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# Preliminary study on the effect of tidal current power on salinity distribution in the Zhoushan Area, China

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*Abstract*—**For the multi-channel marine system with significant transport of different water masses, harvesting energy from the tidal current may affect the transport regime of these waters. However, understanding of this effect is lacked by previous research. To address such issues, a high-resolution three-dimensional model of the Zhoushan Area was developed. Through the momentum sink approach, a theoretical array of 200 turbines in the Guanmen Channel was embedded. Considering the realistic operation of a generic tidal stream turbine, the annual mean power production of this array is estimated to be 22.07 MW. As the removal of tidal current energy, significant deceleration of the currents is observed downstream of the turbines, with a maximum value of 0.15 m/s. It is also found that the blockage of the array not only induces the reduction of tidal flux in the Guanmen Channel but also causes the water flux increment in the neighboring channels. This, in turn, affects the transport of the Changjiang Diluted Water. Increments of the salinity are detected in the vicinity of the array. Simultaneously, due to the increase of the freshwater input, waters in the neighboring channel become fresher. These alterations indicate that tidal current energy extraction could influence the transport regime of local water masses and subsequently induce the redistribution of the ocean thermohaline fields.**

*Keywords*—**Environmental impacts, numerical modelling, tidal current energy, water transport regime, Zhoushan Area.**

## I. Introduction

ENERGY extracted from the tidal current has a high potential to supply global energy consumption. However, except technological difficulties, the development of the tidal current energy is also challenged by the laws and regulations, as well as the societal norms, which require to show its possible environmental impacts are minimal. As a consequence, a lot of studies have been conducted to figure out the potential effects induced by the tidal current energy extraction. And they have demonstrated that the operation of tidal current turbines could affect the ecological environment [1]–[3], and lead to regional impacts on the tidal regime [4]–[6] and sediment transport [7]–[9].

Recently, the first 1 MW unit of a 3.4 MW tidal current power generator set was deployed in the Zhoushan Area [10], where the channels are deep and constricted. It is important to note that this region is the primary southward path for the Changjiang Diluted Water (CDW), which is fresh and contains a large number of nutrients. These waters flow into the Zhoushan Area and meet the warm waters from the Taiwan Warm Current [11], [12]. Along with the subtropical monsoon climate, the mixed waters provide a superior living environment for marine wildlife [13]. In this context, Without considering the potential impacts on the transport regime and mixing pattern of these waters, the exploitation of tidal current energy may be disastrous.

However, so far relevant studies are still few. In 2015, Yang et al. [14] utilized a 3D unstructured-grid Finite Volume Community Ocean Model (FVCOM) coupled with a tidal turbine module to investigate how the removal of tidal current energy affects the stratification in an idealized estuary. The results show that the vertical mixing is strengthened and consequent weakened stratification is observed: the difference between surface salinity and bottom salinity decreases as the number of turbines installed increases. Whereas for the far-field stratification, Dominicis et al. [15], [16] found the alteration is entirely opposite. In their study, a realistic operation of a large turbine array in the Pentland Firth was simulated. It is found that the reduction of vertical mixing due to the operation of turbines can increase water stratification. Nonetheless, previous studies only focus on the energy extraction effects on the vertical mixing of the stratified waters without consideration of the alterations to the horizontal transport of these waters. In particular, in the case of the region like the Zhoushan Area with considerable input of freshwater, modifications to the transport regime of these waters induced by the blockage of the turbine array may significantly change the distribution of salinity and subsequently affect the ecological environment.

To figure out these effects, a three-dimensional numerical model was adopted in this study. A 200 turbines array was implanted in this model to include tidal current energy extraction feedback on the flow. Freshwater discharge, tides, wind shear stress, and the net sea-surface heat flux were also imposed on

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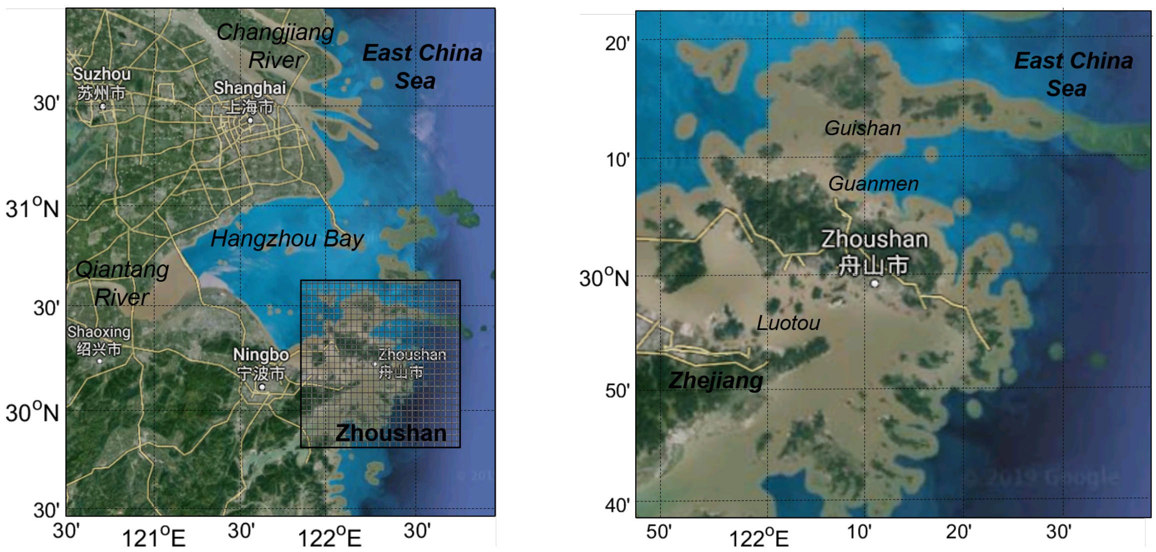


Fig. 1. Bathymetry and grid configurations of the ECS model (left) and the nested Zhoushan Area model (right). These maps are derived from the Google Map. Box in the left figure shows the location of the nested model.

the model. Thus we could capture the alterations in the thermohaline field, providing valuable insight into the modifications to the transport regime of the water masses.

The rest of the paper is organized as follows. Section II introduces the numerical methodology. Modifications to the water transport and salinity distribution are presented in Section III. Section IV concludes this paper.

## II. Methodology

### A. Numerical model

The high-resolution numerical model utilized in this study is the Regional Ocean Modeling System (ROMS) which is widely used in oceanic research, over various scales from idealized studies to regional domains [17]–[19]. The Zhoushan Area model (29.6°N-30.4°N, 121.8°E-122.6°E) is two-way nested [20] in the East China Sea (ECS) model (29.5°N-32°N, 121°E-123°E) (Fig. 1). The horizontal resolutions of the Zhoushan model and the ECS model are $1/96°$ and $1/480°$, respectively. $k-\omega$ turbulence closure [21] was applied to resolve the vertical mixing scheme. And horizontal viscosity and diffusion coefficients were scaled by grid size. This model was initialized with the global HYCOM and NCODA Ocean Reanalysis data [22], [23]. The time scale of this model equals to one climatological year.

The Changjiang River and the Qiantang River were simulated as point sources at the river mouths with uniform discharge along the vertical direction. 10 tidal constituents $(M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_f, M_m)$ were considered, which were obtained from the TPXO8-atlas global inverse tide model with a high resolution of $1/30°$ [24]. Atmospheric forcing including net freshwater fluxes, solar shortwave radiations, momentum stresses, and net heat fluxes were derived from the ERA-Interim global atmospheric reanalysis data set [25].

### B. Representation of tidal current turbine

Tidal current turbine has been represented in the ROMS model as a retarding force through a momentum sink approach [26]. Consequently, horizontal momentum governing equations in this model were modified as follows:

$$\begin{cases} \frac{\partial u}{\partial t}+\vec{v}\cdot\nabla u-fv=-\frac{\partial \phi}{\partial x}+\frac{\partial}{\partial z}\left(K\frac{\partial u}{\partial z}\right)+D_u-F_x \\ \frac{\partial v}{\partial t}+\vec{v}\cdot\nabla v-fu=-\frac{\partial \phi}{\partial y}+\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)+D_v-F_y \end{cases} \tag{1}$$

Where $(x, y, z)$ are the coordinates, $\vec{v}$ is the vector velocity, $(u, v)$ are the $(x, y)$ components of $\vec{v}$, $\phi$ is the dynamic pressure, $K$ is the vertical eddy viscosity coefficient, $f$ is the Coriolis parameter, $t$ is the time, and $(D_u, D_v)$ are the horizontal momentum diffusive terms in the $x$ and $y$ directions. $\vec{F} = (F_x, F_y)$ is the retarding force caused by the operation of the turbine and is calculated by the following equation:

$$\vec{F} = \frac{1}{2}\rho A_d C_t \left|\vec{u}\right| \vec{u} \tag{2}$$

Where $\rho$ is the seawater density, $A_d$ is the flow-facing area swept by the turbines, and $\vec{u}$ is the current velocity. The total power production at any given time can be obtained by the following formula:

$$P_{total} = \sum_{i=1}^{M} (N_i \times \frac{1}{2}\rho C_T A\overline{|\vec{u}|^3}) \tag{3}$$

Where $N_i$ is the number of turbines in the $i^{th}$ grid element and $M$ is the total number of elements containing turbines. The turbine embedded in this model was the generic turbine design proposed by Baston et al. [27], which has 20-meter long blades with a hub height of 15m above the sea bottom. An array of 200 turbines with a thrust coefficient of 0.55 was implanted in the Guanmen Channel to investigate its potential environmental effects.

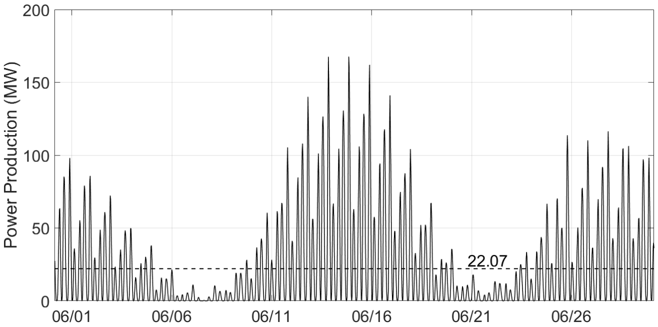


Fig. 2. Temporal variation of power production. Dashed line indicates the annual mean value.

## III. Results

### C. Power production

Given the realistic operation of tidal turbine array, the predicted practical resource available from the array of 200 turbines located in the Guanmen Channel is presented in Fig. 2. The maximum instantaneous power extracted by this array is on the order of 160 MW. Whereas the annual mean power production is approximately 21.5 MW. This significant difference is directly attributable to the proportional relationship between the extracted power and the current speed (refer to (3)). Consequently, strong temporal variation of the current speed leads to the strong variation of power production. Similarly, this figure also shows that the spring tides with faster currents can produce a considerably greater power than the neap tides. The consequent intermittent electricity generated by the turbine array cannot be utilized directly. To solve this problem, a lot of studies have been carried out. One possible solution is to complement in phase to another energy farm [28], [29]. Additionally, it is important to note that the cut-in speed of the tidal current turbine is not taken into consideration in this simulation. As a result, the realistic power production should be less than these theoretical values.

### D. Modification to water transport

The most effective factor to describe the transport of water masses is the current velocity. Therefore, changes in the tidal current speed were examined in this study. Instead of instantaneous values, we quantified the annual mean variations of the depth-averaged velocities to obtain a more general insight, which is shown in Fig. 3. At floods (Fig. 3-a), significant velocity deficits are observed in the northwest of the array, i.e., downstream of the turbines. The maximum differences are in the order of 0.12 m/s, about 10% of the unperturbed annual mean current speed, even though the affected area is relatively small. Due to the blockage of the turbine array, bypass flow along the southern coastline of the Guanmen Channel is also intensified. In contrast, the effects induced by the turbines are much more extensive at ebbs. This phenomenon is a result of the ebb-dominated feature of the Zhoushan Area. Given the proportional relationship between the turbine retarding force and the square of the current speed (refer to (2)), the array operated in the stronger ebb currents produces a larger retarding force on the currents and thereby induces greater impacts on the hydrodynamic environment. As shown in Fig. 3-b, the deceleration of the current speed can reach up to 0.15 m/s downstream of the array. A considerable decrease of the unperturbed current speed is detected in the south of the turbines with the area affected over 20 $km^2$. Similar to the situation at floods, localized hastening with a magnitude of 0.1 m/s of the bypass flow is observed in the vicinity of the turbines where the current is not blocked.

Besides the near-field acceleration of the currents, regional changes in water transport are also detected. On account of the blockage of the flow into the Guanmen Channel and subsequent northward diversion of the waters, it is demonstrated that the currents in the Xihoumen Channel are slightly intensified (Fig. 3). To further quantify modifications to the water transport, tidal fluxes through the Guanmen Channel and the Xihoumen Channel have been examined. Fig. 4 presents the temporal variations and baseline conditions of the tidal fluxes. The unperturbed tidal flux of the Guanmen Channel varies from $5 \times 10^4 m^3/s$ to $1 \times 10^5 m^3/s$. With the operation of the turbine array, the tidal flux decreases a little with a maximum value up to 4000 $m^3/s$, which is approximately 4% of the unperturbed tidal flux. It further proves that the exploitation of tidal energy weakens the local transport of the waters. Moreover, change in the tidal flux through the Xihoumen Channel implies the strengthened transport of the waters (Fig. 4-b), although the magnitude is relatively small, in the order of 1000 $m^3/s$ or about 1% of the total unaltered tidal flux. This figure also shows that the increase of the tidal flux through the Xihoumen Channel is positively related to the flux decrease in the Guanmen Channel. Given the importance of the channels in the Zhoushan Area to the transport of the CDW, modification to the tidal fluxes is expected to alter the CDW transport regime. On the one hand, the blockage of turbines would weaken the flux of CDW into the Guanmen Channel. Subsequently, the amount of organic material, sediments, and freshwater discharged into this channel would be decreased, which has a strong influence on the physical and optical environment and results in a reduction of the primary productivity [30]–[32]. On the other hand, as the blocked CDW was diverted, lower salinity and a higher concentration of dissolved organic material in the neighboring channel would lead to higher primary productivity [33]. As a consequence, the operation of tidal current turbines could potentially affect the survival of marine organism even the whole ecosystem.

### E. Change in salinity distribution

To further figure out the mechanism by which the removal of the tidal current energy can affect the transport regime of relevant water masses, the variation of salinity distribution were examined. As shown in Fig. 5, the spatial variation of the sea surface salinity (SSS) has a similar pattern to that of the depth-averaged salinity; this is inconsistent with the findings of pre-

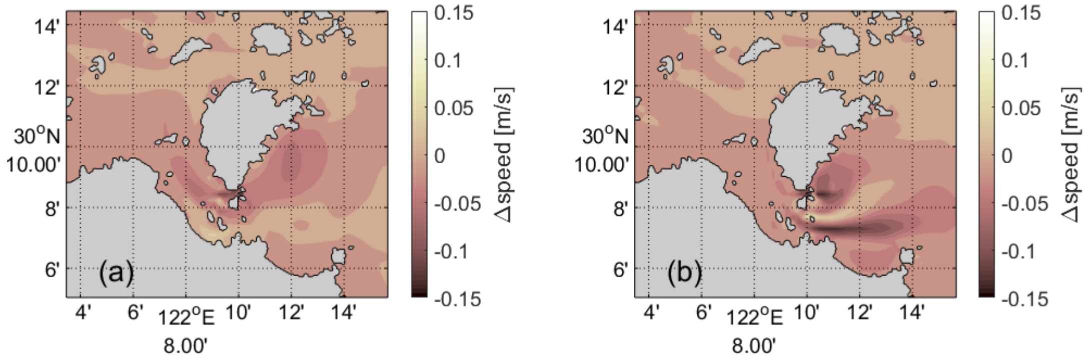


Fig. 3. Changes in annual mean depth-averaged tidal current speed at floods (a) and ebbs (b). Differences are the perturbed run minus the baseline.

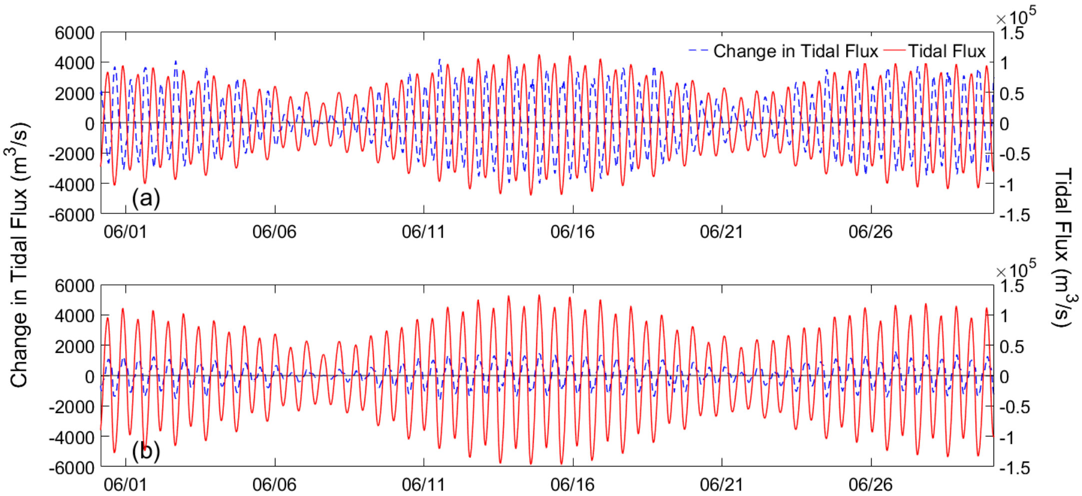


Fig. 4. Baseline condition and change in tidal fluxes through the Guanmen Channel (a) and the Xihoumen Channel (b). Positive (negative) values of tidal flux represent the flood (ebb) tides. Differences are the perturbed run minus the baseline.

vious studies [14], [16]. The discrepancy is mainly because the hydrodynamic environment of the Zhoushan Area is different from that of the previous study region, where the spatial distribution of salinity is to a large extent determined by vertical mixing processes on the water column. Whereas in the Zhoushan Area, the water column is well-mixed and hence the horizontal transport of the waters becomes the major control on the thermohaline field rather than the vertical mixing.

As mentioned above, the presence of the tidal current turbines blocks the flow into the channel and subsequently induces diversion of the waters. The modifications to the tidal flux, in turn, affect the distribution of salinity. As shown in Fig. 5, due to the reduction of the freshwater flux into the Guanmen Channel, we find a small increment of the SSS shown in this channel. That change corresponds to 0.1 PSU, about 0.3% of the unaltered seawater salinity. It is also demonstrated that the variation of the depth-averaged salinity is separated by the island between the Luotou Channel and the Guanmen Channel (see Fig. 1 for the locations), which is also identified as the main island of the Zhoushan Area. Water salinity of the northeastern sea area of the main island increases slightly (about 0.04 PSU). Whereas a reduction with a same magnitude is observed in the southwestern part as the volume of inputted freshwater is increased. Additionally, in the southern sea of the Zhoushan Area, the depth-averaged salinity decreases relatively greatly with a magnitude of 0.06 PSU. This suggests that the incursion of the freshwater flowing along the outer edge of the Zhoushan Area is strengthened.

It is expected that those changes in the thermohaline fields have a high potential to influence the marine ecological system. As an important factor for the development of phytoplankton communities, salinity influences productivity through altering protein synthesis, photosynthesis, and lipid metabolism [30], [34], [35]. Simultaneously, diminution of SSS could lead to destabilization of the water column stratification which triggers enhanced nutrient entrainment and convective mixing leading to enhanced primary productivity [36]. Moreover, modification to the oceanographic condition also alters the habitat selectio n of the marine species [37]. Future work would be required to evaluate the detailed potential effects of tidal current energy exploitation on the ecosystem.

## IV. Summary

A high-resolution three-dimensional hydrodynamics modelling study was conducted to investigate the potential impacts of tidal current energy extraction on the transport regime of water masses in the Zhoushan Area. The annual mean power production of a 200-turbine array is estimated to be 22.07 MW. Meanwhile,

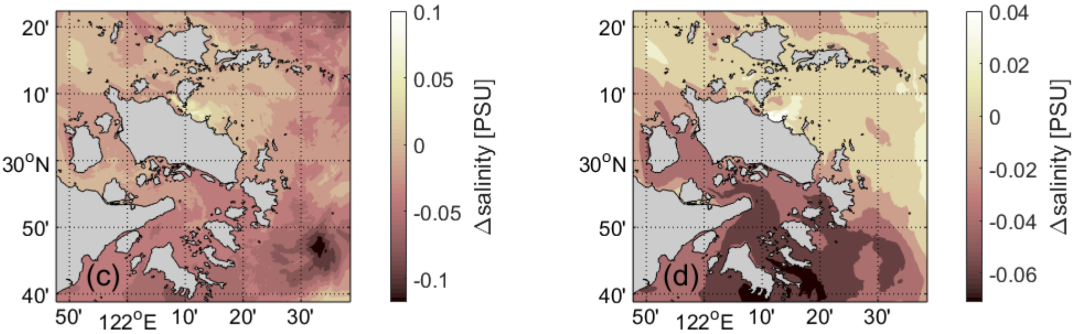


Fig. 5. Changes in the distribution of sea surface salinity (a) and depth-averaged salinity (b). Differences are the perturbed run minus the baseline.

significant velocity decreases are detected downstream of the array with a maximum value up to 0.15 m/s, about 15% of the undisturbed depth-averaged velocities. The blockage of the turbine array not only induces the localized acceleration but also causes diversion of the flow into the neighboring channels. As a consequence, tidal flux through the Xihoumen Channel increases slightly in the order of 1000 $m^3/s$, which is proportional to the magnitude of flux decrease in the Guanmen Channel. This also affects the transport of CDW, which flows through these channels. Increases of salinity are observed in the near field and far field of the array. Simultaneously, water in the Luotou Channel becomes fresher due to the larger input of the CDW. Further studies are needed to investigate the potential effects of the energy extraction on the transport regime of water masses in a comprehensive and systematic way and to figure out the detailed mechanisms behind them. This can help tidal current energy extraction to minimize the harm to the ecological environment, and provide critical information for choosing a site as well as proposing an optimal development project.

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