The Hebridean Wave Model

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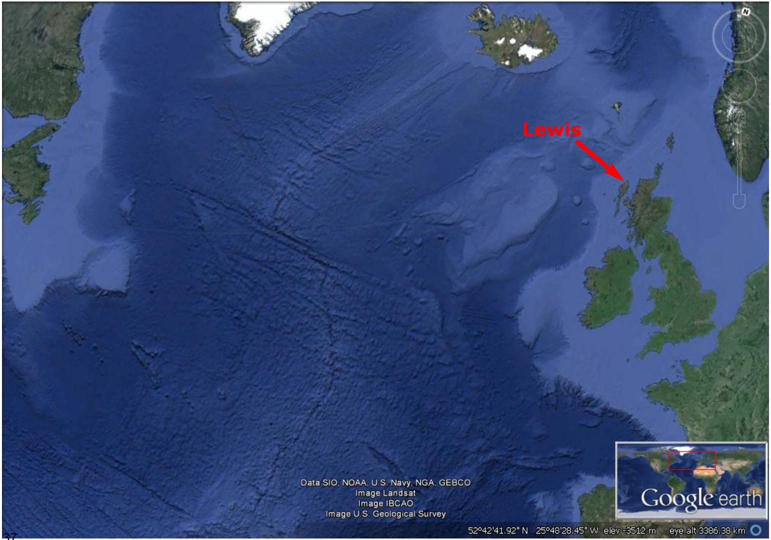
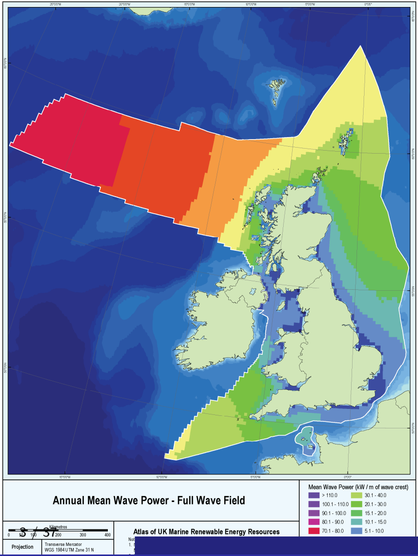
Welcome to Lewis



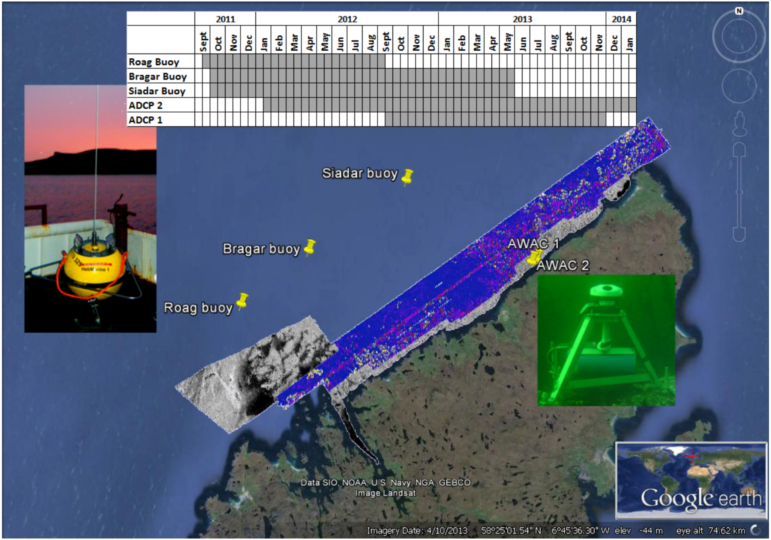
Wave Resource



Wave off Butt of Lewis

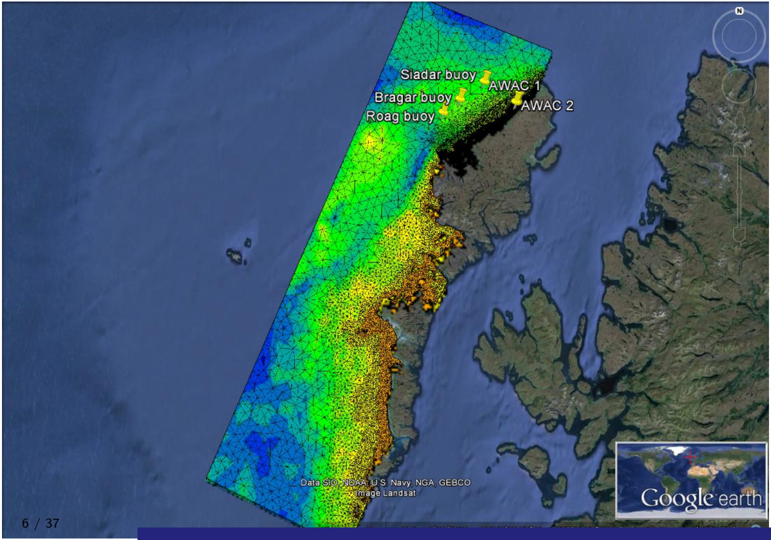
Planned Wave Energy Developments

Hebmarine Sensor Data

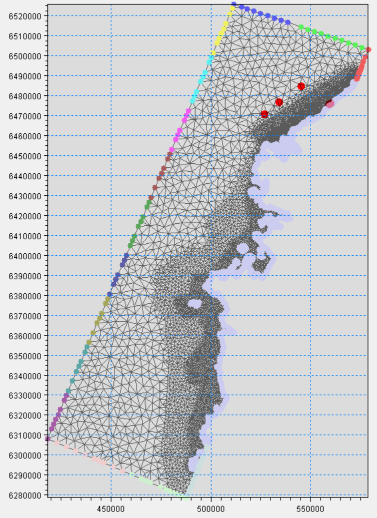


The Hebridean Wave Model Domain

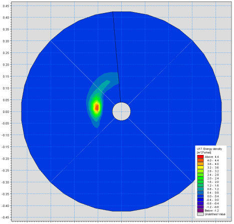
DHI Mike 21 Spectral Wave package



Energy Input



Hourly wave spectra at 15 boundary sections.



Wind input at 10m above sea level from ECMWF 0.75° grid.

Energy Transport and Dissipation

- Mike 21 models the evolution of wave spectra using the Wave Action Conservation Equation

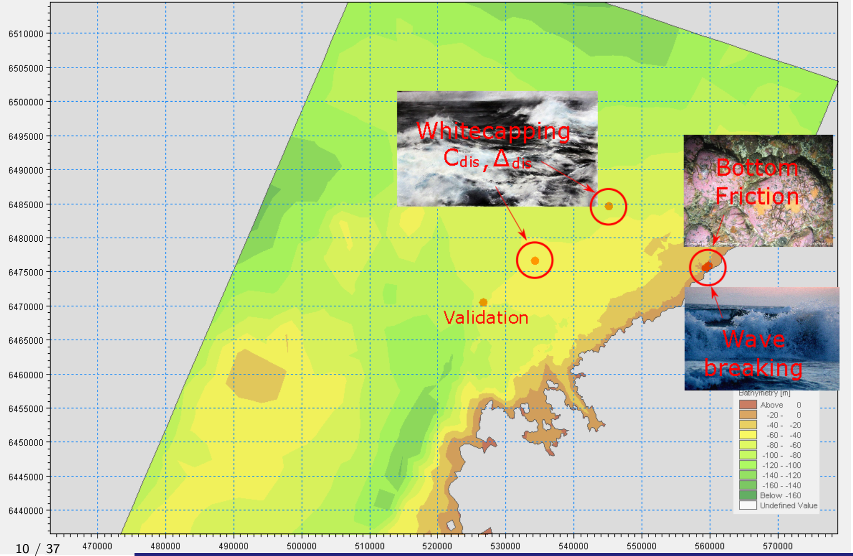
$$
\sigma\left[\frac{\partial}{\partial t}\left(\frac{E}{\sigma}\right)+\nabla.\left(\frac{\mathbf{v}E}{\sigma}\right)\right]=
\begin{array}{cc}
S_{\text{wcap}}(C,\delta,E,\sigma,\theta,d) & \text{Whitecapping} \\
+S_{\text{bot}}(f,E,\sigma,\theta,d) & \text{Bottom Friction} \\
+S_{\text{surf}}(\gamma,E,\sigma,\theta,d) & \text{Wavebreaking} \\
+S_{\text{wind}}(E,\sigma,\theta) & \text{Wind Forcing} \\
+S_{\text{nl}}(E,\sigma,\theta) & \text{Nonlinear Interactions}
\end{array}
$$

- Semi-empirical source terms include free parameters C, δ, f and γ fixed by calibration process.

Model Calibration

- Run the model for various values of each calibration parameter
- Extract timeseries of H_s and T_1 (related to the 0^{th} and 1^{st} spectral moments) at the sensor locations.
- Judicious combinations of the calibration parameters selected for best possible match between modelled and measured data.
- Scatter index for N timesteps $= \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(x_j^{\text{modelled}} - x_j^{\text{measured}}\right)^2}}{\bar{x}}$.
- Bias $= \bar{x}^{\text{modelled}} - \bar{x}^{\text{measured}}$.
- Correlation coefficient$= \frac{\sum_{j=1}^{N}\left[\left(x_j^{\text{measured}} - \bar{x}^{\text{measured}}\right)\left(x_j^{\text{modelled}} - \bar{x}^{\text{modelled}}\right)\right]}{\sqrt{\sum_{j=1}^{N}\left(x_j^{\text{modelled}} - \bar{x}^{\text{modelled}}\right)^2 \sum_{j=1}^{N}\left(x_j^{\text{measured}} - \bar{x}^{\text{measured}}\right)^2}}$

Using the Sensor Data



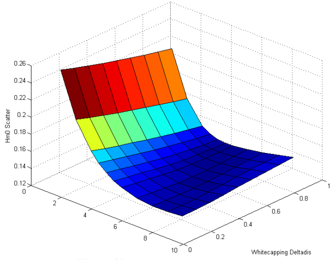
Whitecapping: Scatter Indices

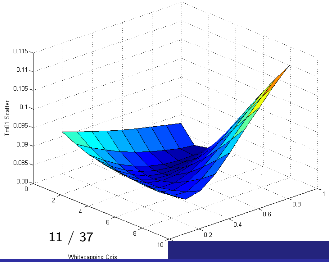
Full 2D parameter space, 43 day run

Scatter index for significant wave height:

Hs Scatter

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DeltaDis
1	0.239388	0.234701	0.230297	0.226107	0.222101	0.21834	0.214761	0.211357	0.208129	
2	0.194344	0.189568	0.18517	0.181136	0.177328	0.173664	0.170178	0.166826	0.163596	
3	0.168188	0.164304	0.160764	0.157436	0.154254	0.151227	0.148342	0.145663	0.143314	
3.5	0.159358	0.156089	0.153001	0.150086	0.147371	0.144766	0.142398	0.140473	0.138989	
4	0.152679	0.149957	0.147337	0.144933	0.142644	0.140579	0.138936	0.137798	0.137069	
4.5	0.147692	0.145478	0.143365	0.141461	0.139633	0.138202	0.13732	0.136872	0.1367	
5	0.144056	0.142341	0.140731	0.139252	0.137963	0.137228	0.137006	0.137066	0.137281	
6	0.139973	0.139032	0.138309	0.137692	0.137638	0.13806	0.138668	0.139306	0.139957	
7	0.138769	0.138507	0.138471	0.138861	0.139779	0.140796	0.141779	0.14272	0.14365	
8	0.139429	0.139706	0.140388	0.141611	0.143024	0.144331	0.145517	0.146639	0.14771	
9	0.141337	0.142069	0.143367	0.145084	0.146747	0.148176	0.149484	0.150698	0.151813	
Cdis										





Scatter index for mean wave period:

T1 Scatter

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DeltaDis
1	0.097832	0.096179	0.094613	0.093122	0.091705	0.090383	0.089142	0.087975	0.086888	
2	0.095231	0.09238	0.089833	0.08757	0.085573	0.083823	0.082311	0.08104	0.080004	
3	0.093224	0.089626	0.086574	0.084023	0.081988	0.080442	0.079468	0.079051	0.079148	
3.5	0.092441	0.088574	0.085359	0.082827	0.08097	0.07984	0.07943	0.079692	0.080444	
4	0.091792	0.087679	0.084397	0.082004	0.080476	0.079867	0.080117	0.08103	0.082425	
4.5	0.0912	0.086923	0.083725	0.081495	0.08042	0.080438	0.081346	0.082875	0.084839	
5	0.090733	0.086347	0.083198	0.081292	0.080768	0.081444	0.082965	0.085068	0.087513	
6	0.090026	0.085543	0.082694	0.081719	0.082433	0.084336	0.08697	0.089969	0.093085	
7	0.089581	0.08509	0.082877	0.083047	0.084987	0.087968	0.091463	0.09507	0.098605	
8	0.089288	0.084992	0.083671	0.085044	0.088113	0.091995	0.096058	0.100043	0.103839	
9	0.089155	0.08523	0.084959	0.08753	0.091561	0.09608	0.100544	0.104781	0.108704	
Cdis										

Whitecapping: Biases

Significant wave height bias (m):

Hs Bias

Cdis	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DeltaDis
1	0.346733	0.336744	0.327196	0.318031	0.309205	0.300789	0.29269	0.284893	0.27738	
2	0.247797	0.235359	0.223632	0.212509	0.201872	0.191568	0.181499	0.171563	0.161717	
3	0.176181	0.16342	0.151362	0.13962	0.127934	0.116197	0.104565	0.09302	0.081816	
3.5	0.146719	0.134238	0.122149	0.110058	0.097961	0.085749	0.073568	0.061854	0.050872	
4	0.120523	0.108324	0.09616	0.083955	0.071427	0.058771	0.046518	0.035113	0.024798	
4.5	0.096861	0.08506	0.073049	0.060559	0.047639	0.034889	0.022924	0.012169	0.002624	
5	0.07552	0.064081	0.05209	0.039348	0.026271	0.01368	0.002306	-0.00774	-0.01659	
6	0.038314	0.027531	0.015499	0.002432	-0.01045	-0.022	-0.03203	-0.04075	-0.04839	
7	0.006773	-0.00348	-0.01564	-0.02864	-0.04054	-0.05085	-0.0597	-0.06735	-0.07408	
8	-0.02054	-0.03045	-0.04262	-0.05486	-0.06566	-0.0749	-0.08273	-0.08952	-0.09552	
9	-0.04467	-0.05424	-0.06604	-0.0774	-0.08718	-0.09541	-0.1024	-0.10848	-0.1138	

Mean wave period bias (s):

T1 Bias

Cdis	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DeltaDis
1	-0.34581	-0.32943	-0.31349	-0.29791	-0.28257	-0.26772	-0.25323	-0.23903	-0.22527	
2	-0.30128	-0.2718	-0.24352	-0.21649	-0.1904	-0.16491	-0.14006	-0.11559	-0.09127	
3	-0.25817	-0.21815	-0.18042	-0.14383	-0.10793	-0.07233	-0.03729	-0.00265	0.031485	
3.5	-0.23742	-0.19328	-0.15084	-0.10937	-0.0688	-0.02847	0.011346	0.050197	0.087572	
4	-0.21775	-0.16918	-0.12202	-0.07652	-0.03101	0.014003	0.057883	0.099743	0.138892	
4.5	-0.19849	-0.14583	-0.095	-0.04456	0.005659	0.054894	0.101814	0.145442	0.185424	
5	-0.18018	-0.12362	-0.06855	-0.01327	0.041244	0.093938	0.142802	0.187434	0.227895	
6	-0.146	-0.08154	-0.0173	0.046761	0.108754	0.165446	0.216225	0.261627	0.302102	
7	-0.11403	-0.04141	0.031797	0.10385	0.169755	0.228341	0.280064	0.325393	0.36539	
8	-0.0835	-0.00223	0.079065	0.15627	0.224666	0.284582	0.336129	0.38082	0.420131	
9	-0.05403	0.035551	0.123864	0.204728	0.274854	0.334835	0.385821	0.429757	0.467979	

Whitecapping: Second Set

Additional 46 days of simulation: narrower region of parameter space, higher resolution.

Hs Scatter

	0.8	0.85	0.9
4	0.148674	0.148522	0.148405
4.25	0.148424	0.148363	0.148335
4.5	0.1484	0.148423	0.148467
4.75	0.148567	0.148653	0.148758

T1 Scatter

	0.8	0.85	0.9
4	0.101312	0.102165	0.103084
4.25	0.102362	0.103348	0.104383
4.5	0.103486	0.10459	0.105744
4.75	0.104676	0.105901	0.107148

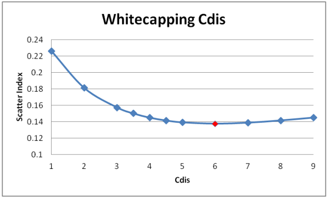
Why use a 2D surface?

Alternative iterative approach - 1

Using default Δ_{dis}, vary C_{dis} to minimise H_s scatter.

Hs Scatter

Cdis	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	DeltaDis
1	0.239388	0.234701	0.230297	0.226107	0.222101	0.21834	0.214761	0.211357	0.208129	
2	0.194344	0.189568	0.18517	0.181136	0.177328	0.173664	0.170178	0.166826	0.163596	
3	0.168188	0.164304	0.160764	0.157436	0.154254	0.151227	0.148342	0.145663	0.143314	
3.5	0.159358	0.156089	0.153001	0.150086	0.147371	0.144766	0.142398	0.140473	0.138989	
4	0.152679	0.149957	0.147337	0.144933	0.142644	0.140579	0.138936	0.137798	0.137069	
4.5	0.147692	0.145478	0.143365	0.141461	0.139633	0.138202	0.13732	0.136872	0.1367	
5	0.144056	0.142341	0.140731	0.139252	0.137963	0.137228	0.137006	0.137066	0.137281	
6	0.139973	0.139032	0.138309	0.137692	0.137638	0.13806	0.138668	0.139306	0.139957	
7	0.138769	0.138507	0.138471	0.138861	0.139779	0.140796	0.141779	0.14272	0.14365	
8	0.139429	0.139706	0.140388	0.141611	0.143024	0.144331	0.145517	0.146639	0.14771	
9	0.141337	0.142069	0.143367	0.145084	0.146747	0.148176	0.149484	0.150698	0.151813	



Conclude our first guess at C_{dis} should be 6.

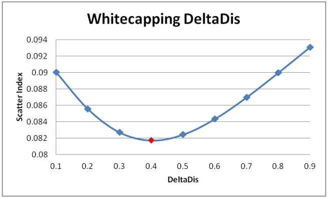
Why use a 2D surface?

Alternative iterative approach - 2

Taking $C_{\text{dis}} = 6$, vary Δ_{dis} to minimise T_1 scatter.

T1 Scatter

Cdis	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9 DeltaDis
1	0.097832	0.096179	0.094613	0.093122	0.091705	0.090383	0.089142	0.087975	0.086888
2	0.095231	0.09238	0.089833	0.08757	0.085573	0.083823	0.082311	0.08104	0.080004
3	0.093224	0.089626	0.086574	0.084023	0.081988	0.080442	0.079468	0.079051	0.079148
3.5	0.092441	0.088574	0.085359	0.082827	0.08097	0.07984	0.07943	0.079692	0.080444
4	0.091792	0.087679	0.084397	0.082004	0.080476	0.079867	0.080117	0.08103	0.082425
4.5	0.0912	0.086923	0.083725	0.081495	0.08042	0.080438	0.081346	0.082875	0.084839
5	0.090733	0.086347	0.083198	0.081292	0.080768	0.081444	0.082965	0.085068	0.087513
6	0.090026	0.085543	0.082694	0.081719	0.082433	0.084336	0.08697	0.089969	0.093085
7	0.089581	0.08509	0.082877	0.083047	0.084987	0.087968	0.091463	0.09507	0.098605
8	0.089288	0.084992	0.083671	0.085044	0.088113	0.091995	0.096058	0.100043	0.103839
9	0.089155	0.08523	0.084959	0.08753	0.091561	0.09608	0.100544	0.104781	0.108704



Conclude our first guess at Δ_{dis} should be 0.4.

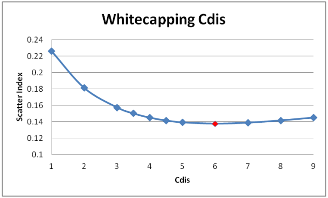
Why use a 2D surface?

Alternative iterative approach - 3

$\Delta_{\text{dis}} = 0.4$, vary C_{dis} to minimise H_s scatter.

Hs Scatter

Cdis \ DeltaDis	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0.239388	0.234701	0.230297	0.226107	0.222101	0.21834	0.214761	0.211357	0.208129
2	0.194344	0.189568	0.18517	0.181136	0.177328	0.173664	0.170178	0.166826	0.163596
3	0.168188	0.164304	0.160764	0.157436	0.154254	0.151227	0.148342	0.145663	0.143314
3.5	0.159358	0.156089	0.153001	0.150086	0.147371	0.144766	0.142398	0.140473	0.138989
4	0.152679	0.149957	0.147337	0.144933	0.142644	0.140579	0.138936	0.137798	0.137069
4.5	0.147692	0.145478	0.143365	0.141461	0.139633	0.138202	0.13732	0.136872	0.1367
5	0.144056	0.142341	0.140731	0.139252	0.137963	0.137228	0.137006	0.137066	0.137281
6	0.139973	0.139032	0.138309	0.137692	0.137638	0.13806	0.138668	0.139306	0.139957
7	0.138769	0.138507	0.138471	0.138861	0.139779	0.140796	0.141779	0.14272	0.14365
8	0.139429	0.139706	0.140388	0.141611	0.143024	0.144331	0.145517	0.146639	0.14771
9	0.141337	0.142069	0.143367	0.145084	0.146747	0.148176	0.149484	0.150698	0.151813



Take $C_{\text{dis}} = 6$.

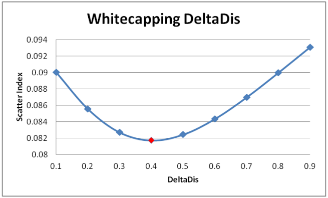
Why use a 2D surface?

Alternative iterative approach - 4

We have already seen that taking $C_{\text{dis}} = 6$ and varying Δ_{dis} to minimise T_1 scatter gives $\Delta_{\text{dis}} = 0.4$.

T1 Scatter

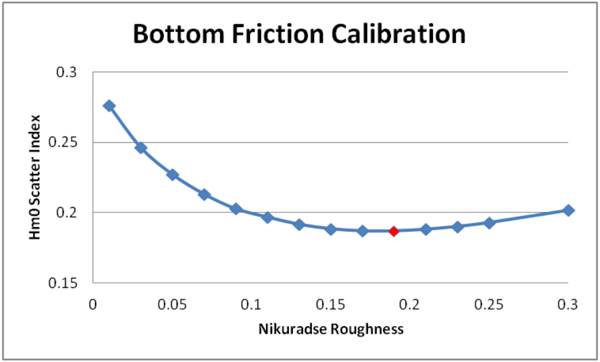
Cdis \ DeltaDis	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0.097832	0.096179	0.094613	0.093122	0.091705	0.090383	0.089142	0.087975	0.086888
2	0.095231	0.09238	0.089833	0.08757	0.085573	0.083823	0.082311	0.08104	0.080004
3	0.093224	0.089626	0.086574	0.084023	0.081988	0.080442	0.079468	0.079051	0.079148
3.5	0.092441	0.088574	0.085359	0.082827	0.08097	0.07984	0.07943	0.079692	0.080444
4	0.091792	0.087679	0.084397	0.082004	0.080476	0.079867	0.080117	0.08103	0.082425
4.5	0.0912	0.086923	0.083725	0.081495	0.08042	0.080438	0.081346	0.082875	0.084839
5	0.090733	0.086347	0.083198	0.081292	0.080768	0.081444	0.082965	0.085068	0.087513
6	0.090026	0.085543	0.082694	0.081719	0.082433	0.084336	0.08697	0.089969	0.093085
7	0.089581	0.08509	0.082877	0.083047	0.084987	0.087968	0.091463	0.09507	0.098605
8	0.089288	0.084992	0.083671	0.085044	0.088113	0.091995	0.096058	0.100043	0.103839
9	0.089155	0.08523	0.084959	0.08753	0.091561	0.09608	0.100544	0.104781	0.108704



Care must be taken that we really have found global optima if we use a 1D iterative approach.

Bottom Friction and Wavebreaking

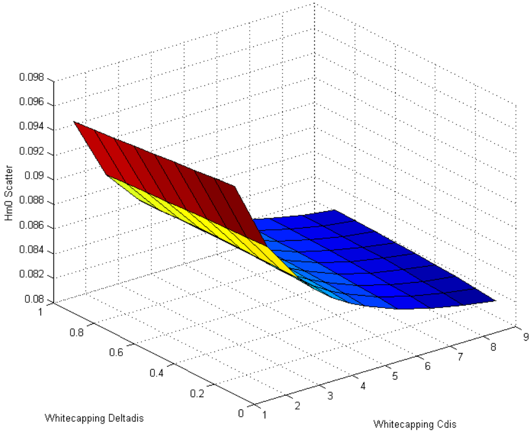
Sensitivity tests indicated that these parameters could be decoupled.



Select roughness of 0.19, wavebreaking γ of 3.

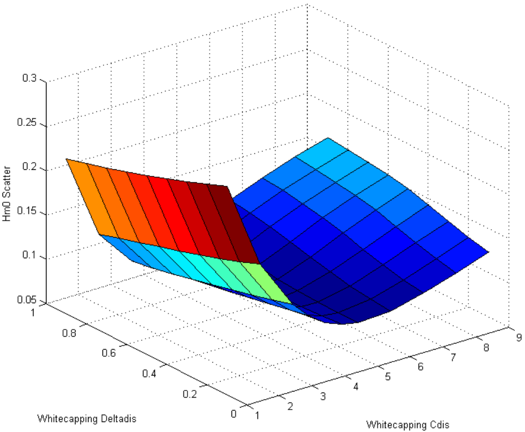
Time period

The behaviour of the model depends on the conditions. The calibration surface for one time period...



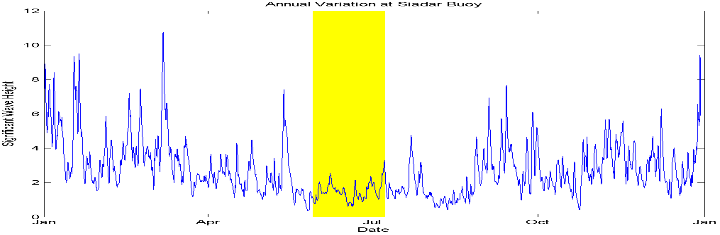
Time period

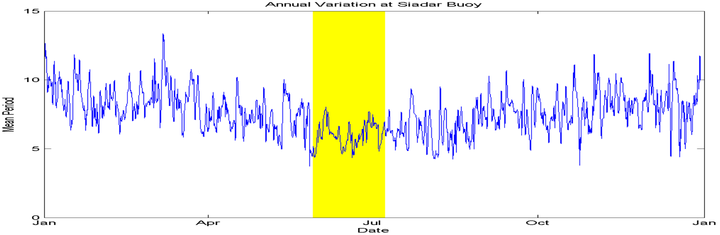
...might be quite different to another period.



Continuous Time Period

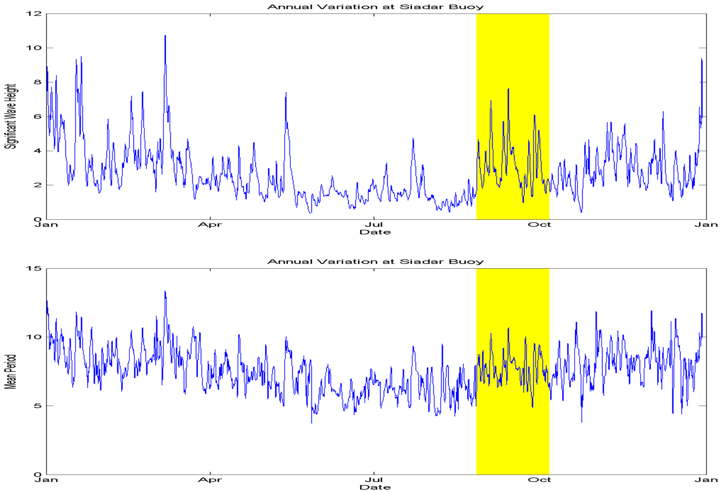
Any time period chosen for calibration...





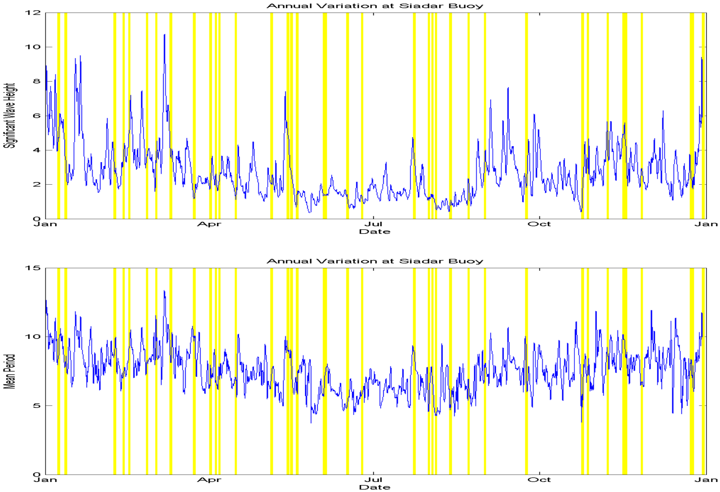
Continuous Time Period

...should represent the range of conditions experienced thoughout the year.

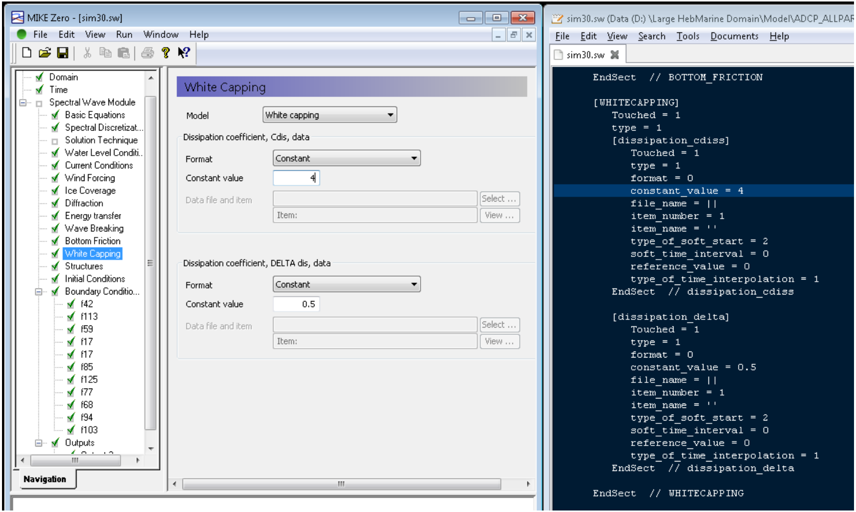


Ensemble

Consider using an ensemble of shorter simulations.

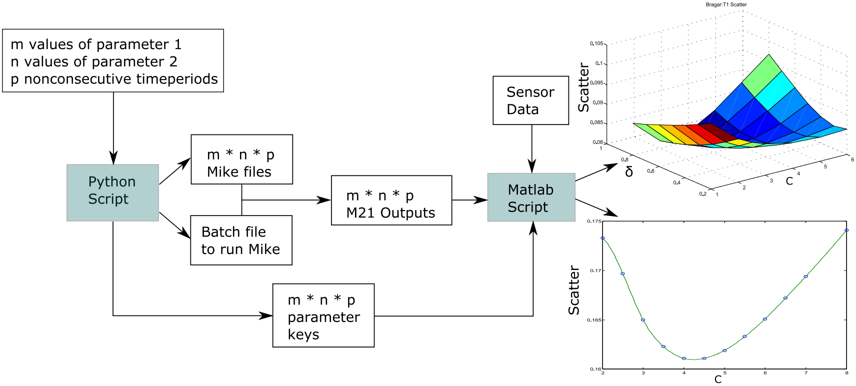


Model Automation: Mike Interface



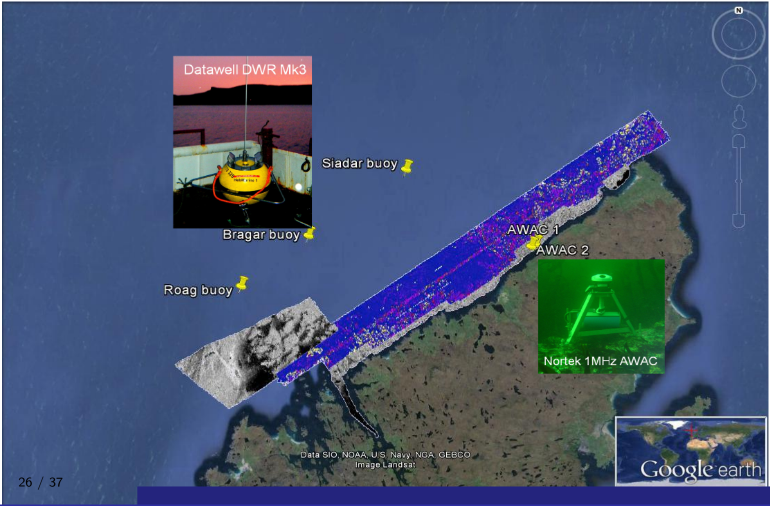
Model Automation: Software Tools

Hebridean Marine Energy Futures



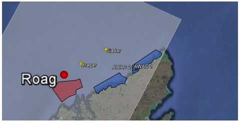
Model Running and Validation

Run the model, validate at Roag buoy and second AWAC and monitor behaviour at other sensors. Model underway, interim results available.

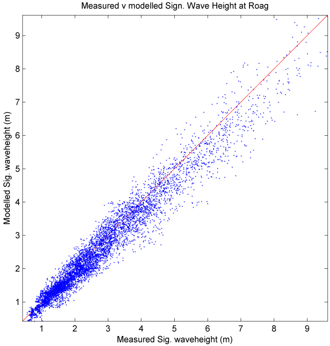


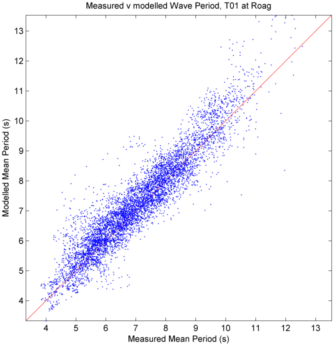
Validation at Roag Buoy

	H_{m0}	T_{01}
Scatter Index:	0.154	0.087
Bias:	-17cm (6.35%)	0.19s (2.68%)
Correlation Coeff.:	0.972	0.928

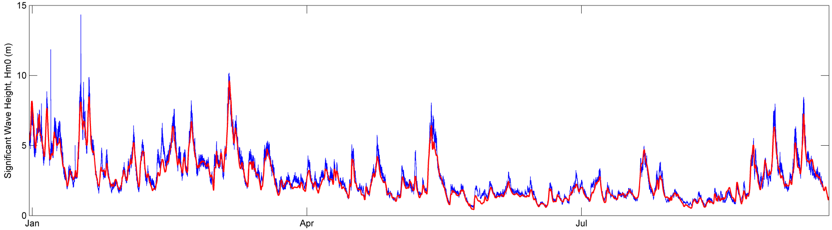


Measured vs modelled waveheights *Hm*0 (left) and mean periods *T*01(right):

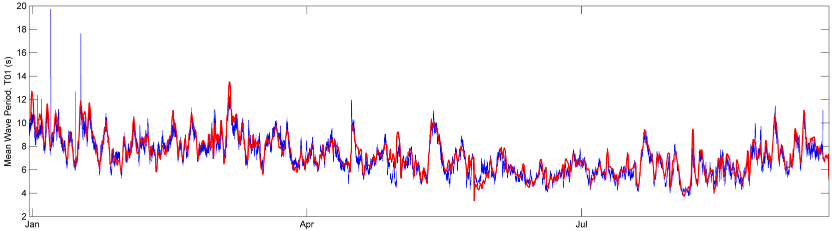




Timeseries at Roag Buoy

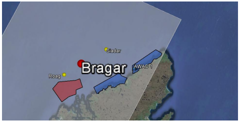


Timeseries of modelled and measured $Hm0$ (above) and $T01$ (below).

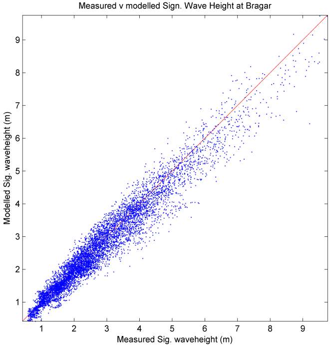


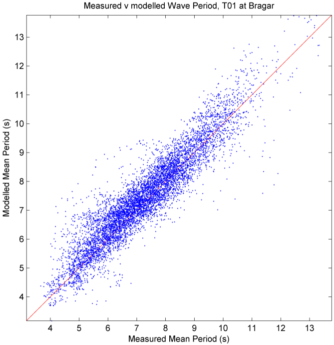
Validation at Bragar Buoy

	H_{m0}	T_{01}
Scatter Index:	0.143	0.086
Bias:	-11cm (4.08%)	0.19s (2.61%)
Correlation Coeff.:	0.969	0.925

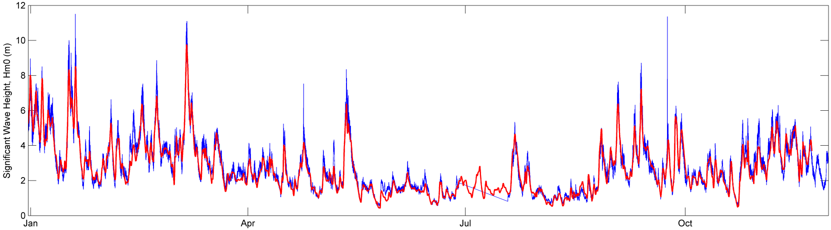


Measured vs modelled waveheights $Hm0$ (left) and mean periods $T01$(right):

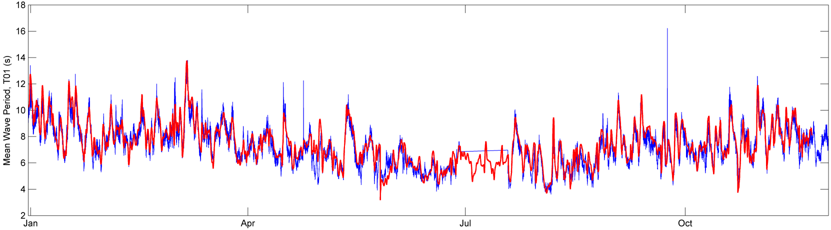




Timeseries at Bragar Buoy

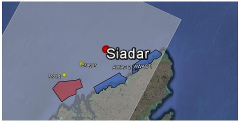


Timeseries of modelled and measured $Hm0$ (above) and $T01$ (below).

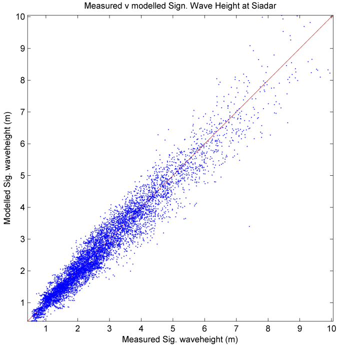


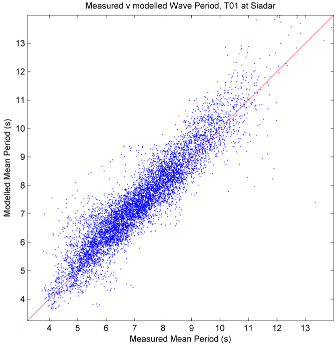
Validation at Siadar Buoy

	H_{m0}	T_{01}
Scatter Index:	0.139	0.090
Bias:	-5cm (1.80%)	0.24s (3.24%)
Correlation Coeff.:	0.968	0.932

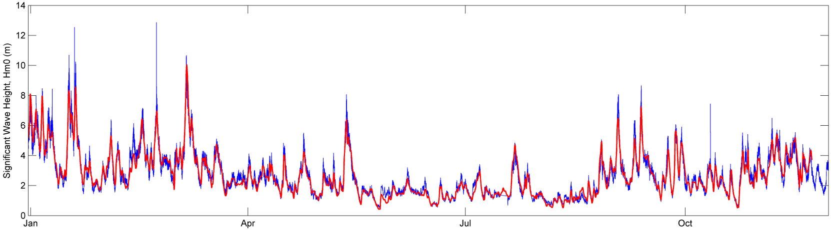


Measured vs modelled waveheights *Hm*0 (left) and mean periods *T*01(right):

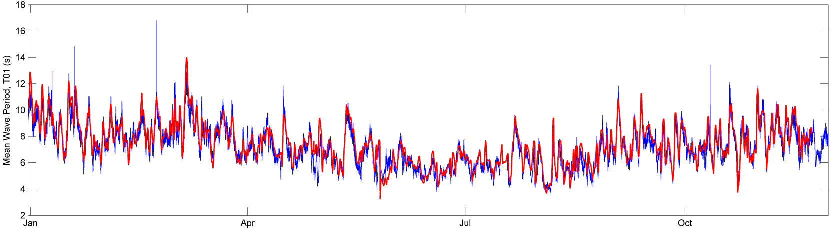




Timeseries at Siadar Buoy



Timeseries of modelled and measured $Hm0$ (above) and $T01$ (below).

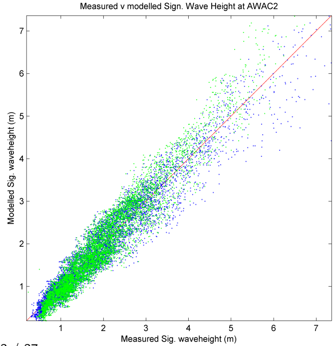


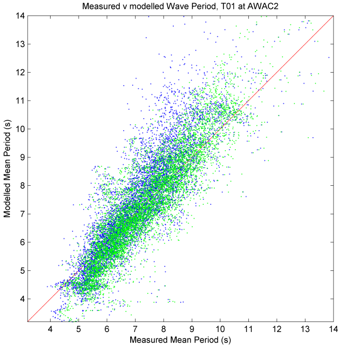
Validation at AWAC2

Pressure and Velocity sensors

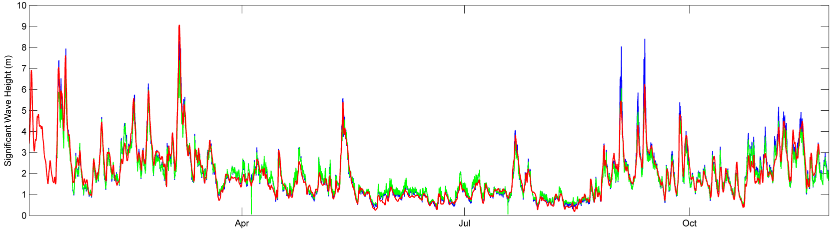
	H_{m0}	T_{01}
SI:	0.172/0.180	0.146/0.117
Bias:	-4cm/-0.3cm(1.84%/0.15%)	0.24s/0.01s (3.33%/0.14%)
Corr.:	0.961/0.961	0.840/0.893

Measured vs modelled waveheights $Hm0$ (left) and mean periods $T01$(right):

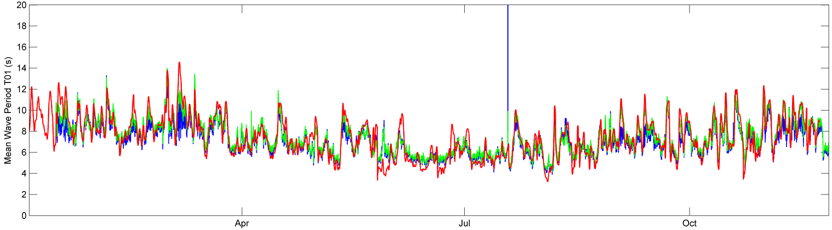




Timeseries at AWAC

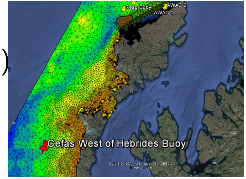


Modelled and measured (pressure/velocity) $Hm0$ (above) and $T01$ (below).

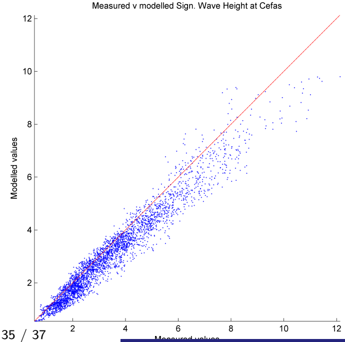


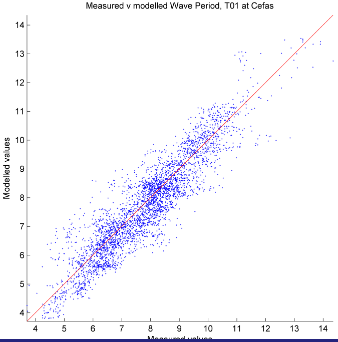
Validation at Cefas Buoy

	H_{m0}	T_{01}
Scatter Index:	0.180	0.087
Bias:	-37cm (11.48%)	-0.11s (1.36%)
Correlation Coeff.:	0.972	0.917

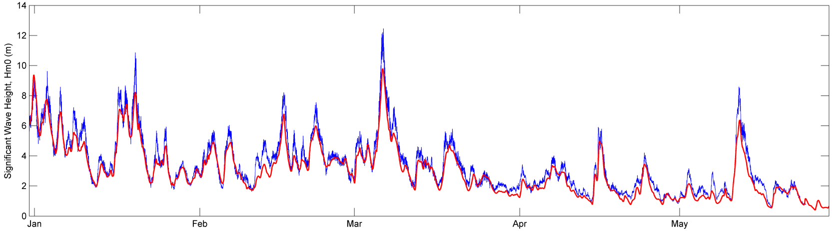


Measured vs modelled waveheights *Hm*0 (left) and mean periods *T*01(right):

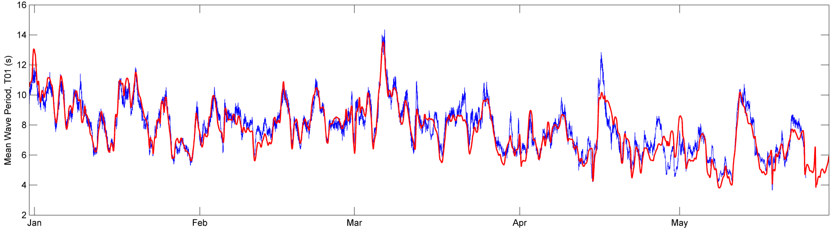




Timeseries at Cefas Buoy



Timeseries of modelled and measured $Hm0$ (above) and $T01$ (below).



Acknowledgements

This work was carried out under the Hebridean Marine Energy Futures project. Acknowledgement is made to the Scottish Funding Council, Aquamarine Wave Power Ltd, and Highlands and Islands Enterprise for funding this research activity.
Further acknowledgement is made to Open Ocean for providing model boundary data to this project free of charge.

Click for Significant Wave Height Animation