On the high resolution coastal applications with WAVEWATCH III®

14th International Workshop on Wave Hindcasting and Forecasting, and 5th Coastal Hazard Symposium

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Marion Huchet[1,2], Fabien Leckler[1], Jean-François Filipot[3], Aron Roland[4], Fabrice Ardhuin[5], Mathieu Dutour Sikirić[6], Héloïse Michaud[1], Matthias T. Delpey[7], Guillaume Dodet[8],

(1) Service Hydrographique et Océanographique de la Marine, Brest, France

(2) École Centrale Nantes, Nantes, France

(3) France Énergies Marines, Brest, France

(4) BGS IT&E, Darmstadt, Germany

(5) Laboratoire de Physique des Océans, UMR 6523 CNRS-IFREMER-IRD-UBO, 29200 Plouzané, France

(6) Institute Ruder Bosković, Zagreb, Croatia

(7) SUEZ Eau France - Rivages Pro Tech, Bidart, France

(8) GEOMER - UMR 6554, CNRS-LETG, Institut Universitaire Européen de la Mer, Plouzané, France

November, 12th, 2015

Plan

Introduction

Context and aim of the present work

Context :

- Increasing need of near-shore high resolution :
  - wave induced near-shore circulation,
  - estimation of wave-setup, storm surges, ...
- Limited computational time for operationnal applications
- Difficulties to create an unstructured mesh efficient for explicit schemes
- Stiffness of the source terms (need of a excessively small time step in relation to the smoothness of the solution)
- Parallelization in WW3 : spectral decomposition for the geographical space, spatial domain decomposition for the spectral advection and source terms
  - Uses of a sophisticated exchange algorithm to minimize the amount of exchanged data
  - However, maximum number of CPU's limited with the number spectral components
    → Not in line with fast increasing of computationnal resources in super-computers

Introduction

Context and aim of the present work

Aim of the current work :
New implementations in WW3 model

- New implicit scheme for unstructured mesh WAE solving
- Estimation of wave-setup
- New parallelization using only the domain decomposition method

Introduction

Explicit vs implicit scheme

The current WAVEWATCH III® explicit integration scheme :

- CFL (Courant-Friedrich-Levy) criterion must be fulfilled in order to guarantee a stable integration in the space domain

$$\mathrm{CFL} = \frac{(C_{\mathrm{g}} + U_{\mathrm{cur}})\,\mathrm{d}t}{\mathrm{d}x} < 1 \tag{1}$$

- Similar stability criterion for the spectral advection that could also show large CFL numbers in the presence of strong depth and current gradients.
- Many limiters needed to make the explicit scheme stable
- Operator splitting methods : Splitting error non-negligible in coastal area where the source terms strongly depend on space (Lanser and Verwer, 1998)
- ... but allows high order schemes

Introduction

Explicit vs implicit scheme

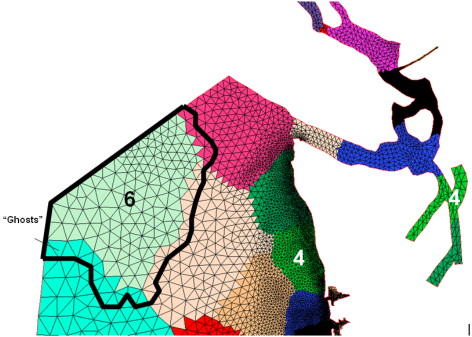
The WAVEWATCH III® new implicit scheme :

- removes the CFL time-step restriction
- is integrated in the Multigrid approach of WW3, which will allow seamless application of the new method nested in coarse WW3 runs
- removes splitting errors (WAE is solved in one "big" matrix)
- ... but is of 1^{st} order scheme in time, space and spectral domains
- revoves so called "Action Limiter" (needed to insure stability of the explicit scheme) on space and spectral advection
- revoves so called "Action Limiter" on bathymetric breaking and bottom friction source terms
- ... but had to be kept for the deep water source terms

$\Rightarrow$ scheme accurate, robust, efficient and stable

Numerical developments

New parallelization : domain decomposition method



Domain decomposition. Numbers indicate process (CPU rank) numbers, and each color represents a sub-domain.

- Inside each sub-domain, the nodes/sides/elements are called "residents"
- Sub-domain of each process may not be contiguous

- Augmented domain adds "ghosts" nodes and elements where the communication takes place between sub-domains
- Each element is owned by 1 (and 1 only) CPU, but each side or node can be owned by many CPUs when they are on the border of adjacent sub-domains
- Decomposition is done in such a way that the communication halo is minimized by trying to reach equally sized domains for each single thread (details in Schloegel et al., 2002)

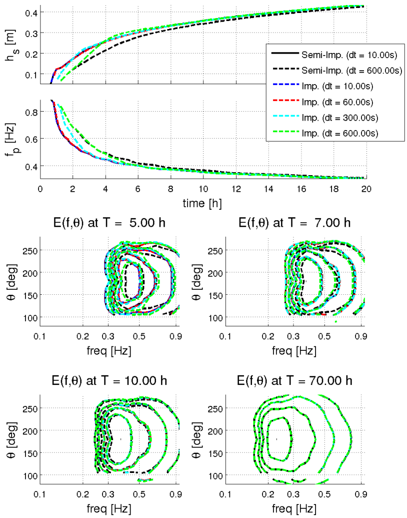
As a result, a more sustainable way for the parallelization of unstructured meshes

Academic test cases

3 Real case
- Iroise sea modeling

Academic test cases

Case 1 : Wave growing under constant wind



$$U_{10} = 5 \text{ m/s}$$

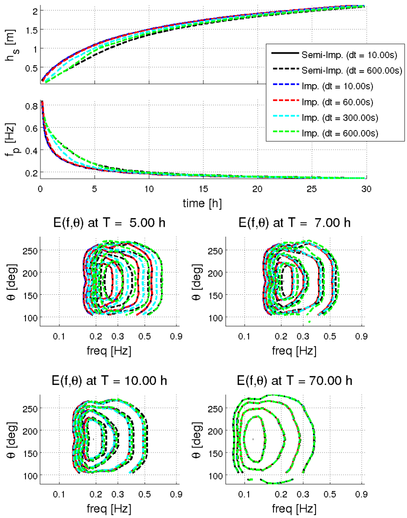
- Uniform deep ocean conditions
- Wave energy advection in space and spectral domains desactivated

$$\frac{\partial F}{\partial t} = S_{\mathrm{atm}} + S_{\mathrm{nl}} + S_{\mathrm{wcap}}$$

- Source terms integration performed on a small unstructured grid for 72 hours
- "ST4" physical package, TEST451 (Ardhuin et al., 2010)

Academic test cases

Case 1 : Wave growing under constant wind



$$U_{10} = 10 \text{ m/s}$$

- Uniform deep ocean conditions
- Wave energy advection in space and spectral domains desactivated

$$\frac{\partial F}{\partial t} = S_{\mathrm{atm}} + S_{\mathrm{nl}} + S_{\mathrm{wcap}}$$

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Academic test cases

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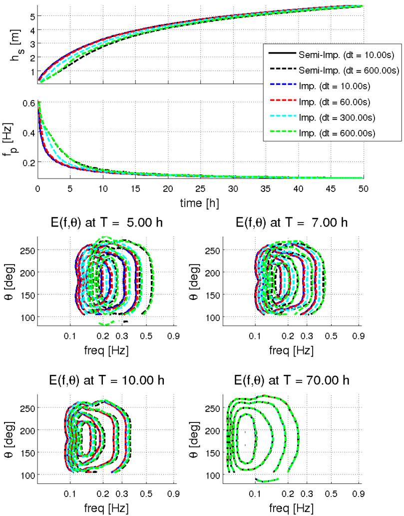

$$U_{10} = 15 \text{ m/s}$$

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Academic test cases

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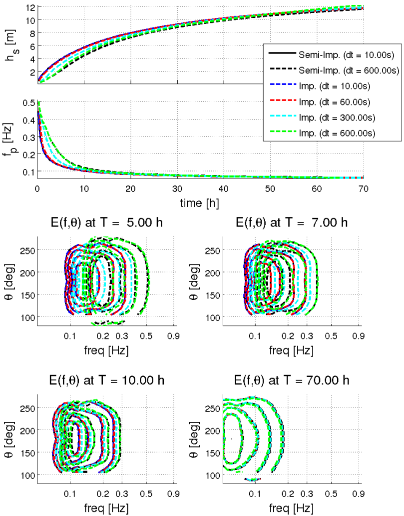

$$U_{10} = 20 \text{ m/s}$$

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Academic test cases

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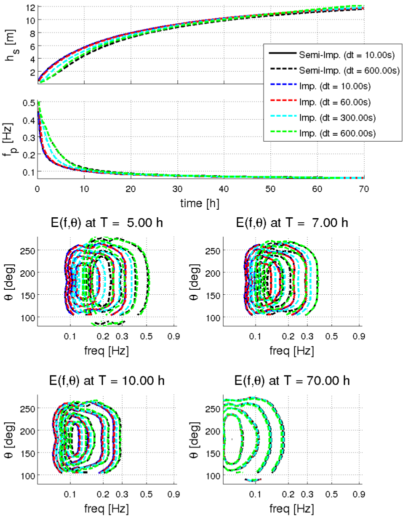
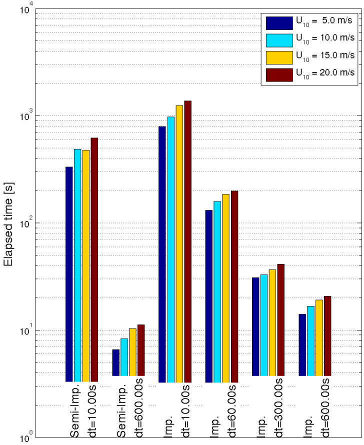


Results :

- Wave growing strongly impacted with used time-step
  ⇒ Limiters are still have a strong impact even with implicit scheme

Academic test cases

Case 1 : Wave growing under constant wind



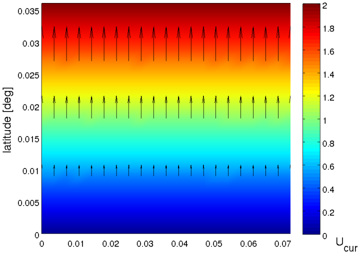
Computational Time :

- 72-hours integration
- sequential run (1 thread)
- computational times extracted from the model log file
  $\Rightarrow$ for the same time step the semi-implicit scheme is lower by a factor 2 than the semi-implicit scheme
  $\Rightarrow$ advantage of the implicit scheme coming with the increase in the time step
  $\Rightarrow$ ... but here, NOT provides similar results.

Academic test cases

Case 2 : Wave-current interactions

- current field with with linear increase of speed from $U_{\rm cur} = 0$ m/s (South boundary) to $U_{\rm cur} = 2$ m/s (North boundary)
- uniform ocean depth ($d = 5000$ m)



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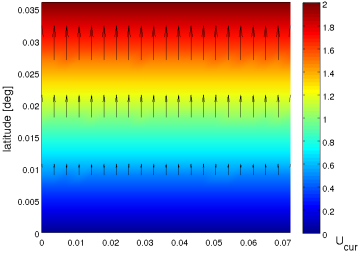
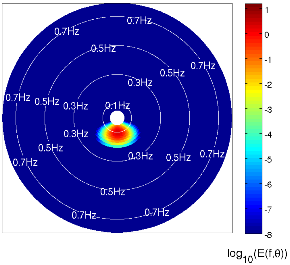


- input wave spectrum is gaussian in frequency (spread of 0.01 Hz) and cosinus power ($N = 20$) type in with $f_{\mathrm{p}} = 0.1$ Hz, $\theta_m = 180$ deg and $H_s = 1$ m
  $\Rightarrow$ very narrow input wave spectrum (swell)
- waves forced at the south boundary
- waves following the current



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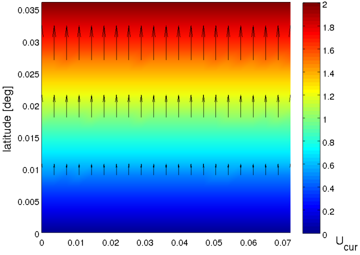
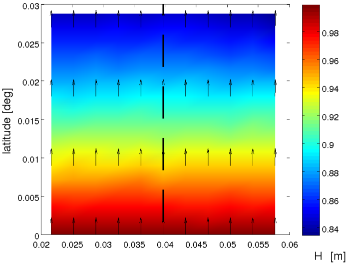


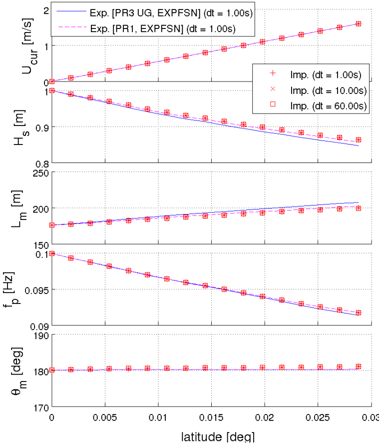
Wave field with explicit 2^{nd} order scheme



Academic test cases

Case 2 : Wave-current interactions

Obtained profiles



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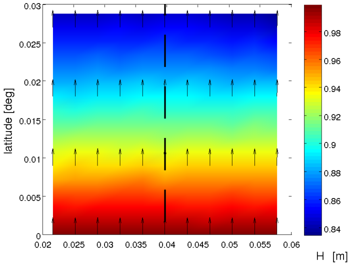
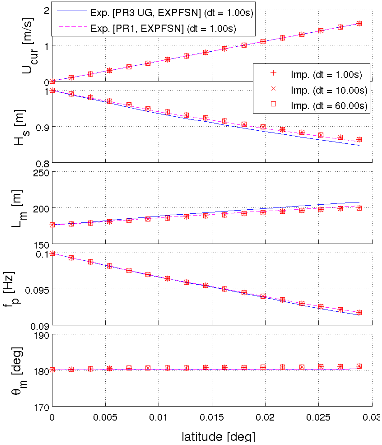


Academic test cases

Case 2 : Wave-current interactions

Obtained profiles



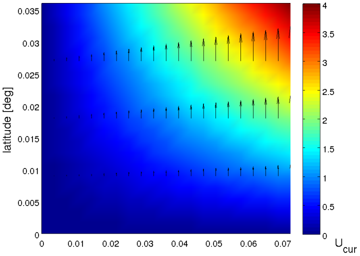
Results :

- the first order implicit scheme perfectly fits the first order explicit scheme
- higher order scheme provides slightly different results, expected to be more in line with the physics
- with implicit scheme, results NOT diverge increasing time step (up to factor 60)

Academic test cases

Case 2 : Wave-current interactions

- current field with with linear increase of speed from $U_{\mathrm{cur}} = 0$ m/s (East and South boundary) to $U_{\mathrm{cur}} = 4$ m/s (North-West corner)
- uniform ocean depth ($d = 5000$ m)



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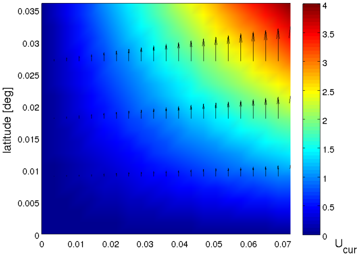
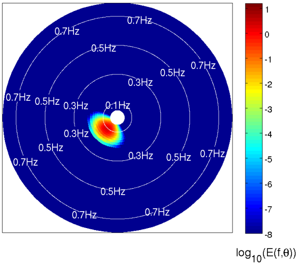


- input wave spectrum is gaussian in frequency (spread of 0.01 Hz) and cosinus power ($N = 20$) type in direction with $f_{\text{p}} = 0.1$ Hz, $\theta_m = 235$ deg and $H_s = 1$ m $\Rightarrow$ narrow input wave spectrum (swell)
- waves forced at the south boundary
- waves following the current



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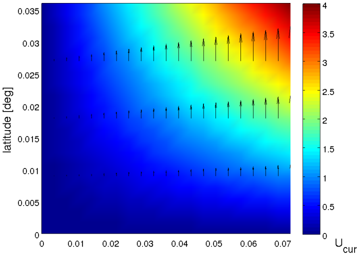
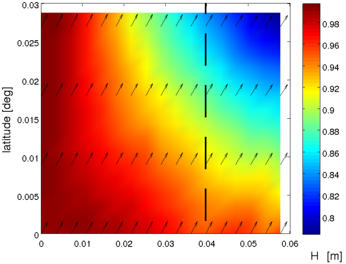


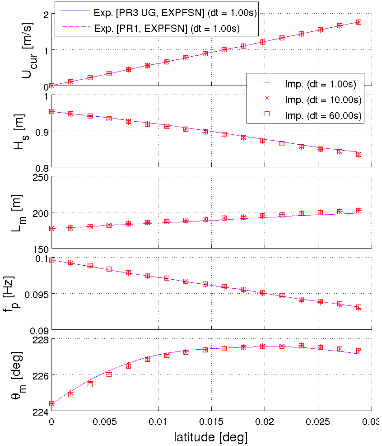
Wave field with explicit 2^{nd} order scheme



Academic test cases

Case 2 : Wave-current interactions

Obtained profiles



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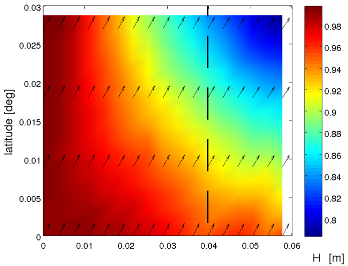

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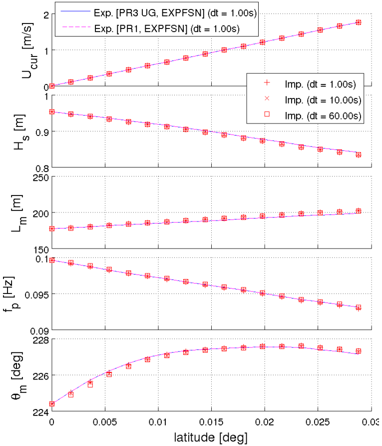
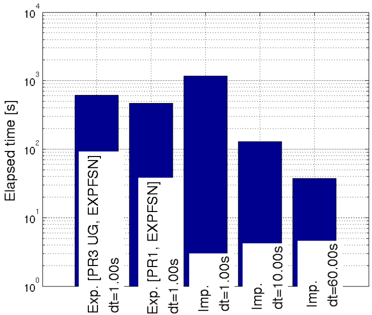


Results :

- the first order implicit scheme perfectly fits the first order explicit scheme
- higher order scheme provides slightly different results, expected to be more in line with the physics
- with implicit scheme, results NOT diverge increasing time step (up to factor 60) $\Rightarrow$ no more need of limiters for spectral advection.

Academic test cases

Case 2 : Wave-current interactions

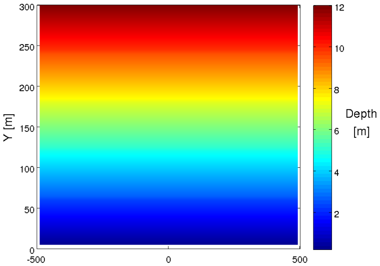


- Implicit scheme with $\mathrm{d}t = 60$ s reduces computationnal time by about 2 order of magnitude compared to explicit scheme with $\mathrm{d}t = 1$ s
- ... providing similar results as 1^{st} order explicit scheme

Academic test cases

Case 3 : Linear beach case

- constant slope of 1 :25 on Y-axis rom $z = -12$ m to $z = 0$ m
- rectilinear grid defined with $\mathrm{d}X = 10$ m (along-shore) and $\mathrm{d}Y = 5$ m (cross-shore)
- unstructured mesh created with diagonal half square



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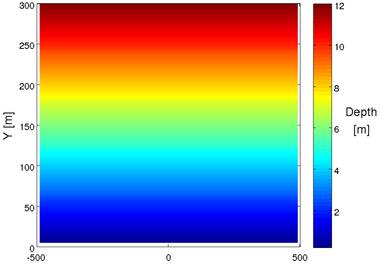
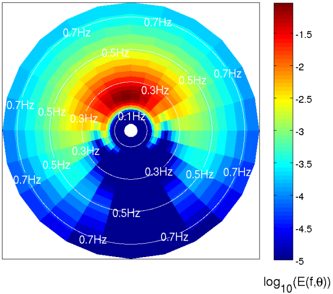


- input JONSWAP wave spectrum with $\theta_m = 0$ deg and $H_s = 0.5$ m with broad directionnal spreading (wind sea)
- BJ breaking parametrization
  $\Rightarrow$ time step for explicit runs dramatically small, $\mathrm{d}t = 0.05$ s, (CFL<<1, stiffness of source terms)
  $\Rightarrow$ limiters desactivated



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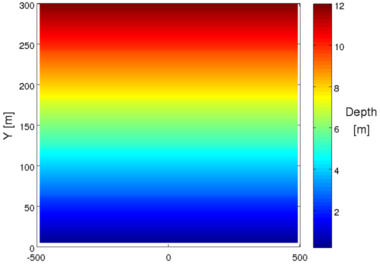
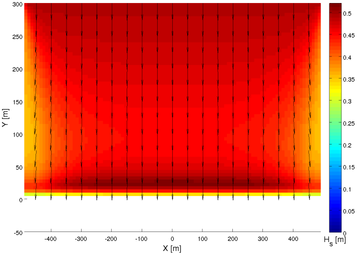


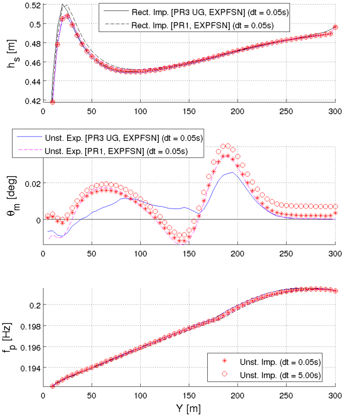
Wave field with explicit 3nd order scheme (rectilinear grid)



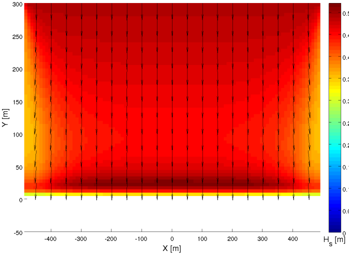
Academic test cases

Case 3 : Linear beach case

Obtained profiles



Wave field with explicit 3^{nd} order scheme (rectilinear grid)



Academic test cases

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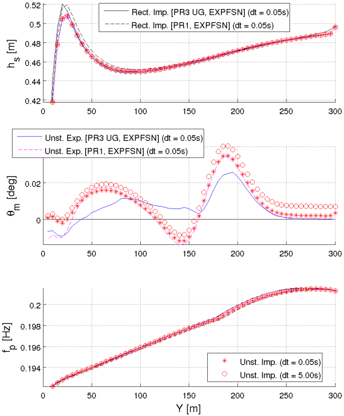

Results :

- shaoling and breaking with implicit scheme well fits all explicit scheme
- with implicit scheme, results NOT diverge increasing time step (up to factor 100)
- H_s DOES NOT tend to 0 when depth tends to 0 for all schemes
  $\Rightarrow$ must be investigated

Academic test cases

Case 3 : Linear beach case

- constant slope of 1 :25 on Y-axis rom $z = -12$ m to $z = 0$ m
- rectilinear grid defined with $\mathrm{d}X = 10$ m (along-shore) and $\mathrm{d}Y = 5$ m (cross-shore)
- unstructured mesh created with diagonal half square
- input JONSWAP wave spectrum with $\theta_m = 25$ deg and $H_s = 2.0$ m with broad directionnal spreading (wind sea)
- BJ breaking parametrization
  $\Rightarrow$ time step for explicit runs dramatically small, $\mathrm{d}t = 0.05$ s,
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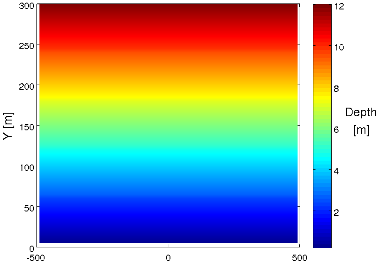

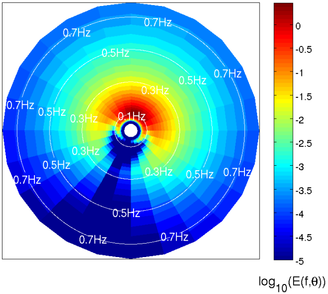

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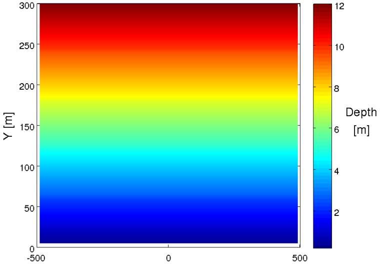
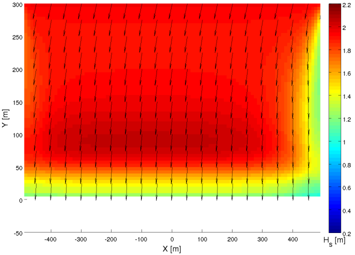


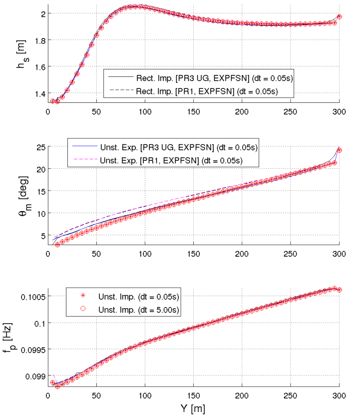
Wave field with explicit 3nd order scheme (rectilinear grid)



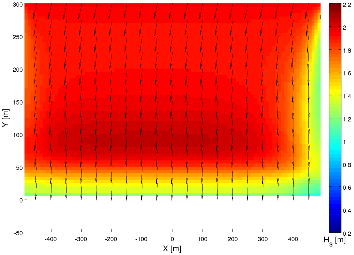
Academic test cases

Case 3 : Linear beach case

Obtained profiles



Wave field with explicit 3^{nd} order scheme (rectilinear grid)



Academic test cases

Case 3 : Linear beach case

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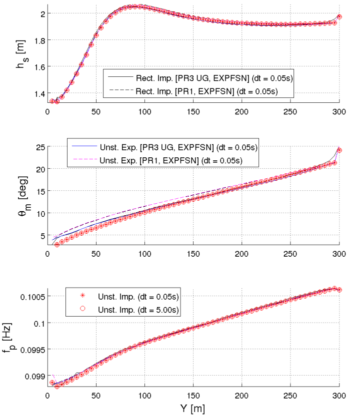


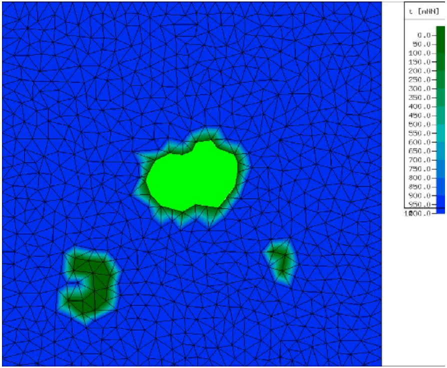
Results :

- again, shaoling and breaking with implicit scheme well fits all explicit schemes
- also, bathymetric refraction with implicit scheme well fits all explicit schemes
- again, with implicit scheme, results NOT diverge increasing time step (up to factor 100)
- again, H_s DOES NOT reach to 0 m when depth tends to 0 m for all schemes
  $\Rightarrow$ must be investigated

Academic test cases

Case 4 : Deep Sea Islands case

- inspired by the paper of Dietrich et al. (2013)
- case with strongly under-resolved bathymetry
  ⇒ one island defined as a hole in the mesh
  ⇒ two submerged island, going from 1000m depth to 10m and 15m depth

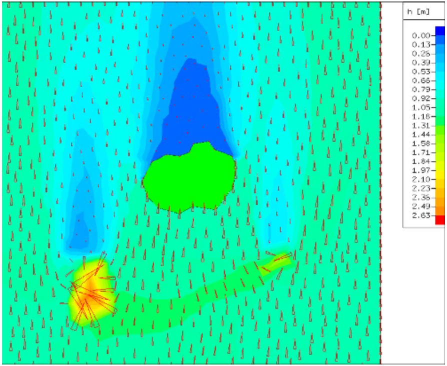


Academic test cases

Case 4 : Deep Sea Islands case

Results :

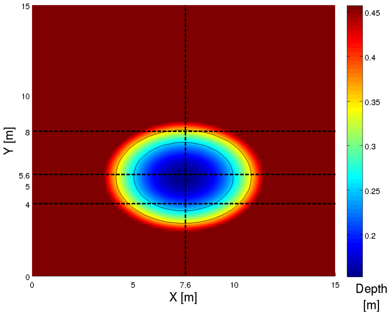
- Results fully convergent up to a solver threshold of 10E-20, stable and monotone
  ⇒ expected from a 1st order monotone implicit scheme
  ⇒ however, robustness of the numerical scheme must be more investigated



Academic test cases

Case 5 : Waves over an elliptic mount

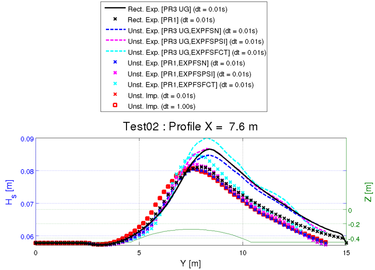
- inspired by the tank experiment of Vincent and Briggs (1989)
  $\Rightarrow$ motivation to compare the refraction/shoaling characteristics of the various schemes
- one rectilinear grid with $\mathrm{d}X = \mathrm{d}Y = 0.2$ m
- one unstructured grid with approximately same resolution
- four cases experimented, corresponding to the tests 02, 03, 16 and 17 of Vincent and Briggs (1989)
  $\Rightarrow$ two non-breaking cases
  $\Rightarrow$ two breaking cases

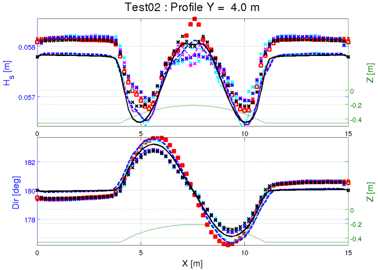


Academic test cases

Case 5 : Waves over an elliptic mount

Profiles obtained after 40 seconds of integration for TEST02 (non-breaking case, narrow spectrum)

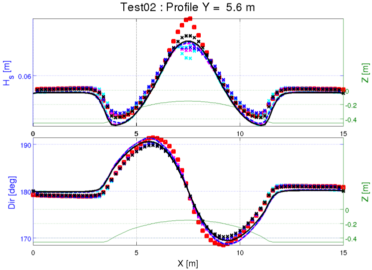


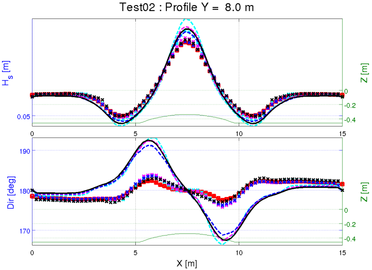


Academic test cases

Case 5 : Waves over an elliptic mount

Profiles obtained after 40 seconds of integration for TEST02 (non-breaking case, narrow spectrum)

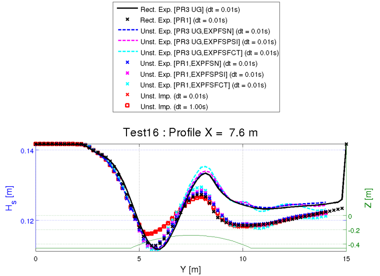


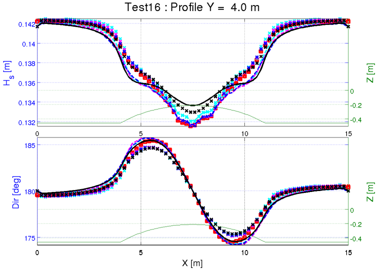


Academic test cases

Case 5 : Waves over an elliptic mount

Profiles obtained after 40 seconds of integration for TEST16 (breaking case, broad spectrum)

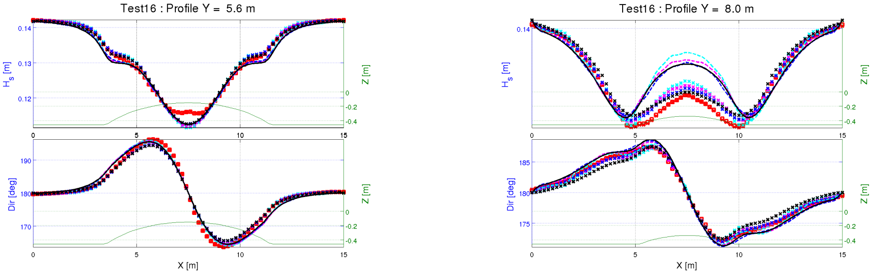




Academic test cases

Case 5 : Waves over an elliptic mount

Profiles obtained after 40 seconds of integration for TEST16 (breaking case, broad spectrum)



Academic test cases

Case 5 : Waves over an elliptic mount

Results

- explicit scheme run with 1^{st} and 3^{rd} order schemes on a rectangular grid
  $\Rightarrow$ time step : $\mathrm{d}t = 0.01$ s (CFL<<1, stiffness of source terms)
  $\Rightarrow$ can be seen as a reference solution
- explicit schemes run up to 2nd order in time and space
  $\Rightarrow$ result in under- and overshooting of the 3^{rd} order results
  $\Rightarrow$ but the 1^{st} order results either implicit or explicit are more or less in line with the explicit results
  $\Rightarrow$ it seems that the implicit scheme is a bit more diffusive than the explicit fluctional splitting schemes
  $\Rightarrow$ the implicit scheme run with time steps increased up to a factor 100 give very similar results
  $\Rightarrow$ the computational time step is reduced by a factor more than 30 for the larger time step compared to all other cases
  $\Rightarrow$ the overshootings obtained for the higher order schemes of WW3 (compared to Ultimate Quickest) are somewhat suspicious and needs further investigation

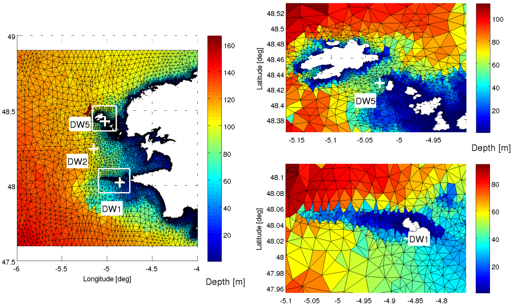
Real case

Iroise sea modeling

Real case is implemented on the Iroise Sea, at the west of Brittany, France

This sea is a perfect playground for complex wave modeling :

- It provides both very strong tide currents and high tide water level variations.
- It is also scattered with many islands and rocky shoals.



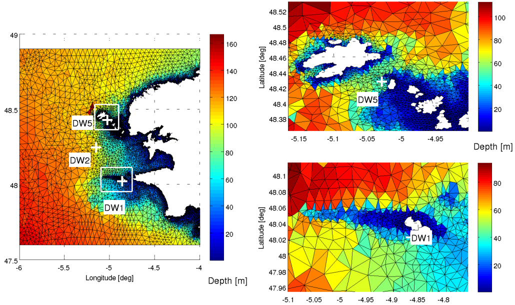
Real case

Iroise sea modeling

Real case is implemented on the Iroise Sea, at the west of Brittany, France

An unstructured 12 518-node mesh (Ardhuin et al., 2012) was implemented :

- mesh done using the POLYMESH tool
- 121 forcing boundary nodes linearly spaced every 5 km at the open boundaries
- resolution of about 200 m at the coastline



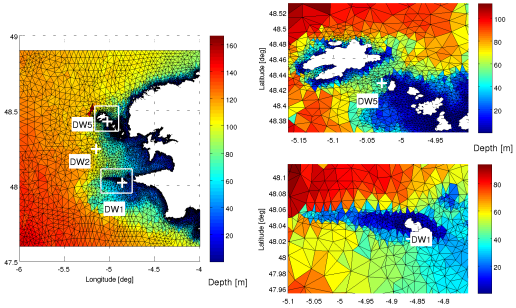
Real case

Iroise sea modeling

Real case is implemented on the Iroise Sea, at the west of Brittany, France

The forcing fields are :

- MARD2D 250m (PREVIMER, IFREMER) for currents and water levels
- ECMWF for winds



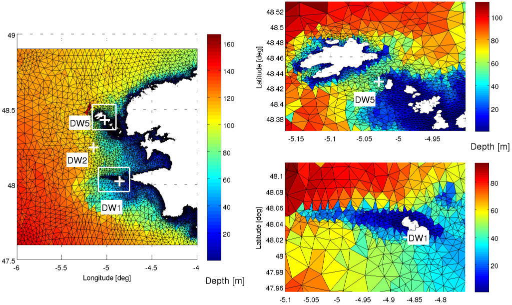
Real case

Iroise sea modeling

Real case is implemented on the Iroise Sea, at the west of Brittany, France

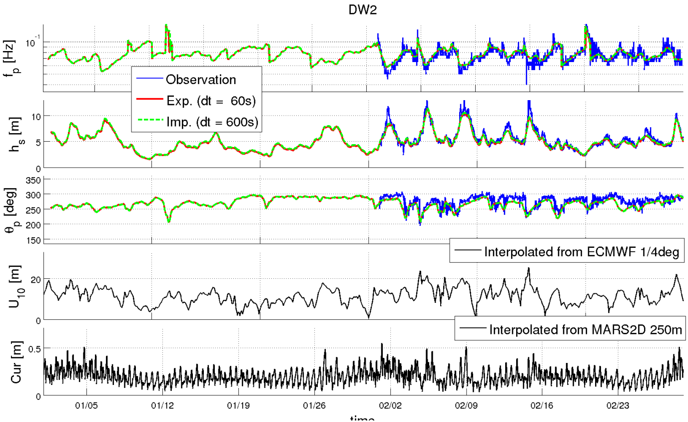
3 datawell for validations :

- One in "clear" ocean (DW2)
- One behind a rocky shoal (DW1)
- One close to a strong current chanel (DW5)



Real case

Iroise sea modeling



Real case

Iroise sea modeling

Explicit run $\mathrm{d}t = 60$ s (DW2 location)

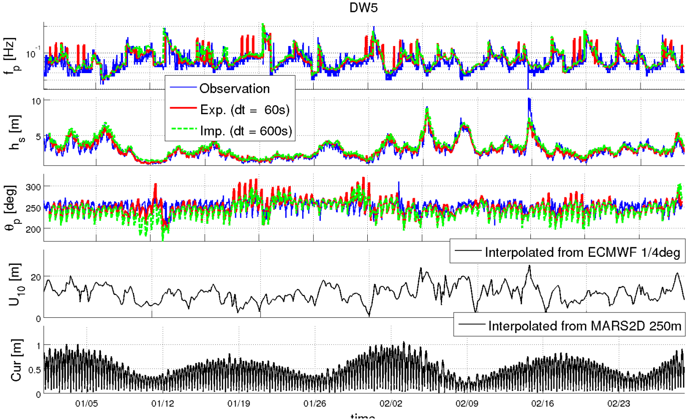
	RMSE	N-RMSE	BIAS
f_p	0.008 Hz	11.10 %	-0.002 Hz
h_s	0.76 m	12.38 %	0.31 m
θ_p	18.6 deg	6.74 %	11.6 deg

Implicit run $\mathrm{d}t = 600$ s (DW2 location)

	RMSE	N-RMSE	BIAS
f_p	0.009 Hz	11.41 %	-0.002 Hz
h_s	0.70 m	11.50 %	0.18 m
θ_p	18.6 deg	6.71 %	11.7 deg

Real case

Iroise sea modeling



Real case

Iroise sea modeling

Explicit run $\mathrm{d}t = 60$ s (DW5 location)

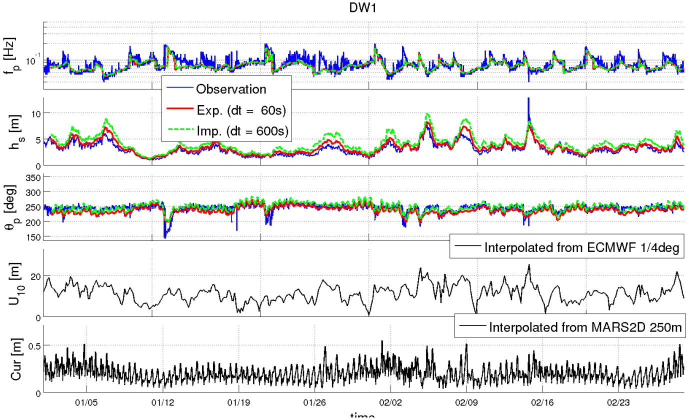
	RMSE	N-RMSE	BIAS
f_p	0.018 Hz	20.95 %	-0.004 Hz
h_s	0.50 m	16.23 %	-0.15 m
θ_p	13.6 deg	5.43 %	2.9 deg

Implicit run $\mathrm{d}t = 600$ s (DW5 location)

	RMSE	N-RMSE	BIAS
f_p	0.017 Hz	20.80 %	-0.007 Hz
h_s	0.596 m	19.37 %	-0.41 m
θ_p	17.8 deg	7.09 %	7.2 deg

Real case

Iroise sea modeling



Real case

Iroise sea modeling

Explicit run $\mathrm{d}t = 60$ s (DW1 location)

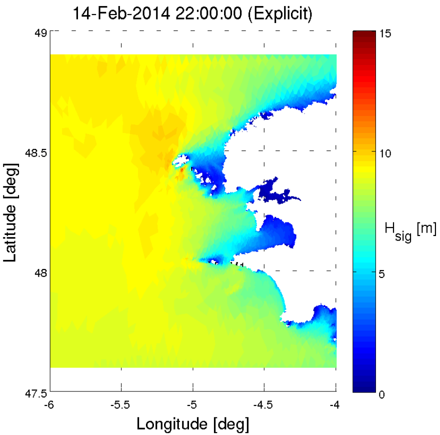
	RMSE	N-RMSE	BIAS
f_p	0.020 Hz	22.27 %	0.007 Hz
h_s	0.60 m	18.57 %	-0.36 m
θ_p	13.0 deg	5.34 %	6.41 deg

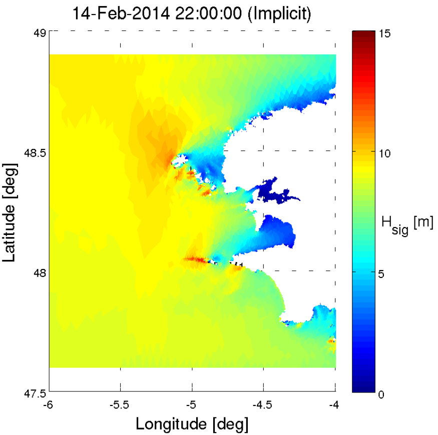
Implicit run $\mathrm{d}t = 600$ s (DW1 location)

	RMSE	N-RMSE	BIAS
f_p	0.0190 Hz	21.24 %	0.006 Hz
h_s	1.29 m	39.49 %	-1.08 m
θ_p	12.4 deg	5.10 %	-4.5 deg

Real case

Iroise sea modeling





Conclusion and futur work

Conclusions

Conclusions

- we implemented a newly developed spectral wave model that was included in the WW3 framework
- we implemented test for verification of the numerical part
- we implemented a 1st real case
- the model results are promising in terms of accuracy and efficiency, but must but deeper checked and validated

Conclusion and futur work

Futur work

Futur work

- increase the validation test suite for unstructured grid models to have a full evaluation of numerics in different environments
- validation of the full model for very high resolution bathymetries
- looking forward to extending this numerical basis for higher order non-linear methods
- developing a fully non-linear solver that will reduce further the time step dependency of the results (Wave Growing)

Thank you for listening