Mathematical modeling of marine environment and control of pollution

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Introduction :

- Owing to the significant advances in computer technology over the past few decades, mathematical modelling and numerical simulations have become indispensable and powerful tools for analysing and understanding real world problems and phenomena in life science.
- They provide an effective mechanism to explain and predict dynamics and behaviour of complex physical and biological systems.
- Such tools offer the ability to anticipate problems before they occur in order to mitigate potential consequences.

In this work, we deal with mathematical modelling and numerical simulations of some hydrodynamic processes in the marine environment.

Introduction :

The objective is to provide a numerical model that reproduces the marine circulation in the central-eastern coast of Tunisia.

Aim of this work

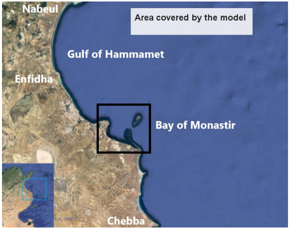
We aim to develop a 3D hydrodynamic model that simulate the circulation of water masses, the heat evolution and the salinity variations as well as the kinetic energy distribution in that region.

Plan

1. Development of a zoomed 3D hydrodynamic model
   - Initial version of model: INSTMBM
   - Improved version of model: INSTMBMZ
2. Numerical simulation and validation
   - Simulation
   - Validation
3. Applications: Pollution Control
   - Transport of a passive tracer
   - Matter transport and sedimentation
4. Conclusion and Prospects

Initial version of model: INSTMBM

- 3D general circulation numerical platform that simulates water temperature, salinity and velocity.
- Study area extends from Nabeul to Chebba with the bay of Monastir in the center.
- The physical model used is based on POM (Princeton Ocean Model) with discretization by finite differences method (Mellor and Blumberg, 1985).



G. L. Mellor, A. F. Blumberg; *Modeling vertical and horizontal diffusivities with the sigma coordinate system*, Mon Weather Rev, 113, 1985, 1379-1383.

Initial version of model: INSTMBM

- Atmospheric weather conditions from the Monastir station.
- Lateral boundary conditions by CMEMS analyses (Copernicus Marine Environment Monitoring Service).
- The model grid is regular and Cartesian with a resolution of 1132 m in longitude and 1400 m in latitude.
- This version of model solves the three-dimensional primitive equations of Navier Stokes in sigma coordinate (x, y, σ, t):

(a) **Continuity equation:**

$$\frac{\partial(Du)}{\partial x} + \frac{\partial(Dv)}{\partial y} + \frac{\partial \omega}{\partial \sigma} + \frac{\partial \eta}{\partial t} = 0$$

Initial version of model: INSTMBM

(b) **The momentum equations:**

- **Horizontal direction:**

$$\underbrace{\frac{\partial(Du)}{\partial t}}_{(1)} + \underbrace{\frac{\partial(Du^2)}{\partial x} + \frac{\partial(Duv)}{\partial y} + \frac{\partial(\omega u)}{\partial \sigma}}_{(2)} \underbrace{-Dfv}_{(3)} + \underbrace{gD\frac{\partial \eta}{\partial x}}_{(4)} + \underbrace{P_{\rho x}}_{(5)} = \underbrace{DF_{KM}(u)}_{(6)} + \underbrace{DF_x}_{(7)}$$

$$\underbrace{\frac{\partial(Dv)}{\partial t}}_{(1)} + \underbrace{\frac{\partial(Duv)}{\partial x} + \frac{\partial(Dv^2)}{\partial y} + \frac{\partial(\omega v)}{\partial \sigma}}_{(2)} \underbrace{+Dfu}_{(3)} + \underbrace{gD\frac{\partial \eta}{\partial y}}_{4} + \underbrace{P_{\rho y}}_{(5)} = \underbrace{DF_{KM}(v)}_{(6)} + \underbrace{DF_y}_{(7)}$$

- **Vertical direction:**

$$\frac{\partial p}{\partial z} = -\rho g$$

(c) **Heat conservation equation:**

$$\underbrace{\frac{\partial(DT)}{\partial t}}_{(1)} + \underbrace{\frac{\partial(DTu)}{\partial x} + \frac{\partial(DTv)}{\partial y} + \frac{\partial(T\omega)}{\partial\sigma}}_{(2)} = \underbrace{DF_{KH}(T)}_{(3)} + \underbrace{DF_T}_{(4)} - \underbrace{\frac{\partial R}{\partial\sigma}}_{(5)}$$

(d) **Salt conservation equation:**

$$\underbrace{\frac{\partial(DS)}{\partial t}}_{(1)} + \underbrace{\frac{\partial(DSu)}{\partial x} + \frac{\partial(DSv)}{\partial y} + \frac{\partial(S\omega)}{\partial\sigma}}_{(2)} = \underbrace{F_{KH}(S)}_{(3)} + \underbrace{DF_S}_{(4)}$$

(e) The closure equations for turbulence:

For the calculation of the turbulent diffusivities, horizontal and vertical this version use a turbulence model developed by Mellor and Yamada (1982):

- **Equation of the turbulent kinetic energy q^2:**

$$\frac{\partial(Dq^2)}{\partial t} + \frac{\partial(Dq^2u)}{\partial x} + \frac{\partial(Dq^2v)}{\partial y} + \frac{\partial(q^2\omega)}{\partial \sigma} = DF_{Kq}(q^2) + Dprod(q^2) + DF_{q^2}$$

- **Equation of the turbulent kinetic energy per length of the mixture q^2l:**

$$\frac{\partial(Dq^2l)}{\partial t} + \frac{\partial(Dq^2lu)}{\partial x} + \frac{\partial(Dq^2lv)}{\partial y} + \frac{\partial(q^2l\omega)}{\partial \sigma} = DF_{Kq}(q^2l) + Dprod(q^2l) + DF_{q^2l}$$

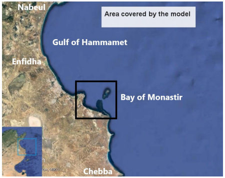
G. L. Mellor, T. Yamada; *Development of a turbulence closure model for geophysical fluid problems*, RevGeophys, 20, 1982, 851-875.

Improved version of model: INSTMBMZ

Our contribution:

Development of an improved version of the 3D hydrodynamic model compared to the initial one by adding:

- **Zooming Concentrate on the bay of Monastir:**
  - Very important economic activity zone (industry, fishing, tourism, aquaculture, ...) that have created very strong pressures on the marine environment of this bay.
  - An area of recurrent episodes of algae proliferation, eutrophication or even fish mortality.

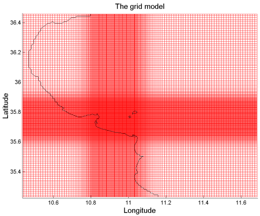


(a) Study area

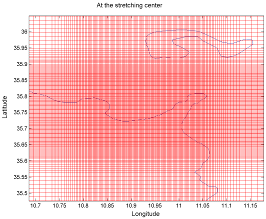
(b) Bay of Monastir

Improved version of model: INSTMBMZ

- A gradual increase in the horizontal resolution ranging in longitude from 1132 to 283 m in the centre and in latitude from 1400 to 344 m in the centre.



(c) The stretched grid

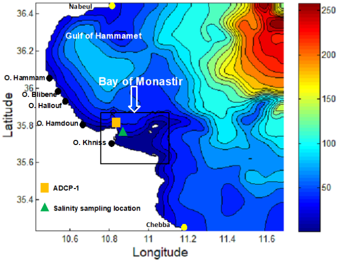


(d) At the center of stretching

- The high resolution of the new grid allows a fine analysis of the water movements in particular in and around the Bay of Monastir which acts as a barrier to the water flow at the larger scale.

Improved version of model: INSTMBMZ

- **Terrestrial water inputs:** included in the simulations by considering different sources: Oued Khnis, Oued Hamdoun, Oued Blibene, Sewers, ...



- The transport equation coupled with momentum ones to study the transport of river discharge and pollutants poured into the study area:

$$\frac{\partial(DP)}{\partial t} + \frac{\partial(DPu)}{\partial x} + \frac{\partial(DPv)}{\partial y} + \frac{\partial(P\omega)}{\partial \sigma} = F_{KH}(P) + DF_P$$

Numerical simulation:

After the implementation of our model, I present here some results of numerical simulations in the zone considered and during a study period from 2008 to 2020.

- **Temperature and salinity evolution:**

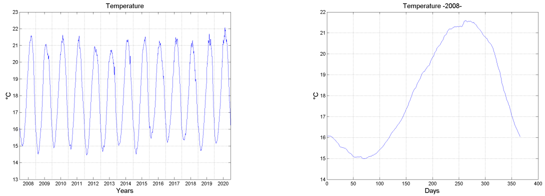


Figure: Temperature evolution

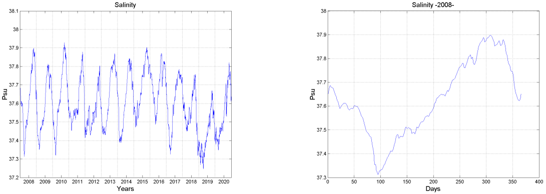


Figure: Salinity evolution

- **Temperature distribution:**

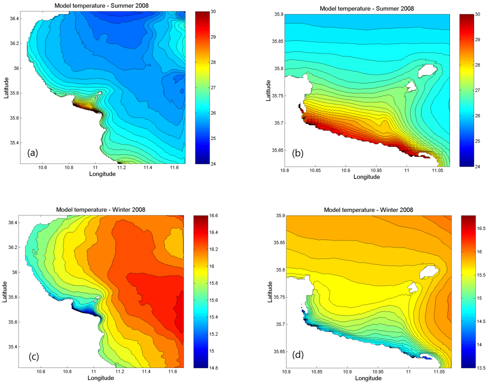


Figure: Surface temperature (2008) in summer (a and b) and winter (c and d) over the entire study area and zoom on the bay of Monastir

• Salinity distribution:

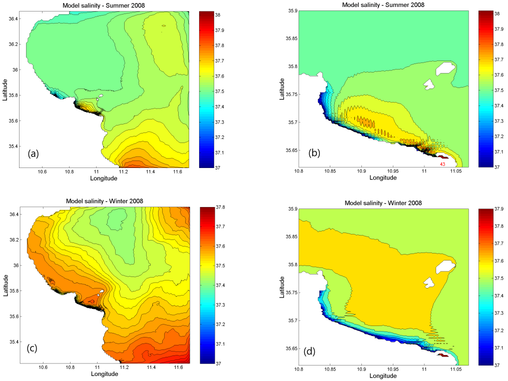


Figure: Surface salinity (2008) in summer (a and b) and winter (c and d) over the entire study area and zoom on the bay of Monastir

- **Transport of terrestrial waters:** impact on salinity in the study area.

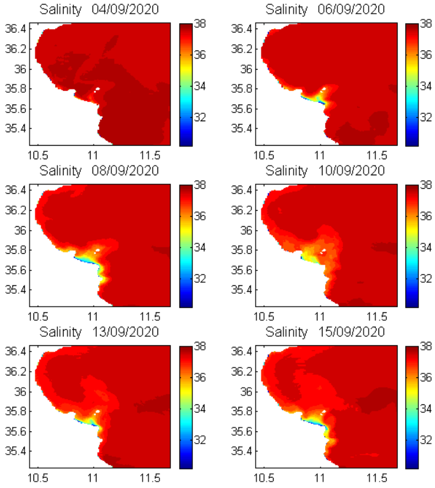


Figure: Spatial distribution of surface salinity

The terrestrial water transport follows the coasts and the surface water circulation.

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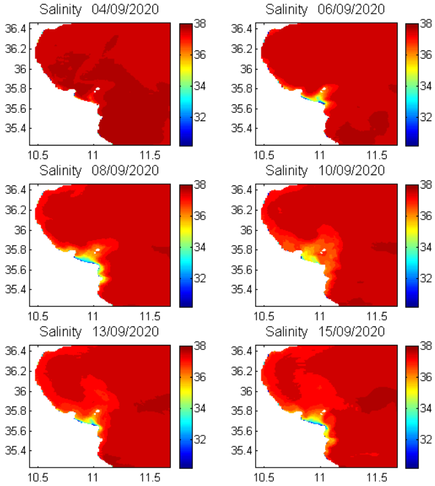

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Validation:

In order to justify the performance of our model, we compared the obtained results:

- CMEMS analyses: Copernicus - Marine Environment Monitoring Service data.
- Real measurements using salinometer and current meter.

(a) CMEMS (b) salinometer (c) current-meter

S. Chaouch, A. Harzallah; *A zoomed 3d circulation model for the Monastir bay: Comparison to operational analyses*, Bull. Inst. Natn. Scien. Tech. Mer de Salammbo, Vol. 47, 2020.

Comparison between the model and CMEMS (2008-2020):

CMEMS (Copernicus - Marine environment monitoring service) data are based on the NEMO hydrodynamic model (Nucleous for European Modeling of the Ocean).

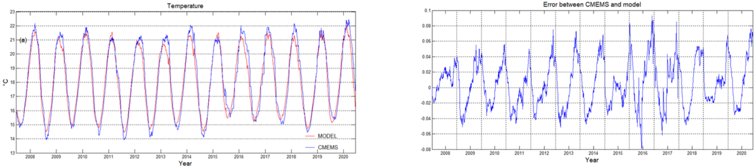


Figure: Comparison of the simulated temperature to CMEMS

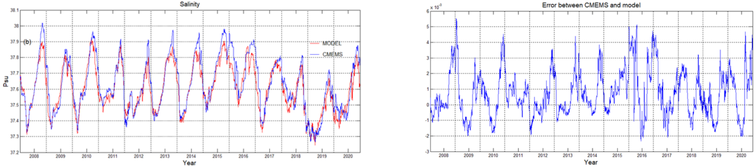
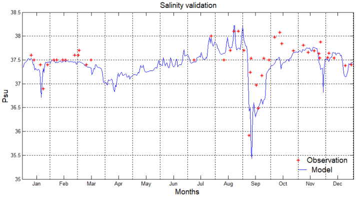


Figure: Comparison of the simulated salinity to CMEMS

Comparison between the model and measurements (2020):



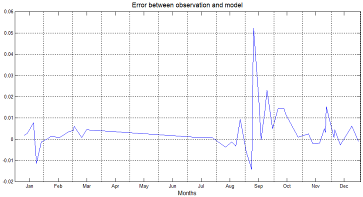


Figure: Comparison of the simulated salinity to observations

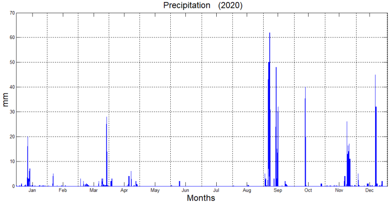


Figure: Variation of precipitation during the year 2020

Comparison between model results and observations:

Current-meter measurements with a current-meter (ADCP-1) installed at the sea bottom during the period from July 13 to July 23, 2019.

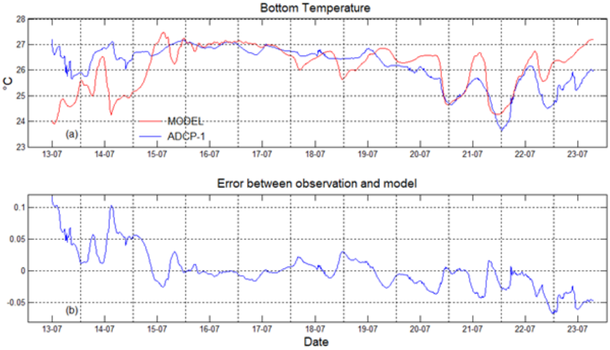


Figure: Comparison between model results and the observations of ADCP-1. (a) Temperature of the water at the bottom (18 m) in °C. (b) Error between ADCP-1 and model.

Application I :

Pollution Control

- An area of recurrent episodes of algae proliferation, eutrophication or even fish mortality.
- Land-based discharges, which have increased sharply in recent years, have surely contributed to the occurrence of these crises.






S. Chaouch and al.; *A three-dimensional hydrodynamic model for the Gulf of Hammamet-Bay of Monastir: model validation and application*, 2022.

First application of model: transport of a passive tracer

Passive tracer: That can represent all matter without weight, is not interacted with the environment and which is transported only by the ocean current.

Second application of model: matter transport and sedimentation

- Particles are emitted from the source, advected by the currents and sink to the sea bottom by the effect of their weight (fall velocity).

$$\frac{\partial(DP)}{\partial t} + \frac{\partial(DPu)}{\partial x} + \frac{\partial(DPv)}{\partial y} + \frac{\partial(P(\omega + w_c))}{\partial \sigma} = F_{KH}(P) + DF_P$$

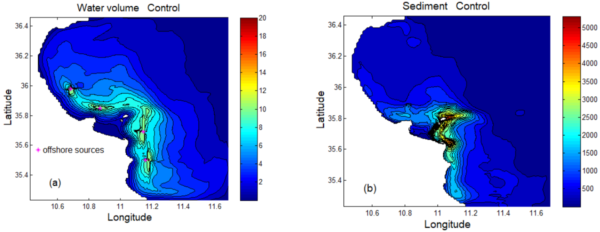


Figure: Regular control case with no interruption of particle input in the source location.

- Significant impact of discharges on the study area and in particular on the coasts.

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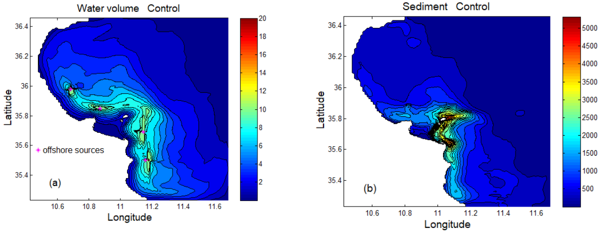

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Matter transport and sedimentation:

• **Management solution:** particle discharge is permitted only during time laps when currents are directed from land to sea

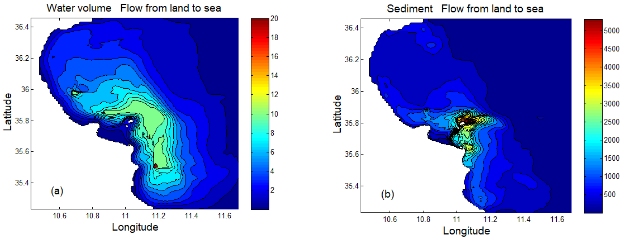

Figure: Particle input only when the flow is directed from land to sea.

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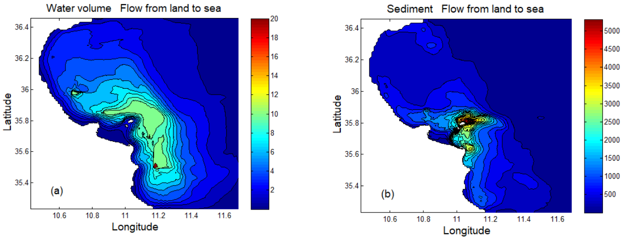

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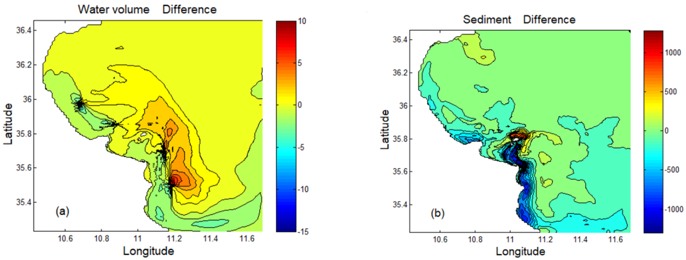

Figure: Differences in particles between the flow directed from land to sea case and the control case suspended in the water volume (a) and deposited as sediment (b) during the summer season.

⇒ Reduced impact on the coast in the intermittent scenario.

⇒ The management solution is effective: the retention of sewage in small scale basin inland for example.

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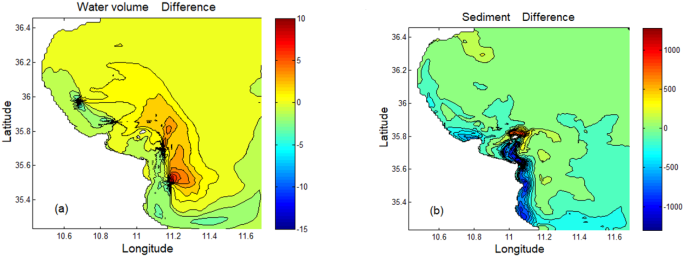

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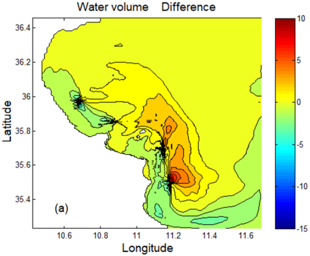

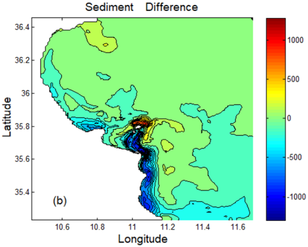

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Conclusion and Prospects

Conclusion:

- Development of a zoomed 3D hydrodynamic model that simulates the water masses circulation, the heat and salinity evolution and the kinetic energy distribution in the central-eastern coast of Tunisia.
- The performance and accuracy of the developed model was evaluated using a comparison study with the European oceanic model CMEMS and real measurements data.
- Development of a particle transport module for following the trajectories of discharges at sea and the influence of ocean currents on the transport and the propagation of terrestrial waters or of a passive tracer.
- Proposal of a management solution: particle discharge is permitted only when the current direction is from land to sea.

Prospects:

- Considering atmospheric forcing that spans the entire area of the domain instead of the nearest weather station will surely further improve the model results.
- The particle transport model needs further studies and validation according to particles characteristics (nature, size, aggregation, floating, chemical, interactions, ...) and particle transport processes (advection, diffusion, sedimentation, re-suspension, ...).
- The particle transport module included in the model can serve as a useful tool for solving inverse problems:

  - Identification of the location of some unknown objects immersed in the sea from real surface measurements.
  - Detection the best sites for aquaculture cages.

Thank you for your attention