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# Coupling TELEMAC-3D with the General Ocean Turbulence Model (GOTM)

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**Abstract**— The General Ocean Turbulence Model (GOTM), a 1DV water column model for coastal, oceanic and limnic waters, was coupled to TELEMAC-3D, expanding the model capabilities for the description of vertical mixing processes. The coupled TELEMAC-3D GOTM model was applied to four cases: the lock exchange test case, the stratification test case, a case of large-scale ocean circulation, and a case of salinity-driven stratification in an estuary mouth. The lock exchange test case shows that the TELEMAC-3D GOTM model with  $k - \epsilon$  closure delivers comparable results to the TELEMAC-3D mixing length model for a simple geometry, and that the increase in computation time due to the GOTM coupling is very limited. The large-scale ocean circulation case shows that TELEMAC-3D with the K-Profile Parametrization (KPP) in GOTM makes it possible to simulate large-scale ocean circulation, including surface boundary layer dynamics under the influence of radiative and atmospheric forcing. The estuarine circulation test case shows that in more complex environments, TELEMAC-3D with GOTM  $k - \epsilon$  closure better captures the physics of salinity density stratification than the simple mixing length model, and this has a significant effect on the macroscale circulation in the estuary mouth.

## I. INTRODUCTION

As TELEMAC-3D is applied to ever larger and deeper domains including (coastal) oceans, the need also grows for flexible, case-specific descriptions of vertical turbulent mixing processes. As an alternative to implementing additional turbulence modules in the existing TELEMAC-3D code, TELEMAC-3D was coupled to the 1DV General Ocean Turbulence Model (GOTM) [1].

## II. GOTM DESCRIPTION

GOTM ([www.gotm.net](http://www.gotm.net)) is an open-source community model for hydrodynamics and turbulent mixing processes in coasts, oceans and lakes, and can be run in standalone mode or coupled to a 3D circulation model. The philosophy behind GOTM is to make different turbulence models available in a uniform, reusable code, creating a user-friendly environment for the application of turbulence models in oceanic studies, as well as a tool for the further development of turbulence schemes. In standalone mode, GOTM solves the one-dimensional vertical (1DV) transport equations of momentum, salt and heat, as well as the turbulent mixing processes of these variables. At the heart of GOTM is a library of several turbulence closure models for the

parametrization of vertical turbulent fluxes of momentum, heat and tracers, including energy models, two-equation models such as the  $k - \epsilon$  closure scheme,  $k - \omega$  closure, the Mellor-Yamada closure scheme, Algebraic Stress Models, and the K-profile parameterisation. The implementation of the  $k - \epsilon$  closure scheme and  $k - \omega$  closure in GOTM is based on a generic length scale equation [2]. GOTM has been coupled to several ocean circulation models including GETM [3], MIT-gcm [4], FVCOM [5], SLIM-3D [6], and now TELEMAC-3D (in a branch version), making it possible to generically employ all GOTM turbulence formulations in the 3D circulation model. A limited biogeochemical water column model (GOTM-bio), was also available in GOTM until version 4.0, and is now superseded by the separate Framework of Aquatic Biogeochemical Models (FABM), which can be coupled to GOTM.

## III. COUPLING IMPLEMENTATION

### A. General

The coupling with TELEMAC-3D is implemented as a two-way online coupling. In the newly added module *GOTM\_coupling.F*, the GOTM main turbulence subroutines (*turbulence.f* or *kpp.f*) are called, with all relevant parameters such as velocity, density, diffusivity, turbulent kinetic energy and dissipation passed from and returned to the main TELEMAC-3D code. In GOTM, a staggered vertical grid is used, with velocities and scalars defined at the cell centres (C-points) and the diffusivities and viscosities at the edges (W-points). In TELEMAC-3D, all variables are defined at the nodes. In order to convert the variables from the TELEMAC edges to the GOTM cell centres, a simple averaging was used:

$$U_j = 0.5(U_{j+1/2} + U_{j-1/2}), \quad (1)$$

with  $U_j$  a GOTM variable at the cell centre and  $U_{j+1/2}$  a TELEMAC variable at the edge above the cell centre. GOTM also requires the buoyancy frequency  $N$  and shear frequency  $S$  as inputs:

$$N^2 = -\frac{g}{\rho} \frac{\partial \rho}{\partial z} \quad (2)$$

$$S^2 = \left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2, \quad (3)$$

with  $U$  and  $V$  the velocities in  $x$  and  $y$  directions,  $\rho$  the potential density, and  $g$  the acceleration due to gravity. The gradients at the edges are obtained from the TELEMAC variables at the layers above and below:

$$\left. \frac{\partial U}{\partial z} \right|_{j+1/2} = \frac{U_{j+3/2} - U_{j-1/2}}{z_{j+3/2} - z_{j-1/2}} \quad (4)$$

At the free surface and the bottom, the velocity gradient at the edge below or above is used.

GOTM uses the potential density in order to define the stratification. Because of the importance of an accurate definition of the density and density gradients, the 25-term equation of state of [7] was also implemented in the code.

Since GOTM is a one-dimensional model, the horizontal advection and horizontal diffusion of the turbulent kinetic energy  $k$  as well as the turbulence dissipation  $\varepsilon$  are neglected in the present implementation of the coupling. It is relatively straightforward to add these terms using a fractional step method. However, for applications in rivers, estuaries, coastal seas and oceans, typically the vertical variation is much larger than the horizontal one, and hence horizontal processes can typically be neglected. By neglecting the horizontal advection and diffusion of  $k$  and  $\varepsilon$ , a substantial amount of calculation time is saved. The same approximation is also used in other coastal ocean models such as DELFT3D and COHERENS.

In the GOTM K-Profile Parametrization (KPP [8]), vertical mixing of scalars (temperature and salinity) is defined using two terms, a local process, and a non-local process:

$$\overline{w'c'} = K_c \frac{\partial c}{\partial z} + \gamma, \quad (5)$$

with  $\overline{w'c'}$  the turbulent vertical scalar flux,  $K_c$  the vertical diffusivity and  $\gamma$  the non-local flux. The non-local flux is typically used to parameterize convective mixing in situations with an unstable stratification. The non-local term was included by specifying a vertical velocity term containing  $\gamma$  in the call to *cvdf3d.f* in which the advection and diffusion of scalars is calculated.

GOTM-specific model settings are specified in a separate namelist file, similar to a standalone GOTM simulation. The TELEMAC-3D – GOTM coupling is freely available in the cookiecuttershark branch of the TELEMAC SVN repository, which is based on Telemac V7P2.

### B. Installation instructions GOTM- TELEMAC

In order to install the coupled TELEMAC GOTM model, the following steps need to be done:

- Download and compile GOTM and (if necessary) FABM using the specifications found on [www.gotm.net](http://www.gotm.net). It is important that the same compiler is used as for compiling TELEMAC. Because GOTM uses some modern additions to FORTRAN such as object orientation, a recent FORTRAN compiler is required (we use gfortran 4.9.4). During compiling, it is recommended to change the variables

stderr and stdout in the file *eppdefs.h* to 6 such that the log messages of GOTM are written to the TELEMAC log files. Further, it may be needed to set some preprocessor flags in order to specify the required settings of the GOTM KPP model.

- In the `$$SYSTELCFG` configuration file, specify the preprocessor flag `-DGOTM` and add the include and library paths to GOTM (`-lturbulence` and `-lutil`).
- Compile TELEMAC as usual using the `compileTELEMAC.py` scripts.

### C. Usage instructions for GOTM-TELEMAC

In order to use GOTM with TELEMAC-3D, two keywords need to be specified:

- The keyword VERTICAL TURBULENCE MODEL needs to be set to:

5: Standard GOTM

6: GOTM KPP model

- The keyword GOTM FILE needs to be set to the file name of the namelist file used by GOTM. In this file, all settings of the turbulence model can be specified, as in a standalone GOTM simulation. Details of the specific meaning of the variables in this file can be found in the GOTM manual.

Note that there are some specific requirements when using the GOTM KPP model, related to the surface fluxes and short-wave radiation. In this case, TELEMAC-3D must be coupled to WAQTEL as well. Further the new 25-term equation of state of [7] is obligatory, using the keyword `DENSITY LAW = 5`. These settings are checked by the code on the first call of the GOTM subroutine. For the standard GOTM model, it is required to use the Nikuradse friction law by setting `LAW OF BOTTOM FRICTION = 5`. Turbulence quantities such as  $k$  and  $\varepsilon$  calculated by GOTM can be exported by specifying them in the keyword `VARIABLES FOR 3D GRAPHIC PRINTOUT`. The surface and bottom boundary layer as computed by the GOTM KPP model can be exported as 2D graphic output variables `BLTOP` and `BLBOT`, respectively. The variables `BLTOP` and `BLBOT` are calculated directly by GOTM and are new to this coupled version.

## IV. APPLICATIONS

### A. Lock exchange test case

The lock exchange test case, one of the standard test cases for TELEMAC-3D, is a simple internal dam break problem, in which a horizontal jump in salinity at  $t = 0$  s induces a baroclinic wave. The V7P2 version of the test case was used. To generate sufficient current velocities and turbulence levels, the salinity difference was set to 10 PSU for this test simulation. Fig. displays the predicted salinity field in the lock exchange test case using TELEMAC-3D with the mixing length turbulence model (with the mixing length parametrization of Nezu and Nakagawa) using the Munk-Anderson stability function (top), the native  $k - \varepsilon$

model (middle) and with the  $k - \epsilon$  closure using an algebraic second order turbulence model to compute the scalar diffusivities in GOTM (bottom). Results using the mixing length model and the GOTM  $k - \epsilon$  model are highly similar, although a closer inspection of the calculated diffusivities shows higher mixing with the mixing length model. The TELEMAC-3D with native  $k - \epsilon$  model displays instabilities, as was also evidenced by the exceedance of iterations in the simulation log file, i.e. the simulation did not converge. Computation times on a single processor were 11 s for the mixing length model, and 12 s for the GOTM  $k - \epsilon$  simulation, indicating that the GOTM coupling step occurs at little additional computational cost, even though a rather advanced turbulence scheme is used.

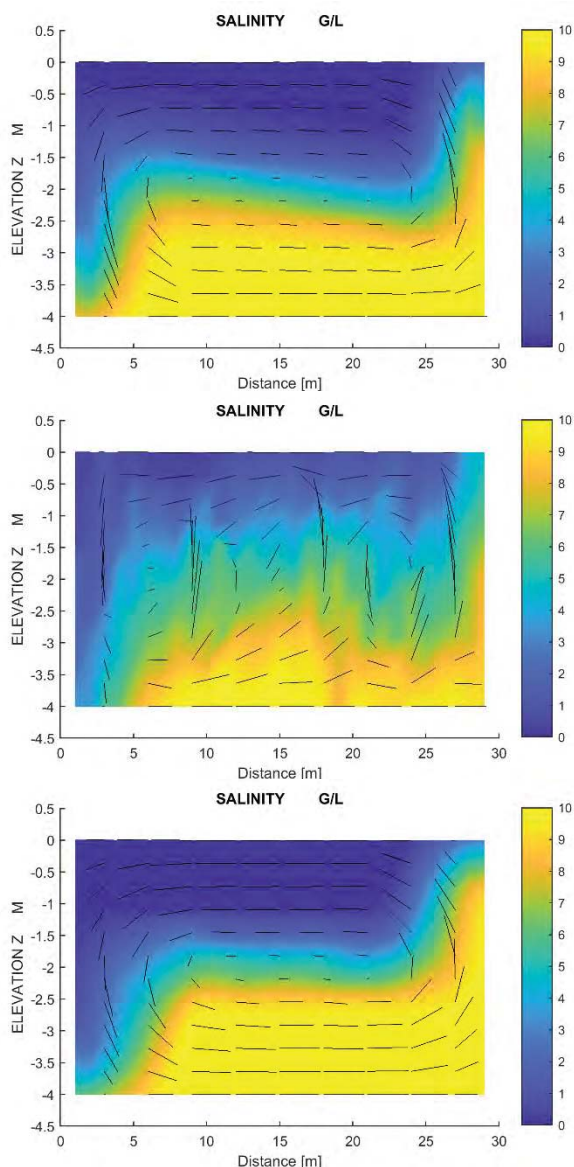


Fig. 1: Salinity field after 100 s for lock exchange benchmark test. Top: TELEMAC-3D mixing length model. Middle: TELEMAC-3D  $k - \epsilon$  model. Bottom: TELEMAC-3D + GOTM  $k - \epsilon$  model.

### B. Stratification test case

The stratification test is one of the standard test cases for TELEMAC-3D. It simulates the development of a velocity profile from the upstream boundary in a stratified flow. The test case was run using the standard setting (except that the friction law was set to Nikuradse) with the TELEMAC-3D  $k - \epsilon$  model and for TELEMAC-3D with the GOTM  $k - \epsilon$  model. The test took 3min29s for the TELEMAC-3D  $k - \epsilon$  model, and 1min59s for the TELEMAC-3D with the GOTM  $k - \epsilon$  model. The velocity and salinity fields are shown in fig. 2 and 3. The differences in the salinity field are extremely limited. Both models show the stratification clearly. There are some slight differences in the velocity field between both models, which can be attributed to the differences in turbulence settings that are used and the fact that the TELEMAC3D - GOTM implementation neglects the horizontal advection of  $k$  and  $\epsilon$ , which may have some influence in the zone where the velocity profile develops.

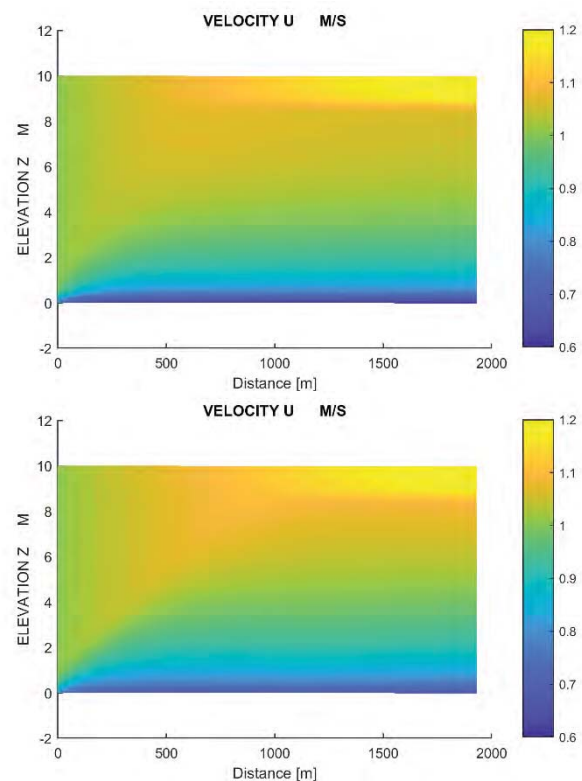


Fig. 2: Velocity field in the final situation for the stratification benchmark test. Top: TELEMAC-3D  $k - \epsilon$  model. Bottom: TELEMAC-3D + GOTM  $k - \epsilon$  model.



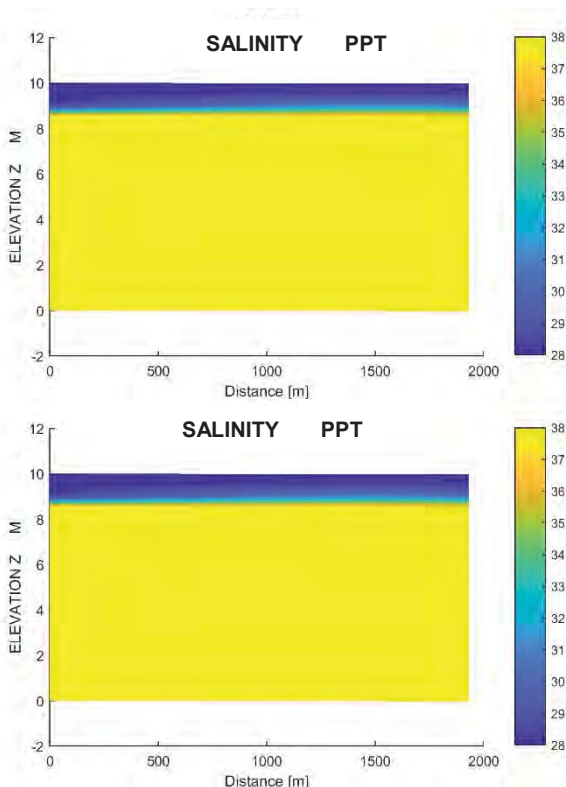


Fig. 3: Salinity field in the final situation for the stratification benchmark test. Top: TELEMAC-3D  $k - \epsilon$  model. Bottom: TELEMAC-3D + GOTM  $k - \epsilon$  model.

### C. Large-scale ocean modelling with K-Profile Parametrization

In the deep ocean, two distinct mixing regimes can usually be distinguished: mixing in the surface and bottom boundary layers under the influence of radiative and atmospheric surface forcing and bottom shear stress, and mixing in the ocean interior due to internal waves and shear instability [8]. The K-Profile Parametrization (KPP) model of Large *et al.* [8] is a frequently used parametrization for oceanic mixing that determines the boundary layer depth based on a bulk Richardson number, and provides expressions for diffusivity and non-local transport in both the boundary layers and in the ocean interior. It is frequently used in large-scale ocean simulations such as the operational HYCOM model ([www.hycom.org](http://www.hycom.org)).

A test simulation of large-scale open-ocean modelling was performed with the TELEMAC-3D/GOTM coupling with KPP on 32 parallel processors. In the open ocean, surface boundary layer thickness is at first order determined by wind shear, temperature- and salinity-driven density stratification, and surface heat fluxes (sensible and latent heat

flux and short- and long-wave radiation). Fig. displays an instantaneous vertical profile of temperature, salinity and vertical eddy viscosity in the surface boundary layer calculated using TELEMAC-3D coupled with GOTM and WAQTEL, using data from HYCOM as forcing [9]. The boundary layer depth extends to approximately 50 m, the limit of stratification. The eddy viscosity in the surface boundary layer scales with the boundary layer depth  $h$ , a depth-dependent turbulent velocity scale  $w_x$  and a prescribed polynomial shape function  $G(\sigma)$  (see [8] for further information):

$$v_z = hw_x G(\sigma). \quad (6)$$

Fig 4 displays a time series of surface boundary layer thickness, wind speed and short-wave radiative forcing over a one-month period. The surface boundary layer thickness displays a strong diurnal cycle with boundary layer thickness of 40-80 m during night time (convective) and high-wind conditions, down to 0-2 m during the daytime due to stabilization by short-wave radiation in the upper water column. Three notable events occurred in the one-month time series, indicated as A, B and C:

A: Strongly reduced day-time stabilization during cloudy conditions (reduced short-wave radiation); large boundary layer persists throughout the day.

B: Increase in maximum boundary layer depth due to increased wind speed.

C: Limited night-time boundary layer formation during low wind speed.

The use of the KPP model in GOTM makes it possible to simulate the impact of these meteorological events on the surface boundary layer within TELEMAC-3D.

### D. Salinity-driven stratification in an estuary

Salinity-induced density stratification has a strong impact on turbulence and general estuarine circulation in many estuaries. Fig. displays vertical profiles of salinity  $c$ , horizontal velocity  $u$ , turbulent kinetic energy  $k$  and diffusivity of salt  $v_{z,sal}$  and momentum  $v_z$  at an estuary mouth at three instances in time: during flood flow (top), flow reversal (high water slack, middle) and during ebb flow (bottom). A simulation was performed with the TELEMAC-3D vertical mixing length model using the mixing length parametrization of Nezu and Nakagawa (red curves), the TELEMAC-3D + GOTM  $k - \epsilon$  vertical turbulence closure with an algebraic second order closure for the scalar mixing fluxes (blue curves), and the TELEMAC-3D internal vertical  $k - \epsilon$  model. The latter simulation displayed instabilities and is therefore not shown in Fig. . Unfortunately, no measurements were available that could be used to compare the results of the different simulations.

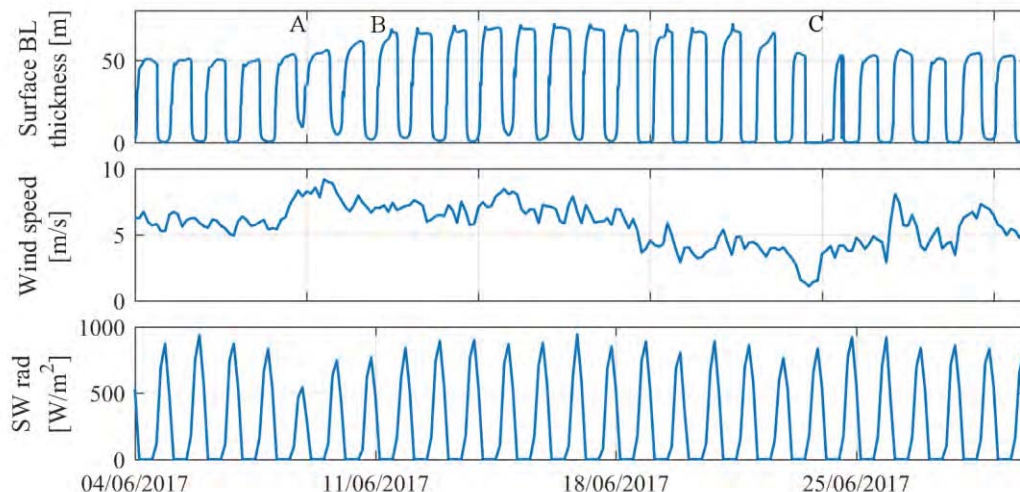


Fig. 4: Surface boundary layer, wind speed and short-wave radiative forcing in the open-ocean test case for the coupled TELEMAC-3D-GOTM model with the KPP turbulence model.

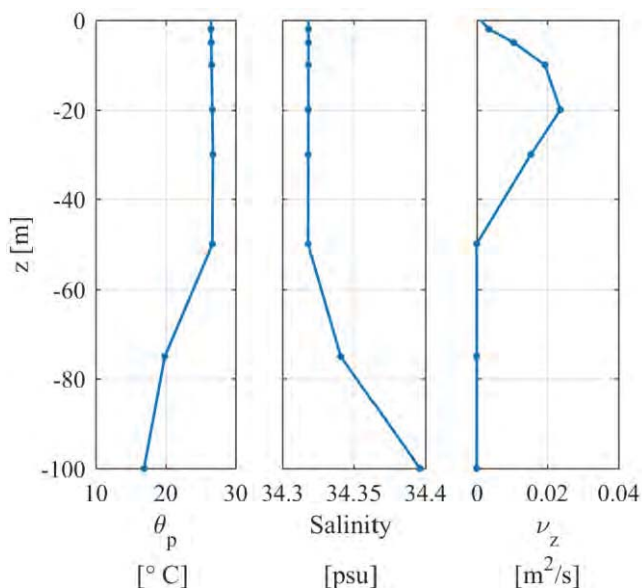


Fig. 5: Temperature ( $\theta_p$ ), salinity and vertical eddy viscosity ( $\nu_z$ ) in the surface boundary layer.

During flood flow (Fig. , top), velocities reach 1 m/s and the turbulent kinetic energy  $k$  reaches up to  $0.013 \text{ m}^2/\text{s}^2$ . Mixing in the  $k - \epsilon$  model is mostly confined to the bottom half of the water column; in contrast, the mixing length model also predicts momentum mixing in the top half of the water column. Around flow reversal (Fig. , middle), turbulence levels are an order of magnitude lower than during flood ( $k$  less than  $4 \cdot 10^{-3} \text{ m}^2/\text{s}^2$ ). More importantly, the turbulence and the vertical mixing are confined to the bottom 2 m of the water column. As a result, significant velocity differences occur between the upper half of the water column (ebb-directed velocities of up to 0.28 m/s) and the center of the water column (flood-directed velocities of up to 0.06 m/s). The mixing length model again predicts more mixing in the upper water column, which results in

much smaller vertical variation in the flow velocity. During ebb flow (Fig. , bottom), the vertical viscosity profile is again markedly different in the GOTM  $k - \epsilon$  model than in the mixing length model, which predicts a parabolic viscosity profile at this instance. The differences in mixing lead to a larger length of the salt tongue when GOTM is used than when the mixing length model is used (Fig. ).

In conclusion of this test case, the TELEMAC3D GOTM  $k - \epsilon$  better captures the physics of shear, salinity stratification, and turbulent mixing than the mixing length model, and this has a significant impact on the predicted macroscale estuarine circulation.

## V. CONCLUSIONS

TELEMAC-3D was coupled to the 1DV General Ocean Turbulence Model (GOTM), enabling the use of various parametrizations and closure schemes for vertical mixing. The functioning of the coupled TELEMAC-3D GOTM model was illustrated with four different usage cases.

The lock exchange test case demonstrates that the GOTM model delivers results that are comparable to a simple mixing length model for the simple geometry of an internal dam-break, and that the GOTM coupling comes at very low additional computational cost. The same was shown in the stratification test case.

The open-ocean case illustrates the use of the non-local K-Profile Parametrization in combination with TELEMAC-3D, making it possible to simulate large-scale ocean circulation with a dynamic surface boundary layer under the influence of wind shear, radiative fluxes and convection.

The estuary model demonstrates that TELEMAC-3D coupled with the GOTM  $k - \epsilon$  closure is capable of realistically simulating the complex interactions between salinity-induced density stratification and vertical turbulent mixing, rendering estuarine circulation patterns that are qualitatively different from simulations with a more rudimentary mixing-length model.

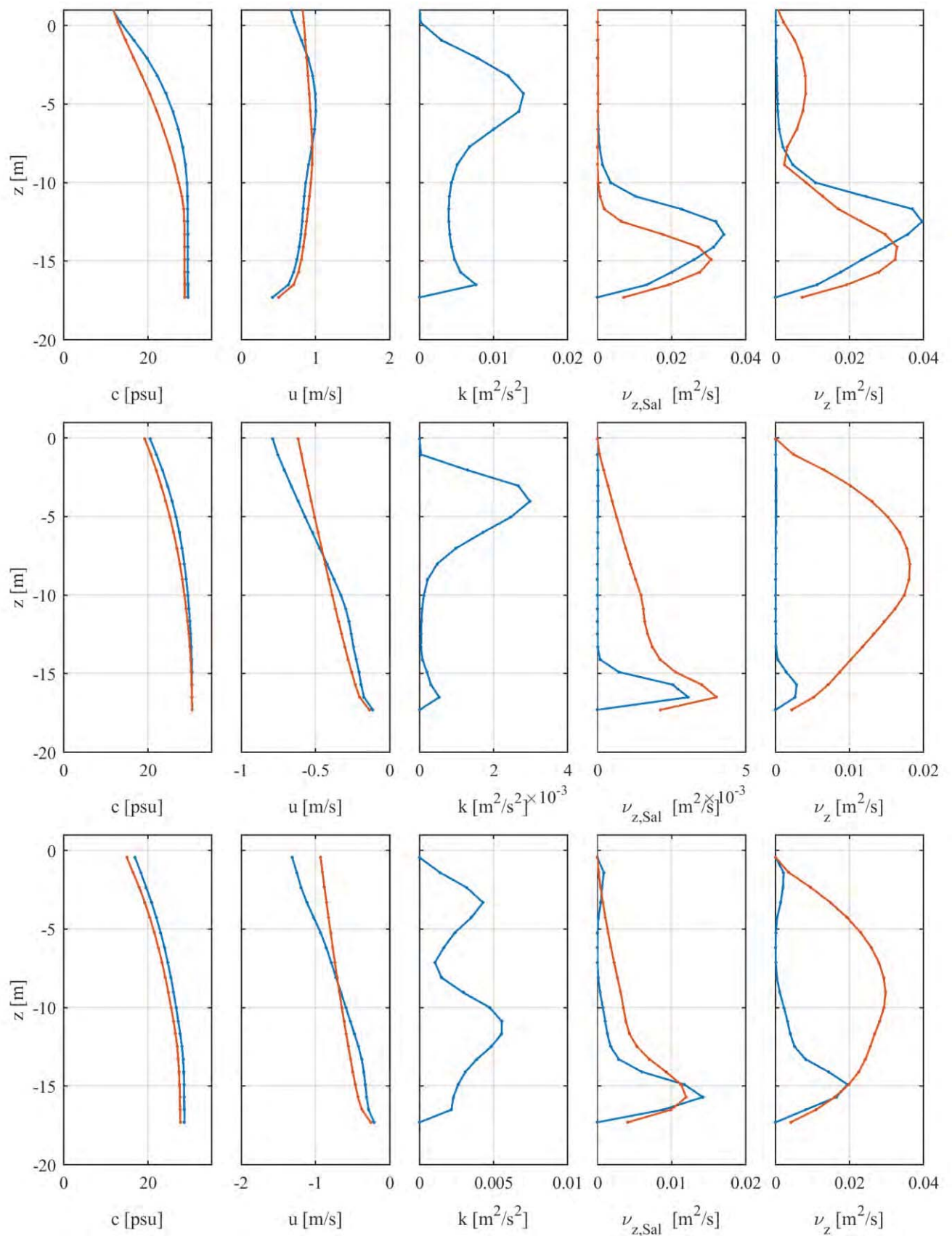


Fig. 6: Vertical profiles of salinity  $c$ , horizontal velocity  $u$ , turbulent kinetic energy  $k$ , salt vertical diffusivity  $\nu_{z,\text{Sal}}$  and vertical viscosity  $\nu_z$  during flood (top), high water slack (middle) and ebb flow (bottom). Red: TELEMAC-3D with vertical mixing length model. Blue: TELEMAC-3D with GOTM  $k - \epsilon$  turbulence closure.

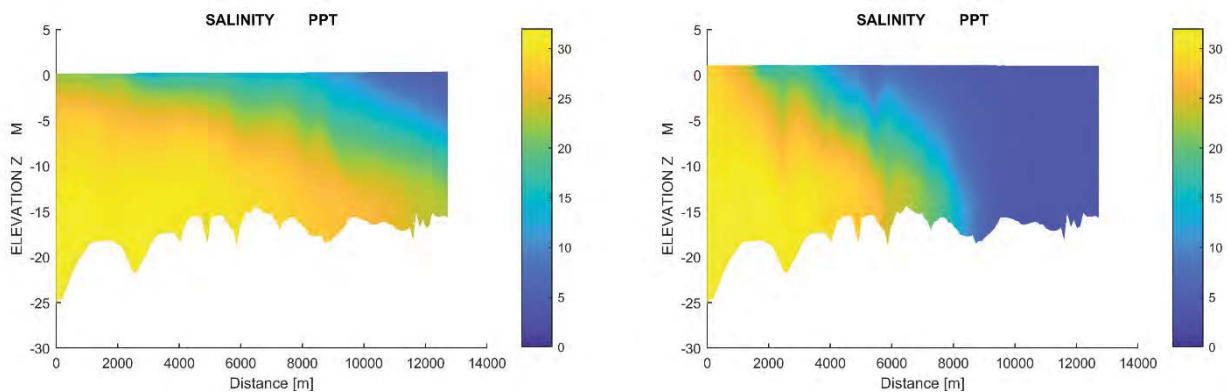


Fig. 7: 2DV profiles of salinity along the estuary thalweg. Right: TELEMAC-3D with vertical mixing length model. Left: TELEMAC-3D with GOTM  $k - \epsilon$  turbulence closure.

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