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Urgent computing for operational storm surge forecasting in Saint-Petersburg

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Abstract

The accurate forecasting of storm surges and decision support for gates maneuvering is an important issue in Saint-Petersburg. The evolution of the numerical hydrodynamic models, hardware performance and computer technologies allow to make Flood Warning System (FWS) in Saint-Petersburg more reliable and appropriate to the real needs. This article describes the key solutions of the development and the present operational set-up of FWS with emphasis on computational issues and decision support on the basis of urgent computing paradigm. It includes a brief description data-assimilation techniques, such as Kalman filtering, the probabilistic real-data forecasting model, forecast quality control, distributed computing of different scenarios and decision support for gates maneuvering.

Keywords: storm surge, forecasting, data assimilation, urgent computing

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1. Introduction

In Saint-Petersburg accurate forecasting of storm surges and decision on Barrier gates maneuvering is very important since large areas may be inundated and it may lead to large economic impact. Over past three centuries, several severe floods have taken place. The most severe disaster was caused by the storm on 7 November 1824. During this storm about 500 people died. The last severe flood took place in 1955. This flood made it clear that the city needs a protection dam. The project was begun in 1979 and completed in 2010. The complex consists of eleven separate dams measuring 25 kilometers across the Gulf of Finland [1] and may prevent the flood up to 5 meters. The complex has two large openings for shipping and six gates for water transmission that can be closed to hold back water. Since normally gates are in open condition this configuration may not prevent flooding. By that reason city protection is provided by gates maneuvering. The critical value of flood in Saint-Petersburg is 160 cm in the gauge point Gorniy Institute. The final decision on gates closing is made by Barrier Authority and partly automated by Flood Warning System (FWS). The quality of automated decision is strongly dependent on forecast accuracy and computation resources [2]. As a consequence, the key solutions of the development are focused on improvement of forecast quality. The main offer is to implement a part of FWS on the basis of Urgent Computing paradigm [3]. It should lead to increase in forecast accuracy and efficiency of gate maneuvering assessment.

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1.1. Input data and boundary conditions

The forecasting is based on two types of initial data: (a) observations data and (b) forecast data from external resources. Observations data include sensor data of FWS and BOOS observation data [4]. As gaps and clogs are possible all the data enters to the system through the special probabilistic model of data control and missing data recovery. This model is based on the knowledge of correlation characteristics of level (and currents) and allows indentifying "suspicious" data from the point of view of observations history. In case of identification of obvious gaps or clogs in data they will be filled up by regression model taking into account observations history on neighboring stations.

Forecast data also include forecast of water exchange through Danish straits, meteorological forecast (wind and sea level pressure), and ice edge position (for winter time). These data are generated by external hydrodynamics models and is updated periodically.

1.2. Storm surge forecast through a hydrodynamic model

Operational storm surge forecasting is based on hydrodynamic model BSM-2010 (Baltic Sea Model). This model is designed for synoptic variations of level for Baltic Sea on a given background level. In practice there is a need to determine this background level in eastern part of Gulf of Finland taking into account observations data. A special assimilation procedure is used for that (see Figure 1). It allows defining a background level and using observations for adjusting a form of storm surge wave in eastern part of Gulf of Finland.

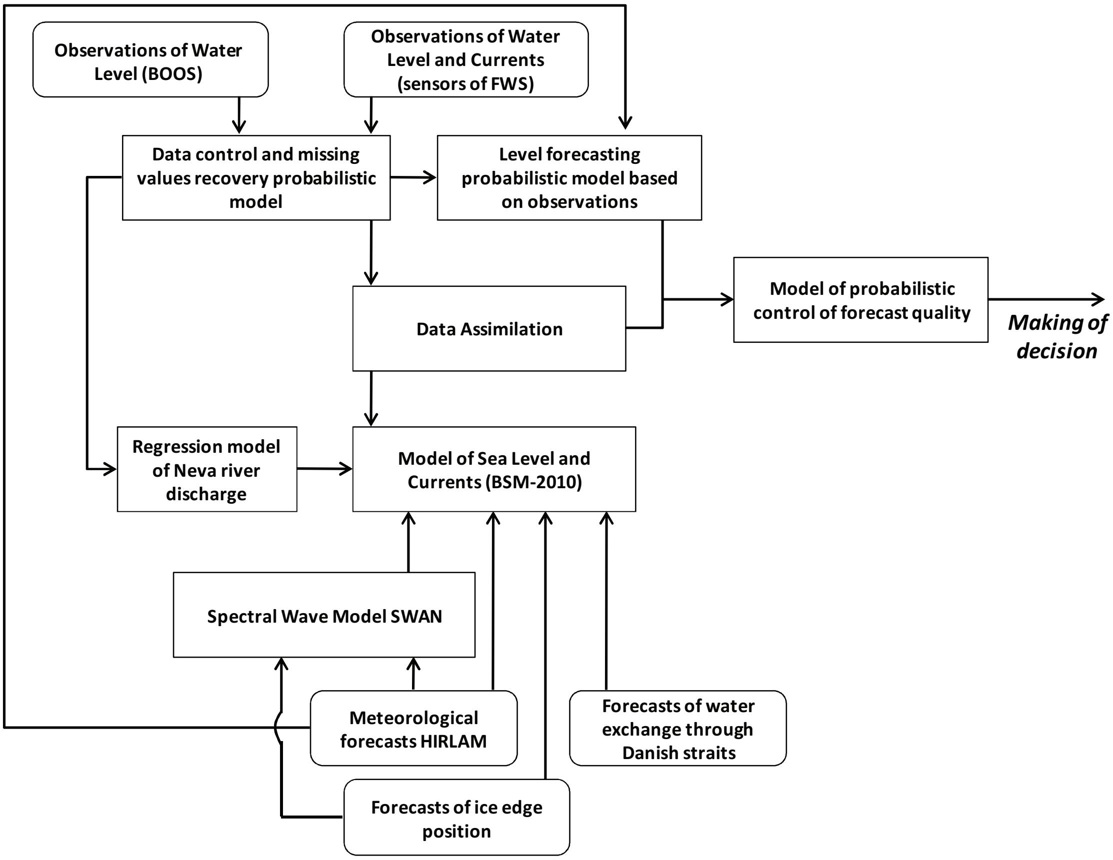

Fig. 1. The structure of models for storm surge forecasting

Water discharge of river Neva is an input parameter of BSM-2010 model. This value defines the sea level rising rate. It may be estimated by climate data or by operational regression model through level in point near Neva river estuary.

For greater accuracy of energy transfer from wind to waves for drag coefficient in BSM-2010 model the characteristics of wind waves are taken into account. There are two options in the model. The first option allows figuring them out parametrically. The second one needs simulation data from spectral wave model SWAN.

1.3. Data Assimilation: Two-stage procedure

The BSM-2010 model is designed for simulation of synoptic variability of sea level and currents under specific atmospheric conditions. The background sea level which is determined by long-term fluctuations (5 days and more) is considered known. As boundary conditions in the model are given in differential form (through discharge in Danish straits and Neva River) it doesn't allow defining a background sea level explicitly and requires a specific assimilation procedure.

The procedure consists of two stages. On the first stage the elicitation of the background sea level is performed. The field of sea level $\zeta(x,y,t)$ and currents $\vec{V}(x,y,t)$ is presented in the form

$$\begin{aligned}\zeta(x,y,t) &= X(x,y) + \zeta_0(x,y,t) + h(x,y,t) + \varepsilon(x,y,t)\\ V(x,y,t) &= \vec{W}(x,y) + \vec{V}_0(x,y,t) + \vec{v}(x,y,t) + \vec{\eta}(x,y,t)\end{aligned}, \qquad (1)$$

where X, W constant climatic field of sea level and current in Baltic sea, $\zeta_0, \vec{V}_0$ long-term constituent of water dynamics (not reproduced by BSM-2010 but may be taken into account through boundary conditions), $\varepsilon, \vec{\eta}$ local small-scale fluctuations induced by subgrid effects (not reproduced by BSM-2010).

From the point of view (1) for water dynamics simulation the first and the second parts of equations $X+\zeta_0, \vec{W}+\vec{V}_0$ determine the systematic error whereas $\varepsilon, \vec{\eta}$ determine nonsystematic error which has to be removed by data assimilation. Thus, (1) allows dividing sources of uncertainty emerging in data assimilation into two constituents with different properties.

In Figure 2 the correlation characteristics of sea level constituents $X+\zeta_0$ (a) и h (b) are shown. For synoptic constituent of level h reproduced by BSM-2010 the sea level rise depends on values in Gulf of Finland. In offshore points of Baltic Sea the dependency turns to zero. On the contrary for long-term constituents $X+\zeta_0$ the correlation dependencies with a given time shift are significant even for offshore points (up to Danish straits).

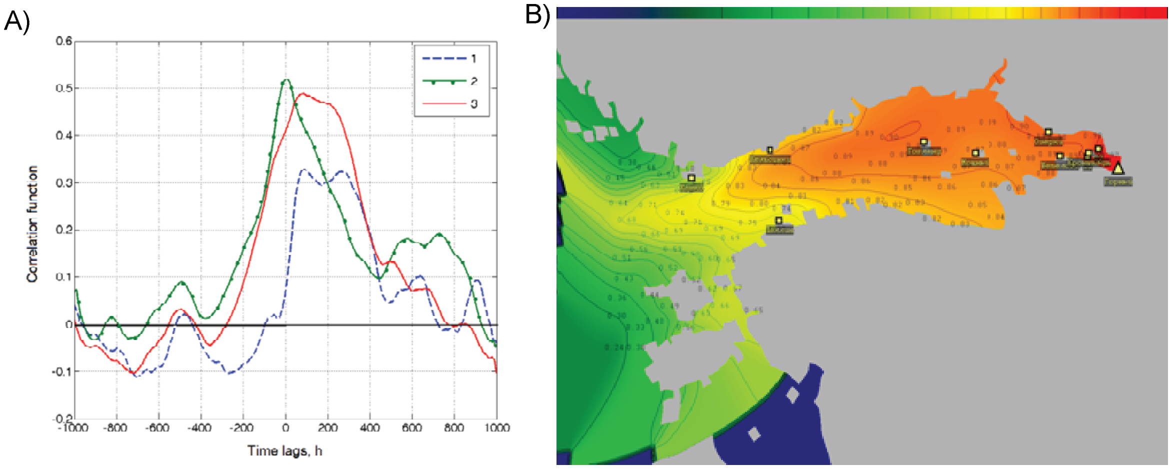

Fig. 2. Correlation characteristics of Baltic Sea level constituents: (a) correlation functions of long-term constituents: 1 - Gorniy Insitute - Klagshaman (Danish Straits), 2 Gorniy Insitute - Tallinn, 3 Gorniy Insitute - Marviken (Sweden). (b) isocorrelates of synoptic variability relative to the Gorniy Institute point

Therefore the procedure of data assimilation has two stages. On the first stage the elimination of systematic error associated with long-term constituents $X + \zeta_0, \vec{W} + \vec{V}_0$ is performed. On the second stage the local uncertainties $\varepsilon, \vec{\eta}$ of sea level in eastern part of Gulf of Finland are removed.

1.4. Data Assimilation: Configuration of the Kalman filter

The procedure of data assimilation is constructed with respect to the phase variable $\Xi(x, y, t) = \{h(x, y, t), \vec{v}(x, y, t)\}$, describing synoptic variability of water dynamics:

$$\Xi^{f} = M\hat{\Xi}, ...\hat{\Xi} = \Xi^{f-1} + K(CY - \Xi^{f-1}) \qquad (2)$$

Here Ξ^{f} is a forecast of sea level and currents fields obtained by the BSM-2010 model (for the next step), M is an operator of model action, $\hat{\Xi}$ is an adjusted field of level and currents, Ξ^{f-1} initial field of level and currents (result of previous forecast), K is a Kalman filter coefficient, Y is an observed field of level and currents, C is a corresponding matrix of observations.

The Kalman filter coefficients are computed through correlation characteristics $h, \vec{v}$ on the basis of calculations obtained with the model BSM-2010 for the period 1999-2008 time step 1 hour.

The estimation of long-term constituents $X + \zeta_0, \vec{W} + \vec{V}_0$ in every point of field is performed in the form of moving average also determined by Kalman filter. Herewith the background level is not uniform in all the points. Generally values $X, \vec{W}$ are tuning parameters because they take into account different reference frames which are used in different countries members of BOOS.

As grid of BSM-2010 model contains 32 thousands of points for acceleration of computing in operational forecasting data assimilation (2) and determination of long-term constituent is performed in points with observation data only. After that an optimal interpolation is carried out. It is based on regression model which uses correlation characteristics of sea level and currents fields.

The general scheme of data assimilation in BSM-2010 is shown on Figure 3.

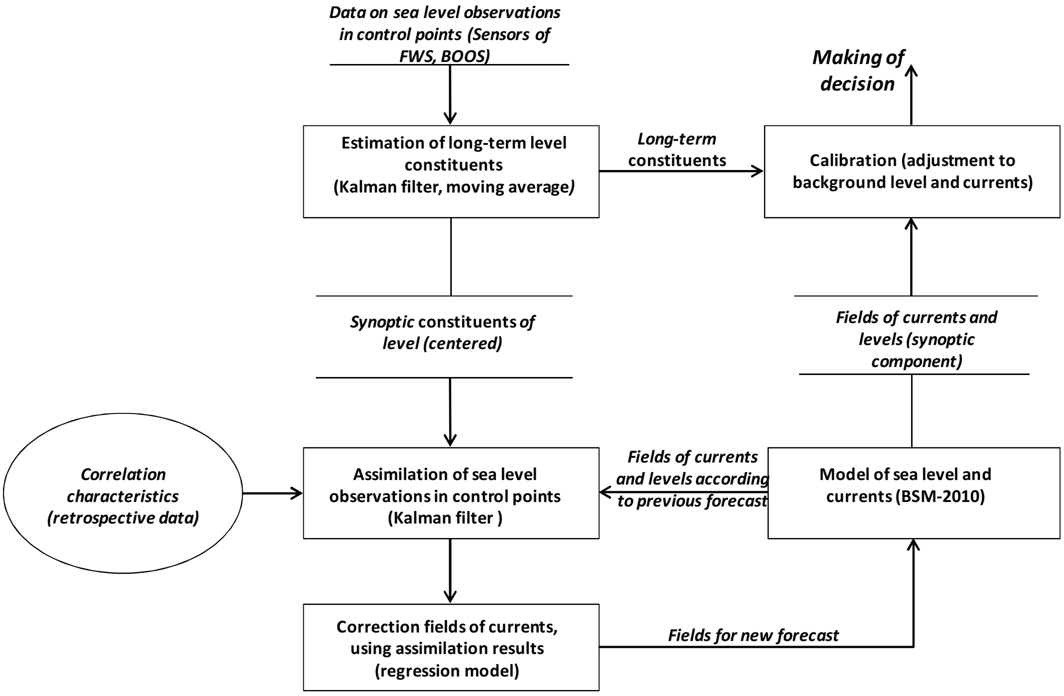

Fig. 3. The procedure of data assimilation in BSM-2010 model

1.5. Alternative model of sea level forecast

For greater reliability of water level forecasting in Saint-Petersburg the alternative probabilistic model is proposed. This model is based on historical data of sea level variations. There is an option to use wind observation in eastern part of Gulf of Finland. This model allows forecasting probability interval for sea level variations which is used in quality control model. If forecasting result is out of the interval boundaries it is considered as "suspicious" and probabilistic forecast is offered as a basis for decision making.

The probabilistic forecast on observed data is based on correlation dependencies between points at construction S-1 and Gorniy Institute (flood control point) from one side and different points in eastern parts of Gulf of Finland from other side. The procedure consists of two stages. On the first stage the forecast is performed for observed data in eastern parts of Gulf of Finland for point at construction S-1. On the second stage the forecast is recalculating for point Gorniy Institute. The model of non-periodic sea level variations at S-1 construction is presented in the form of linear dynamic model with discrete time step $t = 0,1,2\ldots$.

$$\zeta_{t+\delta}^{(S-1)} = m_{\zeta}^{(S-1)} + \sum_{i=1}^{P} \Phi_i (\zeta_{t-i}^{(S-1)} - m_{\zeta}^{(S-1)}) + \sum_{<T>} \sum_{j=P_0^{(T)}}^{P_N^{(T)}} \Theta_j (\zeta_{t-j}^{(T)} - m_{\zeta}^{(T)}) + \sum_{k=R_0}^{R_N} \left(\vec{\Omega}_k, (\vec{V}_{t-k} - m_{\vec{V}})\right) + \varepsilon_{t+\delta} \qquad (3)$$

Equation (3) contains five main sets of summands describing principal mechanisms of sea level variations (lined up in accordance with the emergence in the formula):

- Influence of long-term sea level variations conditioned by seasonal and interannual fluctuations.
- Features of temporal variations (history) at construction S-1 point.
- Influence of synoptic variances of sea level in observation points of FWS located west of construction S-1 in east part of Gulf of Finland on values at construction S-1.
- Influence of wind speed variations in east part of Gulf of Finland on level at construction S-1.
- Specific (local) factors of sea level dynamic not connected with mention before.

Forecast lead time may vary from 4 (there are observations for construction S-1 point only) to 11 hours (there are observations for east part of Gulf of Finland and observations of wind).

The model of probabilistic forecast in point Gorniy Institute model has the following form (index S-1 means point at construction S-1, index G means Gorniy Institute point):

$$\zeta_{t+\delta}^{(G)} = \eta \cdot m_{\zeta}^{(S-1)} + (\zeta_{t+\delta-r}^{(S-1)} - m_{\zeta}^{(S-1)}) \left(1 + \alpha \frac{(\zeta_{t+\delta-r}^{(S-1)} + - m_{\zeta}^{(S-1)})}{\zeta_{100}^{(G)}} \right) + \vartheta_{t+\delta} \qquad (4)$$

Equation (4) contains three main sets of summands describing principal mechanisms of sea level variations (lined up in accordance with the emergence in the formula):

- Influence of long-term sea level variations conditioned by seasonal and interannual fluctuations (presented as model parameter) taking into account stochastic impact of Neva river.
- Nonlinear influence of synoptic variability of sea level at construction S-1 on values at Gorniy Institute point.
- Specific (local) factors of level dynamic not connected with mention before.

Probabilistic model (4) has tuning parameters α, η , which allow adapt this model to local changes of hydrological conditions of Neva bay. It is used jointly with model (3). Forecast lead time when both model are in used ranges from 5 to 12 hours.

1.6. Quality assurance

For the quality assurance the calculations of statistical errors on the results of FWS continuous operation in 2011 were performed. For every synoptic period the forecast error with a given lead time (from 6 to 48 hours) is calculated in points at construction S-1 and Gorniy Institute.

Scatter plots for observations and forecasts with different lead time are shown on Figure 4. It is seen that for short-range forecasting points are closely grouped around bisector of the coordinate angle. It means that model is well calibrated and systematic error is quite small. If forecast range is getting longer the scatter of points is growing and systematic downward bias of sea level appears. The use of SWAN model allows in some degree to correct the growth of systematic error. In particular the rightmost point on scatter plots corresponds to sea level rise in 14 of September 2011. It is seen that the use of SWAN model assures a higher forecast quality even for the forecast with 24 hours lead time.

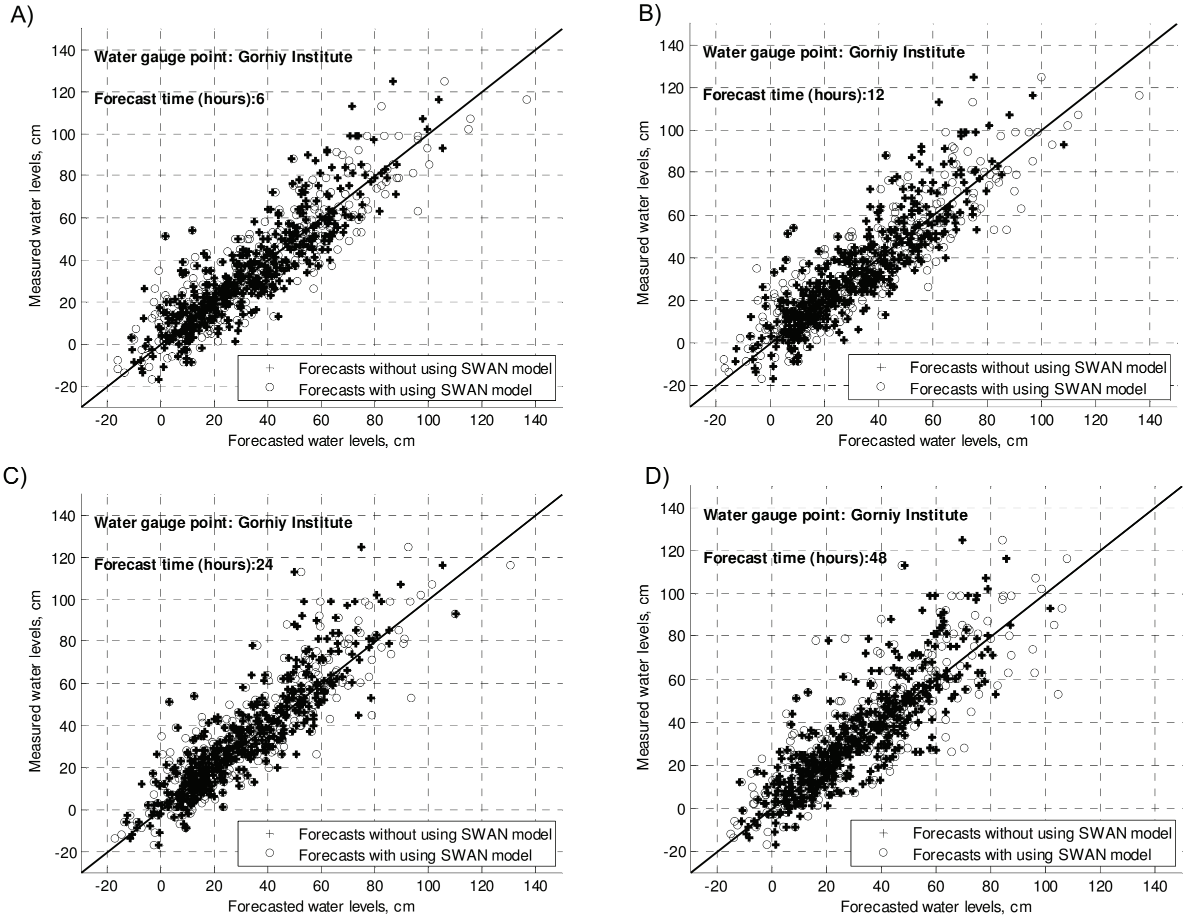

Fig. 4. Scatter plots for measured water level and forecasts with different lead time; (a) - 6 hours, (b) - 12 hours, (c) - 24 hours, (d) - 48 hours

2. Decision making and urgent computing

2.1. Decision making on barrier gates maneuvering

The operational running of the storm surge model is performed at Barrier Authority office in Saint-Petersburg. If the water level in such a forecast exceeds certain thresholds (160 cm) the Decision Making Group is informed and should arrive to Barrier Authority office. The Decision Making Group is performing an additional verification of the forecast and on duty decides that the certain warning levels may be reached. For the help to Decision Making Group to choose an optimal time of gates closing a special software component for calculation the plan of gates maneuvering and decision making support is designed.

The plan of gates maneuvering is based on forecast data and should provide (arranged according to priority):

- Protecting the city from the flood.
- Maintenance of the structures consistency.

- Minimization of the time when devices are in closed position.

Formally the calculation of gates maneuvering plan is a multicriteria optimization problem with nonlinear restrictions. The solution to this problem is complicated by the presence of time constraints on decision-making on (a) exigency and (b) precision time moments of gates maneuvering. These factors rule out the possibility of brute-force search of all the time moments for gates closing. Moreover there are additional factors of uncertainties caused by lack of precise information about Neva river discharge, the limits and errors of forecast. As a result a following procedure for gates maneuvering plan is proposed:

- Processing of the next forecast.
- Reconstruction of the sea level for long-range forecasting (out of 48 hours) by regression model. This step needs for estimation of gates opening time when the final phase of the flood is missing.
- Separation of different floods (through crossing of critical level) within one forecast.
- The calculation of etalon time of gates closing as a boundary for optimal time search through linear model.
- Preparation of plans with closing times (control points).
- Calculations of full maneuvering plans by BSM-2010 model.
- Check of nature restrictions for maintenance of the structures consistency.
- Selection of the best plan in accordance with specified criteria.

An example of calculating the plan of barrier gates maneuvering is shown on Figure 5. The horizontal line denotes a critical flood level (reduced for safety to 130 cm). Dashed line shows a sea level variation without gates maneuvering. Solid line demonstrates an effect of the plan use (the result of hydrodynamic simulation with BSM-2010). Vertical lines show moments of closing and opening gates.

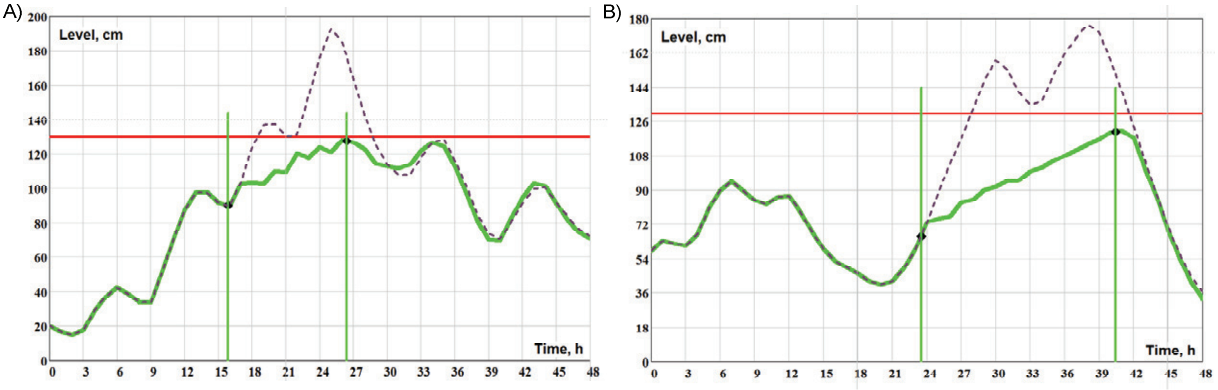

Fig. 5. The plan of barrier gates maneuvering for (a) the flood in October of 2006, (b) the flood in January of 2007

The plan of gates maneuvering shown on Figure 5 could reduce the sea level to less than 130 cm and thus prevent the potential flood.

2.2. Workflow for urgent computing

The distinctive features referring to urgent computing (UC) in comparison with other supercomputing technologies are followings:

- UC systems contains as computational services (or resources) as data services (interfaces to sensors, controllers, technical facilities and so on). the matching between observed and simulated data is performed. During the process of computing the matching between observed and simulated data is performed (for instance data may be assimilated in models [5]).
- Computational processes in the frame of urgent computing paradigm are normally described in the form of branched scenarios. A convenient way to describe a scenario is a workflow (WF).
- Optimization procedure of load-balancing for the urgent WF implies the selection of computational resources sufficient to solve a problem within the time limit.

An interactive process of decision support is the specificity of urgent computing. Thus the decision support may be represented as a sequence of sessions [6].

The applying of urgent computing technologies is typical for natural hazard prediction. An example of urgent WF for operational forecasting and decision support (described in section 2) of gates closing in Saint-Petersburg Barrier is shown on Figure 6.

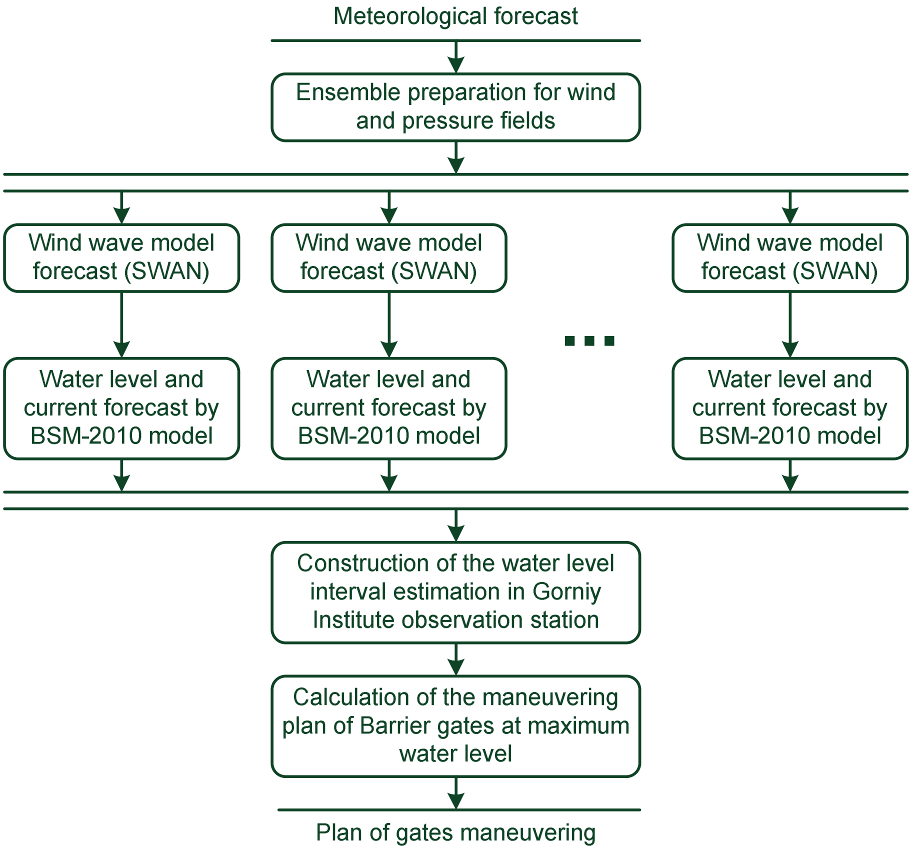

Fig. 6. Urgent workflow for operational forecasting and decision support of gates maneuvering

This WF consists of five connected steps:

- Meteorological data processing. This module carries out converting of initial data to model format and applying of the mask of coefficients to wind field (for ensemble forecast).
- The running of SWAN model for simulation of wave's parameters (distributed computing on different resources with time restriction).
- The running of BSM-2010model for simulation of sea level and currents with the input from SWAN model (distributed computing on different resources with time restriction).
- The analysis of simulation result and sea level probabilistic interval estimation.
- The calculation of the plan of gates maneuvering for the maximum of the interval.

The result of WF is the plan of gates maneuvering which may be used by Barrier Authority for decision support on flood prevention.

3. Conclusions

The applying of urgent computing technologies opens up new possibilities for development and improvement of the Flood Warning System in Saint-Petersburg. It is provided by extensive factors (increase in forecast accuracy, increase in efficiency of gate maneuvering assessment) and improvement of the intelligent support of decision makers. It includes assessment of different kind of uncertainties and prediction of emergency. This approach may be extended to different kinds of processes and objects.

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