The effect of wave-tide interactions on simulations of the ocean renewable energy

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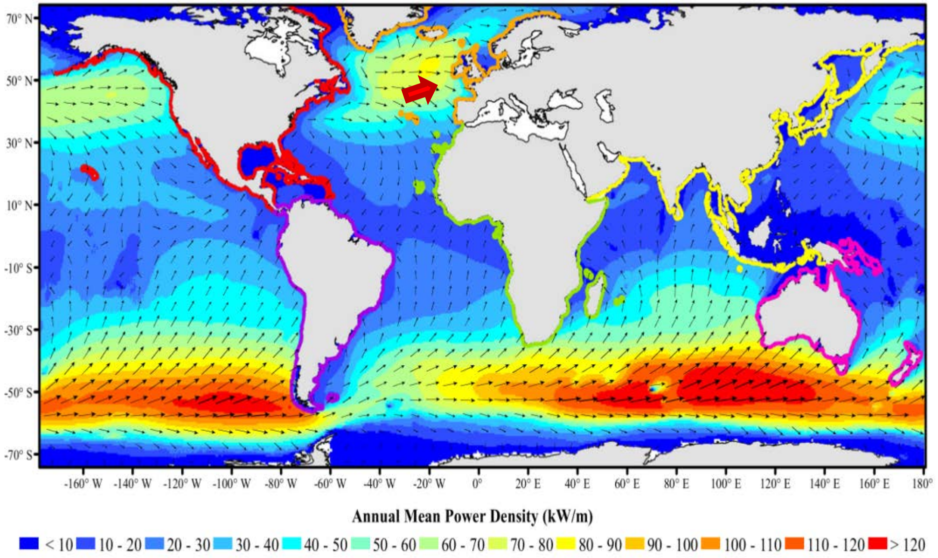
School of Ocean Sciences,
Bangor University, Apri 2014

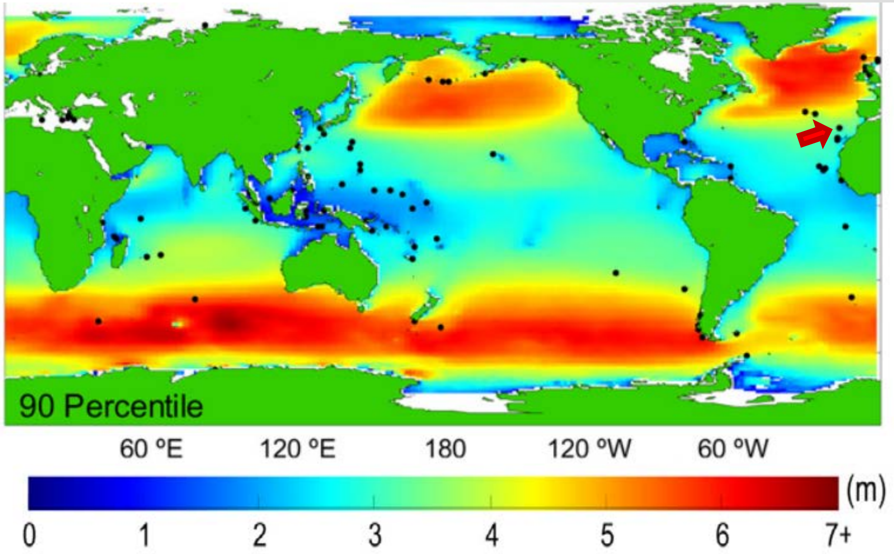
Content

I. Introduction
    I. Wave-tide interactions in ORE

II. Effect of tides on the wave energy
    I. A simplified approach based on the Airy wave theory
    II. More sophisticated approaches based on the COAWST

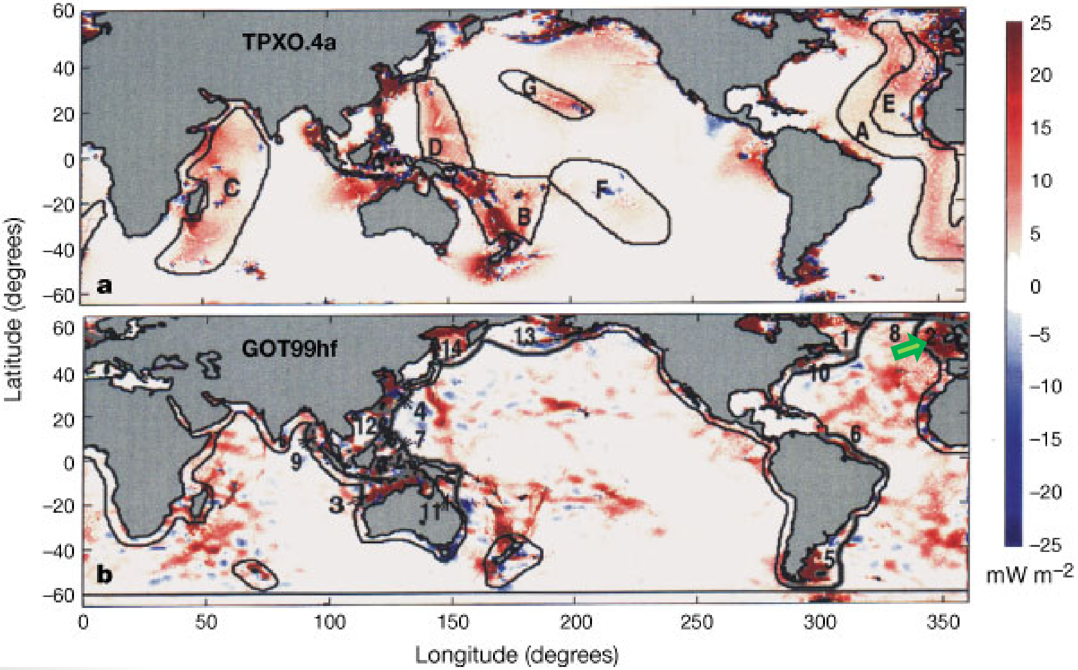
III. Conclusion

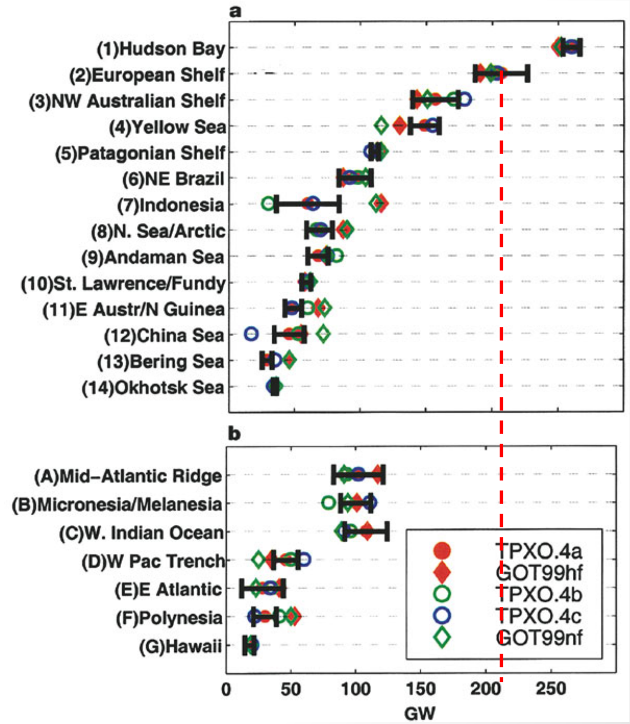




Arinaga and Cheung 2012

Kester and Stock-Williams 2012





Estimates of M2 tidal energy dissipation

Egbert and Ray 2000

Area-integrated dissipation for selected shallow seas and deep-ocean areas

Wave-tide interactions processes

I. Effect of tides on waves (CEW)

- **Tidal currents (Unsteady)**
  - ✓ **Doppler shift**
  - ✓ **Bottom friction**
  - ✓ **Wave generation**
- **Tidal depth variation**
  - ✓ **Wave refraction**
  - ✓ **Wave speed**

EFFECT OF TIDES ON THE WAVE POWER? ⇦

I. Effect of waves on tides (WEC)

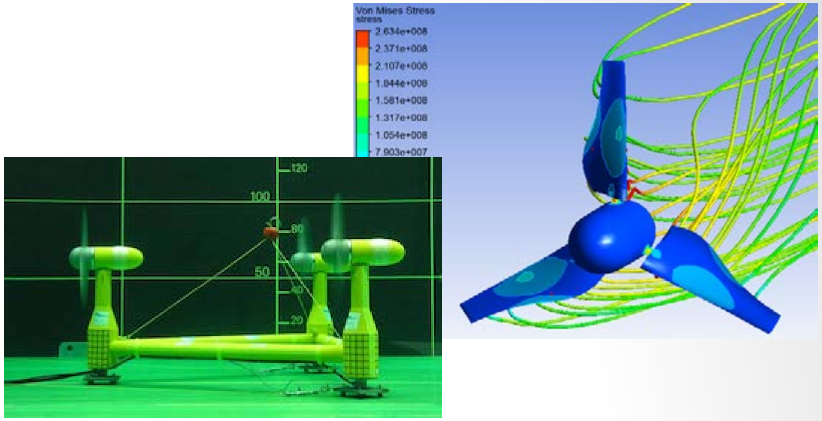
- **Wave radiation stresses**
- **Non-conservative wave forces**
- **Bottom stress**
- **Turbulence**

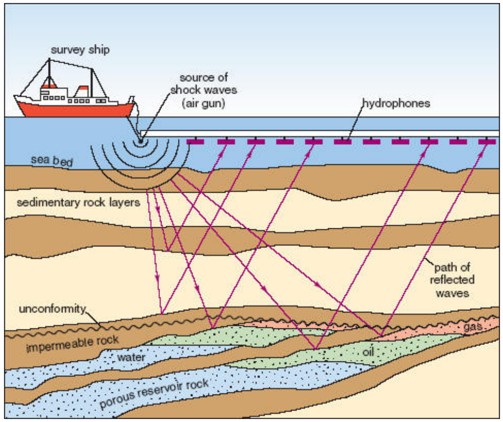
Effect of WAVES on the TIDAL power?

Ocean renewable energy project development

Engineering

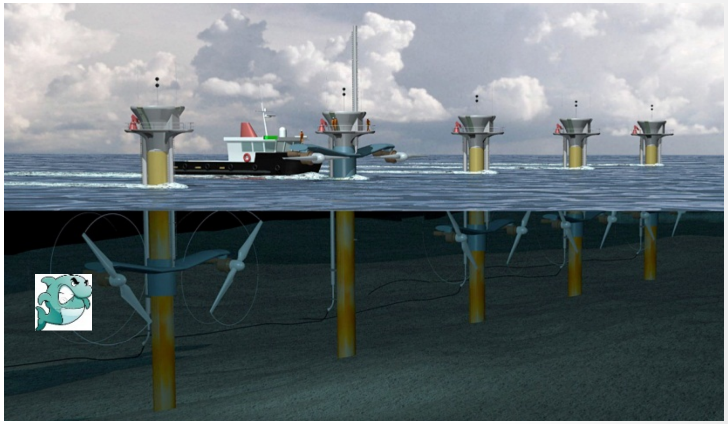
Device specific studies and issues





Oceanography

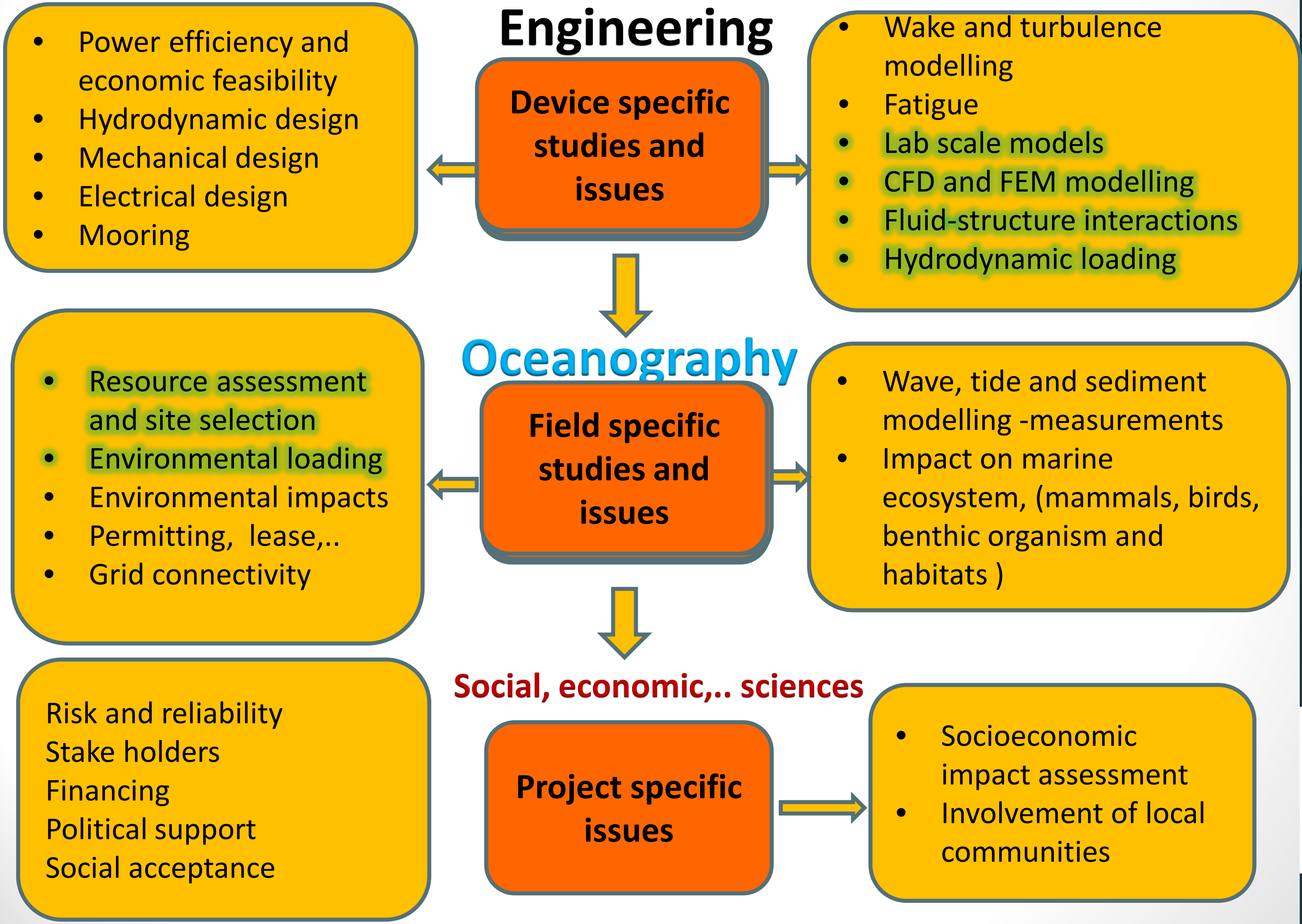
Field specific studies and issues



Social, economic,.. sciences

Project specific issues

Wave-current interaction effects



Engineering

Device specific studies and issues

- Power efficiency and economic feasibility
- Hydrodynamic design
- Mechanical design
- Electrical design
- Mooring

- Wake and turbulence modelling
- Fatigue
- Lab scale models
- CFD and FEM modelling
- Fluid-structure interactions
- Hydrodynamic loading

Oceanography

Field specific studies and issues

- Resource assessment and site selection
- Environmental loading
- Environmental impacts
- Permitting, lease,..
- Grid connectivity

- Wave, tide and sediment modelling -measurements
- Impact on marine ecosystem, (mammals, birds, benthic organism and habitats)

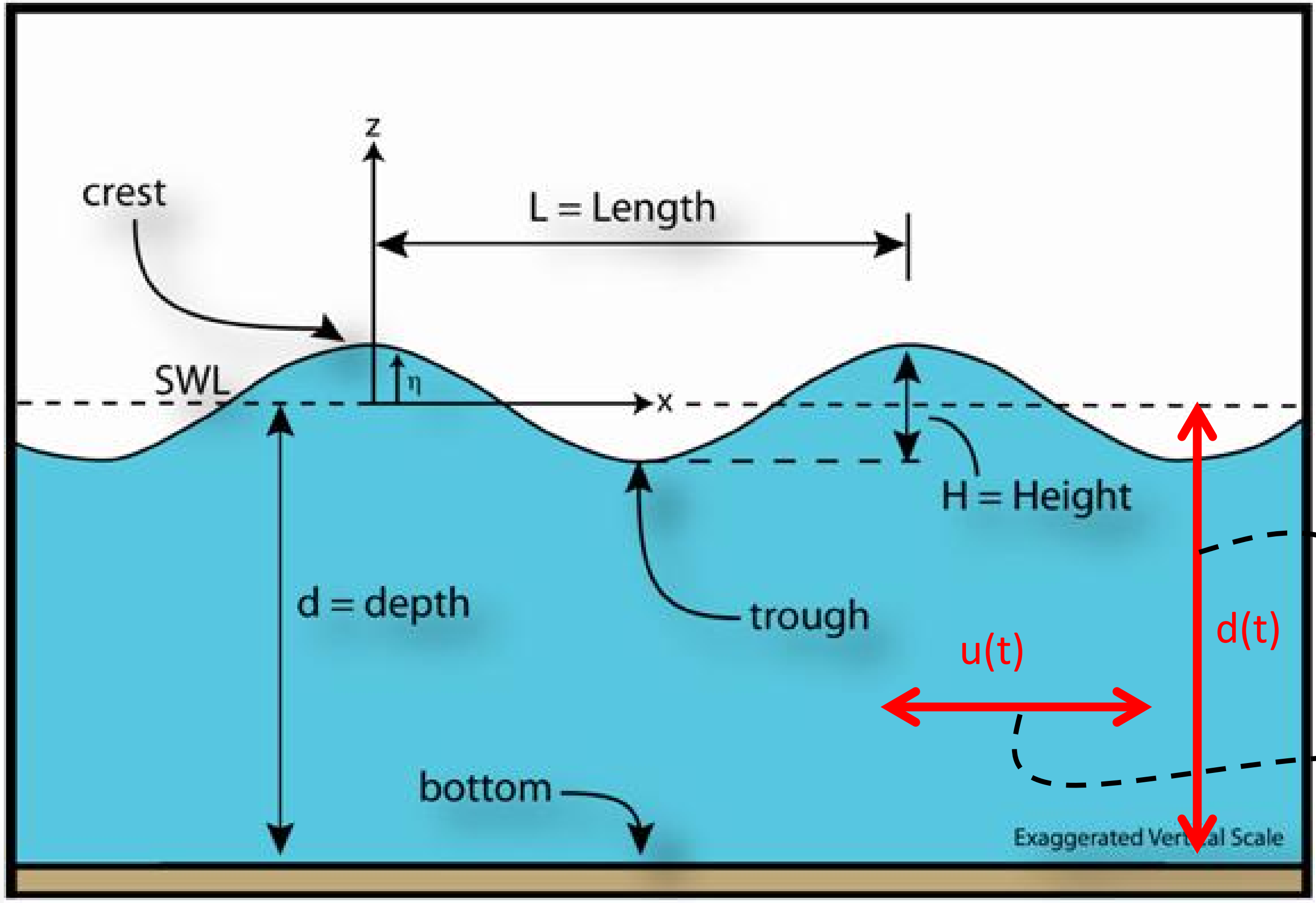
Social, economic,.. sciences

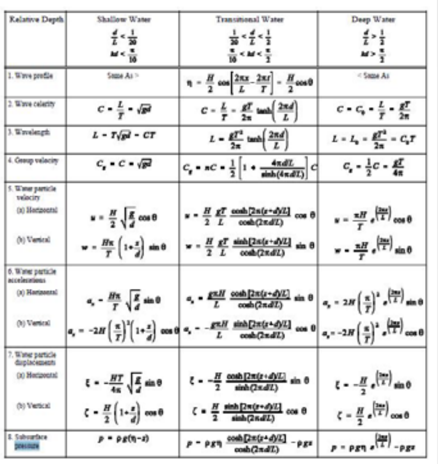
Project specific issues

Risk and reliability
Stake holders
Financing
Political support
Social acceptance

- Socioeconomic impact assessment
- Involvement of local communities

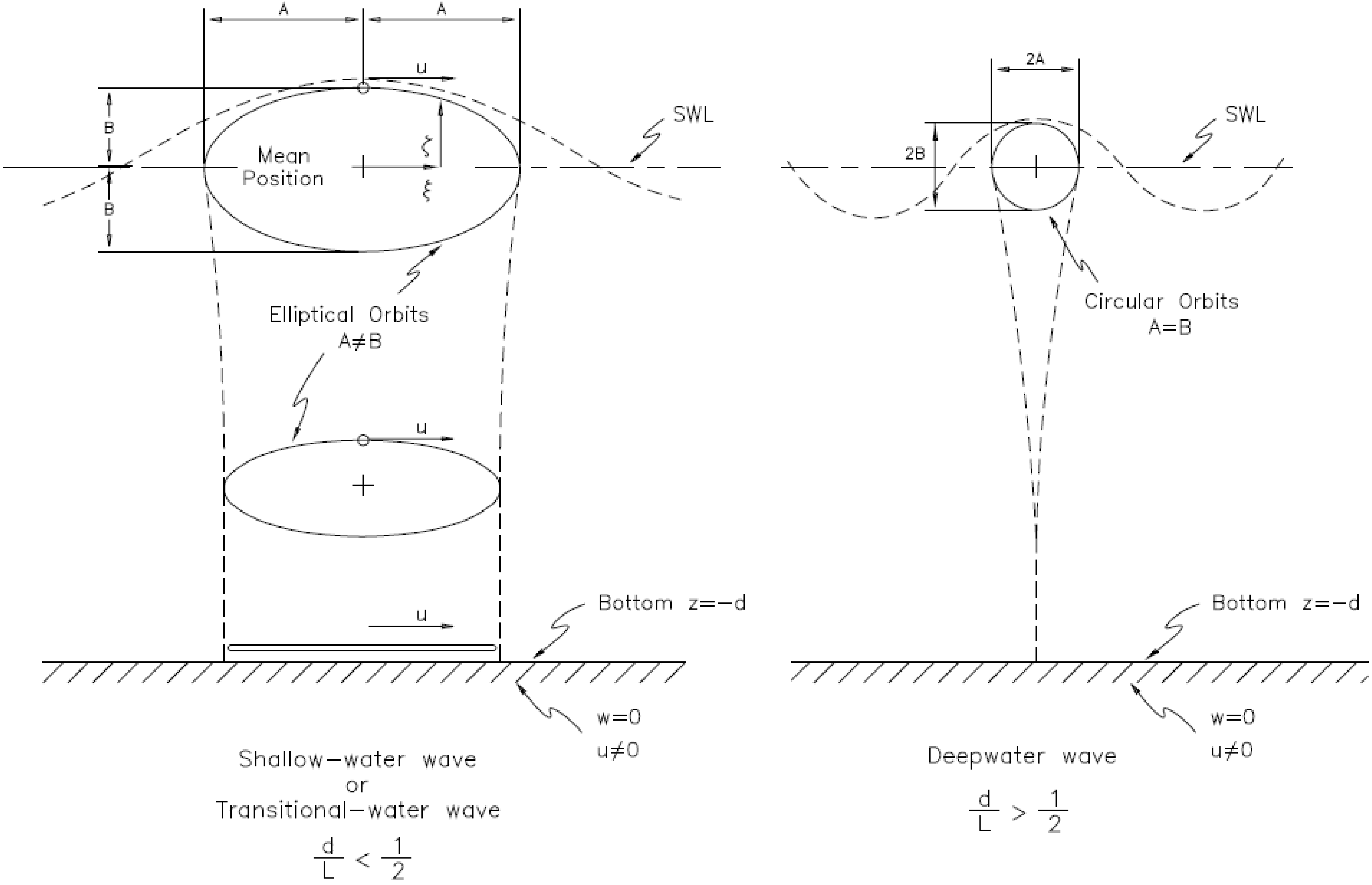
Linear wave theory, approach





Relative Depth	Shallow Water $\frac{d}{L}<\frac{1}{20}$ $kd<\frac{\pi}{10}$	Transitional Water $\frac{1}{20}<\frac{d}{L}<\frac{1}{2}$ $\frac{\pi}{10}<kd<\frac{\pi}{2}$	Deep Water $\frac{d}{L}>\frac{1}{2}$ $kd>\frac{\pi}{2}$
1. Wave profile	Same As >	$\eta=\frac{H}{2}\cos\left[\frac{2\pi x}{L}-\frac{2\pi t}{T}\right]=\frac{H}{2}\cos\theta$	< Same As
2. Wave celerity	$C=\frac{L}{T}=\sqrt{gd}$	$C=\frac{L}{T}=\frac{gT}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$	$C=C_0=\frac{L}{T}=\frac{gT}{2\pi}$
3. Wavelength	$L=T\sqrt{gd}=CT$	$L=\frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$	$L=L_0=\frac{gT^2}{2\pi}=C_0T$
4. Group velocity	$C_g=C=\sqrt{gd}$	$C_g=nC=\frac{1}{2}\left[1+\frac{4\pi d/L}{\sinh(4\pi d/L)}\right]C$	$C_g=\frac{1}{2}C=\frac{gT}{4\pi}$
5. Water particle velocity (a) Horizontal (b) Vertical	$u=\frac{H}{2}\sqrt{\frac{g}{d}}\cos\theta$ $w=\frac{H\pi}{T}\left(1+\frac{z}{d}\right)\sin\theta$	$u=\frac{H}{2}\frac{gT}{L}\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\cos\theta$ $w=\frac{H}{2}\frac{gT}{L}\frac{\sinh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\sin\theta$	$u=\frac{\pi H}{T}e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$ $w=\frac{\pi H}{T}e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$
6. Water particle accelerations (a) Horizontal (b) Vertical	$a_x=\frac{H\pi}{T}\sqrt{\frac{g}{d}}\sin\theta$ $a_z=-2H\left(\frac{\pi}{T}\right)^2\left(1+\frac{z}{d}\right)\cos\theta$	$a_x=\frac{g\pi H}{L}\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\sin\theta$ $a_z=-\frac{g\pi H}{L}\frac{\sinh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\cos\theta$	$a_x=2H\left(\frac{\pi}{T}\right)^2e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$ $a_z=-2H\left(\frac{\pi}{T}\right)^2e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
7. Water particle displacements (a) Horizontal (b) Vertical	$\xi=-\frac{HT}{4\pi}\sqrt{\frac{g}{d}}\sin\theta$ $\zeta=\frac{H}{2}\left(1+\frac{z}{d}\right)\cos\theta$	$\xi=-\frac{H}{2}\frac{\cosh[2\pi(z+d)/L]}{\sinh(2\pi d/L)}\sin\theta$ $\zeta=\frac{H}{2}\frac{\sinh[2\pi(z+d)/L]}{\sinh(2\pi d/L)}\cos\theta$	$\xi=-\frac{H}{2}e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$ $\zeta=\frac{H}{2}e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
8. Subsurface pressure	$p=\rho g(\eta-z)$	$p=\rho g\eta\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}-\rho gz$	$p=\rho g\eta e^{\left(\frac{2\pi z}{L}\right)}-\rho gz$

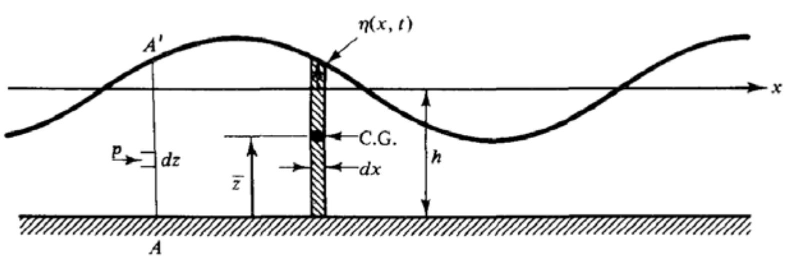
M_2 TIDE


A
A
u
B
B
Mean Position
ζ
ξ
SWL
Elliptical Orbits
A≠B
u
u
Bottom z=−d
w=0
u≠0
Shallow−water wave
or
Transitional−water wave
$\frac{d}{L} < \frac{1}{2}$
2A
2B
SWL
Circular Orbits
A=B
Bottom z=−d
w=0
u≠0
Deepwater wave
$\frac{d}{L} > \frac{1}{2}$

(USACE 2008)

Wave energy in linear theory

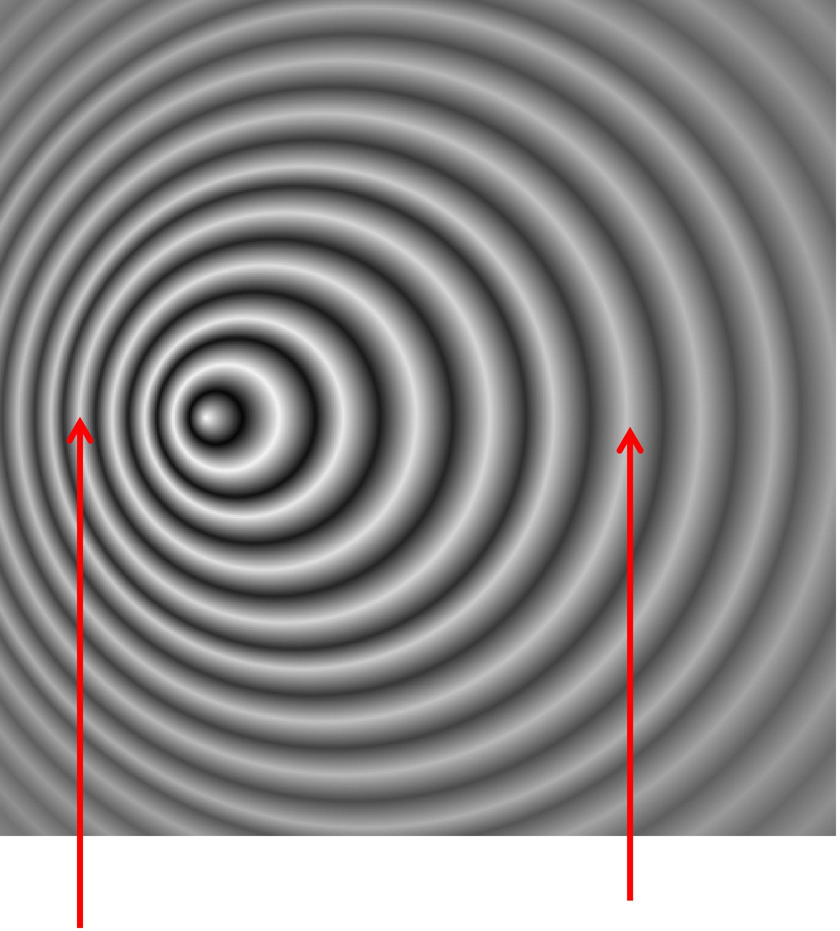
$$P = \int_0^T \int_{-h}^{\eta} p_D u \, dz dt$$



$$= \frac{1}{8}\, \rho g H^2 C\{\frac{1}{2}(1 + \frac{2kh}{\sinh 2kh})\}$$

Wave energy

$$C_g = C\{\frac{1}{2}(1 + \frac{2kh}{\sinh 2kh})\}$$



Doppler shift

$$\sigma + \vec{k}.\vec{U} \ = \omega^*$$

k = wave number,
h = water depth.
σ = the **relative** wave frequency - moving
ω^*= the **absolute** wave frequency - stationary

$$C^* = U_o^t + \sqrt{\frac{g}{k^*}\tanh k^* h}$$

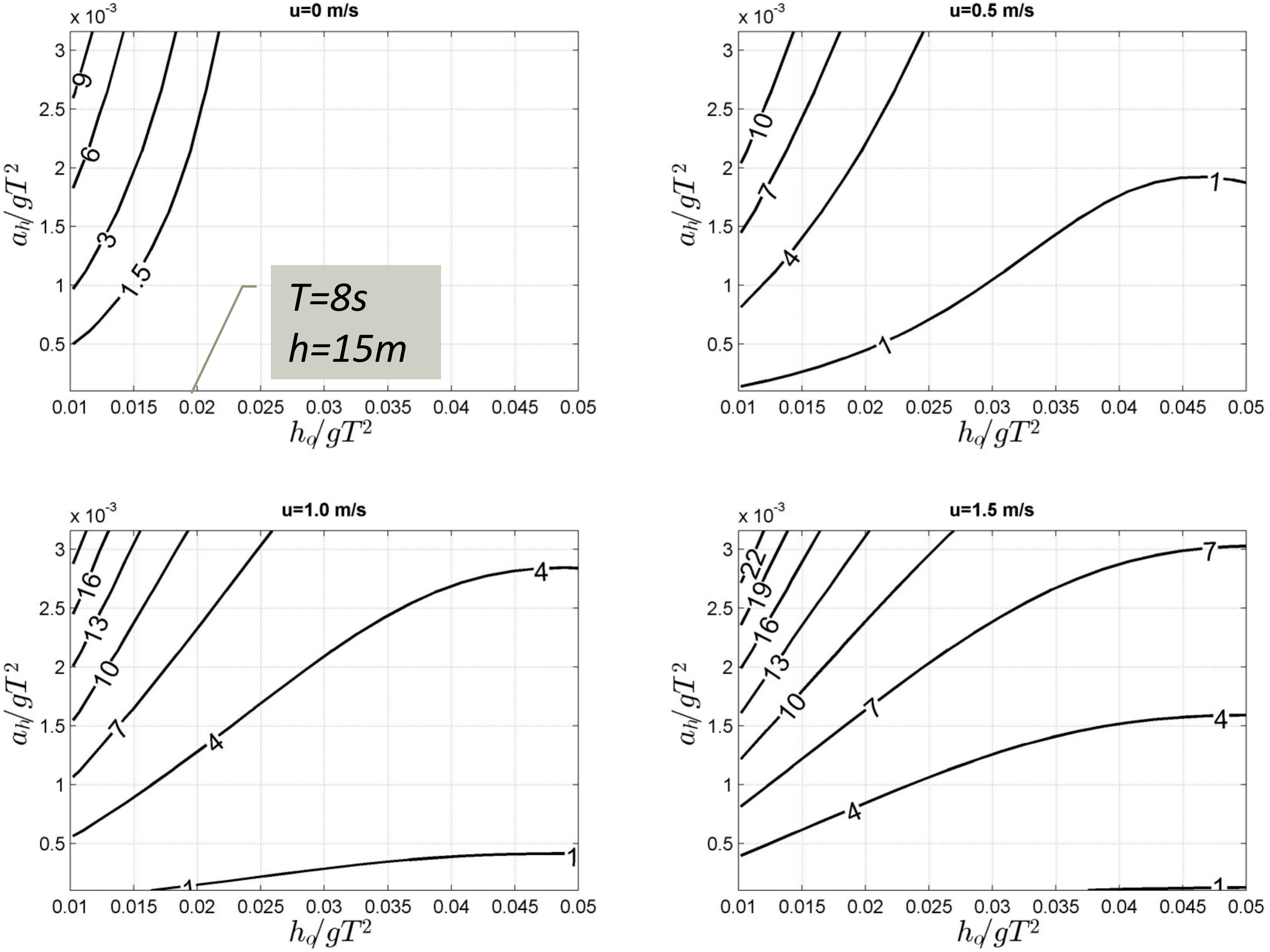
Water depth

$$C_g^* = C^* \{ \frac{1}{2} (1 + \frac{2k^* h}{\sinh 2k^* h}) \}$$

Wave celerity

Wave number

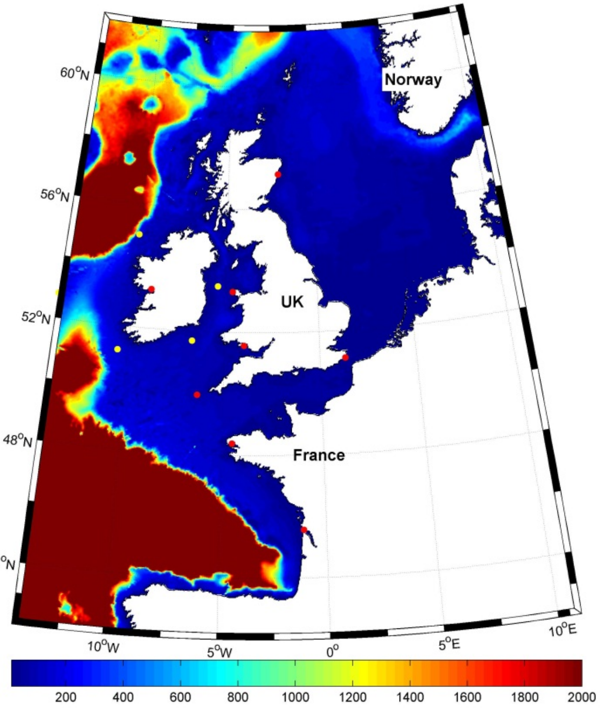
* Affected by tide



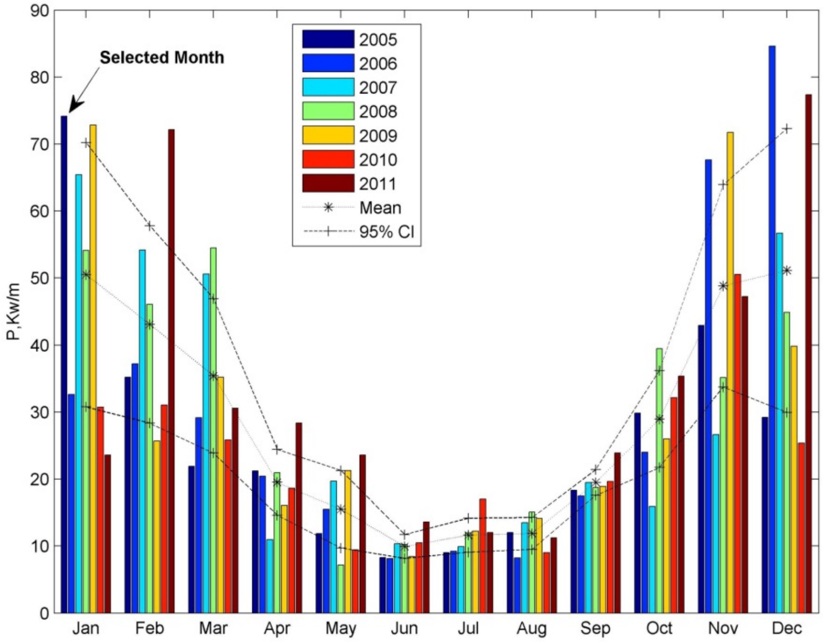
T=8s
h=15m

Effect=f(tidal range, current strength, wave period)

Application to NW European shelf
ROMS and SWAN models



Study area

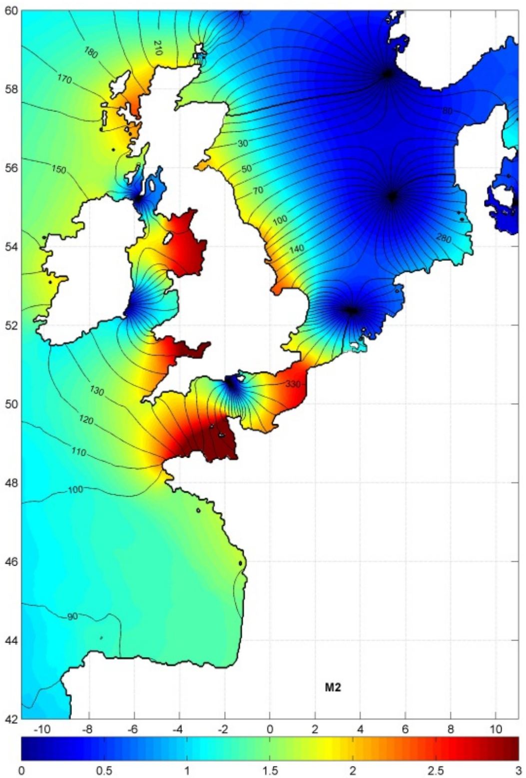


Wave power variability

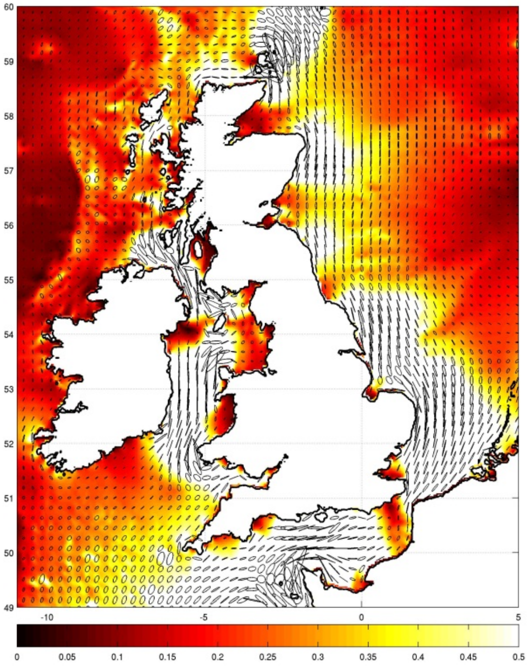
Neill and Hashemi 2013; Hashemi and Neill in press;

ROMS

Tidal range



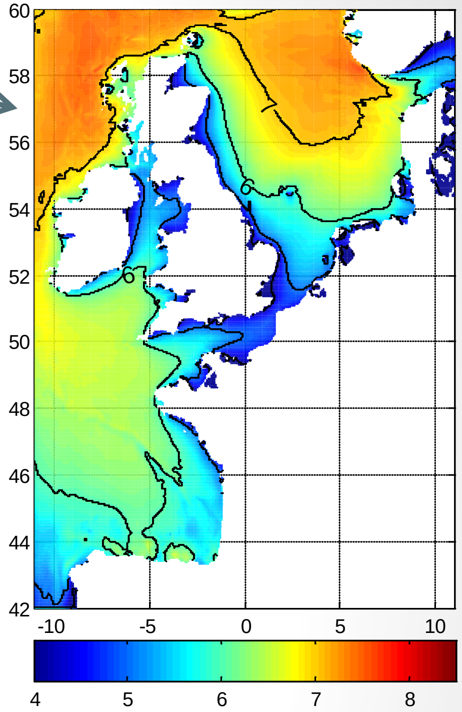
Current

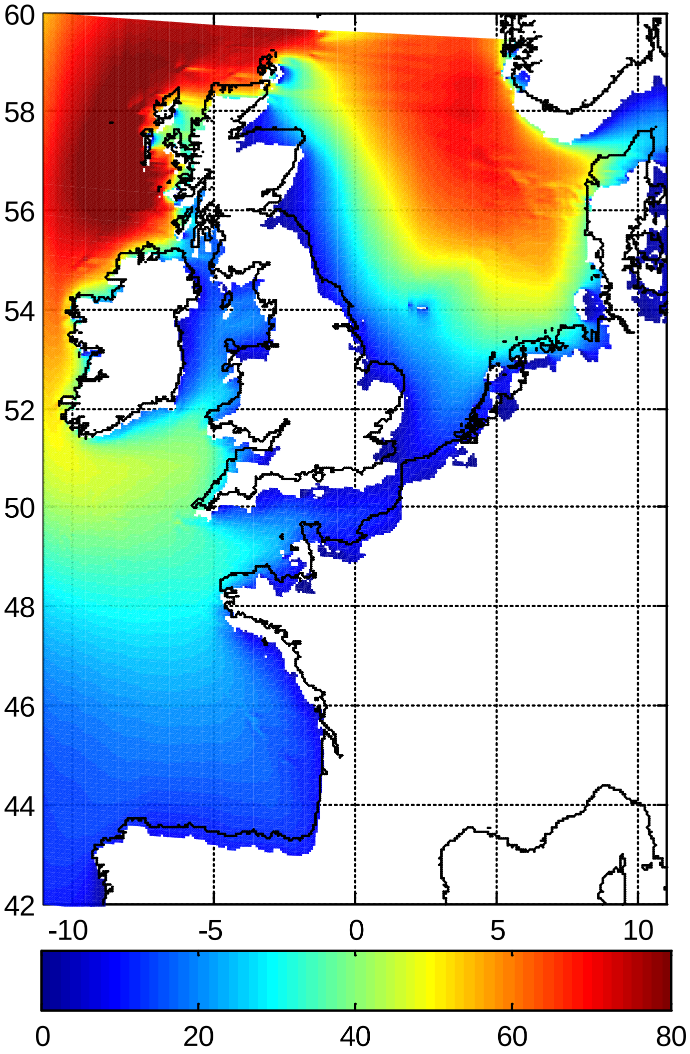


M2

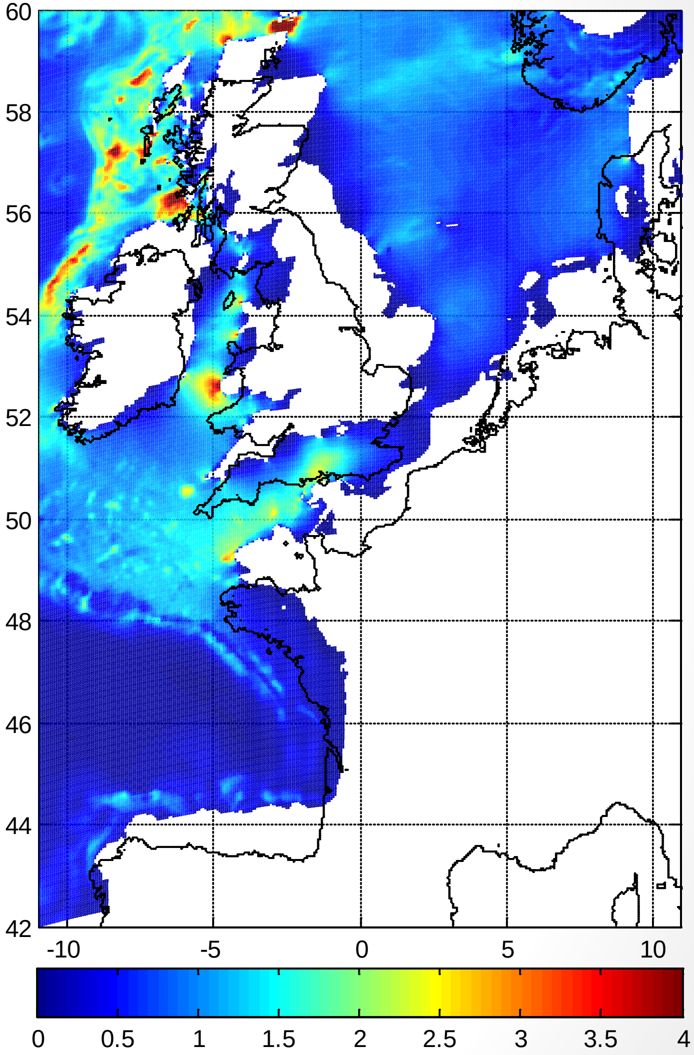
SWAN

Wave period

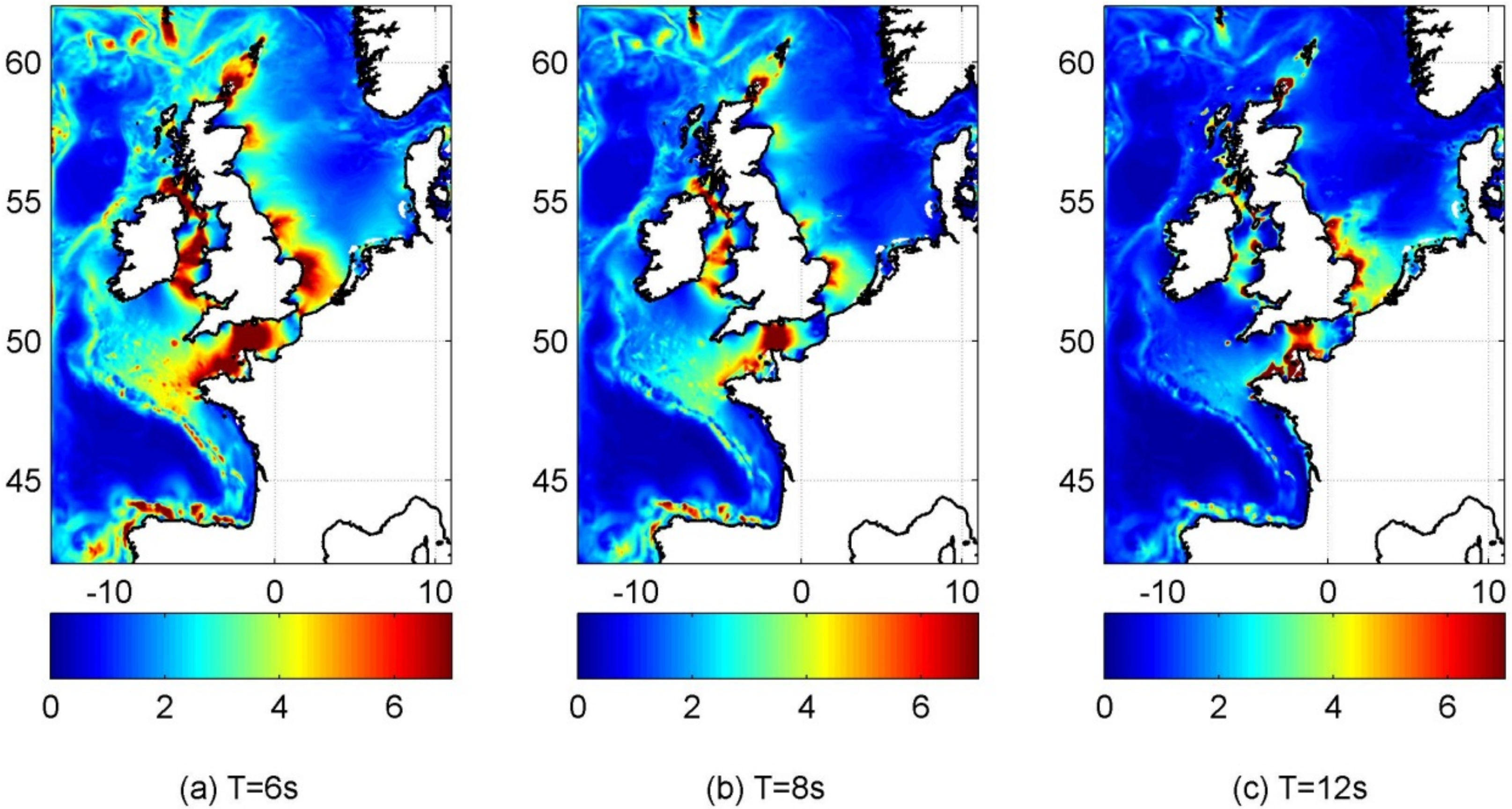




Wave power, Jan 2005



Effect of tides on the wave power



(a) T=6s

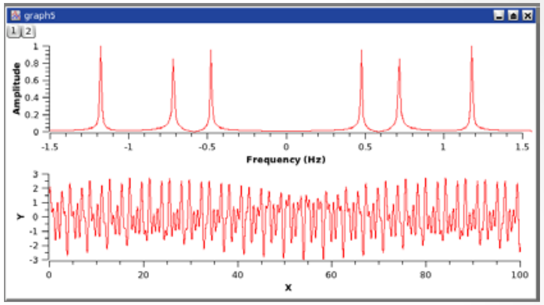
(b) T=8s

(c) T=12s

Effect of tides on the wave power

Shortcomings

I. Effect of tides on the wave height
II. Relative direction of waves and tidal currents
III. Effect of tides on the wave refraction

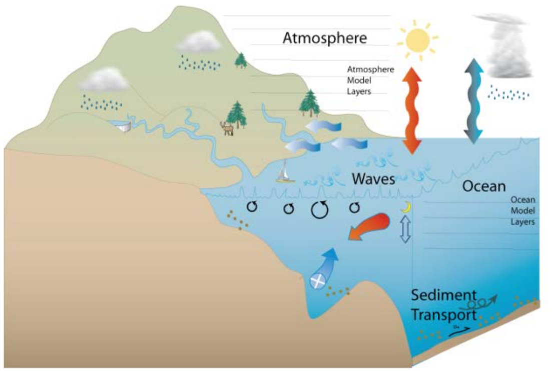


Fast Fourier Analysis

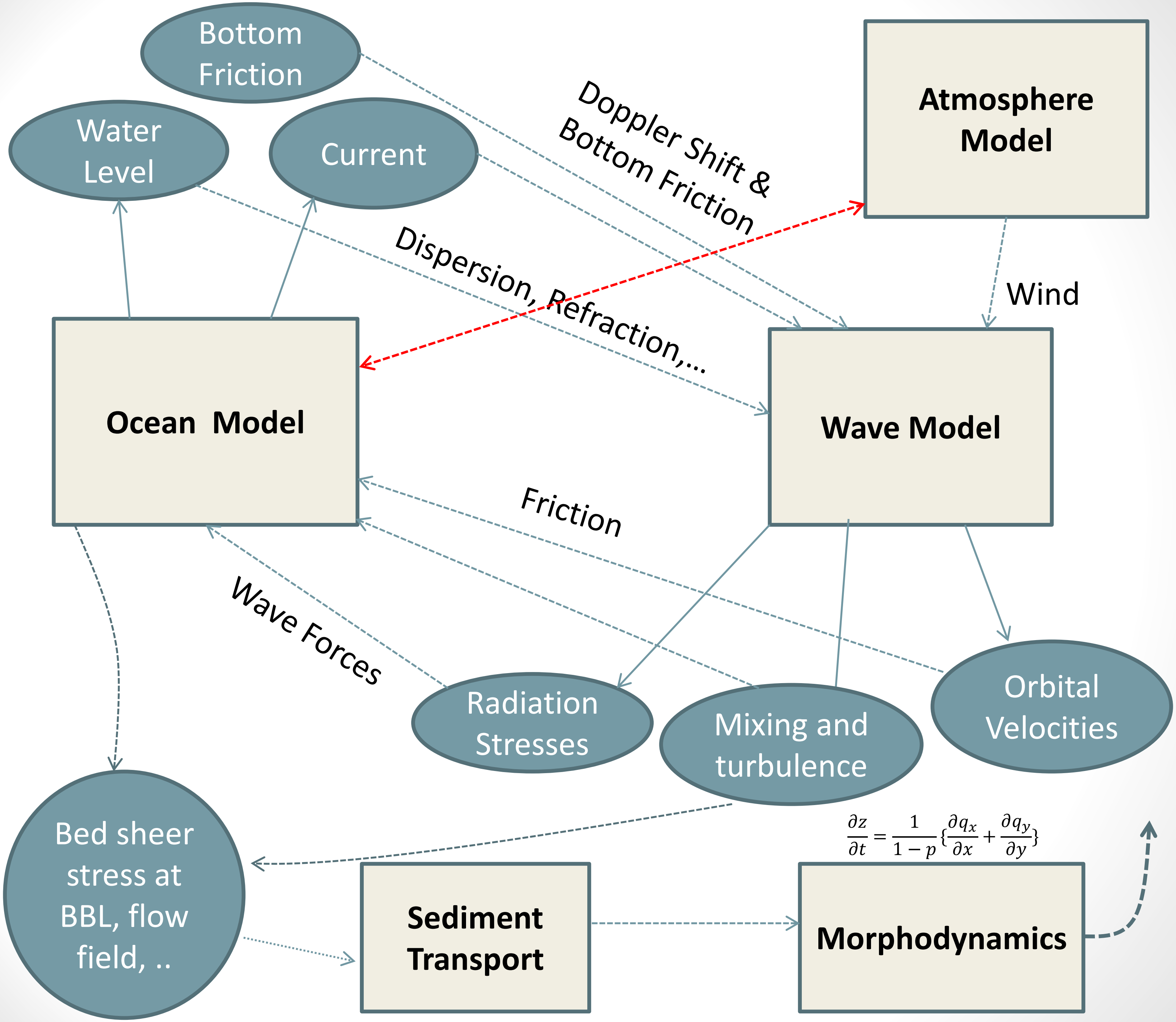
The method is good as a first estimate; More sophisticated modelling?

Model coupling?

Coupled-Ocean-Atmosphere-Wave- Sediment Transport Modelling System (ROMS-SWAN-WRF)



COAWST Modeling System



Bottom Friction

Water Level

Current

Atmosphere Model

Doppler Shift & Bottom Friction

Dispersion, Refraction,…

Wind

Ocean Model

Wave Model

Friction

Wave Forces

Radiation Stresses

Mixing and turbulence

Orbital Velocities

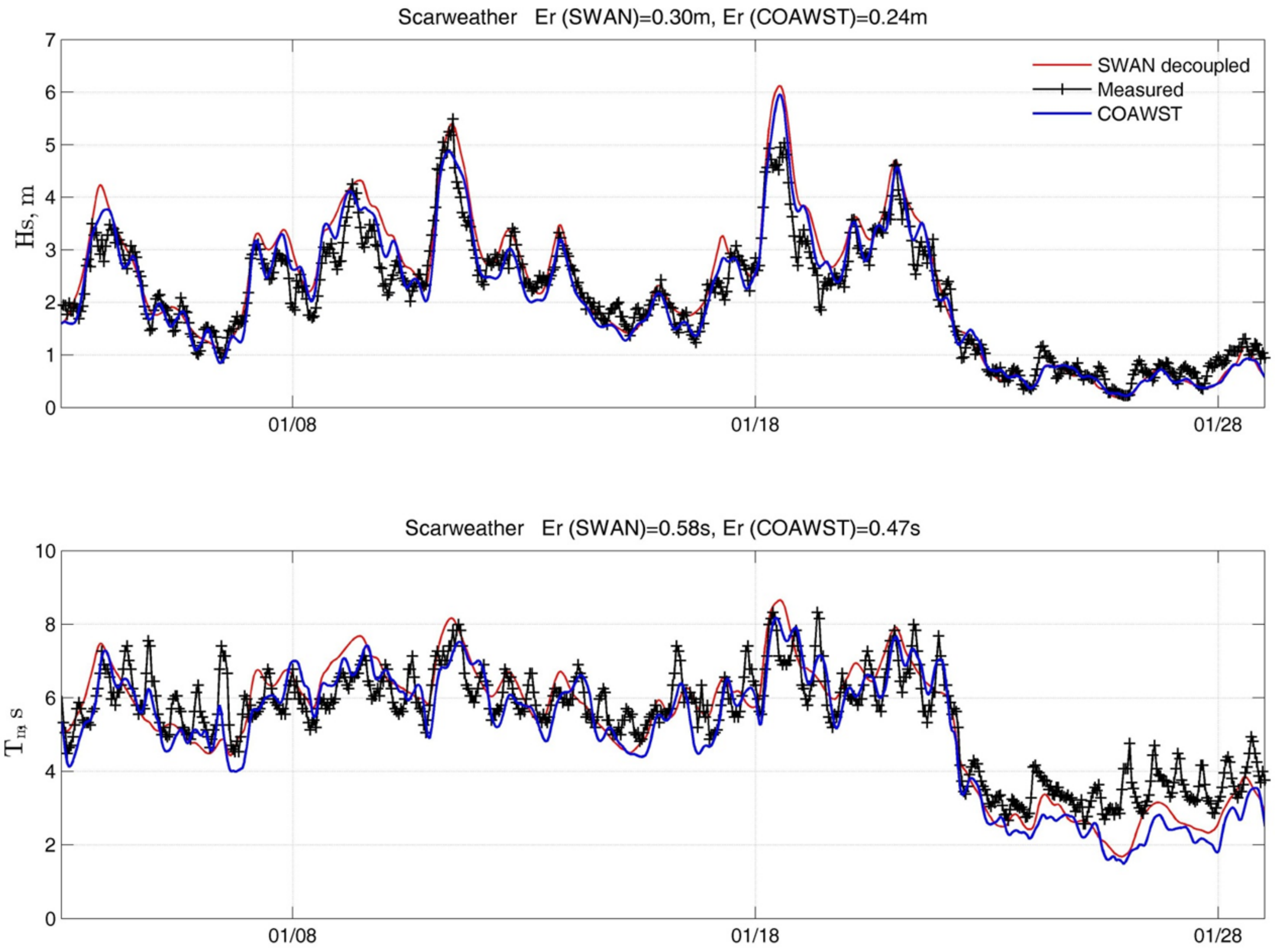
Bed sheer stress at BBL, flow field, ..

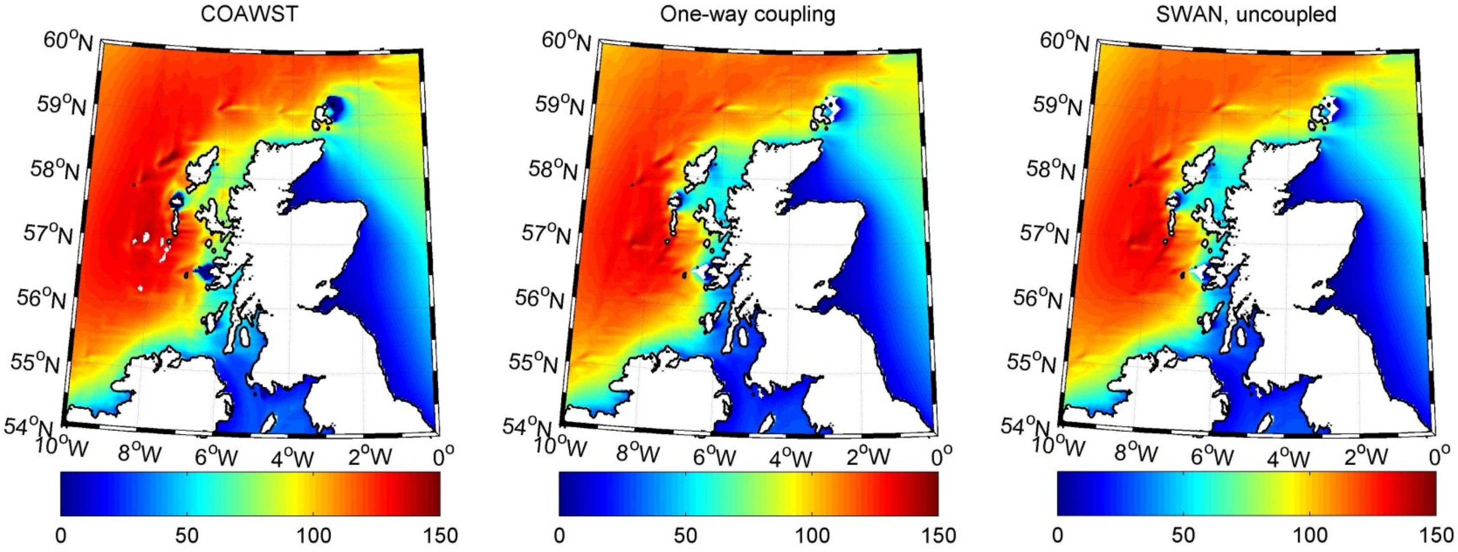
Sediment Transport

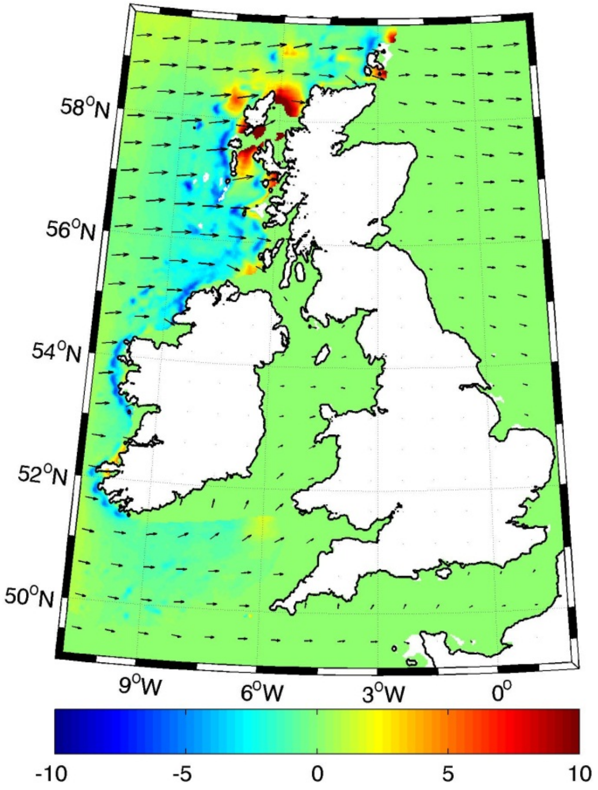
$$\frac{\partial z}{\partial t} = \frac{1}{1-p}\left\{\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y}\right\}$$

Morphodynamics

SCARWEATHER Ceafas Wavebuoy Bristol Channel




COAWST
One-way coupling
SWAN, uncoupled
60°N
59°N
58°N
57°N
56°N
55°N
54°N
10°W
8°W
6°W
4°W
2°W
0°
0
50
100
150



Effect of tides on the wave Power, January 2005 (%)

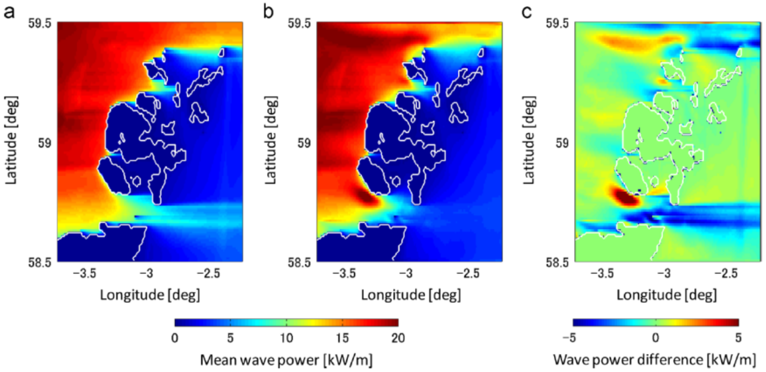


Fig. 10. Mean wave power per metre for the simulations without current (left) and with current (middle), together with the difference in the mean wave power between the two cases (right). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Saruwatari et al. 2013
Pentland Firth

Conclusions

- Simplified method, rapid and convenient, order of magnitude estimate
- Up to 10% impact on wave resource estimation
- Currents are the main source of error
- More impacts on lower wave energy and higher tide regions
- Detail high resolution models for specific sites
- Model coupling challenges (Finding the best formulation, including the relevant processes, scaling issues)

The effect of wave-tide interactions on simulations of ocean renewable energy
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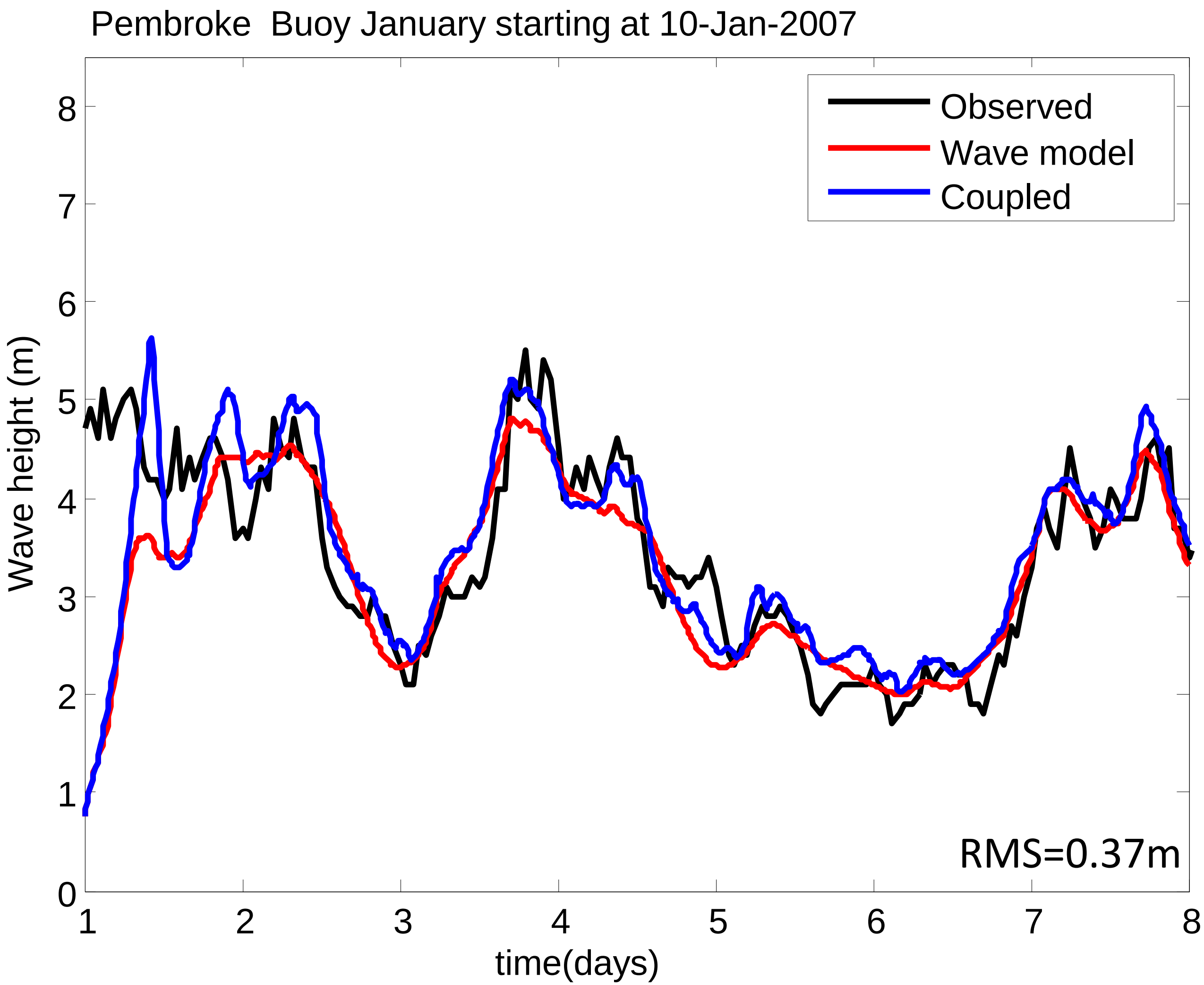
PRIFYSGOL
BANGOR
UNIVERSITY
1884



Estanislao Gavilan

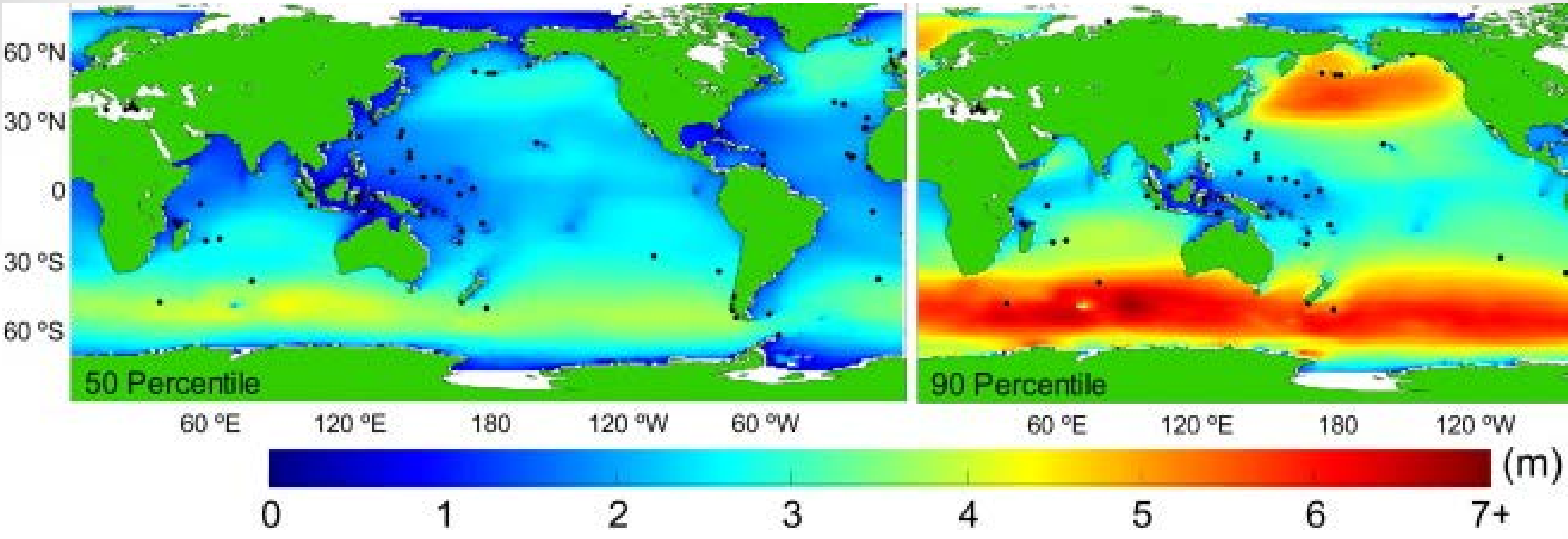
The effect of wave-tide interactions on simulations of ocean renewable energy

School of Ocean Sciences, Bangor University, Feb 2014

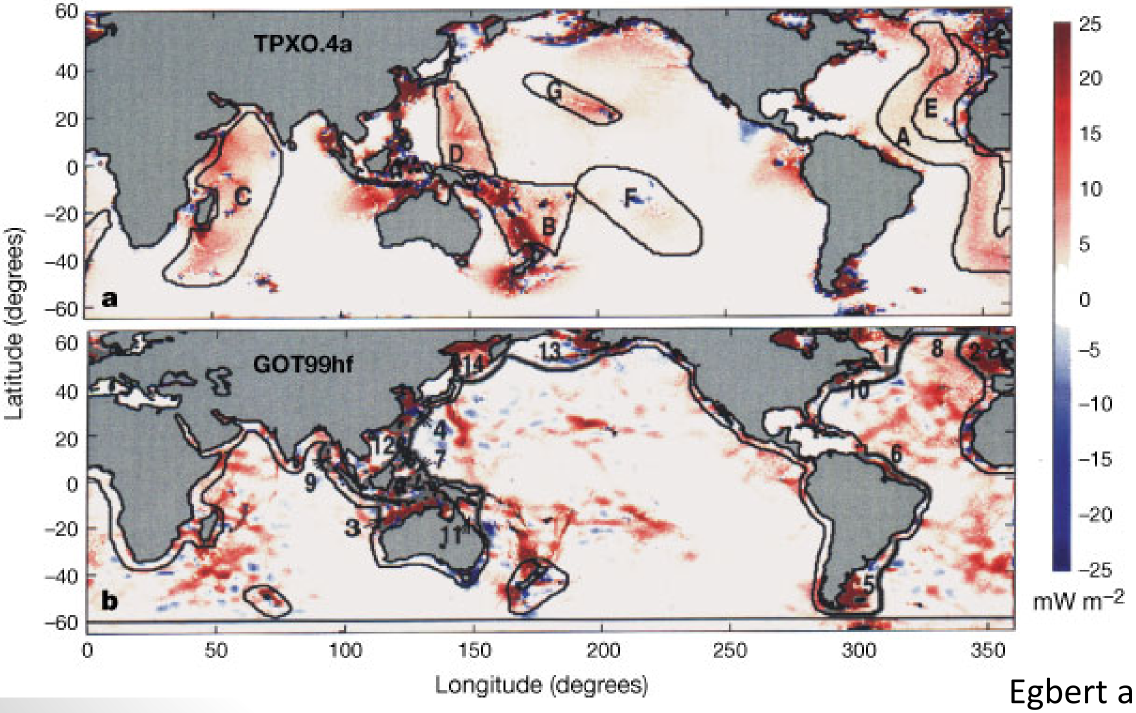
Increasing uncertainty in model coupling?
Uncertainty >> The process ??

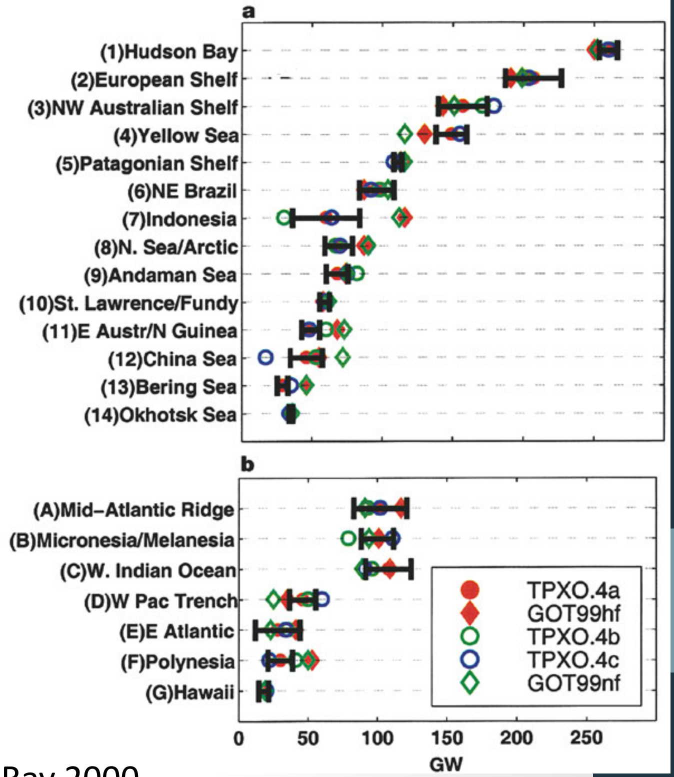
SWAN technical manual

- The effect of a mean current on the wave energy dissipation due to bottom friction is not taken into account in SWAN.
- The reasons for this are given by Tolman (1992b) . He found that the error in finding a correct estimate of the bottom roughness length scale has a much larger impact on the energy dissipation rate than the effect of a mean current

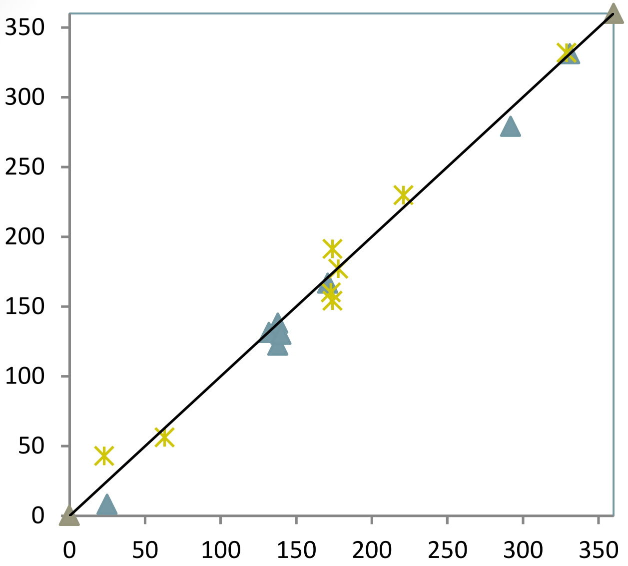


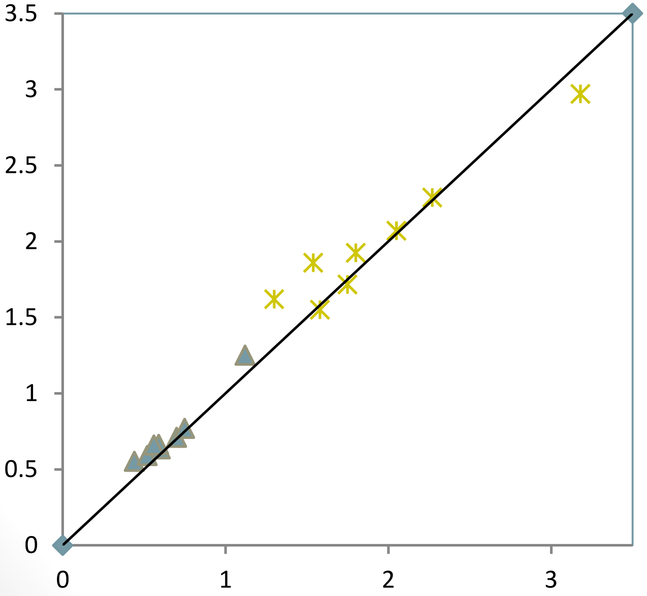
Arinaga and Cheung 2012

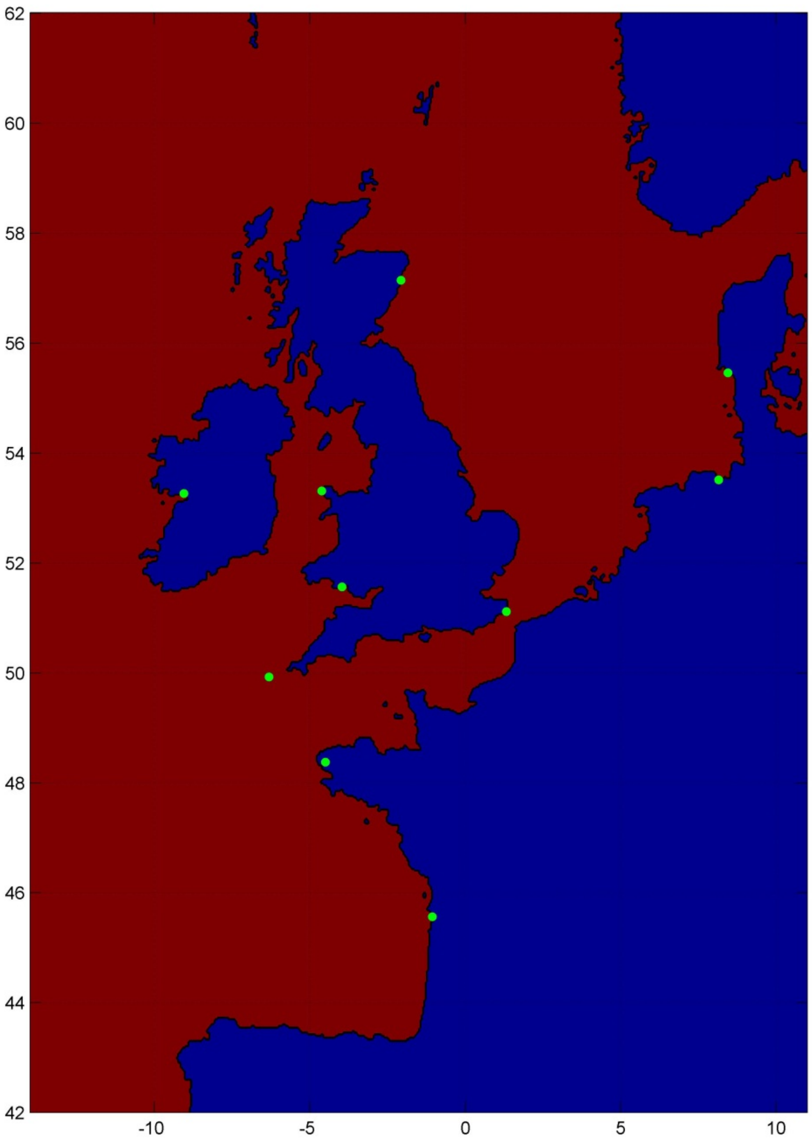




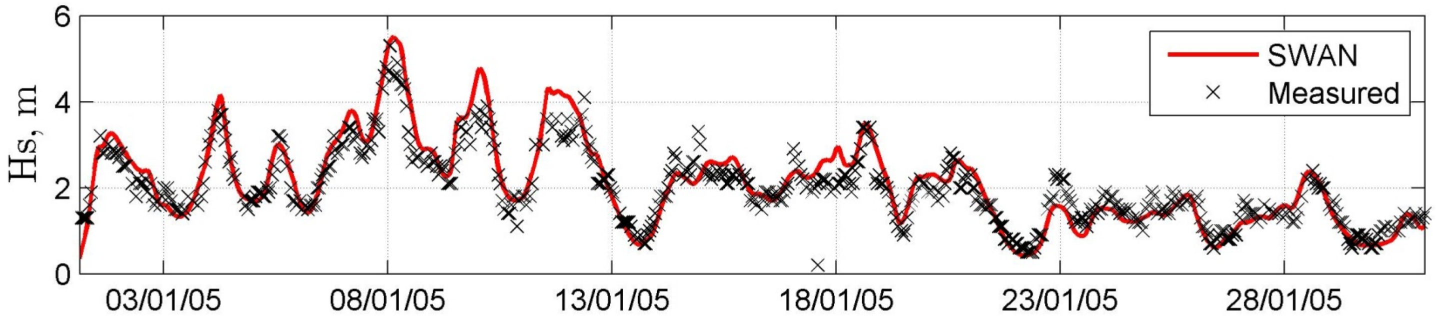
Egbert and Ray 2000


350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350


3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3

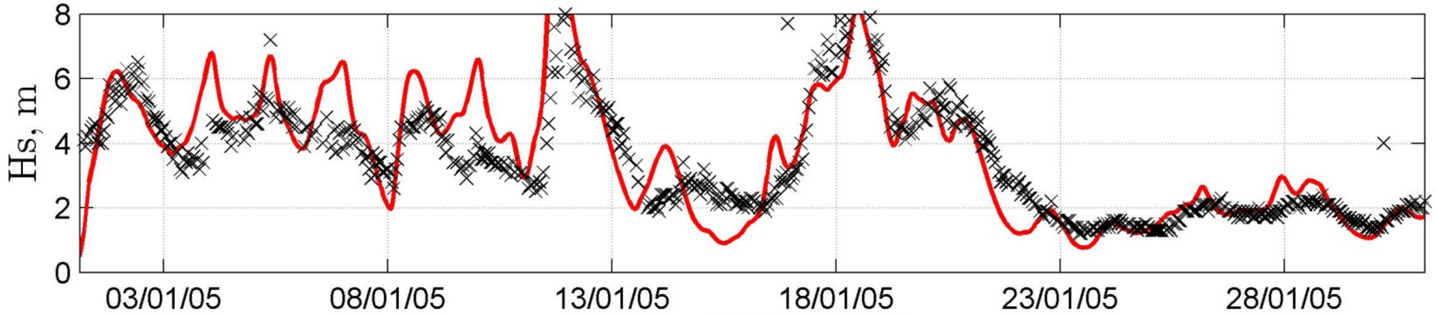

62
60
58
56
54
52
50
48
46
44
42
-10
-5
0
5
10

	M2						S2					
Station	**meas.**	**mod.**		**meas.**	**mod.**		**meas.**	**mod.**		**meas.**	**mod.**	
	g	g	Er	a, m	a, m	Er	g	g	Er	a, m	a, m	
Mumbles	171	167	4	3.18	2.97	0.21	221	230	9	1.12	1.25	0.13
St Marys	132	131	1	1.75	1.72	0.03	174	191	17	0.60	0.63	0.03
Holyhead	292	279	13	1.80	1.92	0.12	329	332	3	0.59	0.66	0.07
Aberdeen	25	8	17	1.30	1.62	0.32	63	56	7	0.44	0.55	0.11
Dover	331	331	0	2.27	2.29	0.02	23	43	20	0.70	0.71	0.01
Brest	138	138	0	2.05	2.07	0.02	178	177	1	0.75	0.77	0.02
Pointe de Grave	138	122	16	1.58	1.55	0.03	174	154	20	0.52	0.59	0.07
Galway	140	130	10	1.54	1.86	0.32	173	160	13	0.56	0.66	0.10
Average			8			0.13m			11			0.07m



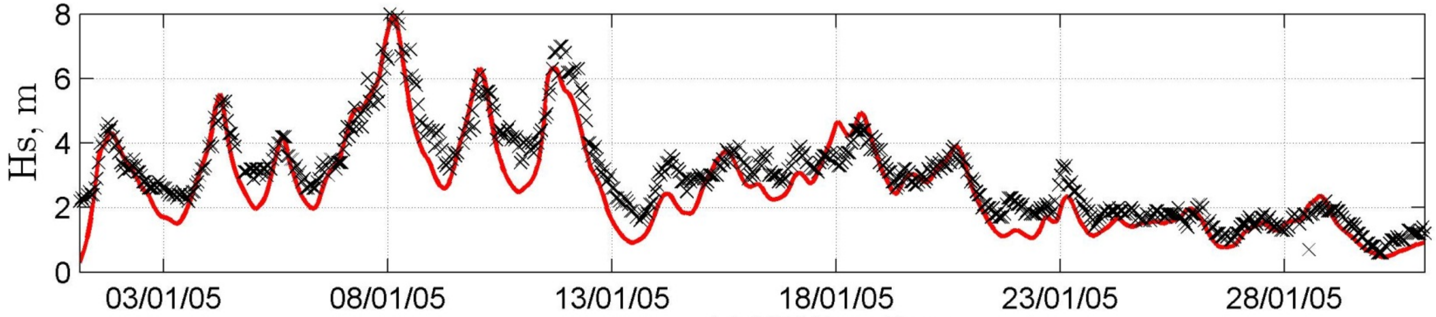
(a) M2 Wave Buoy

Error=0.23m



(b) M4 Wave Buoy

Error=0.70m?



(c) M5 Wave Buoy

Error=0.47m

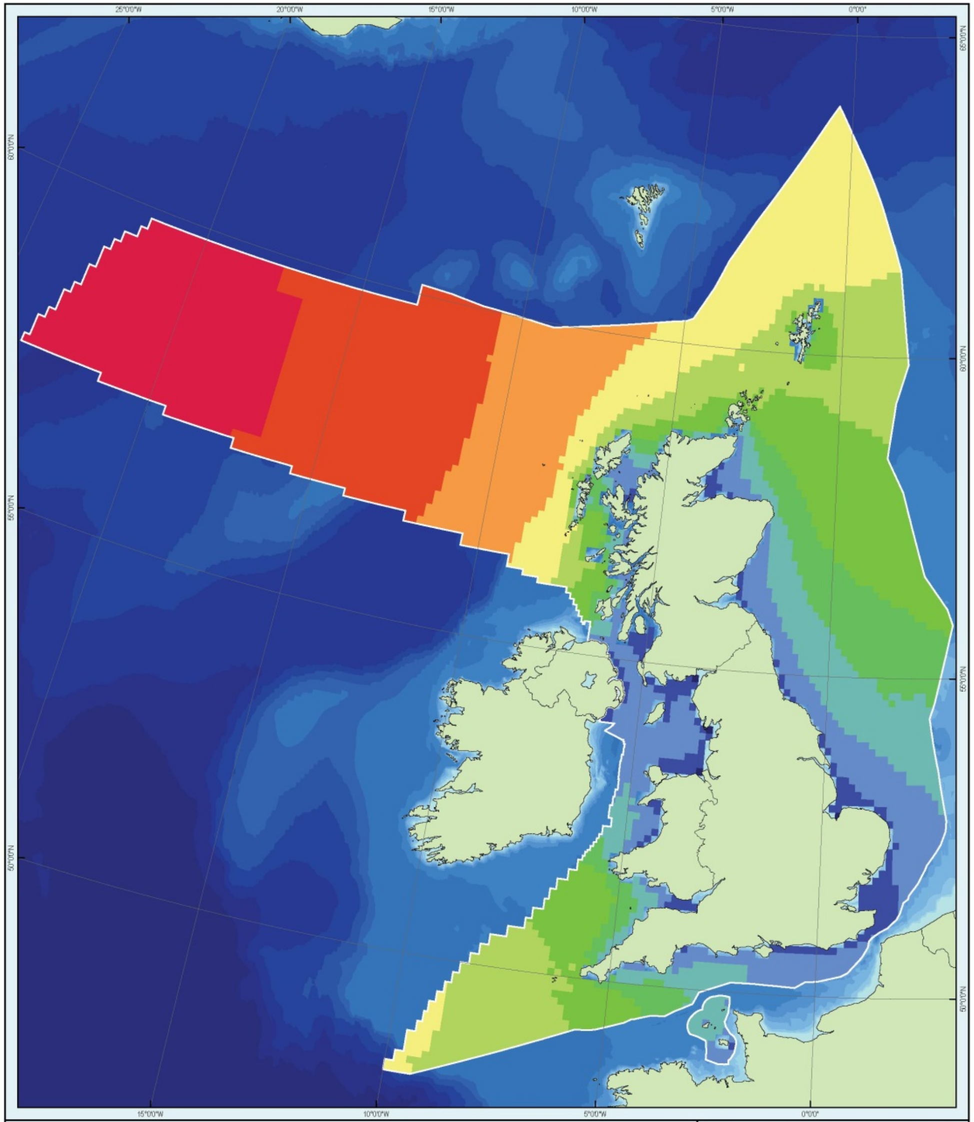


Figure 11 - Annual Mean Wave Power - Full Wave Field

Mean Wave Power (kW / m of wave crest)

■	> 110.0	■	30.1 - 40.0
■	100.1 - 110.0	■	20.1 - 30.0
■	90.1 - 100.0	■	15.1 - 20.0
■	80.1 - 90.0	■	10.1 - 15.0
■	70.1 - 80.0	■	5.1 - 10.0
■	60.1 - 70.0	■	1.1 - 5.0
■	50.1 - 60.0	■	< 1.1
■	40.1 - 50.0		

🟩 Land

□ UK Continental Shelf & Channel Islands Territorial Sea Limits

Kilometres

0 50 100 200 300 400

Projection	Transverse Mercator WGS 1984 UTM Zone 31 N
Scale	1:6,250,000 when printed A3

Map Designed and Produced by ABPmer

BERR Department for Business Enterprise & Regulatory Reform

Atlas of UK Marine Renewable Energy Resources

Notes

1. North of 63^{0} N and West of 12^{0} W, model cell size approximately 60km. Model cell size approximately 12km in all other areas.
2. Modelled wave data will be less robust in shallow water (<20m) and areas of complex bathymetry.
3. Wave data are based on hourly model hindcast values over 7 years.
4. Full Wave Field Power is calculated using the summation of wave power attributed to wind-wave and swell components.
5. Wave power is calculated for each horizontal metre of wave crest using the energy period calculation (T_e).
6. March 2008, Version 2.0.
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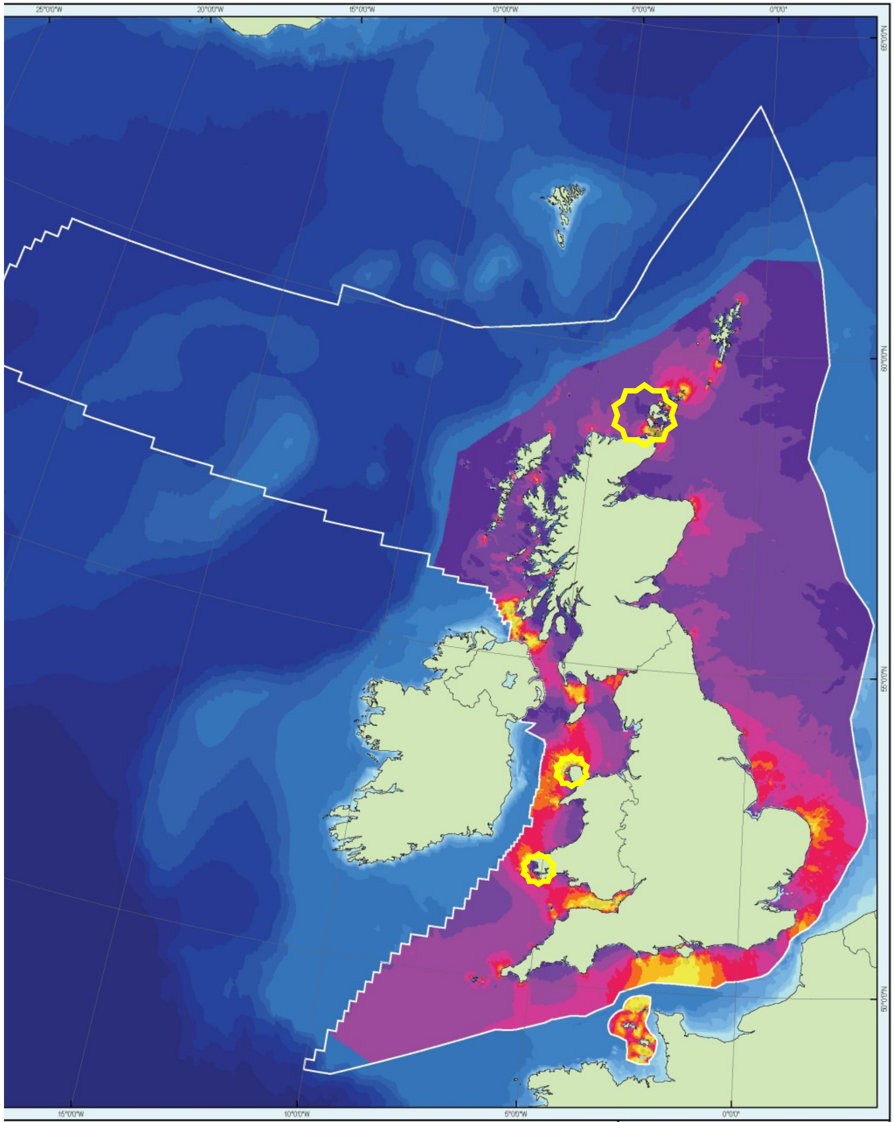

Figure 6 - Peak Flow for a Mean Spring Tide

Peak Flow (m/s)

■	> 4.00	■	1.26 - 1.50
■	3.51 - 4.00	■	1.01 - 1.25
■	3.01 - 3.50	■	0.76 - 1.00
■	2.51 - 3.00	■	0.51 - 0.75
■	2.01 - 2.50	■	0.26 - 0.50
■	1.76 - 2.00	■	0.11 - 0.25
■	1.51 - 1.75	■	< 0.11

🟩 Land

□ UK Continental Shelf & Channel Islands Territorial Sea Limits

Kilometres

200 300 400

	Transverse Mercator WGS 1984 UTM Zone 31 N
	1:6,250,000 when printed A3

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Atlas of UK Marine Renewable Energy Resources

Notes

1. Model accuracy is less robust in areas closer than 1km to land.
2. Tidal model based on data derived for an average tidal year.
3. Tidal flow is calculated in metres per second.
4. Tidal flow is calculated at mid depth in the water column.
5. March 2008, Version 2.0.
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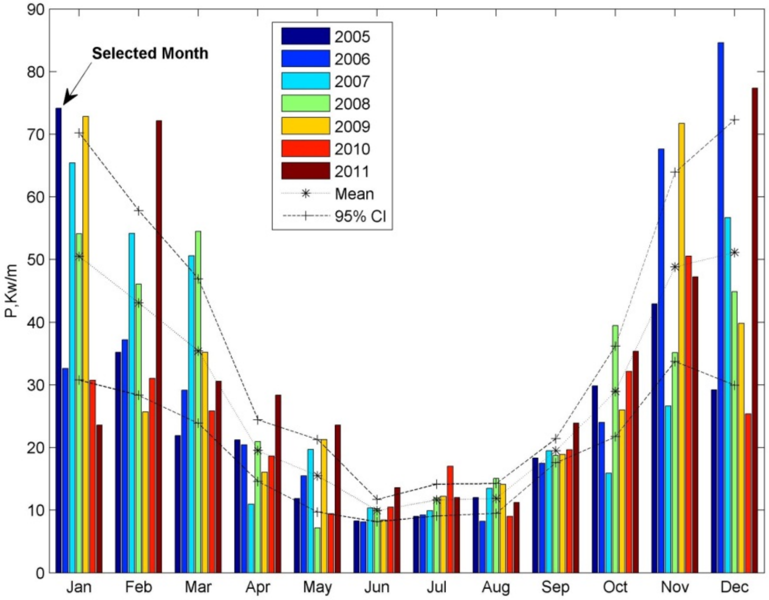
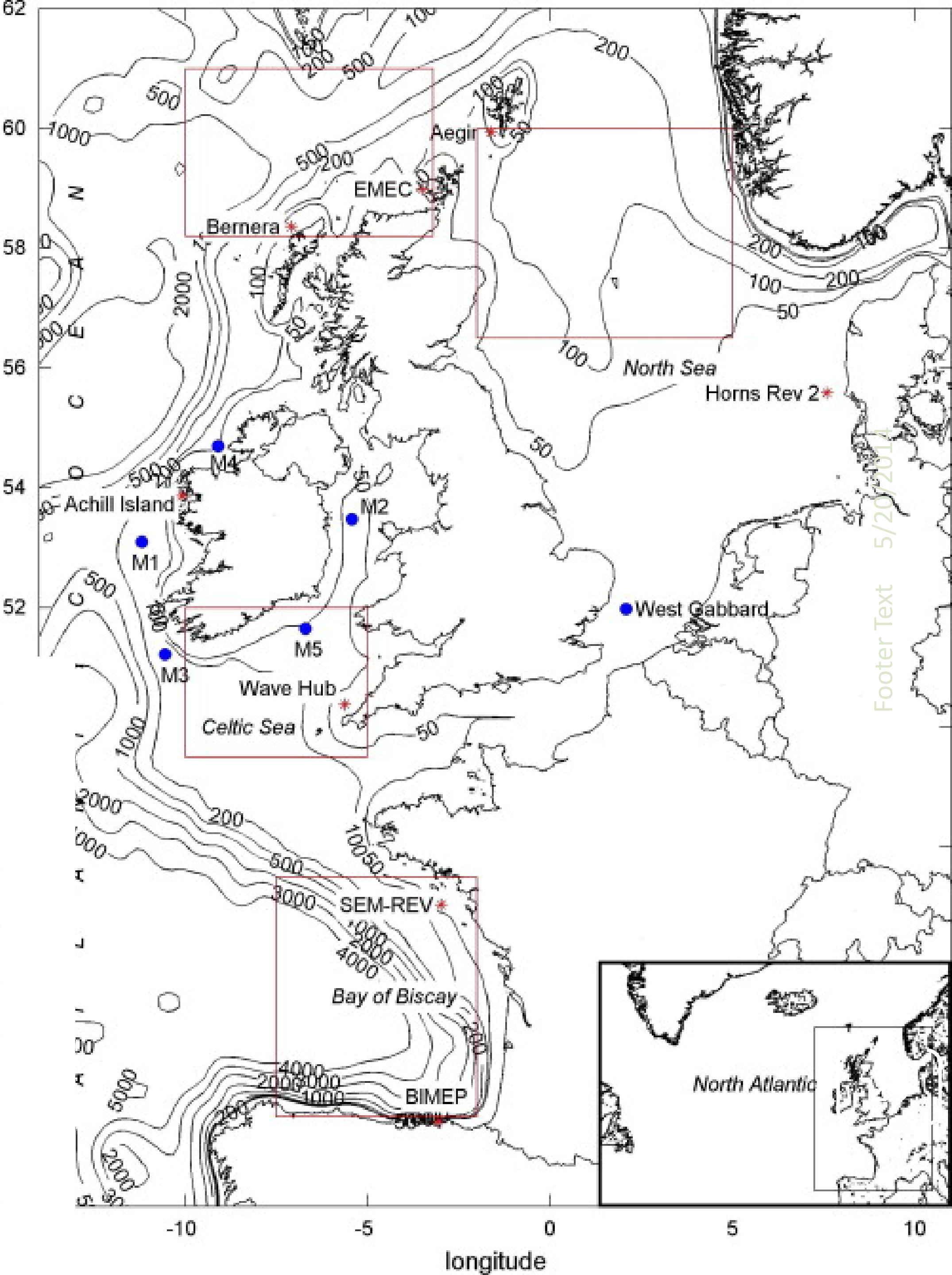
Method

- NA 1/6 Resolution
- SWAN 1/24
- 7 years of simulation
- High Performance Computing Wales





Theoretical background

Effect of tide on wave

Water Level Change
Steady and Unsteady Currents

$$\sigma^2 = gk \tanh kh \qquad \sigma = \omega - \vec{k}.\vec{U}$$

k = wave number,
h = water depth.
σ = the **relative** wave frequency - moving coordinate system
ω = the **absolute** wave frequency - stationary coordinate system

- **Doppler Shift**
- **Depth and current refraction**

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}$$

- **Wave generation by wind**
- **Effect of currents on bottom friction**

N. Guillou and G. Chapalain, "Modeling the tide-induced modulation of wave height in the outer Seine estuary", J COASTAL RES

Theoretical background

Effect of waves on currents

- **Wave radiation stresses**

$$\begin{cases} S_{xx} = \sum \frac{E}{2}\ [2n\,(\cos\theta)^2 + (2n-1)]\Delta\sigma\Delta\theta \\ S_{xy} = S_{yx} = \sum En \sin\theta \cos\theta \Delta\sigma\Delta\theta \\ S_{yy} = \sum \frac{E}{2}\ [2n\,(\sin\theta)^2 + (2n-1)]\Delta\sigma\Delta\theta \end{cases}$$

E = wave energy, *S* = radiation stress, θ = angle of wave propagation

$$n = \frac{C_g}{C} = \frac{1}{2}\ (1 + \frac{2kh}{\sinh 2kh})$$

$n \approx 1$ in shallow water $n \approx {}^{1}/_{2}$ in deep water,

- **Wave induced forces**

$$\begin{cases} F_x = -(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}) \\ F_y = -(\frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{yx}}{\partial x}) \end{cases}$$