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Numerical assessments of ocean energy extraction from western boundary currents using a quasi-geostrophic ocean circulation model

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ABSTRACT

A single-layer, quasi-geostrophic (QG), large-scale ocean circulation model is developed in this paper to study available ocean current energy potentials harnessed by using the ocean current turbines. Power extraction is modeled by adding a parameterized Rayleigh friction term in the barotropic vorticity equation. Numerical assessments are performed by simulating a set of mid-latitude ocean basins in the beta plane, which are standard prototypes of more realistic ocean dynamics considering inter-decadal variability in turbulent equilibrium. The third-order Runge–Kutta scheme for the temporal discretization and the second-order conservative Arakawa scheme for the spatial discretization are utilized to perform Munk scale resolving high-resolution computations. A sensitivity analysis with respect to the turbine parameters is performed for various physical conditions. Results show that the proposed model captures the quasi-stationary ocean dynamics and provides the four-gyre circulation patterns in time mean. After an initial spin-up process, the proposed model reaches a statistically steady state at an average maximum speed between 1.5 m/s and 2.5 m/s, which is close to the observed maximum zonal velocities in the western boundary currents. The probability density function of the available power over a long time period is computed for a wide range of parameters. Numerical results shows that 10 GW mean power can be extracted from the turbines distributed over a length scale of 100 km along the western boundaries. However, it is demonstrated that bigger turbine areas would alter the flow patterns and energetics due to excessive dissipation. An increase in the turbine area results in an increase in the available power ranging from 8 to 22 GW depending on the values of turbine modeling parameters. This first step in the numerical assessment of the proposed QG model shows that the present framework could represent a viable tool for evaluating energy potentials in a highly turbulent flow regime.

1. Introduction

There is a growing interest in harvesting energy from the oceans. The huge energy potential of moving water in the forms of heat, strong currents, waves and tides has recently attracted a great deal of attention due to increasing demand in alternative renewable energy systems [1–9]. Although the biophysical and environmental impacts are under investigation [10], it is conjectured that the oceans could turn out to be an even more benign clean source of power than wind [11]. Among the other forms, as discussed by Yang et al. [12], strong ocean currents are rich in storing hydrokinetic energy since sea water is

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about 800 times denser than air. Since the power is proportional to the fluid density and the cube of the flow velocity, ocean currents of about 1/9 the speed of the wind have comparable kinetic power density with wind. It is anticipated that, with its gathering speed, more than 7% of the worldwide energy production will be harnessed from the oceans by 2050 [5].

The main drivers of ocean circulation are the Earth's rotation and atmospheric winds. The ocean circulation is characterized by large circulation zones, or gyres, which can be identified with the strong, persistent, sub-tropical and sub-polar western boundary currents such as the Gulf Stream [13,14]. Generally, the circulation is clockwise (CW) in the Northern Hemisphere and counter-clockwise (CCW) in the Southern Hemisphere. These circulation patterns emerge when we average over several years. One of the major similarities between the various ocean basins is the strong western boundary currents and weaker flow in the interior and eastern boundaries. Due to its reliability, persistency and stainability, the Gulf Stream ocean current system, carrying billions of gallons of water per minute, is of paramount interest as a potential clean energy resource for Florida and other coastal states.

The process of hydrokinetic energy conversion due to the underwater turbine systems implies utilization of kinetic energy contained in strong streams and currents for the generation of electricity [15]. A variety of ocean current energy turbines (OCTs) are currently being proposed and have been tested [11]. Global energy potentials of ocean currents using turbines have also been identified by VanZwieten et al. [16] discussing eight potential locations where ocean current energy could be potentially viable. One of early studies indicated that 10 GB power could be extracted from the Gulf Stream [17,18]. Von Arx et al. [19] conservatively estimated that the distributed turbine arrays in Florida current can supply 1 GW power without seriously disturbing climate conditions. Interest has grown increasingly over the last few years. An assessment of available ocean current hydrokinetic energy near the North Carolina shore has been performed by Kabir et al. [20]. Assessments of the Kurushio current were also discussed by Chen [21]. In a recent work by Duerr and Dhanak [22,23], it is predicted that an amount of 20–25 GW power can be extracted from Gulf Stream system. Yang et al. [24] provided a theoretical framework to assess available potential of energy from ocean circulations by using a simplified ocean circulation model, known as the Stommel model [25,26]. Their framework have also been utilized in a more realistic general ocean circulation model [27]. As further explained in [28], this approach utilizes a two-dimensional idealized ocean circulation model and represents the presence of turbines as linearized drag force in the form of Rayleigh friction and predicts an average amount of 5 GW available power from the Gulf Stream system corresponding an average of approximately 44 TWh/yr.

Following similar parametrization for representing localized turbines [28], the objective of the present work is to study the potential available energy from the western boundary currents using a single layer (two-dimensional), wind-driven, double-gyre, mid-latitude, beta-plane quasi-geostrophic (QG) ocean circulation model. Capturing the inter-annual and inter-decade variability in large-scale ocean basins, this model utilizes the unsteady baratropic vorticity equation. The barotropic vorticity equation (BVE), also known as the single-layer QG model, is one of the most used mathematical models for forced-dissipative large scale ocean circulation problem (i.e., see [29–39]). Here, the author works in a regime in which the model reaches a state of turbulent equilibrium driven by a double-gyre wind forcing. The time mean circulation patterns are characterized by a four-gyre structure (i.e., southern outer, subtropical, subpolar, and northern outer gyres) when the barotropic vorticity equation is considered under the double-gyre wind forcing in a highly turbulent regime [34,40,41]. The two inner gyres circulate in the same directions as the wind stress curl, while two outer gyres at the northern and southern boundaries of the basin circulate in the opposite direction.

Studies of wind-driven circulation using a double-gyre wind forcing have played an important role in understanding various aspects of ocean dynamics, including the role of meso-scale eddies and their effect on the mean circulation, energy transfer, and seasonal and inter-annual oscillations [42]. When the barotropic vorticity equation is forced by a double-gyre wind stress and the explicit dissipation mechanism is weak, the instantaneous flow is highly turbulent showing a four-gyre structure in the time mean [35]. In this setting the explicit mechanism plays a minor role and the dominant balance is between the wind forcing and eddy flux of potential vorticity (e.g., see [40]). Therefore, the utilized flow setting represents an ideal framework to study the effects of additional turbines to circulation patterns in an unsteady regime. By means of a set of numerical simulations for various ocean basins considering inter-decade variability, this paper investigates the effects of added turbines in the dynamics of circulation zones and energetics of the oceans and computes probability density function of available power in each case. It will be investigated numerically whether the QG model can reproduce the four-gyre flow pattern in the time average when turbines are included by a functional friction term controlling the approximate area of turbine region. Although the present approach does not consider some important factors such as bathymetry, tides and actual wind patters, it extends the study of Stomel's model [28] to a single-layer QG model with the unsteady barotropic vorticity equation.

The remainder of this paper is organized as follows. Section 2 presents governing equations for the quasi-geostrophic ocean model utilized in our assessments. Section 3 contains a brief description of numerical methods including the second-order energy conserving Arakawa scheme for the nonlinear interaction, and the third-order Runge Kutta scheme for the time integration. The results of carefully selected numerical experiments are provided in Section 4 using a huge set of physical and numerical parameters. Section 5 is devoted to conclusions.

2. Quasigeostrophic ocean model

Studies of wind-driven circulation using an idealized double-gyre wind forcing have played an important role in understanding various aspects of ocean dynamics, including the role of mesoscale eddies and their effect on mean circulation. In