

SCALDIS 2020: An updated 3D hydrodynamic model for the Scheldt estuary

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Abstract – The SCALDIS model is a reference model for the entire Scheldt estuary, built in TELEMAC-3D. This paper presents the methodology for the (ongoing) calibration of the new version of this model: SCALDIS 2020. The paper discusses methods for gap filling in water level timeseries, the quantification of mesh quality and systematic model skill assessment. The parallelisation performance on the HPC infrastructure of Flanders Hydraulics is also quantified.

Keywords: Hydrodynamics, Scheldt estuary, Calibration, TELEMAC-3D

I. INTRODUCTION

The SCALDIS model is a reference model for the entire estuary of the Scheldt estuary, built in TELEMAC-3D [1]. The model was initially developed and calibrated for scenario analysis of measures in the Upper Sea Scheldt. Based on the availability of a new spatially covering bathymetry every 6 years, an update cycle with that interval was proposed for a re-calibration of the model [2]. The first SCALDIS model was calibrated for 2013 [3], and a re-calibration was carried out for 2019 [4].

This paper presents a major update of the SCALDIS model with specific attention to the generation of an optimized unstructured mesh and a revision of the type and the location of the open sea boundary condition. The model is optimised for calculation on the High Performance Computing (HPC) cluster of Flanders Hydraulics (FH).

The model is being developed in TELEMAC v8p4r0. The calibration of SCALDIS 2020 is still ongoing; final results are expected in Q3 2023.

II. MODEL DESCRIPTION

A. Model goals

The SCALDIS model is a reference model on which many different applications are based. [1] It provides the hydrodynamic input for sediment transport calculations (sand and mud). [2] The hydrodynamic results are also used to delineate habitats in the subtidal zone of the Sea Scheldt. In particular, the maximum flood current velocity defines robust boundary values for high and low dynamic subtidal zones. [3] The SCALDIS model is also used to evaluate the effect of flood control areas on the hydrodynamics in the Scheldt estuary. [4] Tracer dispersion experiments in the model are used to calibrate

an ecosystem model. [5] The flow fields it produces are processed as a flow atlas, and are implemented in the shipping simulator of Flanders Hydraulics (FH).

B. Model domain and grid

SCALDIS 2020 consists of about 1 million elements per layer and 5 vertical interfaces. The length of element edges varies from 3 m at the upstream end of the tributaries to 160 m in the western Scheldt. The model domain covers the tidally influenced part of the Scheldt estuary (see Figure 1).

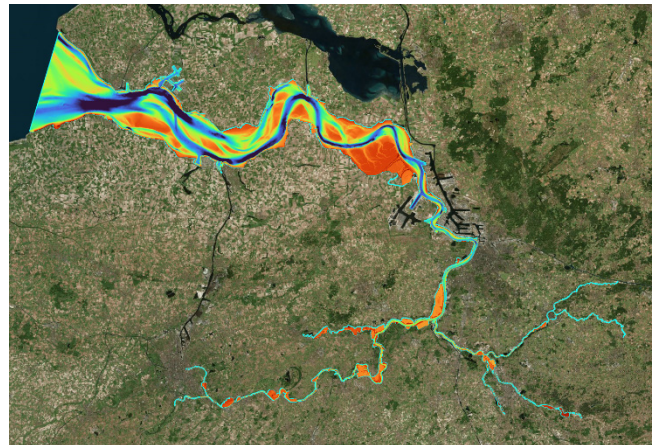


Figure 1. Model domain

Contrary to earlier versions of SCALDIS (2013 and 2019), SCALDIS 2020 does *not* include the Belgian Coastal Zone (part of the Southern North Sea) in its model domain. This is primarily because FH has developed SCALDIS COAST, a sister model that covers the coastal and North Sea domain [5]. Instead of an open boundary in the North Sea, the downstream boundary is now the transect between the (Dutch) measurement stations Cadzand and Westkapelle.

All Flood Control Areas which are currently active or planned are included in the mesh of the SCALDIS 2020 model. During remeshing, the grid quality was monitored with in-house tools, as described in the methodology section IV.B on mesh quality.

C. Boundary conditions

The model is driven by water levels at the downstream boundary (type 5 4 4). The open sea boundary condition is

created by linearly interpolating the measured water level data between the two tide gauge stations: Cadzand and Westkapelle.

The measured water level time series are not always perfectly continuous and may contain gaps (no-data values). These gaps need to be filled up before these timeseries can act as boundary conditions (see also the methodology section IV.A on gap filling).

Time series of river discharge are imposed at the eight upstream boundaries of the model.

D. Initial conditions

The SCALDIS model is initialised using a hotstart condition. The hotstart condition is the result of a 2-days run. Together with the hotstart, the salinity is initialised from an interpolation of measurements.

III. MEASUREMENT DATA

A. Bathymetry

Several topography and bathymetry datasets of the year 2020 are used to update the SCALDIS model. These data have different resolution and reference levels. Some of these data overlap each other in some areas. In those cases, either the most recent dataset or the one with higher resolution is used for model bathymetry interpolation. Overlaps between datasets are checked for continuity in order to avoid vertical datum shifts

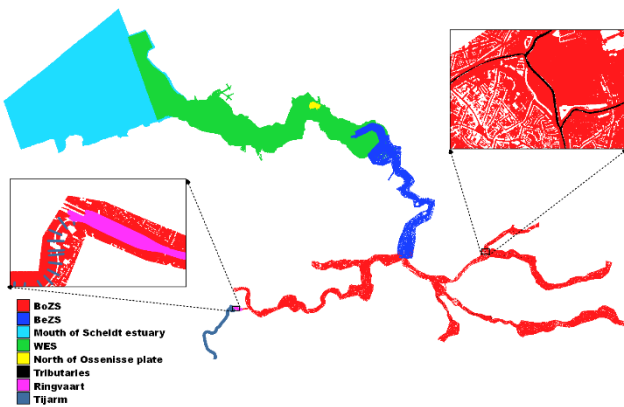


Figure 2. The coverage of topo-bathymetric data used for construction of model bathymetry for the year 2020.

B. Water level

In 2020, water level data are available in 55 stations within model domain (Figure 3). These data are measured by either HIC (BE) or HMCZ (NL) every 10 minutes. Stations WestKapelle and Cadzand are used for the downstream boundary condition. Data from the other 53 stations are used for calibration and validation (see sections IV.C to E).

C. Salinity

Within the modeling domain, there are 13 salinity measurement stations. Salinity data are used for setting the initial condition, for defining the downstream boundary condition, and for validation of salinity in the domain.

Since there are no measurements available in 2020 at the stations Vlakte van de Raan and Hoofdplaat that are located near the seaward boundary, the boundary condition for salinity at the

downstream boundary has to be estimated. The average value of salinity at Vlakte van de Raan (located near the mouth of the estuary) is used as a constant downstream boundary condition for salinity. An average value of 32.5 PSU was calculated from a long timeseries of measurements (2007-2019).

D. Stationary velocity measurements

Continuous deep water velocity measurements for the year 2020 are available at two locations: Lillo and Oosterweel. Other measurement data came from shallow water measurement campaigns in the preceding 5 years (2015-2020). The location of these measurements is shown in Figure 3. In total, data at 84 temporary measurement stations are used in calibration or validation. Data at Baalhoek and Knuitershoek (2018) were kindly provided by RWS.

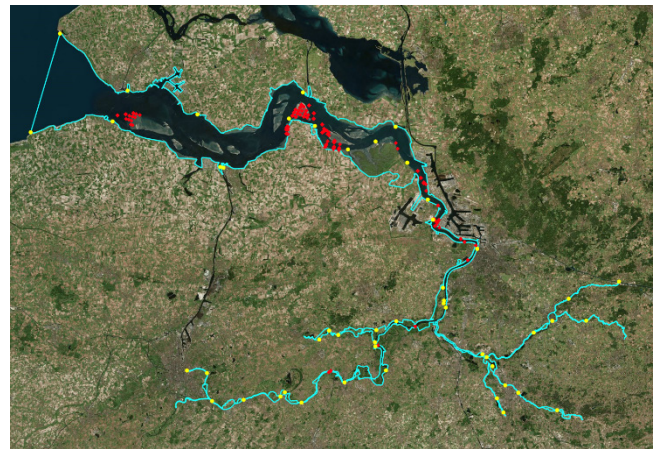


Figure 3. Location of water level (yellow dots) and stationary current velocity measurements (2015-2020) (red dots)

E. Sailed ADCP measurements

In total there are 361 sailed ADCP campaigns available in the Scheldt estuary and Belgian Coast. In order to calibrate and validate the SCALDIS 2020 model, a selection was made among those measured in the recent 10 years. This selection was made using two criteria: the measurement transects should be distributed over the model domain and if a transect was measured multiple times, preference is given to the most recent measurement. In total, 44 campaigns are selected for model calibration, and 27 for model validation.

IV. METHODS

A. Gap filling

Both previous SCALDIS models (2013 and 2019) were nested in the ZUNO model of the southern North Sea. The downside of nesting a model in another model is that any model error in the mother model (e.g. errors in tidal components or in surge) are imported over the boundary and contribute to the total error in the model domain. The upside is that modelled timeseries are continuous (they contain no gaps in time if no drying/wetting occurs at the boundary of the daughter model), which makes the derivation of boundary conditions more straightforward.

With SCALDIS 2020, this argument is reversed. Since the model uses measured water levels as a downstream boundary condition, any gap in the measured timeseries needs to be

resolved. But on the upside, no model error on the water levels is imported at the downstream boundary. In Westkapelle, the gap duration ranges between 1.67 and 42.5 hours for 2020, while in Cadzand the gap durations are between 40 minutes and 42.5 hours.

Three different algorithms are identified that can fill the gaps of a tidal water level signal. They are briefly explained here. The methods (including a decision tree) are implemented in a Gap Filling Toolbox in Matlab at FH.

1) Spline interpolation method

In this method, a spline curve is fitted to the time series of the measured water level. If the gap duration is short, this interpolation method works well. As expected, the interpolation method is ill-suited to fill longer gaps (>4 hours).

2) Comparable Tide (CT) method

In this method, first the water level records over a period of 24 hour before and 24 hour after the gap instance are selected. Then a long historical time series at the same station (or even a nearby station) is scanned to find the most comparable tidal condition. The statistical parameter used to compare these time series is RMSE0 (Bias corrected root mean square error). The gap is filled with the identified comparable tide and any bias at the beginning and end of each gap period is corrected to avoid discontinuity in the time series. This is similar to the comparable tide method that is implemented in the VIMM toolbox [6].

3) Harmonic method

In this method, the amplitude and phase of tidal constituents are calculated by tidal harmonic analysis. These coefficients are then used to predict the time series of water level in the gap period. In order to have a smooth transition between the existing data points and the predicted values during the gap period, a bias correction step is also carried out. The harmonic method can predict the overall shape of the water level time series when the non-tidal signals (like surge) don't vary too much over the duration of the gap.

4) Discussion

The best gap filling method for each specific gap is selected based on the gap duration. In order to determine a suitable decision tree, the performance of each gap filling method is evaluated systematically. Synthetic timeseries are produced by making an artificial gap in a continuous observed time series of water level. The artificial gap duration is varied in steps of 1 hour between 1 and 48 hours. For each gap length, 50 synthetic timeseries are generated by creating a gap of the specific length at a random location in the timeseries. These gaps are then filled using the different methods above.

The performance of the different gap filling methods for varying gap duration is shown in Figure 4. This figure shows the RMSE of the gap-filled timeseries to the original, continuous measurement. The continuous lines are the mean RMSE, the shaded regions show the area between 25th and 75th percentile of the RMSE values, and the scatter points show the individual data points.

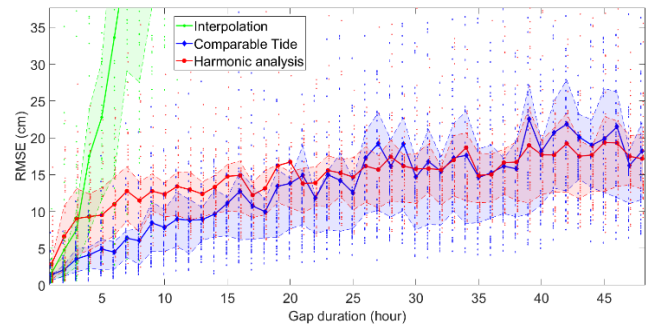


Figure 4. Accuracy of three different gap filling algorithms: Interpolation (green), Comparable tide (blue) and Harmonic analysis (red)

The interpolation method works only for short gap events (<3h). Longer gaps can be better filled by applying either the comparable tide or the harmonic method. For medium-length gaps (3h – 20h), the CT method gives a lower error than the harmonic method. For longer gaps (>20h) the CT method and the harmonic analysis have a similar accuracy. The harmonic analysis method executes much faster though than the CT method. The runtime of the CT method also depends on the length of the long historical timeseries in which the search is performed.

5) Decision tree

The following decision tree is proposed to fill the gaps in both the Westkapelle and Cadzand stations. The thresholds between different algorithms are chosen somewhat arbitrarily based on the results discussed above.

- Gap length less than 1 hour: Spline interpolation method
- Gap length between 1 hour and 24 hours: Comparable tide method
- Gap length between longer than 24 hours: Harmonic method

B. Mesh Quality

The quality of SCALDIS 2020 mesh is checked in MATLAB with the function `Telemac_Mesh_Quality`, which is part of the `WL_Telemac` toolbox. The following parameters are used to quantify the mesh quality:

- Skewness: An angular measure of element quality with respect to the 60° angles of an equilateral triangular element (see eq. 1). The skewness of an ideal element is 0 and the value for a bad element is 1. It's preferred to limit the skewness of elements to 0.5.

$$skewness = \max \left[\frac{\theta_{max} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{min}}{\theta_e} \right] \quad (1)$$

θ_{max} : largest angle of the element

θ_{min} : smallest angle of the element

θ_e : angle of the equilateral triangle (equal to 60 degree)

- Edge length ratio: The ratio of the longest edge to the shortest edge of each element. Large aspect ratios increase the inaccuracy of the finite element representation, because they affect the convergence of

finite element solutions. The aspect ratio of an ideal element is 1. We aim to maintain it between 1 and 5.

- Aspect ratio: Two times the ratio of the radius of the inscribed circle to the radius of the circumscribed circle, with a reporting threshold of 0.5.
- Smoothness: The maximum ratio of the area of an element to the area of its neighbouring elements. This parameter represents the area change ($1 < \text{Smoothness} < 1.5 = \text{good}$, $1.5 < \text{Smoothness} < 2.5 = \text{fair}$, $\text{Smoothness} > 5 = \text{poor}$)
- Overconstrained elements: Triangular elements in which all three nodes are located on boundaries of the model.

For the optimized mesh, 99.95% of elements has a good smoothness; 98% has a skewness lower than 0.5; and 99.99% has a good aspect ratio.

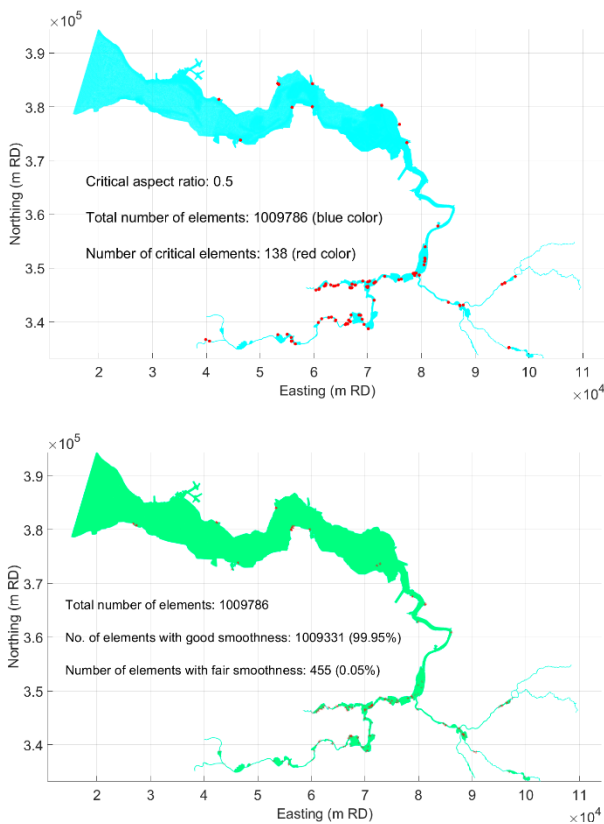


Figure 5. Results of the mesh quality analysis. Top panel: location of elements with a critical aspect ratio; bottom panel: location of elements with fair smoothness

C. Quantified model skill assessment and Cost function

For a reference model with a broad possible set of applications, it is important to have a calibration strategy that is sufficiently broad in scope. In order to achieve this goal, the VIMM toolbox is used for the hydraulic model. It is in-house developed at FH and runs in MATLAB [6].

A weighted dimensionless cost function is calculated for each simulation to assess model performance. Each factor is a particular error statistic with the same unit as the measurements on which they are based. The cost function is made dimensionless by normalizing to the factor score in the reference

run. The task of calibration is to minimize this objective function.

$$\text{Cost} = \sum_i \frac{\text{Factor}_i}{\text{Factor}_{i,\text{ref}}} \text{Weight}_i \quad (2)$$

Several parameters are selected as factors for the calculation of the cost function. [1] For the vertical tide, the RMSE (Root Mean Square Error) of the complete timeseries, as well as the RMSE of the level of high waters are taken into account. A vector difference is aggregated over 6 harmonic components. [2] For the horizontal tide, the RMAE (Root Mean Absolute Error) of sailed ADCP measurements and the RMSE of stationary velocity measurements are included as factors. Given the broad model goals (see II.A), horizontal and vertical tide are given the same total weight. Given that most model applications for SCALDIS are situated in Belgium, also a greater weight is attributed to the Sea Scheldt (Belgian part) than to the Western Scheldt (Dutch part).

D. Calibration on roughness

The Manning law was used to represent the bottom friction in SCALDIS 2013, while the Nikuradse law was applied in SCALDIS 2019. In SCALDIS 2013, the roughness in the Western and Sea Scheldt is between 0.012 and 0.023 $\text{s/m}^{1/3}$. In SCALDIS 2019, the range of roughness height is between $3.3327\text{e-}5$ and 0.1 m. In order to compare the roughness of the SCALDIS 2019 and SCALDIS 2013 models, the Nikuradse roughness height is converted to a corresponding Manning value, using the average water depth along the thalweg.

The previously calibrated values of bed roughness along the thalweg (from the river mouth to upstream Sea Scheldt) are visualized in Figure 5.

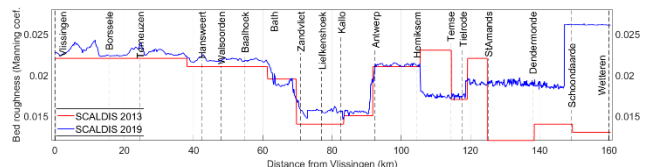


Figure 6. Bed roughness values of SCALDIS 2013 and SCALDIS 2019 models. The roughness of SCALDIS 2019 was converted from Nikuradse roughness height k_s to Manning's n

E. Calibration and Validation periods

The SCALDIS 2020 model is calibrated and validated for different periods in the year 2020. This work is still ongoing. The periods are chosen in a way to cover storm, calm (normal), and high river discharge conditions in the Scheldt estuary.

Calibration and validation data for water level, salinity and continuous velocity measurement stations are separated because the periods do not overlap. The velocity measurements in shallow stations, and the sailed ADCP measurements are distributed between calibration and validation, and over the different conditions.

Table 1. Calibration periods

Condition CALIBRATION	Period in 2020	Duration [days]
Calm	24 Jun to 8 Jul	14 days
Storm	05 Feb to 04 Mar	28 days
High upstream discharge	09 Mar to 16 Mar	7 days

Table 2. Validation periods

Condition VALIDATION	Period in 2020	Duration [days]
Calm	16 Aug to 28 Aug	14 days
Storm	29 Nov to 03 Dec	5 days
High upstream discharge	20 Dec to 31 Dec	11 days
Salinity	01 Jan to 01 Jul	6 months

V. PARALLELISATION PERFORMANCE

The parallel performance of the model was tested on the Bernoulli queue of the HPC cluster at FH. It has 12 nodes with 48 cores/node. Each node has 2 x AMD EPYC 7451 24-Core processors. The model was run for a simulation of 12h on different numbers of cores: 1, 12, 24, 48, 96, 144, 192, and 240 cores. The time step is set to 3 seconds and the culvert function is active in this test. All the benchmark models are started from a hotstart, to avoid the effects of spin up on model speedup.

The total runtime of a TELEMAC model comprises of initialization, partitioning, actual computation time, and I/O time. The runtime of each of the mentioned steps is reported separately. In order extend the output to the logfile with the timing of each step, the `homere_telemac3d.f` Fortran file is modified. The actual computation time is defined as the time elapsed from the moment that the computation starts to the moment that the last processor finishes execution. This step includes the initialization step (to allocate variables and arrays), solving the equations, and closing computation (deallocating variables), but excludes the time to merge the partitioned output files.

The model performance is measured by three different factors: Speedup factor, Efficiency, and Cost. The speedup factor [-] is defined as the ratio of the simulation period (in our

test case = 12 hours) to the actual computation time. It is shown in Figure 6. A speedup factor of 14 is considered to be a minimum for efficient model use (one spring-neap cycle calculated in a day).

$$\text{Speedup factor} = \frac{\text{simulation period}}{\text{actual computation time}} \quad (3)$$

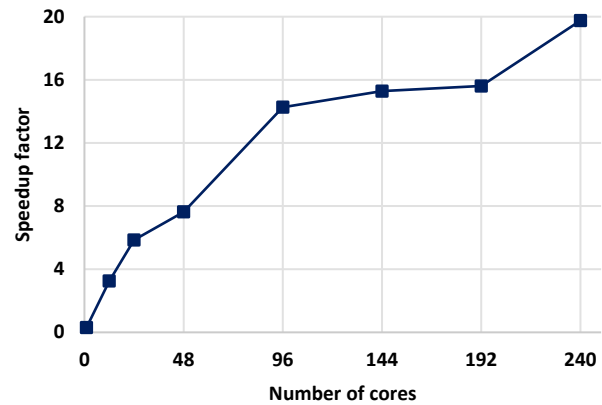


Figure 7. Speedup factor for varying number of cores

The efficiency [-] measures the fraction of time for which a core is usefully utilized. The efficiency of running a model on a single core is 1 by definition. It is calculated as:

$$\text{Efficiency} = \frac{\text{serial runtime}}{\text{parallel runtime} * \text{number of cores}} \quad (4)$$

The cost [h] scales with the number of credits that are used for a single simulation on a High Performance Cluster (HPC) and is calculated as follows:

$$\text{Cost} = \text{runtime} * \text{number of cores} \quad (5)$$

Cost and efficiency of the model are shown as function of the number of cores in Figure 8.

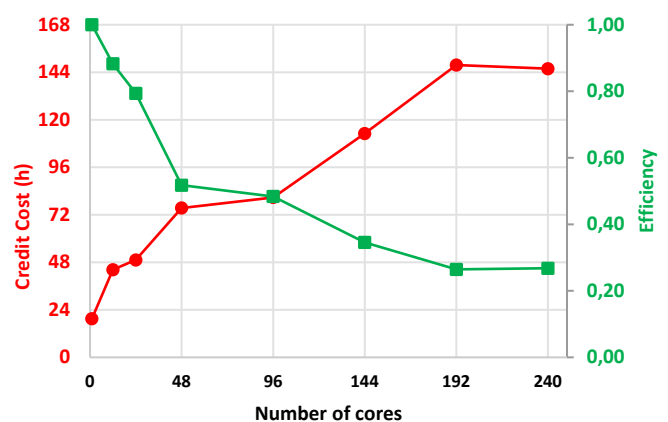


Figure 8. Cost and Efficiency for varying number of cores

CONCLUSIONS

Since the actual calibration and validation of the Scaldis model is still ongoing, this paper focuses on methodological choices that can be of interest to the broader TELEMAC modelling community.

Contrary to earlier versions of SCALDIS (2013 and 2019), SCALDIS 2020 will not include the Belgian Coastal Zone. This gives us the possibility to drive the model at its downstream end with water level measurements. Any gap in the measured timeseries needs to be resolved. This paper presents three possible algorithms for this task, with a validation and a decision tree dependant on the gap length.

A set of parameters is proposed to objectively check the mesh quality: element skewness, edge length ratio, aspect ration, smoothness and the number of overconstrained elements.

Since SCALDIS is a reference model of the Scheldt with a broad possible set of applications, it is being calibrated against a broad dataset of 55 water level stations, 13 salinity stations, 84 temporary stations for velocity and 2 permanent ones, and 71 sailed ADCP transects. The VIMM toolbox is used to perform the task of calculating the error statistics, and a weighted dimensionless cost function is calculated for each simulation to assess model performance.

In order to determine the optimal number of cores to run this model on, the parallel performance of the model is tested and expressed in terms of speedup factor, efficiency and computational cost.

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RWS is kindly acknowledged for providing the velocity data at Baalhoek and Knuitershoek for 2018.

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