

SEA SURFACE HEIGHT SIMULATION METHOD BASED ON QUANTUM WALK

TECHNICAL FIELD

The present disclosure relates to the technical field of physical geography and ocean physics, in particular to a sea surface height simulation method based on a quantum walk.

BACKGROUND

The current modeling model of a change in sea surface height is roughly classified into two categories: a traditional model and a machine learning model. Generally speaking, a traditional prediction method is based on a parametric model, that is, on the basis of determining a time series prediction model, parameters of the model are solved to complete the prediction. For example, an Auto-Regressive Moving Average (ARIMA) model has simple parameters and high computational efficiency, but the ARIMA can only predict stationary series with linear characteristics well, can not dig out nonlinear characteristics, and usually needs to satisfy the assumption of stationarity, so that the ARIMA is not suitable for the simulation and prediction of the sea surface height. The machine learning model, such as an artificial neural network (ANN) and a support vector machine (SVM), is a strong nonlinear function fitter, that is, the machine learning model uses some algorithms to "learn" data, and then digs out hidden information in the data. The ANN has strong self-learning ability and can solve some nonlinear mapping problems according to set input and output, but the ANN is a black-box model, which is sensitive to training data and does not consider the physical meaning behind the change in sea surface height; and the SVM is a machine learning method based on a statistical learning theory, which has unique advantages in solving small samples and nonlinear problems, but the SVM is sensitive to parameters and kernel functions, and performs poorly in massive data samples.

The change in global sea surface height is closely related to human production and life, and is of vital importance to the construction of a human community with a shared future. Preventing natural disasters caused by the change in sea surface height is an important task for the construction of economic and ecological civilization. In recent years, more and more evidences have shown that the classical random walk can predict the nonlinear and dynamic characteristics of the change in sea surface height, and give a scientific revelation. But in fact, the change in sea surface height is not independent, but the result of multi-factor and multi-process superposition coupling, and in most cases, the current modeling model can not satisfy the assumption of independence and randomness of the classical random walk,

resulting in not playing a role in the prediction of the change in sea surface height.

SUMMARY

The technical problem to be solved by the present disclosure is to provide a sea surface height change simulation method based on a quantum walk, which further analyzes the change in sea surface height from the perspective of multi-scale decomposition, explores the relationship between the change in sea surface height and a sea surface fluctuation mode, and realizes the modeling and simulation of the change in sea surface height from the perspective of superposition coupling of multiple components. Therefore, the sea surface height change simulation method makes a great breakthrough in the modeling and simulation directions of the sea surface height.

In order to solve the above technical problem, the present disclosure provides a sea surface height simulation method based on a quantum walk, which includes the following steps:

- (1) generating multiple fluctuation components of a sea surface height based on the quantum walk;
- (2) screening the components of the sea surface height;
- (3) simulating the sea surface height based on a principle of component superposition; and
- (4) performing an experimental verification.

Preferably, in step (1), generating multiple fluctuation components of a sea surface height based on the quantum walk is specifically as follows: when no observation is performed, the sea surface height of any station appears at any elevation at any time with a certain probability, but at the same time, the sea surface height can only appear at any elevation point, which is recorded as $|\delta\rangle = \{|\delta_1\rangle, |\delta_2\rangle, \dots, |\delta_n\rangle\}$, where

$$|\delta_1\rangle = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, |\delta_2\rangle = \begin{pmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{pmatrix}, \dots, |\delta_n\rangle = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{pmatrix} \quad (1).$$

Thus, the state $|\varepsilon(k)\rangle$ of the quantum walk is defined as a linear superposition of all ground states:

$$|\varepsilon(k)\rangle = \sum_{i=1}^n \alpha_i(k) |\delta_n\rangle \quad (2),$$

where $|\alpha_i(k)| \in [0,1]$, which represents the probability amplitude that the sea surface height is in the state $|\delta_n\rangle$ at a given time, and the evolution of a state vector $|\varepsilon(k)\rangle$ with time is represented based on a unitary transformation as follows:

$$\frac{d}{dt} |\varepsilon(k)\rangle = iA |\varepsilon(k)\rangle \quad (3).$$

As shown in the formula (3), the resolution k of the quantum walk is continuously adjusted based on a certain rule, that is, all possible fluctuation components of each station are constructed according to the quantum walk.

Preferably, in step (2), screening the components of the sea surface height is specifically as follows: stepwise regression subset screening is performed on all the possible multiple fluctuation components $(|\varepsilon(k_1)\rangle, |\varepsilon(k_2)\rangle, \dots, |\varepsilon(k_n)\rangle)$ generated in step (1) under the constraint of the actual sea surface change time series φ , which is represented as:

$$\varphi \sim \text{sift} \left(\sum_{n=1}^N |\varepsilon(k_n)\rangle \right) \quad (4).$$

Based on Akaike Information Criterion (AIC), all possible sea surface height change modes $(|\varepsilon(k_1)\rangle, |\varepsilon(k_2)\rangle, \dots, |\varepsilon(k_n)\rangle)$ are screened by using a stepwise regression subset screening method in the formula (4) to obtain a mode screening result, which is recorded as $\{|\varepsilon(k_m)\rangle\}$.

Preferably, in step (3), simulating the sea surface height based on a component superposition principle is specifically as follows: an aliasing coupling relationship between the real sea surface change time series and the sea surface change components is established based on modes $\{|\varepsilon(k_m)\rangle\}$ obtained by screening in step (2), and the relationship is represented as:

$$\varphi = \sum_{m=1}^M \{ \alpha_m \times |\varepsilon(k_m)\rangle \} + b \quad (5),$$

where M is the number of components obtained by screening in step (2), φ is the actual sea surface height change time series, α_m is a sea surface height change scale factor

with the same components $\{\mathcal{E}(k_m)\}$, k_m is a parameter of the component obtained by screening, and an important characterization parameter of the change in sea surface height, and b is a mapping constant term.

Preferably, in step (4), the experimental configuration of the experimental verification is specifically as follows: a group of stations having approximately the same latitude are selected and distributed in increasing longitude, where six stations are respectively named as $N_1, N_2, \dots, N_6$; during the multi-modal extraction, 2000 times of quantum walks are performed at different tide gauge stations in a study area, where k increases from 0.01 to 20, with an interval of 0.01; and in addition, in order to evaluate the modeling effect, a mean absolute error (MAE), a root mean square error (RMSE) and a coefficient of determination R^2 are selected to measure the fitting effect of the model, and the specific definitions are shown in Table 1, where δ_i is the actual sea surface height; $\bar{\delta}_i$ is the average sea surface height; $\hat{\delta}_i$ is the sea surface height obtained by fitting; and n is the number of fitting samples.

Table 1 Definition of evaluation indexes for model modeling effect

Evaluation index	Formula definition
Mean absolute error (MAE)	$MAE = \frac{1}{n} \sum_{i=1}^n \delta_i - \hat{\delta}_i $
Root mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\delta_i - \hat{\delta}_i)^2}$
Coefficient of determination (R^2)	$R^2 = 1 - \frac{\sum_{i=1}^n \delta_i - \hat{\delta}_i ^2}{\sum_{i=1}^n \delta_i - \bar{\delta}_i ^2}$

The sea surface height change simulation method based on the quantum walk has the beneficial effects that the key method of the quantum walk is introduced, the change in sea surface height is further analyzed from the perspective of multi-scale decomposition, the relationship between the change in sea surface height and the sea surface fluctuation mode is explored, and the modeling and simulation of the change in sea surface height is realized from the perspective of superposition coupling of multiple components. Therefore, the sea surface height change simulation method makes a great breakthrough in the modeling and simulation

directions of the sea surface height.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic flowchart of a method according to the present disclosure.

FIG. 2 is a schematic diagram of an experimental area and station selection according to the present disclosure.

FIG. 3 is a schematic diagram of a sea surface height simulation result based on a quantum walk according to the present disclosure.

FIG. 4 is a schematic diagram of accuracy evaluation of a modeling result according to the present disclosure.

DETAILED DESCRIPTION OF THE EMBODIMENTS

As shown in FIG. 1, a sea surface height simulation method based on a quantum walk includes the following steps:

- (1) generating multiple fluctuation components of a sea surface height based on the quantum walk;
- (2) screening the components of the sea surface height;
- (3) simulating the sea surface height based on a principle of component superposition; and
- (4) performing an experimental verification.

In the global ocean current, the same/similar environmental factors are abstracted as quantized driving particles, and the change in sea surface height under the action of such environmental factors can be described as the evolution process of the height of the driving particles with time, which is a single component of the change in sea surface height. When no observation is performed, the particles will appear at multiple possible vertical positions with a certain probability, so as to form a dynamic evolution process of the probability of the particles appearing at each elevation with time under the fluctuation component.

However, in reality, the characteristics and structures of the changes in sea surface height at different tide gauge stations are different, so that characterizing the change in sea surface height by a unified component is unrealistic. Therefore, the quantum walks with different steps are considered to generate multiple sea surface height change components with different

shapes and structures, which not only helps to reveal the superimposed coupling relationship between the complex structure of the sea surface height and multiple components, but also provides a basis for establishing a high-precision and strong-robustness prediction model.

The dynamic evolution process of the sea surface height under a single sea surface height component can be described as the fluctuation process of the same/similar environmental factors (driving particles) between stations, and can be described by the quantum walk. In the process of generating the multiple fluctuation components of the sea surface height, the key is to drive the particles to perform a quantum walk on a basic skeleton composed of adjacent matrixes (topological structures) of the tide gauge stations in the study area from a fixed station under given parameters, so as to form the dynamic evolution of the distribution probability of the sea surface height with time under a single fluctuation component.

Generating multiple fluctuation components of a sea surface height based on a quantum walk is specifically as follows: when no observation is performed, the sea surface height of any station appears at any elevation at any time with a certain probability, but at the same time, the sea surface height can only appear at any elevation point, which is recorded as $|\delta\rangle = \{|\delta_1\rangle, |\delta_2\rangle, \dots, |\delta_n\rangle\}$, where

$$|\delta_1\rangle = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, |\delta_2\rangle = \begin{pmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{pmatrix}, \dots, |\delta_n\rangle = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{pmatrix} \quad (1).$$

Thus, the state $|\varepsilon(k)\rangle$ of the quantum walk is defined as a linear superposition of all ground states:

$$|\varepsilon(k)\rangle = \sum_{i=1}^n \alpha_i(k) |\delta_i\rangle \quad (2),$$

where $|\alpha_i(k)| \in [0, 1]$, which represents the probability amplitude that the sea surface height is in the state $|\delta_i\rangle$ at a given time, and the evolution of a state vector $|\varepsilon(k)\rangle$ with time is represented based on a unitary transformation as follows:

$$\frac{d}{dt} |\varepsilon(k)\rangle = iA |\varepsilon(k)\rangle \quad (3).$$

As shown in the formula (3), the resolution k of the quantum walk is continuously adjusted based on a certain rule, that is, all possible fluctuation components of each station are constructed according to the quantum walk.

Although the change in sea surface height is complex in structure and different in modes by being affected by multiple factors, a part of ideal components are not likely to exist in the change in sea surface height due to different objective constraints such as human intervention and impact factors. All possible sea surface height change components generated in step (1) are only a general component set, which is the "base" of sea surface height modeling and simulation, and can only describe the ideal sea surface height change condition. Therefore, under the constraint of the actual sea surface height change, the sea surface height change components at different tide gauge stations are analytically obtained based on a specific sea surface height fluctuation component screening criterion, which is convenient for the subsequent exploration of the superimposed coupling relationship between the change in sea surface height and the multiple components.

According to the present disclosure, the stepwise regression subset screening method is used as a sea surface height change modal screening method, and stepwise regression subset screening is performed on all possible multiple fluctuation components $(|\varepsilon(k_1)\rangle, |\varepsilon(k_2)\rangle, \dots, |\varepsilon(k_n)\rangle)$ generated in step (1) under the constraint of the actual sea surface height change time series φ , which is represented as:

$$\varphi \sim \text{sift} \left(\sum_{n=1}^N |\varepsilon(k_n)\rangle \right) \quad (4).$$

Based on Akaike Information Criterion (AIC), all possible sea surface height change modes $(|\varepsilon(k_1)\rangle, |\varepsilon(k_2)\rangle, \dots, |\varepsilon(k_n)\rangle)$ are screened by using the stepwise regression subset screening method in the formula (4) to obtain a mode screening result, which is recorded as $\{|\varepsilon(k_m)\rangle\}$.

Based on the multiple sea surface height components of each tide gauge station obtained by screening in step (2), a mapping relationship of one-to-many aliasing coupling between the sea surface height components and the sea surface height is constructed on the basis of the idea of superposition combination, and finally the purpose of simulating the change in sea surface height on the basis of the multiple components is achieved.

Based on the mode $\{|\varepsilon(k_m)\rangle\}$ obtained by screening in step (2), an aliasing coupling relationship between a real sea surface height change time sequence and a sea surface height change component is established and is represented as:

$$\varphi = \sum_{m=1}^M \{ \alpha_m \times |\varepsilon(k_m)\rangle \} + b \quad (5),$$

where M is the number of components obtained by screening in step (2), φ is the

actual sea surface height change time series, α_m is a sea surface height change scale factor with the same components $\{\{\varepsilon(k_m)\}\}$, k_m is a parameter of the component obtained by screening, and an important characterization parameter of the change in sea surface height, and b is a mapping constant term.

The experimental configuration of the experimental verification is specifically as follows: a group of stations having approximately the same latitude are selected and distributed in increasing longitude, wherein six stations are respectively named as $N_1, N_2, \dots, N_6$; during the multi-modal extraction, 2000 times of quantum walks are performed at different tide gauge stations in a study area, wherein k increases from 0.01 to 20, with an interval of 0.01; and in addition, in order to evaluate the modeling effect, a mean absolute error (MAE), a root mean square error (RMSE) and a coefficient of determination R^2 are selected to measure the fitting effect of the model, and the specific definitions are shown in Table 1, where δ_i is the actual sea surface height; $\bar{\delta}_i$ is the average sea surface height; $\hat{\delta}_i$ is the sea surface height obtained by fitting; and n is the number of fitting samples.

Table 1 Definition of evaluation indexes for model modeling effect

Evaluation index	Formula definition
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Root mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\delta_i - \hat{\delta}_i)^2}$
Coefficient of determination (R^2)	$R^2 = 1 - \frac{\sum_{i=1}^n \delta_i - \hat{\delta}_i ^2}{\sum_{i=1}^n \delta_i - \bar{\delta}_i ^2}$

As shown in FIG. 2, the sea surface of the Equator-Pacific region is taken as a research area, a sea surface height change series of a one-month time window is selected as experimental data, a simulation experiment of the sea surface height is completed, and a simulation result is shown in FIG. 3. The mode number of each station (Table 2) shows that the number of sea surface fluctuation modes is between 16 (N6) and 85 (N2), indicating that the sea surface height change condition in the Equator-Pacific region is complex and complex multi-scale oscillations exist. The statistics shown in FIG. 4 show that the average simulation

accuracy (R^2) of the six stations is 0.825, the MAE range is 11.14 (N2) to 26.52 (N6), and the RMSE range is 14 (N2) to 32.32 (N6), indicating that the sea surface height simulation method based on the quantum walk has high modeling accuracy, and can reconstruct and invert the stochastic oscillations of the changes in sea surface height with different frequency components. Among the six stations, the simulation accuracy of the station N2 is the highest, which is 0.97. In addition, the change in sea surface height of the station N6 is the most dramatic, of which MAE is 26.52, RMSE is 32.32, and R^2 is 0.72, indicating that the sea surface height simulation method based on the quantum walk has high simulation accuracy for different stations with generally small simulation errors, and still has high simulation accuracy for stations with big errors, which proves the effectiveness of the method provided according to the present disclosure.

Table 2 Number of sea surface height change modes at each station and evaluation indexes

Station	Number of sea surface height change components	MAE	RMSE	R^2
N1	34	24.31	31.04	0.79
N2	85	11.14	14.00	0.97
N3	50	21.51	27.14	0.83
N4	43	16.87	20.97	0.82
N5	56	20.02	25.69	0.82
N6	16	26.52	32.32	0.72

According to the present disclosure, the sea surface height fluctuation is a complex geographical space-time process formed by the superposition of multiple fluctuation components with different structures. Any tide gauge station in the world is selected, all possible sea surface height change components of the tide gauge station in continuous time are generated by the quantum walk, and under the constraint of the actual sea surface height fluctuation time series, a fluctuation component subset is screened by using specific rules, and the mapping transformation relationship between multiple fluctuation components and the sea surface height is explored to realize the modeling and simulation of the sea surface height.

CLAIMS

1. A sea surface height simulation method based on a quantum walk, comprising the following steps:

(1) generating multiple fluctuation components of a sea surface height based on the quantum walk;

(2) screening the components of the sea surface height;

(3) simulating the sea surface height based on a principle of component superposition; and

(4) performing an experimental verification.

2. The sea surface height simulation method based on quantum walk according to claim 1, wherein in step (1), generating multiple fluctuation components of a sea surface height based on the quantum walk is specifically as follows: when no observation is performed, the sea surface height of any station appears at any elevation at any time with a certain probability, but at the same time, the sea surface height can only appear at any elevation point, which is

recorded as $|\delta\rangle = \{|\delta_1\rangle, |\delta_2\rangle, \dots, |\delta_n\rangle\}$, wherein

$$|\delta_1\rangle = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, |\delta_2\rangle = \begin{pmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{pmatrix}, \dots, |\delta_n\rangle = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{pmatrix} \quad (1),$$

thus, the state $|\varepsilon(k)\rangle$ of the quantum walk is defined as a linear superposition of all ground states:

$$|\varepsilon(k)\rangle = \sum_{i=1}^n \alpha_i(k) |\delta_i\rangle \quad (2),$$

wherein $|\alpha_i(k)| \in [0, 1]$, which represents the probability amplitude that the sea surface height is in the state $|\delta_i\rangle$ at a given time, and the evolution of a state vector $|\varepsilon(k)\rangle$ with time is represented based on a unitary transformation as follows:

$$\frac{d}{dt} |\varepsilon(k)\rangle = iA |\varepsilon(k)\rangle \quad (3), \text{ and}$$

as shown in the formula (3), the resolution k of the quantum walk is continuously adjusted based on a certain rule, that is, all possible fluctuation components of each station are constructed according to the quantum walk.

3. The sea surface height simulation method based on quantum walk according to claim 1, wherein in step (2), screening the components of the sea surface height is specifically as follows: stepwise regression subset screening is performed on all the possible multiple fluctuation components $(|\varepsilon(k_1)\rangle, |\varepsilon(k_2)\rangle, \dots, |\varepsilon(k_n)\rangle)$ generated in step (1) under the constraint of the actual sea surface change time series φ , which is represented as:

$$\varphi \sim \text{sift} \left(\sum_{n=1}^N |\varepsilon(k_n)\rangle \right) \quad (4), \text{ and}$$

based on Akaike Information Criterion (AIC), all possible sea surface height change modes $(|\varepsilon(k_1)\rangle, |\varepsilon(k_2)\rangle, \dots, |\varepsilon(k_n)\rangle)$ are screened by using a stepwise regression subset screening method in the formula (4) to obtain a mode screening result, which is recorded as $\{|\varepsilon(k_m)\rangle\}$.

4. The sea surface height simulation method based on quantum walk according to claim 1, wherein in step (3), simulating the sea surface height based on a component superposition principle is specifically as follows: an aliasing coupling relationship between the real sea surface change time series and the sea surface change components is established based on modes $\{|\varepsilon(k_m)\rangle\}$ obtained by screening in step (2), and the relationship is represented as:

$$\varphi = \sum_{m=1}^M \{ \alpha_m \times |\varepsilon(k_m)\rangle \} + b \quad (5),$$

wherein M is the number of components obtained by screening in step (2), φ is the actual sea surface height change time series, α_m is a sea surface height change scale factor with the same components $\{|\varepsilon(k_m)\rangle\}$, k_m is a parameter of the component obtained by screening, and an important characterization parameter of the change in sea surface height, and b is a mapping constant term.

5. The sea surface height simulation method based on quantum walk according to claim 1, wherein in step (4), the experimental configuration of the experimental verification is specifically as follows: a group of stations having approximately the same latitude are selected and distributed in increasing longitude, wherein six stations are respectively named

as $N_1, N_2, \dots, N_6$; during the multi-modal extraction, 2000 times of quantum walks are performed at different tide gauge stations in a study area, wherein k increases from 0.01 to 20, with an interval of 0.01; and a mean absolute error (MAE), a root mean square error (RMSE) and a coefficient of determination R^2 are selected to measure the fitting effect of the model, and the specific definitions are shown in Table 1, wherein δ_i is an actual sea surface height; $\bar{\delta}_i$ is an average sea surface height; $\hat{\delta}_i$ is a sea surface height obtained by fitting; and n is the number of fitting samples.

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Coefficient of determination (R^2)	$R^2 = 1 - \frac{\sum_{i=1}^n \delta_i - \hat{\delta}_i ^2}{\sum_{i=1}^n \delta_i - \bar{\delta}_i ^2}$