Speeding up TOMAWAC by means of improved numerical methods

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Abstract— **TOMAWAC is a third generation spectral wave model. It is used as a stand-alone wave prediction tool, as well as coupled to TELEMAC and GAIA/SISYPHE in order to perform morphological simulations. Due to the fact that energy is calculated for a full wave spectrum, the wave calculation tends to be relatively slow. Therefore, improvements to the numerical calculations in TOMAWAC were implemented, with the objective to increase the speed of the code, but at the same time also to increase the robustness and stability. The results are illustrated in various test cases.**

I. INTRODUCTION

The calculation of wave energy resources using numerical models become a necessity in order to completely understand the wave climate and reduce the uncertainties. Despite considerable advances in computational power, speeding up wave modelling calculations and improving numerical performance continue to be a challenge. As a part of Blue Energy Resource Assessment (BluERA) research, improvements to the TOMAWAC model were implemented. The results of these improvements are presented in this paper.

II. OVERVIEW OF NUMERICAL TECHNIQUES IN THIRD GENERATION WAVE MODELS

At the moment, various third generation wave models are being used in the coastal and oceanographic community. WAVEWATCH [1] and SWAN [2], two of the most used wave models were reviewed in order to understand their numerical behaviour and to find inspiration for possible improvements in TOMAWAC. Each of these models solve the wave action balance, which is given by:

$$\frac{\partial N(\theta,\sigma)}{\partial t}+\frac{\partial c_j N(\theta,\sigma)}{\partial x_j}=S \qquad 1$$

Here, N is the wave action defined as $N=E/\sigma$, with E the two dimensional wave energy spectrum, and σ the wave frequency ,c_j is the propagation velocity of the wave energy along the different dimensions (x, y, θ and σ) and S are the source and sink terms that parametrize physical processes such wind input, non-linear wave interactions and whitecapping.

WAVEWATCH has a numerical architecture that is rather similar to TOMAWAC. It uses a fractional step method, where different physical processes are solved one after the other, starting with intra-spectral propagation (such as refraction, and frequency shifting due to currents) for half a time step, followed by spatial advection, and the second half time step of intra-spectral propagation (i.e. using Strang splitting). After the spatial advection, the source terms are integrated. For each of these processes, sub-time steps are used to improve the accuracy and stability. For unstructured meshes, the spatial advection schemes are based on the work by Roland (2008) [3], including an explicit and implicit N-scheme as well as an explicit PSI-scheme (second order accurate in space). For intra-spectral propagation, different explicit advection schemes are used, namely a first order upwind scheme, the second order UNO scheme and the third-order Ultimate QUICKEST scheme. Each of these advection schemes is fully conservative and non-oscillatory.

SWAN was specially designed for shallow water wave modelling. Thereto, it uses a fully implicit method, leading to a large matrix. The individual blocks of this matrix are solved using different methods. The intra-spectral propagation typically leads to tridiagonal or pentadiagonal block matrices, which can be solved efficiently using direct matrix solvers. The spatial propagation is solved using a Gauss-Seidel iteration method. However, the Gauss-Seidel method convergences in one iteration in case the solution in the Gauss-Seidel step is advanced in downwind direction. In order to make sure that the solution is in downwave direction, SWAN uses multiple sweeps (four in the version for a structured mesh), in which a quadrant of the spectrum is solved. Iteration is used to account for non-linearities (such as depth-induced breaking). This method has the advantage that arbitrary large time steps can be used (at the cost of a larger cost per time step), and it is very suited for a structured mesh. However, its application is more difficult on an unstructured mesh and is difficult to parallelize (such that the unstructured SWAN version uses OpenMP, rather than MPI, leading to a limited maximum number of parallel processes that can be used). Note that in the unstructured version, SWAN uses the N-scheme, which is only first order in space. However, for spectral propagation a mixture between an upwind and central scheme is used, as it was found that the use of an upwind scheme leads to smoothing of the refraction. Note that the methods used in SWAN can, in some situations, lead to negative wave energies. Hence, in SWAN, a correction routine is implemented that corrects the spectrum after the calculation in order to remove the negative wave energy.

TOMAWAC [4] uses a fractional step method, where advection is solved first using the method of characteristics (for both the intra-spectral and spatial propagation terms. The roots needed for the characteristic methods are not calculated

every time step. Instead, they are calculated at the beginning of the calculation and when the hydrodynamics (flow velocities and water depths) are updated. This procedure leads to a fast and unconditionally stable advection scheme. However, this advection scheme is not fully energy conservative and is only first-order accurate such that there is a reasonable amount of numerical diffusion. Furthermore, the parallel scaling of this method worsens in case the Courant number increases (as for an increasing time step, it can lead to streamlines extending to a larger neighbouring subdomain, leading to more parallel communication). After the advection terms, the source terms are solved. A sub-time step can be used for rapidly varying processes (e.g. depth-induced breaking, and triad interactions), which are solved after the slower varying physical processes (wind input, whitecapping, bottom friction and quadruplet interaction). A disadvantage of the fractional step approach is that it leads to a time step restriction (e.g. [3]) for accuracy reasons. A clear example of this occurs in case of breaking on a bar. In case the time step used is too large, the waves will not break at the bar, but instead, they will be advected over the bar, leading to wave heights that are too high behind the bar.

III. New TOMAWAC numerical architecture

Based on the findings of the review of these different wave models, a new architecture of TOMAWAC was implemented (Figure 1).

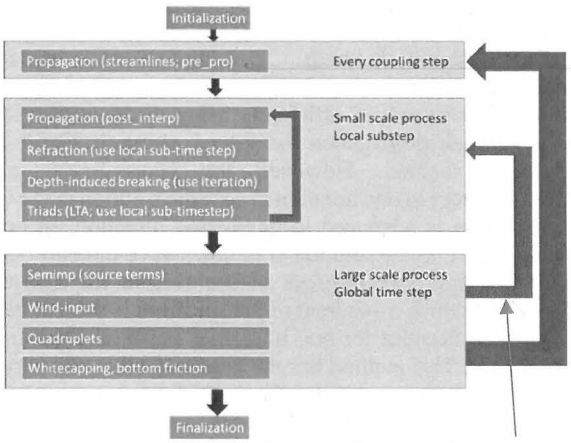

Figure 1 New numerical architecture in TOMAWAC

In this new architecture, a separation is made between fast and slow physical processes. The fast processes, which occur locally in space, need to be resolved using a small time step. These process include spatial advection, intra-spectral propagation (such as refraction), depth-induced breaking and triad interactions. Within these individual processes, sub steps are still used for some of these processes (notably advection and triad interactions, which will be discussed below). The slow physical processes (wind-input, quadruplet interactions, whitecapping and bottom friction) are now solved with a large global time. In this way, calculation time can be reduced substantially, as the calculation of these source terms can be quite slow (especially the calculation of quadruplet interactions). This method resembles what is used in WAVEWATCH, and has also been used in WAM by Monbaliu et al [5]. The loops for small scale and large scale processes are included an even slower loop, which is to update the hydrodynamic data, and update the calculation of the roots of the characteristics. This latter loop is already present in the current version of TOMAWAC.

Furthermore, the review indicates the need for alternative advection methods, in order to have the possibility to use:

- a second order spatial advection scheme that leads to less numerical diffusion
- higher order advection schemes for intra-spectral propagation
- advections schemes that are fully energy conservative

IV. Improvements of the individual source terms/ processes

A. *Advection*

Different changes were made to the advection routines. For the currently available characteristic method, a sub time step was implemented. The objective of this sub time step is to speed-up the code, by calculating shorter streamlines, which in parallel extend less to other subdomains, in order to improve the parallel scaling of the advection, at the expensive of some increase in the numerical diffusion. Furthermore, a fractional step method was implemented similar to WAVEWATCH, where spatial advection and intra-spectral propagation are calculated separately. This has various advantages compared to the original method:

- Fully-conservative intra-spectral schemes are now possible (discussed in the next paragraph).
- As the spatial propagation is now two-dimensional, various existing advection schemes from TELEMAC can now be used in TOMAWAC. In this way, three additional advection schemes become available to TOMAWAC:
  - Two-dimensional characteristic method. This method was newly implemented in the module *streamline.f*. It was found that for efficiency in parallel, it is necessary to have the parallel communication for all streamlines (for all spectral bins) together. This leads to the need of a slightly different version of this method.
  - The first-order accurate NERD residual distribution scheme [11]. This advection scheme was modified in order to be able to deal with velocity-fields that are not divergence free (as discussed in [12]), such that the advection scheme conserves energy exactly.
  - The second-order accurate ERIA residual distribution scheme [11]. This advection scheme was also modified in order to deal with velocity fields that are not divergence free [12], such that the advection scheme conserves energy exactly.

- As the spatial and intra-spectral calculation are decoupled, it is not necessary to calculate the advection for all spectral bins. Instead, in case spectral bins do not contain wave energy, it is not necessary to calculate the advection. The wave energy content of a spectral bin can be checked with a threshold criterium. This threshold method is currently only implemented for ERIA and NERD schemes.

  The disadvantage of this approach is that it can be slower than the original four-dimensional characteristic method (as now a separate method is needed for intra-spectral propagation) and that there is a time step criterion due to the use of a fraction step method.

B. Intra-spectral propagation

The intra spectral propagation methods that were newly implemented uses the same numerical methods as WAVEWATCH. Three different schemes were implemented, each of which is explicit, non-oscillatory and fully energy conservative:

- Upwind scheme (first order accurate).
- UNO scheme (second order accurate).
- Ultimate QUICKEST scheme (third order accurate; this scheme is currently only implemented for refraction, not for frequency shifting).

As these method are explicit, they have a strong time step restriction. In order to make the calculation as performant as possible, the local advection time step is divided into sub steps, to ensure that CFL number is lower than one. The number of sub steps is chosen individually for each point in space, leading to an optimal time step in each spatial point.

C. Shoaling

Shoaling is the change in wave height that occurs by the change in the propagation velocity of the wave energy due to changes in the water depth. In his book, Holthuijsen [10] explains shoaling by the conservation of Ec_g, with E the wave energy and c_g the wave group velocity. In order to simulate this effect a fully conservative discretization of the advection is needed. However, the characteristic method does not use the conservative form, and hence does not fully simulated the effect of shoaling (a test to show this is presented in section VI). Therefore, shoaling is implemented as an extra source term that determined by applying the product rule to the spatial advection term in equation 1:

$$\underbrace{\frac{\partial c_{g,j} N}{\partial x_j}}_{conservative\ form} = \underbrace{c_{g,j}\frac{\partial N}{\partial x_j}}_{non-conservative} + \underbrace{N\frac{\partial c_{g,j}}{\partial x_j}}_{shoaling\ term} \quad 2$$

This term is discretised implicitly in case the divergence of the wave velocity field is negative (i.e. when it acts as a sink term) and explicitly when it is positive and works as a source of wave energy. This source term is currently only included for the two-dimensional characteristic method, not for the original three and four-dimensional characteristic methods (a similar term in included in the ERIA and NERD schemes see [12]).

D. Refraction velocity limiter

As the new refraction schemes are explicit, the CFL number needs to be lower than one, which can lead to small time steps and hence large calculation times. On the other hand, the mesh spacing or time step used in the spatial advection may lead to rather strong changes in the direction of the wave energy. Dietrich et al [6] therefore present a limiter on the propagation velocity in spectral space, in order to prevent excessive turning of wave energy as well as frequency shifting, which is given by:

$$|c_\theta| < \alpha_\theta \Delta\theta \left(\frac{|c_x|}{\Delta x} + \frac{|c_y|}{\Delta y}\right) \quad 3$$

$$|c_\sigma| < \alpha_\sigma \Delta\sigma \left(\frac{|c_x|}{\Delta x} + \frac{|c_y|}{\Delta y}\right) \quad 4$$

Here, the Δx and Δy, are the spatial mesh spacing, c_x and c_y, the spatial wave energy propagation velocity components, c_θ and c_σ, the intra-spectral propagation velocities, $\Delta\theta$ and $\Delta\sigma$ the mesh spacing in spectral space, and finally α_θ and α_σ are both tuning parameters, which are set to 0.90. This limiter has a similar effect as the smoothing of the bathymetry used in WAVEWATCH, which leads to more gentle bathymetric gradients and hence smaller refraction velocities $|c_\theta|$. These limiters are implemented in TOMAWAC in a new subroutine, called *limit_celerity.f*. This subroutine is called after c_θ and c_σ are calculated in the subroutines *conwac.f* or *conw4d.f*. In this subroutine the calculated values of $|c_\theta|$ and $|c_\sigma|$ are decreased to the values in equation 3 and 4, in case the originally calculated values were higher.

E. Depth induced breaking

Depth induced breaking is taken into account in the inner local loop. Hence it is called often, leading to the need for a fast subroutine for the calculation of depth induced breaking. Nevertheless, profiling of the TOMAWAC code showed that the calculation of the depth-induced breaking term used a substantial amount of calculation time. The exact amount depends strongly on the keyword NUMBER OF BREAKING TIME STEPS, which is rather hard to estimate a priori. Therefore, a new implementation was made for depth induced breaking (currently only for the breaking parametrization of Battjes-Janssen [9], which is the default in TOMAWAC). This new implementation of the source term speeds up the calculation of the depth-induced breaking significantly by the following modifications:

- The use of an implicit numerical scheme with Newton-Raphson iteration similar to SWAN. This has the additional advantage that it makes the computation more robust and that the user does not need to specify the number of time steps for the breaking iterations; the number of iterations is determined automatically using a convergence criterion.
- The use of a threshold insures the depth-induced breaking is only calculated on the mesh points, where depth induced breaking is important (i.e. shallow points).

- The calculation of the energy dissipation for the mean action density only, because the source term of Battjes-Janssen leads to an energy dissipation that is constant for each component in the spectrum. Hence, multiple iterations are performed, adapting the wave energy variance. After all iterations are performed, the calculated change in the wave energy variance is distributed over the wave spectrum.

The new breaking term can be activated by setting the keyword DEPTH-INDUCED BREAKING DISSIPATION = 10.

F. *Triad interactions*

It was found that the triad interactions (using the LTA parametrization [13]) can lead to numerical problems. In this source term, energy is transformed from the spectral peak to higher frequencies (Figure 2). The strength of this transfer depends on the energy difference between a frequency and twice this frequency. In case this energy difference is large, the transfer is fast. In combination with a large time step, this leads to transfer that is so large, that negative wave energies are generated around the peak frequency. These negative energies are later set to zero, leading to changes in the wave energy. In order to prevent this issue, a new source term was implement for triad interactions, with the following properties:

- The discretisation is implicit for the points in the spectrum where the wave energy decreases and explicit where it is increasing (thereby strongly decreasing the probability that the wave energy becomes negative).
- Sub steps in time are used that increase according to:

$$\Delta T_{i+1} = \mathrm{n}\Delta \mathrm{T_i}$$

with *n* a used defined parameter. This is the same method that is currently used in the breaking loop in TOMAWAC).

- The number of sub time steps that is used, is determined using a heuristic equation, based on the energy at the peak of the spectrum.

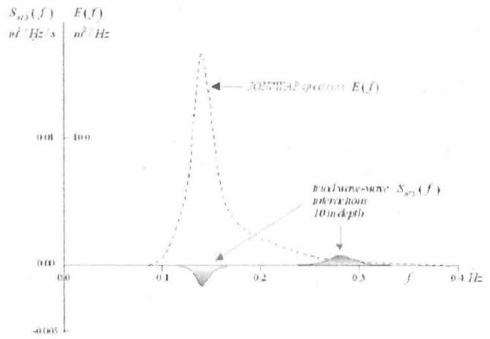

Figure 2 Schematic of the triad interaction source term (from [10])

The new triad source term can be activated by setting TRIAD INTERACTIONS= 10

G. *MDIA*

Some test showed that the use of the Multiple Direct Interaction Approximation (MDIA) [7] took considerable calculation time. A code restructuration was done, changing the ordering of the loops, in order to limit the number of cache losses. This lead to a speedup of this term by 50%, without changing the results (at the expense of a slightly larger use of RAM memory). Nevertheless, this source term remains relatively slow, compared to the DIA. This source term is nevertheless interesting, because it is a more complete approximation of the quadruplets interactions than the DIA, leading amongst others to a better prediction of the directional spreading (which typically is too broad when using DIA). However, the other source terms (wind-input and whitecapping) have typically been calibrated in combination with DIA, rather than MDIA, such that those source terms would have to be retuned for its use in combination with the MDIA.

H. *Linear wind input*

The linear wind input term [8] appeared to take a substantial amount of calculation time (about a factor four more than other source terms such as the whitecapping or non-linear wind input). The reason for this was that there was a substantial number of evaluations of geometric and exponential functions in the inner loop (i.e. evaluated for each spectral points). The code has been restructured, to bring these terms as much as possible to the outer loops, which results in a speed-up of a factor four for this specific source term, bringing the calculation speed in line with the other source terms.

V. NEW KEYWORDS IN TOMAWAC

In order to use the new functionalities, the following keywords were added:

ADVECTION SCHEME: this determines the advection scheme. The options are:

- 1= classical streamlines
- 11=2d streamlines + separate refraction
- 14=NERD + separate refraction
- 15=ERIA 1st order in time + separate refraction
- 16=ERIA 2nd order in time + separate refraction

NUMBER OF ITERATIONS FOR SMALL SCALE PROCESSES: this determines the number sub steps taken in the inner loop (for advection, refraction, depth-induced breaking and triads), thus determining the local time step.

NUMBER OF ITERATIONS FOR ADVECTION: this determines the number of sub steps for spatial advection within the local sub step (as set by the previous keyword). This keyword is only used for ADVECTION SCHEME 1 or 11.

SHOALING: if yes, the effect of shoaling is taken into account (only for ADVECTION SCHEME 11).

ADVECTION SCHEME FOR THETA: determines the advection scheme for propagation along the directions (i.e. refraction). The possible options for the this keywords are:

- 0=off; this option is useful for theoretical test cases but should not be used in practical simulations.
- 1=first order upwind
- 2=second order UNO
- 3=third order ULTIMATE QUICKEST

ADVECTION SCHEME FOR F: determines the advection scheme for propagation along the frequencies (i.e. frequency shifting due current velocity gradients). The possible options for the two keywords are:

- 0=off; this option
- 1=first order upwind
- 2=second order UNO

LIMITER FOR REFRACTION VELOCITY: switches the limiters of the intra-spectral propagation velocities on or off. The options are:

- 0=off
- 1=only for directions
- 2=only for frequencies;
- 3=for frequencies and directions

VI. RESULTS

In this section, a number of test cases is presented that were performed using the new schemes. This is part of ongoing work, for which still some extra test cases need to be added in a later stage.

A. Simple shoaling test

In the first test case, a shoal with a steep bathymetry gradient is studied (Figure 3). Only advection, refraction and shoaling are considered for different advections schemes. Source terms are switched off. The mesh is made of cells with a size of 100m in the wave direction; the time step is 30 s. A rather fine spectral mesh is used, with 72 directional bins. A JONSWAP spectrum is applied at the boundary (monodirectional waves by using a very low directional spreading value, by setting BOUNDARY DIRECTIONAL SPREAD 1 = 500) with H_s = 3.0 m and T_p = 5.0 s.

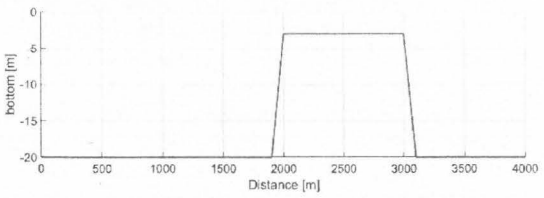

Figure 3 Bathymetry for the simple shoaling case

TABLE 1 OVERVIEW OF THE SETTINGS FOR THE DIFFERENT CALCULATIONS

RUN	SCHEME FOR ADVECTION	SCHEME FOR ADVECTION OF THETA	SHOALING
1	1	n/a	n/a
2	11	0	NO
3	11	1	NO
4	11	0	YES
5	14	0	n/a

The calculated wave heights are shown in Figure 4 for the different simulations that are shown in Table 1. The results are compared with the analytic solution for shoaling of monochromatic waves [10]:

$$\frac{H_s}{H_{s0}} = \sqrt{\frac{c_{g0}}{c_g}} \qquad 5$$

From the result it appears that the case with shoaling on (run 4) as well as with the NERD scheme (run 05) correctly calculate the change in the wave height due to the changes in the bathymetry. For the new two-dimensional characteristic method without refraction or shoaling (run02), the wave height remains constant in the whole model domain. In case refraction is switched on (run03), the wave height increases on the shoal, rather than decreases. This is not very dramatic for the run with two-dimensional -streamlines in combination with the new energy conservative intra-spectral calculation scheme (run03). Note that an additional simulation using the limiter of Dietrich et al [6] eliminated this effect completely and for that simulation, the resulting wave height was the same as the one obtained in run02. Furthermore note that the simulation with the limiter on was substantially faster than the simulation without the limiter.

Simulations with the original scheme in TOMAWAC (run01) show large unphysical increases in the wave height. The reason for this is that some of the streamlines calculated at the downwind side of the bar turn in such a way, that the bring wave energy from the mean wave propagation direction to other directions. This shows the importance of having an energy conservative scheme for the intra-spectral propagation. Hence this test case, clearly shows the improved robustness of the new two-dimensional advection scheme with separate refraction schemes. It furthermore demonstrates the need to take a separate shoaling term into account, in order to correctly reproduce this effect.

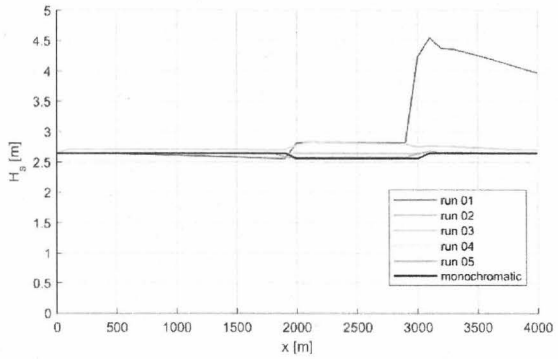

Figure 4 Resulting significant wave height in the simple shoaling case for different advection schemes.

B. *Beach case (breaking test)*

In order to test the new breaking implementation, a test is performed on a beach, with a constant slope of 1/100 and a mesh resolution of 10 m in the wave direction (Figure 5). Monodirectional waves were applied at the boundary condition using a JONSWAP spectrum with H_s = 1.0 m and T_p = 10.0 s. The simulations are performed using advection scheme 11 (two-dimensional streamlines) without shoaling. The only source term that is considered is depth-induced breaking using the method of Battjes-Janssen. Both the original explicit method and the new implicit method are considered.

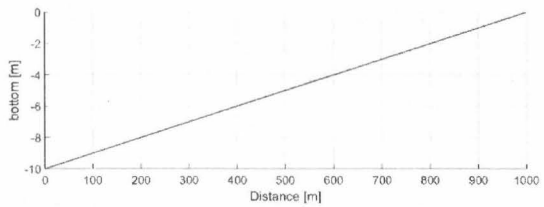

Figure 5 Bathymetry of the beach case.

The results of the different simulations are shown in Figure 6. The results are compared to a simple analytic approximation, which is determined by setting the significant wave height to 0.78 the water depth. The results of both methods are rather similar. The wave height using the original method appears smoother. The result of the new scheme is closer to the analytical approximation. As the results are inconclusive, it is the intention to perform more test for depth induced breaking, in which the results for the different schemes are compared to measurements form literature.

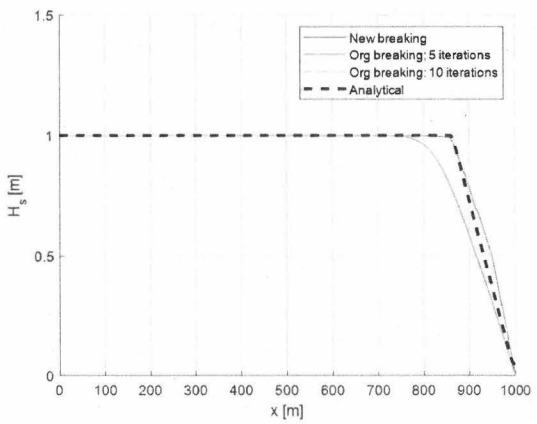

Figure 6 Significant wave height for the beach case for different advection schemes.

C. *Energy conservations (North Sea model test)*

The energy conservation of the different advection schemes was checked in a large scale TOMAWAC model of the North Sea, developed by IMDC. In order to test the energy conservation, an initial wave field with a significant wave height of 2.0 m was applied in the middle of the North Sea (Figure 3). The model was run with different advection schemes, but without any source terms. The water depth was kept constant in time (implying that the streamlines were only calculated once in the beginning of the calculations). The wave height at the open boundaries was set to 0.0 m. The runs were executed on 32 processors. The time step was set to 2 minutes.

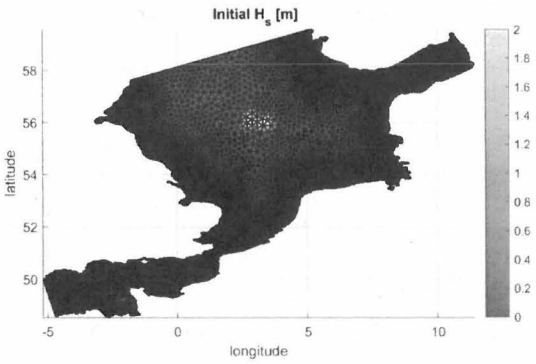

Figure 7 Initial significant wave height in the North Sea model.

In this test, the total initial wave height should stay constant, until the waves arrive at the coast or at the open boundary. Then the wave energy should start to decrease. The settings of the different calculations are shown in Table 2. The results of the total wave energy in the domain are shown are shown in Figure 4. From this figure, it is clear that energy is not conserved for the characteristic method (run 1). The new two-dimensional streamline scheme in combination with a separate method for refraction and the shoaling parametrization (run 3) ,shows a similar energy loss as the original scheme in TOMAWAC (run 1), whereas the same scheme without shoaling (run 2) actually gains energy (but the

difference with the exact conservation is lower than for run 1 and 2). The original method is faster than the two new methods (with a very limited change in calculated speed due to the inclusion of shoaling). This is due to the extra calculation time needed in the refraction calculation. Note that the limiter from Dietrich et al. [6] was not used in these calculations. A simulation similar to run 2 with the limiter switched on, finished in 154 s (substantially faster). Then the simulation with the new scheme is only 15% slower than the calculations with the original scheme (run01), this difference is not substantial for real calculations, as then the calculation time is for a large part determined by the source terms, or updating of the streamlines in the case of varying currents or water depths. The residual distribution schemes (run 4 to 6) conserve energy, but are substantially slower than the schemes based on the characteristic method. Especially the ERIA scheme is slow. Note hereby that limited effort was put into optimizing the calculation speed of these schemes for TOMAWAC, such that some improvements still might be possible for these advection schemes.

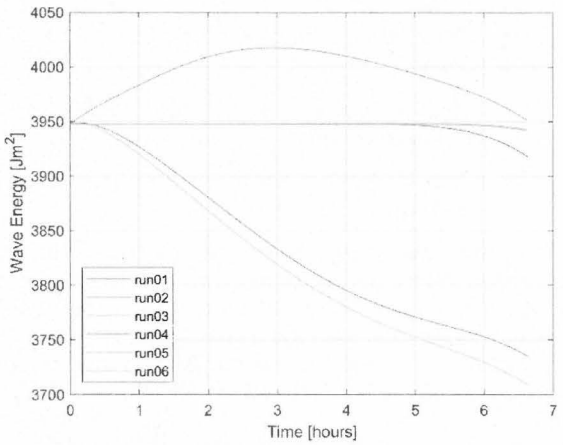

Figure 8 Total wave energy in the domain as function of time for the different simulations.

TABLE 2 SETTINGS AND CALCULATION TIME FOR THE DIFFERENT RUNS.

RUN	Advection scheme	Advection scheme for theta	Shoaling	Calculation time [s][
1	1	n/a -	n/a	134
2	11	1	NO	181
3	11	1	YES	185
4	14	1	n/a	360
5	15	1	n/a	790
6	16	1		880

D. Beji-Battjes bar (triads)

In order to test the new implementations for the triad interactions, the experiment Beji- and Battjes [15] is simulated in TOMAWAC. In this experiment, waves are approaching a shallow bar (Figure 3), where triad interactions occur. A model of a channel was made, with a mesh resolution of 0.1 m. The only source-term that is considered are the triad interactions. Advection is simulated using the original characteristic method (ADVECTION SCHEME =1). Monodirectional waves with a JONSWAP spectrum were used as boundary condition with H_s = 2.9 cm and T_p = 2.5 s. the different simulations that were performed are shown in Table 3.

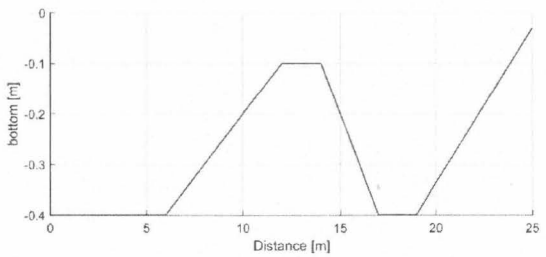

Figure 9 Bathymetry of the Beji-Battjes test case. The water level is at 0.0m.

TABLE 3 OVERVIEW OF THE DIFFERENT SIMULATIONS FOR THE BEJI-BATTJES TEST CASE

RUNS	Time step	nr of sub steps for triad interactions	triads scheme	calculation time
run01	0.5	1	1	45
run02	0.5	5	1	97
run03	0.5	10	1	168
run04	0.05	1	1	421
run05	0.5	1	10	58

The wave spectra at x = 17 m (behind the bar) are shown in Figure 4. It appears that all schemes give the transfer of energy to the higher frequencies. There is a substantial difference with the measured spectra, where the peaks are much less pronounced. This difference is likely due to deficiencies in the LTA method used for the parametrization of triad interactions. The results of the simulations with the new scheme (run05) resemble the results from the original scheme, for simulations which uses multiple sub steps for triads (run02 and run03) or a smaller global time step (run04). The increase in calculation time of the new scheme is limited, compared to the simulation using the original scheme with one sub step for triads (run01). However, the results in run01 are somewhat different for the high frequencies, suggesting that more iterations are needed. The increase in calculation time is modest (30%) compared to run01. However, the new method is faster than the other runs (02 to 04).

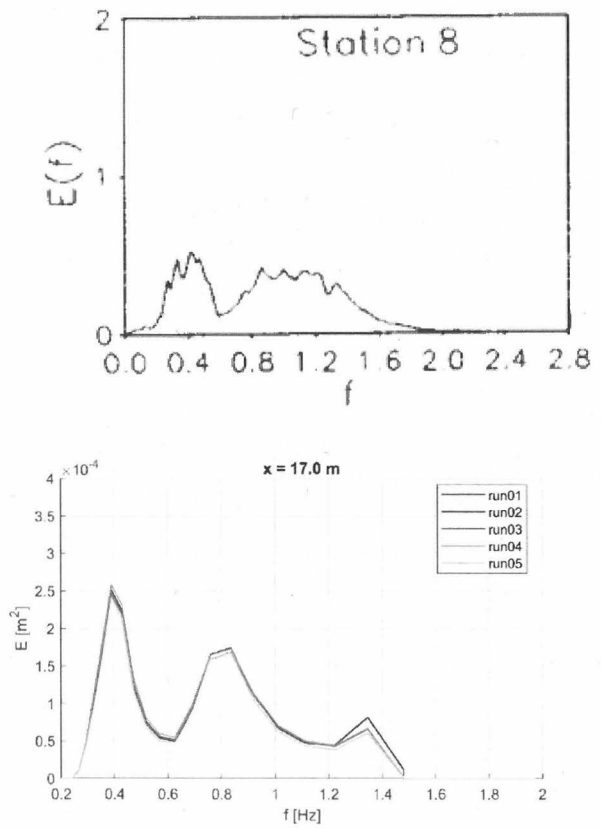

Figure 10 Wave spectra at 17 m (behind the bar) for the different simulations Top: measurement [15]. Bottom TOMAWAC result

In recapitulations, for this specific test cases, the issues with energy loss due time steps that are too high (see section IV) do not occur and both the original and the new give adequate results. The new method automatically choses the number of sub time steps, and hence leads to converged results with a relatively modest increase in calculation time

E. Haringvliet case (SWAN)

Finally, the new methods were applied in a real test case. The case that was used for this is the model of the Haringvliet, which is used to validate the SWAN unstructured mesh version [14]. The bathymetry is shown in Figure 3. The model contains 5961 nodes. The model is run with one single processor for some time until the wave conditions are in equilibrium, using advection scheme 1 (full characteristics). The source terms that were considered are wind-input (linear and exponential), whitecapping, quadruplets (DIA), bottom friction and depth induced-breaking.

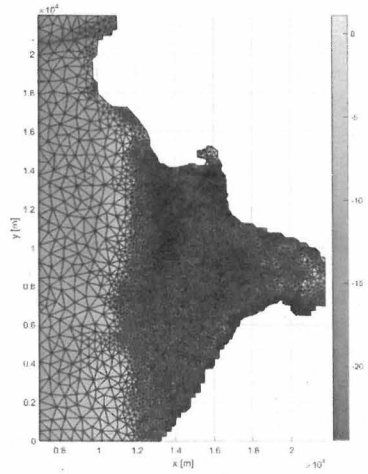

Figure 11 Bathymetry and mesh of the Haringvliet model

The different runs that were performed are:

- Run 1: Original TOMAWAC code
- Run 2:using improved version for linear wind-input.
- Run 3: Run 2 + new implicit depth induced breaking scheme
- Run 4: Run3: + five sub time step for local processes.

The results were compared between all four simulations, and it appeared that the results were very similar between the different runs, except for the change of the depth-induced breaking scheme (i.e. comparing run 2 and 3). This is not unreasonable, as a different numerical method is used. Calculation times of the different simulations are shown in Figure 4. It can be seen that the total speed up is about a factor four in this case, with the largest speed-up obtained from the change in numerical scheme for depth-induced breaking.

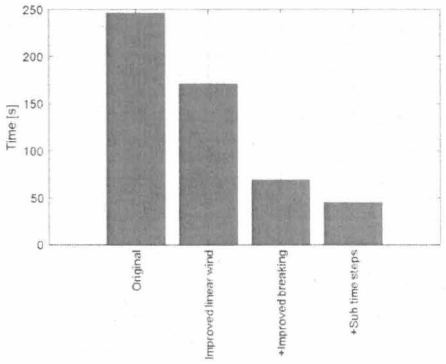

Figure 12 Calculations times

V. CONCLUSIONS

In this paper, a new computational architecture for TOMAWAC was presented, in which separate time steps are used for local, small scale processes (depth-induced breaking, advection, intra-spectral propagation and triad interactions) and for large scale slow processes (quadruplets, wind input, whitecapping and bottom friction). New numerical algorithms were introduced for triad interactions and depth-induced breaking. Additional advection schemes, as well as intra-spectral propagation schemes were introduced and the effect of shoaling was added to these schemes, which was previously not taken into account. The robustness of the new methods is shown in various academic test case. In a small real-life example case, it is shown that a speedup of a factor of four can be achieved using the newly developed functionalities.

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