Report No.

Analysis of long-term trends in the SOTEAG rocky shore monitoring programme: responses to climate change 1976-2014

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Summary

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Background

The Sullom Voe Environmental Advisory Group (SOTEAG) has presided over a 40-year programme of environmental monitoring in and around the Sullom Voe Oil Terminal in Shetland. The aim of this programme is to detect effects of the operations associated with the terminal on the ecology and chemistry of the local environment. To confidently attribute observed changes to such local operations, it has been important to understand the magnitude of natural fluctuations in biological populations and sources of potential contaminants other than the Terminal itself. Over the period of the programme, the warming influence of anthropogenic greenhouse gases on the global climate has become increasingly evident. In this report, the changes in rocky shore communities associated with climatic warming in Sullom Voe are documented using a measure of the average thermal affinity of the species present in the area; a novel method that shows that the composition of the communities around the shores of the Voe have tracked changes in sea surface temperature since 1976.

Main findings

- The composition of rocky shore communities in and around Sullom Voe has changed in line with expectations from the rise in sea surface temperature since 1976.
- Community Temperature Index values, the average thermal affinity of rocky shore species weighted by each species' abundance, increased from an average of 8.6°C in the late 1970s to around 9.3°C in the period since 2000. Average annual sea surface temperatures increased from around 9.4°C to about 10.3°C over the same period.
- Changes were consistent across all the sites in the survey programme with 13 out of 15 sites analysed showing significant increases in Community Temperature Index.
- The shift in average thermal affinity of community members was produced by a tendency for cold water species to decline and warm water specie to increase over the duration of the survey.

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1 INTRODUCTION

The Shetland Oil Terminal Environmental Advisory Group (SOTEAG) has maintained a programme of survey and monitoring centred on Sullom Voe since 1976, with the primary aim of detecting environmental effects of operations at the Sullom Voe Oil Terminal. Interpretation of changes in the ecology of the Voe and the coasts of Shetland and attribution of those changes to Terminal activities demands a broader understanding of changes in ocean systems in general and broader-scale change across the Scottish coast, the northwest European continental shelf, the north Atlantic and the global ocean. The resulting datasets on marine species and communities, mainly seabirds, benthic macrofauna and rocky intertidal animals and plants are large but have been well documented and are now available in digital form. Efforts to analyse patterns in the data have been fairly limited, but where analyses have been done, the results are very informative, showing, for example while changes in some species are highly localised some appear synchronised across the whole area (Burrows *et al.*, 2002).

A growing realization that increased anthropogenic greenhouse gases have caused significant climate change has focussed international efforts to understand the effects of such change on the oceans. The latest evidence for the causes of climate change and its effect on marine systems is summarized in the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC AR5), particularly in Chapter 30 of Working Group II (Hoegh-Guldberg *et al.*, 2014). Improved understanding of these changes, the ready availability of high quality climate data and the now-compiled nature of the SOTEAG long term ecological data have made the analysis of climate-related change in Shetland coastal ecosystems a priority. This is not just an academic exercise: identifying those ecological changes that are likely to be due to climate will improve the ability of the monitoring programme to detect effects of the Terminal itself.

1.1 Rationale

The annual reports of surveys of the rocky shores of Sullom Voe and nearby reference areas give species-by-species accounts of changes since the previous survey and statements of the long-term trend (Moore and Howson, 2015). The methodology is designed to detect effects of the terminal in several ways but mainly by showing that changes are localised to the area of the terminal, and/or are associated with a documented event such as a contaminant spillage or physical disturbance of the shoreline. All other changes are attributed to natural fluctuations. The purpose of this study is to determine the climate signal in the reported natural fluctuations. Here I follow the methods of Devictor *et al.* (2008); Devictor *et al.* (2012) who showed how communities of butterflies and birds responded to climatic change across Europe over the last 30 years.

This approach characterises each species by its thermal affinity, here taken effectively as the mid-point temperature in the geographical range and termed the Species Temperature Index (STI). The average of species thermal affinity across an entire community is obtained by weighting each species thermal midpoint (STI) value by the average abundance of that species, to give the Community Temperature Index (CTI). CTI values can be calculated for each site and averaged across all sites to give an average index for each year of the survey. Changes in annual CTI can be directly compared to annual changes in temperature, with the relationship between CTI and temperature showing the climate change response of the community.

Trends in the abundance of each species can also be related to their thermal affinity to see whether cold water species have declined and warm water species have increased, given an increase in sea temperature around Shetland over the last 40 years.

2 ANALYSIS

The analysis took two parts: the extraction of data on sea surface temperature changes around Shetland, and the analysis of species trends and thermal affinities and their aggregation into an index of community response to temperature.

2.1 Climate data

The focus of this analysis is confined to detecting responses to changes in temperature Sea surface temperatures (SST) were obtained from the UK Met Office's Hadley Centre HadISST v1.1 global sea-ice and SST dataset (Rayner *et al.*, 2003). These data are based on in situ observations and satellite-derived estimates, and were obtained from the British Atmospheric Data Centre (11). Data are available as monthly 1° grids from January 1870 to May 2014.

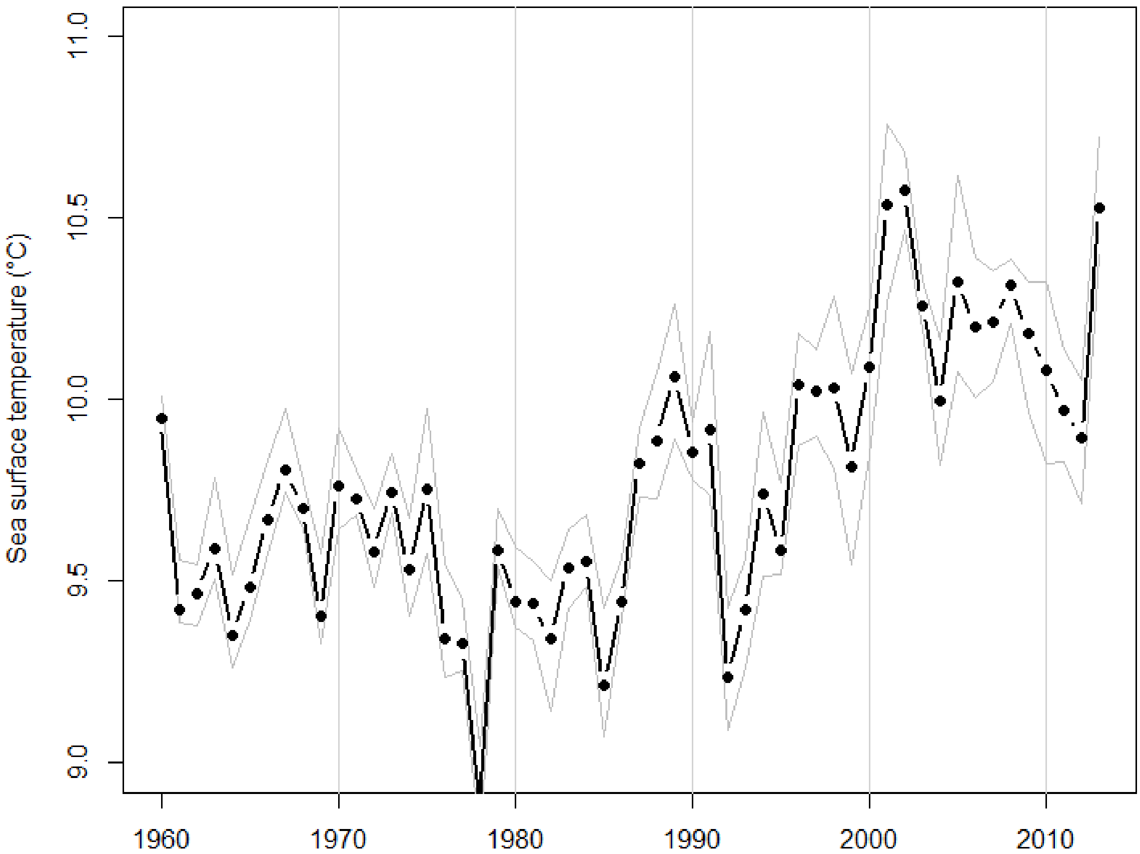


Figure 1: Changes in climate in seas around Shetland since 1960: (a) Sea surface temperature from the Hadley Centre HadISST1.1 dataset, extracted for the region (8°W to 1°E, 54°N to 61°N) and shown as the overall average annual temperature of the region (solid symbols and grey lines) and the maximum and minimum (upper and lower grey lines) average annual temperatures in 1° areas (62km EW by 111km NS).

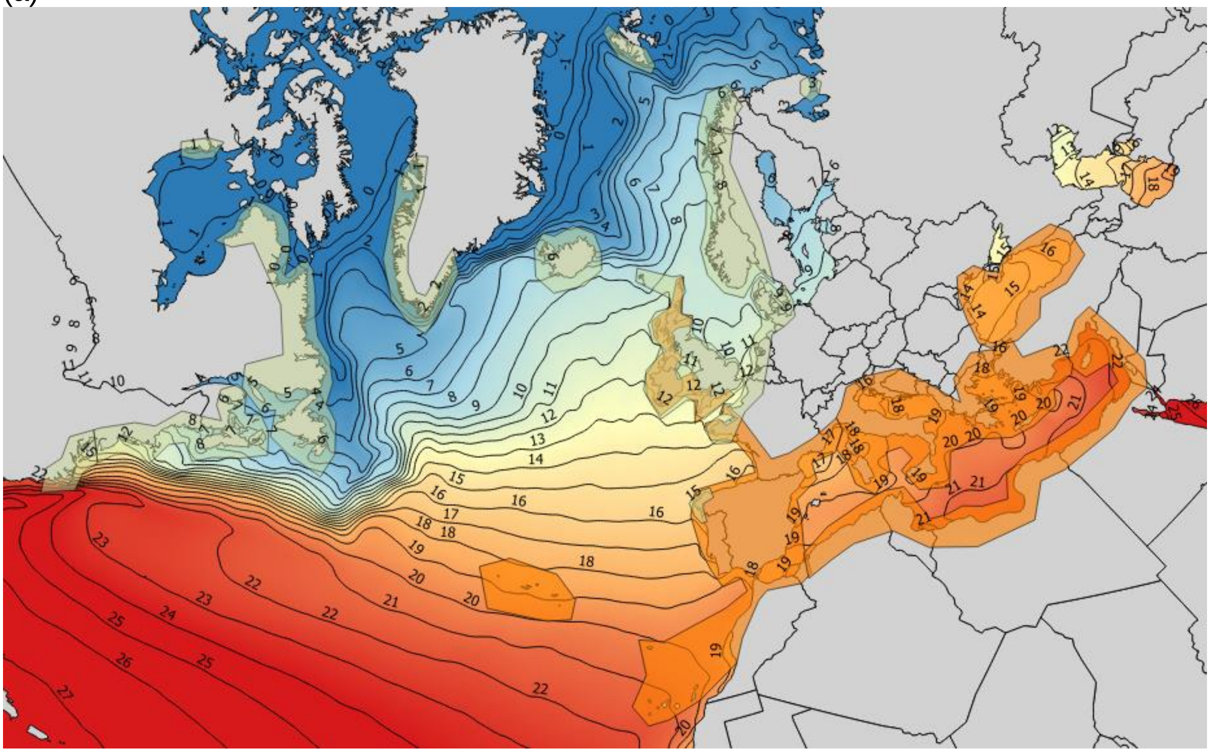
2.2 SOTEAG rocky shore data

The Community Temperature Index (CTI) is the average of all species' thermal affinities of all the species in a community weighted by each species' abundance (Devictor *et al.*, 2008; 2012). Global distributions of species are used to define their thermal niches, (STI here designated T_i), the temperature in the middle of the geographical range of the species weighted (w_i) by their abundance or presence in a community of *n* species to produce index values:

$$CTI = \sum_{i}^{n} T_i w_i \Big/ \sum_{i}^{n} w_i$$

Geographical ranges for species present in SOTEAG surveys were derived from literature records and drawn as polygons (Figure 2a). The polygons were then used to extract values for average sea surface temperature in coastal 0.25 degree latitude/longitude cells over the period 1982-2011 from the NOAA OISST HR dataset. The percentiles of the distribution of SST values occupied by the species were then used to describe the species thermal range, with the 50%ile (median) value giving the Species Temperature Index (Figure 2b). This process has been completed for 58 species to produce STI values (Figure 3)

(a)



(b)

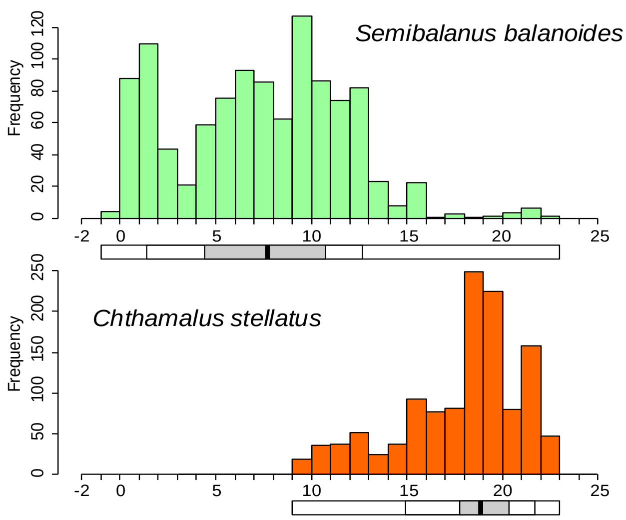


Figure 2: (a) North Atlantic distributions of two UK barnacles: Lusitanian *Chthamalus stellatus* (orange) and boreal *Semibalanus balanoides* (light green) from literature records. (b) Frequency distribution of temperature in 0.25dg coastal cells within each species range. Horizontal bars show thermal niches as minimum, 10%ile, interquartile range (grey), median (thick line), 90%ile and maximum. Temperatures from the NOAA Optimal Interpolation Sea Surface Temperature (SST) dataset (OISST HR), showing the average annual SST for 1982-2011.

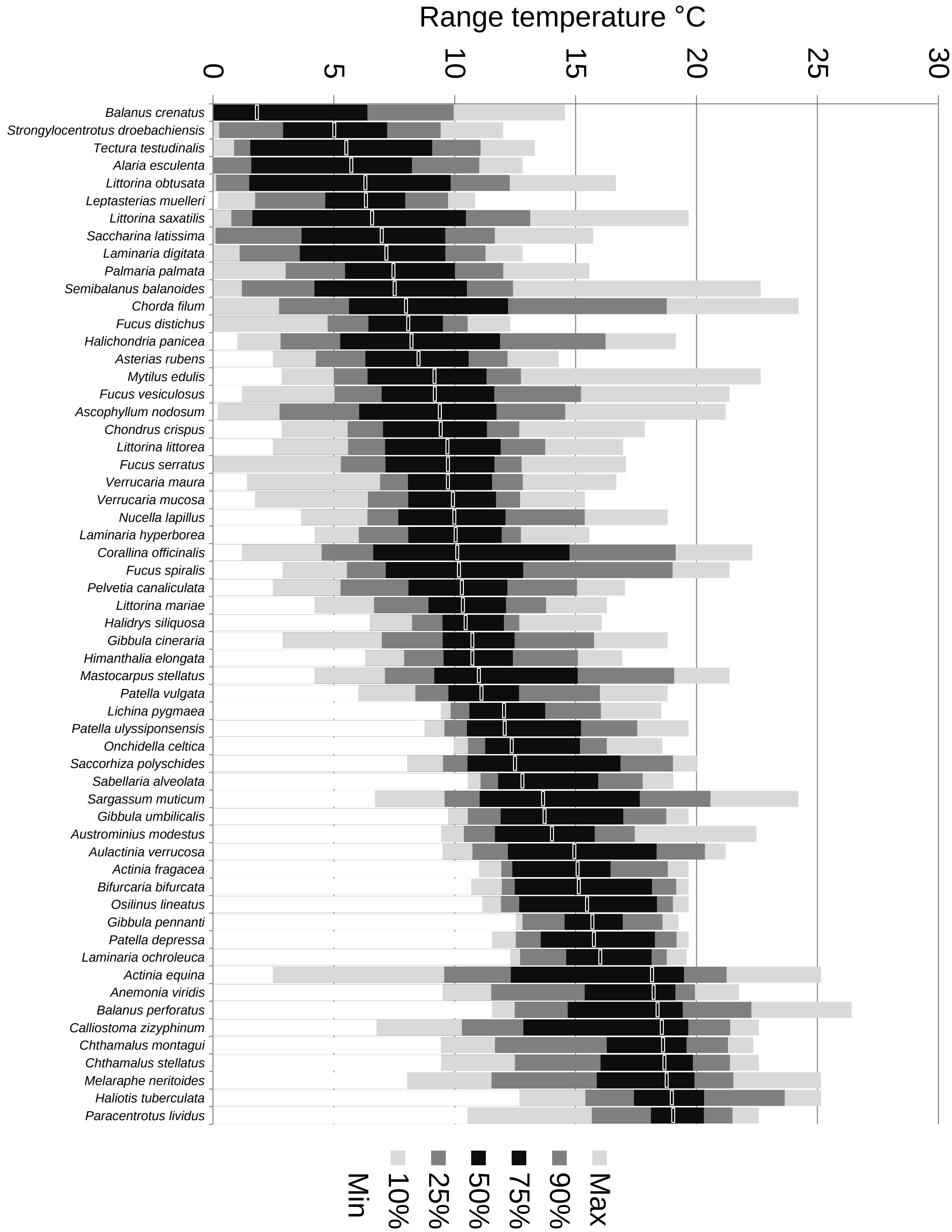


Figure 3: Thermal ranges for UK rocky intertidal species as defined by percentiles of average sea surface temperatures throughout their global distributions. Species are arranged in order of their Species Temperature Index values; the 50%ile or median average sea surface temperature across their range.

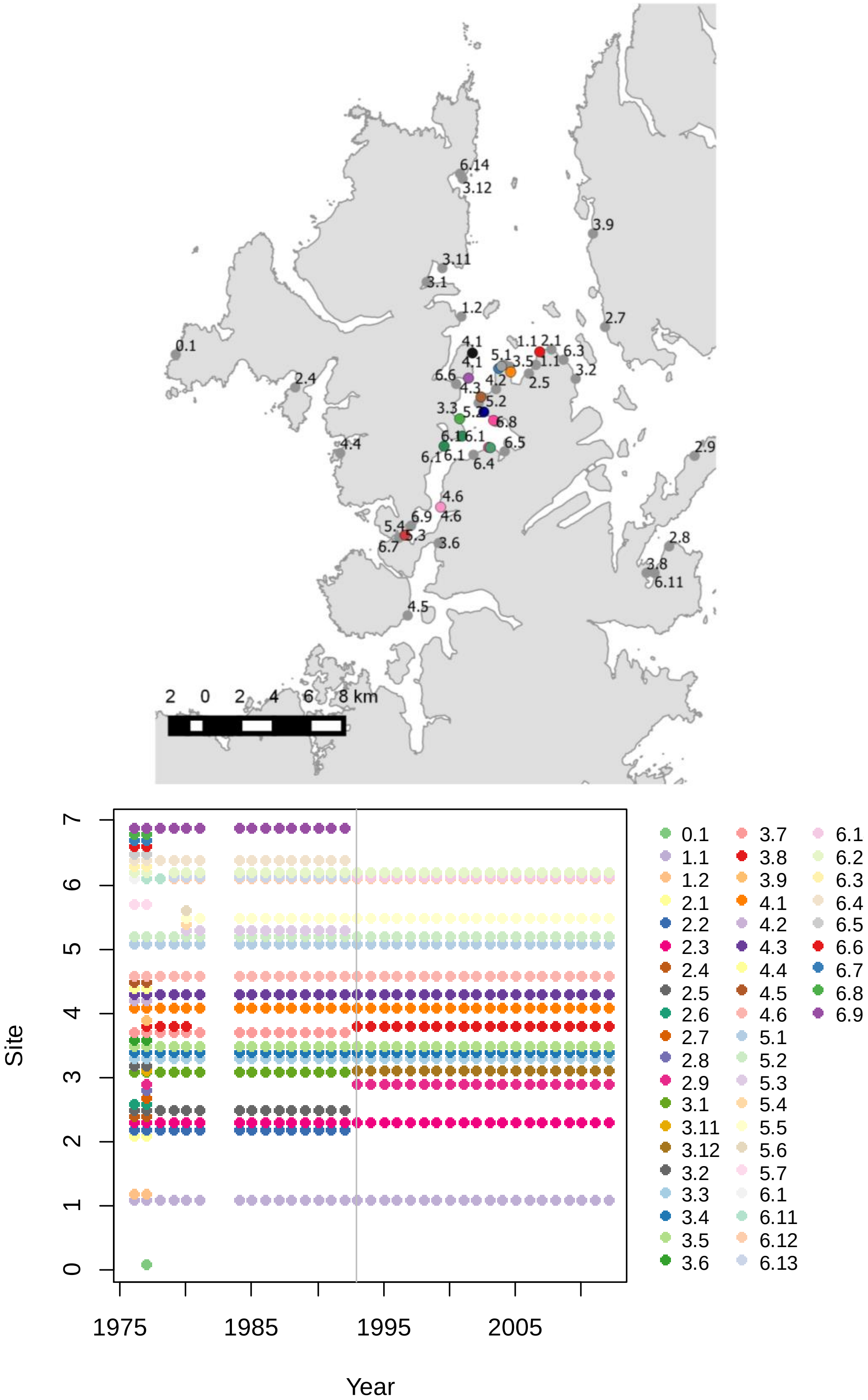


Figure 4: (a) Locations of SOTEAG rocky intertidal monitoring sites. Locations used in the analysis in this report are shown by coloured symbols, those not used are shaded in grey. (b) Spatio-temporal coverage of the monitoring scheme. The scheme was modified in 1993 to allow more robust surveys of fewer sites in the Voe and more reference sites outside the Voe. Note colours for sites do not correspond in plots (a) and (b).

2.2.1 Changes in Community Temperature Index from 1976-2014

The rocky shore programme has had several distinct phases during which different sets of sites were annually surveyed in summer. In 1976-1977 at the start of the programme, 41 sites (Figure 4) were surveyed to give a broader perspective on rocky shores in the area (Hiscock, 1981). Of these, 22 were then regularly surveyed until 1992, when a change in methodology required a refocussing of effort from many shore levels assessed cursorily at sites in the Voe, to a more thorough survey of fewer levels at Voe sites and additional extra Voe sites to give better localisation of changes. Since this report aims to determine the climate-driven element of long-term change, a subset of 15 sites was selected (Table 1) including those sites that were surveyed for the longest span of years in the survey.

For the selected sites, average abundances were calculated for each site and for those shore levels surveyed throughout the period. Categorical abundance values (SACFORN) were replaced by the integers 0 to 7, representing absent (0) to superabundant (S), for calculations of average abundance. Where species were not recorded at a particular shore level on a survey, the abundance at that level was set to zero. The average abundance class was used in the calculation of the Community Temperature Index for that site/year.

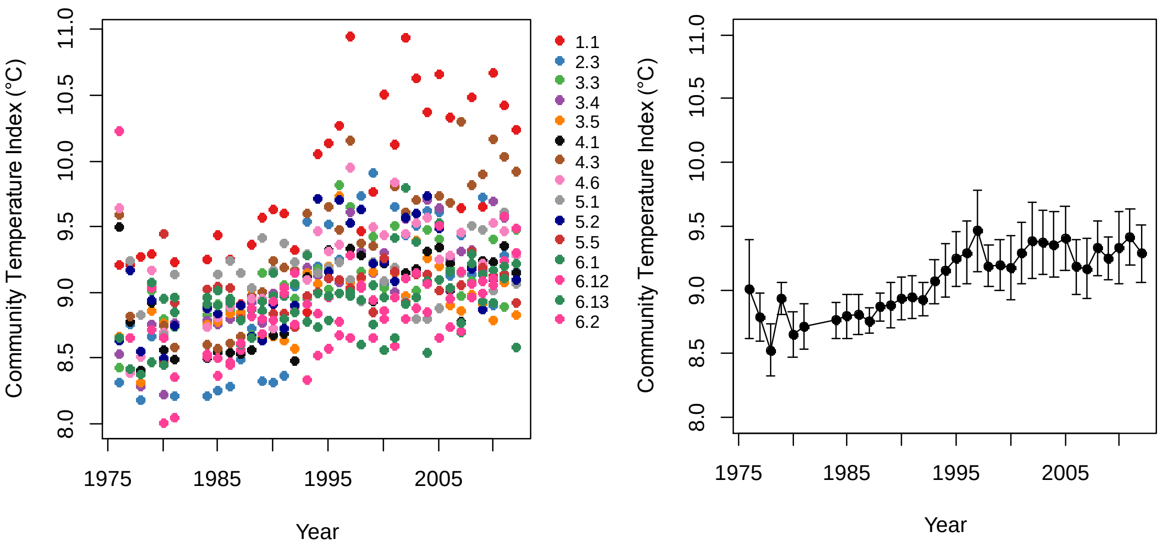


Figure 5: Community Temperature Index values (a) for selected sites sampled nearly annually between 1976 and 2012; (b) as an annual mean with 95% confidence intervals based on the standard deviation of the mean and n=15 sites (Student's t for 14 degrees of freedom multiplied by the standard error of the mean).

Table 1. Trends in CTI by site from linear regressions

Site	n	Slope (°C/yr)	P	Sig	Site	n	Slope (°C/yr)	P	Sig
1.1	35	0.04442	<0.00001	***	5.1	35	0.00488	0.19528	ns
2.3	35	0.03629	<0.00001	***	5.2	35	0.01781	0.00073	***
3.3	35	0.02047	0.00002	***	5.5	31	0.00476	0.13848	ns
3.4	35	0.03116	<0.00001	***	6.1	35	0.01396	0.00624	**
3.5	35	0.01064	0.00900	**	6.12	32	0.01168	0.00664	**
4.1	35	0.01921	0.00008	***	6.13	32	0.00647	0.02971	*
4.3	35	0.03991	<0.00001	***	6.2	34	0.01889	0.00702	**
4.6	35	0.02198	0.00005	***					
5.1	35	0.00488	0.19528	ns					

A general increase in Community Temperature Index values was seen, shown by the increase in mean CTI across all 15 selected sites (Figure 5b) and significant (P<0.05) regressions of site-specific CTI values over time for 13 of the 15 sites (Table 1). The average rate of change in CTI across all sites was 0.201 (± 0.003 standard error) °C/yr.

2.2.2 Species changes as a function of thermal affinity

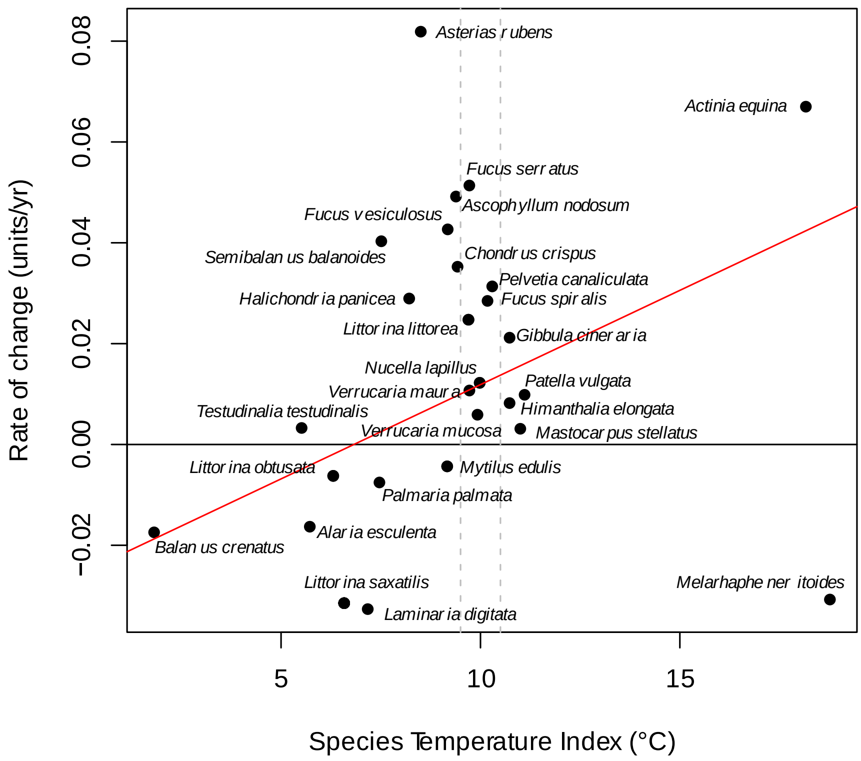


Figure 6: Trends in abundance by species for the period 1976-2012 shown by regression of site-year average abundance values against year of survey. Regression line in red (P=0.02). Vertical dashed lines show the range of average annual sea surface temperatures in Shetland during the same period.

As expected from the changes in Community Temperature Index, the trends in abundance among species approximately followed a pattern of decreases where the species thermal affinity was for temperatures less than those experienced in Shetland (cold-water species), and increases for those affinity was for temperatures the same or warmer than as those experienced in Shetland (Figure 6). The relationship between change and STI was, however, not so strong and potentially influenced by one or two outliers in the dataset, notably the rarely recorded high shore snail, *Melarhaphe neritoides.*

2.2.3 *Community Temperature Index versus sea surface temperature change from 1976-2014*

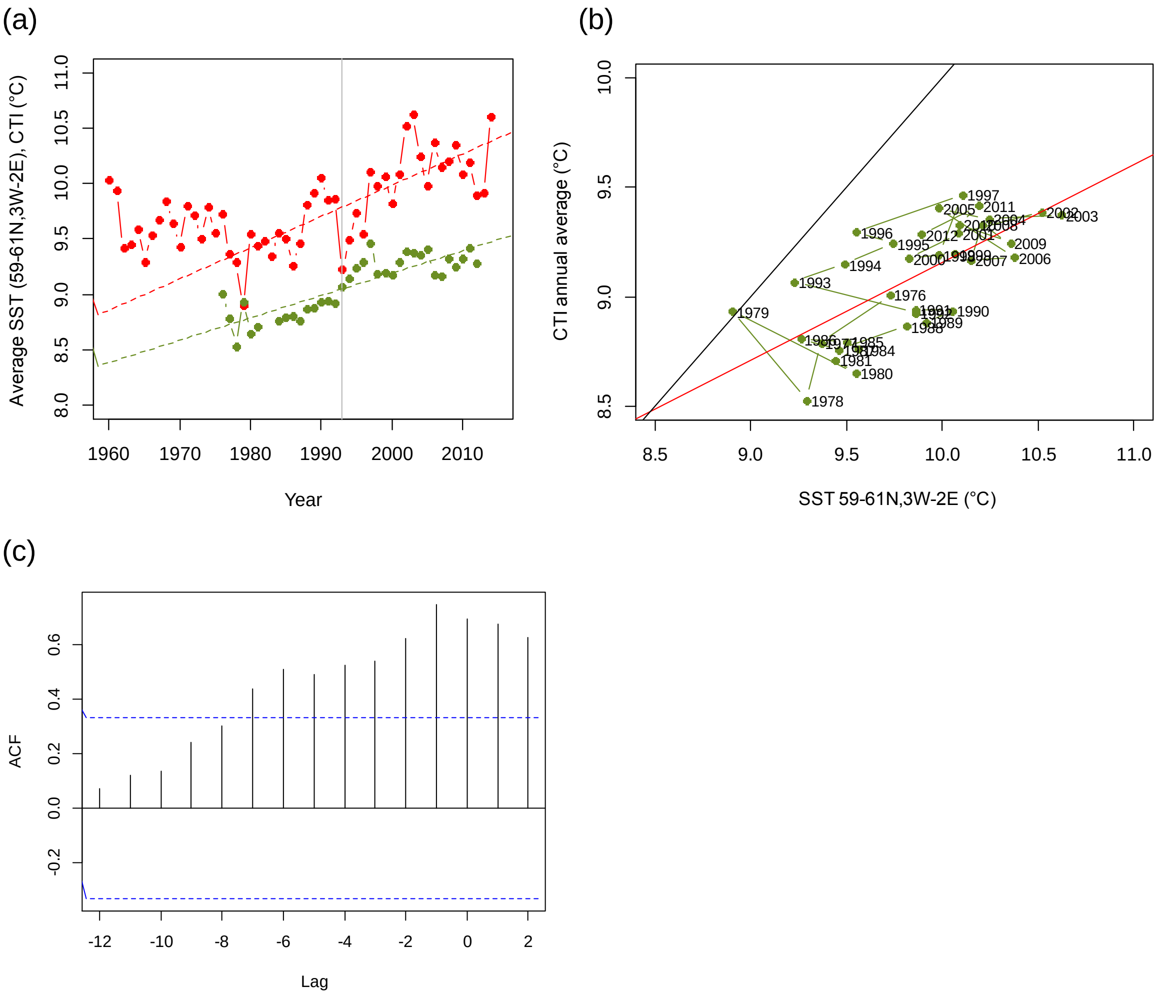


Figure 7: Community Temperature Index versus sea surface temperature (SST) from 1976 to 2012 (a) as time series (CTI, green; SST, red). Dashed lines show linear trends from 1976-2012; (b) as a bivariate plot, with the linear trend line shown in red (CTI = 4.69 (± 0.79 standard error, henceforth s.e.) + 0.446 (± 0.080 s.e.).SST; P<0.001, df 33) and the line of equality shown in black. (c) Cross-correlation function of CTI against SST, showing significant positive correlations (above blue dotted line) between CTI and temperature for time lags up to 7 years.

Sea surface temperature and average annual Community Temperature Index showed very similar changes between 1976 and 2012 (Figure 7a), with SST increasing at 0.028 °C/yr (± 0.004 s.e.) and average annual CTI by 0.020 °C/yr (± 0.004 s.e.). The slower increase in CTI relative to SST is reflected in the relationship between the values of each across 35 years of surveys (Figure 7b), where a 1°C rise in SST scaled to a 0.45 °C in CTI. The change in methodology (vertical grey line on Figure 7a) did not produce a noticeable change in CTI. The potential for a time lag in response of the community species composition is shown by Figure

7, a cross correlation plot showing significant correlation between CTI and SST annual values up to 7 years before the time of surveys. This pattern of significant correlations over a long lag period may be expected with two time series dominated by a gradual upward shift in values.

3 DISCUSSION

This analysis has produced powerful evidence to show that changes in rocky shore communities around Sullom Voe since 1976 are in line with the expectations of a warming climate. The composition of shore communities has shown a shift in dominance from cold-water species towards warm-water ones, with the latter tending to increase while the former decreased over the same period. The Community Temperature Index approach (Devictor *et al.*, 2008; Devictor *et al.*, 2012; Stuart-Smith *et al.*, 2015) captures this shift in dominance very effectively and produces a metric whose changes closely follow changes in sea surface temperature when applied to rocky intertidal communities around Sullom Voe.

Changes in abundance of dominant species in a community as a measure of a response to climate have been used in the rocky intertidal for many decades. Southward and Crisp (1954); (1956), for example, noticed that the cold water barnacle *Semibalanus balanoides* had declined significantly between the mid-1930s and early 1950s in southwest England, while the warm water barnacle *Chthamalus stellatus* had increased, probably because of a release from competition with its northern competitor (Poloczanska *et al.*, 2008). Monitoring of these two species (now three since the separation of *C. stellatus* into two similar species) showed that the sensitivity of these barnacle species to decadal changes in temperature continues to the present day (Mieszkowska *et al.*, 2014). The cold water *Semibalanus balanoides* re-emerged in a colder period in the 1960s and 1970s only to decline again in the warming 1990s and beyond. The ratio between these two species has been suggested as a 'Warm Index' for barnacle populations in the UK. Using the Community Temperature Index is a natural progression from this climate-sensitive species approach, albeit with the requirement for tracking changes in abundance across the whole rocky shore community. While this is more demanding in terms of data collection than just assessing a handful of sensitive species, usually those at the edges of their geographical distribution ranges, CTI is a more representative measure for the whole community.

Community composition showed a smoother change than did sea surface temperature, with a steady increase over the period of the monitoring scheme. This is not surprising given the longevity of most organisms living on rocky shores. Large brown seaweed plants of the genus *Fucus*, the wracks, typically live for two to four years (Knight and Parke, 1950), with some species living considerably longer, notably the egg wrack, *Ascophyllum nodosum* (Rees, 1932) where individual fronds can last for 10-20 years and holdfasts, the bases of the plants, are effectively perennial and last for 100s of years. Short-lived species, such as the barnacle *Semibalanus balanoides,* living for 1-2 years may be more responsive to short term fluctuations in climate. Differences in the timescales of sensitivity to change may be worth investigating further. The implications for the interpretation of changes in the SOTEAG rocky shore dataset are clear: climate change effects at the community level are likely to emerge over decadal timescales and longer.

The SOTEAG dataset is one of few globally that can be used to detect the effects of climate on rocky shore communities across the world. It demonstrates the overriding importance of continuity of such studies in their capacity to detect effects of climate change and, in the current configuration of annual surveys across a network of sites of varying proximity to the Oil Terminal, to discriminate natural fluctuations (here including climate change despite the anthropogenic cause) from local Terminal-related activity. Other similar monitoring programmes were started at the same time in the UK, such as the Coastal Surveillance Unit based at Menai Bridge on Anglesey set up in 1973 and funded by Shell UK (Bennell, 1981; Jones *et al.*, 1979), but few have persisted to the present day in a comparable form. The MarClim project (Mieszkowska *et al.*, 2005), set up in 2000 to repeat surveys first made in the 1950s by Southward and Crisp (such as Crisp and Southward, 1958), collects similar data to the SOTEAG rocky shore surveys but does not have the time span of the Shetland-based work and does not have a solid foundation as a part of an integrated programme. The MarClim project does however, have a much broader geographical scope, extending throughout the UK and Ireland and does have a series of annually surveyed sites in England and Wales, and a more irregularly surveyed (2-4 years) set of sites across Scotland. The broader scale surveys are very useful to put the results of the SOTEAG programme into context. Scottish Natural Heritage recently commissioned a resurvey of the Scottish sites within the MarClim programme, and a similar analysis to the one presented here using that data shows a comparable change in community composition that matched temperature change (Burrows *et al.*, 2016), that is, very little change in CTI and SST across Scotland from 2002-2006 to 2014-2015.

The closest rocky shore survey programme is that set up by the Orkney Marine Biology Unit of Dundee University (Baxter and Jones, 1989; Baxter *et al.*, 1985). Little is known of the changes in Orkney after the mid-1980s, but there is a move to digitise data collected after this time in records currently stored at the Orkney Islands Council Marine Services Marine Environmental Unit (http://www.orkneyharbours.com/marine_environmental_unit.asp). It will be informative to compare the changes in Orkney with those seen in the SOTEAG rocky shore surveys once the process of processing the Orkney data is complete.

Integrating analysis of long-term changes across different components of the SOTEAG environmental monitoring programme, and with global and regional datasets on physical and ecological changes in the ocean, should be a goal of periodic analyses of trends in the SOTEAG data. This analysis has concentrated on the changes in the light of temperature changes in the ocean, and to that end the relatively coarse Hadley Centre 1-degree (latitude/longitude) HadISST dataset has proved effective. Comparison with other datasets, including changes in phytoplankton production from ocean colour data, nutrient concentrations, and within the SOTEAG programme, the changes in the abundance of macrobenthos and seabirds, should be considered as part of any future look at the effects of climate change on the ecology of Sullom Voe and beyond.

4 CONCLUSIONS

It is recommended that this analysis be repeated at 5-year intervals to assess further changes in the rocky intertidal of Sullom Voe. While changes to the design of the monitoring programme may improve its capacity to detect change due to Terminal operations, great care must be taken not to compromise its effectiveness in detecting change over the longer term.

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