Detection of Environmental Change – Evidence from the Western English Channel

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To separate human-induced changes from natural fluctuations in marine life requires a long period of monitoring. The western English Channel has been investigated from Plymouth for over 100 years. The abundance of marine life has been recorded and related to physical changes in the environment. By comparing different parts of the ecosystem we can demonstrate historic natural fluctuations, allowing prediction of effects of future global warming. From the 1920s to the 1950s there was a period of warming of the sea, with increases in abundance of species of fish, plankton and intertidal organisms that are typically common in warmer waters to the south of Britain. After 1962 the sea cooled down and northern cold-water species became more abundant. Since the 1980s regional sea-surface temperature has warmed again and abundances of warm-water species are increasing.

Introduction

When analysing effects of changing climate on marine organisms it is critical to separate natural changes from those caused by human activity. Unlike terrestrial ecosystems, the seas are still at the hunter-gatherer stage of exploitation. As yet aquaculture contributes little to the commercial supply of marine fish and other animals (12.4% in 1999; FAO, 2001a,b), and most cultivated species are reared on fishmeal from wild stocks. At present, there is no effective world control of fishing, and with technological and infrastructural development, total global marine fisheries capture has risen from less than 20 million tonnes after the Second World War to over 90 million tonnes in 1999 (FAO 2001a). It has been estimated that in recent years fishing has taken between 20% and 50% of potential marine fish production of shelf seas, regions where fishing has always been most intensive (Moiseev, 1995; Jennings et al., 2000). This exploitation has had profound direct and indirect effects on marine ecosystems (Jennings & Kaiser, 1998; Pauly, 1998).

Long periods of monitoring are required to separate human-induced change from natural fluctuations (Southward, 1995). Fortunately, the western English Channel, an important biogeographic boundary between northern Boreal and southern Lusitanian fauna, has been monitored from Plymouth for over 100 years by a sequence of researchers from the Marine Biological Association (MBA) (Southward & Roberts, 1987). Occurrence and abundance of marine life have been recorded and related to changes in the physical environment by employing data from parallel hydrographic monitoring. Here we summarize a selection of the long-term changes that have been observed in the marine ecosystem of the western English Channel, including offshore plankton, pelagic fish, bottom-living fish and intertidal rocky shores. We show that many biological fluctuations are related to changes in sea temperature, allowing effects of expected global warming to be predicted. From the 1920s to 1950s there was a period of gradual warming of sea surface temperatures, with parallel increases in abundance of species of fish, plankton and intertidal organisms common to the south of Britain ('warm-water species'). After 1962 the sea cooled, with corresponding increases in abundance of species typically prevalent in the north ('cold-water species'). Since the 1980s Plymouth waters have once again increased in temperature and many warm-water species are now escalating in abundance.

Records and changes

Long-term MBA data series that detail changes in marine species, communities and their environment in the western English Channel and along the coasts of Cornwall, Devon and Dorset are listed in Table 1. Full references can be found in Southward (1963; 1983; 1984), Southward & Butler (1972), Holme (1983), Southward et al. (1988; 1995) and Southward & Boalch (1989). References to other data on the influence of climate on marine life can be found in Cushing & Dickson (1976), Edwards et al. (2001) and Reid et al. (2001). Recording began at Plymouth in 1888 when the laboratory was opened, and was greatly expanded after 1919 with funding from the UK Government Development Commission and subsequently NERC until 1987. Quantitative time-series exist for plankton, sea temperature and salinity from 1903 to 1987. Demersal fishes were assayed at intervals from 1913 to 1986, and surveys of intertidal invertebrate abundance were conducted continuously between the 1930s and late 1980s. Other series of shorter length, undertaken from the 1920s to the 1980s, measured dissolved nutrients, phytoplankton production and infaunal benthos. With restructuring of Plymouth marine science in the mid 1980s many serial observations ceased, but recently analyses of data and limited restart of time-series surveys of rocky shore and demersal fish communities have been resumed.

Temperature

Sea temperatures around the Plymouth area of the western English Channel were first monitored during the latter half of the 19th Century. To date, there have been three main sources of information: 1) offshore measurements taken by MBA vessels 15 miles off Plymouth (ICES station E1 – 50º02’N 04º22’W) 1903 – 1987 (Southward & Butler, 1972; Maddock & Swann 1977); 2) sea surface measurements in Plymouth Sound (approx 50º22’N 04º08’W), taken by city authorities 1898-1989 (Cooper 1958) and by a local resident 1967-present; 3) sea surface data abstracted from authenticated sources by the Hadley Centre for Climate Prediction and Research for area 50-51ºN 04-05ºW from 1871-Present (http://www.badc.rl.ac.uk). These datasets are closely correlated with each other and to additional climate records for the area (Southward et. al., 1988; A.J. Southward & S.J. Hawkins unpublished data). Sea surface temperatures are also now available from satellite observations, which are exceptional at quantifying local variability, but may not always correspond with in-situ measurements (Parker et al., 1995).

Mean annual sea surface temperatures in the western English Channel have undergone considerable interannual fluctuations during the 20th Century, but longer trends can be observed when polynomials are fitted to the data (Fig. 1). There was a rise in temperature during the first half of the century, followed by a lowering of temperature in the middle 1950s, but high values returned in 1958-61. A marked decline in temperature occurred from 1962, and thereafter there was a period of cooler conditions. From the early 1980s temperatures increased slightly until 1990 and there was a substantial increase during the following decade of almost 1ºC, exceeding any changes in the previous 100 years, and suggesting that global warming has begun (Fig. 1a). There is a close correlation with temperature trends in the northern Bay of Biscay (Fig. 1b), an area with impact on the British climate (Lamb, 1977) and an important source of water entering the English Channel, carrying with it warm-water plankton and fish.

Temperature patterns in the North Atlantic have been linked to the strength and direction of the North Atlantic Oscillation (NAO). The NAO winter index quantifies the changes in atmospheric mass between the region of high pressure over the Azores, and low pressure over Iceland during the months Dec-April. A positive phase (high pressure over the Azores and low pressure over Iceland) drives surface westerlies north and results in warm, wet years in northern Europe. In contrast a negative index (high pressure over Iceland and low pressure over the Azores) drives westerly weather further south toward the Mediterranean and results in northern Europe experiencing cool, dry years (Fromentin & Planque, 1997). For the past half century there has been good correlation between the strength of the NAO and sea surface temperatures of the English Channel, indicating that the NAO strongly influences the thermal regime (Sims et al., in press). In addition, temperatures within the western English Channel, for part of the period under study (1925 – 1974), show cyclic patterns largely synchronized with the 11-year cyclic sunspot index (Southward et al., 1975), suggesting linkage between solar activity and sea surface temperature, although Southward (1980) noted that this relationship was beginning to break down.

Changes in plankton

Changes in the offshore plankton over the last 100 years are complicated to interpret. However, during this period there have been major switches in relative abundance of many planktonic taxa (Southward, 1963; 1980; 1984; Southward & Boalch, 1989), and changes appear closely linked to climatic fluctuations. Between the mid 1930s and 1960 there was an increase in abundance of eggs of European pilchard (*Sardina pilchardus*) corresponding to warmer conditions (Fig. 2), and it can be assumed that the spawning stock of this warm-water fish had simultaneously increased (Southward et al., 1988). During the same period catches of other larval fish and plankton invertebrates were much reduced, perhaps as a consequence of enhanced levels of predation by juvenile and adult pilchard (Cushing, 1961; Southward, 1963). The abundance of pilchard eggs declined during the cool spell of the 1970s, but increased again post 1985.

Changes in the arrow worm populations have also been apparent. Between 1930 and 1960 *Sagitta elegans*, a cold-water species, was gradually replaced by *S. setosa*, a warm-water southern species (Southward, 1984). From 1970, *S. elegans* returned in abundance, peaking in 1979, but subsequently declining, and in most of the years sampled since 1985 *S. setosa* has been dominant (Figure 3). There have also been comparable changes among other planktonic invertebrates that appear to be climate-induced, notably among copepods and euphausids (Southward *et. al* 1995).

Changes in pelagic fish

Pelagic fishes have been, and remain, of major commercial importance to the fishing ports of the southwest of England, with European pilchard (*Sardina pilchardus*), Atlantic herring (*Clupea harengus*) and Atlantic mackerel (*Scomber scombrus*) the principal target species. Historical records and catch statistics demonstrate major fluctuations in abundance of these taxa since the 16th century (Southward et al., 1988), and evidence is consistent with suggestions that these fluctuations are to some extent climatically-driven. Landings at Plymouth collated by the UK government fisheries department, clearly demonstrate that herring, a cold-water species, was the major pelagic fish in the area until a warming period during the 1920s, when stocks abruptly collapsed (Fig. 4a) following recruitment failure (Cushing, 1961). Catches of pilchard, a warm-water taxon, were low during this period, but the species became comparatively abundant during the warmer 1950s (Fig. 4b). However, stocks soon declined to previous levels as sea surface temperatures fell in the 1960s. During this cold period herring never returned in the abundance seen during the 1920s even though sea temperatures were comparable. Explanations for the absence of herring are speculative, but as Southward et al. (1988) suggest, it is possible that overfishing reduced remaining spawning stock to a level below capacity for resurgence. Around that time herring stocks were low throughout the coastal waters of the Northeast Atlantic region to the extent that in 1977 a moratorium on North Sea herring fishing was introduced (Jakobsson 1985). We therefore surmise that there were no healthy adjacent stocks from which recolonisation could occur. During the mid 1970s, there was also a striking increase in the abundance of Atlantic mackerel, a cold-water continental shelf species, but these catches soon declined (Fig. 4c). Post 1985 landings of pilchard have increased dramatically, to the extent of record highs in 1996. This increase corresponds with the overall trend of warming in the western Channel. Together, evidence suggests that major changes in pelagic fish abundance within the western English Channel have been, at least in part, driven by climatic variables but may also be influenced by fishing pressure.

Changes in bottom-living fish

Fisheries independent data from surveys conducted by MBA research vessels between 1913 and 2001 on the Plymouth inshore grounds (shoreward of Eddystone Reef) suggest striking changes in the composition of the bottom-living fish assemblage during the 20th century (Fig. 5). The records cover 94 species belonging to 35 families at 130 fishing 'marks'. Plymouth inshore waters have been trawled over for two hundred years, but both effort and capture efficiency of the fleet increased dramatically during the 20th century. Several observed changes in populations are consistent with predictions of fishing impacts. Many species of large, slow growing taxa with low fecundity now appear to have been extirpated or are at least commercially extinct. Particularly striking are changes in abundance of elasmobranchs, such as spurdog (*Squalus acanthias*), a species that supported a major fishery in the region during the early 20th century (Ford 1921), but was rare in survey hauls post 1922 and absent since 1979. The blue skate, *Dipturus batis*, was formerly present in the area (Steven 1931) but has never been recorded in MBA survey logbooks, suggesting it disappeared even earlier. In addition to species changes, there have been community-level declines in average length and length at maturity of individuals, suggesting a switch toward an assemblage dominated by species that mature faster and breed at a smaller size (M.J. Genner, A.J. Southward & S.J. Hawkins unpublished data). These patterns replicate those from other heavily fished regions in European shelf waters (see for example Jennings et al., 1999; Rice & Gislason 1996).

While fishing appears to be have had considerable impact on demersal fish, change may also be in part a consequence of regional climatic fluctuations. One example is an increase in frequency of occurrence of southern sea breams (Family Sparidae) during the warm periods of the 1950s and over recent years. Preliminary analyses of MBA data showed that between 1919/21 and 1950/52 cold-water species such as cod, haddock and lemon sole declined as a proportion of the catch. Between 1950/52 and 1976/79 this trend was reversed and some cold-water species became proportionally more abundant (Southward, 1963; Southward & Boalch, 1993; 1994). However, re-examination of data, including that from 1913 and very recent years revealed few changes in population abundance that could be directly associated with temperature. This may in part be due to the complexity of biotic interactions that determine the composition of demersal fish communities. Many of the taxa differ in ecological and life history characteristics such as body size, food requirements, migratory behaviour and reproductive mode. At the organism-level, changes in climate influence physiology and behaviour that in turn may affect the strength of density-dependent interactions such as competition, predation and parasitism at any stage in a life history. Hence, climate changes may result in counterintuitive population abundance fluctuations, particularly over local scales (Davis et al., 1997). An example is the apparent decrease in abundance of typically warm-water Dover sole (*Solea solea*) during the warm period up to 1952. This complexity, together with an overwhelming impact of fishing, may be responsible for making climatic effects more difficult to detect in demersal species, in contrast to pelagic taxa that appear to respond directly and dramatically to climatic variability.

Changes in intertidal organisms

Intertidal rocky shore organisms are comparatively easy to monitor and one of the most striking biotic responses to climate change observed in this environment involves relative proportions of two groups of acorn barnacles. One species, *Semibalanus balanoides*, is a boreo-arctic form that reaches its main southern limit in the south of England and Brittany. In contrast there are two warm-water species of *Chthamalus* that reach their northern limits in Scotland and dominate shores in southern Europe and N. Africa. There have been substantial changes in the relative abundance of these taxa on the south coast of Devon and Cornwall (Fig. 6). During a baseline survey in 1934, northern cold-water species were dominant, but when full serial observations began in 1950 *Chthamalus* spp. were most abundant and few *S. balanoides* could be found (Southward & Crisp, 1954). A brief cold period between 1952 to 1957 saw a return of some *S. balanoides* (Southward & Crisp, 1956), but *Chthamalus* spp. attained a second peak abundance during another warm period between 1958-61. Subsequently, there was a succession of cold winters and poor summers stretching from 1962 to 1967 during which the populations of *Chthamalus* spp. declined and *S. balanoides* returned in great abundance (Southward, 1967). From 1970 the numbers of the warm-water species increased, while *S. balanoides* numbers fluctuated. Since 1985, records for fewer stations indicate that warm-water barnacle species have become more abundant (Southward 1991; S.J. Hawkins & A.J. Southward unpublished data). Abundance of these taxa at south coast stations showed considerable similarity in temporal trends at different tidal levels (Fig. 6), and these patterns are echoed in barnacle populations from an inlet on the south coast of Devon where there were large fluctuations of the competing species. Monitoring of this site continued until 1998 and data show an increase of warm-water species in recent years (Fig. 7). There are strong correlations between barnacle abundance and sea surface temperature. Abundance of warm-water species (*Chthamalus* spp.) are positively correlated with inshore temperature while abundance of the cold-water species (*Semibalanus balanoides*) is negatively correlated (Table 2). Strongest correlations are found when there is a one to two year lag phase between temperature and the biological changes, related to the typical generation time of the barnacles, implying that temperature strongly affects the stages of the life-cycle between gonad development and new settlement. It should be noted that although sea temperatures have now reached levels observed in 1949-51, recent observations show the northern barnacle, *S. balanoides* is still fairly common in the Plymouth area, though recruitment may be failing. It is also still abundant on the north coast of Cornwall (S.J. Hawkins & A.J. Southward unpublished data), where recruitment is aided by upwelling of cold-water as a result of strong tidal mixing (Crisp & Southward, 1958).

Climate-driven species-level change also seems to have taken place in numerous other intertidal organisms during the study period, including the southern limpet species, *Patella depressa* and the warm-water top-shell, *Osilinus lineatus* (Southward et al., 1995). The former has become increasingly abundant in recent years (S.J. Hawkins & A.J. Southward unpublished data).

Discussion and future prospects

While patterns of change are complex, it has been shown that many changes in offshore pelagic and intertidal rocky shore populations appear to be closely related to climate-driven sea temperature fluctuations. Under predicted global warming scenarios, a 1.4-5.8ºC rise in sea temperature is expected over the next 100 years (Schneider 2001). The changes in the marine ecosystem that may accompany this warming could be of significant consequence to functioning and diversity of marine ecosystems, and may also have considerable impact on the socioeconomic status of coastal communities reliant on marine production (Southward & Boalch, 1994). Thus it is important to keep records of changes in the marine environment that can form a basis for predictive models enabling us to recognize effects of climate as and when they happen. Evidence from the western English Channel suggests that rocky shore organisms can provide inexpensive and reliable indicators of changes that are occurring in important components of the ecosystem such as plankton and fish (Southward et al., 1995).

To this end, a new project has been established to examine historic records and undertake prediction of changes in marine fauna using rocky shore organisms as indicators of change. The project, funded by a consortium of concerned UK and Ireland conservation agencies, government departments and non-governmental organizations, will repeat baseline surveys conducted in the first half of last century and studies undertaken between 1950 and 1980 by UK marine laboratories (e.g. Southward & Crisp 1954; Crisp & Southward 1958; Crisp & Fischer-Piette 1959; Lewis 1986; Southward 1991). Coordinated by the Marine Biological Association and the Scottish Association for Marine Science, the project will incorporate a network of Universities and independent research establishments. Such organisations have an important role to play in stewardship and interpretation of long-term data sets, as is now being recognized by funding bodies. A preliminary analysis qualitatively predicting changes to shore and shallow water life around the coasts of Scotland has already been reported to Scottish Natural Heritage (Hiscock et al., 2001).

Historic records have also been shown over the last decade to be of tremendous value to fisheries ecologists, enabling the patterns of change in marine fish assemblages to be derived and the causes identified (Alheit & Hagen, 1997; Jennings et al., 1999). Perhaps the greatest value of the time series collected on the Plymouth bottom-living fish is that it has been collected independently of statutory requirements and the whole community has been sampled rather than just populations of commercial species. Observed changes replicate those found in a number of other studies of heavily fished regions within European shelf waters (e.g. Jennings et al. 2000). Together, these historic data provide a basis for development of sustainability indices of practical use to fisheries managers (Pauly et al., 1998), enabling the status of fisheries to be evaluated along with the success, or otherwise, of management initiatives aimed at maximizing yield, while preserving marine biodiversity.

In summary, analyses of long-term datasets detailing variability in the western English Channel provide strong evidence that climate-induced changes have taken place, but also that anthropogenic disturbance can have major impacts on certain components of the ecosystem, such as demersal fisheries. To enable us to fully understand the mechanisms that result in change in marine ecosystems, and to disentangle natural variability and anthropogenic impacts, long-term monitoring is now of vital importance. As such, it is important that regular sampling of hydrography, plankton and young fish is restarted in the Plymouth region, and that the effectiveness of modern remote and in-situ sensors are determined by comparison with results from traditional ship-board sampling.

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Table 1. Long-term data series on the western English Channel held by the Marine Biological Association, Plymouth, UK.

Variables	Years surveyed
Temperature and Salinity	1902-2001
Nutrients	1921-1987
Phytoplankton	1903-1987
Primary Production	1964-1984
Zooplankton	1903-1987
Planktonic larval fish	1924-1987
Demersal fish	1913-2001
Intertidal organisms	1950-2001
Infaunal benthos	1922-1950
Epifaunal benthos	1899-1986

Table 2. Pearson's correlation coefficients between barnacle abundance and annual mean inshore sea surface temperature (Plymouth Sound 1951-1998), with lag-phases of 0, 1, 2 and 3 years. There was a strong negative correlation between annual abundance of *Chthamalus* spp. and *Semibalanus balanoides* over the time period (r = 0.59).

Species	Sea surface temperature			
	No lag phase	1 year lag-phase	2 year lag-phase	3 year lag-phase
Chthamalus spp.	0.27	0.48	0.43	0.25
Semibalanus balanoides	-0.22	-0.25	-0.41	-0.17

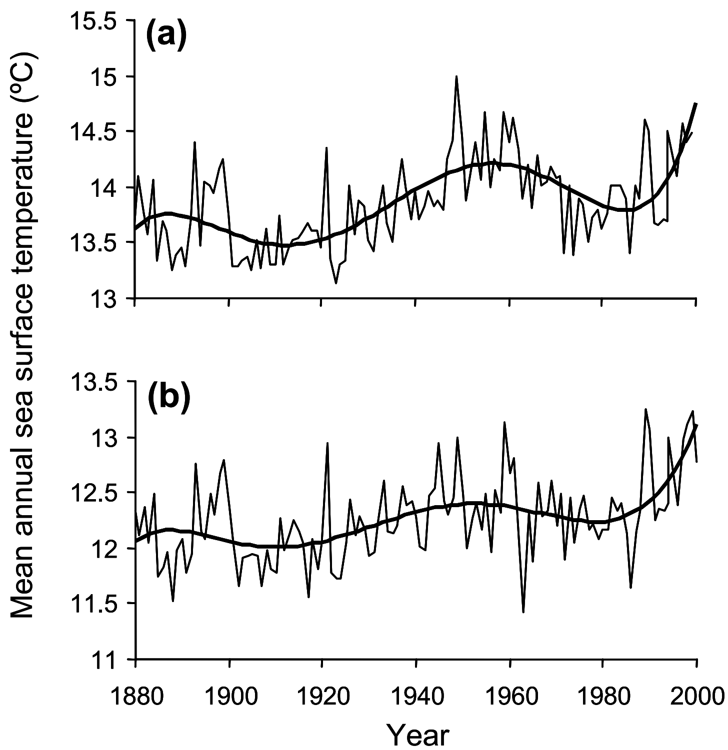

Figure 1 Annual mean sea surface temperatures (a) north Bay of Biscay, 5 degree square, 45-50°N, 05-10°W; (b) western English Channel off Plymouth, degree square 50-51°N, 04-05°W. Fitted lines: 6th order polynomials. Data: Hadley Centre for Climate Prediction and Research (http://www.badc.rl.ac.uk).

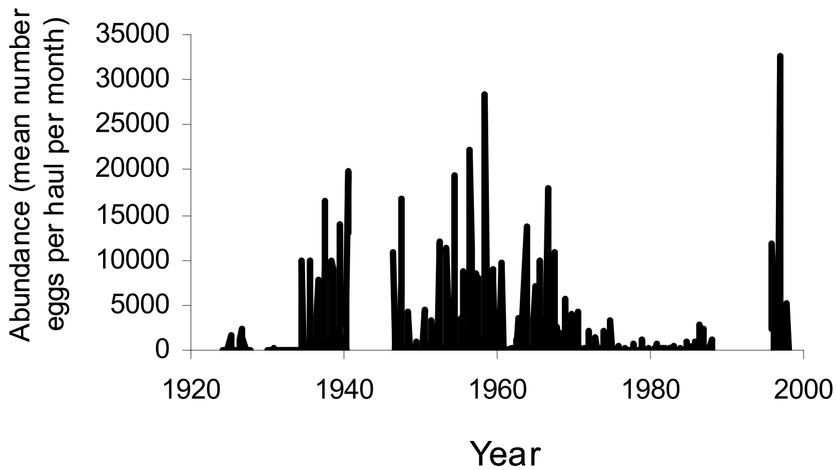

Figure 2 Monthly mean abundance of European pilchard eggs at ICES monitoring station L5 (50°11'N, 04°18'W).

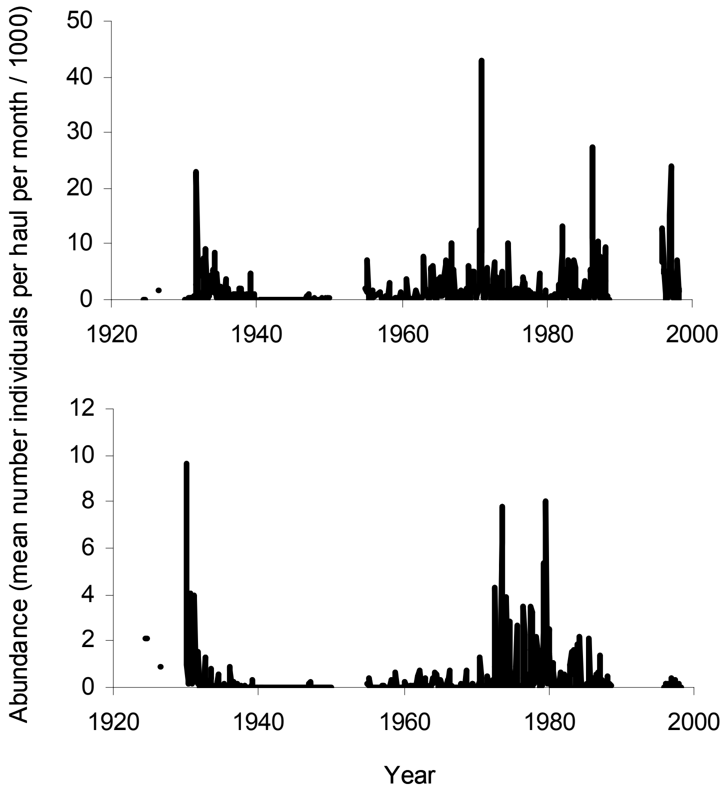

Figure 3 Monthly mean abundance of chaetognaths (arrow worms) at ICES monitoring station L5 ($50^{o}11$'N, $04^{o}18$'W): (a) *Sagitta setosa*; (b) *Sagitta elegans*.

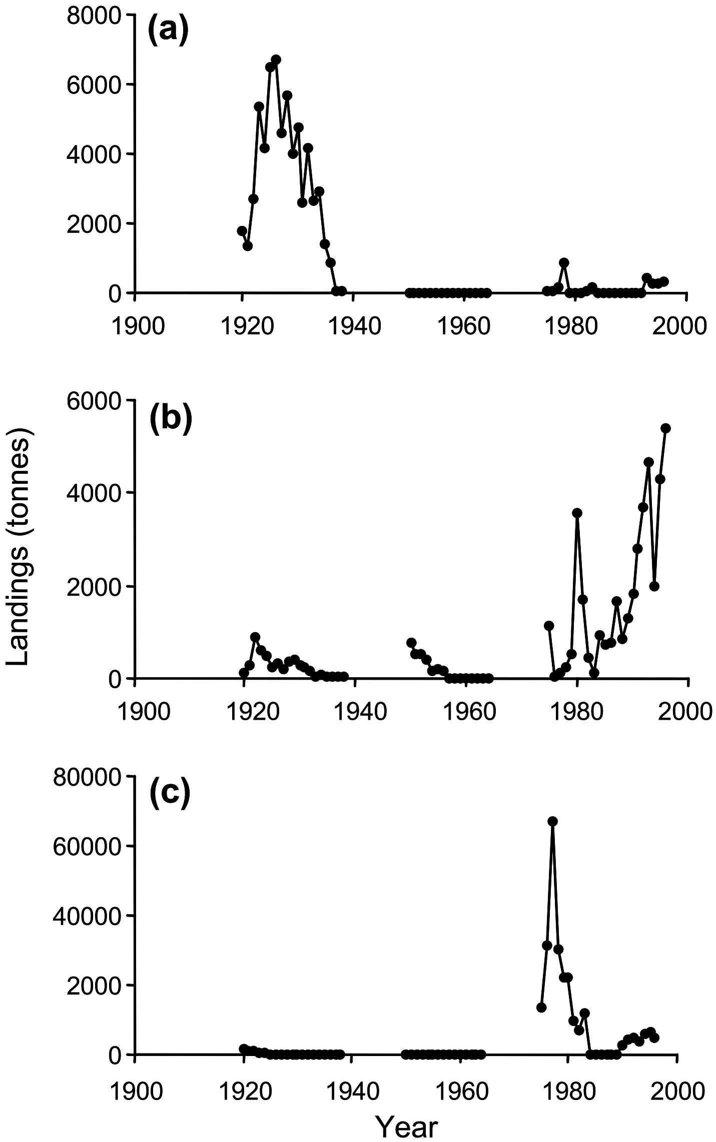

Figure 4 Annual landings of pelagic fish at Plymouth: (a) Atlantic herring; (b) European pilchard; (c) Atlantic mackerel.

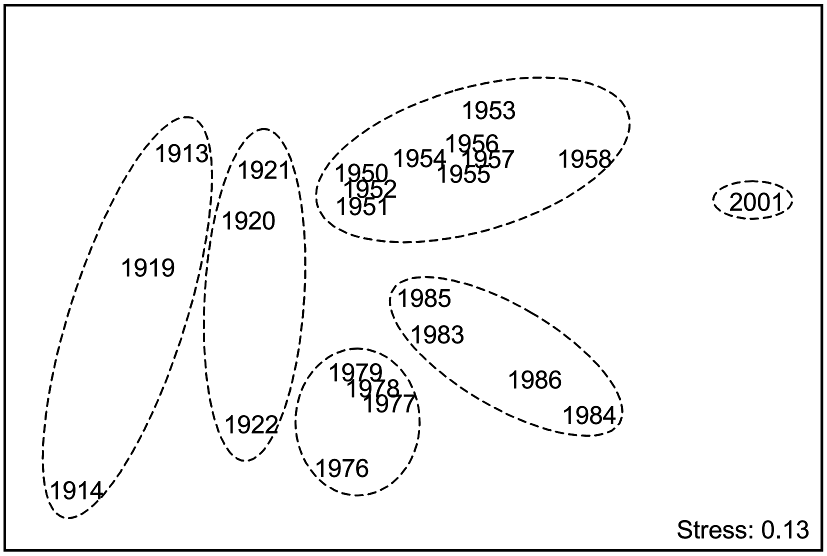

Figure 5 Multidimensional scaling (MDS) ordination plot of change in composition of the demersal fish community off Plymouth. Plot generated using the Bray-Curtis similarity index on annual species frequency of occurrence data within the computer package PRIMER 5 (PRIMER-E Ltd, Plymouth, UK). Closer points indicate more similar communities. Ellipses group decades and have no statistical relevance.

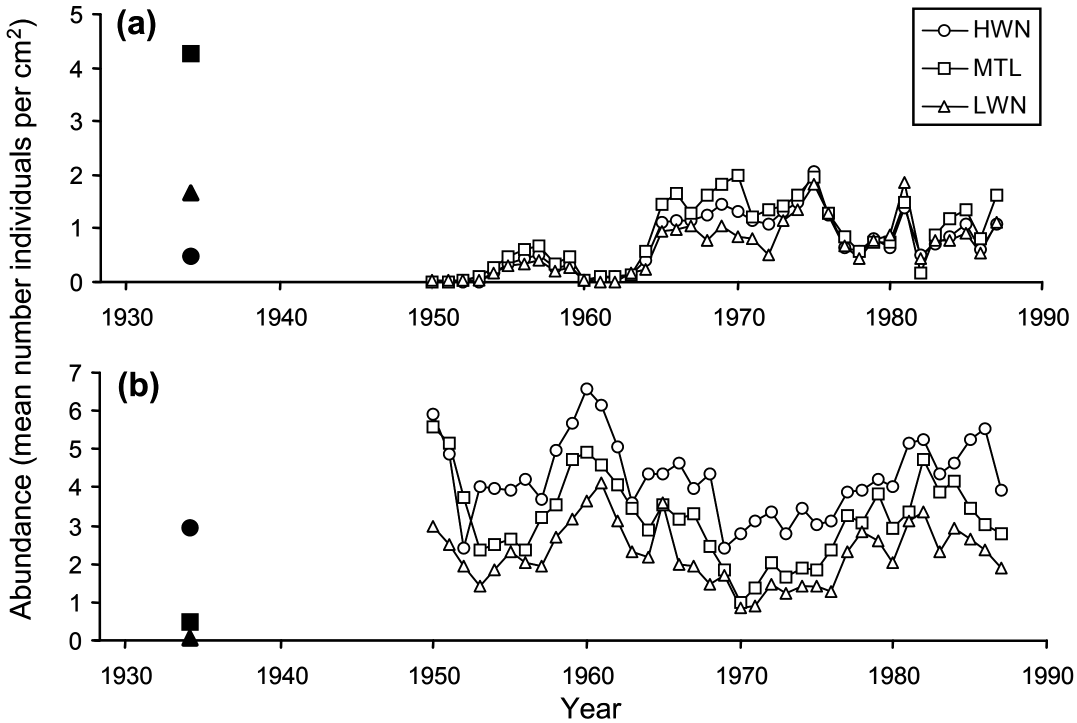

Figure 6 Annual abundance of two common intertidal barnacle taxa along the south coast of Cornwall, Devon and Dorset: (a) *Semibalanus balanoides*; (b) *Chthamalus montagui* and *Chthamalus stellatus* combined. Points represent means of eight localities at three tide levels, mean high water neap tide (HWN), mean tide level (MTL) and mean low water neap tide (LWN). Baseline survey data for 1934, indicated by solid symbols, are from three stations surveyed by Moore (1936).

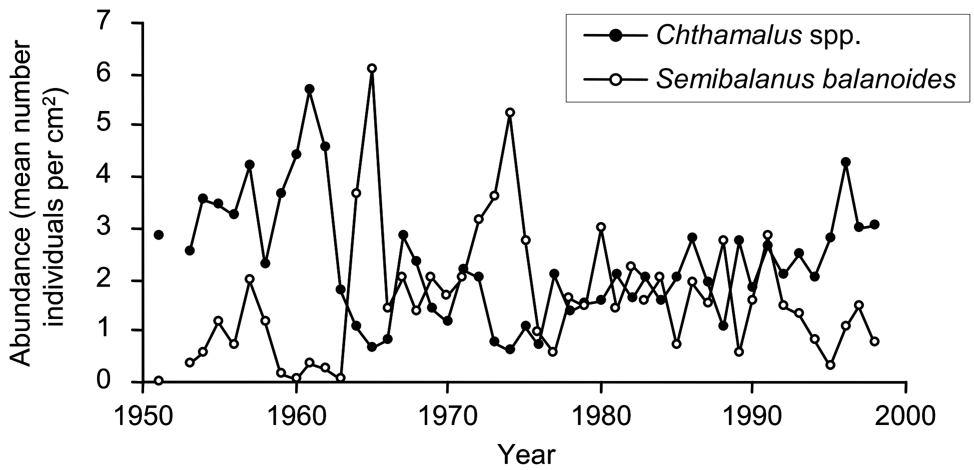

Figure 7 Abundance of *Chthamalus* spp. and *Semibalanus balanoides* at Cellar Beach, Yealm estuary, Devon. Points represent average abundance during each autumn over eight sampling heights between 2.20 to 4.68 metres above chart datum, for further details see Southward (1991).