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Evaluation of the Hydrodynamic Impacts of Tidal Turbine Arrays in Jiaozhou Bay

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Abstract: In this paper, a hydrodynamic model of Jiaozhou Bay was developed using the Regional Ocean Modeling System and validated against observed tidal levels and current data. The model accurately characterizes the tidal and current features of the region. Based on this model, the spatial and temporal distributions of flow fields and tidal energy resources were analyzed. A 100-turbine tidal power plant was simulated utilizing a momentum-based approach that accounts for resource distribution, bathymetry, topography, and turbine parameters. The resulting hydrodynamic changes, including velocity variations peaking at 0.5 m/s within the turbine deployment zone and tidal level shifts confined to the bay (maximum change in ~10 cm), emphasize the importance of localized environmental assessments. However, the findings also highlight broader considerations for the sustainable development of tidal energy in semi-enclosed bays worldwide, where strategic siting and design can mitigate larger ecological disturbances. These findings may provide a scientific foundation for balancing clean energy extraction with minimal environmental impact, thus contributing to global efforts to develop more resilient and sustainable coastal energy systems.

Keywords: Jiaozhou Bay; regional ocean modeling system; tidal and current features; site selection of tidal energy

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1. Introduction

The global depletion of fossil fuels, coupled with the escalating challenges of climate change and energy scarcity, emphasizes the urgent need for sustainable and renewable energy sources. Among these, tidal energy stands out due to its high technological maturity and predictability compared to other renewables, such as wind and solar. Over the past decade, numerous countries have launched tidal energy demonstration projects, including the large-scale Meygen tidal energy project in the United Kingdom (Ward et al., 2018; Thomas et al., 2014) [1,2], the Sabella demonstration project in France, and the Oosterschelde tidal power station in the Netherlands (Mestres et al., 2019; Vennell, 2012; Chong and Lam, 2013) [3–5]. These projects highlight the growing global interest in harnessing tidal energy for sustainable power generation.

In China, tidal energy technology is advancing rapidly. Projects such as the "Endeavour" tidal energy demonstration plant exemplify this progress, supported by extensive research on tidal energy resources assessment along China's coastal waters (Lv et al., 2010; Gao et al., 2012) [6–9]. Several provinces, including Zhejiang and Guangdong, have established tidal energy demonstration zones, paving the way for commercial-scale deployments. However, Shandong Province, despite its extensive coastline and significant tidal energy potential, remains underutilized in this sector.

Jiaozhou Bay, located along the southern coast of the Shandong Peninsula, is a semi-enclosed bay characterized by strong tidal currents, particularly in its narrow and deep channels. The bay's unique geomorphological features make it a promising candidate for tidal energy exploitation. Previous studies have primarily focused on resource assessments and numerical modeling of tidal currents in Jiaozhou Bay (Chen et al., 2011; Shao, 2021) [10,11]. These studies have identified regions with high tidal energy densities, particularly near the Tuandao-Xuejiadao channel, but have not extensively analyzed the environmental impacts of turbine array deployment. Nevertheless, there remains a gap in understanding how large-scale, multi-turbine arrays may affect local flow regimes, sediment dynamics, and coastal ecology in this semi-enclosed system. Considering this research gap, our study combines a robust three-dimensional hydrodynamic model with a momentum-based turbine parameterization to systematically evaluate both the energy extraction potential and the associated hydrodynamic alterations.

While tidal energy is a promising renewable resource, its development may raise significant environmental concerns. The deployment of tidal turbines can alter hydrodynamic conditions, including flow fields, tidal levels, and sediment transport processes. These changes may have cascading effects on benthic ecosystems, sediment dynamics, and water quality. Therefore, a comprehensive assessment of these impacts is essential to ensure sustainable development. Numerical modeling coupled with parameterized turbine representation may provide an effective tool for evaluating these impacts and optimizing deployment strategies [12–16].

Accordingly, the main objectives of this study are structured as follows:

(i) To identify optimal locations for turbine deployment based on tidal energy resource distribution in Jiaozhou Bay [17,18].
(ii) To quantify the hydrodynamic impacts of turbine arrays on flow fields, tidal levels, and vertical current profiles using a three-dimensional, momentum-based modeling approach.
(iii) To propose strategies and insights for minimizing environmental impacts while maximizing energy extraction efficiency, thereby providing practical guidance for sustainably harnessing tidal energy in Jiaozhou Bay and other similar coastal regions.

This paper is structured as follows: Section 2 describes the formulation and validation of the numerical models and the turbine array representation considered. Section 3 presents and discusses the findings on the tidal energy resource distribution and the hydrodynamic impacts of turbine deployment. Finally, Section 4 concludes with a comprehensive summary of the key findings, highlighting their implications.

2. Methodology

Jiaozhou Bay, situated along the southern coast of the Shandong Peninsula in China, is a semi-enclosed bay connected to the Yellow Sea. It features two mouths: the inner mouth between Tuandao and Huangdao and the outer mouth between Tuandao and Xuejiadao, which spans approximately 3.1 km wide with a general depth of less than 30 m. The bay is characterized by regular semidiurnal tides, with the deepest part of the estuary exceeding 60 m due to its steep, narrow channels. These unique topographic and shoreline features generate strong east–west tidal currents at the bay entrance, highlighting its potential for tidal energy development.

2.1. Model

This study utilizes the Regional Ocean Modeling System (ROMS), a three-dimensional open-source numerical model, to simulate the hydrodynamic impacts of tidal turbine arrays in Jiaozhou Bay (Figure 1). ROMS solves the Reynolds-averaged Navier–Stokes equations [19–21] under the Boussinesq approximation and hydrostatic assumption, employing the finite difference method. Bathymetric data were obtained from the General Bathymetric Chart of the Oceans (GEBCO) and digitized nautical charts, ensuring a detailed representation of the underwater terrain. The model grid, spanning 35.685° N to 36.308° N and 119.895° E to 120.656° E, was configured with a horizontal resolution of approximately 180 m and 10 vertical sigma layers to effectively capture key hydrodynamic processes. Tidal forcing was applied using boundary conditions from the TPXO9a global tidal model, focusing on major tidal constituents (M2, S2, K1, O1). A 35-day simulation period was selected, with the initial three days designated for spin-up to achieve dynamic equilibrium.

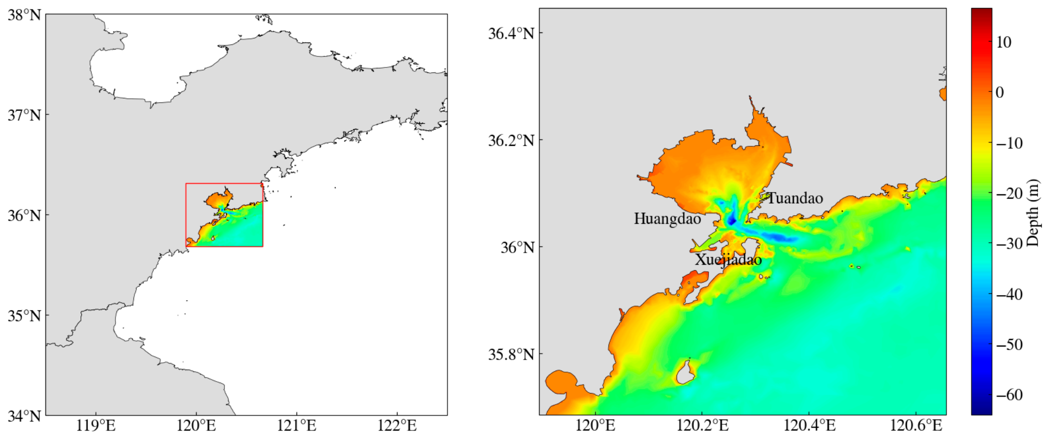

Figure 1. Schematic diagram of the ROMS model grids.

The model was calibrated and validated using observed data from an Acoustic Doppler Current Profiler (ADCP), Nortek 600 kHz AWAC ADCP, located at 120.222° E, 36.068° N. In this region, semi-diurnal tidal characteristics are shown with a maximum tidal range of 6.74 m, a minimum of 3.94 m, and an average of 5.4 m. The numerical results closely matched the measured data, with a root mean square error (RMSE) of 0.17 m and a correlation coefficient of 0.97. Vertical profiles of flow velocity and direction were validated against ADCP measurements. The RMSE for velocity and direction were 0.08 m/s and 2.4°, respectively, with correlation coefficients of 0.88 and 0.83. Minor discrepancies were attributed to the barotropic nature of the model, without accounting for baroclinic effects such as wind-driven circulation or wave-induced dynamics (as shown in Figure 2).

In this study, turbines are parameterized as localized momentum sinks applied within the model's momentum equations. Specifically, a momentum extraction term is introduced in cells corresponding to the turbine locations, accounting for the turbines' rated power, rotor swept area, and efficiency. This approach follows a commonly adopted theoretical framework in tidal energy research, where empirical turbine thrust coefficients are used to represent energy extraction. Due to the limited availability of large-scale field data for array deployments, model validation primarily relies on comparing tidal levels and current velocities with ADCP measurements for scenarios without turbines, and on sensitivity analyses for scenarios with hypothetical arrays.

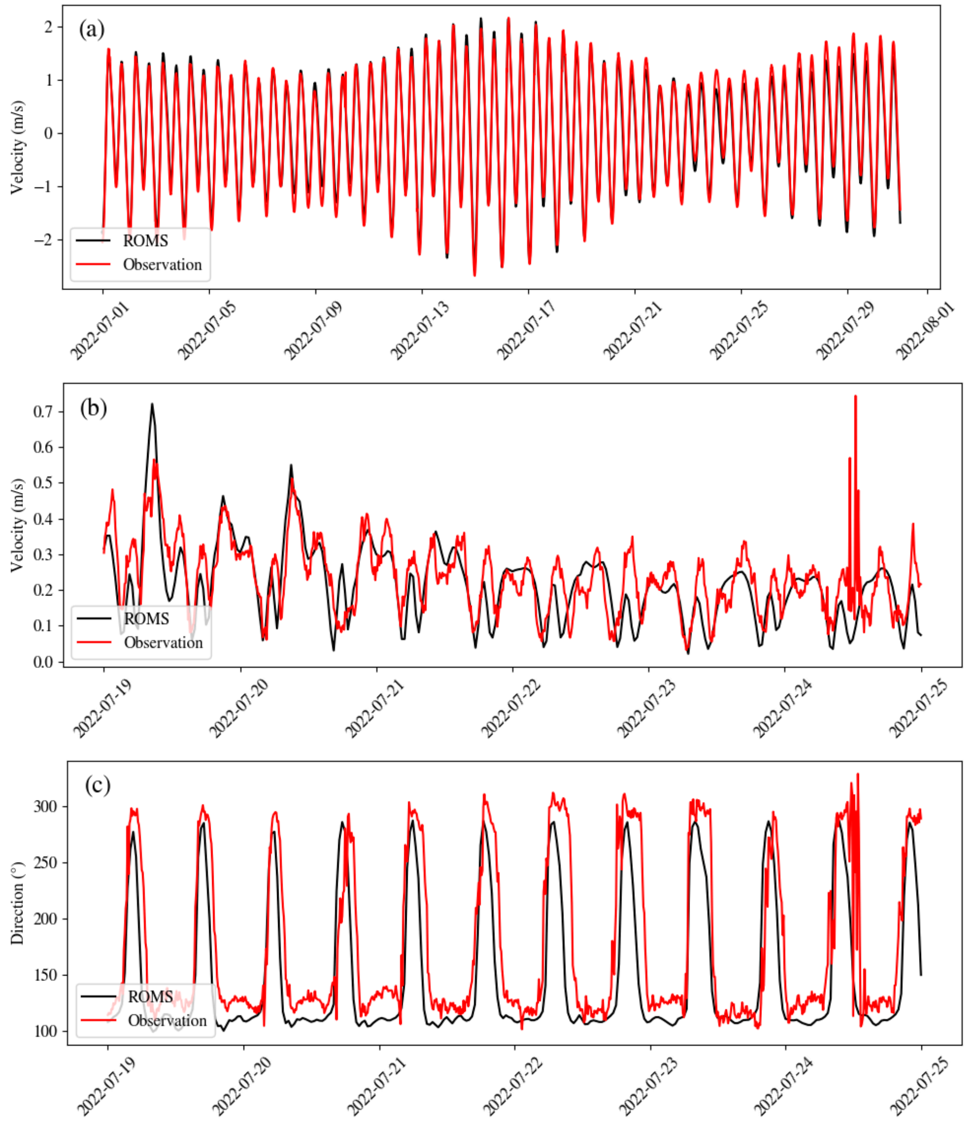

Figure 2. Comparisons of simulated and measured (**a**) tidal level, (**b**) tidal current velocity, and (**c**) tidal current direction.

All simulations are conducted under barotropic assumptions, whereby variations in temperature and salinity are not included. Moreover, wave interactions and wind-driven circulation are omitted based on the relatively moderate wind and wave conditions typically observed in Jiaozhou Bay and the primary objective of focusing on tidal-driven processes. While this simplification reduces computational complexity, it introduces uncertainties in accurately capturing stratification and wave-driven effects, especially during extreme weather events.

2.2. Turbine Array Representation

Table 1 summarizing turbine simulation parameters. The hydrodynamic effects of the tidal turbine array were investigated using a momentum-based parameterization approach. Following the methodology proposed by Roc et al. (2013) [22] and Brown et al. (2017) [23], an external force term (Ft) was introduced into the ROMS momentum equations to represent the turbines' impact on the flow field. The force applied by the turbines (Ft) was calculated as a function of the flow velocity at the rotor location, with the thrust coefficient (Ct) linked to the turbine's porosity and induction factor.

Table 1. Nomenclature/simulation parameters.

Nomenclature/Simulation Parameters		
Acronyms	**Turbine Specifications**	
/	number of turbines	100
/	turbine spacing	100
diam	turbine diameter in meters	10.0
zpos	location of turbine in the water column, between 0 and 1	0.5
r8v	rated velocity of turbine	2.0
kcff	density anomaly correction	1025.0
Ft	an external force term	variable
Ct	dimensionless thrust coefficient	variable

Tidal energy resource potential was quantified using the Tidal Stream Exploitability (TSE) index [24], defined as:

$$\mathrm{TSE} = \frac{\xi}{2v_0^3 h_0}\left(v_f^3 + v_e^3\right)h \quad (1)$$

where v_0 and h_0 are the reference velocity and depth, respectively. v_f and v_e represent the maximum velocities for the flood and ebb tides, respectively, and h denotes the water depth. ξ is the penalty function for tidal stream energy, given as:

$$\begin{cases} \xi = 0, \ \text{if} h - \frac{\Delta h}{2} < h_1 \\ \xi = \frac{1}{h_2 - h_1}\left(h - \frac{\Delta h}{2} - h_1\right), \ \text{if } h_1 < h - \frac{\Delta h}{2} < h_2 \\ \xi = 1, \ \text{if} h - \frac{\Delta h}{2} > h_2 \end{cases} \quad (2)$$

where Δh is the maximum tidal range; h_1 and h_2 are the maximum upper and lower limits of water depth compensation for turbine arrays, respectively.

The TSE index reflects the multiple of the average tidal flow energy power at a given point to the reference velocity and water depth, where v_0 is 2 m/s and h_0 is 20 m. The TSE index distribution in the study area (as shown in Figure 3) indicates that tidal energy in Jiaozhou Bay and its surrounding regions are generally below the reference values. However, the quality of tidal energy at the bay entrance is approximately 1 to 1.5 times the reference value, suggesting that this area is more suitable for tidal energy development. Therefore, the vicinity of Tuandao cape—Xuejiadao channel (Figure 4) is identified as the optimal location for deploying tidal turbine arrays, represented by red square. Zoom in on the turbine locations to clearly show the turbine array.

Horizontal-axis turbines with a rotor diameter of 10 m were selected, designed to operate at half the water depth to minimize seabed and surface interference. A grid of 100 turbines was deployed in a 10 × 10 layout at the Tuandao–Xuejiadao channel, where tidal energy resources are most concentrated. The transverse spacing between turbines was set to twice the rotor diameter (~20 m), following standard design practices [25].

By integrating these modeling techniques and resource assessment methods, this study develops a comprehensive framework for evaluating the hydrodynamic impacts of tidal turbine arrays in Jiaozhou Bay.

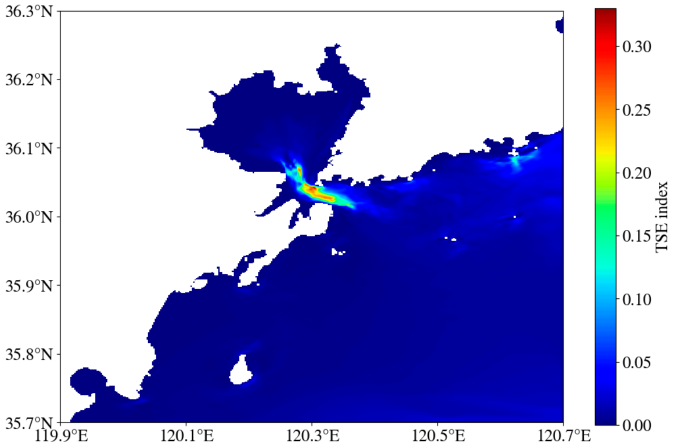

Figure 3. TSE index distribution.

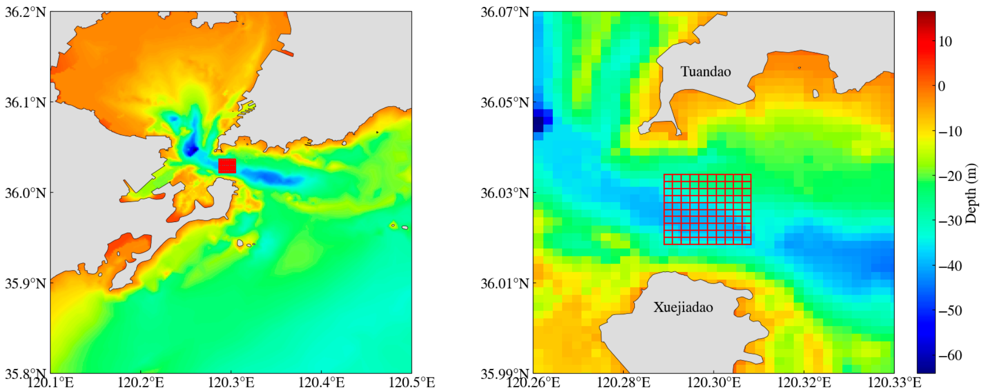

Figure 4. Turbine arrays location diagram.

3. Results and Discussions

The validated hydrodynamic model (Figure 5) was utilized to evaluate tidal energy resources and assess the environmental impacts of deploying a tidal turbine array in Jiaozhou Bay. The results are presented in terms of tidal energy resource distribution and the hydrodynamic changes induced by the turbines.

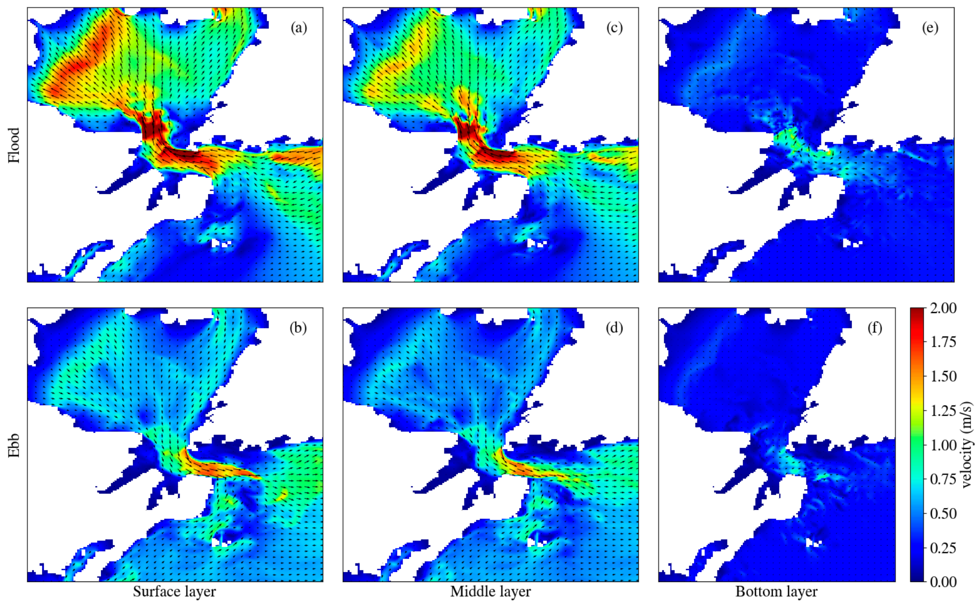

Figure 5. Three-layer flow fields during spring (**a**,**c**,**e**) flood and (**b**,**d**,**f**) ebb tides. Arrows indicate flow direction and velocity magnitude.

3.1. Tidal Energy Resource Distribution

The tidal current in this region exhibits clear asymmetry [26], with the flood tide dominating over the ebb tide in both duration and intensity. The average durations of flood and ebb tides are 6 h 56 min and 5 h 25 min, respectively, suggesting a flood-dominated regime. Compared to existing numerical models of the sea area, despite differences in modeling approaches, similar flow field characteristics are observed (Lv et al., 2010; Liang et al., 2017; Li et al., 2017) [6,27,28]. The TSE index further confirmed the suitability of the Tuandao–Xuejiadao channel for tidal energy extraction. The mean power density in this area reached 600 W/m^2 (Figure 6), with peak values exceeding 6 kW/m^2 during flood tides. This high energy density, combined with the availability of sustained operational hours exceeding 3000 annually (Figure 7), identifies the channel as an optimal site for tidal turbine deployment. The distribution of tidal energy resources aligns closely with the bathymetric and flow characteristics of the region, reinforcing the channel's potential for large-scale energy extraction.

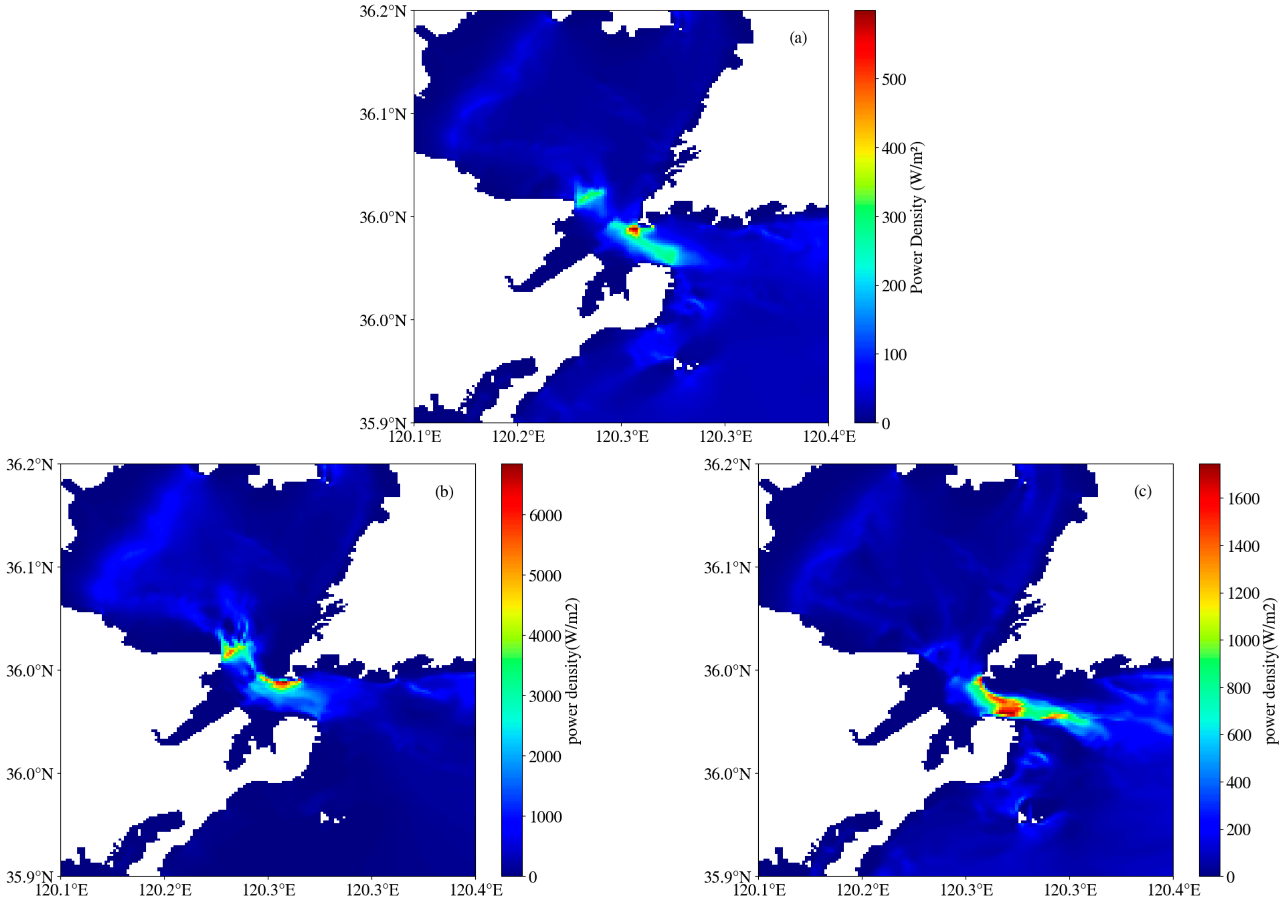

Figure 6. Power density distribution (**a**) mean, (**b**) flood, and (**c**) ebb tides.

3.2. Hydrodynamic Impacts of Turbine Deployment

The introduction of a 100-turbine array significantly altered the flow dynamics within the bay. The impacts were assessed in terms of changes in tidal levels, vertical profiles, and flow velocity.

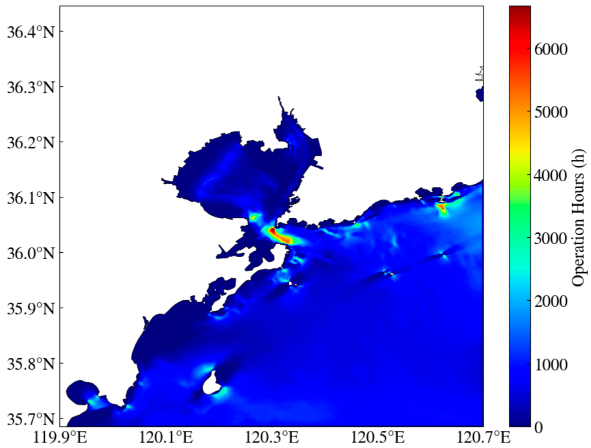

Figure 7. Operation hours distribution.

3.2.1. Tidal Level Changes

To evaluate the spatial effects of the turbine arrays, the distribution of tidal level differences during flood and ebb tide is shown in Figure 8. It is noted that the tidal turbine arrays affect the water levels over a wide range of the surrounding waters. This is attributed to the semi-enclosed bay and the blocking effect caused by the turbines. The obvious tidal level changes occur within the bay, particularly in the narrow inlet channel, which experiences the greatest influence. The tidal level in the outer area of the bay has no significant change, characterizing the differences in the water level as less than 1.0 cm.

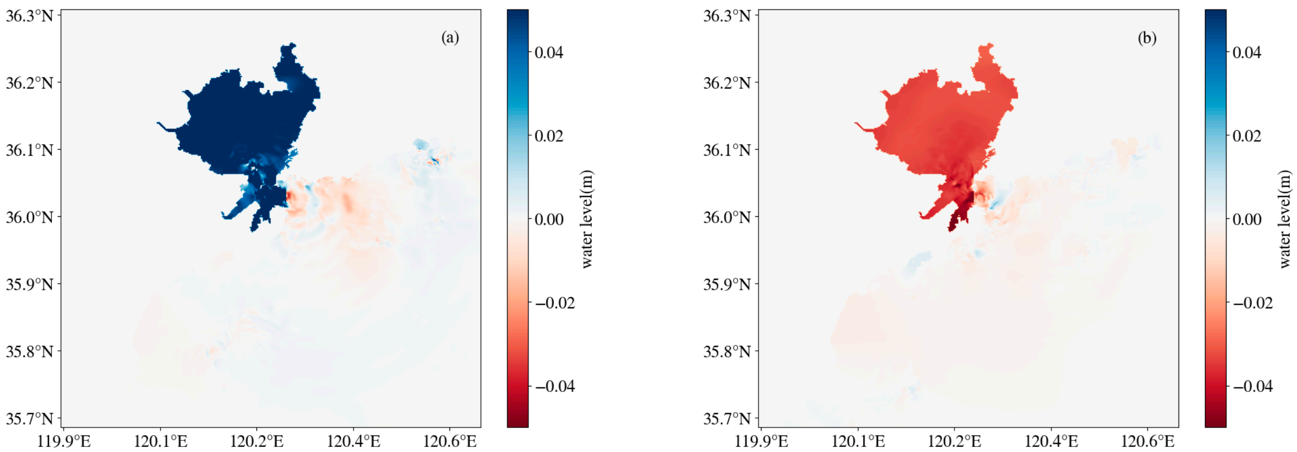

Figure 8. Distribution of water level differences with and without turbines during (**a**) spring flood and (**b**) ebb tides.

To comprehensively describe the spatiotemporal influence, three sites are selected for analysis: inner bay, outer bay, and offshore. The time series of water level changes at different water layers compared with the above three stations are presented in Figure 9.

Overall, water levels dropped slightly due to the operation of tidal arrays. As shown in Figure 9b, the maximum tidal level difference is less than 10 cm at the outer bay (i.e., turbine point), with an average water level drop of 0.3 cm. At the inner bay (i.e., Tuandao—Huangdao) as shown in Figure 9a, the average water level drop is 0.14 cm.

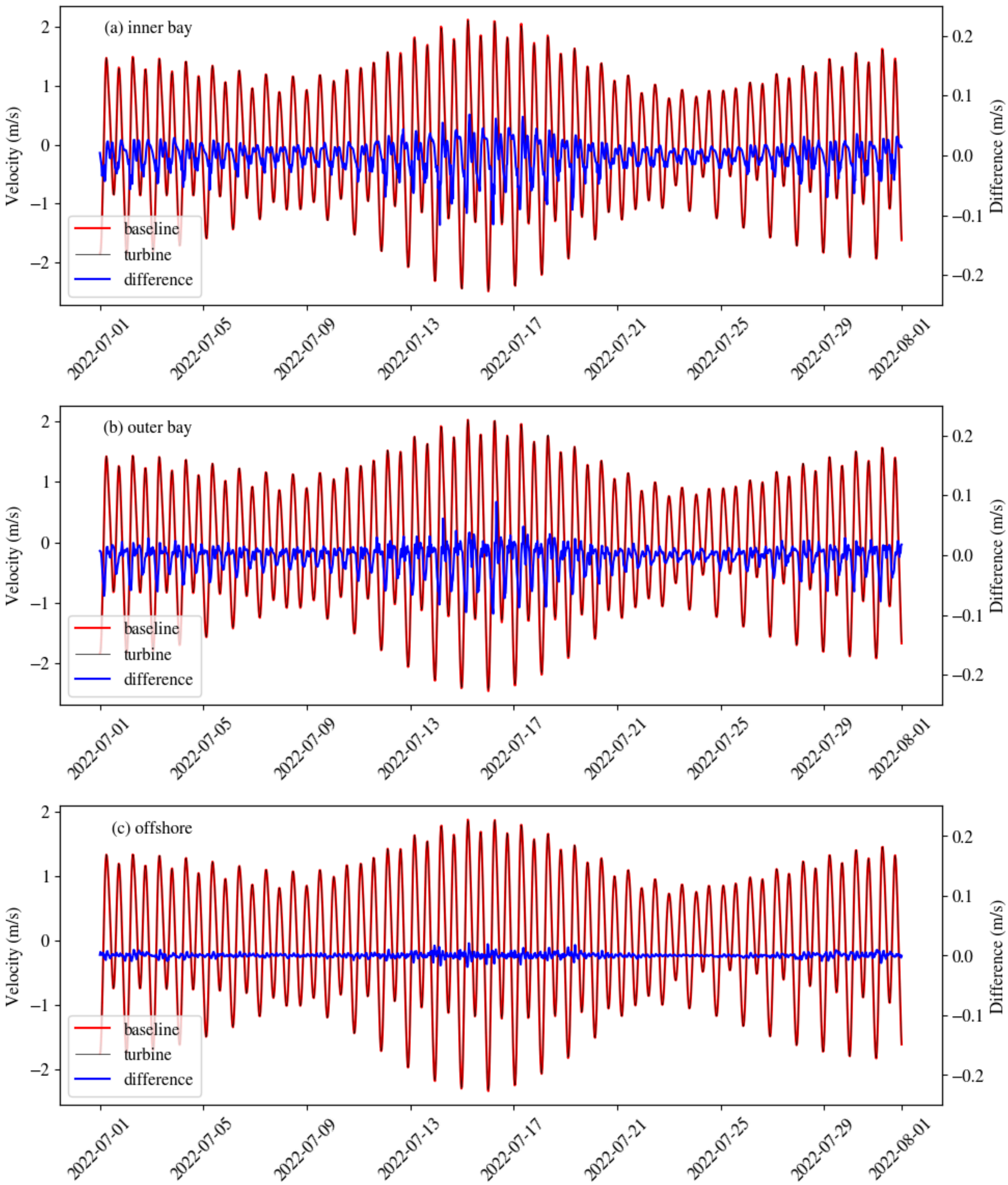

Figure 9. Time series of water levels with and without turbines.

Compared with the case without turbines, the water level rises during ebb tide but drops during flood tide. In the offshore area, as shown in Figure 9c, there is minimal change in the mean tide level. The average water level in the area near the turbine deployment drops by approximately 0.1–0.3 cm. In addition, the hypothetical turbine does not induce a significant phase shift in water level change.

3.2.2. Flow Velocity Changes

The impact of turbine deployment on flow velocity changes is also examined. Comparisons of flow field distribution at two specific moments during flood tide and ebb tide (Figure 10) and vertical mean velocity variation (Figure 11) are calculated, respectively.

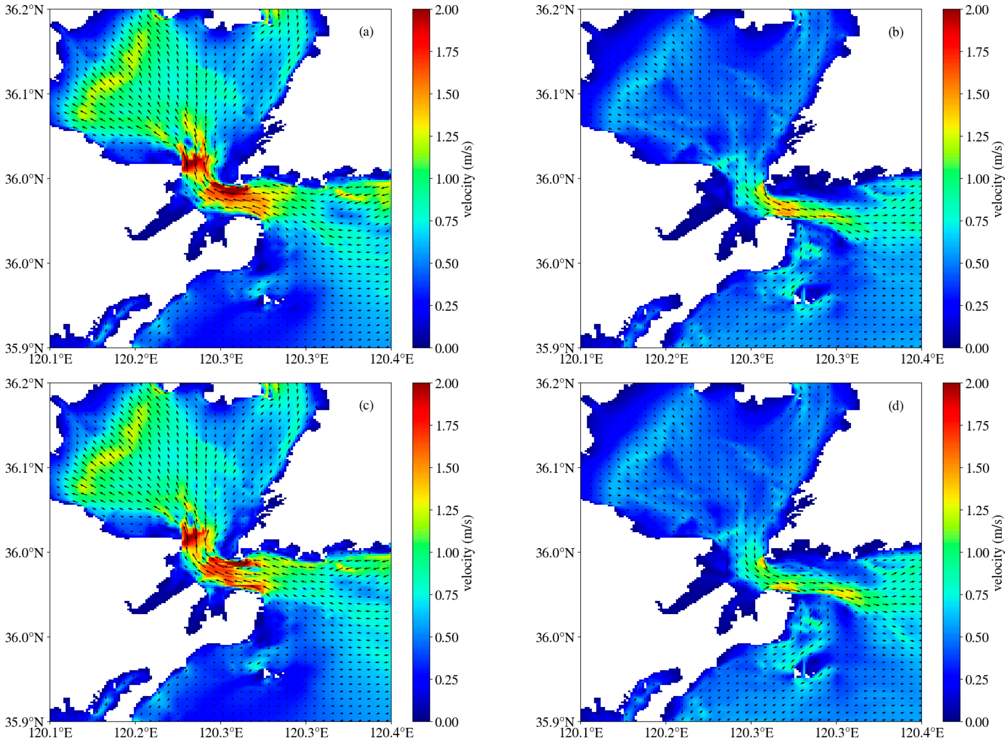

Figure 10. Flow field distribution with and without turbines during spring flood and ebb tides. (**a**) With turbines during flood tide, (**b**) with turbines during ebb tide, (**c**) without turbines during flood tide, (**d**) without turbines during ebb tide.

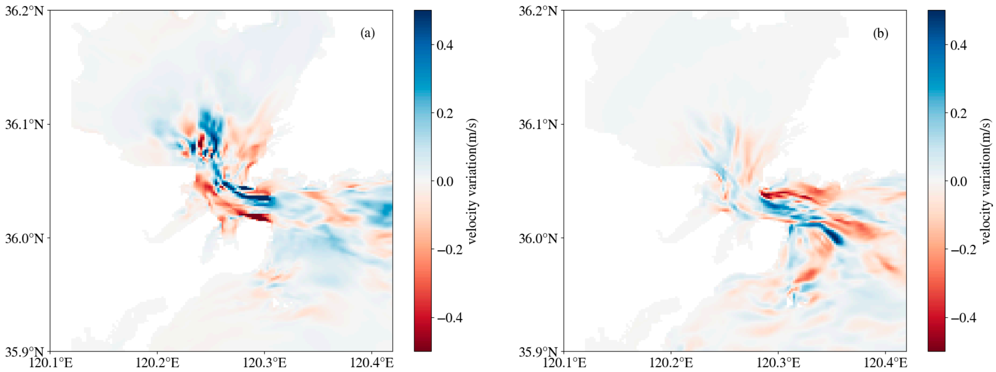

Figure 11. Distribution of vertical average flow velocity variation with and without turbines during (**a**) spring flood and (**b**) ebb.

It can be seen that in the tidal array field wake zone, the flow rate generally decreases, with the maximum reduction in flow velocity exceeding 0.5 m/s. Notably, the flow velocity decreased more significantly in the northern area of the channel during flood tide and in the southern area during ebb tide. In addition, the blocking effect due to tidal turbines accelerates the flow along either side of the channel. For example, at Tuandao Mouth during low tide and north of Xuejiadao during flood tide, the increase in velocity may reach 0.5 m/s, potentially increasing the risk of coastal erosion.

Figure 12 shows a time series of velocity changes at three sites over a 30-day tidal cycle at three depth layers. The results indicate that the flow velocity in the surface and middle layers is significantly affected, while the bottom layer experiences minimal impact. Additionally, the middle layer velocity decreased significantly while the surface velocity increased significantly at the turbine deployment position, and the surface velocity changed more obviously in both inner bay and offshore. Different from the tidal level changes, the phase shift occurs in most areas within 10 km near the turbine, with shifts reaching up to 0.5 h.

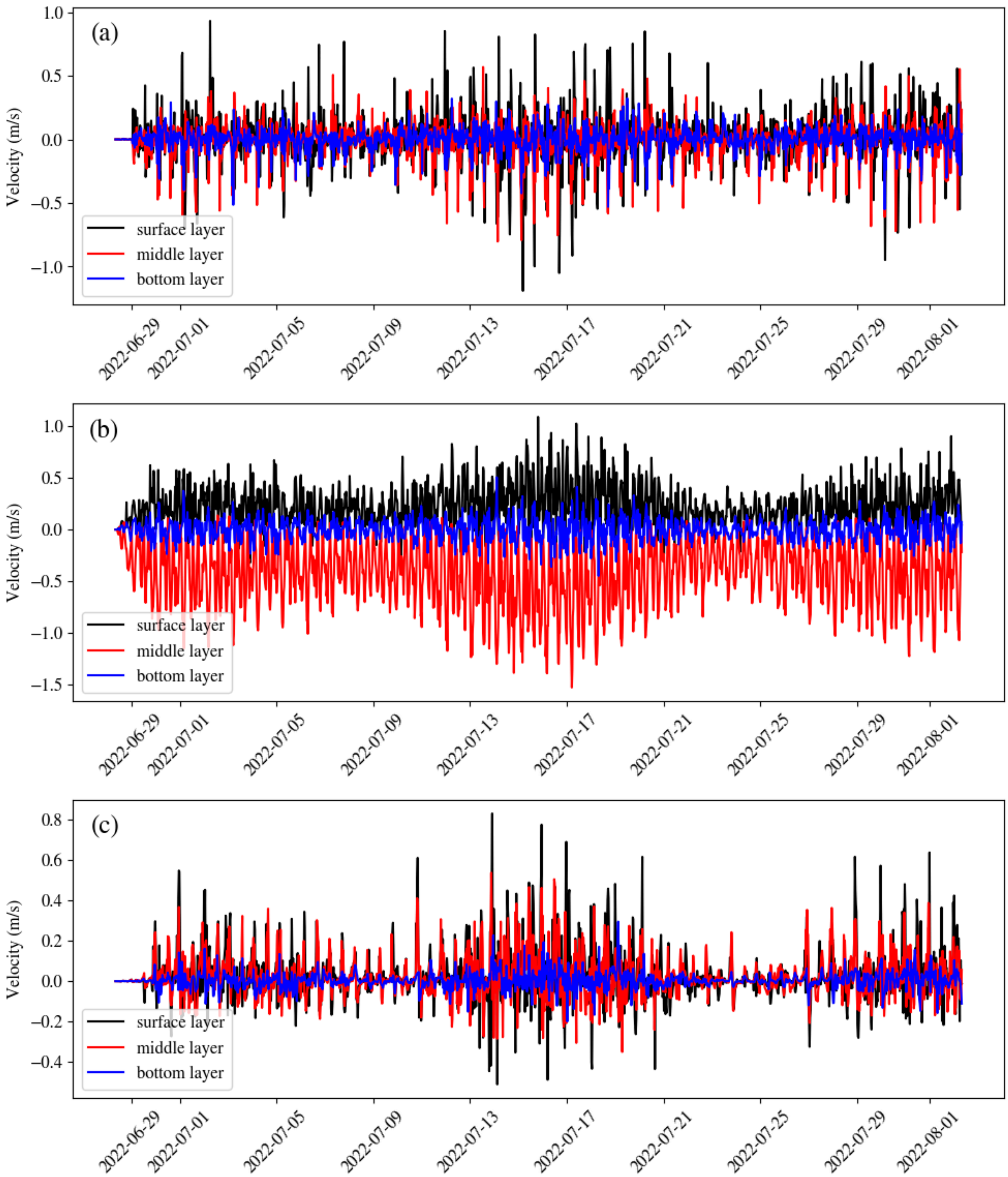

Figure 12. Flow velocity variations across different sigma layers: (**a**) inner bay, (**b**) outer bay, and (**c**) offshore.

3.2.3. Vertical Flow Profiles

Parallel to the main directions of flood and ebb tides, vertical profiles of flow velocities were plotted at a cross-section located at approximately 36.03° N (as shown in Figure 13). Without turbines, the distribution of flow velocities across 10 sigma layers appears generally similar, but slightly different in magnitude. In the cases where turbines were deployed, considering the turbine is deployed at a depth of 1/2 water depth, the kinetic energy of the middle water flow is transformed into electric energy, and the velocity is significantly reduced. Correspondingly, the velocity of the top layer, bottom layer, and both sides of the channel increases.

Although these findings are derived from simulations tailored to Jiaozhou Bay, they hold broader implications for tidal energy developments in semi-enclosed bays and other coastal regions around the world. Similar flow-blocking and wake effects may be observed in regions with comparable geomorphological constraints, such as the Bay of Fundy in Canada or the Severn Estuary in the United Kingdom. Thus, the modeling approach and key insights on tidal level shifts, velocity reductions, and potential erosion hotspots can provide a useful reference for site selection and environmental assessments in other locations.

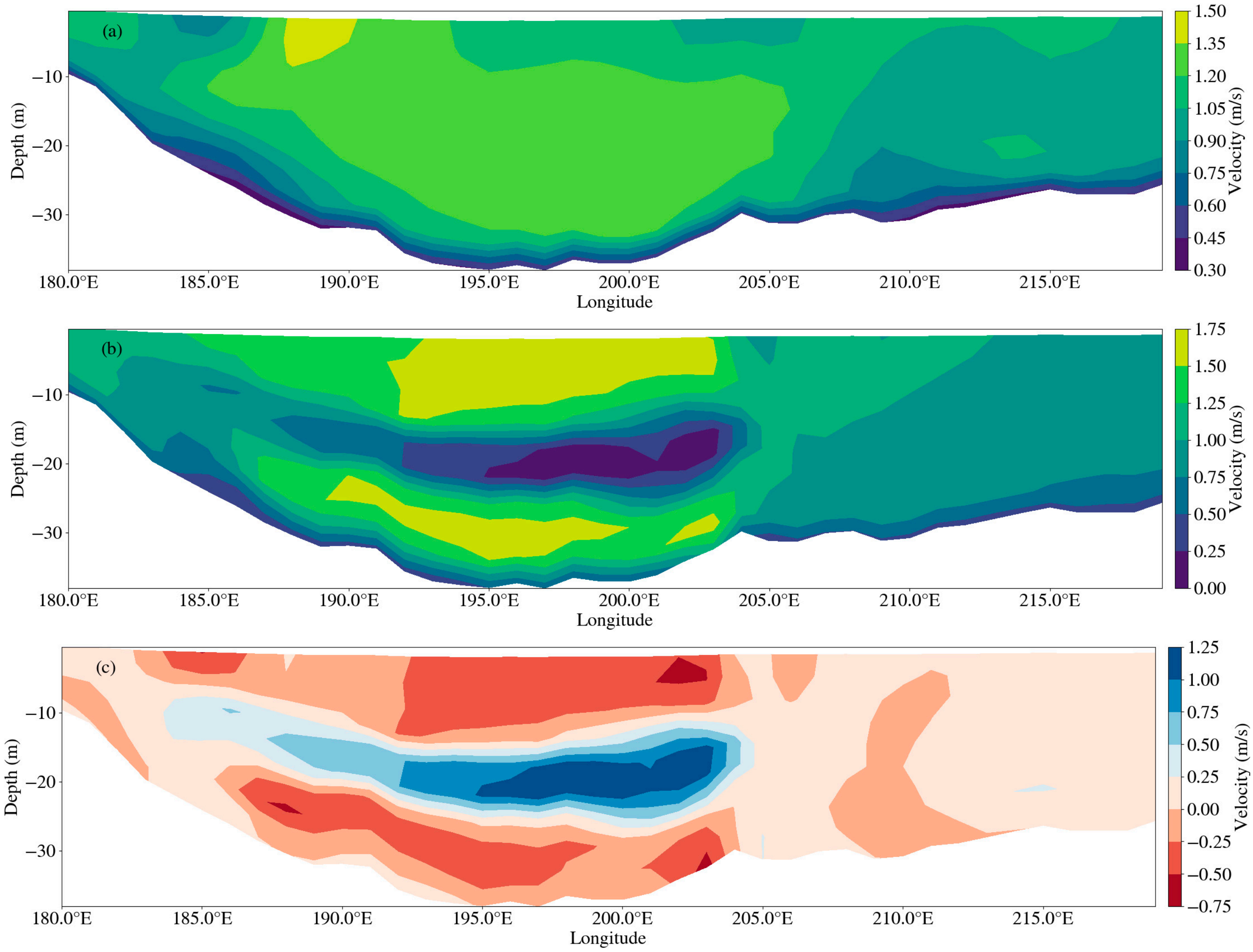

Figure 13. *Cont.*

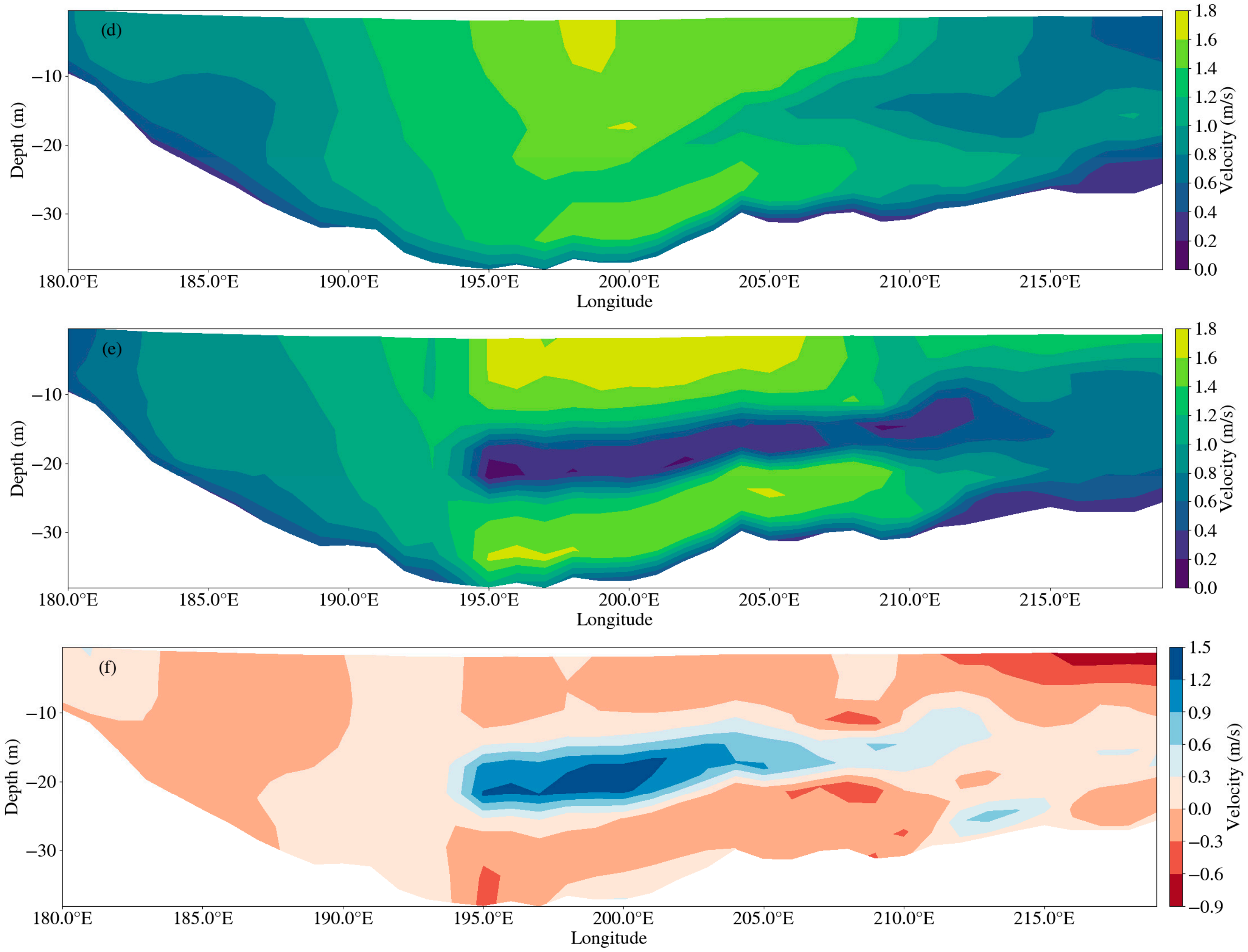

Figure 13. Vertical profile of flow velocities with and without turbines during (**a**–**c**) flood and (**d**–**f**) ebb tides.

It is also essential to recognize that substantial energy extraction comes with trade-offs, including altered flow regimes and heightened environmental risks. The flow acceleration around turbines and the potential for increased erosion demand careful monitoring and risk assessment. To mitigate adverse effects, strategies such as adaptive turbine array layouts, real-time control mechanisms, and ecological buffer zones may be employed. Continuous field measurements and ecological evaluations can further refine turbine placements, ensuring that the benefits of clean energy generation are balanced against ecological conservation and coastal resilience.

4. Limitations

Although this study may provide insights into the tidal dynamics and energy potential of Jiaozhou Bay, several limitations must be acknowledged. First, the model employed here is barotropic, thereby excluding baroclinic effects associated with temperature and salinity gradients. These stratification processes can influence current structures and energy estimates, particularly in regions with pronounced seasonal or spatial variability. Second, the simulations do not explicitly incorporate wind-driven currents, which can introduce additional flow variability and affect both the spatial distribution of tidal energy and the hydrodynamic response under extreme weather conditions. Third, this work does not include ecological assessments of large-scale turbine deployment. Potential impacts on benthic communities, nutrient cycling, and broader marine ecosystems require further exploration, particularly given the observed alterations in flow fields. Finally, the absence of direct experimental validation or field data for large-scale turbine arrays underscores another limitation. Given the relative novelty of such deployments and the scarcity of publicly accessible engineering data, reliance on numerical simulations remains substantial. Future research should therefore integrate baroclinic processes, wind forcing, and comprehensive ecological evaluations to better capture the multifaceted impacts of tidal energy development and refine both the accuracy and sustainability of site selection and turbine array design.

In addition, while this study primarily focuses on spring tides to capture the maximum hydrodynamic impacts and energy extraction potential of the tidal turbine array, we recognize the importance of analyzing average tidal conditions. Such an expanded analysis would offer a more comprehensive understanding of system performance under typical scenarios, providing valuable insights into the long-term operational efficiency and environmental implications of tidal turbine deployments. Therefore, future work will consider including average tides in the modeling framework, thereby further enhancing the robustness of tidal energy assessments.

5. Conclusions

This study developed a three-dimensional hydrodynamic model of Jiaozhou Bay using the ROMS to evaluate the environmental impacts of deploying a 100-turbine tidal energy array. The key conclusions are summarized as follows:

Tidal Energy Resource Assessment: The Tuandao–Xuejiadao channel was identified as the most promising site for tidal energy development, with mean flow velocities exceeding 1.8 m/s and peak power densities surpassing 6 kW/m^2; during spring tides. The TSE index further confirmed this location as optimal for turbine deployment.

Tidal Level Changes: Tidal level variations were predominantly localized within the inner bay, with a maximum change of approximately 10 cm and an average from 0.1 to 0.3 cm. The offshore region remained largely unaffected, suggesting that the turbines' influence on tidal levels is limited to the immediate vicinity.

Flow Field Impacts: The turbine array induced significant hydrodynamic changes, including velocity reductions up to 0.5 m/s in the wake zone and localized accelerations of a similar magnitude along the channel peripheries. Vertical flow redistribution was observed, with mid-layer velocities decreasing by over 50%, while surface and bottom velocities increased. These changes highlight potential risks of sediment resuspension and coastal erosion.

Localized Environmental Effects: The hydrodynamic impacts of the turbine array were confined to the deployment zone and nearby waters, demonstrating the potential to mitigate broader environmental impacts through strategic siting and design. However, further studies are needed to assess sediment dynamics, nutrient mixing, and ecological responses.

The findings of this study provide valuable insights into the feasibility and environmental impacts of deploying tidal turbine arrays in Jiaozhou Bay. The Tuandao–Xuejiadao channel, identified as the optimal site for turbine deployment due to its abundant resources and operational viability, showcases the promise of large-scale tidal energy extraction. However, the hydrodynamic changes induced by the turbine array underscore the importance of thoroughly evaluating environmental consequences.

The reduction in flow velocity within the turbine wake zone and the compensatory acceleration along the channel peripheries highlight the redistributive effects of turbine-induced momentum loss. While localized, these changes may trigger cascading effects on sediment transport, particularly in regions where bottom velocities increase significantly. Enhanced bottom shear stress could lead to sediment resuspension, potentially affecting water quality and benthic habitats. Conversely, reduced flow velocities in the wake zone may encourage sediment deposition, altering local geomorphology. Future studies should incorporate sediment dynamics into the hydrodynamic model to quantify these impacts more precisely.

Changes in tidal levels were predominantly confined to the inner bay, with minimal effects in offshore regions. Although the average tidal level variations were small (i.e., 0.1–0.3 cm), they could still affect intertidal ecosystems, particularly in shallow areas. While no significant phase shifts were observed, the localized nature of these changes aligns with findings from previous studies in similar semi-enclosed bays. Incorporating ecological models into future assessments could provide a holistic understanding of the ecosystem-level impacts of tidal energy development.

The observed vertical redistribution of flow velocities, characterized by mid-layer reductions and increases in the surface/bottom layer, has implications for both engineering and environmental considerations. From an engineering perspective, these findings emphasize the importance of turbine placement within the water column to optimize energy extraction while minimizing adverse effects. Environmentally, the enhanced surface and bottom velocities could influence nutrient mixing and larval dispersal, warranting further investigation.

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