

Ocean surface warming: The North Atlantic remains within the envelope of previous recorded conditions

Victoria J. Hobson^{a,*}, Clive R. McMahon^{a,b},
Anthony Richardson^{c,d}, Graeme C. Hays^a

^a*Department of Biological Sciences, Institute of Environmental Sustainability, Swansea University, Singleton Park, Swansea SA2 8PP, UK*

^b*School for Environmental Research, Charles Darwin University, Darwin, NT 0909, Australia*

^c*Department of Mathematics, University of Queensland, St Lucia, Qld 4072, Australia*

^d*CSIRO Marine Research, Cleveland, Qld 4163, Australia*

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Abstract

Anomalously warm air temperatures in various parts of the world have been widely noted in recent decades. In marine systems, biological indicators such as the range of plankton and fish have been used to indicate impacts of ocean warming, although for many regions recent ocean warming does not exceed short-term warming events over the last two centuries. Here we use International Comprehensive Ocean-Atmosphere Data Set (ICOADS) sea-surface temperature data to update analysis in the North Atlantic to show that present warm conditions are currently no more persistent than those encountered in the last 150 years. We show that the position of various isotherms, which play a central role in influencing the distribution of marine taxa ranging from plankton to fish and turtles, are more regularly found further north in recent years than at any time since the 1850s.

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1. Introduction

There is increasing evidence that warming global temperatures will have profound effects on the Earth's ecosystems (Peñuelas and Filella, 2001; Thomas et al., 2004), with the global mean air surface temperature rising by around 0.6 °C during the 20th century, with 11 of the last 12 years (1995–2006) ranking amongst the 12 warmest years in the instrumental record of global surface temperature since 1850 (IPCC, 2007). Oceans may

play a crucial role in regulating the climate (Folland et al., 2001), and since the 1950s the heat content of the world's oceans has increased by $\sim 2 \times 10^{23}$ J, equivalent to a mean volume warming of 0.06 °C (Levitus et al., 2000). While this increase is an order of magnitude less than that observed for terrestrial systems it may be even more important as water heats at a much slower rate than air because of its heat capacity. The North Atlantic region is of particular importance to the global climate system (Deser and Blackmon, 1993; Hurrell and Van Loon, 1997) because of the formation of bottom water in its northerly latitudes, which drives the thermohaline circulation. This circulation moderates daily

*Corresponding author. Tel.: +44 1792 205678.

E-mail address: bsvhobson@swansea.ac.uk (V.J. Hobson).

and seasonal global temperature fluctuations, regulated by the ocean's high heat capacity. Recent debate over measurements showing the slowing down of the North Atlantic Drift (Bryden et al., 2005; Schiermeier, 2006a) has prompted concern. The North Atlantic has undergone a net warming since 1976, and this recent warming parallels similar warming from 1910 to 1945. Between these two recent warming eras the North Atlantic cooled by 1 °C (Folland et al., 2001). Whether these changes form part of a natural cycle or part of a long-term trend of progressive ocean warming is hotly debated (Levitus et al., 2000; Schär et al., 2004; Bryden et al., 2005; Hegerl and Bindoff, 2005; Moberg et al., 2005). Also of immediate concern is that commercially important fish such as cod and tuna (Block et al., 2001), might become regionally extinct because of rising temperatures with consequent socio-economic impacts (Righton et al., 2001; Beaugrand et al., 2003; Perry et al., 2005). There are portents that the North Atlantic might be entering a state that has not been encountered in its recent history. For example, the North Atlantic Oscillation (NAO), which shows pronounced multi-annual and multi-decadal fluctuations (Taylor, 2005), has in recent years been recorded at its most extreme positive state in the 175-year instrumental record (Hurrell et al., 2001).

Previous analyses using the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (Worley et al., 2005) have revolved around using basin-wide or global views of the oceans (Gregory et al., 2002). The ICOADS has been utilized to reconstruct marine temperatures over the last 150 years in the Pacific (Urban et al., 2000), to examine the El Niño/Southern Oscillation (ENSO) (Zhang et al., 1998) and as the input for climate models (Vecchi et al., 2006). Variations in the sea-surface temperatures (SSTs) in the ICOADS are similar to those in the Hadley Centre reconstruction Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) produced by the Met Office.

Our analysis uses ICOADS (Worley et al., 2005) to give a concise view of the isotherm movements and SST changes in the North Atlantic and the variance in the local environmental conditions over the past 150 years. This novel approach, using isotherms to track the northward variation in SSTs over the last century and a half has enabled us to determine the extent to which marine animal's range extensions may be affected by climate change.

Here we examine pan-North Atlantic SSTs for the last 150 years, updating previous analysis

reported several years ago by the Intergovernmental Panel on Climate Change (IPCC). Specifically we determined the mean position of the 12, 15 and 18 °C isotherms in the North Atlantic for August and September from 1854 to 2005. We show that recent warming is no more extreme than the warming experienced during the 20th century.

2. Materials and methods

SSTs were obtained from NOAA NCDC ERSST version 2, an improved, extended reconstruction of global SST data based on ICOADS (Worley et al., 2005) monthly summary trimmed group data (<http://www.cdc.noaa.gov/>). The data represent the most recently available and complete historical dataset for global SST values. ICOADS (Worley et al., 2005) incorporates up-to-date, sophisticated statistical methods that allow the reconstruction of SSTs from sparse data (Smith and Reynolds, 2004). The SST data consist of monthly means calculated from in-situ measurements aboard ships, drifters and moored buoys, and since 1981, satellite data. There are both spatial and temporal biases in the data; the opening of the Panama and Suez Canals affected ship passages, and the World Wars reduced shipping traffic and restricted areas travelled. Thus, the dataset is more complete, with the least uncertainty in the post-World War II era. The advent of satellite data from 1981 resulted in improved global coverage with fewer data gaps (Smith and Reynolds, 2004). The ICOADS (Worley et al., 2005) Version 2 provides data with a grid spacing of 2° latitude; the latitudes have been interpolated between grid points using a cubic spline regression method. The effective resolution of the interpolation is to 1° latitude.

Kent and Taylor (2006) have shown that there are some discrepancies in the methods of estimation of SST. Inconsistencies arise, for example, from the choice of bucket used to collect surface water, or the method of sample collection (bucket versus engine intake), the bias in SST due to different observational practices may amount to 0.3 °C on average. Corrections have been applied to the data to account for the changing construction and use of buckets used to collect the water samples on ships (Smith and Reynolds, 2002; Kent and Taylor, 2006). The data product is screened to remove any outliers by checking individual normalized anomalies against a normalized local analysis of anomalies (spatially and temporally). Individual observations

differing too much from their neighbours are flagged as bad. The mean value of observations not flagged as anomalous are then applied to the appropriate gridded cell.

The mean summer position of the 12, 15 and 18 °C isotherms in the North Atlantic for August and September from 1854 to 2005 were determined at 2° longitudinal intervals. These three isotherms were chosen as indicators of the summer SST behaviour across the North Atlantic as they lie in the region of most marked seasonal warming and cooling, and so are sensitive indicators of inter-annual thermal variability of the North Atlantic. The sensitivity of ICOADS is affected by many sources of error: observational, sampling and temporal. To determine how sensitive and reliable the ICOAD SST values are we compared the mean summer position of the 15 °C isotherm derived from ICOADS to the mean summer position of the 15 °C isotherm determined from AVHRR pathfinder monthly composites of August for a 20-year period from 1985 to 2005. The latitudinal position of the 15 °C isotherm was located at 2° longitude intervals from 55°W to 10°E from the geo-referenced SST AVHRR pathfinder data supplied by Plymouth Marine Laboratory as part of the NERC Remote Sensing Data Analysis Service. The approximate summer position of these isotherms also corresponds with the distribution of a range of vertebrates (McMahon and Hays, 2006) and invertebrates that have shown marked range shifts (Parmesan and Yohe, 2003; Root et al., 2003; Parmesan et al., 2005). The importance of the 15 °C isotherm for oceanic carbon sequestration is also detailed by Behrenfeld et al. (2006) where this SST indicates the most northerly and southerly limit of net primary production.

Principal component analysis was performed on a matrix of isotherm positions for each year, this included, for the 12 °C isotherm: longitudes 52–1°W, years 1919–1939 and 1948–2005; for the 15 °C isotherm: longitudes 52–11°W, years 1854–2005 and for the 18 °C isotherm: 1874–2005, excluding 1884–1885, 1940–1943 and 1945. Data near the coast were removed from the analysis because of the thermal effects of solar heating of the land and its impact on SST. Principal component 1 (PC 1) was then compared to the mean summer position of each isotherm.

The mean position of the isotherms from 1854 to 2005 was ranked. To ascertain the probability that the observed number of recent extreme years might

occur by chance, bootstrap simulations (10,000 iterations) (Sokal and Rohlf, 1994) were run using the observed mean and standard deviation of isotherm positions for the complete time-series. Each year value was chosen randomly from the entire pool with replacement (Crawley, 2002).

3. Results

The validation of the AVHRR mean summer northerly latitude derived from weekly composites compared to the mean summer northerly latitude derived from the ICOADS data shows a strong correlation (Fig. 1). Although the AVHRR data may not be the most effective for capturing absolute values (Zolina and Gulev, 2003), this exercise demonstrates that although there is variation between the sampling methods, the pattern of isotherm movement is similar, confirming that the ICOADS isotherm estimates are a good approximation of the movement of SSTs. Principal component analysis reveals that the mean position provides a good index of the overall behaviour of the 12, 15 and 18 °C isotherms, where the mean position of each isotherm was strongly correlated with PC 1 ($r^2 = 0.72, 0.98$ and 0.97 , respectively) and the percentage of loading of the first principle component for the three isotherms were 47.0%, 72.6% and 59.4%, respectively.

The mean summer positions of the 12, 15 and 18 °C isotherms show considerable interannual variability. For example, between 1974 and 1975 the mean position of the 15 °C isotherm moved from

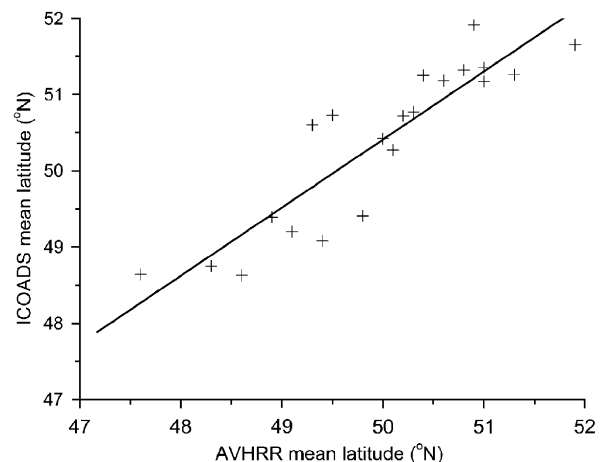


Fig. 1. The correlation of the mean summer position of the 15 °C isotherm from 1985 to 2005 derived from AVHRR images and ICOADS data, $r^2 = 0.807$.

48.20°N to 50.35°N, a distance of 239.3 km with a general northward trend in recent years (1993 to present) in particular (Fig. 2). By reducing the three isotherms to zero mean and unit variance, the summer positions of all three isotherms could be combined in an overall index of isotherm position (Fig. 3). Isotherms have tended to move northwards during two distinct periods: in the 1930s–1940s and then again at the end of the 20th century. The chances of this occurring randomly are negligible ($n = 10,000$; $p > 0.0001$).

Overall the northerly latitude reached by the isotherms was consistent between these two warm eras. This conclusion is reached if the combined isotherm position is examined (Fig. 3a) or the individual isotherm positions (Fig. 3b–d). For example, if we consider the 15 °C isotherm, this reached a maximum latitude of 52.0°N in 1932, and a latitude of 51.7°N in 2005, a difference of approximately 33 km.

The rate of northerly movement varied between isotherms and eras. For example, between 1926 and 1939 the 12 °C isotherm moved northwards at a rate of $\sim 7 \text{ km y}^{-1}$, while between 1992 and 2005 it moved northwards at a rate of $\sim 27 \text{ km y}^{-1}$

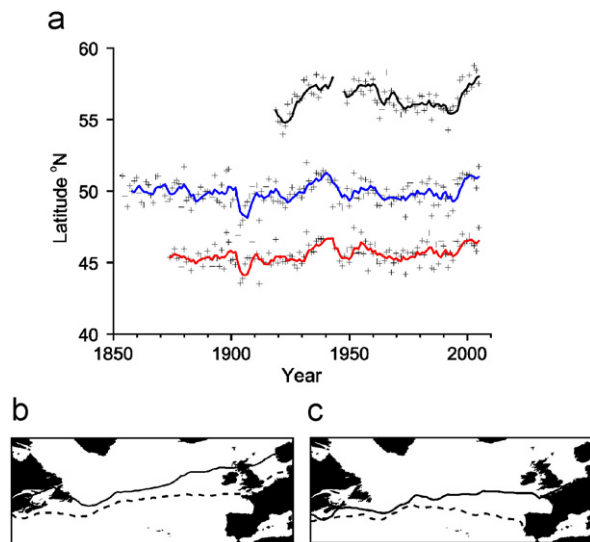


Fig. 2. (a) The mean latitudinal position north for the 12 °C (black, from 1911 to 2005), 15 °C (blue, from 1856 to 2005) and 18 °C (red, from 1876 to 2005) isotherms. The length of timescale varies because of variations in data availability. Also shown are the most northerly (solid line) and most southerly (dashed line) positions for (b) the 15 °C, most northerly year was 2003, and most southerly position was 1903 and (c) 18 °C isotherms, most northerly extent was 2005, most southerly extent was 1912.

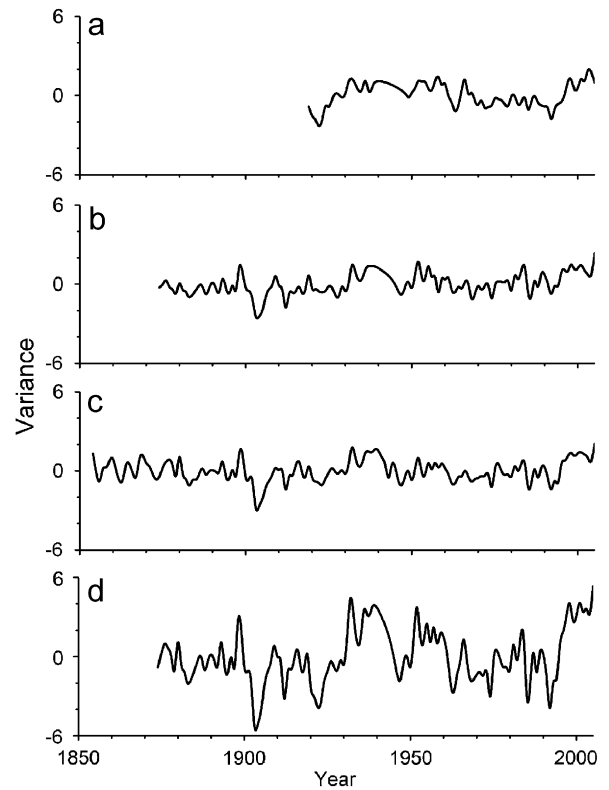


Fig. 3. The index of northerly extent of the (a) 12 °C, (b) 15 °C and (c) 18 °C and (d) isotherms combined. This index was derived by first calculating the mean summer position of each isotherm. Each time-series of mean isotherm position was then reduced to zero mean and unit variance and the two or three time-series summed to provide an overall index of isotherm summer position.

Table 1

Rate of movement north of each isotherm (degrees latitude per year) and r^2 value during the recent warming era and that experienced earlier in the 20th century

Isotherm (°C)	1926–1939	1992–2005
12	0.0616	0.246
15	0.1555	0.1681
18	0.1405	0.1026

During each era, the mean summer position was determined and then a least-squares fit regression determined against year. The slope of this relationship described the rate of change of isotherm position during each era.

(Table 1). Although these warming eras were pre-selected by eye, the rate of warming during these two periods of the 20th century can be seen if the change is measured over a variety of different running means (Fig. 4).

While the recent northerly movement of the overall index of the 12–18 °C isotherm position is broadly within the bounds of previous conditions, recent years have seen a number of extreme northerly isotherm values (Table 2). This impression of two distinct and comparable warm eras is further reinforced by considering years of extreme northerly isotherm position. Of the 10 most extreme years, 4 have occurred in the 1992–2005 warm era (4 in 13 years) and 3 have occurred in the 1926–1939 era (3 in 13).

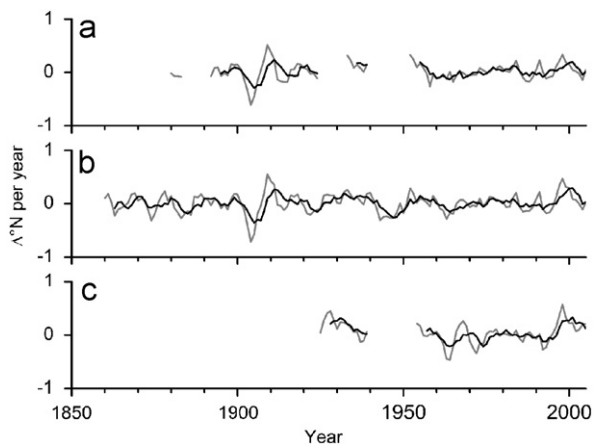


Fig. 4. Time-series of the change of degrees north per year for (a) 12 °C, (b) 15 °C and (c) 18 °C isotherms. Each time-series shows the change in rate over a 10-year (black) and the 7-year (grey) period, calculated in reverse from 2005 to 1850. Values have been smoothed with a 7-year running mean filter.

Table 2

Rank table of most northerly summer positions of the 12, 15 and 18 °C isotherms and the combined index of the northerly extent for these three isotherms

Rank	Index of northerly extent	12 °C isotherm	15 °C isotherm	18 °C isotherm
1	1932	<i>2003</i>	1932	1952
2	1898	<i>2004</i>	<i>2005</i>	<i>2005</i>
3	<i>2005</i>	1966	1880	1932
4	1952	1958	1899	1955
5	<i>1998</i>	1936	1898	1898
6	<i>2001</i>	<i>2001</i>	1939	1984
7	1939	<i>1998</i>	1940	<i>1998</i>
8	1899	1939	1952	<i>2001</i>
9	1936	1932	1936	1937
10	<i>2003</i>	1952	<i>1998</i>	1939
Total	4	4	2	3

Years occurring within the last 10 years have been highlighted in italics.

4. Discussion

The validation exercise we performed comparing the ICOADS isotherm position with that determined from AVHRR imagery shows there are small discrepancies between the datasets. The differences can be attributed to the fact that the AVHRR measures the surface skin temperature of the ocean, whereas the ICOADS data consist of optimum interpolation SST (OI-SST) (Smith and Reynolds, 2003), as well as sub-surface SST measurements. The ICOADS dataset, is based on voluntary observing ship (VOS) reports as the basis of their gridded datasets (Rayner et al., 2003; Smith and Reynolds, 2003), and do not take into account the different methods of data collection, and no bias for bucket versus engine-intake measurements have been implemented post-1970. Prior to 1942, corrections have been applied to the SST data, as a result of changing methodological practices (Folland and Parker, 1995) with corrections increasing from 0.1 in 1950 to 0.4 in 1940. Kent and Challenor (2006) discuss the limits of the methods and values for estimating the random errors that have occurred in the collection of the ICOADS data from VOS, and systematic errors derived from bucket and engine-intake methods.

Determining the behaviour of SSTs in the North Atlantic over the lifetime of instrumental records is important for climatologists, oceanographers and biologists to better assess whether recent warming is natural or anthropogenic. Importantly, biological systems may be important integrators of climatic signals, and therefore examining biological range extents may be a sensitive way of revealing strong climate-related signals when the climate signal itself is noisy (Hallett et al., 2004). Most biological time-series defining a common ‘climatic fingerprint’ for the North Atlantic, northeast American coast and Europe (Ottersen et al., 2001; Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003) have used data collected only over the past 40 years (Fig. 5), during the recent warming phase when the isotherms have consistently moved north.

Marine population responses to climate variability are mediated primarily by trophic interactions with prey species. Links have been shown between physical and biological processes showing that climate variability has an impact on the demographic response of species such as the North Atlantic right whale (Greene et al., 2003). Such studies do not address the magnitude of these recent

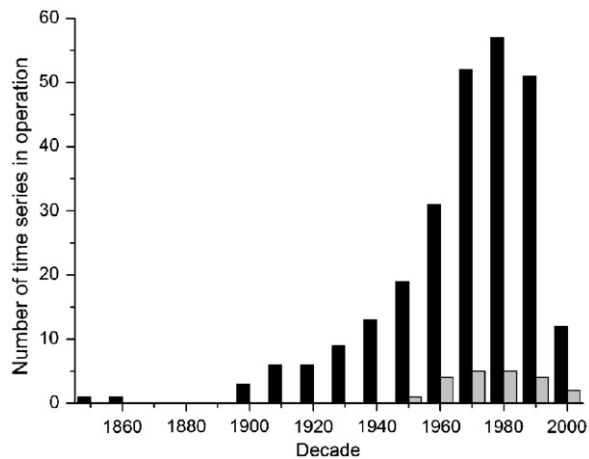


Fig. 5. The distribution of the mean length of the biological studies used to define the globally coherent fingerprint to climate change and distribution of when these studies (terrestrial studies—black; marine studies—grey) were initiated showing that (i) most studies are less than 40 years in length and (ii) that most of the studies were initiated in the 1960s. Together these observations lend support to our hypothesis that biogeographical studies documenting monotonic changes in ranges and breeding phenology may be biased because most of the studies were performed during a period of monotonic warming.

changes when viewed in the longer (100-year plus) context and have assumed that the recent changes are unprecedented. However, biological indicators are subject to several artificial trends due to the evolution in sampling and are notoriously prone to other anthropogenic influences, such as fishing effort (Perry et al., 2005). Prediction of the precise consequences for life on the planet is difficult, and this is especially true for highly mobile marine predators. These are inherently difficult to study and adequately long-term data sets defining marine predators' range and habitat are typically rare. Indeed, Forcada et al. (2005) note that the links between global climatic change and predator responses are 'only just being explored'. In addition, the effects of climate change on higher trophic levels can be difficult to understand because they involve various relationships that may be non-trivial and nonlinear and, possibly, affected by time-lags (Lusseau et al., 2004). The constraints of existing climate models also severely limit predictive ability for any particular species (IWC, 1996), especially when patterns and trends in species diversity and in the open oceans are enigmatic (Worm et al., 2005). Consequently, we urge caution in ascribing changes in range and phenology in marine biota to global warming. Current observations, however, are in-

valuable in providing insights into ecosystem changes that can be expected if the North Atlantic climate continues to change and move beyond the envelope of past conditions. Our results suggest that surface waters of the North Atlantic may not have been impacted by climate warming as greatly as some terrestrial systems.

We have shown that the current 'warm era conditions' do not eclipse prior 'warm' conditions during the instrumental record. One of the key elements evident from our 150-year analyses of the movement of isotherms in the North Atlantic is that the frequency with which warmer SSTs are propagating further north is escalating. In particular, marine species whose range is thermally controlled (McMahon and Hays, 2006) will now be found in areas they have not been seen previously and we can expect increasing reports of warm-water "exotic" marine species in northern Europe (Thomas et al., 2004).

The movement of warmer summer sea temperatures further north has important implications for the control of climate. The majority of analyses investigating the impact of anthropogenic influences on the climate have used air temperature observations (Barnett et al., 2001). In the summer months (August and September), there is significant reduction in the vertical shear in the main development region for Atlantic hurricanes (Wang et al., 2006). The tropical climate response for hurricane development is influenced by both tropical and higher-latitude SST anomalies, thus the variability seen in this analysis showing higher latitude SSTs are moving further from the equator, and may have an influence on the increased hurricane activity in recent years (Sutton and Hodson, 2007). Similar warming patterns are evident in the oceanic environment, with ocean warming indicated by rising SSTs, and the frequency with which warmer SSTs are spreading north. Speculative climatic impacts of this phenomena may result in greater ocean stratification, which in turn could subdue the thermohaline overturning assumed in most climate model predictions (Hegerl and Bindoff, 2005). Significant climate impacts are not restricted to the Atlantic basin, implying that the Atlantic Ocean could be an important driver of global decadal variability. The strongest remote impacts are found to occur in the tropical Pacific region in June–August and September–November. Surface anomalies in this region have the potential to excite coupled ocean-atmosphere feedbacks, which are

likely to play an important role in shaping the ultimate climate response (Sutton and Hodson, 2007). However, our results show that even if the ocean is losing heat (Schiermeier, 2006b), warmer SSTs each summer are being recorded further north more regularly.

5. Conclusion

In short, our analyses suggest in recent years the position of summer isotherms in the North Atlantic has not moved markedly beyond the window of previous values. Yet at the same time there has been a recent tendency for more frequent occurrence of the summer isotherms towards their northern limit. Our approach of examining isotherm positions, as opposed to more traditional analyses using integrated SST values for large ocean areas, reinforces the need to place observations into a longer historical perspective than is conventional in marine ecology. It also highlights the magnitude of biological range expansion and contraction (the order of 300 km over 15 years) likely for marine species whose range is thermally controlled.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.dsr.2007.11.003](https://doi.org/10.1016/j.dsr.2007.11.003).

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