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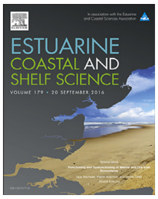

A three-dimensional cohesive sediment transport model with data assimilation: Model development, sensitivity analysis and parameter estimation

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ABSTRACT

Based on the theory of inverse problems, a three-dimensional sigma-coordinate cohesive sediment transport model with the adjoint data assimilation is developed. In this model, the physical processes of cohesive sediment transport, including deposition, erosion and advection-diffusion, are parameterized by corresponding model parameters. These parameters are usually poorly known and have traditionally been assigned empirically. By assimilating observations into the model, the model parameters can be estimated using the adjoint method; meanwhile, the data misfit between model results and observations can be decreased. The model developed in this work contains numerous parameters; therefore, it is necessary to investigate the parameter sensitivity of the model, which is assessed by calculating a relative sensitivity function and the gradient of the cost function with respect to each parameter. The results of parameter sensitivity analysis indicate that the model is sensitive to the initial conditions, inflow open boundary conditions, suspended sediment settling velocity and resuspension rate, while the model is insensitive to horizontal and vertical diffusivity coefficients. A detailed explanation of the pattern of sensitivity analysis is also given. In ideal twin experiments, constant parameters are estimated by assimilating ‘pseudo’ observations. The results show that the sensitive parameters are estimated more easily than the insensitive parameters. The conclusions of this work can provide guidance for the practical applications of this model to simulate sediment transport in the study area.

1. Introduction

Coastal waters are often characterized by the high concentration of suspended sediments derived from discharge of rivers or seabed resuspension (Miller and McKee, 2004). High suspended sediment concentrations (SSCs) have significant impact on phytoplankton productivity (Cloern, 1987; May et al., 2003), coral growth (McLaughlin et al., 2003), productivity of submerged aquatic vegetation (Dennison et al., 1993), the transport of pollutants (Martin and Windom, 1991), nutrient dynamics (Mayer et al., 1998) and geomorphic evolution (Jia et al., 2006; Fan et al., 2014). Consequently, a better understanding of suspended sediment transport process is essential.

The dynamics of suspended sediment transport is very complex in estuaries and coastal areas, and SSC varies as a function of tides, wind, circulation, etc. (Fettweis et al., 2007). In addition, the distribution of suspended sediments in coastal environments has large spatial and temporal variability (Miller and McKee, 2004; He et al., 2013). In-situ measurement is the most direct method to investigate the mechanism of suspended sediment transport; however, it only provides a local description (Amoudry and Souza, 2011). Therefore, the traditional field sampling method is inadequate to synoptically map suspended sediments. Over past decades, polar-orbiting satellite ocean color data (e.g., Myint and Walker, 2002; Warrick et al., 2004; Petus et al., 2010; Zhang et al., 2010) and geostationary meteorological satellite data (e.g., Neukermans et al., 2009, 2012; Salama and Shen, 2010) have been used to map suspended sediments in various coastal regions. However, only the

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surface SSC can be obtained from the satellite data, while the vertical structure of SSC is still challenging our modelling and observing capabilities.

Numerical suspended sediment transport models have gradually become a powerful tool to study suspended sediments (e.g., Hayter and Mehta, 1986; Wang and Pinardi, 2002; Guan et al., 2005; Leupi et al., 2008; Hu et al., 2009; Amoudry, 2014). Bagnold (1935, 1937) firstly attempted to correlate sediment transport with fluid dynamics. The mathematical modelling of sediment transport has become a major subject in coastal sciences since the work carried out by Einstein (1950) and higher development of the computing capacity. Broadly speaking, based on spatial scale, sediment transport models can be divided into one-dimensional models (e.g., Thomas and Prasuhn, 1977; Krishnappan, 1981; Holly, 1990; Papanicolaou et al., 2004), two-dimensional models (e.g., Onishi and Wise, 1982; Van Rijn and Tan, 1985; Jia and Wang, 1999) and three-dimensional models (e.g., Blumberg and Mellor, 1987; Hamrick, 1992; Song and Haidvogel, 1994). The details about the development stages of current representative models and their main applications, strengths and limitations are available in the review article by Papanicolaou et al. (2008).

Amoudry and Souza (2011) reviewed state-of-the-art Eulerian implementations of bottom-up sediment transport and morphological change in coastal ocean hydrodynamic models. They noted that a very important characteristic of present sediment transport models is the high degree of empiricism, and another issue is the mismatch between model results and the experimental data. There are a large number of parameters in sediment transport models, including the initial conditions, inflow open boundary conditions, settling velocity, resuspension rate, and horizontal and vertical diffusivity coefficients. Unfortunately, it is very difficult to assign reasonable values to these poorly constrained parameters, which leads to large discrepancies between modelling results and observational data. This is the one of the largest limitations for the application of sediment transport models.

As we know, in oceanic and atmospheric studies, data assimilation methods have been widely used to reduce the data misfit between models and observations (Zhang and Wang, 2014). For sediment transport models, data assimilation methods also provide possibilities to achieve this goal, which will be studied in this work. The four-dimensional variational (4DVAR) data assimilation is one of the most powerful and effective methods among all of the data assimilation approaches. The adjoint method has been successfully implemented in parameter estimation for different models (e.g., Navon et al., 1992; Zou et al., 1995; Alekseev et al., 2009; Zhang and Lu, 2010; Zhang et al., 2011; Cao et al., 2013). Navon (1998) presented a significant overview on the state of the art of parameter estimation in meteorology and oceanography with respect to applications of 4DVAR data assimilation techniques to inverse parameter estimation problems.

In this paper, based on the theory of inverse problems, a three-dimensional sigma-coordinate cohesive sediment transport model with the adjoint data assimilation is developed. In Section 2, the cohesive sediment transport model and the adjoint model are constructed, and the model settings are described. The parameter sensitivity analysis and the estimation of several constant parameters are performed in Sections 3 and 4, respectively. Finally, a summary is provided in Section 5 of this paper.

2. Models

2.1. The cohesive sediment transport model

The governing equation of the cohesive sediment transport model is a three-dimensional advection diffusion equation with vertical particle settling, which is written as:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{H\partial\sigma}=\frac{\partial}{\partial x}\left(K_H\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_H\frac{\partial C}{\partial y}\right)+\frac{\partial}{H\partial\sigma}\left(K_V\frac{\partial C}{H\partial\sigma}\right)+w_s\frac{\partial C}{H\partial\sigma} \tag{1}$$

where C represents the SSC; t is the time; x and y are the horizontal coordinates; σ is the vertical coordinate; H is the total water depth, including the undisturbed water depth and sea surface elevation; u, v and w are the flow velocity components in the x, y and σ directions; K_H and K_V are the horizontal and vertical diffusivity coefficients; and w_s denotes the cohesive sediment settling velocity.

At the bottom of the water column, the cohesive sediment flux is equal to the combination of deposition and erosion, which is described as:

$$-w_s\cdot C-\frac{K_V}{H}\frac{\partial C}{\partial\sigma}=E-D,\quad \sigma=0 \tag{2}$$

where E and D are the erosion rate and deposition rate, respectively. Erosion occurs when the bottom shear stress exceeds the threshold of erosion (Yang and Hamrick, 2003, hereinafter referred to as YH03):

$$E=\begin{cases}M_0\cdot(\tau_b/\tau_{ce}-1), & \tau_b>\tau_{ce}\\ 0, & \tau_b\le\tau_{ce}\end{cases} \tag{3}$$

Conversely, deposition occurs when bottom shear stress is smaller than a critical value (YH03):

$$D=\begin{cases}w_s\cdot C_1\cdot(1-\tau_b/\tau_{cd}), & \tau_b<\tau_{cd}\\ 0, & \tau_b\ge\tau_{cd}\end{cases} \tag{4}$$

where M_0 is the resuspension rate; τ_b is the bottom shear stress; τ_{ce} and τ_{cd} are the critical shear stress for erosion and deposition, respectively; and C_1 is the SSC near the bottom. Generally, the settling velocity w_s is a function of salinity and sediment concentration (Owen, 1970; Hayter, 1983; Dyer, 1986; Wang et al., 2013). For simplicity, constant settling velocity is applied in this study, without considering the effects of salinity and sediment concentration. According to Einstein (1950), erosion and deposition cannot occur simultaneously; therefore, the same critical shear stress for erosion and deposition are employed in this study.

At the sea surface, the no flux boundary condition is applied, which is written as:

$$-w_s\cdot C-\frac{K_V}{H}\frac{\partial C}{\partial\sigma}=0,\quad \sigma=1 \tag{5}$$

In addition, the model is subject to the first boundary conditions at the inflow boundary Ω1, no gradient boundary conditions at the outflow boundary Ω2 and the solid boundary Ω3, which are given by:

$$C|_{\Omega 1}=C_{obc} \tag{6}$$

$$\partial C/\partial\vec{n}|_{\Omega 2}=0 \tag{7}$$

$$\partial C/\partial\vec{n}|_{\Omega 3}=0 \tag{8}$$

where C_{obc} denotes the SSC at the inflow boundary and $\vec{n}$ is the vector normal to the boundary. Furthermore, the model has initial conditions C_0, which are described by:

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