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Over 10 million seawater temperature records for the United Kingdom Continental Shelf between 1880 and 2014 from 17 Cefas (United Kingdom Government) marine data systems.

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Abstract. The datasets described here bring together quality-controlled seawater temperature measurements, from over 130 years of Departmental government-funded marine science investigations in the UK (United Kingdom). Since before the foundation of a Marine Biological Association fisheries laboratory in 1902 and through subsequent evolutions as the Directorate of Fisheries Research and the current Centre for Environment Fisheries & Aquaculture Science, UK Government marine scientists and observers have been collecting seawater temperature data as part of oceanographic, chemical, biological, radiological, and other policy driven research and observation programmes in UK waters. These datasets start with a few tens of records per year, rise to hundreds from the early 1900s, thousands by 1959, hundreds of thousands by the 1980s, peaking with >1 million for some years from 2000 onwards. The data source systems vary from time series at coastal monitoring stations or offshore platforms (buoys), through repeated research cruises or opportunistic sampling from ferry routes, to temperature extracts from CTD (Conductivity Temperature Depth) profiles, oceanographic, fishery and plankton tows, and data collected from recreational scuba divers or electronic devices attached to marine animals. The datasets described have not been included in previous seawater temperature collation exercises (e.g. International Comprehensive Ocean-Atmosphere Data Set, Met Office Hadley Centre Sea Surface Temperature data set, Centennial *in situ* Observation-Based Estimate Sea Surface Temperature data), although some summary data reside in the British Oceanographic Data Centre (BODC) archive, the Marine Environment Monitoring and Assessment National (MERMAN) database and the International Council for the Exploration of the Seas (ICES) Data Centre. We envisage the data primarily providing a biologically and ecosystem-relevant context for regional assessments of changing hydrological conditions around the British Isles, although cross matching with satellite derived data for surface temperatures at specific times and in specific areas is another area where the data could be of value (see e.g. Smit et al. (2013)). Maps are provided indicating geographical coverage which is generally within and around UK Continental Shelf area, but occasionally extending north from Labrador and Greenland, to east of Svalbard, and southward to the Bay of Biscay. Example potential uses of the data are described using plots of data in four selected groups of 4 ICES Rectangles covering areas of particular fisheries interest. The full dataset enables extensive data synthesis, for example in the southern North Sea, where issues of spatial and numerical bias from a data source are explored. The full dataset also facilitates the construction of long-term temperature time series and an examination of changes in the phenology (seasonal timing) of ecosystem processes. This is done for a wide geographic area with an exploration of the limitations of data coverage over long periods. Throughout, we highlight and explore potential issues around the simple combination of data from the diverse and disparate sources collated here. The datasets are available on the Cefas Data Hub (https://www.cefas.co.uk/cefas-data-hub/). The referenced data sources are:

All Sources https://doi.org/10.14466/Cefasdatahub.4
Source 1 Coastal Temperature Network https://doi.org/10.14466/Cefasdatahub.5
Source 2 Fishing Survey System https://doi.org/10.14466/Cefasdatahub.6
Source 3 Oceanographic Archive https://doi.org/10.14466/Cefasdatahub.7
Source 4 Plankton Analysis System https://doi.org/10.14466/Cefasdatahub.8
Source 5 Fisheries Ecology Research Programme https://doi.org/10.14466/Cefasdatahub.9
Source 6 SmartBuoy Monitoring Network https://doi.org/10.14466/Cefasdatahub.10
Source 7 Defra Strategic Wave Monitoring System https://doi.org/10.14466/Cefasdatahub.11
Source 8 Historical Ferry Routes Monitoring System and RV Surface Logger System https://doi.org/10.14466/Cefasdatahub.12
Source 9 Electronic Data Storage Tag Database https://doi.org/10.14466/Cefasdatahub.13
Source 10 Citizen Science Diver Recorded Temperatures https://doi.org/10.14466/Cefasdatahub.14

Source 11 Lowestoft Sample Data Management System https://doi.org/10.14466/Cefasdatahub.15
Source 12 *Mnemiopsis* Ecology Modelling and Observation Project https://doi.org/10.14466/Cefasdatahub.16
Source 13 Multibeam Acoustics Sound Velocity Profile Temperature https://doi.org/10.14466/Cefasdatahub.17
Source 14 Intensive plankton surveys off the north-east coast of England in 1976 https://doi.org/10.14466/Cefasdatahub.18
Source 15 FerryBox Monitoring https://doi.org/10.14466/Cefasdatahub.19
Source 16 ScanFish https://doi.org/10.14466/Cefasdatahub.20
Source 17 ESM2 Profiler/mini CTD Logger https://doi.org/10.14466/Cefasdatahub.21

Keywords: seawater temperature historic UK Continental Shelf

Copyright statement

Data are subject to Copyright as indicated in the relevant metadata (usually Crown copyright) and the Disclaimer section below.

1 Introduction

The measurement of surface and subsurface seawater temperature has been a standard activity for most, if not all, marine researchers for the past two hundred years. From the physical oceanographer through the marine chemist to the marine biologist, the original purposes for such measurements range from a desire to determine the physical properties and movements of seawater to understanding how temperature influences the distribution of marine species, their migration, growth and reproduction, and, as a dominant feature of the collected works herein, the impacts of and upon commercial activities such as fishing. Furthermore, accurate sea temperature data are necessary for a wide range of applications, from providing boundary conditions for numerical hydrodynamic models and weather prediction systems, to assessing the performance of long-term climate modelling and to understanding drivers of observed changes in marine ecosystems. The importance of sea surface temperature (SST) to climate science is reflected in its designation as an “Essential Climate Variable” of the Global Climate Observing System (Mathews 2013).

The Marine Biological Association (MBA) of the United Kingdom was established in 1884 in order “to foster the study of marine life, both for its scientific interest and because of the need to know more about the life histories and habitats of food fishes”. In 1902 a dedicated fisheries laboratory was established in the port of Lowestoft by the MBA together with the UK Board of Trade. This was the UK’s primary contribution to the newly founded International Council for the Exploration of the Sea (ICES). From its inception, the laboratory in Lowestoft has collected information on fish stocks surrounding the British Isles, but also water temperatures at the surface and near the sea bed. Much of the information collected by the Lowestoft laboratory over the past 115 years has never been made publicly available, but these datasets are now the subject of legacy data rescue (Wyborn, et al. 2015), as part of a drive for “open data” within the UK government. This paper is one result of that ongoing effort. In their Preamble, Griffin et al. (2015) describe the unglamorous reality of legacy data rescue and reasons why heritage data is not as readily accessible as the term “archive” might imply. The approach taken here is to turn, in their terminology, old data into new data and to present, explore and explain the new data so that it can be used within a context that includes the diverse and disparate reasons for which the old data was collected and the differences and limitations of the acquisition and measurement techniques of the day.

The methods of measuring seawater temperature range from the simple thermometer through to the ubiquitous presence, on a modern marine Research Vessel, of a Conductivity Temperature Depth (CTD) instrument of some kind. Such activities have, for well over one hundred years, formed a routine part of the sea going and observational work of the MBA Lowestoft substation and its successors. In 1910 the Lowestoft laboratory transferred to the Board of Agriculture and Fisheries where it then became a Fisheries Laboratory under MAFF (Ministry of Agriculture, Fisheries and Food) in 1920. From 1955 it was known as the DFR (Directorate of Fisheries Research), see Lee (1992) and Graham (1953). It now continues as Cefas (Centre for Environment, Fisheries & Aquaculture Science) under Defra (Department of Environment Food and Rural Affairs), with a remit focusing on the UK Continental Shelf, with occasional forays into more distant waters for projects supporting UK Government priorities.

Data holdings within this institution extend back beyond 1902 although these form only a very small part of the collated temperature dataset described here. The historic focus of our marine research has been biological, specifically fisheries related, but this has changed as both government policy needs and interests have widened. Figure 1 shows the RV *Huxley* which was deployed between 1902 and 1909, with Fig. 2 highlighting the differences between the adapted trawlers of early years and the current bespoke research vessel, the RV *Cefas Endeavour* which started service with Cefas in 2003. A wider, historic, institutional context for the 17 data sources described here is available in Cefas (2014).

Figure 1. RV *Huxley* 1902-1909

Figure 2. RV *Cefas Endeavour* 2003 -

1 Introduction

The methods of measuring seawater temperature have ranged from simple mercury thermometers deployed in buckets of seawater, pumped seawater systems on Research Vessels (see Kent and Taylor, 2006 for an exploration of these methods of measurement), through to the ubiquitous presence, on most modern research vessels, of Conductivity

Temperature Depth (CTD) instruments or, more recently, autonomous surveillance buoys, gliders, profilers and electronic devices attached to animals. Much has been written about difficulties in calibrating information from these various data sources, see, for example, Matthews (2013) and Kennedy et al. (2011a, b). Subtle differences in the methodologies for calibrating such disparate measurements have been found to greatly impact reconstructions of time series of global climate warming (Karl et al., 2015). They specifically identified both issues with ship data sources, including the change from bucket samples to engine intake thermometers and, more relevant here, the increase in data density with time as buoy mounted observation systems were deployed, as sources of time dependant bias in the global SST record. We explore such possible data bias in general terms along with examinations of effects of data source, time dependencies, location and numerical bias.

Many different data-portals now exist housing collated maritime temperature records, the most notable including the International Comprehensive Ocean-atmosphere Data Set (ICOADS), the NOAA Extended Reconstruction Sea Surface Temperature (ERSST) dataset, the Hadley Centre SST dataset (HadSST3), and the Japanese Meteorological Agency's Centennial Observation Based Estimates of SSTs (COBE-SST). All of these are composite SST series that assimilate data from multiple different instrument platforms (ships and buoys as well as some satellite data in the case of COBE-SST), and from different measurement methods to create consistent long-term time-series (see Hausfather et al. 2017). Analysis of these long-term historic datasets show that the sea surface temperatures around the British Isles have warmed at rates up to six times greater than the global average (Dye et al. 2013). Indeed, this region has been identified as one of 20 "hot-spots" of marine climate change globally, based on an analysis of trends in ocean temperature (Hobday and Pecl 2014).

Numerically, the data presented here starts with tens of observations per year, rising to hundreds from the early 1900s, to thousands by 1959, to hundreds of thousands by the 1980s, peaking with >1 million for some years from 2000. The majority of the data included in this paper originates from modern research and monitoring programmes executed by scientists using appropriate QA/QC (Quality Assurance/Quality Control) processes for their designated purposes, which did not include the extensive sharing and repurposing of the current day.

In this data paper 17 separate data systems are described, comprising more than 10 million individual temperature measurements. Most are from the seas around the British Isles (ICES Areas IV, VI and VII) but there are some additional measurements in the Bay of Biscay (ICES Area VIII), off Labrador and southern Greenland (ICES Area XIV) and in the Norwegian/Barents Seas (ICES Areas I and II), see Fig. 3 (ICES - International Council for the Exploration of the Sea).

Dann et al. (2015) specifically recognise the challenges of using "data available from different surveys [that] have been collected for different purposes, using different gears and different sampling strategies over time". They were working on fish and their aim was "to provide a broad view of regional, depth related … and temporal patterns …. by integrating as much information as possible". This paper collates and makes readily accessible, data that can contribute significantly to such integrations of seawater temperature.

The data collection programmes that act here as data sources were designed to measure temperature for a specific purpose, e.g. physical oceanographic measurements and as part of Cefas SmartBuoy programmes focusing on nutrient levels, or as a directly relevant contextual measurement, e.g. WaveNet and RV *Cefas Endeavour* FerryBox. Other datasets arise from research where temperature data are collected for general context and interpretation. Two data sources are from Citizen Science, although the Coastal Temperature Network (CTN), which was established in the mid-1960s (with individual datasets going back over 100 years), preceded the term whilst also relying on volunteers. The majority of these temperature datasets have been previously analysed and integrated into a myriad of diverse and disparate reports and scientific papers, often in the form of summary tables and figures or as contributions to understanding the environment of fish and other biota. Most of the recent data now reside in numerous operational database systems, whilst a significant proportion of the rest now exist in organized and documented electronic forms, thanks to recent legacy data rescue efforts by Cefas (all available through published discovery metadata Cefas Data Hub (http://data.cefas.co.uk), UK Government Metadata Portal - Data.Gov (https://data.gov.uk/data/search) and the MEDIN Metadata Portal (http://portal.oceannet.org/search/full).

The Cefas Data Hub extends the searching of discovery metadata to include direct access to data. It provides direct access to extracts from Cefas operational databases to facilitate data reuse beyond its original purpose. This Data Paper takes an additional step and makes comprehensive, quality assured, extracts for this key physical parameter readily available and easily accessible in simple text files of seawater temperature data, with each record standing alone and not associated with bespoke and specialist data formats. Throughout, we highlight and explore potential issues around the simple combination of data from the diverse and disparate sources collated here.

2 Data sources

The 17 source systems are:

1. The Cefas **Coastal Temperature Network** (CTN) comprises time series of measurements from a number of long-term recording stations throughout the coast of England and Wales, with measurements provided by volunteers and external suppliers, who have agreed that their data can be published as part of the network (Jones, 1981). See also Joyce (2006), Jones and Jeffs (1991), Ellett and Jones (1994) and Norris (2001). Joyce (2006) Appendix A. Table 8 and associated Figures, shows data at Brancaster that result in a yearly anomaly from a base period of 4-5 °C. These data have been excluded from this compilation.
2. The Cefas **Fishing Survey System** (FSS) is a purpose-built database used to hold and maintain Cefas fish survey data, primarily from government mandated surveys.
3. The Cefas **Oceanographic Archive** (OA) is a system for managing data from a CTD system deployed during traditional oceanographic water column profiling.
4. The Cefas **Plankton Analysis System** contains the data from the sampling of plankton which has been carried out by Cefas since the 1940's. In recent decades, sampling has mainly been concentrated on fish eggs and larvae, and other zooplankton. Pre-egg survey temperature data are profiles from Stations. Egg survey temperature data are from a sensor attached to the net. Plankton samples were collected using high-speed towed nets that capture plankton from the surface to near-seabed. At each sampling position the sampler was deployed in an oblique tow from the surface to within approximately 2 m of the seabed. Veering and hauling speeds were manually adjusted with the aim of sampling each depth band equally. Since the early 1980's CTD sensor packages were fitted to the plankton samplers to continuously monitor temperature and salinity throughout each deployment, with positions interpolated from start and end times and positions.
5. The Cefas **Fisheries Ecology Research Programme** covers several activities, in this case the temperature data comes from a study entitled “Diurnal and seasonal changes in water temperature in South Wales estuaries and saltmarshes”. Data were collected in 1995 and 1996 from three estuarine locations in South Wales during a study of the thermal experience and tolerance of estuarine animals. The data comprise hourly records of temperature in brackish water Pills which are only inundated by the sea for part of the tidal cycle. Modelled depths are <2 metre when not inundated.
6. The Cefas **SmartBuoy Monitoring Network** consists of sensors, a platform and supporting data acquisition and processing software. SmartBuoys are autonomous marine monitoring systems making high frequency measurements of physical, chemical and biological parameters (Greenwood et al., 2010). Measurements are made every second in a burst duration of between five and ten minutes and an average is calculated. They have been deployed as part of the UK marine eutrophication monitoring programme.

7. The **Defra Strategic Wave Monitoring System** (WaveNet) supports a network for England and Wales (https://www.cefas.co.uk/cefas-data-hub/wavenet/), providing a single source of real-time wave data from wave buoys located in areas at risk from flooding/inundation. The Waverider buoys are also fitted with a sea surface temperature sensor with data recorded and transmitted half hourly.
8. The **Historical Ferry Routes Monitoring System** and **RV Surface Logger System** contains data on near surface temperature and salinity samples that were collected by ferries operating between Harwich and Rotterdam (Jones and Jeffs, 1991 – see https://www.cefas.co.uk/cefas-data-hub/sea-temperature-and-salinity-trends/data-sets/ for full descriptions of sites and routes) and from Cefas research vessel surface logger systems. The surface logger data were used and stored and processed as part of the vessel management system and was normally run during cruises.
9. The Cefas **Electronic Data Storage-Tag Database** supports the deployment of electronic tags that record temperature and depth. These tags were attached to, or implanted into, several species. The data provided here are from cod caught in the southern North Sea between 1999 and 2009 (for methods see Neat et al., 2014). Data from tags that were returned from recaptured cod were downloaded and the depth time series was used to estimate daily geographic location. This was done by matching the tidal and maximum depth data to known dates and locations as per the method described in Pedersen et al. (2007). Temperature data from each tag were binned into 10 m depth intervals, and then averaged. Cod were at liberty to move at will, so the geographic and vertical sampling is not regularised to a grid or vertical stratification. The data describes the temperature data sampled by a total of 90 cod, and comprises temperature data collected on a total of 10,446 days. Methods used to capture and tag cod are found in Righton et al. (2010) and Neat et al. (2014). Summary data is published in Neat and Righton (2007) and Righton et al. (2010).
10. **Citizen Science Diver Recorded Temperatures** come from a data source that differs from the others in this collection because it arises from an investigation into the potential for Citizen Science to contribute to assessments of the marine environment. The dataset is derived from a database containing over 7,000 records of temperature data collected from temperature compensated dive computers. The lowest temperature is recorded from the thermal sensor. This resulted in a quality assured dataset of just over 5,000 records (including freshwater and lake data). The subset of global dataset provided covers the UK shelf. See Azzopardi and Sayer (2012) and Sayer and Azzopardi (2014) for additional information. Data accuracy for some instruments is limited to one degree Centigrade.
11. The Cefas **Lowestoft Sample Data Management System** (LSDM) was the primary system used before and throughout the 1990s by Cefas (Lowestoft) to manage water sample processing and data. Its function was to provide a vehicle for the management of the ingestion, analysis and recording of measurements on marine samples, ranging from oceanographic water samples through sediments to "environmental materials" and radiological samples; see Sutton (1993) for an example of the supporting role of LSDM in relation to the, usually high level, scientific measurement systems of the day, and Sauer et al. (2002) for an example of its pivotal role in quality assured processes and analyses. As the work profile for the Ministry of Agriculture, Fisheries and Food Directorate of Fisheries Research changed, followed by the creation of Cefas and then Defra, the need for the centralised system for the management of an extensive suite of physical samples decreased. LSDM was closed in 2015 with chemical data transferred to other systems. The temperature data held included the historical ferry routes and historical CTN data; both covered separately. The remainder, from a variety of programmes and cruises, are presented in this section.
12. The ***Mnemiopsis* Ecology Modelling and Observation Project** (MEMO) was part of a wider sampling programme in collaboration with Ifremer and ULCO (France), ILVO (Belgium) and Deltares (Netherlands). The data collected were used to produce models e.g. an Individual Biological Model, and hydrodynamic, ecosystem and socioeconomic models, see Collingridge et al. (2014) and Van Der Molen et al. (2015); these increased the

understanding of the life cycle of Warty Comb Jellyfish (*Mnemiopsis leidyi*). The project collected samples for analysis of fish larvae and fish eggs, microzooplankton and mesozooplankton and phytoplankton. Samples were collected using a 200-micron mesh ring net of 0.5 m diameter (for zooplankton samples) and physical data was collected via a CTD attached to a ring net.

13. The Cefas **Multibeam Acoustics Sound Velocity Profile Temperature Data** comes from the RV *Cefas Endeavour* which has been routinely deploying Multibeam acoustic measurement techniques since 2005, with particular emphasis being placed on habitat mapping projects (Brown and Vanstaen, 2008). As part of the calibration of the various acoustic systems, a CTD cast is performed at relevant stations to provide temperature data for the necessary calculation of sound velocity.
14. **Intensive plankton surveys off the north-east coast of England in 1976** comprised a series of 12 cruises and was carried out in 1976 by DFR staff to investigate the distribution, abundance, mortality and main predators of planktonic fish eggs and larvae of important commercial fish species, e.g. plaice, cod (Harding and Nichols, 1987). Measurements of surface water temperature and salinity, and bottom temperature, were carried out at each sampling station on a planned survey grid.
15. The RV *Cefas Endeavour* **FerryBox Monitoring System** was installed in 2009. Unlike most FerryBox systems (http://www.ferrybox.org and specifically the systems described at http://noc.ac.uk/ocean-watch/shallow-coastal-seas/ferrybox), RV *Cefas Endeavour* runs a combination of regular (usually annual) monitoring cruises in UK Shelf waters (with a focus on ICES Mandated Surveys for fisheries assessments) and bespoke research cruises. This provides a widespread coverage with some repeat components in time and space.
16. Cefas **ScanFish** was a programme that deployed a high performance towed undulating CTD, initially, to aid the understanding of the coupling between physical and biological processes (Brown et al., 1996). It was towed behind the vessel at approximately 8 knots and undulated from the near surface (~4 m) to within a few metres (~5 m) of the bed, down to water depths of 135 m. The vertical ascent rate was controlled so that each undulation covered a horizontal distance of 1 km, regardless of water depth.
17. The Cefas **ESM2 Profiler/mini CTD Logger** is a Cefas developed micro-logger for applications requiring a small low-power logger with integrated sensors and battery. It has standard sensors for conductivity, temperature, depth, optical backscatter and roll & pitch. It was initially developed to be a hand-held profiler that could be used from small boats and/or when a conventional large rosette couldn't be used. It is now used routinely in place of traditional CTD equipment (data held in Source system 3) and it is now widely used on RV *Cefas Endeavour* research cruises, providing profiles of the water column for fisheries and plankton work (replacing or supplementing data in Sources 2 and 4).

The date ranges and numbers of observations for each data source are summarised in Table 1.

3 Data components & methods

Each specialist data collection system is described in detail in the appropriate metadata. The data files have been extracted from source to provide (with field names in bold):

1. Cefas data source reference number (**Source**)
2. Date/time of measurement (**Time**)
3. Position of measurement: Latitude in decimal degrees (**Lat**)
4. Position of measurement: Longitude (**Long**)
5. Sample depth in m (**Depth**)
6. Seawater temperature in degrees Centigrade (**tC**)
7. Type of sampling used (**Sample**)
8. Type of measurement used (**Measure**)
9. Additional source context e.g. Cruise (**Ref1)**
10. Additional source context e.g. Station, location name, etc. (**Ref2**)
11. Unique identifier (**ID**)

The **Ref1** and **Ref2** fields were extracted from the source data files and provide an operational context (where this is appropriate and / or available) for the original source data, e.g. Cruise and Station. The **Sample** and **Measure** fields provide information on the acquisition of data and are included specifically to facilitate understanding, and removal, of sample bias and autocorrelation effects. The accuracy of the data is described in the metadata accompanying the data files. The number of decimal places provided reflects the source files and can generally be taken as a realistic indication of the accuracy of the position, depth and temperature. NOTE all data have standardised formats and trailing zeroes do not imply increased accuracy.

The methods used to measure parameters over the time span of the datasets vary widely in their resolution (the smallest change that can be measured), precision (the repeatability of the system used) and accuracy (the closeness of the measurement to the actual value). The data provided reflect our best estimates of accuracy, using a conservative approach when transforming the data from a wide variety of bespoke measuring, recording and use systems. QA/QC processes for the sources were, and are, appropriate for their particular requirements. The data published here have been subjected to additional checks in the form of minimum and maximum and outlier detection, plus location plotting. These uncovered a variety of data quality issues, primarily around location but also showing sensor related data issues. Best efforts have been made to ensure the data are clean, reliable and representative of what was measured. A degree of selection bias is inherent in this data compilation exercise, ranging from what was originally done, where and when, through what was reasonably accessible for compilation, what was removed on grounds of quality control and uncertainty regarding validity to what users select and do with it. Such are the “statistical” perils of data reuse.

3.1 Source

This denotes which of the 17 data sources the record was extracted from. This field allows data to be integrated across data sources whilst retaining a reference to the source and originating resolution, precision, accuracy and original purpose, for each of the records. A significant numerical majority of data extracted from the data sources come from sensors and platforms that will be familiar to a reader around the time of publication. However, historical data, whilst of particular interest, comes with historical navigation, sensors, data gathering methods and platforms. The following sections describe differences that a re-user of data should take into account.

3.2 Time

Across the data sources, dates and times have been recorded in a variety of ways. We have made the reasonable assumption that all times recorded used Zulu as the time zone which equates to GMT and now UTC. Date and Time were usually recorded for individual measurements unless the operational systems, e.g. point source data buoys, average data at collection. Where times are not specifically recorded (usually old, shore or vessel based manual records) they are taken as standard for the particular source; daily reports are allocated as 12:00, morning as 08:00 and afternoon as 16:00, as best approximations for likely collection times. Some datasets take observations at local High Tide. Some CTD profiles provide a Start Time only; depth and temperature measurements are allocated a time by interpolation using a standardised rate of decent (0.25/s). The plankton data (Source 4) required positional interpolation based on start and end times and positions.

3.3 **Lat** and **Long**

An informed use of the datasets requires an understanding of the changes in methods of measurement of location over time. Past practice separated the detailed recording of navigational data, and associated uncertainties, from the provision of positions to researchers. The former has not been specifically preserved.

The earliest research records consist of data from Lightships which, we assume, were reasonably accurately located. We think, based upon historical statements on intentions of best practice, that overall, navigation on the early vessels engaged in research and monitoring would always have followed good practice at the time (Lee, 1992 p173). When in range, research vessels would have used coastal navigation techniques, including physical aids to navigation, wherever possible and positional accuracy would depend upon the navigational chart's hydrographic survey. In addition, accurately surveyed depth contours were used as position lines when useful and practical (Graham, 1953). Locations close to charted objects would have been more reliable, precise and accurate.

Beyond coastal waters, where astronomical navigation was used, positional accuracies might have been "of the order of one or two miles" (Captain R Jolliffe, pers comm) with uncertainties deriving from the ability of the navigator, the feasibility of sextant observations in weather and the accuracy of navigational tables. Star sights (taken at dawn and dusk, when the horizon and astronomical bodies were both visible) would provide two fixes per day. Morning sun-sights, run up to noon latitude, would give a total of up to 3 fixes per day. In a chapter on Navigation Errors, Royal Navy (2008) indicates an accuracy of 2 miles for an experienced navigator. From fixes of whatever sort, Dead Reckoning (DR) or Estimated Positions (EP) would be applied to derive a station position where no actual fix was possible. DR is a process of a calculating position using distance and direction from the start, whilst EP applied corrections for set (direction) and drift (speed) of the prevailing current. Both were probably used, depending on circumstances and needs, but no records of when and where are available. Pawsey et al. (1920) report that during investigations of Lousy Bank in 1920, taking observations for station fixes based on the sun and/or three stars was the preferred method, but if the weather was inclement, and they had no other option, they used DR but "with concerns about strong currents".

Civilian Decca Navigation systems (in general use from the late 1940s to ~2000) offered positional accuracies of the order of ~200 m to 3 miles depending on the distance from the base stations. The longer-range Loran systems (in general use from ~1974 to ~2010) were less accurate.

Satellite navigation began with the Transit system in the late 1970's, giving global coverage and a fix at intervals, depending upon satellite availability, of anywhere between 1 and 6 hours. Continuous positional information became available in the 1990's with the advent of the US Navstar GPS system. GPS accuracy depended, in part, on the application of Selective Availability (SA) which degraded the accuracy of the system for civilian use to between 30 and 100 m. DFR used differential GPS services to overcome this problem from about 1992, improving accuracy to of the order of tens of metres. In 2000 the US Government abandoned SA, making standard GPS accurate to within about 15-20 m. RV *Cefas Endeavour* routinely achieves positional accuracies of 5 m, falling to less than 10 cm if differential GPS services are used, e.g. on bathymetric surveys.

We make a reasonably secure assumption that the reference coordinate system used from the adoption of satellite navigation was the default of the system; WGS72 and then WGS84.

Other than the stated increase in accuracy with time, from miles to hundreds to tens to single metres, we cannot be clearer on the actual positions of samples other than to note the positions have been extracted "as is" and converted to decimal degrees where needed.

In addition to errors in measurement, positional data also suffers from potential human error, conversion errors and errors in electronic storage, and display. Latitudes and Longitudes are presented as a best estimate representing actual likely accuracy, e.g. 4dp (~4-11 m depending on location) or 3dp (~40-110 m). A position originally recorded in degrees, minutes and integer seconds (2 dp for decimal degrees) would be accurate to ~400 m-1 km.

The long term electronic data storage tags for fish do not use GPS but indirect interpolations of position from depth and time.

3.4 Depth

This is the depth at which the sample (physical or direct measurement) was taken. The main measurement devices use pressure suitably corrected for temperature for a depth below surface. "Surface" temperatures feature widely in the records and are taken as 0 m although there are clear sources of error with the position of the sensors (both depth and temperature) on the relevant instrument/sampling device. Again, these surface measurements can be affected by wind, wave and tide. "Bottom" temperature is less used in the data sources but features for profiles and tows. Its meaning varies from maximum depth of sample measurement (in the water column) to the measurement taken when the sampling gear is on the seabed (where the sensors may be of the order of 1 m plus above the seabed).

Depths are routinely expressed as integers, as they are recorded, except for some profiles, where data are binned, and undulating and other sensors, where depth is provided to +/-0.1m.

The NOAA bathymetric data used to create the maps used in this paper, allows for the interrogation of "water depth", by using the R package *marmap* (Pante & Simon-Bouhet, 2013). This was used as part of the quality control process where positional data alone were insufficient to ensure an appropriate location.

3.5 tC

Values in degrees Centigrade. The accuracy of the seawater temperature measurements varies and is summarised in Table 2 and detailed in the metadata for each data source.

3.6 Sample

The **Sample** codes are:

- MPT (Monitoring “Point” or location)
- PMP (pumped water sample)
- PNT (Point observation)
- PRO (Profile)
- SAM (discrete water sample)
- STA (Station)
- SYS (Static, continuous monitoring system) and
- TOW (towed instrument).

The combination of MPT and SYS indicates a stationary data acquisition system that may need to be treated in a way that allows for data density bias and autocorrelation.

3.7 Measure

The **Measure** codes are:

- MAN (manual) and
- INS (instrument).

3.8 Ref1, Ref2

These fields record contextual data from the source systems with **Ref1** providing a high-level aggregation and **Ref2** a lower level grouping. They allow data to be manipulated or interpreted in relation to their source and any relevant breakdown in activities of the operations of the source system. They also provide ready links to other documentation and context, e.g. Cruise Reports and to other data types that may be available. Direct reconnection to the originating data source is, of course, available through time and position. Since 2009 the terms Cruise and Survey have become interchangeable for the RV *Cefas Endeavour* with the latter mandated at the time of writing.

3.9 Data ingestion quality control

In publishing scientific data, Cefas takes into account the 2013 Shakespeare Review of Public Sector Information (PSI) (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/198752/13-744-shakespeare-review-of-public-sector-information.pdf) which states "*A National Data Strategy for publishing PSI should include a twin-track policy for data release, which recognises that the perfect should not be the enemy of the good: a simultaneous 'publish early even if imperfect' imperative AND a commitment to a 'high quality core'…. get it all out and then improve*".

The use of original, archived, source data files means that any specialist QA/QC processes applied "upstream" during the original uses of the data are covered in general in the relevant publications but the details of the data QA/QC processes deployed are not necessarily available. The historic nature of a lot of the archived data means that the focus was on the often highly specific measurement protocols with temperature either a core or peripheral parameter. If core it was, for the bulk of the data, part of physical oceanographic investigations that utilised a series of, at the time, advanced and accurate electronic measurement systems, each with bespoke acquisition and processing systems, ultimately creating an archive with a reasonably consistent approach but over 10, often subtly different, formats. If peripheral, data accuracy is reduced by dint of sensors used and calibrations employed. Formats again vary, from sensors of fishing trawls feeding into an operational database to sensors on plankton tows feeding into a large and diverse spreadsheet archive over two decades.

Data assembly, transformation and scrutiny were as follows:

- Identification of Cefas data sources with public seawater temperature data and assembly of relevant datasets from Source archives / extraction from operational databases
- Extraction of required elements, primarily from text files and spreadsheets, including derivation of positions and time from Start and End data where required and the reformatting of date and time from several different formats
- The checking of date and time data consisted of format transformations which picked up systematic source differences and manual adjustments where, e.g. sensor logging was not capable of recognising date changes during deployment and, or, issues with early PCs which had similar problems when interfacing with instruments.
- The checking of location by plotting on maps followed by the identification and, in some cases, removal, of plots that indicated errors in the, often manual, recoding of position. Positions on land indicated either a

hemisphere recording error or omission or a manual positional recording error. Where the former were encountered and obvious, the relevant Cruise Reports were checked and adjustments to the extracted data made. Where the latter were encountered, entire stations or sets of stations (probably associated with a watch) were omitted.

- Seawater temperature data included instrument and manual values indicating sensor errors and these were screened by an initial ingestion filter of < -2.5 and >=35°C, followed by specific checks of temperature > 25 °C to remove erroneous values. These ranged from single, starting data points possibly arising from exposure to the air to transposition errors where values of 30 in, e.g. winter, indicated a storage or transposition error in and from the raw data files, usually associated with conductivity. Detection of such high values resulted in reassessment of the bespoke ingestion programs and a re-run to correct errors and maximise data ingestion. Sequential temperature difference plots were used to identify large changes in temperature over short time periods. In some cases, these apparent anomalies were artefacts of this simple analysis, with two sequential data points coming from different vessels in different hemispheres on different days. In other cases, this plot identified datasets, usually profiles, where reasonably significant chunks of a profile were significantly different from the rest. These were removed. Plots of temperature against time and monthly average temperatures also highlighted potentially anomalous data, e.g. 4°C measurements at the surface in summer and significantly higher averages compared to surrounding data. The former were resolved by the identification of an unexplained switch in one source's recording date format from DD/MM/YYYY to MM/DD/YYYY with the days and months involved, e.g. 31/08 to 09/01 rather than the correct 01/09 not triggering date ingestion format check errors.
- Other test plots highlighted 0°C data near the surface in summer in the North Sea. These were identified as sensor, transmission, transcription or storage errors because the value 0.0 appeared in data sequences of, e.g. 10.1, 10.2, 10.3 etc. These were also removed.
- Early plots of what became Fig. 16 indicated unseasonal high or low temperatures (e.g. UK Continental Shelf near surface waters with 14-15°C in February and 1-1.5°C in June) and apparent outliers. These prompted a final systematic check of the fully assembled data by the plotting of data by month, followed by the identification of suspect data. This was then replotted by individual Source to provide a context against which to evaluate apparent outliers. Unseasonal high and low data revealed as outliers in the Source dataset were removed. Other outlier data were removed where appropriate, although the majority of apparent high and low outliers (see e.g. Fig. 16) were attributed to Sources and sites that included shallow and relatively isolated water bodies.

Best efforts have been made to remove all obvious errors but it is possible that some remain amongst the 10 million plus data points made available here. Please contact Data.Manager@cefas.co.uk to report any errors; these will be corrected and the source files on Cefas Data Hub and the relevant metadata will be updated on confirmation of any error. The same contact can be used if external users of the data wish to explore collaboration or need assistance with interpretation.

4 Results - geographic and temporal coverage by source

4.1 Data summary by source

Table 1 provides summary metadata for each of the 17 source datasets, including their temporal coverage, the number of data points as well as the type of measurement (e.g. fixed station, CTD profile, electronic device attached to an animal etc.). Sources 1 and 2 provide the longest time series of measurements (each more than 100 years), but more recent data systems, e.g. Sources 6, 7, 8 (autonomous surveillance systems) and the undulating tow systems for plankton (4) and oceanography (16) contribute the bulk of the assembled observations.

Table 2 provides an overview of the estimated actual accuracy of the data, by data source. Information on sensor resolution, accuracy and precision are available in the relevant data source metadata or in any cited publications and/or associated documents. Where sensor resolution and precision and calibration is unclear or unknown, conservative estimates are made based on local knowledge from internal records or cruise participants.

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4.2 Summary of sources, geographic range, depth range and temporal coverage used in data subsets.

Example potential uses of the data and subsets are described using plots of data in four selected groups of 4 ICES Rectangles covering areas of particular fisheries interest. The full dataset enables extensive data synthesis, for example in the southern North Sea, where issues of spatial and numerical bias from a data source are explored. The full dataset also facilitates the construction of long-term temperature time series and an examination of changes in the phenology (seasonal timing) of ecosystem processes for a wide geographic area with an exploration of the limitations of data coverage over long periods.

Table 3 provides a summary of the subsetting of the data undertaken to illustrate potential uses and limitations of a simplistic approach to synthesis and analysis. Source is a key variable with, in this case, potentially significant temporal, spatial, and sensor resolution differences. The intervals used to subsample the data reflect the requirements of visualisation and plotting rather than any intrinsic temperature related aspect. The highlighted geographic areas were selected to illustrate data coverage and any issues of numerical, spatial and temporal bias. The depth ranges used reflect primary interest in sea surface temperatures with 44 % of the data falling within a 0-5 m depth. The time range selections primarily reflect data availability.

*UKCS - UK Continental Shelf area **,** ** ICES - A selection of four groups each with 4 ICES Rectangles; covers the Irish Sea, the Celtic Sea, The English Channel and the Thames Estuary, ***SNS - Southern North Sea

4.3 Data summary by location

Figure 3 shows the location of measurements across all 17 data sources. It is clear that the majority of coverage is of the English Channel, the North, Irish and Celtic Seas and the UK Continental Shelf area, reflecting historic work focused on fisheries, plankton and oceanography as part of repeated survey programmes or bespoke research. The data from around Svalbard, Greenland and Labrador reflect the historic interest in cod fisheries around the Arctic and the physical oceanography in those regions (see Townhill et al. 2015).

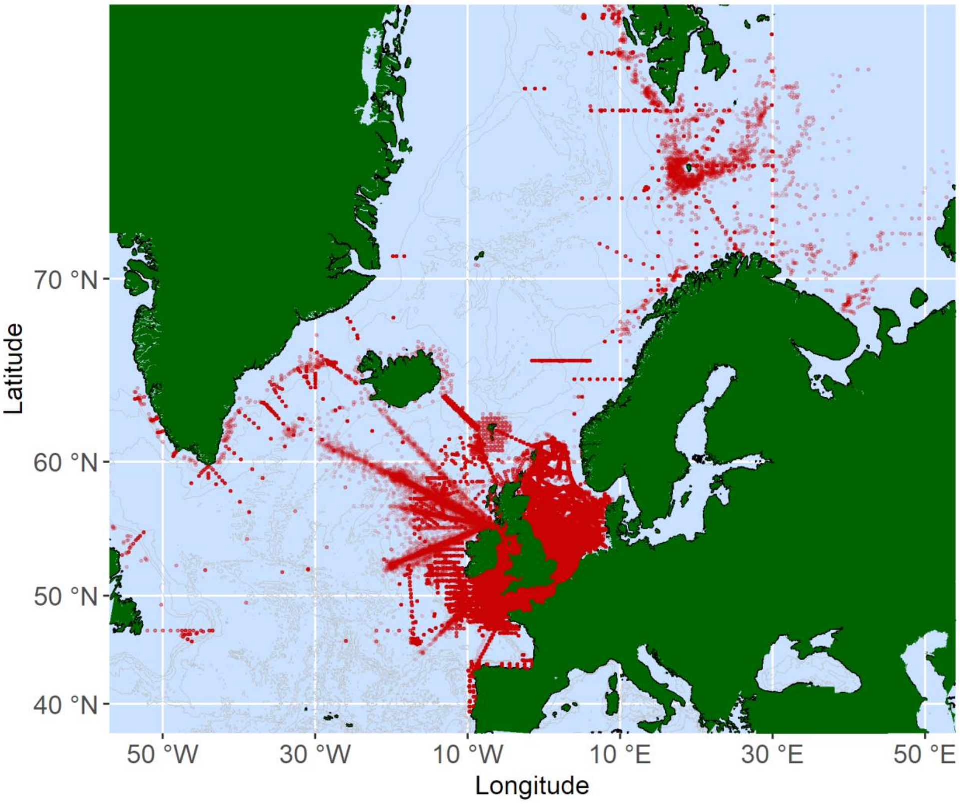

Figure 3. Overview of the locations of Cefas seawater temperature measurements with plotted point intensity reflecting data density.

Figure 4 provides an overview of the relative data density in the English Channel, the North, Irish and Celtic Seas and the UK Continental Shelf area. It highlights the numerical dominance of point source data, e.g. autonomous SmartBuoys (Source 6, primarily in the North and Irish Seas), data from WaveNet (Source 7, see e.g. off east and west coasts of Scotland) and the single year (2014) of near-continuous (1/minute) data from the Coastal Temperature Network at the Port of Dover. Areas of scientific interest in the Celtic Sea (mainly Source 4, plankton studies) and the North Sea (a combination of oceanographic studies, Sources 3 & 16, vessel mounted data from Sources 8 &15 and general purpose CTD data from

Source 17) provide more widespread but significant data densities. Subsequent sections explore data availability by source, time, geographic location and depth in more detail.

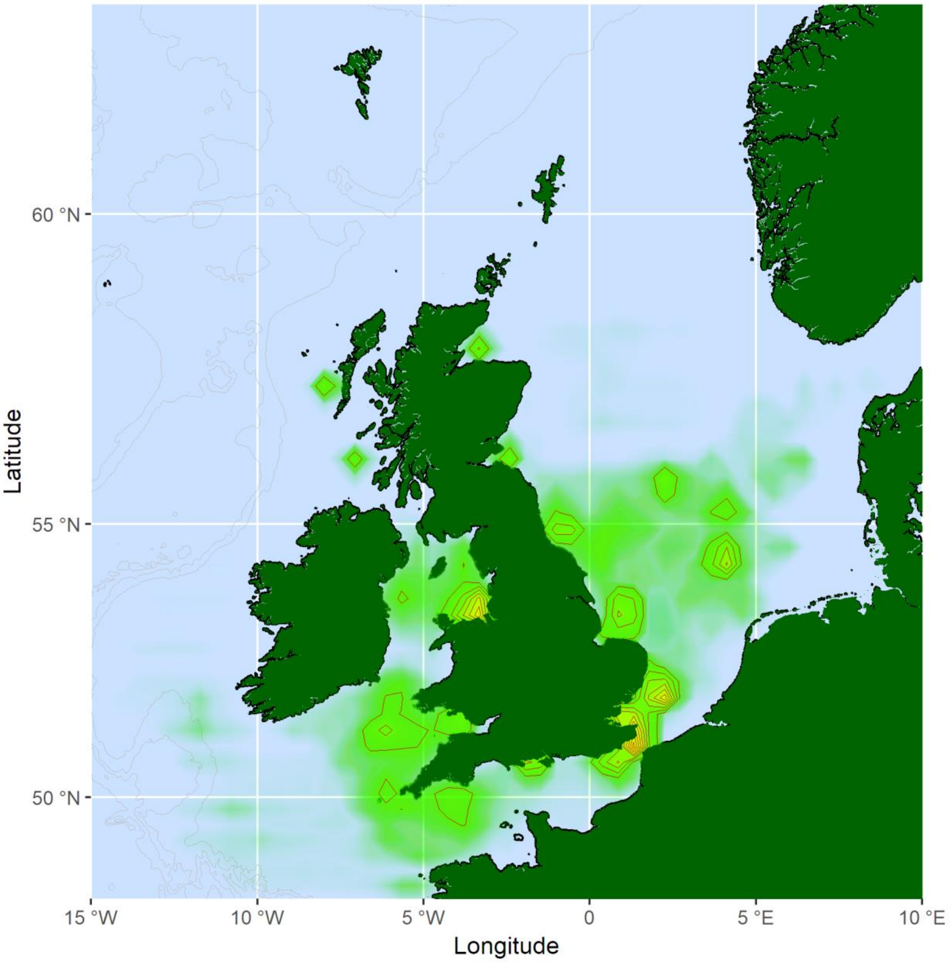

Figure 4 Overview of the relative data density in the English Channel, the North, Irish and Celtic Seas and the UK Continental Shelf area.

5 ### 4.4 Data summary by year

Figure 5 illustrates the inherent differences in the data coverage with time, throughout the 134 years covered, with low, but increasing, numbers of annual records between 1880-1956 and a two order of magnitude increase during the 1980s to around the year 2000. This is followed by a further order of magnitude increase as a result of the introduction of autonomous monitoring platforms that make measurements on an hourly or even minute by minute basis in some cases. These platforms were also deployed in research roles on the North Dogger Bank and Oyster Grounds. 10

Other seawater temperature data compilations (e.g. HadSST3) show similar data acquisition trends. Both provide some challenges when attempting to reconstruct long-term trends in a region, as many thousands of records may derive from one particular sampling locality, with very few data points elsewhere (see below and e.g. MacKenzie and Schiedek 2007).

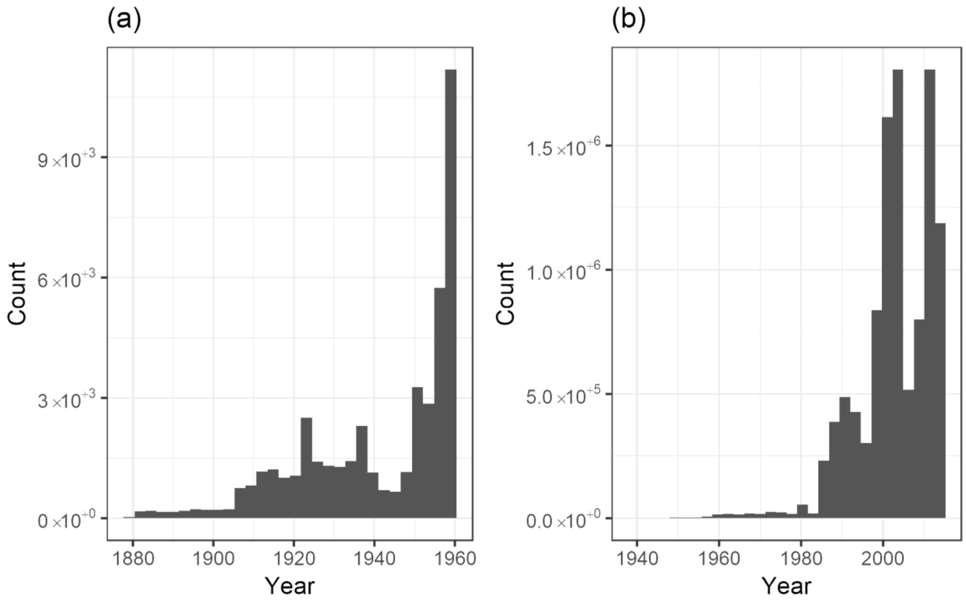

Figure 5. Illustration of data coverage with time (a) 1880-1956 (b) 1957-2014 (note order of magnitude differences in counts).

4.5 Data summary by depth

Figure 6 illustrates data coverage by depth. Figure 6a shows data between the surface and 10 m with high numbers (10^5 to 10^6) reflecting the preponderance of automated data collection platforms and vessel mounted loggers. Figure 6b shows coverage between 10-100 m and Fig. 6c shows data from 100-250 m, covering the Continental Shelf break. Data coverage drops considerably with increasing depth as shown in Fig. 6d which illustrates data availability in the hundreds and then tens per 1 m bin for depths below 250 m.

Most of the sampling programmes involving the Lowestoft laboratory over the past 130+ years have focussed exclusively on the continental shelf, where the most productive commercial fish stocks exist and water depths rarely exceed 200 m. Only occasional forays have been made into the deeper north Atlantic, and these records are contained primarily in Sources 3 and 11.

It is important to note that most of the existing data portals containing seawater temperature measurements (e.g. ERSST, HadSST3, COBE-SST) only accommodate records at the sea surface. Some datasets such as that of ICES (www.ices.dk/marine-data/data-portals/Pages/ocean.aspx) do attempt to provide insights into near-seabed temperature conditions in certain geographical areas, but data are generally sparse. Argo is a global array of 3,800 free-drifting profiling floats that measure the temperature and salinity of the upper 2000 m of the ocean. Argo deployments began in 2000, and by November 2007, the millionth profile was collected, greatly increasing the knowledge-base with regard to open-ocean and deep-water temperature conditions (see Riser et al. 2016).

The emergence of novel undulating platforms such as ScanFish (Source 16) and electronic instruments attached to animals (Source 9) and more recently autonomous gliders, will steadily increase the availability of measurements-at-depth, as will opportunistic data obtained from recreational SCUBA divers (Source 10).

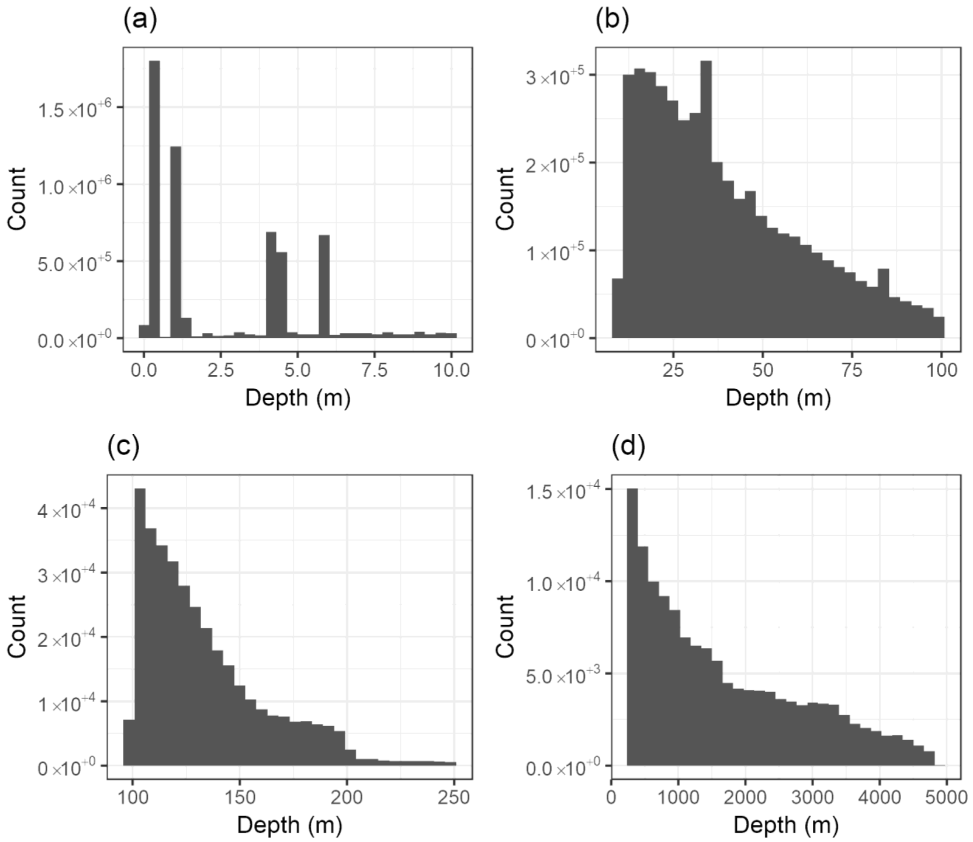

Figure 6. Illustration of data coverage with depth (a) <=10 (b) >10<=100 (c) >100<=250 (d) >250 m (note orders of magnitude differences in counts).

4.6 Data summary by ICES Statistical Rectangle group – areas of fisheries interest.

To demonstrate data coverage in more detail, groups of 4 ICES Rectangles of particular fisheries interest were selected with summary plots of the available “near surface” data (0-5 m). This depth range specifically includes the large datasets from vessel mounted pumped seawater systems. The 4 areas shown in Fig. 7 are (from N, W, S & E):

- Liverpool Bay (Irish Sea)
- Haig Fras (Celtic Sea)
- Brixham (English Channel) and
- Thames Estuary & East Anglian coast (Southern North Sea)

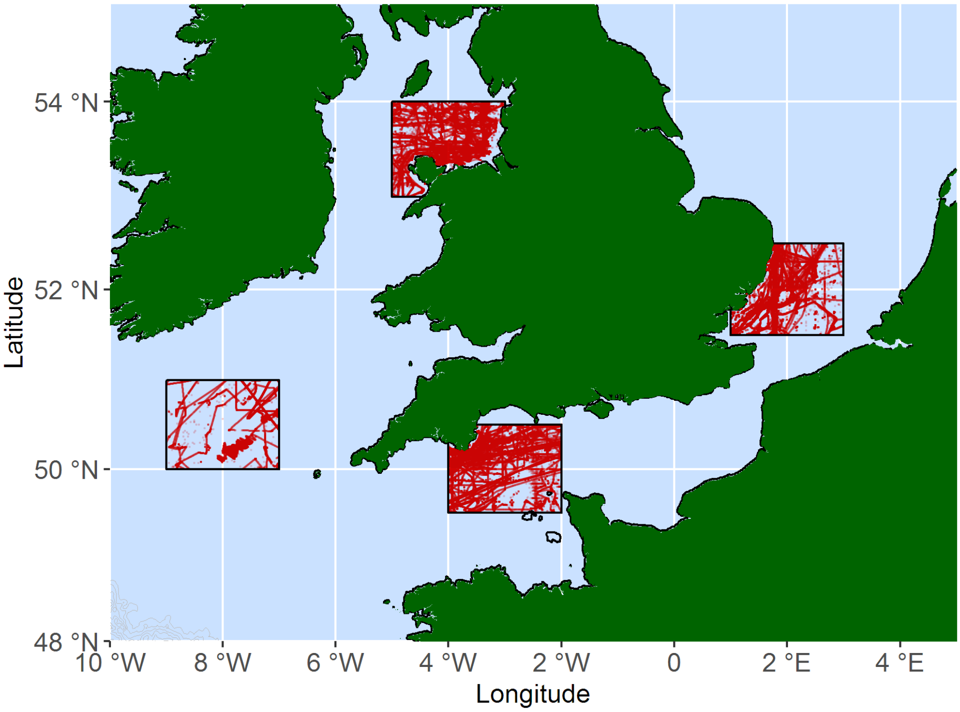

Figure 7. Illustration of "near surface" (0-5 m) data coverage for 4 ICES Rectangle groups; (a) Liverpool Bay, (b) Celtic Sea, (c) Brixham & (d) Thames Area. Plotted point intensity reflects data density.

Liverpool Bay is an inshore area of langoustine (*Nephrops*), herring and plaice fisheries but also an area characterised by major development of offshore windfarms in recent years. The ICES Rectangles selected are: 35E5, 35E6, 36E5, 36E6 with a geographic Bounding Box of 54°N, 3°W, 53°N, 5°W. They include extensive sampling along the north Wales coast as part of fisheries research projects and surveys centred on Red Wharf Bay in the 1960s. Figure 7 shows the intensive sampling efforts that occurred throughout the 1960s and 1970s and again after 2000, when the autonomous Liverpool Bay SmartBuoy (Source 6) was installed, taking hundreds of new measurements each day. A number of long-term Coastal Temperature Network (Source 1) monitoring stations have existed in this area, notably at Wylfa, Amlwch, Moelfre and Bangor.

The ICES Rectangles in the Celtic Sea (29E1, 29E2, 30E1, 30E2 - geographic Bounding Box of 51°N, 7°W, 50°N, 9°W) were selected because this known as an important area for cod, hake, angler fish and megrim. The selected area includes **Haig Fras**, a 45 km long submarine granitic rocky outcrop which, because of the diverse fauna associated with its bedrock reef habitat, is protected as a Special Area of Conservation (SAC). Other seawater temperature records have only ever been collected on an occasional basis in this region, although more surveys have been conducted in recent years, associated with designation of this feature as a new marine protected area.

Brixham is now one of the most important fishing ports in England and home to major beam-trawl fishing fleets. Important sole, plaice and lemon sole fisheries exist inshore, and a cuttlefish fishery extends offshore. The ICES Rectangles selected are: 28E6, 28E7, 29E6, 29E7 with a geographic Bounding Box of 50°30′ N, 2°W, 49°30′ N, 4°W. Temperature sampling in this region, particularly in recent years, has generally been focussed around the annual Channel Groundfish Surveys, with a particular concentration of data measurements in Quarter 1 (March) and Quarter 3 (July)..

The **Thames Estuary & East Anglian coast** are important for seabass, sole and elasmobranch fisheries. The ICES Rectangles selected are: 32F1, 32F2, 33F1, 33F2 with a geographic Bounding Box of 52°30′ N, 3°E, 51°30′ N, 1°E. Some of the longest running time-series exist for this region, in particular, the Coastal Temperature Network (Source 1) monitoring stations have existed at Bradwell since 1964, Leigh on Sea and Southwold since 1966 and Sizewell since 1967. Earlier temperature measurements were taken primarily during fisheries research surveys and, in addition, regular sampling was begun aboard the Harwich to Rotterdam ferry after 1970. A major intensification of sampling occurred after 2000 following the installation of the autonomous Warp and Gabbard SmartBuoys (Source 6).

4.7. Southern North Sea geographic data coverage – spatial, source and numerical bias

The southern North Sea is an area of particular interest because it is one of the regional seas that is reported to have warmed the most dramatically over the 20th Century (Dye et al. 2013; Hobday and Pecl 2014). Figure 8 shows the geographic distribution of Cefas "near surface" between 0 and 5 m seawater temperature data (specifically chosen to include data from vessel mounted pumped systems). It also shows a clear geographical bias in terms of data coverage in the selected offshore area (geographic Bounding Box of 54° N, 4°E, 52°N, 2°E). This does not overlap with the Thames Estuary & East Anglian Coast data plot above. The area selected specifically includes data from autonomous platforms to highlight potential issues with data density in any re-use of this data.

Figure 8 shows concentrations of measurements around major offshore fishing grounds on the North Norfolk sandbanks (e.g. Leman Ground, Smiths Knoll, Swarte Bank, Indefatigable Banks), line transects across the North Sea from ferry routes, ScanFish and the FerryBox system (Sources 8, 15 and 16) as well as a background pattern of gridded stations from the ICES International Bottom Trawl Survey Programme (Source 2).

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Discussion started: 21 June 2017

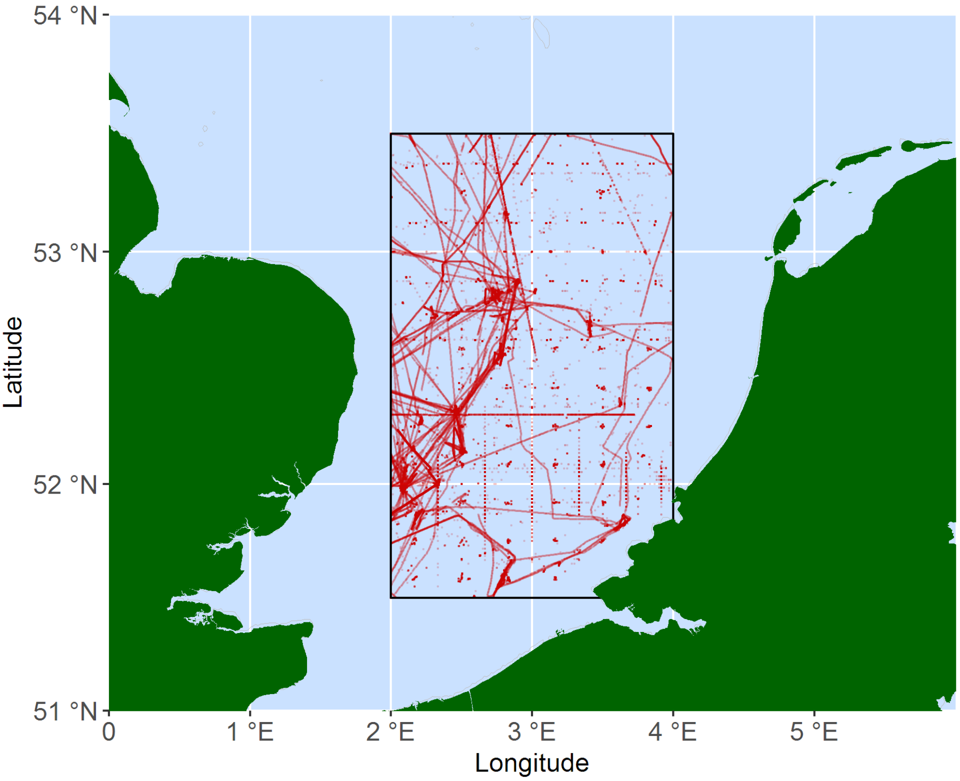


Figure 8. Illustration of "near surface" (0-5 m) data coverage in the Southern North Sea. Plotted point intensity reflects data density. Note the area inside the West Frisian Islands is primarily sandbanks and reclaimed land not sea.

The distribution of numbers of data points within this area led to the Sources being grouped as follows:

- > 100,000 data points (represented as red in Figs. 9 & 10 below)
- >=30,000 <=50,000 (represented as blue in Figs. 9 & 10 below)
- >=2,000 <= 6,000 (represented as green in Figs. 9 & 10 below)
- < 2,000 (removed from this analysis to aid clear visualisation)

Figure 9 breaks down the temporal and numerical coverage of the data illustrated in Fig. 8, illustrating the temporal dominance of Source 8 (Ferry Routes and Surface Logger Systems) and the combined, post 2000, numerical dominance of the single SmartBuoy and WaveNet moored autonomous platforms (Sources 6 & 7), both located in the western part of the selected area.

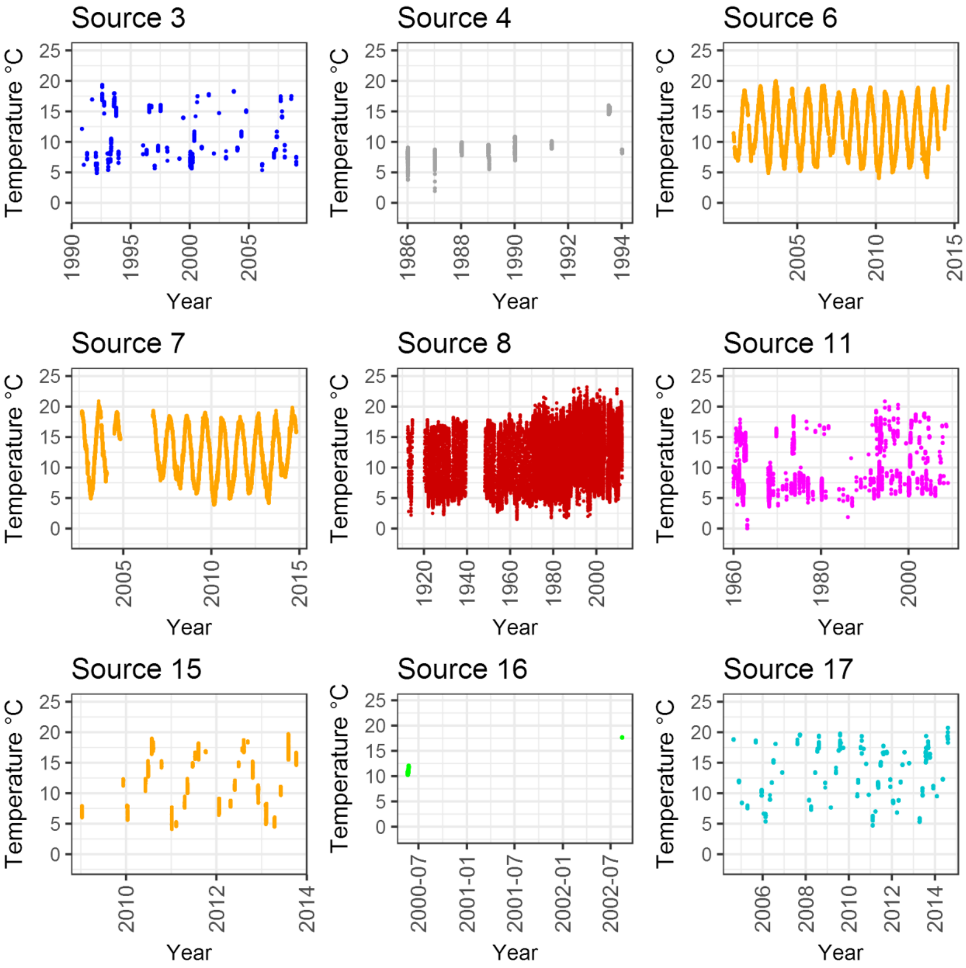


Figure 9. "Near surface" (0-5 m) data coverage and temperatures in the Southern North Sea, by Source and Time. Note different timescales for each data source.

4.8. Southern North Sea data coverage by number and time

Figure 10a illustrates the numerical dominance of Sources 6 and 7 highlighted above. Figure 10b combines plots of the selected seawater temperature records with time, using the colours from Fig. 8 to further clarify the temporal influences of major data sources. Several patterns can be discerned. Firstly, a slight upward trend is apparent across the whole 100-year time-series with generally warmer temperatures at the end of the 20th Century compared to the beginning. There is an absence of data from the periods of both World Wars, when the DFR research vessels were requisitioned by the Admiralty for war service, mines were installed in coastal waters and all research at the Lowestoft laboratory ceased. Several extremely cold winters are apparent, most obviously the winter of 1962–1963 (also known as "The Big Freeze"), one of the coldest winters on record. In February to March 1963 seawater along the coasts of Essex and Kent froze over and catches of dead fish (particularly sole) were recorded throughout much of the region (Woodhead 1964). It is also clear that, from around 2000 onwards, winter minima rarely fall below around 5°C. It is not clear whether this a connection with the related to the beginning of the operational deployments of SmartBuoy and WaveNet stations by Cefas around this time.

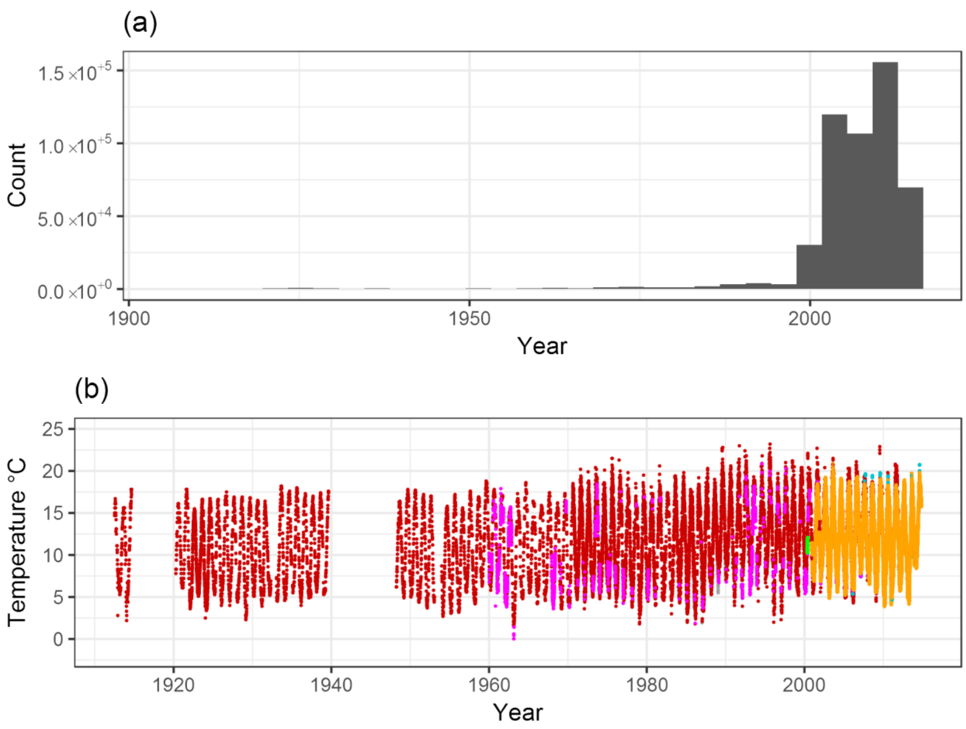


Figure 10. 10(a) "Near surface" (0-5 m) data counts in the Southern North Sea. 10(b) Seawater temperature in the Southern North Sea by year and data source. Blue = Sources 8 & 15 (vessel mounted pumped systems), green = Sources 3,4,11,16 & 17 (other Source) and red = Sources 6 & 7 (autonomous platforms).

In addition to the potential influences of data volumes with time on, e.g. trend interpretation, there are potential geographic and depth biases associated with Source. These are illustrated in Fig. 11 which partitions the data shown in Fig. 7 by time (focusing on the period after the year 2000 identified above in Fig. 10(b)), and by depth. 95 % of all the available data in the selected area is between 0 and 5 m, with 90 % of the 0-5 m data in the top 1 m.

Figure 11(a) shows the geographical distribution of data, post 2000, between 1 and 5 m, whilst Fig. 11(b) shows data between 0 and 1 m (dominated by Sources 6 & 7). The locations of the two autonomous monitoring stations are shown as orange spots in Fig. 11(b); both are in the south west quadrant of the selected area. This provides a numerical, geographical and depth bias in the data available since 2000. These factors would need to be taken into account in any investigation into the causes of the absence of minimum annual data less than around 5°C, e.g. using models that allow spatio-temporal trends and correlation. It is beyond the scope of this Data Paper to construct the statistical models necessary to clarify the influences of data availability in space, time and number, however we do provide a further, simple, examination of the potential effects of depth, location and data number bias.

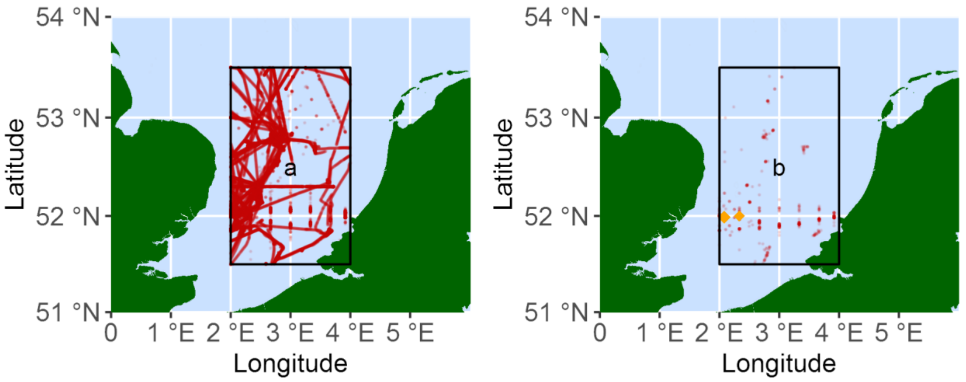


Figure 11. Illustration of potential numerical, geographical and depth biases associated with data source in the Southern North Sea from the year 2000 on. Figure11(a) 1-5 m and Fig.11(b) 0-1 m (primarily autonomous platforms – Sources 6 & 7). Plotted point intensity reflects data density.

Figure 12 compares the seawater temperature records of the data in the selected area, post 2000. Figure 12(a) shows data that do not come from the two autonomous monitoring stations whilst Fig. 12 (b) does. The patterns in the plots of individual data points are similar with some higher individual readings showing in Fig. 12(a), possibly reflecting data acquired at the surface, where aerial exposure during deployment is a known possible influence.

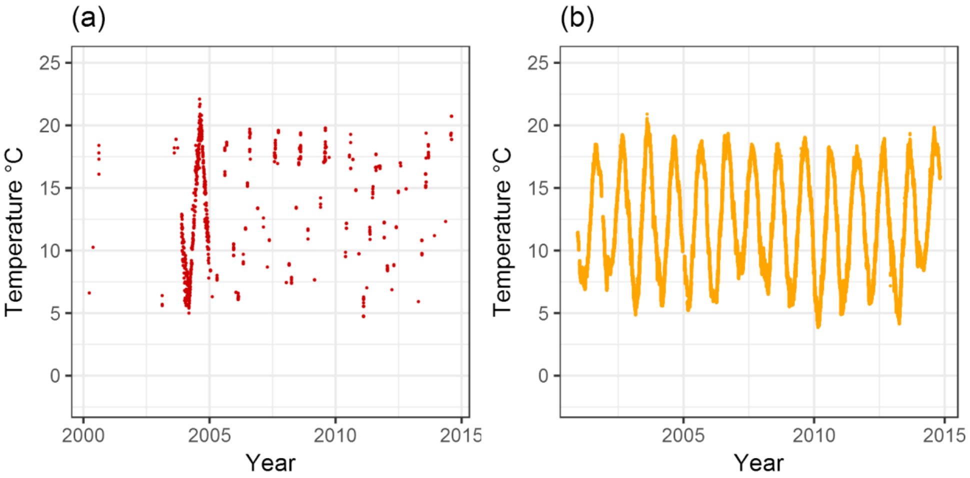
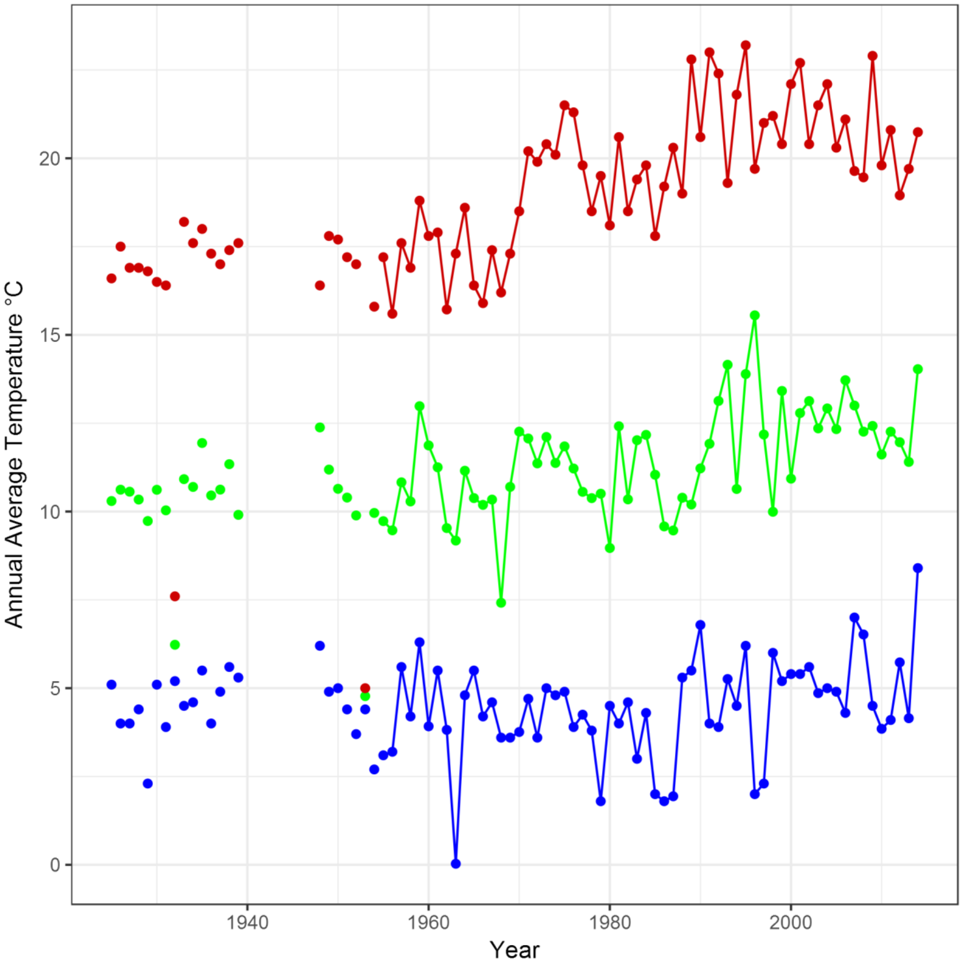


Figure 12. Plot of seawater temperature in the Southern North Sea against time, post 2000. Fig12(a) - data from sources other than autonomous platforms. Fig12(b) - data from the 2 autonomous monitoring stations in the selected area.

Figure 13 explores the potential influence of numerical differences in data numbers with time, using all available data in the selected area of the Southern North Sea to calculate annual seawater temperature statistics. It plots annual statistics (all sources, all depths) as points before 1955, when data are particularly sparse. This limited data coverage gives rise to apparent anomalies with, e.g. maximum average temperatures below 10°C in the early 1930s and one year below 5°C in the early 1950s. Post 1955, the increase in data volumes provides a more coherent picture (plotted as points and lines), reflecting, to some degree, the trend in increasing maximum and mean temperatures expected from the scientific papers cited above. The observed winter of “The Big Freeze” in the early 1960s is, again, very clear. However, the post 2000 absence of data below 5°C at the surface (shown in Fig. 10(b)) is not reflected in the annual minimum data for all depths.



5 **Figure 13** Average, minimum and maximum annual seawater temperatures for the Southern North Sea (all sources, all depths) – green = mean, blue = minimum and red = maximum.

Figure 14 illustrates the depth component of the data sources in a small selected geographic "belt". Source 3 (Oceanographic Archive) is represented by a vertical CTD profile. Source 4 (Plankton Analysis System) shows temperature data gathered during a "V" profile plankton tow. Source 8 shows data from Cefas or predecessor RV surface logging whilst, in complete contracts, Source 9 shows the single data point obtained from a fish tag on a cod. Source 11, the Lowestoft Sample Data Management System, shows data collected from "near surface" and vertical profile water samples. The RV *Cefas Endeavour* FerryBox System (Source 15) shows research and/or transit data collection whilst Source 16 shows the data collected from the CTD mounted on the undulating ScanFish system. Source 17 shows vertical CTD profiles using the ESM2 logging system.

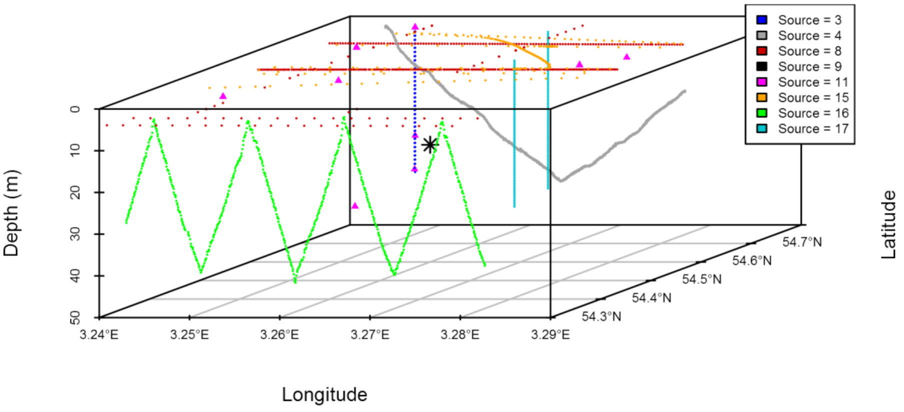


Figure 14. Selected small scale location illustrating the diversity of data sources available and their associated depth profiles. Note, data illustrated were not collected at the same time.

4.9. Distribution and patterns in seawater data for the bulk of the UK Continental Shelf area for "near surface" and "mid-water".

This section widens the geographic coverage of the data exploration to the bulk of the assembled data (Fig. 15, see also Figs.3 & 4 for context). We retain the "near surface" 0-5 m (red) subsetting and extend it to "mid water", 20-25 m (blue). As already shown in the Fig. 7a (Liverpool Bay) subset, "near surface" data coverage is extensive in the Irish Sea area but this is masked to some extent by the over-plotting of the "mid water" data distribution. This over-plotting effect also applies elsewhere.

Figure 15 illustrates some of the characteristics of the data sources. Source 4, the Plankton Analysis System, provides more data at depth and this is illustrated in the south-western quadrant, an area of particular interest for plankton studies. Further north, routes to and from a series of set Stations (Source 8) provides data from the late-1950s to the mid-1990s. In the North Sea, the bulk of data offshore and at depth comes from an extensive series of ScanFish tows (Source 16, see Brown et al., 1966).

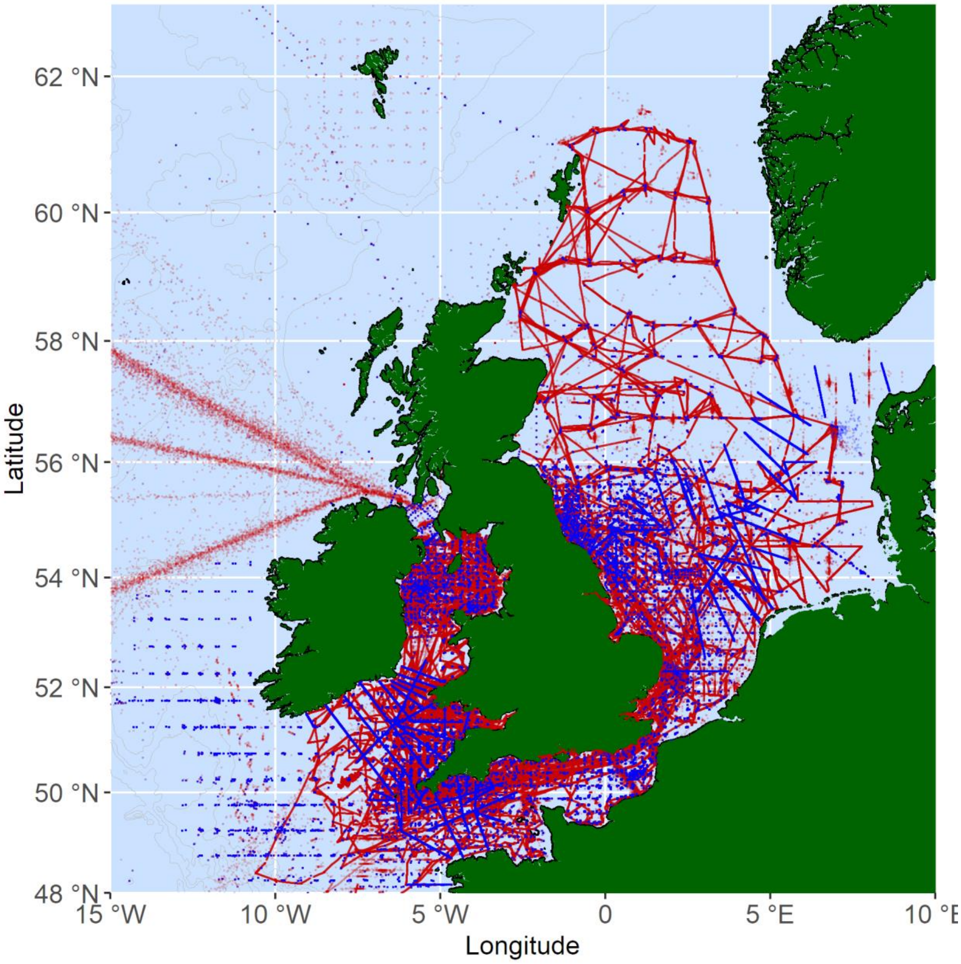


Figure 15. Illustration of the distribution of "near surface" (0-5 m) and "mid water" (20-25 m) data for the bulk of the UK Continental Shelf.

4.10. "Surface" and "mid water" seawater temperature around the British Isles from 1880 to 2015

The data subsets described above comprise surface measurements and temperatures-at-depth, so it is possible to extract time series with different depth bands to illustrate the breadth and depth of the data coverage with time; see Fig.16. There are apparent artefacts in Fig. 16, e.g. high and low values that appear to be outliers (see above). High and low data points in Fig. 16 illustrate the importance of recognising the Source of the data. Source 1 (Coastal Temperature Network) and Source 5 (Fisheries Ecology Research Programme) both have data from relatively isolated bodies of water that have higher and lower temperatures than the surrounding sea (e.g. North Norfolk Coast and South Wales inlets respectively). In addition, there are other Source affected influences on patterns and plots. In August 2001, for example, the surface data was primarily coastal, in the south and in the Liverpool Bay area. The mid-water data were in the eastern North Sea, were dominated by ScanFish measurements and were in and around the thermocline. In August 2009 the mid-water data were from CTD casts in the North Sea as far north as the Orkney Islands whilst the surface data are coastal and in or south of the Humber Estuary. In the summer of 2012, The majority of surface data is from the RV *Cefas Endeavour* FerryBox system (Source 10) which recorded tracks across the North Sea, again as far north as the Orkney Islands whilst the mid-water data was dominated by Citizen Science diver data, especially on the coast of Northern Ireland.

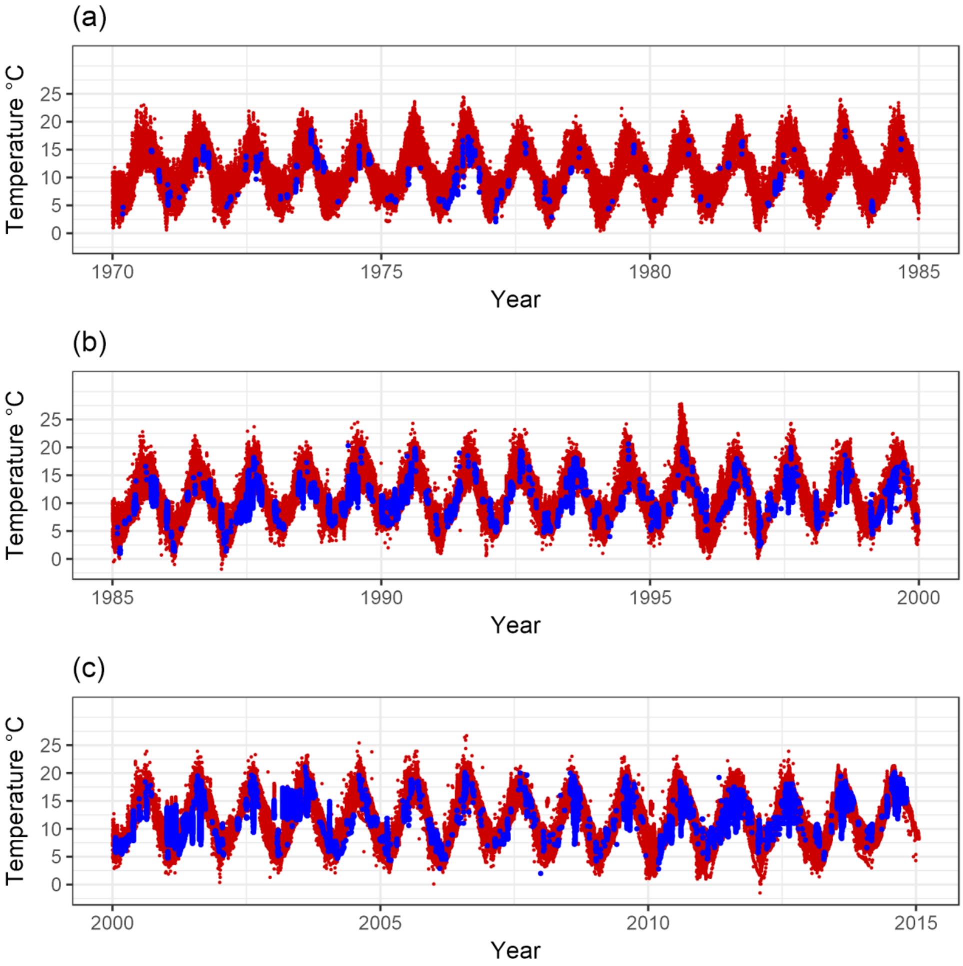


Figure 16. Seawater temperature cycles for three 14-year periods: 1970-1984 (upper chart), 1985-1999 (centre chart), 2000-2015 (lower chart) for seas around the British Isles (area 48°N to 58°N and 10°W to 10°E), separating "near surface" 0-5 m (red) and 20-25 m (blue) data.

Figure 16 clearly shows the annual cycle of seawater temperatures around the British Isles, as well as particularly cold winters (such as 1962/3) and warm summers (1989, 2003). The datasets are very comprehensive for the sea surface (0-5 m depth), but are sparser for deeper depths (in this case 20-25 m). Typically, and as expected, sea surface temperatures are slightly higher than temperatures-at-depth in this region. Dulvy et al. (2008) has shown that many fish in the North Sea have responded to rising seawater temperatures by shifting their distributions into deeper, and therefore cooler, waters. They suggested that the whole North Sea demersal fish assemblage deepened by ~3.6 m per decade in response to climate change between 1980 and 2004.

4.11. Average "Surface" and "Mid Water" Seawater Temperature around the British Isles by Month from 1880 to 2015 – limitations of data density and coverage with time

Figure 17 shows the "near surface" and "mid water" seawater temperatures for seas around the British Isles (UKCS area 48°N to 58°N and 10°W to 10°E) from 1880 to 2015, plotted by month. It shows that, for most months of the year, the sea surface temperatures around the British Isles increased throughout the 20th Century, with stronger upward trends in the spring and summer months (March to August) and smaller increases in Autumn and Winter (September to February).

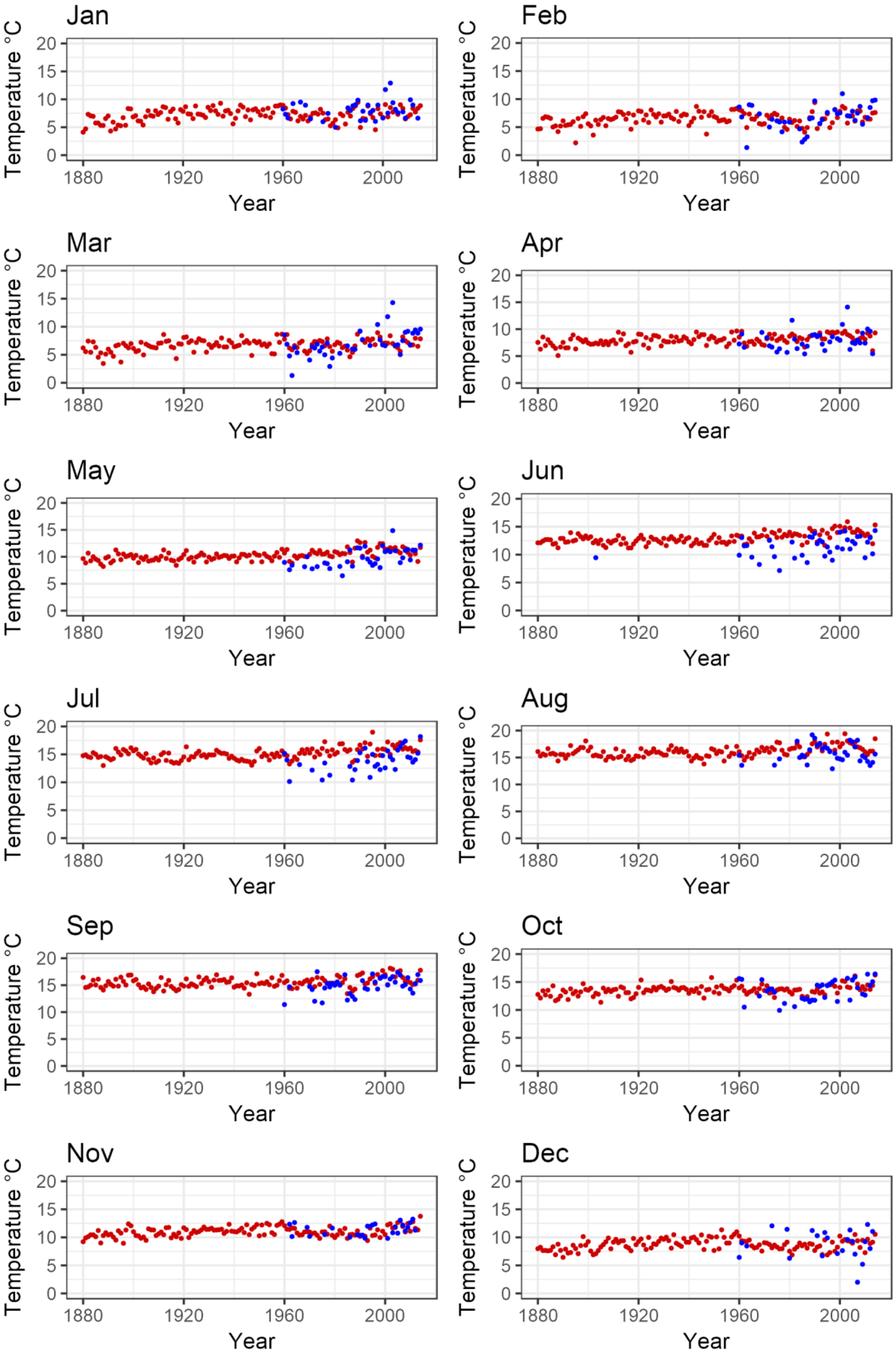


Figure 17. Average "Near Surface" and "Mid Water" Seawater Temperature around the British Isles by Month from 1880 to 2015 (surface 0-5 m in red, mid-water 20-25 m in blue)

Such long-term trends have been associated with a number of observed changes in biological systems, including a clear seasonal shift to earlier appearance of fish larvae at Helgoland Roads in the southern North Sea (Greve et al. 2005), linked to marked changes in zooplankton composition and sea surface temperature in this region (Beaugrand et al. 2002). Greve et al. (2005) suggested that in ten cases, both the 'start of season' and 'end of season' (Julian date on which 15 and 85 % of all larvae were recorded respectively) were correlated with sea surface temperature. Similarly, ichthyoplankton sampling suggests that winter breeding species in the English Channel region also spawn earlier in cooler years, while summer spawning fish tend to spawn later (Genner et al., 2010). Phenology is the study of the timing of recurrent biological events, such as the return of migrating species or the first flowering of certain trees each year. Though most examples of phenological change in the literature have been drawn from terrestrial systems, the year-class size of marine fish is greatly influenced by the timing of spawning and the resulting match–mismatch with their prey and predators (Cushing, 1990), that are in-turn greatly influenced by seawater temperatures.

The data now readily available here can contribute to further explorations of these changes although we note the low average mid-depth seawater temperatures for the month of December in 2007 and 2009 arise from single data points forming that average. The high data point for mid-water in April 2011 comes from a diver. The following statistics (Table 4) derived for the data used in Fig. 17. They indicate the importance of the statistical modelling outlined above, especially for earlier periods and for large areas.

5 Data availability

Data are available from the Cefas Data Hub:

- **All Sources** https://doi.org/10.14466/Cefasdatahub.4
- Source 1 **Coastal Temperature Network** https://doi.org/10.14466/Cefasdatahub.5
- Source 2 **Fishing Survey System** https://doi.org/10.14466/Cefasdatahub.6
- Source 3 **Oceanographic Archive** https://doi.org/10.14466/Cefasdatahub.7
- Source 4 **Plankton Analysis System** https://doi.org/10.14466/Cefasdatahub.8
- Source 5 **Fisheries Ecology Research Programme** https://doi.org/10.14466/Cefasdatahub.9
- Source 6 **SmartBuoy Monitoring Network** https://doi.org/10.14466/Cefasdatahub.10
- Source 7 **Defra Strategic Wave Monitoring System** https://doi.org/10.14466/Cefasdatahub.11
- Source 8 **Historical Ferry Routes Monitoring System** and **RV Surface Logger System** https://doi.org/10.14466/Cefasdatahub.12
- Source 9 **Electronic Data Storage Tag Database** https://doi.org/10.14466/Cefasdatahub.13
- Source 10 **Citizen Science Diver Recorded Temperatures** https://doi.org/10.14466/Cefasdatahub.14
- Source 11 **Lowestoft Sample Data Management System** https://doi.org/10.14466/Cefasdatahub.15
- Source 12 ***Mnemiopsis* Ecology Modelling and Observation Project** https://doi.org/10.14466/Cefasdatahub.16
- Source 13 **Multibeam Acoustics Sound Velocity Profile Temperature** https://doi.org/10.14466/Cefasdatahub.17
- Source 14 **Intensive plankton surveys off the north-east coast of England in 1976** https://doi.org/10.14466/Cefasdatahub.18
- Source 15 **FerryBox Monitoring** https://doi.org/10.14466/Cefasdatahub.19
- Source 16 **ScanFish** https://doi.org/10.14466/Cefasdatahub.20
- Source 17 **ESM2 Profiler/mini CTD Logger** https://doi.org/10.14466/Cefasdatahub.21

6 Conclusions

This data rescue, assembly, integration and publication exercise stemmed from what seemed at the time, to be a relatively simple plea, made at an internal workshop, to make all temperature datasets held within the Lowestoft laboratory available via a common data portal. What emerged was a general realisation that there were 17 separate Data Systems each containing records of varying quality, on paper and stored electronically in a myriad of different formats and archaic file types, some of which could no longer be easily be read without bespoke computer software. Potentially valuable information was collected for various operational reasons over the past 134 years, but every system was tailored for a specific purpose. Where temperature was specifically measured by oceanographers, some form of CTD was deployed and in these cases, semi-standardised data were often transferred to national repositories for example the British Oceanographic Data Centre (https://www.bodc.ac.uk/data/online_delivery/ctd/) or the ICES Data Centre. However, in most cases, the data described here have never been made publicly available before, except within the context of summary outputs from the individual research projects published in peer-reviewed journal articles. The internal workshop wanted “all the temperature data in one place in the same format” so that anyone could use it. The initiating request for access without having to understand the originating formats was driven primarily by requirements for studying long-term climate change but also encompassed biological and ecological uses and work on Linked Data. These requirements became even more pressing given a UK government-wide drive to make available publicly-funded scientific datasets. Whomersley et al. (2015) describes a re-use of data by specialists who did not need to understand the dataset and format and associated limitations. This paper has taken a step further and decomposed the original data formats with a view to making the seawater temperature data more accessible as well as available; widening access and re-use.

In June 2015 Defra’s Secretary of State, Elizabeth Truss, announced her vision for the future of British food, farming and the natural environment, stating that “at least 8,000 datasets—will be made freely available to the public, putting Britain at the forefront of the data revolution”. She stated that “Vast data reserves from Defra are set to transform the world of food and farming in the single biggest government data giveaway the UK has ever seen”. As a result of this initiative Cefas has released more than 1,950 individual datasets via the Cefas Data Hub (www.cefas.co.uk/cefas-data-hub/), a majority of which currently provide data in the original format.

The data presented here have not been corrected or adjusted in any way to take account of the different sampling methodologies used, as has been attempted for the most well-known data collation efforts such as ERSST, HadSST3, COBE-SST (see Mathews 2013; Kennedy et al. 2011a, b). Inherent biases have been partially addressed by the provision of contextual fields (Source, Sample, Measure, Ref1, Ref2) and areas for easy to do but potentially misleading uses of the data have been explored above. Some of the datasets described here, have contributed to the ICES Report on Ocean Climate (IROC), that provides summary information on climatic conditions in the North Atlantic on an annual basis (see https://ocean.ices.dk/iroc/).

The archive of processed Coastal Temperature Network data has been widely cited (see (https://scholar.google.co.uk/citations?hl=en&user=GkV5fMwAAAAJ&view_op=list_works). This paper has made the underlying data readily available (Source 1). Other datasets, such as Source 10, comprising temperature and depth records obtained via a ‘citizen science’ project from recreational scuba divers (see Wright et al. 2016) represent a hither-to largely untapped resource for oceanographic researchers.

7 Author contribution

S. Dye, L. Fernand and O. Williams provided data, data processing and deeper insights into specialist areas along with S. Flatman, who also advised on the choice of ICES Rectangles to demonstrate data in areas of high fisheries interest. J. Pinnegar was the Cefas staff member who, during a the workshop, in frustration, asked "*Why can't I just get access to all*

Cefas temperature data?". This paper provides the requested access and expands on "*just*". D.J. Morris took on the challenge, identified and ingested the data, decomposed the temperature data from their multiple originating formats, ran the QA/QC and prepared the manuscript. D. Maxwell provided statistical inputs regarding selection and presentation of data designed to illustrate the effects of bias and spatial and temporal influence. S. Rogers (through Cefas Seedcorn) provided the internal funding (part of Cefas Seedcorn DP705 "Delivering Linked Data"), early comments on the form of the manuscript, the support and resources needed to build the Cefas Data Hub and ongoing support for what turned out to be more than a year of effort.

The authors declare that they have no conflict of interest.

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WaveNet Data (Source 7) is published with specific permission from: Agri-Food and Biosciences Institute, Defra, Environment Agency, Met Office, Natural Resources Wales, Scottish Environment Protection Agency UK Coastal Monitoring and Forecasting.

Citizen Science Diver Recorded Temperatures - This work was part of the Defra funded Citizen Science Investigations - empowering the public through the use of novel technologies to collect policy-relevant marine data (CSI) - MF1230 http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18553

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Brian Lockwood provided external Python programming to extract data from the multiple legacy CTD formats that emerged and evolved during the early decades of electronic oceanographic measurements.

Extensive use was made of R (R Development Core Team, 2008) and RStudio (RStudio Team, 2015) to handle and present the data. The R code used to generate the data subsets and Figures is provided in a separate document.

9 Disclaimer

9.1 Cefas Data Hub

The contents of the Cefas Data Hub website are provided as part of Cefas' role as a Defra Agency under the Defra Open Data Strategy.

Cefas requires the user to make their own decisions regarding accuracy, reliability and applicability of information provided. The data provided by the Cefas Data Hub are believed, by Cefas, to be reliable for their original purposes and are accompanied by Discovery Metadata that provides a copy of the information available to Cefas scientists, describing the original purpose/s for data collection. It is the responsibility of the data user to take this information into account when reusing data. Regardless of any quality control processes, Cefas does not accept any liability for the use the data provided; use is at the users' own risk. Cefas does not give any warranty as to the quality or accuracy of the information or the medium on which it is provided or its suitability for any use. All implied conditions relating to the quality or suitability of the information and the medium, and all liabilities arising from the supply of the information (including any liability arising in negligence) are excluded to the fullest extent permitted by law.

Use of data from the Cefas Data Hub requires that the correct and appropriate interpretation is solely the responsibility of the data users, that results, conclusions, and/or recommendations derived from the data do not imply endorsement from Cefas, that data sources must be acknowledged, preferably using a formal citation, that data users must respect all restrictions on the use of data such as for commercial purposes and that data may only be redistributed, i.e., made available in other data collections or data portals, with the prior written consent of Cefas.

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Table 1. Summary metadata for the 17 seawater temperature sources.

Data source	**Name**	**Type**	**Start year**	**End year**	**Number of data points**
1	Coastal Temperature Network	Fixed coastal stations	1880	2015	836,179
2	Fishing Survey System	Surface measurements and net tows	1903	2014	35,764
3	Oceanographic Archive	CTD profiles	1981	2009	365,239
4	Plankton Analysis System	Surface measurements and net tows	1982	2004	2,639,842
5	Fisheries Ecology Research Programme	Fixed coastal stations	1995	1996	21,504
6	SmartBuoy Monitoring Network	Offshore monitoring buoy	2000	2014	1,268,832
7	Strategic Wave Monitoring System	Offshore monitoring buoy	2002	2014	1,784,092
8	Ferry Routes and Surface Logger System	Surface measurements	1906	2011	656,103
9	Electronic Data Storage Tag Database	Devices attached to animals	1999	2010	13,856
10	Citizen Science – SCUBA divers	Devices attached to humans	1992	2012	2,205
11	Lowestoft Sample Data Management System	CTD profiles	1960	2009	52,631
12	*Mnemiopsis* Observation Project	CTD profiles	2011	2012	506
13	Multibeam Acoustics Sound Velocity Profile Database	CTD profiles	2005	2008	9,628
14	Intensive plankton surveys of NE England in 1976	Surface measurements and net tows	1976	1976	2,064
15	FerryBox Monitoring	Surface measurements	2009	2013	652,305
16	ScanFish Undulating Profiler	CTD profiles	1998	2003	2,129,341
17	ESM2 Profiler/mini CTD Logger	CTD profiles and net tows	2004	2014	210,349
ALL	Complete Dataset – all sources	All types	1880	2015	10,680,440

Table 2 Summary of the estimated actual accuracy of seawater temperatures, by data source.

Data source	Instrument type	Estimated actual accuracy ± °C	Point/average	Comment
1	Thermometer / Thermistor	0.1-0.2	Point and average	The sensors vary from thermometer in a bucket for very early data through handheld thermometers to in-line thermistors for the Port of Dover sensor. Calibration varies from 'uncertain' to Cefas Laboratory (allowing 0.1 estimated actual accuracy).
2	CTD type sensor	0.1-0.2	Point	The sensors used vary with early data being less accurate. Calibration varies from 'uncertain' to Cefas Laboratory (allowing 0.1 estimated actual accuracy) – these data were collected for biological not oceanographic purposes.
3	CTD	0.005	Point	CTD physical oceanographic profiles, resolution 0.001.
4	CTD type sensor	0.1-0.2	Point / average / binned	The sensors used vary with early data being less accurate. Calibration varies from 'uncertain' to Cefas Laboratory (allowing 0.1 estimated actual accuracy) – these data were collected for biological not oceanographic purposes.
5	Venco Minilog	0.3	Point	Resolution 0.1
6	CTD sensor	0.1	Averaged	Resolution 0.01, Cefas Laboratory calibrations before deployments.
7	CTD sensor	0.1-0.2	Averaged	Resolution 0.01, Cefas Laboratory calibrations before deployments or data provider calibrations estimated to provide the lower accuracy.
8	Thermometer / Thermistor	0.2	Point	Calibrated thermometers for Ferry Route data and pumped seawater for RV surface logger data (calibration status uncertain).
9	Thermistor	0.1	Point	Cefas Laboratory calibration. Resolution 0.03125°C at 12bit setting (https://www.cefastechnology.co.uk/media/1105/g5.pdf)
10	Dive Computers	0.2-1	Point (at max depth)	Unknown. Knowledge of genera diver practice suggests factory calibration followed by no calibration.
11	Reversing Thermometer	0.1	Point	0.01
12	CTD sensor	0.1	Point	Cefas Laboratory calibration.
13	CTD sensor	0.1	Point	Cefas Laboratory calibration.
14	CTD sensor	0.1	Point	Cefas Laboratory calibration (plus pumped seawater for surface temperatures, see Source 8).
15	CTD sensor	0.1	Point	Resolution 0.01, Cefas Laboratory calibrations before deployments.
16	CTD	0.005	Point	CTD physical oceanographic profile instrumentation, resolution 0.001.
17	CTD sensor	0.1	Binned	Resolution 0.01, Cefas Laboratory calibrations before deployments.

Table 3. Summary of data source - geographic, depth, and temporal ranges for the subsetted data used in the figures.

Figure	Sources	Subset by interval	Subset by geographic area	Subset by depth range (m)	Subset by time range	Comment
3	All	1	None	None	None	
4	All	5	UKCS*	None	None	
5	All	1	None	None	a) < 1960 b) >=1940	
6	All	1	None	a) <=10 b) >10<=100 c) >100<=250 d) >250	None	
7	All	1	ICES**	<=5	None	
8	All	1	SNS***	<=5	None	
9	3,4,6,7,8, 11,15,16,17	1	SNS	<=5	None	
10	3,4,6,7,8, 11,15,16,17	1	SNS	<=5	None	
11	3,4,6,7,8, 11,15,16,17	1	SNS	(a) <=5 (b) <=1	>= 2000	SmartBuoy sensor ~ 1 m WaveNet sensor ~0.4 m
12	(a) 3,4,8,11, 15,16,17 (b) 6,7	1	SNS	(a) >1<=5 (b) <=1	>= 2000	
13	All	1	SNS	<=5	>= 1925	Missing and few data before 1925
14	All	All	Small "belt" around 3.2°E 54.5°N	None	None	3,4,8,9,11,15,16,17 only in selected areas
15	All	1	UKCS	<=5 (red) >=20<=25 (blue)	None	
16	All	1	UKCS	<=5 (red) >=20<=25 (blue)	1970-1984 1985-1999 2000-2015	Mid-water data sparse before 1970 Source 1 (coastal) excluded from mid-water subset by definition
17	All	1	UKCS	<=5 (red) >=20<=25 (blue)	None	Monthly averages by year

Table 4 Rounded statistical summary of data used to calculate monthly averages.

Date Range	**Statistical Summary of Number of data points used in calculation of monthly averages**			
	SURFACE			
	Minimum	Median	Mean	Maximum
Pre 1950	4	25	27	89
1950 to 1990	50	425	535	6,746
Post 1990	198	9,380	14,731	89,235
	MID-WATER			
Pre 1950	2	2	2	2
1950 to 1990	1	14	395	7,212
Post 1990	1	98	1,596	67,822