Journal of Sea Research 129 (2017) 89–104

Contents lists available at ScienceDirect

Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Spatio-temporal variability of sea surface temperature in Irish waters (1982–2015) using AVHRR sensor

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A R T I C L E I N F O

Keywords:
Sea surface temperature
Time series
Trend
Fisheries
Climate change

A B S T R A C T

Temporal and spatial variability of Sea Surface Temperature (SST), a key variable linked to climate change, was analysed using a continuous 34-year time series of Advanced Very-High-Resolution radiometer (AVHRR) data (1982–2015). The climatological analysis showed a significant latitudinal SST gradient; waters were warmer in the south and colder in the north. A seasonal effect was evident, with lowest SST values in March and highest SST in August. Results suggest that the temporal and spatial variability in Irish waters is mainly related to the Atlantic Multi-decadal Oscillation (AMO) and the warming from anthropogenic CO_2 emissions. Overall, the warming trend was significant (p-value of ≤ 0.05) and positive (0.26 °C decade^{-1}) for the whole study area. However, this trend was not spatially homogeneous and varied between the International Council for the Exploration of the Seas (ICES) Divisions, having the most significant positive trends in the north (VIa, VIb, VIIb and VIIc) and east (VIId and VIIe). Seasonal SST trends were similar to the annual trends but warming was more intense in the autumn.

1. Introduction

The Earth has warmed consistently and unusually over the past few decades (Purkis and Klemas, 2011) with the Ocean absorbing 93% of this extra heat and most of the warming (64%) occurring in its upper layer (0 to 700 m) (Hoegh-Guldberg et al., 2014). As a result, the rate of global ocean warming has increased by 0.13 °C decade^{-1} between 1971 and 2010 (Hoegh-Guldberg et al., 2014) and this rate is predicted to continue over the next 100 years with values ranging between 1.5 °C and 5 °C (Philippart et al., 2011). Since 1970 the Atlantic Ocean, where the present study is focused, warmed more than any other basin (0.3 °C decade^{-1}) with the greatest warming rates recorded in European continental shelf seas (González-Taboada and Anadón, 2012; Levitus et al., 2009; MacKenzie and Schiedek, 2007).

Taking into account this background, the monitoring of sea temperature becomes of environmental and climatic importance internationally. Initiatives such as the Global Climate Observing System (GCOS) have designated Sea Surface Temperature (SST) amongst the key climate variables for ocean, defined as “essential climate variables” (ECVs; GCOS, 2011). SST also considered in the European legislation as, for example, being one of the physical characteristics listed in Table 1 of Annex III of the Marine Strategy Framework Directive (MSFD; 2008/56/EC). As such, it should be used by Member States to describe the physical characteristics of their marine waters and thus their Good Environmental Status (GES); essential in coastal and marine management strategies.

Although warming is occurring at a global scale, rates of warming differ according to location with some places even showing long-term cooling (Rahmstorf et al., 2015; Trenberth et al., 2007). This variability implies that temperature-induced changes in marine organisms will likely vary dramatically within a given study area (Mills et al., 2013). Marine species and ecosystems have historically responded to large SST variations in their environment (Root et al., 2003). However, the rate of change observed in the last 15–20 years has not occurred before (Philippart et al., 2011). A broad number of marine species ranging from plankton to fish and seabirds can be affected by these alterations (Beaugrand and Reid, 2003; Hoegh-Guldberg et al., 2014; Pinaya et al., 2016). Generally, biological changes are species-dependent and involve community reassembly in time and space being considered the most worrisome consequence of climate change (Parmesan and Matthews, 2006). Consequently, an understanding of historical SST variability, in time and space, will be valuable for interpreting how populations, species and entire ecosystems might react to future increases in SST (MacKenzie and Schiedek, 2007) and how anthropologic drivers impact in the marine environment. Only with long time-series datasets will be possible to detect trends in the ocean-climate variables and assist in making appropriate adaptation decisions (Dwyer, 2013).

SST has routinely been observed by satellites since the late 1970s. In particular, historical satellite data records in the infrared (IR) cover > 30 years and provide accurate (~0.5 °C), stable and consistent time series data (Reynolds et al., 2002, 2007) that are suitable for many

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http://dx.doi.org/10.1016/j.seares.2017.07.006
Received 7 October 2016; Received in revised form 5 July 2017; Accepted 10 July 2017
Available online 12 July 2017
1385-1101/

applications (Pisano et al., 2016). The synoptic view from space allows SST to be mapped globally in regions where ships and in situ measuring devices are sparse or non-existent. The data acquired by sensors on satellites is a source of essential information to trace global (e.g. Bulgin et al., 2015; Good et al., 2007; Hansen et al., 2006; Hausfather et al., 2017; Lawrence et al., 2004) and regional SST variability as well monitoring SST trends (e.g. Goela et al., 2016; Marullo et al., 2007; Pisano et al., 2016; Stramska and Bialogrodzka, 2015).

Currently, there are a variety of historical satellite SST datasets with different spatial and temporal resolutions, which are generated and distributed by several agencies worldwide. As examples:

- The HadISST (1871 to the present) that was developed by the UK Meteorological Office, Hadley Centre for Climate Prediction and Research, and provides monthly data on a 1° grid (Rayner et al., 2003);
- The Improved Extended Reconstructed SST (ERSST) dataset (1984 to present) developed by the National Oceanic and Atmospheric Administration (NOAA) and that provides global monthly SST on a 2° grid (Smith et al., 2008) or
- The Pathfinder AVHRR SST dataset (1981 to 2013), i.e. Pathfinder Version 5.2 (PFV52), which provides non-interpolated daily data on a 0.04° grid.

In addition, new reanalysis products have also become available through programmes such as the Copernicus Marine Environment Monitoring Service (CMEMS) and ESA Climate Change Initiative (CCI); these datasets provide improved (e.g. merged) products, but are limited in time and do not cover the most recent years. For example, the Global Ocean OSTIA SST and Sea Ice Reprocessed products only cover the period from 1985 to 2007 and the ESA SST CCI dataset only covers the period from 1991 to 2010. In other cases, like the OSTIA reanalysis, the use of different input datasets, different sensor types and different in situ data makes the dataset less homogeneous and non-consistent in time (Merchant et al., 2016, 2012). As the objective of our study was the assessment of spatio-temporal SST variability on long timescales, we decided to use the longest satellite time series available (1982 to Near Real Time) that corresponds to the Reynolds Optimal Interpolation SST, version 2 (OISST v2).

Regarding the application of satellite data to marine environment it has been demonstrated that the data acquired by sensors on satellites are a source of essential information to trace global (e.g. Bulgin et al., 2015; Good et al., 2007; Hansen et al., 2006; Hausfather et al., 2017; Lawrence et al., 2004) and regional SST variability as well as trends over time (e.g. Goela et al., 2016; Marullo et al., 2007; Pisano et al., 2016; Stramska and Bialogrodzka, 2015). The use of SST satellite data to study SST variability (e.g. Hughes et al., 2009; Costoya et al., 2015) as well as its effect on marine ecosystems (e.g. Harris et al., 2014; Sandvik et al., 2005) is not novel in the North Atlantic Ocean. Different studies have been carried out in this area, endorsing the accuracy of satellite data for studying SST spatio-temporal variability at regional and more local scales (e.g. González-Taboada and Anadón, 2012; Gómez-Gesteira et al., 2008). However, studies involving satellite data are still scarce for the waters surrounding Ireland (Casal et al., 2015). In this region, oceanographic parameters such as SST are generally collected by a variety of oceanographic platforms e.g. shipboard campaigns and oceanographic stations. These sampling methods involve inherent logistical difficulties coupled with the need to cover vast areas and rapid oceanographic changes in time and space. The use of satellite would offer an effective alternative to monitor SST and to characterise habitats and ecosystems in Irish waters.

Thus, the primary aim of this study is to reinforce the use of satellite data as a tool to monitor spatial and temporal changes of SST and establish the background of their usefulness in ecological applications in waters around Ireland. In order to reach this objective we will 1) generate a time series of surface water temperature with spatial and temporal continuity 2) analyse the spatial and temporal variability in the study area and in the International Council for the Exploration of the Seas (ICES) Divisions surrounding the country 3) analyse the temporal trends. This information could then be used to inform marine environmental management in areas such as fisheries, climate change and indeed the design of future policy.

2. Materials and methods

2.1. Study area

Due to its proximity to both the European continental landmass to the east and the deeper more exposed waters of the Atlantic to the west, the coastal waters off Ireland have a high oceanographic variability. These characteristics make this marine environment very productive supporting a rich and diverse range of ecosystems, habitats and species. Some of the largest and most valuable sea fisheries resources in Europe are found off the Irish coast and the region is an ideal location for finfish, shellfish and seaweed aquaculture (Atlas of the Commercial Fisheries around Ireland, 2009). In 2012, Ireland's ocean economy had a turnover of €1.2 billion and provided employment for 17,425 FTE (full time equivalent with direct employment) with sea fisheries and aquaculture being one of the most important sectors (Vega et al., 2012). However, the marine physical, biological and biogeochemical characteristics are susceptible to the effects of climate change. For this reason, it is important to examine and quantify the likely impacts on the marine environment and the sectors that make up Ireland's maritime economy (Nolan et al., 2010). In this sense, the availability of an accurate, stable and consistent time series of SST data takes special importance. Given the close relationship between organisms and ecosystem physics and chemistry, changes in SST could have profound implications in Irish marine ecosystems and economy.

At the largest spatial scale, the Northeast Atlantic waters are divided into a series of Divisions and Sub-divisions; geo-reference boundaries of fish stocks and fisheries management areas used to coordinate scientific oceanographic and marine resource research. Fisheries and aquaculture sectors have profound implications in Irish economy and society. For this reason, the study area was defined taking into account these geo-political boundaries established by the ICES Divisions (Fig.1). The areas considered in this study are Sub-area VI composed by the ICES Divisions: VIa (West of Scotland) and VIb (Rockall) and Sub-area VII composed by ICES Divisions VIIa (Irish Sea), VIIb (West of Ireland), VIIc (Porcupine Bank), VIIf (Bristol Channel), VIIg (Celtic Sea North), VIIh (Celtic Sea South), VIIj (Southwest of Ireland-East) and VIIk (Southwest of Ireland-West).

2.2. Remote sensing data

The daily Reynolds OISST version 2 (OISST v2) reanalysis is a global, daily analysis produced on a 0.25° grid from 1982 to the present day using the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and AVHRR Pathfinder data (Reynolds et al., 2007); as AVHRR was not designed as a climate sensor it has limitations, and so dynamically stabilizing it to in situ data improves the climate quality. Operational AVHRR products were used together with in situ data, from ships and buoys, to allow for a large-scale adjustment of satellite biases in OISST v2 (Reynolds et al., 2007). Due to the satellite bias correction relies on having adequate in situ data, in areas with sparse in situ observations, the bias correction cannot be applied, but this occurs particularly at high latitude regions such as the Arctic. Spurious variability has been further reduced by the continuous use of the same sensor type over the entire time series, operated from 9 different satellites (NOAA7 to NOAA19 and METOP-A (Branzon and Reynolds, 2017). Additional information on the Optimum Interpolation (OI) algorithm and its bias treatment can be found in May et al. (1998), Reynolds et al. (2007), Reynolds (2009) and Casey et al. (2010).

The biggest challenge in retrieving SST from an IR instrument is