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Circulation and mixing in greater Cook Strait, New Zealand

Cook Strait
Upwelling
Tidal mixing
Circulation
Plume

Détroit de Cook
Upwelling
Mélange
Circulation
Panache

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ABSTRACT

The shelf seas of Central New Zealand are strongly influenced by both wind and tidally driven circulation and mixing. The region is characterized by sudden and large variations in bathymetry; winds are highly variable and often intense. Cook Strait canyon is a mixing basin for waters of both subtropical and subantarctic origins. During weak winds, patterns of summer stratification and the loci of tidal mixing fronts correlate well with the h/u^3 stratification index.

Under increasing wind stress, these prevailing patterns are easily upset, particularly for winds blowing to the southeasterly quarter. Under such conditions, slope currents develop along the North Island west coast which eject warm, nutrient depleted subtropical water into the surface layers of the Strait. Coastal upwelling occurs on the flanks of Cook Strait canyon in the southeastern approaches.

Under storm force winds to the south and southeast, intensifying transport through the Strait leads to increased upwelling of subsurface water occupying Cook Strait canyon at depth. This spreads seaward as a cool, nutrient laden mesoscale plume $\sim 10^4$ km^2 in area. It is suggested that this source of nutrients may have an important influence on the long streamers of apparent phytoplankton patches which stretch southeastwards in the Pacific Ocean from the mouth of the Strait.

Satellite imagery has identified a large ($\sim$ 100 km dia.) anticyclonic eddy which may permanently occupy the deep slope waters east of the southeastern approaches.

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RÉSUMÉ.

Circulation et mélange dans le détroit de Cook et ses alentours, Nouvelle-Zélande

Les eaux du plateau continental du centre de la Nouvelle-Zélande sont influencées par la circulation et le mélange causés par le vent et les marées. La région est caractérisée par des variations de bathymétrie subites et de grande ampleur. Le détroit de Cook est un bassin où se mélangent des eaux d'origine subtropicale et subantarctique. En périodes de faibles vents, les conditions de stratification estivale et les positions des fronts associés au mélange par la marée, sont bien corrélées avec l'index de stratification h/u^3.

L'accroissement de la tension superficielle du vent perturbe ces conditions, particulièrement lorsque le vent souffle vers le quadrant Sud-Est. Des courants de pente sont alors créés le long de la côte Ouest de l'Ile du Nord, qui injecteront en surface les eaux chaudes subtropicales, démunies de matières nutritives, dans le détroit de Cook. Une remontée d'eaux est aussi observée près des flancs du canyon du détroit de Cook, dans l'approche Sud-Est.

Des vents de tempête soufflant vers le Sud et le Sud-Est intensifient le transport d'eau dans le détroit, et provoquent une remontée des eaux profondes du canyon. Celles-ci forment ensuite une langue d'eaux froides et riches en matières nutritives qui s'étend sur une superficie d'environ 10^4 km². Il est suggéré que cette source de matières nutritives est étroitement liée à la présence de « patch » de phytoplanctons, qui s'étendent en filons de l'embouchure du détroit vers le Sud-Est dans le Pacifique. Des images de satellite ont permis d'identifier un large (~ 100 km de diamètre) tourbillon anticyclonique, qui pourrait être localisé en permanence dans la région des eaux profondes de la pente continentale, à l'est de l'approche Sud-Est.

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INTRODUCTION

Recent studies of oceanography of greater Cook Strait have focused on the effects of tidal stirring variations on the structure of summertime stratification (e.g., Bowman *et al.*, 1980; 1983 *a*). This research has clearly established that a close correlation exists, at least during settled weather, between the h/u^3 mixing index, observed stratification and the location of shelf-sea fronts.

During the last decade, the shelf-sea fronts around the United Kingdom have been studied with spectacular success, through the combined use of ship observations, satellite thermal IR imagery and numerical modeling simulations (e.g., Simpson, Hunter, 1974; Pingree, Griffiths, 1978; Pingree *et al.*, 1978; Simpson *et al.*, 1977; 1978). Simpson (1981) attributes the persistence and predictability of these fronts partly to the weak residual flows that exist on the UK shelf as compared to the tidal currents. He suggests that frontal regions are particularly sensitive to advection of buoyancy from adjacent stratified waters; a mean flow of only a few cm sec.$^{-1}$ in the cross-frontal direction can dislocate or erase shallow sea fronts in some areas.

Although both are characterized by strong tides, the shelf seas of central New Zealand differ in many respects from those around the UK. One pronounced difference is the very high number of gales that frequent central New Zealand and the wind driven circulations that result. Another significant difference is the appearance of water mass boundaries near, or in Cook Strait; such fronts can be confused with tidal mixing fronts.

To put the tidal stirring studies in perspective, it was considered important to devise field programs to investigate circulation and mixing in greater Cook Strait not only under settled conditions but also during and after strong wind events. It will be shown that such events can significantly alter the prevailing structure of the shelf seas around Cook Strait; these variations can also have significant biological consequences.

The main purpose of this paper, then, is to interpret measurements of surface and water column properties (temperature, salinity, inorganic nutrients) and results of drifter tracking exercises made during the austral summers of 1980 (January) and 1981 (January and February). These data were collected during fluctuating moderate to high winds (up to 60 knots), mainly blowing towards the south and southeast quarters. These measurements have helped synthesize a better understanding of the interacting processes active in this complex region.

Perhaps the most interesting discovery was of a storm driven flow through the Strait, sufficiently intense to eject a plume of cool, upwelled, nutrient rich water out over the deep slope waters southeast of Cook Strait. This plume entrained Southland Current water along its southwestern flank and was sufficiently persistent to allow a mesoscale patch (~ 75 km diameter) of phytoplankton 150 km offshore to bloom to concentrations some six times background levels. The search for such a plume was prompted by observations in December 1973 by astronauts aboard Skylab. They witnessed a bluish-green colored apparent jet current flowing southeastwards from Cook Strait with associated frontal boundaries, long internal waves, and sites of coastal upwelling. The astronauts also sketched swirls of bluish-green water (presumed to be phytoplankton patches) which at times stretched southeastwards some 750 km from Cook Strait. They observed plumes from an altitude of 435 km on five separate occasions, and managed to photograph one of them (Stevenson *et al.*, 1977; Fig. 11-10).

THE STUDY REGION

New Zealand represents a major obstruction to the predominantly eastward circulation of the subtropical waters of the Tasman Sea (Heath, 1973). The dynamic topography of the sea surface surrounding New Zealand implies that the flow deflects both to the north and the south of the landmass, as well as experiencing significant deflections by smaller scale bathymetric features of the southwest Pacific Ocean (Stanton, 1973).

One might also expect a minor component of the zonal transport to flow through Cook Strait, separating the North and South Islands (Fig. 1). However circulation and mixing in Cook Strait are also determined by a number of local factors which interact in a complex way. The western shelf is relatively broad and flat. The Egmont Terrace forms a 100 m sill linking the two islands, underlying the western approaches and effectively excluding the deeper waters of the Tasman Sea from penetrating into the Strait. As might be expected, local winds over the relatively shallow, exposed western approaches exert a strong influence on the surface circulation within the South Taranaki Bight.

Cook Strait possesses a minimum width of 23 km and a cross-sectional area of 2.65 km². Although the immediate approaches are oriented along a northwest-southeast direction, the narrows are aligned almost north and south. Cook Strait is the head of a deep

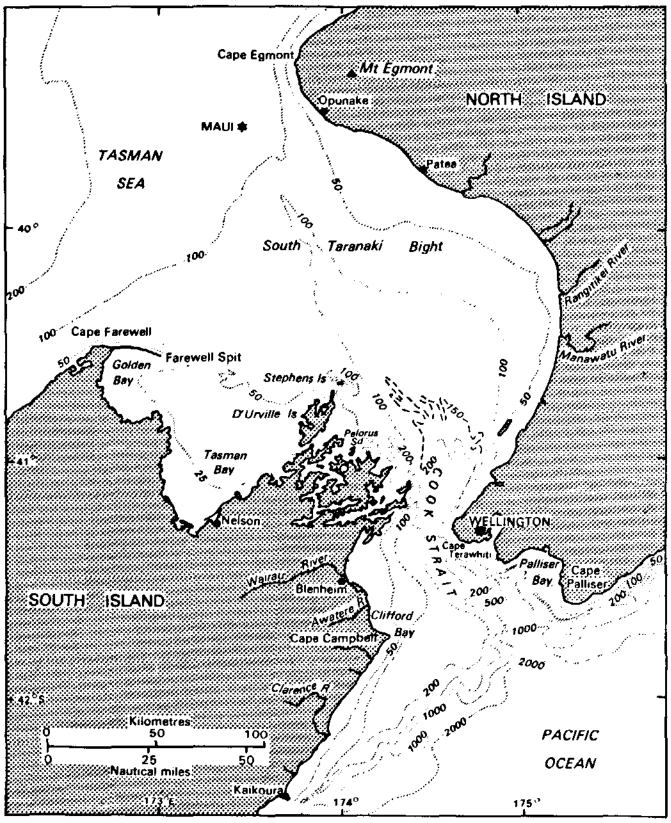

Figure 1

Locator map and bathymetry (m) of greater Cook Strait. The star marks the position of the Maui gas drilling platform.

canyon that penetrates through from the east coast, an extension of the 4000 m Hikurangi Trough. This allows the deeper waters of the Strait to be filled from the east with both modified subtropical water flowing around the North Island (East Cape Current) and subantarctic water flowing around the South Island (Southland Current) which meet at the subtropical convergence near eastern Cook Strait (Heath, 1971). The appearances, locations and proportions of these constituent water types within the Strait at any given time strongly depend on the recent history of wind driven circulation patterns, upwelling events and tidal mixing in the surrounding region.

Prevailing winds in these latitudes are westerly, with the weather dominated by a more or less regular succession of cyclones and anticyclones passing from west to east across the country (Garnier, 1958). Cook Strait is the only significant break in New Zealand's 1,500 km meridionally oriented chain of mountains. Local winds are highly variable and tend to be funnelled into Cook Strait by these mountains, often leading to sharp accelerations and frequent gale conditions in the narrows (Brodie, 1960). Such events set up wind driven currents (Heath, 1978; Kibblewhite, 1982), waves and swell over both the South Taranaki Bight and the Strait which can interact with the strong and variable tidal streams to produce heavy seas and dangerous navigation conditions.

Cook Strait possesses some of the world's strongest tidal currents. The M_2 tide propagates anticlockwise around New Zealand as a trapped shelf wave (Heath, 1977); Cook Strait essentially short circuits the shelf waveguide and the 140° phase difference across its entrances leads to steep surface slopes and strong currents, which can reach 7 knots during spring tides in some locations (Hydrographic Department, 1958). We believe that this combination of an island centered amphidrome, bisected by a narrow strait, is unique. Away from the narrows of Cook Strait, tidal streams diminish rapidly.

Adverse sea conditions have made it difficult to deploy current meters in the narrows for long periods, and consequently, until recently, most of the knowledge about the directions and scales of variability of non-tidal circulation was based on Lagrangian measurements such as radio tracked drifters (Sanderson, 1979), surface drift cards, and sea bed drifters.

These studies do suggest a bias in the net flow through the Strait (from north to south), albeit a highly variable one, but it has been difficult to arrive at reliable estimates of the corresponding transports. Some measurements over single tidal cycles have shown almost no residual current through the narrows (*e.g.*, Gilmour, 1960); at other times the non-tidal flow is stronger than the tidal component and the observed flow may not reverse for 18 hours (Ministry of Transport, 1981; Kibblewhite, 1982).

These complex patterns of circulation and mixing exert important influences on the productivity of the surrounding coastal seas (*e.g.*, Bartle, 1972; 1976). The results of biological experiments conducted during our cruises will be discussed elsewhere.

SAMPLING METHODS

We discuss results from two cruises (January 9-February 5, 1980 aboard R/V Tangaroa, and January 22-February 13, 1981 aboard HMNZS Tui). Temperature and conductivity with depth observations were made with an Interocean 550 CTD. Water bottles were used to gather nutrient samples from depth. For continuous surface mapping, the CTD was placed in a deck bucket of running sea water (from 2 m) which was also used to supply a Mark II Autoanalyser. The available time at sea was allocated between continuous mapping, station profiling and tracking of the radio drifters (Sanderson, 1979) on an opportunistic basis.

RESULTS

We discuss findings from three surveys of the region in order of increasing wind speed encountered. This is out of chronological order but a more logical way in which to discuss the oceanography.

Survey I (January 9-19, 1980)

This survey of the South Taranaki Bight was made during a period of fair weather and provided an opportunity to evaluate the role of tidal stirring variations in influencing summer stratification without the disrupting effects of strong advection. Winds were blowing towards the northwest during the ship's passage through Cook Strait and no evidence of intrusion of D'Urville Current water from the western approaches was found. A significant correlation (r ~ 0.6) between observed bulk stratification and the h/u^3 stratification index was found. Also three classes of fronts were observed; an upwelling front off Cape Farewell (Bowman *et al.*, 1983*b*), tidal mixing fronts around D'Urville Island and across Cook Strait, and a shelf break front to the east of the Strait. Further details are given in Bowman *et al.* (1982), Murtagh (1982) and Bowman *et al.* (1983*a*).

Survey II (January 22-30, 1981; Fig. 2)

This survey was also conducted during fair weather, but with winds now blowing to the south and southeast with maximum speeds ~ 15 m sec.$^{-1}$. We observed a buoyant plume of oligotrophic subtropical water driven from the South Taranaki Bight into Cook Strait. This plume was evident in all measured properties. Strong horizontal gradients in surface nutrients, presumably due to localized variations in uptake through primary production in waters of contrasting stratification, were especially useful in mapping this intrusion (Fig. 2). The presence of this tongue of surface Tasman Sea water suggests that a southeastward directed wind blowing across the western approaches drives a surface Ekman flux across the South Taranaki Bight. It is thought that water then sets up against the North Island coast, and produces a southward slope current in a favorable alignment to flow as a buoyant plume of thickness ~ 50 m over the surface waters of Cook Strait (see Fig. 13, Bowman *et al.*, 1983*a*, for a vertical section through Cook Strait during this event). The western flank of the intrusion coincided with the tidal mixing front located in the offing of Marlborough Sounds. Elevated inshore nutrient concentrations reflected intense tidal stirring in waters of ~ 100 m depth.

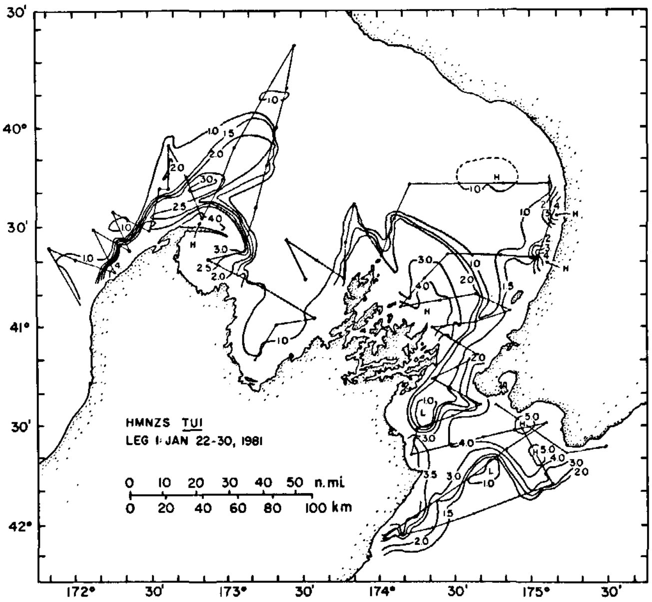

Figure 2
Cruise track, station positions and surface SiO_4 distribution during survey II, January 22-30, 1981.

Bartle (1972) has surveyed and photographed similar events. When present, warm oceanic D'Urville Current water showed up as a sharply bounded plume of a clear blue color, overflowing the cloudy green waters of Cook Strait. He also noted that no blue D'Urville water has ever been observed south of the narrows, presumably due to intense mixing in the Strait. The frontal boundaries he observed were particularly sharp on the western (South Island) and eastern (North Island) sides of the narrows, with the surface front marked by accumulations of foam and flotsam. Patches of green water mixed in with the blue water plume were also seen near Cape Terawhiti where tidal mixing is most intense (Bowman *et al.*, 1980).

There were two other features of interest mapped during survey II. First, a well developed frontal system was located off Cape Farewell. This was explored in more detail later in the cruise, and identified as a persistent upwelling front. The unstable frontal zone was a prolific source of mesoscale cyclonic eddies which detached and propagated into the western approaches (Bowman *et al.*, 1983*b*).

Second, a shelf break front was located over the southeastern approaches where the well mixed waters of southern Cook Strait abutted against the stratified surface water of the Pacific Ocean. In survey II there was no evidence of a plume emanating from the Strait; time constraints did not allow a repeated survey to determine whether the intrusion from the north continued to propagate through to the east coast or whether it was mixed away in the turbulent narrows. Elevated concentrations around the flanks of the Cook Strait Canyon also suggested considerable mixing and upwelling were occurring there.

Survey III (January 26-February 4, 1980; Fig. 3, 4)

The first part of this survey (January 26-30) was dedicated to resurveying Cook Strait, again under mainly southward winds. As in Survey II, D'Urville Current water was again observed penetrating into the narrows as a warm, low nutrient plume, extending as far south as Cape Terawhiti (Fig. 5). Attention was then focused on southern Cook Strait and the adjacent coastal waters for the following five days.

Winds began blowing gently at speeds ~ 5 m sec.$^{-1}$ from the afternoon of the 31st to midnight on the 2nd. Wind speeds then picked up rapidly on the 3rd to ~ 25 m sec.$^{-1}$; the storm continued until the end of the cruise; winds were directed southwards. A patch of cool (T ~ 14°), high nutrient ($NO_3 + NO_2$ ~ 6-8 μM), dense (σ_t ~ 26.0) water appeared at the surface in Southern Cook Strait (Fig. 5-7).

From a T-S-N analysis of this surface patch (Fig. 8, 9), it was determined that it was an upwelling center of "Cook Strait" water whose origin was near the head of the canyon from depths of 60-125 m. Cook Strait water is here defined as water with salinity between 34.6 and 34.9, a mixture of Southland and East Cape Current water, with perhaps a small infusion of D'Urville current water driven into, and then mixed in the narrows. It was also clear from the T-S-N analysis that

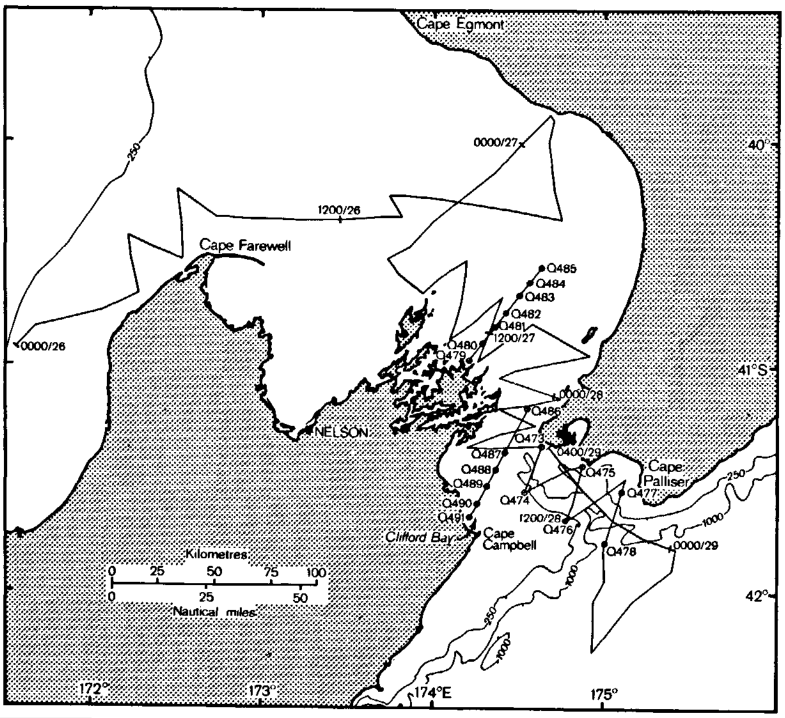

Figure 3
Cruise track and station positions during the first portion of survey III, January 26-29, 1980.

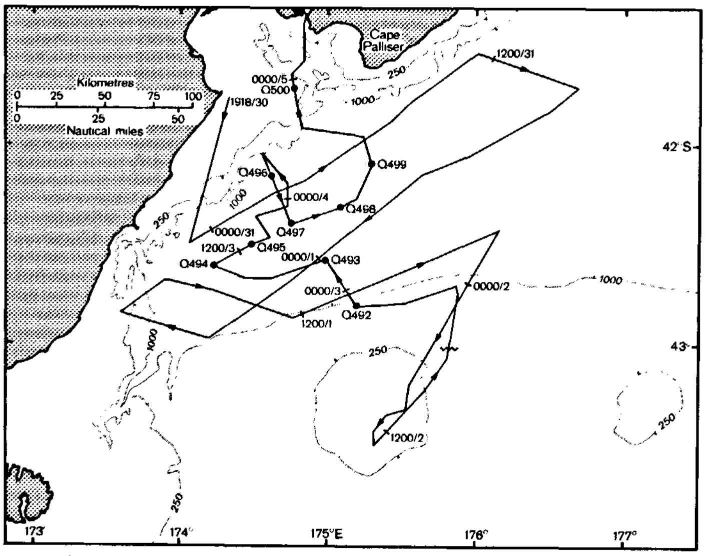

Figure 4
Cruise track and station positions during the second portion of survey III, January 30-February 4, 1980.

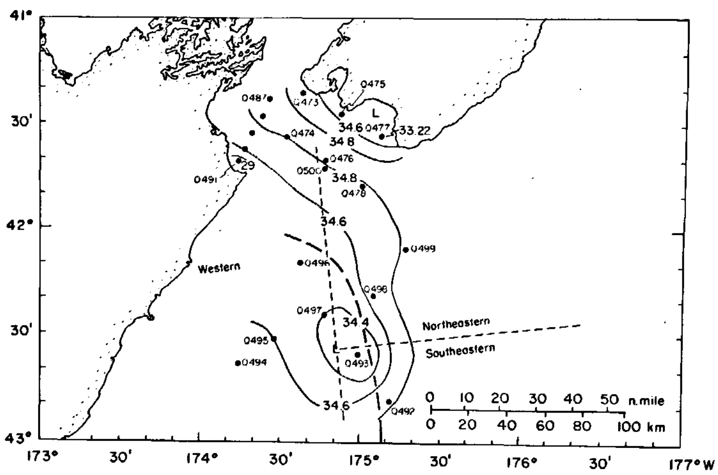

Figure 6
Surface salinity during the second portion of survey III. The water to the left of the dashed curve is of Southland Current origin.

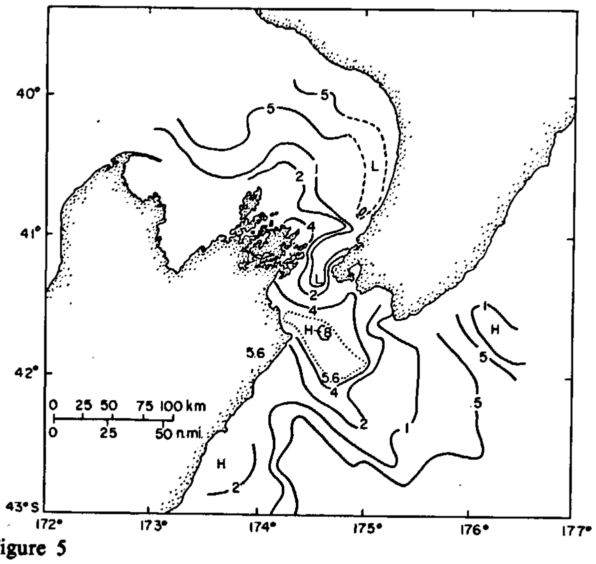

Figure 5
Composite map of surface nitrate-nitrite (μM) during survey III, January 26-February 4, 1980.

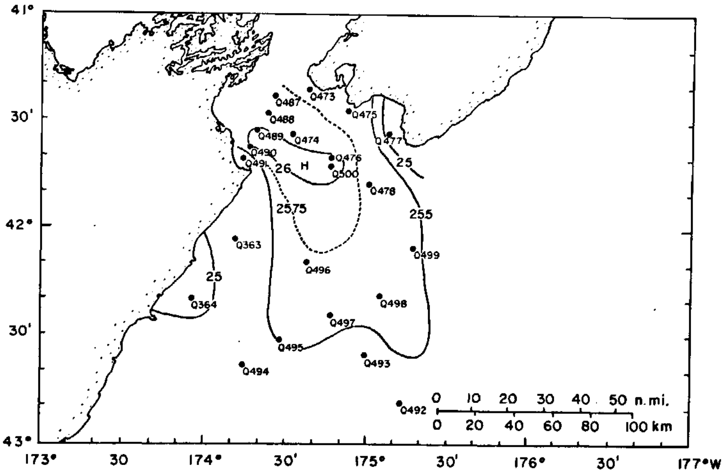

Figure 7
Surface sigma-t during the second portion of survey III.

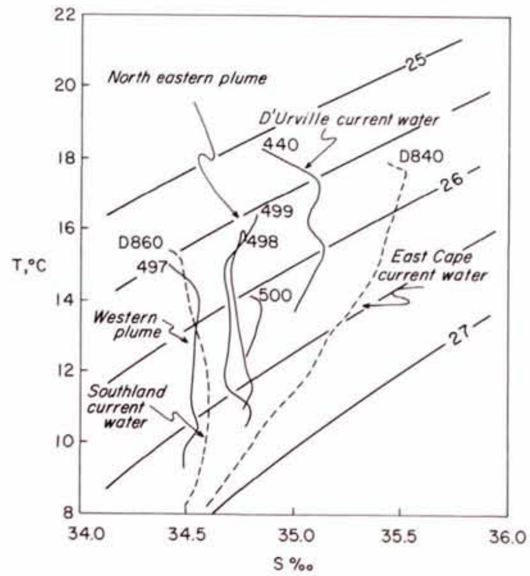

Figure 8

T-S diagram for selected stations in the plume, with characteristics of Southland, East Cape and D'Urville Current water for comparison. Station D 860 and D 840 data from Heath (1975).

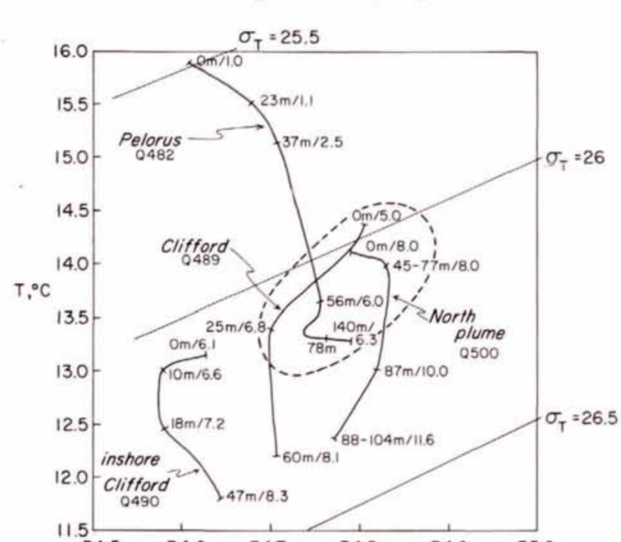

Figure 9

T-S diagram identifying source region of upwelling center (Q 500) in plume.

low salinity (~ 34.4) Southland Current water was entrained along the western edge of the plume (Fig. 6, 8).

About 100 km southeast of Cape Palliser, the temperature mapping (not shown) suggested the presence of a mesoscale eddy (~ 100 km diameter) located just east of the plume. Satellite thermal IR images consistently have eddies in this location (Fig. 10, 11; also see Bowman *et al.*, 1982). They appear to be formed of subtropical East Cape Current water surrounded by cooler Southland Current water originating below the Subtropical Convergence. Sdubbundhit and Gilmour (1964), Garner (1967) and Heath (1968; 1972; 1975) each found evidence of similar mesoscale anticyclonic eddies lying two to three degrees east of our observations. Heath (1975) also suggested that smaller eddies are shed from the East Cape Current as it abruptly turns east near 42°S.

Two drifters released on the 13th and 15th of January in the South Taranaki Bight were carried through Cook Strait and relocated about two weeks later off the east

Figure 10

NOAA-6 thermal IR image, January 8, 1980. Note the warm water in northern Cook Strait, the mixing patterns in the narrows, and the convoluted patterns of warm and cool water off the South Island east coast (C = cloud, E = eddy, SC = subtropical convergence).

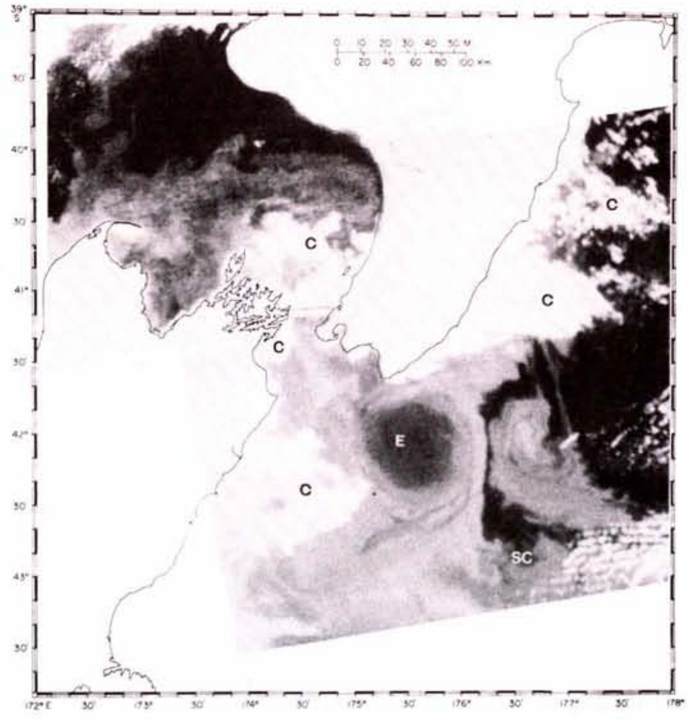

Figure 11

NOAA-6 thermal IR image, May 3, 1980 (early winter). A convoluted front stretches east-west across the South Taranaki Bight, separating the warmer, stratified subtropical waters to the north from the cooler coastal and shelf water to the south. The slope waters to the east of Cook Strait are dominated by a 100 km diameter anticyclonic eddy (C = cloud, E = eddy, SC = subtropical convergence).

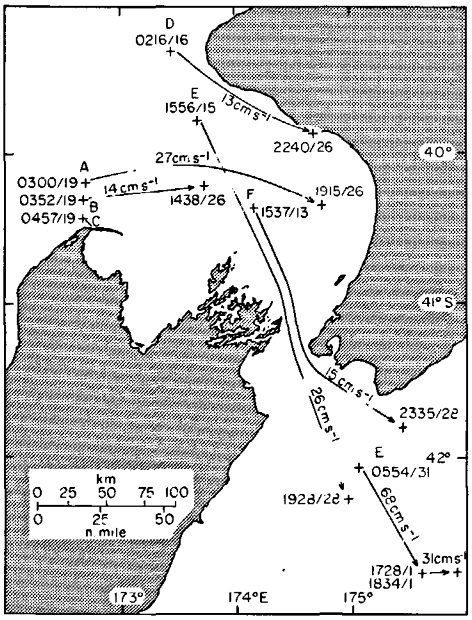

Figure 12

Drifter release and recovery locations, January 15-February 2, 1980. The trajectories, representing the shortest paths between release and recovery points, are used to estimate the minimum speeds.

coast. Their trajectories would certainly be much more convoluted than those suggested in Figure 12, but these hypothetical tracks provided estimates of the minimum surface drift (15 and 26 cm sec.$^{-1}$ respectively). Drifter E tracked over a 36 hour period in the slope waters southeast of Cook Strait drifted with a mean speed of at least 68 cm sec.$^{-1}$: This latter estimate compared favorably with a geostrophic calculation from hydrographic station data taken across the plume (stations Q494, 495, 497, 498, 499). These suggested the existence of a jet current centered at station Q497 with a maximum southeastward surface velocity component of $\sim$ 48 cm sec.$^{-1}$ (relative to 1,000 dbar).

DISCUSSION

A search of all 1980 hydrographic data found only two stations with the appropriate T-S-N values to be source water for the upwelling center at Q500. These were Q482 bottom water at Pelorus Sound entrance in Northern Cook Strait and Q489 surface water from Clifford Bay.

A more thorough investigation of Cook Strait waters was made using the 1981 data set. Again the appearance of relatively heavy ($\sigma_t = 26.0$) water in southern Cook Strait suggested an upwelling center (Fig. 13). Water of this density was traced by contouring the depth of the $\sigma_t = 26.0$ layer and the values of T, S, and N on that surface (Fig. 13-16). In and north of the narrows, "Cook Strait" water of salinity 34.6-34.9 filled the canyon at depths centered around 50-100 m. Tempe-

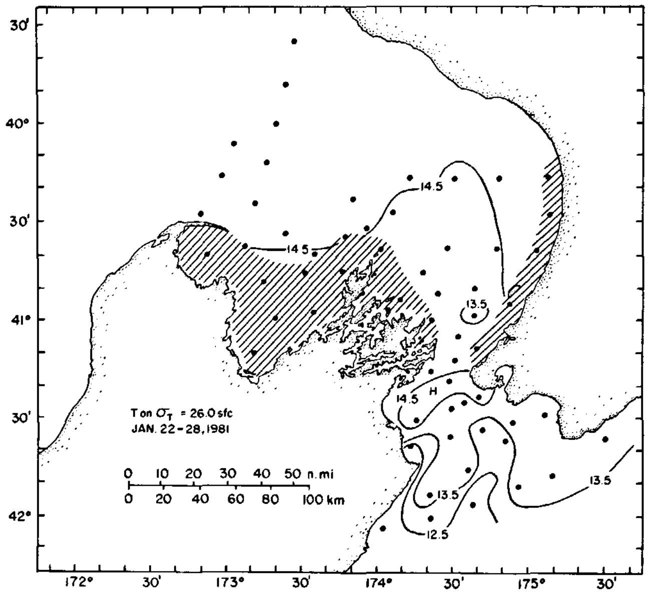

Figure 14

Temperature (°C) on $\sigma_t = 26.0$ surface, January 22-28, 1981 (survey II). In shaded areas, $\sigma_t < 26.0$ throughout the water column.

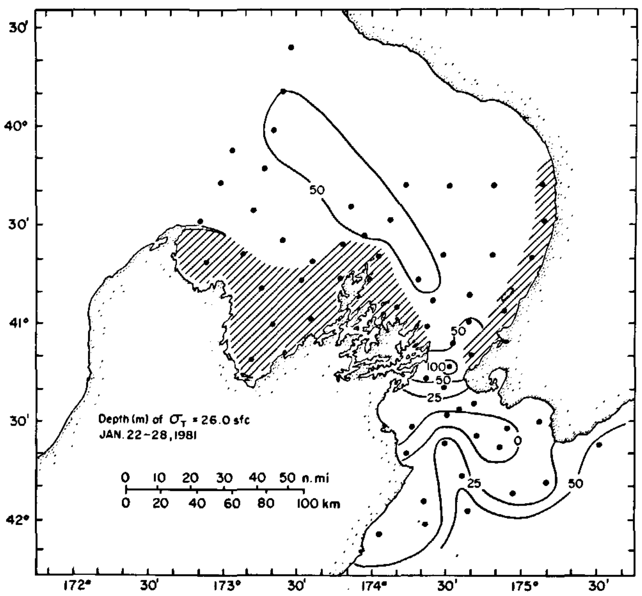

Figure 13

Depth (m) of $\sigma_t = 26.0$ surface, January 22-28, 1981 (survey II). In shaded areas, $\sigma_t < 26.0$ throughout the water column.

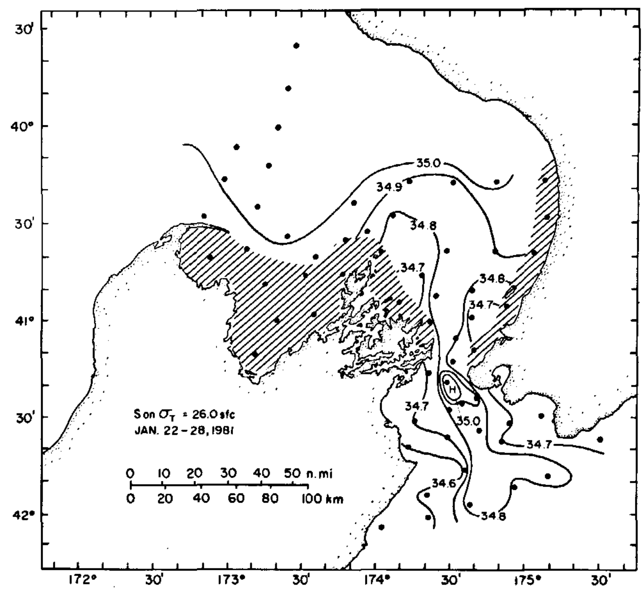

Figure 15

Salinity on $\sigma_t = 26.0$ surface, January 22-28, 1981 (survey II). In shaded areas, $\sigma_t < 26.0$ throughout the water column.

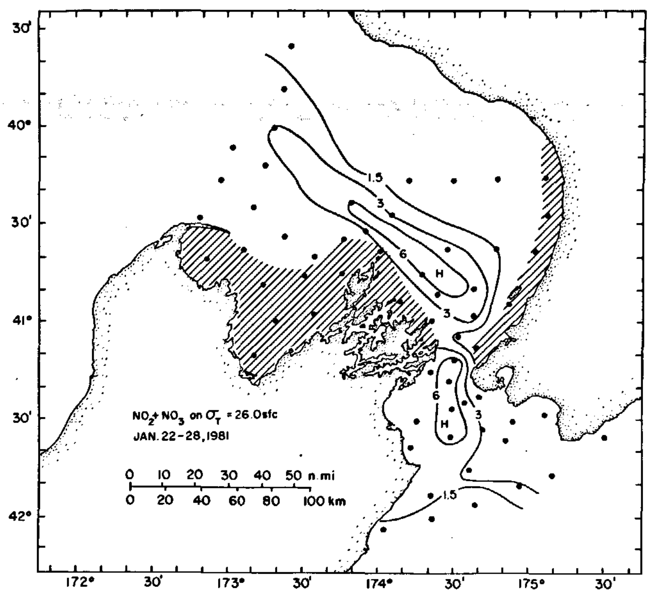

Figure 16
Nitrate-nitrite (μM) on $\sigma_t = 26.0$ *surface, January 22-28, 1981 (survey II). In shaded areas,* $\sigma_t < 26.0$ *throughout the water column.*

rature and nutrient values were also consistent with those found in the plume during Survey III.

This analysis leads us to the following conclusions, which are summarized in Figure 17. Cook Strait water filled the narrows and canyon to the north. A shallow intrusion of D'Urville water flowed down the North Island west coast and over narrows water. Southland Current water appeared south of and offshore the Strait; East Cape Current water flowed around Cape Palliser and penetrated at depth into the narrows. Tasman Bay water did not enter this mixing zone, and was formed of highly stratified, lower salinity water diluted by land runoff.

We conclude that Cook Strait water is continually being formed within the canyon by violent tidal stirring of the constituent water types present at any given time. Under storm force southward winds, a strong flow through the Strait is set up, at least in the top 100 m, both by local wind stress, and as the extension of a slope current established along the North Island west coast. This surface current is mixed into the turbulent waters of Cook Strait or is forced against the southern coast of the North Island. If winds are persistent enough, subsurface water from northern Cook Strait then upwells on the southern slope of the canyon near Clifford Bay. This plume then spreads laterally and sinks into the slope waters to a level of about 75 m.

A model has thus emerged which suggests that stratification patterns established by tidal stirring variations during settled weather can be rapidly modified and erased by the effects of strong wind events, which are by nature particularly intense near and within Cook Strait. Winds to the southeasterly quarter are particularly effective in funneling South Taranaki Bight water into Cook Strait and beyond.

Further studies are needed to determine the frequency of appearance and persistence of Cook Strait plumes and the implications of injecting nutrient laden water into the otherwise oligotrophic surface waters east of New Zealand. It is of considerable interest to discover if the elongated (~ 750 km) streamers of apparent phytoplankton patches observed by astronauts adjacent to eastern Cook Strait (Stevenson *et al.*, 1977) are nourished by this source, or whether the Cook Strait plume can be safely discounted as a candidate for the nutrient fluxes necessary to sustain elevated levels of primary production in these streamers.

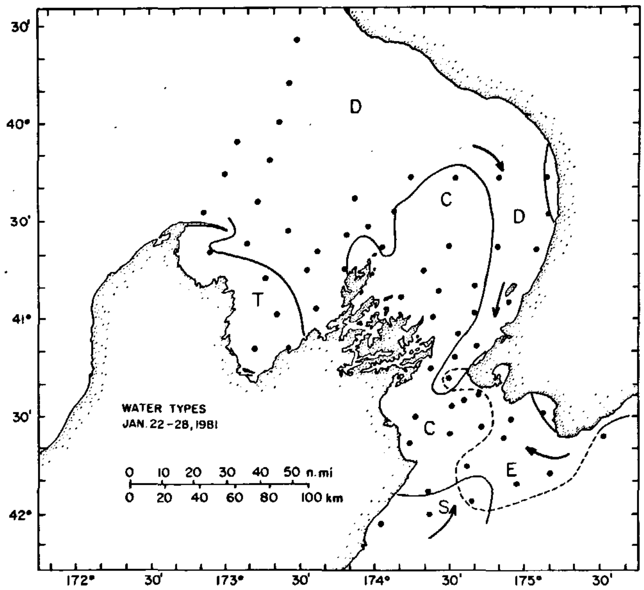

Figure 17
Water types present in study region, January 22-28, 1981 (survey II) based on T-S analysis of station data (E = East Cape Current water, found at depths > 175 m; D = D'Urville Current water; C = Cook Strait water; S = Southland Current water; T = Tasman Bay water (surface T > 20°, S < 34.8)).

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