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Inference of turbulence parameters from a ROMS simulation using the k-ε closure scheme

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ABSTRACT

Comparisons between high resolution turbulence data from Admiralty Inlet, WA (USA), and a 65-meter horizontal grid resolution simulation using the hydrostatic ocean modelling code, Regional Ocean Modeling System (ROMS), show that the model's k-ε turbulence closure scheme performs reasonably well. Turbulent dissipation rates and Reynolds stresses agree within a factor of two, on average. Turbulent kinetic energy (TKE) also agrees within a factor of two, but only for motions within the observed inertial sub-range of frequencies (i.e., classic approximately isotropic turbulence). TKE spectra from the observations indicate that there is significant energy at lower frequencies than the inertial sub-range; these scales are not captured by the model closure scheme nor the model grid resolution. To account for scales not present in the model, the inertial sub-range is extrapolated to lower frequencies and then integrated to obtain an inferred, diagnostic total TKE, with improved agreement with the observed total TKE. The realistic behavior of the dissipation rate and Reynolds stress, combined with the adjusted total TKE, imply that ROMS simulations can be used to understand and predict spatial and temporal variations in turbulence. The results are suggested for application to siting tidal current turbines.

1. Introduction

Oceanographic circulation models use turbulence closure schemes to represent processes at scales smaller than the resolution of the computational grid. Central to many of these schemes is Kolmogorov's theory for spectral energy transfer in three-dimensional turbulent flows, wherein energy is input into a flow at large scales and transferred to smaller scales. According to this theory, at and above some critical wavenumber, the spectral energy density in the system is approximately a function of only the wavenumber, the turbulent dissipation rate, and the viscosity. This region is called the equilibrium range and can be subdivided into two regions: the inertial subrange and the viscous subrange. In the inertial subrange, the energy can be interpreted as eddies which degenerate into eddies of smaller scale (or larger wavenumber), cascading the energy to smaller and smaller scales at the turbulent kinetic energy dissipation rate, ε, without the influences of viscosity. The spectral form of the inertial subrange is

$$k(\kappa) = \alpha\varepsilon^{2/3}\kappa^{-5/3}, \quad (1)$$

where k is the turbulent kinetic energy spectral density (also referred to as the TKE), κ is the horizontal wave number, and α is a universal constant whose approximate value has been found experimentally. The turbulence is three-dimensional in nature and the three components of the root-mean-square velocities are assumed to be isotropic in the inertial range. The viscous subrange is at higher wave numbers where viscosity becomes important, and in which energy is removed from the system at the turbulent dissipation rate.

Differences in the mixing predicted by various turbulence closure schemes have been shown by comparisons of model-predicted salinity along an estuary (*e.g.*, Warner et al. (2005a,b)). However, fewer comparisons can be found between model predictions and turbulence velocity data itself, partially due to the difficulty of obtaining the data. Two such studies, one of which was in a tidally-dominated flow, found reasonable comparisons for dissipation rate (Simpson et al., 2002; Stips et al., 2002). Another study in a shallow tidal estuary compared model predictions with data for Reynolds stresses, and found reasonable results (Wang et al., 2011). In a partially stratified estuary, Stacey et al. (1999) found a model over or underestimate of the TKE depending on the stratification. Here, we use a new set of turbulence comparisons from Admiralty Inlet, WA, to understand the performance of the turbulence closure scheme in the Regional Ocean Modeling System (ROMS), and to obtain more insight into the turbulence

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dynamics. These comparisons focus on three parameters: turbulent kinetic energy, turbulent dissipation rate, and Reynolds stresses.

Admiralty Inlet is the main entrance to the Puget Sound, a fjord estuary in western Washington State. Admiralty Inlet has peak currents of over 3.5 m/s, depths between 50 and 180 meters, and is 5 km wide at the northern-most constriction (see Fig. 1). Dynamically interesting features are known to occur in the area, including the development of fronts (Thyng, 2012), tidal headland-generated eddies (Mofjeld and Larsen, 1984; Thyng, 2012), and areas of hydraulic control (Seim and Gregg, 1995). The large kinetic energy resource over a wide area makes Admiralty Inlet a strong candidate for tidal hydrokinetic power development (Polagye et al., 2007; Previsic et al., 2008; Haas et al., 2011; Kawase and Thyng, 2010).

A high level of turbulence is expected in Admiralty Inlet due to strong shear and periodic density variations in the water column. Turbulence is known to be a concern for turbine siting. In wind energy, many studies have examined turbulence as a cause of turbine failure (Frandsen, 2007; Madsen and Frandsen, 1984; Sheinman and Rosen, 1992; Thomsen and Sørensen, 1999; Wagner et al., 2010). Turbulence is known to decrease turbine efficiency as well as add additional stress onto the turbines (Sheinman and Rosen, 1992; Wagner et al., 2010). This has also been found to be the case with tidal turbines (Maganga et al., 2010). Results herein are proposed for use in selecting tidal turbine sites within Admiralty Inlet that have acceptable levels of turbulence.

2. Methodology

2.1. Field data

Multiple data sets of the currents in Admiralty Inlet were collected in 2011, as analyzed and discussed in Thomson et al. (2012). A set of acoustic wave and current (AWAC) data were gathered at a 56-meter-deep site near Admiralty Head from May to June 2011. One acoustic Doppler velocimeter (ADV) set and one acoustic Doppler current profiler (ADCP) set were gathered at a 22-meter-deep site near Nodule Point on Marrowstone Island in February 2011, for which period measurements indicated that stratification was not important during nonslack tides. Data locations are shown in Fig. 1. The ADV data were taken at a nominal turbine hub height of 4.7 meters above the seabed. They have less noise (error) in the measurements than the ADCP data, and are thus the most trusted source for comparison. The ADCP gives data

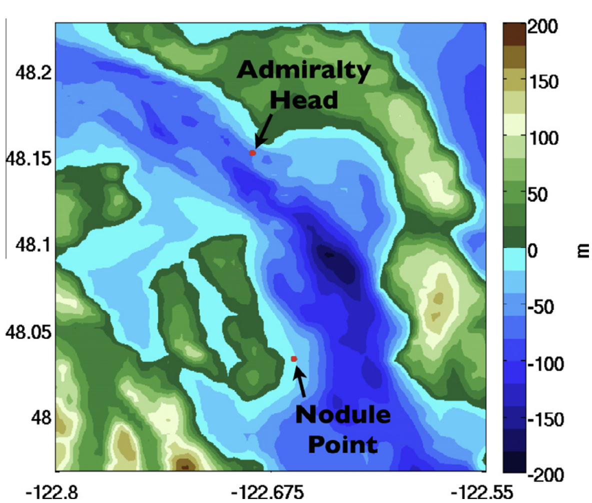

Fig. 1. Map of Admiralty Inlet with turbulence data locations indicated with red circles and colored contours showing bathymetry/topography in meters.

with height above the seabed, up to above 20 meters above the seabed. Note that ADCPs and AWACs are similar devices from different manufacturers and will here be generally referred to as ADCPs.

An additional ADV was deployed near Admiralty Head in June of 2012 to test the effectiveness of a new Tidal Turbulence Mooring, a method of suspending an ADV mid-water column using strongly heavy and buoyant attachments at the seabed and the top of the line, respectively, to hold the system nearly vertical (Thomson et al., 2013). This system is desirable for collecting high resolution ADV measurements at a depth that is pertinent to tidal hydrokinetic turbine deployment. Post-processing of the data is necessary to remove motion contamination. This will not be used as the primary data in this work, but will be used in the discussion in Section 5.

In order to use the ADCP data as well at the ADV data at Nodule Point, the ADCP data are "pinned" to the ADV data such that data taken at approximately the same height above the seabed by the two systems have approximately the same values for the turbulent kinetic energy and for the turbulent dissipation rate. In other words, to roughly account for the larger error present in the ADCP data, the ADCP data at Nodule Point are multiplied by a single factor (the ratio of the average value from the ADV over the average value from the ADCP at hub height) for the TKE and the dissipation rate (Reynolds stress is not calculated from the ADCP data) in order to match the hub height ADCP data to the hub height ADV data.

The data at are taken at sampling rates of 1 to 32 Hz, depending on the instrument, and processed using five minute windows, which was found in Thomson et al. (2012) to be the shortest time scale with a stable mean and variance in the data (i.e., stationarity). The processed data sets include five-minute running average estimates of speed (the mean flow), turbulent dissipation rate, and horizontal and vertical turbulent kinetic energy (referred to as TKE_{obs} for future differentiation) for both sites at hub height, as well as for a 20 meter profile above the seabed (from the ADCPs). In addition, the ADV set at Nodule Point is used to estimate turbulence spectra and Reynolds stresses.

The horizontal currents are rotated to be along and across the principal axis, which is defined for each averaging window separately. For each five minute averaging window, the mean flow pointing along (across) the principal axis is called u_p (v_p) and the velocity fluctuations, u_p' (v_p'), are taken as deviations around the mean flow in each direction. By design, the turbulent kinetic energy is largely contained along the principal axis. However, the energy contained in the perpendicular direction will also be considered because the model-predicted mean flow cannot be rotated to the same axes as the data, since the data is rotated for each five minute window and information from the model is output every fifteen simulation minutes. Both horizonal axes of information are included in comparisons in order to be as consistent as possible between the data and model. The relationship between the horizontal components of the TKE_{obs} at Nodule Point is used to infer the size of the across-axis component for the ADCP data sets, as $\sum(\overline{u_p'^2}+\overline{v_p'^2})/\sum\overline{u_p'^2} = 1.64$. This may be a low estimate for the relationship between v_p' and u_p' at Admiralty Head since the flow behavior there is different from the behavior at Nodule Point, with evidence that the TKE_{obs} in the directions of the principal axes are similar in size over a larger frequency range than at Nodule Point (see discussion in Section 5.1).

Turbulence spectra are calculated from the ADV data at Nodule Point using three overlapping sub-windows of 128 s, which are then averaged together to reduce confidence intervals in the five minute period analysis. Fig. 2 shows the time-averages of the TKE_{obs} spectra along and across the principal axis and along the vertical axis at Nodule Point from Thomson et al. (2012).