RECIRCULATION IN THE LEE OF COMPLICATED HEADLANDS : A CASE STUDY OF BASS POINT

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Abstract: It has been argued in recent papers that the nature of headland and coastal island wakes can be highly dependent on the level of turbulence caused by complicated coastal geometry and bottom topography, as well as on the loss of energy and momentum to the sea-bed due to friction. A series of field experiments was conducted around Bass Point (a 4 km long headland near Sydney, Australia) using moored current meters and an acoustic Doppler current profiler. The off-shore component of currents, measured off-shore of the point, showed a high degree of spectral energy at about the seven day cycle with a small amount at the diurnal frequency, but the reverse was found in the lee of the headland, where most of the recirculation was at the diurnal frequency. Numerical experiments resulted in similar spectra being obtained from locations behind the headland when the numerical model was forced with a spectrum of frequencies resembling the spectrum of the off-shore free stream current, which was derived from the field results. The size and frequency of eddy-shedding in the lee of the headland depended on the degree of variability of the inflowing free stream, with a diurnal component in the free stream appearing to cause the oscillations in the wake also of diurnal frequency. The numerical experiments also show that the size of the recirculating wake was affected by the complexity of the headland's geometry.

1. INTRODUCTION

Flow past headlands and the subsequent wakes generated downstream have important applications in the areas of pollutant dispersal, fisheries, and current predictions for safety and rescue purposes. Indeed, in the course of the field experiments for this paper, some of the authors were called upon to offer estimates of the magnitude and direction of the current, in an attempt to locate and rescue a missing scuba diver. Despite the importance of understanding this type of oceanic flow, most literature on the subject is confined to the analyses based on the horizontal eddy Reynolds number which, in practical ocean conditions, is defined on rather imprecise length and velocity scales and an even more imprecise horizontal eddy viscosity.

A recent paper by *Pattiaratchi et al.* [1987] reported that the eddy Reynolds number did not adequately describe all the features of flows around a variety of headlands and coastal islands off southern Britain. They postulated a parameter based on bottom friction. Analytical solutions to barotropic flow past a rectangular shaped headland were found by *Freeland* [1990], who noted the downstream generation of topographic Rossby waves in a frictionless coastal ocean. *Signell and Geyer* [1991] argued that in shallow water, bottom friction is a better parameter than horizontal eddy Reynolds number in describing the nature of headland wakes, owing to its ability to cause the flow to separate as soon as an adverse pressure gradient is established. *Black and Gay* [1987] claim that the transience of the free stream plays a crucial role in the type of wake generated and the frequency of any vortex shedding in the lee of a headland. They show that the inertia associated with tidal reversals leads to stronger recirculation than might have been expected. More recently it has been shown [*Denniss and Middleton*, 1994] that flows controlled by bottom friction do not necessarily exhibit the same features as those controlled by horizontal eddy viscosity, and that equal values of the respective non-dimensional numbers (i.e. eddy Reynolds number and its bottom-frictional counterpart) can often produce totally different flow regimes if the other dynamical process is absent. It has also been argued that complicated coastal geometry and bottom topography in the vicinity of the tip of a headland significantly alters the nature of the subsequent recirculation behind the headland, owing to enhanced turbulence altering the overall pressure field [*Middleton et al.*, 1993].

In the case of coastal flows past headlands in relatively shallow water, most terms in the depth-averaged equations of motion become important in some part of the flow, thus it appears that the processes responsible for headland wakes should be far more complex than the scenarios predicted by simple Reynolds number theory. Indeed, the effects of bottom friction, unsteadiness, and complicated bathymetry will most likely produce flows which cannot be categorized simply in terms of any single dimensionless parameter. It is the aim of this paper to study the role played by complicated geometry and topography, as well as unsteady forcing, in determining the nature of any recirculating flow in shallow water, in the lee of a headland.

In order to investigate some of the features described above, a series of field experiments were conducted in the vicinity of Bass Point, a jagged headland situated approximately 100 km south of Sydney, Australia, protruding about 4 km into the Pacific Ocean. The local waters can be considered shallow, averaging roughly 30 m in depth near the headland. The free stream is forced by currents that are often strongly to the south, due to the East Australia Current (EAC). It was hoped that the analysis of the current-meter results from these field experiments would elucidate the nature of both the off-shore current (the forcing) and the resulting recirculation (the response). Comparison of the time series and energy spectra of these regimes might then reveal the types of dynamics involved in the Bass Point region. It was decided to numerically compare the effects of steady and unsteady forcing (since the EAC can be quite variable), so a corresponding series of numerical simulations was performed for the region around Bass Point.

A description of the field results is contained in Section 2, and Section 3 includes a description of the numerical model and the numerical results obtained from a variety of runs involving realistic bathymetry and inflow current. Section 4 incorporates numerical testing of various hypotheses by altering the subsurface features and the coastal geometry. Conclusions are drawn in Section 5 from these results.

2. THE FIELD EXPERIMENTS AND RESULTS

Four InterOcean S4 current meters were deployed in the vicinity of Bass Point between 19 August and 12 September, 1992; one directly off the tip of the point to measure the strength and direction of the free stream current, and three to the south of the headland to detect any wake that may occur due to the interaction of a southwards flowing current with Bass Point. The meters recorded current magnitude and direction at 4 minute intervals, at a depth of approximately 10 metres. A winter deployment was chosen because of the greater likelihood of the waters being well mixed and essentially barotropic. Temperature and salinity profiles were obtained by deployment of a Yeo-Kal submersible data logger, and confirmed the essentially barotropic nature of currents at depths shallower than about 30 m. The positions of the current meters are shown in Figure 1. In addition to the current meters, a series of Acoustic Doppler Current Profiler (ADCP) transects were conducted, using a RD Instruments 300kHz Broadband ADCP aboard a small vessel, to gain a greater insight into the detailed spatial structure of currents.

Examination of Figure 2, showing hourly averaged vector stick plots (with varying vertical axis scale) for each mooring, indicates a degree of unsteadiness in the forcing flow for the free stream (mooring A). Although the current is predominantly to the south, it varies in both magnitude and direction (varying through an angle of approximately 40^o from 180^oT to 220^oT).

Figure 3 shows the spectral energy densities for each mooring, smoothed over five frequency bands via a moving average in the frequency domain. There are thus 10 degrees of freedom resulting in 95% confidence limits lying in the range $0.488 \geq log_{10}\left(\phi/\hat{\phi}\right) \geq -0.311$, where $\hat{\phi}$ is the smoothed estimate and ϕ is the true value of the spectrum at each frequency. The vertical axes are scaled differently according to the amount of energy at each site. There is a significant amount of spectral energy in the offshore mooring (A) at about the 7 day cycle, which is probably attributable to a coastal trapped wave (CTW), as has been observed on the East Australian continental shelf by, for example, *Church and Freeland* [1987] and *Griffin and Middleton* [1991]. In addition there is a weak signal at the diurnal frequency, more evident in the cross-shelf current spectrum of mooring A, due probably to a diurnal tide propagating equatorward as a CTW along the east Australian coast, as observed by *Freeland* [1988]. These diurnal oscillations can have an amplitude of up to 15 cm s^{-1}. The ratio RY of diurnal energy to the seven-day-period CTW energy in the long-shore direction is about 0.17 for mooring A, and the corresponding ratio RX in the cross-shelf direction is 0.41 . The spectrum for mooring A also exhibits some energy at frequencies intermediate to the seven-day-period CTW and the diurnal frequency. Such energy appears to be the result of the nonlinear interaction of the CTW and the EAC, but may possibly be the signature of other weaker CTWs of higher frequency than the dominant CTW. There is also spectral energy at approximately the semi-diurnal frequency and in the 1.5 cycles per day band. It is not clear whether this energy is independent, or if it is simply a higher-frequency harmonic signal. In general, the semi-diurnal tidal currents off the east Australian coast are relatively weak, and the spectrum is not likely to exhibit any major signal at this frequency.

While data from the offshore mooring exhibits some spectral energy at the diurnal frequency with the majority of the energy being sub-diurnal, the data from moorings in the lee of Bass Point show a much greater level of energy at the diurnal frequency. Moorings B and C are clearly dominated by diurnal oscillations, although the effect of the lower-frequency CTW is still evident. The ratio RY is about 1.26 and 1.96 for moorings B and C respectively, while RX is 1.88 and 2.71 respectively.

The energy at mooring D is predominantly at the lower frequency with RY and RX being 0.39 and 0.26 respectively. There is virtually no energy at any other frequencies for this mooring except for a very small amount in the semi-diurnal band. The lack of energy at the intermediate frequencies (between 0.14 and 1.0 cycle per day) at moorings B and C is consistent with the spectral valley at mooring D.

It is possible that the dominant diurnal signal at moorings B and C is a uniform reversal of flow along the coast as the direction of the diurnal tidal CTW current changes. However, it is more likely to be due to a recirculation behind the headland spinning up and perhaps shedding and decaying at this frequency. The following diagrams lend support to this latter hypothesis. Figure 4 is an extract from the complete data set for the days August 27 - 31 inclusive, for each of the four moorings. While Moorings A and D have currents predominantly to the south with variations in magnitude and to a lesser extent direction, Mooring B, which is tucked in behind the headland, exhibits definite oscillatory currents at the diurnal frequency. Mooring C, which is further downstream, shows some of the same features as B, but the currents are weaker in magnitude. While these observations alone do not prove the existence of a zone of recirculation, the much reduced velocity magnitudes at B and C suggest these moorings do lie within the headland's wake region.

These results are largely consistent with those of *Middleton et al.* [1993]. These authors found the off-shore current near Bass Point to be predominantly to the south, with small diurnal and even smaller semi-diurnal energy present at all moorings. Their moorings in the wake of the headland did not, as expected, exhibit the strong low- frequency energy of the off-shore mooring.

An ADCP transect conducted on 12 September (when similar conditions to those in Figure 4 prevailed) clearly shows an eddy with a diameter of some 3-4 km (Figure 5) in the vicinity of Mooring B. Owing to the time needed to traverse the oceanic domain at slow speed with an ADCP operating from the vessel, this diagram is not a true 'snapshot' of any particular moment in time. Each velocity vector was recorded at a different time, with a total range between the first and last measurement of approximately 7 hours. This is a time scale over which an eddy, that is possibly influenced by diurnal effects, can vary significantly. Despite the possibility of variations in structure, it is still obvious there is large-scale recirculation in progress in the lee of the headland.

Figure 6 illustrates the evolution and decay of an eddy on 31 August, using a series of frames of the time series data. Over this 24-hour period a strong free-stream current at mooring A can be seen to spin up an eddy, firstly at mooring B, and as this eddy grows in size it moves south-west to impinge on mooring C. Coincident with the free stream varying in direction and magnitude towards the last frame, the eddy appears to be decaying. The current at mooring D is predominantly in the same direction as that at mooring A, which possibly suggests that the eddy in the lee of Bass Point does not shed, but rather decays because of friction with the shallow bottom in the region around moorings B and C.

It should should be pointed out that *Middleton et al.* [1993], while finding evidence of large scale circulation in the lee of Bass Point, did not find such circulation to be a regular feature of the region. It is not clear why this discrepancy exists (they argued that the appropriate Reynolds number was too small in all but two events), but their data indicates a slower off-shore free stream current, which was strongly to the south on only six of the twenty days of the deployment. This contrasts with the present study, which encountered strong southwards off-shore currents on twenty-one of twenty-three days.

The data gathered in this field study indicate there is some large scale recirculation at the diurnal frequency, while the off-shore current merely shows signs of small diurnal oscillations imposed upon a lower- frequency mean flow. It appears that an unsteady forcing current can lead to a complex array of flow scenarios even if this forcing current is predominantly in one direction. Small variations in direction and magnitude seem to further complicate the resulting recirculation. Fluctuations in the free-stream forcing current at the diurnal frequency may cause any natural recirculation in the lee of the headland to respond at this frequency. This appears to be the case for the Bass Point region, as the oscillations in the forcing current at the diurnal frequency may be causing eddies to spin up and shed or decay at this frequency. This possibility will be investigated in the next section.

3. THE NUMERICAL MODEL AND RESULTS

(a) A Description of the Numerical Model

The numerical model solves the nonlinear, barotropic shallow water equations, namely

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla\mathbf{u} + 2\mathbf{\Omega} \times \mathbf{u} = -g\nabla\eta + \nu_h\nabla^2\mathbf{u} - \frac{C_D}{H+\eta}\mathbf{u}|\mathbf{u}|, \tag{1}$$

$$\frac{\partial \eta}{\partial t} + \nabla.[(H+\eta)\mathbf{u}] = 0, \tag{2}$$

forced by a current $\mathbf{U}$ at the upstream boundary. Equation (1) includes an horizontal eddy viscosity term $\nu_h\nabla^2\mathbf{u}$, and a quadratic bottom friction term $C_D(H+\eta)^{-1}\mathbf{u}|\mathbf{u}|$, which represents $H^{-1}\int_{-H}^{\eta}(\nu_v\partial^2\mathbf{u}/\partial z^2)dz$, the vertical diffusion of momentum into the sea bed.

The nomenclature used here is as follows : η is the fluid surface displacement from equilibrium, ν_h and ν_v are the horizontal and vertical eddy viscosities respectively, C_D is the frictional or drag co-efficient, $\mathbf{\Omega}$ is the Earth's angular velocity, H is the undisturbed fluid depth, g is the gravitational acceleration, t is time, and the velocity components (u, v) correspond to the spatial co-ordinates (x, y). It is assumed that $H \gg \eta$. The operators are

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right) \text{ and } \nabla^2 = \nabla.\nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}.$$

It was decided to use a quadratic bottom friction formulation (consistent with a logarithmic boundary layer), in line with many past papers and numerical models [e.g. *Pingree and Maddock*, 1980; *Pattiaratchi et al.*, 1986; *Black and Gay*, 1987; *Middleton et al.*, 1993; *Denniss and Middleton*, 1994]. The model is based upon that of *Flather and Heaps* [1975]. *Fandry* [1981] used a linear version of this model to successfully model various aspects of oceanic flow in nearshore regions of Australia. *Pingree and Maddock* [1979] used a similar nonlinear model to investigate the recirculation around a promontory due to tidal flow. An earlier version of the present model was used by *Middleton et al.* [1993] in modelling the Bass Point region, and a more recent version by *Denniss and Middleton* [1994] was used in a more theoretical study comparing the effects of bottom friction and viscosity on recirculating flows. The above examples demonstrate the robust nature of this type of model.

Discretized forms of equations (1) and (2) are solved on a regular Arakawa C-grid [*Arakawa and Lamb*, 1977]. The model consists of 380 gridpoints by 280 gridpoints with grid size dx = dy = 33.33m, and a half-slip boundary condition was assumed along the coast and the side wall (i.e. the along-shore velocity at the coast is assumed to be one half of that one grid point offshore), in order to allow for the formation of lateral boundary layers.

Open inflow and outflow boundary conditions are invoked at the northern and southern boundaries, and at these boundaries barotropic gravity waves were allowed to radiate out of the domain via the modified Orlanski radiation conditions [*Orlanski*, 1976] of *Camerlengo and O'Brien* [1980]. To prevent the build-up of large amplitude barotropic gravity waves, sponge layers were included at the northern and southern boundaries. The extent of the sponge layers was 10 grid-points from either end. The sponge layers were of the form suggested by *Israeli and Orszag* [1981] whereby the co-efficient of bottom friction r varies as

$$r(x) = r_0 + A(n+1)\frac{(x - x_0)^n}{X - x_0} \tag{3}$$

where r_0 is the value of r in the model interior; x_0 is the cut-off of the sponge layer; X is the along-flow extent of the sponge layer; and A and n are tuneable parameters, chosen by trial and error so as to make the along-flow gradient of $r(x)$ not too large; otherwise gravity waves are reflected by the sponge layers.

The model was driven by a spatially variable but perpendicular inflow along the model's northern boundary, and a spatially corresponding outflow. The model's length was chosen so as to ensure that such parallel inflow and outflow conditions did not interfere with the natural flow variations caused by the headland. In addition, the side wall was placed far enough away from the coast to avoid interfering with the flow.

Mass continuity was ensured by adjusting the outflow boundary condition such that at each time-step the total volume of water within the model domain remained constant. There is no reason why this condition should be exactly satisfied in a real flow, but it introduces only small errors since $\eta \ll H$, and is computationally convenient. In fact, water depth was usually at least 1000 times the sea surface displacement. The model parameters are $A = 0.5$, $n = 4$ and $C_D = 0.0025$ (a value attributed by *Proudman* [1953] to estuaries and coastal waters, and used by various authors, e.g. *Pattiaratchi et al.* [1986]; *Pingree and Maddock* [1980]; *Middleton et al.* [1993]; *Denniss and Middleton* [1994]). Since the small grid scale of the model allows a high level of eddy resolution, a reasonably small value for horizontal eddy viscosity ν_h of 0.1 m^{2}s^{-1} was used. According to the theory of *Denniss and Middleton* [1994], even a much higher value of horizontal eddy viscosity would have little effect on the nature of the flow around Bass Point, as the scales indicate it is highly dependent on bottom friction.

The time-step was set at 2/3 s so as to satisfy the CFL criterion (i.e. $\Delta t < \Delta x/c$) for numerical stability. The rotational parameter $\mathbf{\Omega}$ was given the value of -4.067 $\times$ $10^{-5}s^{-1}$, appropriate for the latitude of Bass Point. A map of the model domain with realistic bottom topography is shown in Figure 7.

(b) A Description of the Numerical Results

It was decided to run the model with a free stream current having a similar direction and time dependence to the observed off-shore data, in order to provide a valid comparison of the numerical results with the field data in the wake. For this reason RUN 1 employed an inflow angle of 202°T (roughly the average angle of the real current), and a variable current magnitude was invoked, consisting of 7 day, 1 day and 1/2 day period components in the same proportions as those of the frequency spectrum results derived from the time-series as shown in Figure 4, for the period 27-31 August, 1992. The very small semi-diurnal component was included to cover the possibility of such frequencies having some effect on the flow response. The current profile was selected as being proportional to the depth along the northern boundary with a maximum velocity attained (momentarily) of 50 cm s^{-1} at the eastern wall. The average inflow velocity at the eastern wall (where the depth, and consequently the current velocity, was largest) was about 40 cm s^{-1}. The average velocity along the entire northern boundary was about 25 cm s^{-1}. The model was then run for the equivalent of 3.5 days of real time in the ocean. Figure 8 shows the resulting numerical time series for grid points corresponding to the real moorings. While the directional uniformity of the results at mooring A is a function of the inflow condition, the other mooring results indicate reasonable overall agreement with the results of the field experiment - mooring B shows definite reverse flow at the diurnal frequency, mooring C shows the weakest flow though it is not as turbulent as that of the field experiment, and mooring D shows currents predominantly to the south but variable in magnitude and direction.

Figure 9 illustrates the spectral energy densities for moorings B, C and D from the numerical run (the numerical spectrum for mooring A is, by definition, that of the real spectrum for mooring A). The ratios RY of diurnal to seven-day period energy in the long-shore direction are 1.28, 0.85, and 0.18 respectively, and the corresponding ratios RX in the cross-shelf direction are 1.92, 3.17 and 0.20 respectively. Except for the longshore component at mooring C, this compares favourably with these ratios for the real spectra of Figure 3, which were 1.26, 1.96 and 0.39 longshore and 1.88, 2.71 and 0.26 cross-shelf respectively. In addition, the magnitude of energy at each real and numerical mooring is roughly equal, although there is less energy at mooring D in the numerical run, compared to the real results. Qualitatively, the general shape of the respective spectra are in agreement, other than the longshore component of mooring C. This was the mooring with the least energy, and so is more susceptible to noise.

Given that the numerical model appears to be satisfactorily simulating the real spectra, the next stage is to test the nature of the diurnal oscillations in the lee of Bass Point, to determine whether they are due to eddy generation at this frequency, or to some other process. From the real data, figures 5 and 6 indicated an eddy with the scale of the headland occupying the region of moorings B and C. Since these moorings show currents dominated by diurnal oscillations, it is reasonable to suspect that this recirculation may be at the diurnal frequency.

In terms of the spatial distribution of currents, the numerical run produced the following results. Figure 10 is a plot of current vectors at every fourth grid point depicting an eddy in its early stage of evolution. The eddy remained relatively static for the next several hours, growing slightly and migrating a little to the south, until the free stream current began to diminish in magnitude, at which time the eddy decayed rapidly due to bottom friction as it moved quickly into the shallow waters to the south-west. Figure 11 shows the same eddy 12 hours later. It is somewhat weaker and nearer to shore, and a new eddy can be seen spinning up nearer to the tip of the point. It is likely that this scenario models the life-cycle of the real eddy seen in Figure 6. This process occurred regularly in the numerical run, with eddies continually spinning up at the diurnal frequency, confirming the possibility of diurnal recirculation in the real ocean.

The similarity of the numerical results to those of the field experiment may do more than verify the usefulness of the model in predicting coastal flows. Together, the results indicate that relatively small fluctuations in a mean flow at set frequencies can result in eddies generating and decaying at the same frequencies. It seems that while the free stream is increasing in magnitude it feeds the eddy so that it grows to some natural size depending on the local scale, but when the free stream starts to decrease in magnitude the eddy subsequently breaks away and decays rapidly in shallow water.

To be sure that the scale of the local coastline does not naturally induce eddies at a frequency coincidentally that of the tides, RUN 2 was conducted identically to the previous run, except that the current was kept constant, with an eastern wall (maximum) value of 40 cm s^{-1}. An eddy did spin up but it grew to a larger size, and persisted for many days. It appeared that the momentum lost to bottom friction was systematically being replenished by the constant mean flow. Figure 12 shows this eddy four days after it first started to appear. At this point the run was discontinued with the eddy still in existence and apparently static. This result correlates fairly well with the constant-depth steady theory of *Denniss and Middleton* [1994] regarding coastal flows dominated by bottom friction. For the flow around Bass Point, the horizontal eddy Reynolds number is of the order of thousands, whereas the bottom friction number $B = H/C_D L$ (the non-dimensional equivalent based on the ratio of non-linear to bottom- frictional terms in the momentum equations, where H and C_D are as defined in Section 3a, and L is the horizontal scale of the obstacle in the flow), is between 4 and 5, which indicates there should be low frequency quasi-shedding with periods of the order of several days (*Denniss and Middleton*, 1994). It is possible that the more complicated coastline and bathymetry trapped this particular numerical eddy, preventing an eventual shedding.

Another interesting feature produced by the steady-inflow numerical model, as evidenced in Figure 12, is the instabilities which show up as almost sinusoidal wiggles in the shear layer. These oscillations have an approximate period of two hours and spatial scale of about 200 m, and bear close similarity to the Kelvin-Helmholtz-like instabilities shown in *Van Dyke* [1982] (plate 81, pp.48). These instabilities are even clearer in the close-up view of Figure 13 (this close-up is at a later time than that of Figure 12). Such finer-scale flow features could easily be missed in a coarser-scale model, but are detected by this model, which has the ability to resolve eddies to a far finer scale than most oceanic numerical models. While there are also signs of the same phenomenon occurring in the non-steady inflow runs, the effect is less pronounced.

It was not possible to numerically vary the inflow angle as a dynamic temporal variable, so it is difficult to ascertain the effect that small directional fluctuations in current may have on recirculation. However, a steady (in magnitude) RUN 3 was performed with an inflow angle of 216^oT (as opposed to the previous 202^oT case) to see how a simple change in inflow direction might alter the flow behind the headland. The field observations indicate that the free stream current did at times approach Bass Point at this angle.

This change of angle has the effect of reducing the length scale of the headland as 'seen' by the current, and the subsequent bottom friction number B [*Denniss and Middleton*, 1994] thus increases to a value close to 8, which implies vortex shedding (at least for the flat bottom case). Examination of Figure 14 shows that this is indeed the case, with no quasi-steady recirculation visible at all when the inflow angle is 216^oT. Therefore it would seem that directional variations are important in addition to magnitudinal variations in inflow current, which would result in even more complicated scenarios in the real ocean. It appears, however, that the main features of the real flow, as found from the field experiment, were adequately captured by the simulations of the numerical model when reasonably realistic inflow conditions were applied.

4. NUMERICAL EXPERIMENTS

Given there is some degree of confidence in the ability of the numerical model to simulate the flow around Bass Point, it was felt appropriate to investigate other areas of interest which are difficult to examine without the aid of a numerical model. One such concern is the relationship between the geometry of the headland and its surrounding bathymetry, and the size and shape of any resulting recirculation zone. In RUN 4 a simplified southward flowing inflow current, proportional in magnitude to the depth at each gridpoint, was imposed on the numerical domain for Bass Point with real bathymetry. The average current speed across the northern boundary was 25 cm s^{-1}. This run is essentially the same as the steady run of Section 3 where the inflow angle was 202^oT. The 180^oT (pure south) flow of RUN 4 increases the length scale slightly, thus reducing the bottom friction number to around 4. This produces a slightly larger quasi-steady eddy, as seen in Figure 15, which is the current vector plots for the entire domain, 24 hours after commencement. Once again the instabilities in the shear layer are visible.

RUN 5 was conducted under identical conditions, except for the headland shape being smoothed and the depth held constant at 30 metres throughout the domain (roughly the average depth near the tip of Bass Point). This yielded an interesting result in terms of eddy size. As can be seen in Figure 16, the eddy had grown to a larger size (than in Figure 15) after the same time interval (24 hours). It had also 'tucked' itself in under the headland where the now 30 m depth close to the coast allowed much less dissipation than would normally have been the case with shallower waters. Similar additional runs were done with idealized rounded headland geometry with real bathymetry, and real geometry with idealized flat bottom bathymetry. The idealized geometry / real bathymetry run produced results (not shown) almost identical to those of Figure 15, while the real geometry / idealized bathymetry results were likewise similar to Figure 16. These results suggest that it is the local bathymetry in the vicinity of the headland which determines the size and shape of the eddy. This result is in keeping with the theory of *Middleton et al.* [1993] concerning the generation of turbulence by complex subsurface topography near the tip of headlands. The only detectable difference caused by the headland's geometry was that the smoother coastline shape produced a slightly smoother eddy, lacking in smaller scale variability.

If a flat bottom does produce a bigger eddy it could be hypothesized that it is complicated bathymetry which predominantly leads to the injection of energy from the mean flow into turbulence. One might expect roughly equal amounts of energy dissipated by bottom friction in each numerical run, yet the more complicated real bathymetry clearly produces a smaller (less energetic) eddy. The eddy in the 'real' run positioned itself farther offshore in the deeper water where it obviously would suffer less from dissipation of its energy. It appears possible that a balance, between minimizing energy loss due to bottom friction and maximizing energy gain from the mean flow, may be important in determining the position of an eddy. The net effect of this balance would also have a crucial bearing on the size of the eddy.

5. DISCUSSION

A number of conclusions may be made from the combination of field and numerical experiments elucidated throughout this paper. Firstly, it appears that relatively small oscillations at the diurnal frequency in the magnitude of an otherwise steady free-stream forcing current will lead to the generation and decay of eddies at the same frequency in the wake. This phase-locking is not unlike the phase eddy result obtained by *Black and Gay* [1987]. In reality there are small oscillations in direction as well, which probably further complicate the flow regime, but it is difficult to examine such variations numerically. These directional fluctuations have the effect of varying the perceived length scale of the headland, which leads to variations in both the non-dimensional bottom friction number B and the Reynolds number Re. With these flow parameters changing dynamically the resulting recirculation will obviously be more complex.

Numerical trials with steady inflow conditions showed that an eddy takes about half a day to spin up in the lee of Bass Point. Thus the 'natural frequency' of the Bass Point system is of order one day, rather than, say, seven days. If the inflow conditions contain a number of frequency components, it is the component with significant magnitude closest to the natural frequency that will be amplified in the lee of Bass Point. This is the diurnal component. Thus, a resonance effect is the most likely explanation for the diurnal frequency observed in the lee of Bass Point.

The shear instabilities, generated in the shear layer close to the tip of the headland, eventually find themselves injected into the interior of the eddy, having the effect of producing a more variable zone of recirculation. These instabilities, which closely resemble Kelvin-Helmholtz instabilities, could easily be interpreted as a degree of turbulence, especially when viewing current meter mooring data from sparse moorings. Physically, these appear as smaller scale eddies on the shear line, as can be seen from the close-up view of Figure 13. They may be responsible for an interchange of ocean waters (and nutrients, biological life, and pollutants etc.) from the faster flowing mean flow to and from the calmer zone of recirculation.

Another important result is that rough bottom bathymetry appears to produce a smaller eddy. Although only deduced numerically by changing the model sea floor from flat to rough, it seems that complex bathymetry can lead to a decrease in the amount of energy transferred from the mean flow to a neighbouring eddy. It would appear reasonable to assume that the excess energy is transferred into smaller scale turbulence and then dissipated. This result is consistent with the findings of *Middleton et al.* [1993] that high levels of turbulent energy existed near regions of complex subsurface topography in the vicinity of the tip of Bass Point. Complicated jagged coastline shapes near the point of eddy generation do not seem to have the same profound effect on the recirculation as does the subsurface topography, possibly because a far greater proportion of the water is affected by the bottom than the coastline itself. The ability of the numerical model to resolve eddies was a crucial feature of the present results.

Freeland (1990) showed analytically that steady flow past a headland could generate standing topographic Rossby lee waves at sub-inertial frequencies. In the present case with poleward incident flow, any topographic waves would tend to travel equatorward. Thus it is conceiveable that the background diurnal variability could enhance a diurnal oscillation in the lee of Bass Point via a similar mechanism. However, a detailed study of this mechanism is beyond the scope of this paper.

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REFERENCES

Arakawa, A. and V.R. Lamb, (1977), Computation and Design of the Basic Dynamical Processes of the UCLA General Circulation Model, *Methods in Computational Physics, 17*, 174–265.

Black, K.P. and S.L.Gay, (1987), Eddy Formation in Unsteady Flows, *Journal of Geophysical Research, 92*, 9514–9522.

Camerlengo, A. and J.J. O'Brien, (1979), Open Boundary Conditions in Rotating Fluids, *Journal of Computational Physics, 13*, 522–535.

Church, J.A. and H.J. Freeland, (1987), The Energy Source for the Coastal-trapped Waves in the Australian Coastal Experiment Region, *Journal of Physical Oceanography, 17*, 289–300.

Denniss, T. and J.H. Middleton, (1994), Effects of Viscosity and Bottom Friction on Recirculating Flows, *Journal of Geophysical Research, 99*, 10183–10192.

Fandry, C.B., (1981), Development of a Numerical Model of Tidal and Wind-driven Circulation in Bass Strait, *Australian Journal of Marine and Freshwater Research, 32*, 9–29.

Flather, R.A. and N.S.Heaps, (1975), Tidal Computations for Morecambe Bay, *Geophys. J. R. Astr. Soc., 42*, 489–517.

Freeland, H.J., (1988), Diurnal Coastal-trapped Waves on the East Australian Continental Shelf, *Journal of Physical Oceanography, 18*, 690–694.

Freeland, H.J., (1990), The Flow of a Coastal Current Past a Blunt Headland, *Atmosphere-Ocean, 28*, 288–302.

Griffin, D.A. and J.H. Middleton, (1991), Local and Remote Wind Forcing of New South Wales Inner Shelf Currents and Sea Level, *Journal of Physical Oceanography, 21*, 304–322.

Israeli, M. and S.A. Orszag, (1981), Approximation of Radiation Boundary Conditions, *Journal of Computational Physics, 41*, 110–135.

Middleton, J.H., D.A. Griffin and A.M. Moore, (1993), Oceanic Circulation and Turbulence in the Coastal Zone, *Continental Shelf Research, 13*, 143–168.

Orlanski, I., (1976), A Simple Boundary Condition for Unbounded Hyperbolic Flows, *Journal of Computational Physics, 21,* 251–269.

Pattiaratchi, C., A. James and M. Collins, (1987), Island Wakes and Headland Eddies : A Comparison Between Remotely Sensed Data and Laboratory Experiments, *Journal of Geophysical Research, 92*, 783–794.

Pingree, R.D. and L. Maddock, (1979), The Tidal Physics of Headland Flows and Offshore Tidal Bank Formation, *Marine Geology, 32*, 269–289.

Pingree, R.D. and L. Maddock, (1980), The Effects of Bottom Friction and Earth's Rotation on an Islands Wake, *Journal of the Marine Biological Association of U.K., 60*, 499–508.

Proudman, J., *Dynamical Oceanography*, 409pp., Methuen, N.Y., (1953).

Signell, R.P. and W.R. Geyer, (1991), Transient Eddy Formation Around Headlands, *Journal of Geophysical Research, 96*, 2561–2575.

Strykowski P.J. and K.R. Sreenivasan, (1990), On the Formation and Suppression of Vortex Shedding at Low Reynolds Numbers, *Journal of Fluid Mechanics, 218*, 71–107.

Van Dyke, M., (1982), *An Album of Fluid Motion*, Parabolic Press, Stanford, Cal.

Wolanski, E., J. Imberger and M.L. Heron, (1984), Island Wakes in Shallow Coastal Waters, *Journal of Geophysical Research, 89*, 10553–10569.

Figure Captions

Figure 1 : Map of the Bass Point region showing the positions of the field moorings and the bottom bathymetry.

Figure 2 : Vector stick plots of hourly averaged data for each mooring during the entire time of deployment. The vertical scale varies in order to show more detail.

Figure 3 : The energy spectrum for each field mooring. The cross-shelf velocity U is represented by the dashed line and the longshore velocity V is the full line. The vertical scale varies in order to show more detail.

Figure 4 : Vector stick plots for each mooring for the period Aug 27-31, 1992. The scales are the same as in Figure 2.

Figure 5 : Velocity vectors for the ADCP transects conducted on 12 Sep., 1992. Definite reverse flow can be seen in the lee of the headland.

Figure 6 : Cartoon depiction of the current vectors at each mooring on Aug 31, 1992. The state of the flow varies from no eddy through to a strong eddy, and finally this eddy dies out. The velocity scale is represented at the bottom right.

Figure 7 : Contour plot of the topography near Bass Point as used in the numerical model. Complicated sub-surface features can be seen near the tip.

Figure 8 : Numerical vector time series of velocities at each mooring over a 3.5 day run with inflow matched closely to the real inflow data of mooring A from the field experiment. The scales are the same as that of Figure 4. Comparison with Figure 4 shows reasonable overall agreement between field and numerical results, although the numerical results lack the "noise" of the field results.

Figure 9 : The numerical energy spectrum for each near-shore mooring. The cross-shelf

velocity U is represented by the dashed line and the longshore velocity V is the full line.The vertical scale varies in order to show more detail. Comparison with the corresponding spectra of Figure 3 indicates a general qualitative agreement between the spectral energy densities of the field and numerical results. The vertical scale for D is different to that of B and C.

Figure 10 : Numerical current vectors showing an eddy soon after forming. Bottom topography is real and the inflow current has diurnal variations, and flows toward 202^{o}T.

Figure 11 : Current vectors showing the eddy scenario of Figure 9, twelve hours later. The original eddy has broken free of the tip of the headland and is decaying due to bottom friction in the shallower near-shore waters. A new eddy is starting to spin up at the tip.

Figure 12 : Numerical current vectors showing an eddy four days after forming. Bottom topography is real but the inflow current is kept constant in time, and flows toward 202^{o}T.

Figure 13 : A close-up of current vectors near the tip of Bass Point, 30 hours after commencement, showing Kelvin-Helmholtz-like instabilities. The bottom topography is real and the current is constant in time toward 202^{o}T. These instabilities can be detected in the larger scale plots but are less clear without the high spatial resolution shown in this diagram,

Figure 14 : Numerical current vectors showing no eddy 24 hours after commencement. Bottom topography is real and the inflow current is kept constant in time, but is toward 216^{o}T.

Figure 15 : Numerical current vectors showing an eddy 24 hours after commencement. The bottom topography is real, and the inflow current is constant in time to the south.

Figure 16 : Numerical current vectors showing an eddy 24 hours after commencement. The bottom topography is flat, and the inflow current is constant in time to the south. The headland geometry has been smoothed near the tip.