Wave Energy Assessment | North Sea Wave Database
Dutch-Wave And Tidal Energy ResourceS

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Dutch-WATERS

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Wave Energy Assessment | North Sea Wave Database

Marine Renewable Energies Lab

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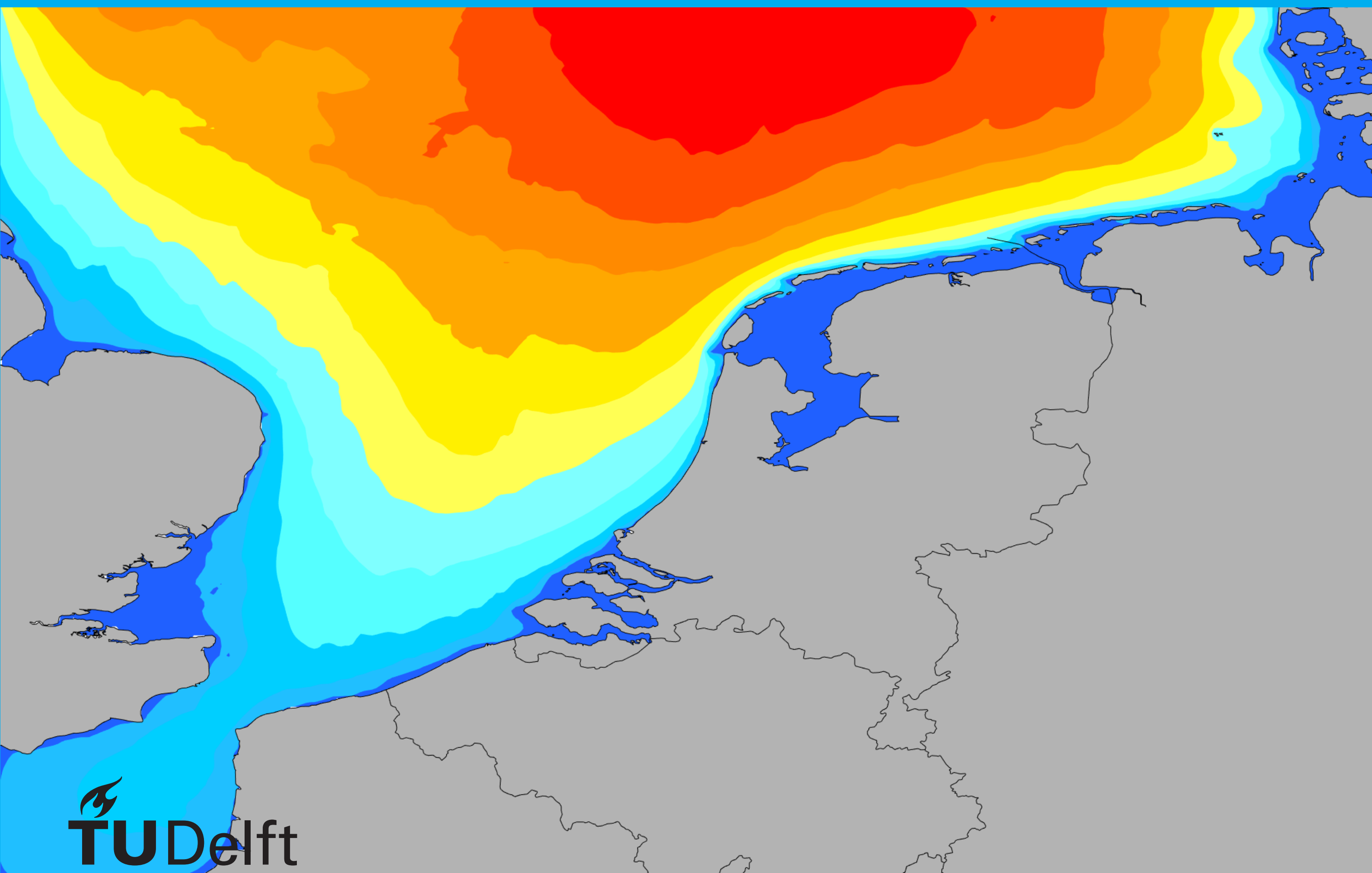

Dutch-WATERS

Dutch-**W**ave **A**nd **T**idal **E**nergy **R**esource**S**

by

Marine Renewable Energies Lab (MREL)
Offshore Engineering (OE) Group
Hydraulic Engineering Department
Faculty of Civil Engineering and Geosciences

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TU Delft

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Dutch-Wave And Tidal Energy ResourceS

The Netherlands with its long coastline and strong offshore expertise is optimally suited for implementing renewable offshore marine energy solutions. To complement and support the energy transition driven by wind and solar, also wave and tidal resources should be exploited. A quantification of the role of these resources in the Dutch energy system requires quantifiable wave and tidal resources. Dutch-WATERS generates wave and tidal datasets with state-of-the-art modelling, which are verified with in-situ measurements.

Dutch-WATERS primarily contribute to mission F: The Netherlands as the best-protected and most viable delta in the world, with timely future-proof measures implemented at a manageable cost. Within this mission, the main focus is on MMIP F4: Energie uit water. The objective of MMIP F4 is to use water as a source for renewable energy. Both wave and tidal stream energy are named in this MMIP. Dutch-WATERS develops calibrated numerical wave and tidal models to support the development of wave energy, tidal barrages, small hydro-electric and tidal stream technologies, ultimately, enhancing the metocean information for the North Sea. The interaction with Dutch companies will allow to link this metocean data directly to potential electricity production capabilities. Both, the resource assessments as well as the production data also connects to MMIP F3, Nederland digitaal waterland, by providing direct input to a digital twin of the Dutch North Sea to improve human activities.

Secondary, benefits of the in Dutch-WATERS generated resource assessment are of added value for future analysis on coastal protection (MMIP F2, Aanpassen aan versnelde zeespiegelstijging) and a more sustainable North Sea (MMIP E1). In MMIP F2 the resource assessment can provide insight into increasing tidal differences and wave heights, which can contribute to a safer and more future-proof delta. In MMIP E1 the data can provide new insights necessary for a sustainable balance between ecological capacity and water management vs. renewable energy, food, fishing and other economic activities. Especially the development of marine spatial planning for the Dutch North Sea can greatly benefit from assessing wave and tidal resources.

Besides the contributions to three MMIPs linked to TKI Deltatechnology Dutch-WATERS also connects to the MMIP 1 offshore renewable energy, which is led by TKI Wind op Zee (Topsector Energy). This MMIP focuses on enabling the required scale-up for offshore renewable energy, especially offshore wind energy, and also other forms of offshore energy in the longer term. The project specifically addresses the sub-themes of energy system integration and environmental integration within this MMIP. However, the primary focus of this TKI is on offshore wind, therefore the TKI Deltatechnology was chosen as the best suited for the Dutch-WATERS project.

2

Wave Modelling

The Netherlands have long been exposed to harsh weather events and danger of floods. The Dutch coastlines often experience severe storms, and due to the position of some cities below the water level, coastal protection has been developed to protect the re-claimed areas. There are several measurement stations dispersed regionally, including a very detailed and well-maintained buoy network. The Dutch government has increased its interest in developing offshore renewables and aquaculture in the Dutch Exclusive Economic Area. However, the Netherlands do not have a comprehensive resource assessment of wave and tidal conditions suitable to describe the resources in the nearshore.

Fully calibrated models for the Netherlands will be used to quantify the marine resources. Their accuracy will be assessed via use of in-situ and/or satellite data. Focus will be given to the bottom friction calibration of nearshore areas, where wave transformations occur and other activities such as coastal protection, tourism can also benefit by improved metocean conditions knowledge.

The wave climate is highly variable across the globe on spatio-temporal scales, local bathymetry, coastlines, and winds greatly influencing formation and propagation of waves. Currently third generation numerical wave models are utilised for historical (hindcast) and forecast studies. A properly calibrated, validated wave model is the basis to reduce uncertainties both for long and short term resources examination. Developments in our understanding of wave theory, and improvements of infrastructure in computer advancements, have allowed significant enhancements in understanding of waves. This has put the use of numerical models at the forefront of climatic research, climate change and energies [10, 31, 32, 39, 41]. With accuracy improved, numerical wave models have found utilisation within the research and energy communities [5, 15, 19].

A key component for the accuracy and confidence in a model is user experience and expertise. Proper set-up of a numerical wave model is a cumbersome process that comprises of many inputs and careful consideration on physical tuning solutions. Indicatively, models are highly sensitive to winds which are driving the evolution/propagation of waves, tuning of physical properties, and propagation schemes. Current numerical models have different solutions which may affect their applicability.

Results from numerical wave models are not without limitations, and have inherit uncertainties by our lack of exact solutions for several wave theory problems such as whitecapping. Calibration of a wave model involves "random errors", such as deviations from the site measurements due to the dependency of components (i.e wave heights, wave period) on wave spectrum and solutions applied [9, 19, 28, 43]. While alterations are usually not major, they are affected pending on the model [7, 48], set-up [7, 24], coefficients and solvers for physical process [6, 7, 34, 37, 47], spatio-temporal quality of inputs and boundaries [1, 6, 7, 20, 46].

One major disadvantage of numerical wave models is the missing of the "peaks" phenomenon [6]. Most models have a tendency to under-estimate wave heights at low frequencies and over-estimate at higher ones. Another driver is the quality, of the wind input and the scheme for wave generation and propagation [6, 20, 40, 46]. Wind datasets are also derived by larger atmospheric models which exhibit different performances depending on their area of application [40, 41],such irregularities propagate into the estimation of spectra by wave models.

Replacing a low temporal wind component with higher resolution one, may alleviate some of the underestimations, but physical tuning is required to ensure that an optimal performance of a wave model with regards to the wind input, bathymetry, location, physics and solving approaches. Several physical problems are resolved within the wave models by "suggested" coefficient, which the user has to bear in mind that they may not have universal applications for optimal results [34, 36, 42, 45, 47]. Several of the models presented, offer significant parametrisation options which can improve the results after calibration.

2.1. Simulating WAves Nearshore (SWAN)

To obtain necessary information, for climate analysis on any type of renewable resource, a minimum duration of 10 years is required [4, 14, 27, 38, 51]. Furthermore, to have a good understanding of climate conditions and their persistence, additional considerations on Climatological Standard Normals (CSN) are required. CSN suggest a minimum period that allows long-term extrapolation and proper estimation of averages for climatological parameters, computed for consecutive periods of ≥30 years [52]. Without long-term data, any estimation on coastal infrastructure, or in the case of ocean energies development/estimation of energy production, will be highly flawed, since it will not account resource changes and variability. Hence, it is important to consider the high impact value of resource assessments in any offshore activity.

To obtain long-term uniform datasets uses Numerical Wave Models (NWM). These tools are under continuous development, and improved upon as more insight into the complex ocean processes is gained. Since the first numerical model attempt [49], NWM provide valuable information for climate change, shipping, energy, weather forecasts, and metocean operations. NWM are able to deliver high fidelity spatio-temporal information, with suitable long-term characteristic for resource assessments. They can have varied resolution, multi-nested domains, and focus at different regions. However, this does not mean that NWM are without limitations.

As in any modelling effort, it is paramount that the user/modeller has knowledge of the processes involved, and is able to select the different physical processes, pending on desired application and scale. Currently, there are several models that are able to resolve different physical processes. However, one thing that it is important to note, most processes in NWM are based on (semi-)empirical coefficients and are often very sensitive to local environments. It is of importance for the model to be configured and set-up according to the application. In addition, reliable results have to be obtained by careful validation, after model calibration [25].

For generation of the database a third generation spectral phased averaged model, Simulating WAves Nearshore (SWAN) was used. The model has been developed and is maintained by TU Delft [9], the version used is 41.30AB. However, prior to developing a reliable dataset several considerations must be addressed. Firstly, the construction of useful boundary and feed-in information. For the development of such a long-term dataset we have to ensure that proper methods are used and most importantly a suitable wave model is utilised [25]. The SWAN model is suitable to provide reliable information at the nearshore, as it contains the possibility of modelling complex non-linear interactions that exist near the coastlines. This is highly important, as most first generation wave energy converters (WECs) will be placed near the shoreline, at depths were bathymetry has influence over the metocean conditions.

The methodology for development of an analysis requires thorough calibration and validation of the dataset. Calibration of the model is conducted for the year 2015, after the calibration an “optimal” model is selected and used to generate the 30 year (1990–2020) hindcast. Buoy data are used for calibration evaluation and subsequent validation of the hindcast [33].

2.2. Configuration of the North Sea Wave Database model

The model has been set-up with spherical coordinates and a resolution of 0.025°, corresponding to ≈2.5 km longitude (λ) and ≈2 km latitude (ϕ), also accounting for the Earth’s curvature. Coastline data have been obtained by Amante et al. [2] and the latest Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) [50]. Based on this information a bathymetry domain was constructed as input for the model, see Figure 2.1. The Dutch coastlines are located at a continental shelf, neighbouring Denmark and the United Kingdom. As seen in Figure 2.1, the depth is varying “smoothly” without the existence of very sharp depth gradients, for the domain of this database depth does not exceed 100 m.

As driver of wave generation the ERA5 wind dataset, by the European Centre for Medium-Range Weather Forecasts (ECMWF) was utilised [12]. There is a high-correlation between wind resource as a driver, wind-wave generation/propagation and model performance. Spectral boundary conditions were re-constructed by the WAve Model (WAM) from ECMWF and applied at domain open boundaries. Most important boundary region is the open upper North side where swell waves from the Atlantic and Norwegian Sea propagate inwards. The model was set-up with a “warm-up” configuration to minimise initial ramp-up periods.

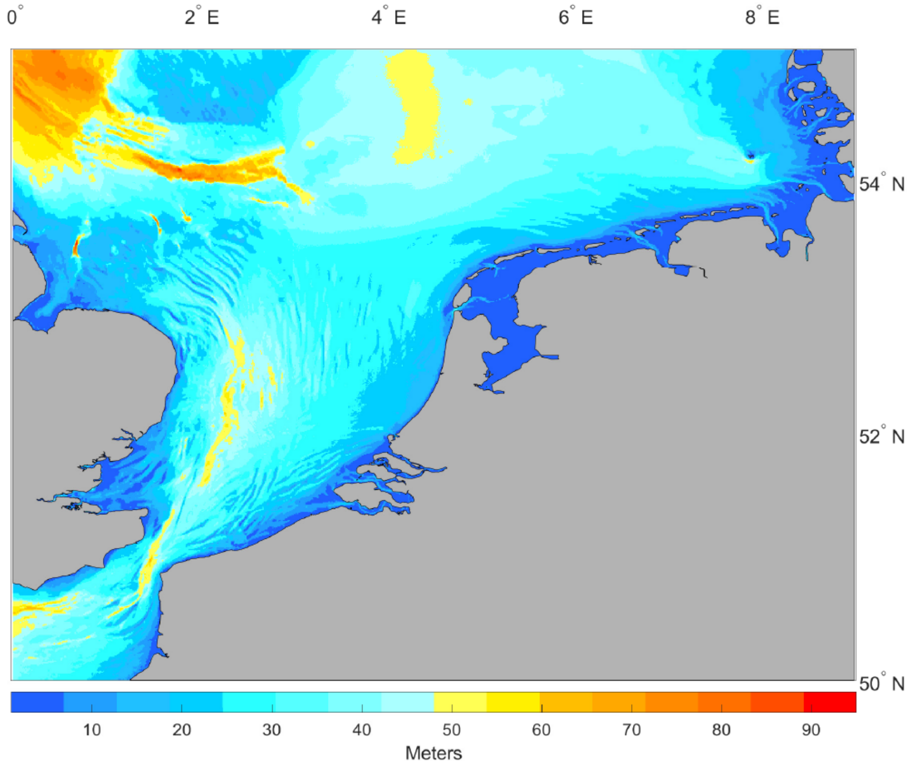


Figure 2.1: Developed domain for the study, depth in meters.

2.2.1. Parametrisations

SWAN is a third generation spectral phased-averaged wave model, that accounts multiple physical processes suitable for deep and shallow waters, although arguably it is more efficient for nearshore and Shelf Seas. The wave spectrum is described in time (t) by the action density equation (E), dependent upon angular frequency (σ), direction (θ), frequency (f), energy propagation (c) over latitude (ϕ) and longitude (λ). Sink source terms are used to estimate the wave parameters (see Equation (2.1)), given a specific set of inputs and physical coefficients, with wind input (S_{in}), triads (S_{nl3}), quadruplet (S_{nl4}) interactions, whitecapping ($S_{ds,w}$), bottom friction ($S_{ds,b}$) and ($S_{ds,br}$) depth breaking.

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \tag{2.1}$$

In wave models, generation, propagation and spectrum evolution is dependent on various parameters. Most important source terms are mechanisms of wind S_{in}, and dissipation $S_{ds,w/b/br}$, as they are responsible for wave generation and dissipation. Waves are created by wind surface pressure on the ocean, in wave models this term is modelled by considering a wind drag coefficient (C_D) that contributes to the growth. Wind wave generation is a summation of energy density $E(\lambda,\phi)$ from the S_{tot} (over Spherical coordinates).Wind drag coefficients can differ and may enhance or reduce the wave generation capabilities in the model. With regards to dissipation mechanisms, the most obscure and least understood is the white-capping $S_{ds,w}$ that is predominately based on a wave steepness coefficient (Γ), depending on a term adjustable and quite different for each methodology. It is known that wave models tend to under-estimate at lower frequencies, with accuracy affected by wind components used.

Recently, SWAN 41.20 introduced an adjusted formulation for wind and whitecapping, similar but not the same to Wavewatch3 (WW3) ST6 [29, 30]. The wind drag parametrisation requires fine tuning in the white-capping coefficient. Interestingly with this new addition the solutions both for the wind drag formulation, stress re-computation, allows for bias wind corrections. In addition, the new formulation can also be configured to include swell dissipation mechanisms. For the models developed an exponential growth coefficient is assigned, and all models have a “hot” start configuration that ensures a fully developed wave field. The sink term of wind input that gives wave generation is given by Equation (2.2)

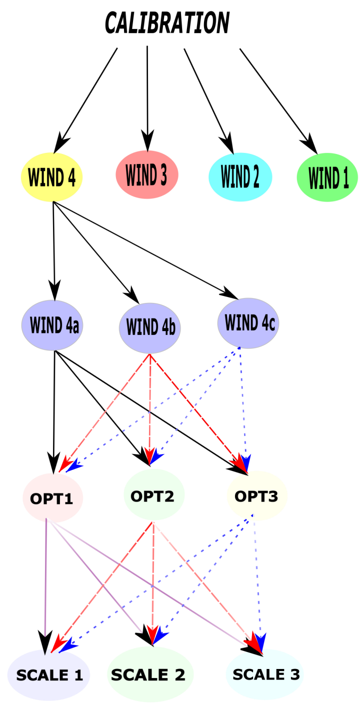


Figure 2.2: Configuration for the calibration phase.

$$S_{in} = A + \beta E(\lambda, \phi) \tag{2.2}$$

where A is the linear growth, and βE is the exponential growth, both A and β depend on wind parametrisations. This in turn affects the momentum flux that is the driver between atmosphere and the ocean surface for wave generation, as the model translates wind at 10 m (U_{10}) to a surface wind, see Equation (2.3) with an estimation wind drag coefficient (C_D) that depends on U_{10}.

$$U_*^2 = C_D + U_{10}^2 \tag{2.3}$$

Wind drag estimations have limitations especially for higher wind speeds, where they are known to underestimate and even limit wave growth, therefore, for every different configuration, the C_D should be adjusted. Kamranzad et al. [18] indicated that even though wind drag parametrisations in models are good at generating waves, they are limited in their performance especially at higher wind values, where wave growth reduces. The performance of the wave model depends highly on the parametrisation of the wind scheme, therefore, four different wind schemes have been used and parametrised to obtain the optimal solution.

For Wind 1 the configuration uses Komen et al. [19] set-up, where the wind drag coefficient (C_D) is dependent on the friction velocity of wind speed (U_{10}) with adjustments $U_{10} < 7.5$ m/s and $U_{10} \geq 7.5$ m/s, see Equation (2.4). For Wind 2 the adjustments are based on Janssen [17], where critical height is iteratively estimated according to its non-dimensional value from $\tilde{U} = \frac{U_{10}}{U_{ref}}$, see Equation (2.5). For Wind 3 option drag is based on the alternative description of van der Westhuysen et al. [44], that uses a re-formulation of white-capping to weakly and strongly forced waves.

$$C_D = \begin{cases} 1.2875 \times 10^{-3} & U_{10} < 7.5 \text{ m/s} \\ (0.8 + 0.065 \times U_{10}) \times 10^{-3} & U_{10} \geq 7.5 \text{ m/s} \end{cases} \tag{2.4}$$

$$C_D = (0.55 + 2.97\tilde{U} - 1.49\tilde{U}^2) \times 10^{-3} \tag{2.5}$$

Wind 4 represents the newly added ST6 package, and evaluates a different parametrisation in wind drag (see Equation (2.6)), wind stress and whitecaps [53]. This newly adopted package is similar to WWIII but they are implemented differently. The package includes influence of swell dissipation in the estimations. Wind 4a the C_D is adjusted according to Hwang et al. [13], in wind 4b according to Fan et al. [11] and Wind 4c based on Janssen [17]. Within all different wind configurations, the stress calculation is iteratively vectorally estimated. This means that higher wind speeds are better represented and higher magnitude waves are better resolved.

$$C_D = (8.058 + 0.967U_{10} - 0.016U_{10}^2) \tag{2.6}$$

For whitecapping, Wind 1 and 4 use [19] (WAM3 cycle), but a noticeable difference of the ST6 package, from WWIII and the other SWAN options for whitecaps is the use of a swell steepness dependent dissipation coefficient, is set at 1.2 according to Ardhuin et al. [3]. Wind 2 uses the WAM4 cycle formulation [16]. Bottom friction has been adjusted according to Zijlema et al. [54] 0.038 m^2 s^{-3}, nearshore breaking, triad interactions, and diffraction are all enabled based on their respective suggested values in SWAN. Quadruplets interactions for deeper water are resolved with a fully explicit computation per sweep, which makes the computation a bit more "expensive", but retains good agreement.

In the ST6, dissipation is described by local and cumulative terms, that can be accordingly scaled; based on previous works on derivation of these terms, the following "pairs" are utilised for dissipation (whitecapping effects) [35, 53]. Option 1 has local dissipation (lds): 5.7^{-7} cumulative dissipation (cds): 8^{-6}, option 2 lds: 4.7^{-7}, cds: 6.6^{-6}, and option 3 lds: 2.8^{-6}, cds: 3.5^{-5}. The scaling option parametrisation aims to correct the mean square slope, in this new term, the suggestion is that the scale is over 28. Therefore, seeking to ensure a potential noticeable improvement, we opted for three different tuning parameters, scale 1:28, scale 2:32 and scale 3:35. Whilst more scaling can be attempted, it is expected that the difference from 28 to 35 will be adequate to display any impacts on the hindcast. Tuning this option has to do with how much energy (more or less) is allowed to migrate in higher frequencies. The higher the number, the lower the amounts that are allowed there, therefore, this can be beneficial to not under-estimate lower frequencies.

2.3. North Sea Wave Database (NSWDv2)

The physics used to drive the North Sea Wave Database version 2 (NSWDv2) were developed after 30 calibration models were assessed and their performance was determined by taking into account the aforementioned indices and runtime. From experience, we are aware that using the ERA datasets reduce the maxima performance if no calibration of the whitecapping coefficient is made [21–23, 26]; so as a final qualitative metric, we also examined the ability of modelled data to be close to the maximum wave height value. Ideally, the bias will be near zero, and the maximum values will be closely followed, as they are important for extreme value analysis, moorings and structural estimations. If we were only interested in obtaining higher maxima values, we would have opted for using Climate Forecast System Reanalysis (CFSR) data which have shown a better maximum peak performance with means over-estimations and larger scattering in the North Sea [26].

2.3.1. NSWD Validation

To assess and validate the NSWDv2, several indices are used, Pearson's correlation coefficient (R) indicates how well the hindcast performed (see Equation (2.7)), the root-mean-square-error ($RMSE$) underlines the differences between hindcast and buoy measurements (see Equation (2.8)), the Scatter Index (SI) give an indication on the relationship between observed and modelled data (see Equation (2.9)). The goal of a good hindcast is to obtain high correlation values of significant wave height (H_{m0}) $R \geq$ 85–90%, with small $RMSE$ showing a close "positioning" with the mean values, a low $SI \leq$ 25–30% (or high inverse $SI_{inv} \geq$ 85–90%) indicating that the trends are well followed. From experience we are aware that wave models have a tendency to under-estimate, therefore, we also compare the maximum values of significant wave height (H_{max}), to ensure that not only the mean bias is low (see Equation (2.10)), but the bias of maxima of events is also reduced by the model. This is considered helpful as it will translate to improvements in statistically estimating extreme return wave periods, and making the final model more versatile.

$$R = \frac{\sum_{i=1}^{N}((M_i - \overline{M_i})(O_i - \overline{O_i}))}{\sqrt{((\sum_{i=1}^{N}((M_i - \overline{M_i})^2)((\sum_{i=1}^{N}((O_i - \overline{O_i})^2)}} \tag{2.7}$$

$$RMSE = (\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2)^{0.5} \tag{2.8}$$

Table 2.1: Buoy information and compared data length.

In-Situ (Buoy)	Longitude (ϕ)	Latitude (λ)	Data Availability
Brouwershavensegat	3.61°	51.76°	69%
Eurogeul DWE	3°	51.94°	64%
Europlatform 3	3.27°	51.99°	71%
IJgeulstroompaal 1	4.51°	52.46°	67%
F161	4.01°	54.11°	68%
F3 platform	4.72°	54.85°	94%

$$SI = \frac{RMSE}{\frac{1}{N}\sum_{i=1}^{N} O_i} \tag{2.9}$$

$$BIAS = \sum_{i=1}^{N} \frac{1}{N}(M_i - O_i) \tag{2.10}$$

$$MPI = |1 - \frac{RMSE}{RMSE_{change}}| \tag{2.11}$$

where M_i is the simulated wave parameter, O_i recorded and N measurements. Finally, the Model Performance Index (MPI) diagnosis performance, indicating the degree to which the model reproduces observed changes of the waves ($RMSE_{change}$). Wave data from buoy measurements were gathered from 2012-2016 [33], filtered by removing non-operational days, see Table 2.1.

In order to obtain any valuable information that represent climatic conditions, and provide an appropriate resource assessment for metocean conditions, climate statistics, wave energy, and extreme value analysis. The dataset has to include at least 10 years of un-interrupted homogenous data, with at least 3 h of temporal resolution, and favourably ≥30 years [14, 52]. This is extremely important as renewable resources are climate dependent and have to be properly resolved. When estimating the resource content, and potential energy output or wave characteristics a long-term suitable dataset can be confidently used for the next 20 years.

The North Sea Wave Database version 2 (NSWDv2) covers the years 1980–2020, and its performance is compared with in-situ measurements. The NSWD is homogenous and all available years are compared with in-situ buoy measurements to assess confidence. In-situ measurements are dispersed and located at various depths, focus is given especially at nearshore and shallow water locations, which are both of imminent interest for wave energy deployments and where larger oceanic models have limitation. All available buoy locations were filtered, analysed and compared with NSWD, validation results are given in Tables 2.2-2.3. There is never gonna be a “perfect” model, however by utilising a calibrated/validated model, we can identify the areas of interest and/or limitations. Subsequently, additional analysis can be developed, with higher focus to specific regions via use of multi-domain nesting. The NSWD hindcast allows such future cases to be developed at later stages, as the primary domain contains information relevant for re-constructing internal boundary condition.

The majority of locations indicate a high agreement for H_{m0} with R within ≈92–96%. For Southern parts of Dutch coastlines (Brouwershavensegat, Europlatform 3, Eurogeul DWE), R shows a high agreement following the generation trend. Most of the years exhibit a good MPI with values consistently ≥ 99%. Regarding the bias performance,all modelled data show an over-estimation by ≈14 cm on average, with a range from 0.06-0.25 m. It has to be noted that while usually the bias is used as a good order of merit, we have decided to also look into the maxima values differences. Although, this can somewhat inferred by the Scatter Index (i.e., a low scatter index, may indicate good “maxima” capture). Unlike, the trend of bias slight over-estimation, most maxima values are only slightly under-estimated, usually with a difference of ≈ -0.5 to 0.6 m. However, there is an instance where the modelled data under-estimated significantly with 1.25 m at Brouwershavensegat in 2012. For the assessment of T_{m01} the MPI is consistently ≥96%, indicating a good model agreement. R for wave periods is usually lower than H_{m0} as it relies on the frequency distribution choose, which carry inherit assumptions in the numerical model. Scattering values for all years are with 14–20%, indicating a strong diagonal agreement, and the periods are characterised by mid to high frequency waves, simulated accurately by the model with small under-estimation in magnitude of ≈ 0.24-0.4 s.

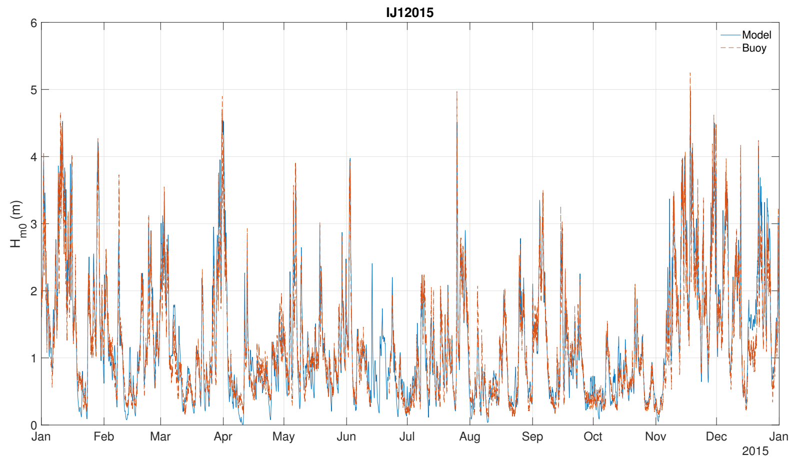
Table 2.2: Validation indices for H_{m0}

	Brouw				Europlatform 3				Eurogeul DWE			
	2012	2013	2015	2016	2012	2013	2015	2016	2012	2013	2015	2016
R	0.94	0.92	0.94	0.93	0.94	0.94	0.96	0.94	0.95	0.94	0.96	0.94
RMSE	0.24	0.23	0.27	0.24	0.34	0.34	0.40	0.34	0.36	0.35	0.41	0.35
MPI	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Buoy	0.91	0.83	0.98	0.90	1.23	1.18	1.34	1.21	1.22	1.12	1.32	1.22
SWAN	0.97	0.91	1.10	0.97	1.36	1.33	1.58	1.35	1.39	1.29	1.57	1.37
Bias	0.06	0.09	0.12	0.07	0.13	0.14	0.24	0.14	0.17	0.17	0.25	0.15
SI	0.26	0.28	0.28	0.27	0.28	0.29	0.30	0.28	0.30	0.31	0.31	0.29
Max Buoy	5.17	4.04	4.00	4.59	5.22	4.69	4.76	5.74	5.06	4.88	5.25	5.57
Max SWAN	3.92	3.39	3.52	3.54	5.84	5.85	5.30	5.59	5.86	5.90	5.24	5.59
	F161				F3				Ijgeulstroompaal 1			
	2012	2013	2015	2016	2012	2013	2014	2015	2012	2013	2015	2016
R	0.87	0.91	0.91	0.88	0.81	0.86	0.89	0.90	0.94	0.91	0.96	0.92
RMSE	0.61	0.61	0.66	0.59	0.66	0.66	0.55	0.57	0.26	0.26	0.26	0.28
MPI	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Buoy	1.50	1.56	1.47	1.45	1.56	1.60	1.67	1.85	1.07	0.85	1.20	0.99
SWAN	1.72	1.81	1.81	1.63	1.66	1.72	1.68	1.84	1.07	0.89	1.26	0.98
Bias	0.22	0.25	0.33	0.19	0.10	0.12	0.01	0.00	0.00	0.05	0.06	-0.01
SI	0.40	0.39	0.45	0.41	0.43	0.41	0.33	0.31	0.24	0.31	0.22	0.28
Max Buoy	6.78	7.56	5.61	5.62	7.84	9.52	7.58	7.98	5.29	3.51	5.25	6.27
Max SWAN	7.17	7.98	6.53	7.03	7.26	8.07	7.53	7.09	4.76	3.84	4.70	4.54

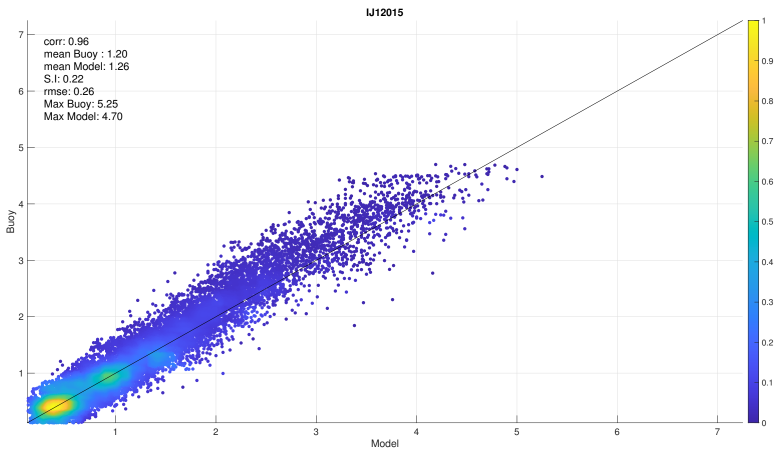
Table 2.3: Validation indices for T_{m01}

	Brouwershavensegat				Europlatform 3				Eurogeul DWE			
	2012	2013	2015	2016	2012	2013	2015	2016	2012	2013	2015	2016
R	0.68	0.59	0.74	0.68	0.68	0.67	0.80	0.71	0.73	0.70	0.82	0.72
RMSE	0.85	0.83	0.71	0.83	0.97	0.91	0.76	0.83	0.84	0.80	0.67	0.83
MPI	0.97	0.96	0.97	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Buoy	4.10	4.03	4.08	4.09	4.57	4.48	4.60	4.57	4.43	4.33	4.44	4.43
SWAN	3.67	3.60	3.83	3.66	3.97	3.93	4.17	3.95	3.97	3.90	4.14	3.96
Bias	-0.44	-0.43	-0.24	-0.43	-0.60	-0.54	-0.43	-0.61	-0.45	-0.43	-0.31	-0.47
SI	0.21	0.21	0.17	0.20	0.21	0.20	0.17	0.18	0.19	0.18	0.15	0.19
Max Buoy	15.80	7.20	7.00	7.40	7.70	7.80	7.80	8.10	7.80	7.90	7.60	7.60
Max SWAN	7.68	7.02	6.90	6.93	7.93	7.68	7.36	7.57	7.83	7.66	7.22	7.56
	F161				F3				Ijgeulstroompaal 1			
	2012	2013	2015	2016	2012	2013	2014	2015	2012	2013	2015	2016
R	0.60	0.69	0.72	0.63	0.46	0.56	0.61	0.65	0.67	0.57	0.78	0.68
RMSE	1.05	1.01	0.89	1.03	1.45	1.45	1.27	1.24	0.90	0.97	0.86	1.02
MPI	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.97	0.96	0.97	0.96
Buoy	4.80	4.83	4.69	4.73	5.19	5.21	5.05	5.20	4.29	4.08	4.40	4.30
SWAN	4.35	4.41	4.44	4.27	4.30	4.32	4.32	4.50	3.81	3.51	3.99	3.64
Bias	-0.45	-0.41	-0.25	-0.45	-0.89	-0.90	-0.73	-0.69	-0.48	-0.58	-0.41	-0.66
SI	0.22	0.21	0.19	0.22	0.28	0.28	0.25	0.24	0.21	0.24	0.20	0.24
Max Buoy	8.70	9.50	7.70	7.90	9.00	10.50	9.50	9.40	7.90	8.30	7.90	8.20
Max SWAN	8.26	8.90	7.98	8.32	8.42	9.05	8.80	8.39	7.75	7.08	7.58	7.50

Ijgeulstroompaal 1 (see Figure 2.3) is located at nearshore waters at the central part of the Netherlands. Waves hidncasted have good R and high values of MPI indicating good agreement for H_{m0} by the model. Unlike, southern locations, biases are very low with no mean bias modelled for Ijgeulstroompaal 1 in 2012. However, H_{max} values are mostly under-estimated with typical differences ≈50 cm. The wave period is also well modelled, as in the case of Southern points, mean bias of the periods is under-estimated and the MPI indicates that the hindcast is of high fidelity, with values ≥96.5%. Similar to the H_{m0}, $T_{m01_{max}}$ is under-estimated from ≈20 s, indicating that the model is able to capture the peaks well.



(a) In-situ vs hindcast timeseries



(b) Scatter plot

Figure 2.3: IJ1 statistical validation for 2015

F161 and F3 are locations far away from the coastline, within the Dutch economic zone. For H_{m0} the MPI is consistently above 99%, and the mean biases show a tendency for minor over-estimations ≈ 0.1 m, although in 2015 the F3 shows perfect agreement (no mean bias). In terms of maximum both locations for all years so a very good performance with small underestimations for F161 throughout the years ≈ -0.4 to -1.4. On the other hand, the F3 locations record an over-estimation for H_{max}.

3
Wave energy flux

Wave power is derived by the calculation of wave energy flux, which denotes the available resource that is generated and propagated within waves. It corresponds to the notion of available energy flux contained per one unit of crest width, expressed usually in kW/m, estimation of which is not straightforward. Starting from a simplistic approach, wave energy flux estimations are initially based on linear wave theory, in which depth considerations are taken as having small or no effect. In the simplest of terms wave energy is the summation of kinetic and potential energy per unit surface area of a wave.

$$E_{wave} = E_{kin} + E_{pot} = \frac{1}{8}\rho g H_{sig}^2 C_g \tag{3.1}$$

with E_{wave}: Energy in waves, C: Wave celerity, λ_{wave}: Wavelength, T: Wave period

$$C_g = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right]C \tag{3.2}$$

$$C = \frac{\lambda_{wave}}{T} \tag{3.3}$$

$$\lambda_{wave} = T\sqrt{\frac{g}{k}\tanh(kh)} \tag{3.4}$$

The potential energy flux per unit of wave crest (height) depends on the wave group and its celerity (wave group velocity). The relation between wavelength, depth and period is based on the dispersion relationship (see Equation 3.1 - Equation 3.4). Although deep and shallow water interactions in regards to depth alter the estimated energy flux. In deep waters, energy calculations are approached as regular waves with not many variations in frequency and directions (see Equation 3.5).

$$P_{wave} = \frac{\rho g^2 H_{sig}^2 T}{32\pi} \tag{3.5}$$

In the cases of actual sea states and wind seas the situation is much more complex. Waves are a summation of different wave numbers and frequencies interacting in the area, with the power propagated within waves, depending on the energy density travelling with varied frequency and directions. This is expressed by the $2D$ spectrum, $N(\sigma,\theta)$. This reforms the propagated summation of energy as seen in Equation 3.1.

$$P_{wave} = \rho g \int_0^{2\pi}\int_0^{\infty} C_g(\sigma,h)N(\sigma,\theta)d\sigma d\theta \tag{3.6}$$

with

$$C_g(\sigma,h) = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right]C \tag{3.7}$$

The fact that several frequencies and directions exist, alters as well the calculation of wave group and velocities, with C as given in Equation 3.2–3.3. However, in this case k is immediately affected by the presence of these quantities, $k(\sigma,\theta)$ [8].

$$E_{wave} = \frac{1}{16}\rho g H_{sig}^2 C_g(T,h) \tag{3.8}$$

This led to the calculations of wave energy for irregular waves in regards to the period as affected by depth (see Equation 3.8). The period that is required to assess the energy is known as energy period and is extracted by zeroth (m_0) and minus one (m_{-1}) spectral moments. The energy period is calculated as below, while it is also known to be connected with the mean-zero crossing period (T_z) and the peak period (T_{peak}).

$$T_e = \frac{m_{-1}}{m_n} \tag{3.9}$$

$$m_n = \int_0^{2\pi}\int_0^{\infty} \sigma^n N(\sigma,\theta) d\sigma d\theta \tag{3.10}$$

With $m_0....m_n$ denoting the n^{th} moment of the wave spectrum. For these kind of locations and due to the fact that investigation is expressed for coastal waters, the non-linear formulation of wave energy calculation is considered, representing wave energy for coastal locations as [48]. The energy contained within waves expressed, in W/m, which corresponds to the energy per crest unit length. Energy components are computed with a formulation appropriate for the realist representation of resource. Over the summation of very different wave numbers frequencies (f) and directions (θ), see Equation 3.11.

$$P_x = \rho g \int\int C_{gx} E(f,\theta) df d\theta \tag{3.11}$$

$$P_y = \rho g \int\int C_{gy} E(f,\theta) df d\theta \tag{3.12}$$

where $E(f,\theta)$ the energy density spectrum over an x (longitude) y (latitude) system. C_g are the components of absolute group velocities, water density (ρ), g gravitational acceleration. Total wave power is estimated in kW/m as seen in Equation 3.13.

$$P_{wave} = \sqrt{P_x^2 + P_y^2} \tag{3.13}$$

Having established the interpretation of wave parameters and their transformation into wave energy, the resource assessment for the examined period is presented. The annual and seasonal power levels are expressed in kW/m, although this is the available resource.

North Sea conditions are mostly dominated by wind generated waves at the Southern part, and a mixture of wind and swell waves at the Northern [23]. Wave power (P_{wave}) can be clustered into three regimes (i) North of the Netherlands has the “highest" resource, with magnitude at accessible depths from 10-20 kW/m, (ii) moderate/mild magnitudes are at the central areas of the Netherlands, from $4-8^o$ E and $53-54^o$ N to $3.5-4^o$ E and $51.5-52^o$ N (Rotterdam) with magnitudes 6-12 kW/m, (iii) lowest resources are below Zeeland from 4-10 kW/m, see Figure 3.1.

In terms of monthly wave energy distribution, highest magnitudes are met in the winter season of December-January-February (DJF) with January presenting the most energetic. Upper North Sea latitudes have higher P_{wave}, specifically the Wadden islands ≈ 25-30 kW/m. At deeper waters near that region propagated resource is consistently ≥ 30 kW/m, with values nearshore throughout DJF of ≈ 25-28 kW/m. The lowest conditions are encountered June-July-August (JJA), at the same area with magnitude $\leq 10-15 kW/m$, a decrease almost 50%. As expected autumn (September-October-November (SON)) and spring (March-April-May (MAM)) seasons are anti-diametrical, from MAM the energy flux slowly is reduced, and in SON it increases until peaking across the coastlines in DJF, see Figure 3.2-3.3.

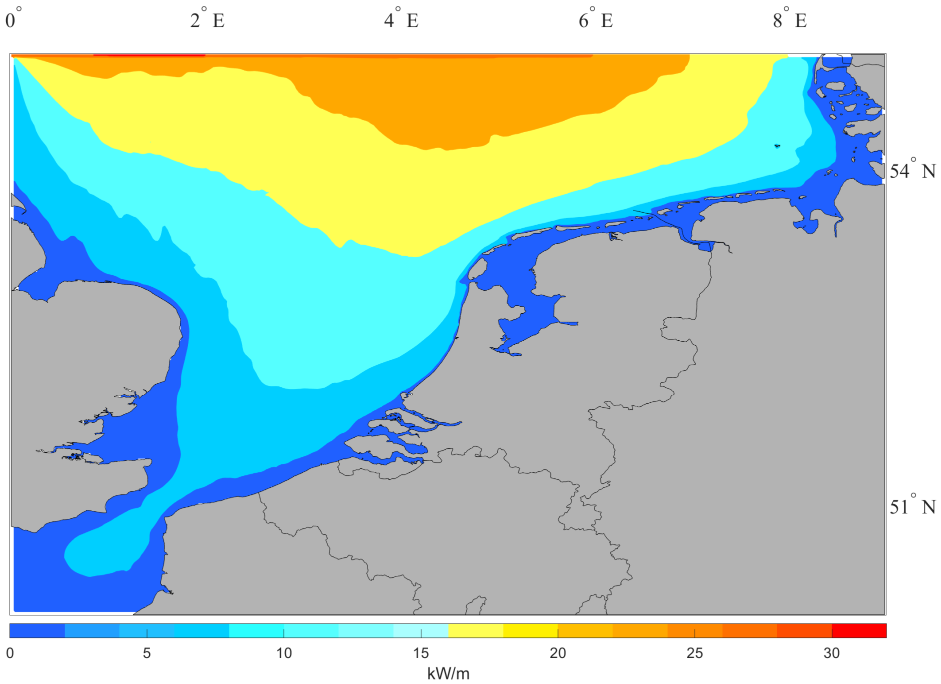
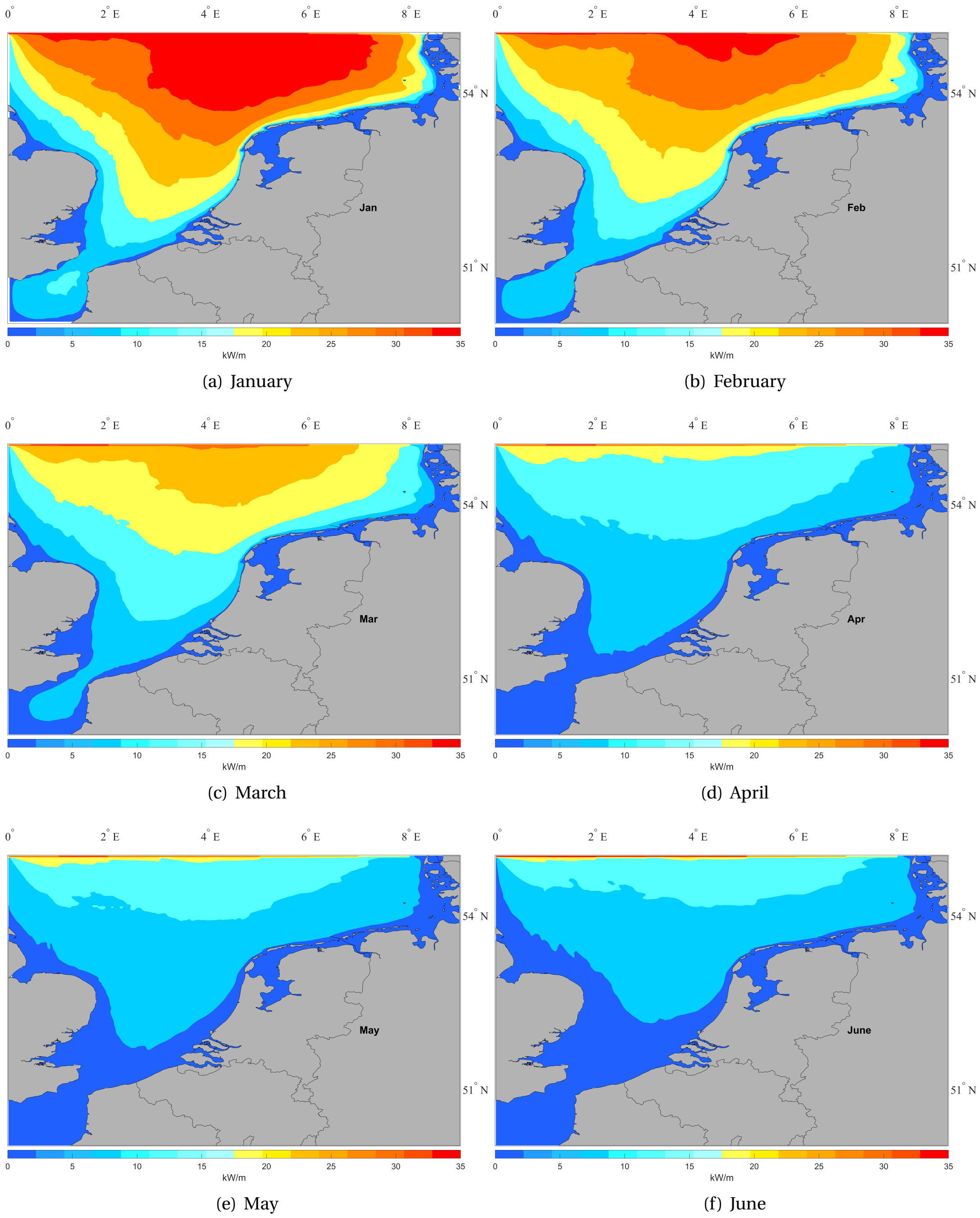
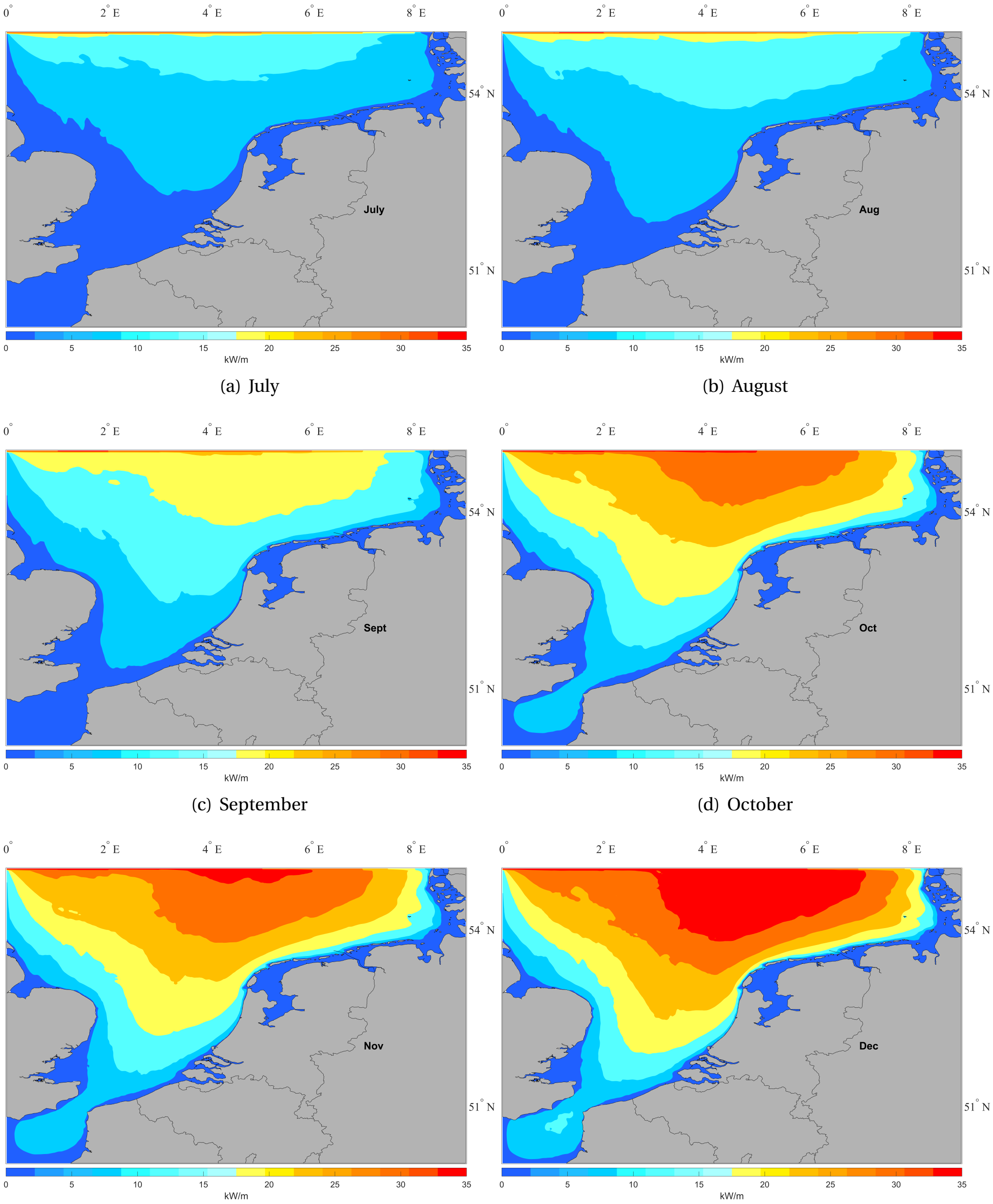


Figure 3.1: Wave energy flux (mean) from 1980-2020



(a) January (b) February (c) March (d) April (e) May (f) June

Figure 3.2: Monthly mean wave energy flux from January until June, from 1980-2020



(a) July

(b) August

(c) September

(d) October

(e) November

(f) December

Figure 3.3: Monthly mean wave energy flux from July until December, from 1980-2020

4
Conclusions

The model was modelled for 40 years and developed a comprehensive dataset with metocean conditions. It is often overlooked how important wave resource assessments are, and the level of intricacies they require to be considered. Especially, for extrapolation of resource characteristics and/or renewable energies, using datasets without appropriate considerations as per international peer-reviewed standards should be discouraged. Resource assessments have to be gradual and multi-levelled, as there is no perfect model. However, with detailed model calibration and validation, the assumptions can be minimised, and provide information which can quantify the uncertainty, giving confidence in any further analysis.

Although we cannot expect that numerical wave models will be explicitly deterministic in their assessment, a major improvement has been introduced with this configuration. When also compared with other wind drag and dissipation parametrisations, it is observable that the bias is reduced, but most importantly, the highest waves are "captured". The NSWDv2 managed to reduce mean under-estimations, and have a close agreement with maxima H_{m0} values, which are hugely important in the survivability of structures and are usually under-estimated significantly. Some locations showed an over-estimation of mean and maxima, though these locations are at regions where currents influence the wave resource, and since the NSWD model did not include such current information, it is advisable that higher resolution modelling is employed for these locations. Especially, the ones that are located in the outlets of estuaries. The biases trend indicated a close agreement with mostly a slight over-estimation that for all locations averaged 15 cm. Central and Northern parts of the Netherlands were better hindcasted and gave higher agreements with almost zero biases. Similarly, the configuration and tuning used for the NSWDv2 reduced under-estimation of maxima events within ±25–30 cm.

This analysis provides information vital to reduce assumptions, especially for offshore energies, structures and performance evaluation. To that end, reliable databases are vital for any future development. When considering reliability, we should expect that there will not be a total agreement, but rather we should seek to improve the databases produced by elaborating on physical configuration and performance limitations. Knowing the limitation of each solution provides valuable information and confidence in the use of any subsequent database. The NSWDv2 has shown a very good agreement with higher values at the Northern parts, indicating that the nearshore and swell interactions are resolved. Due to the scale, very shallow locations show a small reduction in accuracy. Influence of currents reduce the wave resource at very nearshore areas, and influence their potential variance, indicating that further nesting is necessary. Nevertheless, **NSWDv2 offers significant information and addresses the lack of quantifiable metocean and wave power assessment for the North Sea region, revealing that the level of wave energy is higher than anticipated.**

NSWDv2 builts upon NSWD [23], utilising the next generation of wind fields, constituting a high-fidelity database metocean conditions and wave energy flux. The North Sea is considered of low energy, however, the mean energy flux indicates that there is more energy content, and it is highly accessible. In terms of wave energy, interesting regions are the Northern provinces, including the Wadden and Texel islands, which have a P_{wave} of 8–22 kW/m at low depths where WECs can be potentially deployed cost-effectively and benefit from high vessels accessibility ≥90%.

5

Recommendations

The North Sea benefits from good levels of wave energy resource. Wave energy converters should not only be considered for high energy resources, on the contrary, milder and moderate resources offer better consistency on the potential with less variability. An added advantage of the North Sea region are the “slow” gradients and change in bathymetry which significantly influences wave energy content. Even at very close proximity to the shore and depths from 20 m, P_{wave} is significant ≥8 kW/m and can arguably foster the development of ocean wave energies in a cost-efficient and competitive way.

Future research recommendations:

1. Couple the wave model with high-resolution tidal information, to improve interaction resolution.
2. Enhance collaboration with developers to re-structure their devices for the Netherlands, assess optimal power performance and minimise loading.
3. Investigate the applicability of wave energy arrays using the Selection index for Wave Energy Deployments (SIWED), and evaluate the profitability.
4. Research impacts of wave energy converters array configuration both in latitudal and longitudal distances, and investigate both staggered and non-staggered approaches.
5. Introduce complex wave energy converters arrays in spectral models to quantify wake effects.
6. Research the potential for coastal protection (overtopping) and reduction of coastal erosion, via wave energy converters arrays. Consider both active and passive ways for mitigation.
7. Expand to the use of a wave 3D model to improve the impact of wave energy converters arrays at coastlines.
8. Assess the noise from wave energy converters arrays and its environmental impact during operation.
9. Optimise wave energy converters arrays configuration for optimal power production or coastal mitigation efforts.
10. Quantify the qualitative mitigation measures by wave energy arrays, such as coastal protection enhancement, erosion avoidance. Assign monetary values that can benefit deployment of wave energy, as ”hidden benefits" are revealed.

Wave energy converters and subsequent array need to adapted for the North Sea regimes to optimise their performance. Simultaneously, this will give the opportunity to have Dutch WEC innovations applicable to several international markets, with similar resources i.e. Mediterranean, Black Sea, Baltic Sea, Java Sea, etc. The inclusion and coupling of a tidal-wave model, though challenging, can open the way to reduce uncertainties even more, and at the same time provide valuable information for coastal elements. The interaction of tidal elevations and currents, interferes with local wave conditions and often lead to changes that a non-coupled approach cannot estimate. Furthermore, it will allow us to estimate moorings and infrastructure impacts (.e. foundations, electrical substations) more accurately hence reducing costs.

Large scale wave energy converter arrays will have an impact on energy extracted (see wake effects), with their spacing influencing coastal systems. Reducing or increasing packing density of wave energy farms will have an effect on erosion, and loading on coastal structures. That is something that is still under-investigated, and has the potential for immense techno-socioeconomic impact. This will allow us to quantify monetarily the “hidden" benefits of wave energy and the clear synergies it has with coastal applications.

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