NIWA

Taihoro Nukurangi

Alternative biosecurity management tools for vector threats – ballast water discharge and exchange areas

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Final Research Report for
Ministry of Fisheries Research Project ZBS2000/02
Objectives 1, 2 and 3

National Institute of Water and Atmospheric Research

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Final Research Report

Report Title: Alternative biosecurity management tools for vector threats – ballast water discharge and exchange areas

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7. Executive Summary

This study provides a statistical description of currents at several sites around New Zealand within the 12 mile territorial zone, with the main aim of identifying ballast water discharge areas that minimise the risk of marine organisms present in the ballast water having an impact on the New Zealand marine environment.

Output from a numerical model of the tides, data from current meters moored in the coastal zone and two surface drifter tracks were analysed to estimate expected maximum displacements from a point source of discharge.

Tides are relatively unimportant in the dispersion of potentially invasive marine organisms over most of New Zealand's coastal waters where they will transport the organisms only a few kilometres. However tides are important in transporting material in and out of harbours, and they also help to mix material within the coastal zone.

Of more importance in advection and dispersion of ballast water are the coastal currents which are set up by the large scale oceanic circulation, and modified by local winds.

The appropriate timescale for most marine organisms discharged in ballast water probably lies somewhere between several days and several weeks, but can be as high as two to three months. Trajectories, displacement histograms, and direction roses derived from long-term current meter moorings provide some information about the expected distribution of a contaminant at 1, 10 and 60 days after release.

At timescales of 1 day, mean maximum displacements range from 7 to 26 km. At timescales of 10 days, the mean maximum displacements range from 38 to 178 km. For timescales of 60 days, maximum displacements can range as high as 750 km. Except for off the east coast of the South Island, these maximum displacements are too short to expect discharge to be advected away from New Zealand quickly enough to avoid introduction of invasive species.

A map of site discharge risk level is presented based on these analyses. Highest risk areas are off the northeast coast of the North Island between North Cape and Bay of Plenty. Lowest risk areas are between East Cape and Mahia Peninsula.

Sources of near real-time information that could be accessed quickly to identify discharge sites on a case by case basis are documented.

8. Objectives

The overall objective of this project was:

- To identify areas in which ballast water can be exchanged or discharged so as to minimise the risk of marine organisms present in ballast water having an impact on the New Zealand marine environment.

Specific Objectives were:

1. Using available information, characterise the oceanographic features within New Zealand's territorial sea (12 nautical miles) and identify areas that minimise the risk of marine organisms, discharged as part of the ballast water, having an impact on the marine environment.

2. Identify the relative efficacy of the discharge areas identified in objective 1.

3. Document the availability of real-time information that could be accessed quickly to identify discharge sites on a case by case basis.

The submission of this final research report achieves the revised final reporting requirement for ZBS2000/02.

9. Introduction

The introduction of invasive marine species into new environments by ships' ballast water, attached to ships' hulls and via other vectors has been identified as an area of great concern to New Zealand. Particularly high-profile arrivals presumed to be from ship's ballast include the seaweed *Undaria pinnatifida* (Cranfield et al., 1998) in New Zealand, and toxic algal blooms in Tasmania (Bolch, 1990; Hallegraeff & Bolch, 1992). However, because the life history of many marine animal species includes a larval phase, and some larvae can be hardy enough to survive long ocean crossings in ballast water, potential arrivals include zooplankton, benthic invertebrates (Willan, 1987), and even small fishes (Willis et al., 1999).

New Zealand has a disproportionately large number of endemic marine species. Marine assemblages of several of New Zealand's offshore islands are particularly significant. The Kermadec Islands, are unique in the archipelago and have affinities with the marine floras of warmer waters of South Africa and the eastern Pacific. Many species on the Kermadecs do not occur elsewhere in New Zealand. Similarly, because of their distance from the mainland, coastal waters of the Chatham Islands contain many endemic species. On the main islands, Spirits Bay, Fiordland, and Kaikoura Peninsula are known to support rich marine assemblages with high levels of endemism (Inglis, 2001). In addition, there is little doubt that marine shellfisheries and aquaculture in areas such as Foveaux Strait, Marlborough Sounds and Tasman and Golden Bays could potentially be devastated by the arrival of exotic organisms.

The overall objective of this work is to identify areas where ship's ballast water can be discharged in order to minimise the risk of the introduction of exotic marine organisms into New Zealand's marine environment.

Before such an identification can be made, however, one must define the criteria that establish 'minimal risk' of introduction. A complete and proper assessment of the potential hazard from any particular ship's ballast water would require not only knowing the species content and life cycles contained in that ship's ballast water, but also a full understanding of the potential impact of such species introduction on New Zealand's marine and economic environment. For example, a ship containing a short-lived species that could have a devastating impact on a particular marine ecosystem might be directed to a different discharge location than a ship containing longer-lived, but less threatening, species.

The issue of minimising potential introduction of invasive species into New Zealand's waters is therefore too complex to be dealt with comprehensively here. Instead we define the risk criteria in terms of minimising the time ballast water discharge spends in the coastal environment. Thus for this report, 'minimal risk' is defined solely in terms of minimising the time that discharged ballast will spend in the coastal zone (taken here to be to the 12 nautical mile territorial limit).

For this report, we concentrate on the problem of determining the most likely distributions of a passive tracer from an initial source. This means that we assume that any introduced species has no active behavioural patterns. For species such as phytoplankton this may be a valid assumption, but for small fish and even some larval species there is the possibility that the new arrivals may have some behaviour that increases their chances of introduction beyond those investigated here. An example may be a species that actively seeks the coastal environment by swimming into shallower or less saline environments.

Some species of plants and animals have remarkably long-lived cyst or larval stages. Resting cysts of toxic dinoflagellates can be viable for more than six months (Baldwin 1992). Other potential invaders have juvenile phases of variable length. For example, planktotrophic larvae of the Northern Pacific seastar, *Asterias amurensis*, have a maximum life of ~150 days (Bruce et al., 1995). Eggs and larvae of the Asian mussel, *Musculista senhousia*, are planktonic for 45–55 days (Furlani 1996). Spores of the seaweed, *Undaria pinnatifida*, can remain viable for up to 14 days, but remain suspended in the water column for relatively short periods. Experiments done in the Marlborough Sounds suggest that most spores of this species disperse no further than 10 m from their release point (Forrest et al., 2001).

The length of the viable larval stage considerably impacts the chances of introduction. Species with long-lived cyst or larval stages are more likely to survive ocean crossings in ships' ballast, but there is still the chance either that short-lived species, or long-lived species that can adapt quickly to a new environment, will arrive in ballast water. Thus we chose three time-scales (1, 10, and 60 days from ballast discharge) for this analysis and present the results in terms of these timescales.

The timescale represents both the intrinsic larval cycle and the time required to disperse the discharge to the point that the concentration (in terms of organism densities) is so low that the discharge is not a threat. What timescale is relevant for the marine discharge problem is not entirely obvious. If organisms have survived long ocean trips in ships' ballast tanks, we presume the biological timescale can be quite long, probably it is of the order of days to weeks. To some extent, this potentially long timescale is offset by the effects of dispersion and mixing, but given that the introduction of an invasive species may require only the arrival of a few individuals, it may be that dispersion and mixing do not significantly reduce the timescale. Based on the length of ship voyages to New Zealand, we speculate that the timescale is at least 10 days, and may be as high as two to three months. The 10 day timescale is chosen as representative of relatively short-lived larvae, and the 60-day timescale as representative of longer-lived larvae. The 60 day timescale is chosen in part because it is a practical limit to the timescale that can be investigated with the relatively short current meter records (see later).

The area under direct threat from a discharge of ballast water can be estimated from the probable loci of locations that the discharge can be advected to in the timescale of interest. Of course, once introduced, exotic organism can spread well beyond their introduction zone. World-wide, most marine invasions have been reported in sheltered bay and estuarine environments (Ruiz et al., 1997; 2000; Cranfield et al., 1998; Reise et al., 1999). This includes a broad range of taxonomic and trophic groups that have occupied a diverse range of habitats within these sheltered environments. Comparatively few invasions have been reported from rocky and sandy shorelines of outer coasts (Ruiz et al., 1997). In New Zealand, almost all of the currently recognised NIS are confined to harbours or embayments (Cranfield et al., 1998). The large incidence of invasions in estuarine and harbour environments probably reflects the location of international ports and anchorages and also the similarity in environmental conditions between the source of immigrants and recipient ports. Ballast water is usually taken from, and discharged into bays and estuaries. Species whose larvae or adults are able to tolerate estuarine conditions are, therefore, most likely to colonise ship ballast and hulls and, subsequently, to survive in the discharge environment. Most invasions, however, have been reported from high salinity zones (salinities of 18–35) of estuaries, rather than from the freshwater reaches (Ruiz et al., 2000). Also, establishment is most likely when a sufficiently large number of potential colonists arrive at a time when environmental conditions at the recipient site are conducive to the survival of adult or resting stages. Propagule supply hypotheses suggest that the likelihood of invasion is a function of the total number of individuals that arrive in a region over a given period of time. Their basic tenet is that the chances of successful establishment increase in proportion to the number and density of arriving individuals ("propagule pressure"). High risk areas for deballasting are likely to be those where water is delivered relatively rapidly to coastal environments so that dilution of the discharge is minimal.

Three sources of data were used in this study. The first is a numerical model of the tides around New Zealand developed at NIWA. The second is a set of current meter measurements from moorings that have been deployed sporadically within the coastal zone over the last couple of decades. The final data source is the tracks of three surface drifters that passed through the New Zealand region. In this report, we have broken down New Zealand's coastal region into seven regions defined by their oceanographic characteristics.

9.1 Circulation in the New Zealand Region

New Zealand sits in the eastward-flowing southern branch of the South Pacific gyre (Roemmich and Sutton, 1998). This flow, sometimes known as the Tasman Current, is essentially the extension of the East Australian Current (Stanton, 1981), which is the south Pacific's western boundary current. Western boundary currents are strong currents set up on the east coast of the major land masses by the combined influence of the global winds and the world's spin (Pond and Pickard, 1978). The Tasman current bifurcates as it approaches New Zealand so that the flow is clockwise around northern New Zealand and anticlockwise around southern New Zealand. Figure 1 is a schematic of the generally accepted flows around the country.

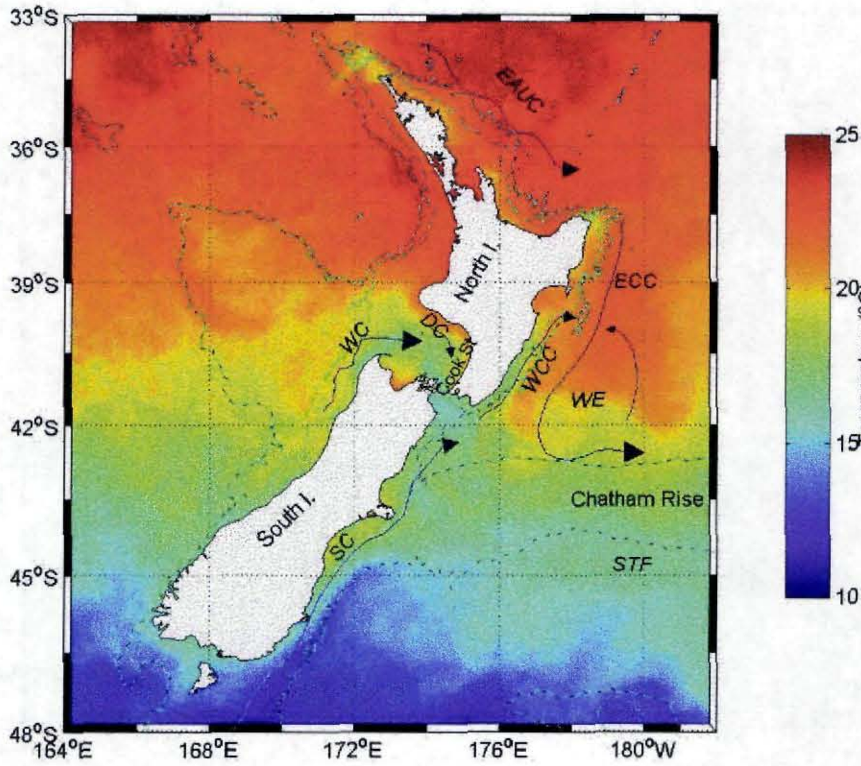

Figure 1. Schematic of flow around New Zealand. EAUC = East Auckland Current; ECC = East Cape Current; WCC = Wairarapa Coastal Current; SC = Southland Current; WC = Westland Current; WE = Wairarapa Eddy; DC = D'Urville Current.

The country blocks the flow so that west of New Zealand the currents are relatively weak and unstructured. Near the west coast of the South Island, the circulation is known as the Westland Current, off the west coast of the North Island, the flow is known as the West Auckland Current. Both these currents are generally considered to be weak and variable. In contrast, the reattachment of the western boundary current to New Zealand results in strong southwards flowing East Auckland and East Cape Currents along the east coast of the North Island (Stanton et al., 1997). Other topographical constraints result in strong northwards flow along the east coast of the South Island, known as the Southland Current (Heath, 1972). The other main currents in the New Zealand area are the D'Urville and Wairarapa Coastal currents

(Chiswell, 2000), which are principally North Island coastal currents and combine to feed into the East Cape Current by retroflection.

Individually and collectively, these currents will be the main control of the dispersion of any alien species introduction into New Zealand coastal waters, but along- and cross-shelf mixing, wind-driven circulation and tides will also have an impact. These latter processes will be more important on the shelf than offshore, and at local scales could be more important than the large scale circulation.

Unfortunately, from the point of view of assessing areas with minimal impact from ballast water discharge, both the large-scale and small scale oceanic processes tend to be extremely variable near New Zealand. The major currents such as the EAUC are set up by Pacific-wide conditions and are modified by more local wind-forcing: both of these components are impossible to predict with any accuracy. The small scale onshore processes are highly influenced by the wind, and again difficult to predict – in some cases, even the mechanisms of how the wind influences the coastal environment are unknown.

10. Methods

Three sources of data were used to characterise patterns of current movement in New Zealand's coastal waters: a tidal model, analyses of coastal current meters, and surface drifter records.

10.1 Tidal model

This numerical model was developed by NIWA to predict tidal currents and elevations for the ocean around New Zealand, including the coastal regions. Details of the model can be found in Walters and Goring (2001).

Tidal currents are generally oscillatory and have low mean values, thus their impact on the dispersion of alien species is to move them back and forth about their release point. For tides experienced around New Zealand the tidal excursion is usually a few kilometres. For example, a semi-diurnal tide with a peak speed of 50 cm/s (about 1 knot) has tidal excursion of about 14 km.

Tides around New Zealand are principally semi-diurnal, but because of the interaction of various components of the tides, the amplitudes are not constant in time but instead change over weeks or months. The most well known example of this is the spring-neap tidal oscillation where relatively strong spring tides are followed about one week later by relatively weak neap tides.

To accommodate this temporal variation in tidal currents, the model was run to generate tidal data for a one-year period. For each site within the model we report the maximum tidal excursion within the year.

10.2 Current meter data

Figure 2 shows the locations of all current meter moorings that have been deployed by NIWA in waters less than 250 m deep (which approximately corresponds with the 12 nautical mile limit). These moorings were deployed for varying lengths of time, but were mostly relatively short deployments. Of a total of 228 moorings in shallow water, 154 were for less than 60 days, 43 were for 60-120 days, 19 were for 120-180 days and only 8 deployments exceeded 180 days.

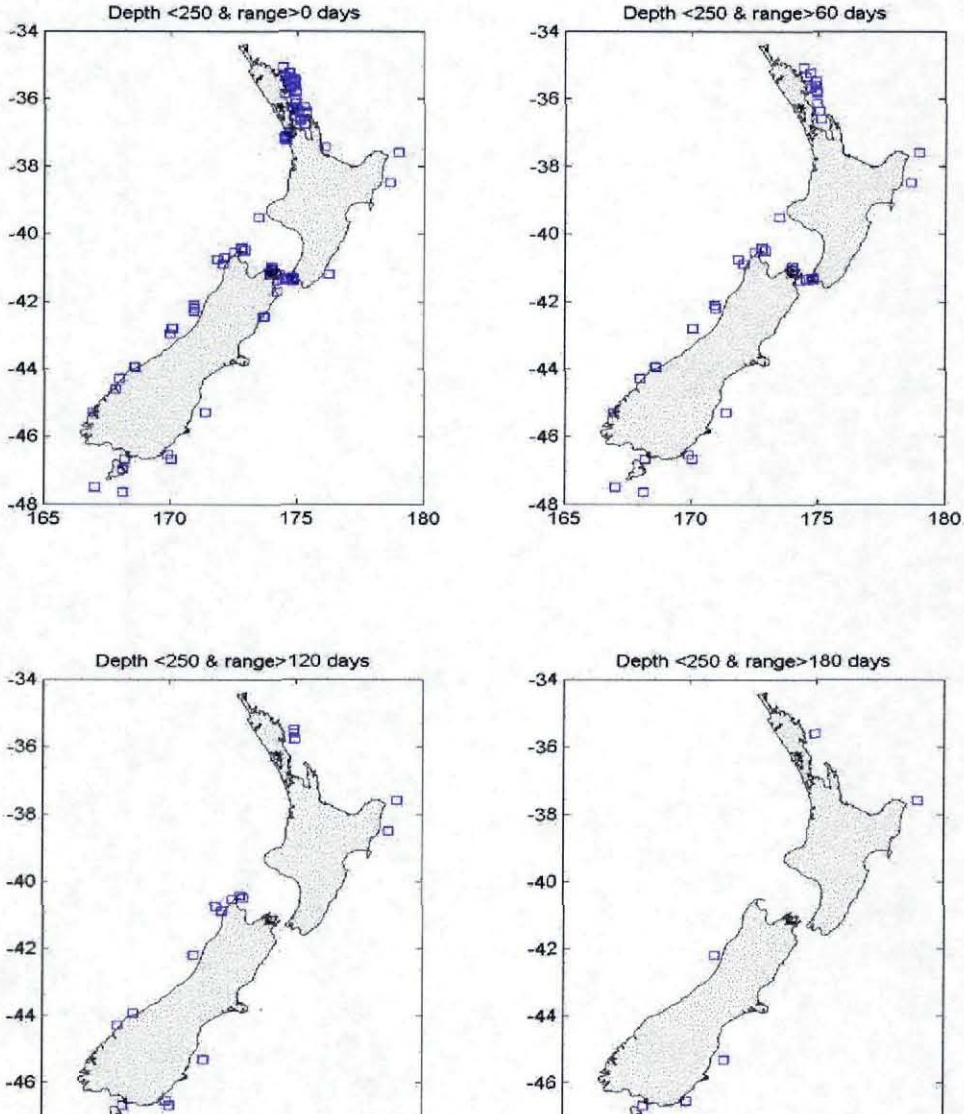

Figure 2. Locations of current meter moorings within the coastal zone. Some sites had meters at several depths, and sometimes there was more than one deployment at a given site.

The short duration of these mooring deployments is of serious concern because there can be large month-to-month differences in the currents. For example, Fig. 3 shows the zonal (east-west) and meridional (north-south) currents from a site off East Cape. In this region, the dominant current is the East Cape Current. For most of the early part of the record, the current was directed southwards, but during the latter part of the record the current was directed northwards. This indicates that analyses based on short-term records can be misleading.

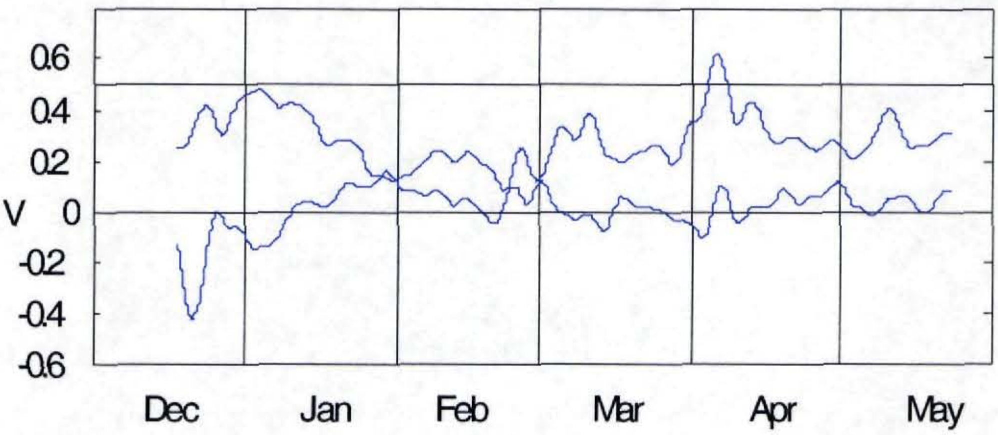

Figure 3. Zonal (u) and meridional (v) currents from near East Cape during 1995. Zonal current (lower trace) is plotted with no offset, meridional current (upper trace) has been plotted with 0.5 m s^{-1} offset.

Because of this variability, we have used the following approach. For each timescale, τ, the record is broken into contiguous segments, each as long as the timescale, and trajectories calculated for each segment. The zonal and meridional displacements within each segment are given by integrating the respective currents:

$$x_i = \int_{t=(i-1)\tau}^{t=i\tau} u dt \text{ and } y_i = \int_{t=(i-1)\tau}^{t=i\tau} v dt \qquad (1)$$

where u and v are the tidal currents.

This provides n segments of x and y, where n is the record length divided by the timescale. For example, a 150-day record provides 15 independent estimates of 10-day trajectories, and thus 15 estimates of the maximum distance travelled in 10 days. Plots of the trajectories allow an estimate of the variability in the dispersion. Here we report the maximum distance travelled during each of the n segments in histogram form, and also the direction of the trajectory at maximum distance.

It should be stressed that in order to interpret the trajectories as possible discharge tracks, this procedure makes the assumption that the currents measured by the current meters are indicative of the currents experienced by the passive tracers during the entire 10 days, i.e., it assumes there are no spatial gradients in the velocity fields. For some locations and timescales, this may be a realistic assumption, but for others it is clearly unrealistic.

Generally, for long timescales and locations with strong currents, we expect that this procedure needs further interpretation.

10.3 Surface drifters

As part of the international WOCE programme (World Ocean Circulation Experiment), surface drifters were released around the earth's oceans by various groups. These drifters report their latitude and longitude regularly by satellite. The drifters consist of a surface float tethered to a drogue, and are designed to give as accurate as possible measurements of the near surface circulation. They mimic the trajectories of passive tracers in surface waters.

By chance, two drifters passed through the New Zealand region in 1997 and 1998, became entrained in the coastal zone, and then drifted into the Pacific Ocean. They provide an excellent example of two point sources of release.

11. Results

11.1 Tidal model

Fig. 4 shows the tidal excursion around New Zealand.

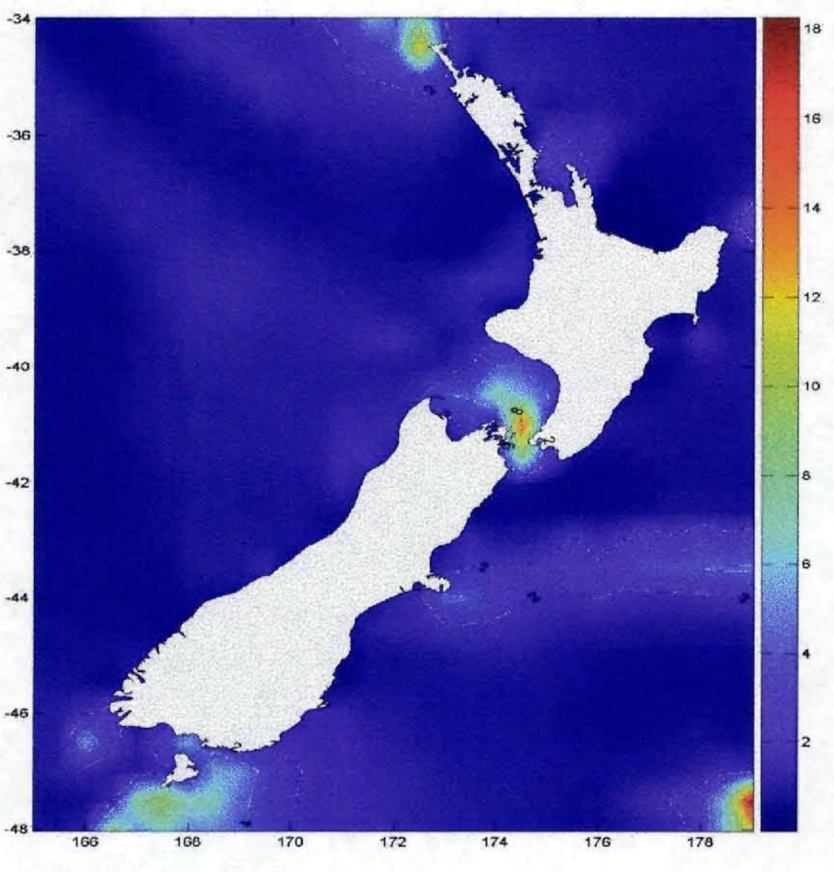

Figure 4. Maximum tidal excursion around New Zealand.

Except in Cook Strait, near North Cape, and around Stewart Island, the excursion is 2 km or less. For most of New Zealand, the tides are thus important primarily in small scale dispersion of potentially invasive species only. Locally, tides can be extremely important in controlling exchange into and within harbours. For example, Stanton (1997) illustrates the potential importance of tides in dispersing contaminant released near Picton within the Marlborough Sounds.

Strong tides in Cook Strait may be important in transferring material between the western and eastern ends of the strait.

11.2 Coastal Current Meter Analyses

Of all the current meter moorings in coastal waters, only 8 sites returned records longer than 180 days. The sparseness of this dataset illustrates the major difficulty encountered in this analysis, since we have had to characterise large areas of coast based on single deployments. For example only one long record exists for the entire northeast of the North Island, and there are no data from the west coast of the North Island.

For each of the long records, trajectories were calculated at each timescale according to Equation 1. Histograms of the maximum displacement during each trajectory are also shown (e.g., for a 250 day record, there are 25 10-day trajectories and 25 maximum displacements). Also shown are direction roses of the directions relative to the current meter of the maximum displacements.

11.2.1 Northeast North Island. (North Cape to East Cape; Fig. 5)

One mooring near the 250 m isobath outside of Hauraki Gulf returned data for 243 days. Mean velocity from the record was about 1 cm/s to southeast. For a timescale of 1 day, the mean displacement is about 7 km, with a maximum displacement of about 20 km. The trajectories are common in all directions, but show a slight preference for travel to the southeast. For a timescale of 10 days, maximum distances range between 15 and 70 km. Again the trajectories are occur in all directions. Only four 60-day segments could be extracted from the 243 day record , and the resulting maximum distances are about 200 km.

As previously mentioned, these trajectories are calculated assuming that the currents have no spatial variation. Clearly this assumption does not hold for the 60-day calculations (the trajectories cross the land), and with only 4 independent records, one cannot obtain robust statistics. Nevertheless, the figure shows clearly that currents at this location are variable. It appears that any discharge within this region is likely to remain within the discharge site for a considerable time.

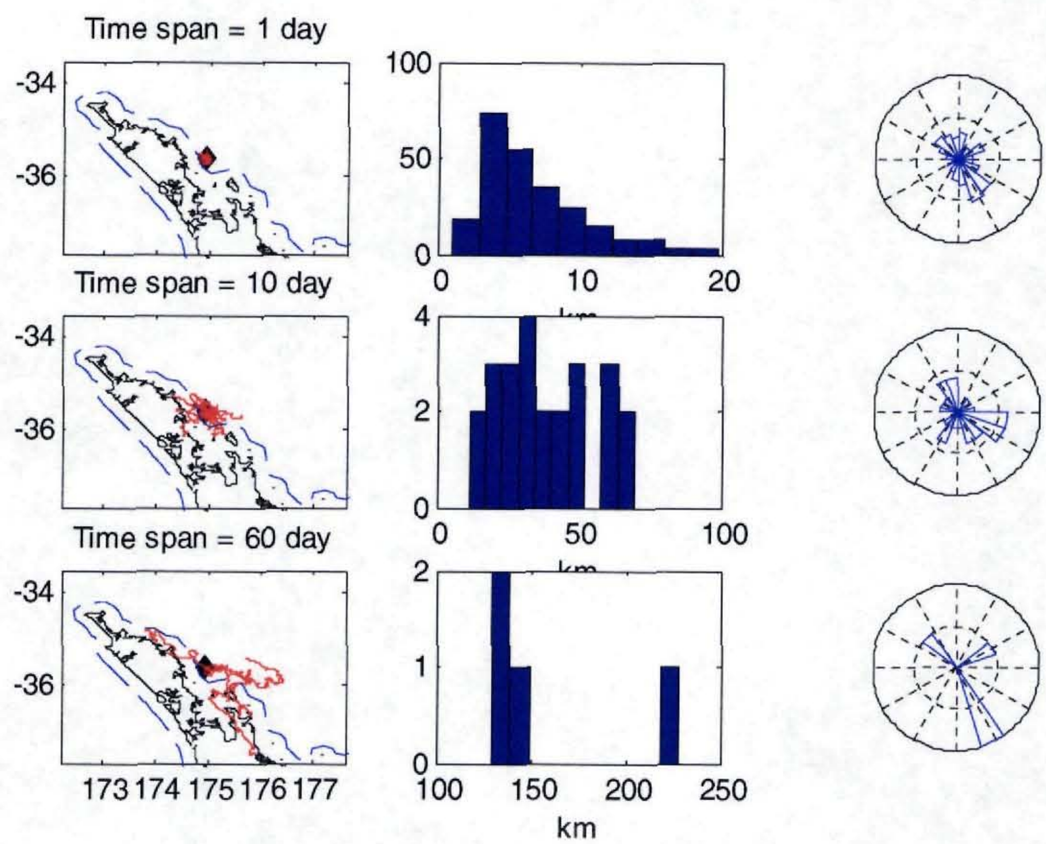

Figure 5. Simulated trajectories of a release in the vicinity of a current meter off the northeast coast. The left hand panels show the simulated trajectories for 3 timescales (1,10 and 60 days). The middle panels show the histograms of the maximum distance travelled from the source during each simulation. The right hand direction roses show the frequency of travel in each direction from source at time of maximum displacement.

11.2.2 East coast North Island. (East Cape to Wellington; Fig. 6a, b)

Two current meter moorings just east of East Cape returned data for 164 days. One mooring was inshore, the other offshore in about 1600 m water depth.

At the inshore site (Fig. 6a), the mean maximum displacement for timescales of one day is about 8 km, although displacements of up to 30 km can occur. For 10 day timescales, displacements range between 25 and 150 km, and for 60-day timescales, maximum displacements were 240 and 270 km. At this site, currents tend to run either northeast or southwest (i.e., parallel to the local bathymetry), and the direction roses reflect this.

Offshore (Fig. 6b) the situation is quite different, with currents generally stronger and almost always directed to the southeast, away from coastal environments. This is the East Cape Current. In a study of this region, Chiswell and Roemmich (1998) interpreted these records to suggest that while the currents inshore are quite variable, the inshore current commonly recirculates into the offshore East Cape Current.

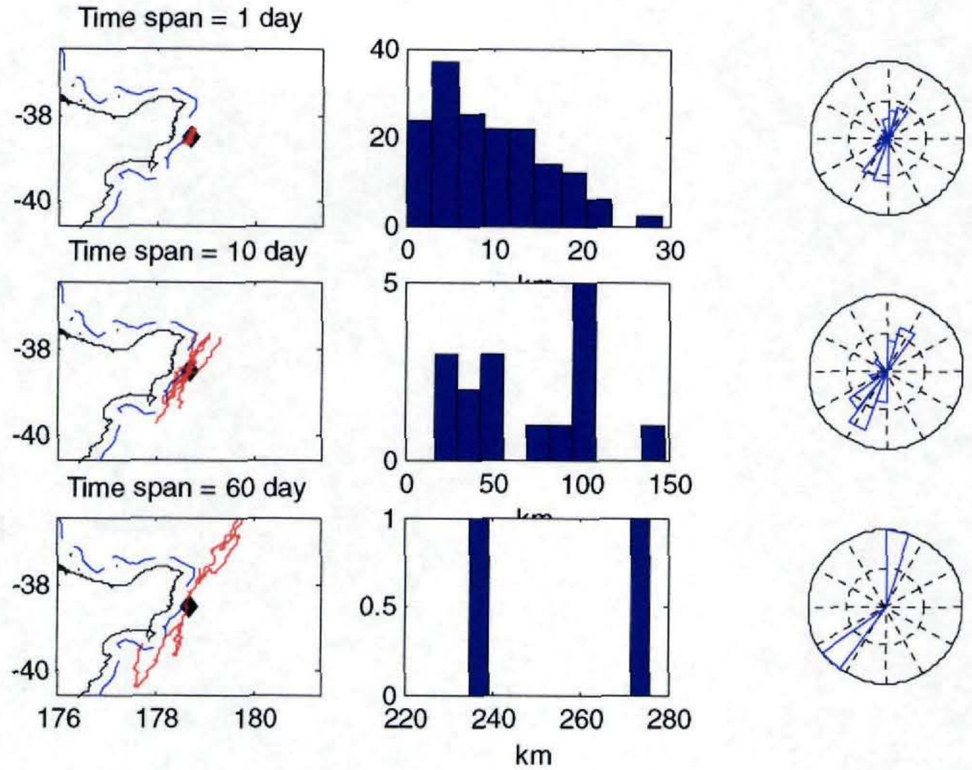

Figure 6a. As in Fig. 5, but for current meter at inshore location off East Cape.

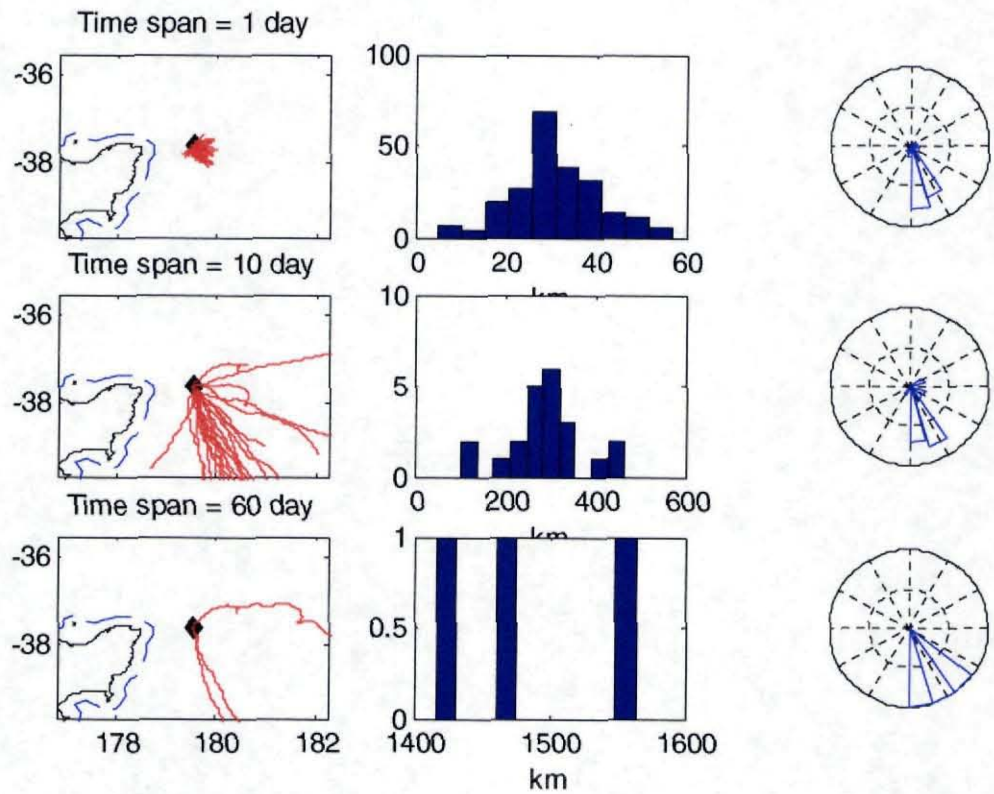

Figure 6b. As in Fig. 5, but for current meter at offshore location off East Cape.

11.2.3 Cook Strait (Fig. 7)

One current meter mooring within Cook Strait returned data for 58 days, so for this site analysis is limited to 1 and 10-day timescales.

Tides and currents in Cook Strait are extremely spatially variable, and data from one site are very unlikely to be representative of the region as a whole. Nevertheless, the 58-day record shows general flow out of Cook Strait to the southeast, but displacements during some of the 10-day trajectories were in the opposite direction into the strait.

This agrees with accepted wisdom that the long-term mean flow in Cook St is from west to east, but that there can be periods when the flow is reversed (e.g., Heath, 1986).

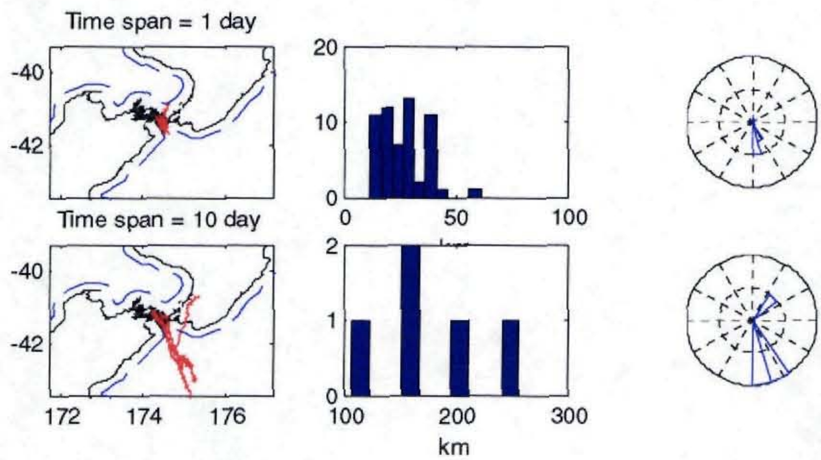

Figure 7. As in Fig. 5, but for current meter within Cook Strait.

11.2.4 East coast South Island. (Fig. 8)

A mooring off Otago returned data for 222 days. A second mooring farther to the south returned similar results but the data from that site are not presented here.

These moorings were within the Southland Current. Currents there consistently run to the northeast, as illustrated by the direction roses. There is some variation in the Southland Current, which is probably wind-driven (Chiswell, 1996), and the histograms of maximum displacement reflect this, but on the whole, currents at this site are probably the most predictable of all the locations in this study. Any discharge within the Southland Current is almost certain to be advected in a northeasterly direction along the shore.

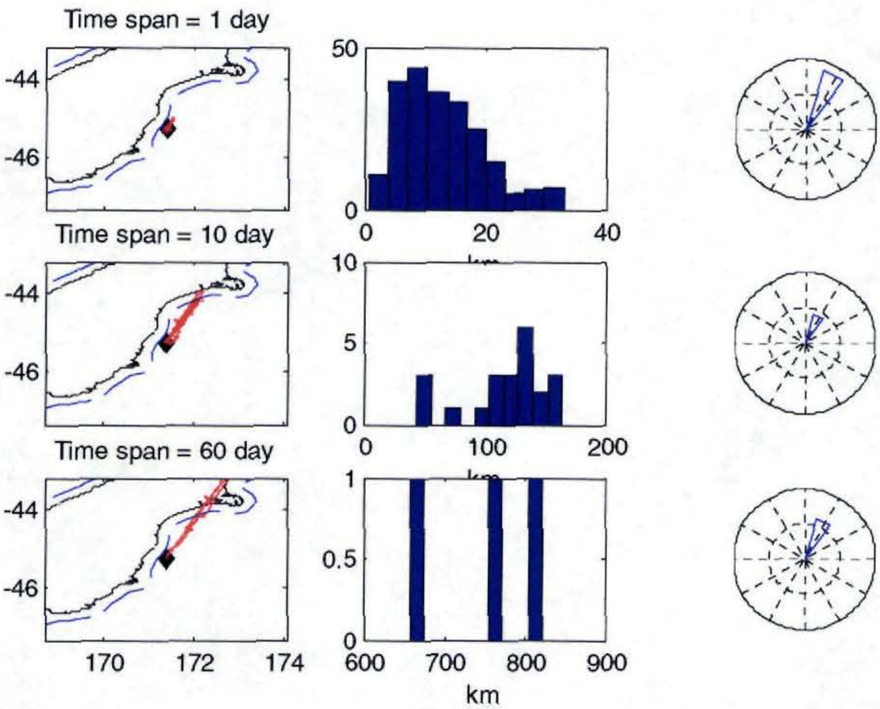

Figure 8. As in Fig. 5, but for current meter off east coast of South Island.

11.2.5 Stewart Island (Fig. 9)

Current meter moorings from south of Stewart Island maximum displacements at 10 day timescales are typically less than 150 km, with a mean of 45 km. At 60 day timescales, mean maximum displacement is 224 km. Histograms of direction show quite variable direction, although southwesterly flows predominate. Interpretation of these data is complicated because the long timescale trajectories run perpendicular to the bathymetry, and perpendicular to the generally accepted ideas that flow south of Stewart Island is to the east, and is principally contained in the Southland and Subantarctic Fronts. Presumably, strong curvature in the flow around the Snares Plateau is not reflected in these trajectories.

Not shown here, but short records from Foveaux Strait show flow is usually, but not always, to the east, and that water from Foveaux Strait feeds into the Southland Current.

Foveaux Strait must be considered an high-risk location for ballast water discharge because of the valuable oyster industry in the region, and we interpret Figure 9 to show that while discharge south of Stewart Island is most likely to bypass Foveaux Strait, there will be times when northwesterly flows will bring material to the west of the island and into the strait.

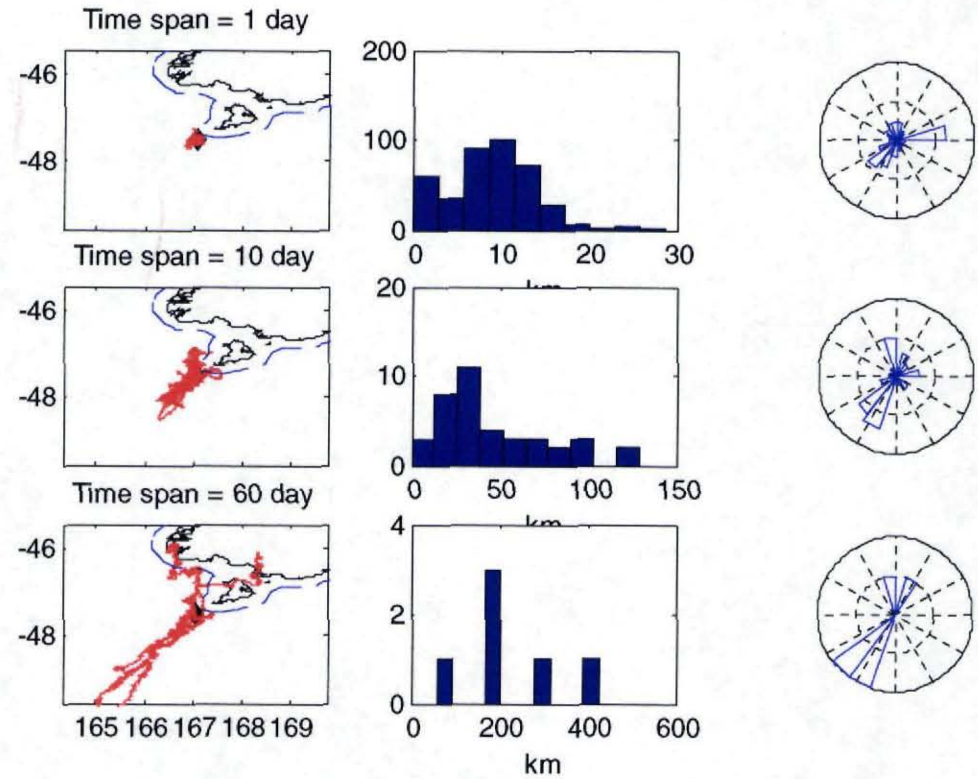

Figure 9. As in Fig. 5, but for current meter off Stewart Island.

11.2.6 Fiordland (Fig. 10)

A mooring from off Milford Sound provided 169 days of data. During this time, flow was uniformly to the southwest, along the fiords. Fiordland is an area of large socioeconomic importance, being one of NZ's premier tourist destinations. The fiords contains diverse biotic assemblages that contain many endemic and rare species. The data from the mooring indicate that the current is relatively weak and flows parallel to the shore. Because of the chance of it flowing into the fiords, discharge of ballast in this region could be considered high risk.

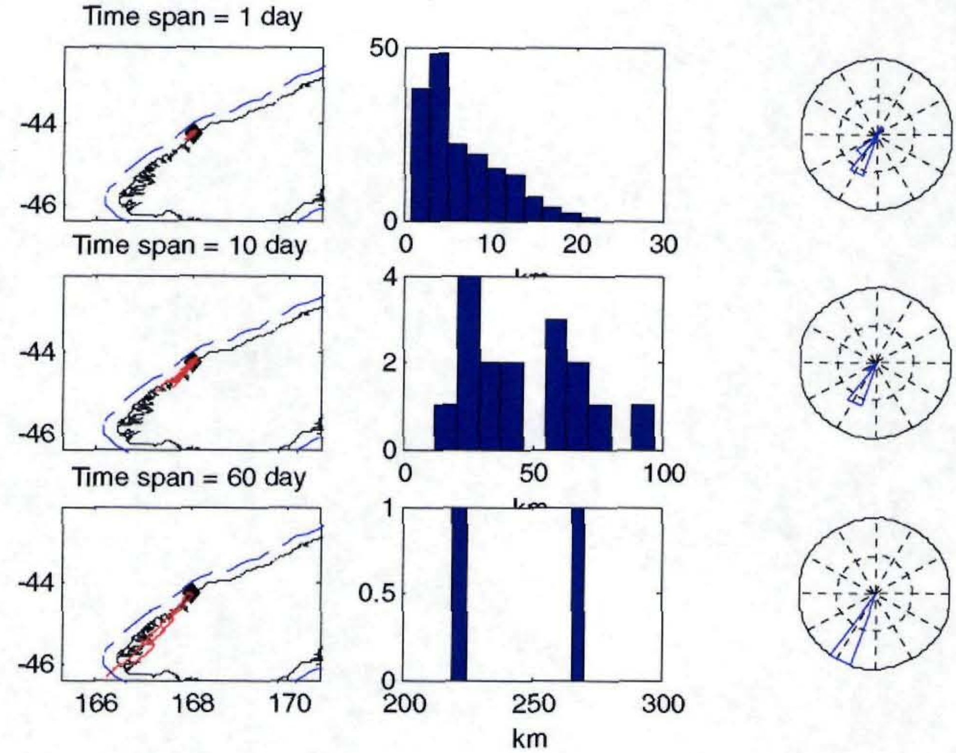

Figure 10. **As in Fig. 5, but for current meter off Fiordland.**

11.2.7 West coast of South Island (Fig. 11)

A mooring off Hokitika provided 189 days of data. At this site, currents are generally to the northeast, although some trajectories during this deployment went to the southwest.

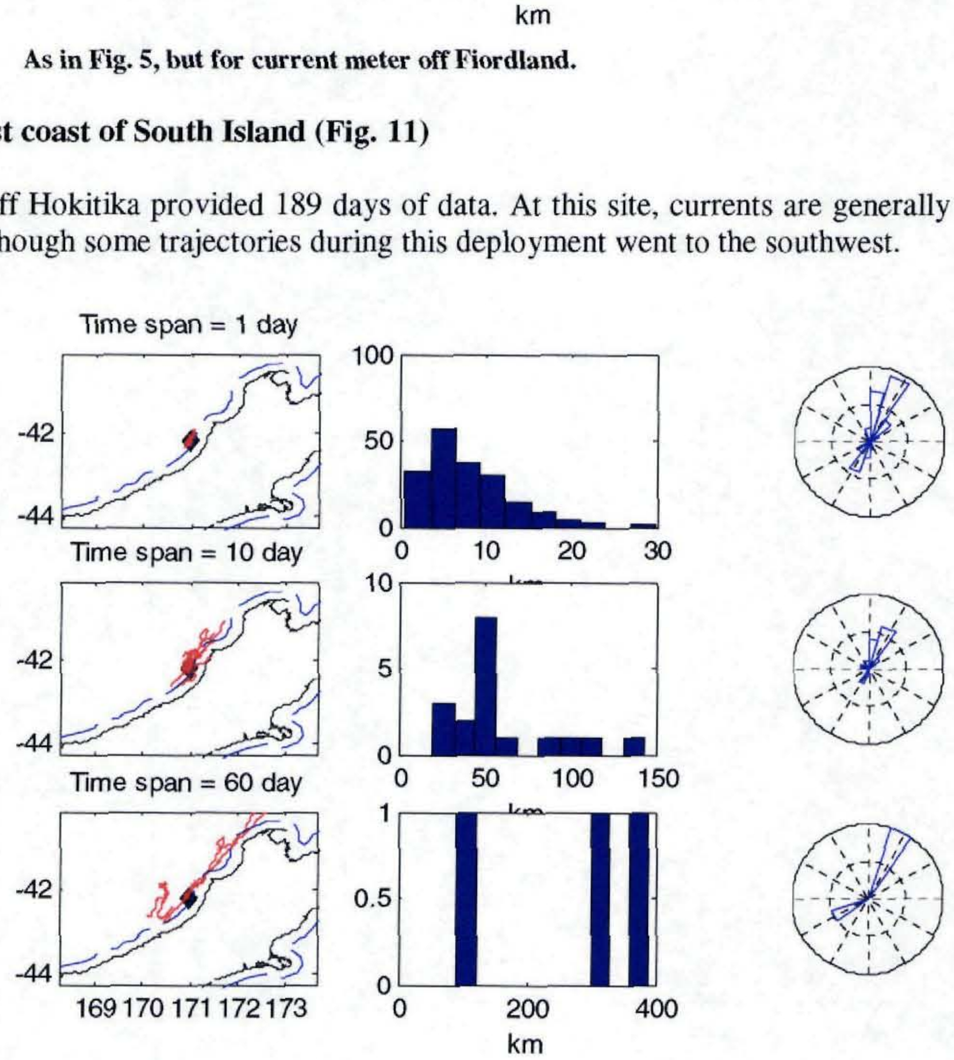

Figure 11. **As in Fig. 5, but for current meter off Hokitika.**

11.3 Surface Drifter tracks

During 1997, two WOCE drifters entered the Cook Strait Region. We can assume that drifter trajectories represent possible paths for discharged ballast water, although in practice, discharge will be diluted with time.

The first drifter (Fig. 12) crossed the Tasman Sea, and was found within the 12-mile territorial sea off Hokitika on 1 Jan 1997. The drifter then flowed north in the Westland Current, and entered Cook Strait in early February. It left Cook Strait on 14 [redacted]. This drifter then spent about 5 months entrained within the mesoscale eddyfield to the east of New Zealand, and in July returned to within 12 miles of the coast, near the Mahia Peninsula.

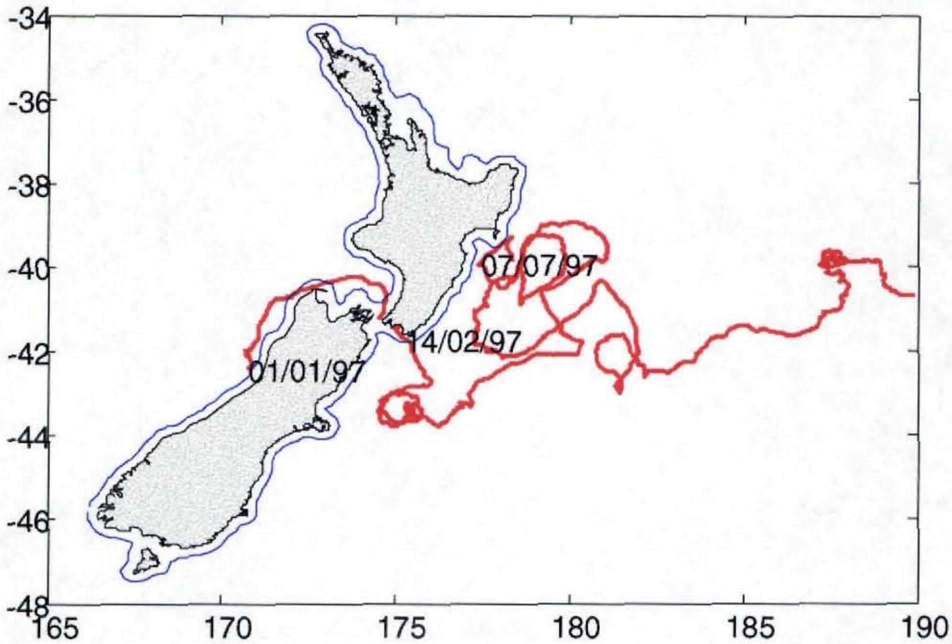

Figure 12. WOCE drifter (No. 1) track from 1997.

The second drifter started the year off the east coast of the South Island in the Southland Current (Fig. 13). It flowed north in this current through Cook Strait into the South Taranaki Bight. It then reversed its path, again passing through Cook Strait, and became entrained in an eddy to the east of Kaikoura. This drifter spent some time in the eddy field, and then again became entrained in the Southland Current sometime in April 1997 (Fig. 14). This time, however, instead of entering Cook Strait, the drifter entered the Wairarapa Coastal Current and flowed northeast close inshore. It appears to have grounded on the Wairarapa Coast for some time, but then freed itself and about 10 May, the drifter left the Wairarapa Coastal Current and became entrained in the East Cape Current. It then passed in to the Wairarapa Eddy, where it did about 5 loops before finally leaving the New Zealand region.

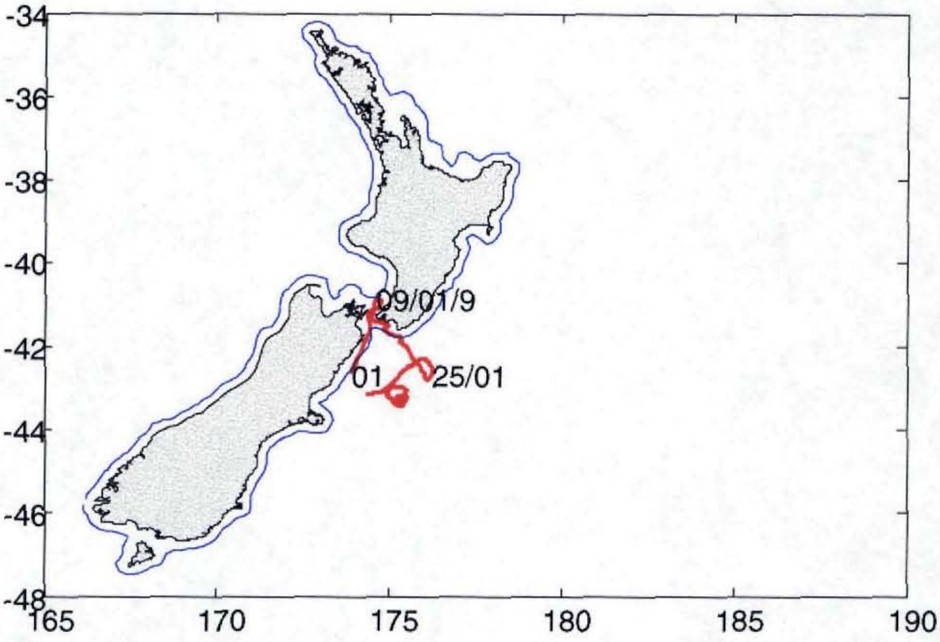

Figure 13. WOCE drifter (No. 2) track.

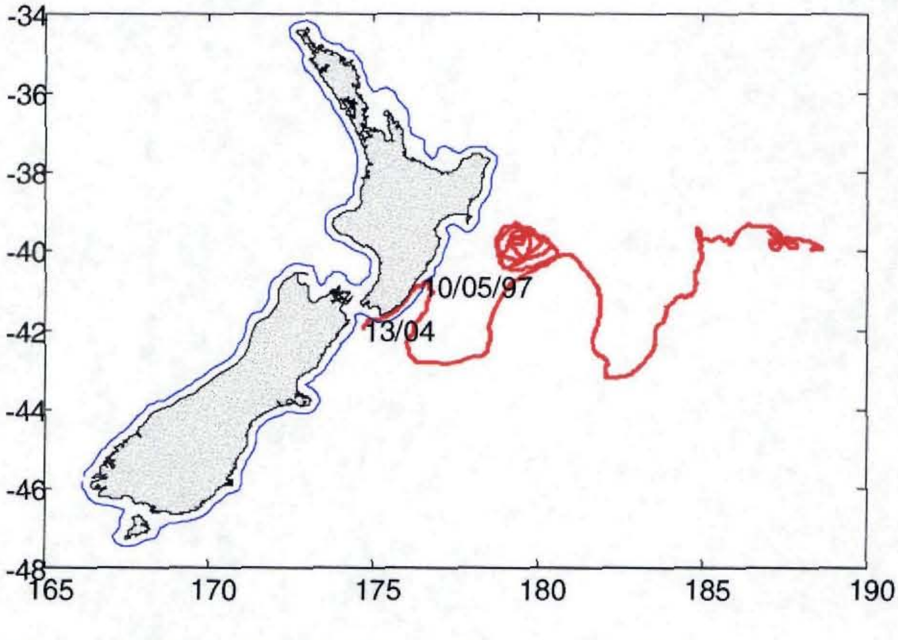

Figure 14. WOCE drifter track - this is the same drifter (No. 2) as shown in Fig. 13.

The paths of these drifters illustrate two important features of the circulation around New Zealand. The first is the variability. All three trajectories passed into Cook Strait, but subsequently had quite different routes. The second is the long retention time around New Zealand. Both drifters spent between 5 and 8 months in the New Zealand region, and entered the coastal zone several times.

The paths of these drifters also emphasise the difficulty of estimating larval trajectories from point location current meter records. The second drifter (Fig. 13) made an incursion into the South Taranaki Bight; an incursion of this kind would not have been predicted from the current meter data alone. In this case, the discrepancy probably results from the extreme spatial changes in currents across Cook Strait, so that the currents measured by the meter are not representative of the currents even a short distance from the mooring.

Discussion and Conclusions

12.1 Characteristics of the oceanographic features within New Zealand's territorial sea (12 nautical miles)

This study has provided a statistical description of currents at several sites around New Zealand within the 12 mile territorial zone, with the main aim of identifying the potential risk of invasive marine organisms present in ballast water discharged in the zone having an impact on the environment.

This potential risk has two components. The first is the physical likelihood that organisms from ballast water remain in the coastal zone long enough to settle. The second is related to the biological impact on specific coastal locations. Clearly, not all coastal regions have the same vulnerability to invasion by exotic species. Inglis (2001) comments that world-wide, most marine invasions have taken place in sheltered bay and estuarine environments, and that these environments are most at risk from future incursions.

As a result of these two components, the ideal discharge site would be one with low retention time, low local importance commercially or culturally and be biologically robust. The lowest risk will be at discharge sites where water movement is predominantly offshore or alongshore, and where there are low residence times. There are so many sites along the coast that are valued for one reason or another by different sectoral interests that it is difficult to prioritise their importance. Our prioritisation is, therefore, based predominantly on risk of incursion, rather than likely impact.

Over much of New Zealand, the 12 mile territorial boundary coincides with the shelf-break. Where it does not, the shelf generally extends further than 12 miles, so that the only places where the 12-mile territory extends beyond the shelf break are off Fiordland, eastern Cook Strait and off Kaikoura. For this report, we have assumed that the waters inshore of the shelf break are well mixed. We believe this assumption to be well founded. Winds, tides and other nearshore processes can all transport material the width of the coastal zone in a matter of hours to days. A direct result of this assumption is that we have not explicitly examined onshore currents, since any organism found within the 12 mile territorial zone has a high chance of making it to the coast.

Tides are relatively unimportant in the dispersion of potentially invasive marine organisms over most of New Zealand's coastal waters where they will transport the organisms only a few kilometres. However tides are important in transporting material in and out of harbours, and they also help to mix material within the coastal zone.

Of more importance in advection and dispersion of ballast water are the coastal currents which are set up by the large scale oceanic circulation, and modified by local winds. For the most part, these are impossible to forecast and a statistical analyses of extant data must be used to get some idea about potential impacts. The trajectories, displacement histograms, and direction roses derived from long-term current meter moorings described in section 11 provide some information about the expected distribution of contaminants at 1, 10 and 60 days after release. Because data are available from only a handful of long-term moorings, these results have to be interpreted for other locations using existing knowledge about the circulation around New Zealand.

Analysis of interannual variability in the coastal currents as a direct result of large-scale oceanic changes such as those due to El Nino/Southern Oscillation (ENSO) is well beyond the limited data set available. ENSO events are suspected to have an effect on New Zealand's climate and oceanic environment. However, the directions, magnitudes and predictability of these events are entirely unknown at the present time, and we can only assume that interannual variability in the large scale oceanic systems will increase the variability seen in the coastal zone.

Table 1 summarises the results of the current meter analyses, and shows the expected maximum displacement for each region at each timescale. At timescales of 1 day, mean maximum displacements range from 7 to 26 km. At timescales of 10 days, the mean maximum displacements range from 38 to 178 km. For timescales of 60 days, maximum displacements can range as high as 750 km.

As discussed previously, the appropriate timescale for marine discharge probably lies somewhere between 10 days and two to three months. At timescales of 10 days, expected maximum displacements are clearly so short that there is little likelihood that discharge will be advected away from New Zealand. For example the expected displacements off the northeast coast are only about one quarter the distance between the Bay of Islands and Auckland. Off the east coast of the South Island, expected displacements are about half the distance between Banks and Kaikoura Peninsulas. At timescales of 60 days, expected displacements are about 4 times those of 10 days, and except for within the Southland Current, displacements are comparable to the distance between the Bay of Islands and Auckland.

Table 1: Mean of maximum displacement (km) for each region at each timescale.

Location	Timescale = 1 day	Timescale = 10 day	Timescale = 60 day
Northeast N.I.	7	38	158
East Cape	10	69	255
Cook Strait	26	178	–
Southland	13	119	750
Stewart Island	9	45	224
Fiordland	7	47	245
West Coast S.I.	8	58	266

Northeast North Island. (North Cape to East Cape)

This coast is influenced primarily by the East Auckland Current (Fig. 1). This current has been recognised as being extremely variable (Stanton et al., 1997), and the results from the one long current meter record from this region indicate no consistent direction of trajectories at any of the time-scales (Fig. 5).

Maximum distances travelled for this region are the lowest of all those studied here. The expected displacement for 1 day timescale is 7 km, at 10 days the expected displacement is 38 km.

We conclude that the northeast is a region of relatively low dispersion. Discharge here is likely to remain within the region.

East coast North Island. (East Cape to Wellington)

Offshore the flow is the East Cape Current, which flows to the southwest. The coastal current in this region is the Wairarapa Coastal Current which flows to the northeast. This current is strongest near Cape Palliser and as it flows north it recirculates into the East Cape Current. As a result, south of Mahia Peninsula the flow is generally to the northeast. North of Mahia the flow is more variable (Fig. 6).

The drifter tracks show that discharge off Cape Palliser can either move directly offshore (Figs. 12, 13) or move north in the Wairarapa Coastal Current (Fig. 14). If released in the Wairarapa Coastal Current the discharge is likely to eventually entrain in the offshore East Cape Current and then get advected offshore.

Between East Cape and Mahia Peninsula is the most downstream location in New Zealand, and we conclude that this is probably the best location for marine discharge.

East coast South Island

The flow along this coast is the Southland Current. The current meter data (Fig. 8) indicate that discharge anywhere along this coast is almost certain to flow northeast along the coast.

Maximum distances travelled along this coast are the highest of all those studied here. On average, we expect discharge within the Southland Current to advect north and then turn offshore at about the latitude of Kaikoura Peninsula. However, the drifter data show that there is a good chance that discharge along this coast would end up in Cook Strait with the possible consequence of affecting the Marlborough Sounds, the main mussel-producing area of New Zealand.

Stewart Island

The current meter data (Fig. 9) indicate moderately variable flow in the region of Stewart Island. There are known to be strong spatial gradients in the flow here, which means that the trajectories shown in Fig. 9 are unlikely to be realistic. Hydrographic measurements (Chiswell, 1996) indicate that water mass properties in this region are similar to those found inshore along the east coast of the South Island, and we conclude that discharge off Stewart Island will become entrained in the Southland Current and get advected along the east coast of the South Island.

West coast South Island

From Fiordland south, the flows are consistently to the southwest. Discharge in this region is likely to advect either south of Stewart Island or through Foveaux Strait and then become entrained in the Southland Current. While exchange between fiords and the shelf is likely to be influenced by a number of factors, including freshwater input into the fiord, tides, tides and the sill depth, we believe that there is a high probability that material in the coastal zone can be advected into the fiords.

North of Fiordland, the currents are more variable. The coastal current here is the Westland Current. Discharge in this region is most likely to get advected into Cook Strait, but on occasion, it could go to the southwest for a period of time before currents reverse.

West coast North Island

Currents on the west coast of New Zealand have traditionally been believed to be quiescent, and consequently have been less well studied than on the east coast. We have few data from the west coast of the North Island, but believe there is a small net flow to the south. The currents off Hokitika and the WOCE drifter tracks point to retention within the coastal zone of a month or more for any discharge on the west coast of the South Island. Although we do not have data for the west coast of the North Island we believe that currents there are weaker than in the South Island, and the retention times will be correspondingly longer.

12.2 Relative efficacy of the discharge areas identified in objective 1

Prioritising valued sites for protection from exotic species requires balancing the interests of different sectors of society. The choice of sites will depend upon the relative magnitude of threat that particular species or groups of species pose to different site values. This will vary according to the species and values under question. The complexity of marine ecosystems and the novelty of interactions of each invader with its new environment mean that it is difficult to predict the course and outcome of any invasion in advance. Because not all uses of the marine environment are equally dependent on the natural integrity of native ecosystems, they are not equally vulnerable to the effects of NIS. New Zealand's indigenous marine biological assets are especially important to:

- Industries based on native or established species and their quality (e.g., wild fisheries and aquaculture),
- The tourism industry, which relies on the provision of natural experiences through the integrity of unique biological landscapes, and the lack of threatening species,
- The recreational and aesthetic values of landscapes, plants, and wildlife which are important to the majority of New Zealanders
- The cultural, spiritual, and other values of tangata whenua

Fisheries that are likely to be most at threat from introduced species are likely to be based on relatively sedentary (i.e. site-attached) stocks that inhabit shallow coastal waters. This includes farmed Greenshell™ mussels and salmon, wild stocks of rock lobster, paua, scallops and other shell-fisheries. Important locations for these fisheries include the Marlborough Sounds, Tasman & Golden Bays, Kaikoura, Coromandel, Hauraki Gulf Fiordland, Foveaux Strait, Stewart Island and the Chatham Islands (Inglis 2001).

The east coast of the North Island, north of East Cape, has highly variable currents and retention time is high. Given the economic and social importance of the Waitemata Harbour, this region must be rated as being the least desirable discharge area of those studied here. Even though currents are generally to the southeast, discharge could be advected in either direction. Discharge of ballast water north of the Hauraki Gulf will almost certainly eventually make it to the coastline. We have no data from the Bay of Plenty, but believe that currents there are likely to be almost as variable as those further north. As a result discharge in the Bay of Plenty could also make it north.

Discharge anywhere on the west coast of the North Island or on the west coast of the South Island north of Fiordland is likely eventually to make its way into the South Taranaki Bight and then into Cook Strait and the Marlborough Sounds.

Discharge on the west coast of the South Island south of Fiordland and anywhere on the South Island east coast is likely to make its way northwards along the east coast of the South Island. On average, one would expect the discharge to separate from the South Island near Kaikoura Peninsula and flow away to the east over the Chatham Rise. But the drifter track shown in Fig. 13 shows that at some times, the discharge could be advected into Cook Strait.

The most efficient region for coastal discharge of marine ballast is off the east coast of the North Island. This region is the most downstream with regard to the flow around the country. On average the East Cape Current will advect discharge away from the country. Probably the best location is between East Cape and Mahia Peninsula, where we expect the discharge to become advected in the East Cape Current. The efficiency of offshore transport from this region decreases as one progresses south, but generally discharge in the Wairarapa Coastal Current will progress north until it recirculates in the East Cape Current.

Based on this analysis of high risk locations, we show in Fig 15 a map of relative risk to the environment from marine discharge. It must be stressed that this map takes no account of the relative cost in social or economic terms of the arrival of invasive species since this requires detailed risk analysis. The map rates the potential effect of marine discharge on a qualitative scale from 0 to 10, where 0 represents no risk to the environment, and 10 represents almost certain environmental impact if the discharge contains invasive species that can adapt to the local environment.

Most of the northeast coast, the west coast of the North Island and much of the South Island has been rated 10. This is because a high percentage of any coastal discharge within the 12 mile territorial seas anywhere in these regions would almost certainly remain in New Zealand's coastal environment for timescales of days to weeks with a high probability of entering coastal embayments. In addition these regions are upstream of the major high risk harbours and locations identified above.

The east coast of the South Island has been rated as only of slightly less risk than the highest risk areas. This is because although we expect the Southland Current in general to aid in quick removal of discharge from the territorial zone, there is a real risk that discharge along this coast will enter both the bays and inlets around Banks Peninsula, Cook Strait and the economically important Marlborough Sounds region.

The lowest risk region identified is along the east coast of the North Island south of East Cape, where the risk has been rated 5. This rating is somewhat arbitrary, but has been chosen to stress that there are no sites within the 12 mile territorial zone that pose zero risk. This location is where there is most chance that discharge will get into the East Cape Current and be taken away from the land, even though the drifter trajectories show that water from well offshore can make it back to the coastal zone on some occasions. Further south along this coast, the risk is rated slightly higher, since discharge will enter the East Cape Current by entrainment of the Wairarapa Coastal Current.

It must be noted here, that the choice of the east coast as a preferred discharge location brings with it its own set of considerations. This coast is of particular importance to New Zealand's Rock Lobster fishery since it is an important area for puerulus settlement and recruitment (Booth, 1994). It is also an area of high spiritual value to Maori.

It should also be stressed that even though we expect the coastal region to be well mixed horizontally, discharge in all cases should be made as far out to sea as possible.

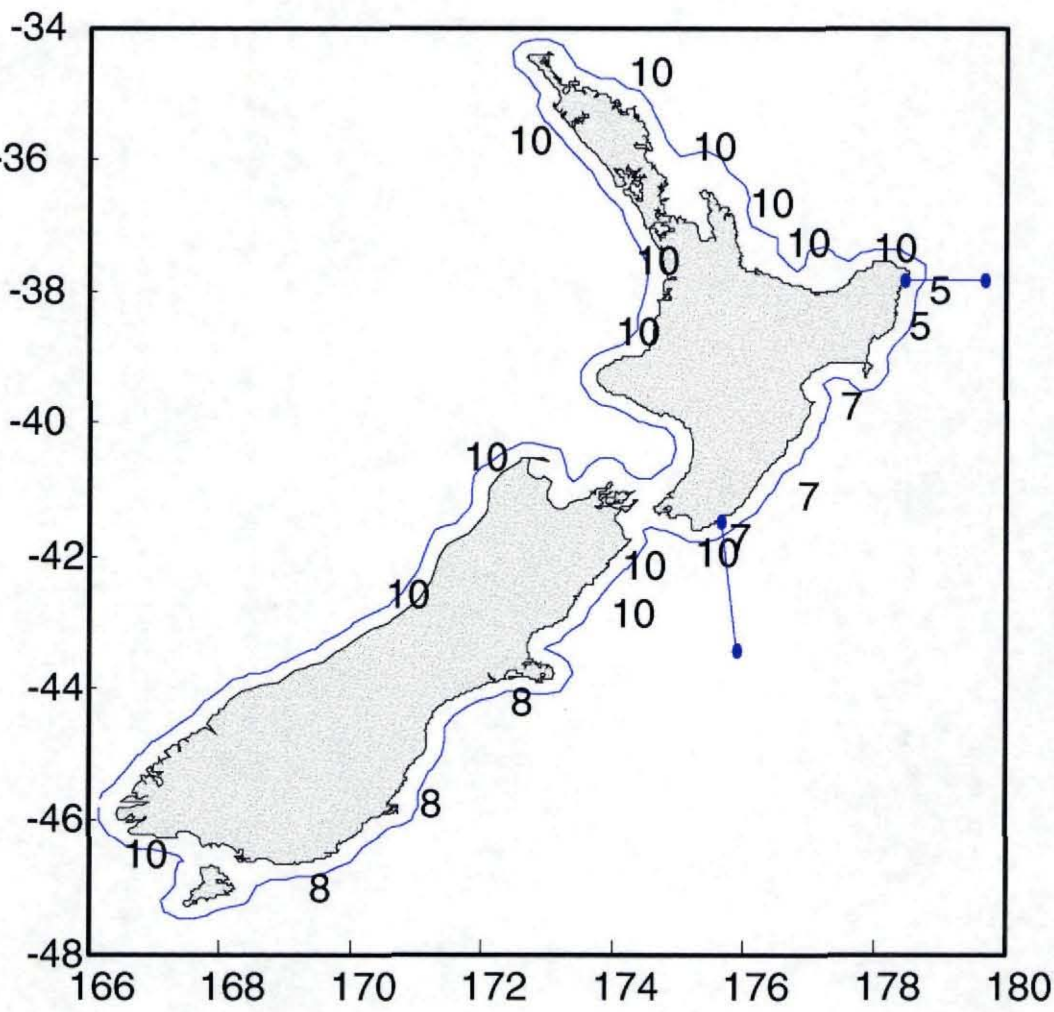

Figure 15. Relative risk factor for discharge within the 12 mile limit. A factor of 0 would indicate no risk to the environment, and 10 indicates almost certain impact if the discharge contains invasive species that can adapt to the local environment. Lines indicate the approximate limits of the least-risk coastal zone for ballast discharge.

12.3 Availability of real-time information that could be accessed quickly to identify discharge sites on a case by case basis

As previously discussed, coastal currents which are set up by large scale oceanic circulation and modified by local winds, are the currents most likely to be involved in the advection and dispersion of ballast water discharged in coastal waters. Therefore, the two most useful information sources for determining the potential impact of these currents on discharged ballast on a case by case basis would be direct measurements of currents and/or results from a model of coastal circulation. Unfortunately no such models yet exist for the New Zealand region. Similarly, there are no real time reporting measurements of coastal currents around New Zealand. NIWA maintains coastal current meters to support various research programmes, but these instruments record and store the data internally and are recovered and/or replaced at infrequent intervals.

The Topex/Poseidon satellite measures sea surface height using a radar altimeter. Maps of sea surface height and surface velocity are produced in near real-time by the Colorado Center for

Astrodynamic Research (CCAR), University of Colorado, and made available on the internet. Figure 16 shows such a map, and some of the major currents around New Zealand can be seen clearly. Unfortunately, altimeter-derived surface velocity is completely unreliable for depths less than about 1000 m, but these maps may give some information about offshore circulation, which in turn may give some information about the inshore circulation.

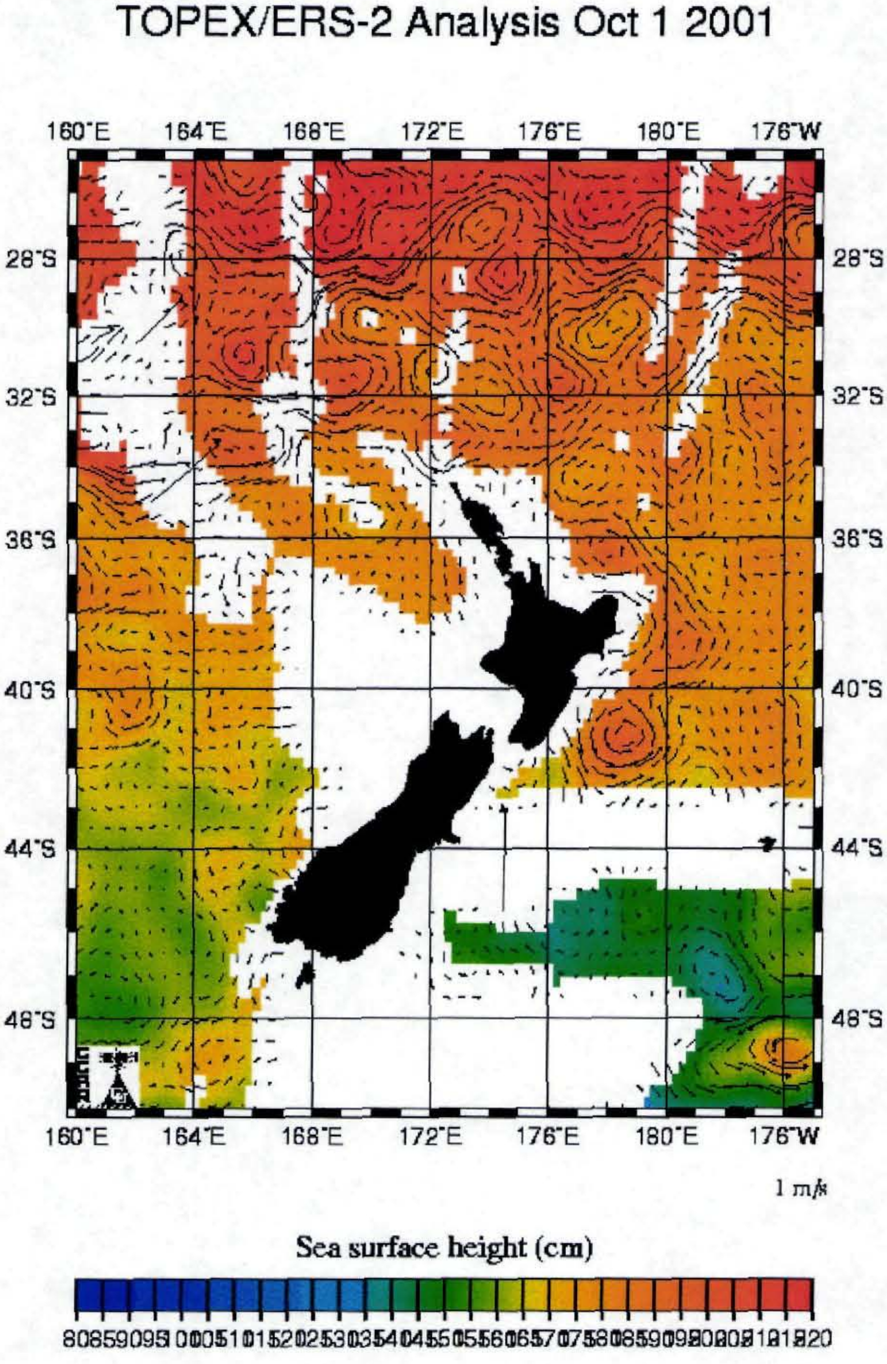

Figure 16. Sea surface height and surface currents from CCAR web page.

In some cases, sea surface temperature may be an indication of surface flows around New Zealand. Temperature is inherently an unreliable measure of circulation because it is affected by local heating and cooling processes. However, qualitative estimates of current direction can sometimes by made by interpretation of the temperature patterns by someone with a good understanding of oceanography. Circulation features such as eddies and intrusions can sometimes be seen when there are large temperature gradients. It should be born in mind, however, that satellites do not measure sea surface temperature under cloud, and cloud occurs often over the New Zealand region. Sea surface temperature measured by satellite is acquired in near real-time by NIWA, and daily images are routinely processed.

Because surface circulation in New Zealand has a strong wind-driven component, an accurate prediction of the wind-driven coastal circulation would require development of a numerical modelling capability that does not yet exist. However, we do know that certain currents show a near-direct relationship with the wind (e.g., the Southland Current), and qualitative estimates of the wind-driven components could be made from predicted winds. These estimates would be likely to have a high degree of error, even when made by an expert in coastal circulation.

Although tides are relatively unimportant in the transport of potentially invasive marine organisms around coastal waters, they are important in transporting material in and out of harbours, and they also help to mix material within the coastal zone. The NIWA tide model accurately predicts tidal currents for any area in New Zealand (Stanton et al., 2001) and thus could be a used to predict the likely extent of dispersion and mixing of the ballast water once it has reached the coast.

Various organisations measure coastal sea level around New Zealand, but sea level is of extremely limited use in estimating coastal circulation. In conjunction with temperature and winds, however, it may provide some additional information to aid in identifying discharge sites. NIWA records sea level in real time at Dog Island (Foveaux St.), Charleston (near Westport), Sumner Head (Christchurch), Kaikoura, Little Kaiteriteri, Kapiti Is, Riversdale (Wairarapa coast), Moturiki Island (near MT Maunganui), Mokohinau Island (Hauraki Gulf), Anawhata (Auckland west coast) and Jackson Bay.

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14. Publications

No publications were produced during this project.

15. Data Storage

No new data were collected during this project.