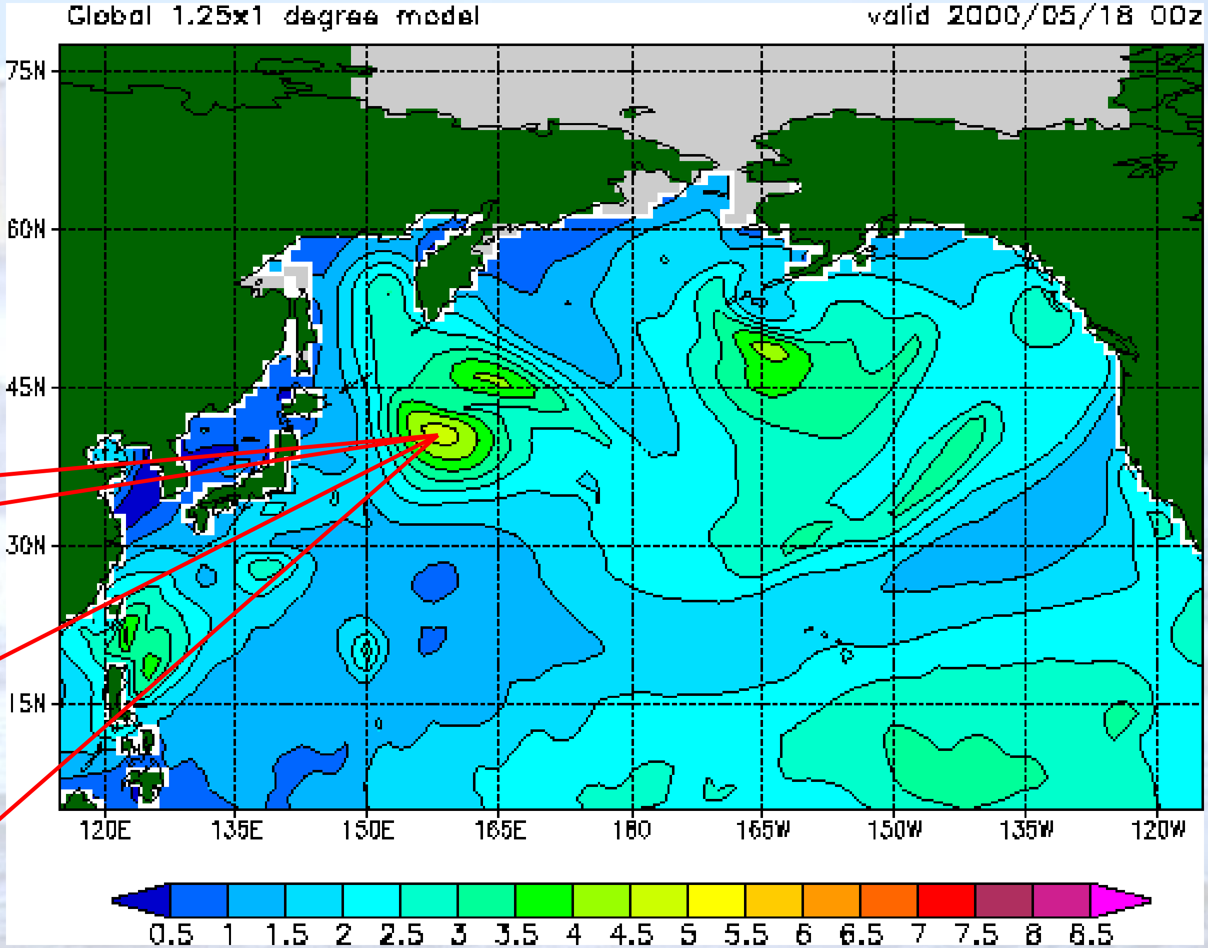


- Typical output: Hs, Tp, Dp, θ_{spr}, T_{m02}, etc.
- In recent public release (v4.18) 90 wave related variables
  - Wave partitioned quantities
  - Atmosphere-ocean boundary layer quantities: u_*, S_{xx}, U_{ss}, Energy flux ($C_g E$)
  - higher order moments: mss

Significant Wave Height Example

- Wave spectra are computed for every computational grid point
- 24 directions x 25 frequencies x 720 nx x ny 361~ 10^8





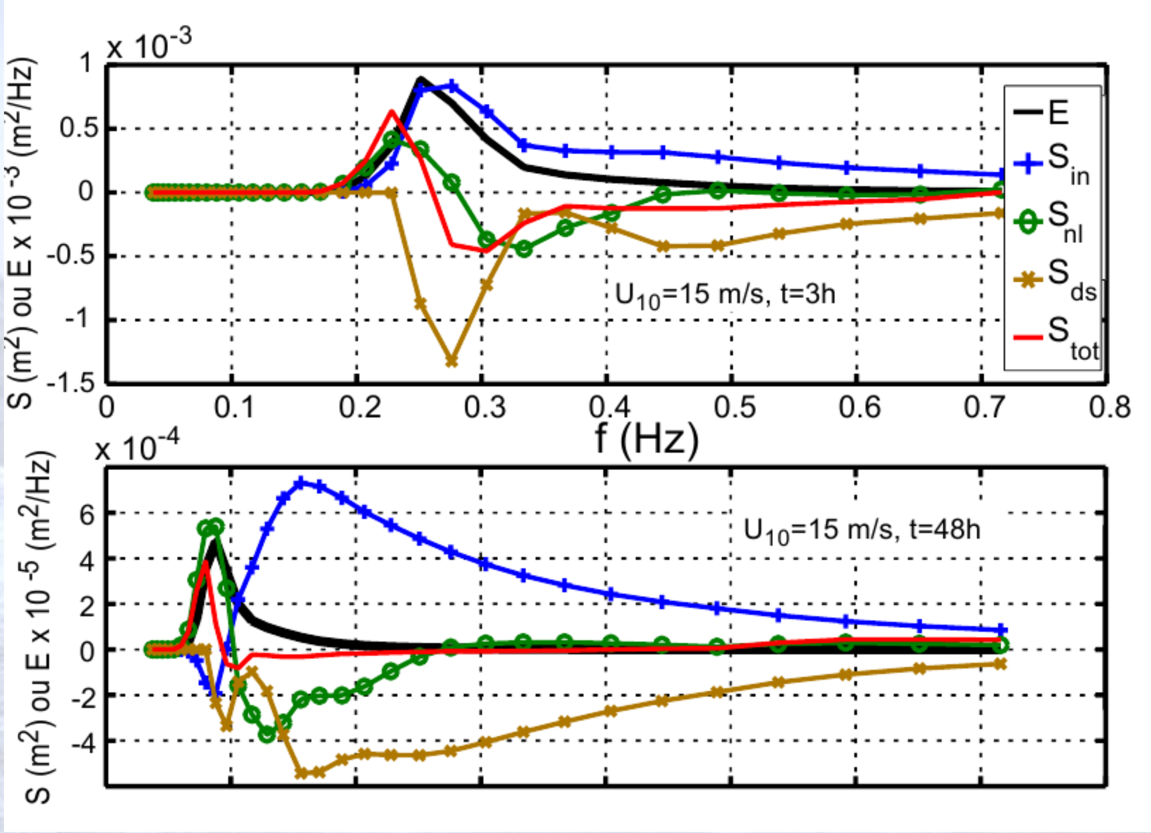
Source Terms

$$S_{tot} = S_{in} + S_{ds} + S_{nl} + S_{bot} + S_{db} + S_{tr} + S_{sc} + S_{ice} + S_{ref} + ...$$

- input, dissipation (breaking), nonlinear interactions (4-wave)
- bottom friction, depth induced breaking, triad interactions, bottom scattering, wave-ice interaction, wave reflection

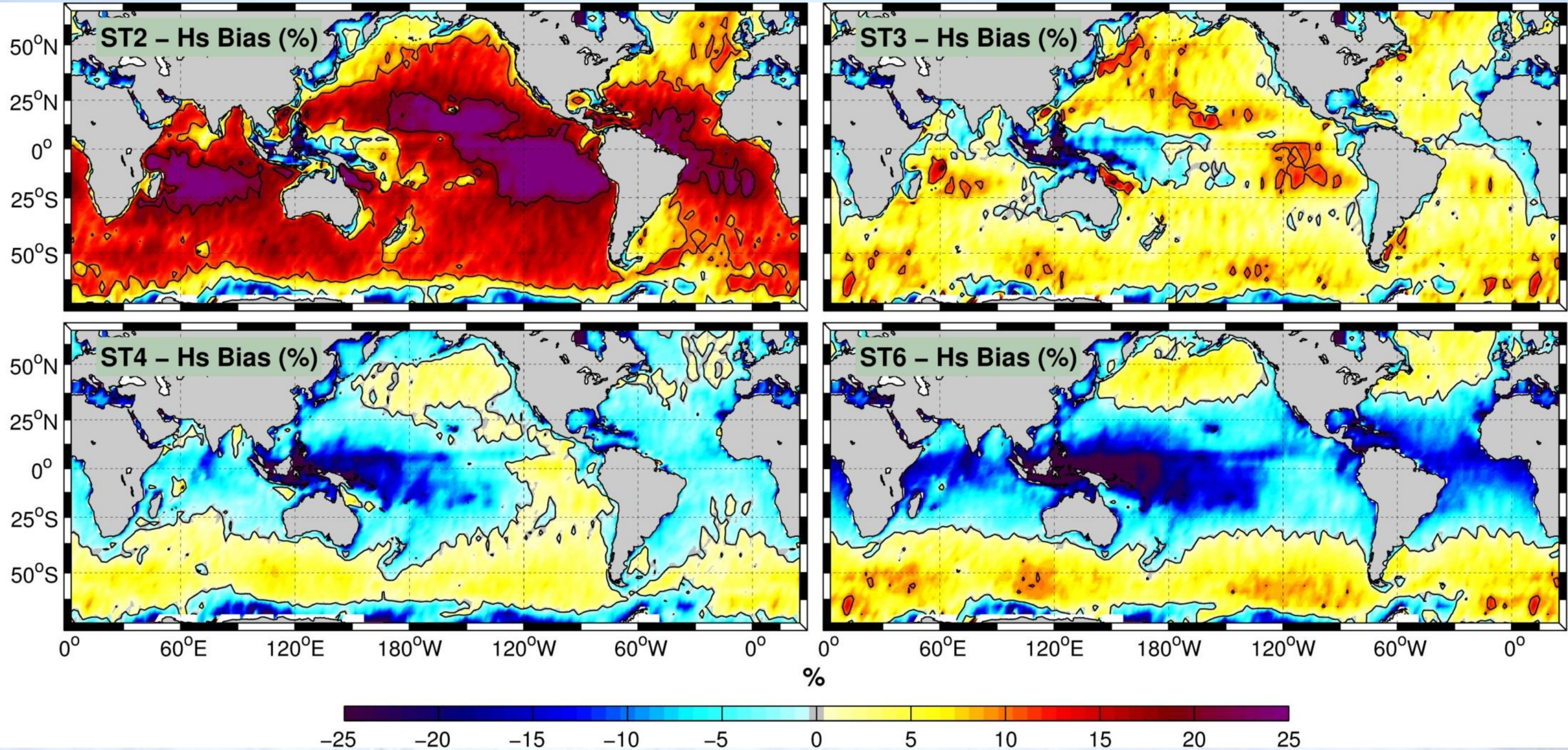
- The proper balance between components is paramount… however this is difficult in practice

- Source terms and physics options available:
  - **ST2** (Tolman & Chalikov 1996)
  - **ST3** (Bidlot et al. 2007),
  - **ST4** (Ardhuin et al. 2010)
  - **ST6** (Zieger et al. 2015)



Ardhuin, Valor ID (2009)

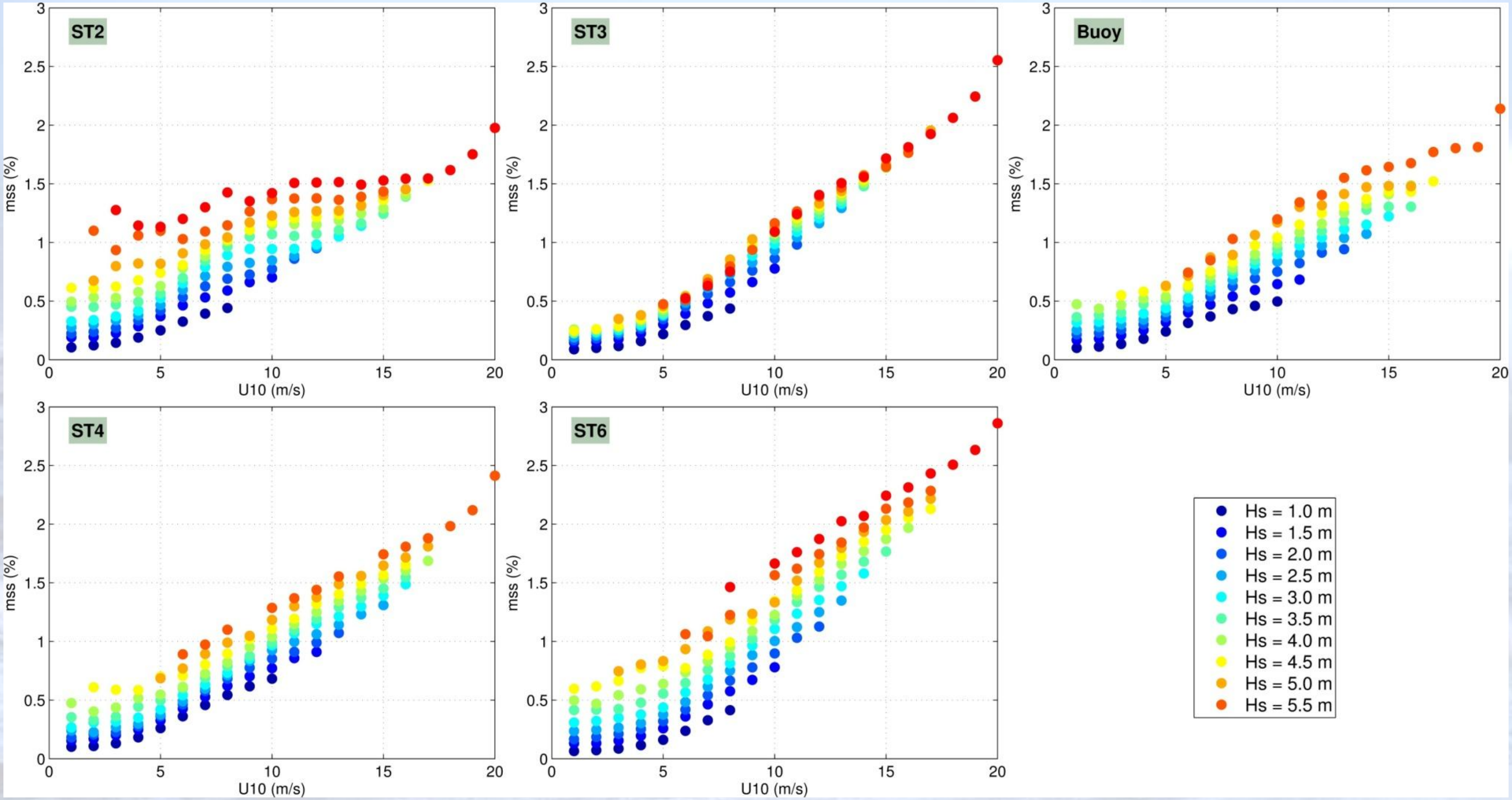
Hs Comparison with Satellite Altimeters



- ENVISAT derived significant wave heights for 2011
- Classic way to validate a wave model on the global scale
- Reveals full spatial distribution of errors important for source term evaluation

Higher Order Wave Moment Comparison with Buoys

$$\text{mss}=\int\int k^2 E(k,\theta)\mathrm{d}k\mathrm{d}\theta \simeq \int\int \frac{(2\pi f)^4}{g^2} E(f,\theta)\mathrm{d}f\mathrm{d}\theta$$

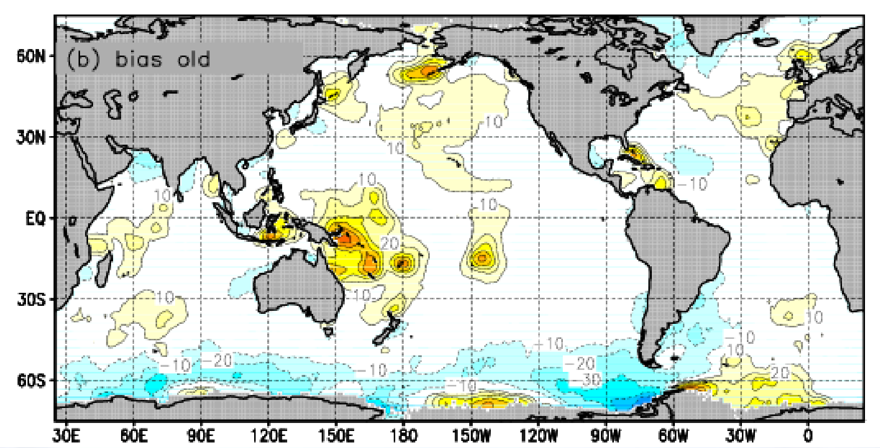


- Mss measure of the high frequency components
- Intuitively increases with wind speed and wave height
- Some models have more realistic physics than others…

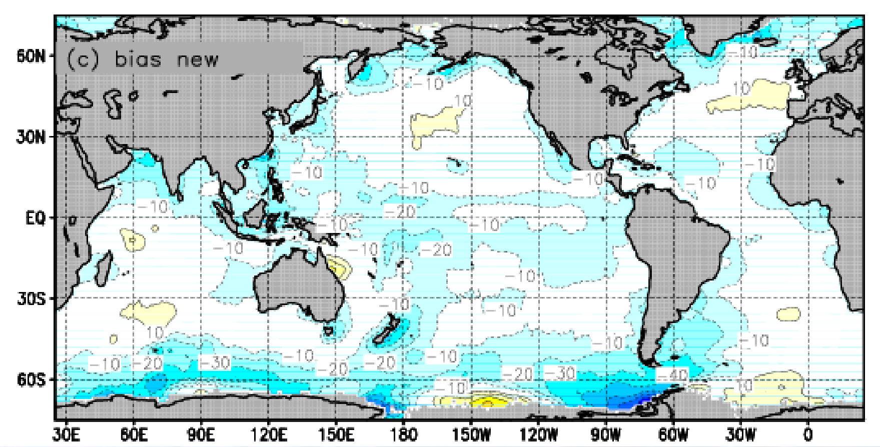
Summary of important features

- Structure
  - Modular code written in F90
  - Can be compiled with OMP or MPI
- Numerics
  - Explicit finite difference solver
  - 1,2,3 order propagation scheme available
  - Garden sprinkler alleviation
  - Two-way nesting
- Unresolved obstacles resolved by prorating energy in two directions
- Grids
  - rectilinear,
  - curvilinear,
  - unstructured

No obstructions

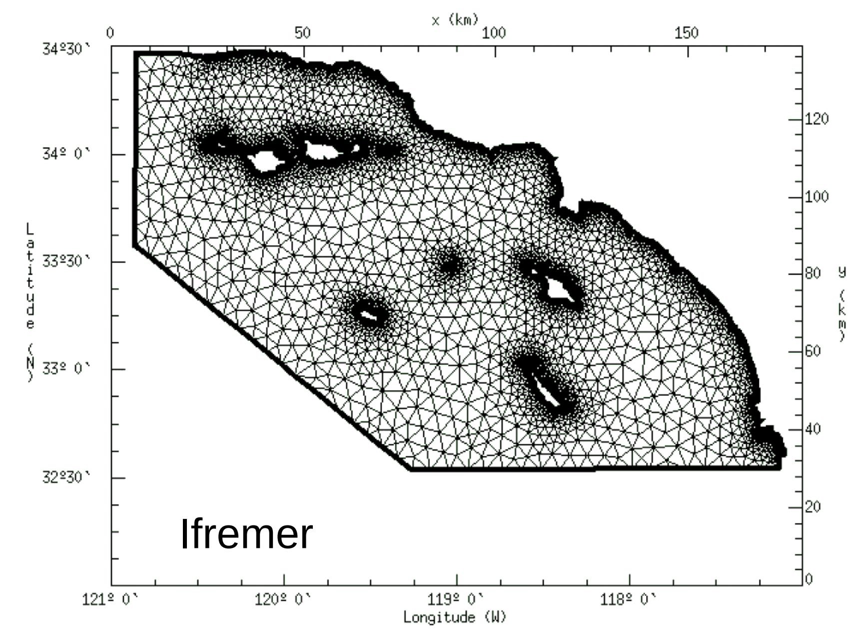


Obstructions

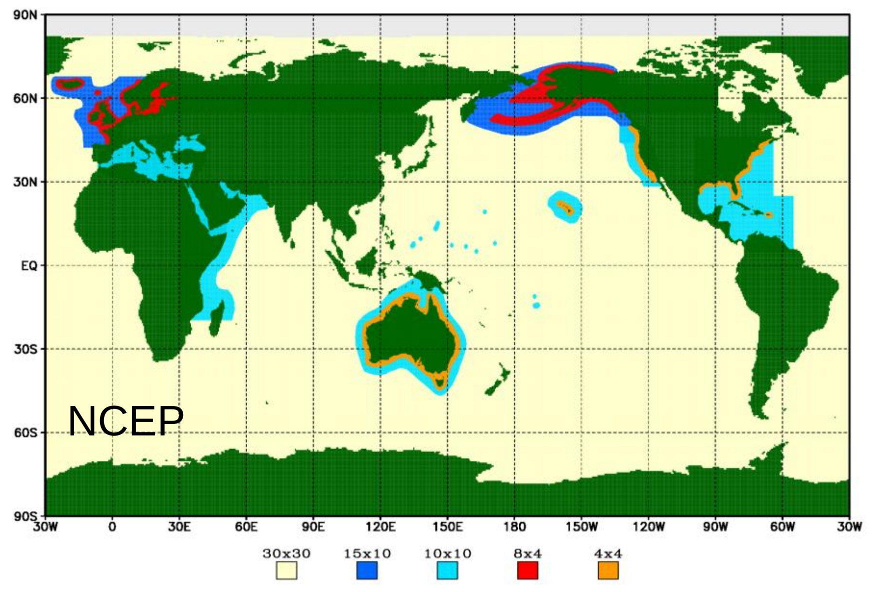


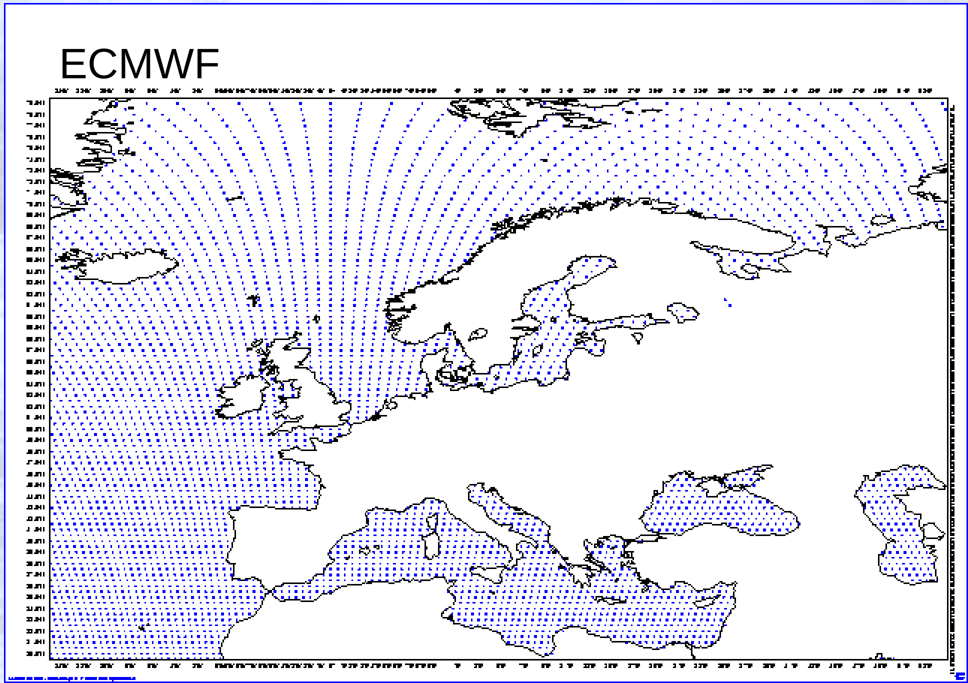
Chawla and Tolman 2008

Example Grids



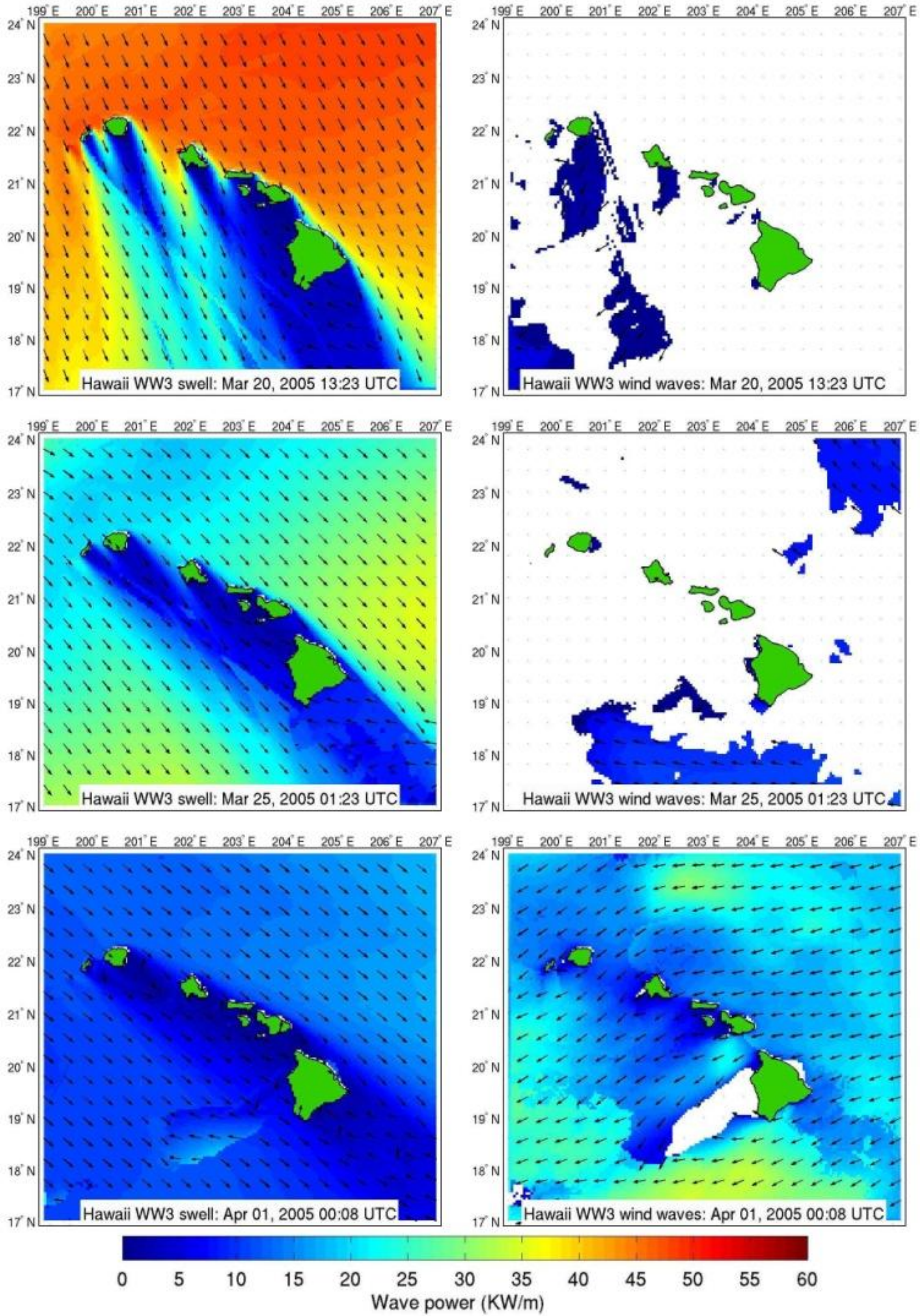
1. Tri-angle mesh (unstructured) – resolve large scale and small scale simultaneously
2. Rectilinear – remove deep water points and make use of 2-way nesting
3. Curvilinear – same CFL timestep at low and high latitudes





3.) Applications

1. Wave Energy (engineering)
2. Acoustic Noise (scientific)
3. Nearshore Example of IG waves



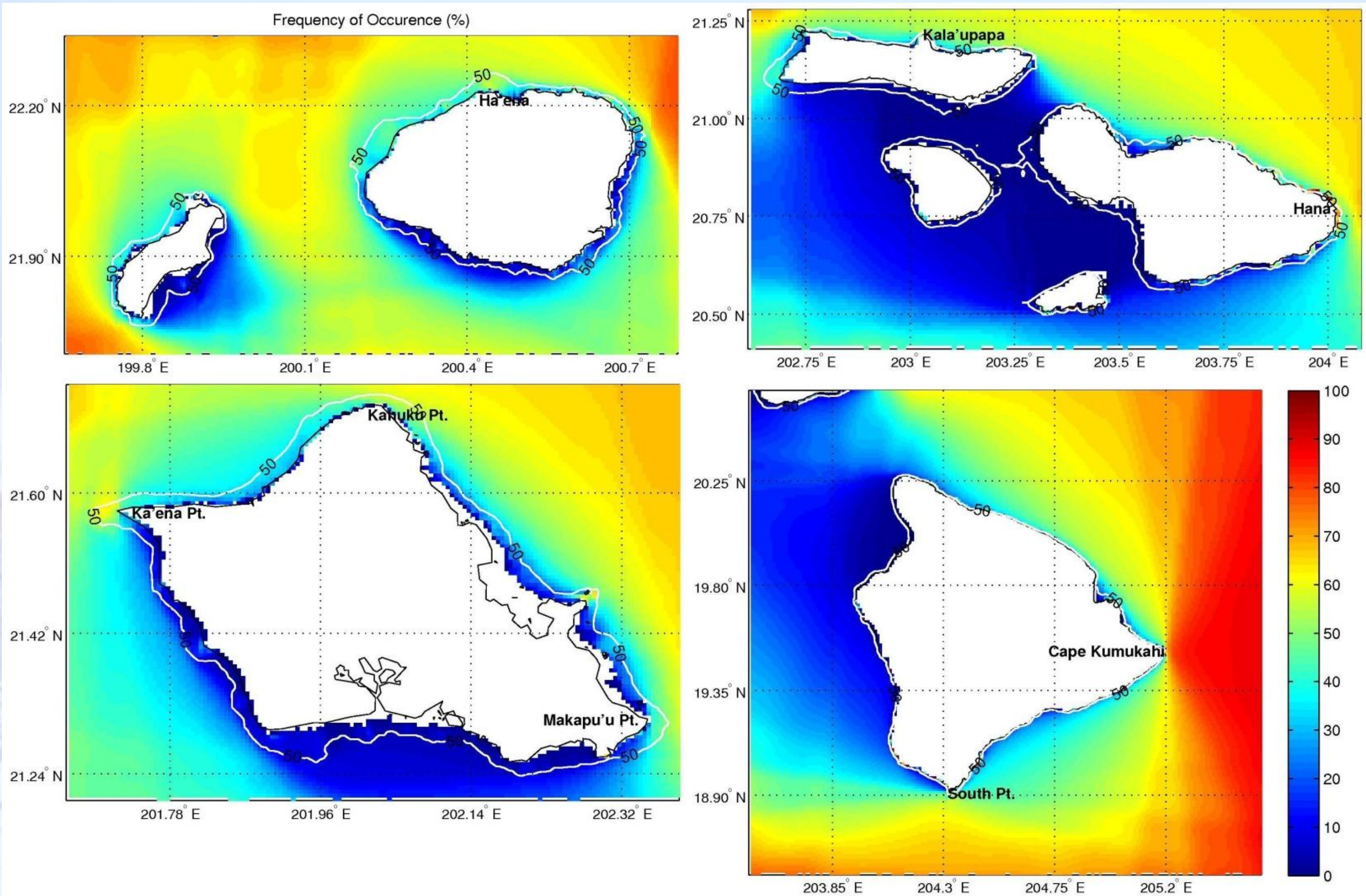
1.) Wave Energy

$$P_w = \rho g \int_0^\infty \int_{-\pi}^{\pi} C_g(f) F(f,\theta)\, d\theta\, df$$

- Due to Hawaii's isolation alternative sources of energy are being considered
- What is the optical location for deployment of a wave energy converter?
- How much wave power is in a typical event?
- NW swell ~60 kW/m
- Wind waves 15-35 kW/m
- Consistency?

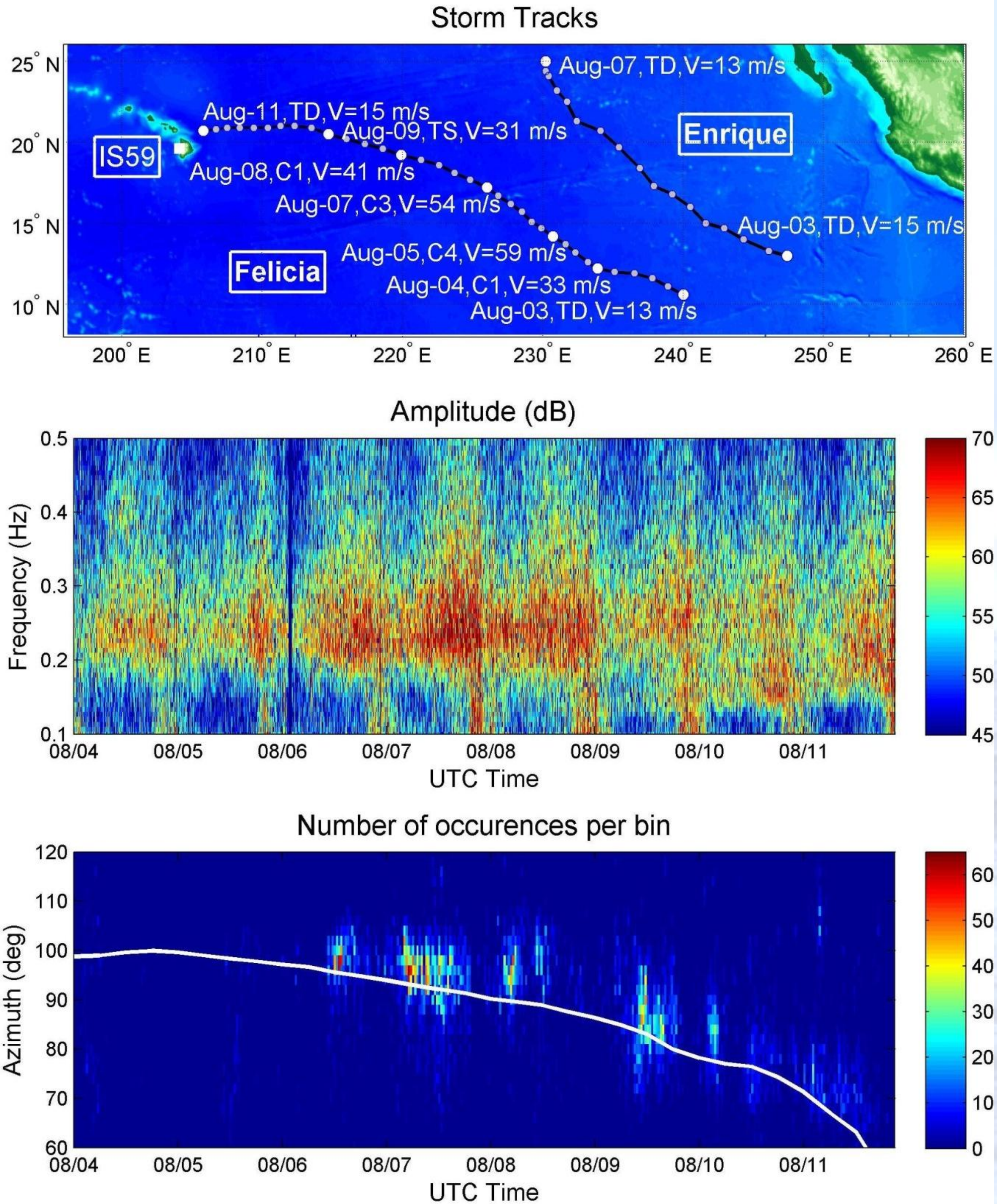
Stopa et al. 2013

Consistency



- Occurrence of events > 15 kW/M
- NW swells have large amounts of energy, however E wind waves are a consistent source of energy

Stopa et al. 2014

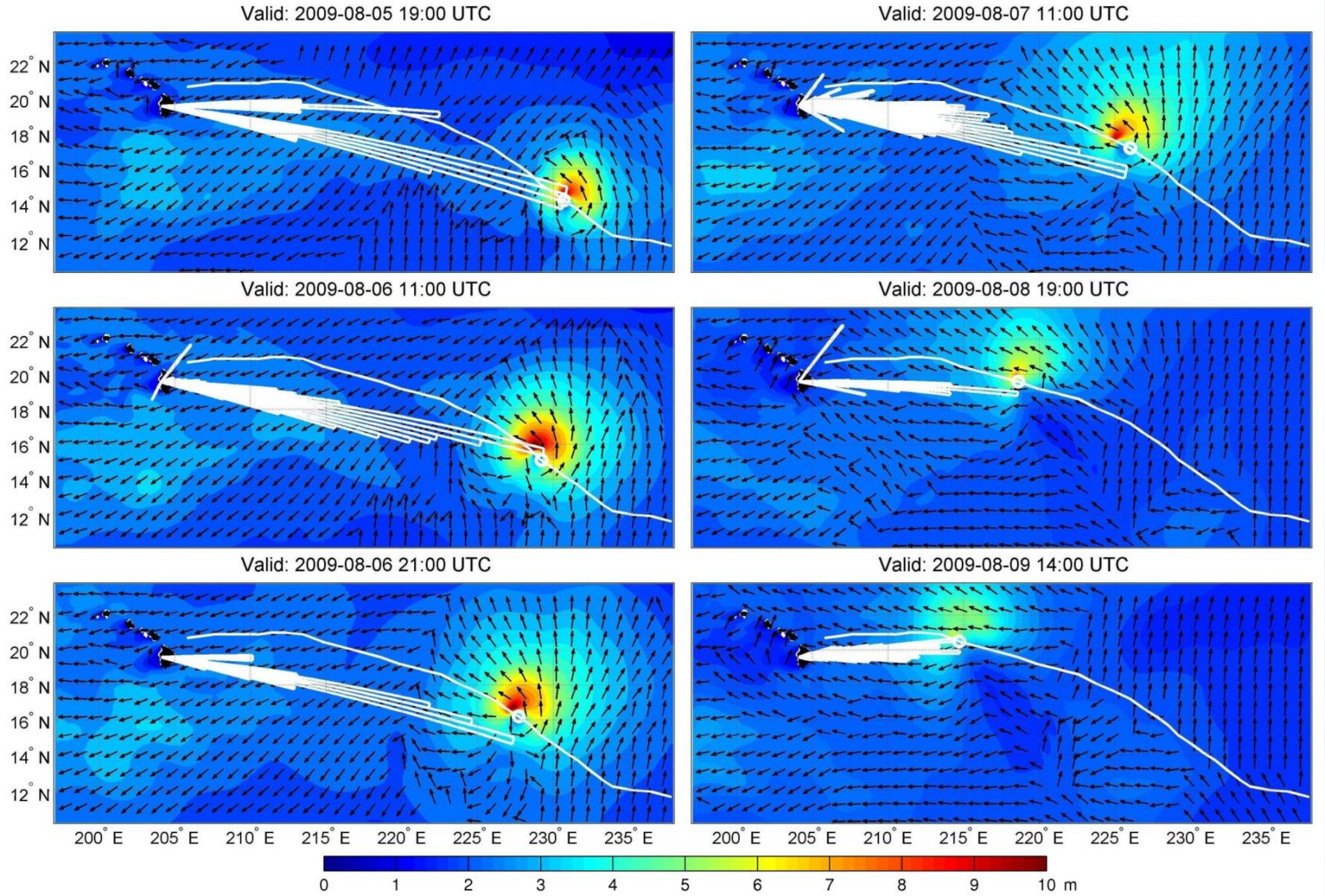


Acoustic Noise

- Acoustic sound recorded at IS59
- Diurnal fluctuations filtered… coherent records show a clear signal in direction
- Energy comes from the wake of the storm
- Relationship with tropical storms?

Stopa et al. GRL 2009

Hs with IS59 observations



- 3 wave events: E wind waves, S swell, storm waves
- Acoustic source are difficult to interpret from Hs

Theory

- Waves with equal frequency and opposing directions create large pressure changes capable of generating noise
- Originally based on Longuet-Higgins (1950) here we use Waxler & Gilbert's (2006) formulation

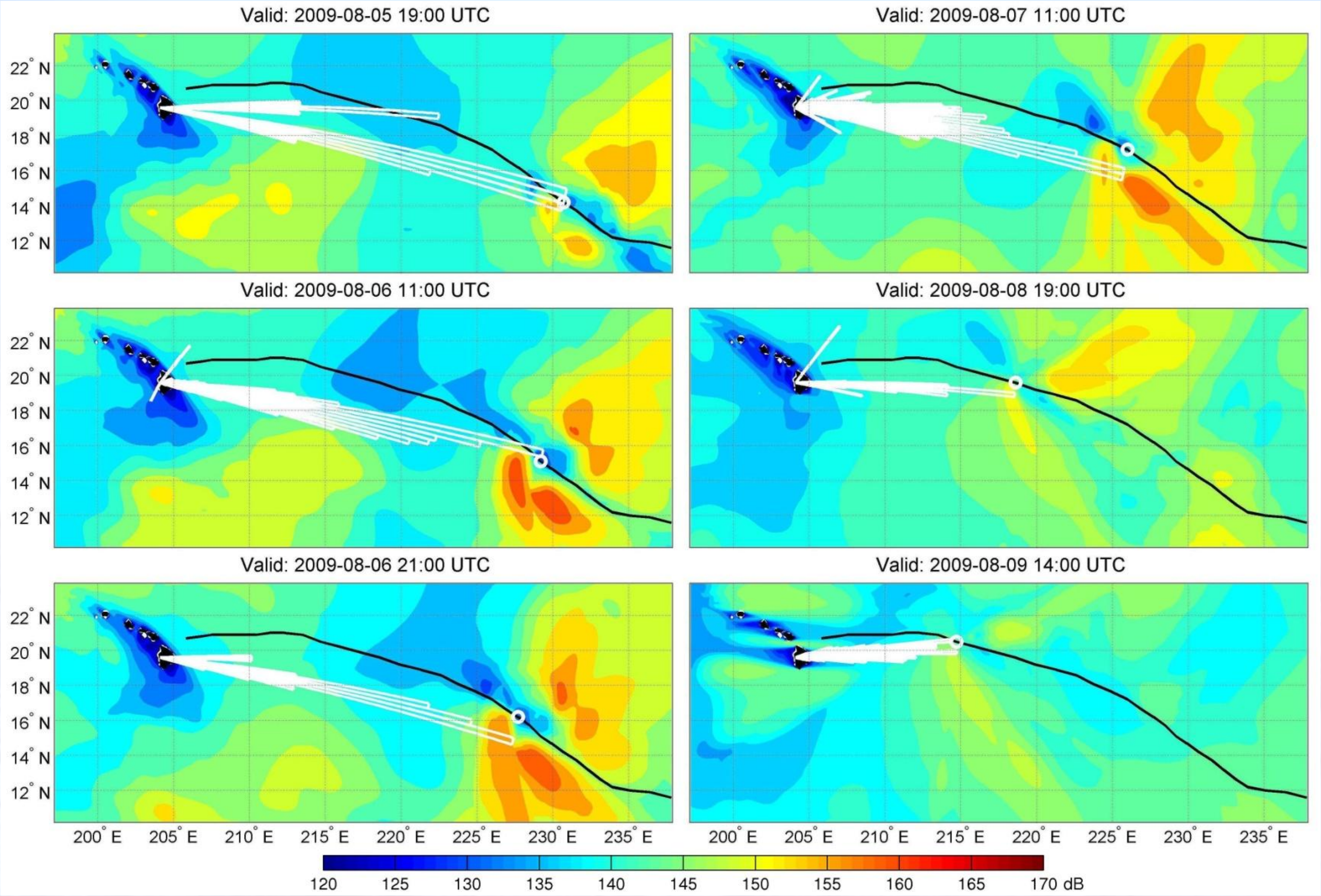
$$D(f) = H(f)\left(\frac{4\rho_{air}^2 g^2 \pi^4 f^3}{c_{air}^2}\right)\left(\frac{9g^2}{4\pi^2 c_{air}^2 f^2} + \frac{c_{air}^2}{c_{water}^2}\right)$$

$$H(f) = \int_0^{2\pi} F\left(\frac{f}{2},\theta\right) F\left(\frac{f}{2},\theta+\pi\right) d\theta$$

- in units of $Pa^2/Hz/m^2$, where g is the acceleration due to gravity, c_{air} and c_{water} are the speeds of sound in air and water, and ρ_{air} and ρ_{water} are the density of air and water

- F estimated from WaveWatch

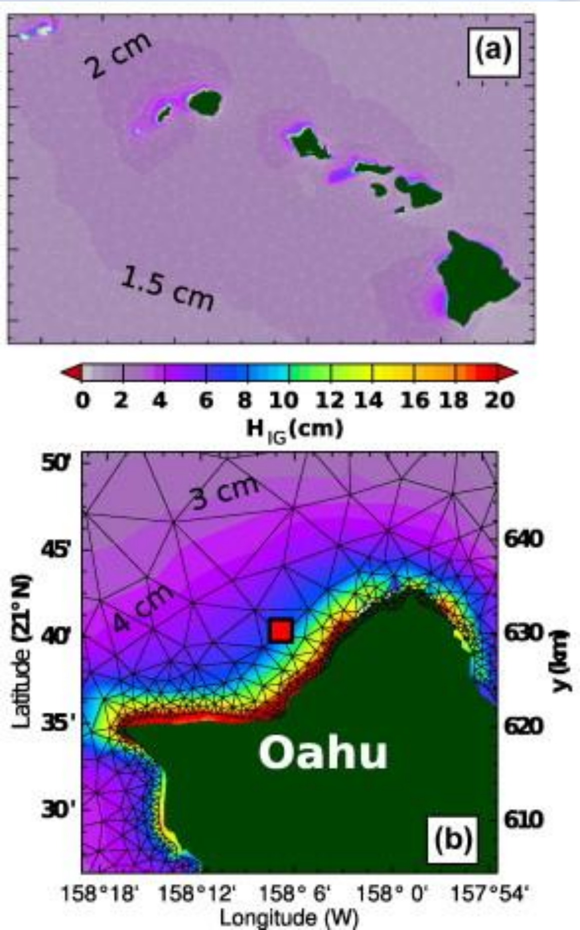
Peak D with IS59 observations



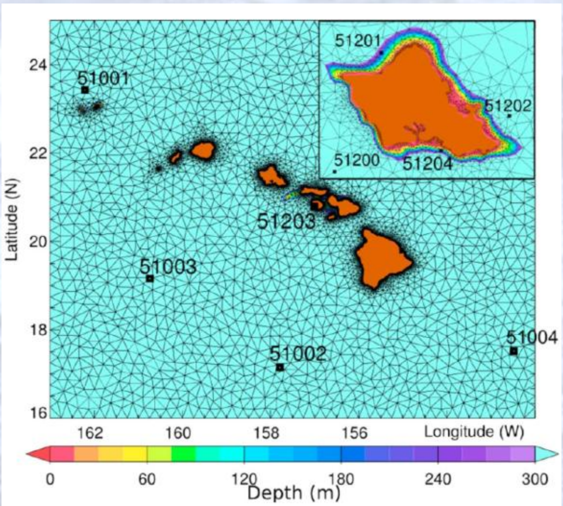
- Qualitatively match the observations
- Peak to N interaction from TS Enrique
- Peak to S self-interaction from Hurricane Felicia

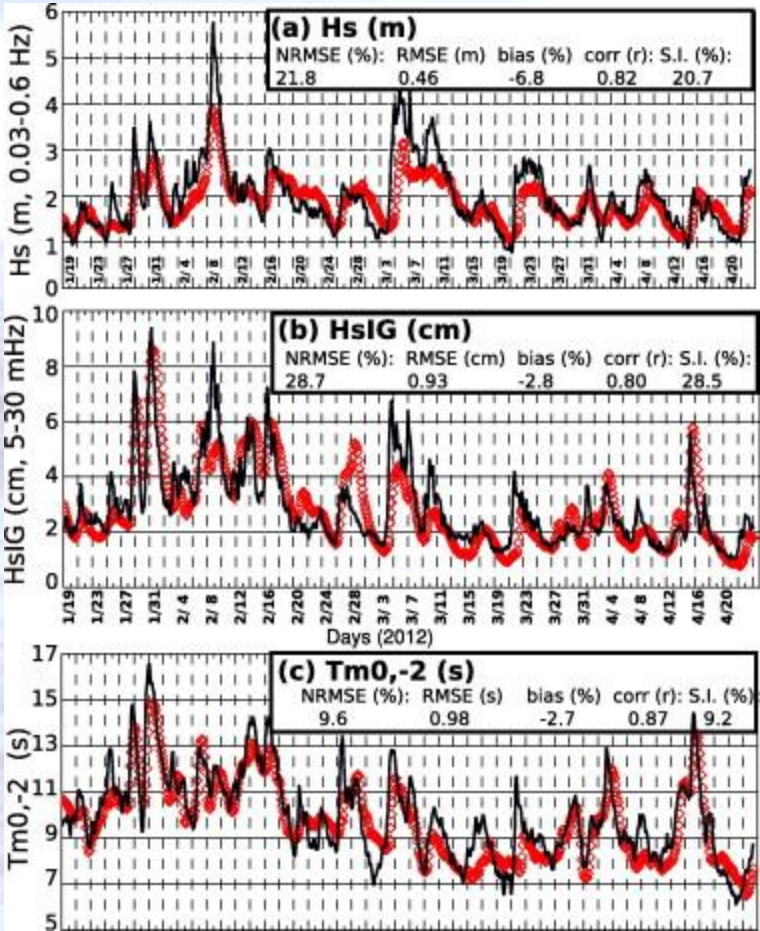
Nearshore Example

- Unstructured grid is most economical for this application
- Empirical formulation of an IG source term
- Hs, HsIG, TM02 are well described at nearshore buoy



Ardhuin et al. OCEMOD 2014





Thank you

Questions / Comments