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Recent improvements for the Berre lagoon modelling with TELEMAC-3D

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***Abstract*— The Berre lagoon (South East of France near Marseille) is among the largest brackish lagoons in Europe, connected to the Mediterranean Sea through the Caronte channel, while receiving freshwater from two tributaries and a hydroelectric power plant. An average depth of 6 m makes the lagoon strongly sensitive to wind conditions, i.e. when the mistral is not blowing, thermohaline vertical stratification occurs in the lagoon. Anthropogenic activities (i.e. industry and urbanisation since mid-20th century) have seriously affected its ecosystem (strong variability of salinity, water column stratification, pollutants, and eutrophication). A continuous and real-time hydro-environmental monitoring program has been carried out since 2006. Previous TELEMAC-3D models of the Berre lagoon had been developed at Laboratoire National d'Hydraulique et Environnement (LNHE) for simulating hydrodynamics, salinity and temperature. The aim of this paper is to present recent improvements of the TELEMAC-3D model to accurately reproduce stratification and mixing in the Berre lagoon, with particular focus on the effects of the advection schemes and turbulence models. The use of the LIPS scheme for the advection of tracers salinity and temperature, combined with the Yap correction for the *k*-ε turbulence model are the options that have mostly improved the previous TELEMAC-3D model of the Berre lagoon without tidal flats.**

I. INTRODUCTION

EDF manages hydropower plants along the Durance-Verdon chain to produce electricity. This chain releases fresh water into the Berre brackish lagoon, which is connected to the Mediterranean Sea and has two tributaries. One of the main characteristics of the Berre lagoon is the strong haline stratification (i.e. freshwater and saltwater entering the lagoon do not mix easily due to the difference of density).

One of the goal of the TELEMAC-3D modelling of the Berre lagoon is to reproduce accurately stratification and mixing events, which is a key factor to represent the lagoon behaviour. It has been used and improved for years. The aim of this paper is to show recent improvements by using some recent features in TELEMAC-3D, dealing with less diffusive advection schemes and variants of turbulence models.

The second section of this paper presents the studied area and available measurements. The third section describes the preliminary TELEMAC-3D model of the Berre lagoon and the features that are tested (mainly advection schemes and turbulence models). Results of different tests and comparison with *in situ* measurements are given in section 4, followed by conclusions in section 5.

II. PRESENTATION OF THE STUDIED AREA

A. *Location and environment*

The Berre lagoon is located in the south of France (west of Marseille), at the end of the Durance canal (a chain of hydropower plants) that diverges the water from the Durance River (250 km long) to the lagoon. The lagoon has a surface of 155 km^2 with a volume of water around 980 Mm^3. Being connected to the Mediterranean Sea through the Caronte channel, the lagoon receives sea salty-water in tide-driven pulses. Two rivers (Arc and Touloubre) and the EDF Durance Canal releases fresh water (through the Saint-Chamas hydropower plant) into the lagoon, in addition inputs from rain, runoff and wastewater treatment plants. The mean annual flowrate through Saint-Chamas power plant is between 20 to 30 m^3/s (since 2006), whereas mean flowrate of rivers Arc and Touloubre is around 6 m^3/s. Dense seawater enters during rising tide and plunges to the bottom, whereas fresh water spreads over the surface where it mixes vertically in the first few meters. Therefore, the lagoon remains stratified when there is no strong wind (the salinity difference between the bottom and the surface can be up to 10 g/L). During summer and with weak wind, anoxia (oxygen depletion) often appears in the bottom layers. Anoxia enhances the release of unwanted components and lethal gases from the sediments as well as it produces mortality of organisms by asphyxia. Only long and strong wind events (mistral events) can mix completely the lagoon and re-oxygenate the bottom layer.

B. *In situ measurements*

Many *in situ* measurements are available in the lagoon: EDF owns four measuring stations where temperature and salinity (CTD Seabird SBE-19) have been recorded every hour since 2006. Three stations (SA1, SA2 and SA3) are located inside the lagoon, whereas the fourth (SA4) is located in the Caronte channel (Fig. 1). Measurements are recorded at five different depths. At SA4 station, velocity in the water column (Teledyne-RDI ADCP) is also measured every hour, so that flow rate exchanges between the lagoon and the Mediterranean Sea could be calculated. At the three other stations, a 3-month period in 2008 of velocity measurements is also available.

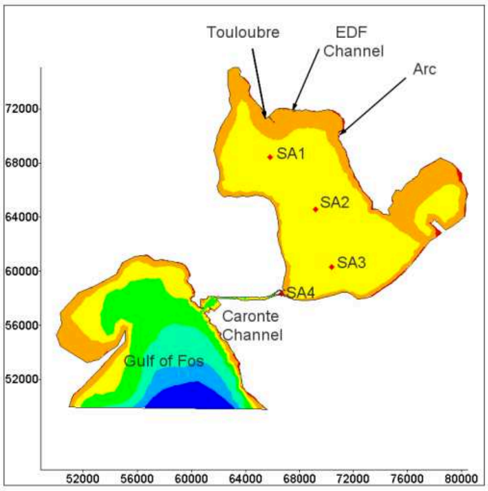

Fig 1: Berre lagoon extent and location of the measurement stations.

Metocean data are also used in this paper as input of the TELEMAC-3D model: meteorological data, flowrates of rivers or tidal levels. Meteo France data at Marignane are used, on the Berre lagoon bank: wind magnitude and direction, air temperature, relative humidity, air pressure, cloud coverage, rain and solar radiation. For the Gulf of Fos, tidal levels at Marseille and in the Gulf of Fos, as well as salinity and temperature in the Gulf of Fos are used. Flowrates and temperatures of the rivers are regularly measured by the Rhône-Méditerranée-Corse Water Agency. The flowrates and temperature of water released by the Saint-Chamas station are provided by EDF every hour.

III. Presentation of the TELEMAC-3D model

The previous release of the TELEMAC-3D Berre lagoon model was built in 2016. The main characteristics of the 3D model have been kept for this paper and are reminded here.

A. Model domain and bathymetry

The computational area includes the Gulf of Fos, the Caronte channel and the Berre lagoon (Fig. 1).

The mean depth of the lagoon is 6 m and maximum depth is around 10 m, reaching 45 m in the Gulf of Fos.

B. Computational mesh

The 2D mesh is made of 4,214 nodes and 7,707 triangular elements, refined where velocities are large: in the Caronte channel and the three freshwater intakes (Arc and Touloubre rivers, and Saint-Chamas power plant). The elements sizes vary from 1 km for the largest elements to 3 m for the smallest ones.

There are 41 horizontal planes over the vertical with fixed elevation (except the last one following the free surface). Combined with the 2D mesh, the 3D mesh is made of 172,774 nodes and 308,280 prisms. The horizontal planes are tightened where the salinity gradients are strong, around 8 m deep. As the bottom is not flat, and in order to prevent from artificial velocities, some planes are crushed, in particular near the solid boundaries.

The 3D mesh can be seen in Fig. 2 with the vertical direction distorted with a ratio of 250.

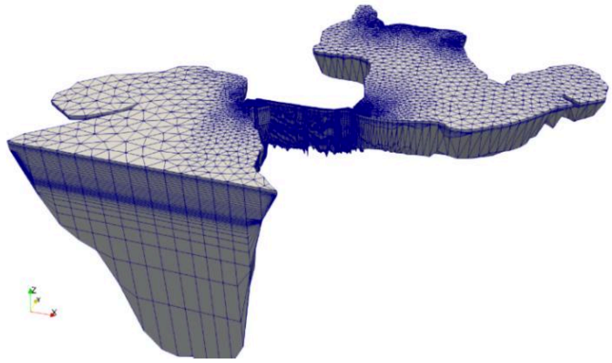

Fig 2: The Berre lagoon 3D mesh.

C. Initial and boundary conditions

The TELEMAC-3D model of the Berre lagoon has four open boundaries. Three of them where flowrates are prescribed corresponding to freshwater (Arc, Touloubre and Saint-Chamas power plant): daily data for the two rivers and hourly data for the power plant are interpolated at each time step. Salinity and temperature are also prescribed at these open boundaries with the same frequency.

The fourth and last liquid boundary corresponds to the interface between the Gulf of Fos and the Mediterranean Sea where the free surface elevation is prescribed, corresponding to the sea level estimated from both Marseille and Fos tidal gauges. At this location, the flowrate is not prescribed, so the flow can be entering or exiting. At every time step, if the flow comes in, temperature and salinity are prescribed; if the flow goes out, the two tracers are let free.

A few freshwater intakes have not been measured: they are mainly runoff on the banks (more than 70 km long). This flowrate has been estimated and is taken into account by increasing the Arc and Touloubre flowrates with a few cubic meters per second (~ 2 m^3/s).

Meteo data (wind, temperature, pressure, humidity, cloud coverage, rainfall, and solar radiation) are given as input of the TELEMAC-3D model since the THERMIC model of the WAQTEL module is coupled to TELEMAC-3D to take into account heat exchange of water with atmosphere. Meteo data are available hourly and linearly interpolated at every time step.

At the initial time step, zero velocities are taken. The water level is taken equal to the one prescribed at the Gulf of Fos boundary. Temperature and salinity are initialised in different areas, in particular with salted concentration = 38 g/L in the Gulf of Fos. In the Caronte channel and inside the Berre lagoon, the computation is initialised with the measurements at SA4 and SA3 respectively. As the stratification is usually around 8 m deep, initial values below 8 m are taken equal to the deepest measurement, whereas above 8 m, initial values are taken equal to the average of the four other measurements.

D. Numerical settings

The initial setting for advection schemes is:

- Method of characteristics (MOC) for velocities and *k*-ε variables,
- PSI scheme for tracers (temperature and salinity).

Since TELEMAC release v7p2, recent advection schemes belonging to the MURD family are available in TELEMAC-3D after Sara Pavan's PhD [1]: Predictor-Corrector schemes (PC) [2] which does not work with tidal flats and LIPS (Locally Implicit Predictor-corrector Scheme) which works with tidal flats [3].

To prevent from issues with tidal flats, in the TELEMAC-3D model of Berre lagoon, which used the PSI scheme (this one also does not work with tidal flats as the PC scheme), the bottom elevation is lowered at a maximum value of -0.5 m to be always wet. To compare the results obtained from different advection schemes, the same modification of the bottom elevation is kept.

Accuracies to solve linear system are equal to 10^{-6} except for the diffusion of tracers where an accuracy of 10^{-9} is retained to ensure mass conservation of tracers (salinity and temperature).

E. Physical settings

Nikuradse law is chosen to model friction on the bottom with a roughness height equal to 0.1 mm in the Berre lagoon (fine sand) and 10 cm in the Caronte channel (concrete bottom covered by mussels).

To model thermohaline stratification of the lagoon, a density law of water depending on temperature and salinity is used (corresponding to keyword DENSITY LAW = 3):

$$\rho = \rho_0\left(1 - \left(7.10^{-6}(T - T_0)^2 - 750.10^{-6}.S\right)\right),$$

With ρ density, T temperature, S salinity, T_0 reference temperature (= 4° C) and ρ_0 reference density at T_0 (= 999.972 kg/m^3).

The non-hydrostatic version of TELEMAC-3D is used.

The Coriolis force is taken into account due to the wide surface of the Berre lagoon.

In 2016, the standard *k*-ε turbulence model was used both in horizontal and vertical directions. Other turbulence models (mixing length models with various mixing length formulae with or without damping functions, *k*-ω) have been tested and compared in this paper, but also variants of the *k*-ε model (limitation of the production term and the Yap correction).

F. Parallel setting

Every computation is run on a cluster with 112 cores (= 4 nodes of 28 cores, 128 Go RAM, Intel Xeon CPU E5-2680 v4 @ 2.4 Ghz).

IV. RESULTS

In order to study the impact of advection schemes when modelling salinity, two 1-month periods have been chosen:

- September 2006 when hourly measurements of salinity started in the lagoon. During this month, two periods when mistral blew occurred, from 18th to 19th and from 26th to 27th. Large water releases from the power plant were observed during this period: from 13th to 16th and from 25th to 26th. This month is representative of how the lagoon behaves,
- January 2008, when four measurement stations were active. There was a lot of wind during the first half of this month and water releases from the power plant were often done, in particular during the second half of this month.

Salinity measurements are compared to computational results at stations SA3 and SA4 at the surface and at the bottom.

From this section, "reference" means the options used in 2016 (in particular PSI scheme for the advection of tracers, method of characteristics for the advection of velocities and *k*-ε, and a 10 s time step).

A. Advection of tracers salinity and temperature

Results with LIPS and PC schemes are compared to results from the PSI scheme (used as a "reference" computation) for the advection of tracers only. The advection of velocity components and *k*-ε is computed with the method of characteristics.

For the PC scheme, a 5 s time step has to be used (instead of 10 s for the "reference" model) so that advection steps converge. Although with other schemes, larger time steps can be used, comparisons are shown only with a 5 s time step. Whereas computations with PSI and LIPS schemes need similar CPU times (3 h 15 min, 4 h 15 min respectively), using the PC scheme requires nearly a time twice longer without sub-steps or corrections (8 h 20 min).

During September 2006, the succession of stratification and mixing is well reproduced by the computation. Nevertheless, the measured stratification (6-7 g/L between bottom and surface) is stronger than the modelled one (~ 4 g/L). (Fig. 3).

However, at SA3 station, using the LIPS scheme yields a stronger stratification than the "reference" PSI scheme (around 1 g/L), as the PC scheme but better modelled with the LIPS scheme (Fig. 3). We can assume that numerical diffusion is partly responsible for the stratification weakness and that the LIPS scheme (less diffusive) may correct this drawback. A longer simulation lasting one whole year confirms this idea for the LIPS scheme (Fig. 4). No result is given for one year with the PC scheme as CPU time is big.

As the LIPS scheme is suitable for CPU time and quality of results, it should be used when advecting tracers for this TELEMAC-3D model and is then used from subsection IV.C.

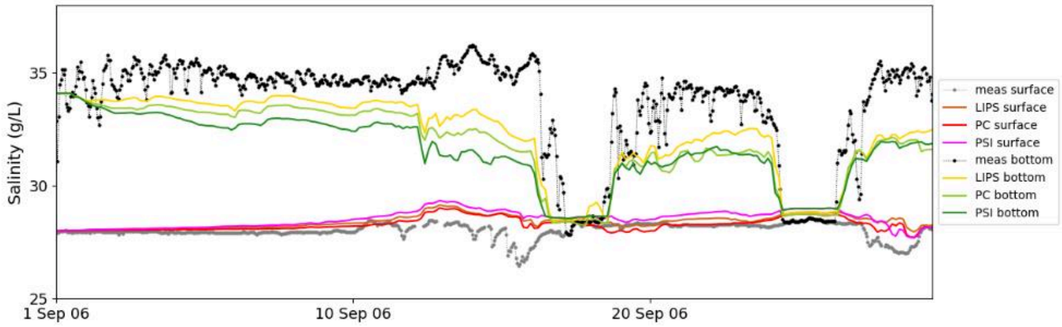

Fig 3: Salinity at SA3 in September 2006. Measurements (points), LIPS, PC and PSI schemes for tracers only (solid lines).

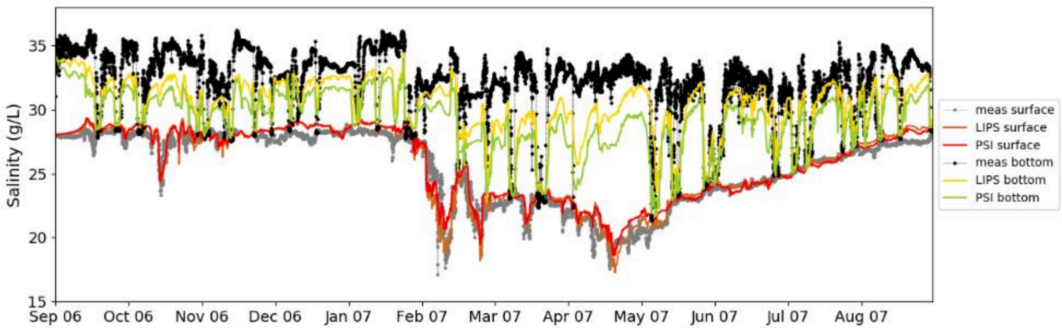

Fig 4: Salinity at SA3 from September 2006 to August 2007. Measurements (points), LIPS and PSI schemes for tracers only (solid lines).

B. Advection of velocity components

In this subsection only, the same advection scheme is used for the advection of both velocity components and tracers (replacing the method of characteristics for velocity components and PSI for tracers): PC and LIPS schemes are tested.

The PC scheme requires the use of a 2 s time step to converge, but the CPU time strongly increases (27 h). For that reason, this choice is dropped out.

Using the LIPS scheme does not require decreasing the time step. Comparisons are then done with the same time step as the “reference” model, i.e. 10 s. Using the LIPS scheme for velocity components is slower than the previous choice (method of characteristics): with the same time step, CPU time increases by 50 %.

Inside the lagoon at SA3 station, salinity values computed with LIPS and PC scheme are close to the ones from the “reference” model with PSI scheme. Contrary to the comparisons with advection schemes for tracers, no improvement is observed for stratification (Fig. 5).

On the other hand, using LIPS and PC schemes for velocities improves the salinity results in the Caronte channel. Fast variations of salinity due to tide (a few hours time scale) are better modelled (Fig. 6).

In the Caronte channel (direction East-West), velocity is directed alternatively toward the lagoon (rising tide) or toward the Gulf of Fos (falling tide) and maximum velocities are around 1 m/s. Velocity are well modelled, which is mandatory to reproduce correctly the exchanges between salted water and brackish water coming from the lagoon. When looking at velocity, small differences may appear depending on the advection scheme. If only the advection scheme is modified for tracers, the differences for velocity are minor. However, with LIPS for the advection of velocities, the maximum velocity is increased by around 25 % (Fig. 7), which may explain the fast variations of salinity above. Compared to measurements, this is also an improvement of the numerical model. Inside the Berre lagoon, velocities are very low (a few cm/s), which cannot be reproduced accurately.

Regardless of the advection scheme, during mistral events the surface current from North to South and the bottom current from South to North are well reproduced (Fig. 8).

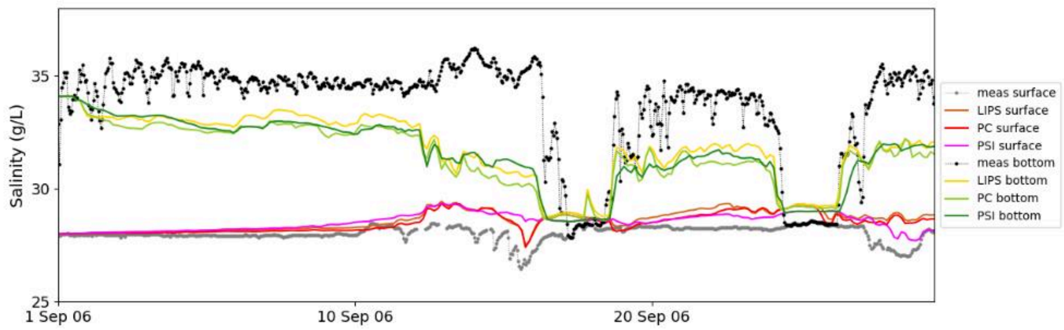

Fig 5: Salinity at SA3 in September 2006. Measurements (points), LIPS, PC and PSI+MOC schemes for tracers and velocities (solid lines).

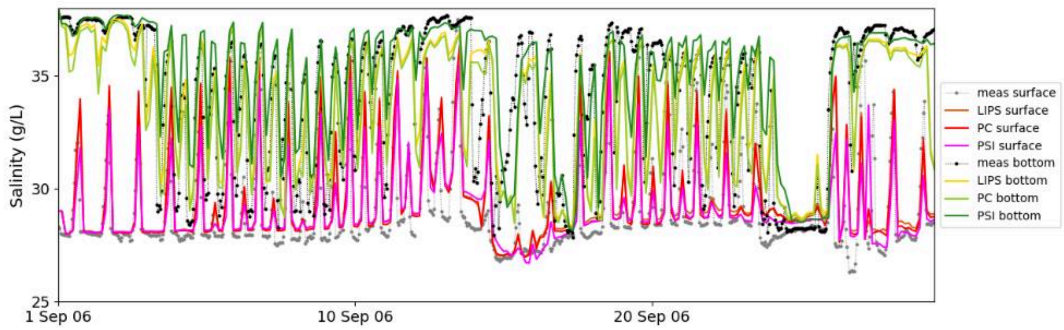

Fig 6: Salinity at SA4 in September 2006. Measurements (points), LIPS, PC and PSI+MOC schemes for tracers and velocities (solid lines).

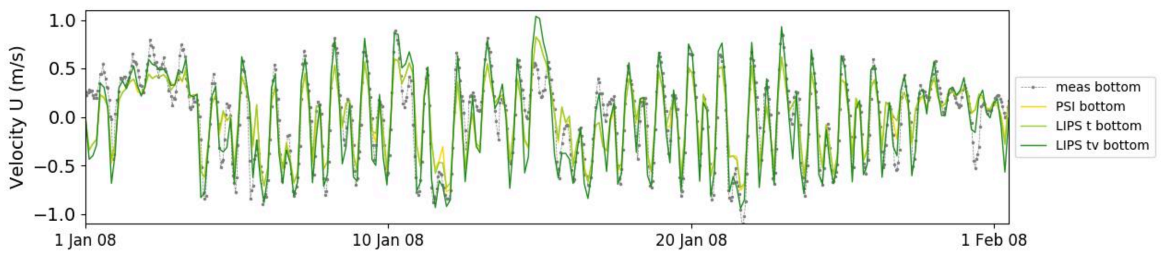

Fig 7: Velocity in the Caronte channel in January 2008 (LIPS t = LIPS for tracers only and MOC for velocities, LIPS tv = LIPS for tracers and velocities).

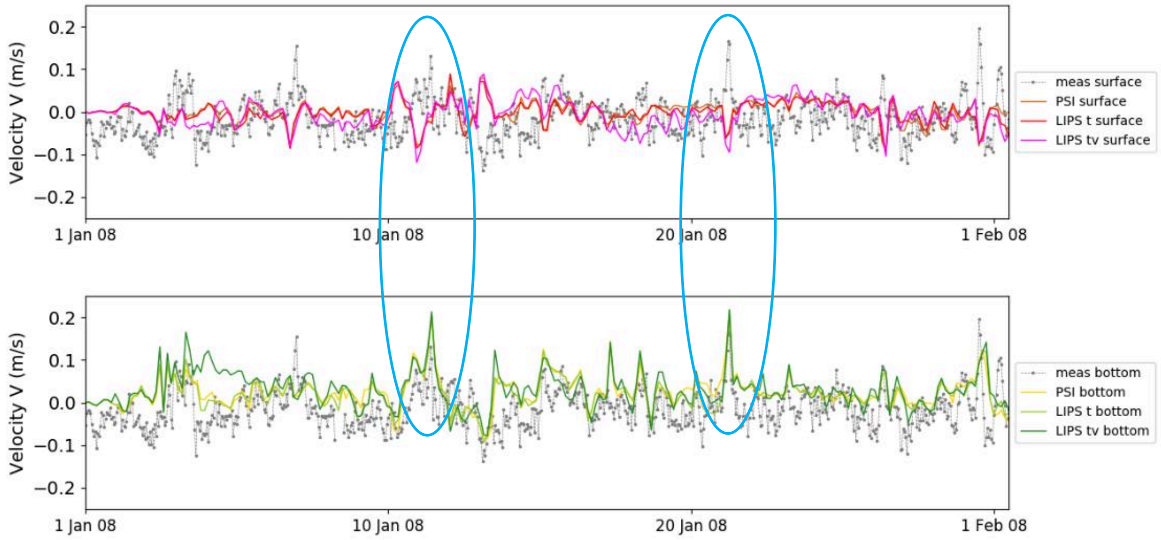

Fig 8: North-South velocity in the lagoon (SA3), January 2008 (LIPS t = LIPS for tracers only and MOC for velocities, LIPS tv = LIPS for tracers and velocities). In blue are shown events with strong mistral where a circular current appears in the lagoon.

Salinity of the lagoon is not well reproduced during a whole year (Fig. 9). On the one hand, the salinity difference between surface and bottom is divided by two compared to the measurements. On the other hand, a salinity shift of around 2 g/L can be seen after one year.

Although the exchanges through the Caronte channel fit the measurements, the results inside of the lagoon are not improved. This leads us not to retain this set of advection schemes (LIPS for tracers and velocity components).

C. Sensitivity analysis for the advection schemes

A 3 min time step accelerates the computation, but the results are worse. Using a time step below 30 s does not change the results: convergence with time step is reached. A balance between CPU time and accuracy has led us to choose a 60 s time step with LIPS for tracers (compared to 10 s with PSI for tracers) (Fig. 10). For the sensitivity to sub-iterations, nearly no influence on the results is observed but the CPU time increases: this feature is not chosen. For the sensitivity to the number of corrections, which is an option available with the LIPS scheme (at least and by default, one is done), tests with two and four corrections do not show modifications of results nor strong increase of CPU time: this feature is also not chosen.

The LIPS scheme for the advection of tracers enables a better modelling of stratification than the PSI previous “reference” scheme for tracers. The LIPS scheme for velocity components better replicates large velocities in addition to fast variations of salinity, but there is a salinity drift when modelling one whole year. The LIPS scheme is then chosen only for tracers and the method of characteristics is kept for velocity components and turbulent variables. No sub-iterations and additional correction are retained.

A whole year can be modelled with 7 h CPU time using a 60 s time step.

D. Turbulence modelling

After choosing the numerical parameters dealing with advection schemes, we would like to better model the physics of stratification. In particular, we would like to model succession of stratification and mixing correctly so that water quality can be studied afterwards. Modelling turbulence is then a key factor to take into account the exchanges in the Caronte channel, the mixing with incoming fresh water and weak exchanges between the two layers of different densities of water when the lagoon is stratified.

Some turbulence models available for TELEMAC-3D have been tested:

- Mixing length turbulence model with various mixing length formulae (Prandtl, Nezu & Nakagawa, Quetin, Tsanis) coupled with a damping function to better reproduce stratification (e.g. Toorman or Munk and Anderson functions),
- Transport equation turbulence model: k-ε as used in the “reference” model and some variations.

Mixing length turbulence model:

In case of a stratified lake like the Berre lagoon, a simple mixing length solution is not accurate without any damping function because the stronger the density gradient, the smaller the eddies: the turbulent kinetic energy k available is not sufficient to mix two layers of large density differences. Hence the use of a damping function equal to 1 in case of unstable stratification and decreasing with density gradient in case of stable stratification.

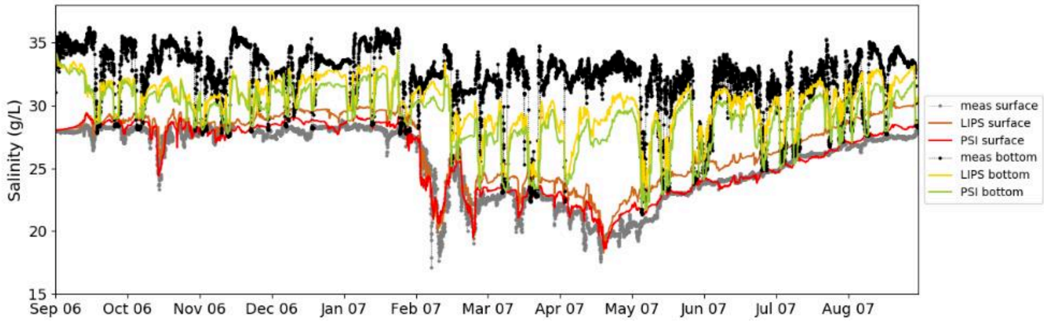

Fig 9: Salinity at SA3 from September 2006 to August 2007. Measurements (points), LIPS and PSI schemes for tracers and velocities (solid lines).

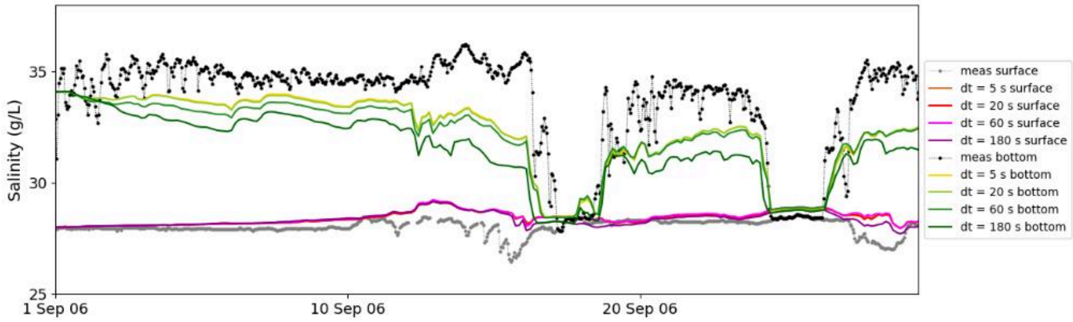

Fig 10: Salinity at SA3 in September 2006. Comparison between results with different time steps (5 s, 20 s, 60 s, 180 s).

The four mixing length formulae provide similar results. Fig. 11 shows results with Munk & Anderson damping function. Tsanis model seems to give better results as the modelled stratification is the strongest, but no model can reproduce a stratification as strong as the one measured.

Nevertheless, Toorman damping function combined with any mixing length model enables keeping a strong stratification, in particular when the lagoon is stratified. But the mixing periods and the mixing at stations SA1 and SA2 are not well reproduced (see Figs 12 and 13).

To summarize: although modelling stratification quite well, the mixing length model with damping function does not fit during strong mistral periods (in particular during the mixing of deep and surface layers).

k-ε turbulence variants:

Sensitivity to the Schmidt turbulent number (ratio between the turbulent viscosity and the turbulence diffusivity) has been tested. In the literature, this coefficient can vary from 0.8 to 1.3. As there are few variations of results, the default value of 1. is kept.

Among the options of the *k*-ε model, some can limit the turbulence production or the turbulence kinetic energy, what may *a priori* limit the mixing.

One first solution is to limit the production term:

$$P = C_\mu \frac{k^2}{\varepsilon} S^2,$$

With P production term, C_μ the Prandtl-Kolmogorov constant, S scalar mean rate of strain.

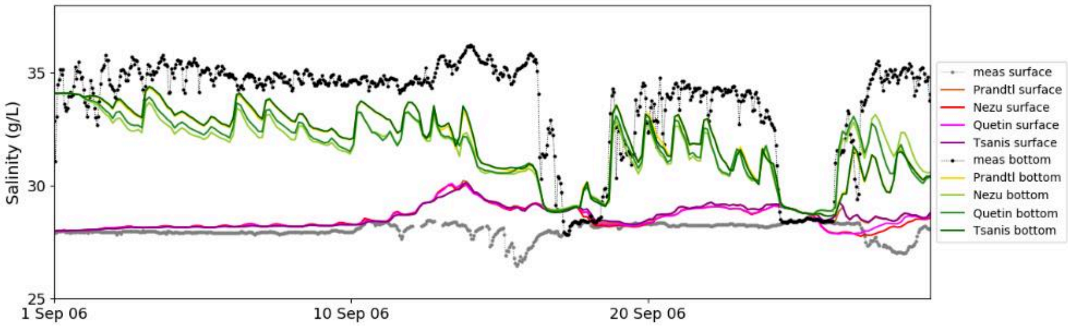

Fig 11: Salinity at SA3 in September 2006. Comparison between results with various mixing length models combined with Munk and Anderson damping function.

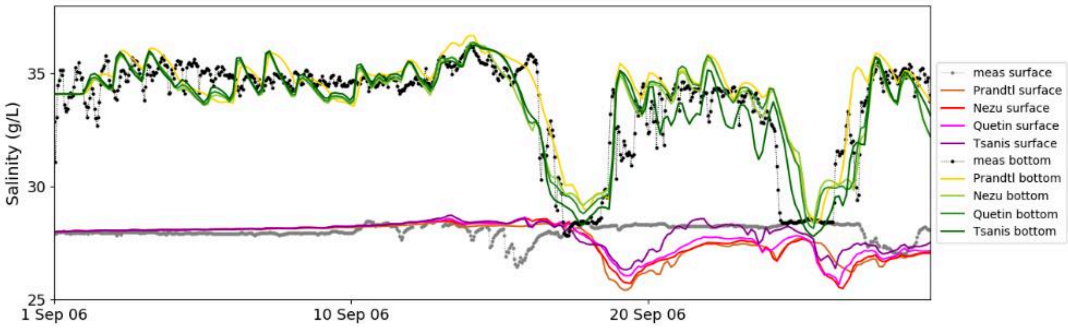

Fig 12: Salinity at SA3 in September 2006. Results with mixing length models combined with Toorman damping function.

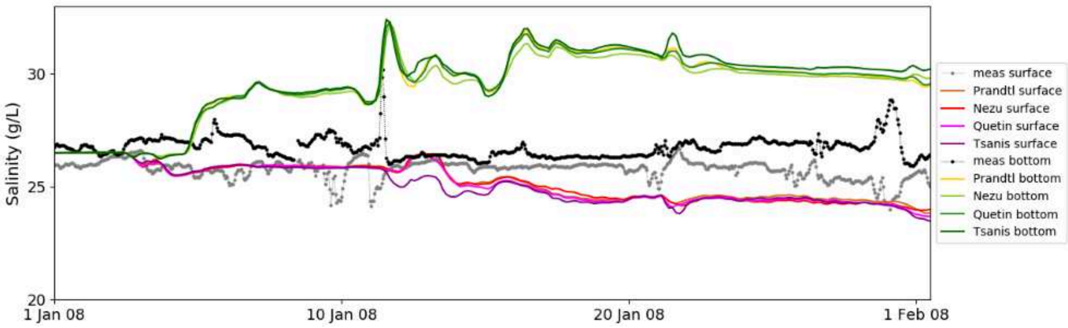

Fig 13: Salinity at SA2 in January 2008. Results with mixing length models combined with Toorman damping function.

If the dissipation is larger than the production, the production term is kept. If not, the production term is replaced by the square root of the product production times ε (*i.e.* $\sqrt{P\varepsilon}$). For the Berre lagoon, this variation has a slight positive effect for representing the stratification, around 0.5 g/L (Fig. 14). This can be done by setting the variable OPTPROD to 1 in the CSTKEP subroutine, and implementing this correction for the surface nodes in the SOUKEP subroutine.

A second limitation of turbulence comes from a physical criterion on the size of large vortices: the size cannot be larger than the distance between the considered point and the lagoon bottom. Yap (1987) suggested a correction to decrease the coefficient $C_{\varepsilon 2}$. This leads to the increase of dissipation ε:

$$C_{\varepsilon 2} \rightarrow C_{\varepsilon 2} - 0.83\left(\frac{LL}{\kappa\delta} - 1\right)\left(\frac{LL}{\kappa\delta}\right)^2,$$

With $LL = C_\mu^{3/4}\frac{k^{3/2}}{\varepsilon}$, κ Karman constant and δ is the distance to the bottom.

This correction strongly improves the modelling of stratification in the Berre lagoon: the salinity difference between the bottom and the surface increases around 1 g/L (see Fig. 14). A one-year simulation confirms this result. This Yap correction is then kept to model the Berre lagoon. It can be activated by setting YAP = .TRUE. in the CSTKEP subroutine.

Other modifications of the *k*-ε model have not been chosen, as they do not improve the results. Moreover, the GOTM module has not been investigated so much due to the lack of both relevant preliminary results and experience of this module.

Regarding the turbulence modelling of the Berre lagoon, the *k*-ε model seems to better fit the results. Contrary to the mixing length models, it enables to model alternating periods of stratification and vertical mixing, but also the mixing of incoming water (fresh or salted with brackish water of the lagoon).

Compared to the initial setup, two variations are chosen: the limitation of the turbulence production and the Yap correction. This leads to the modelling of stratification closer to the measurements with a slight trend to underestimate measured stratification.

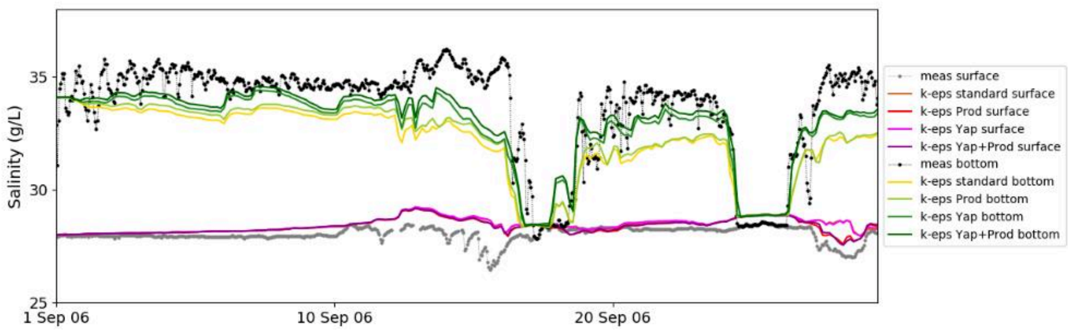

Fig 14: Salinity at SA3 in September 2006. Results with or without the modification of the production term and with or without the Yap correction.

V. CONCLUSION

Modelling the Berre lagoon is a tough task, which has been carried out for years. Reproducing stratification and mixing events is crucial to deal with water quality. In case of a TELEMAC-3D model without tidal flats, some improvements have been obtained using not so usual options:

- LIPS scheme for the advection of tracers salinity and temperature which is less diffusive,
- A variant to limit the turbulent production term and the Yap correction to tune the *k*-ε model.

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