The Earth by TELEMAC

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***Abstract*—This article describes the development of a highly detailed model of the Earth, based on the TELEMAC system, applied to modelling various physical processes including tides, storms, tsunamis and waves. Comparisons against known global datasets demonstrate the capability of the TELEMAC system to bridge the gap between environmental hydraulics and oceanography. Preliminary results in forecasting internal tides and 3D ocean currents are also presented.**

I. Introduction

A. Mind the gap

Numerical modelling for environmental hydraulics studies, whether for research or consultancy, has been historically focused on inland and coastal areas. It has been financed over decades by human activities as water affects, is sourced and is somewhat tamed by growing populations. Consequently, advanced solvers have been developed to provide scientists and engineers with flexible unstructured meshes fitting manmade or natural waterlines, interaction of physical processes such as hydrodynamics, waves, or sediment processes, as well as advanced mathematics and parallelised domain decompositions to greatly speed up computation for ever more detailed simulations. The TELEMAC system is one of those flexible, industry-driven, solvers that choose to open up its source code to further benefit from research and development carried out by growing communities of users worldwide.

Contrarily, numerical modelling for the oceans has mainly been restricted to the research arena, and is mainly used to represent decades or centuries of evolution mostly in the context of climate changes. While their global resolution and the complexity of their underlying density driven physical processes has increased with computer power to include coupling with atmospheric models, for instance, these developments have steered investments away from the underlying solvers: ocean models remain few in number, based on regular grid and legacy codes, with perhaps simpler mathematics compared to their shallow water counterparts.

With the rising costs of sourcing raw material such as oil, gas, bio-chemical compounds, human activities are gradually linking the shores to much deeper waters. It has, therefore, become essential for scientists and engineers to bridge the gap between environmental hydraulics and oceanography.

B. Objectives

In order to anticipate and meet the needs of its consultancy activities, it was essential for HR Wallingford to bridge the gap between environmental hydraulics and oceanography. The first of two objectives of the work presented here is to deliver the most comprehensive and detailed global modelling resources yet to support all sorts of shallow- and deep-water environmental hydraulics studies, providing hind-casts and forecasts at local, national or global scales.

The solution identified was to start a phased internal research project to demonstrate the capability of the TELEMAC system to model all physical processes present in these waters, whether independently or combined, and to develop a world leading global modelling resource: The Earth by TELEMAC.

The first four phases of the project were:

Phase 1. *Model setup and preliminary testing:* Finding the most efficient way to build a model of the Earth's waters and testing the capability of the TELEMAC system to run simulations over the entire globe. The existing functionality of TELEMAC-2D in modelling the propagation of Tsunami waves from source was selected for testing purposes.

Phase 2. *Modelling global tides and comparative validation*: Preliminary modelling of tides around the Earth based on the existing functionality of TELEMAC-2D to compute gravitational forces, which are accurately known. Resulting prediction of free surface elevations were compared against known global tidal datasets.

Phase 3. *Modelling storms through atmospheric parameters:* As a trivial application of the TELEMAC-2D component, temporally and spatially varying winds and pressure fields were derived for major known storms (large cyclones, typhoons and hurricanes) and used to predict surges.

Phase 4. *Modelling waves driven by atmospheric datasets:* As a trivial application of the TOMAWAC component, the model was driven by temporally and spatially varying, high resolution, wind data to compute waves propagation and transformation around the globe.

Subsequent development phases include the application of the Earth by TELEMAC to predicting internal tides (resulting from the combination of stratified waters and tides), computing mean dynamic topography (caused by temperature variations) and to forecasting ocean currents.

The second objective of the work presented here is to open up research and collaboration with national and international organisations, from around the world, to enhance the Earth by TELEMAC model with further knowledge, expertise and data. Already, separate research and development activities carried out by HR Wallingford in collaboration with renowned universities will be combined with this project to extend its capabilities. For instance, work done on Algorithmic Differentiation will be combined to extend the Earth by TELEMAC to possible data assimilation. Similarly, work done on Ice Modelling will help with the characterisation of the influence of the cold regions.

II. Setup of the Earth by TELEMAC

The purpose of the model is to represent the entire Earth, more specifically its water bodies, at a higher resolution than the current state of the art, below the kilometre if possible. The first step in setting up a model with TELEMAC is to setup an unstructured mesh of the computation domain as defined by its extent and its resolution. The second step in setting up a model is to map the bathymetry. The third step is to define its temporally and spatially varying open boundary conditions. Luckily, the advantage of modelling the whole Earth is that there are no open boundaries!

A. *A scalable unstructured mesh of the Earth*

A data source often used to define the shoreline of coastal waters is the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) database. GSHHS is a high-resolution shoreline dataset that has undergone extensive processing and is said to be free of internal inconsistencies (see [1]). It can be accessed from www.ngdc.noaa.gov or from www.soest.hawaii.edu/pwessel/gshhs.

Based on these shorelines, mesh generators can generate the unstructured mesh given a constant or variable resolution (triangle edge-length). At this stage, a constant mesh resolution is assumed, the value of which will depend on the computing resources available.

Unfortunately, currently available mesh generators are based on iterative methods that are too slow for extremely large number of vertices. Besides, most generator cannot deal with a round Earth, i.e. the fact that 0 deg = 360 deg.

The solution was, therefore, not to generate the mesh but to directly compute it, ignoring for a while the complication due to the presence of landmasses. Working on a full sphere, the main idea was to start from a known triangularly facetted 3D shape and to recursively refine it using the existing mesh refinement tools available within the python scripts of the TELEMAC system: the icosahedron, a 3D shape of 20 triangles (elements), was chosen.

Fig. 1 below shows the initial icosahedron rounding up the contours of the Earth, the first refinement (splitting each triangle into 4 smaller triangles) together with the re-projection of the new vertices on the sphere, and the subsequent refinement from iteration 2 through iteration 8.

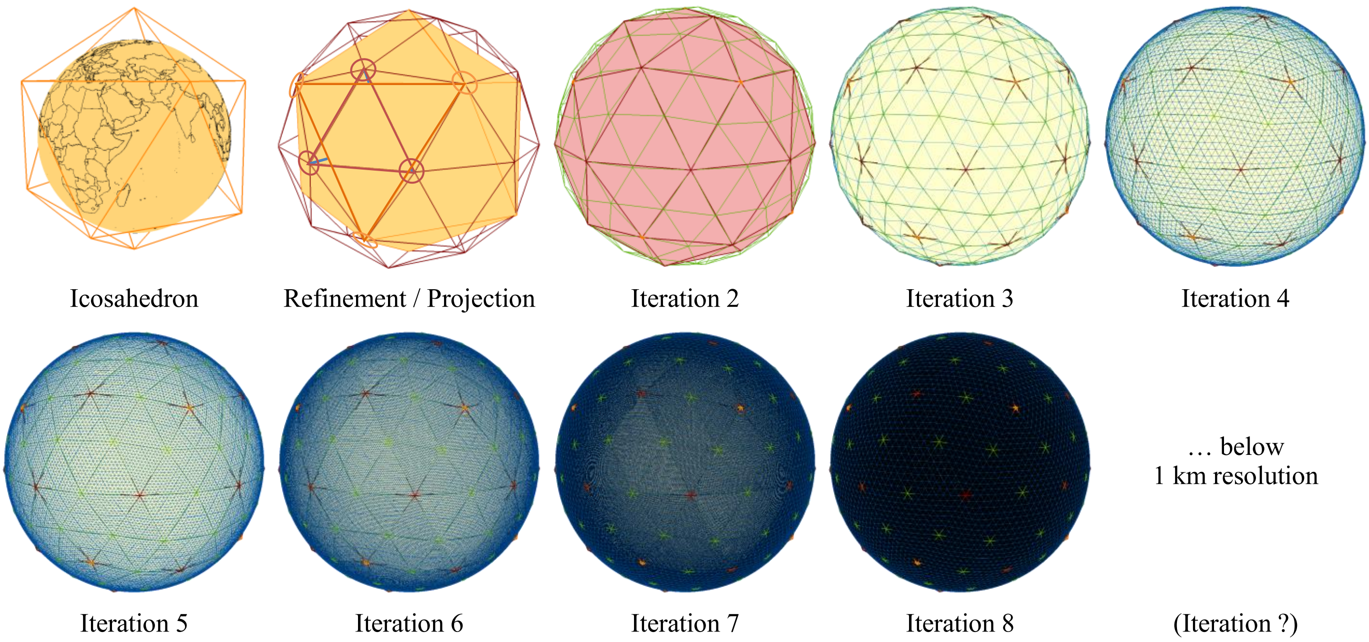

Figure 1. *Subsequent refinements of the icosahedron*

If we start with the 360 degrees of the circumference of the sphere based on a circle going through the poles, the icosahedron splits the sphere in 6 divisions, i.e. of 60 degrees for each foot of the triangle. The edge-length of a triangle is, therefore, slightly larger. If we now look at the circumference of the sphere based on a circle going along the equator after the first refinement, icosahedron splits the sphere in 10 divisions, i.e. 36 degrees for the first refinement, or 72 degrees for the icosahedron (5 divisions). In fact, depending on which pair of nodes, the edge length of the first refinement is either 31.72 or 36 degrees.

Let us chosen the longest of the edge lengths (i.e. 72 degrees), approximating the radius of the Earth, R, by 6,371,000 m, the circumference is $2\pi R = 40{,}030{,}173$ m. With that said, the "edge length" (distance when projected on the surface of the sphere) of the icosahedron is $(2\pi R/5) = 8{,}006{,}035$ km.

Subsequent refinements of the icosahedron multiply the number of elements by four while halving the edge length (following the curvature the sphere). TABLE 1 below shows the resulting metrics for subsequent mesh refinements.

TABLE 1 REFINEMENTS OF THE ISOCAHEDRON

Iterations	**Unstructured mesh characteristics**			
(sphere)	***360 (deg)***	***40,030,173 (m)***	***(elements)***	
isocahedron	72	8,006,034.7	20	
1	36	4,003,017.4	80	
2	18	2,001,508.7	320	
3	9	1,000,754.3	1,280	
4	4.5	500,377.2	5,120	
5	2.25	250,188.6	20,480	
6	1.125	125,094.3	81,920	
7	~ 1 / 2	62,547.1	327,680	
8	~ 1 / 4	31,273.6	1,310,720	
9	~ 1 / 7	15,636.8	5,242,880	
10	~ 1 / 14	7,818.4	20,971,520	
11	~ 1 / 28	3,909.2	83,886,080	*a*
12	~ 1 / 57	1,954.6	335,544,320	
13	~ 1 / 114	977.3	1,342,177,280	
14	~ 1 / 228	488.6	5,368,709,120	

a. *Current stage of the Earth by TELEMAC*

b. *Signed integers: 32bits = 2,147,483,647; 64bit = 9,223,372,036,854,780,000*
Unsigned integers: 32bits = 4,294,967,295; 64bit = 18,446,744,073,709,600,000

Several comments can be made:

- It is noted that the current state of the art of global datasets and model results available are based on a resolution of about 1/12th of a degree. This is the case of global tidal harmonic dataset TPXO (see [20]), or the global 3D oceanic model HyCOM (see [21]).
- The highest resolution used so far to a compute an unstructured mesh for TELEMAC has been for Iteration 12. Higher iterations would require slight modifications to the existing python scripts to include long integers, as well as heavy modifications to the TELEMAC source code to allow long integer in appropriate places.
- Computation of the mesh for Iteration 11 takes about 10 minutes (on a standard computer) and 45 minutes for Iteration 12. This remains acceptable and far more efficient than generating the mesh. Iteration 13 (below the kilometre resolution) should not take more than 4 hours, although this was not tested.
- The chosen methodology (based on subsequent refinements) to compute the unstructured mesh of the Earth could be an advantage in the future to support multi-grid methods in order to accelerate further solutions for the TELEMAC system (although not part of the current research project). In any case, the approach taken has been beneficial to the project as testing of functionalities can be done on coarser meshes, while developing final results are based on the finer mesh.

B. *Mapping Bathymetry and Topography*

Having created an unstructured mesh of the Earth, the bathymetric and topographic datasets are then mapped using a trivial 3-point weighted interpolation method.

Using the software Blue Kenue (see [4]) Fig. 2 below shows a coloured rendering of the resulting mesh, with mapped values of bathymetry (in shades of blues) and topography (in shades of green).

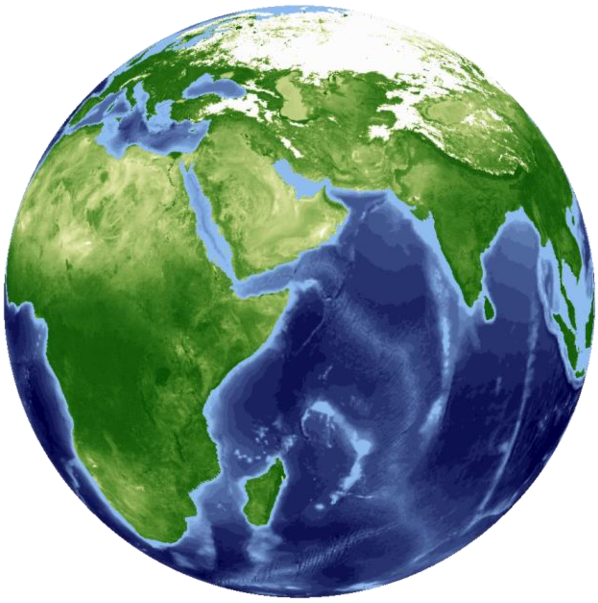

Figure 2. *The blue (and green) marble*

The GEBCO dataset was selected at this stage (see [2]). It has a resolution of about 1/16th of a degree. As the Earth by TELEMAC is refined further towards the kilometre, other sources of local bathymetries will have to be assembled for accurate results, particularly near the coasts. For instance, the marine data provider SeaZone (see [3]), can be put to the contribution by HR Wallingford.

The shades of green shown on Fig. 2 are here, in fact, not representing topography but were rather extracted from the "Blue Marble" satellite photo of the Earth surface (see [5]).

C. Landmasses

Having computed a mesh for the entire surface of the Earth imprinted with bathymetry and topography values, one can think of several approaches to deal with landmasses.

A first approach could consist in using TELEMAC's ability to deal accurately with wetting and drying. This approach implies that the mesh together with its mapped values remains untouched. However, this is not computationally efficient as all vertices on landmasses become dormant in a TELEMAC simulation.

A second approach could consist in using the shorelines of the GSHHS dataset (see [1], introduced in Section II.A), "checking" if a particular vertex is in one of the closed polygons defining landmasses, for every vertex in the mesh, and removing the vertex if so. Unfortunately, the "checking" step is also time consuming and would be prohibitive beyond Iteration 9.

Rather, the approach considered for the model of the Earth was to use the values (of bathymetry and topography) for the whole sphere, and simply / efficiently filter out values higher than a chosen mean sea level.

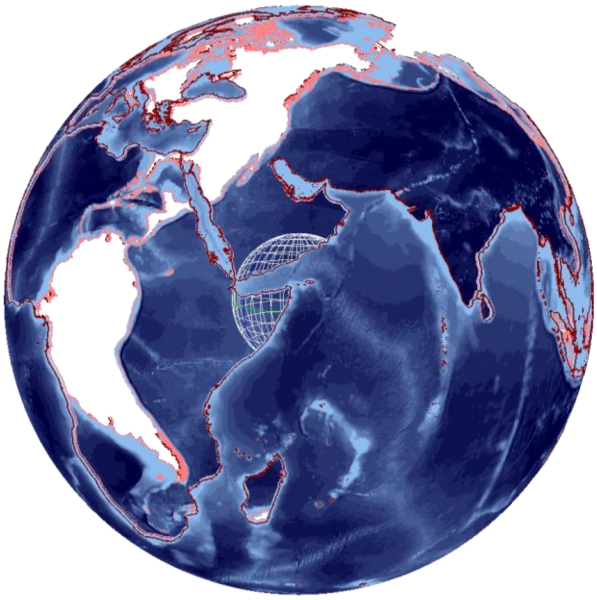

Figure 3. *The Earth by TELEMAC*

Fig. 3 above shows the resulting model: The Earth by TELEMAC in a see-through manner as the landmasses have been removed (the Pacific Ocean is visible through the Asian continent, South America through the African continent, …). The gridded sphere inside the Earth is only shown for perspective.

As previously said, several models of the Earth were developed in the course of this project, at various resolutions (mainly between Iteration 9 and 11), in order to effectively develop, test, validate and finally forecast various physical aspects of all water bodies.

III. Applications of The Earth by TELEMAC

A. Propagation of Tsunami waves

Having setup the model of the Earth, the first phase of the internal research project was to conclude on the ability of the TELEMAC system to deal with a complete sphere with no open boundaries. The application considered was to the propagation of tsunami waves, based on the TELEMAC-2D component. This application is one of the simplest to setup as all water bodies start at rest and the tsunami characteristics are provided through the steering file. It is important to note that the appropriateness of TELEMAC-2D to model the propagation of tsunami waves has been previously demonstrated in [6].

After corrections to the source code were made (in particular to account for the connection between 0 deg and 360 deg in the method of characteristics), model results were favourably compared with previous consultancy studies carried out at HR Wallingford. So far, local models had been setup for various projects in different parts of the world, including for the Lisbon 1755, Sumatra 2004, Tohuku 2011.

Unfortunately, because those consultancy study results remain confidential, they cannot be presented. Instead, the applicability of TELEMAC-2D to the propagation of tsunami waves over the entire globe was demonstrated through an animation posted on YouTube (see [7]), bringing 10 of the most devastating tsunami events together within a 24 hour simulation. Fig. 4 below shows two insets (two sides of the Earth), of snapshots of that animation.

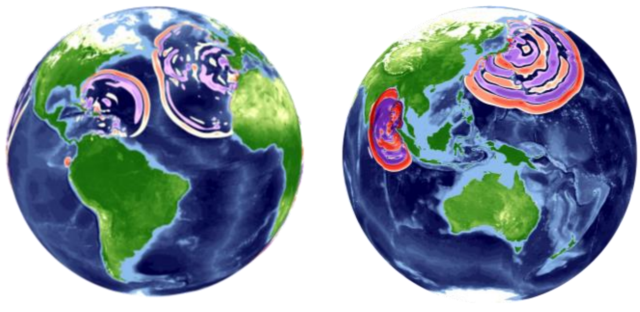

Figure 4. *Modelling tsunami waves over the Earth by TELEMAC*

Tsunami characteristics are set in TELEMAC through the Okada generator (see [8] and [9]). It is widely used in earth sciences to simulate seafloor deformation produced by local perturbation like earthquakes and was integrated within the TELEMAC system in 2012, by the authors of this article. The tsunami is characterised by its focal depth, its fault length and width, its dislocation, its strike direction, its dip angle, and its slip (see illustrative Fig. 5 below).

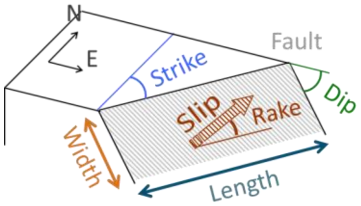

Figure 5. *Tsunami characterisation*

It should be noted that release v7p2 of the TELEMAC system only includes the possibility to define one tsunami source, using the keywords:

- ✓ OPTION FOR TSUNAMI GENERATION; and
- ✓ PHYSICAL CHARACTERISTICS OF THE TSUNAMI

It is anticipated, as a result of this internal project, that the keywords above will be extended in release v7p3 to the definition of multiple sources, whether combined to define one event, and / or triggered as separate events at different times.

For reference, the selected events shown in the animation posted on YouTube were: Solomon Islands 2007 (see [10]), Tohuku 2011 (see [11]), Sumatra 2004 (see [12]), Makran/Balochistan 1945 (see [13]), Greece 1956 (see [14]), Lisbon 1755 (see [15]), Dominican Republic 1946 (see [16]), Ecuador/Colombia 2016 (see [17]), Valvidia 1960 (see [18]) and Kamchatka 1952 (see [19]).

With a resolution of about 4 km (Iteration 11) and a time step of 1 minute, the 24 hour simulation was computed in less than 5 hours on 36 compute cores only. Higher speed up can be achieved with a higher number of cores, particularly for a possible forecasting mode.

B. Forecasting tides

In order to fulfil the first objective of this internal project (to deliver comprehensive and detailed global modelling resources to support environmental hydraulics studies anywhere in the world), the second phase looked at an important aspect of all coastal models: the forecasting of tidal information.

Typical of the setup of a coastal (hydrodynamic) model, one would extract tidal harmonic information from a global dataset or from a range of tidal gauge observations and re-synthetize a signal on its open boundary for various periods. The TPXO dataset (see [20]) is one such global dataset. It is widely used in earth sciences and was first integrated within the TELEMAC system in 2011, by the authors of this article. It provides several harmonic constituents computed from a best-fit of tidal levels measured along remote sensing tracks from the TOPEX/POSEIDON and its subsequent JASON satellite programs.

As previously noted, the Earth by TELEMAC has no open boundaries. Therefore, the forecasting of tides could not have been imposed but rather directly computed from known gravitational forces (relative rotations of the Sun, the Moon, the Earth and various corrections in orbit trajectories), a feature that is already available in the TELEMAC system, using the keyword:

- ✓ TIDE GENERATING FORCE

After calibration of the hydrodynamic model based on the TELEMAC-2D component (to account for 3D phenomenon such as internal tides), model results of surface levels and depth average velocities were favourably compared with the TPXO dataset.

In order to demonstrate the applicability of TELEMAC-2D to forecast tides over the entire globe, another animation was created and posted on YouTube (see [22]). For reference, an arbitrary 15-day period starting on January 13, 2017 was selected. Fig. 6 below shows two insets (two sides of the Earth), of snapshots of that animation of the Earth by TELEMAC. Colours represent the maximum tidal range computed over a spring tide (with red indicating the highest and blue the lowest variation in tidal range). For comparison purposes, Fig. 7 shows the same snapshots but extracted from the TPXO dataset.

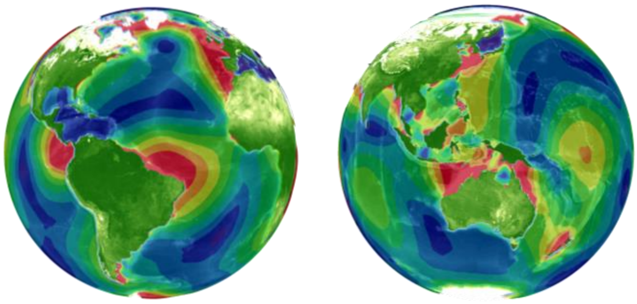

Figure 6. *Forecasting tides over the Earth by TELEMAC*

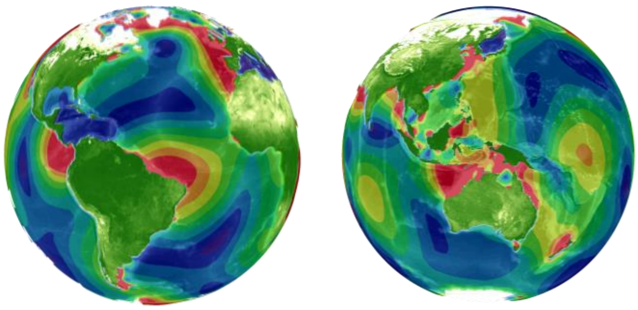

Figure 7. *Extraction of observed tides from the TPXO dataset*

While there are differences between the TELEMAC-2D forecast and the TPXO dataset, these could be explained by the absence 3D processes. It is expected that TELEMAC-3D, with an appropriate representation of ocean currents and internal waves / tides as well as a self-attracting force would provide a fairer comparison (see Chapter V).

C. Forecasting storm surges

In the continuation of Phases 1 and 2, the third phase of the project looked at atmospheric drivers, such as winds and atmospheric pressure. Atmospheric temperature and other aspects of the thermal balance would be tested later, before going 3D. Atmospheric drivers (whether drivers of the hydrodynamic or the heat budget) are existing features of the TELEMAC system and are often used on a wide range of consultancy studies, particularly in metocean studies.

Therefore, similarly to the application of the Earth by TELEMAC to the propagation of tsunami waves, the applicability of TELEMAC-2D to predicting storm surges over the entire globe was simply tested and demonstrated through another animation posted on YouTube (see [23]).

The animation shows water surges (ranging from red: highs, down to purple: lows) driven by storms (shown by wind vectors) running across the globe for 11 known storms within an 85-day sequence. Fig. 8 below shows two insets (two sides of the Earth), of snapshots of that animation. Note that the winds are shown several hundred kilometres above the surface so that the surge and wind field can be seen more readily.

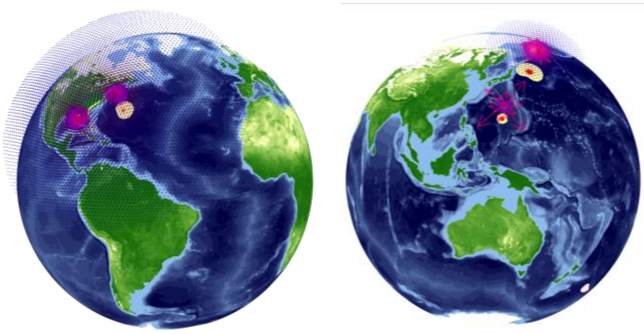

Figure 8. *Forecasting storms over the Earth by TELEMAC*

For reference, the selected storms shown in the animation posted on YouTube were: Cyclone Inigo 2003 (see [24]), Typhoon Haiyan 2013 (see [25]), Bangladesh Cyclone 1991 (see [26]), Cyclone Gonu 2007 (see [27]), Hurricane Allen 1980 (see [28]), Hurricane Ten 1924 (see [29]), Hurricane Katrina 2005 (see [30]), Hurricane Patricia 2015 (see [31]), Cyclone Pam 2015 (see [32]), Hurricane Ioke 2006 (see [33]) and Typhoon Tip 1979 (see [34]). Storm characteristics were extracted from the IBTrACS (see [35]) database for each of those, from which the wind and pressure field were computed (within TELEMAC) using the Holland model (see [36] and [37]).

D. *Forecasting waves*

Having demonstrated that the Earth by TELEMAC can be driven by atmospheric inputs, the fourth phase of the internal research project looked to forecasting waves on the entire globe, since these are resulting principally from winds.

Similarly to the tides, typical setup of coastal (wave) models would include the extraction of wave information from a global dataset or from a range of wave gauge observations and use these at its open boundary for various periods. The ERA-5 dataset (see [38]) available since July 2017 (or the ERA-Interim before then) is one such global dataset. It is widely used in earth sciences and often used in consultancy studies by HR Wallingford. The python scripts, developed for the TELEMAC system by the main author of this article, include a direct link to the dataset.

Again, the Earth by TELEMAC has no open boundaries. Therefore, the forecasting of waves has to be the sole results of winds. A simulation of the TOMAWAC component was, therefore, setup for the Earth by TELEMAC, with waves driven only by temporally and spatially varying winds. Winds were extracted from the ERA-5 dataset as well as waves for comparison purposes.

In order to demonstrate the applicability of TOMAWAC to forecast waves over the entire globe, another animation was created and should be posted on YouTube in early November 2017. For reference, an arbitrary 60-day period starting on November 1, 2016 was selected. Fig. 9 below shows two insets (two sides of the Earth), of snapshots of that animation of the Earth by TELEMAC. Colours represent the wave heights computed (with red indicating the highest waves blue the lowest waves). For comparison purposes, Fig. 10 shows the same snapshots but extracted from the ERA-5 dataset.

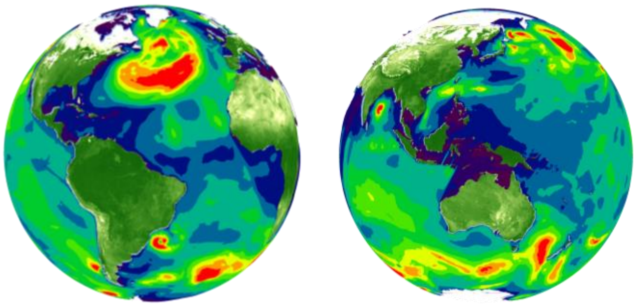

Figure 9. *Forecasting waves over the Earth by TELEMAC*

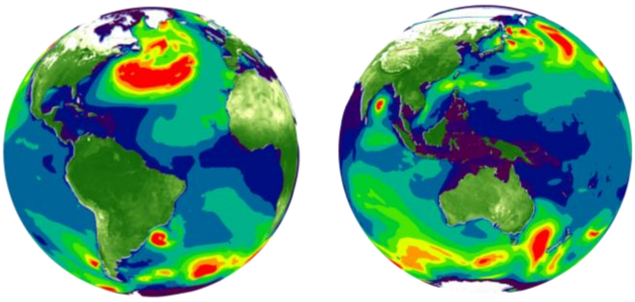

Figure 10. *Extraction of wave heights from the ERA-5 dataset*

While there are differences between the forecast and the ERA-5 dataset, the comparison remains favourable. A more detailed calibration and validation of TOMAWAC against observations at wave buoys should follow. Nonetheless, the applicability of the Earth by TELEMAC to model waves on the entire globe is here demonstrated.

For reference, with a resolution of about 15 km (Iteration 9), a time step of 5 minutes and a spectrum defined over 26 periods and 12 directions, the 60 day simulation was computed in a little more than 2.5 days on 36 compute cores only. Higher speed up can be achieved with a higher number of cores, particularly for a possible forecasting mode.

IV. Conclusions

HR Wallingford has setup the Earth by TELEMAC as an internal research project with the objective to demonstrate the open source community that TELEMAC is capable to bridge the gap between environmental hydraulics and oceanography.

The first four phases of the project have already broken new ground, particularly in terms of resolutions both spatial and temporal, while providing forecasts comparable to often used global datasets. The absence of boundary conditions facilitates the modelling greatly; its parallelisation to great number of computing units makes the modelling possible.

However, this project will continue for another year as the two objectives set out remain to be fulfilled:

- While this project already provides a detailed and wide ranging platform of metocean data (tides, surges, extremes, waves, etc.) at high resolution over the entire globe, the project now needs to move to 3D processes.
- While the recipe of the Earth by TELEMAC is here published for everyone to copy, HR Wallingford is looking to focus and lead interests from national and international organisations from around the world, in order to create a larger pool of resources (computing, human, financial, observed data, …).

Future applications of the Earth by TELEMAC could include: forecasting activities (such as vulnerability to coastal flooding, or for the tracking and circulation of pollution, debris or plastics); engineering designs (for example for detailed 3D metocean analysis, extremes and climates); and resource assessments (such as for renewable energy, for deep sea mining, or for global environmental impact).

V. Preliminary 3D Applications

In anticipation to a follow-up article to be published at the user conference in 2018, the following shows two preliminary results of the Earth by TELEMAC based on TELEMAC-3D, further highlighting its potential to fulfil our objectives.

A. Ocean currents

The TELEMAC-3D component has been used here to investigate whether the Earth by TELEMAC can generate sensible ocean currents starting from still. The main driver to the model is a vertical density profile. The air temperature and the solar radiation extracted from the ERA-5 dataset (see [38]) are also imposed through the thermal exchange model, with the following keyword:

- ✓ ATMOSPHERE-WATER EXCHANGE MODEL = 2

Fig. 11 below shows the magnitude of the currents predicted at the surface, for the two sides of the globe. The simulation was run for a preliminary period of 30 days, starting with no water movements. The "coarse" mesh (based on Iteration 9) was used with only 4 planes in the vertical.

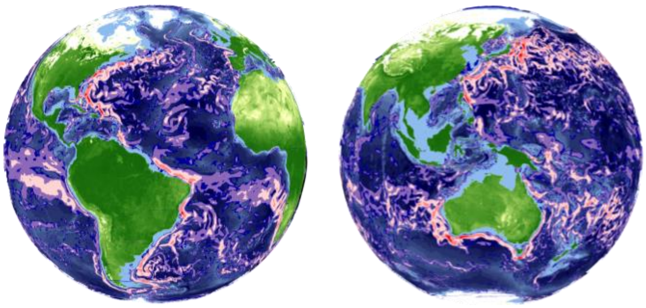

Figure 11. *Surface currents over the Earth by TELEMAC*

Despite the short duration and the coarse resolution of the model, some of the major ocean currents are formed in various places of the globe. While further calibration and validation of these results over much longer periods and finer meshes will be carried out in the next phases of the project, these results are extremely encouraging in TELEMAC ability to bridge the gap between environmental hydraulics and oceanography. Other 3D oceanic model such as HyCOM (see [21]) will be used as approximate hot-start conditions or at least for comparison purposes.

B. Internal tides

The TELEMAC-3D component has been used here to investigate whether the Earth by TELEMAC can generate a specific sort of internal waves: internal tides. These waves are particularly critical to offshore projects with risers or seabed facilities within the first kilometre of the water column. HR Wallingford has identified this phenomenon in several oil and gas and deep sea mining studies. These waves are the result of a combination of a strong stratification and the presence of tides, a combination of processes that is not available in any of the global models or datasets.

Fig. 12 below show a snapshot in time of the surface current (top plane) of a TELEMAC-3D results based on 10 planes.

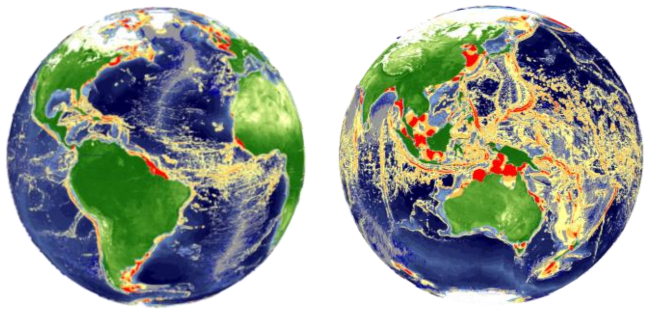

Figure 12. *Forecasting internal tides over the Earth by TELEMAC*

While high currents are predicted in places known for their high tidal energy the Earth by TELEMAC is able to also highlight places of internal tides. In fact, these results compare favourably with publish literature on the subject (see for instance [39]).

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