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A method for inversion of periodic open boundary conditions in two-dimensional tidal models

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Abstract

For parameter estimation problems, it is of great importance to reduce the number of spatially varying control variables because of the ill-posedness of inverse problem. A new method for the inversion of periodic open boundary conditions in two-dimensional tidal models is developed in this work. In this method, the open boundary curves are generated by linearly interpolating the values at feature points (FPs). The FPs are selected by calculating the second-order derivatives of discrete curves. The advantage is that most of the variations of the curves can be reproduced by the minimum number of control points. The adjoint-based 4DVAR data assimilation method is then applied to simulate the tides in the Bohai, Yellow and East China Seas by optimizing the Fourier coefficients at FPs. The model and the method are calibrated in twin experiments where the prescribed distributions along open boundaries are successfully inverted. The results of twin experiments demonstrate that the effect of inversion is in inverse proportion with the number of FPs which characterizes the complexity of open boundary curves. In order to test the method in practical application, real experiments are performed and the FPs are selected by analyzing the background information from a global tidal model DTU10. During the assimilation, both the data misfit between observations and modeling results and L_2 norm of gradients of cost function with respect to control variables have decreased significantly. The relation between the number of control variables and parameter inversion is discussed. It is concluded the method developed in this work will be especially useful and effective when dealing with complex open boundary forcing or applying in highly refined models.

Keywords: Open boundary conditions; Data assimilation; Tidal model; Satellite altimetry; Inverse problem

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1. Introduction

In oceanic and atmospheric studies, data assimilation methods have been more and more widely implemented. They are especially useful and efficient in dealing with large amount of data, for example, satellite or radar data. The data assimilation methods, especially the complex ones like four-dimensional variational (4DVAR) and Kalman Filter, are developed on rigorous mathematical theories, including inverse problem theory and optimal control theory. The ultimate purpose of applying data assimilation method is to reduce the data misfit between model results and various observations, by either improving the models, or by dynamically interpolating the observations. Among all the data assimilation methods, 4DVAR is one of the most effective and powerful approaches. It is based on the optimal control methods and perturbations theory [1,2], and allows us to retrieve an optimal data for a given model from heterogeneous observation fields [2]. The adjoint-based 4DVAR method has the advantage of directly assimilating various observations distributed in time and space into numerical models, while maintaining dynamical and physical consistency between the model and observations.

The earlier applications of adjoint assimilation method in oceanography were addressed by Bennett and McIntosh [3] and Prevost and Salmon [4] who applied the weak constraint formalism of Sasaki [5] to a tidal flow problem and a geostrophic flow problem, respectively. Thacker and Long [6] then employed the strong constraint formalism in which the model equations were imposed as exact constraints on the minimization. The adjoint method is a powerful tool for parameter estimation. Navon [7] presented an important overview on the state of the art of parameter estimation in meteorology and oceanography in view of applications of 4DVAR data assimilation techniques to inverse parameter estimation problems. Zhang and Lu [8] studied the parameter estimation problems with 4DVAR and a three-dimensional tidal model, and also summarized relative works. More recently, Kazantsev [2] briefly revealed the history of data assimilation starting from Lorenz's pioneering work and then deeply studied the sensitivity of a shallow-water model to parameters by applying adjoint-based data assimilation technique. One can find more details about adjoint parameter estimation from the works above.

As noted by Yeh in the work of ground water flow parameter estimation, the inverse or parameter estimation problem is often ill-posed and beset by instability and non-uniqueness, particularly if one seeks parameters distributed in space and time domain [9]. The same viewpoint has been put forward by references [10–14]. Consequently, how to reasonably reduce the number of estimated parameters became into an important aspect. For example, bottom friction coefficients are crucial parameters for ocean models. When estimating spatially varying bottom friction coefficients, Das and Lardner [11,12] suggested that the number of estimated bottom friction coefficients should be related to the number of observations. Ullman and Wilson [13] concluded that it was impractical and unjustified to define the friction coefficient at each grid point as a model parameter and they selected 10 nodes in their work. Heemink et al. [14] advised that it was impossible to take the bottom friction coefficients at every grid point as a parameter because too many model parameters would then lead to identifiability problem and they chose the estimated friction coefficients by analyzing the parameter gradients, while Lu and Zhang [15] achieved this purpose by analyzing the gradient of water depth under the assumption that the bottom friction effect was closely related to the ocean topography.

The tides and tidal currents are the basic motion forms of ocean water [16]. They are especially important in the marginal seas. However, the tides and tidal currents in coastal areas and semi-enclosed seas are often difficult to be modeled than those in the deep ocean because of the complex topography [17]. For tidal models, open boundary conditions (OBCs) are the most important parameter. Solutions in model interior are uniquely determined by the tidal OBCs. Traditionally, tidal OBCs can be obtained from either available observations near the open boundaries [18], or large scale numerical models [19]. However, observations at open waters are often scarce and the global tidal model results are either of low resolution or less accurate in shallow waters [20]. Therefore, how to obtain accurate OBCs for regional tidal models has been a subject of ongoing research.

As described in the previous paragraph, the inversion of OBCs distributed in space and time domain was also contaminated by ill-posedness [21,22], which implied that one would have to seek the balance between the accuracy of simulation and number of estimated OBCs. Zhang et al. [19] performed two-dimensional Princeton Ocean Model to simulate the tides for the East Coast of United States. In their work, in order to reduce the number of control variables, amplitude and phase of each tidal constituent at a given open boundary grid