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Aspects of the hydrodynamics of Beatrix Bay and Pelorus Sound, New Zealand

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Abstract Hydrographic and current meter measurements were performed to determine the important physical processes in Beatrix Bay, an enclosed bay in Pelorus Sound, South Island, New Zealand over a 9-month period. The water within the bay was highly variable in temperature, salinity, and density, but strongly stratified on all occasions, with the stratification approximating a two-layer system. The stratification was usually dominated by salinity, but on one occasion, following a period of low rainfall, the stratification was dominated by temperature. A crude estimate of the residence time for the water in Pelorus Sound is calculated from the relaxation towards oceanic salinities during the dry period. The currents measured were largely tidal, and showed evidence of a strong internal tide as a result of the quasi-two-layer stratification. The tidal flows were larger than those predicted by a simple model.

Keywords Beatrix Bay; stratification; currents; freshwater residence time

INTRODUCTION

Beatrix Bay is an enclosed bay about two-thirds towards the seaward end of Pelorus Sound, one of two main sounds in the Marlborough Sounds on the northern end of the South Island of New Zealand (Fig. 1). Beatrix Bay is roughly circular with a diameter of about 4.5 km. To its south are two other enclosed bays, Crail Bay and Clova Bay. All three bays are approximately flat-bottomed and 30–35 m deep.

From September 1994 to June 1995 a hydrographic observational campaign was conducted in and around Beatrix Bay. The aim was to identify the important dynamics and flow regimes. In particular, the circulation and flushing rates of the water in the bay were of interest in light of the intensive mussel farming taking place. Measurements consisted of current meter data, thermistor chains, a tide gauge, and five CTD surveys.

We begin this paper by summarising information about Pelorus Sound to establish the larger picture. We then use the data collected within Beatrix Bay over the 10-month period to look at changes in the stratification of the bay. A period of effectively zero freshwater input allows an estimate of residence times of the entire Pelorus Sound system to be made. Finally, we use the current meter data to examine tides, internal tides, and non-tidal flows.

PELORUS SOUND

In order to understand and interpret Beatrix Bay data, it is necessary to study Pelorus Sound, as this Sound provides the source and sink of the water and dominates the dynamics which occur within Beatrix Bay. Pelorus Sound is about 50 km long, and has a surface area (including Kenepuru Sound, which forms a blind arm) of 290 km^2. Pelorus Sound is aligned roughly south-west to north-east, opening into the western end of Cook Strait. The depth of the main channel decreases from 70 m near the entrance to 30 m near the head. The Pelorus and Kaituna Rivers empty into the head of Pelorus Sound, with average transports of 43.0 and 5.4 m^3 s^{-1}, respectively. These rivers have catchments of 880 and 155 km^2, respectively, and the total

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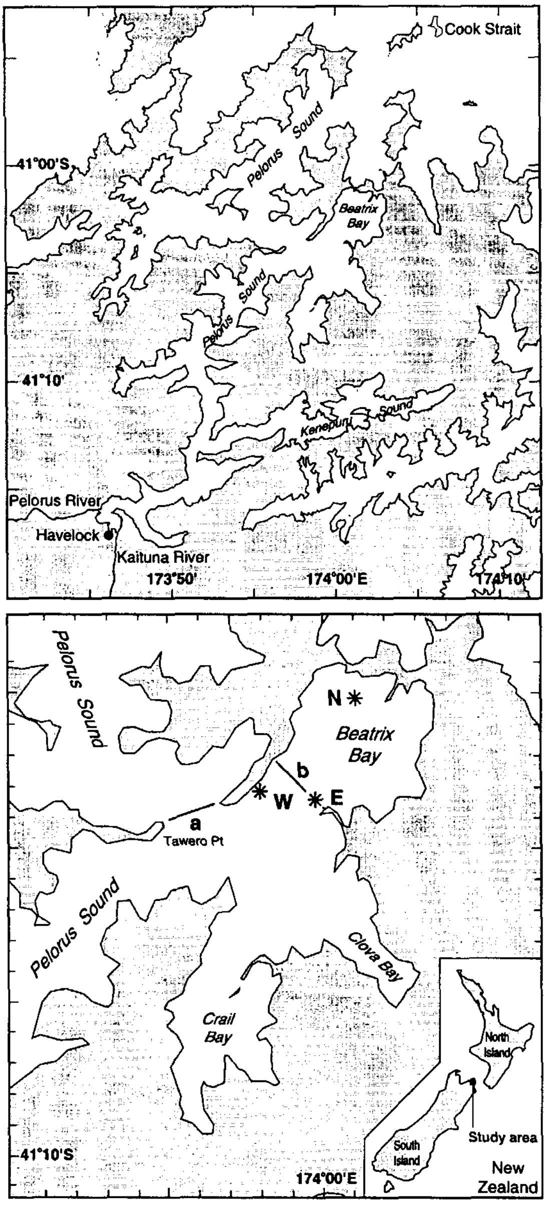


Fig. 1 Beatrix Bay location, mooring and repeat CTD locations, South Island, New Zealand.

catchment of Pelorus Sound, including the surface area of the sound itself, is 2110 km^2 (Heath 1974). The annual average freshwater input was estimated by Heath (1974) to be 99 m^3 s^{-1}. This implies a net input rate averaged over the catchment of 1.48 m year^{-1} and an average input rate over the area of the Sound of 3 cm day^{-1}. From the volume of freshwater in the sound during a salinity survey in June-July 1973 (180×10^6 m^3) and the mean freshwater input rate (8.55×10^6 m^3 day^{-1}), Heath (1974) estimated a freshwater turn-over time (Zimmerman 1988) of 21 days.

Rainfall onto the catchment is normally higher in winter than in summer and is intermittent. Since river flows respond quickly to high-rainfall events, freshwater input to the sound is also intermittent. In a typical year, several rainfall events deliver between 50 and 200 mm of rain in one day (Heath 1982). This range of daily rainfalls corresponds to a water volume falling on the catchment of 110–420 $\times 10^6$ m^3 and if all of this water were delivered to the surface of the sound and spread evenly over the surface, it would form a layer 0.4–1.5 m thick. An example of the sound's response to heavy rainfall events was seen in June 1975 (Carter 1976), when a thin (c. 2 m) surface layer of turbid, low-salinity water moved seawards through the sound at 0.65–0.90 m s^{-1}, implying a transit time over the 50 km length of the sound of about 1 day. The temporal variability of freshwater input means that Pelorus Sound undergoes a cycle in which freshwater spreads quite rapidly along the surface and is then mixed down and eventually flushed out.

The predominant tide in Pelorus Sound is semi-diurnal. The tidal range varies through a typical spring-neap cycle from 1.1 to 2.4 m (Lamont 1994). Tides at the head of Pelorus Sound lag the tides at the entrance by 75 min. There is a pronounced ebb dominance, i.e., the ebb tide duration is shorter than the flood tide and ebb currents are proportionally stronger than flood currents (Heath 1974). The ebb dominance results largely from overtides generated in Cook Strait, but there may be a contribution from shallow-water effects in the sound (Heath 1982).

Evidence of internal tides has been found in the Pelorus Sound system. Current meter readings in the main channel of Pelorus Sound in August 1974 showed that the semi-diurnal oscillations in the near-surface flow lagged those in the deeper water by 4.5 h (Heath 1976); the phase difference was smaller in October 1976 (Heath 1982). Material surfaces in the water (marked by isolines of salinity, nutrient, or chlorophyll concentration) move vertically with a different amplitude and phase from the surface (Heath 1976; Gibbs et al. 1991, 1992). For example, Gibbs et al. (1991) show the nutricline in Crail Bay oscillating with an amplitude (relative to a fixed depth) of 3 m while the free surface oscillates with an amplitude of 0.9 m. Heath (1976) concluded that the internal tide in the main channel

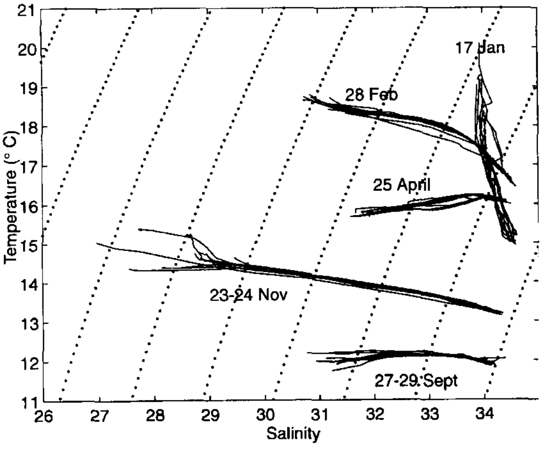


Fig. 2 T-S relations for the 5 CTD samplings.

of Pelorus Sound was generated by the abrupt change in depth in Pelorus Sound near its junction with Kenepuru Sound.

METHODS

From September 1994 to June 1995 an observational campaign was conducted in and around Beatrix Bay. There were permanent moorings at three sites labelled W (west side of the entrance), E (east side of the entrance), and N (north end of the bay) in Fig. 1. Current measurements were made continuously at two depths on moorings W and E and temperatures were measured at 9–10 depths at 48-min intervals at all three locations on secondary moorings. On five occasions, profiles of salinity and temperature were measured at a set of 10 sites in the bay and immediately outside the entrance. In addition, a tide gauge was deployed at the head of the bay (N in Fig. 1). Finally, some drogue measurements of currents were performed.

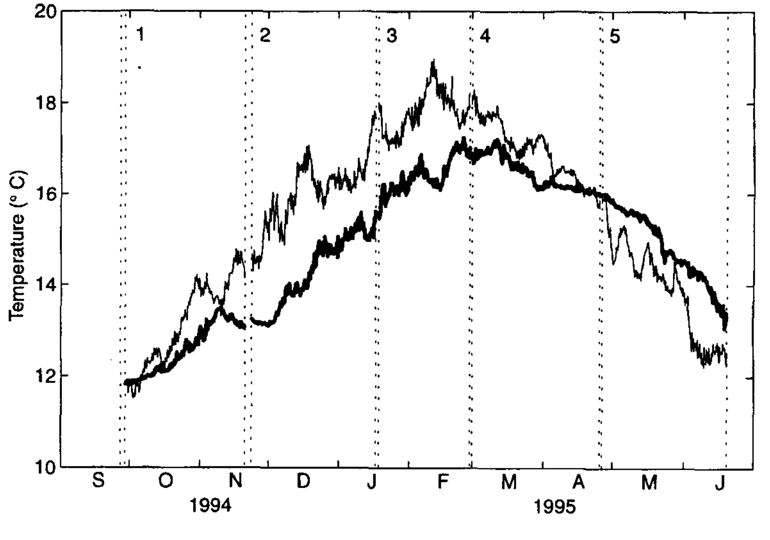
BEATRIX BAY RESULTS

Water properties

Conductivity (salinity), temperature, and depth (CTD) casts were performed at 10 stations within Beatrix Bay on five occasions between September 1994 and June 1995. Figure 2 shows the temperature-salinity (T-S) relations for each of these stations and each of the samplings. The dotted lines on the figure are isopycnals (lines of constant density). In addition, three thermistor chains were deployed (see N, W, and E in Fig. 1). The thermistor data are summarised in Fig. 3 which shows average recorded temperatures for depths < 10 m (fine line) and depths > 15 m (thick line). In the following paragraphs we describe the conditions seen in each sampling and describe the transitions between samplings.

The first sampling took place over 27–29 September 1994 and showed salinity stratification only; there was no significant temperature stratification in the bay, as shown by the flat T-S curve (Fig. 2) and the thermistor data (Fig. 3). A layer of freshwater-influenced water (salinity

Fig. 3 Temperature averages from the thermistor chains for two layers; < 10 m (thin line) and > 15 m (heavy line). The vertical dotted lines show the times at which the 5 CTD surveys were performed; the thermistor chains were recovered and redeployed at each of these surveys.



S ≈ 32) about 5 m deep overlays a halocline to the bottom (S ≈ 34). By the time of the second sampling (23–24 November 1994), there had been an influx of fresh water, with resulting surface salinities as low as 27. In addition, the entire water column had warmed by at least 1°C and there was significant temperature stratification with surface water up to 2°C warmer than the water at the bottom of the bay. The stratification again approximated a two-layer system, with a 10 m thick surface layer with (T ≈ 14.7°C, S ≈ 29) overlaying a bottom layer (T ≈ 13.1°C, S ≈ 34).

The third sampling (17 January 1995) showed a huge change in characteristics, with the salinity stratification now minimised and 5°C of temperature stratification. The thermistor time series gave no corresponding indication of this marked change in salinity stratification. At this time, the temperature stratification was fairly linear between the surface and the bottom. In addition, over this transition the whole water column showed significant warming and the bottom water became saltier. The lack of surface freshwater could be attributed to a period of low freshwater inflow, as indicated by the Pelorus River flow data (Fig. 4). The cool temperatures at the bottom are approximately equal to contemporaneous sea surface temperatures in Cook Strait, suggesting a deep inflow of sea water. With the November-January time period being the height of summer, strong surface heating would be expected and would account for the temperature stratification.

By the time of the fourth sampling (28 February 1995), the surface water was beginning to cool and showed some dilution (again, consistent with the Pelorus River flow and the ebb of summer). However, the bottom water was continuing to warm, an indication of the thermal inertia of the deeper water and different time constants for the shallow and deep water masses. There was a fairly well-defined halocline at depths varying between 7 and 12 m, whereas the temperature decreased more linearly with depth.

Between the fourth and fifth samplings, the surface temperature continued to cool, and the deeper water began to cool, but at a slower rate. The difference in cooling rates meant that by the time the final sampling took place on 25 April 1995, the surface waters were 0.4°C cooler than the bottom waters. The stability of the water column was maintained by the salinity stratification, with a very well-defined shallow layer about 7 m deep in the north-eastern end of the bay and the rest of the bay showing a gentler transition between the layers.

Although there are no later CTD data, the thermistor time series (Fig. 3) indicates that the surface layer continued to cool more rapidly than the deeper layer reaching 1.5°C cooler than the deeper layer in June. This implies that the surface layer must have been much fresher in order to maintain static stability. Thus, although our data do not span a year, the existence of a cool, fresh layer overlaying a warmer, saltier layer through May and June, together with the evidence that this condition occurred the previous September (right at the beginning of our sampling), indicate that this scenario may persist as a winter condition between May and September.

Residence times

The residence time is the representative time which a particle of water spends in a certain volume. This time is of interest for non-conservative properties, for example, the "older" the water, the more depleted in nutrients it becomes. With intensive mussel farming taking place in Pelorus Sound, an estimate of residence times will aid understanding of the biology and any later development of physical or biological models.

We can model the entire Pelorus Sound system as a simple single-box model. If we define the salinity of the resident water as $S(t)$, input salinities as S_F (freshwater) and S_S (seawater) and assume input fluxes F_F and F_S, respectively, with an outgoing flux of F_0, then we can write (with V being the volume of Pelorus Sound):

$$V.S(t+\Delta t) = V.S(t) + F_F \Delta t.S_F + F_S \Delta t.S_S - F_0 \Delta t.S(t)$$

and $F_O = F_F + F_S$, (conservation of mass).

The freshwater flux is known to be highly variable (Fig. 4), however, between samplings 2 and 3 (23–24 November 1994 and 17 January 1995) (a period of 55 days), there is very low Pelorus River flow and we can assume $F_F = 0$. The seawater flux F_S could be assumed to be approximately constant, as the source (Cook Strait) is relatively constant. The above equation therefore becomes:

$$\frac{dS}{dt} = \frac{1}{V}\left[F_S S_S - F_0 S\right]$$

which has a solution:

$$S = \frac{F_S}{F_0} - Be^{\frac{V}{F_0}t}$$

with B an arbitrary constant.

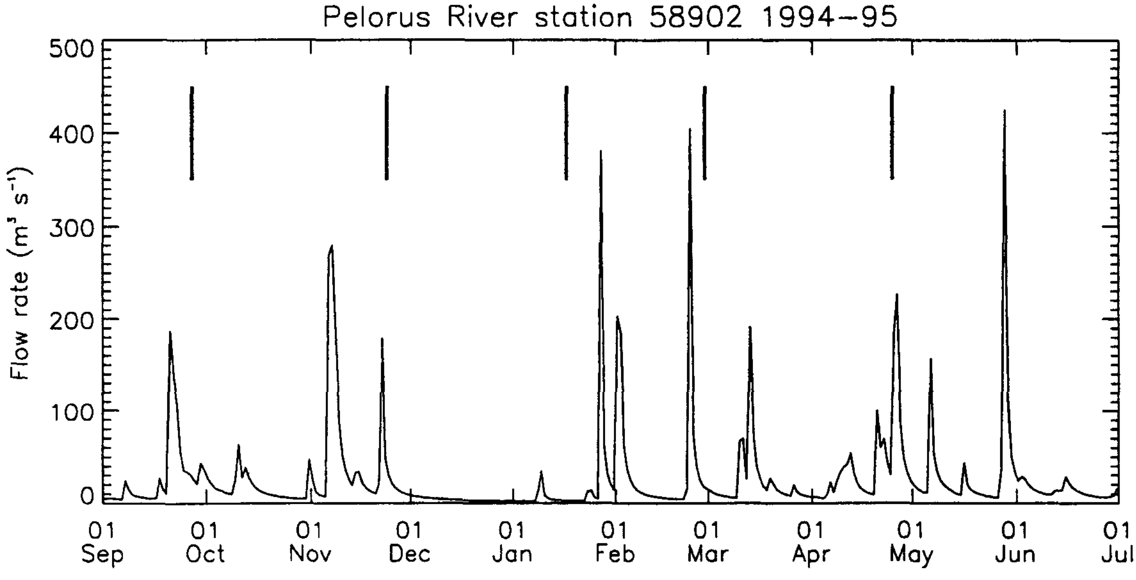


Fig. 4 Pelorus River flows; the vertical bars denote the 5 CTD sampling times.

Applying boundary conditions from the CTD data: @t = 0, S = 32.0, @t = 55 days, S = 34.25, enables the time constant, $\tau = \frac{V}{F_0}$, to be calculated as 24 days. This can be interpreted as a crude estimate of the residence time of water in Pelorus Sound, and compares well with an estimate of freshwater turn-over of 21 days by Heath (1974).

Currents, tides, and internal tides

The current meter data collected in Beatrix Bay were dominated by tidal energy. This is to be expected since the tidal prism volume, i.e., the volume of water between low and high tide levels, greatly exceeds the mean freshwater input over a tidal cycle. The tidal prism varies with the tidal range from 320×10^6 m^3 (neap) to 700×10^6 m^3 (spring). There is evidence of a strong internal tide, as could be expected given the propensity of the stratification to resemble a two-layer system.

From the sea level record, the major tidal constituents have been identified, and a sea-level time series has been calculated for the whole measurement period. The major constituents are the three semi-diurnal constituents M_2, S_2, and N_2 with the combination of these leading to a lunar semi-diurnal tide (period 12.43 h) modulated on a spring-neap cycle (as normally occurs around New Zealand) but with some variation in the amplitude. The tidal range varies from 1.1 m (typical neap) to 2.5 m (typical spring) and high and low tides at Beatrix Bay lag those at the entrance to Pelorus Sound by 40 min (Lamont 1994).

Figure 5 shows time series of velocity from the shallow (c. 5 m) current meter on the western mooring, W_1, on two different time scales; the current vector is separated into components directed into the bay (towards 45° T) and across the bay entrance (towards 135° T). Power spectra for the same components are shown in Fig. 6. There is a pronounced semi-diurnal oscillation in the current into the bay (see especially Fig. 5B), but not in the current across the entrance. The semi-diurnal oscillation maintains a more-or-less fixed phase relative to the astronomic tides and is therefore tidal in origin. The amplitude of this oscillation tends to be larger at spring tide than at neap tide (Fig. 5A), but the modulation of the amplitude is much less regular than it is for sea level oscillations. The velocity power spectra show the tidal peak at semi-diurnal frequency (0.08 h^{-1}), and also show that there is significant energy below 0.02 h^{-1} (0.5 d^{-1}). Currents at the other three meters also show a tidal oscillation, but it is not as pronounced at the meters on the east mooring.

The current associated with a cross-sectionally uniform tide has been calculated across a pair of cross-sections ("a" and "b" in Fig. 1) from the rate

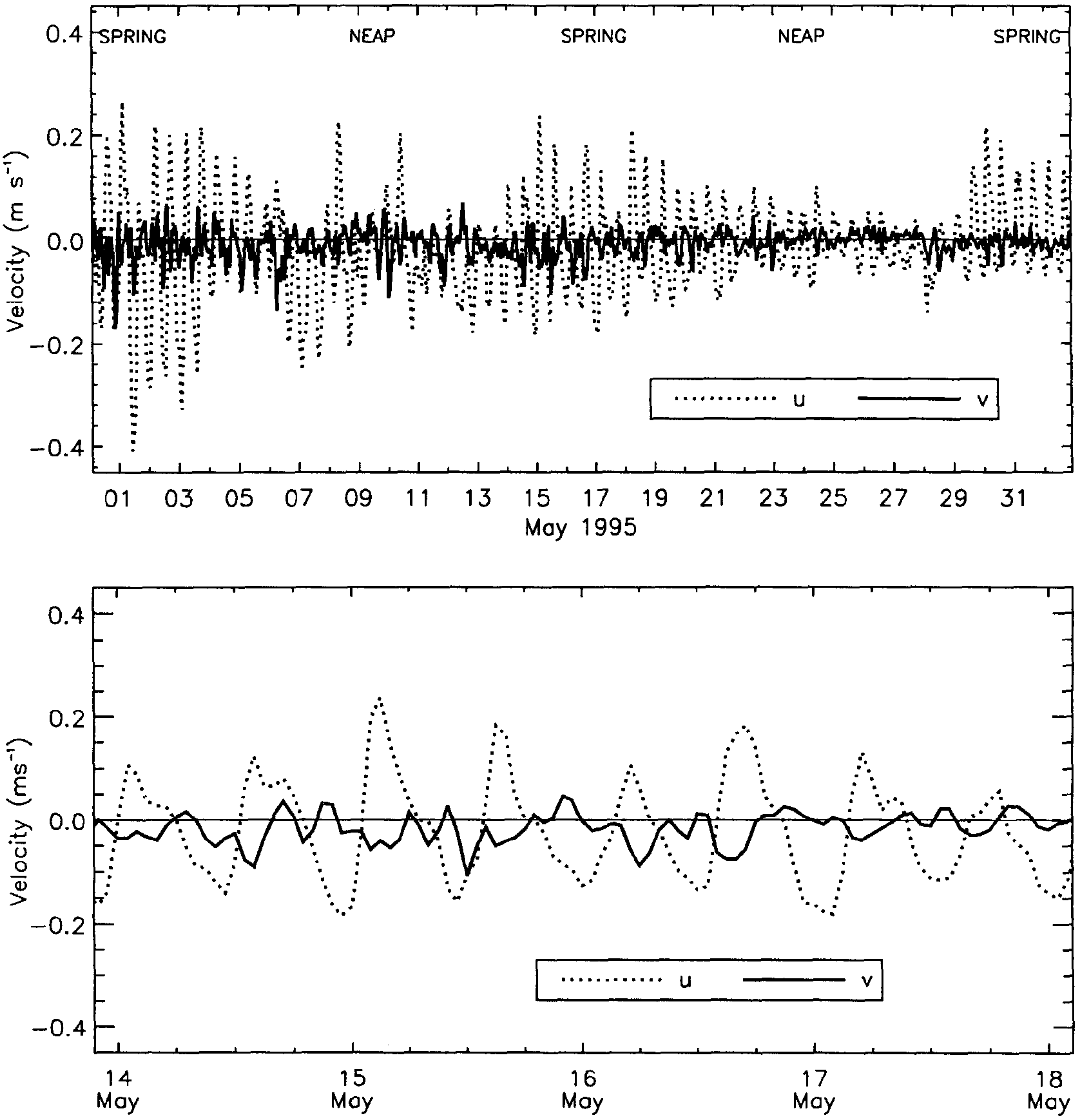
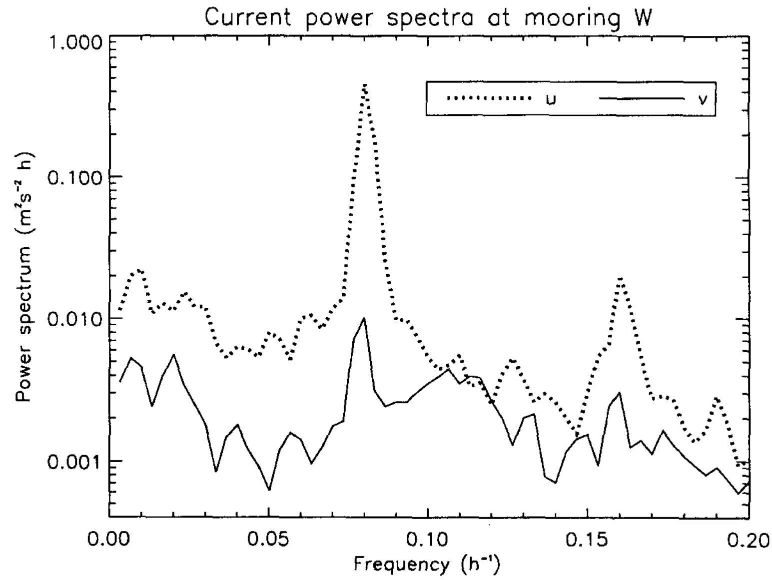


Fig. 5 Time series of velocity components at a current meter c. 5 m deep at location W on two different time scales. Component u is directed into the bay (towards 45° T) and v is directed across the bay entrance (towards 135° T).

of change in the predicted sea level. These are plotted in Fig. 7. The current through Section b (the entrance to Beatrix Bay) can be compared with the measured currents (Fig. 5). The current through Section a (the main channel of Pelorus Sound immediately to the west of Beatrix Bay) is of interest because it is rather large, and the inertia of this current is expected to have an effect on the hydrodynamics of Beatrix and Crail Bays. The ebb dominance of the tides in Pelorus Sound is manifested in the fact that the peak ebb currents (negative in Fig. 5 and 7) are 25% larger than peak flood currents.

The relationship between currents and the tidal forcing was investigated using a cross-spectral analysis between the current meter velocities at moorings W and E and the cross-sectionally uniform current. The results are expressed as a

Fig. 6 Power spectra of currents at a current meter c. 5 m deep at location W. Component u is directed into the bay (towards 45° T) and v is directed across the bay entrance (towards 135° T).



transfer function; Table 1 shows the magnitude and phase of that transfer function in the tidal, semi-diurnal frequency band. Tidal currents into Beatrix Bay exceed the cross-sectionally uniform current by a factor of about 3, except at E_2, where the tidal current is very weak. Note also the phase difference between tidal currents at the surface and bottom at mooring W. For the final row in Table 1, velocities were averaged over all four meters to estimate the average current over the Bay entrance. Ideally this should give the same result as the value calculated from the water level, in which case the transfer function would have an amplitude of 1 and a phase of 0°. The amplitude estimated from the analysis is 1.7, which indicates that a set of two current meters on each side of the entrance is

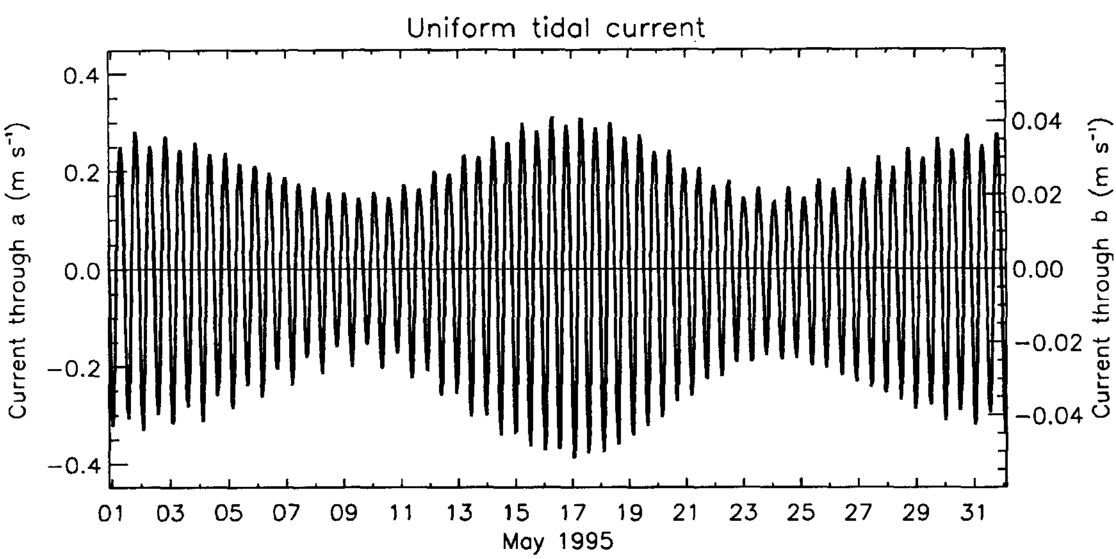


Fig. 7 Spring-neap variation in a uniform tidal current through sections a (Pelorus Sound main channel) and b (entrance to Beatrix Bay) (see Fig. 1).

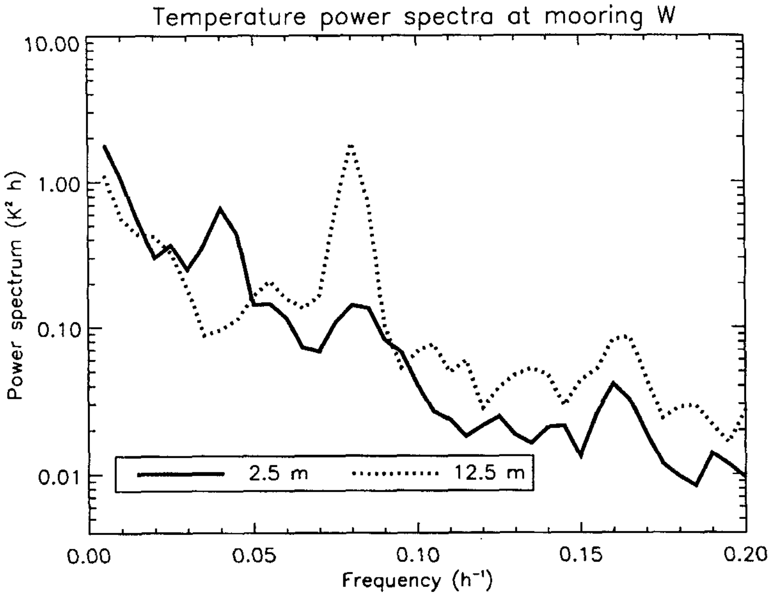


Fig. 8 Temperature power spectra at location W at depths of 2.5 and 12.5 m.

inadequate to characterise the mean velocity through the entrance.

The 90° phase difference between tidal currents at the surface and bottom at mooring W suggests an internal tide. The variation in the amplitude of the tidal oscillation (Fig. 5) is presumably related to stratification. Unfortunately, we do not have continuous salinity data that would enable this to be confirmed. The fact that the phase of the tidal oscillations at mooring W relative to the forcing is very consistent suggests that the internal tide is generated locally; it may be generated by the strong currents through the main channel of Pelorus Sound interacting with the bend in the channel at Tawero Point.

Table 1 Relationship between tidal currents and cross-sectionally uniform currents at tidal (semi-diurnal) frequencies.

Tidal velocity into Beatrix Bay at meter ...	...has amplitude = cross-sectionally uniform amplitude times ...	...leads cross-sectionally uniform tide by ...
W_1 (3 m deep)	3.2	+60°
W_2 (23 m deep)	2.8	–30°
E_1 (6 m deep)	2.4	0°
E_2 (27 m deep)	0.2	Variable
$\frac{W_1 + W_2 + E_1 + E_2}{4}$	1.7	+5°

Further evidence for the existence of internal tides in Beatrix Bay comes from the thermistor records. Power spectra from thermistors at all three moorings (e.g., Fig. 8) show a pronounced semi-diurnal peak; this is strongest in summer at the depth of the summer thermocline (10–15 m). Shallow thermistors (e.g., 2.5 m in Fig. 8) show a diurnal peak, probably caused by direct diurnal heating. The area under the semi-diurnal peak at 12.5 m depth in Fig. 8 corresponds to an oscillation of amplitude about 0.3°C. We interpret this to be a result of variations in the thickness of the layer above the thermocline (the thermistor depths being fixed relative to the surface). Taking the mean temperature gradient in the thermocline in summer to be 0.15°C m^{-1}, the amplitude of the oscillations in surface layer thickness is 2.0 m. The phase differs by 180° between the W and N moorings.

There were no current meters inside Beatrix Bay, but further information on the flow patterns inside the bay has been inferred from drogues which were tracked on several days. Drogue velocities are generally similar to current meter velocities when the two are adjacent, and drogue velocities in the middle of the bay are frequently between 0.1 and 0.3 m s^{-1}. Drogues frequently travel 1–2 km over 6 h. On some days there appears to be a clockwise circulation in the bay, but on others there is a predominantly in and out flow. These observations all suggest that surface water within the bay is flushed out by the tidal circulation. The drogue data do indicate that wind has significant influence on the circulation patterns.

CONCLUSIONS

Over all of the samplings, the water in Beatrix Bay almost always approximated a two-layer structure, the pycnocline being at 5–15 m; the density contrast resulted sometimes from salinity, sometimes from temperature, and sometimes from both. The exact structure of the pycnocline varied both within and between samplings, with the extremes being a well-defined two-layer system and a more gradual stratification. There is typically a difference in salinity between the surface and the bottom of –3 to –5 (surface less saline than the bottom); the temperature difference is positive (surface warmer than the bottom) from October to April and negative after that. The density gradient is dominated by salinity, except in January 1995 where the temperature difference is large and the salinity difference small. The water column was at no time well-mixed despite the shallow depth of the bay. The salinity of the bottom water was fairly constant at about 34.4–34.7, consistent with salinities in open Cook Strait. This indicated that oceanic water inflow occurs along the bottom of Pelorus Sound while diluted water flows out along the surface of Pelorus Sound in a classical estuarine circulation. The surface waters showed extreme variation in both temperature and salinity, forced by local heat fluxes and freshwater input while, interestingly, the maximum density in the water column decreased throughout the sampling progression.

The flow within Beatrix Bay results predominantly from the semi-diurnal tide with an ebb-dominance. Velocities at the mouth of the bay typically exceed those predicted by a cross-sectionally uniform tide by a factor of 3. The strong stratification results in the currents being highly baroclinic (variable with depth), with a strong internal tide. Unfortunately, because of gear failure, no meteorological forcing data were collected in Beatrix Bay over this period. The bay is surrounded by complex topography indicating that the wind stress should be non-uniform.

The stratification dominates the physical environment in Beatrix Bay, with the exact nature of the stratification determining residence times and horizontal and vertical processes. The freshwater input to Pelorus Sound together with local heat fluxes are therefore pivotal in understanding this environment.

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REFERENCES

Carter, L. 1976: Seston transport and deposition in Pelorus Sound, South Island, New Zealand. *New Zealand journal of marine and freshwater research 10*: 263–282.

Gibbs, M. M.; James, M. R.; Pickmere, S. E.; Woods, P. H.; Shakespeare, B. S.; Hickman, R. W.; Illingworth, J. 1991: Hydrodynamic and water column properties at six stations associated with mussel farming in Pelorus Sound, 1984–85. *New Zealand journal of marine and freshwater research 25*: 239–254.

Gibbs, M. M.; Pickmere, S. E.; Woods, P. H.; Payne, G. W.; James, M. R.; Hickman, R. W.; Illingworth, J. 1992: Nutrient and chlorophyll availability at six stations associated with mussel farming in Pelorus Sound, 1984–85. *New Zealand journal of marine and freshwater research 26*: 197–211.

Heath, R. A. 1974: Physical oceanographic observations in Marlborough Sounds. *New Zealand journal of marine and freshwater research 8*: 691–708.

Heath, R. A. 1976: Tidal variability of flow and water properties in Pelorus Sound, South Island, New Zealand. *New Zealand journal of marine and freshwater research 10*: 283–300.

Heath, R. A. 1982: Temporal variability of the waters of Pelorus Sound, South Island, New Zealand. *New Zealand journal of marine and freshwater research 16*: 95–110.

Lamont, I. C. 1994: New Zealand Nautical Almanac 1995. Hydrographic Office, Royal New Zealand Navy, Auckland.

Zimmerman, J. T. F. 1988: Estuarine residence times. *In*: Kjerfve, B. *ed*. Hydrodynamics of estuaries. Vol. 1, pp. 75–84. CRC Press, Boca Raton, Florida.