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Technical information related to hindcast forced wave climate estimation for the Faroe Islands ano 2012

B. A. Niclasen

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Technical information related to High resolution Wave climate for the Faroe Islands

Bárður A. Niclasen, December 2012

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1 Introduction

This report aims at documenting the technical details behind the wave climate results presented in the technical report “High resolution wave climate of the Faroe Islands” (Niclasen and Simonsen, 2012).

At our disposal we have 44-year of integrated wave parameters DMI hindcasted data, which we can use to force the high resolution hindcast. We have to get as high spatial resolution as possible, while at the same time being able to run the model on a few workstations. In order to do this we have to simplify the computational task as much as possible while retain as much accuracy as possible. We could do the classical approach and derive the wave statistics offshore and subsequently only propagate a few statistically derived cases into the nested model domain. This would do, but here we rather want to derive time series in all model points, as this will be beneficial for subsequent local wave studies.

In the end we therefore limit the real incoming sea state into being composed by a series of pre-computed idealized cases. The challenge task is therefore to limit the number of pre-computed idealized cases as much as possible while keeping the accuracy as high as possible.

2 Forcing data

Forcing is obtained from DMI reanalysis wave model which is a implementation of WAM. The model has a spatial resolution of 0.1° Latitude and 0.2° Longitude or approximate 10 km. The spectral resolution is 32 frequencies and 24 directions. The parameters used are:

- wind velocity at 10 meter height: U_{10}
- significant wave height: H_{m0}
- energy wave period: T_{m-10}
- mean wave direction Dir_{mean}.

The wave parameters are given for swell and wind-sea. On top of this there also is T_{m01} wave period and peak wave period T_p for total sea. The parameters are available at 1-hour intervals spanning from 1960 to 2003, both years included. These parameters are available in all model points in an area 150x150 km.

3 Simplifying assumptions

In this study we need very high spatial resolution hindcast over a long time span and using limited computational power (a few powerful workstations). Due to forcing type but mostly due to the computational limitations we have to resort to simplifying the problem at hand. The most important are:

- Forcing by average parameters rather than wave spectra
- Stationarity rather than dynamic evolution in time
- One incoming sea state rather than different forcing on each border
- Homogeneous wind forcing

in the following sections we have a closer look at the validity and implications of these

3.1 Average parameters

We do only have average parameters at the boundaries, and this does limit the correctness of the incoming wave field. Without being able to document this properly, it is assumed the correct amount of energy and simplified 1D shape of the spectrum should be correct (general spectrum is fitted to parameter values, see “spectral fitting from parameters” section below).

The unknown spreading is a issue which cant be solved, and the spreading is set to recommended values for wind sea and swell respectively.

To ensure that the main properties of the wave field are represented in a continuous time evolving manner we use T_{m-10} rather than T_p wave periods to force the model.

The critical problem with using parameters and not spectra at the boundaries, is that the parameters lack most of the directionally information represented in the full 2D-wave-spectra. This is particularly a problem if the modeled region has open boundaries on all sides, as is the case in this investigation. The problem is, that wave energy going out trough a border in the forcing model, is included in the wave height used to force the nested model. It is therefore expected that parameter forcing rather than spectral forcing inflicts a positive bias in the imposed wave height.

3.1.1 Spectral fitting from parameters

Using the DMI-hindcast (Danish Meteorological Institute), the nested model could be forced by several ways. To get an idea about which of these options best fit with the physics in the forcing model, time-series from all parameters in an open-ocean forcing-model-point are compared. What is done is that wave height and one type of wave-period (of either from total sea or a combination of wind-sea and swell) are used to predict two other partly independent wave periods (T_p and T_{m01}) of total-sea using different assumptions. In this manner we can see what combination of parameters and assumptions are most suited for describing the most representative sea state of the forcing model. PM is used below as an an abbreviation for Pierson-Moskowitz spectral estimate for fully developed seas.

The tested options are:

1. Use total-sea H_{m0} only and assume fully developed PM-spectrum .
2. Use total-sea H_{m0}, T_{m-10} and assuming generalized PM-spectral shape.
3. Use total-sea H_{m0}, T_{m-10} and assuming generalized JONSWAP-spectral shape.

4. Use H_{m0}, T_{m-10} from wind-sea and swell, assuming that both have generalized PM-spectral shape.
5. Use H_{m0}, T_{m-10} from wind-sea and swell, assuming that wind-sea has generalized JONSWAP-spectral shape while swell has generalized PM-spectral shape.
6. Use H_{m0}, T_{m-10} from wind-sea and swell, assuming that both have generalized JONSWAP-spectral shape.
7. Use H_{m0}, T_{m-10} from wind-sea and swell, assuming wind-sea has generalised PM-spectral shape, while swell has generalized JONSWAP-spectral shape.

Abbreviations are:
ME: Mean Error
MAE: Mean Absolute Error
SdE: Standard deviation of Error

	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**	**Option 7**
MAE H_{m0}	0.00044	0.00000	0.00101	0.00001	0.00042	0.00101	0.00058
MAE T_{m-10}	1.60540	0.00259	0.00213	0.00255	0.00284	0.00210	0.00182
MAE T_p	2.50682	0.90998	1.13006	0.82333	1.24534	0.87756	0.87328
ME T_p	2.21174	0.46709	0.97679	-0.03818	0.63934	0.42090	-0.14686
SdE T_p	2.05144	1.19586	1.18135	1.16280	1.73212	1.19336	1.23724
MAE T_{m01}	1.12216	0.44115	0.60001	0.16073	0.19718	0.21919	0.16140
ME T_{m01}	0.95130	-0.39496	-0.59356	-0.00068	-0.08002	-0.18893	-0.10822
SdE T_{m01}	1.23786	0.41249	0.40509	0.21990	0.23643	0.20277	0.20104

From the Table above it is clear that representing the ***forcing model sea state as a combination of wind-sea and swell, where both are assumed to have the from of a generalized PM-spectrum is the best option***.

3.1.2 A few words on spectral fitting in SWAN

The nested model (SWAN) can only by default be forced by T_p or T_{m01}, both of which are not given by the DMI-hindcast wind-sea and swell. So there is a need to translate from T_{m-10} to T_p. This of cause dependent upon the shape of the spectrum. The simplest spectra that can be fitted is the generalized PM spectral see Tucker and Pitt (2001) section 5.5.1.2. which is accordance with the average shape of measured spectra south of the Faroe Islands i.e. smooth with peak lower than usual PM spectrum only based on H_{m0}.

$$S(f)=A\ f^{-5}\mathrm{e}^{-B f^{-4}}$$

where H_{m0}=2(A/B)^0.5 and T_z=0.751*B^-0.25. Which can be fitted to any values of H_{m0} and T_z. It is possible as also done in Tucker and Pitt to use other periods by using the general formula for spectral moments, which is reasonably accurate for this spectra.

$$m_n=¼\ A\ B^{n/4-1}*\Gamma(1-n/4)$$

Using this we find that $T_{m-10} = m_{-1}/m_0$ = . . . and comparing this to T_p=1.057*B^-0.25 we get:

$T_p = 1.1662 * T_{m-10}$

This is this relationship which will be used to force SWAN with T_{m-10} data from DMI.

After taking out the boundary spectral-shape generation routine from SWAN (written in Fortran) and importing it into Matlab some tests were done in order to check how they compare with what has been mentioned above. It was found that:

1) In the general PM spectrum T_p is best expressed by T_{m-10} by the following expression

   $T_{p\ PM}$ = **1.1662** * T_{m-10} (same as mentioned above)

2) In the general JONSWAP spectrum T_p is best expressed by the following expression

   $T_{p\ JP}$ = **1/0.9035** * T_{m-10}, which is inspired by table in Goda (2010) but fitted somewhat) gave almost identical results i.e. T_{m-10} from the spectra returned the same value of T_{m-10} and H_{m0}.

3.2 Stationarity

Assuming stationarity means:

1:
The modeled area (size approximately 100 km in its longest direction) is small compared to the speed of the waves. This assumption implies that all waves propagate fully trough out the model instantly i.e. wave dispersion is assumed not to play any role. This causes a positive time lag in the model as wave field travel too fast from the borders and into the model areas. As this is a statistical rather than an regular hindcast investigation, the implications of this error is believed to marginal for the final outcome.

According to the south buoy Niclasen and Simonsen (2007), the mean measured wave periods are T_{m02}=6.4 s and T_p=10.6 s. If we assume that it is reasonable to say that the wave/wind field is approximately stationary for an hour, this means that the average dominant waves travel a distance of 40-60 km according to the deep water wave speed $c = T*g/(2*pi)$. So in average the assumption is not fulfilled, but it is not way off either.

2:
If wind is imposed on the wave field all waves are fully developed i.e. fetch limited according to the fetches within the model. This most likely causes a positive bias in the estimated wind-wave height within the model.

A thorough review of the implications of the stationary assumption is given in Rogers et al (?).

3.3 One-sea-state

If the model domain is small compared to the forcing swell and wind-sea systems, then the same forcing can be applied on all model borders, if the model domain is situated in open ocean conditions. That is the same forcing wave-height, -period and -direction are imposed on all borders.

This is clearly a wrong assumption for the boundary opposite to the incoming wave field, i.e. the side which is sheltered from the land within the model domain, but this has no serious implications as the imposed waves are directed out of the model.

This simplification greatly reduces the computational task as it is not necessary to combine wave systems from the 4 surrounding boundaries, i.e. one model run covers all incoming swell or wind-sea systems.

3.3.1 Determining the “one-sea-state”

If the nested model domain is truly small compared with the forcing wave field, then the forcing can be determined by using the average values from the border with the largest wave height. Alternatively the forcing could also come from only one forcing point on each side (the coarse model, nested model side mid-point) or from the locations where the buoys are located. Inspections showed that these methods gave almost equal results.

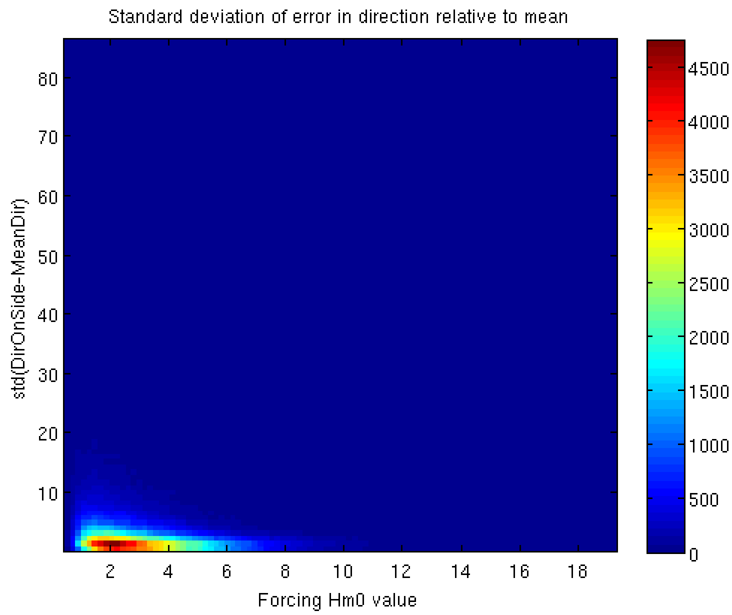
Height only version:

- Average the wave height on four borders in the forcing model.
- The side with largest average wave height is set to be the defining side of the one-sea-state. This means that wave-direction and wave-period of the one-sea-state are taken as the average values derived from this border.

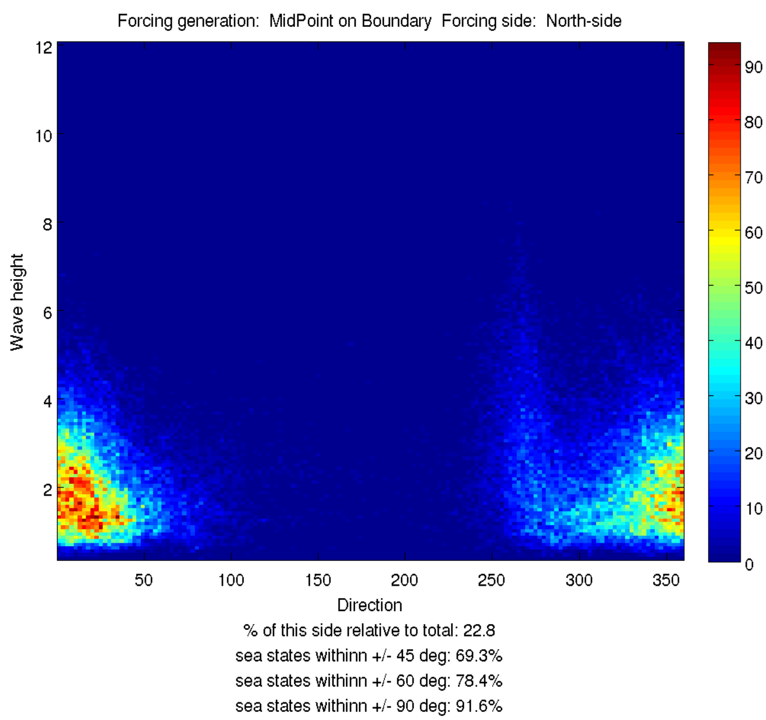
One test to see if this assumption about the nested model side being small compared with the size of the nested model domain, can be obtained by looking at how much the wave heights vary on the forcing side according to the forcing model. When this is done we see that the standard deviation of the error of the H_{m0} values relative to the mean value of the side, is only 7.8 cm or in average the error has a standard deviation of 2.5%. So in the majority of the cases the variation in H_{m0} along the forcing side are negligible.

```
mean(S.Forc_StdEr_Hm0./S.Forc_Bord_Hm0)
        ans =  0.0251
mean(S.Forc_StdEr_Hm0)
        ans =  0.0784
```

Using this definition lead to some controversy when looking at the mean-wave-direction relative to the normal of the respective forcing sides. If the “one-sea-state” assumption was in perfect accordance with reality, at least reality as represented in the forcing model, then the forcing mean-wave-direction would be expected to be aligned with the normal to the respective side +/- 45°. In average this is a reasonable assumption as can be seen by the following contour plot of of the standard deviation of the directional difference between



but looking in more detail it was found that the error was too large to be ignored. In the following plot showing how the mean direction on the north border is aligned with the normal direction of the north side in those cases where the north-side is the “one-sea-state” defining side according to the original criteria mentioned above



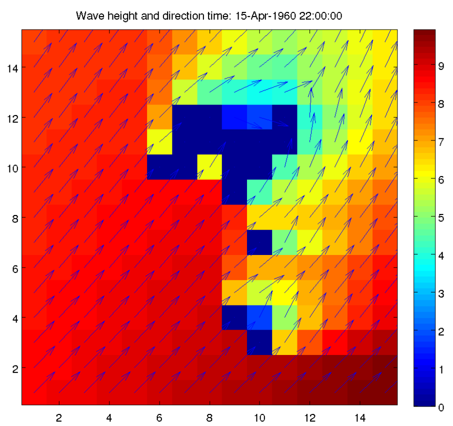
We would expect that close to 100% of the cases the mean wave direction were aligned with the side normal (here 0° or 360°), but less than 70% of the cases are. The problem is even more evident when looking at all cases in the range from [270°; 90°] which correspond to all cases where waves, accordant to their direction, travel inwards trough the north-side, but this only covers some 92% i.e. in 8 % of the cases the imposed forcing waves travel out and not in trough the “one-sea-state” defining side.

The plot shown above is for swell and the corresponding errors in total-sea of wind-sea are even worse. To correct for the apparent deficiency in determining the forcing side of the one-sea-state, an alternative definition was used

<u>Directionally filtered version:</u>

- Average the wave-direction and wave-height on four borders in the forcing model.
- Only sides with waves traveling close to the normal direction of that side (+/- some tolerance) can be used as one-sea-state defining sides.
- The remaining side with largest average wave height is set to be the defining side of the one-sea-state. This means that wave-direction and wave-period of the one-sea-state are taken as the average values derived from this border.

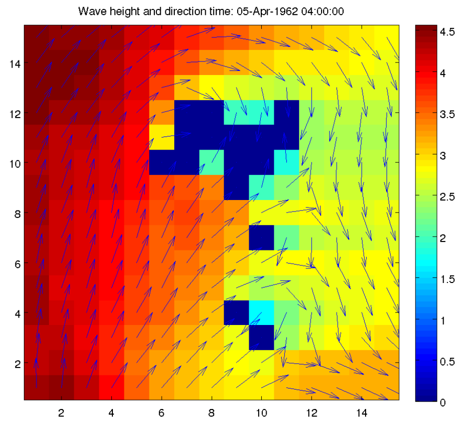
Using this version of selecting the one-sea-state defining side, the strictest directional tolerance (i.e. of side normal +/- 45°) could represent 98% of all cases. One example of a situation which could not be represented under this condition is the following



As can be seen from the figure, the south side has the largest average wave height but the incoming wave-direction is closer to the normal direction of the west side. This figure also illustrates the strength and weakness of method: the area is typically small compared to the spatial dimensions of the forcing wave fields, but using the side with the largest average wave height as the one-sea-state defining side does inflict a positive bias for some regions of the nested model domain.

If the tolerance was expanded to +/- 60°, only 21 cases out of 385.512 could still not be represented. A closer look revealed that these cases were relatively calm (H_{m0} = 2.5 to 4.6m) and adjacent to situations which are more accurately represented by the one-sea-state assumption. In general the sea states with large wave heights were more compatible with the one-sea-state assumption compared with sea states of low wave height.

Here is the case with largest wave height that could not be represented when using the +/- 60° tolerance. As there were so few cases that fell outside this limit, combined with the fact that none of them were severe states, it did not do any difference if these were included or excluded in the long term statistics.

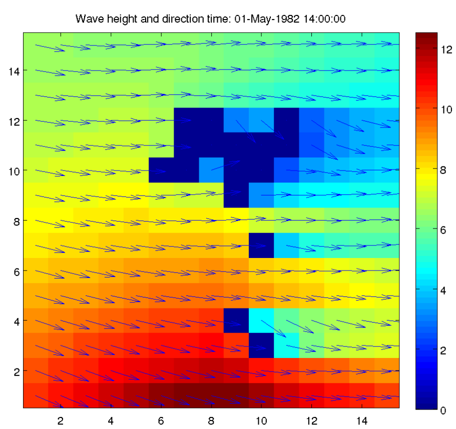


Comparing the forcing wave heights derived from the two different selection procedures we get:

directionally filtered:

mean(Forc2_Bord_H_tot),	std(Forc2_Bord_H_tot),	max(Forc2_Bord_H_tot)
ans = 3.2752	ans = 1.9312	ans = 19.2995
original version:		
mean(Forc1_Bord_H_tot),	std(Forc1_Bord_H_tot),	max(Forc1_Bord_H_tot)
ans = 3.2898	ans = 1.9355	ans = 19.2995

So overall there is only a marginal difference. Looking into the specific cases where the difference was largest we get situations like this one which is the one with largest difference

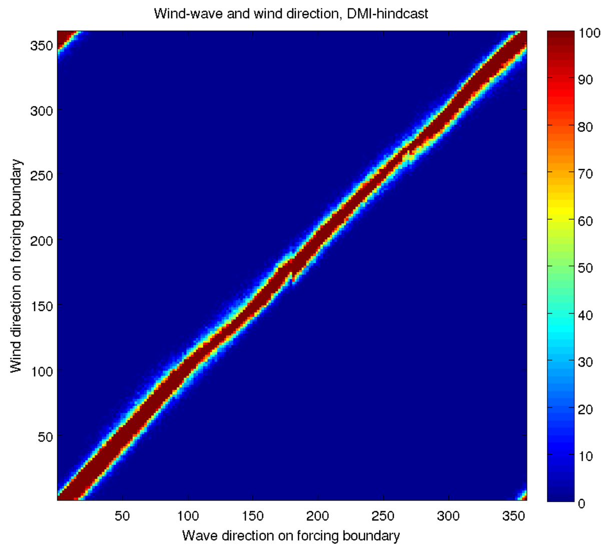


In this particular case the first forcing would give 12.0m while the second much more realistically has H_{m0}=8.4m (both from approximately same direction).

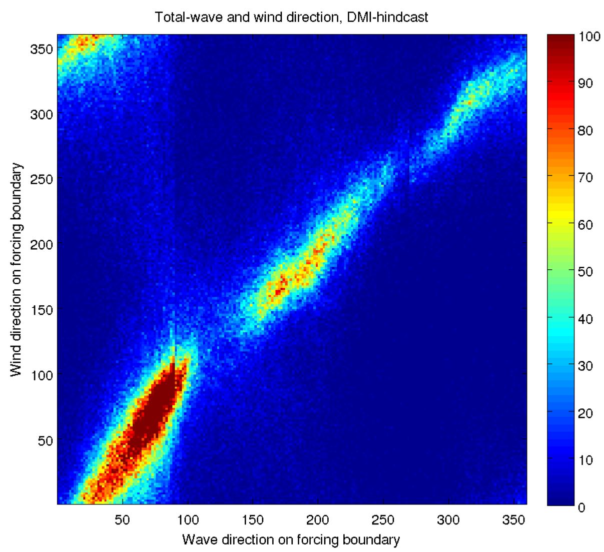
It is nevertheless apparent from this example that there are situations where the one-sea-sate assumption does not fit, and the size of the forcing wave field is not large compared with the size of the nested model domain.

3.3.2 The wind-field

Assuming that the wind-wave direction is almost equivalent to the wind direction is a good approximation as can be seen from the following figure

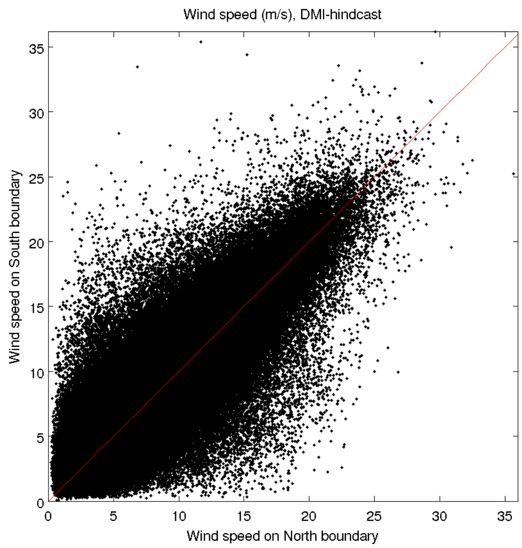


The same assumption about total-sea is far from as good as can be seen from the figure below

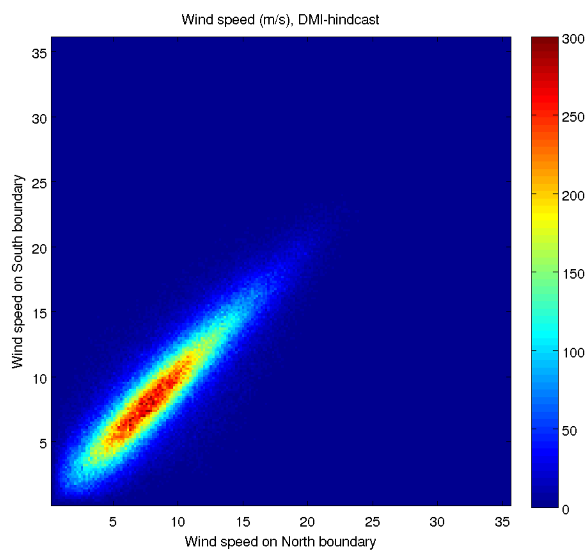


To get reasonable representation of the wind field in the nested model, we therefore need to model the sea as a combination of wind-sea and swell and not only as a total-sea.

To get an impression about if the wind field is approximately homogeneous or not we can compare the average wind speed and average direction on opposing sides of the nested model domain. As can be seen from the figure below there is quite a lot of spreading when comparing the average speeds on the north- and south-boundaries:



but seen as a contour plot (number of occurrences given in color) the fit is much better as can be seen from the figure below:

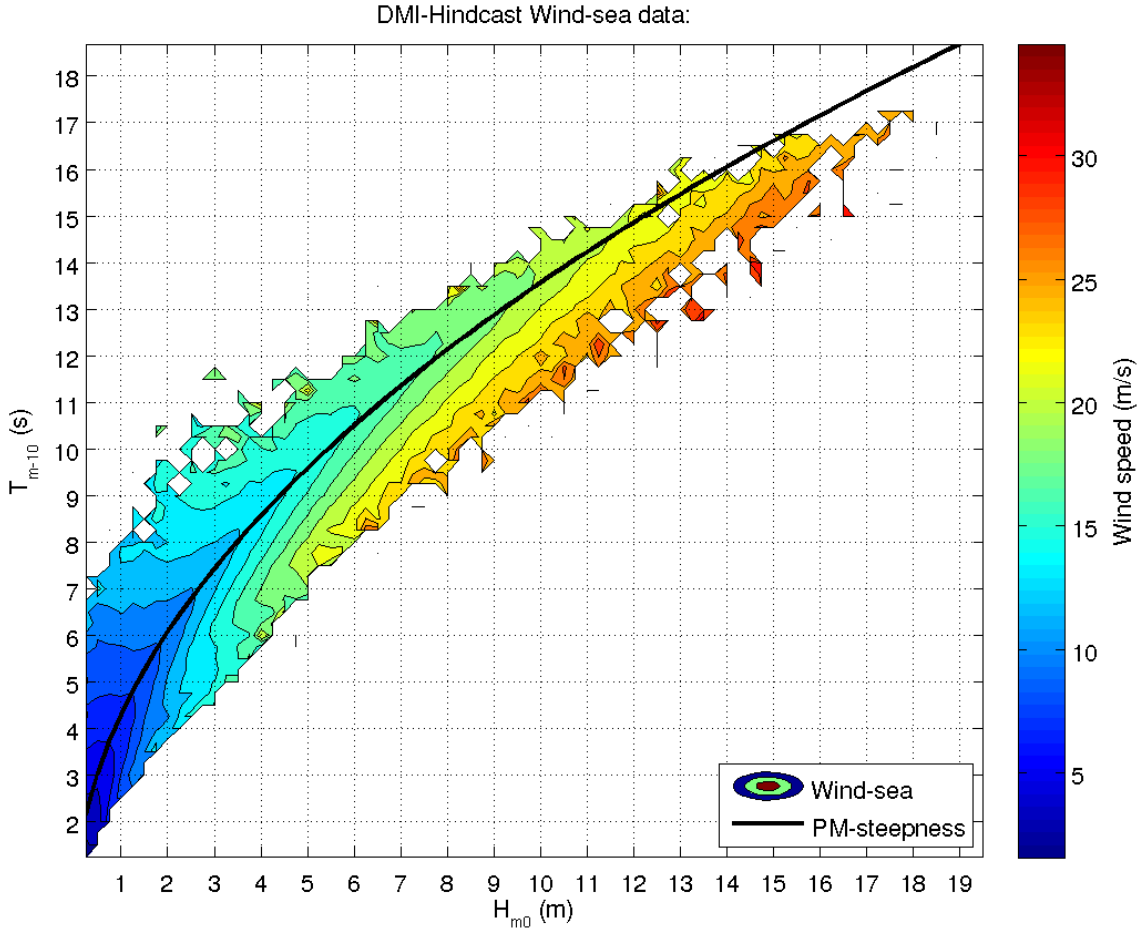


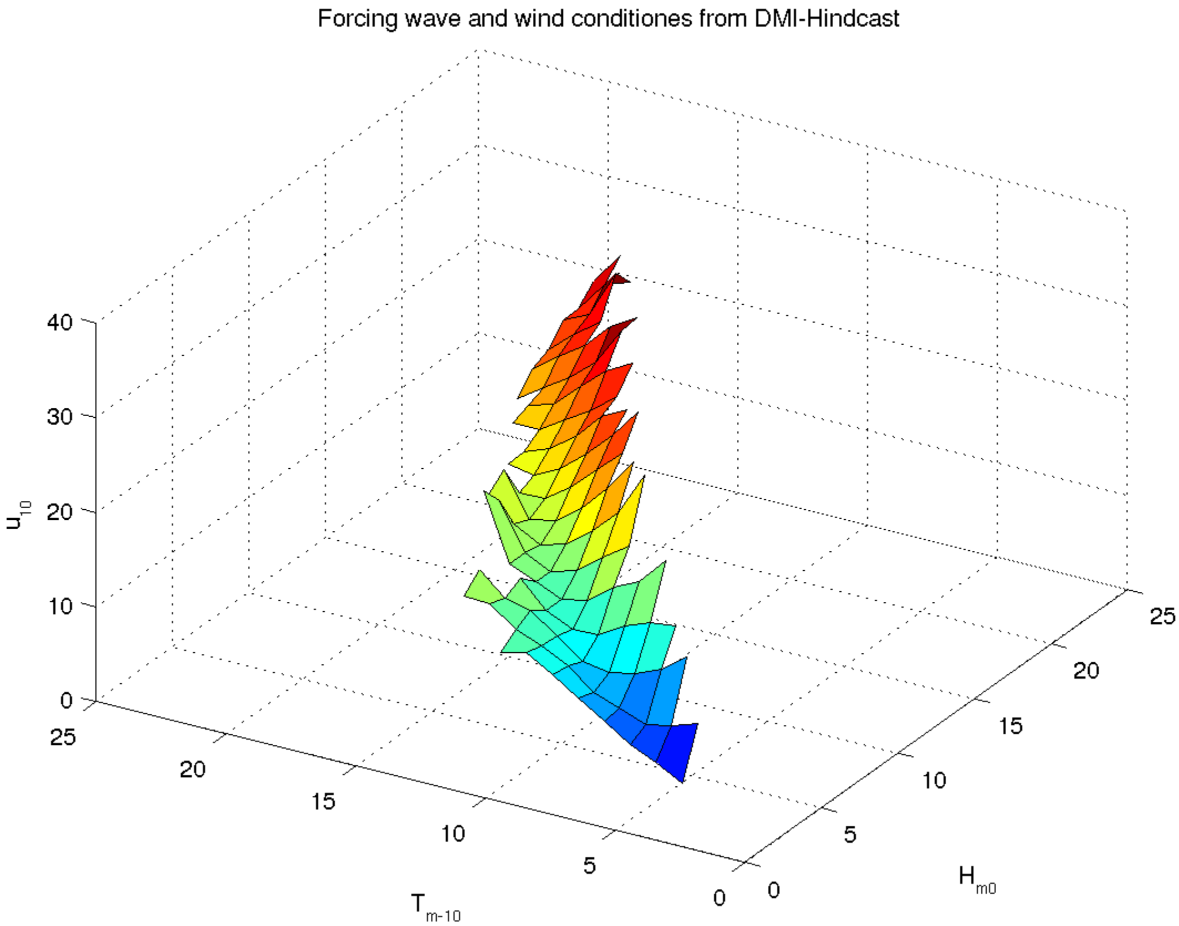
The average absolute error between the wind speeds on the two sides is 1.72 m/s, and the standard deviation of the absolute error is 1.70 m/s. All in all this supports the assumption that the wind field is usually quite homogeneous, and the error of assuming that it is always so is in average quite small.

Correlation between wind-wave height and wind-speed

In order to limit the number of idealized cases that need to be modeled, we must find a correlation between the wind-wave height and the wind-speed. The usual procedure is to find a best fitting linear correlation between the wave height and the wind speed, and use this fitted value of the wind speed in the idealized wind-wave model runs (having wind-wave height and wind-speed as intendant parameters would result in a much too large number of model runs).

The PM wind speed is *U=6.38*H^0.50*, and this fitted quite well with the data. We tried out different parameterizations, but the skill of these was not much better than the PM-wind speed. After some investigations it became apparent that the wave period should also be included to get the best fit between wind-speed and wind-wave-height. It proved very hard to parameterize this dependency, so the data were binned and the average value in each H_{m0}, T_{m-10} bin was used to determine the wind-speed for that case. The result is a given in the two figures below:




Forcing wave and wind conditiones from DMI-Hindcast
u_{10}
40
30
20
10
0
25
20
15
10
5
0
T_{m-10}
0
5
10
15
20
25
H_{m0}

4 Database of idealized cases

When this project was initiated it was speculated wetter it would be sufficient to represent the incoming wave fields as purely fully developed PM-sea-states. Wave measurements on the Faroe Shelf suggest that the average wave conditions resemble PM-spectra only with lover peak periods. As wave periods and wind speeds are uniquely defined for a given PM wave height (the sea is fully developed and wind and waves are assumed to be steady), the idealized database covering all incoming wave fields would be quite limited. Data investigations suggested that at lest 18 directions needed to be modeled in order to get an accurate representation of the wave climate, and design wave heights up to 18m H_{m0} could be expected. This would give wave heights from 1-18m and 16 or more directions i.e. the database could consist of as little as 18x16=288 idealized model runs.

4.1 Influence of wave period

When investigating the forcing data, and how to represent the incoming wave field as accurately as possible, it became apparent, as documented partly above, that this PM-option could be much improved. Getting the wave period right could in some cases seriously affect how much of the wave field could enter deep into some of the fjords.

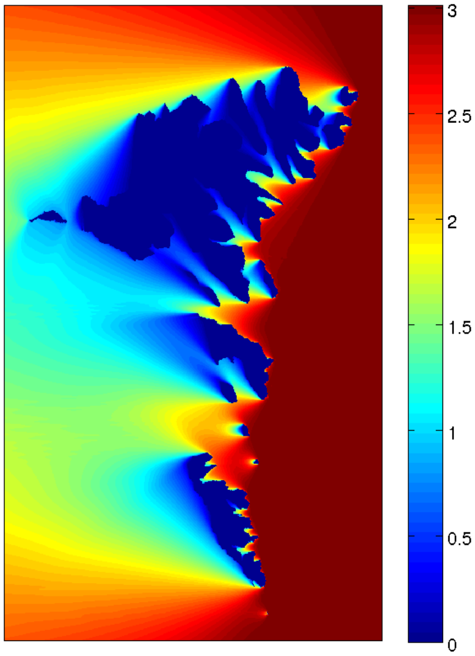
Waves that are long compared to the water depth will 'feel the bottom' and turn towards shallower areas (refract). To illustrate this and to argue for the need to represent the wave periods correctly an illustration is given below from three real sea states.

- The first plot is from a steep wind sea H_{m0}=3m and T_{m-10}=5.5s.
- The second plot is a equivalent representation of a total-sea state with H_{m0}=3m and T_{m-10}=10.5s.
- The third plot is of an equivalent swell sea state with H_{m0}=3m and T_{m-10}=18.0s.

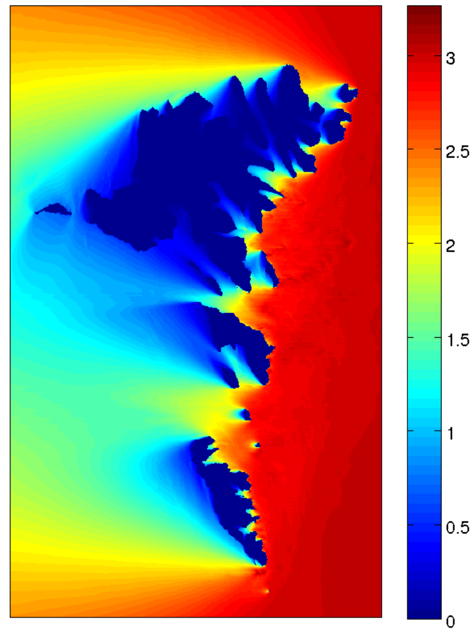
There is clearly a growing influence by refraction which gives not only larger waves on shallow banks along the travel path but also significantly reduced wave height in the inner parts of some fjords that are otherwise exposed by the waves coming from east. One point from the inner part of in Gøtuvík gives the following results from the different runs:

```
Hsig_H30T55 (995,560) = 1.4042
Hsig_H30T105(995,560) = 1.0027
Hsig_H30T180(995,560) = 0.5377
```

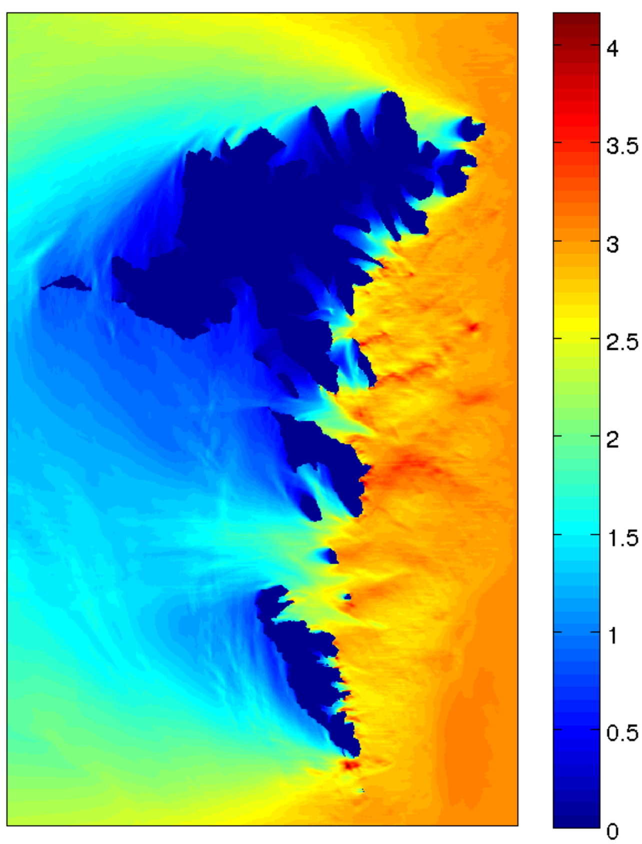
In other words the wave height can vary by a factor of 3 all depending on the average wave period. An alleviating factor regarding modeling storm events is that the realistic period-span decreases as the wave height increases, so for the extreme events the PM assumption might not be that that far off.



3
2.5
2
1.5
1
0.5
0

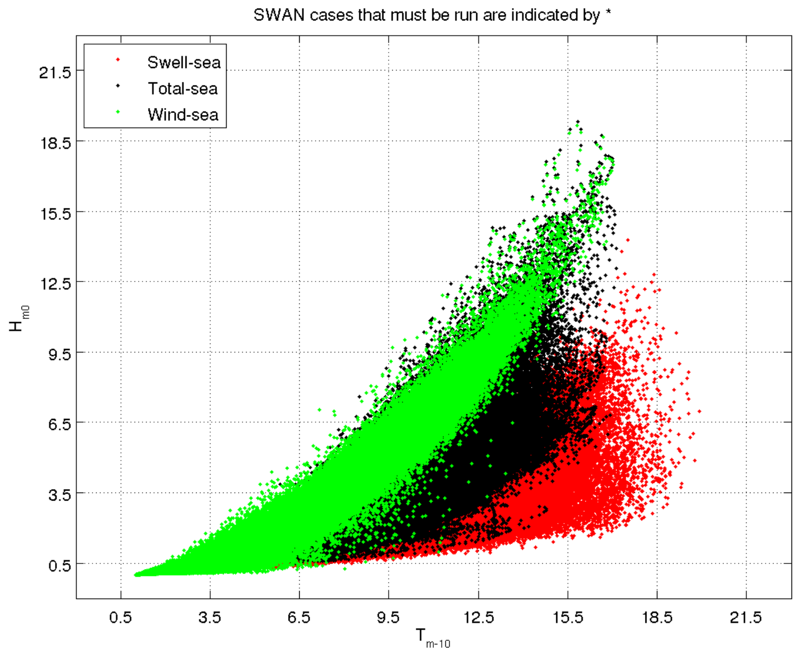


3
2.5
2
1.5
1
0.5
0



4
3.5
3
2.5
2
1.5
1
0.5
0

It was decided to get as accurate results as possible under the one-sea-state assumption, and therefore to model wind-sea and swell separately and in each case model the wave period as accurately as possible. Plotting all possible forcing values of wave height and wave period gave the following figure:



One option would to cover all these cases with some interval in wave height dH and some interval in wave period dT. It became apparent that covering all directions with a reasonable dH and dT values, would result in a too largde database that would make the post processing problematic.

In stead of covering all possible cases with some intervals dH and dT, and interpolate these cases to represent a specific situation. It proved much more appropriate to have an even narrower resolution but only model those situations that really occurred. The rationale behind this is that some (H,T) combinations only occur from some directions and not in others.

The result was that one idealized model runs was made for all existing wind-sea and/or swell cases, binned into dH=1m and dT 1s and dDir=15°.

4.2 Recombining wave parameters

Except from Tp all usual wave parameters are based on momenta of the wave spectra.

$H_{m0} = 4 * m_0$^0.5

$T_{m01} = m_0/m_1$

$T_{m02} = (m_0/m_2)$^0.5

$T_{m-10} = m_{-1}/m_0$

where the momenta are defined as:

$$m_n = \int_0^\infty f^n \, E(f) \, df$$

As this formula is linear respective to *E(f)* the momenta add linearly if the total sea state (i.e. *E(f)*) is the sum of two independent sea states such as wind-sea and swell.

Expressing the momenta as functions of wave parameters we get

$m_0 = (H_{m0}/4)$^2

$m_1 = m_0/T_{m01}$

$m_2 = T_{m02}$^2/m_0

$m_{-1} = m_0 * T_{m-10}$

Expressing the total parameters as function of the old parameters (labeled a and b below) we get:

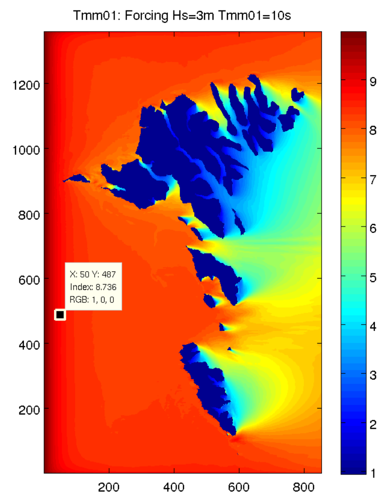
$H_{m0\ tot}$ = ($H_{m0\ a}$^2 + $H_{m0\ b}$^2)^0.5

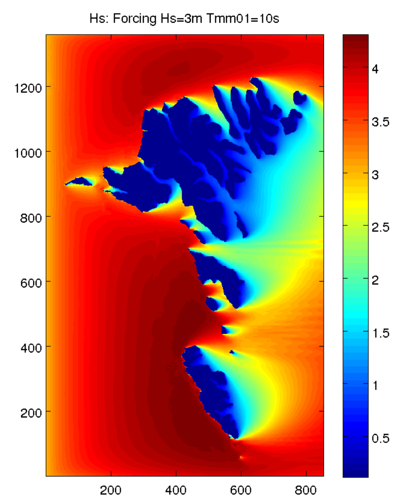
$T_{m01\ tot}$ = $H_{m0\ tot}$^2 * $T_{m01\ a}$ * $T_{m01\ b}$ / ($T_{m01\ b}$ * $H_{m0\ a}$^2 + $T_{m01\ a}$ * $H_{m0\ b}$^2)

$T_{m02\ tot}$ = 1/64 * $H_{m0\ tot}$ * $H_{m0\ a}$ * $H_{m0\ b}$ * ($T_{m02\ a}$^2 + $T_{m02\ b}$^2)^-0.5

4.3 Issues with wind runs

Wind and swell are separated in the forcing wave model (WAM cycle 4) by which frequencies receive net energy input from the wind. This distinction can change from time step to time step and is dependent on the source term balance of this particular model. The wind-sea parameters derived form the forcing model can therefore correspond to wind-sea situations which are out of balance with the source-term balance for wind-sea in the nested SWAN runs. This misfit between the models can result in quite abrupt parameter changes near the nested model boundaries. The result is that some of the information imposed by the forcing model is lost due to model source-term balance differences at the boundary. One such example is given below





5 Wave model setup

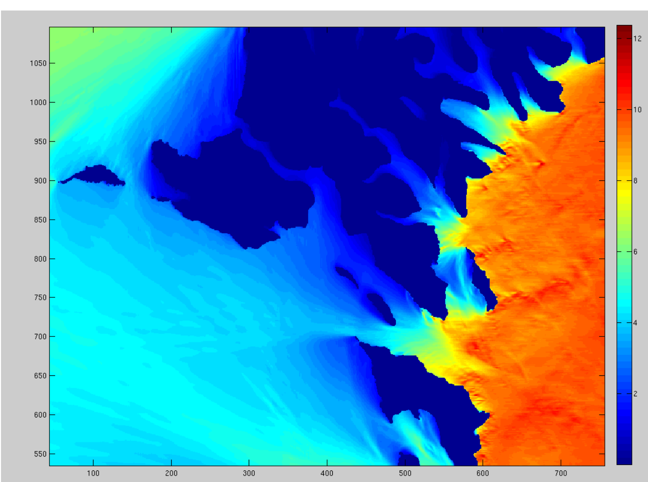
The wave model SWAN (Booij et al, 1996) is used to model the idealized sea-states. This model has been used previously with good results for the area around the Faroe Islands. In accordance with the best practice running the model (Niclasen, 2006), the WAM3 source-terms are used with tuned whitecapping source-term.

The model runs were executed on powerful workstations, and the bottleneck in these computations was the RAM restrictions of these machines. In order to get as much resolution in space and in spectra some optimizations had to be made in order to get as much performance from the model/machines as possible.

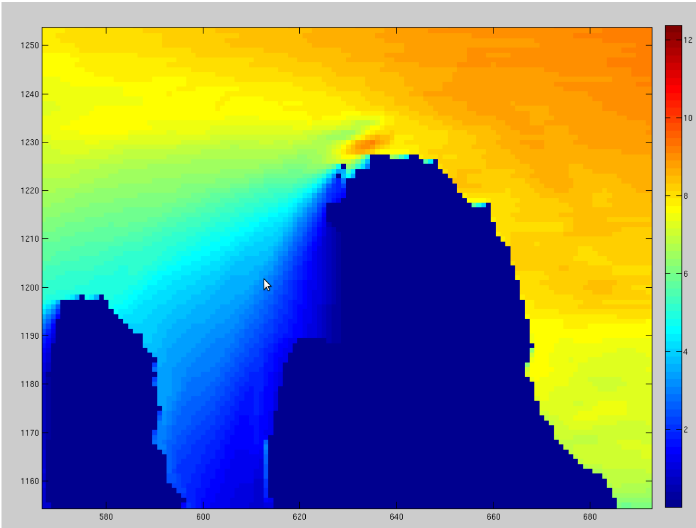
The nested model domain was chosen as small as possible, with as high resolution as possible. The result was a resolution in space of 100m by 100m, and a model domain with mxinp=852 myinp=1356. Land points can be excluded from the computations by using exception values for land points (releasing RAM which can be used to increase model resolution). The draw back of using exception values for land points, is that the wave-propagation in adjacent water model points becomes less accurate. For this reason the optimal solution was to only use exception value (-3.00) for interior land points while having water depth less than zero (-1.00) in land points adjacent to the sea.

Using 100m by 100m resolution gave Garden-Sprinkler problems in short wave-period runs that traveled trough narrow fjords. Different options were tested and using the diffusive but fast BSBT propagation-scheme seemed to be the best option under the given circumstances. One positive additional benefit of using BSBT is that the results resemble very much those which are obtained with more precise numerical propagation including approximated diffraction, but without the potential numerical instability and larger computational burden.

One example with not so short wave-period where the garden-sprinkler effect is still seen is given in the figure below.



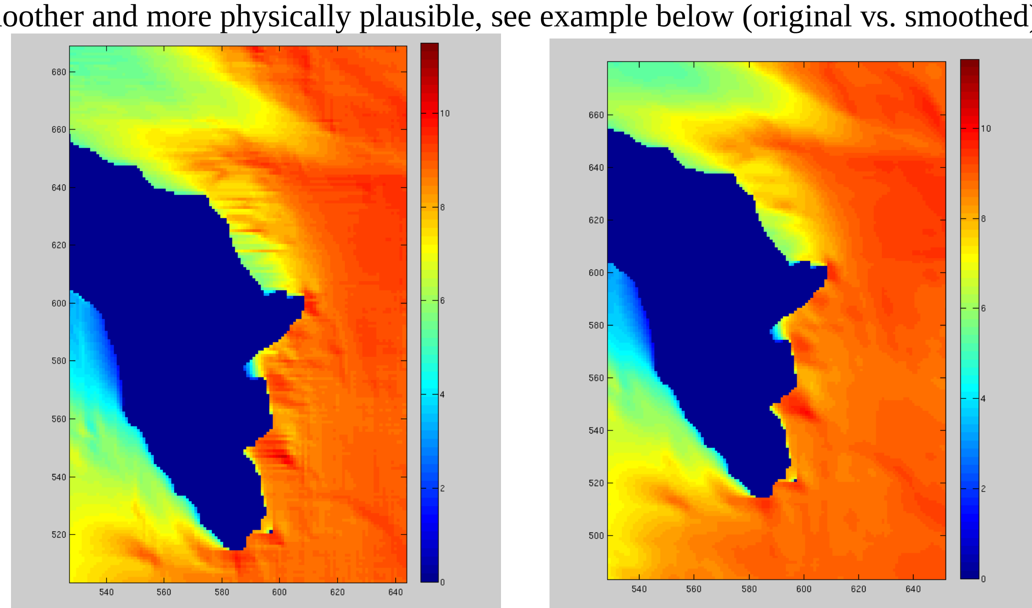
Another issue is the seemingly unphysical rapid increase in wave height in some lee locations. These are locations typically exhibit same abrupt decrease in water depth and turning on refraction limitations or altering propagation scheme does not influence this. One example is given below.



5.1 Smoothing of depth matrix

We are using dx=100m and describing how waves of over 700m wavelength (H_{m0}=18 T_p=21) travel and are influenced by the depth variations. It seems necessary to smooth the depth matrix, and the way this is done is by conducting point-wise averaging where all adjacent water-points are used (with equal weight) to determine the new value (i.e. 9 point average). To achieve a smoothing effect compatible with the long waves (smooth one time averaging ~300m) this smoothing is applied twice. This does effect the depth matrix quite a bit, specially in the grid points closest to land where the gradients previously were quite high.

A general result is deeper water closer to land and slightly less depth in the middle of the fjords, and finally the wanted effect that small scale features are smoothed out. The results also seem much smoother and more physically plausible, see example below (original vs. smoothed):



An extra bonus is that the unwanted jumps in the wave height in some water grid points adjacent to land, are now significantly reduced due to the smoothing.

It also seems as if one time smoothing would take most of the issues, but there is still some 2dx left in some areas if one one smoothing routine is conducted. On the negative side the ray bending around some shallow near-shore points is reduced when using 2-time smoothing.

5.2 Numerical options

The final version of the numerical option-line in the INPUT file looks like this:

```
NUMeric ACCUR drel=0.01 dhoval=0.01 dtoval=0.01 npnts=99.0 &
STAT mxitst=100 alfa=0.0 DIRIMPL cdd=0.5 cdlim=4
```

Activating ACCUR options influences the criterion's for terminating the iterative procedures in SWAN.

Options drel and dhoval are made stricter as the default value is 0.02. These values are related to how much the wave height can change in a point or all points from one iteration to the next, and still satisfy the stopping criteria. Dtoval is the same but based on the mean wave period T_{m01}. Npnts is also made stricter as the default value is 98, and refers to how many percent of the total number of wet points must satisfy the mentioned stopping criteria before the computation is found satisfactory. The STAT options mxits and alfa are maximum number of iterations and frequency dependent under relaxation. The variable mxits=100 is twice the default value. The variable alfa is the default value of 0.00; it is recommended to be 0.01 if diffraction is activated, but as the BSBT-propagation is almost indistinguishable from the SORDRUP-runs with diffraction on, this variable is not used. If diffraction is not activated and alfa>0, the model seems to need more itterations. The variable cdd is set to be its default value, could be set =1 to get more diffusive refraction, or =0 to get more accurate refraction, but numerically unstable results. The variable cdlim is set =4 (default=-1 i.e. no limiter) which according to the SWAN-manual ensures that the waves cannot turn more than 90° over one grid step. I just ran one test and the impact in the unsmoothed grid was small and active in very few points, so when running the smoothed grid the effect should be even smaller, if any, but is turned on just in case.

5.3 Wave reflection

Wave reflection is defined as the ratio between the reflected wave amplitude over the incoming wave amplitude:

$$K_{refl} = \frac{a_r}{a_i} = \frac{\sqrt{E_r}}{\sqrt{E_i}}$$

where the *a*'s refer to amplitudes of the waves and the E's refer to the respective wave energy of the reflected and incoming wave fields. If we want to estimate the wave height just in front of a reflecting structure that is perpendicular to the incoming waves, we get:

$$E_{new} = E_i + E_r$$

$$E_{new} = E_i + K_{refl}^2 \cdot E_i$$

$$H_{new}^2 = H_i^2 + K_{refl}^2 \cdot H_i^2$$

$$H_{new} = H_i \sqrt{1 + K_{refl}^2}$$

The assuming perfect reflection (i.e. reflection coefficient equal to unity), the greatest increase in wave height achievable due to reflection is square root of two or approximately 41% (Tested in SWAN and gave same result).

All references I've come across use the Iribarren-parameter also called the surf-similarity-parameter to describe wave reflection. This is given as:

$$N_{ssp} = \frac{\tan(v_b)}{\sqrt{H/L_0}}$$

where v_b is the bottom slope, H the wave height and L_0 the deep wave wave length e.g. Holthuijsen (2007). Using linear theory and assuming deep water (just to get a rough guess) we can write $L_0 = gT^2/2\pi$ where T is the wave period and g the gravitational acceleration. Rewriting we get:

$$N_{ssp} = \tan(v_b) \cdot T \sqrt{g/2\pi H}$$

We see that the value is high if we have steep bottom slope, long periods and small wave height.

Based on a different experiments/measurements of reflections from different types of structures, there exist several expressions that calculate the reflection coefficient as a function of the surf-similarity-parameter. As I here only want a qualified first guess, I'll use the following formula taken from a lecture note by T.S. Hedges, and originates form Seeing (1983).

$$K_{refl} = r_r \cdot \tanh(0.1 N_{ssp}^2)$$

where r_r is an empirical coefficient related to slope types with a value about 1.0 for smooth slopes and about 0.6 for rubble mounds.

In the first simulations that will be done, we will use constant reflection coefficients, and can therefore not take all parameters into account, as SWAN reflects all frequencies with the same reflection coefficient. As the simulations will be based on PM wave spectral form, we can use the PM formulas to simplify the situation somewhat. Assuming PM spectra the following formulas can be used:

$$H_{m0} = 0.0246 U_{10}^2$$

$$T_p = 0.783 U_{10}$$

where U_{10} is the 10-meter wind speed. If this is inserted into the formula above using peak period as the period and significant wave height as wave height we get (assuming that the peak period remains mainly constant even in sheltered regions):

$N_{ssp} \simeq 6.25 \cdot \tan(v_b)$, PM wave field

$N_{ssp} \simeq 8.84 \cdot \tan(v_b)$, PM wave period but only half PM wave height

$N_{ssp} \simeq 12.50 \cdot \tan(v_b)$, PM wave period but only quarter PM wave height

These values as represent respectively

- unprotected shore lines that are impacted directly (full wave height)

- semi-protected shore lines that are impacted after some sheltering (half wave height)
- protected shore lines that are sheltered (quarter wave height)

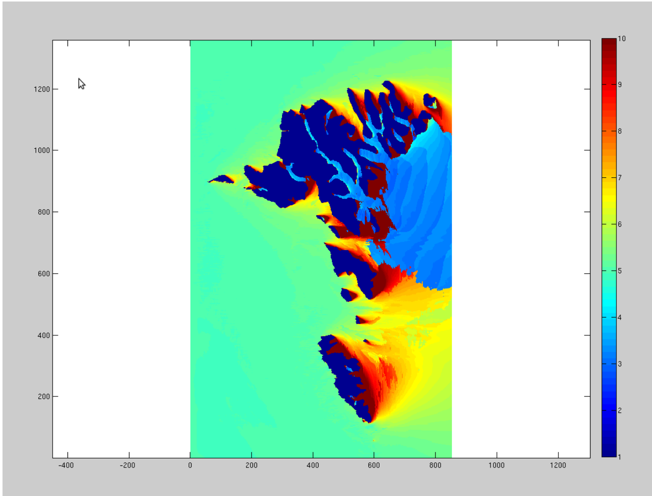
As the bottom slopes up to the shores of the Faroe Islands are not smooth nor rubble mounds we choose r_r = 0.8. The depth matrix used in the model (resolution of 100m x 100m) will be used to get a guess of the bottom slope. Say a point adjacent to the shore has the depth of 20m, then the depth from the center of the grid point towards the shore is assumed to decrease linearly to zero (that is 20m increase in height over the 50m to shore). Using the three sheltering categories mentioned above we can now generate the following table which can be used when assigning reflection coefficients to some stretches of shore lines.

Table of: Estimated reflection coefficient / adjacent wave height increase

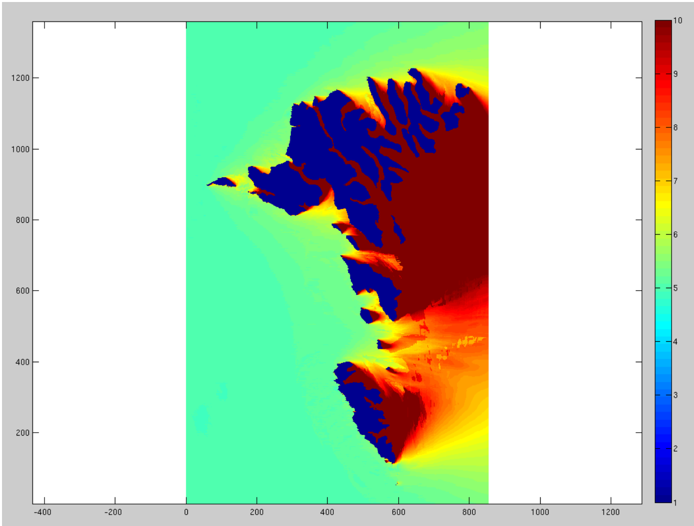
Land adjacent depth	**Unsheltered**	**Semi-sheltered**	**Sheltered**
10	0.12 / 1%	0.24 / 3%	0.44 / 9%
15	0.27 / 4%	0.48 / 11%	0.71 / 23%
20	0.44 / 9%	0.68 / 21%	0.79 / 27%
25	0.60 / 17%	0.76 / 26%	0.80 / 28%
30	0.71 / 23%	0.79 / 27%	0.80 / 28%
35	0.77 / 26%	0.80 / 28%	0.80 / 28%
40	0.79 / 27%	0.80 / 28%	0.80 / 28%
≥50	0.80 / 28%	0.80 / 28%	0.80 / 28%

In order to choose correct reflection coefficient values in areas that are sheltered from some wave directions, a first round of model runs without reflection must be made so the wave height/period assumption about the area can be based on a qualified guess.

Looking at the ratio between T_p*H_{m0}^-0.5 wee see the following for situation with forcing PM-spectra and all source terms on:



Here is the same situation with all source terms turned off:



That is the ratio is larger than the PM ratio in all sheltered regions that are dominated by wave components traveling from offshore, and the ratio is only less In regions where the wind-sea is dominant. From this we can deduce that it is OK to assume PM-ratio or higher in all unsheltered or semi sheltered areas. Areas dominated by wind sea are: 1) confined areas or 2) down wind sites in the shadow of the islands. Regarding to case 2) reflection coefficients are without influence on the wind sea (as the wind part of the waves are propagating away from shore), only the swell part of the wave field is influenced by reflections. Regarding case 1) it is quite possibly most correct to disregard reflections, as wind sea is already overestimated at short fetches when using WAM3 source terms.

Reflections will be limited to swell, in order to alleviate the oversimplified reflection scheme in SWAN which reflects all wave energy and does not take frequencies into account.

In the propagation only run the PM-ratio is always equal to or greater than the ratio at the border.

Taking this into account and looking at the table given above, it can be seen that there is almost always perfect reflection in all locations, i.e. depth and sheltering do not seem to be nearly as important as the totally unknown parameter r_r. This makes it obvious that applying reflections in this manner is a highly questionable process that can only be trusted to the extent that local wave measurements support the used values of the unknown parameter r_r. For this reason a conservative estimate is used in the runs including reflections.

6 Discussion and outlook

In this wave climate investigation idealized model runs make it possible to transport offshore wave conditions, here provided by the DMI-hindcast. The initial quick solution of only modeling the incoming wave height and incoming wave direction correctly, was soon abandoned. In stead the idealized model runs were made for wind-sea and swell separately and in both cases the mean wave period was also modeled as an independent parameter as well. This made it possible to more accurately transport the offshore forcing into the near-shore areas.

As the forcing model as well as the simplifying assumptions made, induced a positive H_{m0} trend in the nested model results vs. reality, this trend was linearly corrected by inter-comparison to overlapping wave measurements south of the islands.

By using this approach a 44-year time-series was available at all model points which, that at least in the offshore areas, should be without model bias or trend. This made it possible to derive the wave climate results presented in Niclasen and Simonsen (2012).

During this investigation a few points were noted:

- The wave conditions along the forcing boundaries could be represented by a single sea-state in most cases.
- Using forcing side average or forcing side midpoint gave almost identical results. Using the model results at the buoy locations was also an option, but with slightly less accuracy.
- Using the stationarity and one-sea-state assumptions were gave realistic but positively biased results.
- Some wind-sea cases were difficult to model correctly by using pre-calculated idealized model runs.
- The wind speed correlated better with wave period and wave height as independent parameters, rather than the usual correlation to wave height only.
- It was not possible, due to RAM-limitations, to generate wind-wave results totally without garden-sprinkler effects.
- It was necessary to use diffusive propagation (BSBT) in order to limit the garden-sprinkler effect in the wind-wave runs.
- Using BSBT gave almost the same results as running with higher accuracy but with diffraction turned on.
- In order to get smooth results, where the underlying model grid orientation did not show, required that the bottom depth was smoothed.

After his model investigation we are left with a database of pre-calculated idealized cases which can be used to transport offshore wave conditions which can be used as a tool in forecasting, hindcasting or nowcasting (using buoy measurements).

To insure that the derived results are accurate more data vs. model comparisons are needed, and this will hopefully be possible in the future.

From a modeling perspective the idealized results could be even better if:

- the forcing sides were modeled separately

- if the propagation scheme was more accurate
- if the directional resolution was higher in wind-sea cases
- if the individual frequencies were modeled separately
- if reflection of the individual frequencies were modeled separately

Fortunately such model runs have already been conducted as requested by Fiskaaling. The new single frequency database and the respective documentation and model vs. data comparison are expected to be available in the near future.

7 References

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