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Modeling the world oceans with TELEMAC

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***Abstract*—This paper presents the development and application of a highly detailed metocean model of the world oceans. Thanks to its adaptive resolution, the model is able to resolve the main ocean processes (tides, surges, tsunamis), using the TELEMAC suite [1][2], with an unrivalled level of spatial and temporal resolution at global, regional and local scale.**

I. THE SMARTWAVE PROJECT

The model of the oceans has been developed in the context of the SmartWave project, funded by Regione Sicilia. The SmartWave platform aims to support a broad range of activities linked to the Blue Economy. The platform refers to the most up-to-date metocean databases and assimilates them with state-of-the-art evolution models. Advanced analysis techniques are used to provide a new class of services to the actors of the sea. The metocean data on the SmartWave platform will be made available using different thematic layers. The quality of data is ensured by the quality of both the databases and the modelling tools. Input data are combined and completed by SmartWave models, allowing a timely and constant update of forecasts over the blue planet.

II. GLOBAL MODELLING

A. Short literary review

Constant advance in computational power and efficiency has enabled modelling of metocean processes at global scale with increasing accuracy and spatial/temporal resolution. While a full review of the state of the art global models is outside of the scope of this paper, a brief overview of some among the most established models is useful to set the context within which the development is happening and is therefore given in what follows.

- ERA5 [4] dataset by the European Centre for Medium-Range Weather Forecasts (ECMWF) is the fifth generation ECMWF reanalysis for the global climate and weather; it combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics; it provides metocean data over the entire globe at a spatial and temporal resolution of ~ 0.25° (~ 25km) and 1hrs, respectively for the atmosphere and ~ 0.5° (~ 50km) and 1hrs, respectively for the ocean waves;
- WaveWatch III [7] reanalysis is a thirty-year global wave hindcast generated from the NCEP Climate Forecast System Reanalysis and Reforecast (CFSRR) homogeneous dataset of hourly high-resolution winds. The time period covers from 1979 through 2009. The spatial resolution is 0.5° (~ 50km).
- CMEMS [8] reanalysis datasets. The Copernicus Marine Service provides various datasets; forecasts and hindcasts and information on waves or circulation parameters at a global and regional scale (Mediterranean and other seas around Europe). The global models deliver metocean data on a 0.083° (~ 9km) resolution grid with an hourly time step.

A case study of the world oceans has already been done [3] on a regular unstructured mesh using different components of the multipurpose finite element hydrodynamic suite TELEMAC [2]. This paper presents the preliminary results of a further improved global model of the Earth, using a further advanced mesh capable of resolving various physical processes.

III. A MODEL OF THE BLUE PLANET

A. The world oceans as we know it

Constant improvement of the bathymetric and atmospheric databases and increasing availability of field observations are improving the reliability of metocean evolution models at both regional and global scale.

Global bathymetric data sets include:

- GEBCO [10], General Bathymetric Chart of the Oceans, operates under the joint auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) (of UNESCO); it provides gridded bathymetry data which covers lands and oceans around the whole globe with a resolution of ~ 0.004° (~ 460m);
- EMODnet [11], European Marine Observation and Data Network; it provides bathymetry data which covers lands and oceans mainly around Europe and Northern Africa with a resolution of ~ 0.001° (~ 110m).
- SRTM [12], the Shuttle Radar Topography Mission is an international research effort. It provides terrestrial digital elevations models at a resolution of 1 arc-second (~30m) resolution.

As part of the SmartWave project, an assessment has been conducted of datasets around the world (including but not limited to the above) to create a bathymetric datasets that is "fit for purpose".

Similarly, datasets exist of forcing system, to include surface winds that are provided, among others, by:

- ERA5 [4] dataset, detailed in I.A above.

- CFSR [5] dataset, by National Centre for Atmospheric Research (NCAR) is a third generation reanalysis product; it is a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system designed to provide the best estimate of the state of these coupled domains over this period.; it provides wind over the entire globe at a spatial and temporal resolution of ~ 0.25° (~ 25km) and 1hrs, respectively;
- GFS [6], the Global Forecast System is a National Centre for Environmental Prediction (NCEP) weather forecast model that generates data for dozens of atmospheric and land-soil variables; among which, the dataset provides wind, pressure and temperature over the entire globe at a spatial resolution of ~ 0.25° (~ 25km) and an hourly timestep from now to 16 days in the future, respectively;

These were assessed to identify the best database subset to be used to force the system for specific areas and period of time.

B. Global unstructured meshes

The need to resolve multiscale, multiphysics metocean processes points to the use of unstructured over structured meshes, which adapt to enable efficient modelling of the relevant processes: offshore deep ocean dynamics as well as coastal processes.

C. Framework for modelling

The triangle mesh has an adaptive resolution, an optimised procedure has been developed to size the mesh elements to effectively resolve the features of the bathymetry and the coastlines, this has allowed us to optimise the computation and reproduce the processes we are interested in, in the most efficient way.

As a certain range of different physical processes - tides, storm surges, waves, tsunamis or a combination of these – are modelled for the purpose of the SmartWave project, an unstructured mesh that would be able to resolve all of these processes is meant to be generated. Whilst higher resolution meshes have been created and are used in the SmartWave project, this paper presents the results of a 10 km mesh and give insights on the quality and the limits of this model resolution. This has been found to provide reliable boundary condition for use in higher definition regional meshes (discussed in the twin paper Cozzuto et al. 2021). The boundary conditions are critical for a good generation of a regional model, especially for those processes that evolve on a global scale, i.e. the tides.

The main focus in this paper will then be on the tides, since boundary condition for waves can be inferred from the world most renowned open databases [7].

Meshes with various resolutions have been generated for the purpose of the SmartWave project. The coarsest one (50km) was used for testing purposes, as its resolution was not sufficient to resolve coastal hydrodynamics.

TABLE 1 MESH SPECIFITIES DEPENDING ON THE TARGET RESOLUTION

Mesh target resolution	**Number of triangles**	**Number of nodes**
50 km	145,639	76,029
10 km	2,011,308	1,021,527
5 km	5,166,806	2,586,806
2 km	19,539,778	9,773,292

The more detailed meshes are better suited for the scope of project i.e. resolving deep ocean dynamics as well as coastal processes up to a resolution of a few kilometres close to the coastline. For the equivalent resolution, the unstructured meshes generated allow us to have 30 to 40 times less nodes compared to the regular triangles meshes presented in "The Earth by TELEMAC".

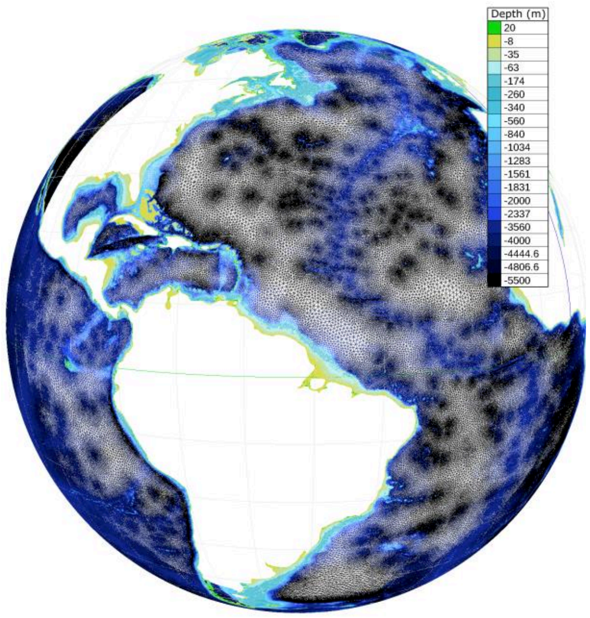

Figure 1. Mesh of the whole world. This version has a 10 km resolution at the coasts. Visualisation on BlueKenue

III. GLOBAL SCALE PROCESSES

A. Tsunamis

For the purpose of this paper, historical tsunamis have been modelled using the TELEMAC 2D model. This has been found to be adequate given the spatial and temporal scale of the events considered in this analysis (large seismic events generating transoceanic tsunamis), that are expected to be well represented by a model solving the non-linear shallow water equations. Given the seismic nature of the tsunami-genic events considered in this paper, the tsunami events have been initiated using the Okada model (Okada, 1985) which allows determining the initial free surface deformation resulting from a given seismic event.

B. Tides

Tides have been modelled cold-starting the model from a "still water condition" and applying gravitational forces only. Working with a global mesh defined in spherical coordinates has facilitated accounting for the Coriolis force.

Figure 2. Representation of the global tides around the globe

IV. GLOBAL TSUNAMIS

Once the model had been created, a set of simulation were run of global tsunamis to validate the ability of the model to reproduce the propagation and transformation of very long waves over the world oceans.

- *Historical Tsunamis*

Some of the most known and research tsunamis of the history have been remodelled in order to assess the ability of the TELEMAC model to simulate the propagation of tsunamis (i.e. waves with important wavelengths).

TABLE 2 HISTORICAL TSUNAMIS USED TO VALIDATE THE MODEL

Tsunami location	a	Seismic magnitude
Lisbon, Portugal	1755	8.5-8.7
Kamtchatka, Russia	1952	9.0
Valvidia, Chile	1960	9.5
Prince William sound, Alaska, USA	1964	9.2

D. Forcing the model

Given the seismic nature of the tsunami-genic events considered here, these have been forced by imposing an initial free surface elevation derived using the model proposed by Okada [13]. This latter computes the deformation of the ground using the theory of elasticity in an idealized homogenous medium. The deformation of the free surface is obtained with an instantaneous translation of the ground distortion.

C. Model validation

To test the performances of the model, a qualitative comparison with the TTT (per Tsunami Travel Time) contour plots published by NOAA has been conducted for the tsunami events in Table 2.

Lisbon, Portugal, 1755

Model predictions of the evolution of the 1755 Lisbon tsunami at different times from its activation are compared in Figure 3 with the tsunami travel time maps published by [14] NOAA.

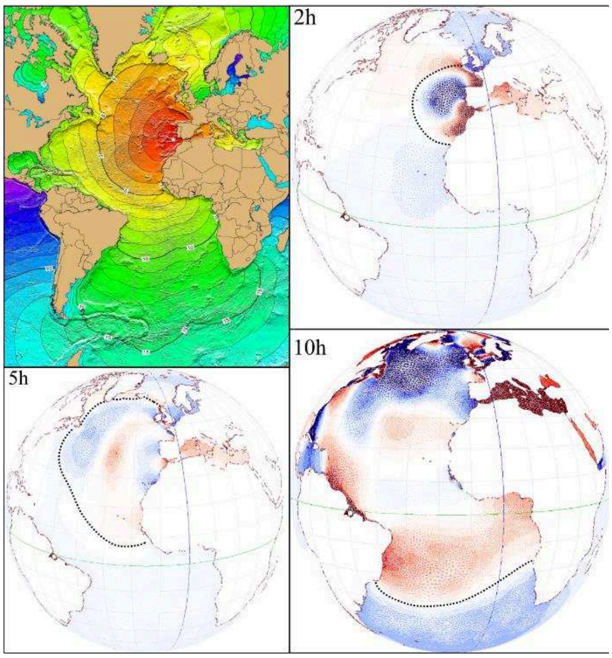

Figure 3. TTT maps from NOAA (top-left) and TELEMAC-2D results 2 hours (top-right), 5 hours (bottom-left) and 10 hours (bottom-right) after the seism for the tsunami of Lisbon, Portugal in 1755.

Kamtchatka, Russia, 1952

Model predictions of the evolution of the 1952 Kamtchatka tsunami at different times from its activation are compared in Figure 4 the tsunami travel time maps [14] generated by NOAA.

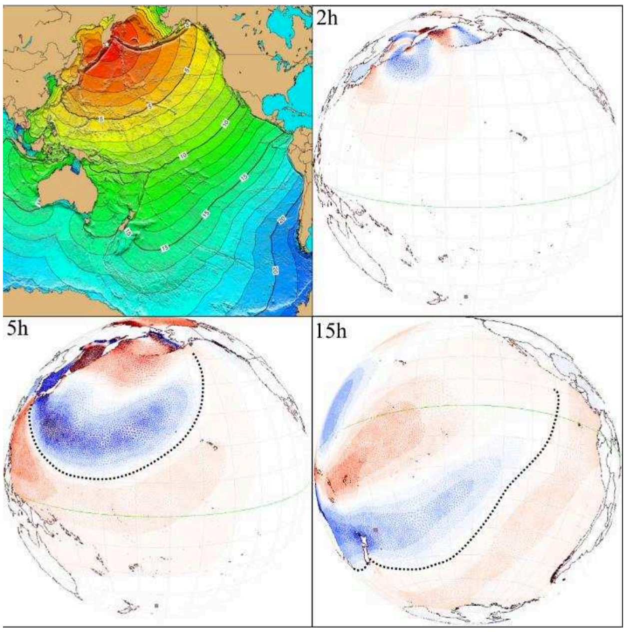

Figure 4. TTT maps from NOAA (top-left) and TELEMAC-2D results 2 hours (top-right), 5 hours (bottom-left) and 15 hours (bottom-right) after the seism for the tsunami of Kamtchatka, Russia in 1952.

Valvidia, Chile, 1960

Model predictions of the evolution of the 1960 Chilean tsunami at different times from its activation are compared in Figure 5 with the tsunami travel time maps published by the [14] generated by NOAA.

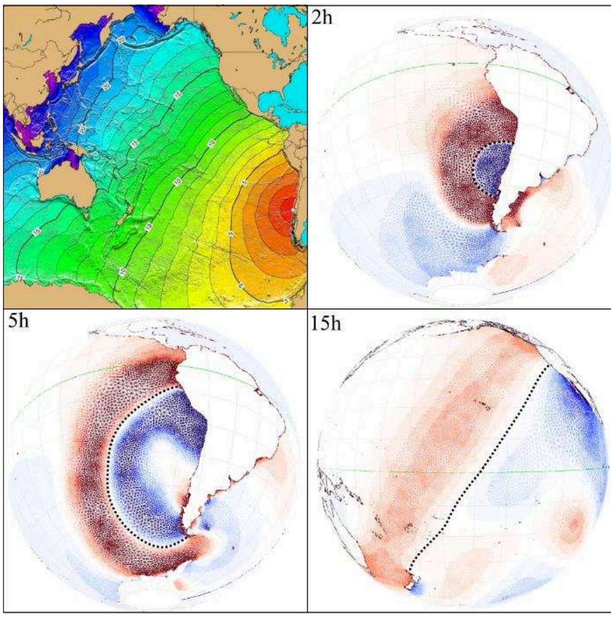

Figure 5. TTT maps from NOAA (top-left) and TELEMAC-2D results 2 hours (top-right), 5 hours (bottom-left) and 15 hours (bottom-right) after the seism for the tsunami of Valvidia, Chile in 1960.

Prince William sound, Alaska, USA, 1964

Model predictions of the evolution of the 1964 Alaska tsunami at different times from its activation are compared in Figure 6 with the tsunami travel time maps published by the [14] generated by NOAA.

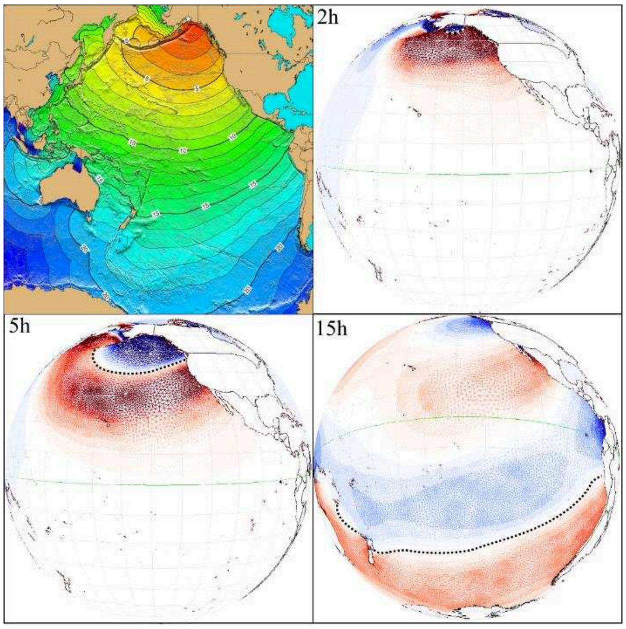

Figure 6. TTT maps from NOAA (top-left) and TELEMAC-2D results 2 hours (top-right), 5 hours (bottom-left) and 15 hours (bottom-right) after the seism for the tsunami of Prince William sound, Alaska, USA in 1964.

V. GLOBAL TIDES

A. *Tide forcing*

Since we are working with a global mesh, which is defined in spherical coordinates, the Coriolis force is automatically switched on. Global tides, were forced directly by imposing a gravitational field varying in time and space in a similar fashion to what done for "The Earth by TELEMAC". Indeed, the TELEMAC code offers the particular feature to activate the known gravitational forces (from the relative rotations of the Sun, the Moon, the Earth and various corrections).

E. *Model validation using satellite data*

The results of the model were then compared to the TPXO model [9]. To validate the results from the global tidal model, more than 60 random points were taken into the ocean and the result of the TELEMAC-2D model (solid line) were compared to satellite observations (TPXO model, dashed line) respectively. Two comparisons are shown in the Figure 7 and Figure 8 and are represented by a yellow star in the Figure 9.

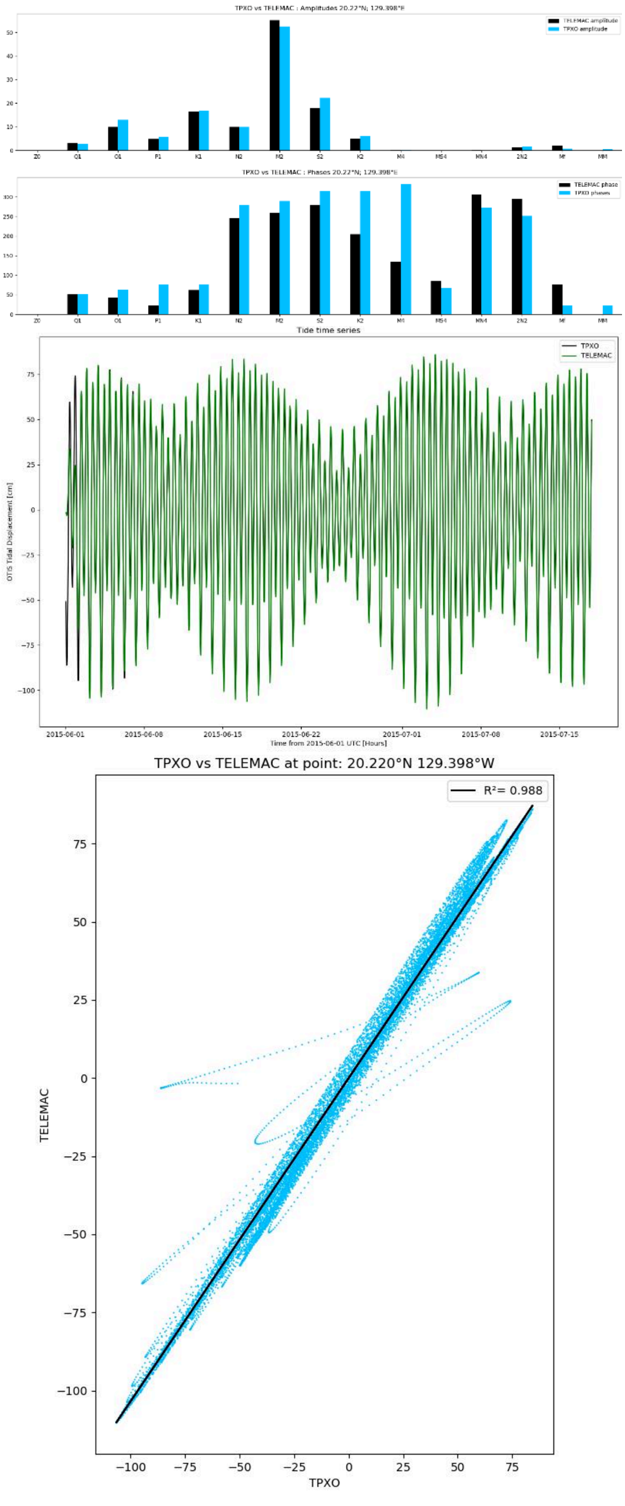

Figure 7. Harmonic (top) and temporal (middle) comparison between the TELEMAC results and the TPXO model at the latitudes and longitudes 20.22N, 129.398E respectively. The correlation between both signals is shown on the bottom graph.

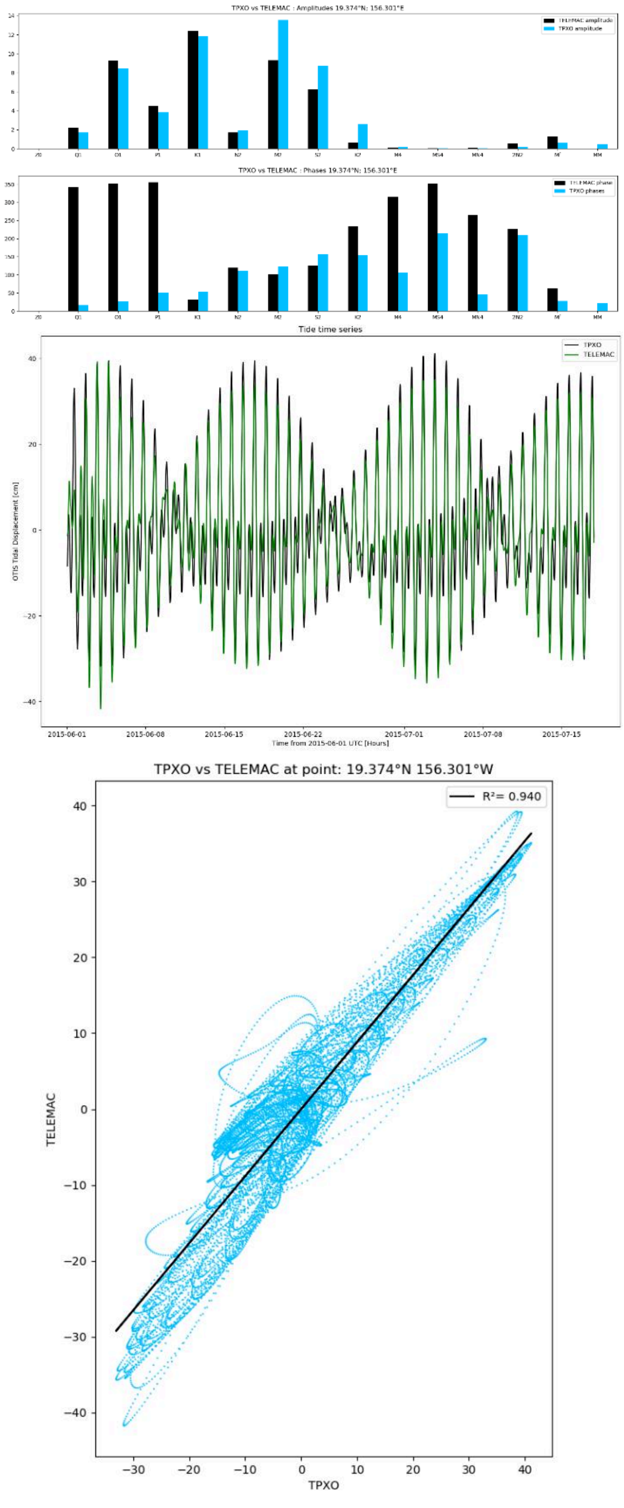

Figure 8. Harmonic (top) and temporal (middle) comparison between the TELEMAC results and the TPXO model at the latitudes and longitudes 19.374N, 156.301E respectively. The correlation between both signals is shown on the bottom graph.

The correlation between the TELEMAC results and the TPXO model has been calculated at all random locations mentioned above and represented in the map of Figure 9. Correlations at all locations has been identified with a colour from worst (red) to best (green) fitting.

The distribution of the correlation coefficients is represented in the histogram of Figure 9.

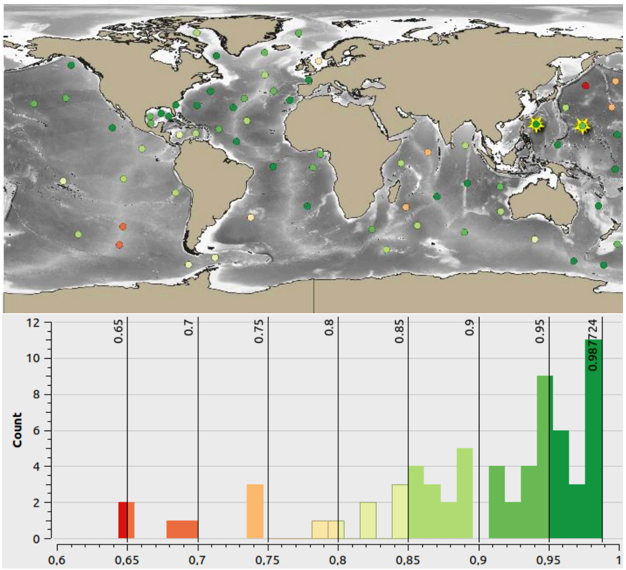

Figure 9. Localisation of the random points (top) taken for the comparison between the TELEMAC-2D model and the TPXO model and the distribution of all correlation values r^2 (bottom).

VI. Initial conclusion and on-going work

Within the framework of the SmartWave project funded by Regione Sicilia, a global hydrodynamic model has been developed using TELEMAC which is capable of modelling the evolution of tsunamis and tides over the world oceans.

The model has been validated using both field observations and satellite data.

Whilst the system is capable of higher resolutions, all results presented in this paper have been obtained for demonstration purposes using a desktop machine and computational times shorter than 30 minutes.

At time of writing we are tackling the following challenges:

1) Higher resolution

Higher resolution inevitably implies more complex mesh that comport a higher number of elements and nodes. As the resolution increases, the time step decreases to respect of the CFL conditions. The processing power required for the computation thus increases.

Deep ocean dynamics

Internal tides is a specific type of internal waves that is critical to a number of offshore applications [3]. These waves are the result of a combination of a strong stratification and tides, and are not currently represented in any of the global models or datasets.

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References

[1] Galland J.C., Goutal N., Hervouet J.M. (1991) – “TELEMAC: A new numerical model for solving shallow water equations”, Advances in Water Resources, Volume 14, I. 3.

[2] JM Hervouet, R. Ata (2017). User manual of open software TELEMAC-2D, Report, EDF-R&D, http://www.opentelemac.org/, ISBN:9780470035580.

[3] Bourban, SE; Turnbull, MS; Cooper, AJ (2017): The Earth by TELEMAC. Proceedings of the XXIVth TELEMAC-MASCARET User Conference (Dorfmann, Clemens; Zenz, Gerald (Hg.)), 17 to 20 October 2017, Graz University of Technology, Austria. Graz University of Technology. S. 1-8.

[4] Hersbach, H. et al. (2020) The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049.

[5] E. Kalnay et al. (1996) The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society.

[6] National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2015, updated daily. *NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive*. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D65D8PWK. Accessed 20 mar 2021.

[7] Chawla, A., and H. L. Tolman, 2007: Automated grid generation for WAVEWATCH III. NOAA / NWS / NCEP / OMB Technical Note 254, 71 pp.

[8] F. Ardhuin et al. (2010) Semi empirical dissipation source functions for wind-wave models : Part I, definition and calibration and validation at global scales. Journal of Physical Oceanography.

[9] Egbert, Gary D., and Svetlana Y. Erofeeva. "Efficient inverse modeling of barotropic ocean tides." Journal of Atmospheric and Oceanic Technology 19.2 (2002): 183-204.

[10] GEBCO, “The General Bathymetric Chart of the Oceans, the most authoritative, publicly-available bathymetry data sets for the world’s oceans”, 2017, http://www.gebco.net/

[11] Martin Miguez, Belen & Novellino, A. & Vinci, Matteo & Claus, Simon & Calewaert et al. (2019). The European Marine Observation and Data Network (EMODnet): Visions and Roles of the Gateway to Marine Data in Europe. Frontiers in Marine Science. 6. 10.3389/fmars.2019.00313

[12] Farr, T. G. et al. (2007), The Shuttle Radar Topography Mission, Rev. Geophys., 45, RG2004, doi:10.1029/2005RG000183.

[13] Okada Y (1985) Surface deformation due to shear and tensile faults in a half-space. Bull Seismol Soc Am 75:1135–1154

[14] Shokin, et al. (1987). Calculations of tsunami travel time charts in the Pacific Ocean, Science of Tsunami Hazards, vol. 5, p. 85-113

[15] R. Ata, M. Le Gal and D. Violeau (2017). An overview on the capabilities of the TELEMAC-MASCARET system to deal with tsunamis: feedbacks from TANDEM project. Proceedings of the XXIVth TELEMAC-MASCARET User Conference (Dorfmann, Clemens; Zenz, Gerald (Hg.)), 17 to 20 October 2017, Graz University of Technology, Austria. Graz University of Technology. S. 1-8.