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Shelf fronts and tidal stirring in Greater Cook Strait, New Zealand

Tidal stirring
Fronts
Stratification
Mixing efficiency
Cook Strait
Marée
Fronts
Stratification
Mélange
Détroit de Cook

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ABSTRACT

Numerical tidal simulations and hydrographic data from two austral summer (January 1980 and 1981) cruises were used to study tidal mixing variations, upwelling and circulation in the shelf seas of central New Zealand. Four classes of fronts were identified; the Cape Farewell upwelling front, two tidal mixing fronts spanning Cook Strait, a plume front bounding an intrusion of subtropical water driven into Cook Strait from the northwestern approaches, and a shelf break front east of Cook Strait. Bulk stratification correlated well with the h/u^3 stratification index ($r \sim 0.6$); potential energy deficit and surface to bottom temperature differences less well ($r \sim .53$ and $.38$, respectively); potential energy deficit showed some tendency to follow the bathymetry. A critical value of the stratification index $s \sim 1.5$ (c. g. s. units) appeared to separate mixed from stratified water at the tidal mixing fronts, in good agreement with results obtained in other semi-enclosed shelf seas in temperate latitudes. The data suggest that prevailing patterns of stratification can be considerably modified by the variable and often strong winds that frequent the region.

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RÉSUMÉ

Mélanges par la marée et fronts hydrologiques sur le plateau continental du détroit de Cook, Nouvelle-Zélande.

Des simulations numériques de la marée et les données hydrologiques recueillies lors de deux campagnes de l'été austral (janvier 1980 et 1981), ont été utilisées pour étudier les variations du brassage par la marée, le phénomène d'upwelling et la circulation dans les mers du plateau continental du centre de la Nouvelle-Zélande. Quatre types de fronts ont été mis en évidence : le front de l'upwelling du Cap Farewell, deux fronts transversaux dans le détroit de Cook associés au mélange par la marée, un front en panache limitant une intrusion d'eau subtropicale en provenance du Nord-Ouest, et un front au bord du plateau continental à l'est du détroit de Cook. Le gradient vertical moyen de densité est bien corrélé avec l'indice de stratification (h/u^3), ce qui n'est pas le cas du déficit en énergie potentielle et de l'écart de température entre la surface et le fond. Le déficit en énergie potentielle tend à suivre la bathymétrie. Aux fronts de mélange par la marée, la séparation entre les eaux bien mélangées et les eaux stratifiées correspond à des valeurs critiques de l'indice de stratification $s \sim 1{,}5$ (unités c. g. s.). Cette valeur de l'indice s est en bon accord avec les résultats obtenus pour d'autres mers semi-fermées à des latitudes tempérées. Les résultats suggèrent que les traits généraux de la stratification peuvent être facilement modifiés par les vents variables et souvent violents de cette région.

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INTRODUCTION

Tidal stirring variations in energetic shelf seas and some shallow estuaries can exert an important influence on the seasonal onset, progression and final distribution of summer water column stratification.

Although any study on the control of thermocline development must obviously include the important effects of wind stirring and advection, a number of investigators have demonstrated that a predictable pattern of summer stratification can often be identified with tidal mixing variations. These studies, first made in the shelf seas of the United Kingdom (Simpson, 1976; Simpson, Hunter, 1974; Simpson *et al.*, 1977; 1978; Pingree *et al.*, 1978) and later in the Bay of Fundy (Garrett *et al.*, 1978), the Bering Sea (Schumacher *et al.*, 1979) and Long Island-Block Island Sounds (Bowman, Esaias, 1981) were based on comparing the h/u^3 stratification index (where h is water column depth and u^3 the mean cubed tidal current; Simpson, Hunter, 1974) with hydrographic data.

The basic premise behind the stratification index is that two criteria must be met in the vicinity of a steady state tidal mixing front. First the power demand by a water column to maintain a given stratification while experiencing a surface buoyancy flux (arising from insolation) must be matched by the available power for mixing derived from the tides. Second, the stratification must be marginal. The first condition states that the water column is in a state of equilibrium (or perhaps slowly changing over a seasonal or biweekly cycle). The second defines the boundary between the mixed (low h/u^3) and the stratified (high h/u^3) water. A contribution to mechanical mixing can of course be provided by the winds.

These ideas are contained in the potential energy deficit V (relative to the mixed state) equation, developed by Simpson *et al.* (1978):

$$\frac{dV}{dt} = -\frac{\alpha g \dot{Q} h}{2c} + \varepsilon k \rho u^3 + \delta k_a \rho_a W^3, \qquad V \leqq 0. \quad (1)$$

The left hand side is the power deficit. This is the difference between the demand for (1st term rhs), and the supply of (2nd and 3rd terms, rhs) power from the tides and winds to maintain a steady density profile. In principle, V could be obtained for a given location by integrating equation (1) from the beginning of the heating season with a knowledge of the time histories of $\dot{Q}$, u and W (*see* Fig. 1).

Thus at a location of frontogenesis as depicted in Figure 1 *b*, both dV/dt and $V \sim 0$ during the summer months. Hence, in the absence of winds,

$$\frac{h}{u^3} = \frac{2\varepsilon k \rho c}{\alpha g \dot{Q}}, \quad (2)$$

defines the location of the front if the right hand side is considered constant for a given locality.

The stratification parameter has also proven to be a useful biological index in understanding the spring, summer and autumn phytoplankton production in the Celtic Sea and English Channel (Pingree, 1978; Pingree *et al.*, 1978), in explaining phytoplankton patchiness at a morphological group level in a major moderately stratified estuary (Bowman *et al.*, 1981) and the distribution of major herring spawning areas (Iles, Sinclair, 1982).

Results of several physical oceanographic studies are summarized in the Table. The stratification index is expressed as $s = \log_{10}(h/ku^3)$ in c. g. s. units where $k \sim .0025$ is the dimensionless bottom drag coefficient and u^3 is the mean cubed value of the depth averaged M_2 current. The ku^3/h can be identified as the kinetic energy dissipation rate per unit mass of water column. The value of h/ku^3 in c. g. s. units is roughly equal to the numerical value of h/u^3 in S.I. units preferred by some workers where u is now the amplitude of surface spring tidal currents.

Critical values of s ranged from 0.5 to 2.2, with a suggestion of an increase with increasing latitude. In higher latitudes one would expect a lower value of u in water of a given depth to provide sufficient dissipation to prevent the establishment of stratification. Some of these experiments allowed the estimation of the mixing efficiency, ε, the ratio of the kinetic energy used for mixing to that dissipated. Values ranged between 1.2 and 3.7×10^{-3} with the exception of the Bering Sea estimate which was much higher (20×10^{-3}).

We designed a study in the coastal ocean of central New Zealand (Fig. 2), a semi-enclosed shelf sea with strong tides, a great diversity in bottom depths, variable winds and the presence of water types of both subtropical and subantarctic origin. This provided an opportunity to test whether the stratification index has applicability to a southern hemisphere shelf sea of intermediate scale ($\sim 4 \times 10^4$ km^2), and whether or not tidal mixing fronts could be identified in the presence of upwelling fronts, water mass boundary fronts and meteorologically forced circulation patterns.

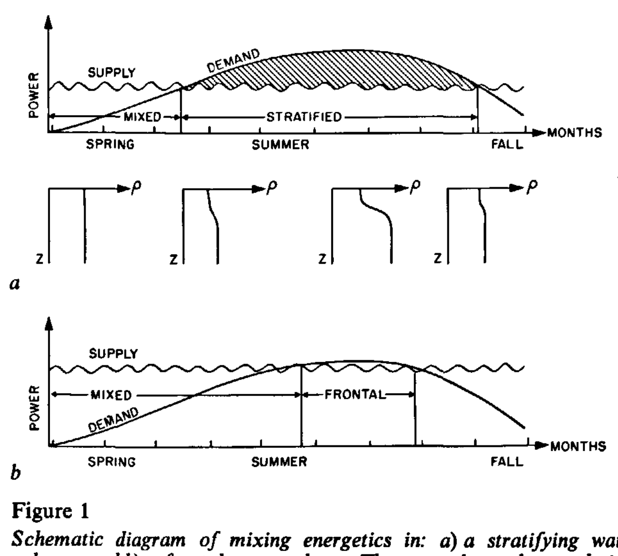


Figure 1

Schematic diagram of mixing energetics in: a) a stratifying water column; and b) a frontal water column. The power demand curve derives from the seasonal insolation cycle. The undulations in the power supply curve represent fluctuations in energy dissipation rates due to wind events and spring-neap cycles of tidal stirring. The shaded area is a measure of the work, V, required to mix away the stored buoyancy in the stratified water column. Typical density profiles are shown for the stratifying column.

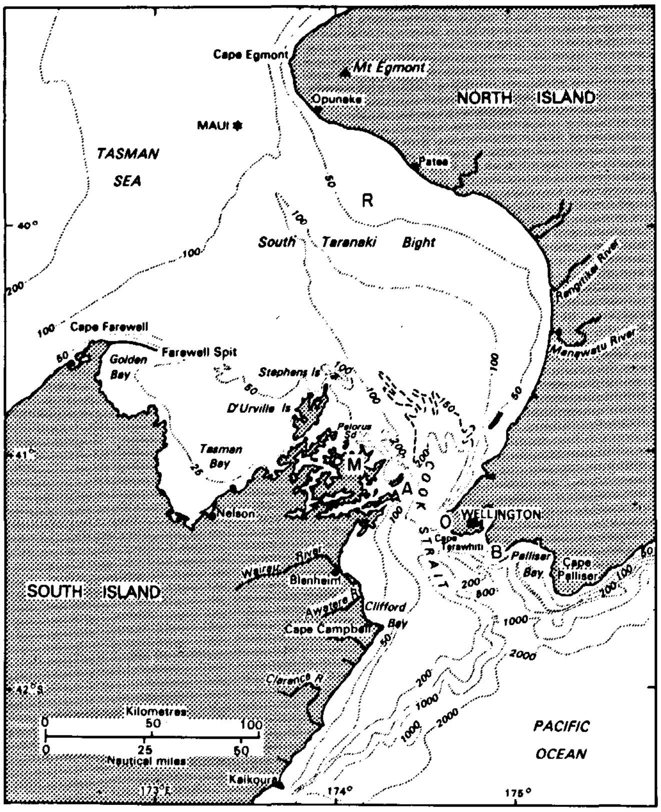


Figure 2

Locator map and depth contours (m) for Greater Cook strait. A, Arapawa Island; B, Baring Head; O, Oteranga Bay; R, the Rolling Ground; M, Marlborough Sounds.

GEOMORPHOLOGY

The bottom topography of the region includes the broad, flat, western continental shelf of South Taranaki Bight (Heath, 1974*a*; Ridgway, 1980) exposed to strong prevailing westerly winds, and the shallow sheltered embayments of Golden and Tasman Bays (Heath, 1973; 1974*a*; Ridgway, 1977) protected by Farewell Spit, a bar over 40 km in length built by easterly littoral drift around Cape Farewell. Cook Strait canyon rises steeply from over 2 000 m, penetrating westward through the Cook Strait narrows; the 200 m contour extends westward more than 100 km from the east coast. This submarine canyon is an extension of the 5 000 m Hikurangi Trench, a major feature of the island arc system of the southwest Pacific plate margin. The Marlborough Sounds are a series of drowned river valley estuaries which form a dendritic system of navigable waterways.

TIDES

The strong cooscillating tide in Greater Cook Strait is a consequence of the degenerate amphidrome on which New Zealand is centered, the semi-diurnal tide rotating counter clockwise around the land mass as a resonant trapped shelf wave (Bye, Heath, 1975). Cook Strait represents a short circuit across the center of the shelf waveguide, leading to strong currents driven by the

Table

ℑeographic ɔcation	Latitude	Time	h (m)	Current source	Drag coefficient k ($\times 10^{-3}$)	$\log_{10} h/ku^3$ ($cm^{-2}.sec.^3$)	ε ($\times 10^{-3}$)	Sensor	Reference
˥lamborough Head (East ɔoast, England)	54 N	July 1977	30	Model	2.5	1.2	–	STD, XBT	Pingree *et al.*, 1978
Jshant (Southwestern English ℑhannel)	49 N	July 1977	100	Model	2.5	1.5	–	STD, hose	"
Ɔrkney-Shetland Isles (North-vest North Sea)	59-60 N	July 1977	30-100	Model	2.5	2.0	–	XBT, hose	"
slay to Malin Head (between ;cotland and Ireland	55-56 N	July 1977	50	Model	2.5	1-1.5	–	STD	"
		June 1977	50	Model	2.5	1.0-2.05	–	STD	Simpson *et al.*, 1977
Vestern Irish Sea	53-54 N	August 1969 June 1973	100	Model	–	1.4-1.6	2.8-3.7	STD, thermal IR	Simpson and Hunter, 1974 Simpson *et al.*, 1977; 1978
;outhwestern approach to rish Sea (station Georges ℑhannel)	52 N	August 1972	30-100	Tidal atlas	–	1.3 1.1-1.6	2.8-3.7	STD, thermal IR	Simpson and Hunter, 1974 Simpson *et al.*, 1976; 1978
;ntrance to Bristol Channel, ;ngland	51° 15′ N	August 1972	60	–	–	1.1-1.6	–	STD	Simpson *et al.*, 1976
ℑomposite of UK shelf	48-57 N	February-August	<200 m	Tidal atlas	–	0.5-1.6	2.8	Hist'l station data	Simpson *et al.*, 1977
;ay of Fundy and Gulf of ⁄laine composite	41-46 N	July-August	<200 m	Model	2.1-2.4	1.1	2.6	hist,l station data	Garrett *et al.*, 1978
;astern Bering Sea	55-59 N	June 1976 July 1977	50	Moored meters	3.1	2.2	20	CTD, XBT	Schumacher *et al.*, 1979
.ong Island and Block Island ;ounds	41 N	September 1978	10-50	Tidal atlas	–	0.8-1.1	–	CTD	Bowman and Esaias, 1981
ℑreater Cook Strait, New ;ealand	39-42 S	January-February 1980	10-200	Model	1.3-3.5	1.5	1.2	CTD	This paper

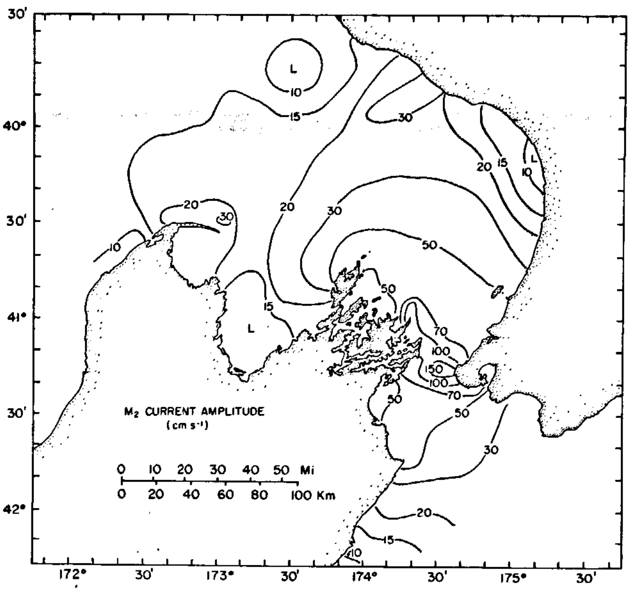


Figure 3
Isotachs of M_2 *current amplitudes (cm.sec*$^{-1}$*) derived from a numerical model (Bowman* et al.*, 1980). The contour intervals are in an approximately geometric progression.*

140° phase shift across its ends. We believe this configuration is unique, although there are other islands which support a 360° M_2 phase shift around their coast (e. g., Madagascar; Schwiderski, 1979).

The ratio of the M_2 to S_2 amplitudes is quite variable, ranging from 1.5 at Oteranga Bay to 21.3 at Cape Campbell (Heath, 1978). The age of the tide is about 2 days in the western approaches.

Much of the present understanding of the tidal circulation in the region is derived from numerical simulations of the M_2 tides (Heath, 1974*b*; Bowman *et al.*, 1980). Isotachs of model predicted M_2 currents are shown in Figure 3. Highest speeds ~150 cm.sec.$^{-1}$ are found in Cook Strait narrows, lowest values ~10 cm.sec.$^{-1}$ are found off Cape Egmont and the North Island nearshore waters of the South Taranaki Bight. Tidal flow intensifies around Farewell Spit where currents reach 35 cm.sec.$^{-1}$. A broad region, with currents in the range of 15-25 cm.sec.$^{-1}$, spans much of the Taranaki Bight, Golden and Tasman Bays.

The few current measurements that have been gathered (Heath, 1976; 1978; Garner, 1979; Kibblewhite *et al.*, 1982) are in general agreement with the model, showing the presence of a dominant semidiurnal component, superimposed on a highly variable, meteorologically forced non-tidal flow.

WEATHER PATTERNS

The prevailing weather pattern in central New Zealand consists of a succession of anticyclones and cyclones propagating eastwards between 35 and 45°S during all seasons. In summer the strongest westerlies are found further south beyond 50°S. New Zealand's mountainous terrain greatly affects coastal winds, with Cook Strait being the only significant break in the North and South Island mountain chains. Here local winds are highly variable, often of gale force; and tend to be oriented northwesterly and southeasterly (Garnier, 1958).

COASTAL CURRENTS

The Westland Current flows equatorward along the west coast of the South Island (Garner, 1961) as the coastal component of the eastern boundary current of the Tasman Sea (Brodie, 1960). The current is strongly influenced by coastal winds (Heath, 1969; Stanton, 1971; 1973; 1976), but historical measurements, mainly drift card studies, show a persistent flow northeastwards. A component of the Westland Current sweeps into Cook Strait as the D'Urville Current (Brodie, 1960) with speeds up to 35 cm.sec.$^{-1}$ (Heath, 1969). This current is reinforced by northwesterly winds as Ekman transport across the Taranaki Bight sets up a slope current along the North Island coast and into Cook Strait (Heath, 1978). Under southwesterly or southerly winds the Westland Current appears to continue flowing across the western approaches and around Cape Egmont, halting or reversing residual flows through the Strait (Brodie, 1960). Thus patterns of summer stratification in South Taranaki Bight and northern Cook Strait are expected to be sensitive to local weather conditions. A more definitive account of the meterological influences on the west coast current regime has been given recently by Kibblewhite (Kibblewhite *et al.*, 1982, chapter 4).

Mixing and circulation in southern Cook Strait is complex, representing the confluence of D'Urville, East Cape and Southland Current waters (Heath, 1971).

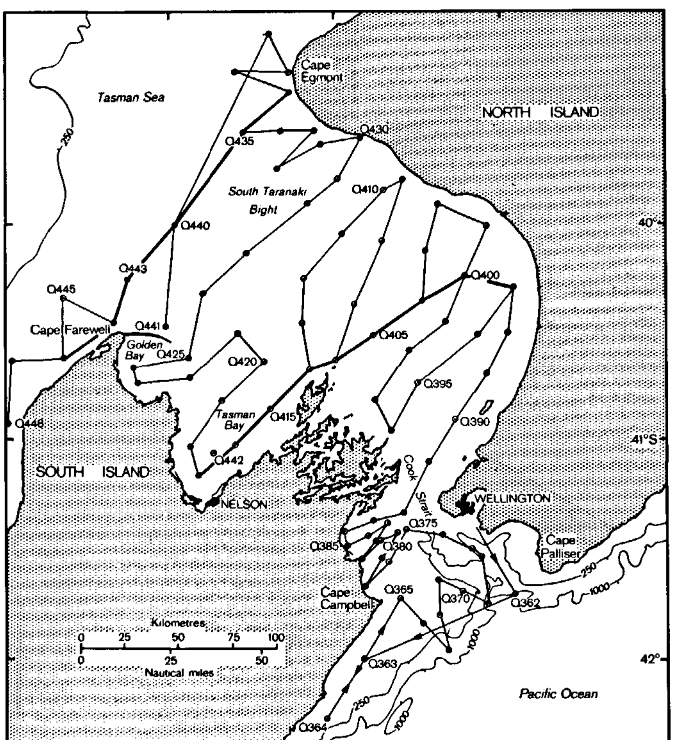
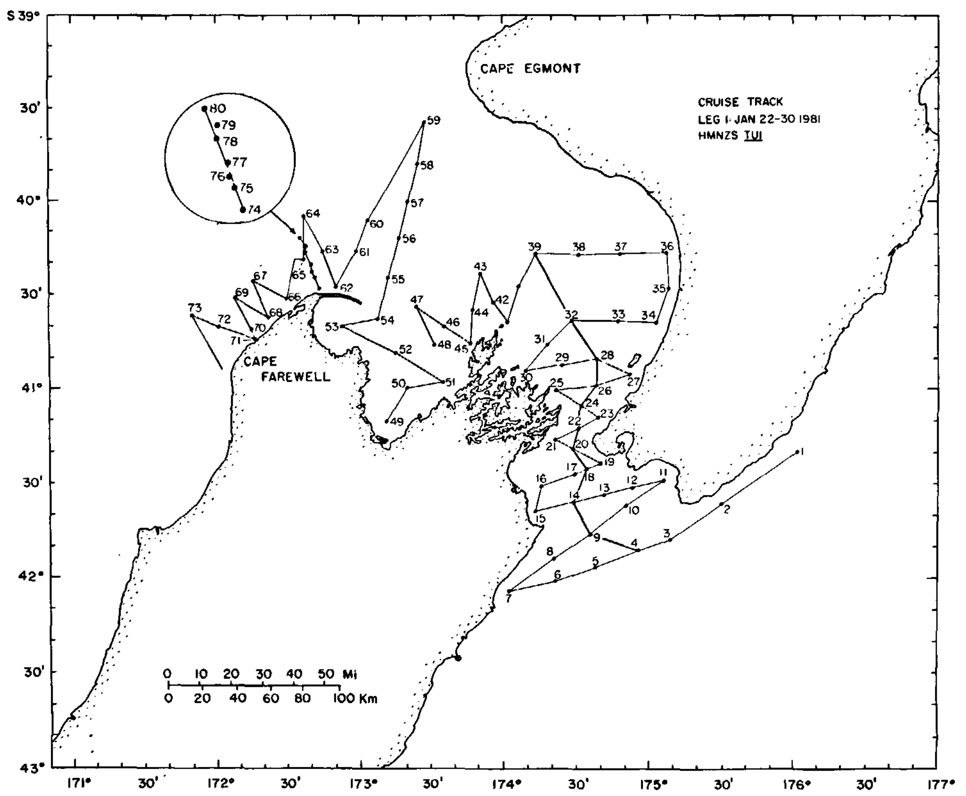


Figure 4
Cruise track and station locations for the R/V *Tangaroa survey, January* 9-19, 1980.

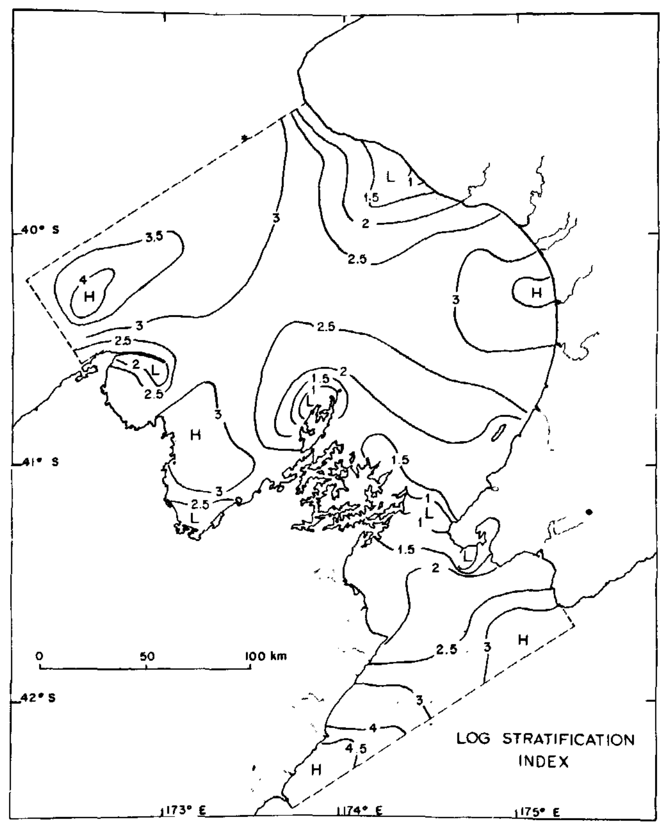


← Figure 5

Cruise track and station locations for the HMNZs Tui survey, January 22-30, 1981. The bolder line represents the location of the vertical axial section (Fig. 1).

Figure 6

Stratification index $s = \log_{10} h/ku^3$ in c.g.s. units derived from the numerical model (Bowman et al.*, 1980; the contours in that paper were labelled incorrectly).* ↓



Brodie (1960) found that the Southland Current sweeps across the southern entrance to Cook Strait before continuing northeastwards up the North Island coast, as a mixture of D'Urville, Southland and East Cape water (Heath, 1975).

The results discussed in this paper pertain to periods when fair weather was encountered; thus an identifiable tidal mixing signal was expected to be present. A discussion of circulation and mixing patterns observed during and after strong wind events which modify the prevailing stratification patterns is beyond the scope of this paper and will be discussed in a later publication.

SAMPLING METHODS AND STRATEGIES

Two summer sampling cruises were undertaken in greater Cook Strait, the first aboard R/V Tangaroa in 1980 and the second on HMNZS Tui in 1981. Opportunities were taken during fair weather periods on both cruises (January 9-19, 1980 and January 22-30, 1981) to map and identify regional patterns of stratification, fronts, eddies and intrusions.

Hydrographic measurements (CTD profiles plus continuous measurements of surface (2 m) temperature and salinity) were augmented with hydrocast samples of inorganic nitrate plus nitrite ($NO_3 + NO_2$), and continuous surface nutrient measurements made with an Autoanalyzer. Maps of surface nutrient concentrations were particularly useful in demarking freshly upwelled bottom water. Lapennas *et al.* (in prep.) have shown for the Farewell front that due to biological uptake, the half life of these nutrient concentrations in upwelled water were about one quarter that of the accompanying temperature and salinity anomalies from ambient values. Thus these elevated nutrient distributions tended to be located close to their source regions.

Cruise tracks (Fig. 4 and 5) were planned with the aid of the model predicted stratification index patterns (Fig. 6). These suggested that the waters of Tasman and Golden Bays, most of the South Taranaki Bight, and to the south of Cook Strait should stratify, while marginally stratified frontal zones should separate mixed water off D'Urville Island, over the Rolling Ground and in the narrows of Cook Strait. We attempted to sample each of these regions, crossing s contours orthogonally wherever possible.

HYDROGRAPHY

Many of the features observed during the two surveys were essentially similar. Selected results are presented which display these as well as some contrasting patterns. Winds during the 1980 survey began by blowing weakly from the southerly quarter at speeds ≤ 5 m.sec.$^{-1}$, but swung around to the northwest on January 12 to blow steadily from that direction until January 16 with a mean speed of ~ 9 m.sec.$^{-1}$ (Fig. 7 *a*).

During the 1981 cruise winds were northerly from January 23-27, with speeds generally less than 8 m.sec.$^{-1}$, but gusting to ~ 15 m.sec.$^{-1}$. On January 27, winds shifted to the northwesterly quarter, blowing at 10-15 m.sec.$^{-1}$ for the rest of the survey (Fig. 7 *b*).

The two surface temperature distributions were similar in a number of respects (Fig. 8 and 9). Temperatures over the outer western shelf were about 18-19° except for the Cape Farewell upwelling zone where coastal temperatures dropped to less than 14°. Highest temperatures, over 21°, were found in sheltered southern Tasman Bay, where low wind stress and weak tidal currents favored the development of a strong thermocline. Low temperatures (13-15°) were located in central and southern Cook Strait as a consequence of tidal mixing in the narrows and upwelling on the flanks of Cook Strait canyon.

Surface temperatures in the offing of Marlborough Sounds lay in the range of 14-16°C, bounded by a semicircular front during 1981 but not in 1980. This front coincided with the western boundary of an incursion of modified subtropical (D'Urville Current) water flowing down the lower reaches of the west coast of the North Island (known as the Manawatu coast) and into the narrows of Cook Strait. The presence of

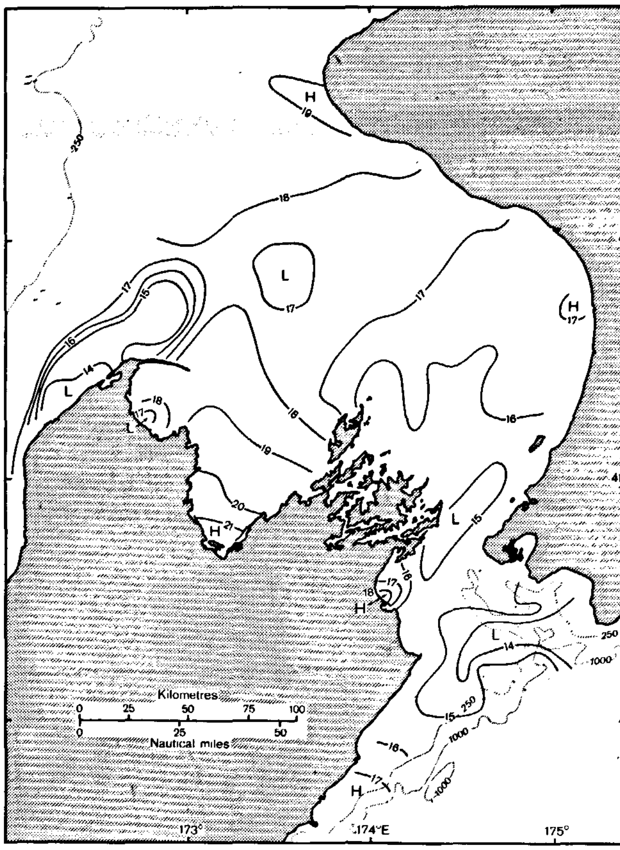
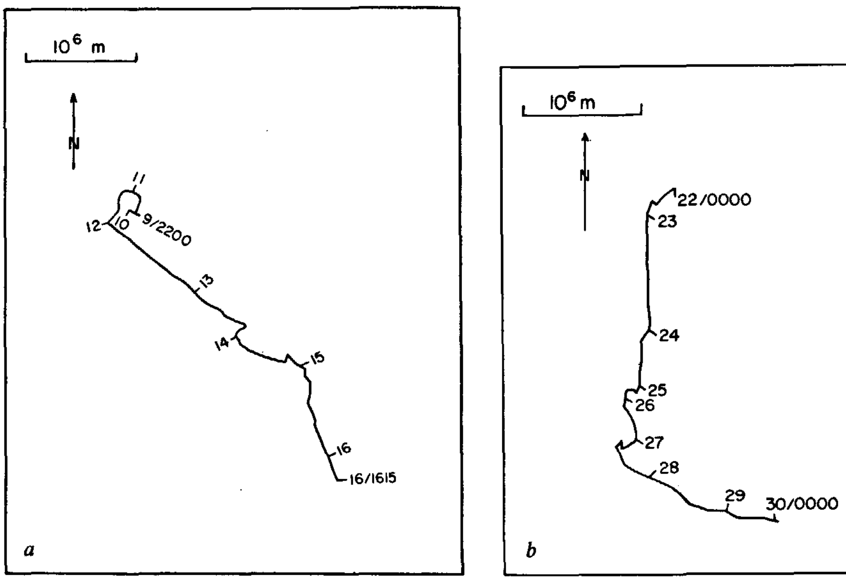


Figure 8
Surface (2 m) temperature (°C), 1980 survey.

this intrusion was consistent with a slope current driven by the northerly winds during the early part of the 1981 survey. The absence of this plume during the 1980 survey thus seems attributable to the southerly winds blowing before and during the first few days of that cruise.

The most pronounced hydrographic feature in the southwestern approaches was the Farewell front, first described by Stanton (1972). Recent evidence (Bowman *et al.*, in press) suggests this to be a bottom-frictionally induced upwelling front. It is a persistent feature, apparently driven by the equatorward flowing Westland Current, reinforced both by southerly wind gusts lasting

Figure 7
Progressive vector diagrams derived from masthead anemometers (10 m). a) January 9-16, 1980; b) January 22-30, 1981.



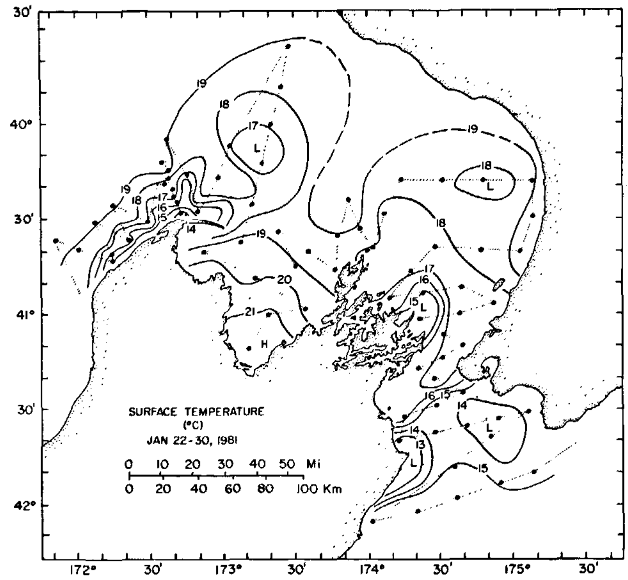


Figure 9
Surface (2 m) temperature (°C), 1981 survey.

a few days, and centrifugal effects at the convex coastal bends at and south of Cape Farewell. During both surveys, mesoscale (~20 km diameter) eddies, apparently broken off the front, with core temperatures <16°C, were located ~75 km northeast of Cape Farewell. Their identical location was coincidental since these eddies are known to advect with the D'Urville Current into northern Cook Strait (Bowman *et al.*, in press).

Surface salinity patterns were also similar in nature and showed the presence of subtropical D'Urville Current water (S > 34.9) over much of the South Taranaki Bight, modest runoff dilution near land, and "Cook Strait water" (S ~ 34.6-34.8), a mixture of subantarctic Southland Current water (S < 34.4) and D'Urville Current water in central and southern Cook Strait (Fig. 10). The Farewell front was evident as a coastal band of elevated salinity (S > 34.9) water of shelf bottom origin. A plume of high salinity (S > 35) surface water

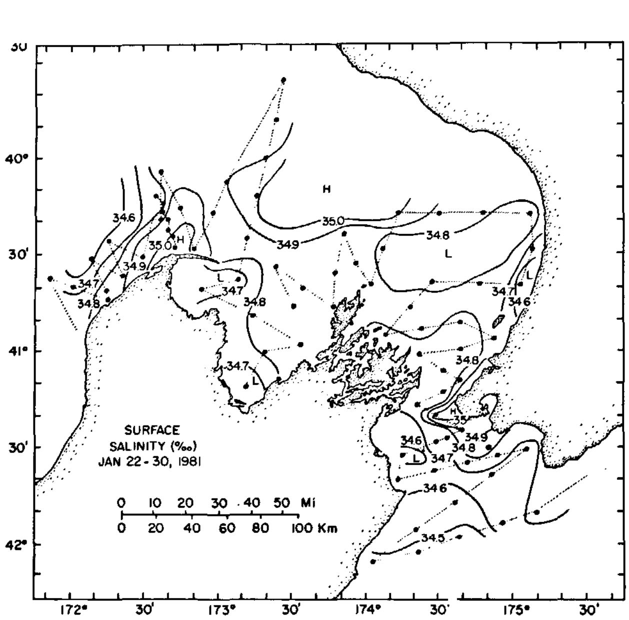


Figure 10
Surface (2 m) salinity (× 10⁻³), 1981 survey.

occurred off Cape Terawhiti as the leading edge of the intrusion into the narrows of Cook Strait.

Concentrations (<0.25 μM) within nutrient depleted surface shelf water over the western portions of the study area contrasted sharply with those of nutrient enriched upwelled bottom water (~6-8 μM) near Cape Farewell, southern Marlborough Sounds and southern Cook Strait (Fig. 11 and 12). Strong surface gradients

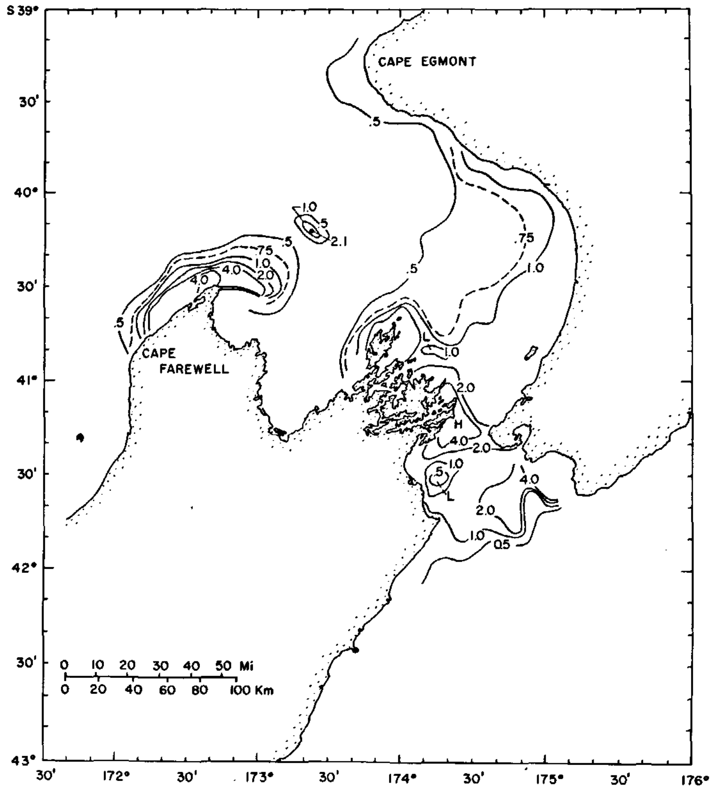


Figure 11
Surface inorganic nutrients (nitrate + nitrite) (μM), 1980 survey.

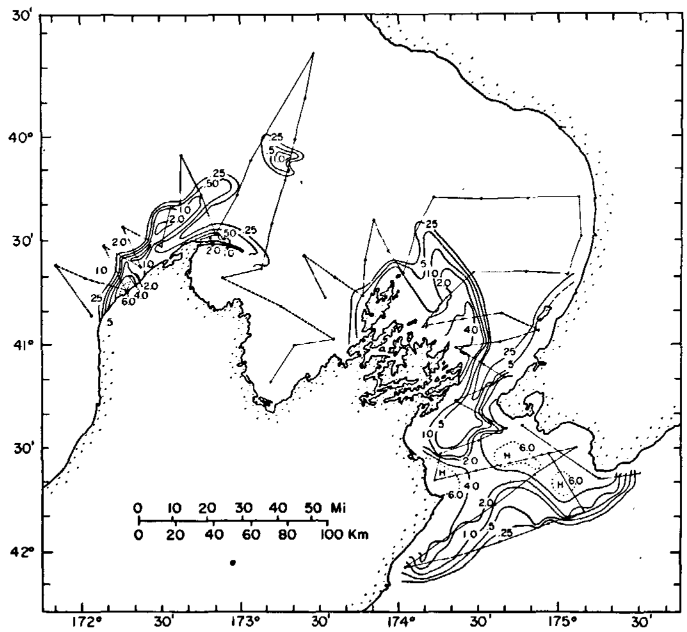


Figure 12
Surface inorganic nutrients (nitrate + nitrite) (μM), 1981 survey.

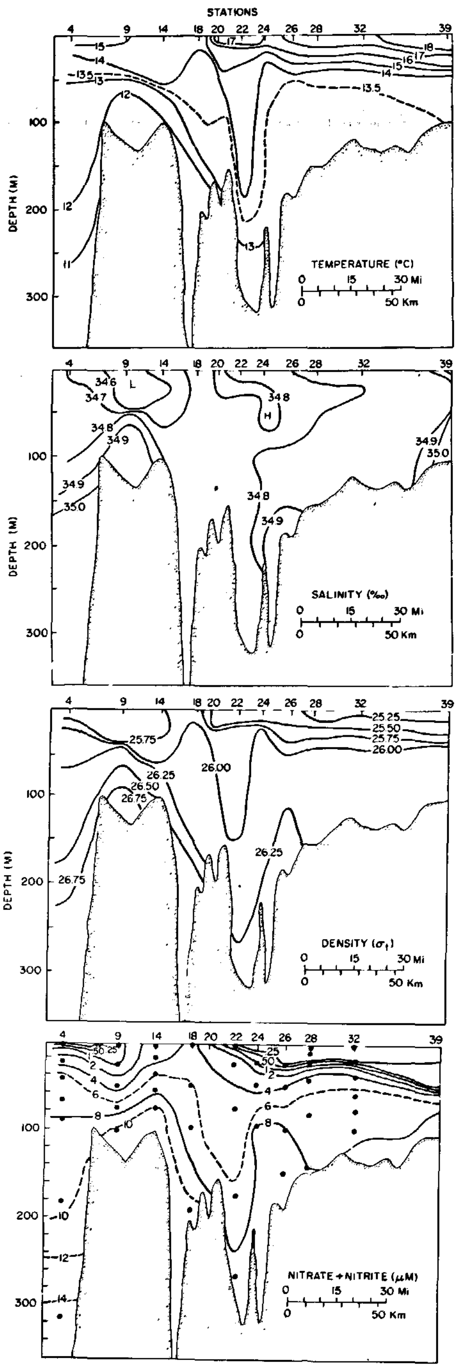


Figure 13
Vertical axial section stations 4-39, 1981 survey (see Fig. 5). a) temperature (°C); b) salinity (×10⁻³); c) sigma T (gm.cm⁻³); d) nitrate+nitrite (μM).

surrounded each of these regions. Intermediate surface concentrations (2-4 μM) were associated with tidal mixing fronts [around D'Urville I and across the narrows of Cook Strait (in 1980)]. The two eddies apparently spawned from the Farewell front were also identified by their elevated nutrient concentrations (~2 μM).

Nitrate-nitrite concentrations were low over The Rolling Ground shoals (Fig. 11). Here the bottom topography rose through the surrounding shelf thermocline; hence the water mixing over the shoals was already nutrient depleted through primary production. The plume of low nutrient water intruding into Cook Strait from the north was clearly resolved during the 1981 survey, but completely absent during 1980. The leading edge of this buoyant plume lay over water that is known to be highly turbulent and would otherwise be expected to contain elevated surface nutrient concentrations (*see* Fig. 13). Gradients beneath this plume were weak over the bottom 100 m. Tidal stirring was apparently most intense at station 18; the surface to bottom temperature difference here was only 3.5° over 200 m (and 2.3° over 270 m at Q389 in 1980). A benthic temperature front separated the mixing zone from southern stratified shelf and slope waters (stations 4, 9, 14). Highest surface nitrate-nitrite concentrations were found at station 18 located between the depleted surface waters both to the north and south, again indicating violent vertical mixing in the narrows of Cook Strait.

Selected T-S curves along the vertical section through Cook Strait are shown in Figure 14. Station 39 was located at the southeastern fringe of D'Urville Current water, station 32 at the northern extent of Cook Strait water. Sub-thermocline water from station 32 and near surface water at station 18 possessed similar properties. Similar water (T=13.5-14.5°C; S=34.75-34.82; σ_T=25.85-26.20; NO_3+NO_2=2.0-7.0 μM) appeared at 20-55 m at station 4 (encircled region), while deep water at this location had an East Cape Current origin. These curves suggest that Cook Strait water, a mixture of Southland and D'Urville Current water is formed within Cook Strait and penetrates at depth northward up the Cook Strait canyon into the South Taranaki Bight. The presence of these water types apparently modified the tidal mixing fronts to a detectable but minor degree.

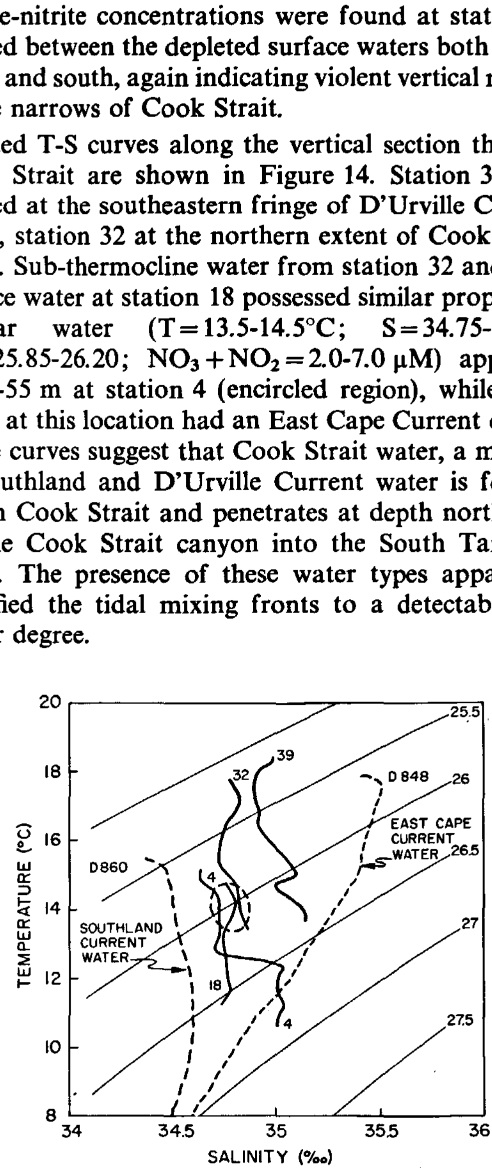


Figure 14
T−S *diagram for stations* 4, 18, 32 *and* 39, 1980 *survey.* T−S *characteristics of Southland Current and East Cape current water are shown for comparison (Heath, 1975). The encircled region is discussed in the text.*

STRATIFICATION

Three measures of stratification were evaluated:

1) potential energy deficit per unit volume V/h, where:

$$V=\int_{-h}^{0}(\rho-\bar{\rho})\,gz\,dz \quad \text{and} \quad \bar{\rho}=\frac{1}{h}\int_{-h}^{0}\rho\,dz, \qquad (3)$$

V is the work required to mix a stratified water column of depth h;

2) water column temperature difference $\Delta T = T(0) - T(-h)$, and

3) bulk stratification $B = [\rho(-h) - \rho(0)]/h$.

POTENTIAL ENERGY DEFICIT V/h

If equation (1) is integrated for a given location over a period t_1 from the beginning of net heating of the water column and if spring-neap stirring variations are neglected, then:

$$V = \frac{\alpha g h \bar{Q} t_1}{2c} + \varepsilon k \rho u^3 t_1 + \delta k_a \rho_a \overline{W^3} t_1,$$

where $\overline{W^3}$ is the mean cubed wind speed and $\bar{Q}$ the mean insolation. Thus, assuming other variables are in fact constants,

$$\frac{V}{h} = c_0 + \frac{c_1 k u^3}{h} + \frac{c_2}{h}.$$

Figure 15 is a plot of V/h contours derived from equation (3) for the 1980 data set. Although some correspondence with the s distribution can be seen, e. g., The Rolling Ground and D'Urville Island lows, the contours of V/h show a marked tendency to follow the bathymetry. A multiple regression of V/h *versus* u^3/h and $1/h$ provided estimates $c_0 = -64\ J.m^{-3}$; $c_1 = +6.4 \times 10^6\ J.s^3.m^{-5}$; $c_2 = +350\ J.m^{-2}$; $r = .53$. Thus:

$$\varepsilon = c_1/\rho t_1 = 1.2 \times 10^{-3},$$

$$\delta = c_2/(\rho_a k_a \overline{W^3} t_1) = 0.94 \times 10^{-3},$$

$$\bar{Q} = 66\ J.m^{-2}.sec.^{-1}\ (4.1 \times 10^3\ cal.cm^{-2}.month^{-1}),$$

assuming $t_1 = 60$ days, and $\overline{W} \sim 9\ m.sec.^{-1}$.

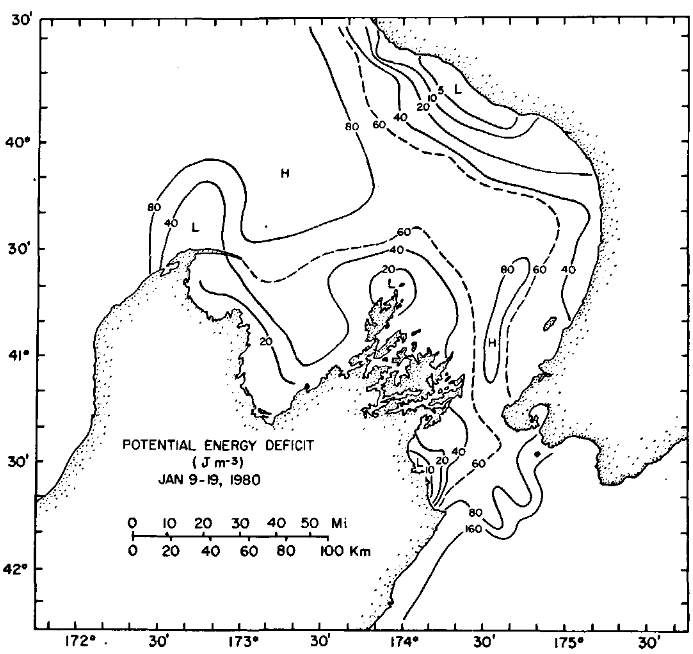


Figure 15
Potential energy deficit, 1980 survey ($J.m^{-3}$).

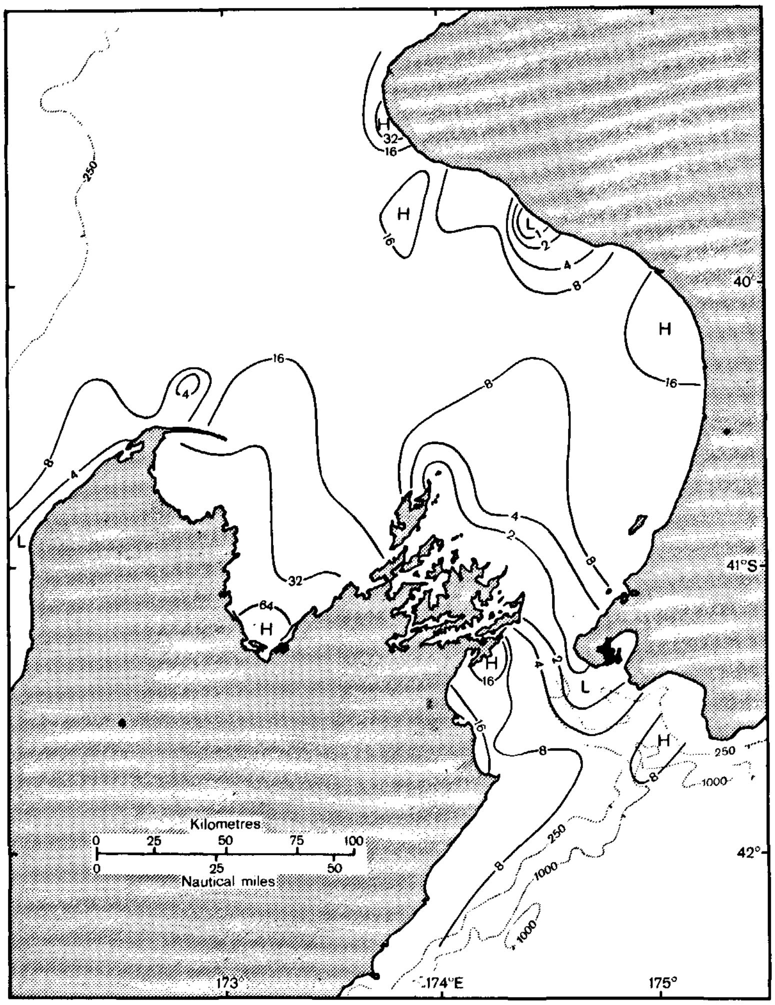


Figure 16
Bulk stratification, 1980 *survey* (10^{-5} σ_T *units* cm^{-1}).

BULK STRATIFICATION B

Bulk stratification B is an appropriate stratification measure since it includes, like V, the effects of both temperature and salinity gradients on stability. Also, isentropic mixing results in smoother density profiles than either temperature or salinity alone, and so minimizes distortions due to horizontal mixing.

A preliminary assessment of B based on a composite of all available historical summer hydrographic data (Bowman *et al.*, 1980) showed fair agreement with the s distribution, but obviously lacked synopticity. Figure 16 illustrates the 1980 distribution of B (the 1981 distribution was similar). Highest stratification was found in Tasman and Golden Bays, with moderate stratification $8 < B < 16$ formed over the western approaches, Kaikoura coast and Palliser Bay. Marginally stratified water ($2 < B < 4$) was located around The Rolling Ground, and in two meandering bands across Cook Strait: the first extending from D'Urville Island, across the Marlborough Sounds entrances to Cape Terawhiti; and the second extending from Arapawa Island across to Baring Head. These three zones closely followed the $s = 1.5$ contours (Fig. 6).

An empirical fit between B and s was (excluding southern Cook Strait and Farewell upwelling zone and neglecting wind mixing) $\log_{10} B = 0.4s - 5$, B in σ_T units cm^{-1}, s in c. g. s. units, $r \sim 0.6$.

Equation (2) leads directly to an estimate of ε. Taking $s=1$ as a measure of weak stratification towards the mixed side of fronts and $\dot{Q} = 10^4$ cal.cm^{-2}.$month^{-1}$ for midsummer conditions, gives $\varepsilon \sim 0.4\%$. This is marginally higher than the estimate derived in the last section, but there a portion of the mixing was ascribed to the winds.

TEMPERATURE DIFFERENCE ΔT

Surface to bottom (or −200 m; whichever was less) temperature differences are plotted in Figures 17 and 18. The 1980 distribution shown in Figure 17 roughly conformed to the patterns of s (Fig. 6; $r \sim 0.38$). The Farewell front and its eddy are clearly visible in the western approaches. There was a notable lack of horizontal gradients in Cook Strait, although a sharp shelf break front was found across the southern reaches where the relatively mixed Cook Strait water abutted the Pacific slope water to the east.

The modification of these patterns by the northerly winds during the 1981 Cook Strait passage is illustrated in Figure 18. A tongue of warmer surface water within the slope current penetrated into Cook Strait, replacing South Taranaki Bight coastal water with less stratified water (ΔT < 2°C) presumably originating farther up the Patea coast.

DISCUSSION

Patterns of bulk stratification B showed the best agreement with contours of the stratification index s, although the constant efficiency model of Simpson *et al.* (1978) suggests that V/h is the relevant stratification measure.

A simple relationship exists between V/h and B if we assume that the density profiles can be approximated as parabolae:

$$\rho(z) = a_0 + a_1 z + a_2 z^2, \qquad \text{say,}$$

then:

$$V = \frac{gh^3}{12}(a_1 + a_2 h).$$

For example, for station Q412,

$a_0 = 25.3$; $\quad a_1 = -0.0167\ m^{-1}$;

$a_2 = -7.3 \times 10^{-5}\ m^{-2}$; $\quad h = 90$ m,

and so:

$$\frac{V}{h} \sim \frac{g a_1 h^2}{12} \sim \frac{g B h^2}{12}.$$

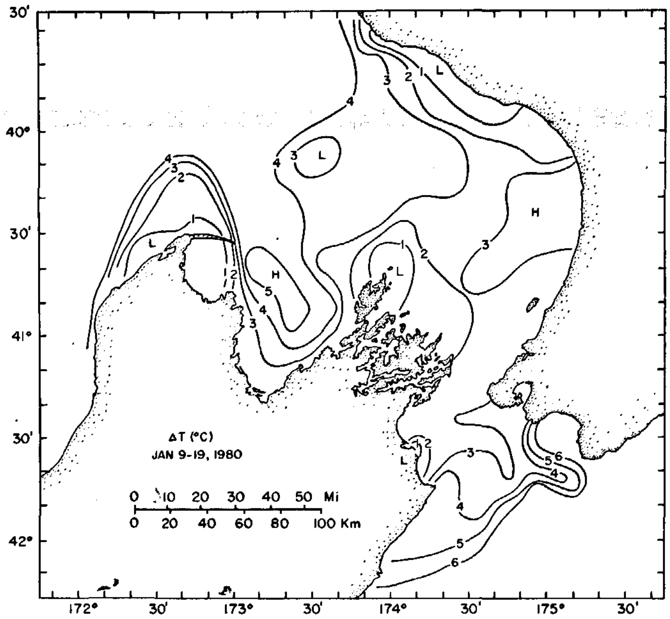


Figure 17
Water column temperature difference, 1980 *survey* (°C).

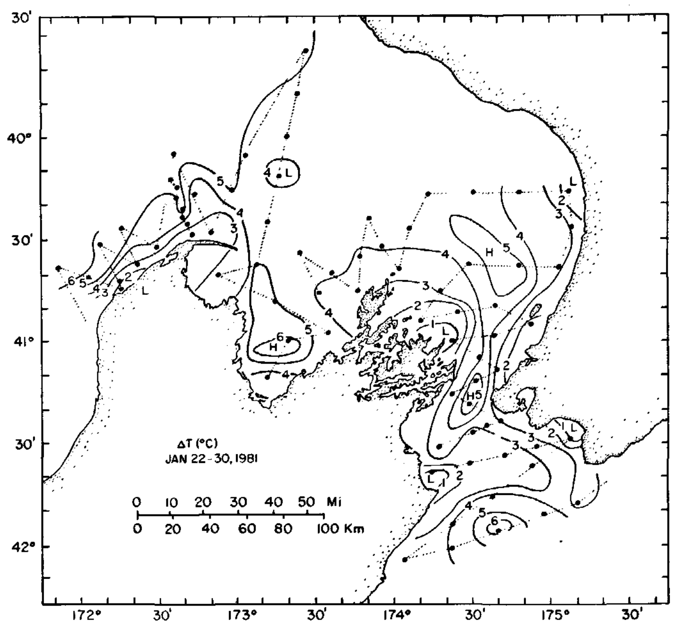


Figure 18
Water column temperature difference, 1981 *survey* (°C).

While h over the study area of interest varied by a factor ~20 (10 m < h < 200 m), B varied by a factor ~16 (2 < B < 32). Thus V/h is a strong function of h within these limits.

The potential energy deficit model is difficult to assess properly. Since the local weather is so temporally and spatially variable, the onset of stratification will vary with location, and the advection of potential energy will be important in some areas and negligible in others.

The role of tidal mixing has been investigated and shown to be significant in controlling summer stratification in greater Cook Strait. However, even moderate winds can rapidly disturb prevailing conditions. These effects are particularly evident in the constricted narrows of Cook Strait where the funneling of winds and currents from the South Taranaki Bight lead to rapid acceleration in the flows.

Acknowledgements

This project was carried out as a major component of the Maui Development Environmental Study, which was commissioned by Shell, BP and Todd Oil Services Ltd (acting on behalf of Maui Development Ltd) as part of the development of the Maui gas field off the Taranaki coast. The study was carried out by the University of Auckland (coordinator, Pr. A. C. Kibblewhite). The research program was facilitated by a Memorandum of Understanding in Marine Sciences between the State University of New York at Stony Brook and the University of Auckland, New Zealand. Staff of the Marine Sciences Research Center were able to participate extensively with joint support from the National Science Foundation (US/NZ Cooperative Science Agreement, NSF-INT grant 78-01159; and NSF-OCE grants 77-26970 and 81-8283) and the Maui Study. We also wish to acknowledge the help of Dr. D. E. Hurley, Director of the New Zealand Oceanographic Institute and Mr. B. H. Olsson, Director of the Defence Scientific Establishment for the use of the R/V Tangaroa and the HMNZS Tui, and to Captain N. Gillstrom and Lt. Commander G. C. Wright, RNZN, for assistance at sea. Contribution 332 of the Marine Sciences Research Center (MSRC).

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NOTATION INDEX

a_0, a_1, a_2,	constants;
B,	bulk stratification;
c,	specific heat at constant pressure;
c_0, c_1, c_2,	constants;
g,	acceleration due to gravity;
h,	water column depth;
k,	bottom dimensionless drag coefficient $\sim .0025$;
k_a,	surface dimensionless drag coefficient $\sim 6.5 \times 10^{-5}$;
M_2,	semi diurnal lunar tidal constituent;
$\dot{Q}$,	net heat flux into water column;
r,	correlation coefficient;
S,	salinity;
S_2,	semi diurnal solar tidal constituent;
s,	stratification index;
T,	temperature;
t,	time;
t_1,	time period from onset of stratification to time of measurement;
u,	root mean cubed tidal current;
V,	potential energy deficit of water column;
W,	wind speed;
z,	vertical ordinate, positive upwards, origin at sea surface;
α,	linear expansion coefficient;
δ,	mixing efficiency due to wind stirring;
ε,	mixing efficiency due to tidal stirring;
ρ,	density;
ρ_a,	air density.

Environmental isotopes in the hydrosphere

par V. I. Ferronsky et V. A. Polyakov,
publié par John Wiley and sons, Wiley Interscience Publ., 1982,
traduit de « Prizodnye isotopy gidrosfery » (1975, en russe) par S. V. Ferronsky,
1 vol., 466 p., £ sterling 31.00.

Les domaines qu'entend couvrir ce manuel : revue exhaustive de toutes les techniques utilisant les isotopes stables ou radioactifs dans les eaux naturelles, ont fait de tels progrès et ont été l'objet de tant de nouveautés pendant ces 10 dernières années que certainement un spécialiste de la question n'y verra que peu d'intérêt. Bien qu'il soit annoncé comme ayant été remis à jour au moment de la traduction, on ne peut le considérer comme faisant le point en 1982. En effet, si pour certains chapitres la bibliographie est mise à jour, jusqu'en 1979 essentiellement, ce n'est pas le cas dans d'autres où elle s'arrête en 1973. Sur les 800 références citées, seulement 150 sont postérieures à 1976, et encore représentent-elles essentiellement quelques conférences faites et publiées dans quelques symposium internationaux de l'Agence Internationale pour l'Énergie Atomique. Quelques références toutefois sont postérieures à 1979, mais ce sont surtout (une dizaine) des références russes. Ceci nous conduit à parler de l'intérêt de ce livre, qui donne un panorama très complet des travaux russes, souvent méconnus des occidentaux... On peut toutefois regretter, par exemple dans le domaine océanique, que les très importants progrès obtenus au cours du programme Geosecs ne soient qu'à peine effleurés, les apports hydrothermaux inexistants, et la paléoclimatologie, arrêtée aux premiers articles d'Emiliani et de Savin, et ignorant les progrès réalisés par le programme Climap.

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The geomorphology of the Great Barrier Reef. Quaternary development of coral reefs

par D. Hopley,
publié par John Wiley and sons, Wiley Interscience Publ., 1982,
453 p., 165 fig. et photos, 20 tab., £ sterling 46.90.

La Grande Barrière du Queensland, le plus vaste ensemble de récifs coralliens du monde d'un seul tenant, déjà étudiée de près lors de l'expédition de Sir Maurice Yonge en 1928, a fait l'objet d'excellentes recherches ultérieures, surtout celles de la Royal Society et des Universités du Queensland en 1973. Aussi était-il opportun qu'un tableau d'ensemble détaillé des faits et problèmes fût ré-élaboré. Ce qui est l'œuvre de David Hopley, de l'Université James Cook de Townsville, l'un des acteurs des travaux récents sur le terrain. L'ouvrage, abondamment et utilement illustré, concerne surtout les géomorphologues, géologues et biologistes marins, mais aussi, plus ou moins, les spécialistes des autres branches de l'océanographie.

Les problèmes considérés, évidemment fort nombreux, ne sont pas envisagés que dans le domaine de la Grande Barrière, mais aussi dans une perspective d'ensemble du monde récifal, dans lequel l'aire étudiée est ainsi toujours replacée : ce qui est fort éclairant, et accroîtra beaucoup l'audience du livre sans pourtant étendre indûment les discussions au-delà du sujet que le titre annonce.

Le milieu climatique et marin est défini avec précision. Sur les points fondamentaux, les conclusions sont nuancées et modérées, l'argumentation préalable faisant appel aux résultats des techniques et à la considération des points de vue que l'on attendait, avec un appareil bibliographique considérable encore que quelquefois lacunaire, ce qui était sans doute inévitable. On verra ainsi que l'édification de ces récifs a commencé bien avant l'Holocène, mais que l'histoire de détail ne peut pas encore être aussi précise que pour les atolls à grands forages; qu'il faut combiner dans l'explication une subsidence darwinienne modérée, la glacio-isostasie habituelle, et une hydro-isostasie accompagnée de petits mouvements différentiels qui ont introduit des décalages altitudinaux locaux dans les niveaux marins holocènes (p. 241, 243, 180, 183). Une karstification durant les bas niveaux marins pléistocènes est certes intervenue et a laissé un héritage essentiel, mais la théorie de Purdy, du contrôle des formes actuelles par cette karstification antécédente, n'est pas applicable d'une façon systématique.

La sismique a montré la présence de chenaux de bas niveau marin complètement obturés par la croissance corallienne d'époque transgressive (fig. p. 215; d'autres enregistrements analogues auraient pu être cités) : c'est un fait capital pour l'interprétation des passes et de leur nombre actuel (certainement résiduel) dans la barrière *sensu stricto*. La question des doubles barrières (p. 386 et 292) est expédiée un peu vite. Sur le grès de plage (*beach rock*) et ses modalités, l'information, répartie sur plusieurs chapitres, est excellente, de même que celle sur les micro-atolls et leur interprétation. Sur les récifs réticulés (p. 206), des comparaisons avec certains autres récifs (Mataiva, Canton) auraient été utiles, de même que pour les vasques étagées (p. 110). La Grande Barrière est extraordinairement riche en récifs à cayes, dont la variété est bien analysée au long des 39 pages du chapitre 11 (le lagon calédonien eût pu être plus évoqué en regard). L'étude des éperons et sillons (*spurs* and *grooves*) est enrichissante, avec des blocs-diagrammes suggestifs p. 289.

Plus généralement, la figuration est de grande qualité, et de nombreuses images de répartition des faits dans le domaine considéré, comme aussi beaucoup de figures séquentielles évolutives (ex. : p. 244 et 253) feront apprécier hautement le bel ouvrage de David Hopley par tous les géomorphologues et biologistes récifaux.

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ERRATUM

Two misprints took place in the paper "Étude biométrique de la croissance d'*Eledone cirrhosa* [LAM 1798 (Cephalopoda, Octopoda)] du Golfe du Lion", by M. Moriyasu, published in the last issue (Vol. 6, 3, p. 35-41) :
1) in the general title: read "LAM 1798" instead of "LAM 1978";
2) in the English abstract, last line: read "$[1\text{-Exp-}0.12\ (t+0.11)]^{2.57}$" instead of "$[(1\text{-Exp-}0.12\ (t+0.11)]^{2.357}$".