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Atmopheric forcing impact study in Météo-France storm surge model

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Abstract

A depth-averaged, numerical storm-surge model has been developed and configured to provide storm-surges forecasts along coastlines of France. The primary data requirement for modelling storm surges is accurate surface wind and atmospheric pressure fields, in particular in the vicinity of maximum winds. These fields are taken from atmospheric numerical models: IFS (European Center for Medium Range Weather Forecasts), ARPEGE and ALADIN (Météo-France). The system has been operated since October 1999.
One particular case is studied: a severe storm that hit Atlantic coast of France on December 27th, 1999. Storm surges forecasts were lower than observations.
The effect of both spatial and temporal interpolation of wind is investigated. Spatial interpolation on wind components from the atmospheric model grid to the storm surge model grid leads to a loss of energy. Spatial interpolation on intensity and direction of wind is preferable. Temporal interpolation is critical when a fast low is crossing the calculation domain. That was the case on December 27th, 1999. Then, wind fields with 1-hour interval instead of 6 hours are required. Initialisation process is also important and has been investigated.

1 Introduction

A storm surge is the elevation of water generated by strong wind-stress forcing and by a drop in the atmospheric pressure. Far from the coast, the surge is mainly controlled by the atmospheric pressure. This effect called the inverted barometer effect is the hydrostatic answer of the ocean. Close to the coast, dynamic effects become pronounced. Local bathymetry, shallow waters and

coastline configuration amplify the surge height. The surge may reach several meters.
A brief description of the model and of the numerical solution is given in the next section, then the input (bathymetry and atmospheric forcing) is described and the case of December 27th storm is analysed.

2. The storm surge model

2.1 Equations

A depth-integrated model has been adopted for the surge prediction. Initially, the model was developed for the French overseas territories to forecast tropical cyclones storm surges [1]. Then the model has been adapted for the coastline of France and also to the Black Sea [2].

The model is driven by wind stress and atmospheric pressure gradients. It solves the non-linear shallow-water equations written in spherical coordinates:

$$\frac{\partial q}{\partial t} + q.\nabla q + f.k\Lambda q = -g.\nabla\eta - \frac{1}{\rho}\nabla P_a + \frac{1}{\rho.H}\left(\tau_s - \tau_b\right) + A.\nabla^2 q$$

$$\frac{\partial \eta}{\partial t} + \nabla\left(H.q\right) = 0$$

where q is the depth-integrated current, η is the sea surface elevation, H is the total water depth, f is the Coriolis parameter, P_a is the atmospheric surface pressure, τ_s is the surface wind stress, τ_b is the bottom frictional stress, ρ is the density of water, g is the gravitational acceleration and A is the horizontal diffusion coefficient (2000 m^2/s).

The surface wind stress components are computed using the quadratic relationship:

$$\begin{cases} \tau_{sx} = \rho_a.C_d.\left|W_{10}\right|.W_{10x} \\ \tau_{sy} = \rho_a.C_d.\left|W_{10}\right|.W_{10y} \end{cases},$$

where W_{10x}, W_{10y} are the horizontal components of wind velocity 10 m above the sea surface, ρ_a is the air density C_d is the drag coefficient calculated by the Wu [2] formulation.

The bottom stress components are computed using the quadratic relationship:

$$\begin{cases} \tau_{bx} = \rho_w.C_b.\left|q\right|.q_x \\ \tau_{by} = \rho_w.C_b.\left|q\right|.q_y \end{cases},$$

where q_x, q_y are the horizontal components of the depth-integrated current, ρ_w is the water density (ρ_w = 1026 kg.m^{-3}), C_b is the drag coefficient (C_b = 0.002).

2.2 Boundary conditions and bathymetry

At coastal boundaries the normal component of velocity is zero. At open boundaries, the sea surface elevation is given by the tide plus the inverted barometer effect. 17 tide waves are included.

The bathymetry has been hand extracted from nautical charts. The grid mesh is 5 minutes in latitude – longitude.

2.4 Operating procedure

The model is activated two times. First with tide only and then with tide and atmospheric forcing. The surge is the difference between the second simulation and the first one.

3. Case study: December 27th, 1999

3.1 Storm description

A deep low (965 hPa) reached Brittany (Ushant island) on December 27th, 1999 at 15 UTC and crossed France in 12 hours at a 100 km/h speed. Maximum winds were recorded in south-west of France near Gironde estuary with 194 km/h at Royan and 198 km/h at Oleron.

A significant surge occurred in the Gironde estuary in the evening of December 27th. The surge height is estimated to about 2 meters in the end of the estuary and 1.5 meters at Le Verdon in the entrance of the estuary (figure 1). Exact values are unknown since a cut of electricity stopped the data recording. The surge lead to a partial flooding of a nuclear power station near Le Blayais close to the end of the estuary.

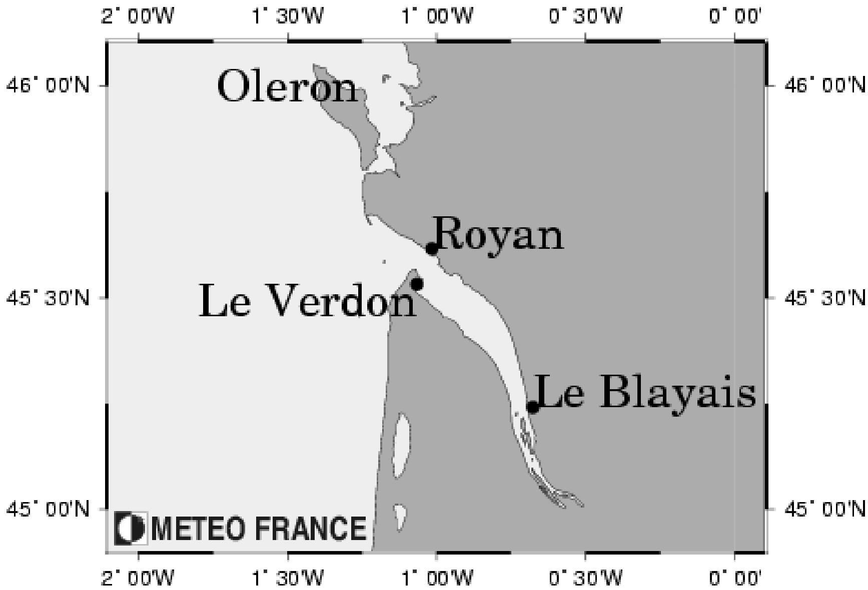


Figure 1: Map of the Gironde estuary area.

3.1 Operational surge forecast

On December 27th, 1999, the Meteo-France storm surge model was not fully operational. Daily forecasts were delivered, on an experimental basis, with atmospheric forcing coming from IFS (European Center from Medium range Weather Forecasts) atmospheric model. IFS is a global model with a fixed mesh of 0.5 degree. Since the storm surge model is not adapted for flow modelling in the estuaries, we focus here on a port located in the entrance of the estuary: Le Verdon. In this particular location, the storm surge forecasted by the model was about 20 cm (figure 2a), far below the reality which has been estimated to 150 cm.

3.2 Atmospheric forcing comparison

Simulations are conducted with forcing from several other atmospheric models in same conditions (forecast mode) as if they had been available at the time of the surge. ARPEGE is a global model with a variable grid mesh. Its grid is stretched and has the thinnest resolution over France (0.25° degree). ARPEGE was improved on June 2000 with inclusion of four dimensional variationnal data assimilation (4DVAR). This latter version is referred here as ARPEGE/4DVAR ALADIN is a limited area high resolution model initialised by ARPEGE. ALADIN has a resolution of 0.1 degree. ARPEGE and ALADIN belongs to

Météo-France. The temporal frequency of forcing is 3 hours for ARPEGE and ALADIN and 6 hours for IFS.

Simulations with these atmospheric forcing are shown below (figures 2). With ARPEGE and ALADIN, the forecasted surge is much better than with IFS.

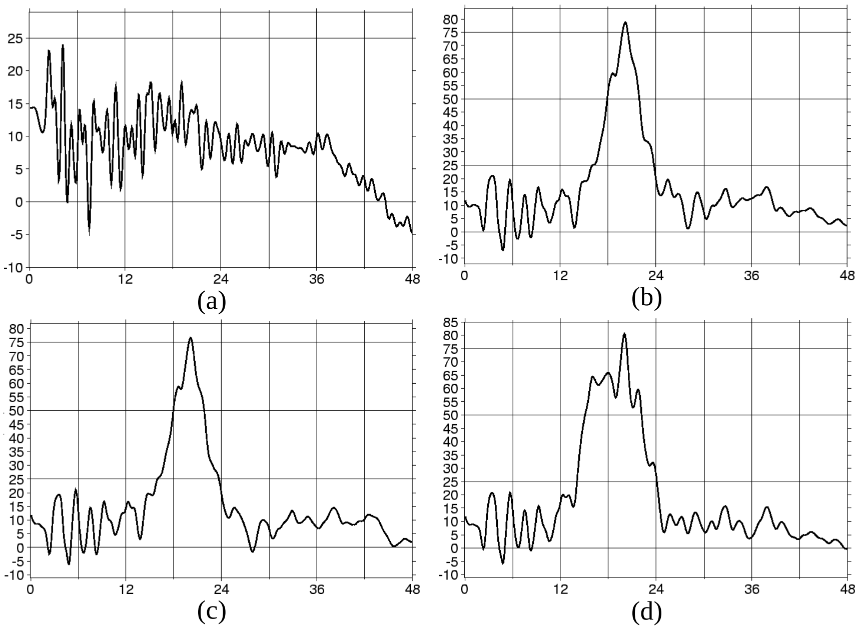


Figure 2 : Modelled storm surge in cm at Le Verdon with atmospheric forcing from IFS (a), ARPEGE (b), ALADIN(c) and ARPEGE/4DVAR (d). Hours starting on December 27th, 0 UTC.

In hindcast mode (forcing with analysed winds), the model simulates a 120 cm surge in the Verdon (ARPEGE/4DVAR analyses, figure 3).

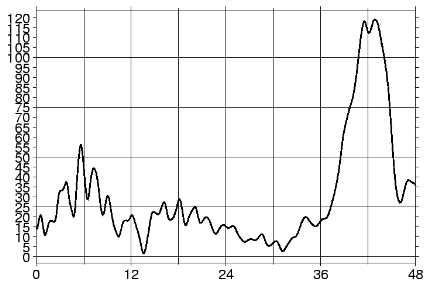


Figure 3 : Modelled storm surge in cm at Le Verdon (ARPEGE/4DVAR analyses forcing). Hours starting on December 27th, 0 UTC

Table 1: modelled storm surges comparison

Atmospheric forcing	Grid mesh (degree)	Time step (hours)	Surge at Le Verdon (cm)	Figure
IFS forecast	0.5	6	20	2a
ARPEGE forecast	0.25	3	79	2b
ALADIN forecast	0.1	3	77	2c
4DVAR forecast	0.25	3	81	2d
4DVAR hindcast	0.25	3	120	3

Now, in operational mode, three different atmospheric models are used to give daily storm surge forecasts up to 48 hours: IFS, ARPEGE/4DVAR and ALADIN.

3.3 Impact of interpolation method

The storm surge model mesh is fixed with a 5' resolution. Time step is 15 seconds. Atmospheric forcing is interpolated both in space and time. The impact of the interpolation is investigated below.
Winds and sea level pressure are interpolated from the atmospheric grid mesh to the storm surge grid mesh in the following way.

$$W_i = (1-x).(1-y).W_1 + (1-x).y.W_2 + x.y.W_3 + x.(1-y).W_4$$

where W_1,W_2,W_3 and W_4 are atmopheric parameter (wind or pressure) on the atmopheric model grid. *Wi* is the interpolated value on the storm surge model grid.

The wind interpolation can be done in two different ways: on wind components or on wind intensity and direction. The first method leads to a loss of energy that can be important in case of strong wind rotation. More details can be found in Skandrani [5]. Interpolation of the winds on force and direction, rather than on zonal and meridian components minimize the energy loss and seems to be preferable in most meteorological conditions.

Temporal interpolation is done in the same way than spatial interpolation. Figure 4a shows a common pattern of the effect of temporal interpolation on components. A strong gap on wind speed intensity occurs between 15 and 18 hours because of an important wind rotation. Figure 4a should be compared with figure 4b where there is no energy loss between two atmospheric forcing time-steps. The incidence on storm surge is significant and is about 10% in this situation.

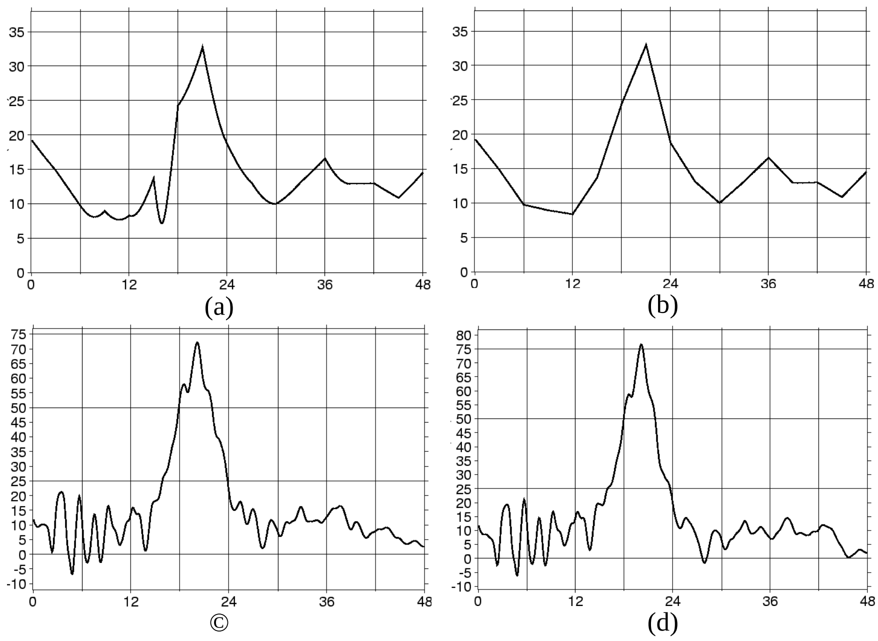


Figure 4: ARPEGE winds in knots at Le Verdon with interpolation on components (a) and on intensity (b). Modelled storm surges in cm at Le Verdon with ARPEGE winds interpolated on components (c) and on intensity (d). Hours starting on December 27th, 0 UTC

Table 2: modelled storm surges comparison

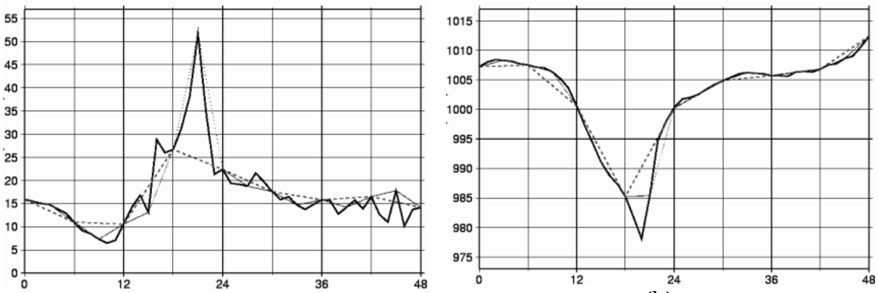
Interpolation method	Surge at Le Verdon (cm)	Figure
Components	72	6c
Intensity	79	6d

3.4 Impact of atmospheric input temporal frequency

The impact of atmospheric input frequency is checked here. The storm surge model is run with wind and pressure from ALADIN model. ALADIN is initialised with ARPEGE 4D-VAR analyses (not operational at that time) and is forced at its lateral boundaries by ARPEGE forecasts. We carried out three surge forecasts from December 27 at 00h UTC which differ only by the temporal frequency of atmospheric forcing: one hour, three hours and six hours. These forecasts would have been available in early morning of December 27th .

Modelled storm surges are shown below (figure 5c) for each forcing. The surge reached 120cm with hourly forcing, 85cm for three hours and 70cm for six hours forcing. The maximum surge is reached at 19h45 for 6 hours forcing, at 20h05 for 3 hours forcing and 20h40 for hourly forcing. The time of the maximum surge is important because it should be compared with the full tide time. On December 27, 1999 the full tide at la Verdon was at 20h15 UTC.

Figures 5a and 5b show the wind at a 10m elevation and sea level pressure at the Verdon for each considered forcing. The impact of temporal interpolation on quickly varying wind and pressure is shown. We must keep in mind that storm surge is not a local phenomenon: the wind and pressure differences in the Verdon are not supposed to explain modelled surges differences. However, the fact that the maximum of wind occurs towards 21h UTC (either at a 3 hours forcing time) tends to decrease the surge difference between hourly forcing and and 3 hours forcing.



(a) (b)

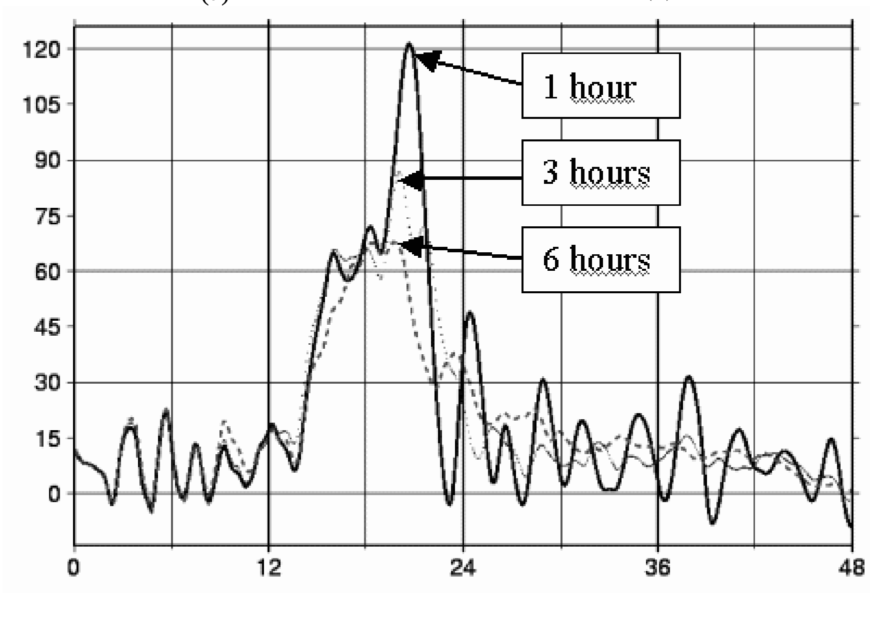


Figure 5 : Modelled wind in knots (a), sea level pressure in hPa (b) and storm surge in cm (c) at Le Verdon for three different temporal forcing frequencies.

Table 3: modelled storm surges comparison

Time step (hours)	Surge at Le Verdon (cm)	Figure
6	70	
3	85	7
1	120	

4 Impact of initialisation process

In operational mode, the storm surge model is activated once a day. The simulation starts with oceanic data (currents and sea elevation) from the 24 hours forecast of the previous day. But there is a gap in the atmospheric data: the temporal sequence of forcing at the time of the restart is not homogeneous. For ARPEGE, at the last time-step before the restart, atmospheric forcing is almost identical to the 24 hours forecast. At the first time-step after the restart, atmospheric forcing comes from ARPEGE analyses at 00 UTC and can be very different. This discontinuity produces oscillations in the storm surge model. The oscillations are likely to make unusable the first 24 hours forecast.
A modification has been adopted. Now, the storm surge model starts with oceanic data 24 hours before (at 00 utc the previous day). The simulation begins with atmospheric analyses for 24 hours so as to obtain an initial state for the forecast launched starting at 00 UTC.
The impact is significant: the oscillations are strongly reduced (figure 6).

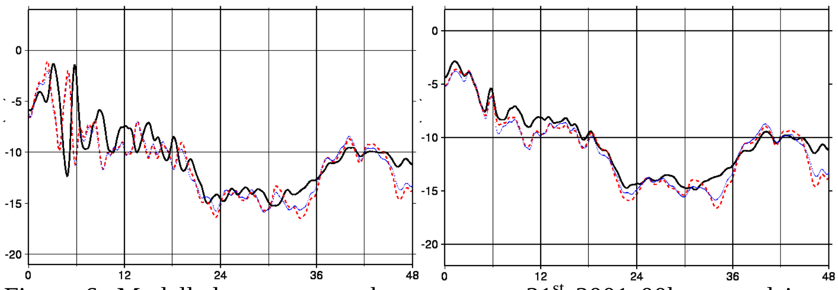


Figure 6: Modelled storm surge between may 31st 2001 00h utc and june 2nd 2001 00h utc at Le Verdon (cm) for the former initialisation process (left) and for the new one (right). The three plots are for the three models (IFS, ARPEGE and ALADIN).

5. Conclusions

The increasing of the temporal frequency of forcing is very positive on the December 27th storm situation. The forecasted surge is even comparable with the simulated surge in hindcast mode. This study is certainly limited to an exceptional situation, but it is this type of situation which is likely to cause significant surges. The impact of initialisation process is also significant.

6. References

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