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ABOUT THE INFLUENCE OF DENSITY-INDUCED FLOW ON TIDAL STREAM POWER GENERATION IN THE SUNDA STRAIT, INDONESIA

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ABSTRACT

In this paper, the results of a numerical model study evaluating the influence of density-induced flow on tidal stream power generation in the Sunda Strait, Indonesia are summarized. Tidal stream currents with speeds reaching about 2-3m/s and total extractable power of around 300MW turn the Sunda Strait into a promising location for renewable electricity production from the ocean. Furthermore, seasonally varying share of the density currents on the energy flux through the Sunda Strait emphasize the importance of a more comprehensive modelling approach for the selection and evaluation of the deployment sites of tidal turbines. A high-resolution, three-dimensional circulation model providing sufficient spatiotemporal coverage has been developed to simulate tidal currents in barotropic and baroclinic modes. Simulation outputs have been used to reveal the influence of density-induced flow on tidal stream power generation during both northwest and southeast monsoonal seasons. Up to 100% increase in current speeds has been simulated in the strait due to the density gradients, which leads to an enormous increase of the kinetic power. Additionally, energy hotspot shows significant changes due to the variations in density. Energetic section of the strait becomes significantly larger with an overall increase of the kinetic power densities. The findings may help us to understand the importance of including the ocean water density to resolve flow fields with better precision, which can lead to more accurate assessment and more efficient use of the resources of marine renewable energy.

Keywords: renewable energy; tidal stream current; density-induced flow; numerical model; Indonesia

1 INTRODUCTION

Humankind is drifting deeper into global economic, environmental, geopolitical and societal problems every day. Environmental risks such as failure of climate change mitigation and adaptation, extreme weather events, natural disasters, biodiversity loss and ecosystem collapse are intensifying alongside societal risks like water and food crises together with economic risks like energy price shock (WEF, 2019). Storms, forest fires, droughts, coral bleaching, heatwaves and floods, which we already experience due to the global warming, are likely to get significantly worse in the upcoming decades, and impacts are expected to be felt across ecosystems, human communities and economies (IPCC, 2018). To mitigate further damage requires a quick and strengthened global response, which involves greater policy design and decision-making regarding energy system transitions and universal access to renewable electricity. Meanwhile, ocean energy remains a largely untapped renewable energy source (REN21, 2018).

Horizontal axis tidal turbines are closest to technological maturity among other ocean renewable energy (ORE) technologies (TRL 8), and they have reached a pre-commercial state. In 2017, tidal stream power production achieved a net capacity addition of 17MW, mainly from the tidal turbine arrays deployed in Scotland. However, the tidal sector is still in a critical phase of development, where demonstration farms are needed for systems to be proven in the actual operational environment (Magagna et al., 2016; REN21, 2018). Thus, a clear focus on prioritizing deployment is required.

Concerning the identification of suitable areas for tidal turbine deployment and optimization of tidal energy farms, it is of utmost importance to define flow patterns with precision as well as to understand hydrodynamics within the areas of interest before and after the deployment. In recent years, computational models to evaluate the energy potential of tidal currents have been developed for many regions of the world. However, often for the sake of simplicity and because only tidal currents were of interest, density gradients due to horizontal salinity or temperature variations were neglected in simulations. In reality, patterns of tidal currents and currents resulting from density differences add to complex flow structures. The “tide-only” approach might be highly misleading for domains such as Sunda Strait in Indonesia (Kamphuis, 2010; Uihlein & Magagna, 2016).

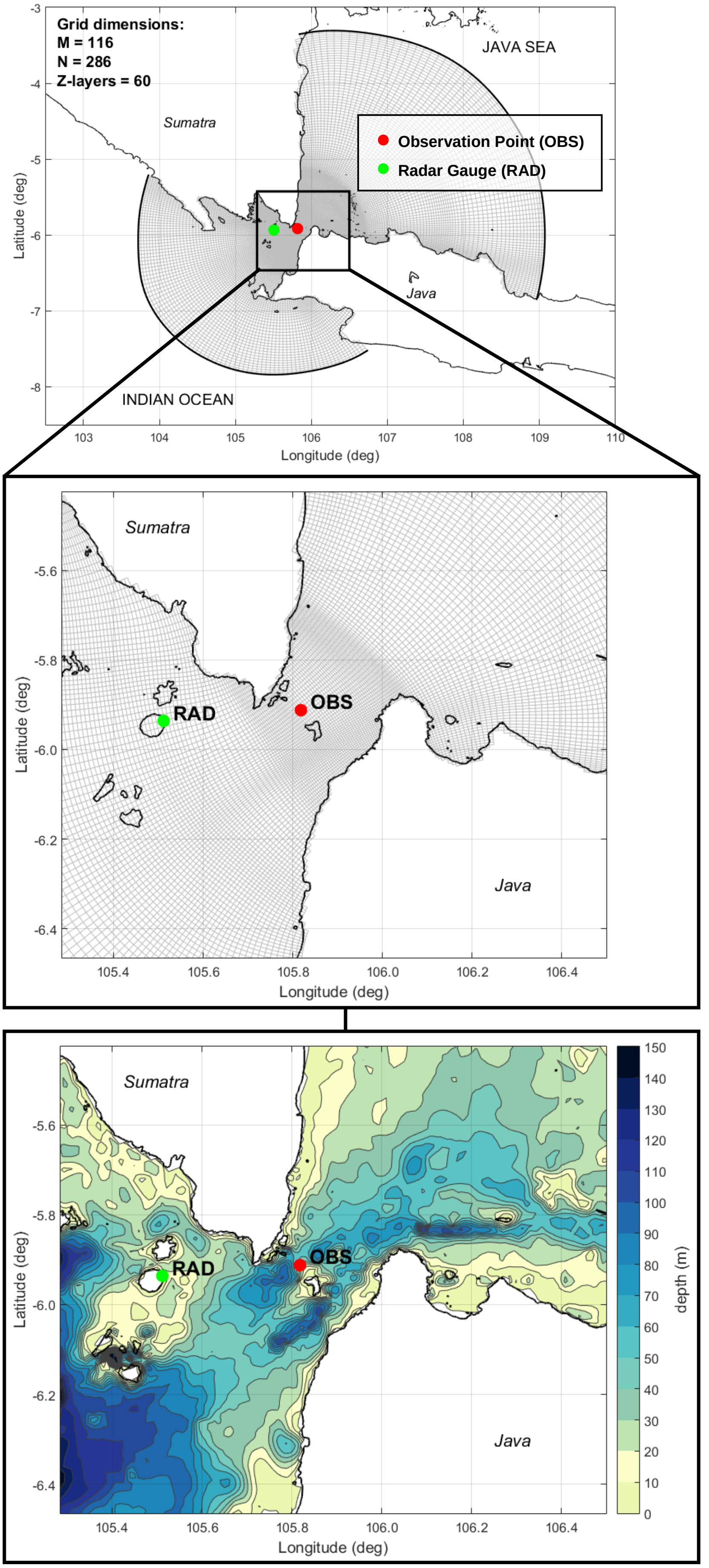

Figure 1. Computational grid and bathymetry of the Sunda Strait circulation model.

The Sunda Strait, located between the Sumatra and Java Islands, connects the Java Sea and Indian Ocean (Figure 1). The Strait has a width of 24km in its bottleneck. It exhibits a large slope with 18km width and 35m depth near the Java Sea along with 50km width and 500m depth near the Indian Ocean (Putri, 2005). The tidal range is mostly around 1m in the strait, and current velocities are exceeding 3m/s during peak periods. Meanwhile, flow conditions in the Sunda Strait are strongly affected by the regional excess of freshwater entering into Pacific waters through the Sunda Shelf as well as the monsoon and other sea-air-land interactions such as El Niño and Dipole Mode Event (Gordon, 2005; Putri, 2005; Mayer et al., 2012).

Previously, within the framework of the joint research project “Potentials of Ocean Renewable Energy in the Indonesian Seas (ORE-12)” funded by the German Ministry of Education and Research, tidal stream resources of several promising straits between the Indian Ocean and inner Indonesian seas, involving Sunda Strait, have been investigated (Orhan et al., 2016; Orhan & Mayerle, 2017). Orhan et al. (2016) provided an overview regarding the energy potential of tidal stream currents within the straits in question, utilizing state-of-the-art measurements and high-resolution, 3D flow models. The total extractable power from the Sunda Strait was calculated as 300MW based on a variation of the “per-generator” method (Blunden et al., 2013). The extracted energy was calculated from the flow fields in their natural states, considering the size and performance of the devices and packing density within the energy hotspot. The wake effects of turbines were ignored, avoided by setting the spacing among generators to minimize the interferences. Orhan and Mayerle (2017) studied the possible impacts of the tidal turbines on the flow conditions in the Strait of Larantuka, located in the eastern part of the Indonesian archipelago. Research regarding the hydrodynamic impacts and the performance of a commercial-scale tidal farm is currently underway.

This paper summarizes the results of a modelling experiment showing the influence of density-induced flow on tidal stream power potential of the Sunda Strait. Considering the stratified nature of the strait’s flow structure and higher hydrokinetic power densities observed closer to its free surface, emphasis in this paper is put on surface currents. The effect of the density currents has been evaluated throughout the year and a close look is given to the changes occurring during the northwest and southeast monsoon seasons of the region. Seasonal changes of the density gradients and their influence on current speeds and kinetic power densities (temporal & spatial) are demonstrated.

2 METHODOLOGY AND APPLICATION

Currents are computed with the Delft3D, a numerical integrated flow and transport modelling system developed by Deltares, the Netherlands (Delft Hydraulics, 2006). The 3D finite element model was adapted with a z-layer grid. Z-layers, fixed in the vertical direction, are preferred in the model for the accuracy of the vertical distribution of salinity and temperature (Cornelissen, 2004). Grids with various resolutions both in the horizontal and in the vertical have been tried to provide the highest resolution with acceptable run time. The selected grid is constructed with a resolution up to 500m in horizontal (at the bottleneck), and 10m in vertical (near the free surface). Thus, hydrodynamic conditions are resolved in sufficient detail around the Sunda Strait, and also density gradients within the model domain can be captured, which show significant changes mainly in the upper 400m (Gordon, 2005; Mayer et al., 2012). To reduce the computational costs, the mesh size of the model is gradually increased towards the open sea boundaries in the horizontal plane, and towards the seabed in vertical. Computational grid and bathymetry of the model are illustrated in Figure 1. For the simulations, three different time frames were chosen. To understand the annual trends and seasonal changes, and to represent the cycles of the main forcing components (water level & density), the model was run throughout the year 2012 (Ozturk et al., 2017). Afterwards, to have a more temporally detailed look at the regional hydrodynamics during dry and wet seasons, the model was run throughout the July 2012 and February 2012, respectively. For temporal discretization, a time step of 3s was described, corresponding to the maximum Courant-Friedrichs-Lewis criterion of 0.8 (Ozturk et al., 2017). The model has been forced by the tide only (barotropic mode with constant water density, 1029kg/m^3) and by tide combined with the density gradients to include the density-induced flow (baroclinic mode). Meteorological forcing was involved in both scenarios. Model grid (Figure 1, top) was extended into the Java Sea in the north, and into the Indian Ocean in the south to capture the impacts from both systems. Model bathymetry has been obtained from SRTM15_PLUS, data fusion of global seafloor topography from satellite altimetry and ship depth soundings (Olson et al., 2014). Much attention has been given to the meteorological forcing and conditions at the open sea boundaries to adequately capture the density gradients and flow fields along the strait. Tidal forcing is extracted from TPXO Indian Ocean Atlas (1/12° regional model) and prescribed as time series (Egbert & Erofeeva, 2002). 11 harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) are considered in this study. Data to determine the salinity and the temperature at the open sea boundaries are supplied from HAMSOM, the Hamburg Shelf Ocean Model, which is a 3D free surface baroclinic hydrodynamic model developed in the Institute of Oceanography at the University of Hamburg (Mayer et al., 2010). Data from Global Forecast System of NOAA’s National Climatic Data Center have been used as meteorological input (Environmental Modeling Center, 2003). Thus, effects of air cloudiness, air temperature, atmospheric pressure, relative air humidity and wind (in E and N directions) have been considered in simulations. To specify the exchange of heat through the free surface, ocean heat flux module of Delft3D is activated, which typically applies to large water bodies (Lane, 1989). Due to its significant advantages in resolving stratified flows, k-ε model, which is a second-order turbulence closure scheme, is selected to include the effects of the turbulent kinetic energy and turbulent kinetic energy dissipation (Burchard and Baumert, 1995; Postma et al., 1999).

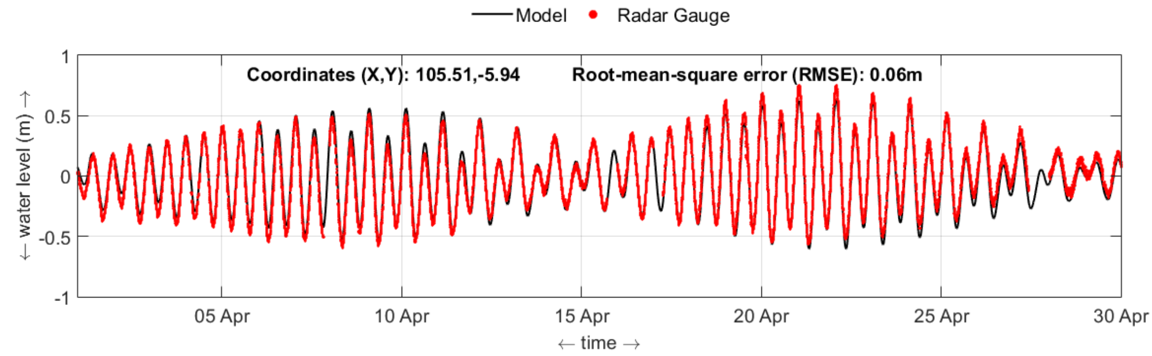

Figure 2. Comparison of modelled and measured tidal water levels at the radar gauge location.

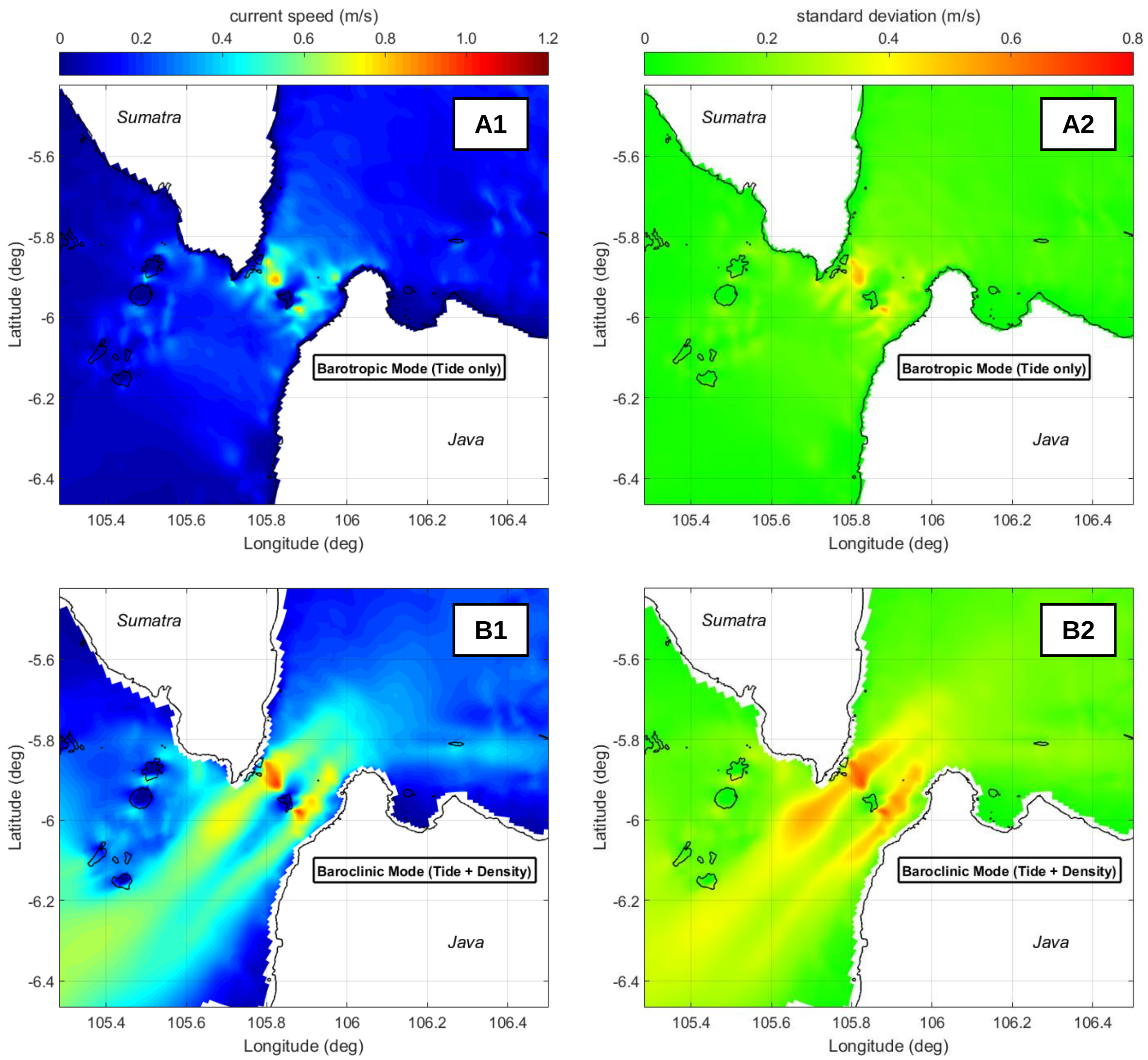

Figure 3. Simulated annual mean current speeds and their standard deviations for barotropic (A1, A2) and baroclinic (B1, B2) model runs.

Model verification using tidal records shows a strong positive linear correlation between the modelled and the measured values (Figure 2). Location of the operational radar gauge is indicated in figure 1 (the point RAD with green colour), and figure 2 shows the comparison of the modelled values and the values measured by the indicated device, from 1st to 30th of the April 2019. The agreement between modelled and measured values was tested with the RMSE method. The RMSE value was resulted in equal to 0.06m, which indicates a good agreement.

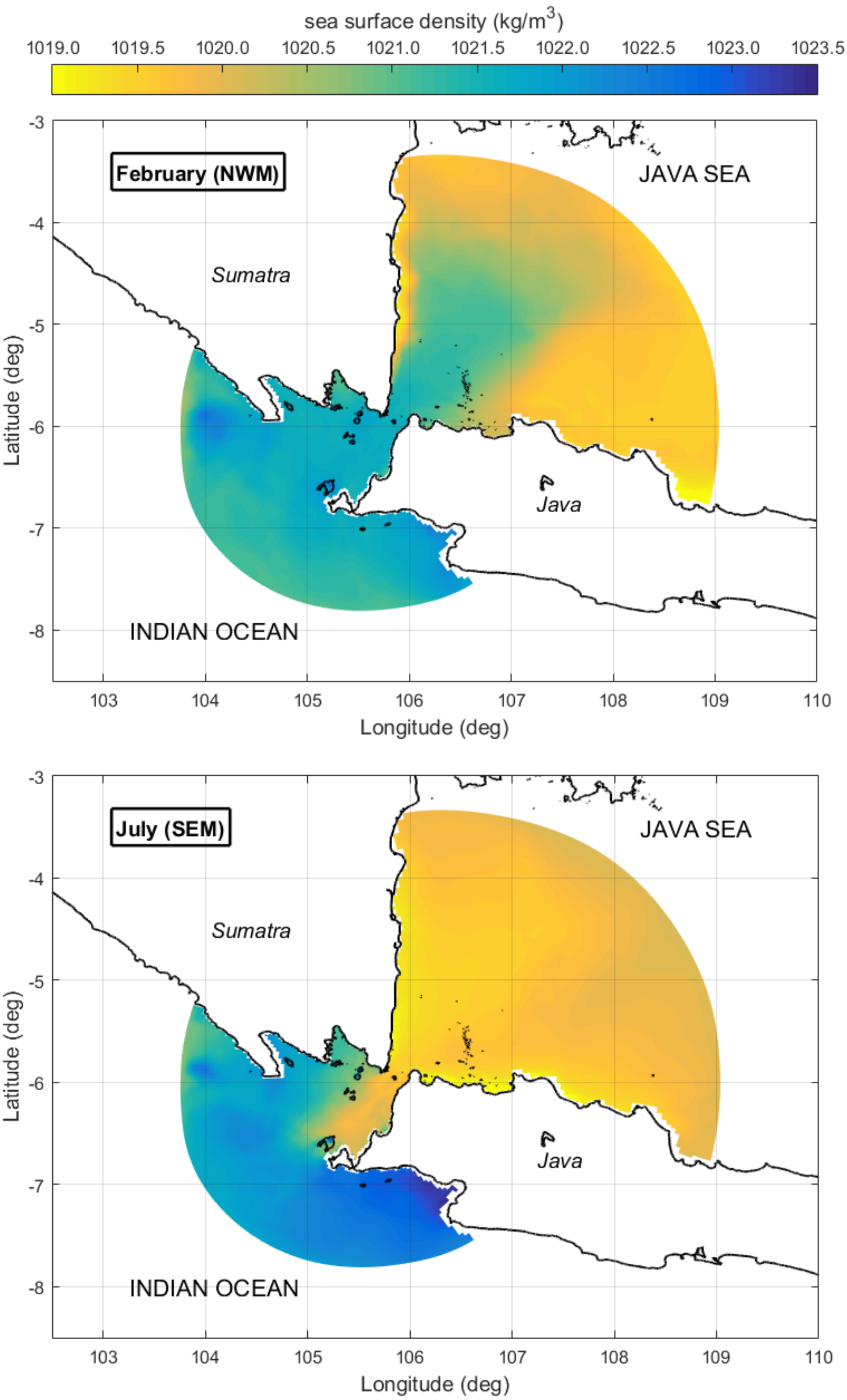

Figure 4. Spatial variation of the monthly mean sea surface density during February 2012/NWM (top) and July 2012/SEM (bottom).

3 RESULTS

3.1 Seasonal changes in flow conditions

Mainly dominated by the M2 lunar semidiurnal constituent governed by the Indian Ocean and K1 lunar diurnal constituent governed by the Pacific Ocean, phase or amplitude of the tidal water level elevations don't change much in the region throughout the year (Ray et al. 2005). Figure 3, top and bottom panels (A1-A2, B1-B2), illustrate the spatial distribution of the annual mean tidal current speeds at the free surface and their standard deviations, based on the simulation results in barotropic and baroclinic modes. As it can be easily noticed, although tidal water level elevations do not show much seasonal variation, under the influence of the density-induced flow, important changes occur in the characteristics of the tidal currents. It can be seen that the baroclinic tidal currents are much stronger compared to the barotropic tidal currents. In baroclinic mode, the energetic section of the strait becomes significantly larger with higher standard deviations.

The Java Sea is highly influenced by the semi-annual reversing monsoon system in the region (Pohlmann, 1987). Generally, from June to September, the wind is directed towards Asia (Southeast Monsoon, SEM), and from December to March, the wind is directed towards Australia (Northwest Monsoon, NWM) (Putri, 2005). Among other things, these monsoonal winds have a great impact on the water exchange of the Java Sea with the South China Sea and the Indian Ocean, which mainly occurs through Karimata and Sunda Straits, respectively. Figure 4 illustrates the spatial distribution of the sea surface density (density of the model's surface layer of 10m) within the study area during the NWM (February 2012) and the SEM (July 2012) seasons. The overall transport through the Sunda Strait (Sunda Strait throughflow) is predominantly directed to the Indian Ocean (Potemra et al, 2016) but the direction varies with the seasons. Therefore, an influence of the high-density Indian Ocean waters can be observed over the waters of the Java Sea during the NWM (Figure 4, top). On the contrary, during the SEM, waters of the Java Sea move towards the Indian Ocean (Figure 4, bottom). This phenomenon is likely to be one of the main underlying causes of the seasonal variations of the baroclinic tidal currents in the Sunda Strait. Figure 5 presents the simulated surface current velocities at the point OBS (with red colour, see Figure 1) with the tide and tide+density type of forcing for 2012 (Figure 5, top) as well as for the NWM (Figure 5, middle) and the SEM (Figure 5, bottom) seasons. From the top panel, it is obvious that the magnitude of the tidal currents shows no significant seasonal change in both cases. However, including density-driven currents alters the hydrodynamics and does it due to the season.

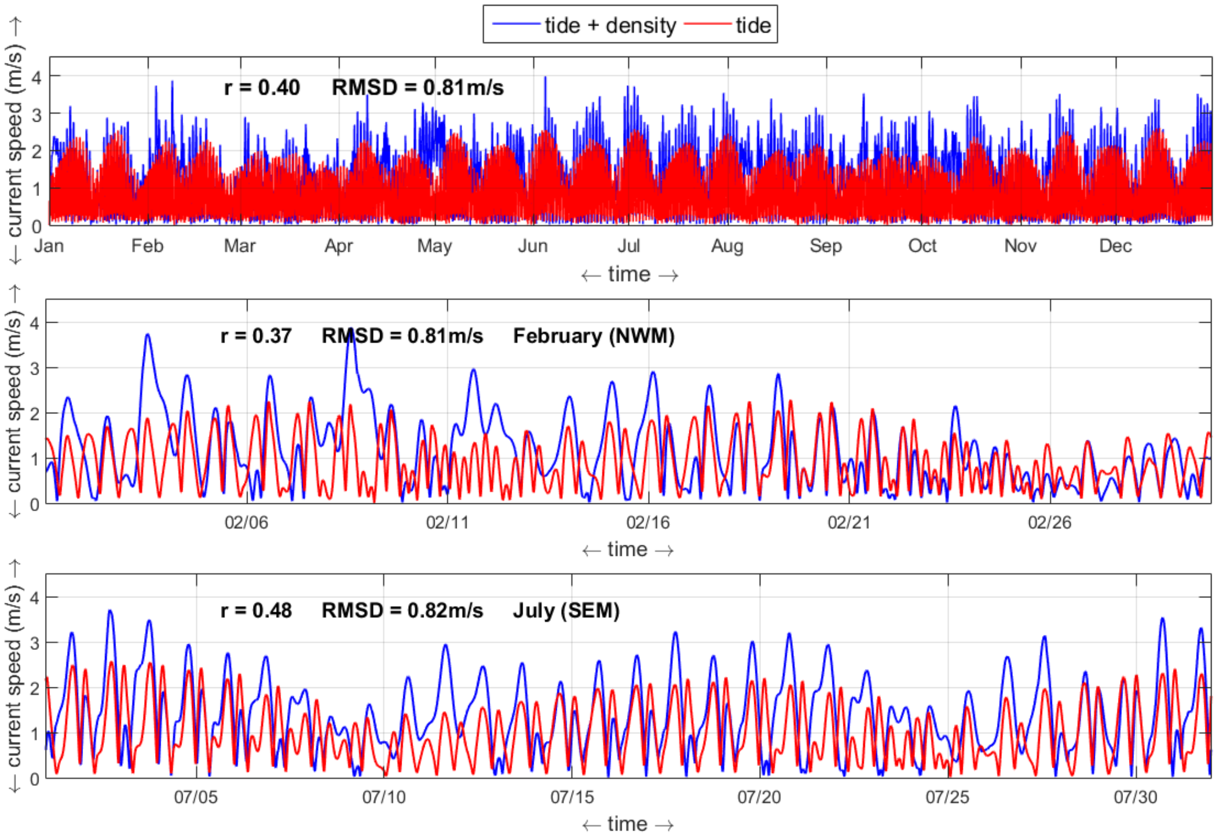

Figure 5. Time series of surface current speeds simulated by the model at the point OBS (see Figure 1). 2012 (top); February 2012/NWM (middle); July 2012/SEM (bottom). r correlation coefficient and RMSD values have been used to demonstrate the change between the baroclinic and barotropic tidal currents.

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To demonstrate the change between the currents simulated for tide+density and tide alone scenarios more understandably, root-mean-square deviation (RMSD) and Pearson's r methods have been used. While the RMSD does not show a significant change throughout the year between the baroclinic and barotropic tidal currents (ca. 80cm/s), we can see that the amplitude of the currents is altered less by the density gradients during the SEM (r = 0.48) than during the NWM (r = 0.37). During both seasons, we can observe an increase of the velocity magnitudes at the point of observation up to 100% during tidal peaks.

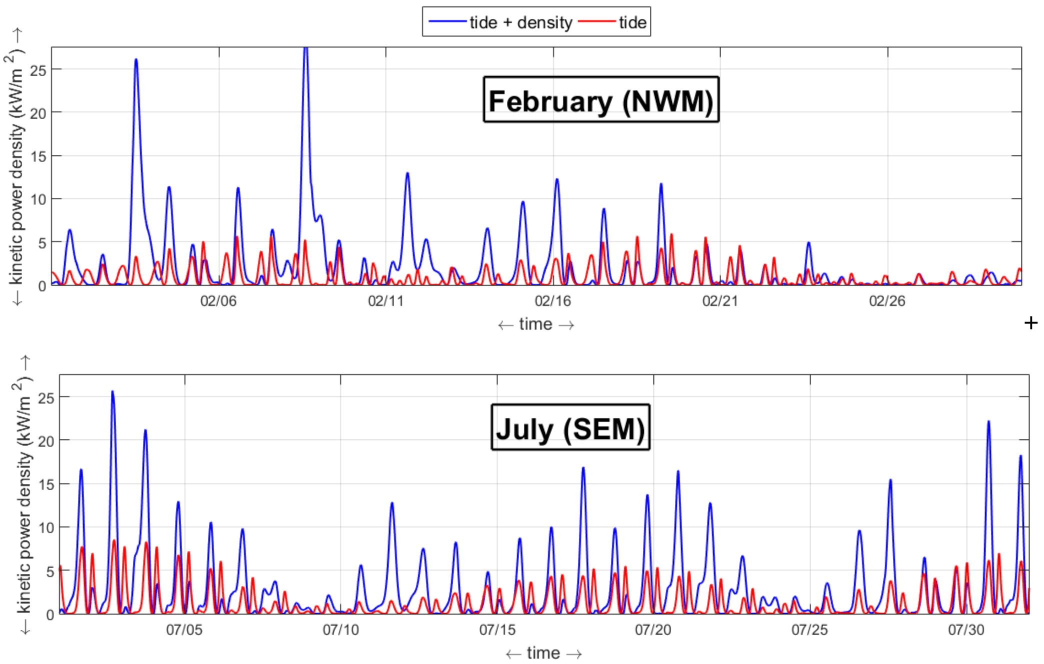

Figure 6. Time series of surface kinetic power densities estimated at the point OBS (see Figure 1) during February 2012/NWM (top) and July 2012/SEM (bottom).

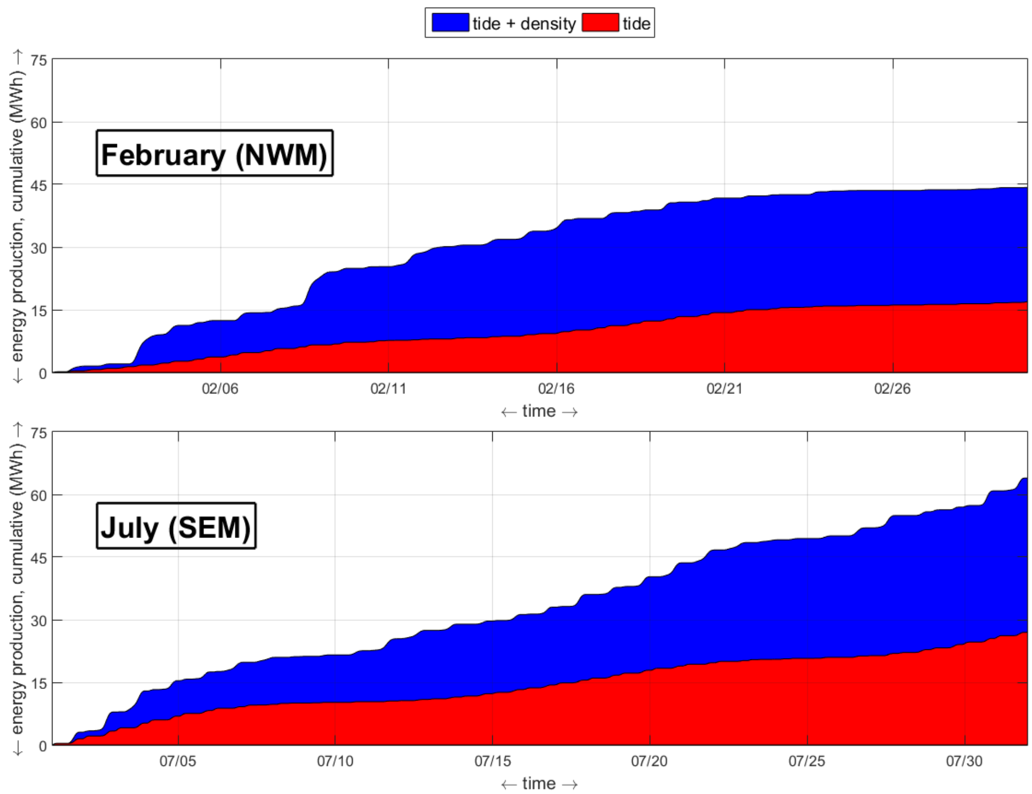

Figure 7. Time series of cumulative energy production estimated at the point OBS (see Figure 1) during February 2012/NWM (top) and July 2012/SEM (bottom). A horizontal axis tidal turbine with a 10m rotor diameter has been considered in calculations.

3.2 Impacts on tidal stream power generation

As Figure 5 illustrates, density currents in the Sunda Strait can amplify tidal current speeds by up to 100% at the free surface (i.e. from 2m/s to 4m/s). The hydrokinetic power increases with the cube of the current speed. It is given by $P = ½ \times \rho \times U^3$, with ρ=water density [kg/m^3], U=current speed [m/s]. Thus, a 100% increase in the current speed might lead to a much larger increase in power density. Figure 6 shows the time series of the current power densities simulated by the model at the free surface during NWM and SEM. During NWM, when tidal currents have a power density in the order of 5kW/m^2 during a peak spring tide, current power density increases to the order of 25kW/m^2 under the influence of the density-driven currents. Similarly, during SEM, it can be observed that the density currents can amplify the power densities of the tidal currents by up to 150% at the peaks of tidal cycles. To demonstrate the cumulative impact of the density-induced flow in both seasons, accumulation of the electricity produced by a generic, horizontal axis tidal turbine with a 10m rotor diameter (fitting into the surface layer of the model), located at the point OBS (see Figure 1), is illustrated in Figure 7. The method introduced in the Orhan et al. (2016) and Orhan and Mayerle (2017) has been used for the calculation of the energy output. It can be seen that during both seasons, electricity production in the baroclinic mode is more than twice of electricity production in the barotropic mode.

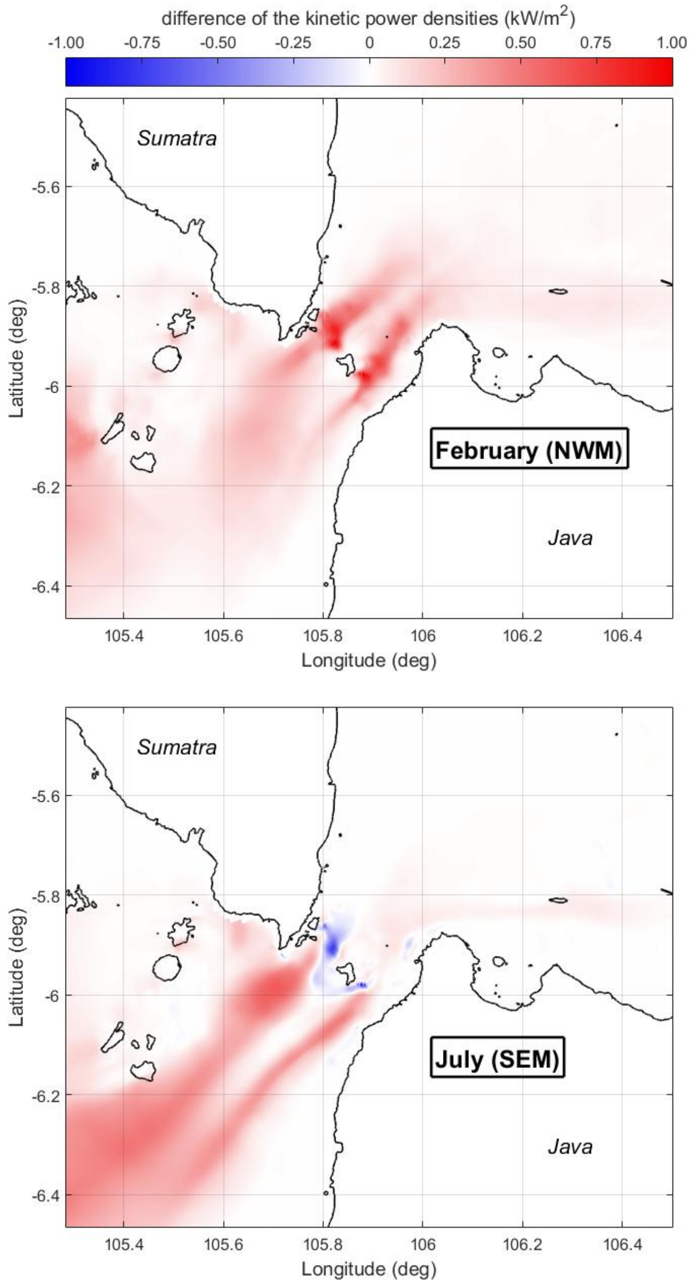

Figure 8. Differences between the simulated monthly means of the surface kinetic power densities of the tide and the tide + density cases during the NWM (top) and the SEM (bottom) seasons.

Generally, tidal stream devices require a minimum current velocity (cut-in velocity) to start operating, which ranges from 0.5m/s to 1m/s depending on their design. Thus, regions with an average kinetic power density larger than 0.5kW/m^2 (corresponding to a current velocity of 1m/s), with adequate surface area for tidal farm deployment (ca. 0.5km^2) and with adequate depth to install tidal turbines are defined as energy hotspots, suitable locations for tidal stream power conversion (EPRI, 2006; EMEC, 2009; Orhan et al., 2016; Orhan & Mayerle, 2017). Figure 8 shows the spatial distributions of the differences between monthly averages of the current power densities within the domain of interest, estimated for tide and tide + density scenarios. During NWM, an overall increase can be observed in the monthly means of the power densities. Especially at the bottleneck of the strait, where the cross-section of the strait is divided in half by the Sangiang Island, increases of up to 1kW/m^2 can be observed. On the other hand, during SEM, we have a different outcome. Although we have an increase of the monthly means of the current power densities of up to 0.5kW/m^2 towards the south entrance of the Sunda Strait, around the Sangiang Island, a decrease of the similar magnitude can be observed. When it is considered that the limit of suitability for the deployment of tidal turbines is a kinetic power density of 0.5kW/m^2, the importance of the alterations in flow conditions caused by the density-driven currents can be understood in a better way. Average kinetic power densities spatially changing in the order of 0.5kW/m^2 - 1kW/m^2 means great differences in the geometries of determined energy hotspots. Therefore, it can be said that ignoring the influence of density gradients might be highly misleading for the assessment of the power potential of tidal currents. We can easily underestimate or overestimate the magnitude of the currents, the size of the energy hotspot and eventually the technically extractable power from the area of interest.

4 CONCLUSIONS and OUTLOOK

In recent years, potentials of the tidal stream power generation have been evaluated for many regions of the world via numerical models. Due to numerous reasons such as an emphasis put mainly on tidal currents, density gradients due to salinity or temperature variations were neglected in evaluations. However, the “tide-only” approach might be highly misleading for domains like the Sunda Strait in Indonesia, where patterns of the tides, the tidal currents and the density currents add to complex flow structures. Sunda Strait, with tidal current velocities reaching about 2-3m/s and with a total extractable power around 300MW, has a great potential for electricity production from tidal stream currents. Furthermore, impacts of the seasonally varying density currents make Sunda Strait a great example for showing the importance of a holistic modelling approach for the selection and evaluation of the deployment sites of tidal turbines.

A high-resolution, three-dimensional circulation model providing sufficient spatiotemporal coverage has been developed to evaluate the hydrodynamics of the Sunda Strait. The model has been used to simulate spatial and temporal variations of the sea surface density in the region as well as its influence on the tidal currents. It was seen that the density currents resulting from the water exchange between the Java Sea and the Indian Ocean can amplify tidal current speeds by up to 100% at the free sea surface. Thus, the tidal power densities, which increase with the cube of the tidal current speeds, show a significant and seasonally varying change in the Sunda Strait. The results showed that during both NWM and SEM seasons, electricity production calculated in the baroclinic mode is likely to be more than twice of electricity production in the barotropic mode. During NWM, at the bottleneck of the strait, where the cross-section of the strait is divided in half by the Sangiang Island, increases of up to 1kW/m^2 have been observed in the monthly means of the hydrokinetic power densities due to the density currents. Whereas during SEM, increases in the monthly means of the hydrokinetic power densities of up to 0.5kW/m^2 have been observed towards the south entrance of the Sunda Strait, alongside a decrease of the similar magnitude around the Sangiang Island. Considering the limit of suitability for the deployment of tidal turbines and renewable electricity production from the tidal currents (a kinetic power density of 0.5kW/m^2), the alterations in flow conditions have been found extremely important.

The findings may help us to understand the importance of using more comprehensive numerical models for future resource assessments. Especially today, in the application stage of tidal current energy where demonstration farms are needed for systems to be proven in the actual operational environment, resolving flow fields with better precision is of utmost importance for the optimization of tidal farm configurations and efficient use of the resources of marine renewable energy. Modelling approaches must be refined to this end, as well as measurement techniques. Especially in megacities with more physical and socio-economic constraints, it is important to have the right approach for site selection as well as energy forecasting and harmonization of the ORE resources. To this end, a project is currently underway.

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