

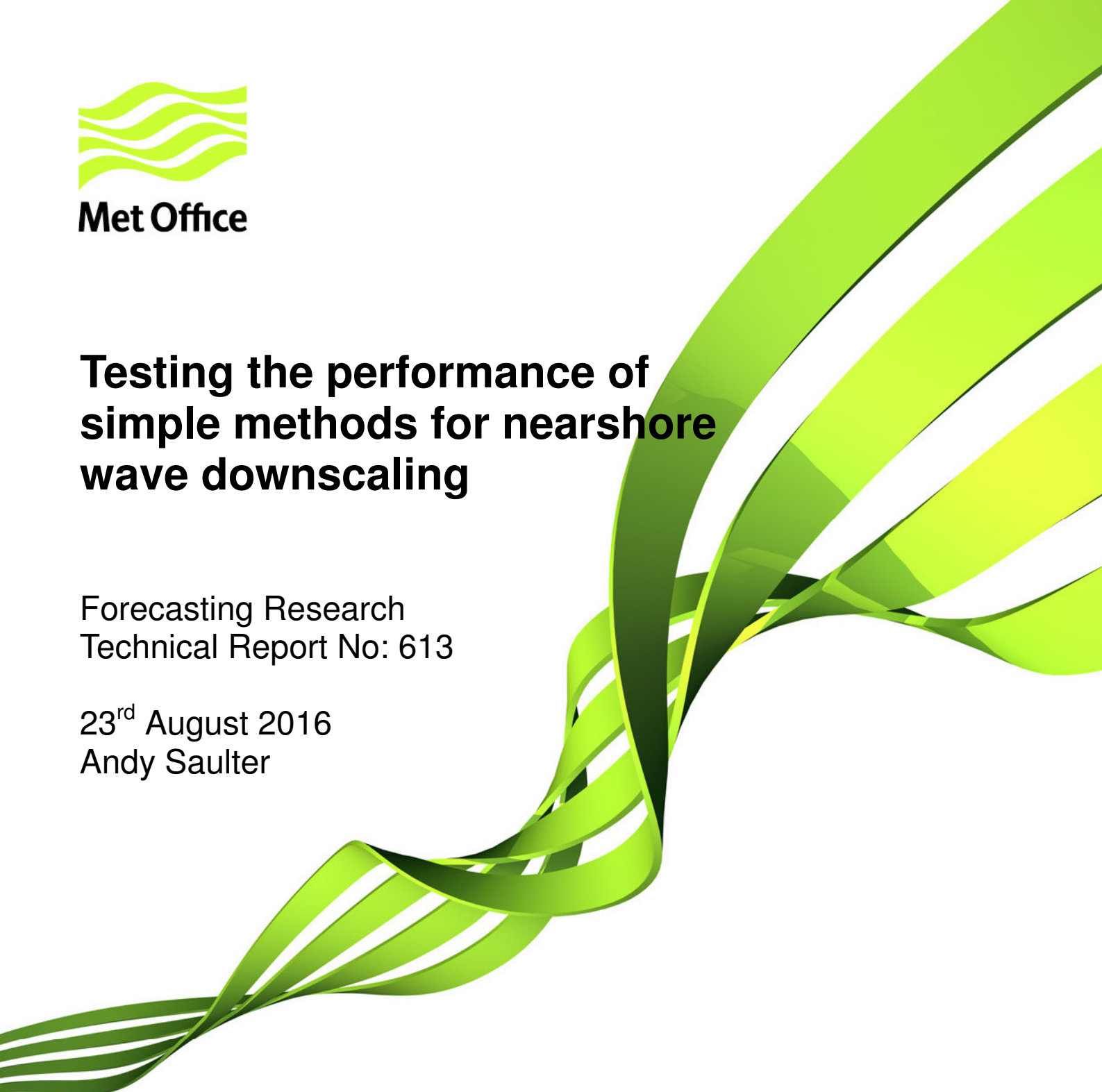


**Met Office**

# **Testing the performance of simple methods for nearshore wave downscaling**

Forecasting Research  
Technical Report No: 613

23<sup>rd</sup> August 2016  
Andy Saulter





## **Summary**

Simple methods for estimating nearshore wave conditions, which assume that the primary effects on shoreward directed wave energy are offshore wave direction relative to the coastline, topographic sheltering and bottom friction dissipation processes, have been tuned and compared against idealised and practical (two-dimensional) applications of the third generation spectral wave model SWAN.

Results suggest that in relatively simple circumstances (e.g. a reasonably open stretch of coastline without complex bathymetry or sheltering islands offshore and limited influence of currents) the methods have only marginally lower skill in representing nearshore wave conditions than SWAN, whilst being significantly quicker to both set-up and run. These models therefore have a potential role in making rapid first guess nearshore corrections to a coarse resolution open waters wave model, or providing scaleable corrections to models that only partially resolve nearshore effects (e.g. the present UK Waters wave model run at the Met Office).

## **1. Introduction**

High accuracy prediction of nearshore wave conditions (i.e. the wave field within a few hundred metres to 1-2 kilometres of land and often in shallow water) requires configuration and running of spectral wave models with resolutions of orders 10s to 100s of metres. Configuring and running such models requires user expertise and significant computing resource. This level of resource may not be available in operational frameworks that are also committed to running larger domain models predicting 'open water' conditions (several kilometres or more offshore), or if multiple instances of high resolution models are needed in order to cover a large area of coast.

However, if some of the accuracy requirement can be sacrificed, there are relatively simple first order corrections that can be made to open water wave conditions in order to produce an appropriate estimate of nearshore waves. For example, the amount of wave energy incident to the nearshore zone will be a function of the wave direction offshore and the angle of the coastline, which implies that offshore wave energy can be 'filtered' in order to estimate the nearshore wave conditions. In shallow waters, wave shoaling and dissipation of wave energy, due to bottom friction or depth limited breaking, are competing processes occurring due to wave interactions with the sea bed. Various parameterisations exist to estimate all three effects (e.g. Hasselmann et al., 1973; Battjes and Janssen, 1978).

Over the last few years the Met Office has worked on methods that enable a 'first guess estimate' of nearshore wave conditions to be made. The aim has been to produce an easily configurable tool (requiring only limited user expertise) that enables a rapid estimate of nearshore wave heights to be calculated using a minimum of computing resource. Specifically, the tool has been designed to provide inputs for surf prediction algorithms, which are dependent on the amount of wave energy incident on a given beach.

This report describes the principles underpinning these methods, which are based on directional filtering and refraction-dissipation corrections to the offshore wave field. Results are presented of tuning, idealised conditions and validation runs conducted against the state of the art nearshore third-generation spectral wave model SWAN (Booij et al., 1999; which was run as a 2D gridded model). The report is laid out as follows. Section 2 describes the nearshore wave estimation models that have been developed (QRefrac and IRefrac). The use of QRefrac data as a boundary condition for the surf prediction system QSurf is included for context. Section 3 presents the results of idealised experiments used to test a bottom friction dissipation parameterisation that has recently been incorporated to both models. Validation experiments using hindcast wave boundary conditions, which include two case studies and a comparison against measured nearshore wave data, are presented in section 4 and discussed in section 5. Conclusions are presented in section 6.

## **2. Nearshore wave estimation models**

### **2.1 The QRefrac-QSurf system**

QRefrac-QSurf is a package used to provide estimates of surf zone breaking wave heights. In this system QSurf is used to test for the onset of wave breaking using a 1-D beach profile and breaking wave energy dissipation parameterisations defined by Battjes and Janssen (1978), Goda (2000), and Weggel (1972). All these parameterisations require input of deep water wave conditions (height and period), local water depth and beach profile steepness.

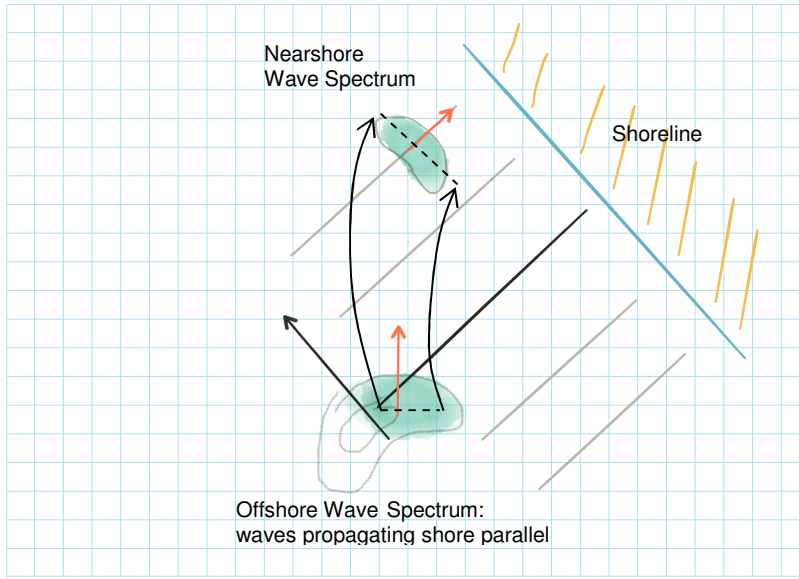
In the parameterisations used by QSurf the offshore conditions are idealised, assuming that the waves offshore are unaffected by bathymetry and propagate directly toward the beach (i.e. all the wave energy offshore is incident on the beach). In practise however, the wave model boundary conditions provided to QSurf are very likely to be representative of an intermediate water depth and waves approaching oblique to the

coastline (for example when using Met Office global or regional models scaled on the order of 1-10s of kms). The role of QRefrac is to adjust these 'open waters' wave data in order to account for both oblique wave energy approach and any dissipation effects occurring between the global/regional model grid point and a beach boundary point just seaward of the outer edge of the surf zone. For application in QSurf, QRefrac evaluates wave conditions without accounting for wave shoaling, in order to estimate an 'equivalent offshore wave height' that can be correctly applied to the QSurf algorithms. However, by applying a shoaling coefficient, QRefrac can also be used to estimate shoaled wave energy in nearshore waters.

## **2.2 Components of the QRefrac model**

Within the QRefrac model (which has been written as a set of FORTRAN 90 modules) the following aspects of wave modification in the nearshore zone are applied.

1. QRefrac is designed to be applied to two-dimensional (frequency, direction) wave spectra as output from a standard third-generation wave model, e.g. the present generation of Met Office wave models discretise the wave spectrum into 24 direction and 30 frequency energy bins. The energy in each bin is modified separately in the model before being integrated to yield significant wave height, period and direction parameters.
2. Energy in the offshore spectrum is filtered; eliminating direction bins that are not associated with shoreward propagation of wave energy (see Figure 1). For a totally open coast the permissible range of directions are those within  $\pm 90$  degrees of the shoreline orientation. In this case, when waves are propagating shore parallel slightly less than half the energy in the offshore spectrum would be expected to be in directions that pointed shoreward. For more sheltered coastlines, the range of permissible directions can be lowered by setting a directional window which is defined by the local coastal features (see examples in Figures 8 and 9).
3. (One-dimensional) Refraction, relating to changes in wave direction as oblique wave energy offshore turns toward shore normal in shallower water, is used to account for two modifications to the offshore wave energy:



**Figure 1.** Schematic of key filtering and refraction processes underpinning change in wave energy from offshore to outer surf zone. Directional filtering applies such that only the shoreward propagating components of wave energy contribute to the nearshore wave spectrum; the effect of refraction in shallow water leads to an increase in along-crest distance between wave rays, resulting in a reduction in wave energy density.

3a. First, in the case of a constrained directional window, the larger degrees of refraction associated with long period waves allow the window to be expanded for low wave frequency bins whilst the constraint is maintained for higher frequency waves. This accounts for the longer period waves being able to ‘turn in’ toward the coast as the waves pass through increasingly shallow water. The expansion of the directional window is evaluated using a backward calculation of Snell’s law,

$$\sin \theta_{off} = \sin \theta_{near} \frac{c_{off}}{c_{near}},$$

( $\theta$ : angle relative to shore normal;  $c$ : wave celerity) from a first guess nearshore point depth to the offshore depth.

3b. The second, counter-effect, is that a larger change in refraction angle is associated with a ‘stretching’ of along-crest spectral energy (see for example the wave ray diagram in Tucker and Pitt, 2001, and Figure 1) and a reduction in energy density. In this case a refraction coefficient is introduced based on:

$$K_{refrac} = \cos\left(\frac{\theta_{off} + \theta_{near}}{2}\right),$$

i.e. using the ‘half-angle’, relative to the shore normal, between the offshore waves and refracted nearshore waves.

4. Dissipation of wave energy due to bottom friction is estimated using a derivation from the JONSWAP parameterisation proposed by Hasselmann et al. (1973), where:

$$S_{bot} = 2\Gamma \frac{n-0.5}{gh} N,$$

( $\Gamma$  is an empirical constant estimated as -0.038 for swell, -0.067 for wind-sea;  $n$  is the ratio of wave group velocity to phase velocity;  $g$  is acceleration due to gravity;  $h$  is water depth; and  $N$  is the wave spectral energy). Since QRefrac does not use a gridded bed profile, this is adapted for a single gradient slope defined using the offshore model grid point depth, nearshore depth and distance between the two points. The average water depth and associated wave speed are used to calculate  $n$  and the time integration of  $S_{bot}$  over the distance from offshore to nearshore point, yielding the bottom friction dissipation coefficient:

$$K_{bot} = 2\Gamma \left( \frac{n_{mean} - 0.5}{gh_{mean}} \right) \left( \frac{xlen}{cg_{hmean}} \right),$$

( $xlen$ : cross-shore distance;  $cg$ : wave group speed). To prevent the parameterisation over-estimating the dissipation process when distance between offshore and nearshore is large, the profile is discretised such that wave energy is incrementally adjusted using the bottom friction dissipation coefficient over 20 iterations. Finally, the cross-shore distance is extended for oblique (from shore normal) wave directions, so that energy in those bins is dissipated more strongly than for the bins containing wave energy at close to shore normal. The extended distance is estimated using an approach angle defined as the mean of the offshore-nearshore approach ‘half angle’ (as per the refraction coefficient calculation).

In order to make the model as computationally efficient as possible, wave speed changes in intermediate water depths are estimated directly, derived from the wavelength calculation described by Fenton and McKee (1990):

$$\lambda = \frac{gT^2}{2\pi} \left[ \tanh\left(\frac{4\pi^2 h}{gT^2}\right)^{\frac{3}{4}} \right]^{\frac{2}{3}},$$

( $T$ : wave period).

For this study, where QRefrac is being used to estimate a nearshore wave condition rather than the equivalent wave height needed by QSurf, a linear theory shoaling coefficient was also applied using:

$$K_{shoal} = 1 + \left( \frac{cg_{off} - cg_{near}}{cg_{hmean}} \right).$$

### 2.3 IRefrac

IRefrac (written as a set of Python functions) is designed to perform the same downscaling task as QRefrac, but is applied to a set of integrated wave parameters (significant wave height, period and direction) that summarize one or more individual partitions of the wave spectrum (e.g. the full spectrum, wind-sea and/or multiple swells).

The processes applied in IRefrac are identical to those described previously for QRefrac, with the key difference that IRefrac is applied to far fewer components of the wave field (and hence runs faster than QRefrac). In order for this approach to be effective, it is necessary to apply an assumption regarding (at least) the directional spreading of each component in order to filter the offshore wave energy. In this case it is assumed that all components have a directional spread represented by a cosine squared spreading function, such that the first and second moments of the wave energy travelling shoreward for a specified swell window can be estimated from the cosine squared integral:

$$m_0 = \int (\cos \theta)^2 d\theta = [0.5\theta + 0.25 \sin 2\theta],$$

and

$$m_1 = \int \theta \cos^2 \theta = [0.25\theta^2 + 0.25\theta \sin 2\theta + 0.125 \cos 2\theta]$$

(the range of  $\theta$ , relative to shore normal, defines swell window wave directions). Shoreward propagating significant wave height and direction are then calculated by comparing the windowed wave energy moments with the moment values for an integral over the full offshore wave spectrum.

As for QRefrac, the filtering window is expanded for longer period waves using a refraction value estimated from the partition's offshore wave period. This period is also used in subsequent refraction, bottom friction and shoaling coefficient calculations.



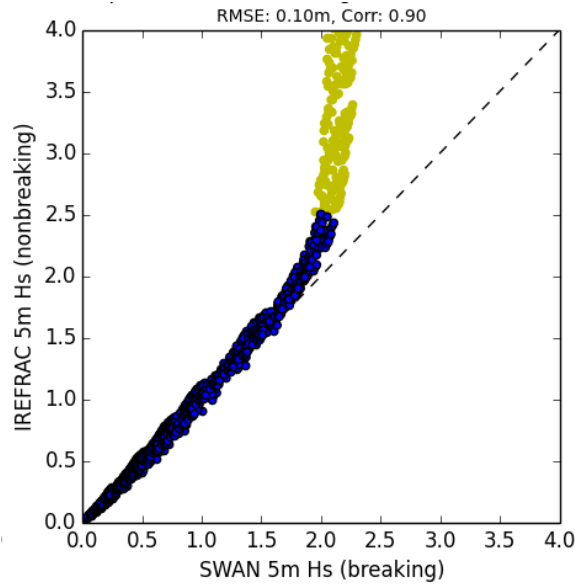
### 3. Idealised tests versus SWAN

The parameterisations in QRefrac and IRefrac include a number of numerical assumptions and tunable constants that can be used to vary their outputs. As an initial test of the validity of the methods, QRefrac and IRefrac were compared with the third-generation spectral wave model SWAN, using a set of idealised wave conditions and uniform nearshore profiles. SWAN performs the same functions described above, but stepwise on a two-dimensional grid. This model is a very well established and validated tool for studying and predicting coastal waves, so it serves as a good baseline for 'best in class' performance against which to check the simplified offshore to nearshore wave transformations.

Spectral wave boundary conditions for SWAN and QRefrac were generated by applying a set of significant wave height ( $H_s$ ), peak period ( $T_p$ ), mean direction and directional spread data to the spectral reconstruction routine of Bunney et al. (2013). Intervals in  $H_s$  were set every 0.25m up to 6m, with periods set every 1 second from 4 to 20 seconds. Conditions where deep water wave steepness fell below 0.0008, or exceeded 0.045 were rejected. Directions, relative to a shore normal value of zero degrees, were set every 15 degrees up to a limit of 135 degrees and directional spread was set at 30 degrees. Idealised coastal bathymetries used in the SWAN models were based on a linear slope defined using offshore depth (values of 10, 20, 30 and 40m), nearshore depth (set at 5m) and distance from offshore to nearshore point (set at 5, 10, 15, 20 and 25km). The SWAN grids used the same number of x,y grid cells (40x240 cells) and were scaled with an alongshore distance a factor of six times the cross-shore distance, in order to minimise loss of oblique wave energy travelling from the offshore boundary to the nearshore point. As a result, the SWAN grid resolution varied from 125m, for the shortest offshore to nearshore distance of 5km, to 625m for the 25km run. The JONSWAP bottom friction coefficient for all the models was set using the 'swell dissipation' factor of 0.038.

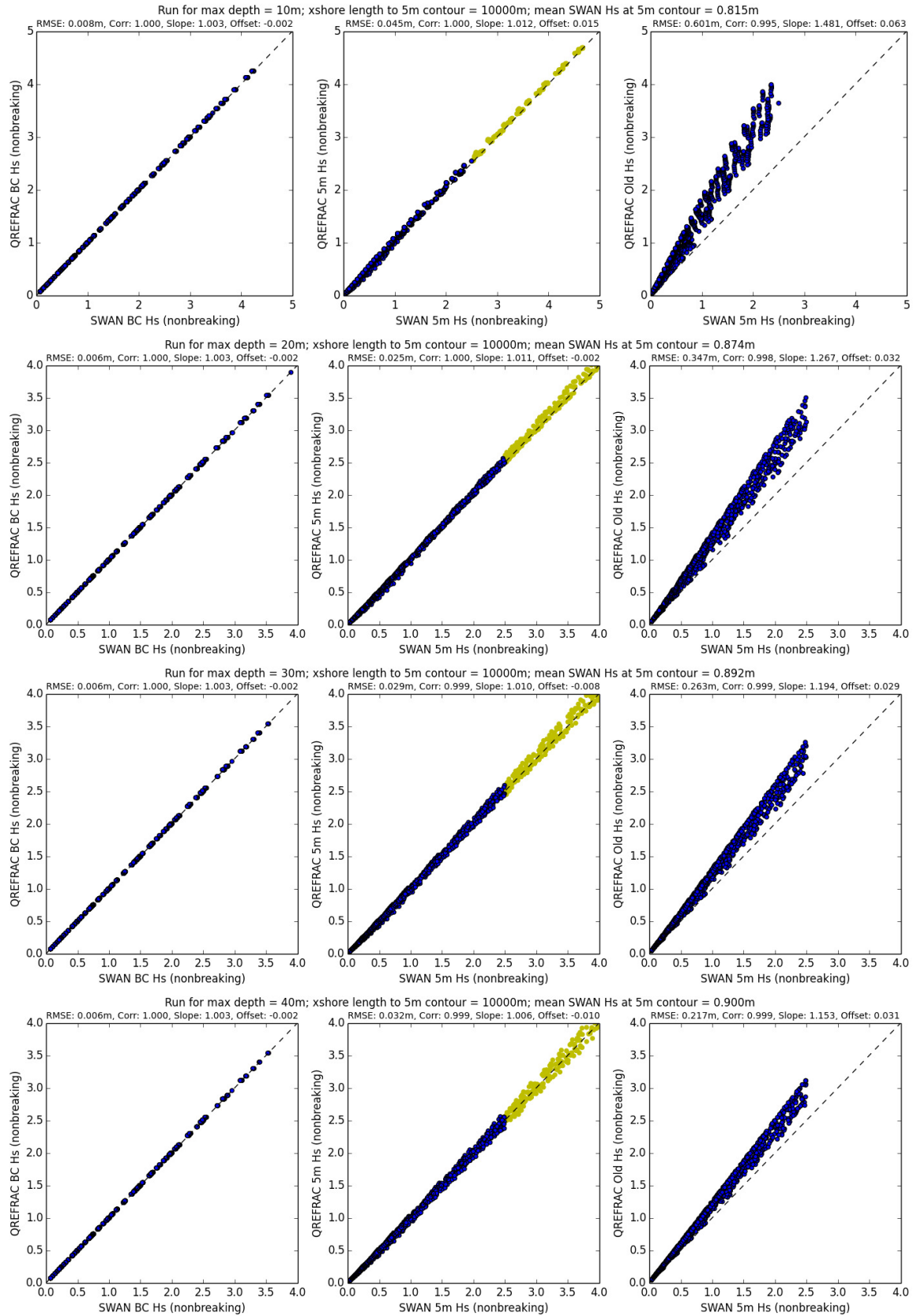
In order to make the experiments consistent, SWAN was run in a mode where additional processes representing wind-sea wave growth and dissipation, nonlinear wave-wave quadruplet and triad interactions, and wave breaking were switched off. Wave breaking has a particularly strong effect on wave energy in shallow water so, in order to only use cases which were independent of the breaking process, an upper cut off was applied to the nearshore data (and used when establishing statistical relationships between downscaling methods and SWAN). This cut-off was set where the shoaled nearshore

wave height exceeded half the nearshore depth, i.e. 2.5m for these runs. The effect of the cut-off is illustrated in Figure 2, in which IRefrac is compared to a SWAN run for which the wave breaking parameterisation is switched on. The data in blue represent non breaking conditions, based on the 2.5m cut-off, whilst the data in yellow are cases where breaking is likely to constrain nearshore wave heights.



**Figure 2.** Comparison of IRefrac nearshore (5m water depth)  $H_s$  versus SWAN run with breaking term switched on. Data in blue mark values falling below the 2.5m cut-off used to calculate statistics in idealised experiments.

Examples of the results for QRefrac with and without the bottom friction parameterisation are shown in Figures 3 and 4. Panels in the left hand column compare the SWAN and QRefrac boundary conditions, which result after applying the directional windowing process; for all runs the agreement (illustrated by data points collapsing along the 1:1 diagonal line) is excellent. Panels in the centre column compare QRefrac data with SWAN values at the 5m water depth nearshore point. From the upper to lower panels in Figure 3 the boundary point water depth increases whilst offshore to nearshore distance is held constant. The increase in depth leads to a steeper profile and a small increase in scatter results. Panels in the right hand column show QRefrac without the bottom friction parameterisation; compared to the runs with bottom friction, scatter versus the SWAN data is increased and the slope of the data departs from the 1:1 relationship. This is most marked in the shallower slope runs.



**Figure 3.** Comparison of QRefrac including bottom friction and QRefrac without bottom friction against SWAN runs for varying maximum offshore depths. Plots are discussed in section 3.

Figure 4 shows the effect of increasing distance between the offshore point and nearshore point. Increasing distance both reduces profile steepness and increases the length of time for which waves are propagating and having energy dissipated through the nearshore zone. For the most extreme cases (e.g. lowest panel in Figure 4; 25km distance for 20m offshore depth) scatter in the run with bottom friction is significant (RMSE approximately 14% of nearshore SWAN Hs) but the relationship is still much better than for the run without bottom friction.

Figure 5 is the equivalent of Figure 3 for the IRefrac routine. The boundary condition calculation used by IRefrac introduces some scatter compared to the QRefrac runs, whilst errors in the nearshore comparison with SWAN are also increased slightly. The slope implies a small positive bias from these runs, which could be reduced by increasing the JONSWAP bottom friction constant slightly. In this figure the right hand panels show the comparison between boundary condition and nearshore SWAN Hs; the large amount of scatter in these results illustrates that the application of the bottom friction and other nearshore transformation routines in IRefrac add significant value to the nearshore Hs versus using the directional window only.

Within this report, the performance of the various models are quantified based on three metrics:

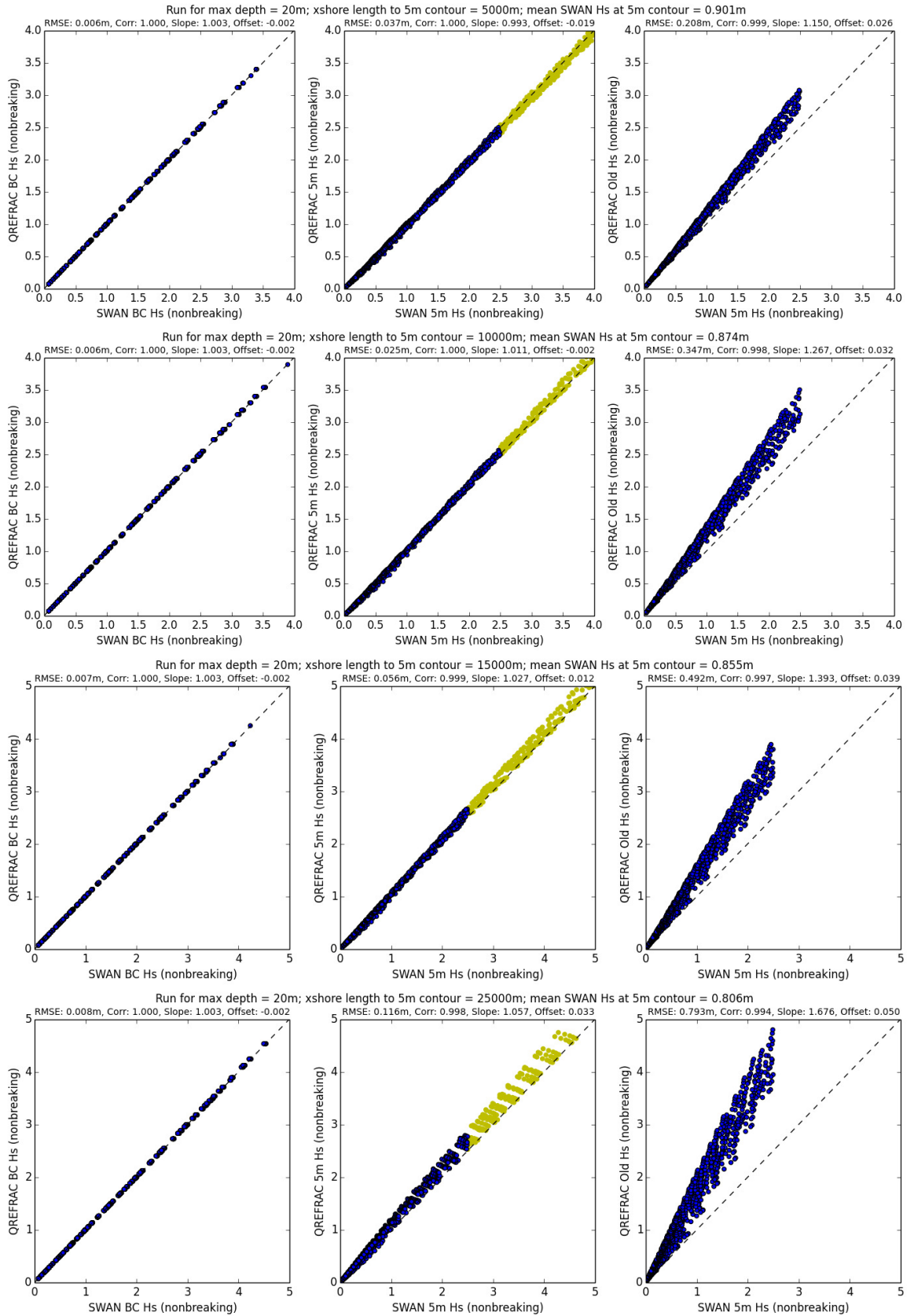
1. A normalised root mean squared error:

$$NRMSE = \frac{\sqrt{E[(x_{prediction} - x_{truth})^2]}}{E|x_{truth}|},$$

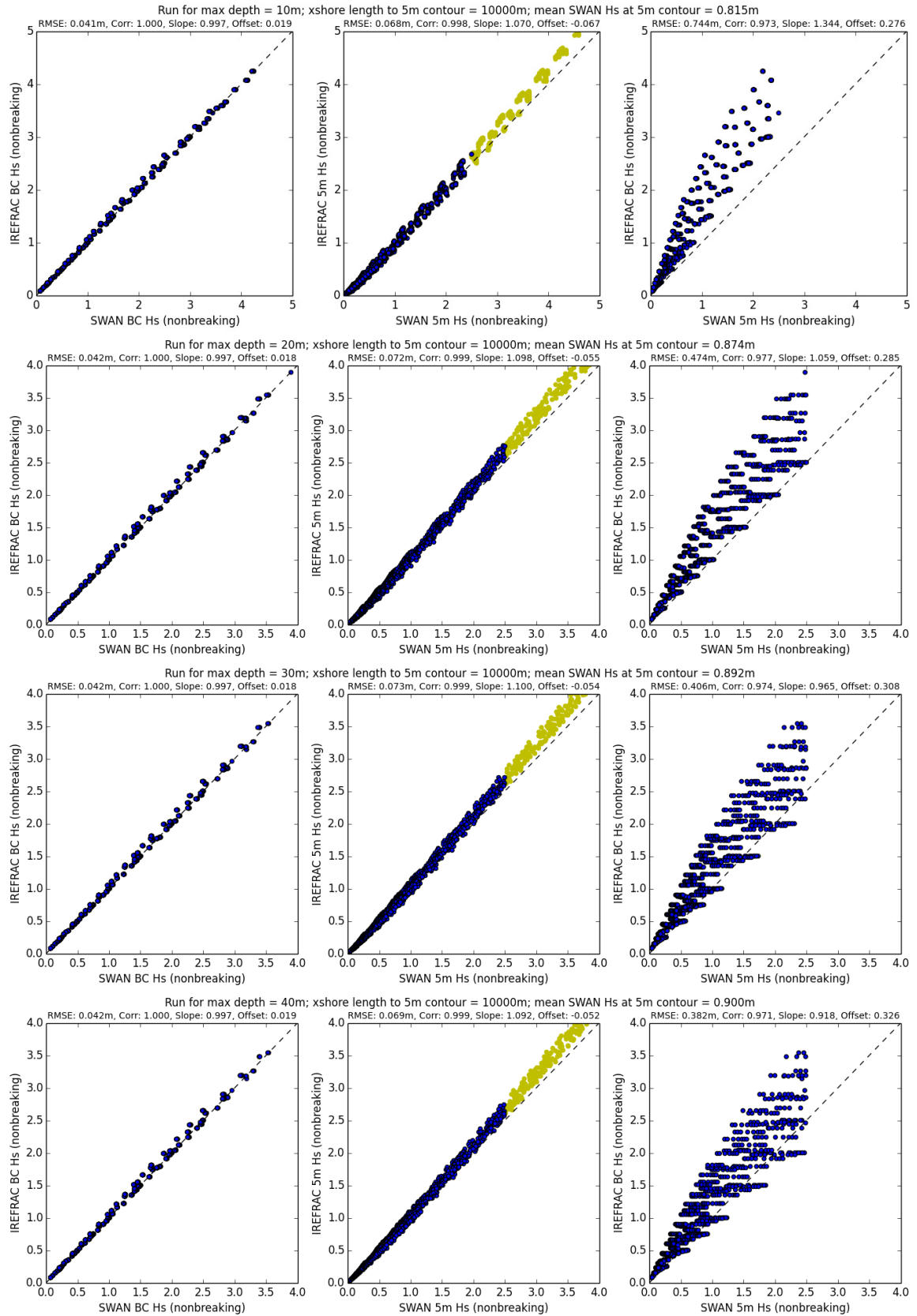
expressed as a percentage. This metric characterises the distribution of ‘prediction minus truth’ errors and incorporates both systematic biases and random errors, which are then framed relative to the mean background condition in order to allow cross-comparison of experiments with different background conditions; relative skill values are noted using the differential between NRMSEs for different runs and are expressed in percentage terms.

2. The (Pearson) correlation coefficient between predictions and truth is used as a secondary metric which implies whether the changes in NRMSE are mostly associated with the random part of the error distribution (i.e. when an increase in NRMSE is associated with a significant decrease in correlation).

3. The slope and offset from a linear least squares fit between truth (independent variable) and prediction (dependent variable) are used to assess systematic biases in the predictor.



**Figure 4.** Comparison of QRefrac including bottom friction and QRefrac without bottom friction against SWAN runs for varying offshore to nearshore distance. Plots are discussed in section 3.



**Figure 5.** Comparison of IRefrac and IRefrac boundary condition against SWAN runs for varying maximum offshore depths. Plots are discussed in section 3.

**Table 1.** Results of Qrefrac and IRefrac (predictions) versus SWAN (truth) idealised tests.

Offshore Water Depth (m)	Distance to 5m contour (km)	Mean SWAN Hs (m)	Qrefrac		Irefrac	
			NRMSE (%)	Slope	NRMSE (%)	Slope
10	5	0.876	3.5	0.991	8.4	1.054
10	10	0.815	5.5	1.012	8.3	1.070
10	15	0.777	10.6	1.028	9.0	1.078
10	20	0.725	13.9	1.039	10.5	1.080
10	25	0.669	16.0	1.045	12.0	1.076
20	5	0.901	4.1	0.993	6.8	1.079
20	10	0.874	2.9	1.011	8.2	1.098
20	15	0.855	6.5	1.027	10.2	1.114
20	20	0.83	10.5	1.042	12.3	1.129
20	25	0.806	14.4	1.057	14.3	1.142
30	5	0.909	4.4	0.993	6.7	1.082
30	10	0.892	3.3	1.010	8.2	1.100
30	15	0.872	5.8	1.027	10.3	1.117
30	20	0.861	9.4	1.044	12.7	1.133
30	25	0.843	13.3	1.061	14.8	1.149
40	5	0.906	5.2	0.985	5.8	1.070
40	10	0.9	3.6	1.006	7.7	1.092
40	15	0.882	5.3	1.025	9.5	1.111
40	20	0.872	8.4	1.044	11.7	1.128
40	25	0.862	11.9	1.062	13.9	1.144

Table 1 lists the NRMSE and slope statistics for Hs predicted by QRefrac and IRefrac in all the idealised experiments. The mean Hs values given in the table are those calculated by SWAN at the nearshore (5m depth) location. The effect of increasing the offshore to nearshore approach profile slope (either by increasing offshore depth or decreasing offshore to nearshore distance) is to allow more wave energy to transition to the nearshore, resulting in a higher mean Hs value. For the shorter offshore to nearshore distances (10km or less) NRMSE values are less than 6% for QRefrac and less than 9% for IRefrac. The agreement between these models and SWAN decreases with increasing offshore to nearshore distance (up to 16% for the 25km case); this coincides with an increase in slope implying that SWAN Hs is overestimated by the models for longer distances. This is an issue that could, for example, be resolved by using a higher JONSWAP bottom friction coefficient. The variation in statistics when offshore water depth is changed is smaller when the offshore to nearshore distance is

altered. Overall, QRefrac is approximately 3-4% more representative of the SWAN data than IRefrac.

## **4. Validation experiments**

Two sets of experiments were used to assess the performance of QRefrac and IRefrac in practical applications. The nearshore models were run using a 1-year sample of offshore boundary conditions derived from Met Office wave hindcast models covering European (8km horizontal resolution) and Global (50km horizontal resolution) domains; these large area wave models generate integrated wave characteristic parameters (significant wave height, period, energy at peak frequency, direction and spreading) for up to four spectral components, enabling reconstruction of multi-modal wave spectra following the technique of Bunney et al. (2013).

### **4.1 Sensitivity to wave climate**

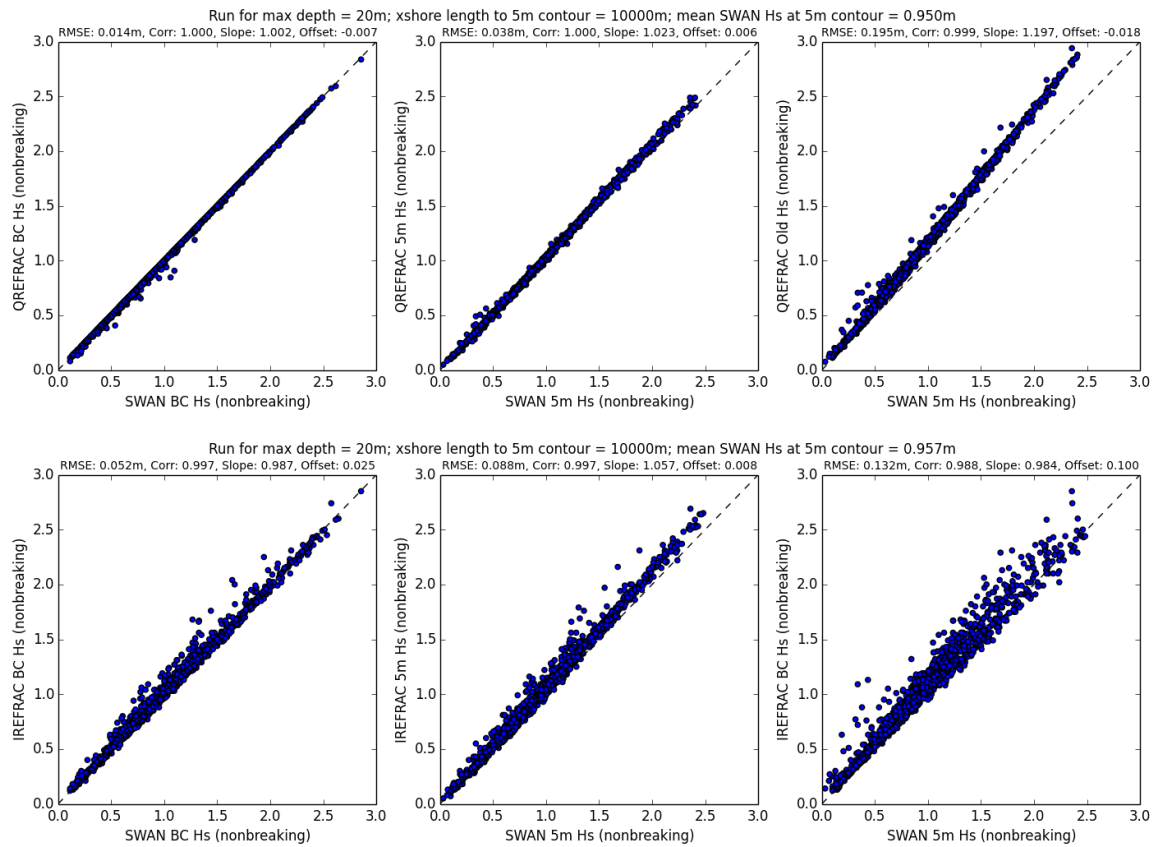
For the first set of experiments, the effect of applying these more complex boundary conditions (compared to the tuning experiments) was tested by selecting two sites with differing wave climates and running these through an idealised linear profile (offshore depth 20m, offshore to nearshore distance 10km) with a westerly facing shore normal. Similar to the idealised runs, the nearshore depth was set at 5m and the analysed nearshore data were cut off at 2.5m in order to ignore cases where wave breaking might usually be present.

- Bideford Bay is exposed to swell and wind-seas generated in the north Atlantic and Irish Sea. The spectra represent a predominantly single or bi-modal wave climate.
- Freetown (Sierra Leone) was used to represent the scenario where the wave climate has a higher frequency of multi-modal seas, being exposed to swells from both north and south Atlantic as well as local wind-seas.

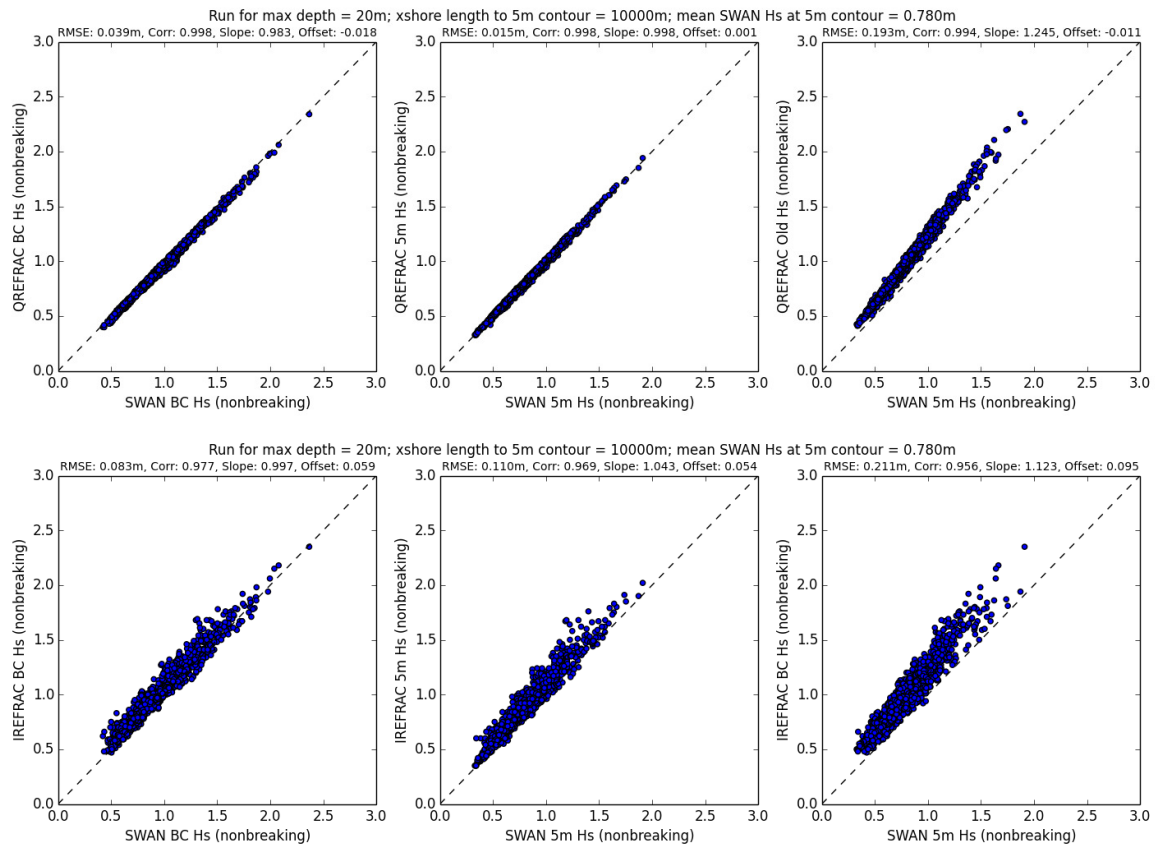
Results from these runs are shown in Figures 6 and 7. The panels in each figure compare model Hs values and follow the same layout; top left, comparison of QRefrac boundary condition versus SWAN boundary condition; top centre comparison of nearshore (5m contour) point QRefrac run with bottom friction versus SWAN; top right comparison of nearshore (5m contour) point QRefrac run without bottom friction versus



SWAN; bottom left, comparison of IRefrac boundary condition versus SWAN boundary condition; bottom centre comparison of nearshore (5m contour) point IRefrac run with bottom friction versus SWAN; bottom right comparison of IRefrac boundary condition versus SWAN nearshore point. Although the cases are different, the results show some common behaviours. The most important differential between the QRefrac and IRefrac runs appears to be the calculation of shoreward propagating energy at the offshore boundary; the more simplistic IRefrac approach introduces some level of scatter compared to SWAN, whilst QRefrac maintains a very good 1:1 relationship. This effect impacts IRefrac most significantly in the more complex Freetown case. NRMSE values for the comparison with SWAN Hs are 2-4% for QRefrac and 9-14% for IRefrac. For both models some additional scatter, over and above that at the boundary, is introduced via the nearshore transformation. However both methods show a significantly better replication of the SWAN results than predictions based on QRefrac without bottom friction or the IRefrac boundary condition (order of 10-15% skill improvement for QRefrac and 5-11% for IRefrac), demonstrating that the refraction and bottom friction parameterisations add significant value.



**Figure 6.** Wave climate sensitivity runs using the Bideford Bay wave spectra. Plots are discussed in section 4.1.



**Figure 7.** Wave climate sensitivity runs using the Freetown wave spectra. Plots are discussed in section 4.1.

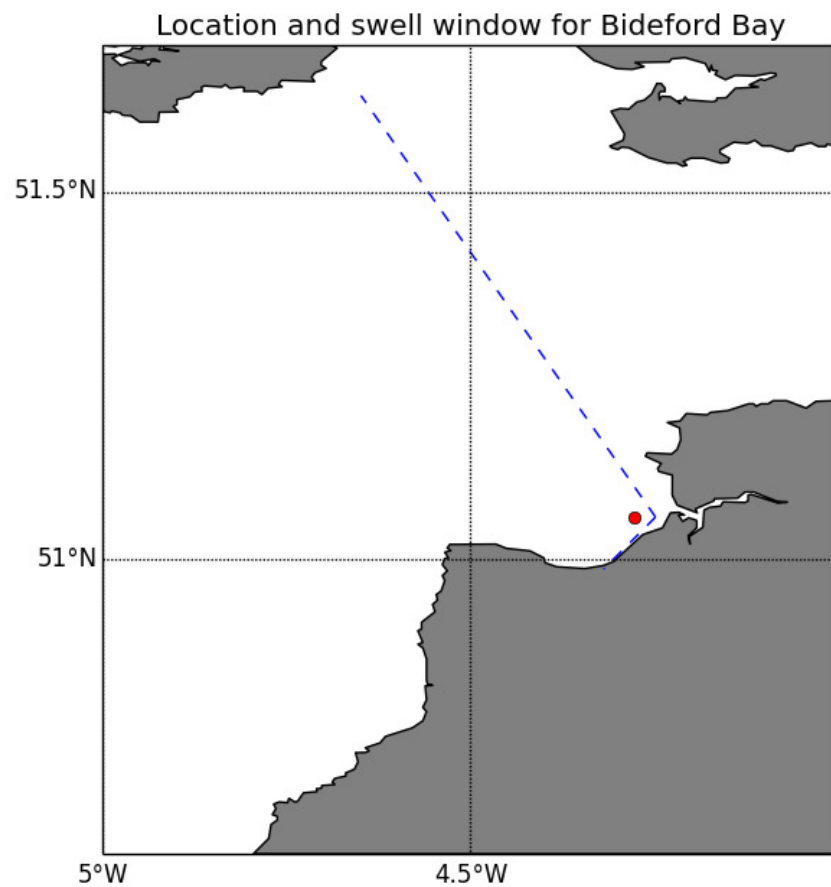
## 4.2 Comparison against buoy data

In the second series of experiments 1-year runs using hindcast offshore wave spectra were applied to full practical applications, using more constrained beach windows for QRefrac and IRefrac and properly configured gridded bathymetries for the SWAN models. Runs were made for an exposed coastal case (Bideford Bay) and a more complex sheltered coast (Mount's Bay). Configuration details are given in Table 2 and illustrated in Figures 8 and 9. The results from the model runs were assessed against an observed truth acquired from wave measuring buoys maintained by the Channel Coast Observatory and sited in approximately 10m water depth (versus Chart Datum). Variation in water levels due to tides was not included in the model runs, so a mean water level was used based on an average tidal elevation above chart datum. In these

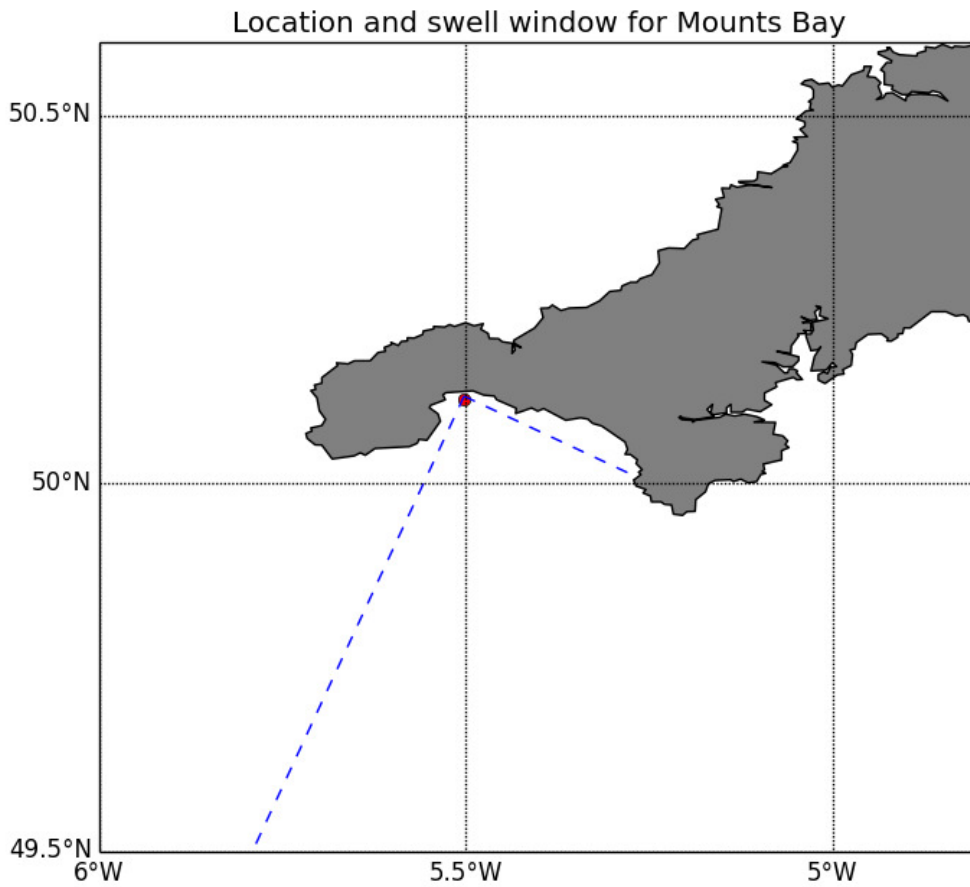
cases, the buoys are sited in sufficiently deep water that the breaking wave height constraint for data analysis did not need to be applied.

**Table 2.** Configuration details for runs to validate models against buoy data

Site	SWAN Domain	QRefrac/IRefrac Set-Up	Buoy Location
Bideford Bay	XSize: 9500m YSize: 11000m DX: 250m DY: 250m	Offshore depth: 22m Buoy depth: 15m Dist to buoy: 6700m Beach normal: 275° Beach half window: 50°	51° 03.48' N; 4° 16.62' W
Mount's Bay (Note: SWAN scales approximated from spherical coordinates)	XSize: 22800m YSize: 16300m DX: 270m DY: 330m	Offshore depth: 50m Buoy depth: 13m Dist to buoy: 15000m Beach normal: 160° Beach half window: 45°	50° 06.86' N; 5° 30.19' W



**Figure 8.** Location and directional window for Bideford Bay run



**Figure 9.** Location and directional window for Mounts Bay run

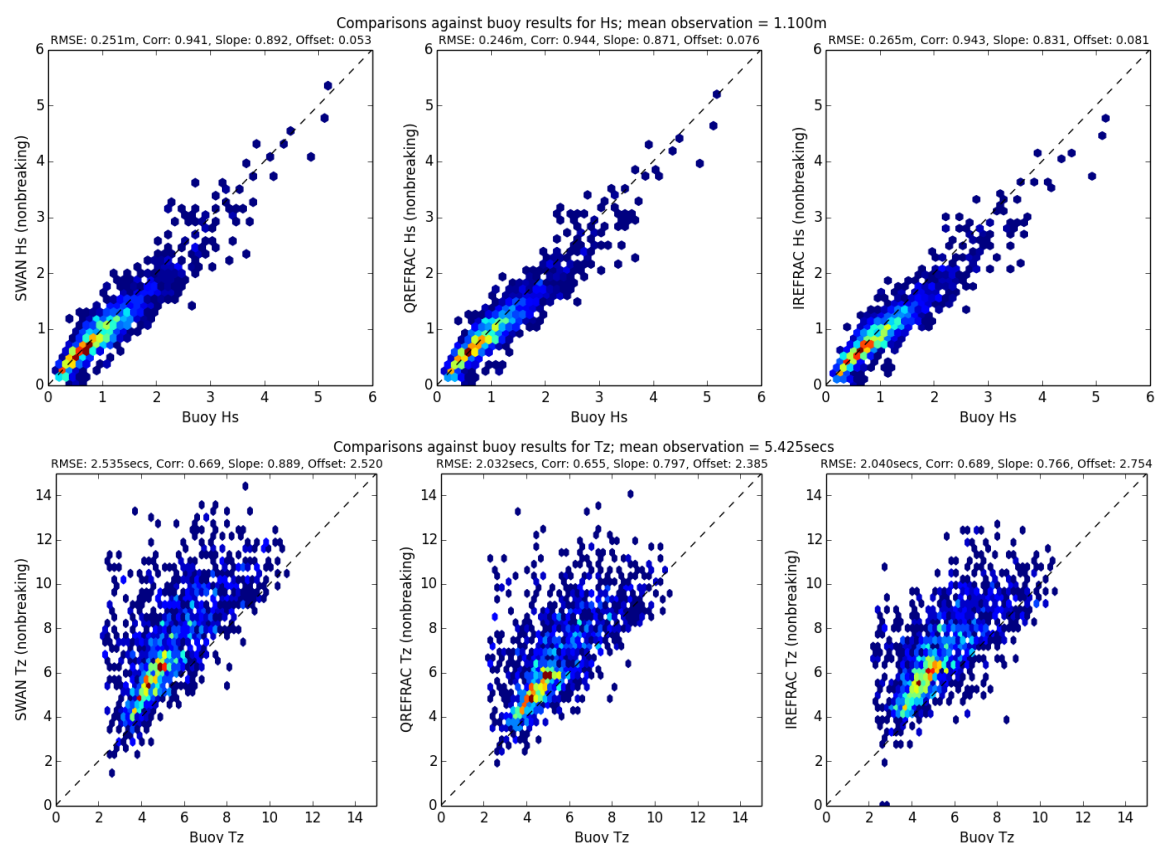
Results from the runs are shown in Figures 10 and 11 and presented in Table 3. In addition to  $H_s$ , the mean zero-upcrossing period ( $T_z$ ) was also compared. At Bideford Bay (Figure 10) the differences between the three model types (QRefrac, IRefrac and SWAN) are almost negligible and performance against measured  $H_s$  is good, with NRMSE of 22-24% and correlation coefficients of 0.94.  $T_z$  scores are not as good, with NRMSEs ranging from 37-46% and correlation values of 0.65-0.69. The scatter plots for  $T_z$  indicate some systematic over-estimation by all the models. This may be influenced by one or both of the offshore boundary conditions used by the runs and the fact that none of the runs shown in Figure 10 include the influence of local winds, which may cause agitation of higher frequency waves and reduce  $T_z$ .

In the more complex Mounts Bay case model  $H_s$  performance is slightly reduced for all models (NRMSE for  $H_s$  increases to 28-32%) and SWAN performs best. However, the

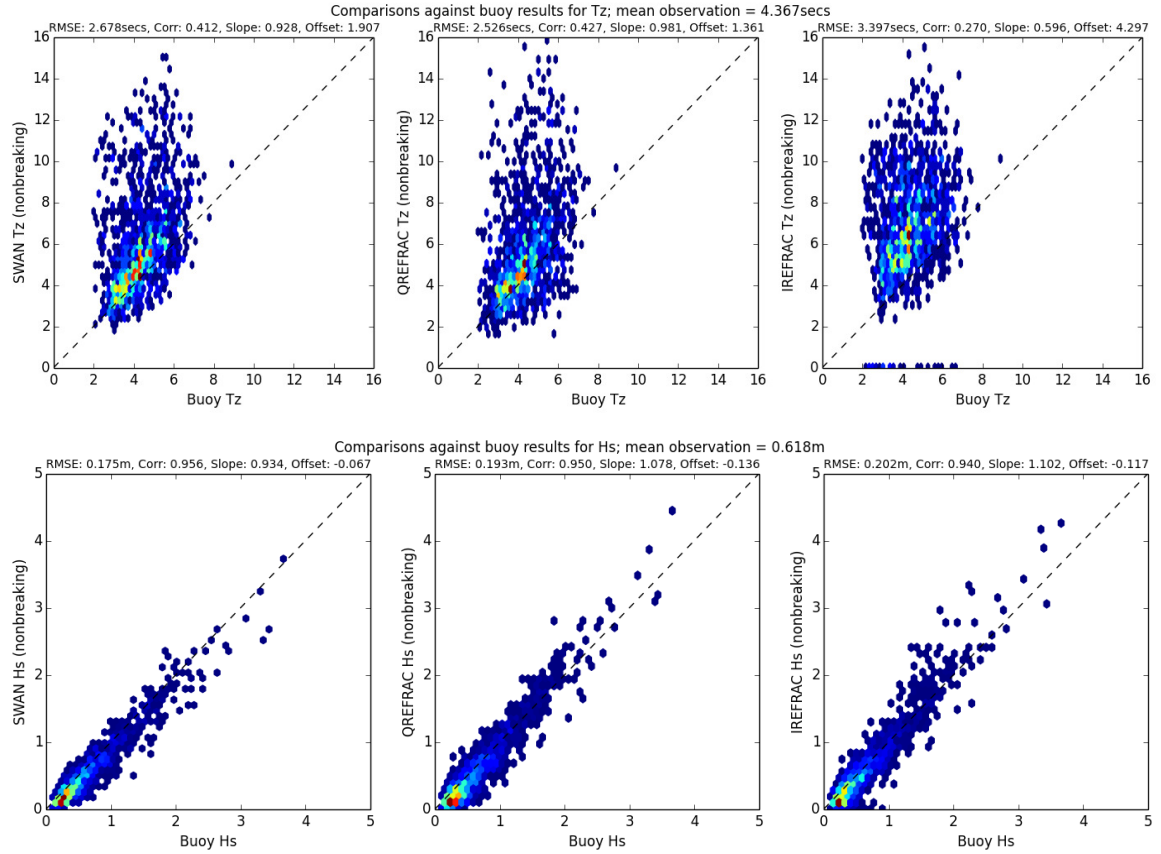
skill differentials are small, being of the order 3%. Tz performance is poor for all three models and, in the case of this sheltered bay, is likely to be heavily influenced by the lack of representation of local wave generation by winds within the bay.

**Table 3.** Performance against wave buoy observations for models run at Bideford Bay and Mounts Bay

		SWAN (wind)		SWAN		Qrefrac		Irefrac	
	Mean Observation	NRMSE (%)	Corr.	NRMSE (%)	Corr.	NRMSE (%)	Corr.	NRMSE (%)	Corr.
Bideford Bay Hs (m)	1.100	21.636	0.945	22.818	0.941	22.364	0.871	24.091	0.943
Bideford Bay Tz (s)	5.425	32.516	0.811	46.728	0.669	37.456	0.655	37.604	0.689
Mounts Bay Hs (m)	0.618	23.463	0.954	28.317	0.934	31.230	0.950	32.686	0.940
Mounts Bay Tz (s)	4.367	43.714	0.489	61.324	0.412	57.843	0.427	77.788	0.270

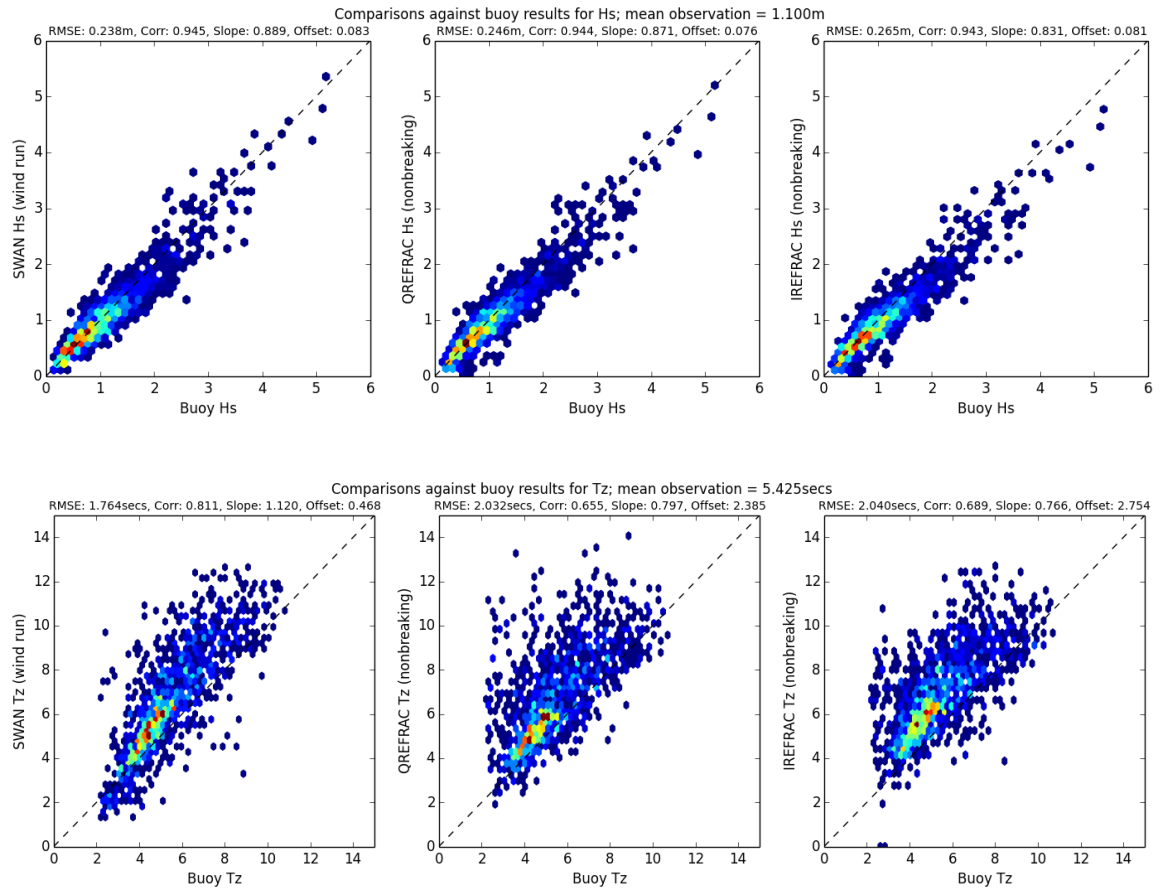


**Figure 10.** Comparison between SWAN, QRefrac and IRefrac versus observations at the Channel Coast Observatory Bideford Bay buoy. Top left, SWAN versus observed Hs; top centre, QRefrac versus observed Hs; top right IRefrac versus observed Hs; bottom left, SWAN versus observed Tz; top centre, QRefrac versus observed Tz; top right IRefrac versus observed Tz.



**Figure 11.** Comparison between SWAN, QRefrac and IRefrac versus observations at the Channel Coast Observatory Mount's Bay (Penzance) buoy. Top left, SWAN versus observed Hs; top centre, QRefrac versus observed Hs; top right IRefrac versus observed Hs; bottom left, SWAN versus observed Tz; top centre, QRefrac versus observed Tz; top right IRefrac versus observed Tz.

In order to test just how much the absence of local wind forcing might affect the skill of these models, the SWAN runs were repeated with a standard forced model set-up using the Komen wave physics and nonlinear interactions for simulating wave growth processes under wind forcing. The results from these SWAN runs are compared with QRefrac and IRefrac in Figures 12 and 13, and in Table 3. In the Bideford Bay case the performance gain is marginal for Hs (approximately 1% NRMSE improvement versus the best performing model) and limited (5% NRMSE differential) for Tz. In the more sheltered Mount's Bay, where local winds would be expected to have a comparatively stronger influence, the gains are more substantial; the SWAN run including winds has an 8% differential for Hs and order 15-30% improvement in Tz (although it should be noted that correlation with the observed series remains low, less than 0.5, even for this run).

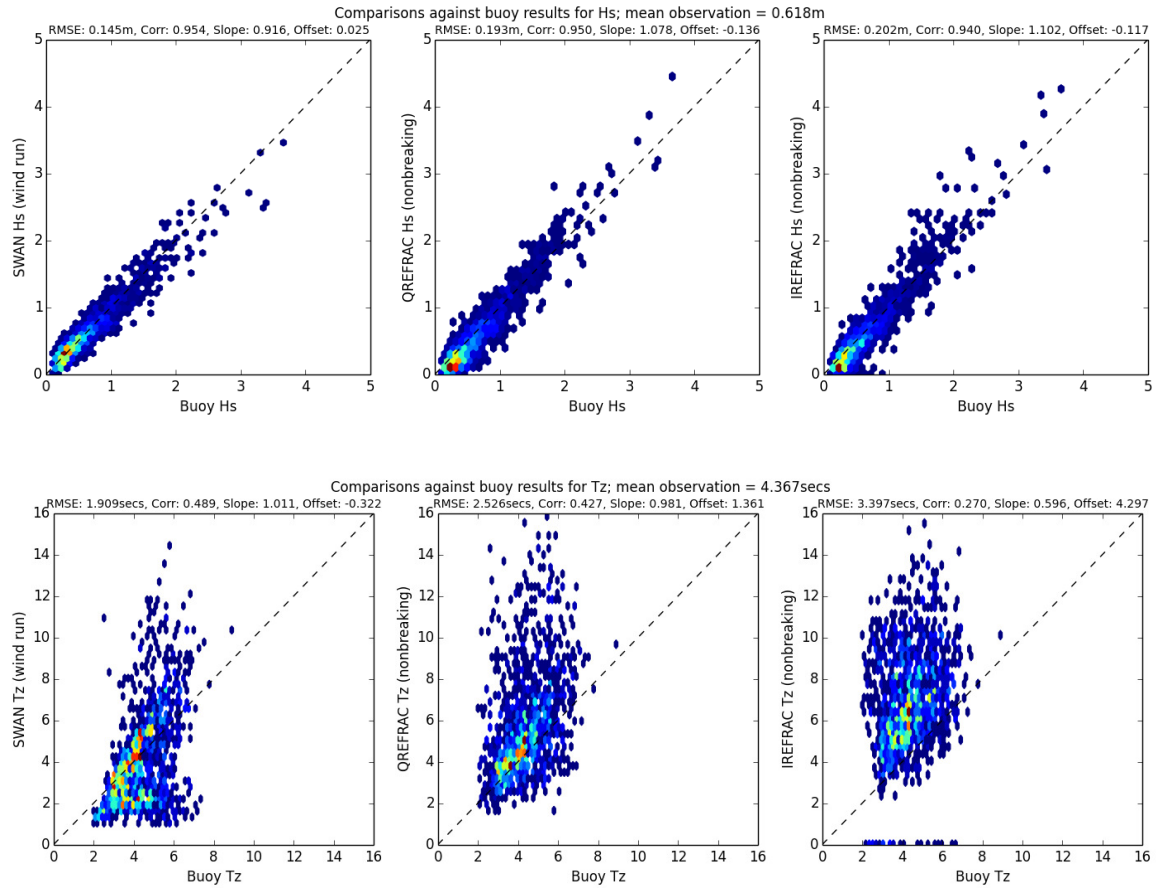


**Figure 12.** Comparison between SWAN run including winds, QRefrac and IRefrac versus observations at the Channel Coast Observatory Bideford Bay buoy. Top left, SWAN versus observed Hs; top centre, QRefrac versus observed Hs; top right IRefrac versus observed Hs; bottom left, SWAN versus observed Tz; top centre, QRefrac versus observed Tz; top right IRefrac versus observed Tz.

## 5. Discussion

The results of the various experiments described in this report suggest that, in certain cases, a significant degree of the value added to an open waters wave model forecast via full model downscaling (e.g. using a high resolution shallow water wave model such as SWAN) can be obtained using simple one-dimensional process models such as QRefrac and IRefrac.





**Figure 13.** Comparison between SWAN run including winds, QRefrac and IRefrac versus observations at the Channel Coast Observatory Mount's Bay (Penzance) buoy. Top left, SWAN versus observed Hs; top centre, QRefrac versus observed Hs; top right IRefrac versus observed Hs; bottom left, SWAN versus observed Tz; top centre, QRefrac versus observed Tz; top right IRefrac versus observed Tz.

The comparisons against buoy data confirm that these methods are not sophisticated enough to be used generically as a direct replacement for a well prepared third-generation spectral wave model, such as SWAN. However, there are circumstances where being able to apply these alternative techniques for nearshore wave prediction may be an advantage due to the relative speeds of the different models. In the trials described in this report QRefrac runs were one or two orders of magnitude faster than the SWAN runs and the IRefrac runs were two orders or more faster. The implication of is that QRefrac or IRefrac provide a much more scalable method of producing site specific nearshore forecasts over multiple sites and large areas of coast. In addition, these models do not have the significant initial set up and re-run costs that are associated with other rapid prediction methods such as wave look-up tables (e.g.



Leonard-Williams and Francis, 2013) and will produce much better results than simply using the offshore wave conditions as an estimator.

The assumptions that underly these methods provide a guide to both the cases where implementation of QRefrac or IRefrac would not be appropriate and reasons for poor performance when using these models to predict nearshore waves. By using a 1D method the two models ignore details of nearshore refraction/diffraction, that may cause 'hotspots' or 'shadows' in the wave field over (or downstream of) shoals, and blocking effects due to nearshore zone islands. Local wave generation or modification by winds and currents are also ignored. This implies that QRefrac and IRefrac are best used when: a) the transition zone from the offshore model coastal cell to the nearshore is characterised by relatively simple two-dimensional bathymetry contours; and b) any embayment being forecast is not so sheltered that local wind effects dominate the climate of the nearshore wave field. These criteria will be met when the models are coupled with boundary conditions from larger area models with 1-10km cell scales.

Based on these limitations, it is not recommended that either method be used as a generic model for predicting nearshore waves; since cases where local waves are generated under offshore winds would be missed. However, the intended purpose of the models is to evaluate the shoreward propagating wave energy as a boundary condition for a surf height prediction algorithm. In the case of these specialised forecasts both models appear fit for purpose, since the assumptions that the majority of wave energy influencing surf heights is generated well offshore and is only influenced to a small extent by local wind conditions should hold for the majority of cases.

In the experiments described here, none of the models used a parameterisation for depth limited breaking. This was a deliberate choice and has been applied since QSurf is designed to perform this calculation in the nearshore zone. In such a system the purpose of the downscaling model is to determine an estimate of the equivalent offshore wave height and period, i.e. the offshore energy and wave steepness that will influence the surf height. In principle, shoaling effects could also be ignored (since the nearshore waves predicted by the downscaler are de-shoaled in QSurf), but this approach would not have enabled the use of SWAN, in which shoaling is an implicit effect of the model's propagation scheme.

A particularly encouraging facet of the study was that there was no need to use significantly different values of the JONSWAP bottom friction constant (from the value used in SWAN of 0.038), when running the QRefrac and IRefrac experiments. This suggests that the simplifying assumptions made for offshore to shoreward wave energy

transformation in these models are robust. Similarly, agreement between the QRefrac and SWAN shoreward propagating boundary conditions were excellent, whilst the boundary condition differences for IRefrac have been identified as an area in which that model could be further improved. The results of the comparisons against the buoy observations indicate that, in any case, the uncertainties from the QRefrac/IRefrac versus SWAN comparisons are significantly smaller than those that are imparted to the models by their offshore boundary condition (in turn a function of wind prediction over a large fetch area, order 100s-1000s kilometres, by a numerical weather prediction model). The SWAN shallow water source term parameterisations may also introduce uncertainties.

Tests against measured data indicate that predictions of significant wave height are more skilful than those of wave period. This is a known issue for all of the present generation of wave models (deep and shallow water). The relative skill differentials between SWAN (without wind forcing), QRefrac and IRefrac in these tests were almost negligible. This result is worth noting since the quality of the wave period prediction has some implications for the skill of the surf prediction routine QSurf, which is built upon relationships between deep water wave steepness and the nearshore breaking wave height to water depth ratio. The implication from the results is that wave period may be over-predicted, which would lead to a subsequent over-prediction of surf heights. Both testing this theory and making a more detailed analysis of the directionality of high frequency wave components measured by the wave buoys (to further check the influence of wind forcing) are proposed as subjects for further work.

## **6. Conclusions**

This study has evaluated two simplified coastal wave downscaling methods, QRefrac and IRefrac, against the established, more complex, third generation spectral wave model SWAN. The results indicate that, for cases where bathymetry in the coastal zone is not particularly complex (e.g. the bathymetry does not include shoals leading to strong two-dimensional patterns of refraction and diffraction), topographic sheltering is limited to coastal headlands (no islands within the nearshore domain) and wind-sea growth effects are secondary processes compared to local refraction and dissipation, the simple methods compare favourably with SWAN outputs. Case studies for a relatively simple (Bideford Bay) and more complex (Mounts Bay) coastal zone have been used to demonstrate that, within a practical application, the downscaling methods also verify well against coastal wave buoys. In these cases, QRefrac and IRefrac showed similar

performance characteristics to the SWAN model (when neglecting local wind effects), particularly for predictions of significant wave height. Crucially, these results were achieved with an order of one to two magnitudes speed up of the models compared to SWAN and a set-up time which took tens of minutes and required no high resolution bathymetry data.

Of the two methods, QRefrac proved the better with approximately 3-10% lower normalised root mean squared errors than IRefrac in idealised comparisons against SWAN and 1-2% lower errors in the practical comparison against observations. A large degree of this improvement is attributed to QRefrac using the full wave spectrum when calculating its shoreward propagating wave boundary condition. The effect of bottom friction was also identified as a key process in the models; the implementation of this parameterisation in QRefrac and IRefrac required no significant alteration compared to the JONSWAP bottom friction constant used in SWAN. Tests against measured data indicate that predictions of significant wave height are more skilful than those of wave period. This is a known issue for all wave models and the relative skill differentials between SWAN (without wind forcing), QRefrac and IRefrac were almost negligible.

These results should be set against the context in which QRefrac and IRefrac are expected to be applied successfully. These are conditions in which: a) the parameters needing to be forecast are primarily a function of the wave energy being transmitted into the nearshore zone; b) the boundary condition wave model correctly represents the main processes developing this wave energy; and c) that the major processes affecting waves in the nearshore zone can be represented using one-dimensional processes. For open coasts, or when the boundary wave model is scaled on the order of kilometres, these conditions will be met quite regularly. However, there will be exceptions when local wave source term processes dominate, for example where local topographic sheltering (e.g. a barrier island is sited between the offshore wave point and the beach) or strong coastal currents may modify the wave field. In these instances a full two-dimensional spectral wave model (e.g. SWAN with wind forcing and wave source terms switched on) will be necessary in order to generate an accurate forecast. That being said, use of QRefrac/IRefrac is still likely to add value over simply using open waters offshore forecast data in such instances.

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**Met Office**  
FitzRoy Road, Exeter  
Devon EX1 3PB  
United Kingdom

Tel (UK): 0870 900 0100 (Int) : +44 1392 885680  
Fax (UK): 0870 900 5050 (Int) :+44 1392 885681  
[enquiries@metoffice.gov.uk](mailto:enquiries@metoffice.gov.uk)  
[www.metoffice.gov.uk](http://www.metoffice.gov.uk)