Acoustic monitoring of large whales in deep waters north and west of the British Isles: 1996 - 2005

PRELIMINARY REPORT

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Summary

For ten years beginning 1 October 1996, the songs of blue, fin, and humpback whales (*Balaenoptera musculus*, *B. physalus*, and *Megaptera novaeangliae*) were monitored in twelve large overlapping regions north and west of Britain and Ireland, using bottom-mounted hydrophone arrays operated by the US Navy. The regions monitored cover a latitudinal range of approximately 2300 km, from 42°N to 63°N, an area of more than 1 million km^2. The objectives of this study were (1) to describe and quantify the seasonal occurrence of song of blue, fin, and humpback whales in 12 deep-water monitoring areas adjacent to the continental shelf break west of the British Isles, and (2) to identify any significant long-term trends in rates of acoustic detections of blue, fin, or humpback whales in these regions. This report provides a preliminary overview and summary of the data collected in this study. Further analyses of these data and comparisons with results of recent visual sighting surveys are planned.

On one to five days during each week, an expert analyst examined sound spectrograms that displayed 24 hours of beamformed acoustic data from hydrophone arrays that monitored each region. Songs of blue, fin, and humpback whales were identified by their distinctive spectrographic signatures. For each day of data collection, an "acoustic detection density" was calculated for each species, which provides a relative measure of acoustic activity. The minimum number of whales of each species that was detected in each day of monitoring in each region was also calculated. Average acoustic detection densities and minimum numbers of whales detected are reported for successive ten-day sampling bins.

Acoustic detections of blue, fin, and humpback whales all displayed distinct annual cycles in all monitoring regions, which were consistent from year to year. Fin whale songs were the most frequently detected signals, occurring in all regions in every month of the year for which data are available. Highest detection densities for fin whales occurred in December and January. Fin whale acoustic detections declined steadily from February to minimal levels in May and June, and then gradually increased from July through the autumn to the following winter peak. No clear evidence of large-scale seasonal migratory movements was observed for fin whales. Over the ten-year study period, the annual peak value of fin whale acoustic detections showed a slight but significant negative trend in eight of the monitoring regions. Although these data suggest the possibility that acoustic activity of fin whales has declined in these regions, we regard the analyses presented here as preliminary and inconclusive, primarily because periods of data outage in each year complicate our interpretation. Further analyses of existing data are planned in order to develop more statistically robust and reliable estimates of true trends in vocal activity.

Blue whales were the second most common species detected, and were detected in all regions, with peak detection densities in November and December in most regions, declining through late winter and early spring to minimal levels in April through June. Blue whale detections increased gradually from mid-July. Most blue whales that could be tracked through the monitoring area during the fall and winter months moved in a southerly direction. During April through June, small numbers of blue whale signals were detected to the west of the reporting region, moving northward. Peak annual detection densities of blue whales did not show any consistent trend over the ten-year study.

Humpback whales were the least frequently detected species overall, occurring mainly in the eight northern monitoring regions, from October through April. There was a north to south progression in the timing of humpback acoustic detections over the four northern pairs of monitoring regions, from January, through February, and into March. This progression, coupled with data on individual humpbacks that were tracked through the monitoring area, suggest that most humpbacks detected were passing through this area in a seasonal migration, most likely *en route* to breeding areas in the West Indies. No returning northward migration of humpbacks was detected, suggesting either that northbound humpbacks do not sing or that they follow a route that does not pass through the monitoring area or both. Peak annual detection densities of humpback whales did not show any consistent trend over the ten-year study.

This study constitutes the most extensive survey of acoustic activity of large whales ever undertaken in the eastern north Atlantic, sampling more than one million square kilometres on a weekly basis for ten years. This work has demonstrated consistent presence of blue, fin, and humpback whales in regions and at times of year where they were not previously known to occur. The annual peak detection periods for all three species occurred during months when few visual cetacean surveys have been conducted in these areas due to poor weather conditions. Continued long-term collection of such data could enable detection of changes in whale populations. Coupled with data on oceanographic, meteorological, and productivity conditions, long-term acoustic monitoring data may yield new insights into how such environmental variables influence the distribution of whale populations in space and time.

Introduction

In recent years, concerns have been expressed regarding the possible effects on cetaceans of the high-intensity underwater sounds generated by seismic airgun arrays (*e.g.*, National Research Council 1994, Murray and Simmonds 1998, Gordon *et al.* 2003). Seismic profiling typically relies on an array of airguns towed behind a survey ship. The airgun array produces short, high-intensity pulses of broadband acoustic energy at regular intervals (often at intervals of 10 s or less) to probe the structure of the earth's crust in order to locate undersea oil and gas deposits. Airgun arrays release significant acoustic energy at frequencies up to 500 to 1000 Hz, with most energy in the < 100 Hz frequency band (Richardson *et al.* 1995). These high-intensity, low-frequency sounds propagate very efficiently underwater and can easily be detected over hundreds of kilometres.

Baleen whales, which vocalise within this same frequency range, are thought to have good hearing in this band, and thus may be vulnerable to disturbance by these sounds (Ketten 1992, 1994; Gordon *et al.* 2003). Disturbance or avoidance reactions to seismic exploration sounds have been documented in gray, bowhead, humpback, and blue whales (*Eschrictius robustus, Balaena mysticetus*; *Megaptera novaeangliae* , and *Balaenoptera musculus*, studies summarised by Richardson *et al.* 1995 and Gordon *et al.* 2003). The low-frequency sounds of baleen whales are thought to function in within-species communication (*e.g.*, Watkins *et al.* 1987, Helweg *et al.* 1992, Clark 1990) and possibly navigation (Clark and Ellison 2003). Disruption of such biologically important functions could adversely affect the reproductive success of individuals and eventually the size of populations.

In order to assess and mitigate any potential impacts of seismic exploration on cetaceans, a critical requirement is accurate information on the geographic and temporal distribution of the animals. The usual approach to acquiring such data is by ship-based visual surveys, in which observers identify and count animals seen during dedicated line-transect surveys or from vessels of opportunity (*e.g.*, Barlow 1995; Stone 1998, 2001, 2006; Murray and Simmonds 1998). However, visual methods of surveying whale distributions suffer from restrictions that limit their geographic and temporal scope. Visual surveys can only be conducted in a limited range of sea states and atmospheric (visibility) conditions, which prohibits surveys during many seasons and throughout many regions. Visual methods can only detect animals when they are at the surface (a small percentage of the time) during daylight hours. A survey vessel can monitor only a small area within visual range (a few km), so it is impractical to achieve a high level of sampling coverage in a large region where distributions of animals may be patchy. It is therefore difficult to quantify large-scale temporal and spatial variability of marine mammal distributions using visual survey data alone.

For several species of baleen whales, passive acoustic monitoring overcomes some of the limitations of visual cetacean surveys because acoustic monitoring can be conducted 24 hours per day, year-round in a wide range of surface weather conditions, and vocalising whales can commonly be detected at ranges exceeding the best visual detection limits by at least an order of magnitude (Clark and Ellison 1989, Clark *et al.* 1996). Bottom-mounted hydrophone arrays that are part of the US Navy's SOund SUrveillance System (SOSUS) have been used to detect and track humpback, blue, and fin whales (Clark 1995, Abileah *et al.* 1996, Stafford *et al.* 1998, Moore *et al.* 1998, Watkins *et al.* 2000, Charif and Clark 2000, Charif *et al.* 2001, Clark and Gagnon 2002), at ranges of several hundred kilometres or more.

The region along the edge of the continental shelf to the north and west of Scotland— known as the Atlantic Frontier— has been an area of intensive seismic exploration for oil and gas deposits in recent years. Concerns about possible effects of oil and gas exploration and development on marine mammals on the Atlantic Frontier were summarised by Harwood and Wilson (2001). Because of such concerns, several visual cetacean surveys have been undertaken in the Atlantic Frontier and have yielded new information on cetacean distributions (Murray and Simmonds 1998, Stone 1998, 2000, 2001, 2006, Pollock, *et al.* 2000). To complement information on whale distribution available from visual surveys in the region, a passive acoustic monitoring programme was initiated with funding from the oil and gas industry in late 1996. The project uses SOSUS arrays, operated by the US Navy, to monitor vocalisations of blue, fin, and humpback whales.

The objectives of this study were (1) to describe and quantify the seasonal occurrence of song of blue, fin, and humpback whales in 12 deep-water monitoring areas adjacent to the continental shelf break west of the British Isles, and (2) to identify any significant long-term trends in rates of acoustic detections of blue, fin, or humpback whales in these regions.

This preliminary report updates the early report of Charif and Clark (2000), and provides a high-level overview based on the analysis of ten years of acoustic monitoring data from this programme, with emphasis on the typical geographic and seasonal patterns of acoustic whale detections, and the possibility of long-term trends in vocal activity.

Methods

Background and geographic scope

Twelve large overlapping regions north and west of Britain and Ireland were monitored using SOSUS arrays operated by the US Navy (Figure 1). These regions cover a latitudinal range of approximately 2300 km, from 42°N to 63°N, and an area of more than 1 million km^2. The regions are arranged in six pairs, with each pair consisting of an eastern and a western region located at approximately the same latitude. Each region was identified by an alphanumeric label, such as A1, A2, B1, B2, etc.; in all cases, 1 is the western and 2 the eastern portion of the region. Pairs of east-west adjacent regions are identified by letters only (*e.g.*, Region A refers to A1 + A2). The eastern region of each pair encompasses deep water immediately adjacent to the continental shelf. Although the regions as shown in Figure 1 include some areas of relatively shallow water (< 500 m), detections of whale sounds by SOSUS are restricted to deeper areas within these regions. Each region is monitored by one or more SOSUS arrays. Although the reporting regions are depicted as being elliptical with sharp boundaries, the shapes and boundary locations shown in Figure 1 should be considered approximate. The number and locations of the hydrophone arrays used cannot be reported because of military security restrictions.

Acoustic data from the arrays were transmitted to an onshore facility in the UK. Digitized data from each array were processed by a beam-forming algorithm that separated sounds arriving at the array from discrete angular sectors, or "beams," centered on different bearings. The widths of beams varied, with beams close to the axis of the array being relatively wide, and beams close to the perpendicular being narrower. Sounds from different beams were displayed on a computer workstation as multi-channel sound spectrograms. An experienced analyst visually identified vocalisations of blue, fin, and humpback whales in the monitoring area by their distinctive spectrographic signatures (Figure 2). A call from any given whale appeared most clearly on the beam corresponding to the bearing from the receiving array to the whale. Since spectrograms of multiple beams were displayed side by side, whales located in different directions from the array that were vocalising at the same time could easily be distinguished. Calls from whales that were very close to an array could appear on many adjacent beams. In this case, the analyst made a judgment as to which beam most closely pointed toward the whale.

Blue, fin, and humpback whales all typically produce long structured sequences of vocalisations, termed *songs*, that continue for periods of one to many hours. Successive notes within a song are typically separated by a few seconds to several minutes. In all three species, song appears to be produced only by males and to function in reproduction (Helweg et al. 1992, Croll et al. 2002, Oleson et al. 2007). In addition to song, males and females both produce a variety of shorter, more variable, less structured vocalisations that appear to function in short-range social interactions (e.g., Thompson et al. 1992, Oleson et al. 2007, Dunlop et al. 2008). However, these less structured social sounds cannot be as consistently and reliably identified by the system used here, and were not monitored for this study. Hence all of the sounds reported here are presumed to be produced by male whales.

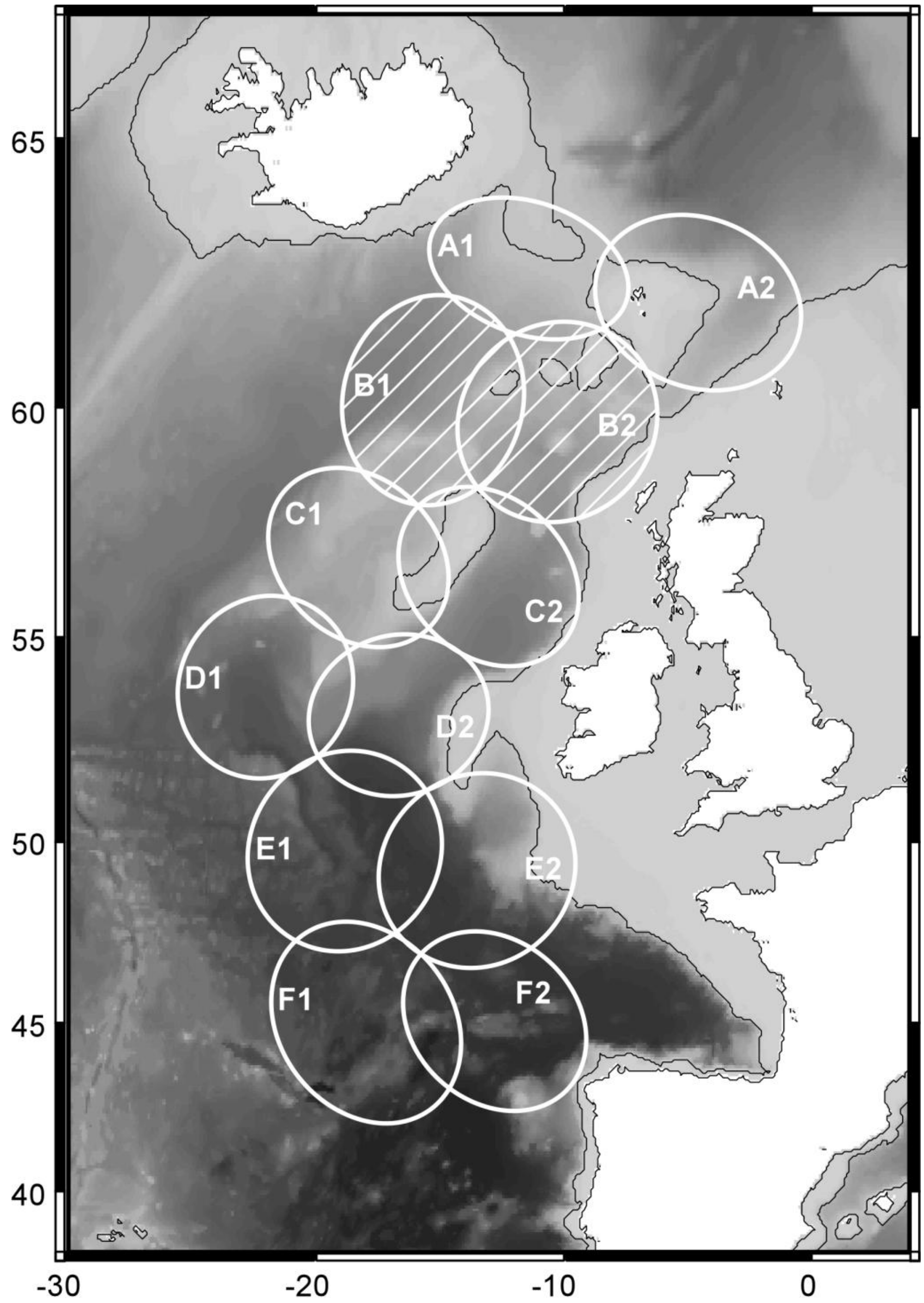

Figure 1. Regions monitored for whale vocalisations using passive acoustic arrays. The edge of the continental shelf is indicated by the 500 m depth contour. Increasing depth is indicated by darker grey shading. Regions B1 and B2 are hatched to indicate that acoustic detection data from these regions are negatively biased relative to the other monitoring regions.

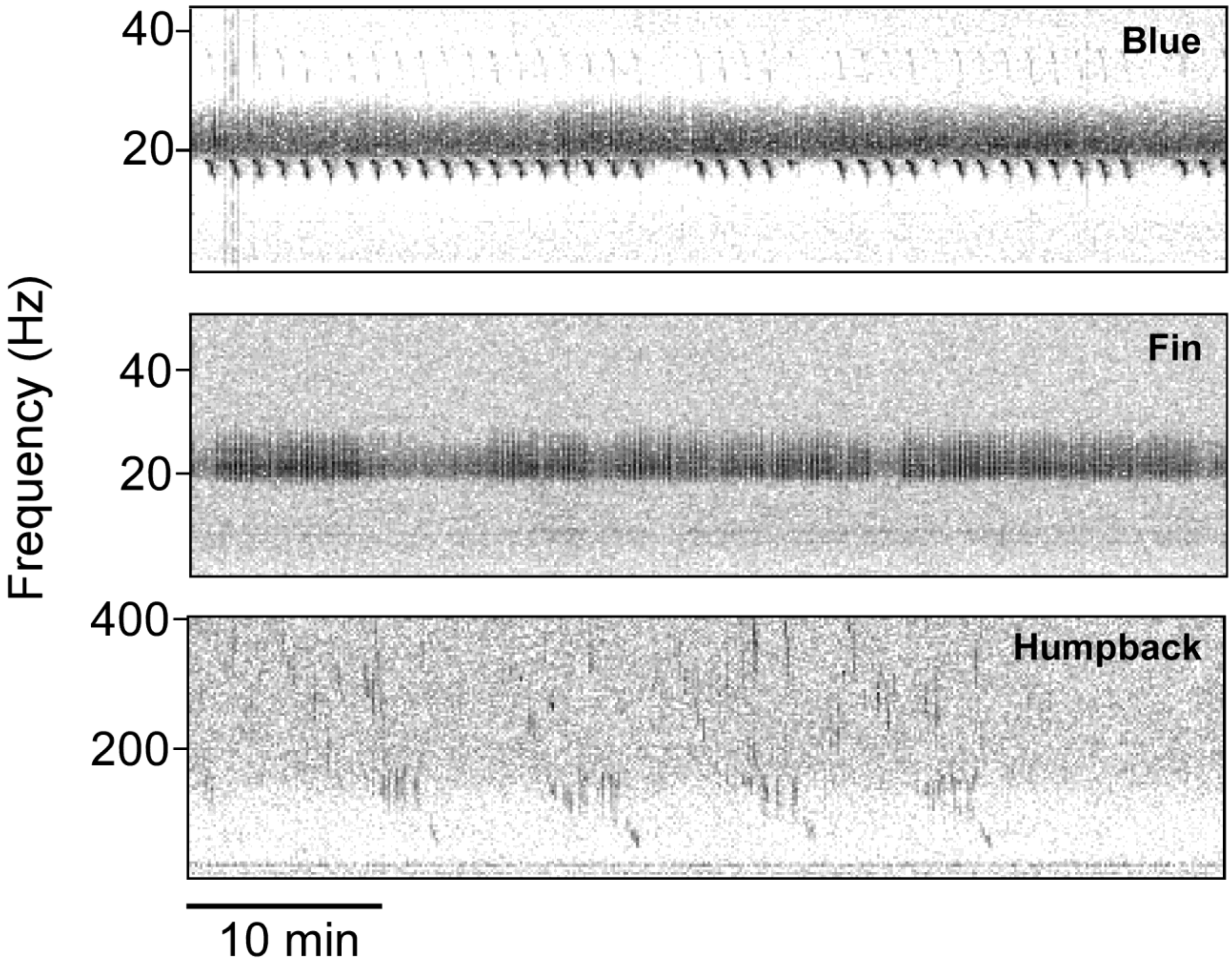

Figure 2. Sound spectrograms of typical vocalisations from three baleen whale species monitored during this study.

In most cases a continuous sequence of song elements can readily be identified as coming from a single whale. It was generally not possible to determine whether two song sequences that were coming from the same beam direction and separated in time by an hour or more of silence were produced by one whale or by two. Two or three whales that were calling simultaneously on a single beam could usually be distinguished.

Data collection

This report summarises data collected during the ten year period beginning on 1 October 1996 and ending on 30 September 2005. Data are presented here in year-long sets. Thus, Year 1 is 1 October 1996 through 30 September 1997, and so on. On one to five days (typically one or two) during each week, the analyst examined sound spectrograms that displayed 24 hours of data from selected directional beams of hydrophone arrays that monitor the regions shown in Figure 1. Songs of blue, fin, and humpback whales were identified, and detections of each species were logged. From October 1996 through February 2004, detections were logged on machine-scannable paper forms that record the number of whales detected on each beam in each hour of a day. Beginning in March 2004, detections were logged in a specially designed Excel spreadsheet. Completed data forms or spreadsheets were sent to the Bioacoustics Research Program (BRP) at Cornell University once per month, along with a qualitative summary of conditions and whale vocal activity during the preceding month. At Cornell, the paper forms were reviewed for errors and electronically scanned, and the data were merged into a cumulative detection file. Data were extracted from the spreadsheets and added to the growing detection file.

Data analysis

Assignment of detections to regions

Detections from each beam were assigned to one of the twelve monitoring regions, depending on the location of the array, and the direction in which that beam points (Figure 3). Some regions were monitored by beams from more than one array.

A few beams are positioned such that they point through one region into another. Whales detected on these beams could be in either the nearer or the farther region, since the range to a detected whale is generally unknown. Detections from these beams were split between the two regions, and one half of a detection value was assigned to each region.

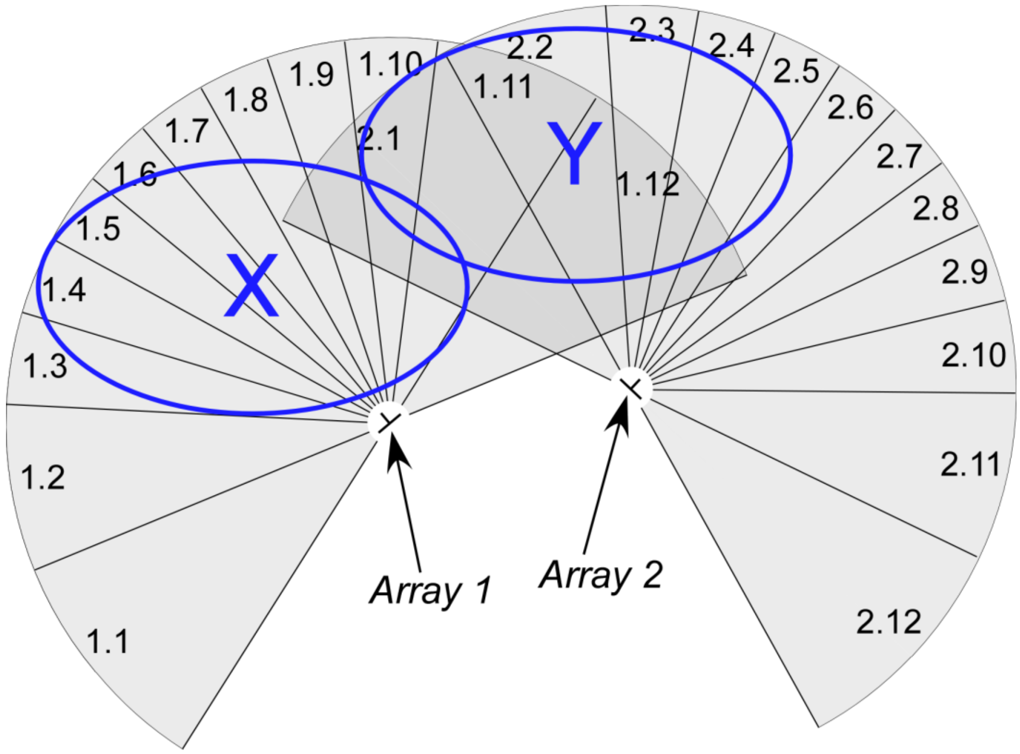

Figure 3. Hypothetical example illustrating determination of spatial sampling effort. Two arrays are shown, each with 12 beams; beams vary in width from 10° to 35°. Region X is monitored by nine beams from Array 1 (beams 1.3 - 1.11). The total angular space sampled in Region X is 120°. Region Y is monitored by three beams from Array 1 (beams 1.10 - 1.12, totaling 74°), and five beams from Array 2 (beams 2.1 - 2.5, totaling 97). The total angular space sampled in Region Y is thus 171° (= 74° + 97°). The acoustic detection density normalizes the acoustic detection data from each region to adjust for such differences in spatial sampling effort (see Methods).

Estimates of the daily minimum number of whales singing

A precise count of the number of whales detected in a region over many hours was not possible because we could not reliably determine whether two song sequences separated by several hours of silence were from one whale or two whales. However, we could reliably count the number of whales detected by an array in any one hour, provided that they were in different directions from the array, as evidenced by the songs from different whales appearing on different beams. On the rare occasions when two or more whales were singing simultaneously in the same beam space (and therefore appearing on the same beam), they could usually be distinguished by differences in the clarity, pattern and intensity of the displayed songs (resulting from differences in distance between the whales and the array, and differences in the way songs are sung). For each day sampled for each region, we used the maximum number of whales detected in any hour on any array monitoring that region as an estimate of the minimum number of whales detected in that region for that day. For each species in each region, we report the daily minimum number of whales detected for successive 10-

day sampling bins beginning 1 October of each year of data collection. By this procedure the daily minimum is a conservative estimate of whales in that region for that day.

The daily minimum number of whales detected in a region has two limitations as an index of whale abundance or vocal activity. First, the minimum whale count has a small and regionally variable upper limit. The number of whales likely to be counted simultaneously in any one region is a function of the number of beams in the largest sector monitored by a single array in that region. For example, if Region X is monitored by five beams from Array 1 and nine beams from Array 2, it would be increasingly difficult to count individual whales per hour as the actual number of calling animals in the region approached and then exceeded nine (one on each beam of Array 2). When this occurs, we say that our ability to identify individual whales in the region has become “saturated.” Since the maximum number of beams per any one array varies among regions, the saturation value of the minimum whale count also varies. Thus, minimum whale counts from different regions are not comparable.

Second, as an indicator of variations in whale vocal activity, the daily minimum number of whales detected relies on data from only one hour out of 24 in each day— *i.e.*, the hour that had the maximum number of whales calling simultaneously. Such reliance on a single value makes this measure more vulnerable to sampling error than a measure based on multiple values.

Nevertheless, the daily minimum whale count in a region can be useful for comparisons over time within a region, provided that the number of whales is small enough that the region is not saturated with whales.

Relative acoustic detection density

In order to compare relative levels of whale vocal activity across regions, we calculated an *acoustic detection density* (henceforth “detection density”) for each species for each day. Unlike the minimum whale counts described above, the acoustic detection density uses all of the data collected throughout a day in a given region. The detection density is a measure of the amount of vocal activity detected in a region per unit of sampling effort over a given period of time. The amount of vocal activity detected is measured in units of *whale detection-hours* (henceforth “detection-hours”). The number of detection-hours in one region is the sum, over all beams monitoring the region, of all of the hourly whale counts for the period, and is not necessarily indicative of the number of whales detected (which typically is unknown). Thus, a region would score 10 detection-hours on a given day if one whale was detected in 10 different hours, or if 10 whales were each detected for only one hour, or if two whales each were detected for four hours and a third was detected for two hours, and so on.

The number of detection-hours during a sampling period is not an unbiased measure of the actual density of whale calls in an area, however, because the sampling effort is not uniformly distributed spatially over the twelve regions or temporally among sampling bins. Variation among regions occurred because regions were monitored by different numbers of beams (Figure 3). Variation over time occurred because various events (equipment outages, personnel schedules, etc.) resulted in differing numbers of hours monitored per ten-day bin. In calculating the detection density, we compensated for these variations by dividing the total number of detection-hours by a measure of spatial and temporal sampling effort for each region and sampling bin. For each region and 10-day bin, sampling effort was measured in "degree-hours," that is, degrees of arc monitored by all beams that contributed data to that region, times the number of hours of data that were available. This hourly detection density is then multiplied by 24 to convert it to an average daily value. Thus, for a given 10-day bin, the acoustic detection density for a region is calculated as

$$acoustic\,detection\,density = 24 \cdot \left(\frac{\sum detectionHours}{\sum degreeHours\ sampled} \right)$$

The acoustic detection density, in units of whale detection-hours per degree-day, provides a useful normalized measure for comparing the temporal and spatial density of whale vocal activity at different times and in different regions. However, there is one exception to this comparability across regions. Because of differences in data collection and processing in Regions B1 and B2, whale sounds are less detectable in these regions than in other regions. We thus expect detection densities in these two regions to be negatively biased relative to other regions. Data from Regions B1 and B2 are comparable to each other, however, and data from the other ten regions are also comparable to each other.

Long-term trends in vocal activity

To test for long-term trends in detection of whale vocal activity, we performed linear regressions of peak annual detection density for each species over the ten years of data collection in each region other than regions B1 and B2. Regressions were performed using JMP 7.0 statistical software (SAS Institute Inc.).

Results

Data availability

In all years, data were unavailable for some 10-day bins in each region, either as a result of equipment problems or analyst absences. Hence the number of years for which data are available varies by region and sampling bin. Figure 4 shows the number of years of data available for each 10-day bin in each region. Figure 5 shows the proportion of all sampling bins in all regions for which varying numbers of years of data are available. Data were successfully collected in all ten years for only 6.1 % of all bins in all regions (region-bins). Seven or more years of data were available for 72.1% of region-bins (seven years: 21.2%; eight years: 30.9%; nine years: 13.9%). 1.4% of regions-bins were sampled in only two years.

The number of days within a 10-day bin on which data were actually collected varied between zero and eight (Figure 6).

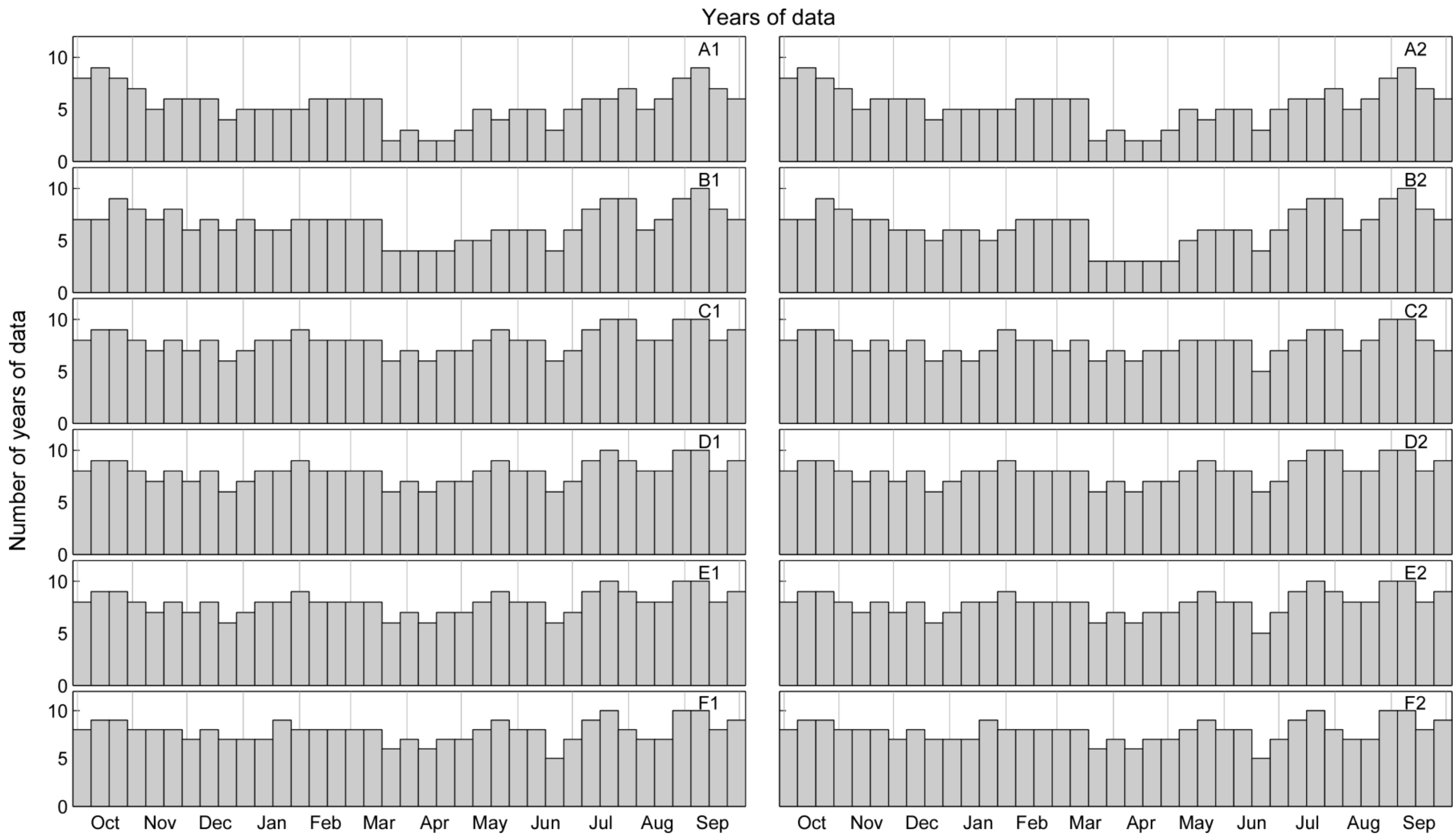

Figure 4. Number of years in which data were obtained for each 10-day sampling bin in each region. The faint grey lines in the background indicate month boundaries.

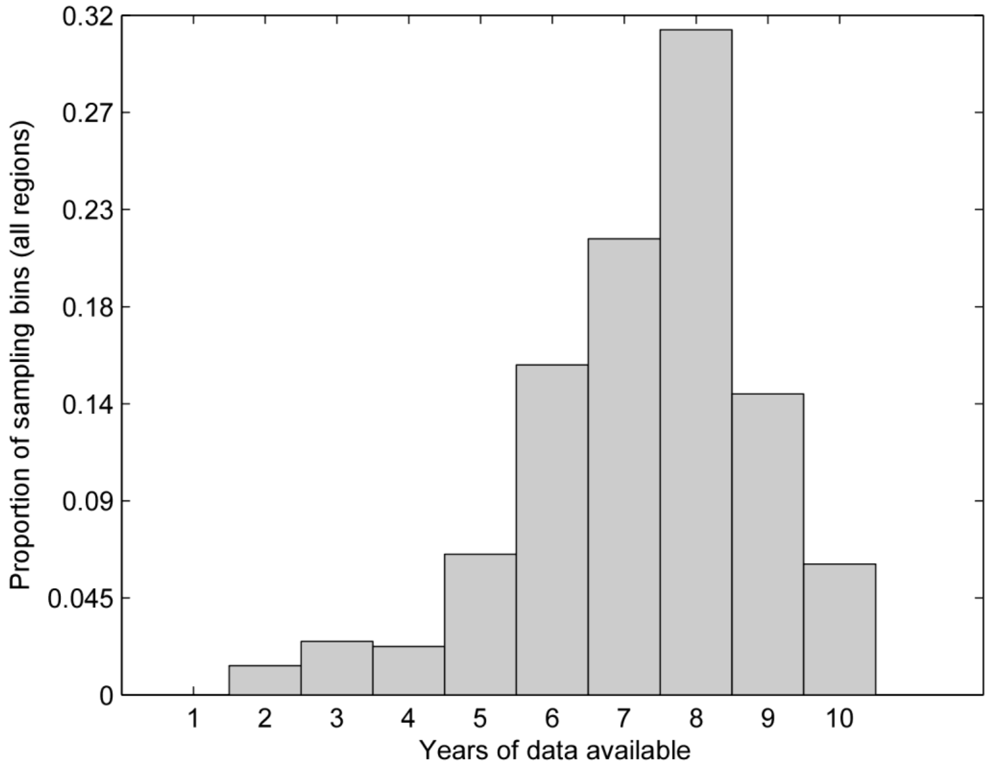

Figure 5. Proportion of all sampling bins in all regions for which varying numbers of years of data are available.

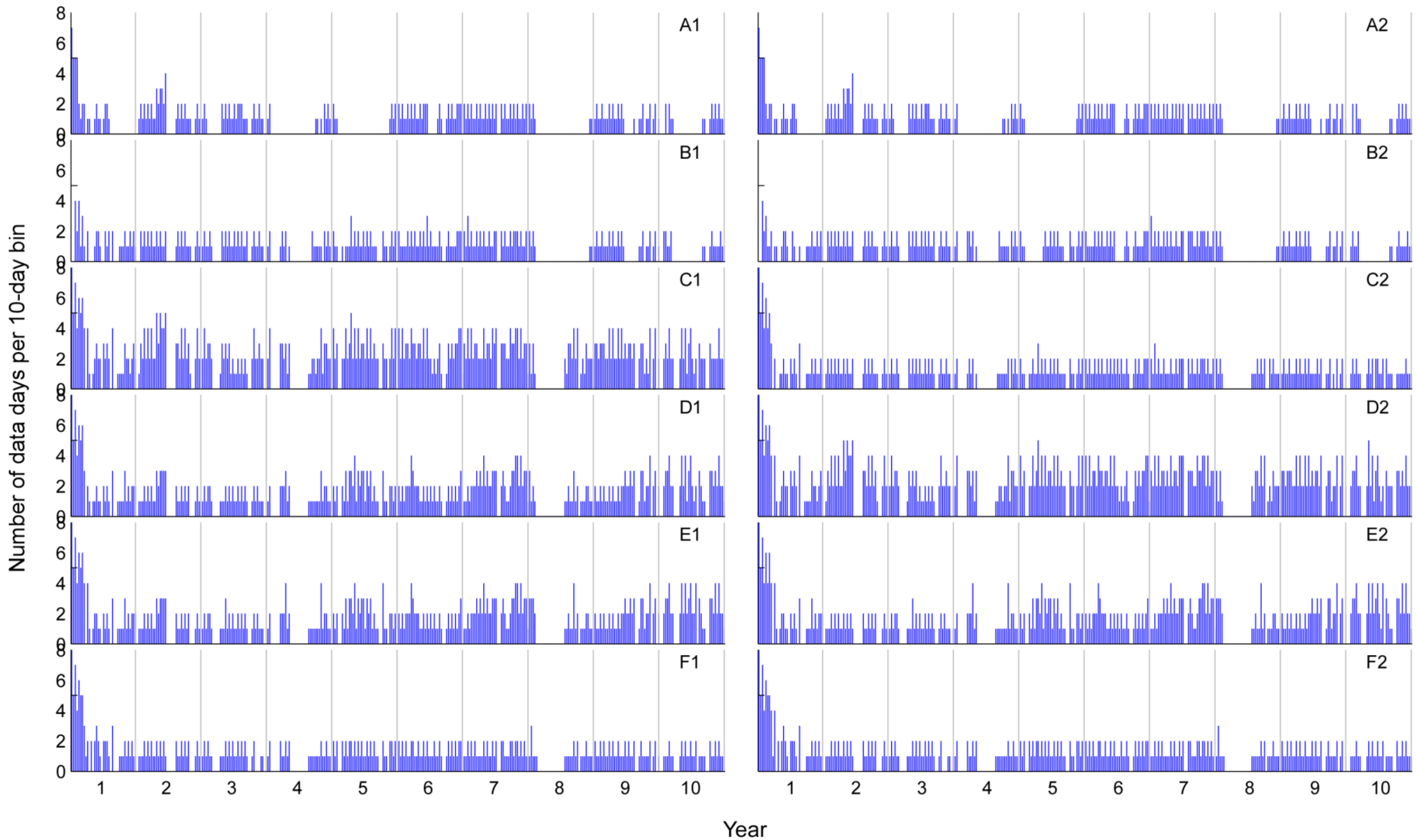

Figure 6. Number of days on which data were collected in each 10-day bin in each region.

Blue whales

Seasonal and geographic variation in vocal activity of blue whales

Blue whale sounds were detected in all regions, and in most sampling bins. Most regions displayed a similar pattern of seasonal variation in acoustic detection density (Figure 1), with peak detection densities in November and December followed by a gradual decline to minimal levels in April, May, and June. Detection densities began to increase again in July, gradually rising to the following winter peak. The one exception to this pattern was Region A2. Detection densities there, which were among the lowest of all regions at any time, dropped to zero in November and December in most years, when peak levels occurred elsewhere. As expected, acoustic detection densities were consistently lower in Regions B1 and B2 than in other regions, at least in part because of differences in the collection and processing of acoustic data in those regions.

The minimum number of blue whales detected also varied seasonally (Figure 8). However, seasonal variation in minimum number of blue whales detected was less pronounced than the variation in detection density (compare Figure 7 and Figure 8), as expected. The maximum number of blue whales ever detected simultaneously was nine, in Region C2 in November 1999.

Long-term trends in vocal activity of blue whales

Figure 9 shows the acoustic detection density for blue whales in all twelve regions as a ten-year time series. Figure 10 shows the same data in greater detail from Region C1 (the region with highest overall blue whale detection density) only, with a fitted spline to help visualize any upward or downward long-term trend in detection density. Linear regressions of annual peak detection density did not show any significant trend in any region (Table 1). Figure 11 shows an example of a least-squares linear regression of the annual peak detection densities against year for blue whales in Region E1 across all years.

Table 1. Trends in annual peak detection density for blue whales over ten years. *p* values indicate significance of slope ≠ 0.

Region	slope	R^2	*p*
A1	-0.0273	0.3539	0.0697
A2	-0.0110	0.0503	0.5333
C1	-0.0235	0.1475	0.2732
C2	-0.0076	0.0143	0.7417
D1	-0.0148	0.0510	0.5304
D2	0.0084	0.0182	0.7099
E1	-0.0025	0.0044	0.8551
E2	-0.0291	0.1760	0.2275
F1	0.0041	0.0038	0.8655
F2	0.0131	0.2948	0.1049

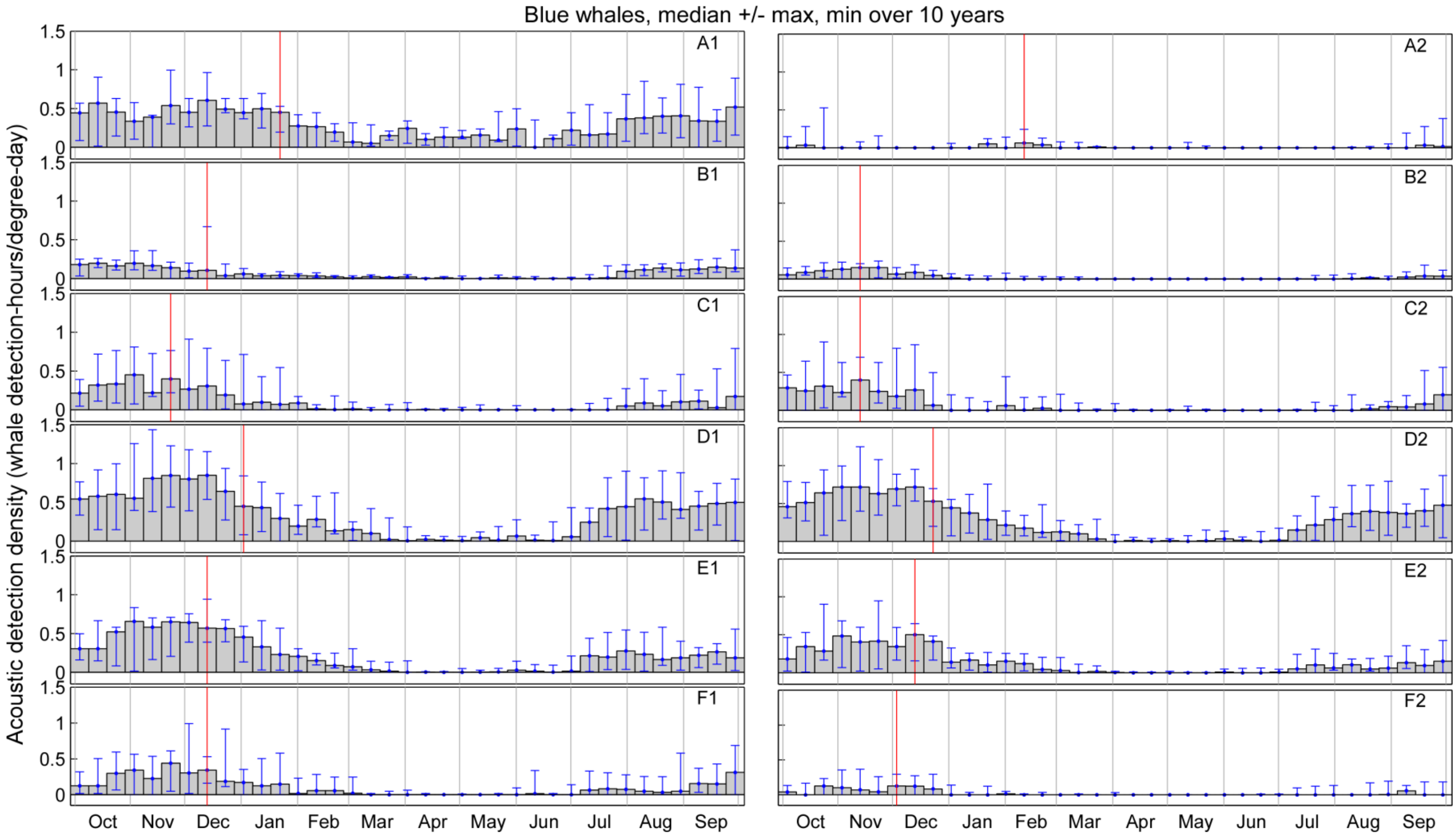

Figure 7. Daily acoustic detection density for blue whales during 10-day time blocks in each region. Bar heights give median values ± maximum and minimum values over the ten-year study. Vertical red lines indicate the median time of each year's distribution.

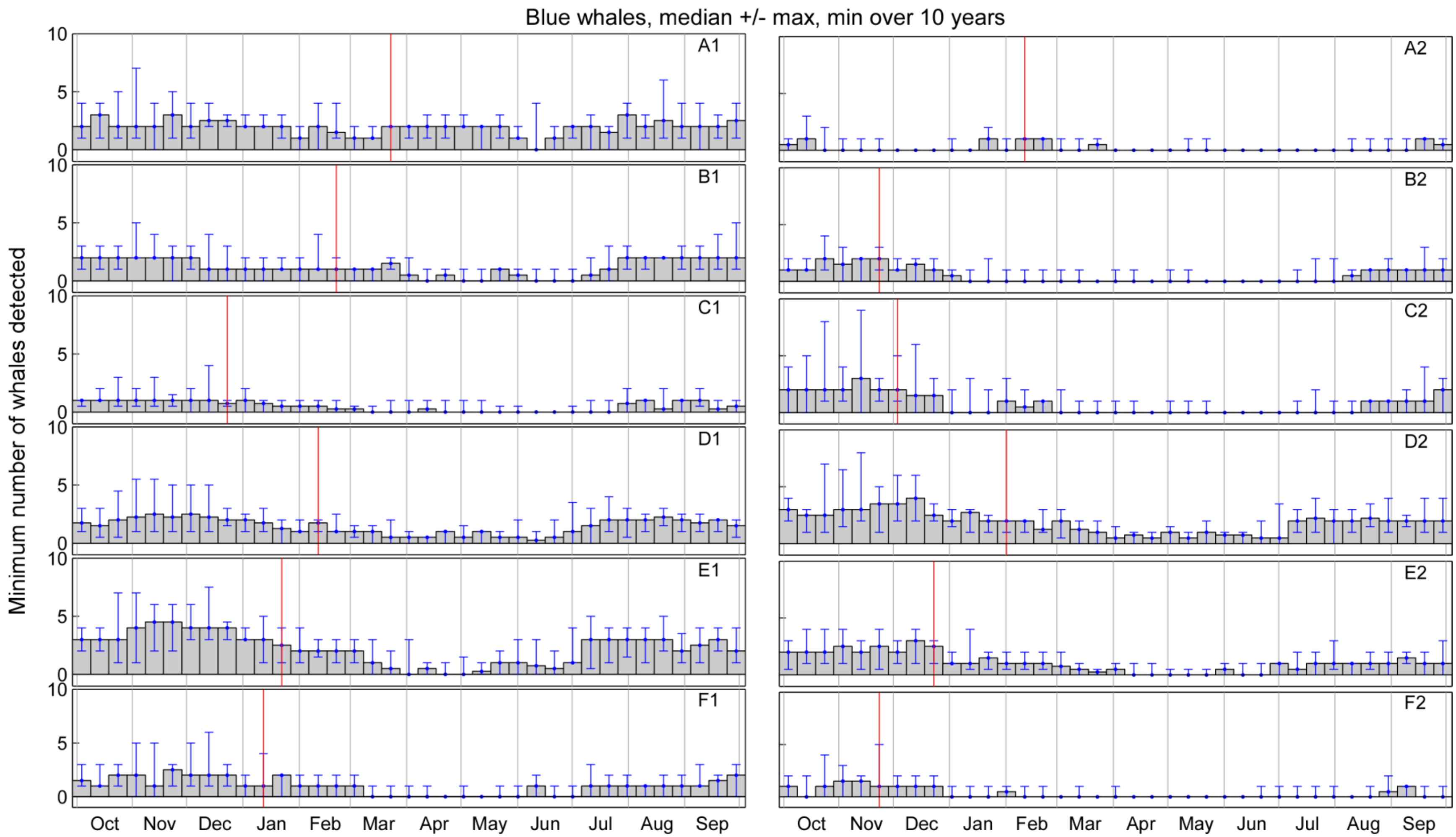

Figure 8. Minimum number of blue whales detected at any one time during 10-day time blocks in each region. Bar heights give median values ± maximum and minimum values over the ten-year study. Vertical red lines indicate the median time of each year's distribution.

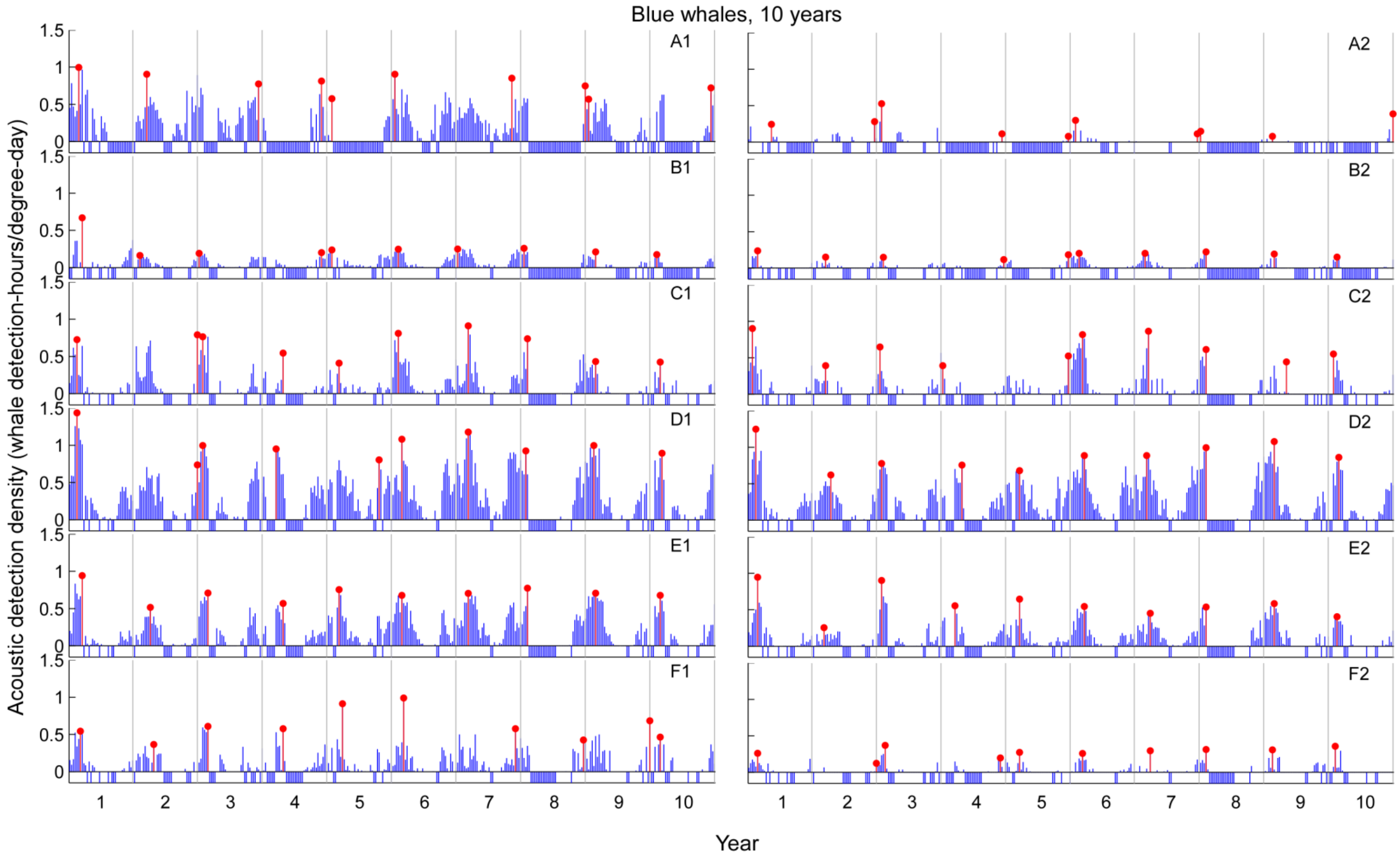

Figure 9. Ten-year time series of acoustic detection density for blue whales in twelve monitoring regions, 1 October 1996 – 30 September 2006. Each vertical bar represents one 10-day time period. Bars below the horizontal axis indicate periods for which no data are available. Vertical grey bars indicate the start of successive years of data collection. Red points indicate highest value in each year.

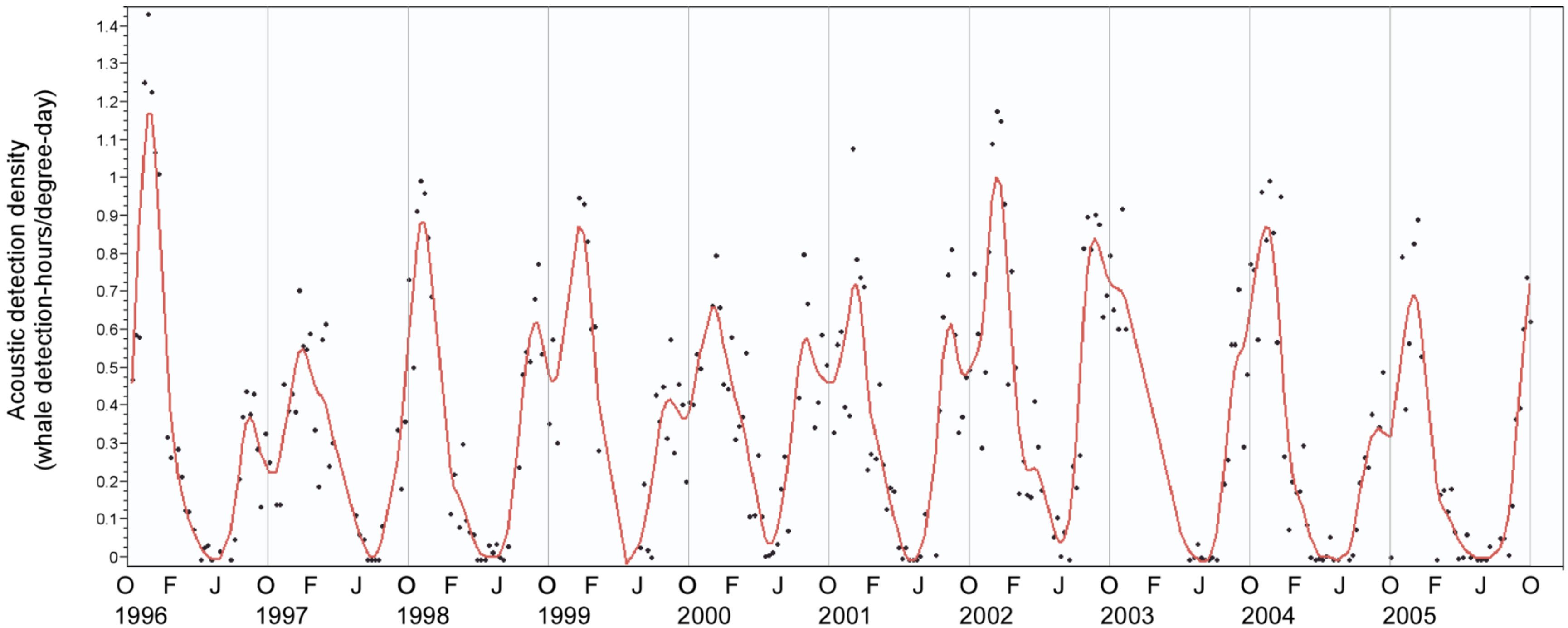

Figure 10. Ten-year time series of acoustic detection density for blue whales in Region E1. Each point represents one ten-day sampling bin. The curve is a fitted spline, with stiffness adjusted by eye. Horizontal axis labels indicate start of October, February, and June of each year.

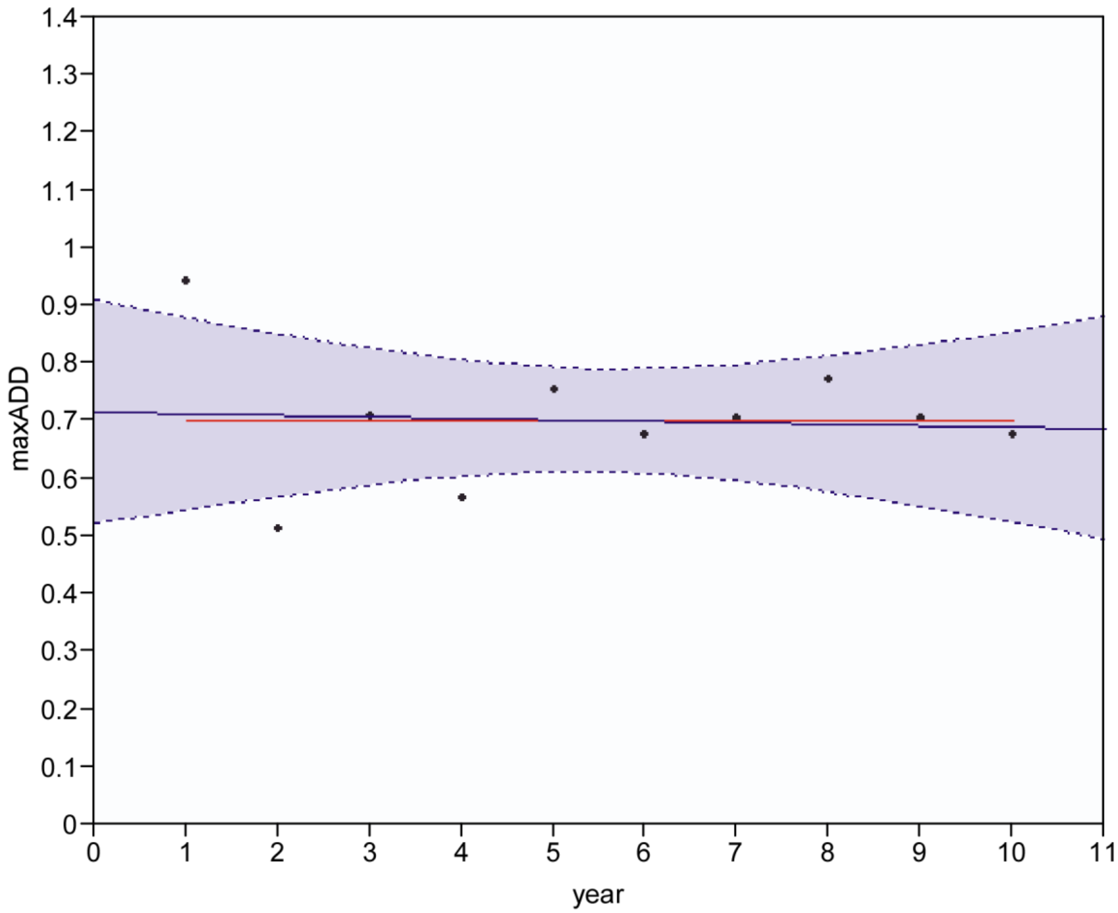

Figure 11. Annual peak acoustic detection density for blue whales in Region E1. The horizontal red line indicates the mean across all years. The blue line is a least-squares linear regression (R^2 = 0.0044); the shaded area is the 95% confidence interval. The slope of the fitted line is not significantly different from zero (*p* = .8551).

Fin whales

Seasonal and geographic variation in vocal activity of fin whales

Fin whale sounds were detected in all regions, with a similar pattern of seasonal variation in detection density across regions (Figure 12). Peak densities typically occurred in December and January, gradually declining through late winter and spring to minimal levels in May and June. Detection densities increased gradually from July through late summer and fall to the subsequent winter peak. Fin whale sounds were detected in at least one year in every sampling bin in every region, with the exception of one bin in July in Region A2 (Figure 13). The highest detection density occurred in Region C1.

Overall, there was only modest seasonal variation in the minimum number of fin whales detected (Figure 13). The maximum number of fin whales ever detected simultaneously was 12, in Region C2.

Long-term trends in vocal activity of fin whales

Figure 14 shows the acoustic detection density for fin whales in all twelve regions as a ten-year time series. Linear regressions of annual peak detection densities indicated a significant ($p < 0.05$) negative relationship between detection density and year in eight out of 10 regions examined (Table 2). In Regions F1 and F2, the slope of the regression was not significantly different from zero. Figure 15 shows the acoustic detection density data from Region C1 only (the region with highest overall fin whale detection density), with a fitted spline to help visualize the long-term trend in detection density. Figure 16 shows one example of a regression of annual peak detection density against year, for fin whales in Region D2 across all years.

Table 2. Trends in annual peak detection density for fin whales over ten years. *p* values indicate significance of slope ≠ 0. Significant trends in boldface.

Species	Region	slope	R^2	*p*
Fin	A1	-0.0556	0.4572	**0.0318***
	A2	-0.0553	0.6565	**0.0045****
	C1	-0.0541	0.4189	**0.0431***
	C2	-0.0537	0.5597	**0.0128***
	D1	-0.0576	0.6805	**0.0033****
	D2	-0.0549	0.5625	**0.0125***
	E1	-0.0434	0.6052	**0.0081****
	E2	-0.0557	0.6835	**0.0032****
	F1	-0.0150	0.0759	0.4411
	F2	-0.0089	0.1421	0.2829

* $p < .05$
** $P < .01$

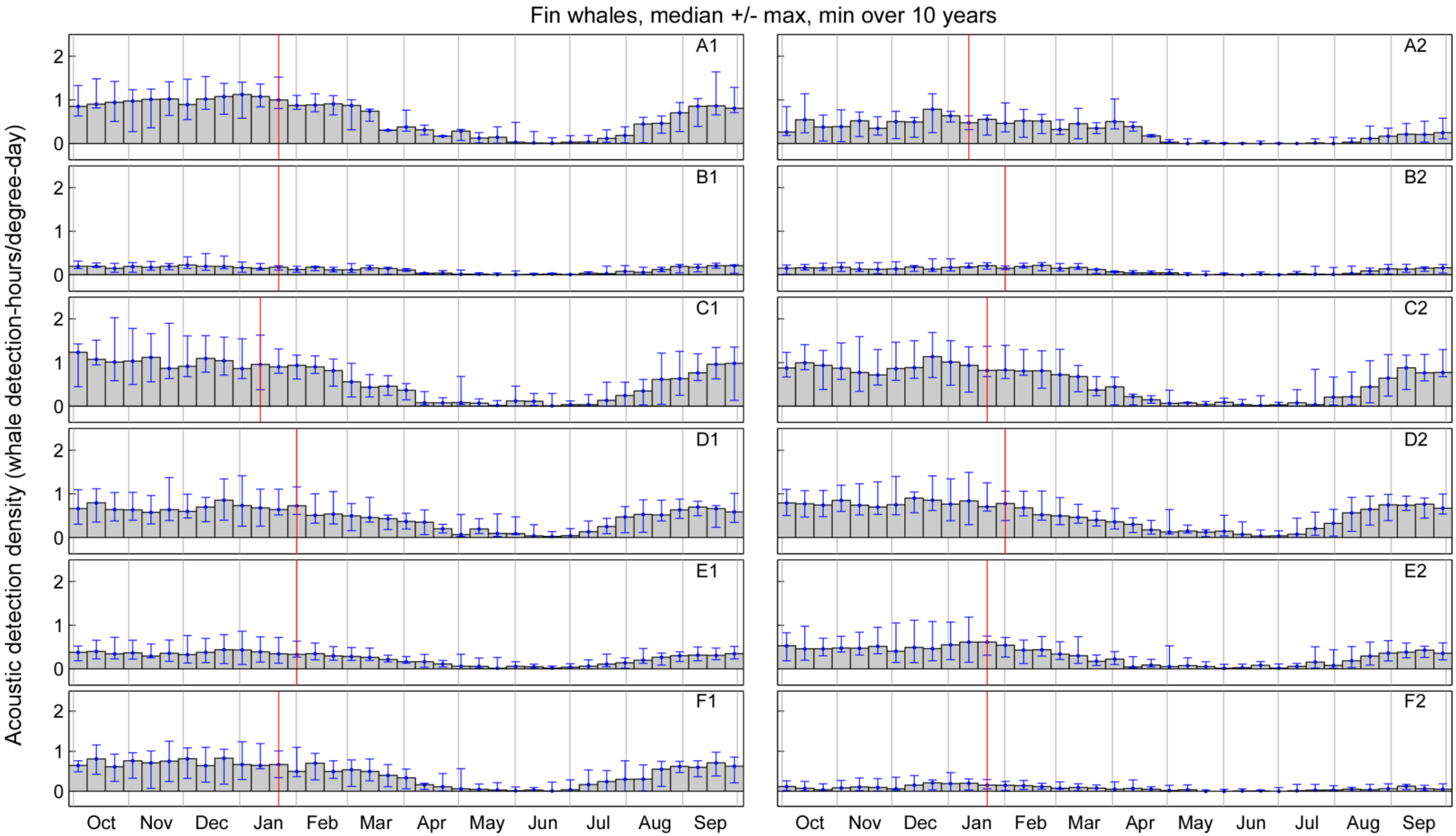

Figure 12. Daily acoustic detection density for fin whales during 10-day time blocks in each region. Bar heights give median values ± maximum and minimum values over the ten-year study. Vertical red lines indicate the median time of each year's distribution.

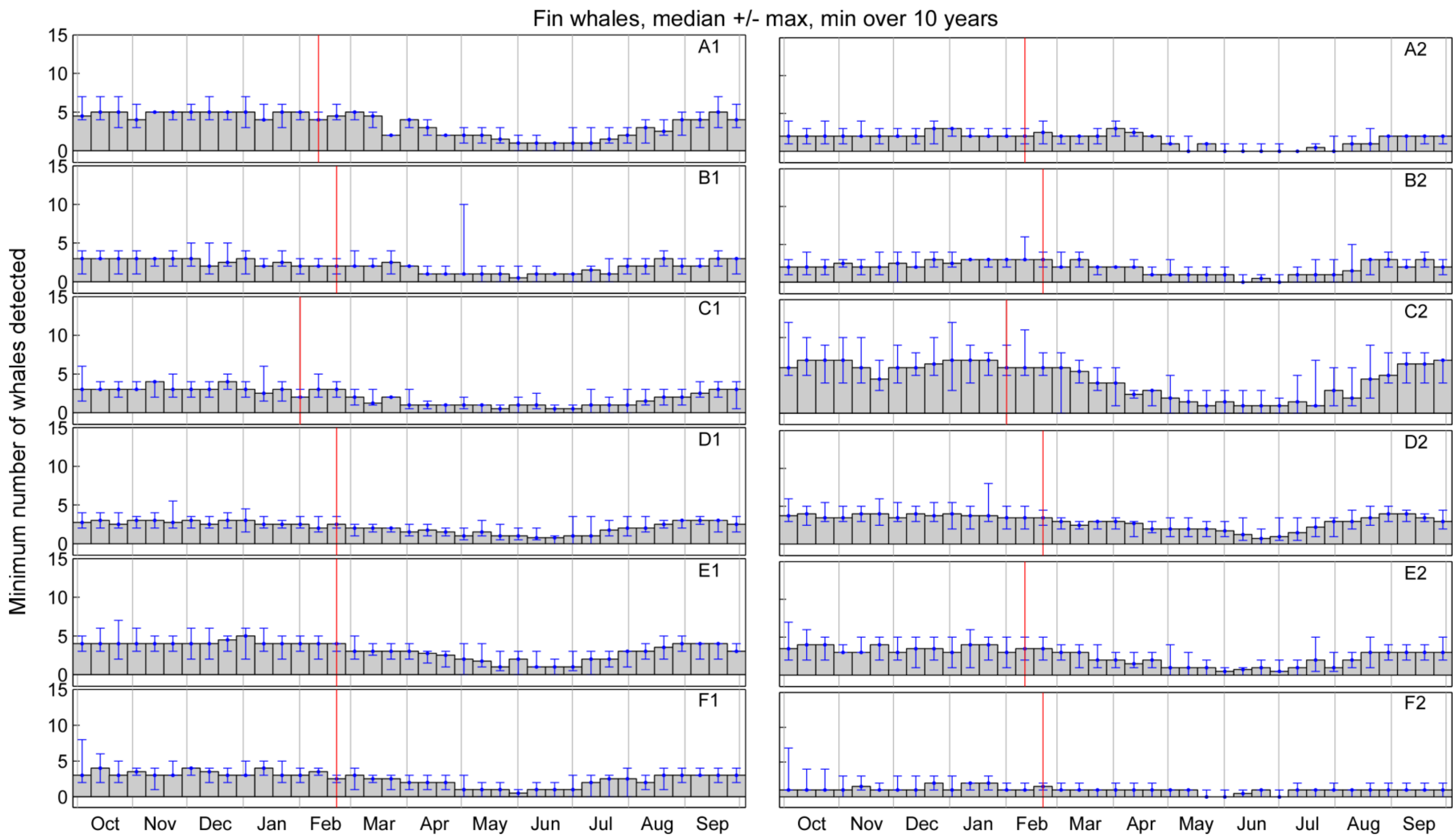

Figure 13. Minimum number of fin whales detected at any one time during 10-day time blocks in each region. Bar heights give median values ± maximum and minimum values over the ten-year study. Vertical red lines indicate the median time of each year's distribution.

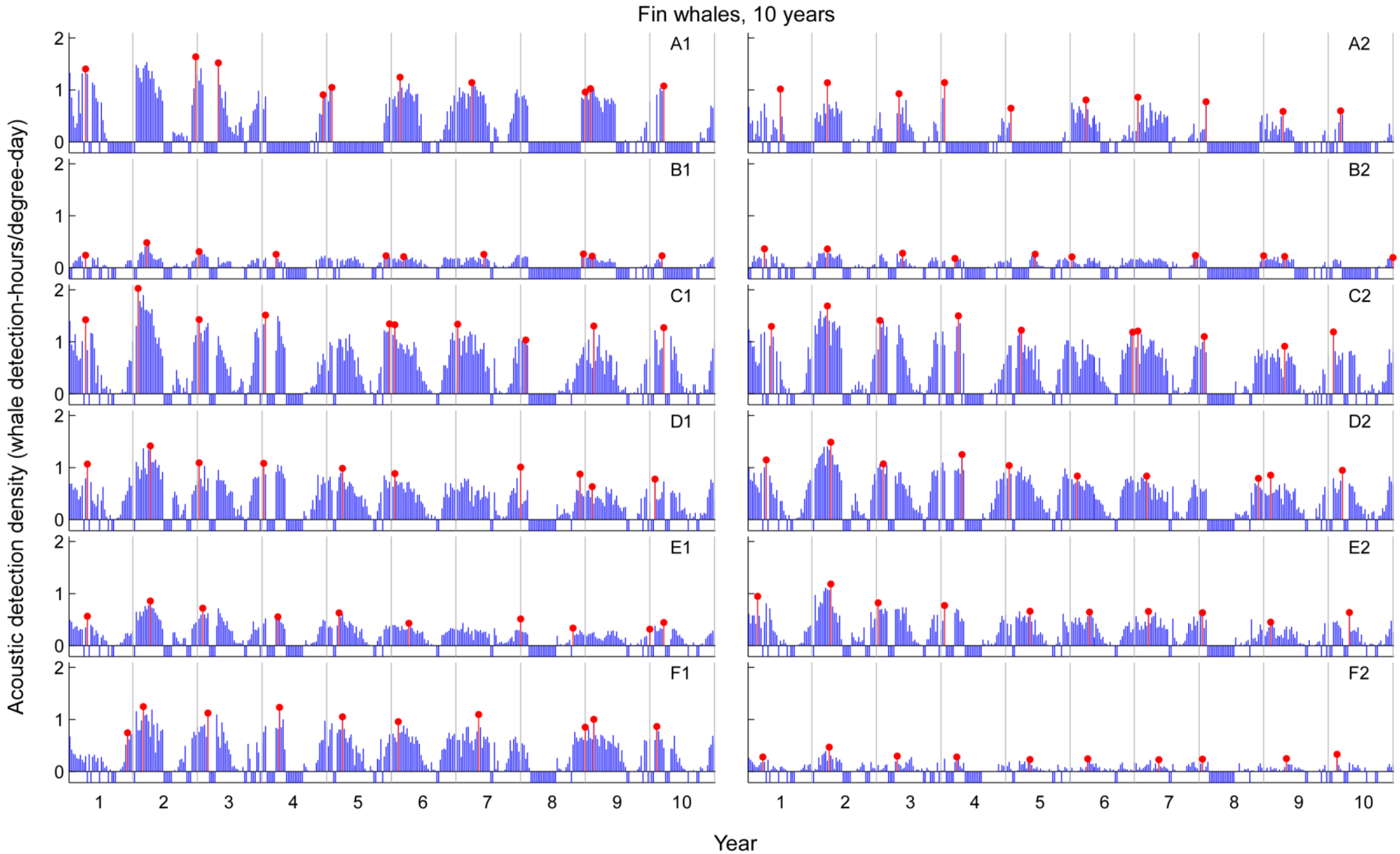

Figure 14. Ten-year time series of acoustic detection density for fin whales in twelve monitoring regions, 1 October 1996 – 30 September 2006. Each vertical bar represents one 10-day time period. Bars below the horizontal axis indicate periods for which no data are available. Vertical grey bars indicate the start of successive years of data collection. Red points indicate highest value in each year.

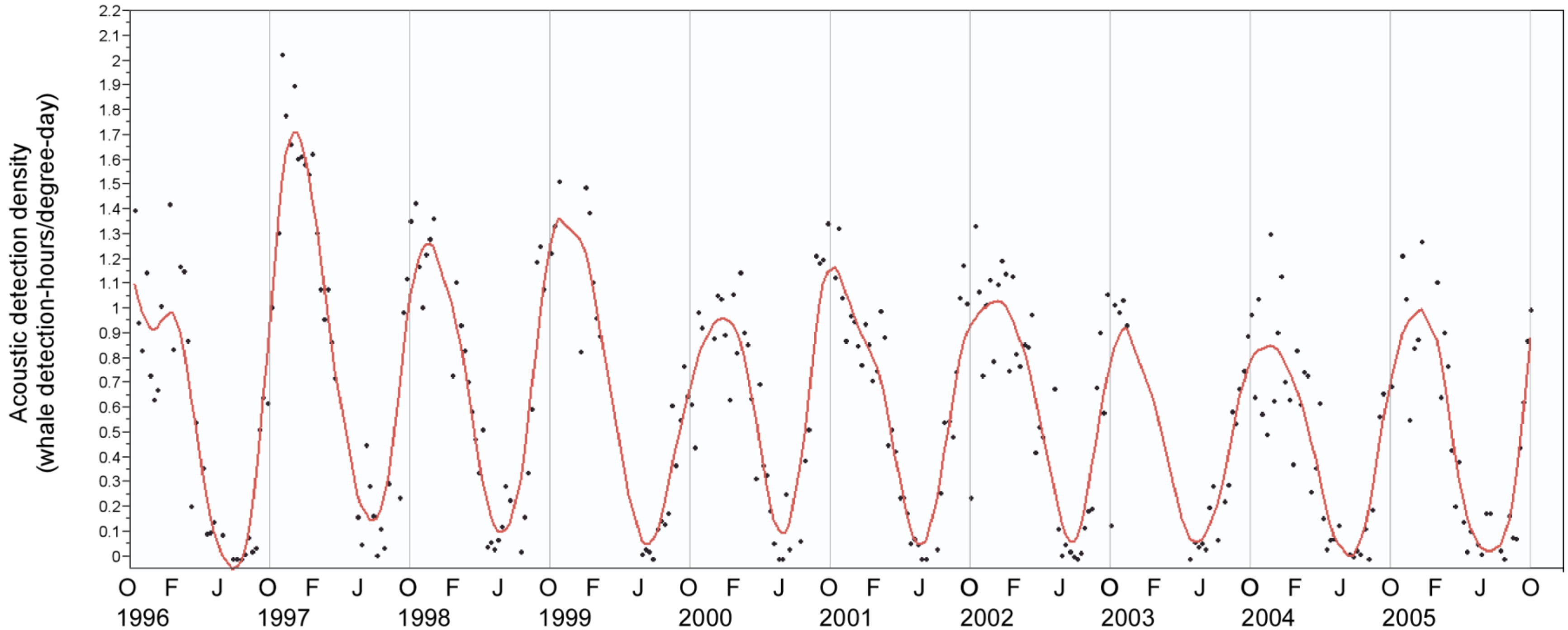

Figure 15. Ten-year time series of acoustic detection density for fin whales in Region C1. Each point represents one ten-day sampling bin. The curve is a fitted spline, with stiffness adjusted by eye. Horizontal axis labels indicate start of October, February, and June of each year.

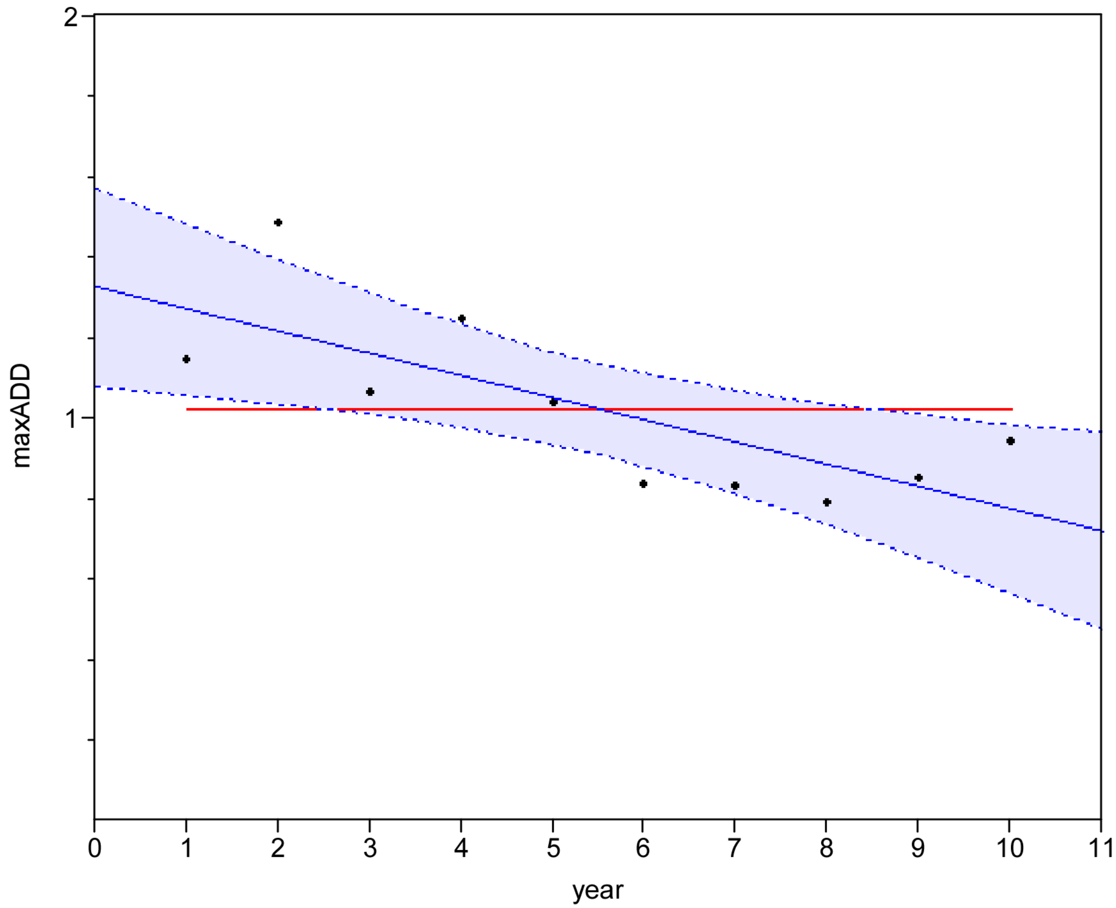

Figure 16. Annual peak acoustic detection density for fin whales in Region D2. The horizontal red line indicates the mean across all years. The blue line is a least-squares linear regression (R^2 = 0.5625); the shaded area is the 95% confidence interval. The slope of the fitted line (-0.0541) is significantly different from zero (*p* = .0125).

Humpback whales

Seasonal and geographic variation in vocal activity of humpback whales

Humpback whale songs were detected only between mid-October and late March (Figure 17 and Figure 18). Detections occurred in all regions, but were rare in Regions E and F. From the earliest autumn detections through February in each year that data were available, groups of singing humpbacks were tracked moving into and through Regions A, B, C, and D from the north, travelling on generally southwesterly courses. By mid-March new groups were no longer entering the northern edge of the monitoring area, and detections had ceased in Region A1. As detections declined in the northern regions, they increased in Regions C and D (west of Ireland), suggesting movement of singing whales into these more southerly regions. Figure 18 shows variation in the minimum number of humpback whales detected in each region. The maximum number of humpback whales ever detected simultaneously in any region was six, in Region A1 in December 1996.

Long-term trends in vocal activity of humpback whales

Figure 19 shows the acoustic detection density for humpback whales in all twelve regions as a ten-year time series. Overall, there do not appear to be any consistent long-term trends in detection density for humpback whales (Table 3). Figure 20 shows the same data in greater detail from Region D1 (the region with highest overall humpback whale detection density) only, with a fitted spline to help visualize any upward or downward long-term trend in detection density. Figure 21 shows a least-squares linear fit of the annual peak detection densities for humpback whales in Region D1 across all years.

Table 3. Trends in annual peak detection density for humpback whales over ten years. *p* values indicate significance of slope ≠ 0. N/A indicates that no humpbacks were detected in this region in five or more years.

Region	slope	R^2	*p*
A1	N/A	N/A	N/A
A2	N/A	N/A	N/A
C1	0.0164	0.0569	0.5069
C2	N/A	N/A	N/A
D1	-0.0051	0.0029	0.8830
D2	0.0060	0.0080	0.8059
E1	-0.0031	0.0131	0.7531
E2	-0.0038	0.0586	0.5004
F1	N/A	N/A	N/A
F2	N/A	N/A	N/A

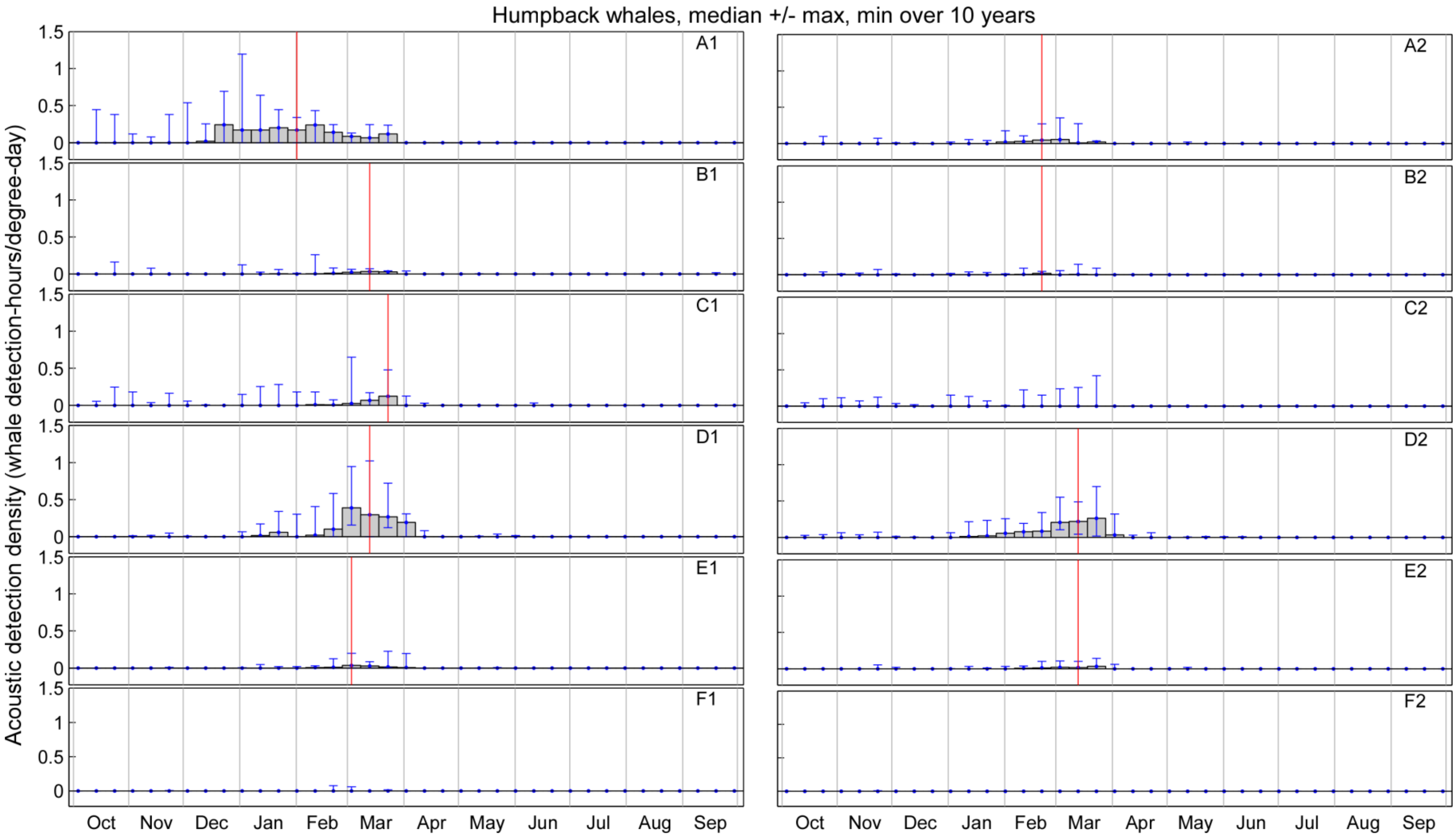

Figure 17. Daily acoustic detection density for humpback whales during 10-day time blocks in each region. Bar heights give median values ± maximum and minimum values over the ten-year study. Vertical red lines indicate the median time of each year's distribution.

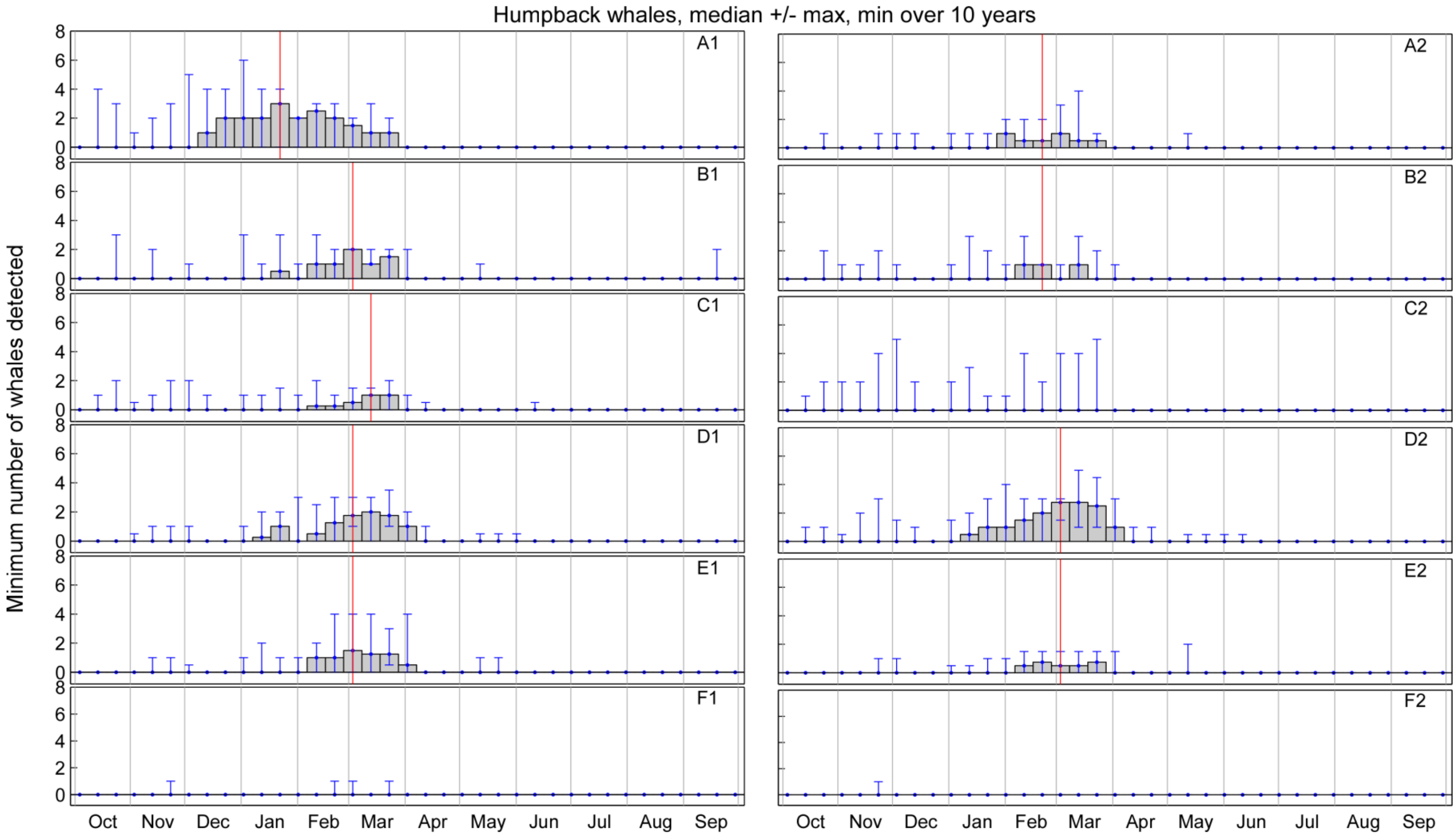

Figure 18. Minimum number of humpback whales detected at any one time during 10-day time blocks in each region. Bar heights give median values ± maximum and minimum values over the ten-year study. Vertical red lines indicate the median time of each year's distribution.

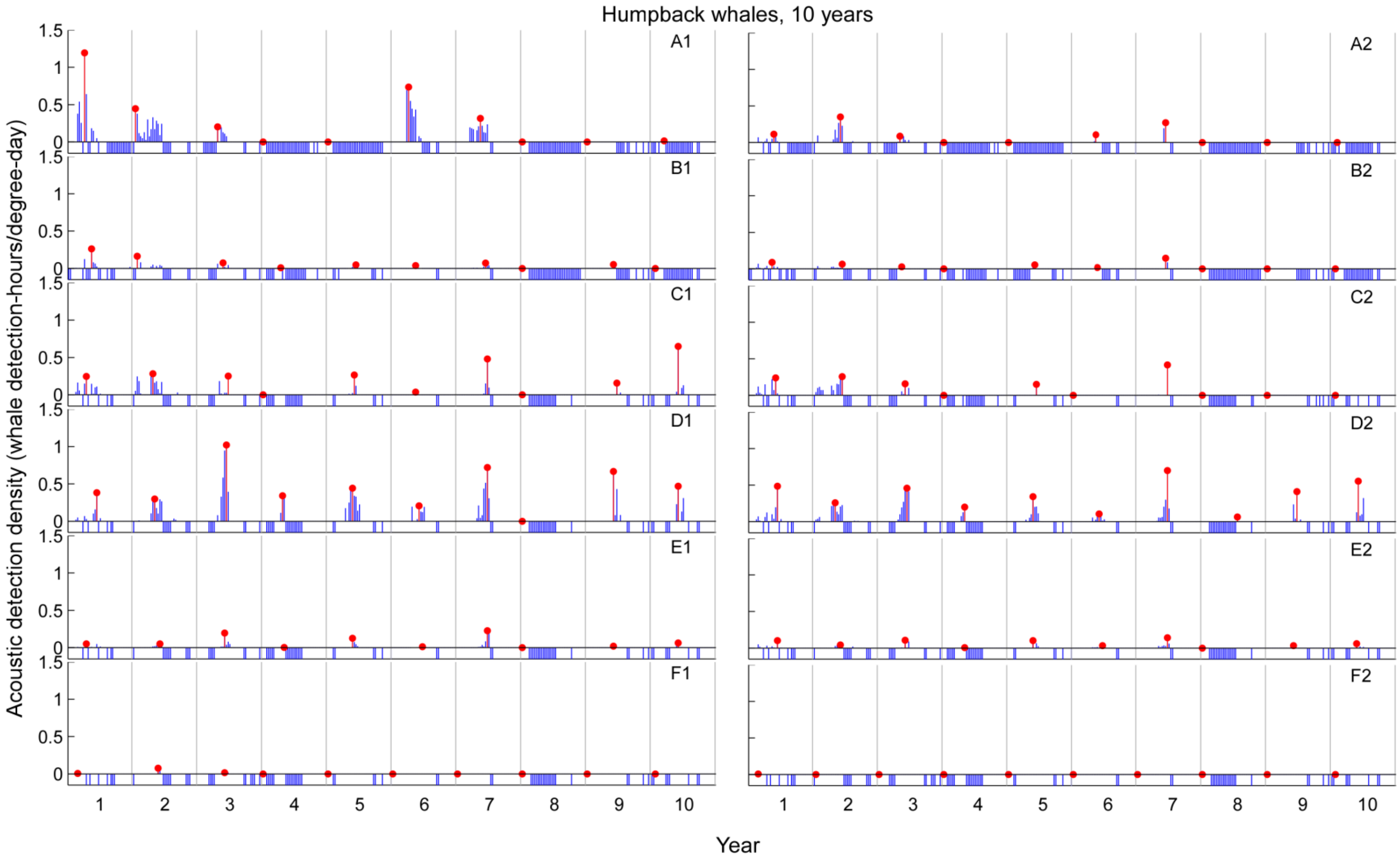

Figure 19. Ten-year time series of acoustic detection density for humpback whales in twelve monitoring regions, 1 October 1996 – 30 September 2006. Each vertical bar represents one 10-day time period. Bars below the horizontal axis indicate periods for which no data are available. Vertical grey bars indicate the start of successive years of data collection. Red points indicate highest value in each year.

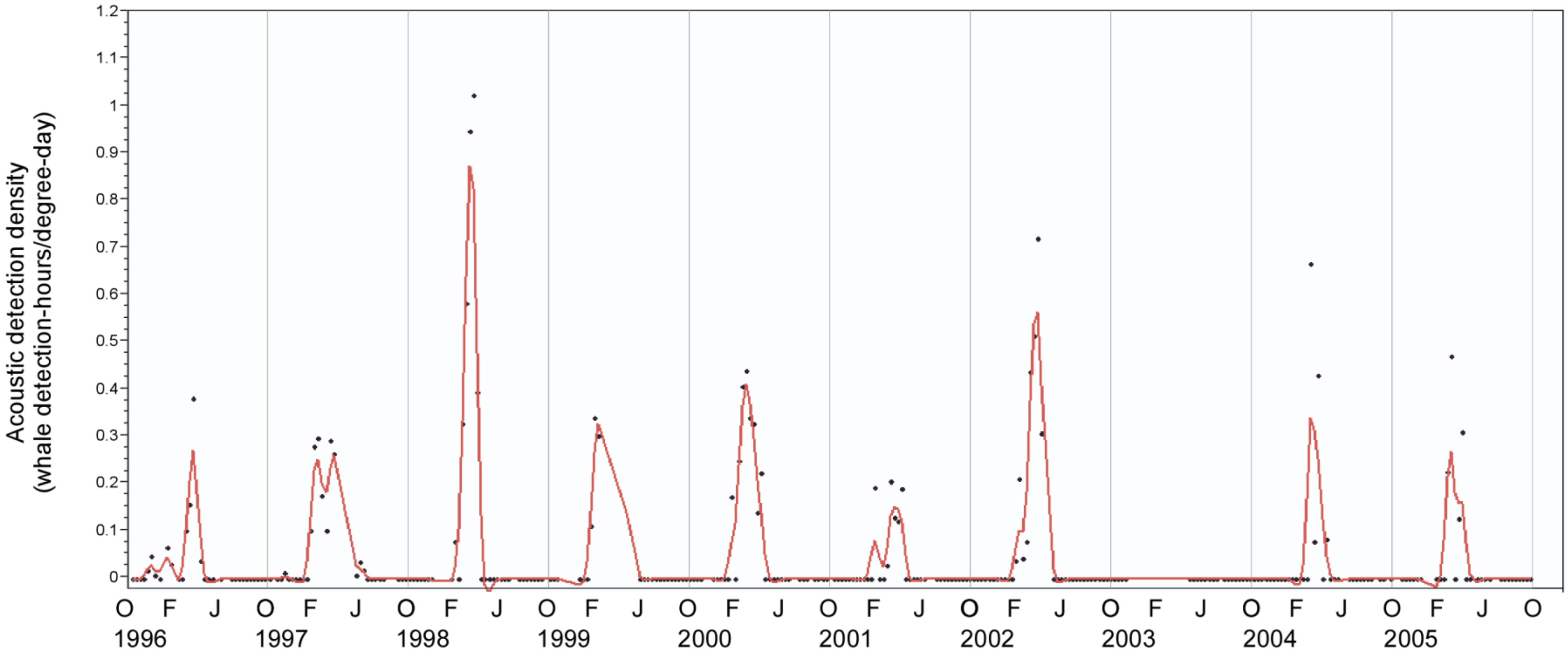

Figure 20. Ten-year time series of acoustic detection density for humpback whales in Region D1. Each point represents one ten-day sampling bin. The curve is a fitted spline, with stiffness adjusted by eye. Horizontal axis labels indicate start of October, February, and June of each year.

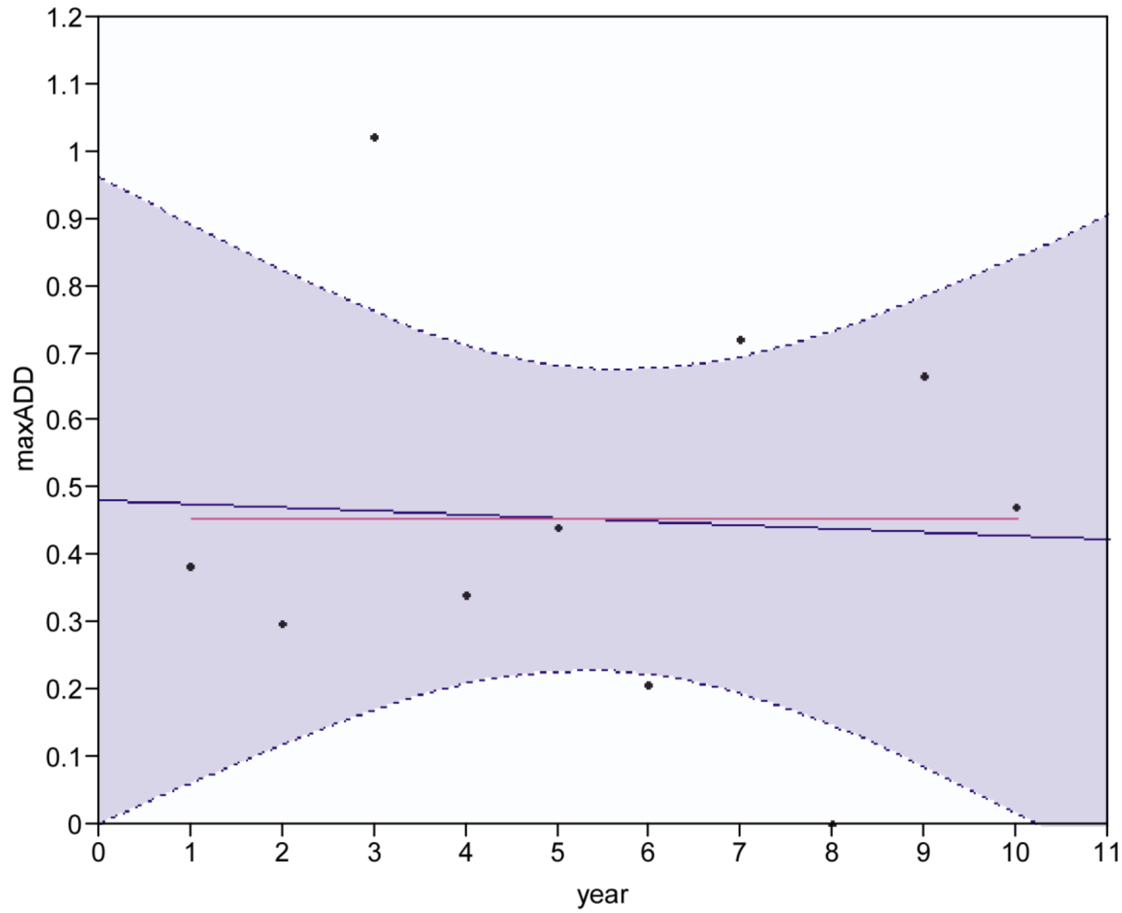

Figure 21. Annual peak acoustic detection density for humpback whales in Region D1. The horizontal red line indicates the mean across all years. The blue line is a least-squares linear regression (R^2 = 0.0022); the shaded area is the 95% confidence interval. The slope of the fitted line is not significantly different from zero (*p* = .8830).

Discussion

This study constitutes the longest continuous effort to monitor acoustic activity of whales over a large ocean area. With ten years of data now available, long-term trends in whale vocal activity should be detectable. Although the study covered a ten-year period, some sampling bins in each region were affected by data outages in one or more years, when data were not available (Figure 4 and Figure 5). Seven or more years of data were available for 72% of regions-bins.

Seasonal and interspecific variation

Blue, fin, and humpback whale songs were detected in all twelve regions at densities that varied both seasonally and geographically. All three species were consistently detected in regions from which no visual sightings are known, although search effort in some of those regions has been limited (Reid et al. 2003). There were pronounced annual cycles of variation in detection density for all three species. Because only singing whales were detected and singers are males, detection density is a function of the number of males present in an area and the probability of singing for individual males. Since no data are available on seasonal variation in singing rate for individuals, no clear inferences can be drawn from these data regarding seasonal changes in local abundance of whales. Detection densities might also be affected by seasonal changes in underwater sound propagation and interfering noise sources. The possible effects of these factors on whale acoustic detections have not been quantified in this or any other long-term study using bottom-mounted hydrophones (Moore *et al.* 1998; Stafford *et al.* 1998, 1999; Watkins *et al.* 2000).

Fin whales were the most frequently detected species, followed by blue whales, with humpbacks being the least frequently detected. Comparison of detection densities across species is not necessarily indicative of relative abundance or rates of singing because the relationship between probability of detection and distance from the hydrophone array differs for the three species. In general, blue whales are detectable at the longest ranges, followed by fin whales, with humpback whales having the most limited range. The fact that fin whale detections far exceed those for blue whales, despite the longer range of detectability for the latter, indicates that fin whale singers do indeed outnumber blue whale singers in the monitoring area. This inference is consistent with visual cetacean surveys in these regions, in which fin whales are the most commonly observed large whales, whereas blue whale sightings are quite rare (Stone 1998, 2000, 2001, 2006; Pollock *et al.* 2000, Reid et al. 2003).

Visual cetacean surveys in British waters have consistently reported the highest sighting rates for all species of large whales during the summer months (Stone 1998, 2000, 2001, 2006; Pollock *et al.* 2000), when acoustic detections are relatively infrequent for blue and fin whales, and entirely absent for humpbacks. Although summer is the time when the greatest effort has been spent in visual surveys, the sighting rates in summer are disproportionately high relative to effort (Stone 2000). Conversely, there are virtually no visual records of blue, fin, and humpback whales during the winter and early spring months when acoustic detections of these species are most frequent. Sea state and visibility are worse at these times than during summer months, and both factors are known to reduce rates of whale sightings (Stone 1998, 1999, 2001, 2006).

Seasonal migratory movements and timing of acoustic detections across regions

Observations of individually tracked blue whales suggest that most individuals detected during the September - January period (when most detections occur) are migrating to the south or southwest. During the months of April to June, small numbers of distant blue whale singers were detected sporadically to the west of Region D1. Although these whales could not be reliably tracked, beam-crossing data indicate that most were heading northward. These data suggest that the northward migratory route for blue whales lies west of the area discussed here, and that fewer blue whales are singing during the northbound migration.

Data on individually tracked humpback whale singers, and the seasonal southward progression of humpback detections suggest that most of the humpbacks detected in these regions are migrating southward. No northward migration of singing humpbacks has been detected. If humpbacks follow a northbound migratory path west of the monitoring regions, they would probably pass undetected (even if they are singing), since the reliable acoustic detection range of humpbacks is only a few hundred kilometres. Southbound humpback singers in these monitoring regions are probably *en route* to breeding grounds in the West Indies (Charif *et al.* 2001).

There was no evidence of large-scale seasonal migratory movements in fin whales. However, few tracking data are available on fin whales because of the difficulties (at many times of year) in distinguishing overlapping call sequences from many individual singers.

In recent years, data have become available on seasonal variation in whale acoustic activity over periods of one or more years in several locations in the Atlantic and Pacific oceans. In all locations, strong seasonal variations such as those described here have been evident. The seasonal pattern described here for blue whale detections is similar in shape to that observed on SOSUS arrays off of the United States coast in the western north Atlantic (Clark and Gagnon 2002), but in that region (at lower latitudes than the present study) blue whale detections occur from October through April, peaking in February, two to three months later than in British and Irish waters. In the northeast Pacific (30° to 45° N latitude, slightly south of the present study), blue whales are detected acoustically from July through December (Watkins *et al.* 2000). For fin whales, the seasonal distribution of acoustic activity at the more southerly western Atlantic SOSUS stations trails the pattern seen in this study by three to four months, with detections occurring from October through June, peaking in March and April (Watkins *et al.* 1987, Clark and Gagnon 2002). In the northeast Pacific, fin whale detections occur mainly from September through April, in a seasonal distribution similar to that observed in this study (Watkins *et al.* 2000). For humpback whales, detections in the western Atlantic off of the northern United States occur between October and May, a period that begins before and ends after the detections reported here. Off the southeastern US coast, humpbacks are detected mainly between March and June, later than any of the humpback detections reported in this study (Clark and Gagnon 2002). In the northeast Pacific (latitude ≈30° N), humpbacks are detected mainly between January and May (Watkins *et al.* 2000), broadly similar to the pattern observed in Region D1. Overall, the annual cycles of occurrence of sounds from all three species at Atlantic SOSUS stations appear to be consistent with seasonal migrations between high latitudes in summer and lower latitudes in winter.

Interannual variation and long-term trends in detection density

Within the broadly consistent seasonal trends observed in each region, there was considerable variation from year to year in details of the pattern of acoustic detection densities. Possible sources of this variation include interannual differences in ocean productivity or distribution of food resources, in physical properties of the water column that affect sound propagation, in interfering noise sources, and sampling error.

For blue and humpback whales, the interannual variations in detection density show no clear trend overall. Peak annual detection densities for fin whales showed a significant declining trend over ten years in eight out of ten regions. However, this preliminary analysis has two major limitations. First, in every year in every region, there were some 10-day bins for which no data were available. In some cases, these data outages persisted for months at a time. If such an outage included the time of year when fin whale acoustic activity was at its peak, then the highest density value recorded for that year might be misleadingly low. Second, even if the data record were complete, the annual peak value would not be a robust summary statistic for representing the overall level of activity each year, as it may be an outlier value that could be misleading. It is used here simply as a readily available value for this preliminary examination of the data. Nonetheless, this trend is intriguing. We plan to investigate these data more rigorously by (1) estimating values for missing data, based on values for those bins from other years and the typical shape of the within-year distribution of detections, informed by trends in adjacent bins, and (2) examining trends in the value of an appropriate summary statistic (e.g., median or 90th percentile) for each year's detection data, using real data where available and estimated data where necessary.

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Literature cited

Abileah, R, Martin, D, Lewis, SD, and Gisiner B. 1996. Long-range acoustic detection and tracking of the humpback whale Hawaii-Alaska migration. In IEEE Oceans '96: 373-377. Fort Lauderdale, FL.

Barlow, J. 1995. The abundance of cetaceans in California waters: Part I. Ship surveys in summer and fall of 1991. US National Marine Fisheries Service Fish. Bull. 93: 1-14.

Charif, RA, and CW Clark. 2000. Acoustic monitoring of large whales off north and west Britain and Ireland: a two-year study, October 1996-September 1998. *JNCC Report,* No. 313.

Charif, RA, PJ Clapham, and CW Clark. 2001. Acoustic detections of singing humpback whales in deep waters off the British Isles. *Marine Mammal Science* 17: 751-768.

Clark, C.W. 1990. Acoustic behavior of mysticete whales. In: *Sensory Abilities of Cetaceans* (J. Thomas and R. Kastelein, eds.). Plenum Press. pp. 571-583.

Clark, CW. 1995. Application of US Navy underwater hydrophone arrays for scientific research on whales. Reports of the International Whaling Commission 45: 210-212.

Clark, CW, and Ellison, WT. 1989. Numbers and distributions of bowhead whales, *Balaena mysticetus*, based on the 1986 acoustic study off Pt. Barrow, Alaska. Rep. Int. Whal. Comm. 297-303.

Clark, CW, and Ellison, WT. 2003. Potential use of low-frequency sounds by baleen whales for probing the environment: evidence from models and empirical measurements. In *Echolocation in Bats and Dolphins* (J. Thomas, C. Moss and M. Vater, eds.). The University of Chicago Press.

Clark, CW, and Gagnon, GC. 2002. Low-frequency vocal behaviors of baleen whales in the North Atlantic: Insights from IUSS detections, locations and tracking from 1992 to 1996. *J. Underwater Acoust.* (USN), 52 (3):609-640.

Clark, CW, Charif, R, Mitchell, S, and Colby, J. 1996. Distribution and behaviour of the bowhead whale, *Balaena mysticetus*, based on analysis of acoustical data collected during the 1993 spring migration off Point Barrow, Alaska. Rep. Int. Whal. Comm. 46: 541-552.

Croll, D. A., C. W. Clark, A. Acevedo, B. Tershy, S. Flores, J. Gedamke and J. Urban. 2002. Bioacoustics: Only male fin whales sing loud songs. *Nature* 417(6891): 809-809.

Dunlop, R. A., D. H. Cato and M. J. Noad. 2008. Non-song acoustic communication in migrating humpback whales (*Megaptera novaeangliae*). *Marine Mammal Science* 24(3): 613-629.

Gordon, J., D. Gillespie, J. Potter, A. Frantzis, M. P. Simmonds, R. Swift and D. Thompson. 2003. A review of the effects of seismic surveys on marine mammals. *Marine Technology Society Journal* 37(4): 16-34.

Harwood, J. and B. Wilson. 2001. The implications of developments on the Atlantic Frontier for marine mammals. *Continental Shelf Research* 21(8-10): 1073-1093.

Helweg, DA, Frankel, AS, Mobley, JR, and Herman, LM. 1992. Humpback whale song: our current understanding. In Marine Mammal Sensory Systems (ed. by J. Thomas, R. Kastelein, and A. Supin), Plenum Press, NY. pp. 459-283.

Ketten, D.R. 1992. The cetacean ear: Form, frequency, and evolution. p. 53-75. *In*: J.A. Thomas, R.A. Kastelein and A. Ya. Supin (eds.), *Marine Mammal Sensory Systems.* Plenum, New York. 773 p.

Ketten, D.R. 1994. Functional analysis of whale ears: Adaptations for underwater hearing. *IEEE Proc. Underwater Acoustics* 1: 264-270.

Moore, SE, KM Stafford, ME Dahlheim, CG Fox, HW Braham, JJ Polovina, and DE Bain. 1998. Seasonal variation in reception of fin whale calls at five geographic areas in the north Pacific. *Marine Mammal Science* 14: 617-627.

Murray, L and Simmonds, M. 1998. The Atlantic Frontier: Britain's last ocean wilderness. Greenpeace UK.

National Research Council. 1994. *Low-Frequency Sound and Marine Mammals: Current Knowledge and Research Needs.* National Academy Press. Washington, DC. xiii +75 p.

Oleson, E. M., J. Calambokidis, W. C. Burgess, M. A. McDonald, C. A. LeDuc and J. A. Hildebrand. 2007. Behavioral context of call production by eastern North Pacific blue whales. *Marine Ecology Progress Series* 330: 269-284.

Pollock, CM, R Mavor, CR Weir, A Reid, RW White, ML Tasker, A Webb, and JB Reid. 2000. *The distribution of seabirds and marine mammals in the Atlantic Frontier, north and west of Scotland.* Joint Nature Conservation Committee, Aberdeen, Scotland.

Reid, J. B., P. G. H. Evans and S. P. Northridge. 2003. Atlas of cetacean distribution in north-west European waters. Joint Nature Conservation Committee. Peterborough, UK.

Richardson, WJ, Greene, Jr., CR, Malme, CI, and Thomson, DH. 1995. *Marine Mammals and Noise*. Academic Press, New York. xvi + 576 pp.

Stafford, KM, CG Fox, and DS Clark. 1998. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. Journal of the Acoustical Society of America 104: 3616-3625.

Stafford, KM, SL Nieukirk, and CG Fox. 1999. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. Journal of the Acoustical Society of America 106: 3687-3698.

Stone, CJ. 1998. Cetacean observations during seismic surveys in 1997. Joint Nature Conservation Committee. Peterborough, UK.

Stone, CJ. 2000. Cetacean observations during seismic surveys in 1998. Joint Nature Conservation Committee. Peterborough, UK.

Stone, CJ. 2001. Cetacean observations during seismic surveys in 1999. Joint Nature Conservation Committee. Peterborough, UK.

Stone, C. J. 2006. Marine mammal observations during seismic surveys in 2001 and 2002. Joint Nature Conservation Committee. Edinburgh.

Thompson, P. O., L. T. Findley and O. Vidal. 1992. 20-Hz Pulses and Other Vocalizations of Fin Whales, *Balaenoptera physalus*, in the Gulf of California, Mexico. *Journal of the Acoustical Society of America* 92(6): 3051-3057.

Watkins, WA., Tyack, P, Moore, KE., and Bird, JE. 1987. The 20-Hz signals of finback whales (*Balaenoptera physalus*). *J. Acoust. Soc. Am.* 82(6):1901–1912.

Watkins, WA, MA Daher, GM Reppucci, JE George, DL Martin, NA DiMarzio, and DP Gannon. 2000. Seasonality and distribution of whale calls in the North Pacific. *Oceanography* 13: 62.