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Kelly, David; Ata, Riadh; Li, Y.

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Modification of TELEMAC 2D for Storm Surge Use

D. M. Kelly[1,*], R. Ata[2] and Y. Li[3]
[1.] W.F. Baird & Associates, Oakville, ON., Canada.
*dkelly@baird.com
[2.] EDF R&D, National Laboratory for Hydraulics and Environment (LNHE) & Saint Venant Laboratory for Hydraulics, Chatou, France
[3.] International Hurricane Research Center, Miami, FL 33119, USA.

Abstract*—Despite the *ad-hoc* use of TELEMAC 2D to predict storm surge over recent years, to-date no coherent effort has been made to develop TELEMAC 2D into a useable, off-the-shelf, storm surge model released via the openTELEMAC website. This has motivated the work presented here in which two distinct parametric wind models and a large variety of drag laws have been introduced into TELEMAC2D. The ability to read both time and space varying wind and rain data is also added. The resulting numerical model is particularly powerful as it can be combined with the existing, curve number-based, rainfall runoff model in TELEMAC in order to provide storm tide simulations that parameterize the effects of hurricane wind, tide, shortwaves (via the spectral wave model TOMAWAC), rainfall and runoff. In order to validate the model in the paper we present results for the forecast mode simulation of the surge due to a number of recent hurricanes in both Puerto Rico and South Florida. The South Florida model includes street level flooding around the City of Miami Beach.

I. INTRODUCTION

The TELEMAC 2D model has previously been used to simulate storm surges, see for example the work presented in [1] in which cyclone Yasi was simulated using the Holland (1980) wind model. In their paper Cooper et al. [1] reported good agreement between simulated results and the available data. Despite the fact that there has been previous promising storm, and combined storm tide modelling, utilising TELEMAC 2D, this has been undertaken in a somewhat *ad-hoc* manner, and the capacity to simulate storm surges has not yet been formally included within the open source release version of TELEMAC. It is with this in mind that a concerted effort has been made to introduce state-of-the-art parametric wind and drag models into TELEMAC2D. This has been combined with the ability to employ time and space varying rain data within the TELEMAC2D model. The aim of this paper is to serve as a brief summary of this work. The structure of the paper is as follows: In Section II we outline the two parametric wind models that have been introduced into TELEMAC2D and also provide an overview of some of the additional wind drag formulations that have also been introduced into TELEMAC2D. In Section III the implementation of these parametric wind models within the TELEMAC framework is briefly outlined. This section also includes details on newly introduced keywords and how to use the newly implemented storm surge model. Finally, in Section IV, results for two distinct example cases are presented, namely the surges due to hurricane Maria (2017) in Puerto Rico and hurricanes Frances (2004), Wilma (2005), Matthew (2016) and Irma (2017) in South Florida. The South Florida model that is presented also includes rainfall, obtained from satellite data, and the associated run-off. Comparisons of model results and NOAA co-ops gauge data as well as contour plots of the maximum surge are presented.

II. WIND AND DRAG MODELS

TELEMAC 2D has been modified to include two parametric wind models. The first wind model is the well known Holland (1980) model [3]. This simple model has been used in TELEMAC before by other researchers, see for example [1], although it has never been included as part of the official open TELEMAC suite. The second parameteric wind model introduced into TELEMAC in this work is the Myers & Malkin (1961) model [9] which is used by the US National Hurricane Center (NHC) Sea, Lakes and Overland Surges from Hurricanes (SLOSH) model [5]. This model is more complex than the simple algebraic Holland (1980) model.

A. The Holland (1980) Parametric Wind Model

The Holland (1980) wind model [3], referred to from hereonin as H80 wind, is the best known of the parametric wind models. Defining the radius of maximum winds as r_{mw}, and the surface pressure at radius r by p_s, the H80 wind is based on a modified rectangular hyperbola to approximate the radial surface pressure profile giving the surface pressure as:

$$p_s = p_{cs} + \Delta p_s e^{-\left(\frac{r_{mw}}{r}\right)^b}$$

The pressure drop from the defined external pressure is denoted by Δp_s. Scaling is achieved via the exponent b which relates the ratio of maximum wind for a given pressure drop to the maximum wind speed [3]. This is then introduced into the cyclostrophic wind equation to give the cyclostrophic wind speed V_c as:

$$V_c = V_m\left[\Psi e^{(1-\Psi)}\right]^{0.5}$$

where:

$$\Psi = \left(\frac{r_{mw}}{r}\right)^b$$

V_m is the maximum wind speed that must be provided in a hurricane track file. Other parameters that must be provided in the same hurricane track file are the centre loction, the pressure drop and the radius of maximum winds. An asymmetric version of the Holland model, accounting for the hurricane forward speed, has also been coded and is available to the user.

B. Myers & Malkin (1961) or SLOSH parametric wind

The Myers and Malkin (1961) model [9], which was adapted for the NHC SLOSH model by Jelesnianski et al. [5], has been added to the TELEMAC model in the form proposed by [5]. The Myers & Malkin (1961) wind model, referred to from here-on-in as the MM61, model is less well known than the H80 model; perhaps because it is more complex to implement. The wind and atmospheric pressure fields are generated based on the parameters of atmospheric pressure drop and radius of maximum wind speed. The pressure, wind speed, and wind direction are computed from a stationary, circularly symmetric storm using the balance of forces along a surface wind trajectory and normal to a surface wind trajectory. The governing equations for the adapted MM61 wind model are [5]:

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{k_s V^2}{sin\phi} - V\frac{dV}{dr}$$

and

$$\frac{1}{\rho_a}\frac{dp}{dr}cos\phi = f_c V\frac{V^2}{r}cos\phi - V^2\frac{d\phi}{dr}sin\phi + k_n V^2$$

where ρ is the air density, r is the distance from the storm center, p is the pressure, φ is the inflow angle across circular isobars toward the storm center, and V is the wind speed. The values of k_s and k_n are empirically determined coefficients and f_c is the Coriolis force. The two equations can be solved for p and φ if the form of wind speed profile V is supplied. The TELEMAC2D-based model follows the same approach employed in the SLOSH model and uses the following wind speed profile for a stationary storm:

$$V(r) = V_R\frac{2RMW \cdot r}{RMW^2 + r^2}$$

where *RMW* is the radius of maximum wind. Solution of the equations is effected in *SLOSHWINDFIELD.f* via a Runge Kutta approach. The MM61 model requires an identical track file to that required by the H80 wind model.

C. Using Reanalysis Wind Field Data

If the user has access to reanalysis wind data the TELEMAC2D model is now able to employ a time and space varying wind field as model input to provide the wind forcing. A typical example of such renalysis wind data would be that provided by the NOAA Hurricane Research Wind Analysis System (H*WIND) [12]. Currently, the input wind field must be converted from its native format into the SELAFIN format.

D. Drag Models for Wind Shear Stress

A number of well-known, and not so well-known, wind drag formulations have been coded into TELEMAC2D for use in storm surge simulation. A small selection of the newly introduced drag models that have been coded is outlined below. The models are defined in terms of the 10-m neutral values for the drag coefficient, C_{10}.

Garratt (1977) [2] – The linear version of the Garratt drag formulation is included:

$$C_{10}x10^3 = 0.75 + 0.067U_{10}, 4ms^{-1} < U_{10} < 21ms^{-1}$$

this is a popular formulation often used in the NHC SLOSH model and the ADCIRC model [15].

Large & Pond (1981) [6]:

$$C_{10}x10^3 = \begin{cases} 1.14 \\ 0.49 + 0.065U_{10}, 10ms^{-1} < U_{10} < 26ms^{-1} \end{cases}$$

Wu (1980,1982) [14]:

$$C_{10}x10^3 = 0.8 + 0.065U_{10}, U_{10} > 1ms^{-1}$$

Peng & Li (2015) [10]:

$$C_{10}x10^3 = -a(U_{10} - 33)^2 + c$$

where, for the South China Sea, *a=0.00215* and *c=2.797*. It should be noted that this is a typhoon model. A number of other wind drag models are included in the release and a full list will be provided in a future issue of the TELEMAC2D User Manual. Importantly, the more complex sector based model of Powell [11], often used in the ADCIRC model [15], has also been implemented. It should be noted that all of the above drag models employ an extinction depth below which the effect of the wind on the water is discounted. The extinction depth is typically taken to be *0.4m* although this is a user defined parameter.

III. IMPLEMENTATION WITHIN TELEMAC2D

A. New/Modified Subroutines

A number of the base TELEMAC2D subroutines were modified in order to allow for the inclusion of these two parametric hurricane wind and pressure models. New subroutines and functions were also introduced; a brief list of some of the key subroutines that were modified and the newly introduced subroutines is provided below. For reasons of brevity it is not possible to detail all the requisite modifications or new routines here. In TELEMAC-2D, the *METEO.f* subroutine is the place where external atmospheric pressure and wind forcing are handled. This subroutine has been modified to include the ability to read a hurricane track file, via a new subroutine called *SLOSHDAT.f*, and make the requisite calls to enable the parametric wind field to be computed via calls to either SLOSHWINDFIELD.f (for MM61) or *HOLLANDWINDFIELD.f* (for H80) which are both called from *SLOSHDAT.f.* The effect of wind extinction is also included in *METEO.f.*

In TELEMAC-2D, the wind forcing is included via the momentum equations in the subroutine *PROSOU.f* . This subroutine has been modified to allow for the inclusion of a number of different wind drag models (which are defined via

FORTRAN functions). Importantly, this subroutine, and the RUNOFF*_SCS_CN.f* subroutine, have been modified in order to allow for the inclusion of time and space varying rain. In addition to these primary modifications the *TELEMAC2D.dico* file and modules have also been made.

B. New Keywords

As part of the development several new keywords have been introduced into the TELEMAC 2D dico these are described in the text below. It should be noted that it is envisaged that, before the official release, this list of keywords is likely to change.

The keyword *TIME AND SPACE VARYING RAIN* has been introduced to allow for the read-in of this data from the *binary atmospheric data file*.

The keyword *OPTION FOR WIND* has been modified to include two new options:

3: Time and space varying wind read in from a binary input file (file format must be native SELAFIN). This data must be included in the *binary atmospheric data file*.

4: Parametric hurricane wind model. Two parametric hurricane wind models are avaiable. A: Holland (1980) model or B: Myers & Malkin (1961), also known as the SLOSH wind, parametric wind model.

The keyword *HURRICANE TRACK FILE* has been introduced. This is the hurricane track file that is used to generate the hurricane wind field internally.

The keyword *HURRICANE EXTINCTION DEPTH* has been introduced. This is the extinction depth (in m). For water shallower than this depth the wind does not impact the hydrodynmamics.

The keyword *HURRICANE RAMP-IN TIME* has been introduced. This is the time over which the shear stress due to the hurricane wind is ramped in to its true value. This is often necessary to stop the transients caused by an impulsive wind leading to numerical instability.

The keyword *HURRICANE RAIN OFFSET TIME* has been introduced. This is the time by which the rainfall will be offset with respect to the track file. This value is used to syncronise the hurricane track file and the input rainfall data file. NB: It is recommended that the huricane track and rainfall data files should be set-up such that they start at the same instant in time.

The keyword *HURRICANE PATH OFFSET X-DIR* has been introduced. The amount by which to offset all the track abscissae.

The keyword *HURRICANE PATH OFFSET Y-DIR* has been introduced. The amount by which to offset all the track ordinates.

The keyword *AIR DENSITY* has been introduced. The density of air used to compute the wind forcing source term.

The keyword *AIR PRESSURE* includes the effect of the air pressure drop due to the hurricane in the simulation. For storm surge simulations this should always be included or the surge will likely be underpredicted. The air pressure is included based on the internally generated parametric model output or the values provided in the input SELAFIN format file.

The keyword *INVERTED BAROMETER EFFECT* has been introduced. Include the inverted barometer effect in the calculation. This is a parameterization of the adjustment of sea level due to changes in barometric pressure A decrease in barometric pressure of 1 mb corresponds to a fall in sea level of 0.01 m. At the time of this paper this is not fully incorporated into the model (it should be included before release).

IV. EXAMPLE APPLICATIONS

A. Hurricane Maria (2017) at Puerto Rico

In the first application of the model we present the results from a simulation of the storm tide due to hurricane Maria (2017) at Puerto Rico. Maria made landfall on the East coast of Puerto Rico as a high-end Category 4 hurricane. For the results presented here the H80 wind model was employed, in asymmteric mode, and the Garratt [2] linear drag model was utilised. The computational grid was derived by triangulating the SLOSH v6 Puerto Rico basin to give ~450,000 computational nodes. For the bathymetry local to Puerto Rico and the U.S. Virgin Islands coastal regions we employed 1 arc-second and 1/3 arc-second digital elevation models (DEMs) developed by the US National Geophysical Data Center (NGDC), and NOAA, for the Pacific and Marine Environmental Laboratory (PMEL) and the NOAA Center for Tsunami Research. For the offshore areas the NGDC ETOPO1, 1 arc-minute, global relief model was used. The bathymetry was interpolated onto the grid from the data using a kernel-based approach. The TELEMAC2D model utilised spatially varying bottom friction which was obtained using the look-up table of Mattocks & Forbes [8] to convert the USGS landcover data into suitable Manning's *n* values. Figure 1 shows a comparison of the free surface time series obtained using TELEMAC2D with the NOAA co-ops data for all of the 9 available gauges. A comparison of the maximum envelope of observed water (MEOW) with the NOAA mean high water mark data is shown in Figure 2. For a forecast mode study the results are very promising and it is envisaged that the results would be improved by the use of re-analysis wind data or a better calibrated parametric wind field. The contribution of short waves, parameytrised via use the TOMAWAC spectral wave model, would likely also improve predictions due to the contribution of static set-up.

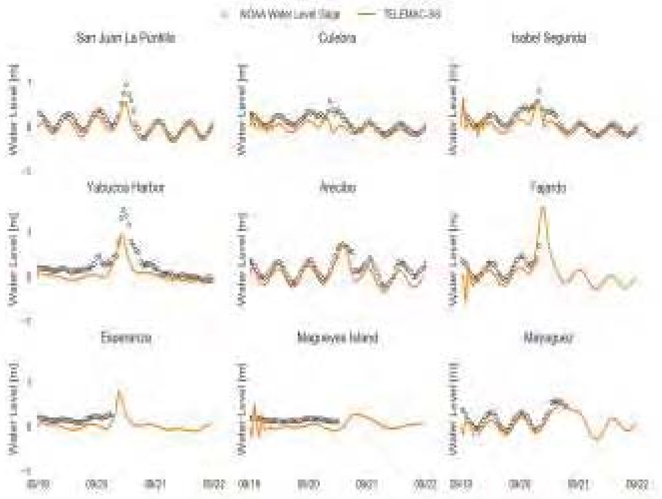

Fig. 1. Comparison of free surface time series at NOAA co-ops gauges at locations around the island of Puerto Rico for hurricane Maria (2017).

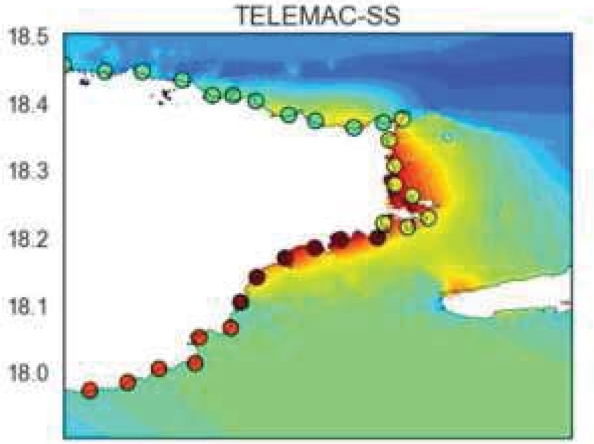

Fig. 2. Comparison of the predicted (contours) and observed (circles) MEOWs around the landfall site, East coast of Puerto Rico, for hurricane Maria (2017). The colour range is 0m(blue) - 2m(red).

B. Combined Tide, Surge and Rain around the City of Miami Beach

The model grid comprised approximately 750,000 computational nodes (~1.5M elements) with grid spacing ranging from O(5km) in the open ocean down to O(10m) around the focus area (City of Miami Beach). Figure 3 shows the model domain and hurricane tracks. The South Florida Water Management District (SFWMD) 5-m digital elevation model (DEM) data was used to derive the bottom elevation over the fine-resolution model grid wherever data was available for the study area. The Florida Geographic Data Library (FGDL) 5-m DEM data was used for areas without SFWMD DEM data. NOAA 2-minute Global Relief Model (ETOPO2), and the 3-arc-second Coastal Relief Model, were combined to obtain bathymetric data for the model grid. Rainfall data for the simulations presented here was obtained from the NOAA Integrated Multi-satellite Retrievals for GPM (IMERG) precipitation product [7]. The IMERG data is created by inter-calibrating, merging and interpolating all available satellite microwave precipitation estimates, together with microwave-calibrated infrared (IR) satellite estimates [7]. Wind fields were created via the asymmteric H80 model employing best track data created by experts at the International Hurricane Research Center, Miami. In Figure 4 we present time series results at Virginia Key (in Biscane Bay) for four historical hurricanes namely hurricane Frances (2004), Wilma (2005), Matthew (2016) and Irma (2017).

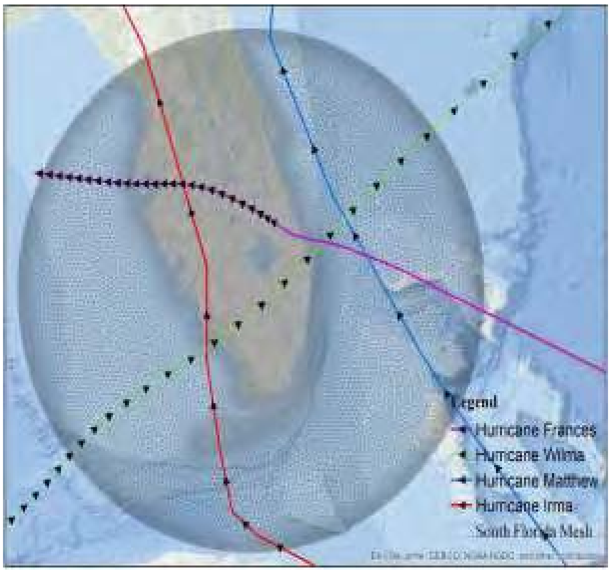

Fig. 3. South Florida mesh based on NOAA domain and comprising ~1.5M elements. Historical hurricane tracks are also shown.

Results shown include the combined effects of tides, wind and rain. We choose to present the reults at NOAA gauge 8723214 (Virginia Key) as this is the closest to the area of the City of Miami Beach which was the primary focus area of the study. In this area significant effort was expended to achieve good bathymetric representation; moreover, the mesh resolution was highest around the City of Miami Beach, with the grid resolution being 10m in this area. Figure 5 illustrates comparisons of the simulated and observed free surface time series. The agreement between the modelled results and observations is reasonable. Good results are obtained for hurricanes Wilma (2005) and Irma (2017) for which we had the best track data. It should be noted that the use of more accurate reanalysis wind data, alongside the fine tuning of bathymetry and friction coefficients, can be expected to improve the results; however, this would result in a hindcast mode simulation. Figure 6 shows an example of the combined maximum surge and street level flooding around the North Miami Beach area. Zoom-in contour plots are shown for hurricanes Frances, Wilma, Irma and Maria (clockwise from top left). As well as the surge the street level flooding, due to the associated rainfall, is clearly evident.

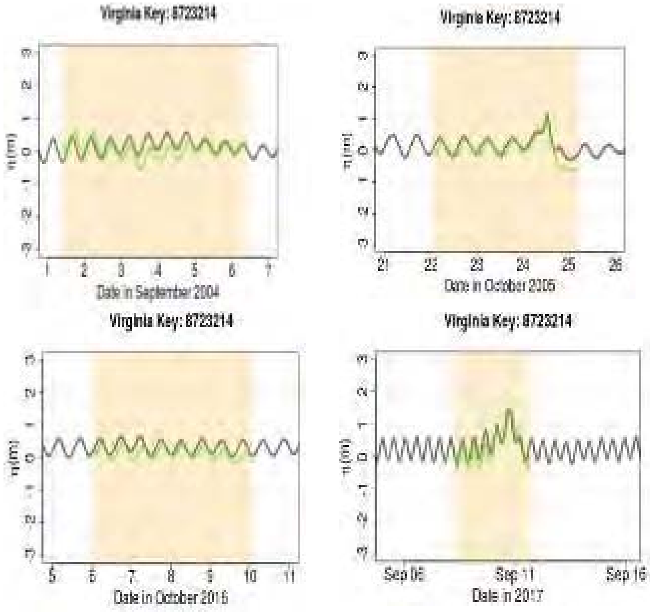

Fig. 4. Comparison of model predictions (green) vs the observed (grey) free surface time series at Vriginia Key in Biscane Bay, Miami (NOAA gauge 8723214) for hurricanes Frances (2004), Wilma (2005), Matthew (2016) and Irma (2017).

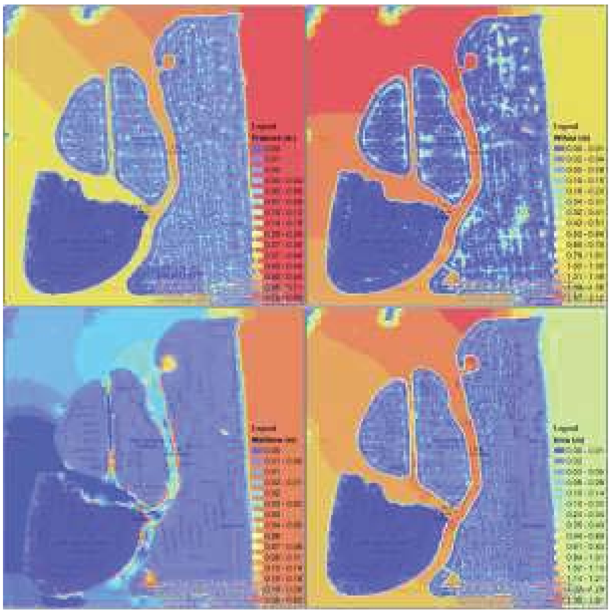

Fig. 5. Zoom-in of the maximum observed water level due to surge and flooding in the North Beach area of the City of Miami Beach, Florida. Refer to the main text for details.

V. CONCLUSIONS

Two distinct parametric wind models, as well as the capacity to read in time and space varying (reanalysis) hurricane wind and rain and a number of hurricane-type wind drag models have been implemented in TELEMAC2D. The introduction of these features, combined with the existing rainfall run-off and spectral wave model (TOMAWAC) makes the TELEMAC-MASCARET suite potentially very powerful for the simulation of storm surge and hurricane induced overland flooding. It is envisaged that this additional functionality will be formally included in the next release of the open TELEMAC-MASCARET suite.

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