SEDIMENT TRANSPORT MODELLING IN THE KOPER BAY (NORTHERN ADRIATIC, SLOVENIA)

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Abstract

A comparison of modelling results computed by two sediment transport models is presented. The PCFLOW3D is z-level based, while the ECOMSED uses σ-layer coordinates. Consequently, their bottom velocities differ slightly. Bottom shear-stress and sediment resuspension were calculated separately for currents, waves and combined forcing conditions. Different typical wind conditions were taken into account.

Although both models use the same approach (van Rijn, 1993) to simulate bottom shear-stress, resuspension and sediment transport, some discrepancies in the results were noticeable. The shear-stress results of the two models are in relatively good qualitative agreement, while the agreements of resuspension and suspended sediment concentrations within the water column are somewhat poorer.

Furthermore, in small areas such as the Koper Bay the open boundary condition can have a significant impact on hydrodynamic parameters and consequently on sediment transport. One-way nesting with a larger computational domain would be necessary.

Introduction

Modelling results of sediment transport computed by two different numerical models are presented. The models are based on different architecture. In the absence of quality measurements, comparison of results represents the best possible verification of the two models.

The case study to verify the two models was performed on the area of Koper Bay, Slovenia. Numerous modelling studies of sediment transport have been carried out in the northern part of the Gulf of Trieste due to mercury pollution caused by the former mercury mine in Idrija, Slovenia (Horvat et al., 1999; Rajar et al., 2000), while such studies are rare for the southern part of the Gulf and for the Koper Bay. The Koper Bay is an area of about 3 km^2 in the easternmost part of the Gulf of Trieste, moderately polluted with metals, hydrocarbons and organotin compounds due to shipping and port activities. Pollutants are mostly bound to fine sediment fractions <63 μm in diameter. In certain meteorological conditions resuspended sediment could be carried northwards to an environmentally vulnerable area protected by the *Natura-2000* programme. A numerical modelling study of sediment transport in a few typical synoptic conditions was performed in order to determine the origin and destination of polluted sediment. The impact of wind-induced currents and waves on resuspension and sediment transport was taken into account. The influence of bottom vegetation and shipping was not accounted for, although both phenomena could have a significant impact on sediment resuspension in such a shallow area.

Methods and models

The three-dimensional models used in this study are based on different architecture: the PCFLOW3D model (Rajar and Cetina, 1997; Rajar et al., 2004; Rajar et al., 2000; Zagar et al., 2007) is z-level based, while the ECOMSED model (http://www.hydroqual.com/ehst_ecomsed.html), developed from the Princeton Ocean Model (Blumberg and Mellor, 1987), uses σ-layer coordinates. The same horizontal numerical grid with an approximately 40 m resolution was used in both models. In the vertical plane the domain was divided into 1 m thick layers in the PCFLOW3D model, while 11 unequally distributed σ-layers were used in the ECOMSED model, as described in the climatic study of the circulation of the Gulf of Trieste (Malačič and Petelin, 2009). At the open (west) boundary of the domain the clamped (fixed) boundary condition was applied in PCFLOW3D and the radiation boundary condition in the ECOMSED model.

The sediment modules of both models follow the principle described by van Rijn (1993). Critical bed shear-stress is computed from sediment characteristics and water viscosity and density. The effective shear-stress is computed as the vectorial sum of shear-stresses caused by near-bottom currents and the motion of waves. The equilibrium suspended sediment concentration depends on the ratio between the critical and effective shear-stress. Resuspension of bottom sediment occurs where critical shear-stress is exceeded, and sedimentation occurs when the equilibrium concentration is exceeded.

The collected wind data from three nearest stations (Port of Koper, a buoy near Piran and Port of Trieste) show that the most frequent winds in the area are easterlies (52%). Due to its occasional extreme strength, the *bora* wind (ENE, 88^{o}) contributes most of the wind energy. Other winds such as *scirocco* (SE, 110^{o}) and westerly winds (260-315^{o}) are not as strong as *bora* and are less frequent. In the four typical cases (Table 1) wind-driven circulation is dominant. Therefore, the momentum and freshwater inflow of rivers was neglected in all simulations. Well mixed winter conditions (temperature 10^{o}C, salinity 35 PSU) were adopted in all cases. Simulations of circulation were performed with both models. All simulations were carried out for 4-6 hours, until steady-state circulation was reached.

Table 1: Typical wind situations in the Koper Bay.

Wind	Strength [m/s]	Direction [^{o}]
Bora	11	88
Scirocco	9	110
Westerly 1	6	260
Westerly 2	6	315

For computation of wind-induced waves the PCFLOW3D model uses approximate formulae by Brettschneider (1952). The computed waves in the first two wind cases (*bora* and *scirocco*) reached the height of up to 35 cm at the period of about 1.5 s, which is in good agreement with observations in the Koper Bay and measurements at the coastal buoy in the southern part of the Gulf of Trieste (http://buoy.mbss.org).

Table 2: Granulometric characteristics of sediment

Sediment sample	Depth [m]	D_{16} [μm]	D_{50} [μm]	D_{84} [μm]	D_{90} [μm]
1	4	3	15	50	70
2	7	1.5	5.6	20	22
3	14	1.5	6.5	20	22
4	**18**	**1.7**	**7**	**23**	**30**
5	12	1.7	7.2	23	30

The characteristics of the topmost layer (0-1 cm) for five sediment samples are shown in Table 2. The mostly silty sediment from the inner part of the Bay (sample 4) was used for modelling. The bulk density of the sediment is 1.3 g/cm^{3}. Sedimentation velocity is between $5 \cdot 10^{-5}$ and $7 \cdot 10^{-5}$ m/s and the critical bed shear-stress is approximately 0.1 N/m^{2}. The initial suspended sediment concentration in the water column and the inflow of sediment from the rivers were set to 0.

Results and discussion

The highest sediment transport occurs during the *bora* wind periods. The results of this case are presented in detail.

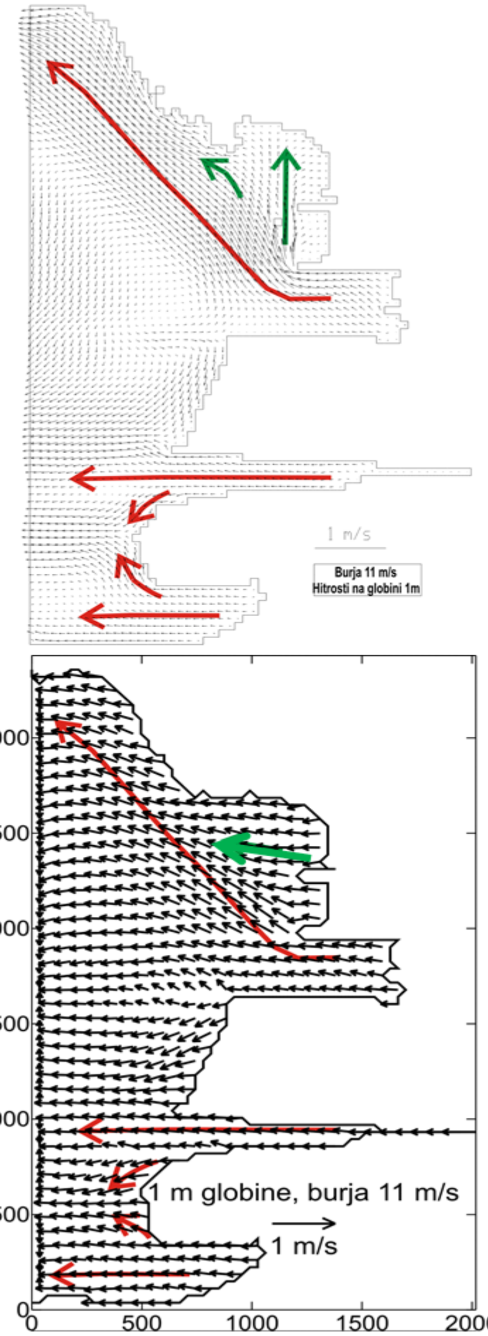

Figure 1a: Circulation in the Koper Bay simulated with the PCFLOW3D model (top) and the ECOMSED model (bottom). The surface layer is shown.

Despite the differences in the circulation models, the general circulation patterns are similar both at the surface and in the deeper layers. The differences occur mostly in deeper layers and close to the coastline. In Figure 1 the similarities are marked with red arrows and the most significant differences in circulation with green arrows. Both models used the same grid resolution. However, for the purpose of better visualisation of the ECOMSED results, only every second velocity vector is drawn.

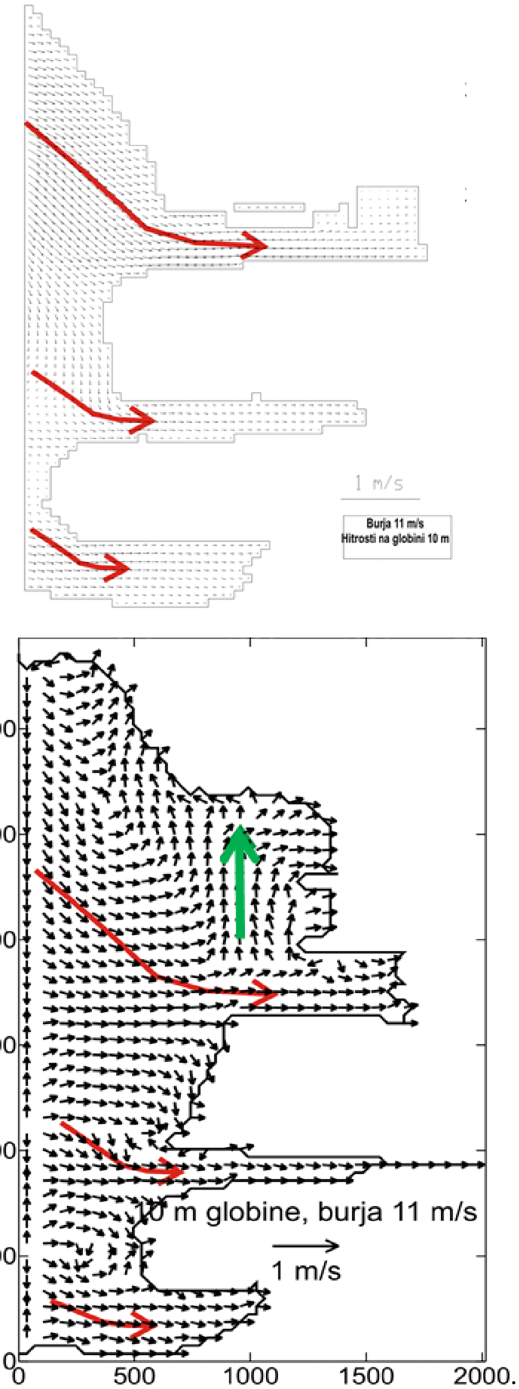

Figure 1b: Circulation in the Koper Bay simulated with the PCFLOW3D model (top) and the ECOMSED model (bottom). The 10 m layer is shown.

The effective bottom shear-stress caused by currents is presented in Figure 2. The critical shear-stress (0.1 N/m^2) is not exceeded anywhere in the computational domain. Both models produce qualitatively similar results, although values of the bottom stress in the ECOMSED model are slightly higher.

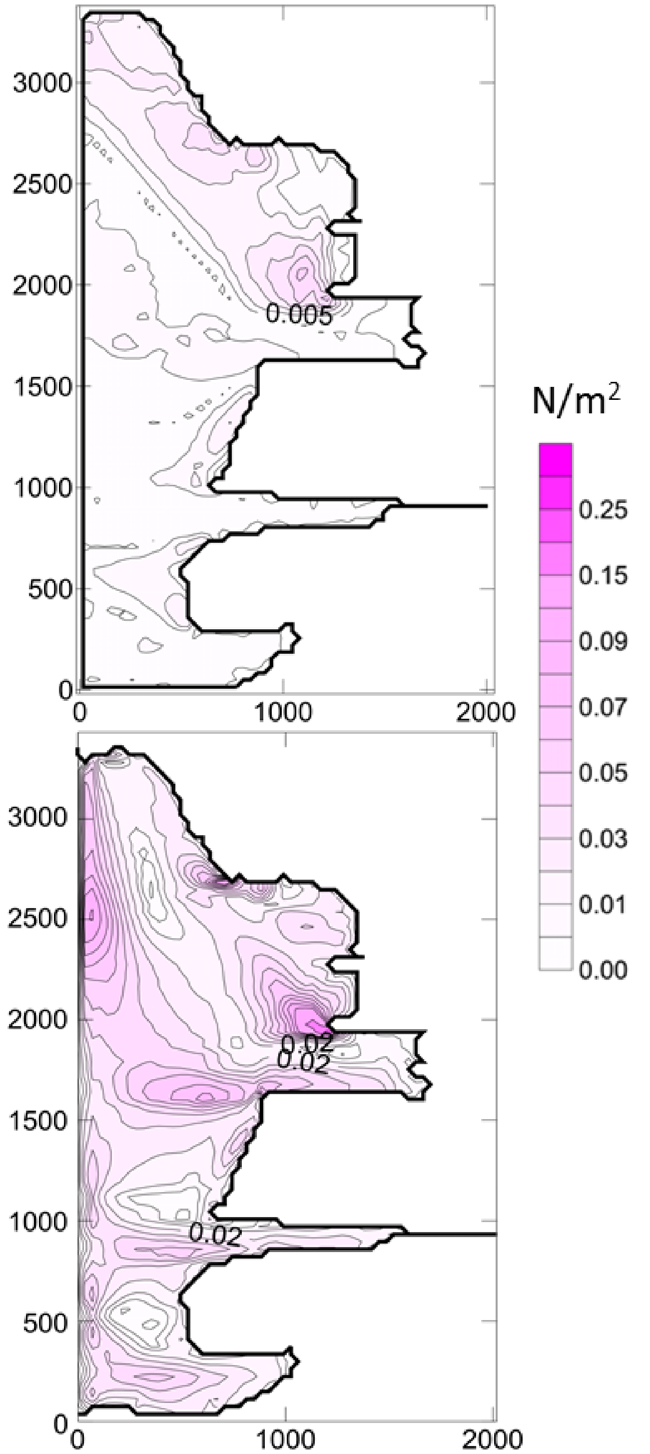

Figure 2: Bottom shear-stress [N/m^2] induced by currents. The PCFLOW3D model (top) and the ECOMSED model (bottom). Critical shear-stress is not exceeded.

The impact of wind-generated waves significantly increases the bottom shear-stress, particularly in the shallower parts of the domain. In this wind case, critical shear-stress is exceeded and resuspension of sediment occurs in the north-eastern part of the domain. Figure 3 shows the bottom shear-stress and Figure 4 the thickness of resuspension and deposition for a 24-hour period. As the computation time was relatively short, the quantity of transported material is extremely low.

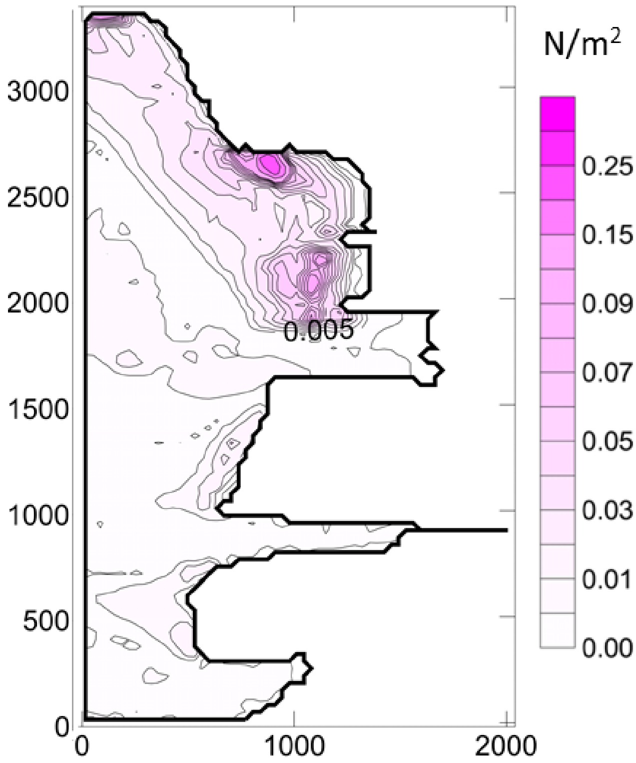

Figure 3: Bottom shear-stress [N/m^2] due to currents and waves computed with the PCFLOW3D model. Critical shear-stress is exceeded in the north-eastern part of the domain.

It is, however, noticeable, that resuspension occurs mostly in the vicinity of the *Natura-2000* protected area. Moreover, during such an event, currents in the area of resuspension in surface and sub-surface layers are mostly oriented northwards, in the direction of the protected area (Figure 1). On the other hand, the suspended sediment concentrations in the bottom layer (Figure 5) were relatively low in the protected area. They exceeded 1 mg/l only at the western border of the area, where the currents are oriented westwards, away from the protected part of the Bay. Furthermore, no area with distinct sedimentation can be observed in Figure 4; the resuspended sediment is being dispersed and settled along the computational domain. Therefore, it is very likely that sediment transport during strong *bora* winds does not significantly impact the state of pollution in the protected area.

Unfortunately, the differences in suspended sediment concentrations between the two models are significant. The PCFLOW3D model gives distinctly higher values than the ECOMSED, and the suspended sediment is distributed in a much wider area. The pattern and the concentrations are similar only in the north-eastern part of the Bay. One of the possible reasons is in the different ways of addressing wave parameters and wave-induced shear-stress, which was not included into the ECOMSED model. This issue requires further investigation in order to perform a correct and relevant comparison of both models.

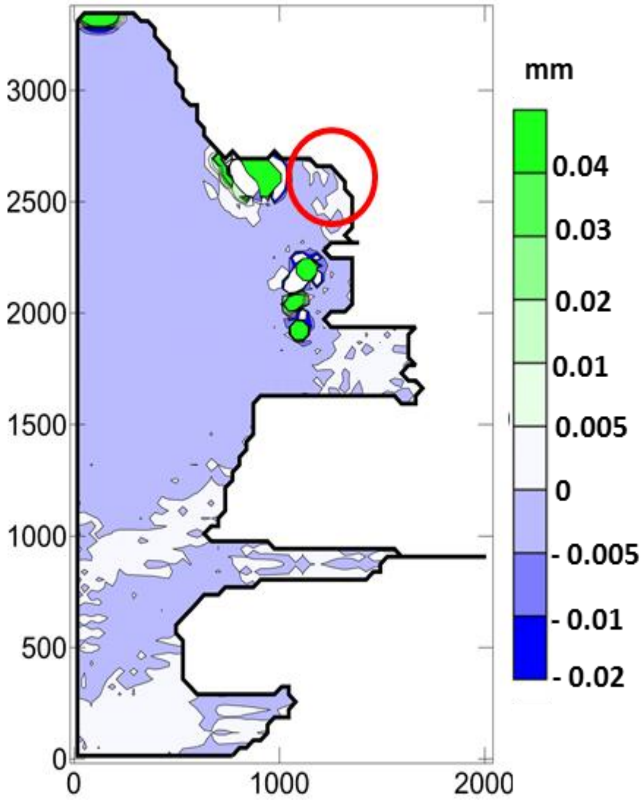

Figure 4: Thicknesses of erosion (green) and deposition (blue) areas, in [mm]; computed with the PCFLOW3D model for a 24-hour time period. The red circle shows the *Natura-2000* protected area.

Another question that needs to be addressed is the impact of shipping on sediment resuspension and transport. Measurements of turbidity in the Koper Bay performed in 2009 showed high correlation between manoeuvring of larger ships and turbidity peaks (Malačič et al., 2010). Moreover, the observed turbidity peaks induced by shipping were higher than any of the peaks measured in high-wind conditions. Therefore, the shear-stress caused by ship propellers should be included into modelling of sediment transport in the Koper Bay in the future. It is, however, difficult to account for momentum of jets, as their dimensions are significantly smaller than the model grid size and their duration is limited. A substantially refined grid and unsteady-state modelling with a shorter time-step (a few seconds) are required to simulate such phenomena. For comparison, the time-step in all the performed steady-state sediment transport simulations was in the order of magnitude of a few minutes.

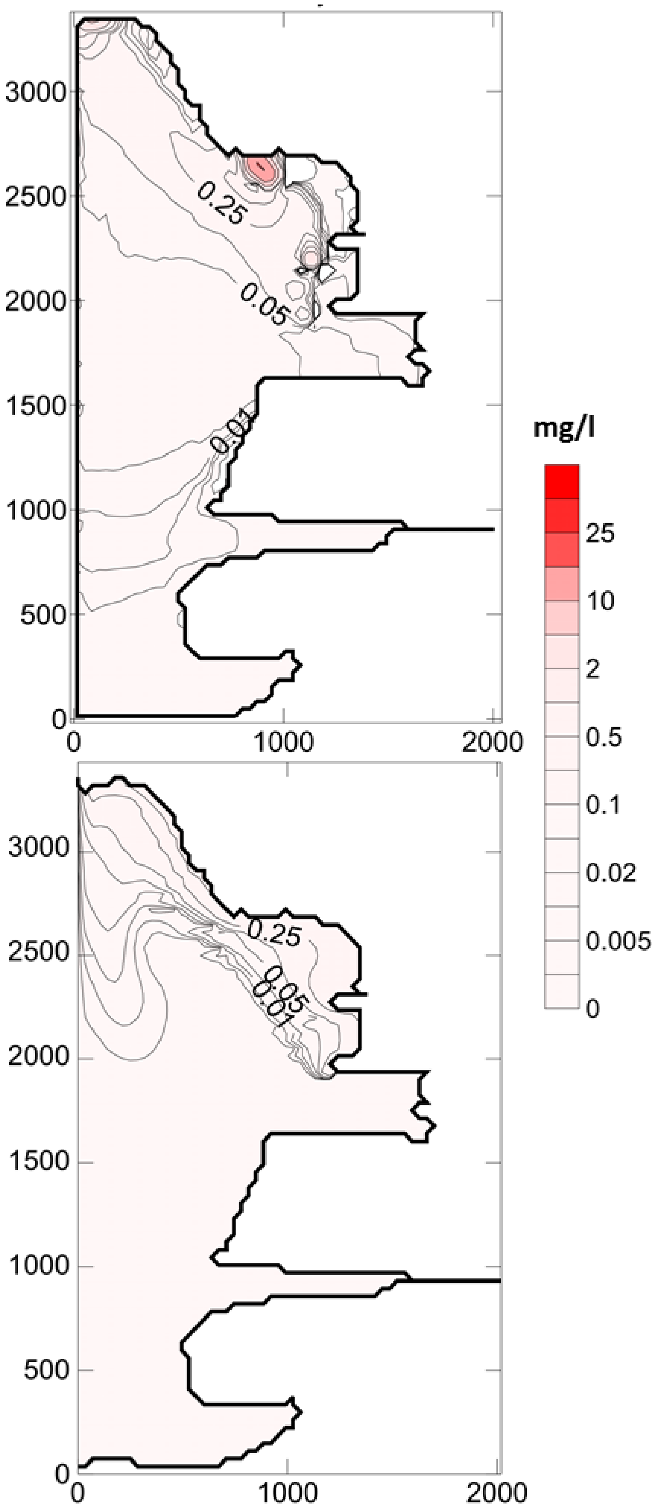

Figure 5: Suspended sediment concentration [mg/l] in the bottom layer computed with the PCFFLOW3D model (top) and the ECOMSED model (bottom), the stress caused by surface waves excluded in the ECOMSED model.

The next question arose when the simulated circulation in the Koper Bay was compared to measurements. During *bora* events (ENE) the measured currents at the surface in the inner Bay (Malačič et al., 2010) are oriented southward (Figure 6), which neither of the models was able to simulate correctly. Instead, both models showed a westward current direction at this position (Figure 1). A possible source of this anomaly stems from the open boundary condition: none of the performed simulations took into account circulation in the wider domain. It is, however, known that in small and wide open computational domains such as the Koper Bay and even the Gulf of Trieste (about 600 km^2), the open boundary quickly overrides all other forcings: an inappropriately chosen boundary condition can result in a wrong circulation pattern after only a few hours of simulation time.

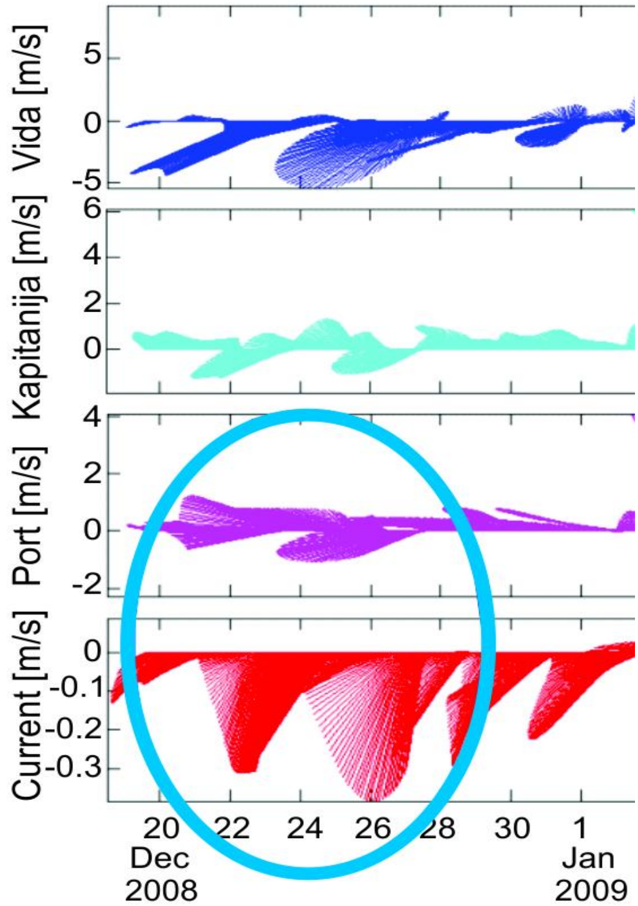

Figure 6: Low-pass filtered wind measurements at the buoy Vida (top plot, blue), at the mareographic station Koper ('Kapitanija', cyan) and in the Port of Koper ('Port', magenta). Measured currents (bottom plot, Malačič et al., 2010) at a depth of 0.8 m in the Port of Koper (red). Hourly velocity vectors are shown and the ellipse marks the bora wind event.

In order to clarify the source of the discrepancy, circulations in wider computational domains (the Gulf of Trieste and the entire Northern Adriatic) were computed with both models and compared to the circulation in the Koper Bay. Again, the agreement between the models was satisfactory. In Figure 7 the similarities and discrepancies between the models at the open boundary of Koper Bay are highlighted. It is evident that the forcing of the wider computational domain through the open boundary of Koper Bay cannot be neglected. The same is valid for the open boundary of the Gulf of Trieste, a sub-domain of the Northern Adriatic. Considering the dimensions of Koper Bay, at least one-level (Gulf of Trieste – Koper Bay) one-way nesting would be required to satisfactorily simulate circulation. Even better results are likely to be achieved using two-level nesting (Northern Adriatic – Gulf of Trieste – Koper Bay). Such simulations (two-level one-way nesting) are already being tested.

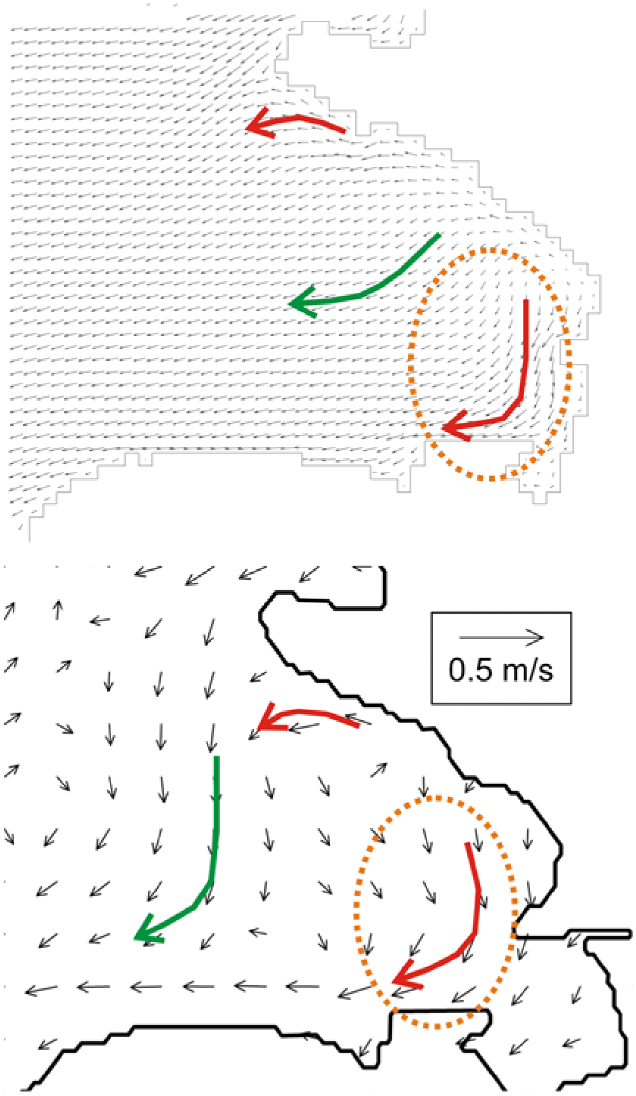

Figure 7: Surface (1 m depth) circulation in the south-eastern part of the Gulf of Trieste during *bora* wind simulated with PCFLOW3D (top, grid 140 by 150 m) and ECOMSED (bottom, grid 600 by 600 m). Similarities are marked with red and differences with green arrows. The southward current in the Koper Bay is marked with orange ellipses.

Conclusions

Circulation and sediment transport were simulated with two different models. The simulations of circulation were in better agreement than simulations of sediment transport. The results of bottom shear-stress were comparable, while the erosion/sedimentation areas and the suspended matter concentrations showed poorer agreement. Compared to measurements, significant anomalies in circulation patterns were found; these anomalies most likely stem from the open boundary condition, as shown by additional simulations over a larger domain. In order to more accurately simulate circulation and sediment transport, at least one-level nesting would be required. The influence of maritime traffic on the sediment resuspension is also important and needs to be taken into account in future studies.

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