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Possible factors affecting bycatch of basking sharks (*Cetorhinus maximus*) in New Zealand trawl fisheries

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Abstract

Basking sharks are caught incidentally in New Zealand trawl and set net fisheries. Previous studies have shown that unstandardised observed trawl catch rates were much higher in 1988–91 than at any time since then. In this study, we tested the hypothesesthat (a) the fluctuations in apparent abundance were driven by environmental factors, and (b) that changes in the composition of trawl fleets, and the way that they operate, have reduced the level of interactions between sharks and trawlers. We calculated raw catch per unit effort (CPUE) indices for three large fishery areas off east coast of South Island (EC), west coast of South Island (WC) and Southland–Auckland Is (SA), and compared them with three environmental variables (two sea surface temperature indices and sea surface height), vessel nationality, and seven operational trawl variables (vessel length, tow speed, tow duration, headline height, seabed depth, latitude and longitude). CPUE peaked in the late 1980s and early 1990s, and thereafterwas considerably lower but variable. In EC and WC, CPUE has been zero for the last seven and six years respectively.A highly significant association was found between the numbers of sharks caught and vessel nationality in all three fishery areas. This was due to relatively large numbers of sharks being caught by Japanese vessels in the late 1980s and early 1990s. Other variables examined were not correlated with shark CPUE. Reasons for the high catch rates of basking sharks by Japanese trawlers are unknown, but may relate to targeting of the sharks for their liver oil, or a high abundance of sharks in the late 1980s and early 1990s.

Keywords

Basking shark, trawl fisheries, catch per unit effort, environmental variables, operational variables

Introduction

Basking sharks (*Cetorhinus maximus*) are the second–largest fish in the world (after the whale shark). They feed on plankton (primarily crustaceans) filtered from the seawater flowing through their gills (Matthews & Parker 1950; Sims et al. 1997; Sims & Merrett 1997; Sims & Quayle 1998). Until recently, basking sharks were considered to inhabit mainly shallow coastal waters and feed in upper water layers where plankton concentrations are highest. This view is based on the fact that most records of basking sharks are of schools of sharks seen swimming lazily at the surface near the coastlines of temperate countries worldwide (Squire 1967; Lien & Fawcett 1986; Kunzlik 1988; Squire 1990; Berrow & Heardman 1994; Fairfax 1998; Sims et al. 2000; Last & Stevens 2009). However, the observation that basking sharks are often caught in bottom trawl nets in depths exceeding 700 m off the west coast South Island (Francis & Duffy 2002) shows that they have a much wider habitat than previously thought. This has been confirmed by tagging studies in the North Atlantic Ocean that have revealed deep diving to more than 750 m, and lengthy oceanic migrations that include trips across the North Atlantic, and from north-eastern USA to Brazil (Sims et al. 2003; Gore et al. 2008; Skomal et al. 2009).

Basking sharks are vulnerable to over-fishing owing to their naturally low population sizes, presumed slow growth rates, and very low reproductive rates (Sund 1943; Matthews 1950; Parker & Stott 1965; Pauly 2002; Natanson et al. 2008). Target and extermination fisheries in the North Atlantic and north-east Pacific have resulted in rapid declines in basking shark abundance, with low or negligible recovery several decades after fishing ceased (Fowler 2005).

In New Zealand, basking sharks are taken as bycatch in trawl and set net fisheries (Francis & Duffy 2002; Francis & Smith 2010). Estimates of unstandardised catch rates in deepwater trawl fisheries were provided by Francis & Duffy (2002) for the period 1986 to 1999, and extended to 2008 by Francis & Smith (2010). The latter authors also fitted Bayesian predictive hierarchical models to observer data from three core fishery areas that accounted for most observed basking shark captures to generate predicted catch rates for the period 1994–95 to 2007–08. They estimated the total trawl bycatch in the same period to be 922 sharks (CV = 19%). Predicted captures peaked in 1997–98 and then declined steadily to low numbers. The predicted strike rates showed no overall trend since 1994–95 in any of the three areas (Francis & Smith 2010). However, unstandardised catch rates from observer data were much higher in 1988–91 than at any time since then (Francis & Duffy 2002; Francis & Smith 2010).

The above estimates of basking shark bycatch underestimate total New Zealand catches. Bycatch in unobserved set net fisheries and in trawl fisheries in shallow coastal waters may also be considerable.

Patterns in unstandardised bycatch rates reported by Francis & Duffy (2002) and Francis & Smith (2010) imply that there was a large peak in basking shark abundance in 1988–91. The comparatively low numbers of sharks observed in trawl bycatch since then, and a lack of basking sharks observed by Department of Conservation aerial survey flights around Banks Peninsula in recent years, are cause for some concern that fishing may be impacting the population. There may not have been large aggregations of basking sharks in New Zealand waters since 1991.

Alternative explanations for the apparent decline in bycatch in trawl fisheries are that (a) the fluctuations in apparent abundance are driven by environmental factors, and (b) that changes in the composition of trawl fleets, and the way that they operate, have reduced the level of interactions between sharks and trawlers. Hypotheses that warrant testing include (a) that high catch rates during the late 1980s resulted from increased water temperatures; and (b) that catch rates may have been higher in early years because fishing vessels operated by some foreign nationalities may have been targeting (or at least not avoiding) sharks because of the value of their liver oil and fins (Boyd 2011). In this study, we tested these two hypotheses and determined whether or not they satisfactorily explain the fluctuations seen in basking shark bycatch rates.

The objective of this study was:

‘To identify factors, including variation in fishing vessels and areas, related to the apparent decline in bycatch of basking sharks over the period 1994/95 to 2007/08.’

Methods

Our analytical approach was to generate a series of indices describing (a) water temperature and (b) trawl fleet composition and operational methods that could be correlated with basking shark bycatch indices. Our analysis was restricted to observed trawl vessels because (a) some of the variables required were not available for the whole commercial fleet, (b) basking sharks were probably not well reported by all commercial vessels over the full time frame of the study, and (c) grooming the commercial data would be a large task beyond the scope of this study.

Basking shark bycatch indices

Two annual bycatch indices were obtained for each of three core fishery areas that accounted for most observed basking shark captures in the offshore trawl fisheries:

1. *Predicted indices*. These were the predicted strike rates estimated by Francis & Smith (2010)for the October–September fishing years 1994–95 to 2007–08 for three fishery areas: East Coast (EC), West Coast (WC) and Southland-Auckland Islands (SA) (Figure 1).
2. *RawCPUE indices*. The predicted indices do not extend far enough back to encompass the peak basking shark captures observed during the late 1980s and early 1990s (Francis & Smith 2010). We therefore derived raw (unstandardised)annual catch rate estimates for observed trawl tows made in the same three areas as used for the predicted indices (Figure 1) over the full period covered by observer data. The index was calculated as the total number of basking sharks observed per 1,000 observed trawl tows per year. Only tows having the same target species as those defined by Francis & Smith (2010; p. 7) were included. Because of the seasonality of these fisheries, the indices for EC and SA areas were based on July–June years (1986–87 to 2010–11), and the indices for the WC area were based on calendar years (1986 to 2011). Observer data were extracted from the Ministry for Primary Industries’ (MPI) Central Observer Database (COD) in August 2012. These indices are similar to, but cover larger geographic areas and longer time periods than, the raw CPUE indices provided by Francis & Duffy (2002) andextended by Francis & Smith (2010).

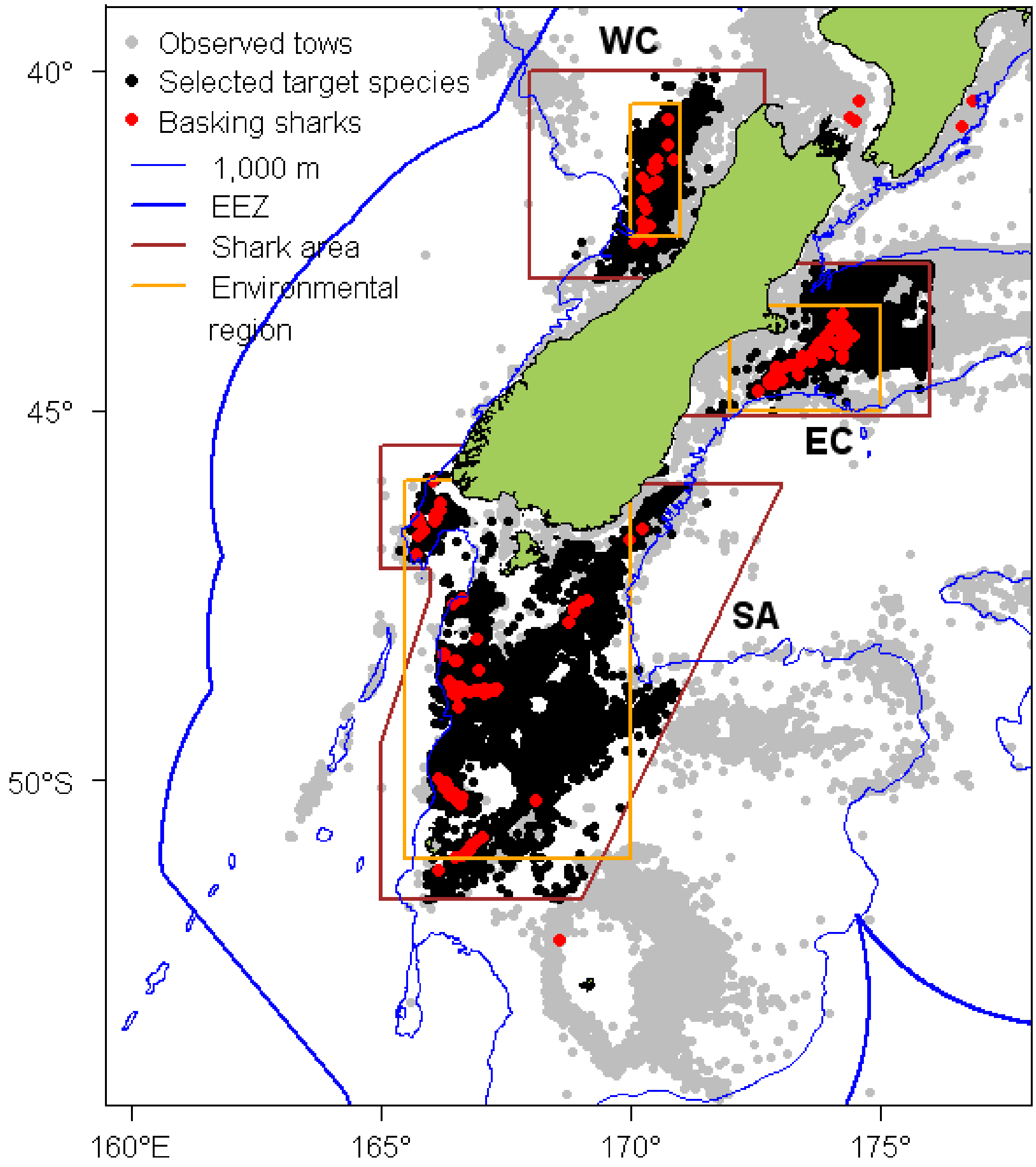

Figure 1.Map of southern New Zealand showing the distributions of observed trawl tows, tows targeting the selected suite of species in each area, and tows that caught basking sharks. Brown boxes indicate the three fishery areas used for estimating basking shark catch rates: East Coast (EC), West Coast (WC) and Southland–Auckland Is (SA). Orange boxes indicate the areas used for summarising environmental variables to generate environmental indices.

Environmental indices

Three data sourceswere used to generate annual temperature indices for sub-areas within each of thethree fishery areas. The sub-areas were defined so that they encompassed most of the basking shark captures (Figure 1):

1. Sea surface temperature (SST) indices were derived from a combination of in situ (ship and mooring) records and satellite remote-sensed records using the NOAA optimum interpolation analysis described by Reynolds & Smith (1994)and Reynolds et al.(2002). These data are available from 1981 onwards. The resulting daily estimates on a 1^{o} spatial grid were averaged across the fishery areas of interest for the peak periods of basking shark captures (EC, November–March; WC, April–July; SA, September–March).

2. Changes in average temperature through the water column were assessed from satellite altimetry measurements of sea surface height (SSH) (Sutton et al. 2005). Warm water is less dense than cold water, so a warm water column expands and stands slightly taller than a cold water column. SSH measurements came from the AVISO ‘reference’ product(Ducet et al. 2000), with weekly resolution and a grid spacing of $1/3^{o}$. The measurements,expressed as deviations from the mean height, were averaged across the same fishery areas and months as for SST (see 1 above).

3. Expendable bathythermograph (XBT) measurements of temperature in the upper 600 m of the ocean were measured along transects made by vessels steaming between Wellington and Sydney at approximately quarterly intervals since 1993(Sutton et al. 2005). The XBT transects are not sampled at the same time each year, so a de-seasoned anomaly was calculated from a harmonically-analysed fit. Average XBT temperature indices were derived for depths of 0, 100, 200, 400, and 600 m along the transect between longitudes 170–171 ^{o}E and latitudes 39–40 ^{o}S. The XBT temperature indices are based on an area near the WC fishery area, and are not relevant to the EC and SA areas.

Trawl fleet composition and operational variables

Trawl fleet composition and operational fishing methods were described using data extracted from the MPI observer database COD,and the vessel registry. For each trawl tow occurring in the three core fishery areas we extracted data on vessel nationality, vessel length, tow speed, tow duration, headline height, seabed depth, latitude and longitude. These factorsmay potentially affect the bycatch rate of basking sharks in trawl nets. Temporal trends in these variables were explored by plotting time series of bar graphs and box and whisker plots.

Vessel nationality is a nebulous concept. It may be variously defined as the port of registration (flag nationality), the home port of the vessel, or the nationality of the officers, fishing master or crew. Several or even all of these measures of nationality may be different for the same vessel. Vessel identity was not known to us during this study for confidentiality reasons; instead we were provided with a ‘vessel_key’ identifier assigned uniquely to a vessel by MPI. Flag nationality is often a ‘port of convenience’ such as Panama, Malta, Cyprus or Belize, and in any event is rarely available before 1999. The measure of nationality that best reflectsa vessel’s *modus operandi* may be that recorded by observersbased on their perception of who dictates the fishing procedures on a particular vessel. Unfortunately, this field was not always populated in the database and missing values were assigned nationalities by considering additional information provided by the MPI Research Data Manager from sources not available to NIWA, and the flag nationality. We grouped vessels from USSR, Russia and Ukraine together as they are essentially the same vessels operating under different political identities at different times.

Relationship between CPUE indices and other variables

Pearson correlation coefficients were calculated between the raw CPUE and environmental and operational variables. Annual indices were used for the environmental variables and median annual values for the operational variables. Because multiple unplanned comparisons were made, significance levels were adjusted with the Dunn-Sidak correction to maintain the experiment-wise Type I error rate at $p = 0.05$ (Sokal & Rohlf 1981).

The hypothesis of an association between shark bycatch and vessel nationality was tested with a Chi-square test of the observed numbers of sharks caught by each nationality and the numbers of sharks expected to be caught based on the proportion of tows made by vessels of each nationality.

Environmental indices and operational variables were used as predictor variables in Generalized Linear Models (GLMs) fitted to raw CPUE, separately for each of the three fishery areas. These models were fitted in the *R* statistical package (R Development Core Team 2008). GLMs were assessed for model fit by examination of the Akaike Information Criterion (AIC), residual patterns, quantile-quantile plots, and the size of the confidence intervals.

Results

Catches, effort and CPUE

Most basking sharks observed caught by trawlers in New Zealand waters have come from three fishery regions: EC, WC and SA (Figure 1). The number of sharks caught and number of trawl tows observed by area for the period 1986–2011 are shown in Tables 1–3. These datasets extend those analysed by Francis & Smith (2010), who focused on the period 1994–95 to 2007–08. Furthermore our numbers are not directly comparable with those of Francis & Smith (2010) because we used July–June or calendar years for analysis whereas they used fishing years (October–September).

The raw CPUEs of basking sharks for the areas in Figure 1 are plotted in Figure 2, and compared with the predicted strike rate of Francis & Smith (2010) and the raw CPUE index developed for similar but smaller fishery areas by Francis & Duffy (2002) andextended by Francis & Smith (2010). The three indices are very similar in the regions of overlap. Raw CPUE (present study) and predicted strike rate were strongly positively correlated: East Coast, $r = 0.96$;West Coast, $r = 0.87$; Southland–Auckland Is, $r = 0.93$ ($N = 14$, all significant at $p < 0.01$). Therefore the raw CPUE index developed in the present study, which covers the greatest time period, is used hereafter as an index of catch rates in the observed trawl fleet.

Table 1. Number of observed tows and basking sharks, raw unstandardised CPUE (present study), predicted strike rate (Francis & Smith 2010), raw unstandardised CPUE (Francis & Duffy 2002), sea surface temperature (SST), and sea surface height (SSH) for the East Coast fishery area (see Figure 1). Year 1987 = July 1986 to June 1987.

July-June year	Observed tows	Basking sharks	Raw CPUE	Predicted strike rate	F & D CPUE	SST (°C)	SSH (cm)
1987	1372	4	2.92	-	4.24	14.42	-
1988	765	22	28.76	-	52.91	13.72	-
1989	505	3	5.94	-	8.90	14.11	-
1990	291	0	0.00	-	0.00	14.39	-
1991	358	29	81.01	-	127.19	13.58	-
1992	268	7	26.12	-	62.50	13.48	-
1993	120	0	0.00	-		13.38	-3.00
1994	497	3	6.04	-	22.56	13.66	-0.79
1995	189	0	0.00	2.25	0.00	13.74	-0.66
1996	608	0	0.00	1.19	0.00	13.90	-0.70
1997	421	1	2.38	5.34	5.08	13.89	-0.03
1998	932	17	18.24	15.63	29.88	13.86	0.17
1999	757	4	5.28	3.85	9.24	15.12	5.41
2000	581	0	0.00	2.08	0.00	13.93	4.25
2001	1033	3	2.90	2.58	5.15	14.46	6.39
2002	650	0	0.00	0.77	0.00	14.48	3.90
2003	493	3	6.09	3.81	12.88	14.06	2.01
2004	318	1	3.14	2.83	4.74	13.84	4.50
2005	610	0	0.00	1.22	0.00	13.84	1.93
2006	483	0	0.00	1.20	0.00	14.42	4.86
2007	552	0	0.00	1.31	0.00	13.51	5.33
2008	451	0	0.00	1.18	0.00	14.37	6.66
2009	745	0	0.00	-	-	13.90	7.00
2010	636	0	0.00	-	-	13.46	-
2011	685	0	0.00	-	-	-	-

Table 2. Number of observed tows and basking sharks, raw unstandardised CPUE (present study), predicted strike rate (Francis & Smith 2010), raw unstandardised CPUE (Francis & Duffy 2002), sea surface temperature (SST), sea surface height (SSH), and XBT temperature at five depths for the West Coast fishery area (see Figure 1).

Calendar year	Observed tows	Basking sharks	Raw CPUE	Predicted strike rate	F & D CPUE	SST (°C)	SSH (cm)	XBT temp 0 m	XBT temp 100 m	XBT temp 200 m	XBT temp 400 m	XBT temp 600 m
1986	1652	1	0.61	-	0.61	15.02	-	-	-	-	-	-
1987	4106	1	0.24	-	0.25	14.18	-	-	-	-	-	-
1988	2706	2	0.74	-	0.74	14.13	-	-	-	-	-	-
1989	1484	25	16.85	-	17.05	15.16	-	-	-	-	-	-
1990	1564	0	0.00	-	0.00	15.05	-	-	-	-	-	-
1991	1277	1	0.78	-	0.91	14.26	-	14.96	13.89	12.54	10.06	8.22
1992	867	0	0.00	-	0.00	13.26	-	14.42	13.49	12.72	10.44	8.44
1993	1512	0	0.00	-	0.00	13.83	-2.53	14.73	13.52	12.53	10.55	8.42
1994	1651	0	0.00	-	0.00	14.46	0.66	15.30	13.52	12.50	10.24	8.33
1995	850	2	2.35	2.90	2.59	14.80	-0.77	15.19	13.22	12.31	10.31	8.28
1996	1074	0	0.00	0.67	0.00	14.84	1.30	14.92	14.19	12.43	10.35	8.56
1997	700	4	5.71	5.03	5.94	15.02	2.94	15.27	14.48	12.80	10.43	8.49
1998	914	2	2.19	4.78	2.19	14.89	5.05	15.92	14.65	12.82	10.61	8.62
1999	1124	1	0.89	2.48	0.92	16.22	11.45	16.66	16.26	13.75	11.31	8.94
2000	1183	1	0.85	2.00	0.88	15.56	10.14	15.67	15.19	13.75	11.02	8.69
2001	1074	0	0.00	0.57	0.00	15.98	10.38	15.83	14.95	13.94	11.26	8.99
2002	1341	0	0.00	0.26	0.00	15.34	2.88	15.38	14.83	13.59	10.99	8.74
2003	962	1	1.04	0.91	1.30	15.51	7.50	16.12	15.28	13.75	11.04	8.78
2004	1407	0	0.00	0.39	0.00	14.28	5.83	15.06	14.33	13.24	10.75	8.60
2005	1074	8	7.45	4.73	0.00	15.06	6.97	15.72	14.90	13.14	10.85	8.68
2006	1127	0	0.00	0.32	0.00	14.90	4.77	15.33	14.61	13.17	10.89	8.78
2007	670	0	0.00	0.72	0.00	15.00	8.13	15.64	14.30	13.57	11.49	9.31
2008	782	0	0.00	0.63	0.00	15.48	10.16	15.71	14.28	13.39	11.03	9.03
2009	706	0	0.00	-	-	14.97	9.09	15.21	14.81	13.60	11.43	9.14
2010	791	0	0.00	-	-	15.11	-	-	-	-	-	-
2011	682	0	0.00	-	-	-	-	-	-	-	-	-

Table 3. Number of observed tows and basking sharks, raw unstandardised CPUE (present study), predicted strike rate (Francis & Smith 2010), raw unstandardised CPUE (Francis & Duffy 2002), sea surface temperature (SST), and sea surface height (SSH) for the Southland – Auckland Is fishery area (see Figure 1).Year 1987 = July 1986 to June 1987.

July-June year	Observed tows	Basking sharks	Raw CPUE	Predicted strike rate	F & D CPUE	SST (°C)	SSH (cm)
1987	4649	6	1.29	-	0.96	11.30	-
1988	2563	2	0.78	-	0.00	10.36	-
1989	1735	32	18.44	-	24.77	10.68	-
1990	1510	16	10.60	-	9.68	11.30	-
1991	1872	0	0.00	-	0.00	10.54	-
1992	1513	0	0.00	-	0.00	10.25	-
1993	2662	0	0.00	-	0.00	10.30	-3.15
1994	1454	1	0.69	-	1.68	10.69	-0.88
1995	1025	0	0.00	0.73	0.00	10.00	-3.78
1996	955	0	0.00	0.84	0.00	10.35	-1.87
1997	1412	0	0.00	0.83	0.00	10.83	-0.89
1998	1250	0	0.00	0.76	0.00	10.13	-2.23
1999	1730	5	2.89	4.35	2.80	11.01	4.23
2000	1689	6	3.55	3.91	7.00	11.03	4.47
2001	3627	4	1.10	1.66	0.78	11.05	4.94
2002	2103	3	1.43	1.55	0.85	11.67	4.15
2003	1910	10	5.24	4.04	3.58	10.66	0.60
2004	2148	7	3.26	2.94	0.59	10.43	2.52
2005	2719	3	1.10	1.40	0.46	10.52	0.46
2006	2030	0	0.00	0.71	0.00	11.13	2.65
2007	1725	6	3.48	2.93	5.63	10.42	3.68
2008	2304	3	1.30	1.65	0.75	10.52	4.12
2009	2085	1	0.48	-	-	10.48	5.44
2010	2095	3	1.43	-	-	10.43	-
2011	1950	8	4.10	-	-	-	-

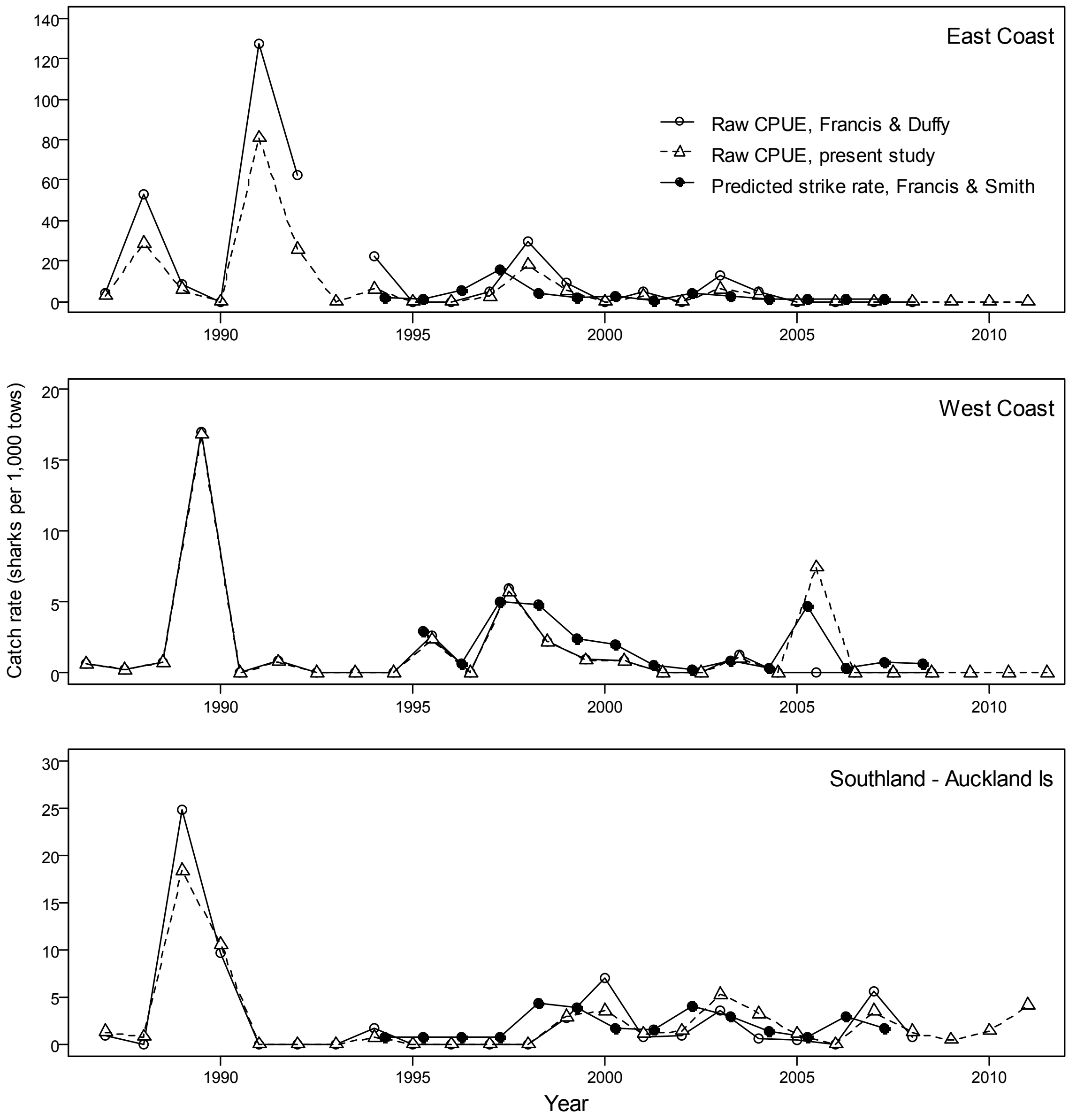

Figure 2. Basking shark catch rate indices for three fishery areas. The index used in the present study was the raw unstandardised CPUE. Also shown are the predicted strike rate from Bayesian models fitted by Francis & Smith (2010) and the raw CPUE index derived for smaller fishery areas by Francis & Duffy (2002). For raw CPUE indices, years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland− Auckland Is. For predicted strike rate, years are fishing years (labelled as the greater of the two years).

Vessel nationality

Despite uncertainties about the quality of the vessel nationality data, some clear temporal patterns were apparent. Japanese vessels made most of the observed tows in the late 1980s and early 1990s in all three fishery areas, but few Japanese tows were observed from the mid 1990s onwards (Figure 3). Conversely, few tows by New Zealand vessels were observed before the mid 1990s. New Zealand tows dominated in East Coast from the mid 1990s, and were also important in West Coast and Southland–Auckland Is from the late 1990s. Tows by vessels from the USSR, Russia and Ukraine (combined under USSR) were frequently observed throughout the time period in West Coast and Southland–Auckland Is, but were only occasionally observed in East Coast. Korean vessels were occasionally observed in all fishery areas throughout the time period, and became more important through time, especially in East Coast and Southland–Auckland Is. Polish vessels were occasionally observed, mainly during the late 1990s and early 2000s. The remaining observed tows grouped as ‘Other’were by vessels from Norway, Panama, Malta, China, Cyprus and USA (in descending order).

Most of the basking sharks observed before the mid 1990s were caught by Japanese vessels, with a few being caught by Korean, USSR and New Zealand vessels (Figure 4). After the mid 1990s, basking sharks were observed mainly on New Zealand vessels in East Coast, Polish and USSR vessels in West Coast, and Korean, Japanese and USSR vessels in Southland–Auckland Is.

Japanese vessels caught 51–60% of the sharks in the three areas, but only accounted for 15–35% of the observed tows (Figure 5). Conversely, the percentages of sharks caught were smaller than the respective percentages of towsfor Korean, New Zealand and USSR vessels. Polish vessels recorded a higher percentage of sharks than tows in West Coast but caught sharks in proportion with tows in the other two areas. There was a highly significant association between shark captures and vessel nationality for all three areas (East Coast: $\chi^2 = 79.2$, $p < 0.001$; West Coast: $\chi^2 = 28.7$, $p < 0.001$; Southland–Auckland Is: $\chi^2 = 121.9$, $p < 0.001$; all tests with 5 degrees of freedom).

Environmental indices

Time series of SST, SSH and XBT are shown in Figure 6 and Tables 1–3. SST showed no major temporal variability or trends in East Coast or Southland–Auckland Is. However, West Coast SST was higher on average during the second half of the time series than in the first half. A similar pattern was seen in West Coast XBT temperatures at 0, 100 and 200 m depth, but the temperature at 400 and 600 m showed a slow overall increase throughout the series. SSH increased sharply between 1993 and about 1999 in all three areas, and then fluctuated about a higher level.

Correlation coefficients between raw CPUE and three environmental variables (SST, SSH and XBT at 0 m) are shown in Table 4. None of the correlation coefficients was significant. In fact, the coefficients ranged between weakly negative (–0.28) and moderately positive (0.45) suggesting there was no consistent relationship between CPUE and the environmental variables.

For each fishery area, a GLM was fitted to raw CPUE with SST, SSH and (for West Coast) XBT temperature at 0 m as predictors. Although the predictors explained moderate percentages of the deviance, the model diagnostics revealed very poor model fits, and the predicted relationships between CPUE and the environmental variables had very large confidence regions, indicating lack of predictive power. The models were therefore regarded as uninformative and were rejected.

Table 4. Correlation coefficients between raw CPUE and three environmental variables and seven operational variables. To maintain the experiment-wise probability level at $p = 0.05$, a Dunn-Sidak corrected significance level for the 10 comparisons per fishery area of $p = 0.0051$ is required. We used tabulated critical values for $p = 0.005$ for our tests. Critical values for the three environmental variables were 0.51–0.61 depending on the sample size. Critical values for the seven operational variables were 0.50–0.51 depending on the sample size.

Area	SST	SSH	XBT 0 m	Vessel length	Headline height	Tow speed	Tow duration	Start depth	Latitude	Longitude
Correlation coefficients										
East Coast	-0.281	-0.219	-	0.089	-0.039	-0.201	-0.136	-0.373	-0.272	-0.334
West Coast	0.129	-0.059	0.181	0.370	0.283	0.038	0.094	0.437	-0.180	-0.423
Southland	0.228	0.449	-	-0.100	-0.180	-0.310	-0.105	-0.083	-0.076	-0.083
Sample sizes										
East Coast	24	17	-	25	25	25	25	25	25	25
West Coast	25	17	19	26	26	26	26	26	26	26
Southland	24	17	-	25	25	25	25	25	25	25

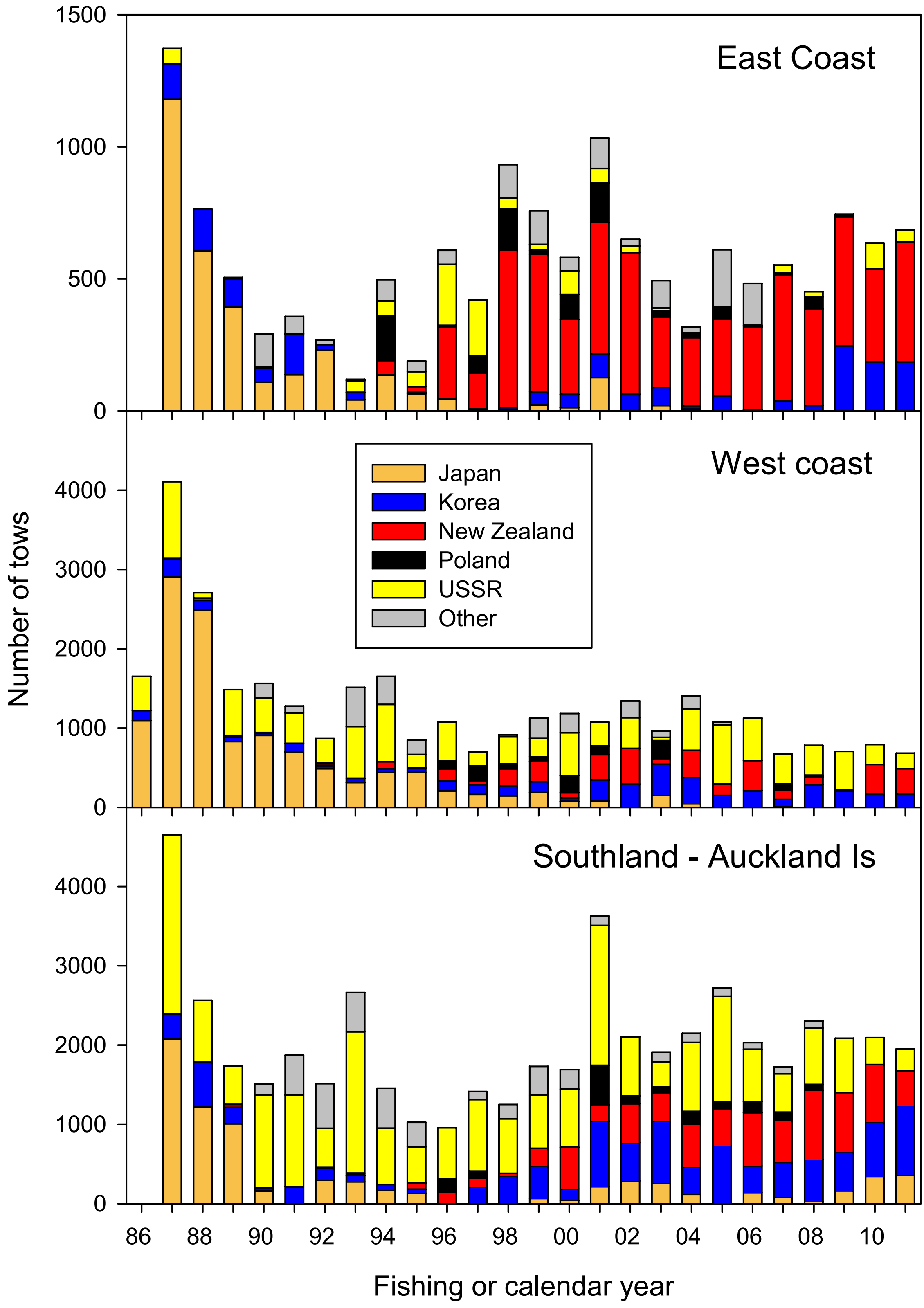

Figure 3. Number of observed trawl tows by fishery area, year and nationality.

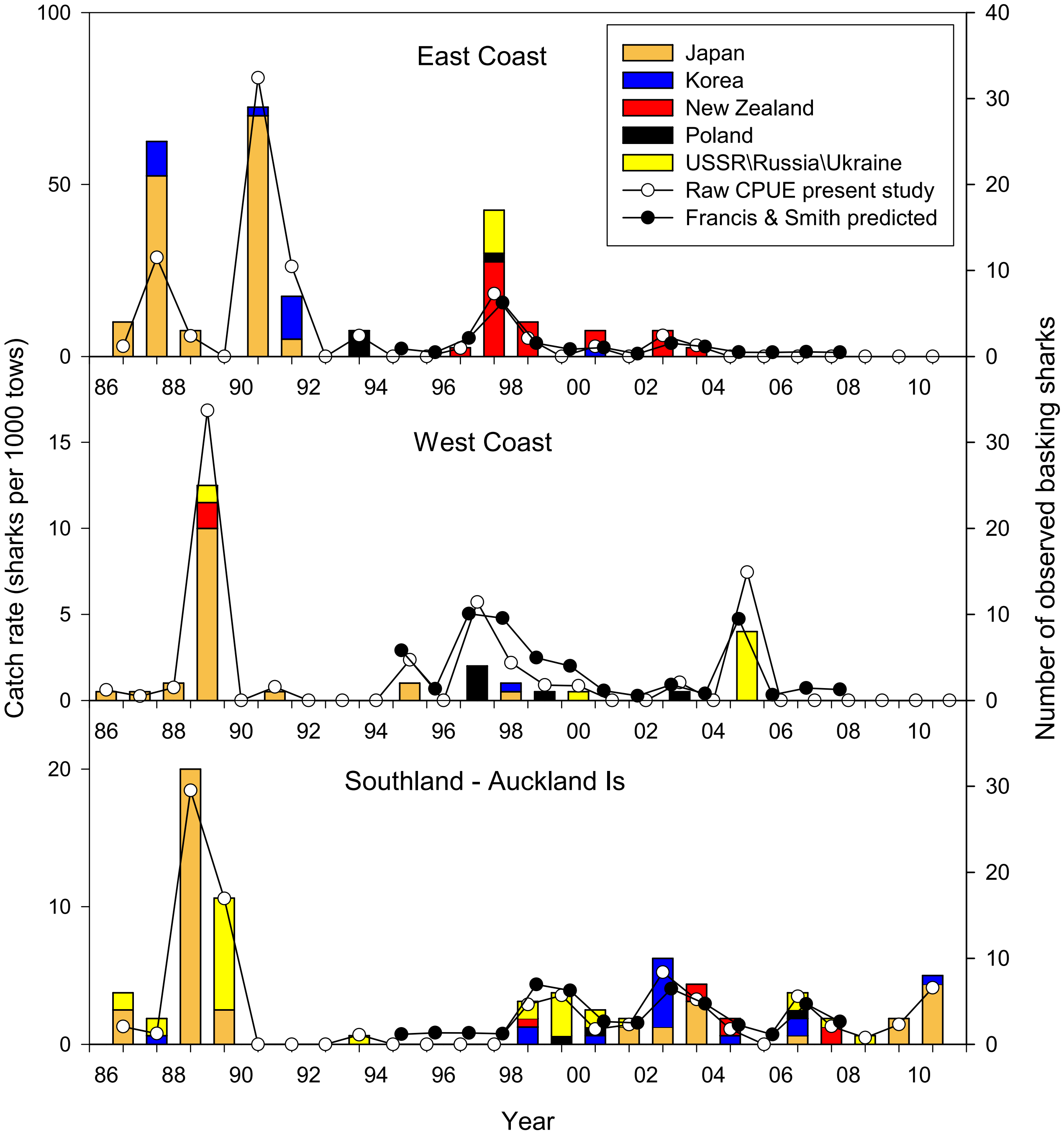

Figure 4. Number of basking sharks observed by fishery area, year and nationality (histograms). Also plotted are the raw CPUE index (present study) and predicted strike rate (Francis & Smith 2010).

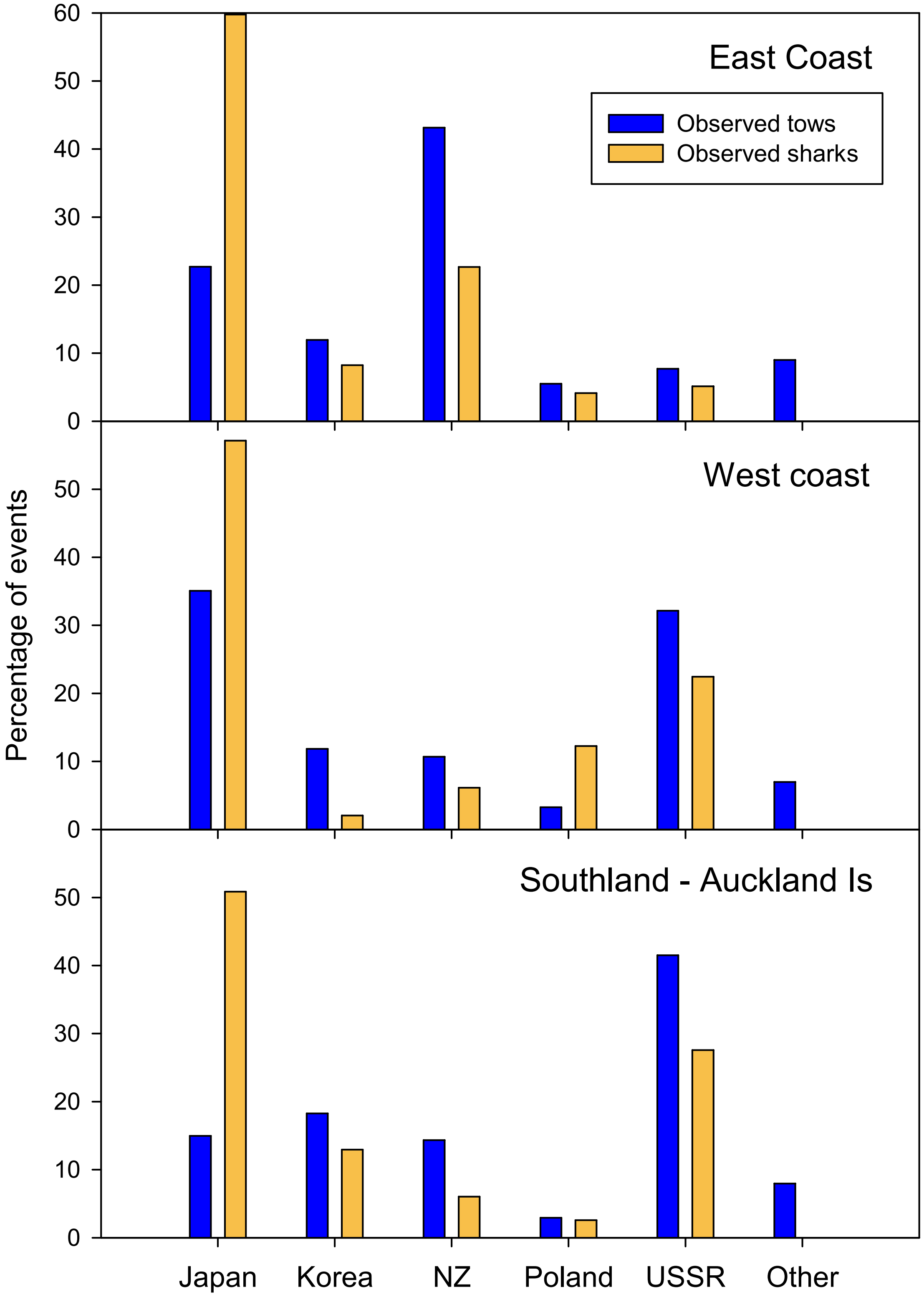

Figure 5. Percentages of observed tows and observed basking shark captures by fishery area and nationality.

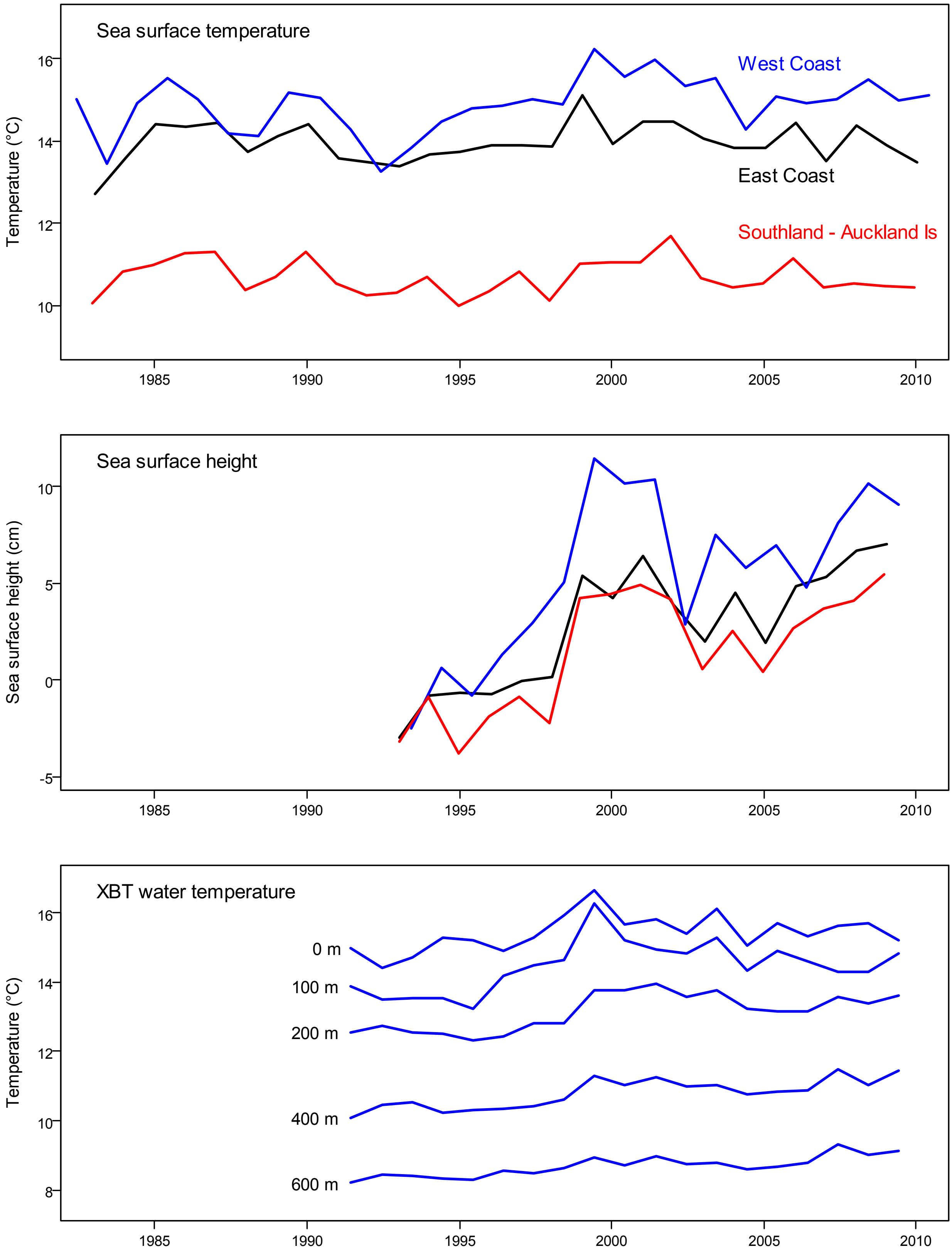

Figure 6. Time series of sea surface temperature and sea surface heightfor three fishery areas, and expendable bathythermograph temperature at five depths for West Coast.

Operational variables

In Figures 7–13, the distributions of seven operational variables are compared between observed tows that caught basking sharks and all observed tows, by vessel nationality. The numbers of tows catching sharks was always low, so caution is required in interpreting any differences. Vessels with nationality ‘Other’ caught no basking sharks, but the distributions of their operational variables are included for completeness.

Vessel length varied substantially among nations in all three fishery areas, with vessels from Japan, Poland and USSR generally being longer than those from Korea and New Zealand. For a given nationality, vessel length for shark tows usually fell within the interquartile range of all observed vessels (Figure 7).

Headline height was generally low (less than 10 m) for Japanese, Korean and New Zealand vessels in East Coast and Southland–Auckland Is, but higher(mainly 20–60 m) for vessels from Poland and USSR (Figure 8). In West Coast, most vessels from Japan, Poland and USSR used high headlines (40–80 m), whereas Korean and New Zealand vessels used small to large headline heights (5–50 m). Headline heights of shark tows were similar to those for all tows, although in Southland–Auckland Is, Polish vessels tended to catch sharks in tows with larger headlines.

Tow speeds were similar across nations and areas, and also between shark tows and all tows (Figure 9).

Median tow durations were about 4 hours for all nations and areas, but there was large variation with many outliers at the upper end of the range (Figure 10). Shark tows had similar durations to all tows, except in Southland–Auckland Is where Korean, New Zealand and Polish vessels tended to catch sharks in longer tows (medians around 6 hours).

Seabed depth at the start of the tow varied significantly among nations and areas (Figure 11). In East Coast and in Southland–Auckland Is, sharks tows were made in similar depths to all tows, but in West Coast, sharks were usually caught at the deeper end of the depth range.

The various nations tended to fish similar latitudes and longitudes in each fishery area (Figures 12–13). In East Coast, sharks were caught in the south-west of the fished area (also clearly apparent in Figure 1).In West Coast, shark towsgenerally overlapped all tows spatially, except for Polish vessels which caught sharks in the north-eastern part of the area fished. In Southland–Auckland Is, sharks were caught mainly in the western part of the fishery area by all nations except Poland (see also Figure 1). Korean vessels caught most sharks in the north and USSR vessels caught most sharks in the south.

Temporal variation in vessel operational variables between 1986 and 2011 is shown in Figures 14–20. Vessel length varied considerably within and between years in all fishery areas, but tended to decline over time in East Coast and Southland−Auckland Is (Figure 14).

Headline height was typically low in East Coast (less than 10 m) apart from four years in the mid 1990s when there was large variation (Figure 15). West Coast tows usually had high headline heights (40–70 m) but an increasing proportion of small headline tows has been made since 1999. Southland−Auckland Is tows used low–moderate headline heights throughout the time series.

Tow speed tended to be lower (median 3.5–4.0 knots) in the first few years of the time series in all three areas, and stabilised at 4.0–4.5 knots thereafter (Figure 16).

Median tow duration increased from about 3 hours to 5 hours in Southland−Auckland Is over the time series (Figure 17). There was also a slight increase in median duration in East Coast, but in West Coast, tow duration was highly variable both within and between years with no overall trend.

Seabed depth was relatively consistent through time in all three areas, but highly variable within years, particularly in Southland−Auckland Is (Figure 18). Latitude and longitude were also moderately consistent across the time series for all three areas (Figures 19–20).

Correlation coefficients between raw CPUE and seven operational variables are shown in Table 4. None of the correlation coefficients was significant.

For each fishery area, a GLM was fitted to raw CPUE with the seven operational variables as predictors. As for the GLMs fitted to environmental variables, the predictors explained moderate percentages of the deviance, but the model diagnostics revealed very poor model fits, and the predicted relationships between CPUE and the operational variables had very large confidence regions, indicating lack of predictive power. The models were therefore regarded as uninformative and were rejected.

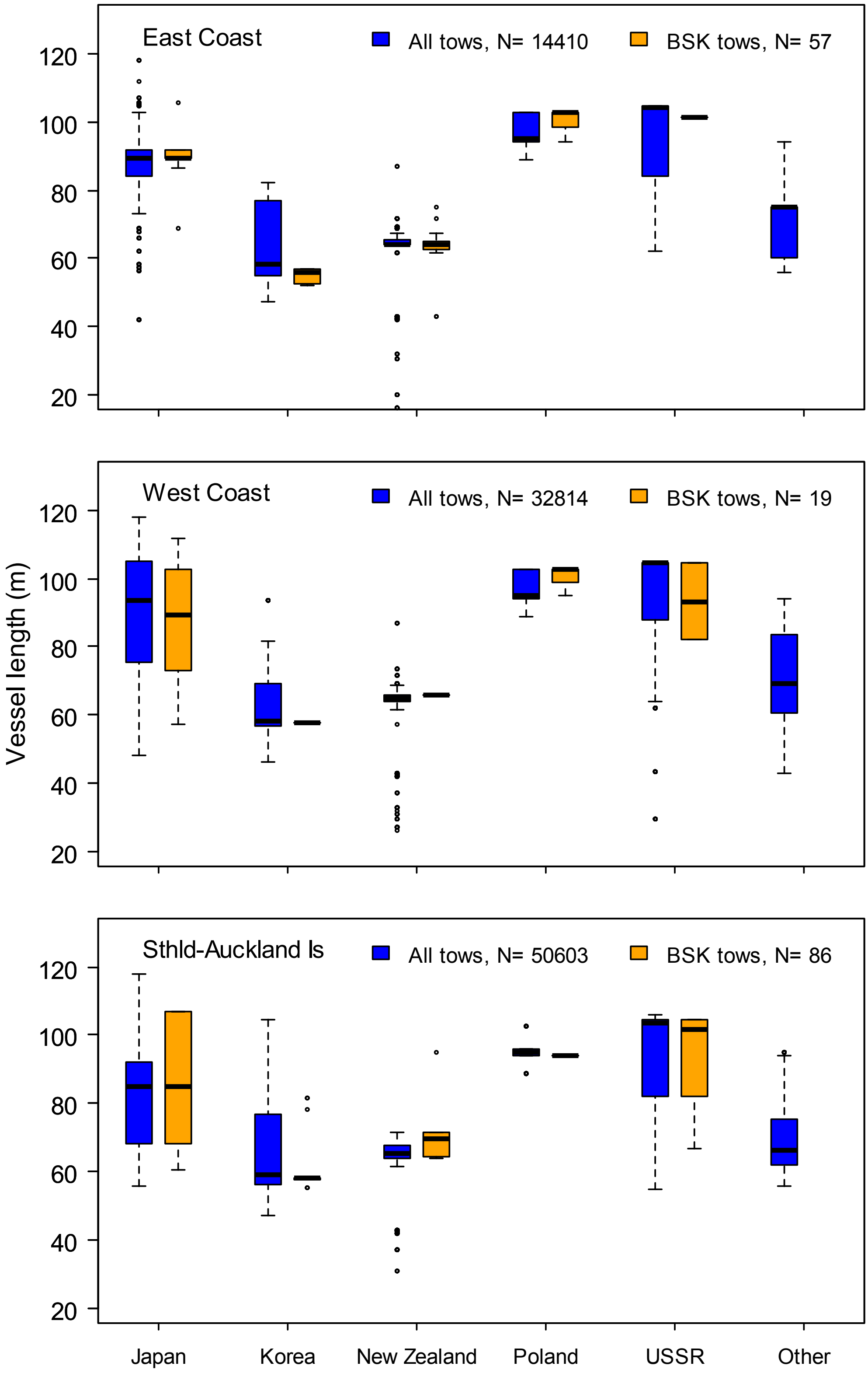

Figure 7. Distribution of vessel lengths for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. N = sample size. The thick black line is the median, the box is the interquartile range, the dashed lines are ± 1.5 x the interquartile range, and the circles are outliers (not all outliers are included in the range plotted).

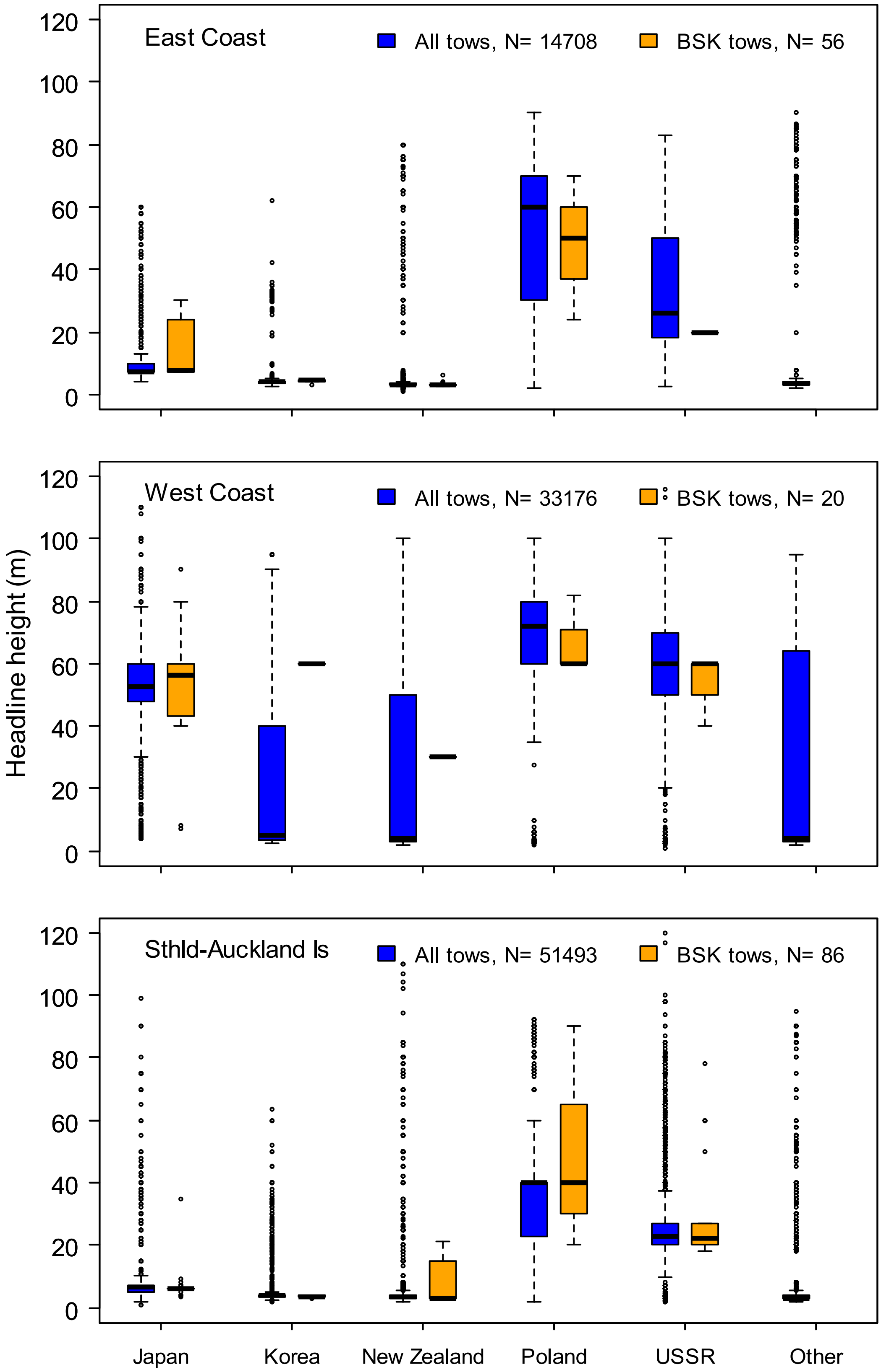

Figure 8. Distribution of headline heights for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. See Figure 7 caption for explanation.

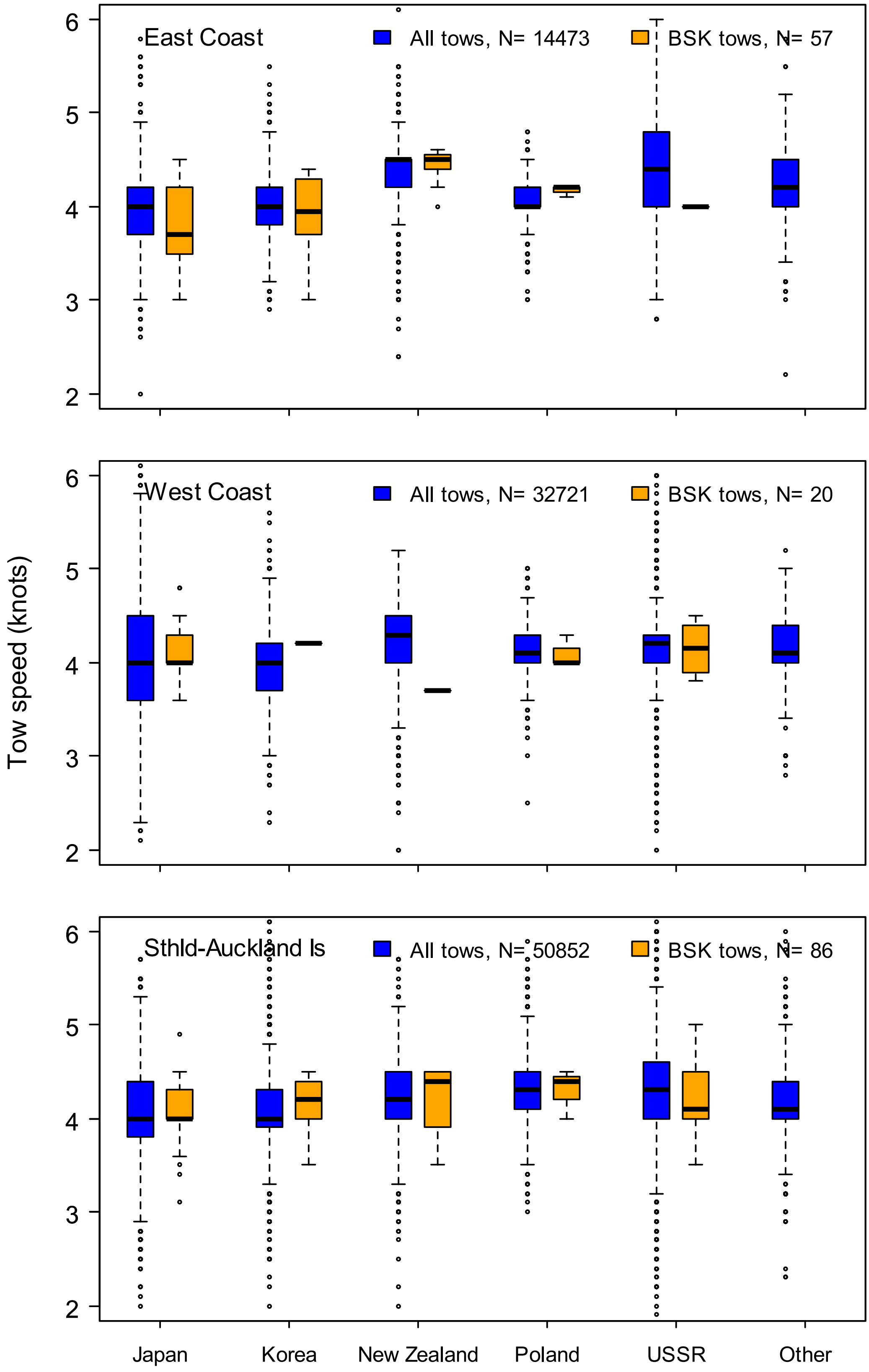

Figure 9. Distribution of tow speeds for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. See Figure 7 caption for explanation.

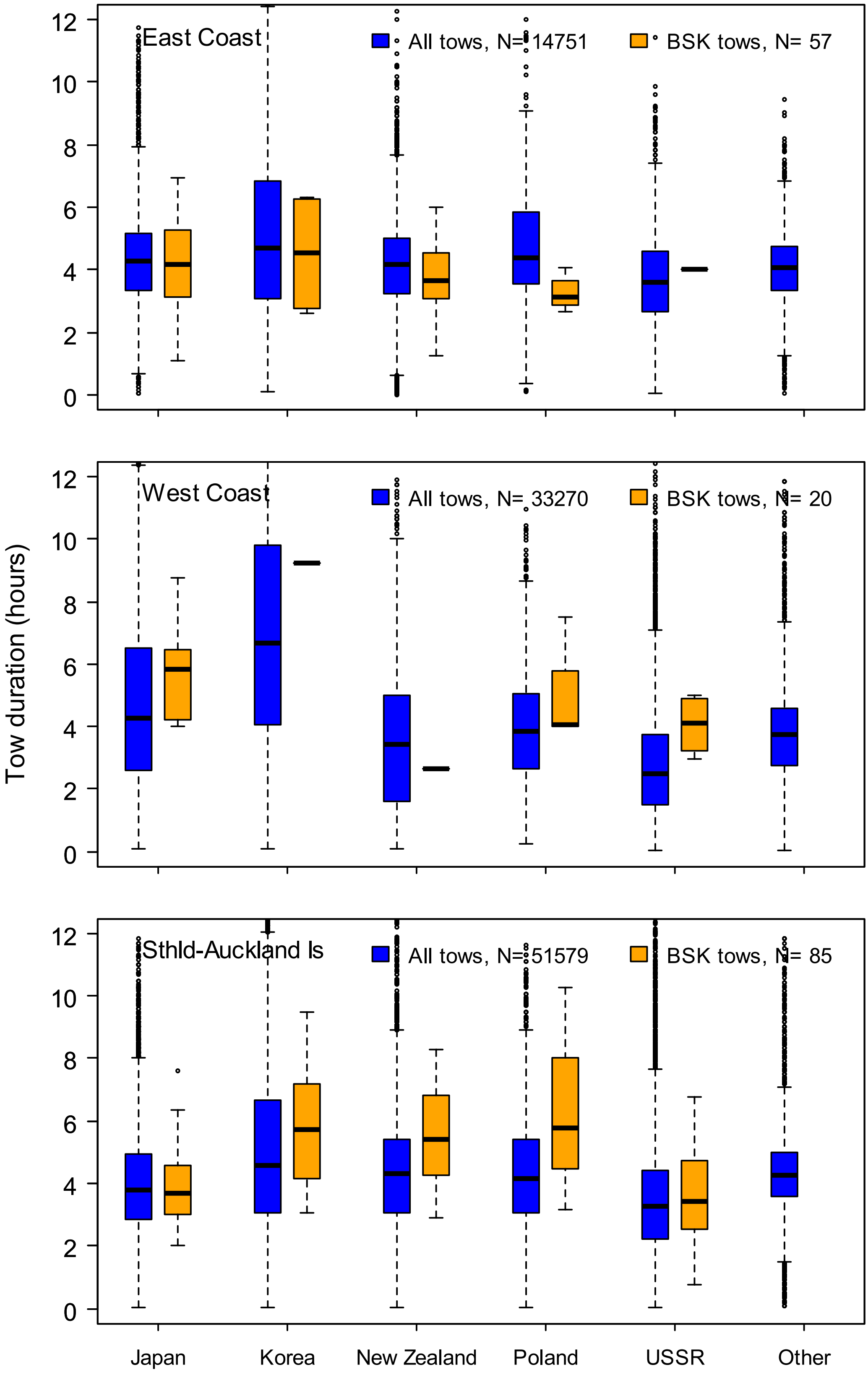

Figure 10. Distribution of tow durations for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. See Figure 7 caption for explanation.

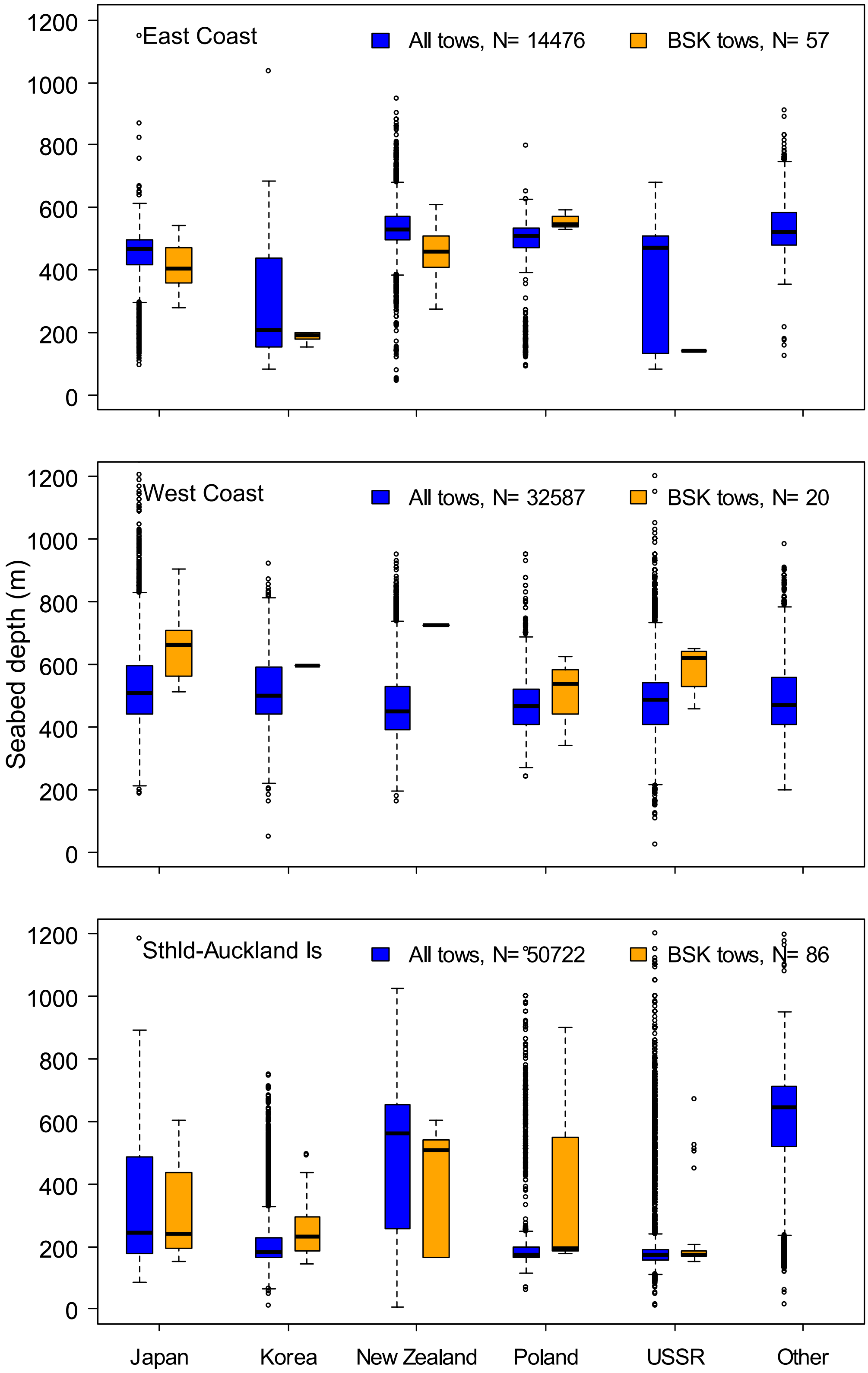

Figure 11. Distribution of seabed depth at the start of the tow for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. See Figure 7 caption for explanation.

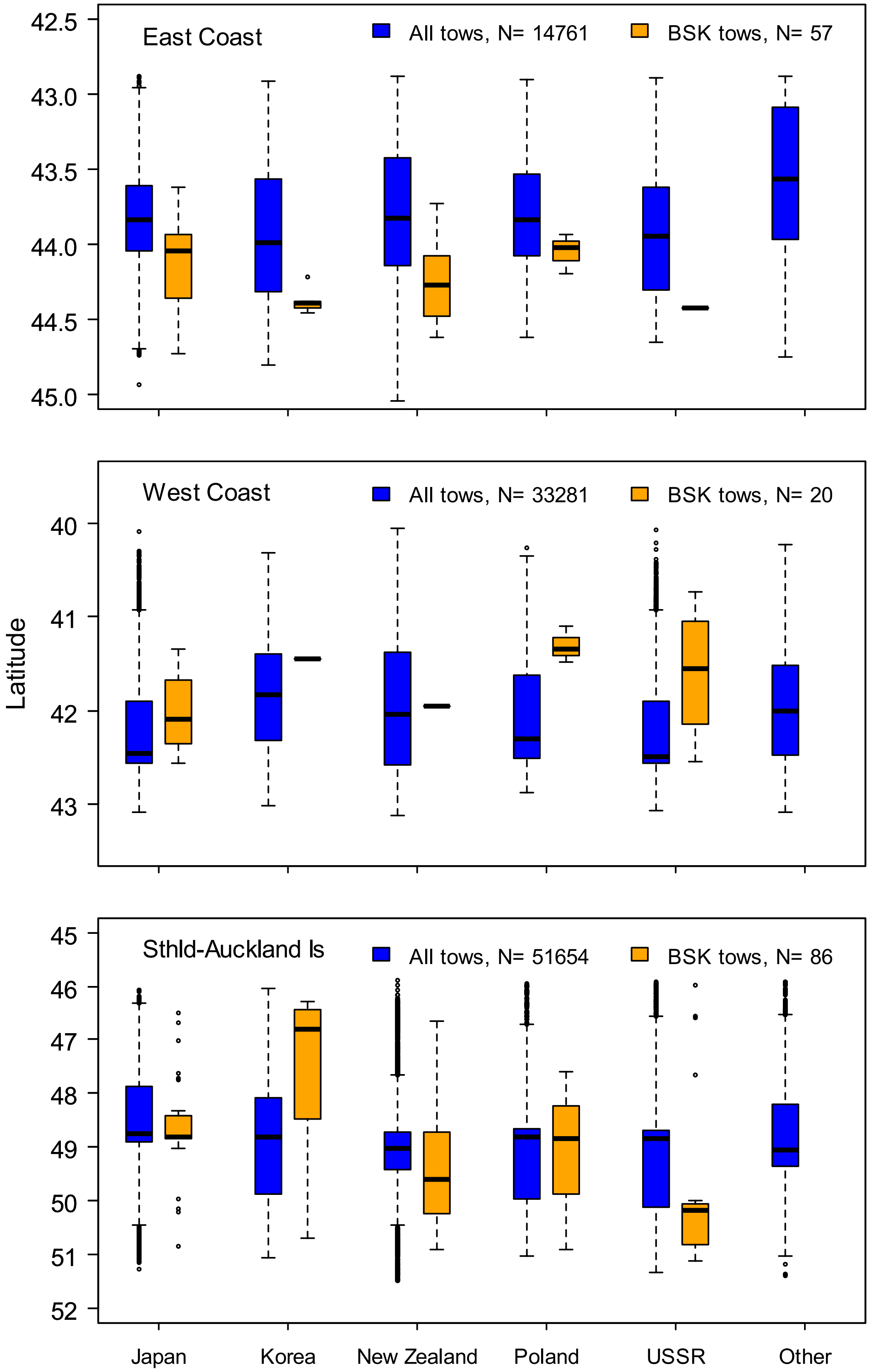

Figure 12. Distribution of start of tow latitudes for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. See Figure 7 caption for explanation.

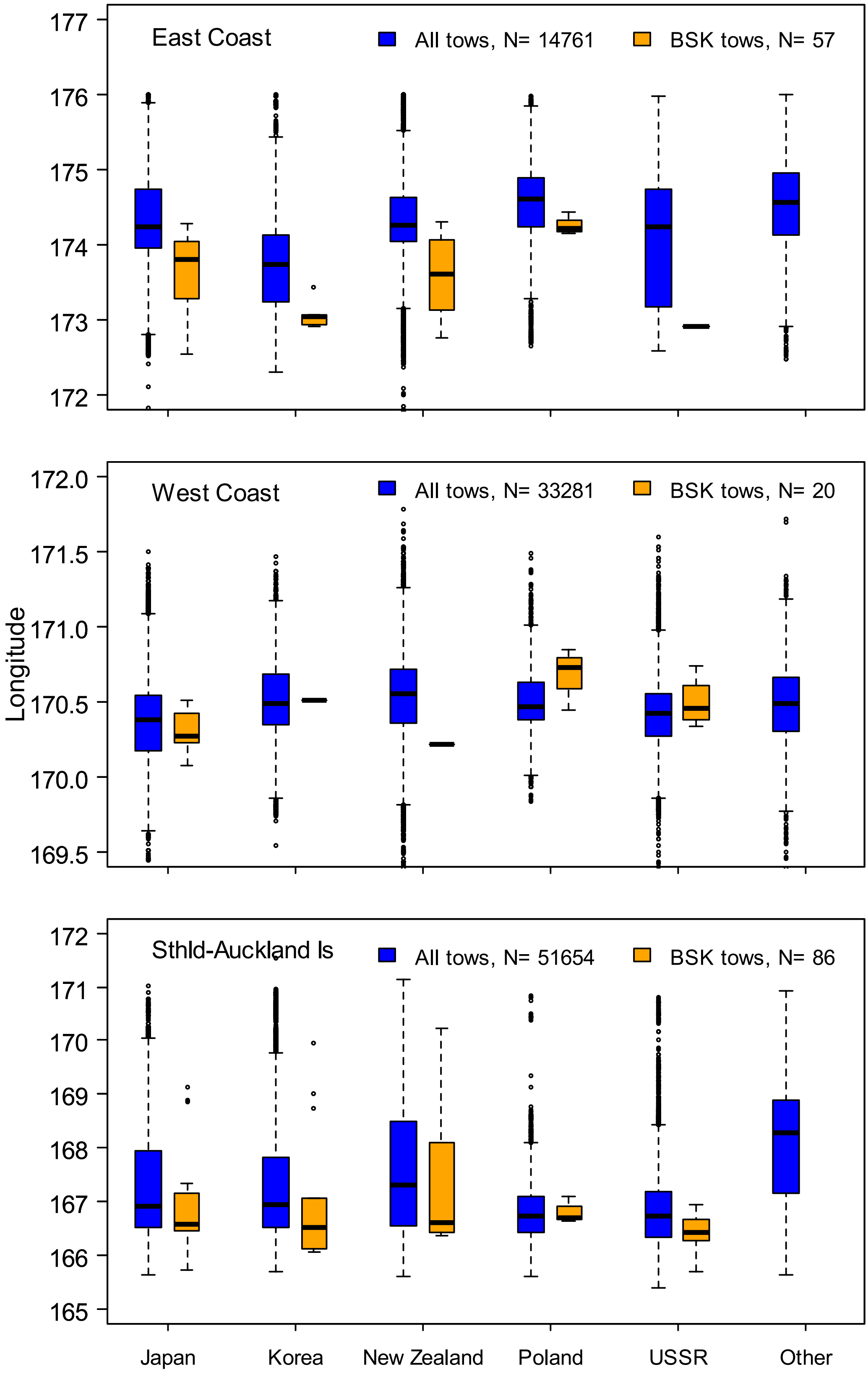

Figure 13. Distribution of start of tow longitudes for all observed trawl tows and observed tows that caught basking sharks in three fishery areas. See Figure 7 caption for explanation.

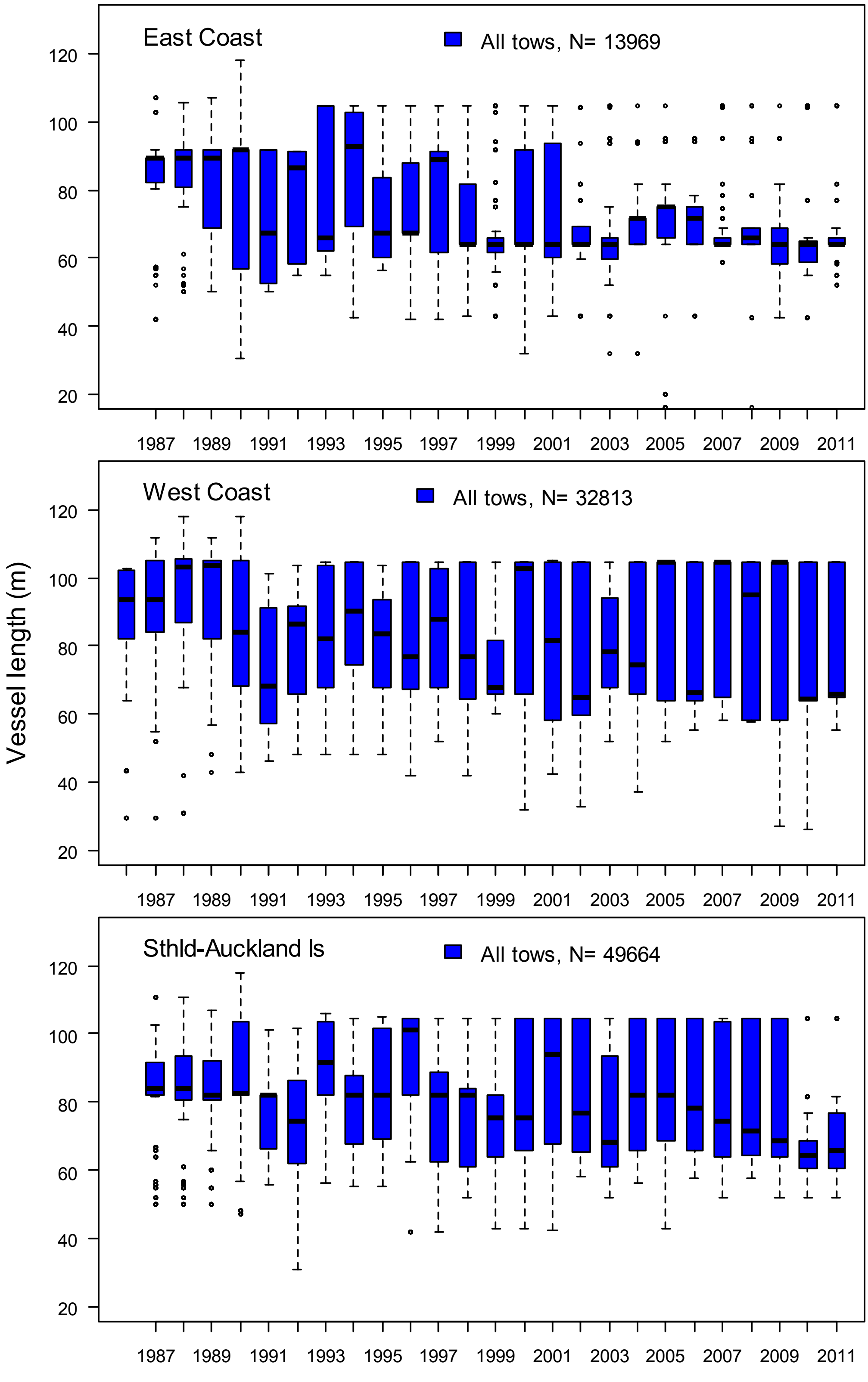

Figure 14. Time series of vessel length for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is.See Figure 7 caption for explanation.

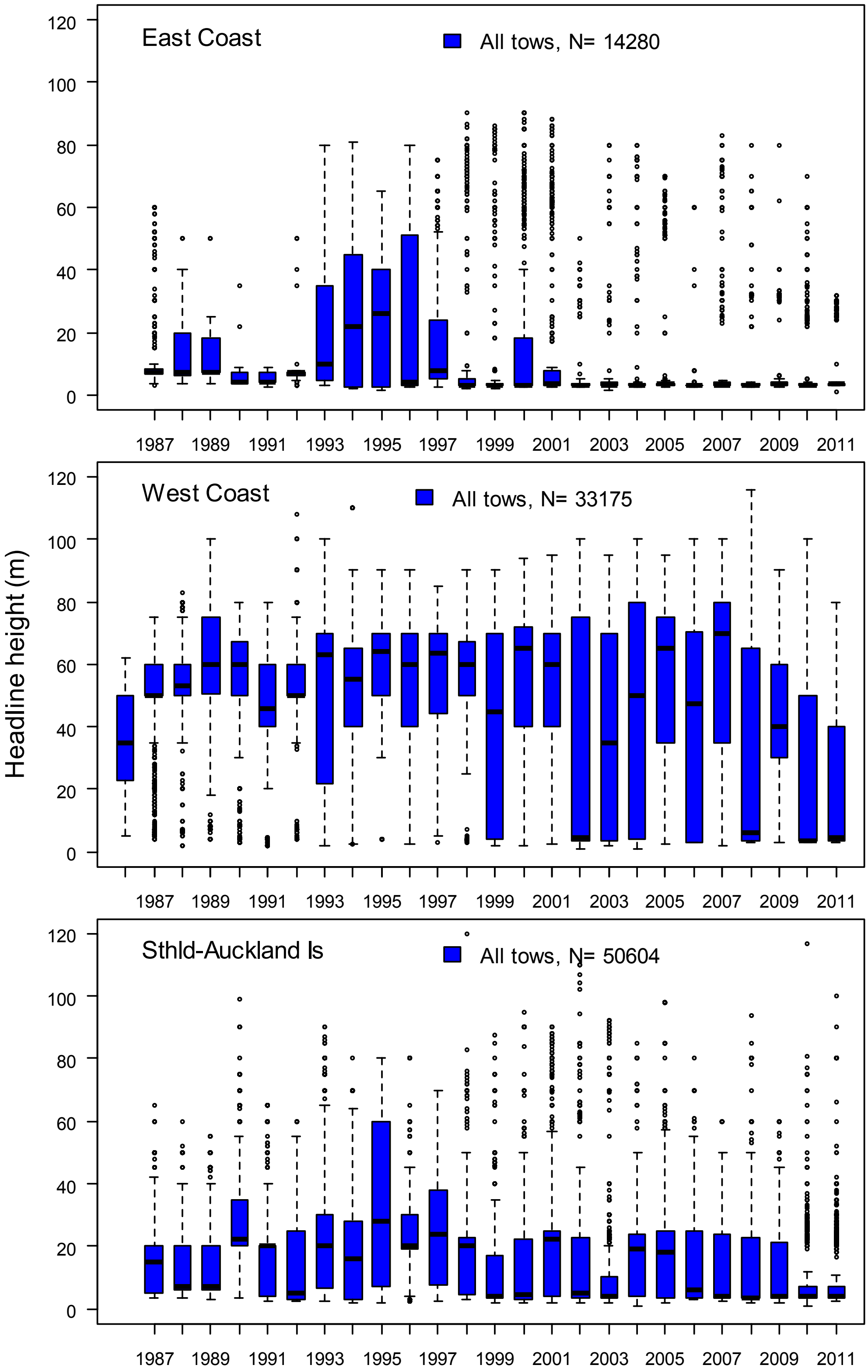

Figure 15. Time series of headline height for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is. See Figure 7 caption for explanation.

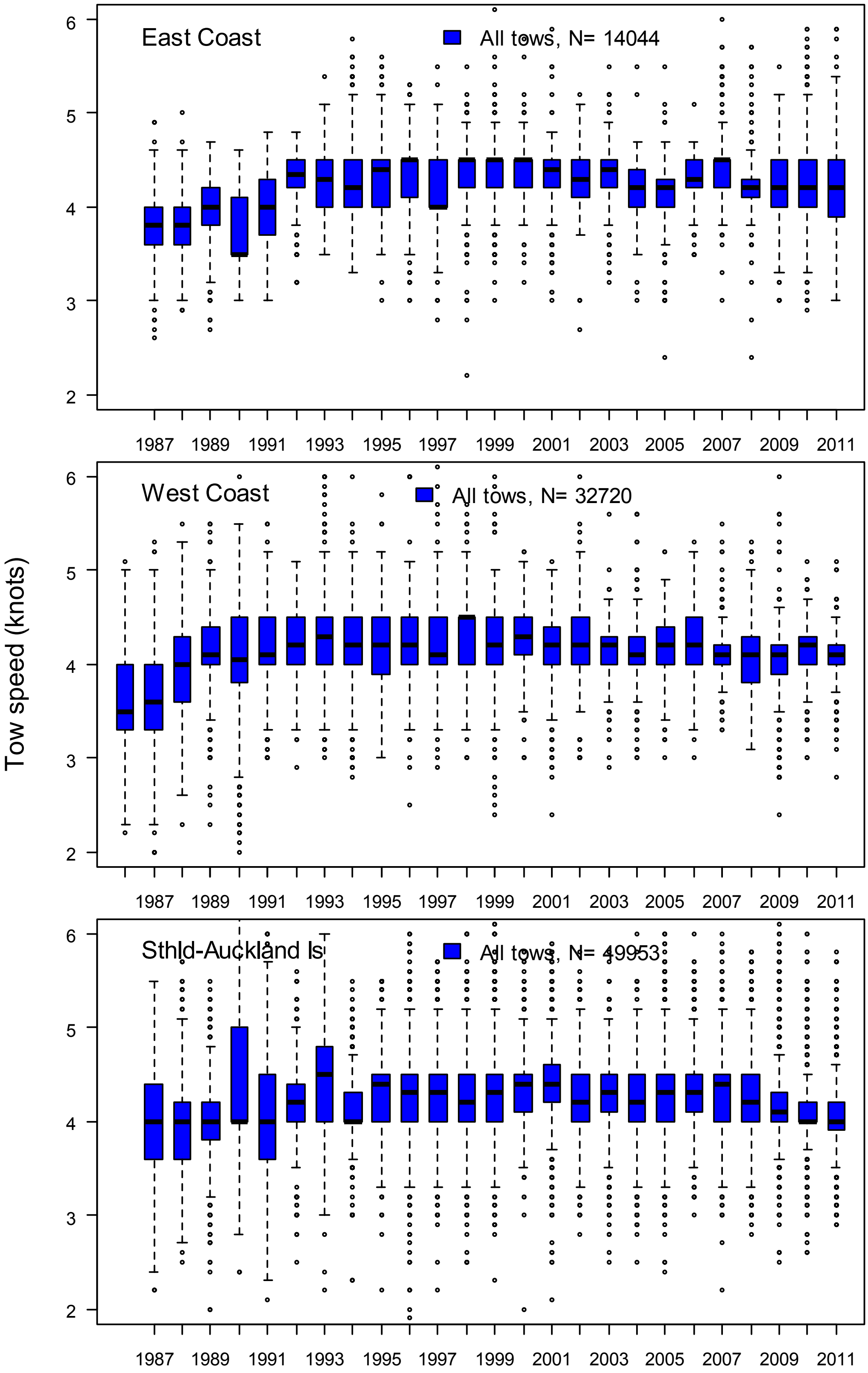

Figure 16. Time series of tow speed for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is. See Figure 7 caption for explanation.

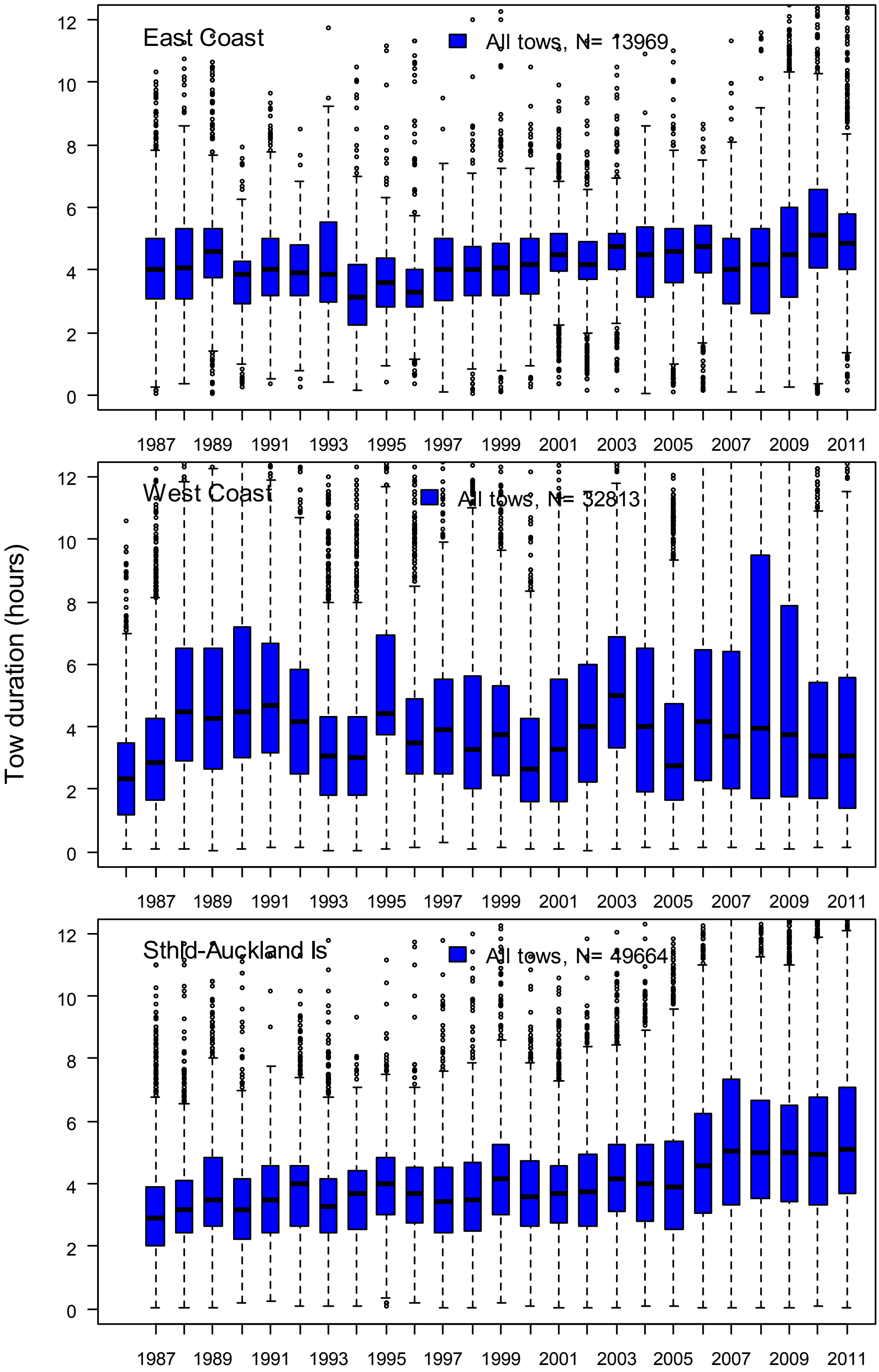

Figure 17. Time series of tow duration for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is. See Figure 7 caption for explanation.

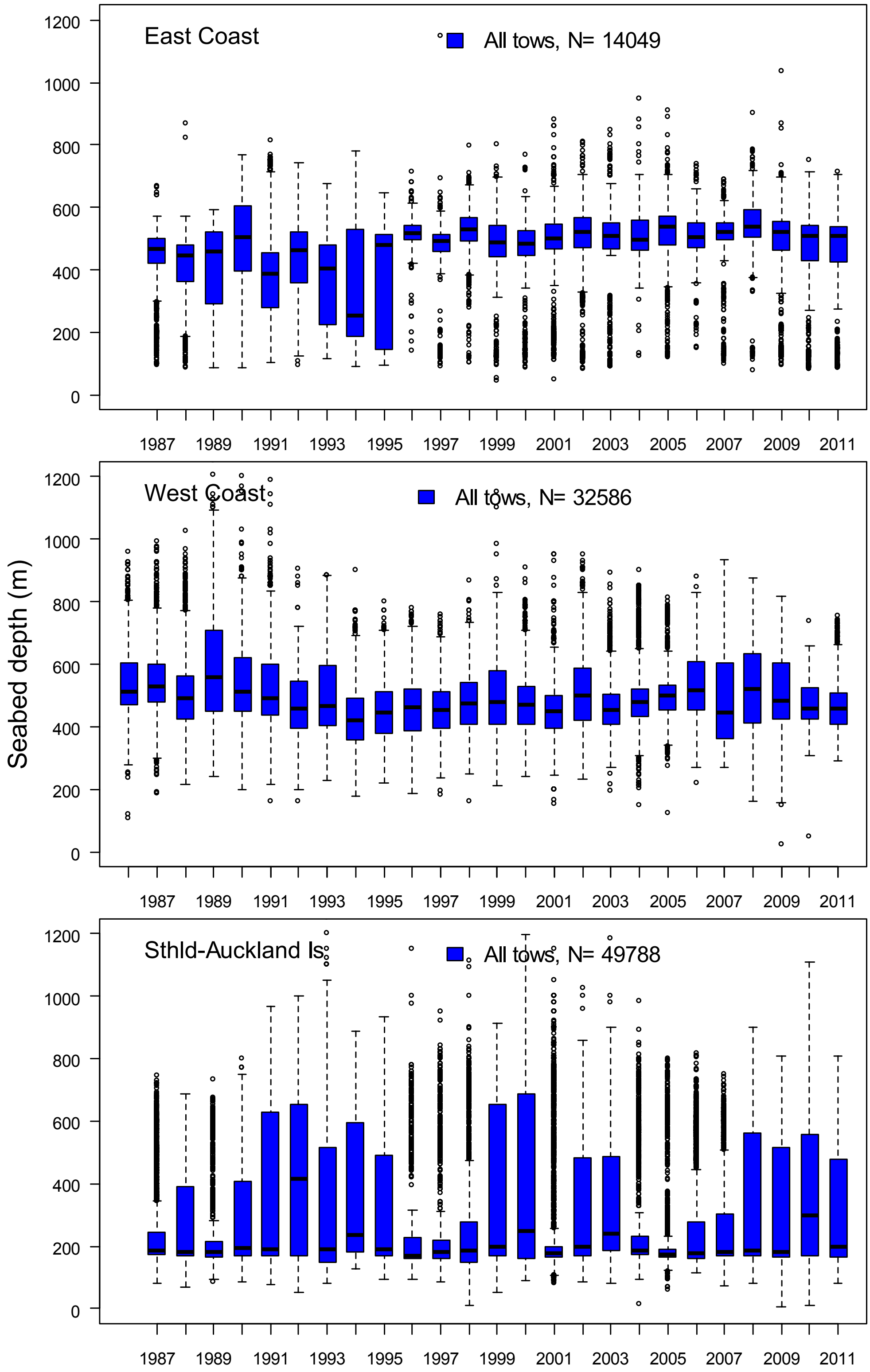

Figure 18. Time series of seabed depth at the start of the tow for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is. See Figure 7 caption for explanation.

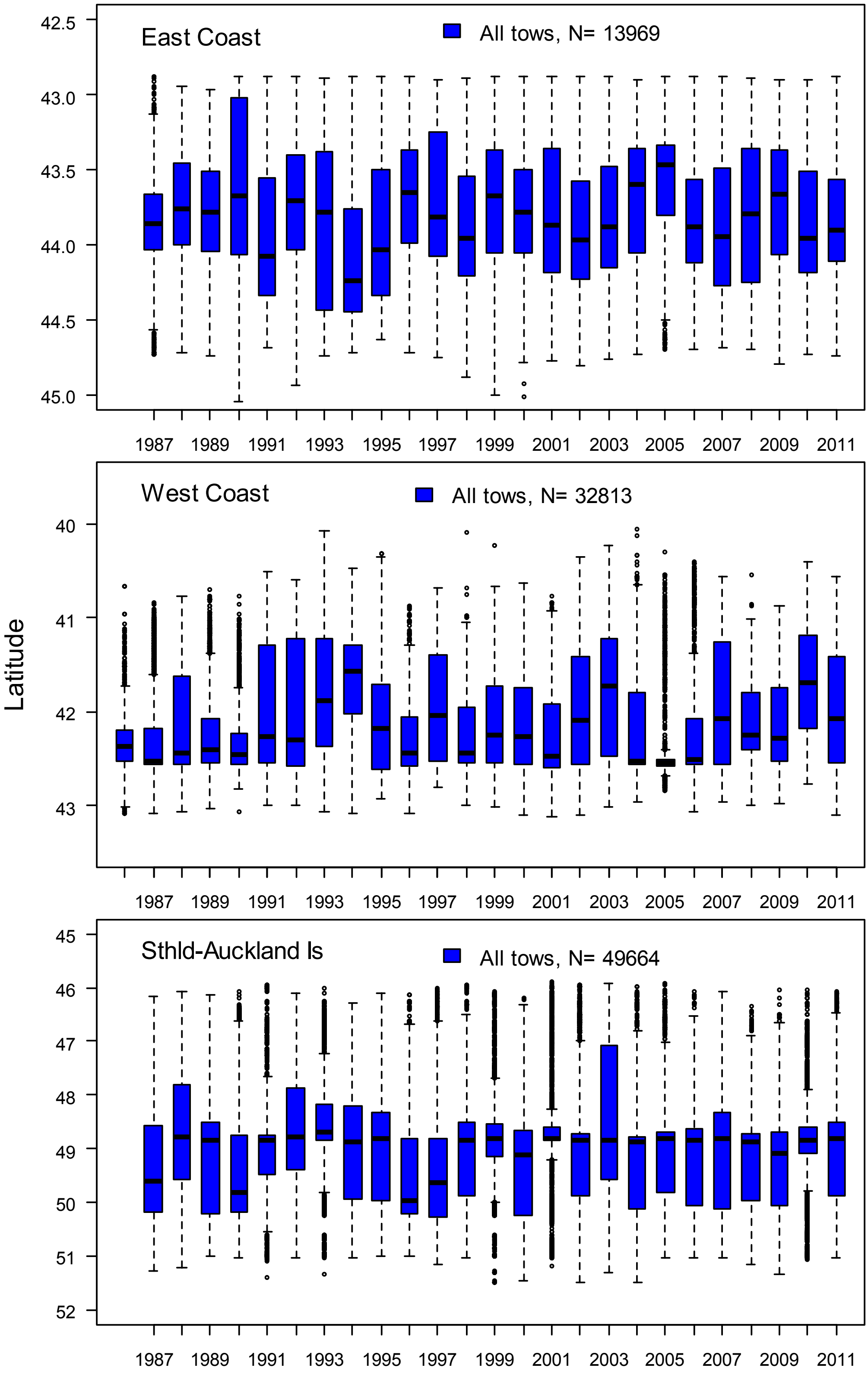

Figure 19. Time series of latitude for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is. See Figure 7 caption for explanation.

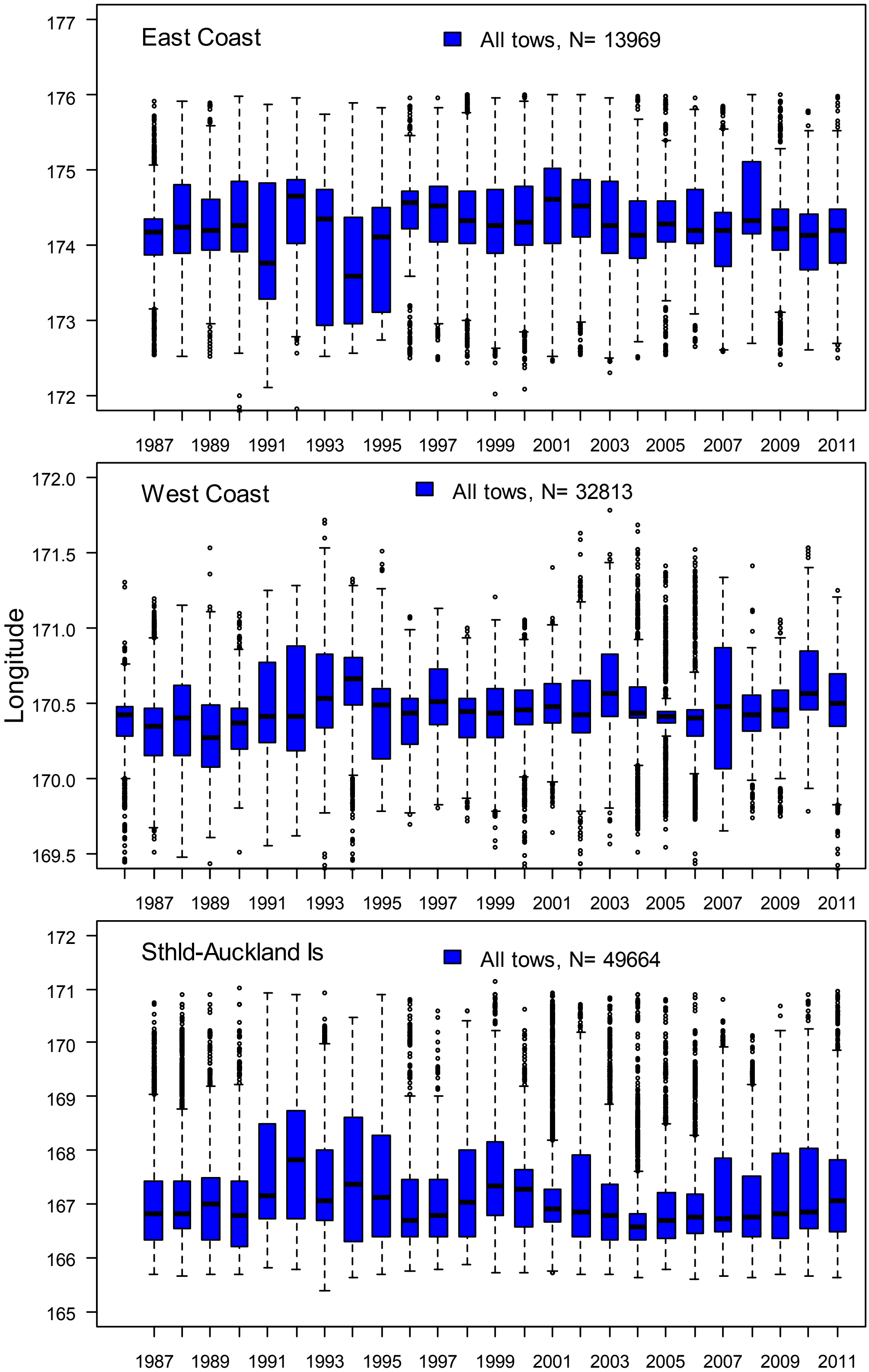

Figure 20. Time series of longitude for all observed trawl tows in three fishery areas. Years are calendar years for West Coast and July−June years (labelled as the greater of the two years) for East Coast and Southland−Auckland Is. See Figure 7 caption for explanation.

Discussion

Raw basking shark CPUE in observed trawl fisheries peaked in the late 1980s and early 1990s (Figure 2). Thereafter, CPUE was considerably lower but variable. In East Coast and West Coast fishery areas, CPUE has been zero for the last seven and six years respectively. Explanations for changes in raw CPUE must discriminate between the period of high catch rates before 1993 and low to moderate catch rates since then.

A strong and highly significant association was found between the numbers of sharks caught and vessel nationality in all three fishery areas. This was due to relatively large numbers of sharks being caught by Japanese vessels in the late 1980s and early 1990s. Korean, New Zealand and USSR vessels all caught fewer sharks than would be expected from their fishing effort. Polish vessels caught more sharks than expected in West Coast, but did not make many tows so this result may be spurious.

Fluctuations in CPUE were not correlated with any of the environmental or operational variables tested. This was not unexpected, given the extreme fluctuations in CPUE. West Coast water temperature indices all trended upwards over the time period studied, but there were no abrupt changes that might explain the CPUE patterns. The other two fishery areas, which showed similar highly variable CPUE patterns to West Coast, did not experience the same SST warming trend (though they did show an increase in SSH).

CPUE patterns were not correlated with any of the operational variables either. Increases in some vessel and trawl gear parameters, for example vessel length, headline height, tow speed and tow duration, might be expected to increase catches of basking sharks. However this was not observed overall. Japanese vessels were no longer than Polish or USSR vessels, and in East Coast and Southland–Auckland Is Japanese vessels had smaller headline heights than those of some other nations. Tow speed and duration did not appear to affect the chances of catching sharks, except in Southland–Auckland Is where Korean, New Zealand and Polish vessels (but not Japanese or USSR vessels) tended to catch sharks in longer tows.

Spatial variables appeared to influence shark catches in some fishery areas. In West Coast, sharks were usually caught at the deeper end of the towed depth range. In East Coast, sharks were caught in the south-west of the fished area and in Southland–Auckland Is sharks were caught mainly in the western part of the fishery area.

Nevertheless, temporal trends in the seven operational variables did not explain variations in shark catch rates. Tow speed and duration increased through time in some areas but were not associated with increased catches. Increased headline heights in the East Coast area during the mid 1990s coincided with very low shark catch rates. Depth of tow, and latitude and longitude showed no temporal patterns that might explain the variation in catch rates.

Our attempt to fit GLMs to the data were unsuccessful. This was likely due to the short lengths of the CPUE time series (24–26 years) and consequent low degrees of freedom for the analyses. Improved analyses could be carried out by incorporating the new variables examined here into Bayesian predictive hierarchical models fitted to individual tows (rather than annual indices) as done by Francis & Smith (2010), but such work was beyond the scope of this project.

There may be several explanations for the strong association found between vessel nationality and shark CPUE. Japanese vessels may have targeted (or at least not avoided) basking sharks in East Coast during the early 1980s. The sharks were visible on the seabed on echosounders,and when caught their livers were removed and processed for their oil (Francis & Duffy 2002). Such targeting may have continued through into the late 1980s when the data series used in this study began. Alternatively, the high catch rates of basking sharks in the late 1980s and early 1990s may reflect high shark abundance. Many observations of surface schools of sharks have been reported from the area off Banks Peninsula during that period (Francis & Duffy 2002) but such sightings have virtually ceased in the last decade. Department of Conservation aerial surveys for Hector's dolphins have failed to see basking sharks in recent years (C. Duffy, DoC, pers. comm.). Thus there may have been a real decline in aggregations of basking sharks in this area over the last 30 years; whether this is a result of a decline in population abundance or migration of sharks to some other region is not known.

Conclusions

Vessel nationality, and a range of environmental, vessel and gear variables were examined for evidence of association with basking shark bycatch rates. A strong and highly significant association was found between the numbers of sharks caught and vessel nationality in all three fishery areas. This was due to relatively large numbers of sharks being caught by Japanese vessels in the late 1980s and early 1990s. Other variables examined were not correlated with shark catch rates. Reasons for the high catch rates of basking sharks by Japanese trawlers are unknown, but may relate to targeting of the sharks for their liver oil, or a high abundance of sharks in the late 1980s and early 1990s.

Acknowledgments

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