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Current power potential of a sea strait: The Bosphorus

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The annual current energy potential of a sea strait, Bosphorus in Turkey, is evaluated by the calibrated and validated three dimensional numerical model results. The numerical approach is based on a number of unstructured flexible meshes (triangle or quadrilateral elements) and uses a cell-centered finite volume solution technique. Three-dimensional incompressible Reynolds averaged Navier-Stokes equations are solved invoking the assumptions of Boussinesq and hydrostatic pressure. The turbulence closure was implemented by using Smagorinsky and k-ε models in the horizontal and vertical domains, respectively. Water level and density differences acting on the model open boundaries combined with the meteorological structure of the region (wind speed, direction and atmospheric pressure difference) are the main forcing mechanisms of the numerical model as inputs. The strait flow is a typical example of a stratified flow among the world's straits, with a possible exception of having a negligible tidal oscillation. The results show that the complex geometry (both horizontally and vertically) of the strait combined with highly variable hydrological and meteorological conditions of the adjacent seas, the Marmara Sea and Black Sea, result in a considerable fluctuation in the kinetic energy potential. Cross-sectional variability of the kinetic energy is also notable both horizontally and vertically with increasing energy upwards and towards the shore. In spatial domain, although it is not the narrowest part of the strait, the highest kinetic energies are calculated at the southernmost part of the strait due to both a decrease in cross-sectional area and the presence of a sill on the bottom, a geometrical feature likely seen in straits that mainly control the flow structure (e.g., flow velocities). For a given cross section taken from a meandering part of the strait, the kinetic energy of the strait is higher at the outer and inner banks of the strait for the upper and lower layer flows, respectively. In time scale, the most energetic time period spans from the late spring to the end of summer related to the increase in water level difference between both ends of the strait due to long-term effects that represent seasonal variations (mainly the river inflows toward the Black Sea) and short-term effects (southward storms in the same direction with the upper layer flow). In winter, however, due to the southerly storms acting opposite to the surface layer flow, the kinetic energy potential of the strait drops to considerably low values occasionally.

1. Introduction

Interest in alternative renewable energy resources has grown recently due to increasing energy consumption and depleting reserves of fossil fuels. In recognition of the pollution associated with generation from fossil fuels, many countries have pledged their commitment to reduce greenhouse gas emissions. Renewable sources of energy, including tidal stream and ocean current energy, are among the possible alternatives for reducing these emissions. Ocean currents, which are mainly induced by tide, wind and Coriolis forcing, have been shown before to be an alternative source of clean energy due to their inherent reliability, persistence and sustainability [4,13,25,33]. The other major components of the oceanic potential energy are wave energy, ocean thermal energy conversion (OTEC) power, and salinity gradient power [6,18]. Tidal turbine is widely accepted as a cost effective method to harness ocean energy compared to wave energy, OTEC power, and salinity gradient power. Exploiting ocean tides for energy production is usually discussed in terms of closing off a bay and generating electricity through the release of water trapped at high tide [2,24]. Having the density about 850 times that of air, a marine turbine in an ocean current may produce as much power as a wind turbine although the current speeds are generally much lower than the wind speeds

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[29]. Considerably high drag on an ocean current device due to the higher water density is also a factor that increases forces acting on the turbine compared to a wind turbine. Thus, ocean currents represent a potentially significant, currently untapped, reservoir of energy [19,30]. The regions with strong currents such as narrow straits, between islands and around headlands exhibit high current power potential, especially at relatively shallow areas with a large tidal range [8]. The resource assessment should be undertaken to determine the technical feasibility of installing marine turbines for power extraction, considering both the technology specific factors such as operational depth, generator operating range, array configuration and spacing, and the external factors that can impact the depth, location and available resource such as shipping routes, commercial fishing activities and marine protected areas [17].

Two-layer exchange generally occurs as two water bodies of different densities are separated by a constriction. Sea straits (i.e., the Gibraltar, the Bal-el Mandab, and the Bosphorus) are the common examples for exchange flows. Various forcing mechanisms control the circulation in different major sea straits around the world. For example, the predominant mechanism is evaporation-induced pressure gradients in the Mediterranean and Middle East Straits, e.g., the Bab El Mandeb, Hormus, Tiran, Gibralter [3], the inertial effect of the Gulf Stream is dominant in the Florida Strait [15], the meridional sea level difference between the subtropical and subpolar gyres drive inflow through the Korea Strait and the outflow through the Tsugaru and Soya straits [5,16], and the large scale meteorological forcing plays a role in the Strait of Belle Isle [10]. The lengths of the straits around the world vary from a couple of ten kilometers (e.g., the Bosphorus with around 30 km or the Gibraltar with 60 km) to a few hundred kilometers (e.g., the Bab El Mandeb with 160 km, the Denmark Strait with 500 km). The importance of inertia to friction in a strait is often defined by the dynamic length (as a function of length, depth and bottom friction of the strait) [36]. With this regard, the straits have been classified into three groups: short channel (e.g., Burlington Ship Canal), long channel (e.g., the Bab el Mandeb) and marginal channel (e.g., the Bosphorus, the Denmark Strait). While bottom friction can be ignored compared to inertia in the first type of channels, it is the opposite in a long channel case. In marginal channels, however, both friction and inertia are significant on the current structure in the strait. Consequently, the hydrological conditions (precipitation, evaporation and river runoff), wind stress and density differences (salinity and temperature differences) of adjacent seas combined to geometrical features (length, width, depth and bottom friction etc.) of the waterway dominantly determine the hydrodynamic structure of the sea strait flow. The regions with a significant variation on the bottom topography (such as sills) are the potentially highest current areas. In this regard, previous studies investigating the feasibility of generating electricity from the streams using marine current turbines, indicate the necessity of using well-conducted 3-D numerical models which enable to simulate spatial variations in the current pattern caused by complicated morphology of the strait (e.g., [34]). A further investigation evaluating the energy potential of a strait flow is warranted.

The present study aims at evaluating the energy potential of a sea strait (the Bosphorus) in light of three-dimensional numerical model results supported by a detailed 3-D bathymetric map allowing for modeling the impact of the complex geometry and bottom topography. Regions with a high energy potential along the strait are identified based on the model results. Both yearly and monthly averages of energy potential are estimated at different energetic cross-sections. Vertical structures of the kinetic energy flux at these sections are also investigated over the year.

2. Study area

The Bosphorus (Fig. 1) is part of the Turkish Strait System with Dardanelles. It is a typical example of an exchange flow through which the exchange occurs between the denser Sea of Marmara (38 psu) and the Black Sea (18 psu) [22,23]. The strait is long and narrow with a length of 31 km and a width varying from 0.7 to 3.5 km, with an average of 1.3 km. The water depth along the main channel varies between 30 and 110 m. At each end, there are sills that largely affect the current characteristics in the strait. The one close to the southern entrance lies between 28 and 35 m depths and causes channel flows at each side of the sill (Fig. 1 bottom panel). The north sill is at a depth of 60 m in the north of the Black Sea entrance and extends like a narrow channel (Fig. 1 bottom panel). The stratified flow structure in the strait is predominantly controlled by the density and the water level differences between the Marmara Sea and the Black Sea. The sum of the runoff and precipitation into the Black Sea is greater than the water loss because of evaporation. The water excess is balanced by an outflow through the Bosphorus (e.g., [21,31]). Generally, the Black Sea has a higher water level than that of the Marmara Sea [35]. reported a variation between −0.20 and +0.60 m, where the positive sign indicates higher Black Sea level than the Marmara Sea. However, due to storm surge created by southerly storms, the water level at the southern entrance of the strait may get higher occasionally. Monthly average of the water level difference between the Black Sea and the Marmara Sea indicates that the largest differences take place in May and June (Fig. 2).

Four main components contribute to the difference in water level: wind set up, meteorological atmospheric pressure, tide, and long-term hydrological changes (river discharges). The first three factors are short-term effects while the last one is a long-term effect that represents seasonal variations [35]. Unlike many straits, the tidal forcing is negligible in the Bosphorus with a maximum amplitude of around 3 cm. The fluctuations in the water level difference caused by long-term effects are more stable (or less variable) than those caused by short-term effects. According to [35]; based on 15 months of current analysis in the Bosphorus, the short-term changes primarily occur between October and April, which result in an unstable current structure, likely associated with extreme weather conditions such as storms. Northerly (blowing from the north) or southerly winds sometimes increase sea levels at the both entrances high enough such that one-layered flow pattern dominates the whole strait in both direction [12,35]. For the rest of the year, however, from April to October, the long-term effects due to fresh water discharges from the rivers (Danube, Dnieper, and Dniester) into the Black Sea from the north drive the current structure of the Bosphorus.

Current pattern of the Bosphorus generally presents a stratified two layer system, with the upper-layer current flowing south toward the Marmara Sea and the underlying current flowing north toward the Black Sea. The thicknesses and velocities of both layers within the entire depth display noticeable changes over time. These overall flow directions exhibit differences arising from the shape of the strait and changes in the sectional areas. During relatively calm periods of the year in terms of meteorological effects (between April and October), the strait flow is characterized by a more stable and less fluctuating nature.

Because the evaporation of the Mediterranean, including the Sea of Marmara, is greater than that of the Black Sea, a density variation caused mainly by salinity difference occurs between these two seas. This is the main mechanism for the northward lower layer flow. Because salinities of the adjacent seas are less fluctuating over a one-year period, the lower layer flow is more stable than that of the upper one [20].

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