Development of Tidal Secondary Flow Generated by Headlands

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Abstract: As tidal currents flow around headlands, the curvature induces secondary flow in the plane normal to the direction of the streamwise flow. ADCP measurements will be made of the area around Cape Saunders in order to quantify the nature and development of this secondary flow during the tidal cycle. The objective of this project is to understand the mechanics of secondary flow about a headland. We hope to attain results that corroborate the theory of curvature induced secondary flow, and are conclusive enough to form an accurate model in order to predict the secondary flow around other headlands.

Secondary flow is important to Māori as it is a possible mechanism that produces coastal upwelling. Upwelling is very important to the coastal marine environment as it provides nutrients which in turn brings an abundance of marine life. By developing a model for secondary flow around headlands, it is hoped that this knowledge will be related to the mātauranga of the tangata whenua for a particular rohe, and used to assist Kaitiakitanga.

Keywords: headlands, kaitiakitanga, tidal flow.

Introduction

Secondary flow is defined to be flow in the plane normal to the direction of the depth average current. Secondary flow can be driven by several forces, some of these being density, curvature, and Coriolis. The magnitude of secondary flow can be up to 10% of the depth average current. Density driven secondary flow occurs in tidal estuaries (Numes & Simpson, 1985). Curvature induced secondary flow (Kalkwijk & Booij, 1986) occurs in river bends (Bathurst & Hey, 1977), and around headlands (Garrett & Loucks, 1976). Secondary flow also occurs within separation eddies generated by headlands (Pingree, 1978). Field measurements have been made of the three dimensional tidal flow around headlands (Geyer, 1993), and in a curved tidal channel (Vennell & Old, 2006). Curvature induced secondary flow is radially outwards near the surface and radially inwards near the bottom.

With secondary flow occurring in different geographical areas, there are several effects it may have on the surrounding environment. Curvature induced secondary flow leads to coastal upwelling. Where coastal upwelling occurs, life giving nutrients are brought from the depths to the surface and coastline providing a necessary ingredient for marine life. Other effects of secondary flow important to Mäori are: the mixing of agricultural run-off and pollutants in rivers, and the mixing between salt and freshwater in estuaries. All these effects have many biological and ecological consequences, hence the importance of understanding the physics of secondary flow.

The Dynamics of Secondary Flow

Secondary flow can be described by using a curvilinear coordinate system, with the streamwise coordinate, *s,* orientated in the direction of the depth averaged flow, and the cross-stream coordinate *n,* orientated normal to the this. In terms of velocity the streamwise component is denoted by u_s, and the cross-stream component by u_n, which is the secondary flow. A model for secondary flow (Kalkwijk & Booij, 1986), is developed by assuming that $u_s >> u_n$, and the density is uniform with negligible vertical advection. An approximation of the cross-stream momentum equation is then

$$\frac{\partial u_n}{\partial t}+u_s\frac{\partial u_n}{\partial s}-\frac{u_s^2}{R_s}-fu_s^2+g\frac{\partial \eta}{\partial n}-\frac{\partial}{\partial z}(A\frac{\partial u_n}{\partial z})=0 \quad (1)$$

Where R_s is the radius of curvature, f the Coriolis acceleration, η the water level, and A the eddy viscosity. Taking the depth average form of (1)

$$\overline{u_s\frac{\partial u_n}{\partial s}}-\frac{\overline{u_s^2}}{R_s}+f\,\bar{u}_s+g\frac{\partial \eta}{\partial n}+\frac{\tau_n}{\rho h}=0 \quad (2)$$

where τ_n is the bottom friction in the cross stream direction given by

$$\frac{\tau_n}{\rho}=[A\frac{\partial u_n}{\partial z}]_{z=-h} \quad (3)$$

By ignoring the depth average streamwise advection term in (2) as being negligible (Kalkwijk and Booij, 1986), and subtracting the depth average form (2) from the approximated cross-stream momentum equation (1), the water level term can be eliminated giving an expression for secondary circulation.

$$\frac{\partial u_n}{\partial t}+u_s\frac{\partial u_n}{\partial s}-\frac{\partial}{\partial z}(A\frac{\partial u_n}{\partial z})-\frac{\tau_n}{\rho h}=-\frac{u_s^2-\bar{u}_s}{R_s}-f(u_s^2-\bar{u}_s) \quad (4)$$

The right hand side of (4) indicates two forces inducing secondary flow. The first term being the centripetal acceleration due to the streamwise velocity and the degree of curvature, the second being the Coriolis acceleration due to the Earth's rotation.

This project focuses on curvature induced secondary flow and the associated coastal upwelling. The driving forces behind curvature induced secondary flow are a streamwise velocity shear due to bottom friction and centripetal acceleration. The velocity shear decreases the velocity towards the bottom resulting in an imbalance in the centripetal acceleration. This drives the flow radially outwards near the surface, and radially inwards near the bottom, creating a helical flow pattern around the curve.

Method

This project is unique in that it will be a first quantitative study of the mechanics of secondary flow generated by headlands. No quantitative study has been made of secondary flow as it develops through the entire tidal cycle. Mathematical analysis will be conducted on the results and a comparison will be made with the current theoretical model (Kalkwijk & Booij, 1986). This will contribute to the development of an applied model which in turn may be used as a template for other locations.

Study Area

The area within the vicinity of Cape Saunders on the Otago Peninsula will be used for this study. The curved tidal flow around Cape Saunders is predicted to have associated secondary flow. This area has been chosen because of the strong tidal flow and the large scale. This in turn will provide greater accuracy for the model which will be representative of the many other headland areas. This area also experiences the presence the Southland Current (Heath, 1971) and (Sutton, 2003), which has variable strength (Chiswell, 1996), potentially adding to the strength of the tidal flow.

ADCP Measurements

Acoustic Doppler Current Profilers (ADCPs) mounted on moving vessels are increasingly being used to measure tidal currents in coastal locations. The ADCP is a type of Sonar that uses the Doppler shift from the echo off objects such as plankton and sediment suspended in the water to measure the velocity of the current. These measurements are 3-dimensional, with echos from shallow water being received by the ADCP before echos from deeper water. The velocity field will be measured using a RDI1 four-beam 615 kHz broadband ADCP. A Trimble GPS receiver operated in conjunction with the hydrographic surveying software HYDRO will provide navigation. The surveys will be carried out from the University of Otago research vessel Polaris II (22m in length).

In order to gain the most from the field measurements several factors need to be taken into account: There needs to be sufficient resolution to resolve an entire tidal cycle. This means that the vessel needs to travel around the survey circuit at least every 90 minutes in order not to miss any sub-tidal nuances present in the tidal cycle; The tide ideally should be a spring tide so the velocity field is maximised; The swell size should be a minimum as swell can adversely affect the velocity field measurements. These factors place constraints on the project. The resolution restricts the area of survey at any one time, as the vessel cannot travel more than 4.5 - 5 knots reducing the circuit to a drawn out length of 7.5 nautical miles at best. The tide and swell limit the number of opportunities to perform the survey.

CTD Measurements

Conductivity, Temperature and Depth (CTD) measurements are one of the main tools in physical oceanography. CTD instruments measure three important parameters, conductivity, temperature and pressure. From these base measurements, the water salinity and density can be calculated. From this other information like the origins of the water can be determined. The CTD instrument is lowered through the water and measurements are made continuously as it travels downwards to the ocean floor. This enables a two dimensional profile to be built up of the vertical water column at a particular location. The CTD instrument can also be used to measure surface water from a moving vessel, giving a two dimensional profile of the surface water where the vessel has travelled. The CTD instrument to be used is a Seabird SBE 19*plus* SEACAT Profiler.

The ideal situation is to have a second vessel following the vessel making the ADCP measurements. Since the vessel has to stop to take a CTD cast, this would not interrupt the ADCP survey, and as a result CTD casts would be able to be taken throughout the entire survey area for the duration of the survey. If a second vessel is not available, the ADCP vessel could take a limited number of CTD casts at the same locations every circuit. This in turn will reduce the circuit length in order to accommodate the time taken for these CTD casts. It is hoped that the CTD measurements will complement the ADCP measurements as a completely independent and physically different set of data about the same body of water.

Data Analysis

The raw data produced by the ADCP contains information about both the spatial and temporal structure of the currents. Recent improved techniques for tidal analysis are used to smooth the spatial and temporal data. By using ideas from Radial Basis Function (RBF) theory, the spatial structure of each velocity component is represented as a 2D polyharmonic thin plate spline RBF. The noise in the velocity field extracted from the ADCP data can be significantly reduced by placing the spline weights at the data points and enforcing side conditions, (Vennell & Beatson, 2006). The evolution of the secondary flow during the tidal cycle is established by analysing the velocity field around the curvature of the cape. The cross stream velocities will be analysed at different depths to corroborate the theoretical prediction of secondary flow due to curvature (Kalkwijk & Booij, 1986).

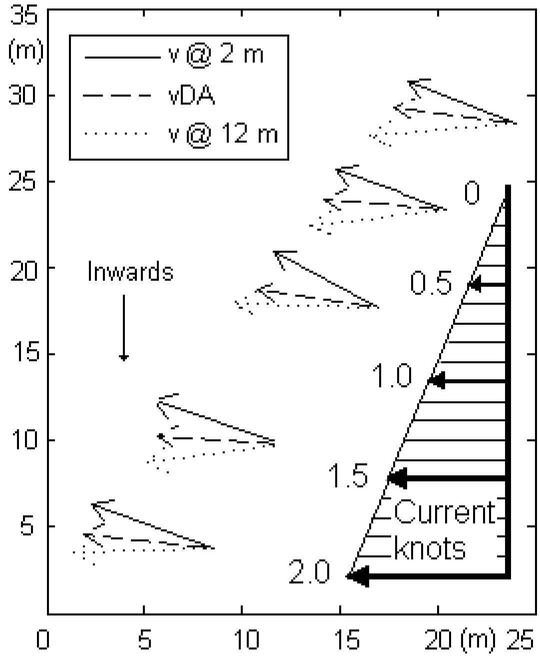

Figure 1. Evidence of secondary flow. (Velocities plotted at 2 m, the depth average, and at 12 m.)

Initially to identify areas of secondary flow the velocity structure is extracted and the raw velocities are rotated so that the streamwise component, u_s, is aligned with the direction of the depth average velocity $\bar{u}_s$, (Vennell & Old, 2006). The cross-stream component or secondary flow, u_n, is normal to this. Thus if a rotated raw velocity has zero cross-stream component at a particular depth, it is orientated in the direction of the depth average velocity. Non-zero cross-stream components will be either inward or outward relative to the curvature. The raw velocity is plotted at different depths (Figure 1), to look for evidence of secondary flow. Curvature induced secondary flow is radially outwards near the surface and radially inwards near the bottom.

Applications

It is hoped that by understanding the mechanics of secondary flow a more accurate model will be able to be applied as a template to other headlands in order to identify locations of significance such as areas of up-welling or where eddies may form. The identification of these locations of significance could be overlaid with the mātauranga of the tangata whenua for that particular rohe in order to determine any commonality in knowledge. This outcome will provide tools and knowledge that will contribute to implementing kaitiakitanga. This may include the potential locations of aquaculture projects, Mätaitai and Taiapure. The location of an aquaculture project in relation to nutrient circulation due to secondary flow could have an impact on productivity. Conversely the protection of some of these locations through Mätaitai and Taiapure will assist in preserving the marine environment for future generations.

An understanding of secondary flow can be applied in other geographic areas beside headlands, such as tidal estuaries or river bends, where any lateral movement will increase the amount of mixing in the water, which has environmental ramifications when looking at issues such as pollutants and nutrient run-off. Tidal estuaries have delicate ecosystems and to what degree pollutants and run-off are mixed will not only have an effect on the ecosystem of the estuary, but also the neighbouring coastline.

Summary

The primary outcome of this research is to gain a greater understanding of the physics of secondary flow generated by headlands. By understanding one headland this knowledge can be applied to the many other headlands around the coastline. Physics underpins all physical processes in the marine environment. Gaining a 'physics' based understanding of a marine process will lead to greater knowledge of that process in other disciplines.

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Author Notes

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