Defining the seaward extent of New Zealand's coastal zone

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Abstract

The seaward extent of New Zealand's coastal zone (defined here in a biophysical sense as the area of terrigenous influence) was determined from remotely sensed ocean colour and turbidity data. The cross-shore behavior of the colour and turbidity fields were quantified at a number of transects around the coastline and the locations where these fields changed from coastal to oceanic signatures were identified. Results from these analyses suggest that the coastal zone can extend several hundreds of kilometers offshore. Furthermore, the seaward extent determined from these analyses was not correlated to the underlying bathymetry of the continental shelf and slope; features commonly used to define the offshore extent of coastal zones. The estimated seaward limits determined from the analyses of the remotely sensed data were compared to limited available in situ data and predictions from a numerical circulation model. Observations of coastal zooplankton species several hundreds of kilometers offshore suggest good agreement with the predicted seaward extent of coastal zones determined from the remotely sensed data. Offshore transport of surface particles predicted by the circulation model also suggested that pelagic organisms and suspended inorganic particles may be advected offshore at least several hundreds of kilometers.

1. Introduction

Coastal zones form the interface or buffer zone between the processes and fluxes occurring at the terrestrial land–sea interface, and the offshore deep ocean environment. The coastal ocean has commonly been defined as the region of water overlying continental shelf margins (Pickard, 1979); however, recent political and environmental imperatives have questioned the utility of this definition based purely on bathymetry. For example, property rights in the form of Exclusive Economic Zones (EEZs) typically define the seaward limit of the coastal zone in terms of a fixed distance from the shore. Bathymetric definitions of the coastal zone may be appropriate where continental shelves modify physical processes such that

hydrographic boundaries coincide with the shelf break, forming shelf break fronts that separate coastal and oceanic water masses. However, from a living marine resource management perspective it is often more appropriate to define the coastal zone in terms of biotic distributions and processes given that these are not always spatially aligned with the abiotic hydrographic or bathymetric structure.

The coastal ocean, defined hereafter in a biophysical sense as the region between the coast and the offshore extent of terrigenous influence, not only supports major fisheries resource (e.g. Springer et al., 1996; Cole and McGlade, 1998) but also forms a sink for contaminants and land-sourced nutrients (e.g. Staunton Smith and Johnson, 1995; McCook, 1996; Matsunaga et al., 1999). The coastal ocean also serves as a retention, mixing and/or dispersal zone for the eggs and larvae of coastal marine organisms (Sinclair, 1988; Prandle, 1990; Bakun, 1996). The offshore boundary of the coastal ocean also potentially serves as a barrier to the exchange of water and many organisms. Hence, the identification of this boundary can

assist marine coastal management in a number of ways. For example, the offshore boundaries of fisheries management areas should reflect both geopolitical and biotic margins. Similarly, identification of the coastal boundary will aid in determining the locations appropriate for ballast water exchange (Hobday and Hewitt, in preparation; Murphy et al., 2004) to prevent incursions of exotic organisms (Carlton, 1985; Ruiz et al., 1997). Furthermore, governments now have a responsibility to manage all the habitats and biological communities in their jurisdiction under the United Nations Convention on the Law of the Sea (UNCLOS) and this has led the development of a number of management tools including initiatives to define and map habitats and communities within EEZs. However, to date these initiatives have largely focused on the benthic habitats and communities (Norse, 1993) and few attempts to comprehensively define the water-column based habitats and communities that surround continents and islands.

Coastal oceans are generally characterized by high concentrations of both suspended organic and inorganic particulate matter when compared with the deep ocean offshore (Pickard, 1979; Springer et al., 1996; Thomas and Strub, 2001). This feature can be exploited to help identify the extent of the coastal zone either directly (e.g. Murphy et al., 2004) or remotely (e.g. Hobday and Hewitt, in preparation). Concentrations of inorganic particles in nearshore coastal regions are generally greater than locations beyond the shelf break as a result of input from terrestrial sources and the re-suspension of sediments over shallower continental shelves (Pickard, 1979), while organic particles consist of phytoplankton, zooplankton or detritus. Concentrations of these biotic assemblages over coastal and continental shelf regions are typically higher than further offshore due to greater nutrient enrichment in coastal waters. Defining the seaward limit of the coastal zone in terms of organic and inorganic suspended particles therefore encapsulates both biotic and abiotic processes.

As highlighted above, the coastal zone can also be "defined" by the increased abundance and identity of organisms associated with benthic habitats. Both sessile and motile marine organisms occupy the waters of the coastal zone, the majority of which undergo a pelagic larval stage in their lifecycle (e.g. Possingham and Roughgarden, 1990; Roughgarden et al., 1998). The distribution of phytoplankton and larvae in the ocean is controlled by both abiotic (e.g. transport) processes and biotic (e.g. production, growth and mortality) processes. For many coastal organisms, recruitment into adult stocks depends in part on the ability of the larvae to find suitable habitat at the end of the larval stage (Sinclair, 1988; Possingham and Roughgarden, 1990; Roughgarden et al., 1991; Bertness et al., 1992; Wing et al., 1995; Alexander and Roughgarden, 1996). Larvae that were restricted to the nearshore portion of the coastal zone may already be in suitable habitat, but the same may not be true for larvae that have moved further offshore.

Almost all of our knowledge of the spatial distributions of planktonic organisms have been derived from intensive water-sampling cruises (e.g. McGowan and Walker, 1985; Venrick et al., 1987). These cruises are limited in spatial and temporal coverage. Hence, despite more than a century of investigation

into the distributions of planktonic organisms (particularly icthyoplankton of commercial fish species), the sheer spatial extent and variability of planktonic distributions thwart attempts to derive robust conclusions of the spatial and temporal distribution of larvae in the oceans (L. McKenzie pers. comm.; to our knowledge no one has really tried to map generalized plankton distributions from in situ data). Thus, attempts to define offshore limits of coastal waters using the presence of coastal species have been limited by the available data. In contrast, data derived from satellite and aircraft-borne instrumentation have provided opportunity to characterize the spatial and temporal distribution of a variety of water-column properties (e.g. Joint and Groom, 2000). This has particularly been the case for the Coastal Zone Colour Scanner (CZCS) and SeaWiFS sensors that measure ocean colour, which has been assumed to be a suitable proxy for chlorophyll *a* and thus provide information on phytoplankton concentrations and distributions (McClain et al., 1992; Joint and Groom, 2000; Yoder et al., 2002). A second SeaWiFS product is a measure of light extinction with depth (k490) and represents a proxy for turbidity (e.g. Brill et al., 2002). Turbidity is related to the amount of light absorbing suspended and dissolved material in the water. As outlined earlier, the coastal ocean is likely to have higher turbidity than the adjacent oceanic water. Thus, identification of seaward limits of coastal zones might be possible based on satellite signals that measure these biotic and abiotic characteristics of the zone.

Hobday et al. (2002) have demonstrated that conservative delineations between coastal and oceanic zones can be identified by consideration of both remote-sensed ocean colour data and turbidity data. The work presented here represents an application of this technique to the waters surrounding New Zealand (Fig. 1). A specific objective was to demonstrate that a combination of satellite products can be used to identify the offshore boundaries of the New Zealand coastal zone. This was achieved by estimating the seaward extent of the coastal zone from remote-sensed data and collaborating features of the identified coastal zone using a numerical hydrodynamic model and comparing the results against in situ biological data where possible.

2. Methods

2.1. Defining the coastal zone using satellite data

Two SeaWiFS data products were used to determine the offshore boundary of the New Zealand coastal zone; ocean colour and k490. Ocean colour is a useful proxy for chlorophyll *a*, but also detects humic substances derived from land-sourced runoff. k490 is a measure of light extinction with depth and is thus a proxy for turbidity. Turbidity is related to the amount of light absorbing suspended and dissolved material in the water. The ocean colour and turbidity data used consisted of SeaWiFS data collected over 61 months (September 1997–September 2002) and composited over 8-day periods at a scale of 9 km to produce a data set containing 230 images for each data type. Compositing images reduces
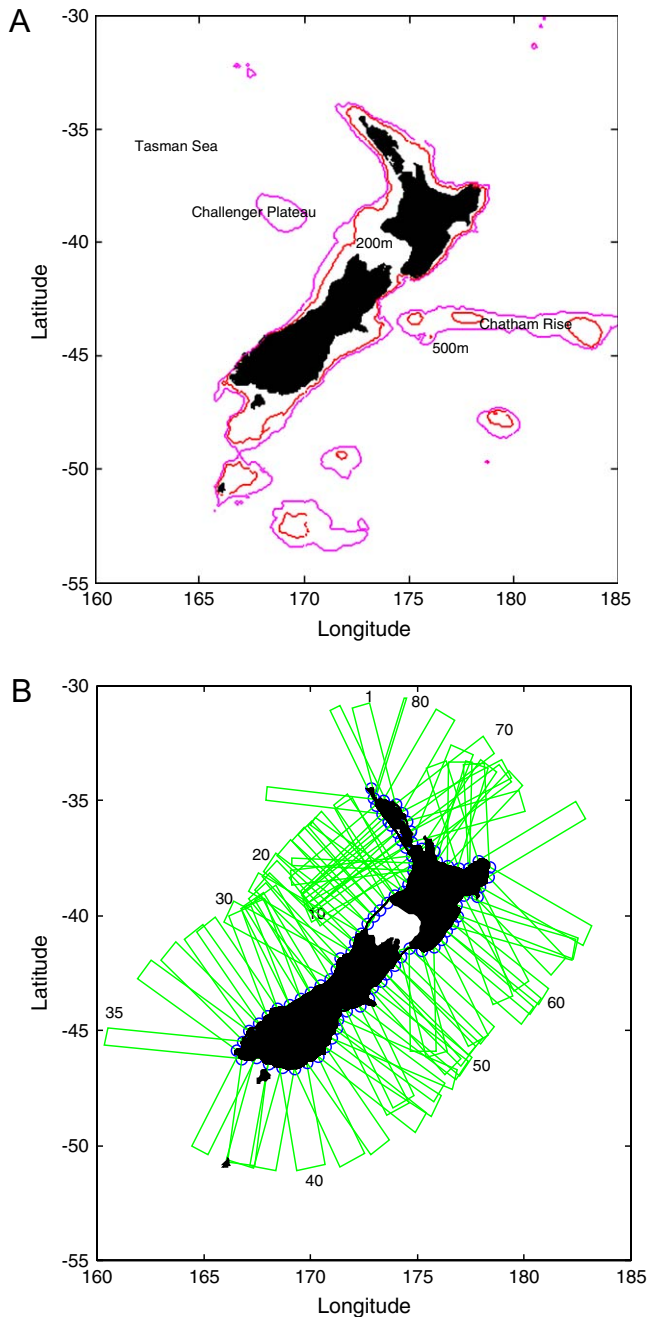
Fig. 1. (A) Bathymetry of New Zealand with the 200 and 500 m depth contours indicated. (B) Transects around New Zealand where SeaWiFS satellite data were extracted (n = 80). Note the single island form of New Zealand with respect to transects. Circles at the coast indicate the center of each transect.

Fig. 2. Example SeaWiFS ocean colour data used in the analysis (8 day 9 km composite images). Note the chlorophyll concentration (mg m^{-3}) is on a log scale. (A) October 19, 2000, (B) March 1, 2000.

some of the problems associated with cloud cover and produces more synoptic coverage (see Fig. 2 for examples).

The first stage of the analysis involved extracting both sets of satellite data for 1° wide (~111 km) transects set perpendicular to the New Zealand coast and extending 500 km offshore. These transects overlapped one another by 0.5° at the coast (Fig. 1B). The algorithm for creating transects along a coastline does not produce perfectly spaced transects around the coast, as shown in Fig. 1B. This is because the coastline is not a straight or smooth line, and where the curvature of the coastline is abrupt a transect base may span a cape of width
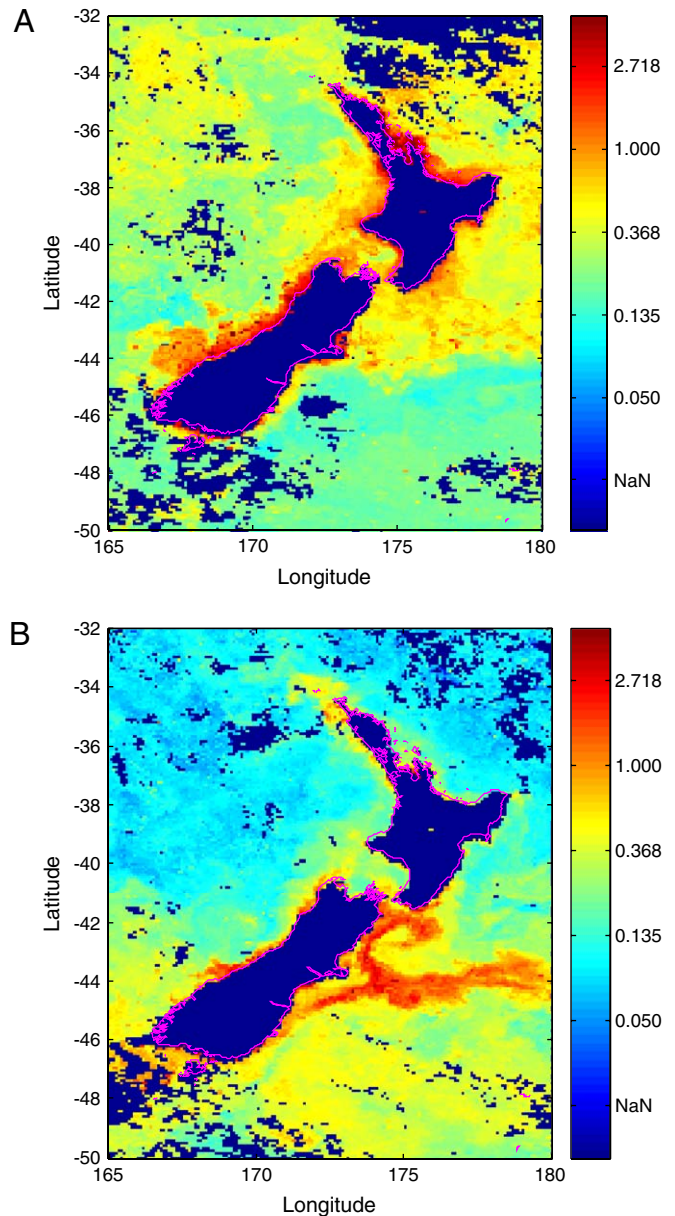
less than 1°, such as in the north-west portion of New Zealand resulting in transects of unequal widths. In regions where the coastline is convex transects will be splayed out, while in concave regions transects will overlap at the distal ends. Transects within Cook Strait (separating the North and South Island) were not long enough to allow determination of the coastal zone. Thus, the coastline of New Zealand was simplified as shown in Fig. 1B; possibly resulting in a conservative (more offshore) boundary to the coastal zone in the region between the two main islands.

Full details of the method for defining the coastal zone are provided in Hobday et al. (2002). Briefly, the coastal zone boundary was defined as the distance at which a smoothing spline (Matlab, Mathworks v5.3) fit to the colour or turbidity

data in each transect first declined to the mean value for the transect. Transect data were binned into 15 km segments and the spline-fitting process interpolated data to a 5-km resolution. The coastal zone was typically narrow compared to the transect length such that the mean value was very similar to the offshore value. Thus, the mean colour or k490 value was assumed to represent the value for the offshore ocean. Using a unique mean value for each transect and data meant that the boundary was independent of the absolute value for the transect location. In fact, it is recognized that coastal and oceanic phytoplankton levels differ in different parts of New Zealand; this algorithm allows the boundary to be identified regardless of the baseline oceanic value. An example of the cross-shore signal in colour data for transect 8 is shown in Fig. 3.

If there were no data within 20 km of the coast, or if gaps in a transect existed (due to cloud), a boundary was not defined for that transect. Thus, each colour or turbidity transect had a maximum of 230 edges (one possible edge per image) to the coastal zone. Outliers were identified and removed from each transect if they were more than 50 km beyond the next furthest offshore edge, this distance is based on maximum possible movement of the coastal zone over the 8-day period. The edge distributions for the two data sets were combined after preliminary analysis showed they were highly correlated, as expected (see Section 3). The maximum extent of the coastal zone for each transect was defined as the maximum coastal zone boundary for the period of time being considered (i.e. maximum of possible 230 edges, or 460 for the combined data sets). The median coastal zone was created from the median distance offshore for edges in each transect. Both monthly (e.g. January, February, etc.) and all months combined for the entire data period were considered. Connecting the maximum

or median values for each transect described the coastal zone around New Zealand at the two temporal scales.

2.2. Elucidating the role of physical oceanographic processes in determining extent of the coastal zone

The offshore extent of the coastal zone around New Zealand is likely to be controlled in part by abiotic processes, in particular cross-shore advection. A numerical circulation model was therefore used in conjunction with the SeaWiFS data to elucidate the role of physical processes in determining the maximum extent of the coastal zone.

The circulation modeling was based on a regional version of the DieCAST three-dimensional ocean circulation model. DieCAST is a numerical primitive equation ocean circulation model that has been successfully applied to a number of regions around the world, including New Zealand (e.g. Dietrich and Lin, 1994; Gibbs et al., 2000). In this case the model domain covers most of the south-western Pacific including the east coast of Australia and New Zealand. In particular the model has been set up on a domain extending from 65°S (Antarctica) to 18°S (Fiji) and from 146°E (Tasmania) to 160°W. The model grid spacing is 0.25° and bathymetry was determined from the NOAA ETOPO5 data set.

The model is forced with NOAA COADS winds averaged for each month of the year and initialized with Levitus (1982) temperature and salinity fields that have been corrected for static instabilities. Temperature and salinity fields were relaxed to seasonal Levitus values at surface and open lateral boundaries. The model is relaxed towards a geostrophically balanced inflow at the eastern side of the northern boundary
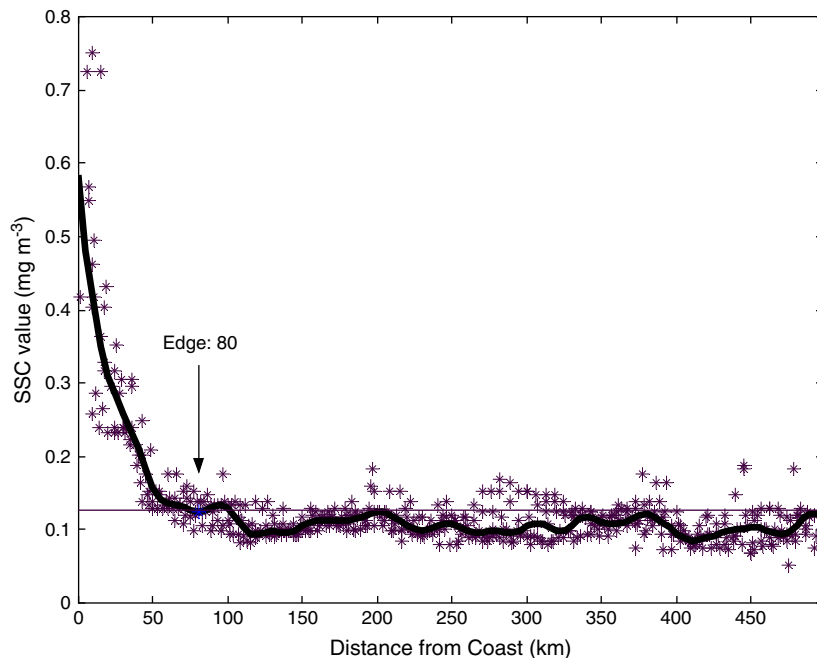

Fig. 3. Example of the ocean colour (SSC) data extracted for transect 8 from the 8-day composite image centered on March 1, 2000. Each star is the SSC value for a pixel in the transect. The spline is fit to binned data for the transect. Note the high values close to the coast declining to "constant" offshore values. The edge of the coastal zone in this transect is at 80 km (see text for additional details).
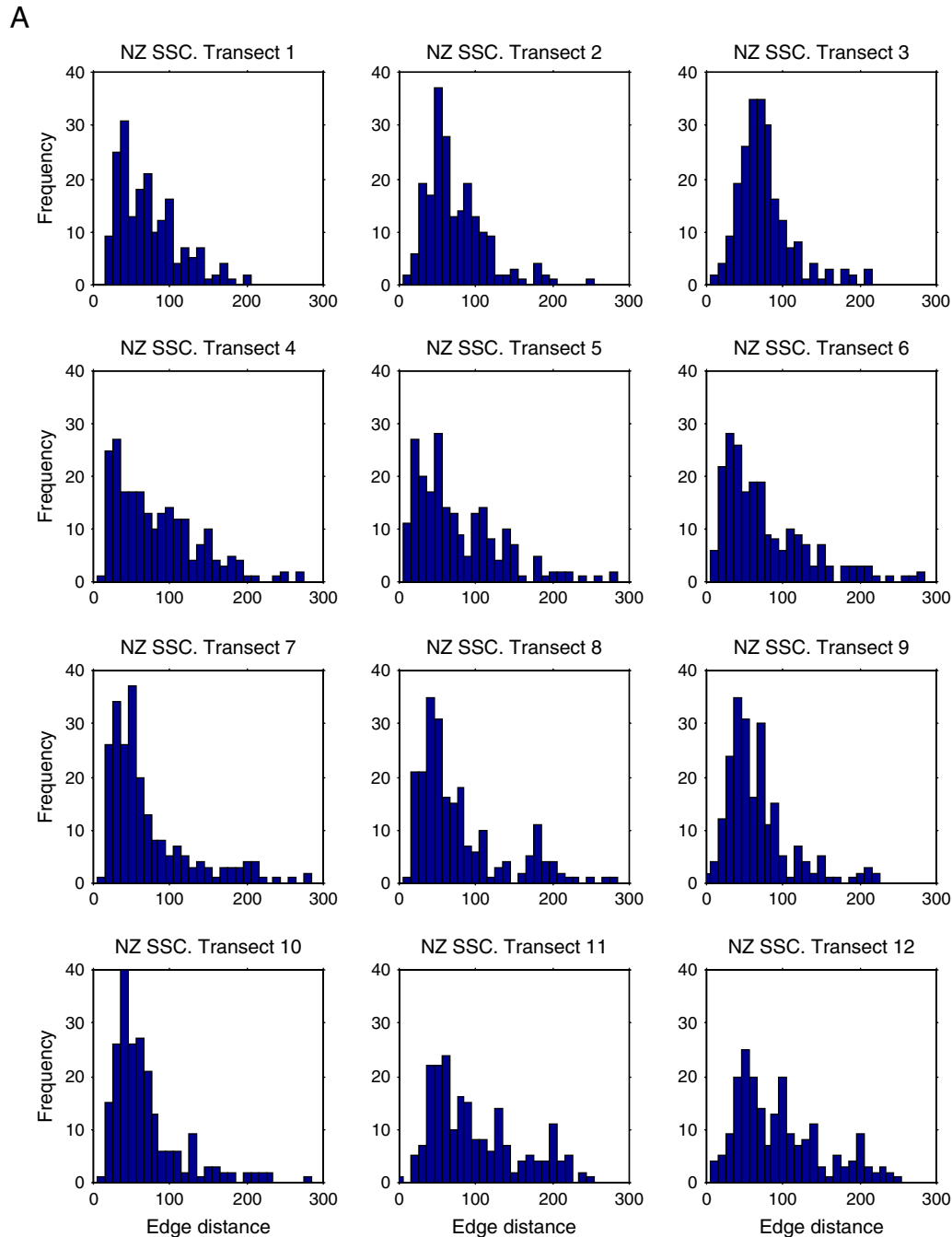
A

Fig. 4. Frequency histograms for the estimated offshore extent of the coastal zone for the first 12 New Zealand transects using the SeaWiFS ocean colour product (SSC) and k490 (turbidity) for Sep-97–Sep-02. Bin size is 10 km. Outliers (more than 50 km from the next nearest inshore edge) have been removed. (A) SSC transects, (B) k490 transects.

in order to simulate inflow of the East Australian Current and a 4 Sverdrup Ekman inflow. The total inflow on the northern boundary is 7.5, 10, 7.8, and 6.4 Sv in winter, spring, summer, and autumn, respectively. Similarly, a geostrophically balanced inflow of 99, 94, 99, 99 Sv (winter, spring, summer, autumn) is applied south of Tasmania at the western boundary to provide a source for the Circumpolar Current and cross-flow was also damped at the western source of the Circumpolar Current. Passive tracers were inserted at pertinent locations

in the surface layers to elucidate transport processes in the coastal ocean.

3. Results

3.1. Coastal zone as defined by SeaWiFS

The offshore boundary of the coastal zone around New Zealand was defined for 80 1° wide cross-shore transects
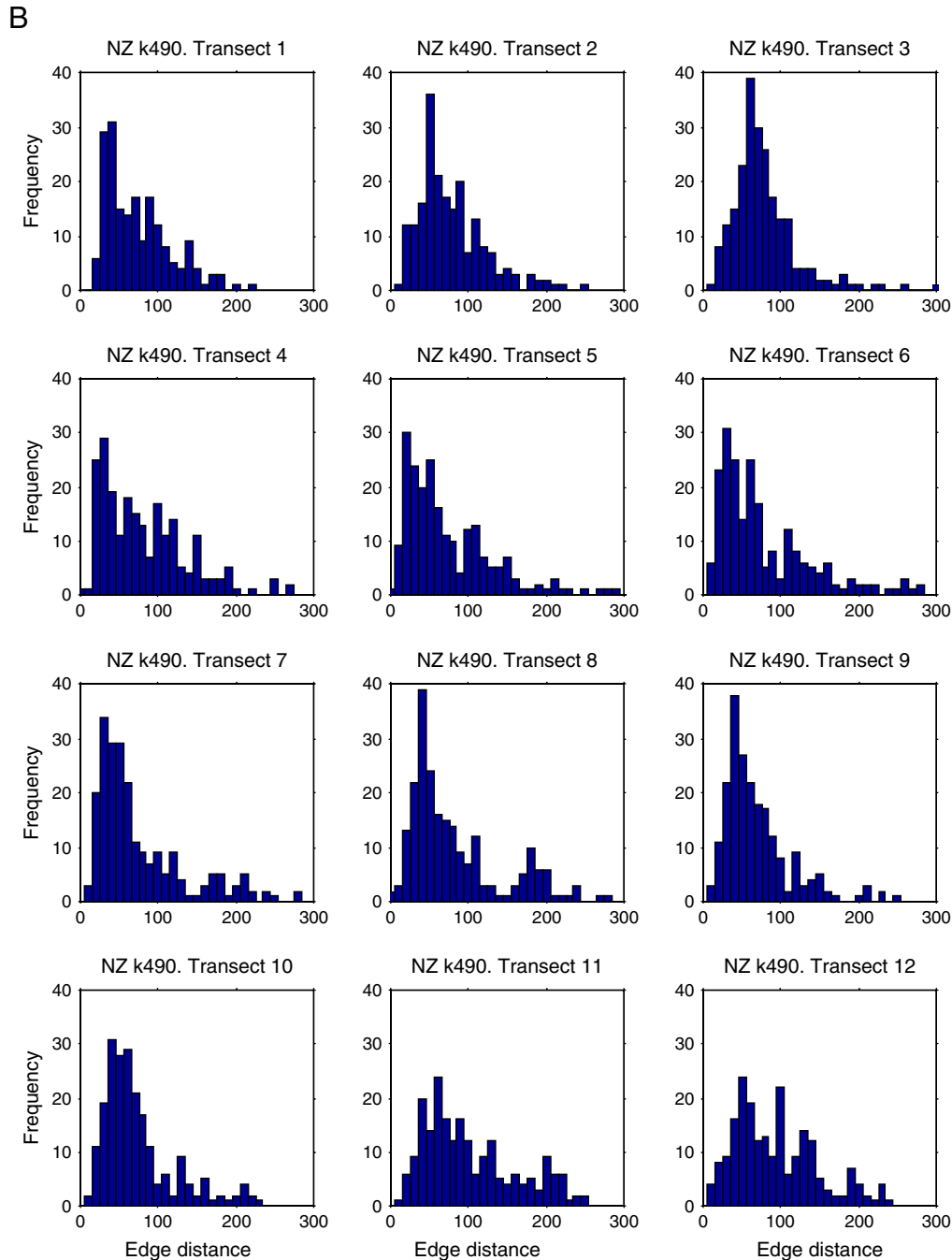
B

Fig. 4 (*continued*).

using the two SeaWiFS data products (Fig. 1B). A total of 16 499 edges were identified using sea surface colour (SSC), and 16 571 edges using k490 (out of 18 400 possible edges 80 transects × 230 images). An example of these results (Fig. 4A) shows frequency histograms of the estimated off-shore extent of the coastal zones defined by the colour data for 12 evenly-spaced transects for all months. Only 18 outliers were identified in each set of transects and these were removed from further analyses. In general there is a non-uniform distri-bution of edge distances with the peak in the frequency

distribution quite skewed to the coast and the maximum edge quite far offshore compared to the median edge. Similar distributions were generated for all transects using turbidity data (Fig. 4B). The median and maximum coastal zone bound-ary was calculated using each of these data. The maximum edge of the overall coastal zone distance around New Zealand ranged in width from 120 to 355 km, depending on the data product (Table 1). Using just the ocean colour data for all trans-ects showed the *maximum* coastal zone extended offshore by an average distance of 241 km (range: 120–345 km; Table 1).

Table 1

Comparison between the distance offshore for the edge of the coastal zone for New Zealand derived from SeaWiFS colour (SSC, chl *a*) and k490 (turbidity) products and for the combined analysis. The overall coastal zone results are for all months and transects combined (i.e. 80 transects), while at the monthly scale the overall maximum and median distance of the coastal zone for each month and transect combination (i.e. 12 months by 80 transects) is listed

Zone	Mean (and range) (km)	
	Maximum edge of coastal zone	Median edge of coastal zone mean
Overall coastal zone		
Colour (SSC)	241 (120−345)	73 (35−135)
k490	251 (125−355)	75 (35−140)
Combined	233 (120−345)	68 (35−140)
Monthly coastal zone		
Combined	164 (28−347)	67 (3−186)

Similarly, the turbidity data indicated that the maximum coastal zone extended offshore by an average distance of 251 km. The *mean* offshore distance of the median edge of the coastal zone was 73 km using the colour data and 75 km using the turbidity component. Both the maximum extent of coastal zone (Fig. 5A) and median extent (Fig. 5B) from colour and turbidity data for the 80 coastal zone transects around New Zealand are significantly correlated ($R^2 = 0.746$ for the maximum extent; $R^2 = 0.915$ for the median extent). Given this strong relationship, these two data sets were combined to derive the final monthly and overall coastal zone boundaries. Maximum extent (furthest offshore) values were extracted from either colour or turbidity boundaries for each transect each month providing the final product. The overall maximum extent of the coastal zone in each transect was determined from the set of monthly maximum extents of either colour or turbidity. The overall maximum offshore extent of the coastal zone was defined by the colour data in approximately half (56%) of the transects and by turbidity data for the remaining transects.

The offshore extent of the predicted coastal zones for all months (overall) and by calendar month is shown in Figs. 6 and 7, respectively. The maximum coastal zone boundary is consistently further offshore than the median boundary, overall and for individual months (Fig. 8). Of particular importance is how far offshore the maximum coastal zone extends. Although there is considerable variability over the months, there is a distinct seasonal signal in both the maximum and median coastal zone (Fig. 8). The coastal zone, by either definition, is narrowest in the winter months (June−September). As a result, the mean of the maximum (median) edge calculated for the monthly coastal zone (Table 1) is less than for the overall coastal zone because it is the average of maximum (median) edge in each transect each month ($n = 12 \times 80$).

The depth at the position of the median and maximum coastal zone boundary was examined to further explore the relationship between water depth and the edge of the coastal zone. A relationship between the location of the seaward edge of the coastal zone around New Zealand and water depth at that edge would then lead to the conclusion that a depth contour could be used to define a coastal zone in the absence of satellite data, and that bathymetry was related to the processes dividing coastal
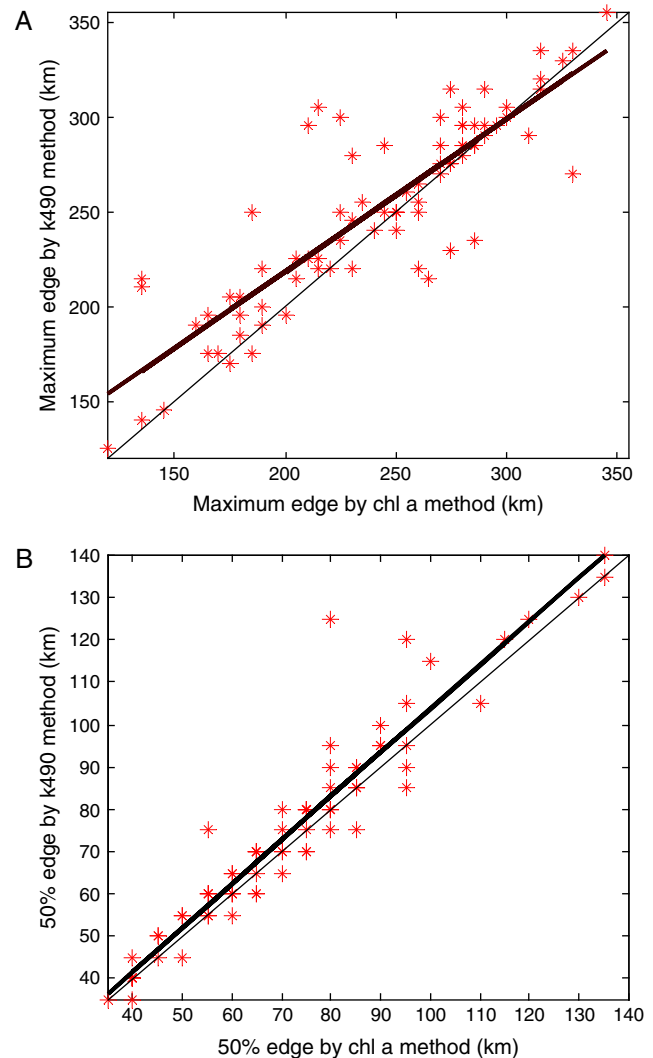

Fig. 5. Relationships between the offshore distances of the edge of the New Zealand coastal zone predicted from ocean colour (chl *a*) and turbidity (k490) data. (A) Maximum edge to the coastal zone ($R^2 = 0.746$). (B) Median (50%) edge to the coastal zone ($R^2 = 0.915$). The 1:1 line and the best-fit line are also shown on each panel ($n = 80$ transects in each case).

and offshore waters. Supporting evidence would be a tight frequency distribution of depths for the coastal zone edge. Comparison of the typical shelf width (Fig. 1) and the coastal zone limits (Figs. 6 and 7) shows that the predicted coastal zone limits often extend far beyond the shelf break (∼200 m), a reference point commonly used when defining coastal regions. The depth of the median coastal zone around New Zealand varies spatially and ranges from less than 100 m and to about 4000 m (Fig. 9B). The mean depth under the median coastal zone boundary is 950 m. The depth distribution using the maximum edge to the coastal zone is skewed to even deeper depths as it is further offshore and so is not shown here.

3.2. Role of physical oceanographic processes

A large number of large eddies were identified in the Die-CAST model (Fig. 10). The larger of these are quasi-permanent
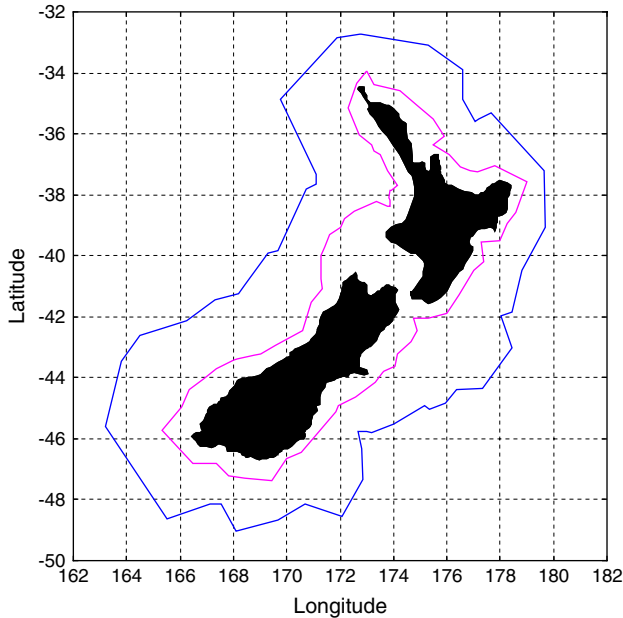
Fig. 6. Overall coastal zones around New Zealand based on the maximum edge (outer line) and median edge (inner line) for the period Sep-97–Sep-02.

features; for example the East Cape eddy off the north-eastern coast of the North Island. The model also successfully reproduced sporadic upwelling events, and associated recirculations (see small eddies off the west coast in Fig. 10) that are known to occur particularly off the west coast of the South Island, resulting from interactions between winds, alongshore currents and bathymetry.

Whilst the eddies identified in the model simulation are all offshore (beyond the 200 m isobath), their influence is likely to result in water masses and the associated plankton being transported inshore or offshore. This was further investigated by inserting tracers in the surface layer of the DieCAST circulation model at pertinent locations around the coastline and examining the trajectories over periods up to 176 days. Fig. 11A shows the trajectories of tracers placed just inshore of the 100 m isobath over a 40-day period. Clearly, most of the passive particles were advected along in a general shore-parallel direction. Similarly, particles injected over the continental slope (slightly further offshore) were also generally advected in a mostly shore-parallel direction. By contrast, running the simulation over 176 days (between 5 and 6 months) resulted in significant offshore transport and, in some cases, particles became trapped in recirculating eddies and returned shoreward (Fig. 11B).

The model suggests that surface particles can be transported considerable distances offshore even on the 'upstream' west coast. Detailed inspection of these regions showed that these particles were advected in offshore-directed upwelling jets and recirculations; an example of which may be seen off the south-west coast of the South Island in Fig. 10B. Once again comparison between this feature in Fig. 10B, the model simulation in Fig. 11B and the offshore extent of the coastal zone shown in Fig. 6 suggests that the coastal zone can indeed

extend several hundreds of kilometers offshore along the west coast.

4. Discussion

The offshore extent of the coastal zone and thus the distribution of coastal planktonic organisms is likely to be a function of both biotic and abiotic processes. The specific objective of the work presented here was to attempt to quantitatively describe the spatial and temporal behavior of the seaward extent of the coastal zone around New Zealand that accounted for both biotic and abiotic processes. The satellite-based method used to achieve this objective (Hobday et al., 2002) involved analyzing remote-sensed ocean colour and turbidity data. The ocean colour data are a proxy for chlorophyll *a*, and hence phytoplankton, and the turbidity data are a proxy for suspended organic and inorganic particulate matter (SPM), dominated by terrigenously-derived material. These signals may be highly confounded in the nearshore waters, however, the independent identification of coastal zone extent obtained from the two products were very similar to the combined approach presented here. Of greatest import is that high colour and turbidity values were restricted to the coastal zone.

The coastal zone defined using satellite information is hypothesized to contain the majority of the coastal phytoplankton and zooplankton species. The results of the analyses of the satellite data suggested that the delineation between coastal and oceanic planktonic assemblages generally lies many tens of kilometers offshore and the maximum extent is sometimes almost 300 km offshore of the coast of New Zealand. A seasonal signal was evident in the extent of the coastal zone, suggesting that the zone responds to seasonal forcing. A similar approach with the same time period of data applied to the Australian coast showed that the coastal zone varied seasonally in some areas and not in others (Hobday et al., 2002). Furthermore, there appears to be no strong relationship between the seaward edge of the coastal zone and the depth of the underlying water, and so it seems that the surface signal that defines the coastal zone is independent of bottom topography. Given that New Zealand is not known for strong widespread, persistent shelfbreak fronts, a weak association between topography and the edge of its coastal zone is not unexpected.

Despite advances in knowledge of chlorophyll (phytoplankton) distributions based on satellite data, inferences about the distribution of zooplankton species via remote sensing remain tenuous at best. This is principally because chlorophyll *a* may be a poor indicator of zooplankton (Tait, 1981). Thus, inferences about the distribution of coastal zooplankton species within the coastal zone remain subject to validation through in situ sampling. At this stage the hypothesis that coastal zooplankton species are restricted to the coastal zone identified on the basis of chlorophyll distributions remains untested.

The influence of oceanographic processes in determining the seaward extent of the coastal zone has been demonstrated in other regions. New Zealand's elongated north-east aspect (Fig. 1) represents a long barrier directly in the path of the general eastward flowing surface flows in the temperate South
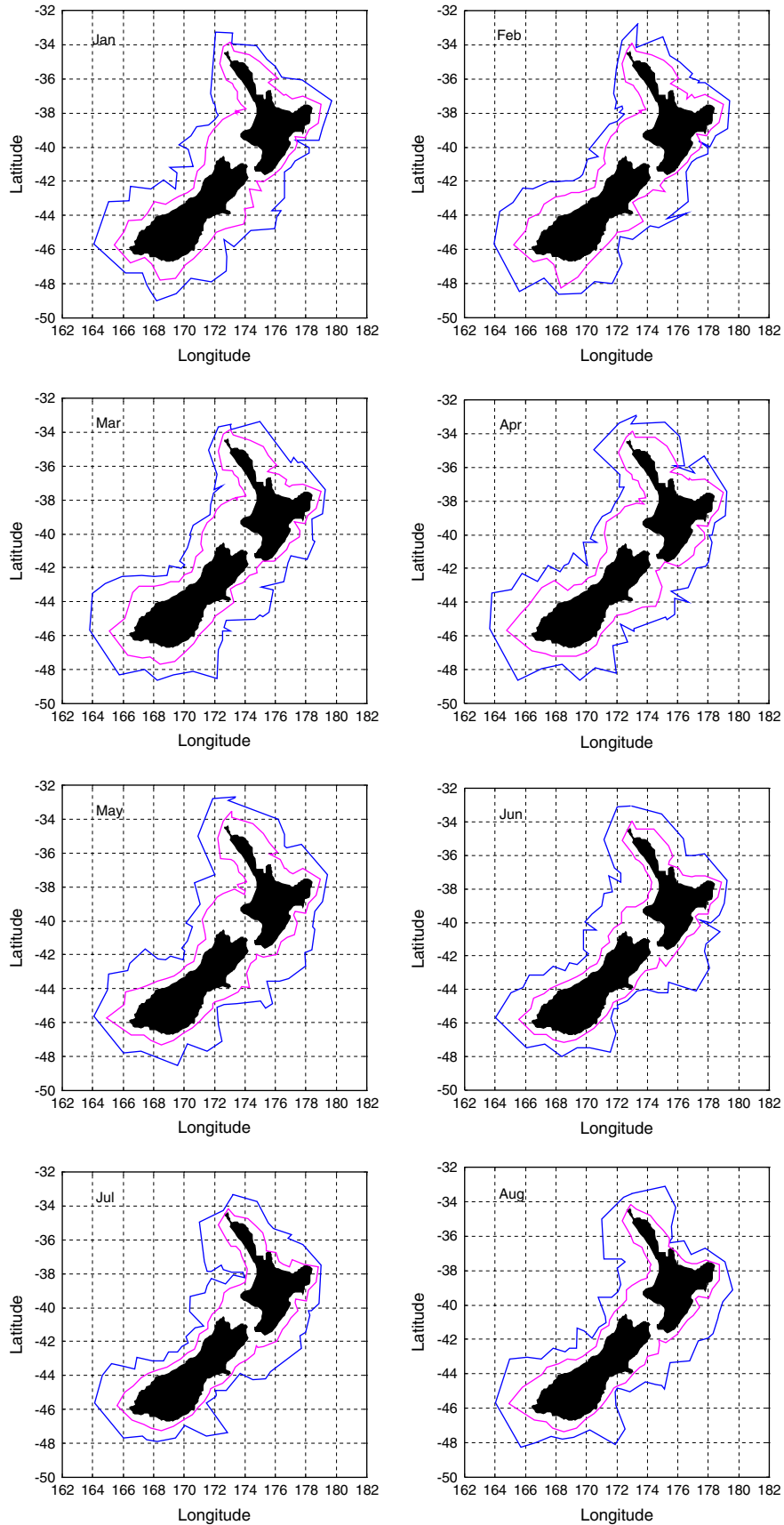
Fig. 7. Maximum (outer solid line) and median (inner solid line) extent of the coastal zone around New Zealand by month (Jan−Dec).
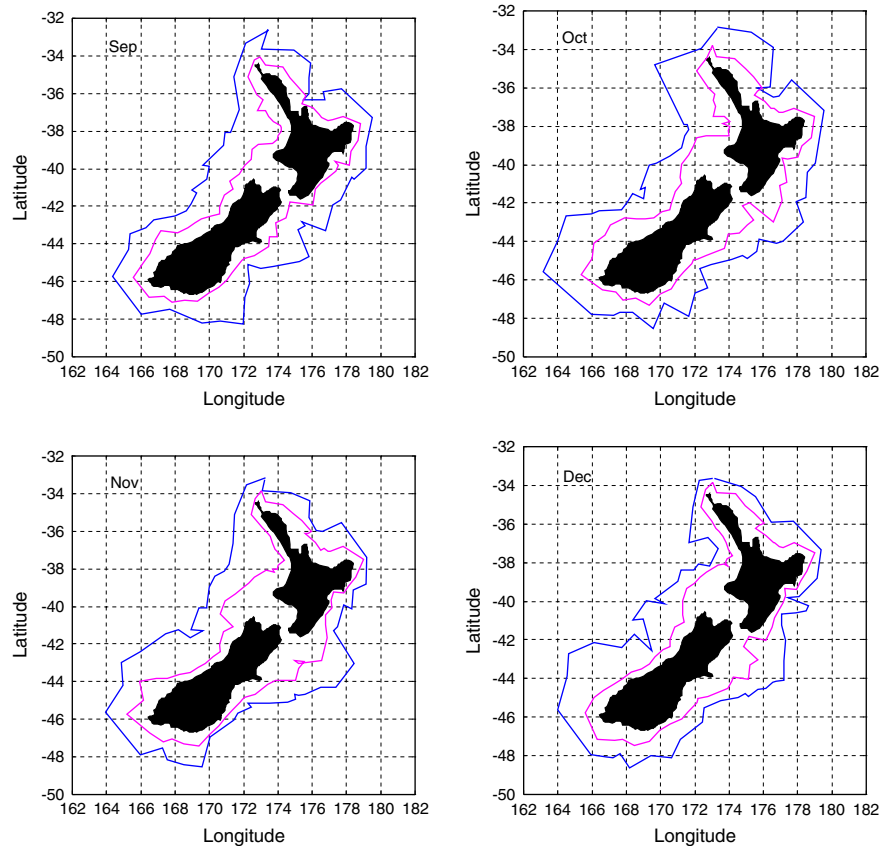
Fig. 7 (*continued*).

Pacific. A simplistic analogy to the surface ocean current flows around New Zealand is that of a long rock placed across the current in a river. In such an analogy we would expect to find large recirculating eddies on the downstream side of the rock (to the east of New Zealand) as is observed in the Die-CAST ocean model simulations (Fig. 10). However, the 'rock-in-the-river' analogy is somewhat simplistic since it does not take into account the other dynamical processes controlling regional circulation. For example, interactions between winds, alongshore currents and bathymetry on the west coasts lead to sporadic upwelling and associated recirculation (see small eddies off west coast in Fig. 10).

Both upwelling regions and eddies play a major role in defining the spatial extent of the coastal zone around New Zealand. For example, upwelling off the west coast of central New Zealand may influence the width of the coastal zone. A major feature of coastal upwelling regions is that the surface currents tend to flow offshore (see Marchesiello et al., 2000 for a recent example). Hence coastal planktonic organisms are often transported offshore in upwelling regions. In many cases transport is enhanced by strong narrow offshore flowing jets. Hence the coastal zone defined by the presence of coastal species may be wide in upwelling regions in comparison with downwelling regions.

The vertical component of abiotic circulation processes can also play a major role in determining the offshore distribution of coastal planktonic communities. This is primarily through the vertical transport of nutrients that underpin pelagic primary productivity in the oceans. Regions where nutrients are transported into sunlit surface waters (upwelling zones) or regions where significant vertical mixing occurs (over wide shallow shelves) can support tremendous biological production (growth and reproduction of phytoplankton) that subsequently supports higher trophic levels. Therefore, the horizontal extent of coastal pelagic species is also often related to the width of the continental shelf, although this result can be confounded by the development of seasonal thermoclines that act to dampen vertical exchange in the water-column. The shelf (defined as the 200 m isobath in Fig. 1) around New Zealand is generally narrow (often only 5–15 nm wide except for south of the South Island, west of central New Zealand and offshore of the central east coast of the South Island). Therefore we might also expect that coastal planktonic organisms may be found further offshore in the regions to the south of the South Island and to the west of central New Zealand by comparison with regions where the shelf is narrow in the absence of upwelling or large eddies.

The most suitable data set for verifying that the satellite-based method used here defines a biologically meaningful coastal zone would be a series of cross-shore transects examining phytoplankton and zooplankton assemblages and abundances over multiple months or years. Demonstrating that either coastal or oceanic species were found inside or outside the coastal zone boundary, respectively, would enhance the results of the satellite-based analysis and numerical simulations.
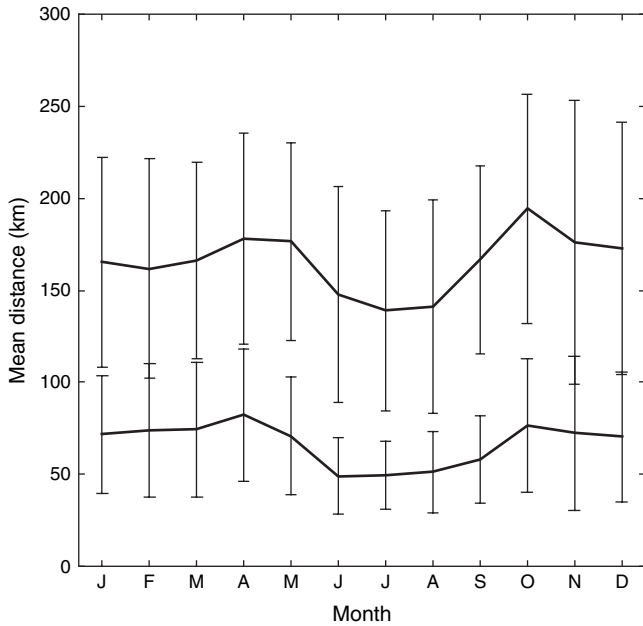
Fig. 8. Mean (±1 SD) distance from the coast for the New Zealand coastal zone defined by the maximum (upper line) and median (lower line) edge distance.

However, a review of the literature failed to uncover such a comprehensive data set around New Zealand. Despite this, results of studies on the Chatham Rise and off the west coast of the South Island provide limited verification of the satellite-based coastal zone identification method.

The extensive shallow regions of the Chatham Rise, that lie to the east of central New Zealand, and the Challenger Plateau to the west of central New Zealand (Fig. 1) support enhanced biological activity. This is indicated in many ocean colour images (e.g. Fig. 2B). However, the apparent high chlorophyll in this region could be abiotic material advected from the coast, or biological material associated with either coastal and/or oceanic phytoplankton species. The results from the satellite-based analyses suggest that the coastal zone in this region can extend halfway out over the Chatham Rise (around 300 km). Therefore, we could expect particles of coastal origin such as planktonic organisms to be found over the western half of the Rise. Bradford-Grieve et al. (1998) provide a description of the abundance and species composition of mesozooplankton samples acquired from several sites located over the Chatham Rise, all around 300 km east of the central east coast of the South Island (the edge of the coastal zone defined in
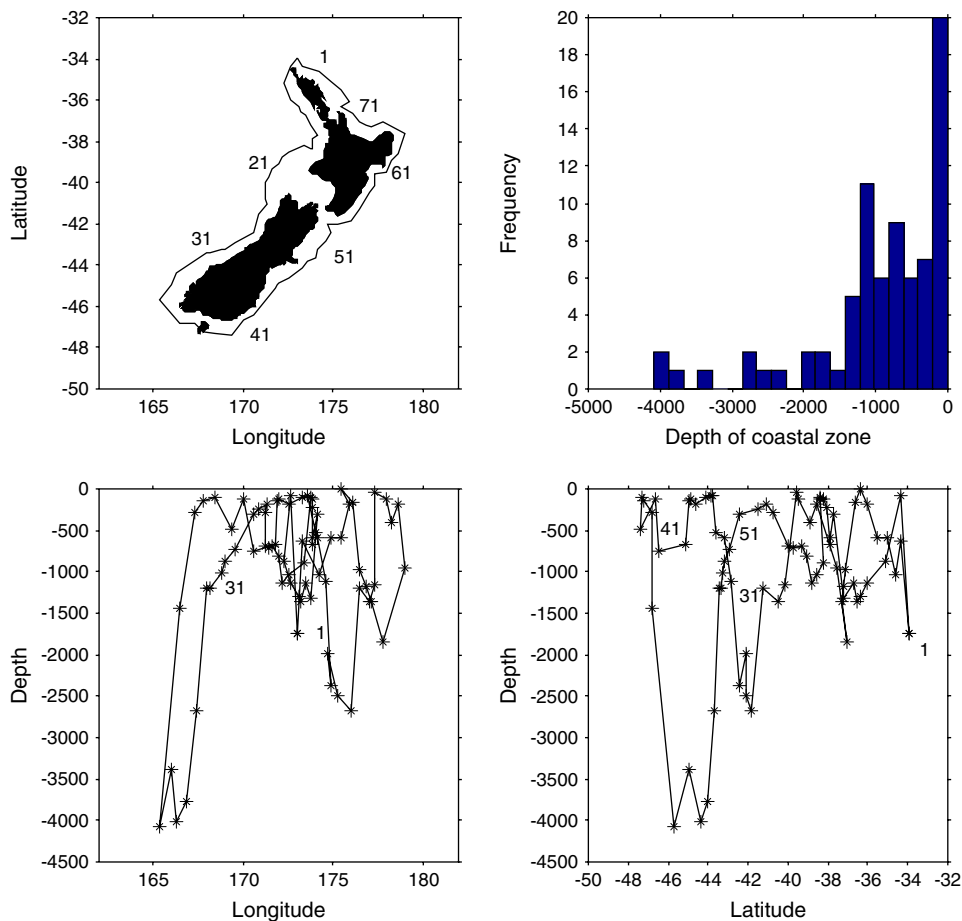

Fig. 9. Relationship between edge of the overall median coastal zone and the underlying water depth. (A) Extent of the median coastal zone around New Zealand (NZ). Some transects are numbered to assist with orientation in the lower panels. (B) The distribution of water depths at locations corresponding to the median edge. Overall median depth is 710 m, mean is 950 m. (C) Longitude and depth of the median coastal zone. The numbers refer to the position of transects around NZ. (D) Latitude and depth of the maximum coastal zone. The numbers refer to the position of transects around NZ.
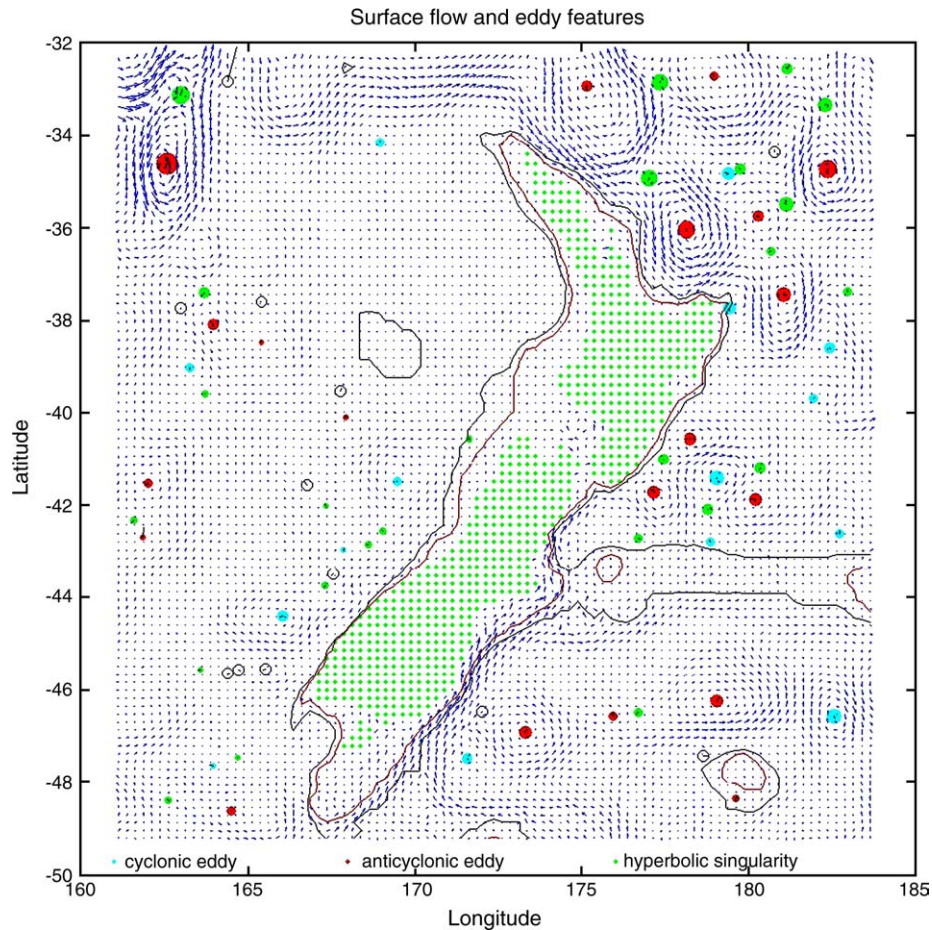
Fig. 10. Numerical simulation of surface ocean currents around New Zealand. Dominant eddies are highlighted by dots.

Fig. 6). The timing of the in situ sampling was prior to the period of satellite data coverage, however, comparison of the patterns is reasonable in this data-poor environment. The samples of Bradford-Grieve et al. (1998) were dominated by oceanic copepods and euphausids, however, the presence of coastal species, such as the amphipod *Themisto australis*, indicated that either coastal water had been entrained into the STC (Subtropical Convergence) over the Chatham Rise in both winter and summer, or conditions were suitable for the coastal species to bloom. While the in situ data were collected during June and October 1993, the position of the coastal zone boundaries for June (1997–2002) and October (1997–2002) (Fig. 6) suggests that the in situ sampling locations were on the edge of the coastal zone during these months and this is consistent with the fact that coastal species were measured this far offshore. Unfortunately, no data further offshore are available. It is also worthwhile highlighting the fact that the boundary of the satellite-based analyses suggests that the coastal zone only extends halfway out across the Chatham Rise despite the relatively shallow water in this region.

In the second in situ study, Bradford-Grieve and co-workers sampled phytoplankton and zooplankton communities off the west coast of the South Island sporadically during 1987, 1988 and 1990. Bradford-Grieve et al. (1996) provide details of the abundances and assemblages of zooplankton from

a number of locations ranging from 5 to 50 nm (9–93 km) offshore. Of interest here is that many of the dominant species of zooplankton were found both at the inshore and offshore sites, for example the "coastal" copepod *Paracalanus indicus* was measured 93 km offshore of the west coast where the continental shelf is particularly narrow. The fact that coastal species were found over 93 km offshore indicates that the coastal zone extends at least this far. This is consistent with the results from the analyses of the SeaWiFS data that suggest that the coastal zone can extend several hundreds of kilometers offshore at this location during all calendar months. However, once again no data are available further offshore and so the outer edge of the coastal zone cannot be verified.

Non-indigenous crustaceans are often considered to be potentially high-risk invasive organisms (Chapman and Carlton, 1991; McDermott, 1991; Carlton and Geller, 1993; Thresher et al., 2000). Understanding the location of the boundaries that separate coastal and oceanic water may be crucial for regulating activities that may introduce such invasive species (e.g. Lafferty and Kuris, 1996; Hobday et al., 2002). One complication is for species that spend considerable times in the plankton and have the capacity to be mixed into oceanic waters. For example, some species of crustaceans also spend particularly lengthy periods in the plankton before settling to benthic substrates (e.g. Chiswell and Booth, 1999; Griffin et al., 2001).

A

Surface flow and trajectories: year 10 day 40

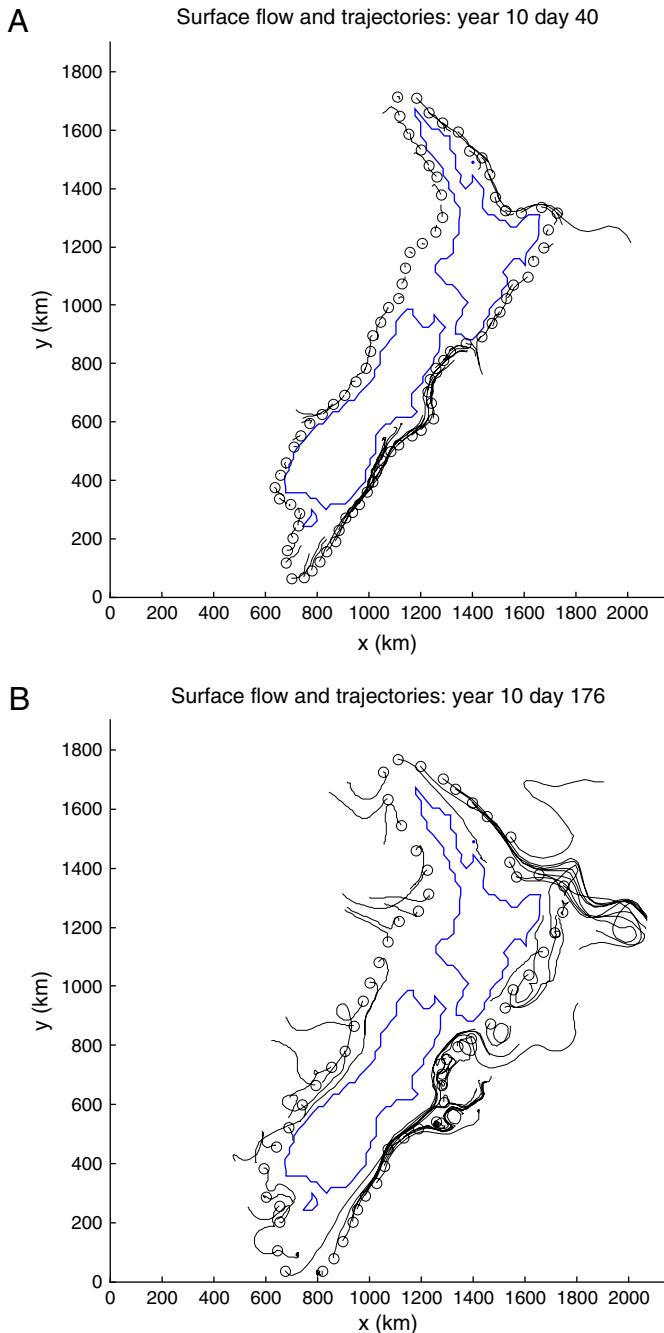
B

Surface flow and trajectories: year 10 day 176

Fig. 11. Trajectories from the DieCAST circulation model. The small circles represent the insertion points of the particles. (A) Trajectories of passive particles after 40 days. (B) Trajectories of passive particles after 176 days.

For example, spiny lobsters (Palinuridae) can spend over 12 months in the plankton and undergo numerous developmental stages. These extended larval periods allow larvae to be transported considerable distances offshore. For example as noted above, Chiswell and Booth (1999) observed sampled developmental stages of *Jasus edwardsii* up to 284 km offshore of the east coast of the lower North Island of New Zealand. The authors suggested that these animals were retained in the quasi-stationary Wairarapa mesoscale eddy. Hence the maximum offshore extent of the larvae may be influenced by the diameter of the mesoscale eddies. The fact that the larval stages of

a coastal crustacean were found 284 km offshore indicates that a coastal zone defined by the presence of coastal species can extend at least this far offshore and concurs with the predicted coastal zones presented here.

Despite this result, using coastal icthyoplankton and other larvae as indicators of the maximum extent of coastal zones can be deceiving since long-lived larvae can be transported far beyond what we are considering to be the coastal zone here (Roberts, 1997; Chiswell et al., 2003). In other words, if we define the offshore extent of the coastal zone to be a point where absolutely no coastal taxa can be found, then in many cases much of the world's oceans would be defined as coastal zone although the larval or zooplankton concentrations are very low. If a zooplankton-based definition to the coastal zone was required, a definition linked to concentration might be more relevant and suitable from a management perspective.

An investigation of the abiotic transport processes was also performed to help validate the method. This involved a consideration of the major oceanographic features and processes occurring around the New Zealand coastline and investigating theoretical transport using a numerical model. Once again the predicted coastal zones were in good qualitative agreement with our understanding of cross-shore transport processes occurring around New Zealand. In particular, the offshore extent of the predicted coastal zones appears to scale to the diameter of the quasi-permanent eddies located off the eastern coast of New Zealand. This was confirmed by simulating the trajectories of passive particles using the numerical circulation models.

5. Conclusions

The coastal boundaries of New Zealand, important for a variety of natural processes and management strategies, were identified in a consistent approach over a five-year period. The use of satellite data allowed temporal and spatial coverage that would not be possible with in situ sampling. It remains important to validate these boundaries, and determine the species composition inside and outside the coastal zone. These boundaries may be used to regulate human activities around the coast, such as ballast water discharge (Hobday et al., 2002), waste disposal, fisheries management and fishing activities. The utility of this classification approach will depend on the purpose to which it is applied. For example, the remote-sensed data classified the coastal zone without regard to community structure. It is expected that different parts of the coastal zone may be dominated by different species, and that community structure will also vary over time. Hence the usefulness of the method for stock management would be limited. However, the predicted zones do provide insight into the spatial scale of zooplankton distributions and the abiotic factors controlling these distributions around New Zealand.

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