PREVIMER: IMPROVEMENT OF SURGE, SEA LEVEL AND CURRENTS MODELLING

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Abstract

The pre-operational system PREVIMER provides coastal observations and forecasts along French coasts. It provides, among other variables, currents, sea levels, surges and waves. This paper describes the development and validation of a high temporal (15 minutes) and spatial (250 m) resolution modeling system, based on MARS hydrodynamic model (Lazure and Dumas 2008), along the Atlantic and English Channel coasts. Models benefit from experiments developed during the PREVIMER project by: (1) taking better into account wind and wave actions (improving surface drag coefficient parameterization), (2) taking into account a better meteorological forcing (improving spatial and temporal meteorological resolution). These high resolution models have been integrated in PREVIMER modeling system since 2013.

Introduction

Being able to properly forecast surges and sea level is essential for many applications, particularly for prevention of marine submersion risk. The developments of sea level and currents models answer many other needs: (1) improvements of wave models, taking into account currents influence on waves (Boudière *et al.* 2013), (2) prediction of presence or absence of some habitats (aquatic plants, laminaria algae); indeed, correlation between observation data and physical parameters linked with their developments (currents for example) allow to set up statistic models, which allow to predict habitats; (3) computation of boundary conditions for higher resolution coastal models (a few tens of meters), (4) study of transport by currents (microplastics, pollutants, larvae, harmful algae)…

The pre-operational system PREVIMER provides currents, sea levels and surges along Atlantic and English Channel coasts. The modeling system is based on MARS (2DH) hydrodynamic model, developed by Ifremer (Lazure and Dumas 2008). This study aims at developing high resolution spatial (250 m) and temporal (15 minutes) hydrodynamic models. The paper presents the model configuration, the improvement of parameterization, the validation and the results.

Models configuration

In order to reproduce surges dynamics, the model extension must be sufficiently extended up to the North and West, in order to properly take into account depressions, generating surges which will propagate in the English Channel and Bay of Biscay. Models are nested models (figure 1), of resolution:

- 2 km for the rank 0 model, covering North East Atlantic,
- 700 m for the rank 1 model, covering the Channel and Bay of Biscay,
- 250 m for the five rank 2 models, covering Eastern Channel, Western Channel, Finistère, South Britanny and Aquitaine areas.

(a)

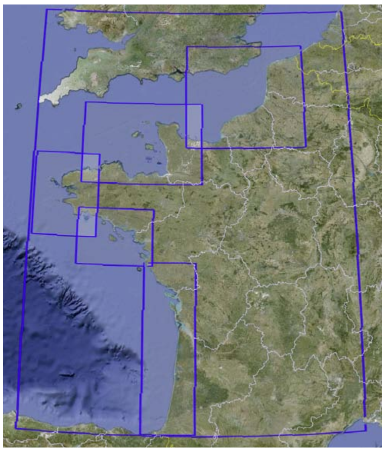
(b)


Figure 1: Extension of 2D models: rank 0 (North East Atlantic), rank 1 (English Chanel and Bay of Biscay) and 5 rank 2 models (Eastern Channel, Western Charnel, Finistère, South Brittany and Aquitaine)

Bathymetry comes from NOOS (North-West Shelf Operational Oceanographic System), EMODNET (European Marine Observation and Data Network), and Digital Terrain Models from Ifremer and SHOM (French Hydrographic Office) at 500 m and 100 m.

Meteorological forcing is provided by Météo-France, based on the meteorological models Arpege (Courtier *et al.* 1991, 1994) and Arome (Seity *et al.* 2011).

Each model runs twice, with and without meteorological forcing. Surges are calculated by subtracting the water level computed without meteorological forcing from the one computed with meteorological forcing. In both runs, the tide is taken into account. First, the tide is imposed at the boundary of the rank 0 model, using the FES2004 database (Lyard *et al.* 2006), which includes 14 harmonics constituents. Then, rank 1 is forced by the rank 0 water levels. Finally, the rank 2 models are forced (1) by tidal model cstFRANCE, developed by SHOM (Simon 2007), which includes 115 harmonic constituents (2) by surges from rank 1.

Parameterization improvement

A sensitive study has been carried out on meteorological forcing. Meteorological data, provided by Météo-France are outputs from Arpege High Resolution (HR) and Arome models. Their temporal resolution is of 6 hours for Arpege and 1 hour for Arpege High Resolution and Arome; their spatial resolution is respectively of 0.5°, 0.1° and 0.0025°. The sensitivity study to meteorological forcing (Pineau-Guillou 2013, Muller *et al.* 2014) showed the influence of temporal and spatial resolution. Comparisons have been made in January 2012 over rank 0 configuration (2 km). The 5th of January 2012, Andrea storm crossed North of France, generating surges up to 2 meters in Dunkerque (figure 2). Three meteorological forcing have been tested: Arpege HR merged with Arome, Arpege HR alone, Arpege alone. Results showed that there is no significant improvement in merging Arpege HR with Arome at this resolution (2 km), because results are very similar with these two forcing: RMS errors are respectively of 12 cm and 11 cm, maximal surge respectively of 1.63 m and 1.62 m. Concerning comparison between Arpege HR and Arpege: results showed also that RMS errors are very similar: respectively 11 and 10 cm at Dunkerque. However, storm surge peaks modelling is really improved with high resolution: maximal surge reaches 1.62 m with Arpege HR, instead of 1.45 m with Arpege, an improvement of 17 cm. Statistics clearly show a diminution of peak error with Arpege HR, and an improvement of maximal surges (Muller *et al.* 2014). The resolution of meteorological forcing improves mainly the storm surge modelling associated to energetic events.

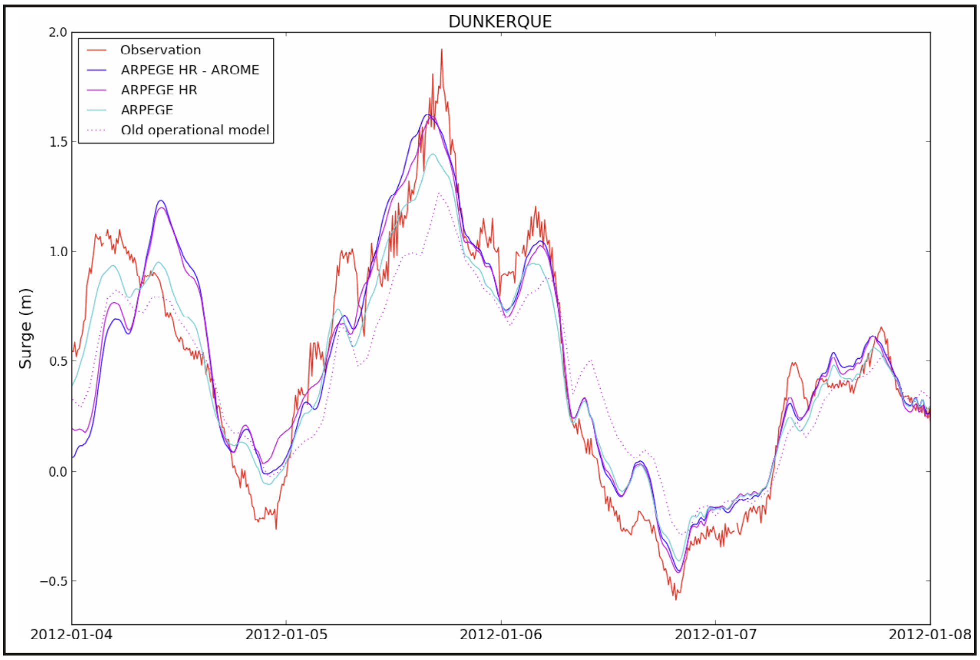


Figure 2: Surges at Dunkerque from 4 to 8 January 2012 (Andrea storm): influence of different meteorological forcing (Arpege HR merged with AROME, Arpege HR, ARPEGE) - Old operational model is forced with ARPEGE

Sea surface drag coefficient used for former PREVIMER operational model was a constant with value equal to 0.0016. Different parameterizations have been tested: wind dependant formulations (Wu 1982), (Moon *et al.* 2007), (Makin 2005) but also a wave and wind dependant formulation (Charnock 1955), inside PREVIMER working group on surges modeling (Idier *et al.* 2012). Charnock formulation takes into account surface roughness du to waves. By definition, the drag coefficient is expressed as:

$$Cd = \frac{u_*^2}{U_{10}^2} = \kappa^2 \left[\ln \frac{z}{z_0} \right]^{-2}$$ at z=10 m (height above surface)

with u_* the friction velocity, U_{10} 10 m-wind, κ Von Karman's constant, and z_0 surface roughness.

Surface roughness is expressed as $z_0 = a_c \frac{u_*^2}{g}$, where a_c is the Charnock dimensionless parameter.

In this study, the Charnock parameter can be constant (0.014), or variable and in this case, issued from WAVEWATCH III® (Tolman 2008, Ardhuin *et al.* 2010, Tolman *et al.* 2013), computed from the IOWAGA modeling system (Rascle and Ardhuin 2013) or from PREVIMER wave models. Sensitivity tests to drag coefficient formulation (constant, Wu, Moon, Makin, Charnock) show that taking into account wind and wave action (Charnock formulation with variable coefficient) give the best results, improving surge peaks modeling (Idier *et al.* 2012, Muller *et al.* 2014). During the Xynthia storm (28th February 2010), the differences using a constant drag coefficient (0.0016) and a Charnock formulation with a variable Charnock coefficient, on rank 0 model, reach 18 cm at La Rochelle (Pineau-Guillou *et al.* 2012b). These results are consistent with results obtained by (Bertin *et al.* 2012). A sensitive study has also been carried out on rank 2 models for the Petra storm (4th February 2014). Comparisons have been made between different drag coefficient parameterization: constant one (0.0016), Charnock formulation with a constant parameter (0.014) and Charnock formulation with a variable parameter, issued from PREVIMER wave models. Results at Brest (figure 3) show an improvement of modeled surge up to 6 cm between constant value and Charnock formulation with constant parameter, and up to 12 cm between constant value and Charnock formulation with variable parameter. These improvements concern mainly peak surges. Generally, surges are still underestimated, compared to observations. However, the particular parameterization of the wave model (Rascle and Ardhuin 2013) improves short wave properties, but removes most of the wave-induced variability in the Charnock coefficient, and limits in our case the impact on results. Such results could still be improved, with different parameterization in the wave model.

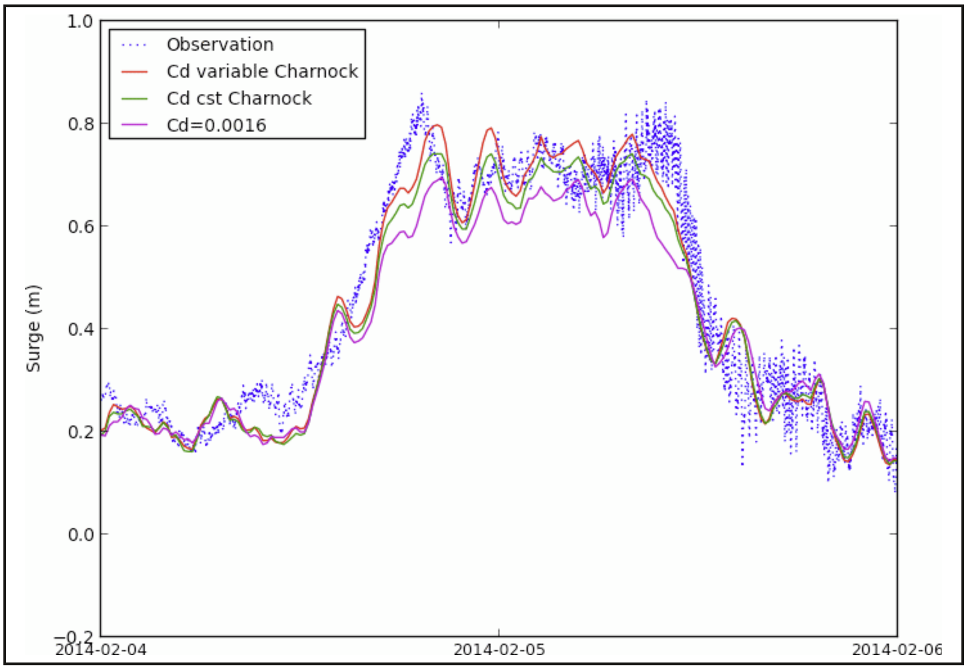


Figure 3: Surges at Brest from 4 to 6 February 2014 (Petra storm): influence of drag coefficient parameterization (Charnock formulation with a variable or constant Charnock parameter, constant drag coefficient)

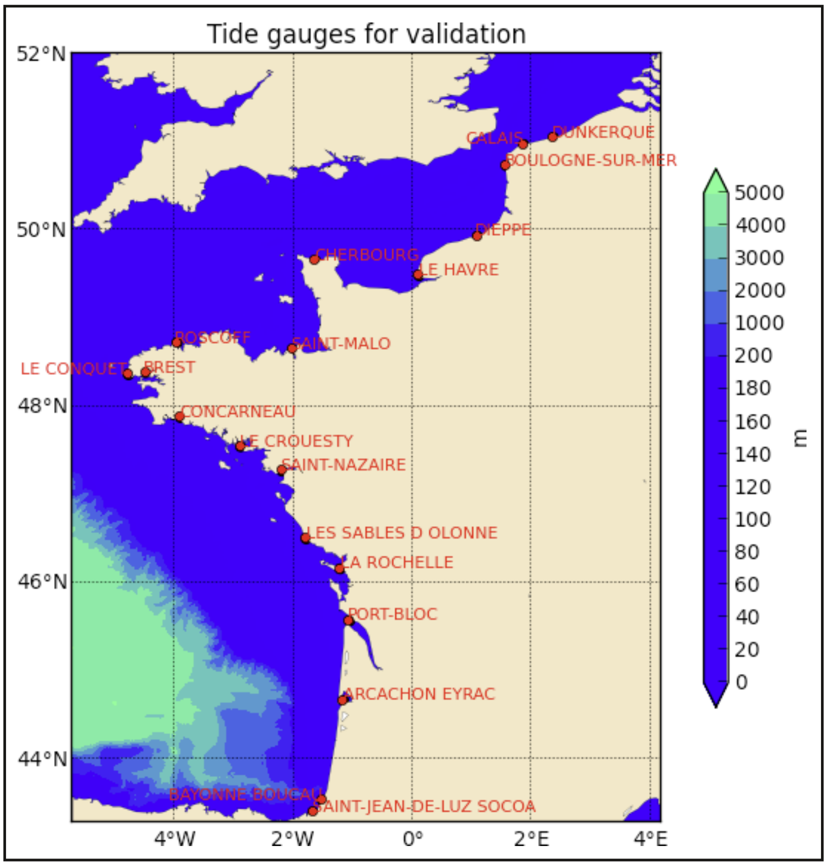


Figure 4: Tide gauges locations for tide, sea level and surges validation

Validation

Validation has been carried out (Pineau-Guillou 2013) in 19 tide gauges (figure 4) from permanent network RONIM (French Sea Level Observation Network, managed by SHOM). For each site, data from numeric tide gauges have been collected through REFMAR (www.refmar.shom.fr), and analyzed in order to compute harmonic components. From these components, tidal predictions have been made, and used to extract the observed storm surge from the water level measurements.

Models have been validated in February 2010, during Xynthia storm (28 February 2010) (Pineau-Guillou *et al.* 2012a). Simulations have been carried from 15th to 28th February 2010 (Pineau-Guillou 2013). Meteorological forcing is a merge between Arome, Aladin and Arpege models outputs every 3 hours (Arpege High Resolution was not available in February 2010).

Tide has been validated by comparing modeled tide (from simulations without meteorological forcing) with predictions (based on observations harmonic analysis) at the 19 points presented figure 4. An example of validation is presented figure 5. RMS errors have been computed for each tide gauge and each model (table 1). They are on average of 22 cm for rank 0, 21 cm for rank 1 and 11 cm for rank 2 models; biases are on average of 3 cm for ranks 0 and 1, and null for rank 2 models. Tide is clearly improved for rank 2 models, which comes from the introduction at rank 2 boundary conditions of cstFRANCE tidal model (115 harmonic constituents, instead of 14 with FES2004 for rank 0), but also from the improvement of spatial resolution (250 m instead of 2 km for rank 0). Comparison between modeled tide with tidal predictions at Le Conquet between 22nd and 25th February 2010, shows clearly improvements between rank 0, rank 1 and rank 2 (figure 6).

Location	**RMS Error (cm)**			**Bias (cm)**			**Rank 2 model**
	Rank 0	Rank 1	Rank 2	Rank 0	Rank 1	Rank 2	MANE
Dunkerque	15	14	10	3	3	-3	MANE
Calais	17	17	11	4	5	0	MANE
Boulogne-sur-Mer	20	20	13	2	2	-4	MANE
Dieppe	22	23	14	5	5	0	MANE
Le Havre	20	21	13	0	1	-4	MANE
Cherbourg	13	15	6	0	2	-1	MANW
Saint-Malo	28	30	15	2	2	-3	MANW
Roscoff	20	21	7 *8*	3	4	0 *3*	MANW FINI
Le Conquet	19	18	7	1	-4	-4	FINI
Brest	32	15	10	1	1	0	FINI
Concarneau	14	14	*8* 7	-2	-2	*-5* -5	FINI SUDB
Le Crouesty	18	18	7	2	2	-1	SUDB
Saint-Nazaire	20	21	10	-1	-1	-6	SUDB
Les Sables d'Olonne	18	19	6	-2	-2	-2	AQUI
La Rochelle-Pallice	24	26	10	3	4	4	AQUI
Port-Bloc	34	19	13	1	0	1	AQUI
Arcachon	56	55	35	31	34	24	AQUI
Boucau-Bayonne	19	19	10	1	1	2	AQUI
Saint-Jean de Luz	12	13	8	3	3	4	AQUI
Mean	**22 cm**	**21 cm**	**11 cm**	**3 cm**	**3 cm**	**0 cm**	

Table 1: Root Mean Square errors and biases of water levels from different ranks (0, 1 and 2) without meteorological forcing (tide only) - Computed from 17th to 28th of February 2010

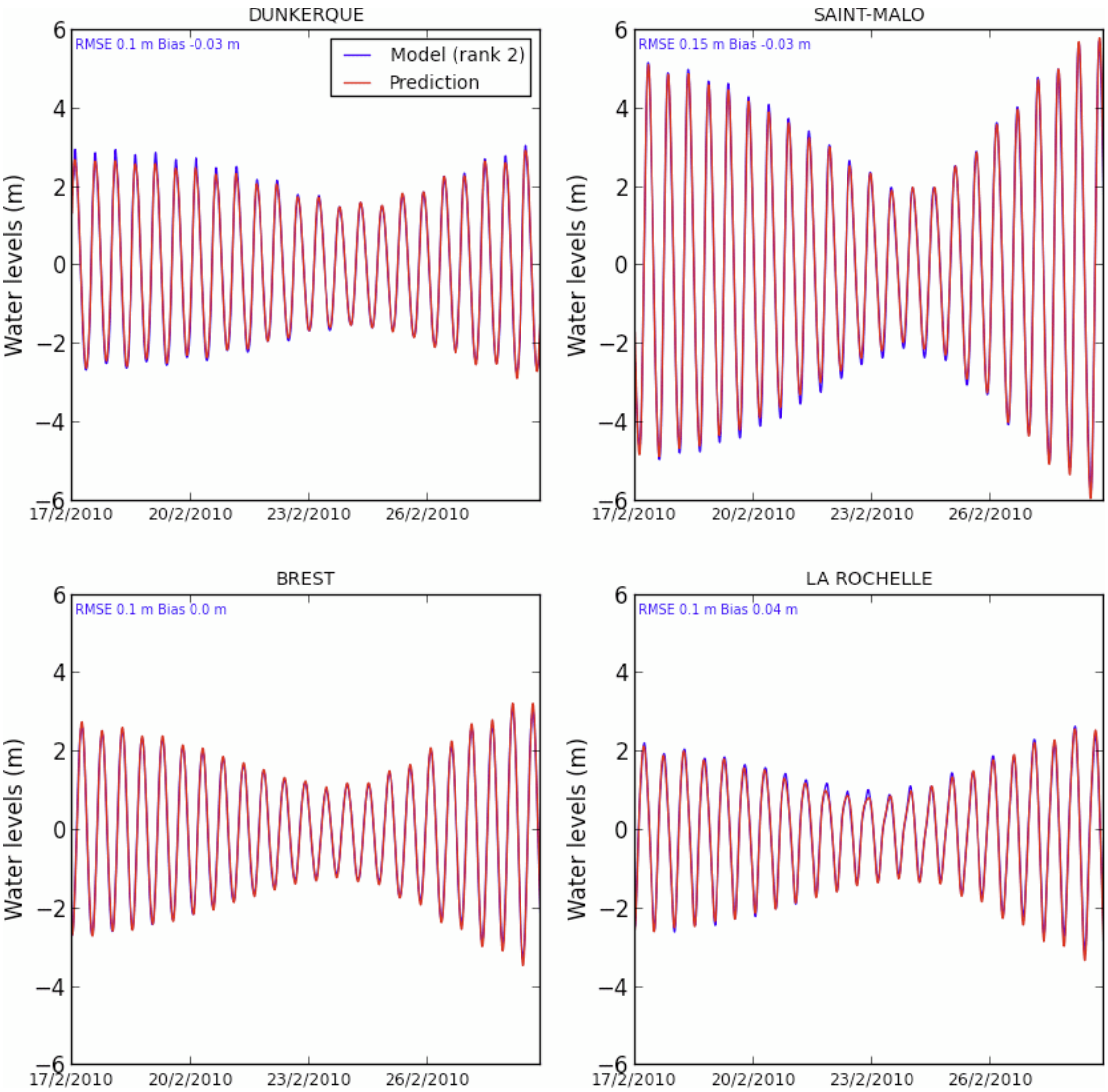


Figure 5: Comparison between modelled tide from rank 2 (without meteo) and predicted tide from observation at Dunkerque, Saint-Malo, Brest and La Rochelle, from 17 to 28th February 2010.

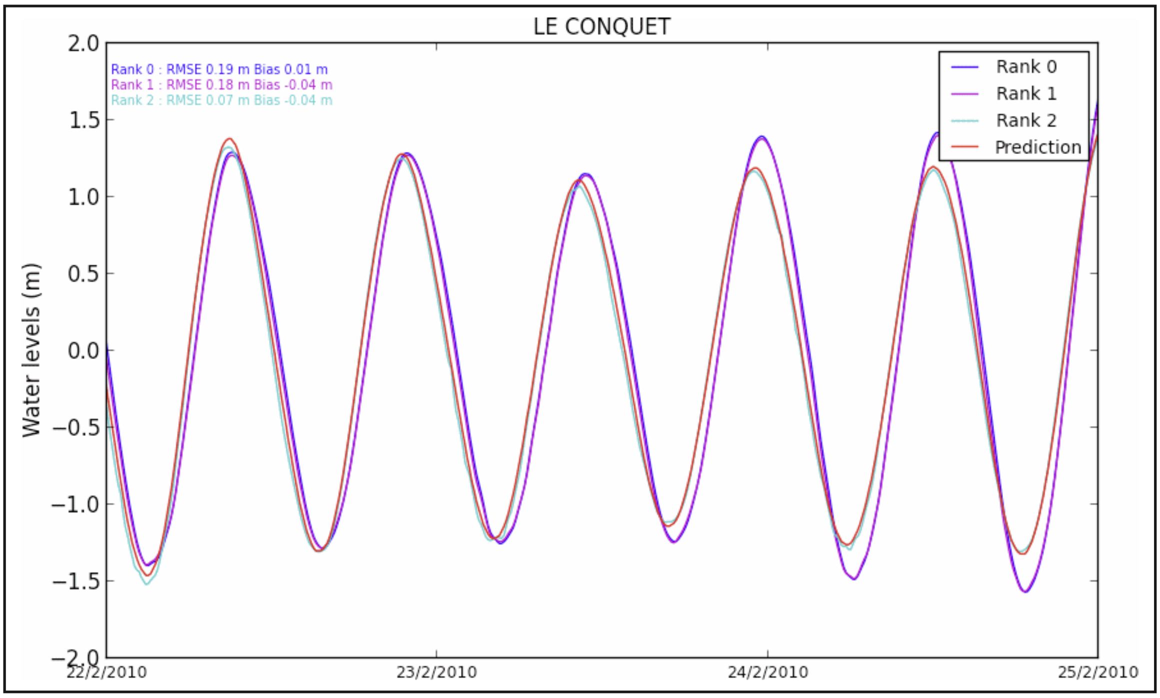


Figure 6: Comparison between modelled tide from rank 0, 1 and 2 models (without meteo) with predicted tide from observation at Le Conquet, from 22nd to 25th February 2010

The total sea levels (including tide and surge) have been validated by comparing modeled sea levels (from simulations with tide and meteorological forcing) with observations at 18 points presented figure 4 (no observations available at Boulogne-sur-mer). RMS errors are on average of 26 cm for rank 0, 24 cm for rank 1 and 16 cm for rank 2 models; biases are on average of -5 cm for ranks 0 and 1, and -7 cm for rank 2 models. Improvement of sea levels at rank 2 comes mainly from tide improvement (explained before).

Surges have been validated by comparing modeled surges (difference of simulations with and without meteorological forcing) with observed surges (differences between tide gauges observations and predictions) at 18 points. An example of validation figure is presented figure 7, at Dunkerque, Cherbourg, Le Conquet and La Rochelle. RMS errors and biases are the same for the three ranks: 13 cm and -8 cm. This result shows that the improvement of spatial resolution does not allow improving significantly surges modeling; surges from these 3 ranks are very similar, even if a small improvement is noticed on rank 2 models. Globally, modeled surges are inferior to measured ones, with a mean bias of 8 cm. This can be explained by the parameterization (drag coefficient can still be improved, see above), but also by wave set-up, which is not modeled here, and is far from being negligible – from few centimeters up to several tens of centimeters in the total surge (Idier *et al.* 2012, Bertin *et al.* 2012), depending of the site configuration.

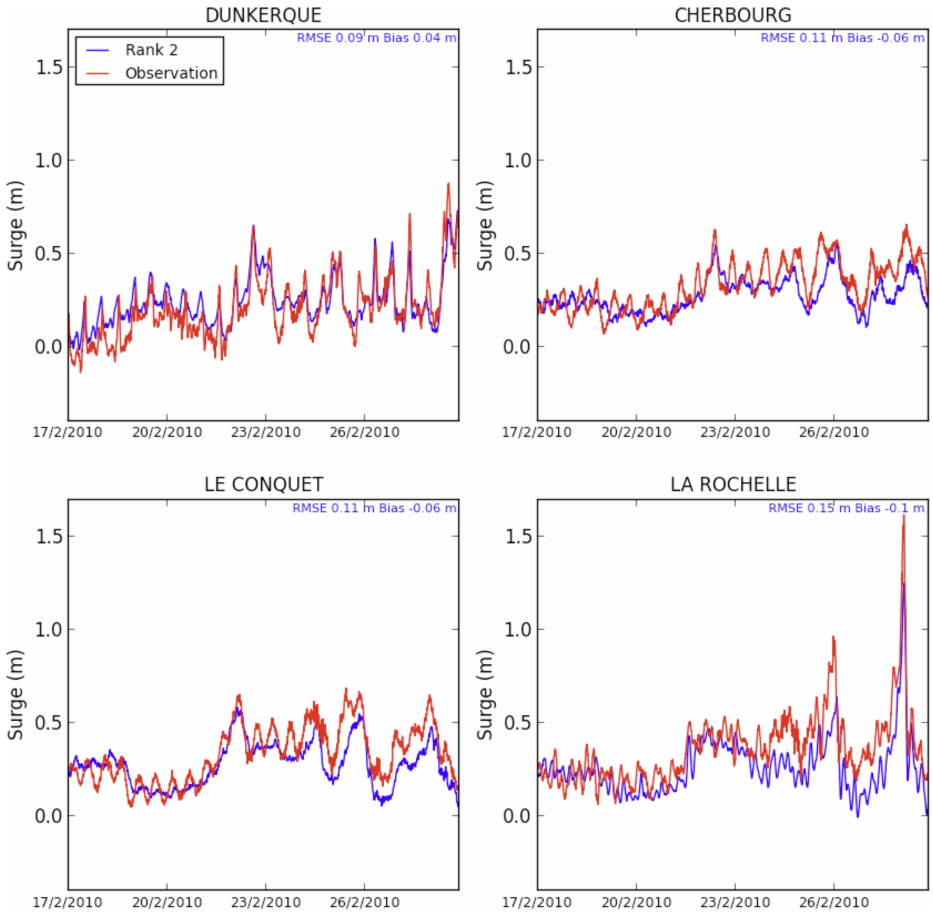


Figure 7: Comparison between modelled surge from rank 2 model and observed surge at Dunkerque, Cherbourg, Le Conquet and La Rochelle, from 17 to 28 February 2010

Comparisons have been made between the old operational model used in the PREVIMER system (rank 0, 5.6 km, forced with Arpege, constant drag coefficient of 0.0016) and the new one (rank 0, 2 km, forced with Arpege HR, variable Charnock formulation for drag coefficient). RMS errors and biases have been computed for the January 2012 period. RMS errors of water levels are, on average, improved, with a reduction from 40 cm to 22 cm. Surges modeling is not significantly improved, with similar RMS errors on average of 9 cm; however, peak storm surges are really improved with differences up to 25 cm (162 cm instead of 127 cm in Dunkerque) (cf Table 2).

Location	**Water levels RMSE**		**Surges RMSE**		**Maximal surges**		
	Old model	New model	Old model	New model	Old model	New model	Observation
Dunkerque	40 cm	18 cm	14 cm	11 cm	**127 cm**	**162 cm**	193 cm
Saint-Malo	43 cm	29 cm	8 cm	9 cm	**32 cm**	**61 cm**	63 cm
Le Conquet	50 cm	17 cm	5 cm	5 cm	**11 cm**	**17 cm**	27 cm
La Rochelle	26 cm	23 cm	7 cm	10 cm	**14 cm**	**37 cm**	31 cm
Mean	**40 cm**	**22 cm**	**9 cm**	**9 cm**			

Table 2: Water levels and surges RMS errors and maximal surges for old operational model and new one (in production since 2013) – Computed for the January 2012 period

Finally, tidal currents have been validated by comparing modeled mean spring tide currents (from simulations without meteorological forcing, the 27th of February 2010, tidal coefficient of 94) with observations (tidal currents in mean spring tide), provided by SHOM (locations on figure 8). Tidal roses have been plotted. Examples of current validation figures are presented figures 9 and 10. They show quite good correlation between model and observations.

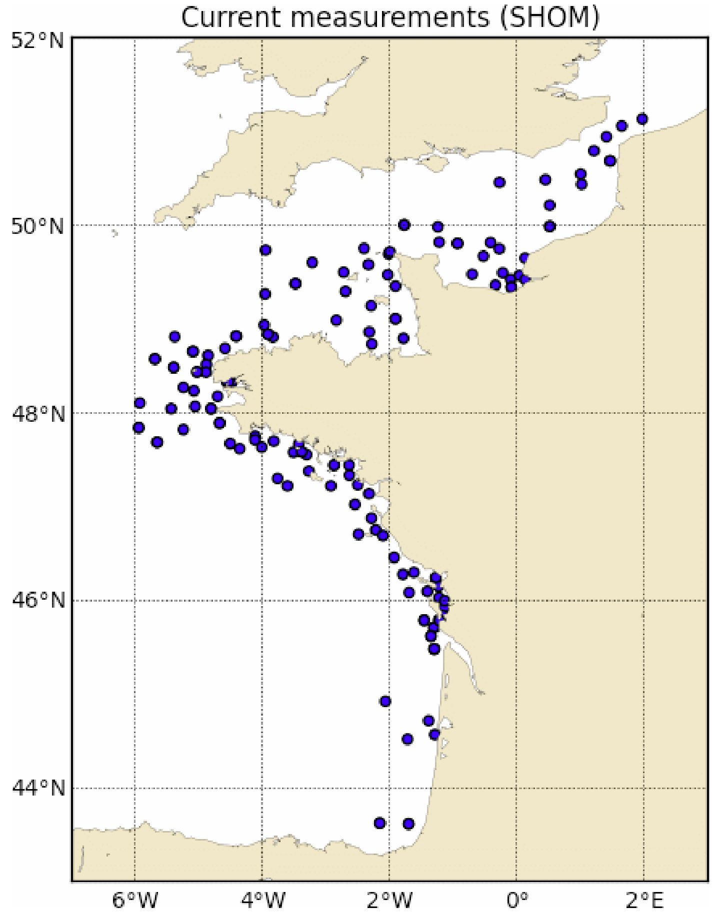


Figure 8: Current measurements location provided by French Hydrographic Office (SHOM)

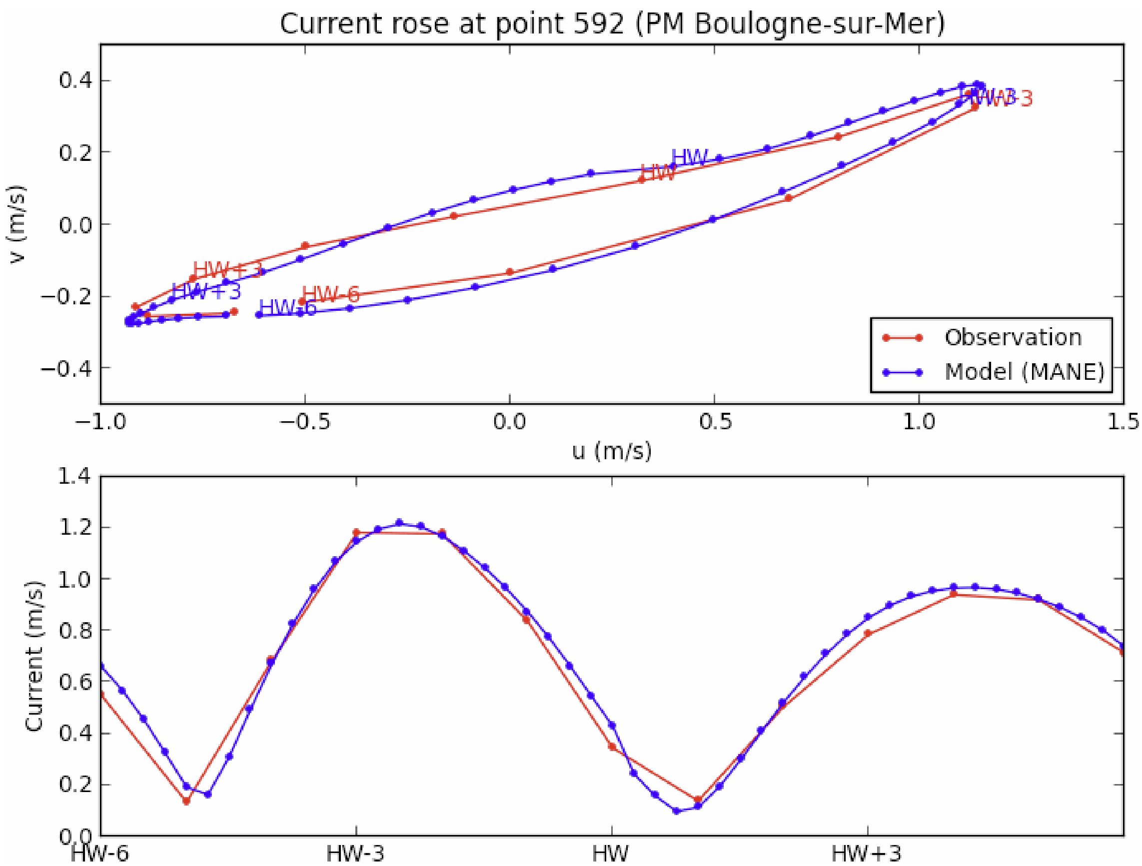


Figure 9: Comparison between modelled and observed mean spring tide currents and observed at point 592 in Eastern Channel

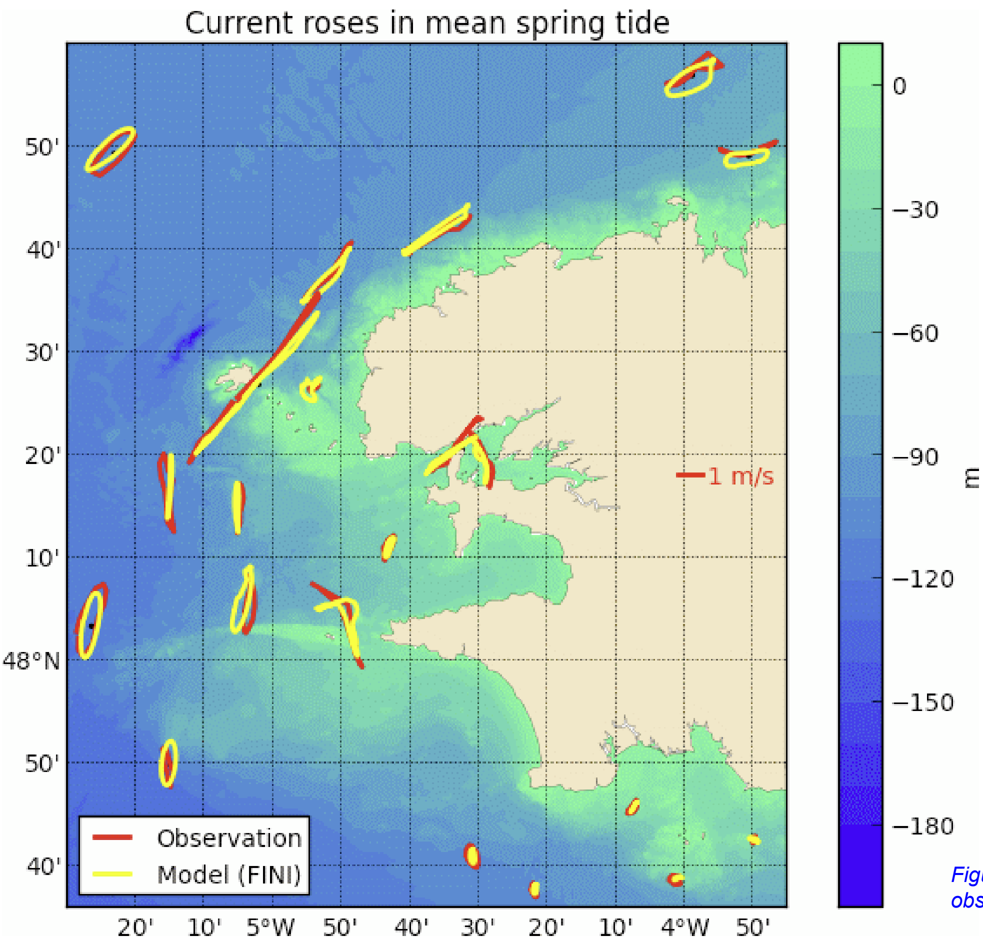
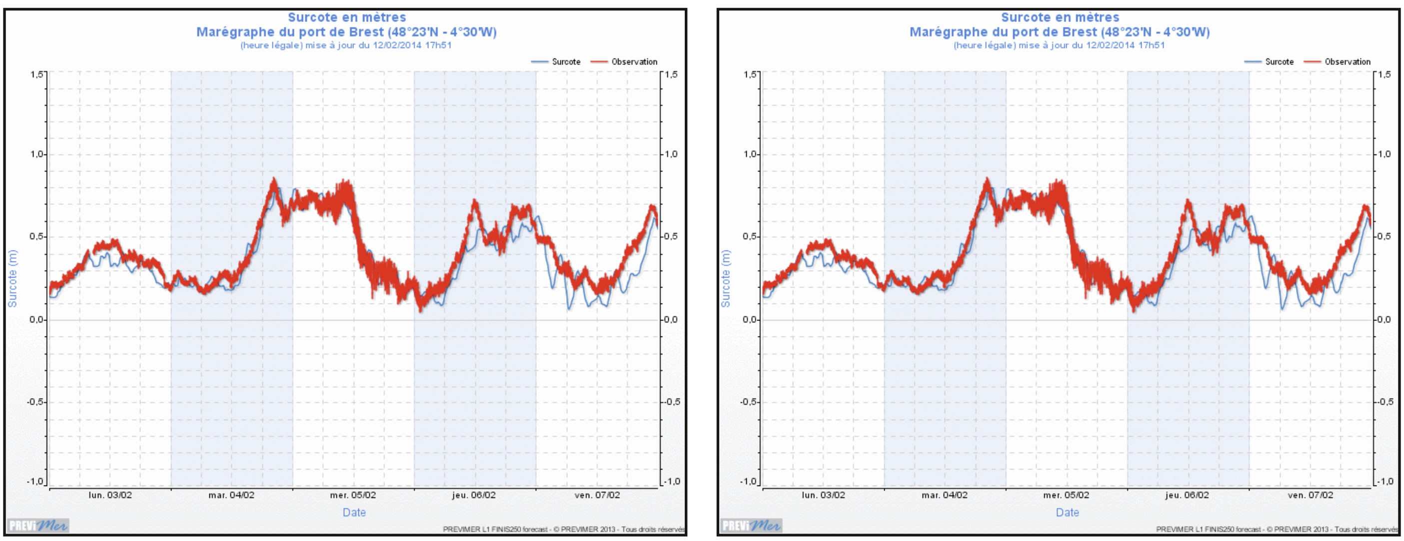


Figure 10: Comparison between modelled and observed current roses in mean spring tide

Results

The operational model is in production since 2013. Every day, MARS simulations are made from the day before up to 4 days in advance (simulation over 5 days). Charnock coefficients are issued from PREVIMER WAVEWATCHIII® operational configuration. 14 simulations are computed (7 models with and without meteorological forcing in order to compute surges) on 64 processors. The data volume represents daily 15Go (for 5 days simulation), a year represents 1.2 To. Hindcasts have been computed from 2006. Data are used by many users: Ifremer for its own needs (detailed in introduction), but also PREVIMER partners like Meteo-France to access to modeled surges, CEREMA (ex CETMEF) for harbour management, or external users like private companies for studies on renewable marine energy or water quality. The website www.previmer.org shows historical and real-time results, but also comparisons between models and measurements. As illustrations of the PREVIMER system outputs, surges at Brest and Calais during Petra storm (4th of February 2014) are presented figure 11, whereas currents in Iroise Sea are presented figure 12.



(a) (b)

Figure 11: PREVIMER website www.previmer.org: comparison between modelled and observed surges at Brest (a) and Calais (b) from 3 to 7th February 2014

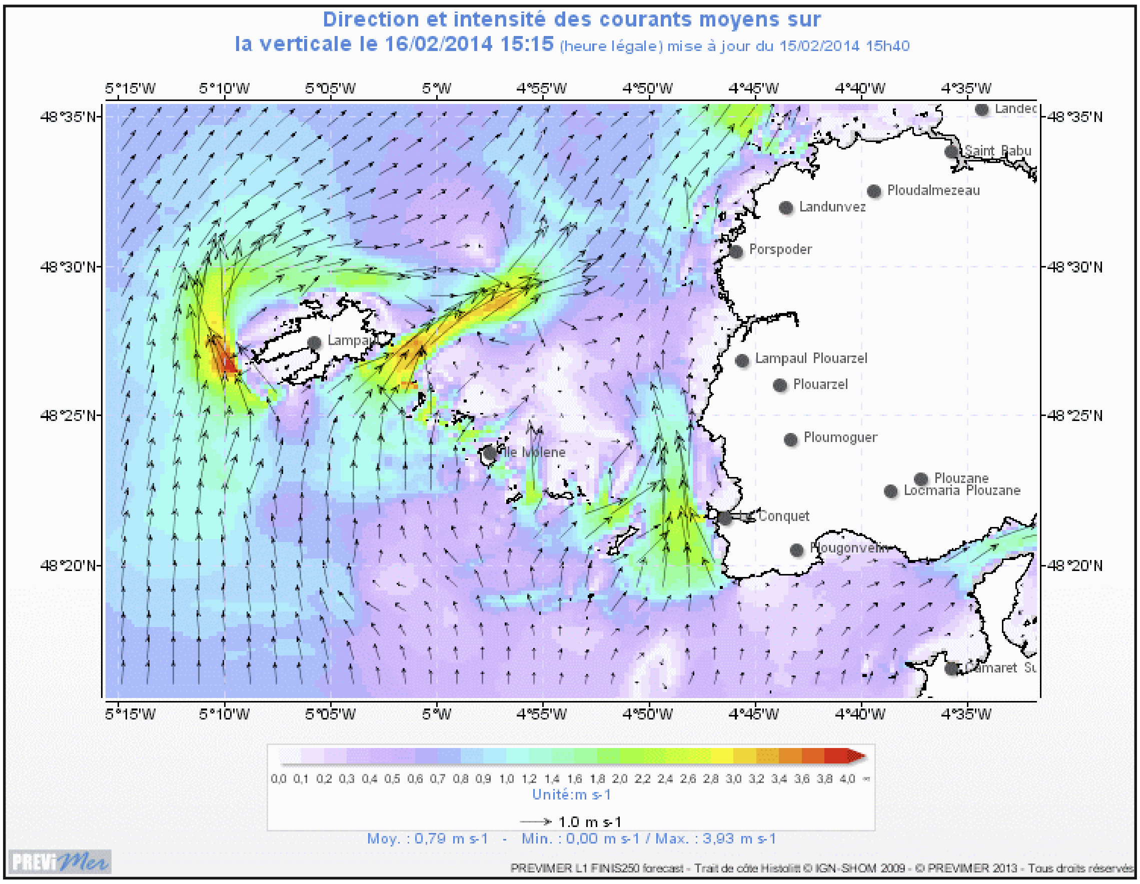


Figure 12: PREVIMER website www.previmer.org: currents in Iroise sea the 16th of February 2014 at 15:15

Conclusion

Sensitivity studies showed the influence of temporal and spatial meteorological forcing in storm surge modeling. Modeled surges have also been improved taking into account a better parameterization of surface drag coefficient. Wave effects on sea surface roughness is taken into account through a Charnock formulation, with a Charnock parameter variable and issued from PREVIMER wave models (WAVEWATCH III®). This parameterization allows improving peak surges, through an error reduction up to around 20 cm.

New parameterization (better space resolution, meteorological forcing and surface drag parameterization) has clearly improved results, dividing by two RMS errors of the water levels on rank 0 model. For rank 2 models, RMS errors for water levels are on average of 11 cm, and biases are null, which is satisfying. Concerning surges, the improvement of space resolution between rank 0 (2km) and rank 2 (250 m) did not allow improving significantly results. Main improvements came from surface drag parameterization and better meteorological forcing.

However, models still underestimate surges. A perspective is the improvement of Charnock parameter: the particular parameterization of the wave model (Rascle and Ardhuin 2013) improves short wave properties, but removes most of the wave-induced variability in the Charnock coefficient, and limits in our case the impact on results. Another improvement will be to take into account wave setup (surge due to wave breaking). This process is generally not taken into account in (pre-)operational coastal modeling systems, but its effect is far from being negligible, up to several tens of centimeters in the total surge (Idier *et al.* 2012, Bertin *et al.* 2012), especially on open coast (eg. Aquitanian coast) or basins (eg. Arcachon basin) sites; it can represents in some area, as Aquitaine coast, 50% of surge (Idier *et al.* 2012). This wave setup can be computed with a wave-current coupling model, or with a wave model, taken into account water level and currents, and then added to the atmospheric surge issued from the circulation model.

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