



Acoustic Doppler Current Profiler measurements of tidal phase and amplitude in Cook Strait, New Zealand

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Abstract—Strong tidal flows are observed in Cook Strait which separates the North and South Islands of New Zealand. The high velocities within the 30 km wide Strait result from a 140° phase difference in the M_2 tide between the ends of the Strait. Extraordinarily 135° of this phase difference occurs over just 40 km in the narrowest section of the Strait. Measurements from a ship mounted Acoustic Doppler Current Profiler (ADCP) over a single tidal cycle are used to determine the horizontal and vertical variation of tidal phase and amplitude in the Strait. Results show that tidal velocity amplitude ranges from 70 cm s^{-1} on the west of the Strait to 140 cm s^{-1} on the east. There was little amplitude variation over most of the water column. The eastern side of the Strait led the west by 20° . Near bottom velocity led surface velocity by approximately 10° due to the effect of bottom friction on the oscillating flow. Results from a subsequent 1 month deployment of ADCPs on the same line as the ship track are used to hindcast the semi-diurnal tide on the day of the shipboard measurements. The shipboard measured semi-diurnal tidal amplitude and phase agree extremely well with the hindcast composite of the three largest tidal constituents. Thus shipboard measurements over a single tidal cycle were able to accurately determine the horizontal and vertical variation of phase and amplitude of the semi-diurnal tide in Cook Strait.

INTRODUCTION

Cook Strait separates the North and South Islands of New Zealand near 41°S (see Fig. 1). Approximately 30 km wide and 100 m deep, the Strait has a reputation for strong winds and tides (HEATH, 1971). The dominant M_2 tide moves as a wave in an anticlockwise direction around the continental shelf of New Zealand. This results in a phase difference of 140° between the ends of Cook Strait (HEATH, 1977). Remarkably a 135° phase difference occurs over just 40 km in the narrowest section of the Strait around Cape Terawhiti. This extraordinarily rapid phase variation results in strong tidal velocities within the Strait reputed to be up to 350 cm s^{-1} (HYDROGRAPHIC DEPARTMENT, 1958). VENNELL and COLLINS (1991) observed bursts of 300 cm s^{-1} in the eastern Strait. In addition, the winds within the Strait are notoriously strong as it is one of a few gaps in the mountain chain extending over 1000 km from the centre of the North Island to the south of the South Island.

To the north of the Strait the shelf is broad, flat and approximately 100 m deep (see Fig. 1). To the south lies the head of the Cook Strait Canyon which falls off rapidly to 1000 m where it joins the head of the 3000 m deep Hikurangi Trench. The 240 m deep Terawhiti

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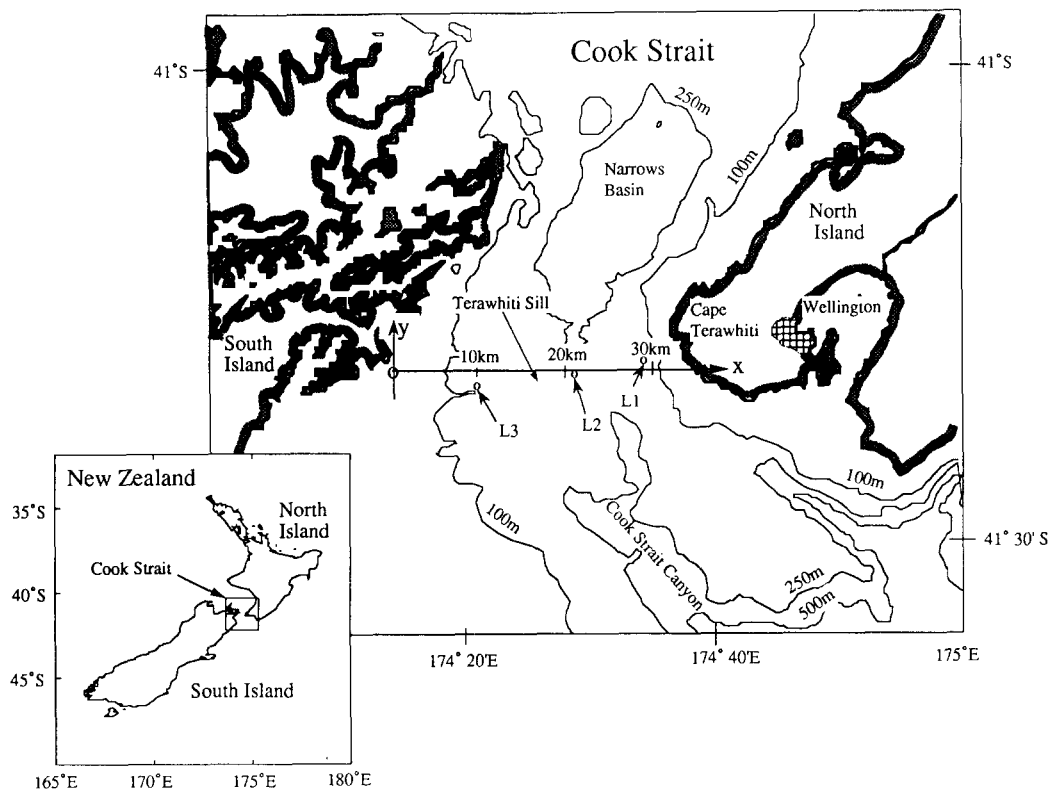


Fig. 1. Map of Cook Strait showing bathymetry. Insert shows location of Cook Strait. Axes give the coordinate system used in the text. The origin of the coordinate system is at $41^{\circ}19.5'S$, $174^{\circ}15'E$. The ship's track consisted of eight crossings of the Strait along the x axis between 0 and 30 km. L1 and L2 give the locations of moored ADCPs, and L3 a current meter mooring of VENNEL and COLLINS (1991).

Sill joins the North and South Islands and separates the Cook Strait Canyon from the 350 m deep Narrows Basin to the north.

Various means have been used to measure flow within the Strait: drift cards; electropotential (GILMOUR, 1960); drogue (SANDERSON, 1979); and even the trajectories of cross-Cook Strait swimmers (HEATH, 1980). Current meter measurements have been made by HEATH (1986). His two moorings within the Strait were deployed for periods of 65 and 82 days in water depths of 92 m and 201 m with meters 5 m and 50 m above the bottom. VENNEL and COLLINS (1991) give the results of a 1 month deployment of upward looking Acoustic Doppler Current Profilers (ADCPs) moored on the bottom of Cook Strait. One ADCP was deployed on the eastern end of the Terawhiti Sill; the other at the saddle point of the Terawhiti Sill (L1 and L2 in Fig. 1). In addition, a pair of conventional current meters were deployed on a mooring at the western end of the Terawhiti Sill (L3 in Fig. 1).

Shipboard ADCPs have been used to measure the spatial variation of tidal flow around a headland by GEYER and SIGNELL (1990) and in a channel by STIMPSON *et al.* (1990). The measurements presented here were made with a ship mounted ADCP during repeated crossings of the Strait over a 14 h period. Although the data set is short the ADCP gave a

spatial resolution, both horizontal and vertical, which would be difficult to achieve with conventional moored current meters. The ADCP data were used to determine the horizontal and vertical variation of tidal phase and amplitude within the Strait for the observed tidal cycle. Tidal analysis of the ADCP measured velocities was done following the method of SIMPSON *et al.* (1990) to determine the flow structure in a channel from shipboard ADCP measurements. The results compare extremely well with the measurements from the moored instruments of VENNELL and COLLINS (1991).

THE DATA

The nominal cruise track across Cook Strait consisted of repeated crossings of the Strait along $41^{\circ} 19.5'S$ turning as close as possible to the sides of the Strait. Eight crossings at approximately 9 knots were made over a 14 h period beginning at 14:00 on 24 July 1989 NZST (NZST is 12 h ahead of GMT). The ship track was generally within 1.5 km of the intended cruise track. On two occasions the ship veered more than 1.5 km off track to avoid other Strait traffic. For the purposes of this analysis the x axis is east, the y axis north and the spatial origin is at $41^{\circ}19.5'S$, $174^{\circ}15'E$ (Fig. 1). Times are in h relative to slack tidal flow in the centre of the Strait which occurred at 20:15 NZST on 24 July 1989. Global Positioning System (GPS) satellite navigation was available for most of the 14 h period. Gaps up to 1 h long within a crossing were filled by integration of the ADCP measured bottom velocity from the last known GPS position. The results of the integration agreed well with the next available GPS position.

The 300 kHz RD Instruments ADCP was used aboard the 70 m R.V. *Rapuhia*. The transducer was 5 m below the surface and the first depth bin began 7 m below the surface. The nominal vertical resolution was set to 4 m, as was the pulse length. The data from the uppermost depth bin was discarded as it appeared to be contaminated by the flow around the ship's hull. Estimated RMS uncertainty of the ADCP measured velocity was $1\text{--}2\text{ cm s}^{-1}$.

The data consisted of 277 ADCP velocity profiles. Each profile was either a 2.5 or 5 min average of once per s pings. Depths where the ADCP returned less than 50% good data during the averaging period were discarded. After rejecting profiles which were taken too far off the nominal cruise track (i.e. those greater than 5 km off) and those profiles where the ADCP was unable to bottom track, 214 profiles remained for analysis. Generally the ADCP returned good data between 11 m below the surface and 85% of the water depth. Over this depth range raw profiles showed the flow to be almost uniform with depth except for a slight weakening near the bottom.

ADCP measurements in the lower 15% ($\sim 15\text{--}40\text{ m}$) of the water column are not useable due to contamination by side lobe reflection. SIMPSON *et al.* (1990) used the quadratic profile of BOWDEN and FAIRBAIRN (1952) to extrapolate their measurements to the bottom. Tidal phase variations, of order 10° , were observed in the lower 30 m in Cook Strait by VENNELL and COLLINS (1991). The quadratic profile does not allow for phase variation, consequently no attempt was made to extrapolate the profile into the lower 15% of the water column. The measurements were extrapolated to the surface assuming there was no shear near the surface.

Four CTD stations conducted on the initial crossing showed the Strait to be vertically well mixed. Even in the deepest section of the Strait vertical variations of temperature and salinity were less than 0.5°C and 0.4 ppt respectively. There were however horizontal

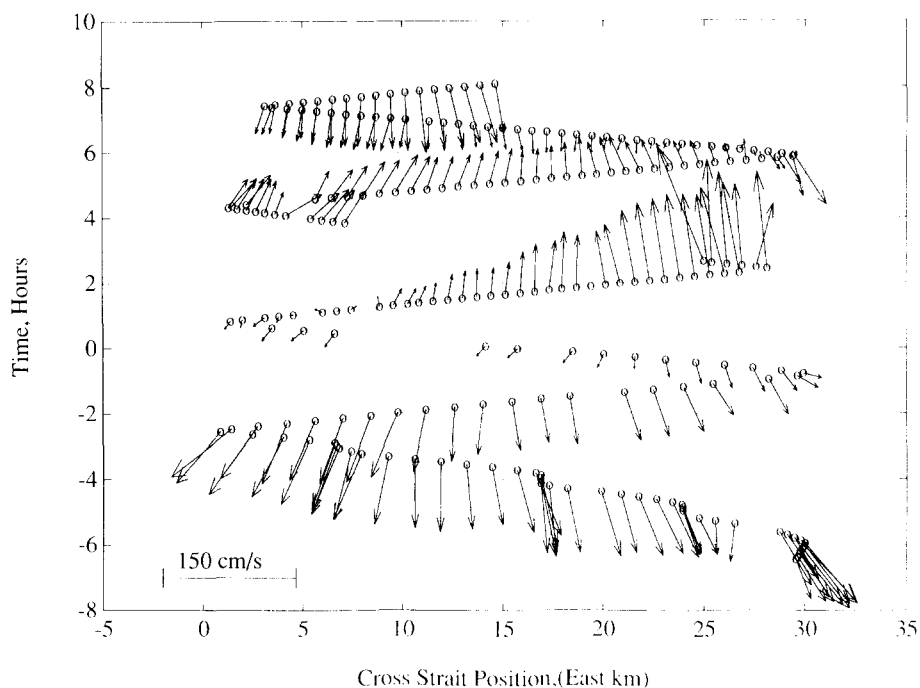


Fig. 2. Space time diagram of ship "position": x axis is the cross Strait position; y axis is time in h relative to 20:15 NZST on 24 July 1989. Circles give ship position and arrows the depth averaged ADCP measured velocity.

differences of 1°C and 0.5 ppt across the Strait which probably result from the influence of several water types which exist outside the Strait.

The "positions" of the good profiles are plotted on a space-time diagram in Fig. 2 together with the depth averaged horizontal velocity for each profile. This figure clearly shows the alternating flow through the Strait. To be consistent with the published tide tables for Wellington Harbour, the northward flow will be referred to as the flood tide and the southerly flow as the ebb tide.

Each crossing took approximately 1.75 h, a significant fraction of the M_2 tidal period. Thus crossings cannot be considered instantaneous and ADCP profiles gathered on any single crossing contain information about both the spatial *and* temporal variation of flow within the Strait. This makes it difficult to isolate spatial and temporal variations when viewing the data as in Fig. 2.

METHOD OF ANALYSIS

The temporal and spatial variation in the 30 km extent of the cruise track can be isolated following the method of SIMPSON *et al.* (1990). The 30 km wide extent was broken into 12 2.5 km wide horizontal bins. Data collected while the ship was in a particular horizontal bin were considered as a time series of profiles representative of the centre of the horizontal bin. The profiles were vertically averaged into 8 m depth bins. The data which falls into a particular horizontal and depth bin was treated as a time series and analysed using

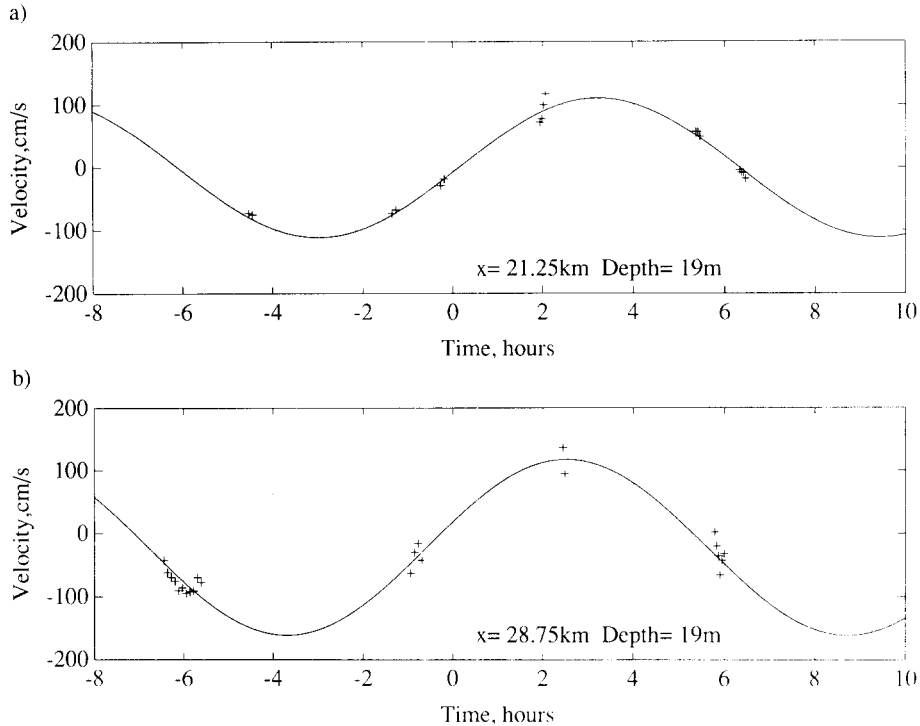


Fig. 3. Comparison of measurements and tidal fit of M_2 period sinusoid and mean offset. Plus symbols (+) give the measurements and the solid line gives the fitted curve of velocity along the major axis of the tidal ellipse. The major axis is orientated approximately north–south. (a) Measurements and fit for a representative bin in the deepest section of the Strait near the surface ($x = 21.25$ km, depth = 19 m); (b) Measurements and fit for a near surface depth bin at the eastern side of Cook Strait ($x = 28.75$ km, depth = 19 m).

conventional tidal analysis techniques (GODIN, 1972). A representative time series is shown in Fig. 3(a). The data form four–seven clusters corresponding to the passage of the ship through the horizontal bin. A sinusoid of M_2 period plus a mean offset was fitted to each time series using the method of least squares. The sinusoidal component of the fit will be referred to as the tidal component and the offset as the fitted mean. Note that the algebraic temporal mean of the data in any bin is a biased estimate of the actual mean as measurements are not evenly spaced in time and occur at different times of the tidal cycle.

The results of the tidal analysis were an estimate of the semi-diurnal tidal ellipse parameters for each 2.5 km wide, 8 m deep bin for which there were sufficient data (>8 data points) [see GODIN (1972) for calculation of ellipse parameters]. Generally 12–20 points fell within each bin. Excluding the easternmost horizontal bin, the variance of the residual not explained by the tidal analysis ranged from 8 cm s^{-1} on the west to 20 cm s^{-1} on the east. This compared to tidal amplitudes of 70 cm s^{-1} on the west and 140 cm s^{-1} on the east. Although each 2.5 km wide, 8 m deep bin was fitted independently, tidal ellipse parameters generally varied smoothly across the Strait and in the vertical.

Sensitivity of the fitting to changes in the period of the sinusoid was tested by fitting the depth averaged velocity in each horizontal bin with sinusoids of periods ranging from 11 to 14 h. The variance of the tidal residuals in all horizontal bins was not very sensitive to

changes in period. The period for which the variance of the residual was a minimum in each bin ranged from 12 to 13 h with a mean of 12.5 h. This mean is reassuringly close to the 12.4 h period of the M_2 tide.

The data and fitted curve for a near surface depth bin in the easternmost horizontal bin are shown in Fig. 3(b). Tidal residuals in this easternmost bin were 50% higher ($\sim 30 \text{ cm s}^{-1}$) than those in other horizontal bins. In addition, tidal ellipse parameters and fitted mean velocity in the easternmost bin did not continue the cross Strait trend exhibited by the other horizontal bins (see Figs 4, 5 and 6). One possible reason for this difference is that the ship made only four passes through the easternmost horizontal bin because it was at the end of the section [compare Figs 3(a) and (b)]. Thus temporal resolution in this bin was lower and consequently estimates of tidal ellipse parameters would be expected to be less reliable. Tidal ellipse parameters from the westernmost bin, which had a similar temporal resolution, had residual variance similar to mid-Strait bins and tidal ellipse parameters were an extension of the cross Strait trend. Thus reduced temporal resolution cannot completely explain the difference observed in the easternmost bin. Another reason for the difference between the easternmost bin and other horizontal bins may be the strong flows of the Karori tidal rip current. The Karori tidal rip extends south from Cape Terawhiti and has velocities of up to 350 cm s^{-1} (HYDROGRAPHIC DEPT., 1958). Strong bursts ($\sim 300 \text{ cm s}^{-1}$) associated with the rip were observed at the easternmost moored ADCP of Vennell and Collins (L1 in Fig. 1). These bursts were observed during the southerly ebb tide and

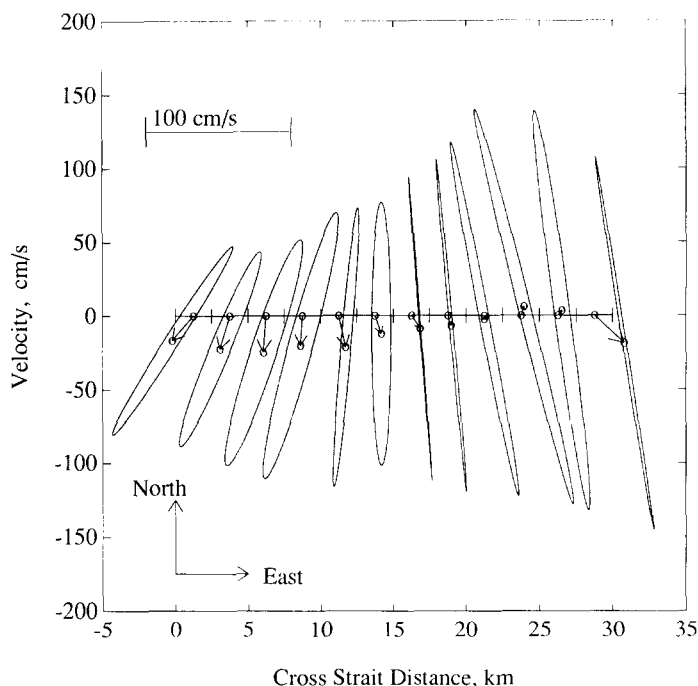


Fig. 4. Tidal ellipses of depth averaged flow for each of the 12 horizontal bins. The arrows joining the centres of the bins to the centres of the tidal ellipses indicate the direction and magnitude of the depth averaged fitted mean velocity. Tidal ellipses are orientated along isobaths which converge in a northward direction.

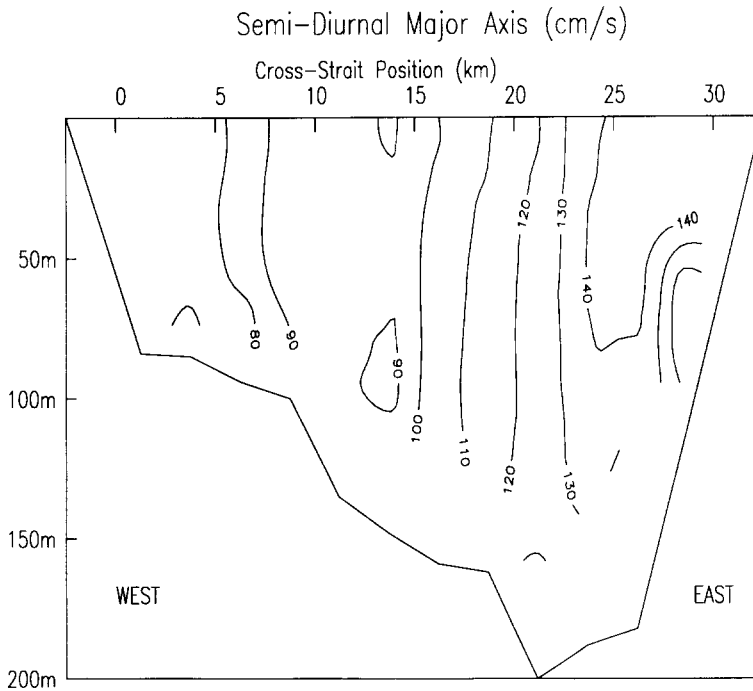


Fig. 5. Vertical cross Cook Strait section of the major axis of the semi-diurnal tide for 24 July 1989. Contours give amplitude in cm s^{-1} . Strongest flows are observed on the east with little vertical variation over the depth range of the measurements.

began with a jump in velocity of up to 100 cm s^{-1} over 2.5 min. These bursts were in addition to the normal tidal flow of up to 100 cm s^{-1} . The tidal residual velocity during these bursts began with a southwesterly burst 1–1.5 h after slack tide. The initial burst is followed by an anticlockwise rotation and decay of the residual velocity vector over a period of 2–3 h. VENNELL and COLLINS (1991) saw the bursts only during the southerly ebb tide. They suggest that inertia of the southerly flow around Cape Terawhiti causes it to move off shore. Thus at their mooring site, which is downstream of Cape Terawhiti during the southerly ebb tide, the rip is seen as a velocity burst as the rip moves offshore. They infer that during the northerly tide the rip lies shoreward of their mooring. L1 is approximately at the eastern extent of the shipboard measurements. Shipboard measurements during the first CTD station at the start of the initial crossing were made near L1 during the southerly tide (see Fig. 2). These measurements at $t = -6 \text{ h}$ begin 1 h after slack water and span less than 1 h [see Fig. 3(b)]. The measurements may be affected by the burst but are of too short a duration to observe the decay of the burst. However almost half the data points in the easternmost bin were made during this period near $t = -6 \text{ h}$. Any velocity associated with a burst is likely to distort the tidal analysis in the eastern horizontal bin. Thus the bursts may be responsible for the differences in tidal ellipse parameters between the easternmost bin and its neighbour.

RESULTS

Figure 4 gives tidal ellipses for the depth averaged flow. The semi-diurnal tide is essentially bi-directional and its orientation varies smoothly across the Strait. The

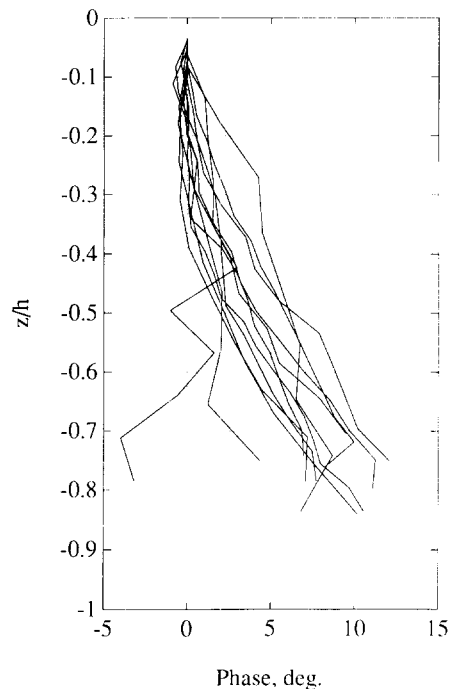


Fig. 7. Profiles of the phase relative to the uppermost measurement of the semi-diurnal tide for each of the 12 horizontal bins. The depth axis is normalised by the average depth within each horizontal bin. With the exception of the easternmost horizontal bin where tidal parameters are less well determined for reasons given in the text, the profiles show a high degree of consistency between horizontal bins.

resulting in the near bottom tide leading the surface tide by up to 10° . Figure 7 shows tidal phase in each bin relative to the surface phase on a normalised depth scale. This figure clearly shows there is a phase advance with depth, in most horizontal bins, of approximately 10° over the water column. This phase advance with depth is due to the effects of bottom friction on an oscillating flow and was explained by LAMB (1932).

DISCUSSION

VENNELL and COLLINS (1991) give the tidal analysis of data collected by 1 month ADCP deployments on the Terawhiti Sill at Locations 1 and 2 (L1 and L2, see Fig. 1). In addition they deployed a conventional current meter mooring on the western side of the Strait (L3 in Fig. 1). Their meters were all within 2.5 km of the nominal ship track (see Table 1). Their moored measurements show that M_2 is the dominant tide in Cook Strait with S_2 and N_2 having amplitudes 30 and 20% of the amplitude of M_2 (see Fig. 8). All other constituents had amplitude of less than 5% of the amplitude of M_2 . They also found that the relative amplitudes and phases of M_2 , S_2 and N_2 were very similar at all three locations on the Terawhiti Sill.

Using the moored current meter measurements of VENNELL and COLLINS (1991) a hindcast of the M_2 , S_2 and N_2 tides were made for a time near the middle of the 14 h period

Table 1. Comparison of shipboard ADCP measurements of semi-diurnal tide with hindcasts for the moored instruments of VENNELL and COLLINS (1991). Comparisons are made at mid-depth. The positions of L1, L2 and L3 are given in x and y for the coordinate system used in the text. Hindcasts of the amplitude and phase of the three largest constituents are given together with the amplitude and phase of a composite of these three constituents. All phases are relative to 20:15 NZST on 24 July 1989. The amplitude and phase of the semi-diurnal tide from the shipboard ADCP measurements at the moored instrument locations are given on the right

Location	Position		Amplitude			Phase at 20:15 NZST 24 July 1989			Composite $M_2 + S_2 + N_2$		Shipboard measured semi-diurnal tide	
	x km	y km	M_2 cm s^{-1}	S_2 cm s^{-1}	N_2 cm s^{-1}	M_2	S_2	N_2	Amplitude cm s^{-1}	Phase	Amplitude cm s^{-1}	Phase
L1	29	1.0	139	45	30	270°	35°	287°	149	288°	144	289°
L2	22	-0.9	124	39	25	250°	13°	262°	133	266°	132	268°
L3	10	-2.2	75	24	17	255°	17°	265°	82	271°	98	260°

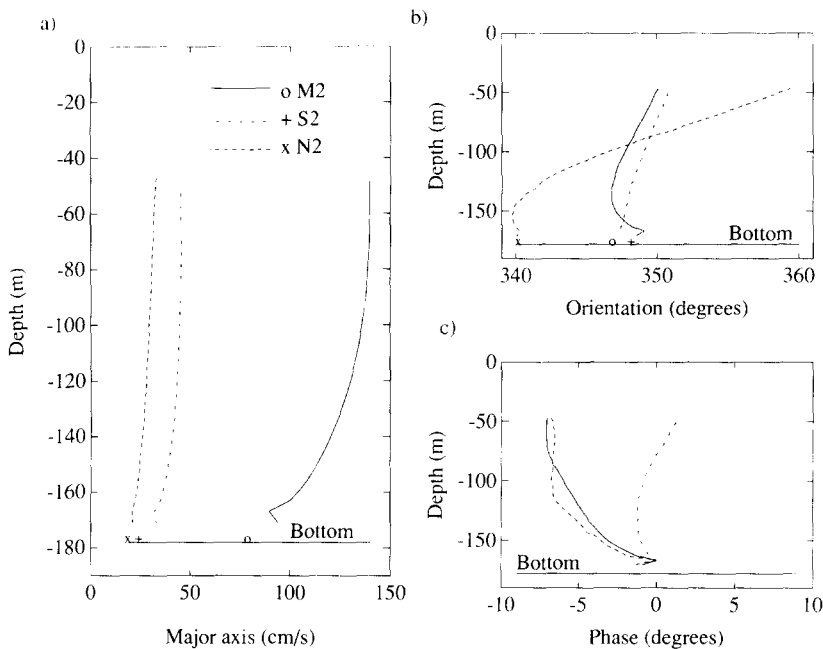


Fig. 8. Profiles of tidal ellipse parameters for the three largest constituents on the eastern side of Cook Strait (L1) (reproduced from VENNELL and COLLINS, 1991). M_2 is the solid line (—); S_2 the chain dashed line (- · - · -); and N_2 the dashed line (- - -). The lowest measurement, 7 m above the bottom, shows some contamination. Vertical resolution is 4 m. Ellipse parameters for a separate deployment of a current meter 1 m above the bottom are shown. Circle (o) the M_2 tide, Plus (+) the S_2 tide at this meter and Cross (x) the N_2 tide at this meter. (a) Major axis; (b) orientation of ellipse major axis relative to true north; (c) tidal phase relative to the second deepest ADCP measurement 11 m above the bottom. The relative phase of N_2 1 m above the bottom was 22° and is not shown in this diagram.

of shipboard measurements (see Table 1). The moored measurements show that at the time of the shipboard ADCP measurements, 93% of the semi-diurnal tide was due to M_2 . N_2 was almost in phase with M_2 at this time and contributed a further 19% to the semi-diurnal tide. S_2 at this time was beyond quadrature with M_2 and contributed -12% to the semi-diurnal tide. Thus the amplitude of the semi-diurnal tide from shipboard measurements in Fig. 5 was comprised of approximately 93% M_2 , -12% S_2 and 19% N_2 .

The amplitude and phase of a composite of the M_2 , S_2 and N_2 tides at the time of the shipboard measurements are given in Table 1. The composite of all significant constituents differed from the composite of M_2 , S_2 and N_2 by only 5% in amplitude and 3° in phase. As the smaller constituents do not significantly influence the composite the shipboard measurements will be compared to the composite of only the three largest constituents. The amplitude and phase of the shipboard measured semi-diurnal phase at the locations nearest to the moored instruments are also given in Table 1. At L1 and L2 the ship board measured total amplitude differs from that of the composite by less than 4%, while the phase differs by less than 3° . At L3 the shipboard measured amplitude is 12% higher than the composite and has a phase 10° behind the composite. The shipboard measurements agree surprisingly well with the hindcast of the moored measurements.

Figure 8 gives VENNELL and COLLIN's profiles of tidal ellipse parameters at their eastern most moored ADCP. Their profiles of amplitude [Fig. 8(a)] show little variation over the upper 85% of the water column as do the shipboard measurements (Fig. 5). They also observed a phase advance of the largest constituents with depth of order $10\text{--}20^\circ$ between the near surface and 10 m above the bottom [Fig. 8(c)]. The shipboard ADCP measurements also show a phase advance of approximately 10° over the top 85% of the water column (Fig. 7). Thus the 14 h period of shipboard measurements not only gave very similar estimates of semi-diurnal tidal amplitude and phase but also showed a vertical variation of phase comparable with the moored measurements.

For the moored measurements, the M_2 , N_2 and S_2 in the eastern Strait lead the saddle point of the Terawhiti Sill by 20° while the western Strait and the saddle point were almost in phase (see Table 1). The shipboard measurements also show the east to lead the west by 20° , though the variation of phase is uniform across the Strait.

HEATH (1977) analysed tidal height records for several sites in Cook Strait. His Fig. 1 shows the ship track along $41^\circ 19.5'S$ to be a line of constant phase for M_2 surface elevation. BOWMAN *et al.* (1980) give the results of a numerical model of the M_2 tide in Greater Cook Strait. In their model of surface elevation of the M_2 tide on the east leads that on the west by approximately 5° at $41^\circ 19.5'S$. Tidal surface elevation and tidal current do not necessarily have the same phase relationship along $41^\circ 19.5'S$, so that a comparison of variations in tidal elevation phase and tidal current must be treated with caution. However the measurement and model of surface elevation show that $41^\circ 19.5'S$ is a constant phase line or there is a slight lead by the eastern side. The shipboard and moored current measurements show a slightly larger, 20° , lead by the eastern side of the Strait.

CONCLUSIONS

The shipboard ADCP measurements clearly show the variation of tidal flow in Cook Strait. Tidal ellipse parameters varied smoothly both across the Strait and in the vertical. Thus a high degree of confidence can be placed in the ellipse parameters calculated from just 14 h of data.

The shipboard measurements of amplitude and phase agree extremely well with a hindcast composite of the three dominant constituents at the moored ADCPs of VENNELL and COLLINS (1991). There is a high degree of consistency between normalized profiles of tidal phase. The phase advance with depth ($\sim 10^\circ$) due to the effect of bottom friction on the oscillating flow is clearly evident in the normalized profiles. The magnitude of this phase advance is similar to that found in the moored ADCP measurements of VENNELL and COLLINS (1991). The western Strait is found to lag the eastern Strait by 20° . This lag is also similar to that of the moored measurements. Overall the results of 14 h of shipboard tidal measurements show extremely good agreement with the tides measured by the moored instruments. Thus shipboard ADCP measurements over short periods are a valuable tool for measuring the horizontal and vertical variation of tidal phase and amplitude in a strait.

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