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COMPARISON OF MODELS MIKE3 AND PCFLOW3D: HYDRODYNAMIC SIMULATIONS IN THE GULF OF TRIESTE

PRIMERJAVA MODELOV MIKE3 IN PCLOW3D: SIMULACIJE HIDRODINAMIKE V TRŽAŠKEM ZALIVU

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Abstract

Coastal sea circulation models are a useful tool for sea forecasting and a good starting point for calculating pollutant transport. Two similar three-dimensional baroclinic hydrodynamic models (PCFLOW3D and MIKE3) were compared on a case study of the Gulf of Trieste. The comparison was not based only on the graphic (visual) parameters, but was also numerically evaluated using the normalised root-mean-square deviation method (RMSDN). Typical cases of circulation were selected, where the similarities and differences between both models are clearly visible. Density-driven flows were studied, as well as the impact of strong wind (bora), mild wind (maestral) and the tide on circulation. In one case, constant coefficients of turbulent viscosity in the horizontal and vertical directions were used. In this case the results show dependence on the different numerical schemes and on the definition of boundary conditions of both models. In all other cases, the turbulence models used were as similar as possible, selected among the ones usually used in circulation models (Smagorinsky in the horizontal direction in both models and in the vertical direction k-ϵ and Mellor-Yamada in MIKE3 and PCFLOW3D, respectively). An additional comparison with refined grid was performed in the events of density-driven flow and strong bora wind in the area of the Soča river inflow. The results of both models are similar. However, there are noticeable local discrepancies due to the differences between the models, mostly the different turbulence models and the boundary conditions definition. The results were also compared to simulations performed by the POM model. This three-way comparison showed in general a very similar picture of circulation. According to the results, both models, MIKE3 and PCFLOW3D, can be used interchangeably in areas with characteristics similar to the Gulf of Trieste.

Keywords: hydrodynamic model, circulation, Gulf of Trieste, MIKE3, PCFLOW3D, model comparison.

Izvleček

Modeli tokovanja priobalnih območij so uporabno orodje za napovedovanje stanja morja, hkrati pa tudi osnova za simulacije transporta onesnažil. V izvedeni študiji smo na območju Tržaškega zaliva primerjali dva podobna tridimenzionalna baroklina modela, PCFLOW3D in MIKE3. Poleg vizualne primerjave smo

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rezultate primerjali tudi numerično po metodi RMSDN, z metodo normaliziranega odstopanja korena povprečne kvadratne napake (RMS). Izbrali smo značilne primere tokov, kjer so podobnosti in razlike jasno vidne. Upoštevali smo gostotne tokove, vpliv močnega in šibkega vetra (burje in maestrala) ter plimovanja. V enem primeru smo uporabili konstantne koeficiente turbulentne viskoznosti v horizontalni in vertikalni smeri, odstopanja so bila v tem primeru odvisna od uporabljene numerične sheme in robnih pogojev v obeh modelih. V vseh drugih primerih smo uporabili kolikor mogoče podobne modele turbulence, ki se pogosto uporabljajo v cirkulacijsih modelih: Smagorinsky v horizontalni smeri, v vertikalni pa k-є v modelu MIKE3 in Mellor-Yamada v modelu PCFLOW3D. Na območju vtoka Soče smo izvedli tudi primerjavo z zgoščeno numerično mrežo v primerih gostotnih tokov in močne burje. Rezultati obeh modelov so podobni, vendar pa so razlike opazne. Izvirajo predvsem iz različnih modelov turbulence in definicije robnih pogojev. Rezultate obeh modelov smo primerjali še z modelom POM. Trojna primerjava kaže v splošnem zelo podobno sliko tokov. Glede na rezultate sodimo, da smemo oba modela, MIKE3 in PCFLOW3D, uporabljati na območjih, ki so po svojih značilnostih podobna Tržaškemu zalivu.
Ključne besede: hidrodinamični model, tokovi, Tržaški zaliv, MIKE3, PCFLOW3D, primerjava modelov.

1. Introduction

During the last decades, development of mathematical models resulted in many studies of circulation of water masses in coastal and deep sea environment. Circulation studies and research projects based on model simulations were performed in the Mediterranean (e.g. Zavatarelli and Mellor, 1995) and the Adriatic Sea and its parts (e.g. Artegiani et al., 1997). One of the recent projects dedicated to the Adriatic Sea was ADRICOSM (2001 – 2005), which demonstrated the feasibility of establishing an operational monitoring and forecasting system at the shelf and coastal sea scale (Castellari et al., 2006). Near real-time monitoring data in some parts of the Adriatic Sea was assimilated into the Adriatic Sea regional model (Celio et al., 2006; Grezio and Pinardi, 2006). Furthermore, some circulation events in smaller scale were simulated for the Gulf of Trieste (Crise et al., 2006; Malačič and Petelin, 2006) and a nested modelling study of the Croatian coastal waters between Split and Dubrovnik was presented (Orlić et al., 2006). Such modelling approach and the simulation results represent not only a valuable set of circulation data; using appropriate modelling tools these results can be further used to simulate transport and transformations of different pollutants on local and regional scales.

The tools usually used in sea forecasting computations are a combination of meteorological and baroclinic hydrodynamic models with a separate or inbuilt wave model. Several scientific and some commercial models are available for calculating circulation. Among the former are POM (Princeton Ocean Model – Blumerg and Mellor, 1987) and its modifications (e.g. Zavatarelli and Pinardi, 2003), MIT-GCM (Massachusetts Institute of Technology – General Circulation Model; Marotzke et al., 1999 and http://www.atmos.ucla.edu/~mechoso/esm/mit.html) as well as the PCFLOW3D model, developed at the University of Ljubljana, Faculty of Civil and Geodetic Engineering and described in Četina (1992), Rajar and Četina (1997) and Četina et al. (1999). Among the commercially available circulation models, the most well known are the 2D model MIKE21 and the 3D model MIKE3, developed at the Danish Hydraulic Institute (http://www.dhigroup.com/).

Quality modelling tools are an essential prerequisite for accurate sea forecasting. These models have to be validated before use, by comparing with available measurements or at least among each other. Furthermore, it is useful to have a wide range of available hydrodynamic models that can be run separately or simultaneously. The latter can be used as a calibration and validation method for each of the models. Known circulation (result of a hydrodynamic model) is the basis for further modelling of transport and transformations of substances, especially pollutants that are either dissolved or bound to particulate matter. Models of transport, dispersion and transformations are often used to predict water quality in cases of accidental events such as oil spills (Rajar et al. 1995; 1997, Ramšak et al., 2013) or in long-term simulations of pollutant distribution in a selected area (Žagar, 1999; Žagar et al., 2001; Ramšak et al., 2013). In the latter cases the pre-calculated velocity fields (with unaltered forcing factors) enable faster simulations of transport and transformations of those pollutants that do not affect water density and consequently the velocity fields.

Both models under study have already been used in the area of Northern Adriatic. Detailed description of the use of PCFLOW3D can be found in numerous publications (Četina, 1992; Rajar et al., 1997; Rajar at al., 2000; Rajar et al., 2004; Kovšca, 2007; Žagar et al. 2007; Dorić, 2008). Many of the simulations of circulation in the Gulf of Trieste were used as the basis for further studies of pollutant transport and transformations. Oil spill simulations were performed (Rajar et al., 1997), as well as sediment re-suspension and transport (Žagar, 1999) and the transport, fluxes and transformations of mercury and its compounds (Rajar et al., 2000; Žagar et al., 2001; Rajar et al., 2004; Ramšak, 2006; Kovšca, 2007). Some of those simulations were also used as the source of input data for the comparison of the two models under study.

Some hydrodynamic simulations performed with the MIKE3 model in the Northern part of the Adriatic Sea are described in the literature. The MIKE3-FM (Flexible Mesh) model was used by Bocci et al. (2006) in their study of hydrodynamics north of the line Ravenna - Pula. The model was further used for short- and long-term simulations of the transport and dispersion of nutrients and micro pollutants from the planned sewer system outlet outside the Venice Lagoon. The authors used the additional ECOLAB module (DHI) to simulate the effect of E. coli on the water quality in the vicinity of the outlet.

The Princeton Ocean Model (POM) has also been used for the study of circulation in the Gulf of Trieste (Malačič and Petelin, 2006). The results of these simulations were compared with the results of both tested models in this study. Suitable 3D models for simulations of coastal sea circulation as well as the results of such simulations in the area under study are relatively scarce. Any opportunity of comparing the results of such simulations is therefore very welcome. Moreover, direct comparisons of two 3D baroclinic models in the Adriatic Sea are rare (e.g. Chiggiato and Oddo, 2008). Since a visual assessment of the agreement of velocity fields calculated by different models is subjective, a numeric method has been applied to compare the PCFLOW3D and MIKE3 models that has not been used before and is described in detail in section 3.1.

The main aim of testing and comparing the two models was therefore to compare the results and their suitability for calculating circulation in the Gulf of Trieste and other coastal seas with similar characteristics. Despite the similar structure of the two models, preliminary simulations (Dorić, 2008) have shown noticeable differences in their results. The simulations shown below were therefore performed also to demonstrate possible sources of error or deviation in the results of both models.

2. Models and simulations

2.1 Description of models

The models MIKE3 and PCFLOW3D are baroclinic non-steady state 3D hydrodynamic models with constant thickness of layers in the vertical direction (»z« coordinates). They are used to simulate circulation in water, especially in areas where the parameters are unevenly distributed along the water column. The models in themselves are designed to study circulation, but with additional modules (transport-dispersion, sedimentation, biogeochemical modules) they can simulate other processes in larger domains, e.g. lakes and seas.

The model MIKE3 was developed at the Danish Hydraulic Institute (DHI) and is described in detail elsewhere (DHI 2007a-e). There are several versions of MIKE3 beside the hydrostatic approximation version, e.g. the full 3D version and the version based on finite elements (MIKE3 Flexible Mesh) which uses the “s” coordinates in the vertical direction. These versions were not used for the described simulations. A detailed description of the structure and functioning of the PCFLOW3D model is given in literature (Četina, 1992; Rajar and Četina, 1997; Rajar et al., 2000; Rajar et al., 2004; Žagar et al., 2007; Dorić, 2008).

The version of MIKE3 applied for the simulations and the PCFLOW3D model are thus very similar circulation models with hydrostatic approximation. Both contain the same basic equations (mass conservation equation for separate layers, momentum equations in the X and Y directions, kinematic boundary condition for the surface layer, fully-3D advection dispersion equations for temperature and salinity and the equation of state). In both models the computational domain is described using a rectangular grid and uniform thickness of layers and both are based on the finite difference (control volumes) discretisation methods. Table 1 lists the differences between the models that could be the source of discrepancies between the results of their simulations. Differences in the numeric schemes and the turbulence models used and particularly the different ways of defining boundary conditions at the open boundary and in the inflow control volumes are possibly the main reason for the observed discrepancies. The PCFLOW3D model does not allow separate definition of inflow momentum and discharge in the inflow cell, which in the case of coarser grid particularly with longer duration simulations can significantly contribute to the worse accuracy of results.

Both models allow the refinement of the numerical grid, which is defined differently in both models. In MIKE3 the refinement is accomplished in the form of nesting in the area of interest and the dimensions of the refined cells are thereby reduced to a third of the original size. PCFLOW3D, however, uses gradual refinement of the grid over the entire definition area along both coordinate directions (Četina et al., 1999). An example of grid refinement in both models is shown in Figure 3.

Table 1: *Comparison of the structure of the MIKE3 and PCFLOW3D models.*
Preglednica 1: *Primerjava zgradbe modelov MIKE3 in PCFLOW3D.*

	PCFLOW3D	MIKE3
Numeric scheme in the transport module:	• hybrid upwind – central difference • quick	• 3D quickest – sharp • ultimate - quickest • simple upwind • fully 3D upwind
Turbulence models:	Any combination of horizontal and vertical model: • constant viscosity vertically and/or horizontally • Smagorinsky horizontally • Koutitas vertically • Mellor-Yamada vertically • Smagorinsky vertically	Choice between given combinations of turbulence models: • constant viscosity (hor. and vert.) • model Smagorinsky (hor. and vert.) • k model (hor. and vert.) • k-ϵ model (hor. and vert.) • k-ϵ model vert./ Smagorinsky model hor.
Boundary condition – inflow cell:	Velocity components in the x and y directions are defined	Direction and absolute velocity of inflow, and discharge are defined

2.2 Input data

The Gulf of Trieste has roughly a shape of a rectangle and the dimensions of the definition area along the main axes are 31800 × 33000 m. In the horizontal plain the area was divided into cells of the dimension 600 x 600 m, and along the depth into 25 layers with equal thickness of 1 m. In the area surrounding the mouth of the Soča River some simulations were made with refined horizontal numerical grid to cells of 200 x 200 m. The distribution of salinity and temperature for simulations of summer conditions were obtained from measurements in 29 points of the Gulf of Trieste performed in August 1995 and the obtained data was further interpolated throughout the computational domain (Žagar, 1999; Žagar, 2001). For the simulations of winter conditions a completely mixed state was presumed with uniform temperature of 8°C and salinity 36.5 %o (Žagar, 1999).

Seasonal discharges of the River Soča are based on measurements performed at the discharge gauge in Solkan (Širca et al., 1999). The discharge of the River Soča at its mouth was estimated to be 120 m3/s for simulations of summer conditions, and for winter simulations 150 m3/s, which are average seasonal values (Žagar, 1999). Measurements of temperature at the mouth of the River Soča were also available (Žagar, 1999). Average summer temperature is 16.3°C and in winter 7.7°C. According to available measurements (Kotnik, 2003) the salinity of Soča at the outflow is approximately 17 %o, which is only true of measurements at low and moderate discharges that were considered in the performed simulations.

In the simulations of winter conditions, strong bora wind (ENE 63°, 13 m/s) was presumed. In summer a windless condition and in one case, a maestral (WNW 288°, 4 m/s) were used for the simulations. Spatially homogeneous wind conditions were adopted.

Where the simulation included tidal influence (case B6), the open boundary was supplied with data on winter tide tables for the Gulf of Trieste (ARSO, 2008) and the average winter amplitude (0.45 m) and period (12.4 h) were calculated.

Simulations were labelled according to 3 types of numerical parameters (A-C) and according to 6 combinations of forcing factors (1-6), as can be seen in Table 2. Details on input data of the performed simulations are given in Tables 3 and 4. In all cases the upwind numerical scheme was used: in PCFLOW3D the hybrid upwind-central difference and in MIKE3 the 3D upwind scheme.

2.3 Simulation speed

A comparison of computational time was made for simulations with constant turbulent viscosity coefficients as well as with different turbulence models applied. MIKE3 was at least six times faster than PCFLOW3D in all cases (Table 5).

Table 2: *The numeric parameters and forcing factors used in the simulations.*

Preglednica 2: *Numerični parametri in vsiljevanja uporabljena v simulacijah.*

Simulation	Turbulence model	Grid density
A	constant viscosity	600 x 600 m
B	Mellor-Yamada/Smagorinsky and k- ϵ/Smagorinsky	600 x 600 m
C	Mellor-Yamada/Smagorinsky and k- ϵ/Smagorinsky	600 x 600 to 200 x 200m

Simulation	Temp/Sal	Wind	Soča	tide
1	Summer	-	-	-
2	Summer	-	120 m^3/s	-
3	Winter	13 m/s ENE	-	-
4	Winter	13 m/s ENE	150 m^3/s	-
5	Summer	4 m/s WNW	120 m^3/s	-
6	Winter	-	150 m^3/s	45 cm/12.4 h

Table 3: *Numerical schemes and turbulence models in individual simulations.*

Preglednica 3: *Numerične sheme in modeli turbulence v posameznih simulacijah.*

Simulation		A1	A2	A3	A4	B2	B5	B4	B6	C2	C4
Dimensions of numerical grid	X	600m				600m				200m – 600m	
	Y	600m				600m				200m – 600m	
Turbulence model	x, y	Constant viscosity				Smagorinsky				Smagorinsky	
		5 m^2/s		5 m^2/s							
	Z	Constant viscosity				MIKE3: k-ε PCFLOW3D:Mellor-Yamada				MIKE3: k-ε PCFLOW3D: Mellor-Yamada	
		0,001 m^2/s		0,004 m^2/s							
Simulation time [h]		48	48	24	24	48	48	24	48	48	24
Numeric scheme		MIKE3: 3D upwind PCFLOW3D: hybrid upwind – central difference									

Table 4: *Hydrometeorological and oceanographic data in individual simulations.*

Preglednica 4: *Hidrometeorološki in oceanografski podatki uporabljeni v posameznih simulacijah.*

Sim.		A1	A2	A3	A4	B2	B4	B5	B6	C2	C4
Wind	speed [m/s]	/	/	13	13	/	13	4	/	/	13
	direction	/	/	ENE 63°	ENE 63°	/	ENE 63°	WNW 288°	/	/	ENE 63°
Density	Temp.	summer	summer	winter	winter	summer	winter	summer	winter	summer	winter
	Sal.	summer	summer	winter	winter	summer	winter	summer	winter	summer	winter
Soča River inflow	flux [m^3/s]	/	120	/	150	120	150	120	150	120	150
	Speed (m/s) MIKE3 (108°)	/	0,141	/	0,177	0,141	0,177	0,141	0,177	0,423	0,531
	Speed (m/s) PCFLOW3D	/	u = 0,1 v = -0,1	/	u = 0,125 v = -0,125	u = 0,1 v = -0,1	u = 0,125 v = -0,125	u = 0,1 v = -0,1	u = 0,125 v = -0,125	u = 0,3 v = -0,3	u = 0,375 v = -0,375
	Temp. [°C]	/	16,3	/	7,7	16,3	7,7	16,3	7,7	16,3	7,7
	Sal. [‰]	/	17	/	17	17	17	17	17	17	17
Impact of Coriolis coefficient		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tide		/	/	/	/	/	/	/	45 cm 12.4 h	/	/

Table 5: *Parameters and comparison of speed of calculation.*

Preglednica 5: *Uporabljeni parametri in primerjava računskih časov.*

Turbulence model	PCFLOW3D	MIKE3
Constant turbulent viscosity (A2)	• Time step: 10 s • Simulation time: 48 h • Number of active control volumes: 39042	
	Computation time: 6.3 h	Computation time: 0.9 h
		6.9 times faster
Mellor-Yamada / Smagorinsky (PCFLOW3D) k-є / Smagorinsky (MIKE3) (B2)	• Time step: 10 s • Simulation time: 48 h • Number of active control volumes: 39042	
	Computation time: 8.5 h	Computation time: 1.4 h
		6.2 times faster

3. Results and discussion

3.1 Criteria for assessing the similarity between modelling results

Results were compared visually but discrepancies between vectors can be difficult to assess objectively and therefore numerical analysis was also used. The assessment of a large number of graphics and vectors of very unequal lengths is especially difficult. It is usually very difficult to visually evaluate the difference where velocities are very small, but this can contribute significantly to the overall difference. A new procedure was therefore introduced to numerically evaluate the differences between vectors in the horizontal plain using the method of normalised root mean square deviation (RMSDN):

$$\text{RMSDN} = \sqrt{\frac{\sum\left[(u_1 - u_2)^2 + (v_1 - v_2)^2\right]}{\sum\left(u_1^2 + v_1^2\right)}} \qquad (1)$$

where u_1 is velocity component in the *x* direction (model PCFLOW3D), u_2 is velocity component in the *x* direction (model MIKE3), v_1 is velocity component in the *y* direction (model PCFLOW3D), v_2 is velocity component in the *y* direction (model MIKE3).

The criteria for assessing the agreement between results of both models are shown in Table 6. The criteria were selected after a preliminary visual comparison of agreement between velocity vectors. For each simulation, the numerical assessment of agreement is given according to the listed criteria. Figures 1, 2, 4 and 5 show examples of excellent, good, acceptable and bad agreements.

Table 6: *Criteria for numerical assessment of agreement between results*

Preglednica 6: *Kriteriji za numerično ovrednotenje rezultatov*

VALUE	ASSESSMENT
RMSDN < 0,20	Excellent
0,20 < RMSDN < 0,40	Good
0,40 < RMSDN < 0,60	Acceptable
RMSDN > 0,60	Bad

3.2 Numerical comparison of results

The results of the RMSDN method for some typical layers are shown in Table 7. The 25th layer signifies the surface and the thickness of each layer is 1 m.

Only in the simulation A1 (constant turbulent viscosity) excellent agreement between the two models was achieved, where density-driven flow due to temperature and salinity gradients without the influence of the Soča River inflow was simulated. The A2 simulation (constant turbulent viscosity, with river inflow) showed a somewhat lower degree of agreement. This was expected, due to the different ways of inflow definition in both models.

Simulations A2 and B2 differ in the chosen turbulence model. In the B2 simulation PCFLOW3D used the Mellor-Yamada model in the vertical direction and Smagorinsky in the horizontal direction, while MIKE3 used the k-ϵ model in the vertical and Smagorinsky in the horizontal direction. Due to the different turbulence models the agreement between the results in the B2 simulation is somewhat lower than in the A2 simulation.

Simulations B2 and C2 differ only in the dimensions of control volumes. The assessment of agreement was calculated only in the vicinity of the Soča River mouth, where the grid was refined to 200 x 200 m. The ways of accounting for river inflows differ between the two models and this is the source of larger discrepancies around the River Soča mouth. The worse agreement of results in the C2 simulation, which only considers the area around the Soča River mouth, was therefore expected.

Simulations A3 and A4, where strong winter wind was taken into account and completely mixed winter conditions were presumed within the Gulf, showed similar results. Despite the influence of the River Soča, which was taken into account in the simulation A4, there were no larger differences between the simulation results. The strong wind is the main influence on movement and therefore the Soča River inflow does not have an important impact on the results.

Table 7: *The results of numerical comparison of MIKE3 and PCFLOW3D models.*

Preglednica 7: *Rezultati numerične primerjave med modeloma MIKE3 in PCFLOW3D.*

Layer/sim.	A1	A2	A3	A4	B2	B4	B5	C2	C4
25	0,195 exc.	0,202 good	0,243 good	0,245 good	0,351 good	0,354 good	0,594 acc.	0,574 acc.	0,321 good
24	______	______	______	______	0,421 acc.	______	______	______	______
20	0,230 good	0,232 good	0,428 acc.	0,429 acc.	0,376 good	0,255 good	0,756 bad	0,644 bad	0,255 good
11	______	______	______	______	0,602 bad	______	______	______	______

Layer/sim_time	B6 24h	B6 27h	B6 30h	B6 33h	B6 36h	B6 39h	B6 42h	B6 45h	B6 48h
25	0,293 good	0,877 bad	0,492 acc.	0,995 bad	0,367 good	0,943 bad	0,776 bad	0,955 bad	0,564 acc.

Layer/sim	A2/B2 MIKE3	A2/B2 PCFLOW3D	A4/B4 MIKE3	A4/B4 PCFLOW3D
25	0,869 bad	0,934 bad	0,666 bad	0,555 acc.

Simulations A4 and B4 differ in the choice of the turbulence model. The agreement in the surface layer is worse in the B4 simulation. In the twentieth layer however, the agreement is better in the B4 simulation. This was ascribed to chance. The C4 simulation differs from B4 only in the dimensions of the numerical grid. The agreement around the Soča River mouth (simulation C4) is therefore slightly better than the agreement in the B4 simulation.

The B5 simulations took into account weak wind (WNW, meastral with the speed of 4 m/s) in summer conditions. The discrepancies between the models were large. The possible reason for this could be the different ways of defining boundary conditions at the open boundary.

Simulation B6 used tide and inflow of the River Soča as the sources of motion. The results for surface layer were compared in 9 time steps (Table 4). The results differ considerably, with the largest differences after 27, 33, 39 and 45 hours. Despite numerous attempts of recalibration, the differences remained. The velocities in the PCFLOW3D, parallel with the open boundary, unexpectedly oscillate. This is probably the main reason of divergence between the models in these simulations.

When simulation results of the same model using different turbulence models were compared (A2/B2 and A4/B4) the results showed relatively bad agreement. This was expected and confirms the suitability of using turbulence closure schemes instead of constant coefficients of turbulent viscosity to calculate circulation in the Gulf of Trieste.

3.3 Graphic (visual) comparison of results

Figure 1 shows the results of the A1 simulation in the surface layer. There are no significant differences between the models, except for smaller differences in velocity vectors in the seventh square. The areas of faster and slower flow coincide in both models, as do the swirls in the fourth square. Despite the use of the simplest turbulence models (constant viscosity in the horizontal and vertical direction), the results are not in complete agreement and the agreement in the deeper layers is worse than on the surface (Table 7).

The results of the B4 simulation in the surface layer are shown in Figure 2. There is a visible deflection of the direction of flow by 10-20° clockwise to the wind direction (Coriolis effect). The deflection calculated by MIKE3 is approximately 10° greater than that of PCFLOW3D. Flow velocities are somewhat smaller in the model MIKE3 compared to PCFLOW3D. The agreement in the surface layer is relatively good and does not significantly alter with the depth (Table 7).

Figure 3 shows the ways of refining the grid in both models. The model MIKE3 refines the grid only in the area of interest, while the PCFLOW3D model requires a gradual refinement over a larger area. MIKE3 therefore calculates using a considerably smaller number of control volumes, which undoubtedly contributes to its faster calculation times. Simulation of the density-driven flow is shown, while the area around the Soča River mouth is depicted in detail in Figure 4.

Figure 4 shows the area of refined grid around the Soča River mouth in the simulation C2. The inflow velocity of the River Soča differs noticeably between both models, which is due to the different ways of defining the boundary condition. There is a surprising discrepancy in the direction of velocity in the inflow cell (River Soča), which seems to be defined differently in both models. In the model PCFLOW3D the defined direction is fixed, while in MIKE3 the velocity direction is evidently influenced also by the parameters of flow in the vicinity and other forcing factors. The overall picture of currents in the vicinity of Soča inflow therefore differs significantly between the two models. In PCFLOW3D the main current is directed southward, while in MIKE3 it is turned in the northeasterly direction. Larger differences in the velocity directions (up to 20°) are noticeable also in the sixth and seventh square.

Figure 5 shows the velocity field of the simulation C2 in the vicinity of Soča inflow at the depth of 5.5 m. The agreement of results is worse than in the surface layer. This is partially due to numeric diffusion, which is more pronounced in the hybrid scheme of the PCFLOW3D model. Different distributions of temperature and salinity in both models can greatly impact the velocity field.

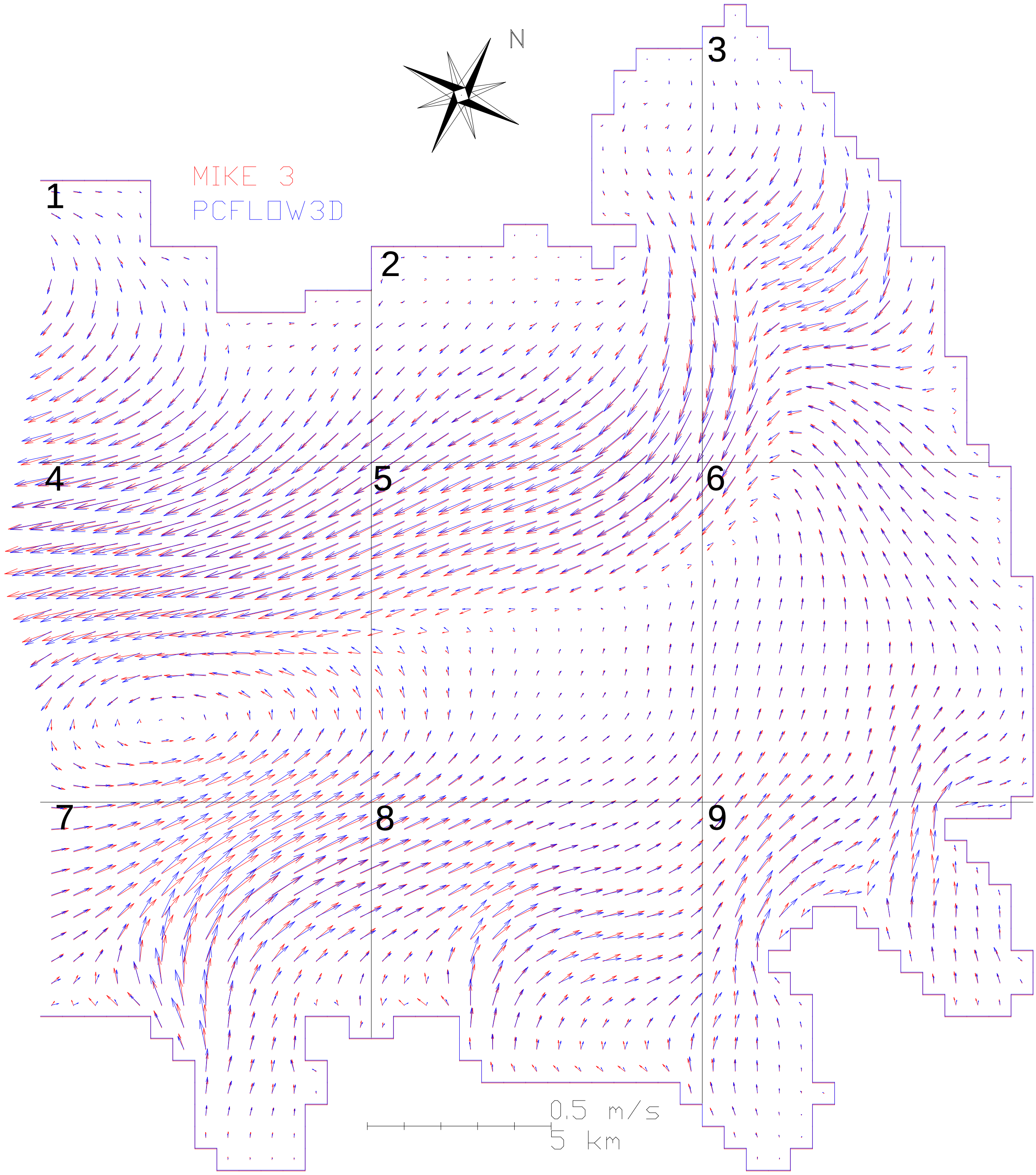

***Figure 1:** Simulation A1 (density-driven flow) – time of simulation 48h (25th layer) RMSDN = 0.195 (excellent agreement).*

***Slika 1:** Simulacija A1 (gostotni tok) – čas simulacije 48 h (sloj 25)RMSDN = 0,195 (odlično ujemanje).*

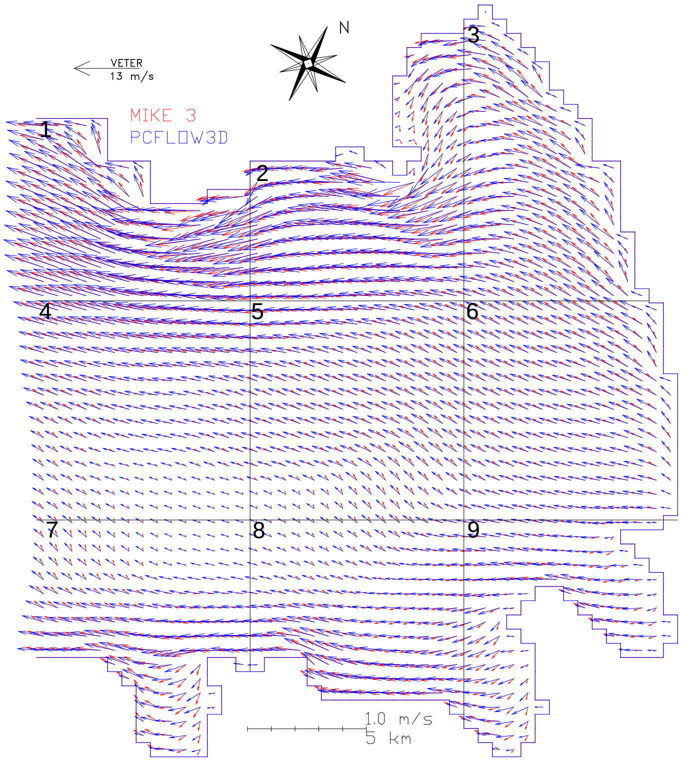

Figure 2: *Simulation B4 (bora wind 13 m/s) – time of simulation 24h (25th layer) RMSDN = 0.354 (good agreement).*

Slika 2: *Simulacija B4 (burja 13 m/s) – čas simulacije 24 h (sloj 25) RMSDN = 0,354 (dobro ujemanje).*

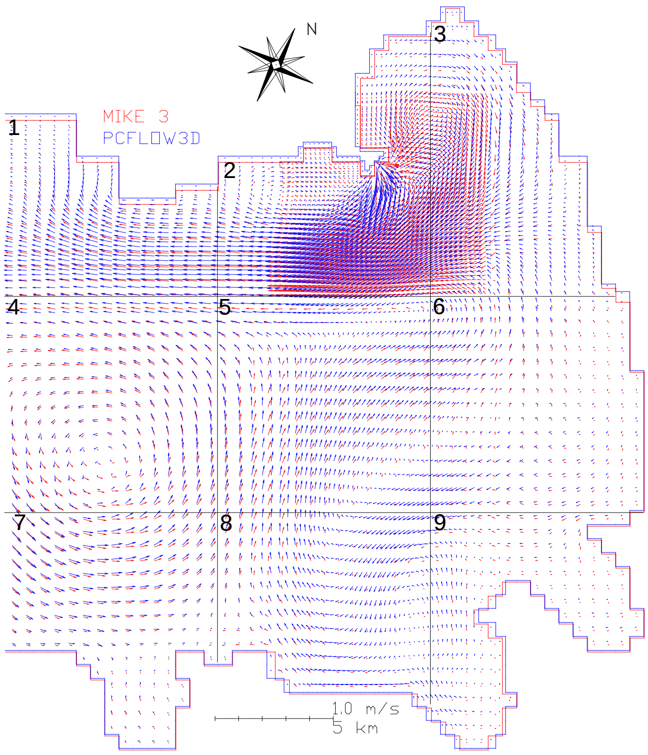

Figure 3: *Simulation C2 (density-driven flow, refined grid around the Soča mouth) – time of simulation 48h (25th layer).*

Slika 3: *Simualcija C2 (gostotni tok, zgoščena mreža v okolici izliva Soče) – čas simulacije 48 h (sloj 25).*

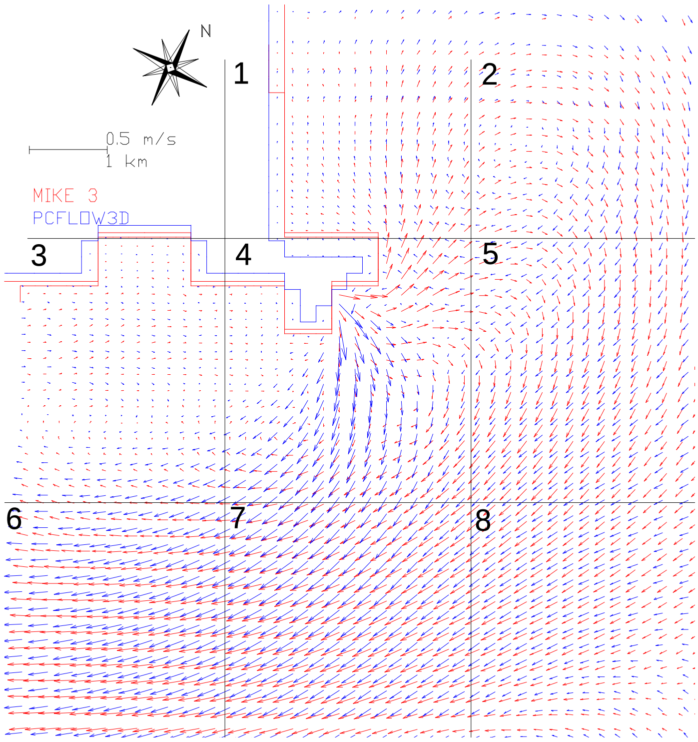

Figure 4: *Simulation C2 (density-driven flow, refined grid, detail close to the Soča River mouth) – simulation time 48h (25th layer) RMSDN = 0.574 (acceptable agreement).*

Slika 4: *Simulacija C2 (gostotni tok, zgoščena mreža, detajl ob izlivu Soče) – čas simulacije 48 h (sloj 25) RMSDN = 0,574 (sprejemljivo ujemanje).*

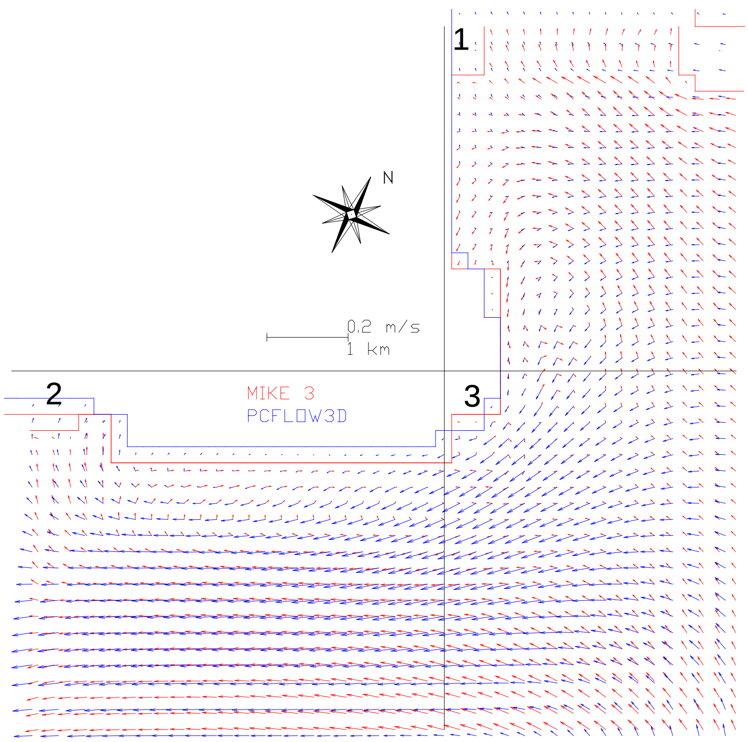

Figure 5: *Simulation C2 (density-driven flow, refined grid, detail close to the Soča river mouth) – simulation time 48h (20th layer, depth 5.5 m) RMSDN = 0.644 (bad agreement).*

Slika 5: *Simulacija C2 (gostotni tok, zgoščena mreža, detajl ob izlivu Soče) – čas simulacije 48 h (sloj 20) RMSDN = 0,644 (slabo ujemanje).*

3.4 Comparison of the simulations with the model POM

A simulation of winter circulation in the Gulf of Trieste with similar input data and a different modelling tool (POM – Princeton Ocean Model) has previously been performed (Malačič and Petelin, 2006). The main difference between the POM model and the tools used in our study is the different architecture of the models (POM applies sigma-coordinates in vertical direction). Furthermore, the treatment of the open boundary was different, as the computation domain was nested into a larger model domain with the POM simulations. Another difference in computations is the use of spatially non-homogeneous wind in the POM simulations. A comparison was made with the simulation B4, where the turbulence models used were Mellor-Yamada and Smagorinsky in PCFLOW3D and k-ϵ and Smagorinsky in MIKE3. The POM model used the same turbulence models as PCFLOW3D. Other input data are shown in Table 8.

In all the simulations a completely mixed Gulf was taken into account and therefore the minor differences in temperature and salinity do not significantly impact the results. The wind direction is the same in all cases. The only additional factor that could importantly influence the results is the relatively large difference in the wind speed, but qualitatively the results should match nonetheless.

A comparison of all three models (Figures 6-8) shows a larger clockwise deflection from the direction of wind in the model MIKE3 compared to the other two models, especially in the two circled areas. Between the circled areas, MIKE3 gives significantly lower velocities than the other two models. In this part of the Gulf the results of POM and PCFLOW3D are in better agreement. In all the rest of the Gulf, qualitative agreement of the results is good. The agreement in the 10th layer (15.5 m below surface) is as good as at the surface. In all three models the current at this depth is oriented inwards (water enters the Gulf) and there are no major differences in the flow direction.

It should be emphasised that appropriate weather conditions that would enable comparison with measurements in quasi-stationary simulations of typical conditions such as those that were performed with both models, are very difficult to obtain. Therefore, only comparisons between the models and modelling results were performed and not comparisons with measurements. Nonetheless, the described models have undergone many comparisons with measurements during numerous simulations in the process of their development and improvement.

Table 8: *Comparison of input data of the models POM, MIKE3 and PCFLOW3D*

Preglednica 8: *Primerjava vhodnih podatkov modelov POM, MIKE3 in PCFLOW3D*

Model		Princeton Ocean Model	MIKE3 and PCFLOW3D
Control volume dimensions		500 x 500 m	600 x 600 m
Density parameters of the Gulf of Trieste	Salinity	36.62 ‰	36.5 ‰
	Temperature	7.19 °C	8 °C
Wind	Speed	8.2 m/s	13 m/s
	Direction	ENE (63°)	ENE (63°)

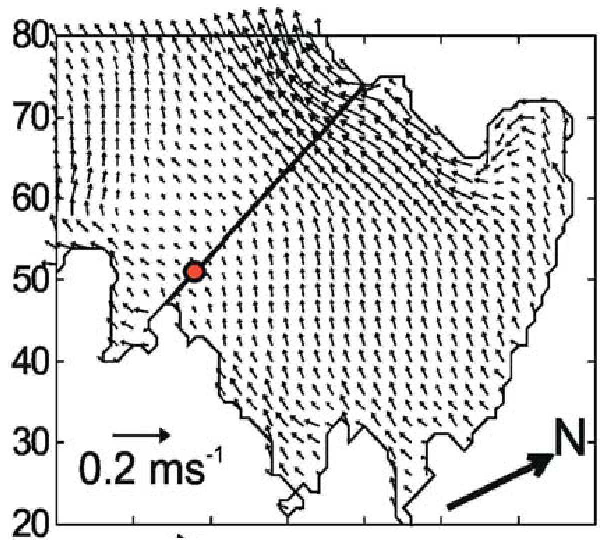

Figure 6: *Model POM (Malačič and Petelin, 2003; p. 213) – winter simulation with bora wind, surface layer.*

Slika 6: *Model POM (Malačič in Petelin, 2003; str 213) – zimska simulacija z burjo, površinski sloj.*

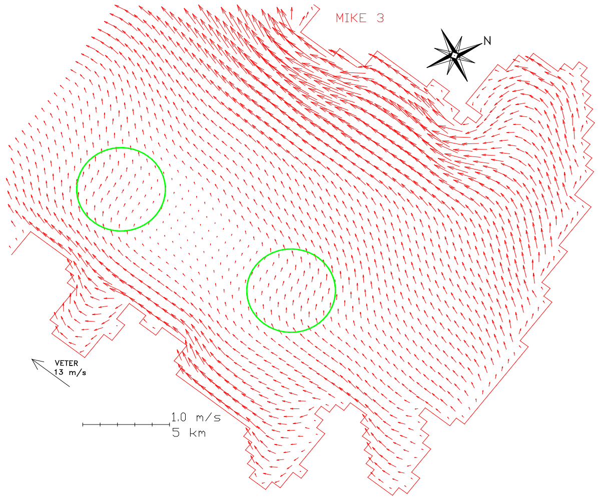

Figure 7: *Model MIKE3 – winter simulation with bora wind, surface layer.*

Slika 7: *Model MIKE3 – zimska simulacija z burjo, površinski sloj.*

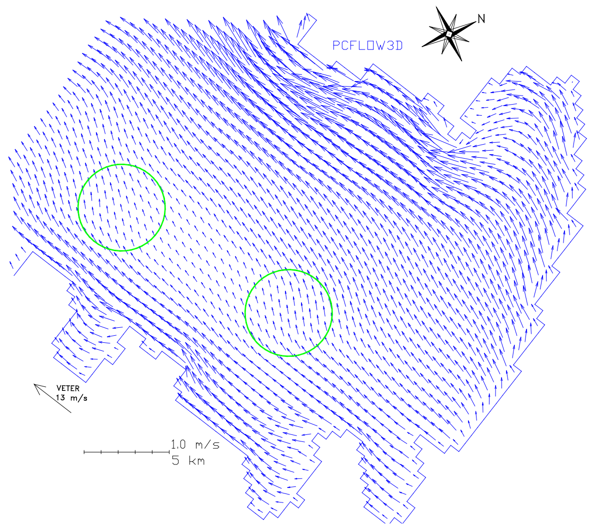

Figure 8: *Model PCFLOW3D – winter simulation with bora wind, surface layer.*

Slika 8: *Model PCFLOW3D – zimska simulacija z burjo, površinski sloj.*

4. Conclusions

Simulations of typical seasonal conditions in the Gulf of Trieste were performed with the models PCFLOW3D and MIKE3. The results of simulations were compared among each other and in one case with the results of the model POM. Visual comparison of results in the case of very variable velocities in the computational area is subjective. The results were therefore also numerically evaluated using the method RSMDN. This is the first time this method was used for this kind of comparisons. Various combinations of turbulence models and forcing factors were used in order to determine the influence of the differences between the models on the results.

The performed simulations have shown that the results of both models are mostly similar and comparable. Therefore, both models can be recommended for further work on similar simulations and in comparable domains. The differences between the models originate mostly from the used numerical schemes and turbulence models and different ways of defining boundary conditions in the inflow cell and at the open boundary. For detailed circulation studies it would thus be necessary to study the magnitude of error that is caused by these influences. This should preferably be done using real-time simulations that should also be compared to measurements. Another source of discrepancies is probably also numerical diffusion, which is more pronounced in the hybrid central difference – upwind numerical scheme of the PCFLOW3D model. Numerical diffusion can be the cause of (irregular) density-driven flows and consequently of incorrect circulation patterns. As expected, the agreement of results of the same model with different turbulence models (A2/B2 and A4/B4) was bad, which confirms the necessity of using up-to-date turbulence closure schemes when simulating circulation in areas with characteristics similar to the Gulf of Trieste. Simulations that incorporated the influence of tide showed very bad agreement between the models. A possible reason for that could be the way of defining the open boundary condition, which is different in the two models. Also the summer weak wind simulations gave relatively poor agreement of the results. This could be due to different definitions of mass transfer and momentum over the open boundary in the two models.

Each of the studied models has certain advantages. MIKE3 has a very easy to use user interface. Data input is relatively simple. The data and modelling results are also very easy to present. Due to the large amount of data this is a very welcome feature which facilitates the search of potential errors. Import and export of data are also relatively simple. It also turned out that the computational time of this model compared to the PCFLOW3D is much shorter. PCFLOW3D, on the other hand, allows for more combinations of turbulence models in the horizontal and vertical directions. Since some turbulence closure schemes are more demanding with regard to computational time, this flexibility is advantageous. An important advantage of the PCFLOW3D model is also that it is a self-developed model. The source code is available and can therefore be supplemented and improved by additional required modules.

In our opinion, the models MIKE3 and PCFLOW3D can both be used for modelling hydrodynamics in areas with characteristics similar to the Gulf of Trieste despite the differences in the results of the performed simulations. A comparison with simulations calculated by the POM model showed good qualitative and mostly also quantitative agreement between the results of all three models, despite the differences in model grid architecture. However, a rigorous validation of modelling results with measured data should be performed in order to reach the final conclusion on accuracy of each model.

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