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Ollscoil na hÉireann, Corcaigh
National University of Ireland, Cork



**Analysis of the sea surface temperature variations
around Ireland's coastline 2002-2020.**

Thesis presented by
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for the degree of
Master of Research

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Signed: Aisling Murphy.

Abstract

This thesis analyses the sea surface temperature variations around Ireland's coastline from 2002-2020, using time series analysis of the one inactive and five currently active marine buoys. In depth analysis of the annual and seasonal sea surface temperature variations were assessed as well as spells of maximum and minimum sea surface temperature for each buoy. Both short term and long-term causations were identified as contributors to the variations in sea surface temperature experienced around Ireland's coastline. Particular focus on the Atlantic Multidecadal Variability, The NAO Index, the North Atlantic hurricane season and the position of the jet stream were assessed and correlated with sea surface temperature changes around Ireland's coastline from 2002-2020. These processes are interconnected and display a proportional relationship to each other as there is a high correlation between changes in these processes and a domino effect of other atmospheric and oceanic processes that influence sea surface temperatures around Ireland's coastline. There were variations in the annual average SST between the buoys. The buoys M4 and M5 both recorded an overall increase in mean annual SST from 2002-2020. Buoys M2, M3 and M6 recorded an overall decrease in the mean annual SST from 2002-2020. No clear connection between the different annual SST trends between the buoys were identified, however their individual location in relation to the continental shelf was a local factor that may have contributed to the variations between the buoys. In depth analysis of the long- and short-term contributors to variations in SST around Ireland's coastline showed that the most significant influencing factors of SST variations around Ireland's coastline were the North Atlantic hurricane season track positions and the varying position of the jet stream. Both of these factors displayed a significant impact on the annual SST variations and the spells of either maximum or minimum SST for each buoy. These factors also contributed to changes in the NAO Index, which further influenced SST variations around Ireland's coastline. The hurricane events contribute to the mixing of waters around Ireland's coastline, causing unstable conditions and a high level of mixing waters during negative NAO Index occurrences. The AMV signal impacts on air temperature, causing an increase in the effect and frequency of hurricane events in the North Atlantic which influence SST around Ireland's coastline. Assessment of ongoing changes in the position of the jet stream would be a critical factor in evaluation of future SST variations around Ireland's coastline.

List of abbreviations

Arctic Oscillation - AO

Atlantic Meridional Overturning Circulation - AMOC

Atlantic Multidecadal Oscillation - AMO

Atlantic Multidecadal Variability - AMV

Climate Forecast System Reanalysis - CFSR

Comprehensive Ocean-Atmosphere Data Set - COADS

Continental Slope Current - CSC

December-January-February - DJF

East Greenland Current - EGC

El Niño Southern Oscillation - ENSO

Greenland Ice Sheet – GIS

Gulf Stream extension - GSST

Hadley Centre Interpolated SST 1.1 - HadISST1.1

Intergovernmental Panel on Climate Change – IPCC

Irminger Current - IC

Marine Data Bank – MDB

Mean sea level pressure - MSLP

National Centres for Environmental Prediction - NCEP

National Oceanic and Atmospheric Administration - NOAA

North Atlantic Current - NAC

North Atlantic Deep Water - NADW

North Atlantic Oscillation - NAO

Sea ice extent - SIE

Sea level pressure - SLP

Sea surface salinities - SSS

Sea surface temperature – SST

Subtropical Mode Water - STMW

The North Atlantic Drift Current - NADC

Thousand years - Kyr

West Greenland Current - WGC

World Ocean Circulation Experiment -WOCE

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Chapter 1 Introduction

1.1 Introduction Sea surface temperature is defined by NOAA (2020, 1) as “the temperature of the water close to the surface of the ocean. The exact meaning of surface varies according to the measurement method employed but is between 1 millimetre and 20 meters below the surface.” Sea surface temperatures in the North Atlantic oscillate on a multidecadal scale. These variations strongly influence the Northern Hemisphere’s climate. This thesis examines the sea surface temperature variations around the Irish coastline, using five currently active marine buoys and one inactive marine buoy. The five currently active buoys record other atmospheric and oceanic data used in the analysis, as well as the historic atmospheric and oceanic data recorded from the one inactive buoy. The marine buoys surrounding the Irish coastline provide innovative marine research technology and analysis methods. The Marine Institute Act 1991 primarily functions to collect, maintain and disseminate information relating to marine matters. Five offshore buoys deployed around the Irish coastline monitor weather and oceanographic conditions in real- time allowing in depth analysis and monitoring of oceanographic changes over time. The network of buoys also assists to provide information and data to enable weather forecasts and severe weather event warnings to the public. Data is currently available from 2000- 2020, and this data is used to create a time series analysis of the sea surface temperature variations around the Irish coastline. Air temperature, wind speed, wind direction, and other atmospheric and oceanic processes are also analysed to examine the correlation between these parameters and the effect that these parameters have on influencing sea surface temperatures around Ireland’s coastline.

According to Grist, et al (2009) the sea surface temperature of oceans is categorised in thermal energy, which is the kinetic energy of atoms and molecules, so temperature in turn measures the average kinetic energy of these atoms and molecules. Kinetic energy governs the transfer of heat energy in water, allowing this transfer of heat energy between substances. Lapointe, et al (2020) highlight that global warming, due to anthropogenic factors can be accelerated or slowed by natural climate oscillations, especially those involving sea surface temperatures in the North Atlantic Ocean, which vary on a multidecadal scale. The multidecadal oscillations of the Atlantic Ocean are characterised by large scale variations in sea surface temperatures. During the positive phase, sea surface temperature anomalies are warmer in the Atlantic, while during the negative phase, sea surface temperatures are cooler. These variations strongly influence the climate around Ireland. Lapointe, et al (2020) acknowledge that global warming, and the influence of this on sea surface temperatures,

strongly influences variations in air temperatures. The alteration of air temperatures can significantly govern the climate of Ireland, as increased air temperatures can cause higher rates of evaporation of water from the sea surface, resulting in increased volume of water vapour in clouds. Lower air temperatures cause the condensation of evaporated water molecules, resulting in increased precipitation. The effect of global warming on sea surface temperatures is also important when examining the causes of extreme weather events or storms.

The Atlantic Ocean is a body of saltwater covering about one-fifth of the earth's surface and separating the continents of Europe, Africa, and North and South America. The name Atlantic Ocean is derived (La Mourie, 2020) from Greek mythology means "Sea of Atlas". Analysis of LaMourie, (2020) highlights that the surface currents of the Atlantic Ocean directly correlate to the system of prevailing winds. These prevailing winds modify the movements of water by land boundaries. Other parameters that influence the currents are regional excesses of evaporation or precipitation, regional differences in cooling or heating of both land and continental crusts, or the earth's rotation.

In the North Atlantic, the prevailing winds maintain a current from east to west, maintaining an accumulation of warm water on the northern side of the current. Large volumes of water carried by this current continues to the Caribbean Sea into the Gulf of Mexico, where it then flows through the straits of Florida. This current is then reinforced by the water that has flowed on the eastern side of the Antilles as the Antilles Current, forming the Gulf Stream, origination off the North American east coast. LaMourie, (2020) highlights that weather over the North Atlantic Ocean is largely governed by large-scale wind currents and air masses originating from North America. Around Iceland, atmospheric pressure tends to be low and air flows in a counterclockwise direction. Conversely, air flows clockwise around the Azores which is a high-pressure area. The union of these winds generates prevailing westerly winds across the North Atlantic and over Western Europe.

NASA, (2020) states that sea surface temperatures largely govern climatic and weather pattern. Alexander, et al, (2018) examines how sea surface temperatures are a key variable in climatic systema, that serves to regulate thermal and dynamical interactions between the ocean and atmosphere. Alexander, et al, (2018) observes that the global mean sea surface temperatures have risen by ~ 0.06 degrees Celsius from 1901- 2012 and ~ 0.0095 degrees Celsius per decade from 1979- 2012. Alexander, et al, (2018) highlights that warming of the

globes sea surface temperatures occurred during this period with the exception of a small area of the Atlantic, and in some areas in the equatorial Pacific. Typically, basin wide changes in the ocean are expected, it is critical to examine temperatures changes along continental margins, as these areas largely influence land heat retention.

Alexander, et al, (2018) examines that climate changes and oscillations not only influence mean sea surface temperatures trends but also influences changes in variability and the frequency of extreme weather events. Climate change can impact the frequency and severity of extreme weather events, due to a dynamic shift in the mean state. Extreme weather events are also influenced by the emission of greenhouse gasses, by altering the probability and distribution of temperatures and other variables in a climatic system.

The properties of seawater result in constant fluctuations of heat, and salinity in order to reach equilibrium. Warm water is less dense than cold water, so as the saltwater cools, it condenses and sinks as warm water replaces it. Both surface and deep ocean currents circulate the salt water in this pattern known as a process called thermohaline circulation (Gibbens, 2019). Warm water originating in the Gulf Stream, heated by a warm air current in the Gulf of Mexico, is transported North by oceanic currents, where it forces cool water to condense and submerge and move South. As this current moves towards Antarctica, the thermohaline circulation process functions to transport water around the world. The impact of global warming on the Atlantic Ocean was assessed (Gibbens, 2019), detailing how instruments located in the Caribbean have detected that the Atlantic Ocean's thermohaline circulation system is slowing down. As there is a direct correlation between ocean and sea surface temperatures, and weather over continental land masses bordering the Atlantic Ocean, a change in the rate of circulation could directly affect seasonal weather patterns on the continental land masses. There is a different causation for the current becoming slower, Gibbens, (2019) highlights an argument between literature that climate change and the melting of global glacier systems are the primary cause, while others argue that these changes are cyclical.

Analysis of Gibbens, (2019) assessment of the 2018 active Atlantic hurricane season, indicated that storm events will become more frequent, and more intense as the atmosphere continues to warm. Warm atmospheric temperatures allow a greater volume of evaporated water to be transported, resulting in heavier precipitation during storm events.

Analysis of sea surface temperatures is a fundamental physical variable used to quantify and predict dynamic interactions between the ocean and the atmospheric conditions. These dynamic processes, cause the redistribution of thermal energy across the world, impacting on both large- and small-scale weather and climate patterns (O’Carroll, et al, 2019). The dynamic nature of the ocean-atmosphere interface highlights the interconnectedness and correlation between these two atmospheric processes. Assessment of global sea surface temperature distribution and temporal variation is necessary for the accurate forecasting and prediction of weather patterns.

1.2 Aims and objectives

Firstly, this thesis aims to analyse daily, monthly, seasonal, and annual variations of sea surface temperatures using marine buoy data. This time series analysis of sea surface temperatures will highlight trends or extreme events and allow further analysis for the causes of this.

Secondly this thesis aims to assess the extreme sea surface temperature variations around Ireland and examine the causations for this based on analysis of trends and other parameters that influence these extreme events.

The third aim of this thesis is to analyse air temperature, wind speed, wind direction and other atmospheric processes to assess the impact of these parameters on influencing sea surface temperatures around Ireland.

1.3 Chapter outline

Chapter 1 – Introduction to topic.

Chapter 2 – Literature review containing previous analysis of sea surface temperatures and the influence of climate change on altering sea surface temperature trends. The causes and parameters that influence sea surface temperatures and extreme temperature changes will also be reviewed.

Chapter 3 – Methodology. This will involve the compiling and analysis of sea surface temperature data from the inactive and active marine buoys around Ireland. Air temperature, wind speed, wind direction, and adjacent cloud cover will also be analysed to examine the effect that these parameters have on influencing sea surface temperatures around Ireland.

Chapter 4 – Results. Upon the completion of the methodology, trends of oscillations of sea surface temperatures around Ireland are analysed. These trends will be analysed and assessed over time to establish the dynamic variations of sea surface temperatures around Ireland.

Chapter 5- Analysis. Analysis of the annual and spells of maximum and minimum SST.

Chapter 6 – SST causations. Analysis of the short- and long-term causation of SST variations.

Chapter 7 – Discussion of the sea surface temperature variations around Ireland, extreme events, and the causes for this are discussed in relation to the data and results of the methodology process.

Chapter 8 – Conclusion of the overall findings and analysis of sea surface temperature variations around Ireland between the years 2002–2020.

Chapter 2 Literature review

2.1 Introduction The ocean accounts for 71% of the earth's surface, therefore analysis of variations of sea surface temperatures globally is essential to understand the dynamic interactions and processes associated with the oceanic- atmospheric interface. The sea surface temperature of the ocean "is indicated by measurements taken at depths that range from 1 millimetre to 20 meters" (NASA, 2020, 1). Historically ship records were used to record variations in sea surface temperatures, however buoys and satellites are primarily used to record sea surface temperature data. The sea surface temperature measurement does not indicate absolute temperature at a precise location, but instead determines the number of positive temperature deviations (anomalies) that exceed the natural range of variation for a given location. Sea surface temperature provides fundamental information and data on the global climate system and is an essential parameter in weather prediction and atmospheric model simulations, due to the proportional relationship between the oceanic and atmospheric interface. Sea surface temperature data is also used to identify the onset of El Niño and La Niña cycles. During El Niño, temperatures in the Pacific near the equator are warmer than normal. During La Niña, the same area experiences colder than normal ocean temperatures. These cycles are caused by multiyear shifts in pressure and wind speeds, and affect ocean circulation, global weather patterns, and marine ecosystems.

2.2 Causes of sea surface temperature variations

The fluctuations of the sea surface temperatures of the Atlantic Ocean have a dynamic effect on influencing climatic conditions on the surrounding continents. The sea surface temperature variations of the Atlantic Ocean are thought to be similar to the dynamic mechanism of the El Niño or Southern Oscillation (ENSO) in the equatorial Pacific according to Richter, et al, (2013). The fluctuations of sea surface temperatures are governed by the principle where air – sea coupling, which leads to a positive feedback mechanism between surface winds in the western basin, sea surface temperature variations in the eastern basin, and equatorial oceanic heat content. Therefore, when examining sea surface temperature variations, climatic data such as wind speed and direction, cloud coverage and meteorological data should also be simultaneously analysed as these parameters have a direct correlation to influencing sea surface temperature variations in an area.

Analysis of sea surface temperature variations showed that some of the warm events cannot be solely attributed to previously identified equatorial wind stress forcing and El Niño

Southern Oscillation (ENSO) -like dynamics (Richter, et al, 2013). Instead, these events are driven by a mechanism in which surface wind forcing just north of the equator induces warm ocean temperature anomalies that are subsequently circulated toward the equator. It was also suggested that the surface wind patterns are associated with long-lived subtropical sea surface temperature anomalies and suggest they therefore reflect a link between equatorial and subtropical Atlantic variability.

2.3 IPCC reports

According to the IPCC, (2019) the ocean has continually warmed since 2005, further continuing the multi-decadal ocean warming trends that were outlined in the IPCC Fifth Assessment Report. The IPCC, (2019, 2) confirms that the “0–700 m and 700–2000 m layers of the ocean have warmed at rates of 5.31 ± 0.48 and 4.02 ± 0.97 ZJ year⁻¹ from 2005 to 2017.” This warming has been largely attributed to anthropogenic influences. The IPCC, (2019) highlights that the surface ocean has become less dense over time, relative to the deeper ocean, due to the convection currents of rising warm water and submerging cold water. This creates a stratification of the ocean based on temperature and subsequently density related to temperature. The upper 200 meters of the ocean stratification has increased from 1970-2017, highlighting the warming of both the ocean and sea surface temperature.

According to the IPCC, (2018) report the ocean has absorbed 93% of excess heat originating from anthropogenic enhanced greenhouse emissions between the years 1971-2010. 64% of this warming occurred in the upper section of the ocean (0 to 700m). The IPCC, (2018) report also states that global average sea surface temperatures have increased since the beginning of the 20th century, as seen in figure 1. The rate of temperature increase is greatest near the surface of the ocean “>0.1 degrees Celsius per decade in the upper seventy-five meters from 1971- 2010 IPCC, (2018, 1664). The IPCC, (2018, 1665) report also states that it is “very likely” that intensification and amplification of this warming near the surface of the ocean has resulted in increased thermal stratification of the upper section of the ocean by approximately 4% (between 0- 200 meters) depth from 1972 to 2010 in all geographical areas of the ocean north of 40°S.

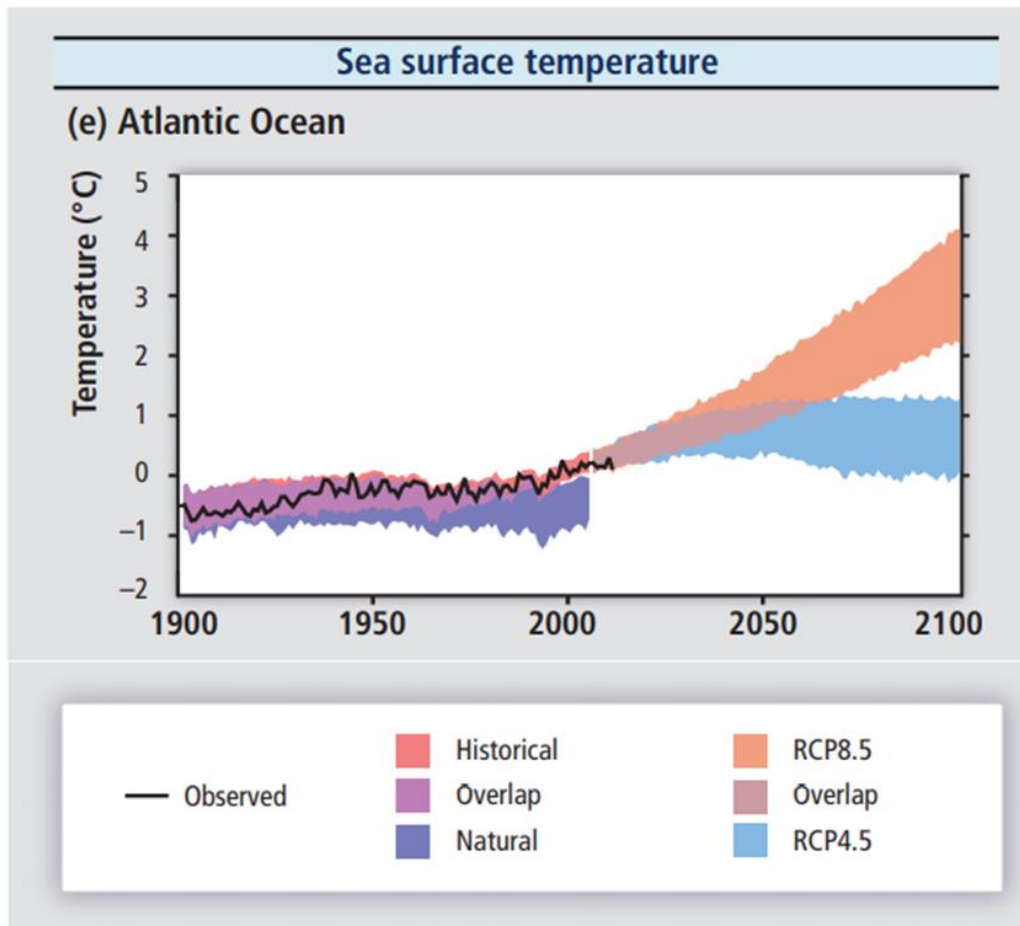


Figure 1 Sea surface temperature trends of the North Atlantic Ocean (IPCC, 2018)

Data archives such as Hadley Centre Interpolated SST 1.1 (HadISST1.1) archive sea surface temperature data from a range of sources, allowing an opportunity to analyse mean monthly, and annual, global sea surface temperature trends from 1870 to the present (Rayner, et al., 2003). The published HadISST1.1 data set was used to explore trends in historic sea surface temperatures within the sub-regions of the Ocean. The median sea surface temperatures for 1871–1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the UK Met Office Marine Data Bank (MDB) to produce monthly globally complete fields of sea surface temperature on a 1° latitude-longitude SST grid from 1870 to present. The IPCC, (2018) states that from 1971- 2010 the Atlantic Ocean has warmed at a rate of 0.07 degrees Celsius per year.

The IPCC, (2018) report examines how circulation of the atmosphere and ocean and their dynamic interactions impacts the physical, chemical, and biological characteristics of the ocean. Alteration of these circulation patterns including the widening of the tropical belt, contraction of the northern polar vortex, and a shift of storm paths and jet streams to higher

latitudes, and changes to the frequency and intensity of extreme weather events experienced over Ireland. Prolonged patterns of variability over time results in changes in atmospheric circulation in wind and wave patterns. Surface waves are influenced and governed by wind stress. IPCC, (2018) states that significant wave height has increased since the 1950's in the North Atlantic. Solar insolation and cloud coverage also are significant parameters that influence the sea surface temperature variations of the Atlantic Ocean.

The IPCC, (2018) also states that the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970's, while trends of inter-decadal changes in storm activity in the Atlantic have also been recorded. Storms can also result in the reduction of local sea surface temperatures, due to the remixing of heat into deeper layers within the ocean.

The IPCC, (2018, 1671) highlights that thermal heat energy has accumulated in the ocean has increased by a rate of 4% since the 1970's, creating thermal stratification of the upper layers of the ocean (0-200 meters) north of 40°S. The global hydrological cycle is governed by evaporation and precipitation patterns over oceanic regions. Parameters influencing the rates of evaporation and precipitation patterns include salinity, temperature, solar radiation, cloud cover and ocean circulation cycles. Alterations of the salinity influences the stratification of water masses and circulation patterns. Ocean salinity varies on a regional scale, and functions to maintain a balance between evaporation and precipitation rates. Evaporation dominated regions such as the Atlantic Ocean have elevated salinity levels compared to precipitation dominated regions such as the Pacific Ocean. This factor is significant as increased rates of evaporation result in an increased volume of condensed water particles. These particles are transported by the prevailing winds of a region, which in Ireland is south westerly winds. This results in the evaporated water cooling and condensing further as it reaches the elevated maritime rim of Ireland's coastline, resulting in excess precipitation occurring in this region.

2.4 Annually resolved Atlantic sea surface temperature variability over the past 2900 years.

According to Lapointe, et al, (2020) global warming due to anthropogenic factors are amplified or dampened by the effects of natural climate oscillations, especially sea surface temperatures of the North Atlantic Region, which vary on a multidecadal scale. The Atlantic multidecadal variability (AMV) has a limited instrumental record, which makes the analysis and prediction of long-term behavioural patterns challenging, however climate

teleconnections of areas surrounding the North Atlantic region allows for the ability to reconstruct AMV from high resolution records in nearby regions. Annually resolved titanium records from Canada shows that there are significant correlations between high Arctic proxies and highly resolved Atlantic sea surface temperatures proxies concluding that there is a multidecadal variability seen in the Atlantic. Lapointe, et al, (2020) also states that current sea surface temperatures are the warmest in the in the past 2900 years.

The Atlantic multidecadal oscillation (AMO) is characterised by large scale variations in sea surface temperatures in the North Atlantic regions. During the positive phase, sea surface temperature anomalies are warmer in the North Atlantic regions, whilst during the negative phase, cooler sea surface temperatures are recorded. Based on analysis of sea surface temperatures, there appears to be a 40-80-year variation in North Atlantic sea surface temperatures, this is based on the limited instrumental record (Richter, et al, 2013) (Lapointe, et al, 2020). This is seen in figure 2, which demonstrates the positive and negative phases of the AMO, which shows warmer and colder SST respectively, varying every 40-80 years.

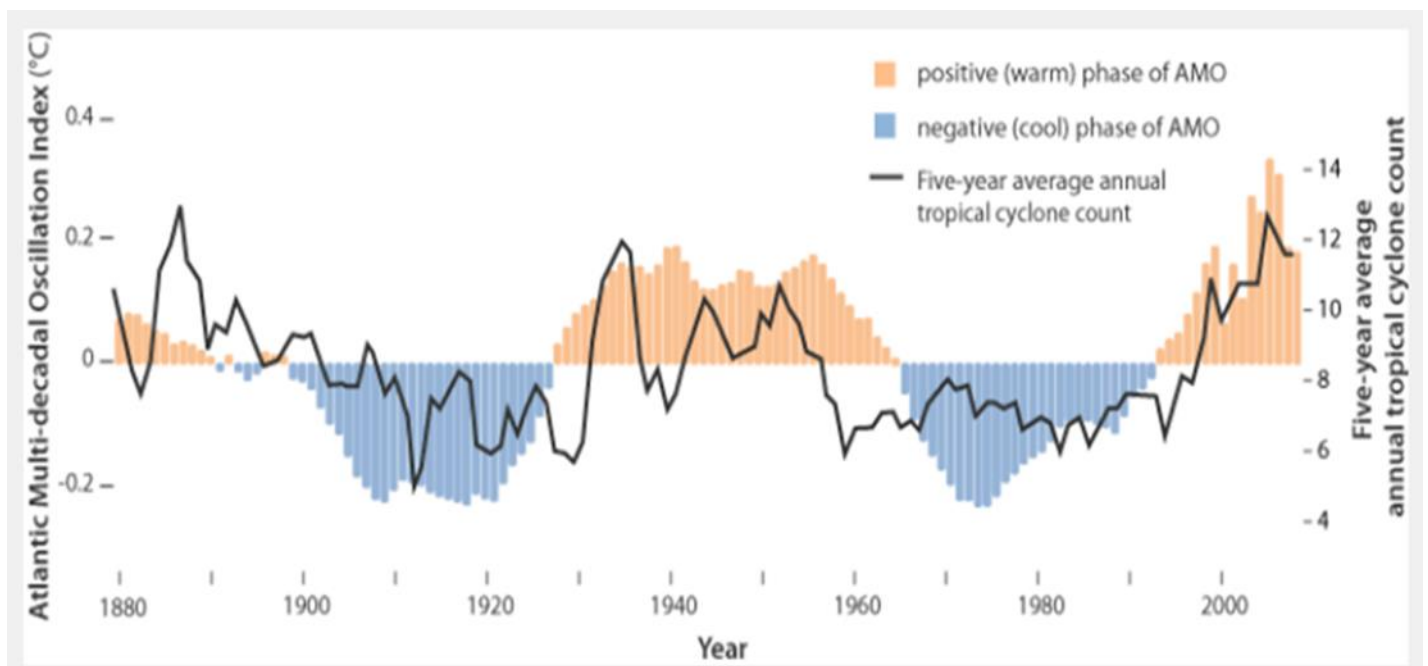


Figure 2 The Atlantic Multi-Decadal Oscillation Index (Cultz, 2018)

Lapointe, et al, (2020) analysed that observational evidence suggests that the AMV has a significant impact on air temperature. Some of the impacts of this include the increase of the frequency and intensity of hurricane events in the North Atlantic region. Analysis of fluctuations of the AMV are therefore critical to understand and predict the potential

destruction and frequency of increased hurricane events in this region, which would contribute to causing variations in SST around Ireland's coastline. Analysis by Lapointe, et al, (2020) shows that Atlantic sea surface temperatures significantly influence summer atmospheric conditions with a direct effect on air temperature. Based on analysis of sea surface temperature records, low pressure dominates during the negative phase of the AMV when sea surface temperatures are below average, and when sea surface temperature values are below average, this directly induces low pressure in the North Atlantic region. Cloud cover also increased significantly when atmospheric pressure was lower, and temperatures were cooler.

Atlantic sea surface temperatures vary on a multidecadal scale, and this has impacted the climatic systems for the past three millennia. The atmospheric pressure patterns during times of positive AMV resembles the negative phase of the North Atlantic Oscillation (NAO). The dynamic interactions between the AMV and NAO are not fully understood. When considering the basin scale sea surface temperature associated with AMV, atmospheric model experiments and trend analysis demonstrate that sea surface temperatures warming leads to more frequent negative NAO.

2.5 Interdecadal variations in North Atlantic sea surface temperatures and associated atmospheric conditions.

Kushnir, (1993) examines a distinctive pattern of ocean- atmosphere relationship that varies on a multidecadal scale in the North Atlantic Ocean. Surface marine observations have been analysed in the mid and high latitude Atlantic Ocean, and sea surface temperatures in this area display long term variations. Negative anomalies were recorded before 1920 and during 1970 and 1980. Positive sea surface temperature anomalies were recorded from 1930-1960. The sea surface temperature interdecadal variations of the positive and negative anomalies are derived by subtracting the average temperature during fifteen cold years from the average temperature during fifteen years of warm years.

The corresponding variations in surface atmospheric conditions such as wind speed, wind direction and air temperature are determined by averaging and subtracting in the method previously described. Analysis of these parameters have shown an anomaly in the centre of the Atlantic Ocean basin, coordinates 45°N and 35°W. This anomaly was characterised by a cyclonic circulation prevailing during warm sea surface temperature years. Anticyclonic anomalies dominated during years of cold sea surface temperatures. Kushnir, (1993)

discusses that the interdecadal variability of sea surface temperatures of the Atlantic Ocean, may be governed by a basin scale dynamical interaction between the large-scale oceanic circulation patterns and the atmosphere.

Analysis of Kushnir, (1993) shows that the interrelationship between the oceans and atmosphere is fundamental to the dynamic process that governs climatic variability. Although oceans do respond to changes in the atmosphere, oceans display an (Kushnir, 1993, 1) “inherently long-time scale” due to their ability to retain heat energy and retain equilibrium. Due to the interrelationship between the ocean and atmospheric interface, the long-time scale of oceans subsequently effects atmospheric circulation. In the midlatitude regions, heat energy is transported poleward by ocean circulations and is subsequently transferred to the atmosphere by turbulent interactions. Fluctuations in the ocean-atmosphere heat exchange process generates large scale anomalies for prolonged periods of time. The cumulative effect of the midlatitude interactions between the ocean and atmosphere, are important to determine the zonally asymmetric part of the atmospheric flow and subsequent horizontal distribution of climatic conditions. These asymmetries affect the pattern and distribution of surface wind direction and speed, resulting in oceanic gyre circulation.

Examination of Kushnir, (1993) highlights the variability of the North Atlantic sea surface temperature and sea level pressure, in order to identify the relationship between ocean – atmosphere interactions. Inter-annual and inter-decadal sea surface temperature variations as well as variations in the meridional pressure gradient across the Atlantic basin were identified (Kushnir, 1993). Analysis of sea surface temperature records shows a gradual warming of sea surface temperatures south of 50°N in 1920. This gradual warming occurred across the width of the ocean from 30°N to 50°N. The sea level pressure corresponded to a positive anomaly at 30°N and a negative anomaly north of 50°N. This pattern implies that the inter-decadal sea surface temperature warming directly correlates with a strengthening of the overlying westerly winds. By contrast, Kushnir, (1993) highlights that inter-annual variability over high latitudes displays a local negative correlation between wind speed and sea surface temperature.

The observations made by Kushnir, (1993) confirm that the interdecadal warming of sea surface temperature is directly correlated to a basin scale interaction in which the Gulf Stream and the North Atlantic Current responded to the intensification of circulation processes in the subtropical cyclone. Inter-annual variations according to Kushnir, (1993) is governed by the

response mechanism of the oceanic mixed layer to the local exchange of heat with the atmosphere.

Analysis by Kushnir, (1993) examines the spatial scale of inter-annual sea surface temperature anomalies and the relation to atmospheric conditions. Inter-annual sea surface temperature variability impact climate conditions in relatively local, dipole like patterns. In the North Atlantic, wintertime anomalies extending from 40°N to 60°N accompanied by positive anomalies in the 20° to 40°N latitude belt. The observed correlation between the pattern of wintertime sea surface temperature variations and sea level pressure fluctuations, both support the theory that interannual sea surface temperature fluctuations are governed by the alternating patterns of wintertime atmospheric circulations. Analysis of Deser, et al, (2010) showed that interannual SST variability was a result of a combination and interaction of atmospheric and oceanic processes. SST anomaly patterns are influenced by modes of atmospheric circulation variability, usually in the form of surface energy fluxes, such as a tripolar pattern of SST anomalies in the North Atlantic associated with the North Atlantic Oscillation, coupled with other oceanic processes. Coupled ocean-atmosphere interactions influence SST variations such as the El Niño Southern Oscillation (ENSO) phenomenon, and the cross equatorial meridional modes in the tropical Pacific and Atlantic. Basin scale SST anomalies result from (Deser, et al, 2010) the large scale organisation of atmospheric circulation anomalies and attendant changes in the radiative and turbulent energy fluxes at the air-sea interface, coupled with the local wind-driven Ekman currents. In midlatitude regions such as Ireland, eastward-moving storms dominate surface energy flux variations on synoptic timescales. These processes and their influence on SST variations around Ireland's coastline are discussed further in Chapter 6.

2.6 Sea surface temperatures and the maximum intensity of Atlantic tropical cyclones.

DeMaria, Kaplan, (1994) conducted a study to examine the empirical relationship between climatological sea surface temperatures and the maximum intensity of tropical cyclones in the North Atlantic basin through analysis of 31-year records (1962-1992). Results show that only about 20% of Atlantic tropical cyclones reach 80% or more of their maximum potential intensity at the times when they are the most intense. Based on analysis storms only reach around 55% of their maximum potential intensity in the Atlantic region, concentrated around the west and northern region.

Analysis of sea surface temperatures confirms that the dynamic nature of sea surface temperatures and the interconnectedness of the ocean-atmosphere interface, contributes to the formation and intensification of tropical cyclones. Consideration of sea surface temperatures as a lone variable is not sufficient for overall accurate assessments of their contribution to the formation of cyclones. This is seen during the 1992 Atlantic hurricane season, which had a sea surface temperature of around 27°C, however the maximum wind speed reached 28m s⁻¹ compared to hurricane Bonnie in a different location with a sea surface temperature of 20°C and a maximum wind speed of 49m s⁻¹ contributing largely to the formation of this hurricane event. For this reason, sea surface temperature alone is not an accurate indicator of intensity changes. Miller, (1958) developed a relationship between the sea surface temperature and the minimum sea level pressure that a storm can attain based upon the pressure reduction that results from lifting air moisture adiabatically to near the tropopause level in the eyewall and then subsiding the air dry adiabatically back to the surface of the eye.

The results of Miller, (1958) analysis indicates that the relationship between maximum intensity and sea surface temperatures is nonlinear where the maximum intensity is more sensitive to sea surface temperature variations at warmer sea surface temperatures. Merrill, (1987) also examined the relationship between storm intensity and climatological sea surface temperatures for a 12-year period of Atlantic tropical cyclones. Analysis of this data concluded that the most intense storms occur over regions with the warmest sea surface temperatures, however the presence of warm water is not a sufficient condition for intensification. This confirms the analysis conducted by Miller, (1958) which indicated that sea surface temperatures provide an indication of the intensity of tropical cyclones. Another study conducted by Evans, (1991) confirmed the results of Miller, (1958) and Merrill, (1987) observed that storms in the Atlantic Ocean were experienced when sea surface temperatures were at their warmest. Analysis of more recent work such as Micheals, et al, (2006) indicates that typically, peak storm wind speeds do not occur over the location of the highest SST along the storm track, with the peak winds usually occurring about 4.4 degrees latitude Northward of the location of the highest SST at the time. Micheals, et al, (2006) conclude that a more accurate indicator of the ultimate intensity of tropical cyclones is the highest SST encountered prior to the time of peak wind.

Darling, (1991) assessed the probability of hurricane events and wind speeds in the Atlantic Ocean. Results of this study concluded that there is an empirical relationship between sea surface temperatures and maximum storm intensities. Goldenberg, et al, (2001) highlights

that the years 1995 to 2000 experienced the highest level of North Atlantic hurricane activity in the reliable record. When compared to the low activity of the previous 24 years (1971 to 1994), the six years preceding this witnessed a doubling of overall activity for the entire Atlantic Basin, with 2.5 times increase in major hurricane events. The increase in hurricane events has simultaneously correlated with an increase in sea surface temperatures in the Atlantic Ocean.

The North Atlantic Basin (consisting of the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico) displays characteristics of substantial inter-annual and inter-decadal variability of tropical cyclone activity. This tropical cyclone activity is pronounced by hurricane events. Local geographic factors have a direct thermodynamic or dynamic connection to the formation of waves during tropical cyclone events. The oceans are the primary energy source for tropical cyclones. Localized sea surface temperatures play a direct role in providing moist enthalpy to provide energy to incipient tropical cyclones (Goldenberg, et al, 2001). Warmer sea surface temperatures decrease atmospheric stability, which increases the penetration depth of a vortex, thus, making developing tropical cyclones more resistant to vertical wind shear. Local sea surface temperatures greater than 26.5°C are usually considered to be a necessary condition for tropical cyclone development, and higher sea surface temperatures can increase overall activity. Multi-decadal variations in major hurricane activity have been attributed to changes in the sea surface temperature structure in the Atlantic because tropical North Atlantic sea surface temperatures correlate positively with major hurricane activity.

Although North Atlantic sea surface temperatures directly impact tropical cyclone activity as a local thermodynamic effect, it appears unlikely that this is their only physical link to hurricane activity. For influencing activity on inter-annual time scales, this local effect plays either a negligible role (for major hurricanes) or a secondary role (for all hurricanes). The dominant local factor for tropical cyclone activity is the magnitude of the vertical shear of the horizontal wind between the upper and lower troposphere (Goldenberg, et al, 2001).

2.7 Greenland melt water

Heat transportation due to ocean circulation patterns can directly and indirectly affect the melting of marine terminating glaciers in Greenland. Analysis of the changes of marine-terminating glaciers reveals the sensitivity of the Greenland Ice Sheet to sea surface temperatures. Loss of mass of ice sheets due to runoff of surface melt water and ice discharge

into the ocean over the past two decades has resulted in the accelerated mass loss from the Greenland Ice Sheet. Aschwanden, et al, (2019) determined that between 1995 and 1998, subsurface ocean temperatures increased by 1.5°C along the west coastline of Greenland due to an increase in subsurface ocean temperature in the subpolar gyre. This process created a positive feedback mechanism between the thinning and outlet glacier acceleration. Thinning of the ice sheet exposes the remaining ice to higher air temperatures while reducing the surface area of the ice sheet. This process creates a surface mass balance–elevation feedback mechanism, contributing to a second positive feedback for overall ice mass loss. These two positive mechanism feedbacks can be responsible for the nonlinear responses of ice sheets to environmental oscillations.

Analysis of Hofer, et al, (2020) identifies that future climatological projections indicate a marked increase in Greenland Ice Sheet runoff during the 21st century as a direct result of the Polar Amplification signal, which indicates the rate of warming of the Arctic region. Regional climate models have been used to assess the local impacts indicated by global climate models, to accurately assess the impact of anthropogenic global warming on the Greenland Ice Sheet melt, associated sea level rise, and alterations to sea surface temperatures. Hofer, et al, (2020) identified a 1.3°C greater Arctic Amplification and associated cloud coverage, as well as increasing the positive feedbacks than previously predicted by regional climate models.

Nakamura, (2013) acknowledges a sudden alteration in the reference Greenland sea surface temperature in 1979. This sudden change in sea surface temperature is found to be part of a complex set of changes in the northern Atlantic seas. This dynamic change in sea surface temperature resulted in major changes in the near- surface baroclinicity, measuring the stratification of the ocean based on temperature and pressure, coupled with a dramatic change in the net surface heat flux at the air-sea boundary over the Greenland Sea. The differences in the atmospheric mean state between two periods, one before and the other after the Greenland sea surface temperature change in the late 1970's, resemble those between the high and low North Atlantic Oscillation (NAO) Index states. These changes in mean state were mirrored by interannual variability of atmospheric processes were recorded. A particularly interesting change in the interannual variability is found in the relationship between July Greenland sea surface temperature and the North Atlantic Oscillation phase in the following February. There is a strong correlation between July Greenland sea surface temperature and the North Atlantic Oscillation phase in the following February before the late 1970s but not at all after

the late 1970's. The characteristics of these changes suggest that they may be a part of the high-frequency details of the Atlantic Multi-decadal Oscillation (Nakamura, 2013).

Interactions between the atmosphere and oceans are a complex and dynamic process. Due to the possibility of the collapse of the North Atlantic branch of the thermohaline circulation, critical assessments of the dynamic interaction between the atmosphere and ocean have been examined. Observational data has been used to analyse the variability of sea surface temperatures and the associated atmospheric variability. Nakamura, (2013) recognises that atmosphere-ocean variability has been identified on regional to global scales and over a wide range of temporal scales ranging from inter-decadal to multi-decadal, associated with the Atlantic Ocean. These studies evaluated that the oceanic anomalies drive the atmosphere at long time scales, inter-decadal and longer, and the atmospheric anomalies force back the ocean, resulting in complex and dynamic loops of feedbacks at various time scales.

The study of the large-scale tropical air-sea interactions has expanded in the last decade to examine the atmospheric and oceanic processes near oceanic fronts along the two major western boundary currents, the Gulf Stream and Kuroshio/Oyashio Extensions, as these currents appear to contribute to the maintenance of the storm tracks and general circulation in the Northern Hemisphere (Nakamura, 2013). Signs of atmospheric anomalies creating anomalies in the tropical ocean and oceanic fronts at monthly to inter-annual time scales have been found in observational data and numerical experiments, evidence of sea surface temperature anomalies along these fronts consistently generating anomalous atmospheric circulation has been difficult to find in data. Nakamura, (2013) reanalysed the data in sea surface temperature anomalies along oceanic fronts in the midlatitudes on the large-scale atmospheric state. The study revealed that the large-scale atmospheric anomalies can be generated by sea surface temperature anomalies when the anomalies modify in the vicinity of the storm tracks and upper-tropospheric jet. A sharp thermal front is created where cold and warm waters meet. In addition, the land/ ice surface of Greenland and the surrounding ocean generate very large surface temperature gradients during winter. A direct impact of sea ice in this area on the storms in the region, presumably by modification of the surface heat flux at the air-sea boundary.

2.8 Greenland sea surface temperature and the NAO.

Examination of the NAO and the Nordic seas has revealed that the ocean region responds to anomalous atmospheric thermal and momentum forcing associated with the NAO on a

monthly to seasonal time scale (Nakamura, 2013). Substantial variability is however recognised in the oceanic state in the region due to the oceanic internal dynamic processes. To investigate a potential correlation between sea surface temperatures and atmospheric anomalies in the Greenland Sea and the interannual variability associated with these processes, the correlation between the Greenland Sea surface temperature index and the NAO Index were examined (Nakamura, 2013). The correlation is especially high and significant between July Greenland Sea surface temperature index and the following February NAO Index with a correlation coefficient value of 0.712. The relationship between July Greenland Sea surface temperature index and the following February NAO Index is likely to be significant (Nakamura, 2013). Changes in the relationship between the NAO and North Atlantic sea surface temperature, that is, between the NAO and the surface atmospheric temperature and between the NAO and the sea level pressure, have been reported (Polyakova, et al, 2006). These results suggest that the North Atlantic climate variability may have changed in a number of parameters in the late 1970's. As sea surface temperature anomalies grow to substantial positive values in the northern Norwegian Sea in the mid-winter and that sea surface temperature anomalies to the south of Greenland and Iceland remain negative throughout the eight-month period up to February. It may be this southwest–northeast contrast between negative and positive sea surface temperature anomalies in the region that plays a significant role in the positive NAO Index in February. This resulted in a change in the reference sea surface temperature in the region.

The accompanying difference in the mean state between two periods, one from 1957 through 1978 and the other from 1979 through 2002, resembles the difference between the positive and negative phases of the NAO (Polyakova, et al, 2006). The evolution of the Greenland Sea surface temperature index and the sea surface temperature in the Nordic seas suggests that the sudden change in the Greenland Sea surface temperature index and, possibly, the climate in March 1979 may represent the final slip into a new climate after the Nordic seas went through a gradual warming in the early and mid-1970's. The climate change in the late 1970's is found in not only the mean state but also in the interannual variability. A particularly intriguing facet of the climate change is a complete change in the relationship between the summer Greenland Sea surface temperature index and the following February NAO Index. Before the change, the July Greenland Sea surface temperature index and the following February NAO Index were strongly correlated. After the change, the correlation completely disappeared. The discovery of the change in relationship between the July

Greenland Sea surface temperature index and February NAO adds one more piece of information to the complex picture of climate variations in the North Atlantic basin. This dynamic change in sea surface temperature implies a possibility of a sudden climate change on the hemispheric scale occurring as a result of internal changes in the sea surface temperature and sea ice in a small area of the Nordic seas (Polyakova, et al, 2006). Jensen, et al, (2016) conducted a study that examined 42 marine terminating Greenland outlet glaciers from 1999-2013 using optical satellite imagery to assess the relationship between interannual variations in SST, and the NAO Index. Jensen, et al, (2016) concluded that thirty-five of the 43 measured glaciers were found to be retreating, during the study period while seven remained stable. Results from this study showed a significant correlation when the Northern Hemisphere summer SST are high, which resulted in the glaciers to retreat. A significant correlation was found between the NAO Index and a retreat in the south-west glaciers of Greenland. Jensen, et al, (2016) concluded that the influence of the NAO Index on the retreat of the south-west glaciers of Greenland was due to the influence of the NAO Index on air temperatures being largest in the south-west of Greenland, coupled with a connection between the NAO Index and the temperature of intermediate and deep water, causing a subsequent impact on sea surface temperatures.

2.9 Arctic Ocean response

The climatically sensitive zone of the Arctic Ocean lies within the domain of the North Atlantic oscillation (NAO), one of the most robust recurrent modes of atmospheric behaviour. The NAO alternates between a high-index pattern, characterized by an intense Iceland low with a strong Azores ridge to its south and a low-index pattern in which the signs of these anomaly cells are approximately reversed.

The NAO Index exhibits considerable long-term variability. The 1960s exhibited the most extreme negative phase of the index, the late 1980s/early 1990s experienced its most prolonged positive phase, and the change from the low-index 1960s to the high-index 1990s became the largest low-frequency change of record (Timmermans, Ladd, 2019). The extreme nature of NAO behaviour has continued into the most recent years. Not only have 17 of the past 20 winters, including winter 1999, been NAO positive, but this period also included one of the largest year-on-year changes of record as the long positive sequence of the 1990s was interrupted by the third-lowest value of the century in winter 1996.

Analysis of Timmermans, Ladd, (2019) highlights that Greenland Sea summer sea surface temperature are governed by the amount of incoming solar radiation absorbed by the sea surface. Solar warming of the Arctic surface ocean is governed by the distribution of sea ice, with greater warming occurring in ice free regions due to a lack of absorption and reflection of solar heat energy from ice sheets. Arctic sea surface temperatures are an essential indicator of the role of the ice albedo feedback mechanism during summer melt seasons. As the area of sea ice cover decreases, incoming solar radiation is absorbed by the ocean, which warms sea surface temperatures and continues to melt more sea ice. Analysis of the sea surface temperature variations of the Greenland Sea concluded that August was the most accurate month to represent summer sea surface temperature variations as it was not affected by the cooling and subsequent ice regrowth that usually occurs in September.

Assessment of Timmermans, Ladd, (2019) showed that mean August sea surface temperatures from 1982 to 2019 demonstrate an overall warming trend over much of the Arctic Ocean shown in figure 3, with a statistically significant linear warming trend of up to 1°C per decade at a ninety-five percent confidence interval. The statistically significant northern Barents Sea cooling trend is not observed in all months; annually averaged northern Barents Sea surface temperatures exhibit a warming trend, which has been attributed to changes in Atlantic Water influence in the region as seen in the Figure 3 (Timmermans, Ladd, 2019). During 2019, the August mean sea surface temperatures ranged from approximately 8 to 9°C, as seen in figure 4. This mean sea surface temperature was around 1-7°C warmer than the 1982-2010 August mean.

As seen above there are many complex and dynamic processes that influence SST in the Atlantic Ocean, and subsequently SST around Ireland's coastline. Both long and short term causations of SST variations around Ireland's coastline are identified, based on the period of time in which these processes operate and have an influence on SST variations around Ireland's coastline. Long term causations in SST variations around Ireland's coastline, such as the El Niño or Southern Oscillation (ENSO), the Atlantic Multidecadal variability (AMV), and the Atlantic multidecadal oscillation (AMO) are examined to assess the influence of these processes on variations in SST around Ireland's coastline. Short term causations on SST variations around Ireland's coastline are identified and discussed further in Chapter 6 which include, the influence of the North Atlantic Hurricane season tracts, the position of the jet stream, and the influence of the NAO. Both the long and short term processes identified

contribute to influencing SST variations around Ireland's coastline, through complex, dynamic and interconnected ocean- atmosphere interactions.

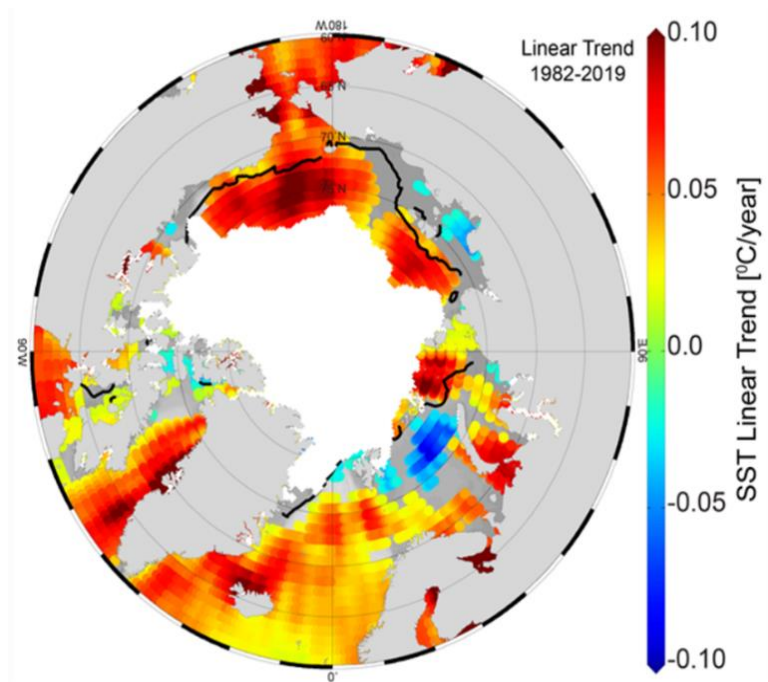


Figure 3 Greenland linear sea surface temperature trend ($^{\circ}\text{C yr}^{-1}$) for August of each year from 1982 to 2019. (Timmermans, Ladd, 2019).

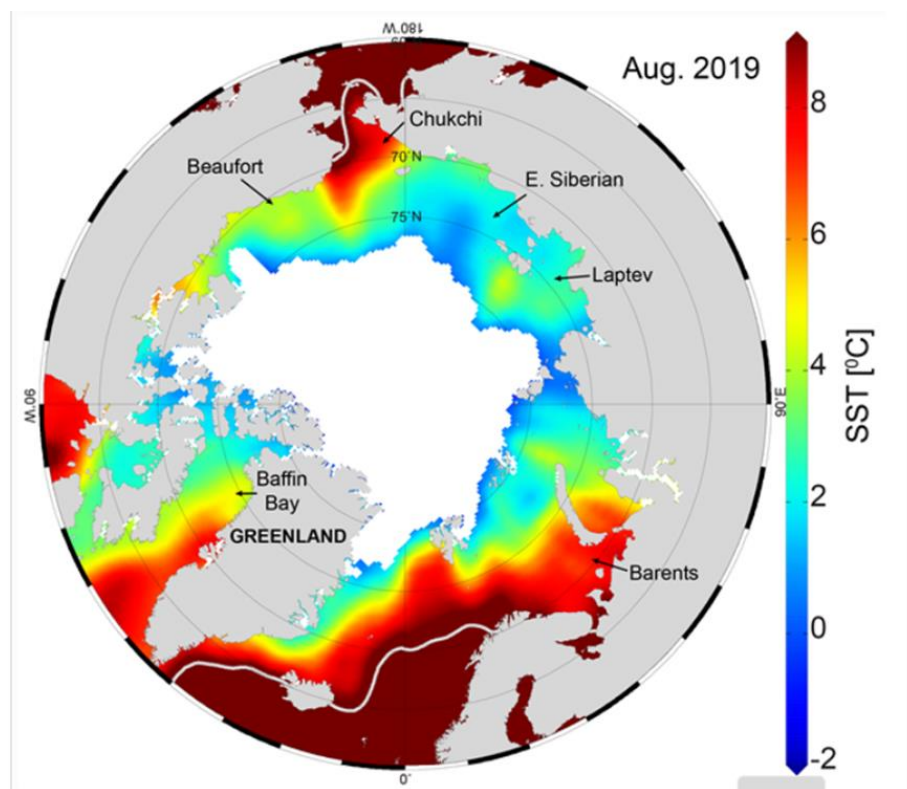


Figure 4 Greenland sea surface temperature variations August 2019. (Timmermans, Ladd, 2019).

Chapter 3 Methodology

3.1 Buoy information

The buoys around Ireland's coastline are equipped with oceanic and meteorological sensors that record and transmit their data to the Marine Institute. The Irish data buoy network has been operational since 2001 and consists of five deep field synoptic weather observing systems around Ireland's coastline. The five active buoys around Ireland's coastline record SST data, atmospheric pressure, wind direction, wind speed, gust speed, wave height, and air temperature data. Each of the five active buoys weigh between five and six tonnes. The buoys undergo regular maintenance and repair works by the Marine Institute, and during this time there is no data recorded by the buoy as it is hauled inshore to receive maintenance works. Figure 5 shows the size and composition of marine buoy M6, located on the East coast of Ireland, image not to scale.

3.2 Data availability

Marine buoys located around the Irish coastline are the primary source of sea surface temperature that will be examined. The network of marine buoys is managed by the Marine Institute of Ireland in collaboration with Met Eireann to provide comprehensive data collection and dissemination to enable the research and analysis of oceanic and terrestrial climatic patterns.

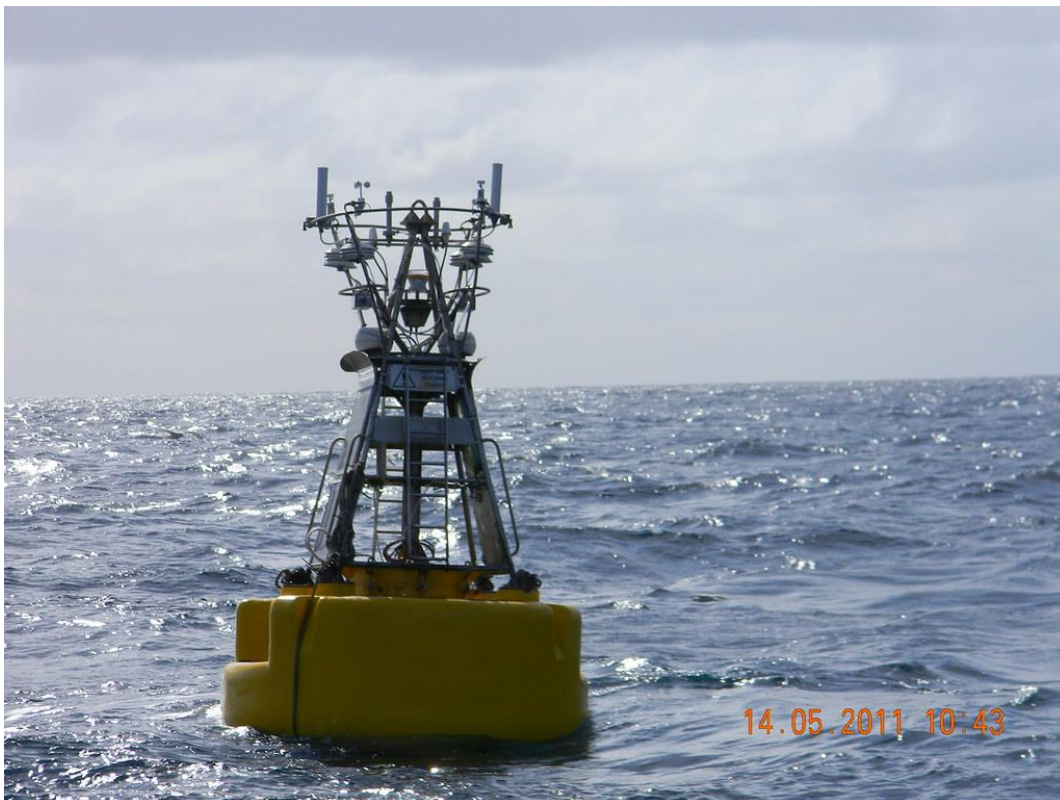


Figure 5 Marine buoy M6 (Marine Institute, 2020)

Currently there are five active marine buoys located around the coastline of Ireland, and one closed marine buoy that contains historic sea surface temperature data. Figure 6, shows the exact location and name of the five active marine buoys around the Irish coastline.

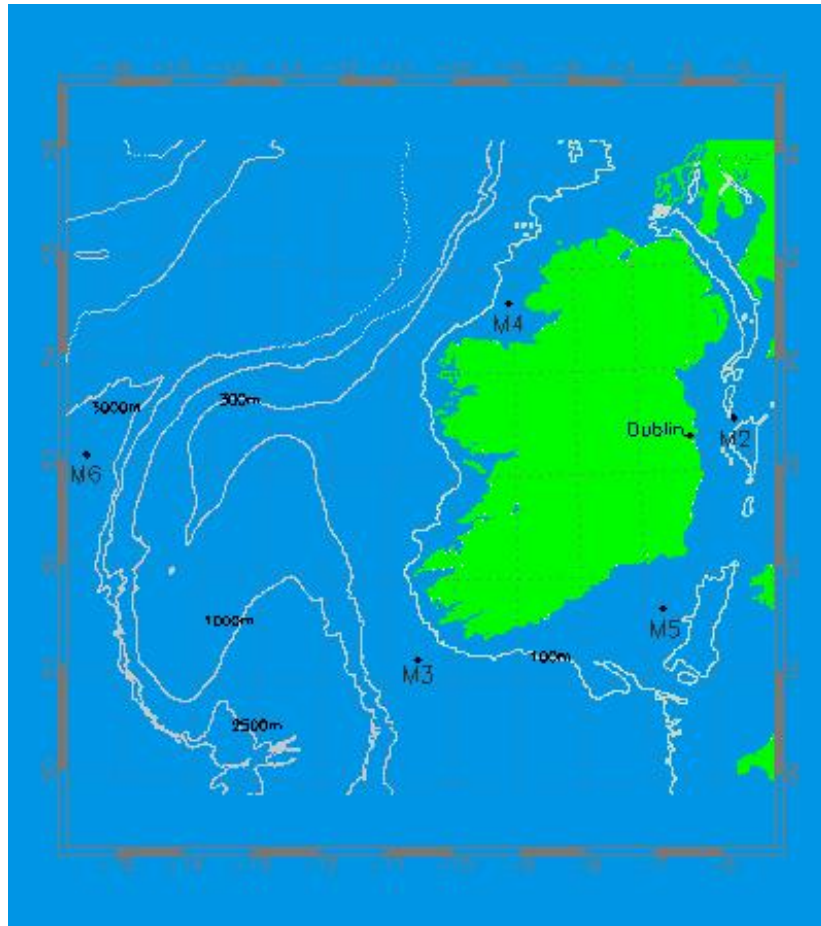


Figure 6 Location of the five active marine buoys around Ireland (Marine Institute, 2020).

Data is recorded on an hourly basis of the sea surface temperature, wind speed, wind direction and air temperature (Marine Institute, 2020).

3.3 Time series analysis and extreme events

Analysis of daily, monthly, seasonal, and annual sea surface temperature variations around Ireland is undertaken using the historical and current data recorded by the marine buoys. This analysis highlights trends and patterns over time of the changing nature of sea surface temperatures around Ireland. Using daily and monthly averages, season and annual variation patterns are recorded and compared to previous records. Extreme sea surface temperature variations become apparent when comparisons are completed between the daily, monthly, seasonal, and annual temperature variations. The causes of the extreme sea surface

temperature variations are examined by analysing weather patterns and ocean offshore currents to establish a correlation between these influencing factors and the resulting extreme sea surface temperature variations (Marine Institute, 2020). Table 1 shows the name, location, activity status and the years of data available from the marine buoys around Ireland's coastline.

Table 1 The name, location, activity status and years of data available for the five active and one inactive marine buoys around Ireland's coastline.

Marine Buoy Name	Marine Buoy Location	Activity Status of Marine Buoy	Years of Data Available
M1	53.1266°N 11.2000°W	Inactive	06/11/2000 – 25/03/2007.
M2	53.4800°N 05.4250°W	Active	1/1/2002 – Present.
M3	51.2166°N 10.5500°W	Active	1/1/2003 – Present.
M4	54.9982°N 09.992154°W	Active	1/1/2003 – Present.
M5	51.6900°N 06.7040°W	Active	1/1/2005 – Present.
M6	53.07482°N 15.88135°W	Active	1/1/2007 – Present.

3.4 Introduction

Time series analysis is a series of data points indexed in time order. Usually, a time series is a sequence taken at successive equally spaced points in time, thus this is a sequence of discrete time data. This method of analysis was the most suitable to analyse sea surface temperature variations around Ireland's coastline from the year 2000 to 2020. The Irish Weather Buoy Network Observations is responsible for the collection and dissemination of oceanographic information. The Irish Marine Weather Buoy Network is a joint project designed to improve weather forecasts and safety at sea around Ireland. The buoy network provides vital data for weather forecasts, shipping bulletins, gale, and swell warnings as well as data for general public information and research. The five active buoys record a variety of oceanographic data such as sea surface temperature, wave height, salinity, and air temperature on an hourly basis. This hourly data was used to analyse the variations in sea surface temperatures around Ireland's coastline. Sea surface temperature data was available from 06/11/2000 to 29/10/2020, and this was used to analyse the variations in sea surface temperature over time. This data was downloaded and transported onto excel for analysis.

3.5 Data source

The Marine Institute of Ireland is the source of the data for this analysis. The Marine Institute of Ireland operate the Irish Marine Weather Buoy Network. The Marine Institute of Ireland is responsible for the deployment, monitoring and maintenance of five active buoys around the Irish coastline. There is also one inactive buoy that contains historic data of sea surface temperature variations that was also used in the analysis. The five active buoys record the sea surface temperature variations at hourly intervals, as well as other relevant parameters such as air temperature, wind speed and wind direction.

3.6 Missing Sea surface temperature data

Analysis of the sea surface temperature data for each buoy from 2002-2020 revealed that there were missing elements from the data source. There were two categories of missing data. The first category of missing data was NaN or blank cells, where the date and time was recorded but there was no subsequent sea surface temperature data recorded in the cell. The second category of missing data was categorised as having no date or timestamp recorded, with no sea surface temperature recorded as a result, for example missing an entire month of timestamp data and subsequent sea surface temperature.

Buoy	Date and Time	SST °C
M2	20/07/2004 09:00	13.9°C
M2	20/07/2004 10:00	13.5°C
M2	20/07/2004 11:00	NaN
M2	20/07/2004 12:00	13.6°C
M2	20/07/2004 13:00	14.2°C

Table 2 An example of NaN or blank cells of missing SST data.

No recording or blank data cells as shown in table 2 is where the timestamp data exists, but no SST data has been recorded. As seen in table 2, although the timestamp for 20/07/2004, 11:00am exists, no SST data has been collected for the period. This is due to faulty buoy equipment that did not record the SST data for the particular timestamp.

Buoy	Date and Time	SST °C
M2	20/07/2004 05:00	14.4°C
M2	20/07/2004 06:00	14.3°C
M2	20/07/2004 08:00	14°C
M2	20/07/2004 09:00	13.9°C

Table 3 An example of SST data missing a time stamp.

Table 3 shows an example where no time stamp data was recorded by the marine buoy. Sea surface temperature should be collected every hour and uploaded to the Maritime database, however when the data was analysed, there were a number of hourly periods missing from the data set for each buoy. Table 3 highlights that the time stamp for 07:00am on 20/07/2004 is missing, which means the sea surface temperature data is also subsequently missing.

Analysis of the overall data for each buoy showed areas of missing data based on both categorises of missing data previously mentioned. Overall, 24.3% of the total data, including every buoy was unavailable due to no time stamp or no recording available. This is demonstrated below.

3.7 Missing SST data impact

Recognising the extent of the missing elements, the impact of missing elements needed to be assessed in order to understand any possible effects in the data correlation. The volume of missing data for each buoy was assessed to determine the total percentage of missing data for each buoy, before the actual analysis of the data could be performed. To calculate the percent of missing data for each buoy, each buoy was assessed on an hourly, daily, monthly, and annual basis, for each month. The results of this missing data analysis are displayed tables 4,5,6,7,8,9, and 10, and are categorised based on the period of time of missing data.

Table 4 shows the total percentage of missing SST data for the five active marine buoys around Ireland coastline. Table 5 shows the total missing annual and monthly SST data for buoy M1 for each of the months and years that it was active. Table 6 shows the total missing annual and monthly SST data for buoy M2. Table 7 shows the total missing annual and monthly SST data for buoy M3. Table 8 shows the total missing annual and monthly SST data for buoy M4. Table 9 shows the total missing annual and monthly SST data for buoy M5. Table 10 shows the total missing annual and monthly SST data for buoy M6. Lastly table 11 shows a simplified version of the total percentage of SST data missing for each buoy.

Data Analysis	M2	M3	M4	M5	M6	Total
Start Date / Time	03/05/2001 14:00	22/07/2002 14:00	03/05/2007 09:00	18/10/2004 10:00	25/09/2006 13:00	03/05/2001 14:00
End Date/ Time	28/10/2020 10:00	28/10/2020 10:00	28/10/2020 10:00	28/10/2020 10:00	28/10/2020 10:00	28/10/2020 10:00
Total Time Slots	170,825	160,145	118,247	140,493	123,522	713,232
No Time Stamp	28,058	37,105	15,199	16,674	19,969	117,005
No Recording	23,699	10,706	7,805	11,186	3,143	56,539
Populated with SST Data	119,068	112,334	95,243	112,633	100,410	539,688
Populated with SST Data %	69.7%	70.1%	80.5%	80.2%	81.3%	75.7%
Total Missing Data %	30.3%	29.9%	19.5%	19.8%	18.7%	24.3%

Table 4 The total percentage of missing SST for the five active marine buoys around Ireland's coastline.

	2001	2002	2003	2004	2005	2006	2007
Jan		H	A	H	T	NONE	H
Feb	T	H	P	H	T	H	H
Mar	H	H	H	H	T	H	P
Apr	H	H	H	T	T	H	T
May	H	H	H	H	P	H	T
June	H	H	H	H	H	NONE	H
July	H	T	H	H	H	H	T
Aug	H	H	H	M	H	H	
Sep	H	H	H	H	H	M	
Oct	H	H	H	H	H	H	
Nov	H	H	H	T	H	H	
Dec	H	H	H	H	H	H	

Table 5 The missing data analysis for M1

Legend:

NONE- No missing SST data.

H- Hourly missing data (random hours), not whole or partial days (0.1%- 9.9% of monthly SST data missing).

T - Hourly missing data (random hours), not whole or partial days (10%-19.9% of monthly SST data missing).

P- Partially missing data (between 20%- 49.9% of SST data missing).

M – More than 50% of SST data missing but less than 100%.

A – Missing All monthly data (100% SST data missing).

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan		H	H	T	P	NONE	NONE	H	H	H	A	H	H	A	H	H	H	M	A	NONE
Feb		H	H	H	T	H	H	H	A	H	M	H	H	A	H	H	H	A	A	H
Mar		H	H	H	T	H	H	H	A	M	H	H	NONE	A	H	H	H	A	A	H
Apr		H	H	T	T	H	H	H	A	A	H	H	H	A	H	NONE	H	A	A	H
May	NONE	H	H	H	H	H	H	P	A	A	H	H	H	A	H	P	NONE	A	A	NONE
June	H	H	H	H	H	NONE	H	A	A	A	NONE	H	H	A	H	A	NONE	A	A	H
July	H	H	H	P	T	H	H	A	A	A	H	H	T	A	H	A	NONE	A	P	NONE
Aug	H	NONE	H	P	H	NONE	H	A	A	A	H	H	M	A	H	A	NONE	A	H	H
Sep	H	H	H	H	H	H	H	A	A	A	H	H	M	A	H	A	H	M	NONE	H
Oct	H	H	T	H	H	M	H	A	M	M	NONE	NONE	A	M	NONE	A	NONE	H	NONE	H
Nov	H	H	H	T	H	A	H	A	P	H	H	H	A	H	H	A	H	T	NONE	
Dec	H	H	H	T	H	T	H	T	P	M	H	T	A	H	NONE	M	H	A	NONE	

Table 6 The missing SST data analysis for M2

Legend:

NONE- No missing SST data.

H- Hourly missing data (random hours), not whole or partial days (0.1%- 9.9% of monthly SST data missing).

T - Hourly missing data (random hours), not whole or partial days (10%-19.9% of monthly SST data missing).

P- Partial days missing (greater than 20% of data missing but less than 49.9% missing.)

M- Mostly missing SST data (greater than 50% data missing but less than 100% missing.)

A – All data missing (100% missing).

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan		T	T	H	NONE	H	H	H	H	H	A	H	A	H	A	A	A	H	M
Feb		T	T	H	H	H	H	H	H	H	A	P	A	H	A	A	A	M	A
Mar		T	H	H	H	H	H	H	H	H	A	A	P	M	A	M	A	A	M
Apr		H	P	H	H	H	NONE	H	H	H	A	A	H	A	A	H	P	M	H
May		H	H	H	H	H	H	H	H	H	A	A	NONE	A	M	H	P	NONE	NONE
June		T	T	H	H	T	H	H	P	H	H	A	H	A	H	T	A	NONE	H
July	H	H	H	H	H	H	H	H	H	H	H	A	A	A	H	A	T	H	NONE
Aug	H	H	H	H	H	NONE	H	H	H	H	H	A	A	A	H	A	H	H	T
Sep	H	H	H	H	H	H	H	H	H	P	H	A	A	A	H	A	H	NONE	A
Oct	H	T	H	H	NONE	H	NONE	H	H	P	NONE	A	M	A	H	P	H	NONE	M
Nov	M	H	H	H	H	H	H	H	H	H	H	A	M	A	H	A	H	NONE	
Dec	P	H	H	H	H	H	H	H	H	M	H	A	H	A	M	A	H	H	

Table 7 The missing SST data analysis for M3

Legend:

NONE- No missing SST data.

H- Hourly missing data (random hours), not whole or partial days (0.1%- 9.9% of monthly SST data missing).

T - Hourly missing data (random hours), not whole or partial days (10%-19.9% of monthly SST data missing).

P- Partial days missing (greater than 20% of data missing but less than 49.9% missing.)

M- Mostly missing SST data (greater than 50% data missing but less than 100% missing.)

A – All data missing (100% missing).

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan		H	NONE	H	H	H	NONE	H	H	H	M	H	A	NONE
Feb		H	NONE	H	H	H	M	NONE	H	H	H	H	A	H
Mar		H	NONE	H	H	H	A	NONE	H	A	H	H	A	NONE
Apr		H	P	H	H	H	A	H	H	A	H	H	M	H
May	NONE	H	NONE	H	H	H	A	H	H	A	NONE	H	H	H
June	H	P	H	H	T	H	P	T	H	A	NONE	A	NONE	H
July	H	M	T	H	H	H	H	A	H	P	NONE	A	H	H
Aug	NONE	H	H	H	NONE	H	NONE	A	NONE	M	NONE	A	H	H
Sep	H	H	H	H	H	P	NONE	A	H	H	NONE	A	NONE	H
Oct	H	NONE	H	H	NONE	M	H	M	H	H	NONE	A	H	H
Nov	H	NONE	H	H	H	A	H	H	H	H	NONE	A	NONE	
Dec	H	H	H	H	NONE	H	H	H	NONE	A	NONE	A	NONE	

Table 8 The missing SST data analysis for M4

Legend:

NONE- No missing SST data.

H- Hourly missing data (random hours), not whole or partial days (0.1%- 9.9% of monthly SST data missing).

T - Hourly missing data (random hours), not whole or partial days (10%-19.9% of monthly SST data missing).

P- Partial days missing (greater than 20% of data missing but less than 49.9% missing.)

M- Mostly missing SST data (greater than 50% data missing but less than 100% missing.)

A – All data missing (100% missing).

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan		H	NONE	H	H	H	H	H	H	H	H	A	A	H	M	H	P
Feb		H	H	H	M	H	P	NONE	H	H	NONE	M	A	H	A	H	NONE
Mar		H	H	H	A	H	H	H	H	H	H	A	A	M	P	H	NONE
Apr		H	H	H	A	H	NONE	H	H	H	H	A	M	A	H	H	H
May		H	H	H	M	H	H	H	H	H	H	A	H	A	H	NONE	NONE
June		H	T	H	H	T	H	H	H	H	H	A	H	H	P	H	NONE
July		H	H	H	H	H	H	H	H	H	A	A	H	NONE	P	H	NONE
Aug		H	H	P	H	T	P	H	H	NONE	A	A	H	NONE	H	H	H
Sep		H	H	H	H	H	P	H	P	NONE	A	A	H	H	H	NONE	H
Oct	P	H	H	H	H	H	NONE	H	M	H	A	A	H	M	H	NONE	H
Nov	H	H	H	H	H	H	H	H	H	H	M	A	NONE	H	H	NONE	
Dec	H	H	H	H	H	H	H	H	H	H	A	A	H	NONE	H	NONE	

Table 9 The missing SST data analysis for M5

Legend:

NONE- No missing SST data.

H- Hourly missing data (random hours), not whole or partial days (0.1%- 9.9% of monthly SST data missing).

T - Hourly missing data (random hours), not whole or partial days (10%-19.9% of monthly SST data missing).

P- Partial days missing (greater than 20% of data missing but less than 49.9% missing.)

M- Mostly missing SST data (greater than 50% data missing but less than 100% missing.)

A – All data missing (100% missing).

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan		H	H	H	H	H	H	P	P	A	H	A	NONE	T	H
Feb		H	H	H	H	H	H	T	A	A	P	P	H	H	A
Mar		H	H	H	H	H	H	H	A	A	M	NONE	H	H	A
Apr		H	H	H	H	H	H	H	M	M	P	NONE	H	H	M
May		H	H	H	T	T	H	H	H	H	M	H	M	T	NONE
June		H	P	NONE	H	H	T	T	P	H	H	H	H	P	H
July		H	H	H	T	T	H	H	A	H	H	NONE	NONE	H	NONE
Aug		H	H	T	T	H	H	H	A	H	H	H	H	H	H
Sep	M	H	H	P	H	H	T	H	A	H	H	H	M	NONE	H
Oct	NONE	H	H	H	H	H	H	H	A	H	H	H	A	NONE	H
Nov	H	H	H	NONE	H	H	H	T	A	H	M	H	M	NONE	
Dec	H	H	H	H	H	H	T	T	A	H	A	H	P	NONE	

Table 10 The missing SST data analysis for M6

Legend:

NONE- No missing SST data.

H- Hourly missing data (random hours), not whole or partial days (0.1%- 9.9% of monthly SST data missing).

T - Hourly missing data (random hours), not whole or partial days (10%-19.9% of monthly SST data missing).

P- Partial days missing (greater than 20% of data missing but less than 49% missing.)

M- Mostly missing SST data (greater than 50% data missing but less than 100% missing.)

A – All data missing (100% missing).

Buoy	% of total missing data
M1	8.2%
M2	30.3%
M3	29.9%
M4	19.5%
M5	19.8%
M6	18.7%

Table 11 The total percentage of missing data for each buoy

3.8 Restoration of missing sea surface temperature data

To reduce the error margin caused by the missing data, it was necessary to reconstitute the missing elements, which in turn would allow the accurate annual comparisons to be made.

Due to the close proximity of buoys M2-M5, see Figure 6, where one buoy was missing a timestamp or recording, it was possible to take an aggregate of the remaining recordings of nearby buoys to populate the missing data field. The rolling average temperatures of the two surrounding buoys were aggregated against each other to accurately predict the missing temperature value of the original buoy. This was completed where hourly time slots were missing, or where monthly data was missing for a particular buoy, where the two surrounding buoys were populated with data. To ensure accuracy and consistency, the aggregated sea surface temperature was assessed against previous patterns of sea surface variations for the particular buoy missing data, to ensure that the aggregated temperature is not an outlier or unusual compared to the usual patterns of sea surface temperature changes. Due to the outlying location of the buoy M6, only M4 and M5 were used to create an aggregate sea surface temperature value where M6 was missing data. This was again compared to previous patterns of sea surface temperature patterns for M6, to ensure an accurate representation of the true sea surface temperature for M6.

Analysis of the data showed that the majority of missing data was hourly, however there are exceptions to this, where whole months of data is missing for individual buoys. The same method of data restoration for both missing hourly and monthly data was used. An aggregate of the sea surface temperature data of the two closest buoys was used to populate the missing data field. The rolling average temperatures of the two surrounding buoys were aggregated

against each other to accurately predict the missing temperature value of the original buoy. Missing data for the currently inactive M1 buoy was also not able to be reconstituted using this method due to its date of inactivity.

3.9 Sea surface temperature data analysis

Time series analysis was performed on the restored full data set of sea surface temperatures for each buoy. Firstly, annual analysis was completed for each buoy to determine the general trend of an overall sea surface temperature increase or decrease for each buoy from 2002-2020. This allowed for general trends and patterns to be identified and provided a foundation for the rest of the analysis. Once this had been completed, line charts were generated using the annual data for each buoy. This identified general trends of sea surface temperature changes for each buoy and identified years of significant sea surface temperature increases or decreases. These line charts are explored more in the results chapter.

After the analysis on the annual trends of sea surface temperature for each buoy had been completed, monthly time series analysis was conducted to establish monthly variations of SST for each buoy. Line charts were produced for each month for each year for each buoy. This allowed for monthly variations for each year and each buoy to be identified, and the results of this are discussed in the results chapter. Seasonal trends in SST variations were also examined for each buoy, and line charts were produced. To analyse seasonal variations in SST, selected months during each season were analysed, such as spring was represented by SST variations for the months of February for each buoy. Summer was represented by SST variations for the months of June for each buoy. Autumn was represented by SST variations for the months of September, and lastly Winter was represented by SST variations for the months of December for each buoy. These selected months were chosen as the most accurate representation of the true seasonal variations in SST for each buoy.

Completion of the monthly variations in SST, allowed for spells of maximum and minimum SST to be identified for each buoy. Further exploration of these spells of maximum and minimum SST revealed significant spells of SST variations for each buoy that required further exploration. Tables of the top ten spells of both maximum and minimum SST for each buoy were created and are available in the appendices. The spells of maximum and minimum SST for each buoy based on clusters of either maximum or minimum SST respectively, that contained two or more of the same SST within 0.2°C of each other, that occurred on the same

day. The top ten spells of maximum or minimum SST were identified by sorting the SST data based on a SST difference of 0.01°C.

The top ten spells of maximum and minimum SST were identified for each buoy. Tables were generated to display these top ten spells of maximum and minimum SST for each buoy which are discussed further in the results chapter.

Lastly, once the spells of maximum and minimum SST were identified for each buoy, daily time series analysis was performed on the two days before and two days after the spells of maximum and minimum SST for each buoy. This allowed for in-depth analysis on the potential causes to these spells of maximum and minimum spells of SST which is discussed further in the causations and results chapters respectively.

3.10 Atmospheric and oceanographic data analysis

Following the analysis of the annual, monthly, seasonal, and daily variations in SST, it was necessary to examine the causations to these variations in SST. In depth analysis of the causations that influenced variations in SST around Ireland's coastline are discussed in Chapter 6, however the methods used to determine the influencing atmospheric and oceanic processes on SST around Ireland's coastline are outlined here.

Atmospheric data

The Marine Institute of Ireland is responsible for the monitoring and maintenance of the five active marine buoys around Ireland. The SST data which was downloaded from the Marine Institute of Ireland contained atmospheric data concurrent with the SST data. The atmospheric data which was available from the buoy transcripts included atmospheric pressure, wind direction, wind speed, gust speed, wave height, and air temperature data. This data was also recorded on an hourly basis as was the SST data.

As seen in the SST methodology, there were two categories of missing SST data. Firstly, the NaN or not recorded SST cells, where there is a timestamp available but no recorded SST data, was sometimes populated with data for the other atmospheric processes mentioned above, and only excluded SST data. The second category of missing SST data was where there were entire timestamps (and subsequent SST data cells) not recorded by the buoy on an hourly, daily, weekly or monthly period of time. In this case, the atmospheric data was also not recorded for the entirety of the missing timestamp period. Unlike the methodology used to restore the missing cells of SST data, there was no restoration of atmospheric data used.

When analysing months and spells of maximum or minimum SST, atmospheric processes such as the ones mentioned above were essential to examine the possible causations of extreme spells in SST. To combat the elements of missing data, as mentioned no restoration of atmospheric processes were conducted. Instead for periods of missing atmospheric data, weather stations that were the closest to the buoy that was being examined were assessed to gather the relevant atmospheric data. Relevant atmospheric data was downloaded from Met Éireann, for the weather station that was the closest in location to the buoy that contained the missing atmospheric data. There was a limitation to this method as Met Éireann only had atmospheric data that was available to view and download from 16/10/2015. Atmospheric data prior to 16/10/2015 was not available in an accessible format from Met Éireann, and therefore could not be used in the analysis. Therefore, atmospheric data that was missing from the original buoy, was gathered from the Met Éireann weather station closest to the original buoy from 16/10/2015 onwards. In depth analysis of these atmospheric processes and their correlation between variations in SST around Ireland's coastline are discussed in Chapter 5.

North Atlantic Hurricane Season

In depth analysis on the influence of the North Atlantic hurricane season is discussed in Chapter 6, however the methods used to analyse this data are discussed here. Examination of the National Oceanic and Atmospheric Administration (NOAA) data for the North Atlantic hurricane season track paths was completed. Data was downloaded and examined on an annual and monthly basis, to assess the frequency, intensity, and tracks of North Atlantic hurricanes, and which particular month they occurred in.

This analysis was used to examine whether the North Atlantic hurricane season influenced variations in SST on a monthly and subsequent annual basis, but also as to whether these North Atlantic hurricane events could have impacted and contributed to spells of maximum and minimum SST around Ireland coastline. To determine the influence of the North Atlantic hurricane events on SST around Ireland's coastline, it was necessary to firstly determine the month in which the North Atlantic hurricane occurred and assess whether a spell of maximum or minimum SST was experienced around Ireland's coastline at this time. After this was completed, analysis of the tracks of the hurricanes were assessed to determine the pathway of the hurricane track to assess if the hurricane in the North Atlantic tracked towards Ireland and could have potentially influenced SST around Ireland's coastline and contributed

to spells of maximum or minimum SST respectively. After this was completed, research was conducted on the NOAA report of each relevant hurricane event to determine the origin, atmospheric factors involved, the intensity and destruction caused by the hurricane event. Results of this analysis are discussed in Chapter 6.

The NAO Index

The North Atlantic Oscillation (NAO) Index is based on the surface sea-level pressure difference between the Subtropical Azores) High and the Subpolar Low. There are two phases associated with the NAO Index, positive and negative. The positive phase of the NAO Index is characterised by below average heights and pressure across the high latitudes of the North Atlantic. The negative phase is categorised by an opposite pattern of height and pressure anomalies over the high latitude regions. Both phases of the NAO Index are associated with changes in the North Atlantic Basin in the intensity and location of the North Atlantic Jet Stream, storm tracks and modulations in the usual patterns of zonal and meridional heat and precipitation transport, which all influence the variations in SST around Ireland's coastline.

The North Atlantic Oscillation Index data was downloaded from the National Oceanic and Atmospheric Administration (NOAA), and this was used in the analysis. Firstly, the annual variations in NAO Index values were assessed. This was completed to examine if there was any correlation between the annual variations in SST for each buoy, and annual variations in the NAO Index values. The annual variations in NAO Index were calculated by adding the monthly NAO Index values for each year and dividing by 12 months to get an average NAO Index value for each year. The average NAO Index values were displayed in the appendices. This analysis was crucial to determine if there were any significant annual variations in NAO Index values.

Once the annual variations in NAO Index values were calculated and assessed against the annual variations in SST for each buoy around Ireland's coastline, analysis of the monthly variations in NAO Index values were assessed with particular focus and correlation with the top ten spells of maximum and minimum SST for each buoy. To assess whether changes in the NAO Index values contributed to the spells of maximum and minimum SST, tables were generated for each top ten spells of maximum and minimum SST that contained the corresponding NAO Index value for the date of the spell of extreme SST. These tables allowed for variations in the NAO Index to be easily determined and are displayed in Chapter

5. The results of these calculations showed variations in the NAO Index values that corresponded with variations in SST that are further discussed in Chapter 5.

Chapter 4 Results

4.1 Reconstituted data annual analysis

Annual results M2

Overall, there was a decrease in SST for M2 from 2002-2020 based on the linear trendline, figure 7. Overall, there were oscillations of SST values from 2002-2020. From 2002-2020 there was an overall SST variation range of 0.09°C between the maximum and minimum SST. From 2002-2010 there were oscillations in SST that were of a higher mean SST value, than the oscillations in SST from 2011-2020. The oscillations in SST from 2002-2010 show a lower range of SST increases and decreases compared to the oscillations from 2011-2020, which displayed more pronounced SST increases and decreases.

From 2002-2004 there was a but gradual increase in SST from 11.6°C to 11.7°C. Following this there was a decrease in SST of 0.2°C from 11.7°C to 11.5°C between the years 2004-2005. Between 2005-2006 there was a increase in SST of 0.3°C, from 11.5°C to 11.8°C, followed by a continued increase in SST from 2006-2007 of 0.1°C.

2007-2008 recorded a decrease in SST of 0.3°C, from 11.9°C to 11.6°C, followed by another decrease in SST of 0.1°C from 2008-2009. Between 2009-2010 there was a increase in SST of 0.4°C from 11.5°C to 11.9°C. There was a slight decrease in SST between 2010-2011 of 0.4°C from 11.9°C to 11.5°C.

From 2011-2014 there were oscillations of increasing and decreasing SST, however from 2014-2015 the joint largest oscillation in SST was recorded showing a decrease in SST of 0.6°C, from 11.7°C to 11.1°C. Following this oscillation there was a subsequent increase in SST from 2015-2016 of 0.5°C, from 11.1°C to 11.6°C. This increase in SST was continued until 2017, showing a temperature increase of 0.3°C from 2016-2017.

Another oscillation was recorded between 2017-2018, showing a SST decrease of 0.6°C, from 11.9°C to 11.3°C, making this the same oscillation variation as the 2014-2015 oscillation. Following this, there was a SST increase from 2019-2020 of 0.4°C, from 11.3°C to 11.7°C. These variations in SST for M2 are shown in figure 7.

Annual results M3

There was an overall decrease in SST from 2002-2020, based on the linear trendline, see figure 8. Overall, there were oscillations in SST from 2002-2020. From 2002-2012 there were greater oscillations in SST, than from 2013-2020. The years 2004-2012 showed the greatest

range of SST oscillations, showing more pronounced increases and decreases than the oscillations in SST values from 2013-2020. From 2002-2020 there was a low variation of SST recordings of 0.3°C, between the maximum and minimum SST.

From 2002-2004 there were no variations in mean SST with these years recording an annual SST of 12.8°C. Between 2004-2005 there was a SST increase of 0.2°C, from 12.8°C to 13°C. From 2005-2008 there were only variations in SST, with the SST remaining relatively stable for these years. Following the stabilisation of SST there was a decrease in SST of 0.3°C, from 13°C to 12.7°C between 2007-2008. This decrease was the largest oscillation in SST. From 2008-2009 there was a continued decrease in SST. Following this, 2009-2010 recorded an increase in SST, following the oscillation that just previously occurred. SST increased by 0.3°C from 12.7°C to 13°C, from 2010-2011.

Between 2011-2012 there was another SST oscillation, recording a decrease in SST of 0.2°C, from 13°C to 12.8°C. There was a subsequent stabilisation of SST oscillations with increasing and decreasing SST from 2013-2020, with low SST variations of 0.1°C. These trends in SST variations for M3 are shown in figure 8.

Annual results M4

From 2008-2020 there was an overall increase in SST, based on the linear trendline, see figure 8. From 2008-2017 there were oscillations in SST. Between 2018-2020 there was a more pronounced oscillation in SST, showing an increase and subsequent decrease in SST. Overall, there was a range of SST variations from 2008-2020, with a range of 1.1°C between the maximum and minimum SST.

From 2008-2011 there was a gradual decrease in annual mean SST. This gradual decrease in SST from 2008-2011, showed a decrease of 0.3°C. 2011 recorded the minimum SST of 11.8°C. Following this, 2011-2012 recorded an oscillation in SST of 0.3°C. This increase of 0.3°C between 2011-2012 recorded the same SST variation in one year as the previous gradual decrease over three years. From 2012-2013 there was a subsequent decrease in SST following the previous increase in SST, forming an oscillating SST. From 2012-2013 there was a SST decrease of 0.2°C.

Following the previous SST oscillation, there was a gradual but increase in SST from 2013-2015. Between these years there was a SST increase of 0.3°C. From 2015-2017 there was a gradual but decrease in SST of 0.2°C. Following this, there was the largest SST oscillation recorded for M4. From 2017-2018 there was a SST increase of 0.9°C. From 2018-2019 the

previous SST increase was followed by a subsequent SST decrease of 0.9°C. 2018 recorded the maximum SST of 12.9°C, with the SST difference of the previous year, and following year showing the same SST variation of 0.9°C. The variations in SST trends for M4 are seen in figure 9.

Annual results M5

2018 recorded the maximum annual mean SST of 12.6°C. 2008 recorded the minimum annual mean SST of 11.9°C. From 2008-2020 there was an overall increase in the annual mean SST for M5, based on the linear trendline, see figure 9. Overall, there were oscillations in SST from 2008-2020. From 2008-2012 there were oscillations in SST, followed by a stabilisation in SST from 2013-2015. From 2016-2020 there were greater oscillations in SST, compared to the oscillations recorded in 2008-2012. From 2008-2020 there was a SST range of 0.7°C.

From 2008-2009 there was a SST increase of 0.3°C. Following this there was a but gradual decrease in SST from 2009-2011 of 0.1°C, to form the first SST oscillation. Following this there was a increase in SST from 2011-2012 of 0.2°C. SST stabilised following the previous oscillations from 2012-2015 with very slight annual mean SST variations. From 2015-2016 there was a decrease in SST of 0.2°C.

Between 2016-2017 there was an increase in SST, marking the beginning of another SST oscillation. SST increased by 0.4°C between 2016-2017. From 2017-2018 there was a increase in SST of 0.1°C. Following this the most pronounced annual mean SST decrease for M5 was recorded between 2018-2019. For these years, SST decreased by 0.6°C. These SST variations for M5 are seen in figure 10.

Annual results M6

From 2007-2020 there was an overall annual mean SST decrease based on the linear trendline. Overall, there was oscillating SST from 2007-2020, see figure 10. From 2007-2020 there was a 0.7°C SST range between the maximum and minimum recorded SST.

From 2007-2008 there was no variation in the annual mean SST recordings. From 2008-2009 there was a SST increase of 0.2°C, marking the start of the first SST oscillation. Following this, there was a subsequent decrease in SST of 0.2°C. Following this there was another oscillation in SST between 2010-2011, showing a SST increase of 0.1°C. Subsequently there was a SST decrease of 0.5°C between 2011-2012. After 2012, SST increase by 0.4°C until

2013. This SST increase continued from 2013-2014, recording an increase in SST of 0.4°C between these years.

From 2014-2015 there was a decrease in the annual mean SST of 0.2°C, marking the start of another SST oscillation. Between 2015-2016 there was a continued SST decrease of 0.4°C. From 2016-2017 there was a increase in SST, of 0.3°C, marking another SST oscillation. From 2017-2018 there was another SST oscillation, showing a decrease in SST of 0.5°C between these years. From 2018-2019 there was a SST increase of 0.3°C. These variations in SST trends are shown in figure 11.

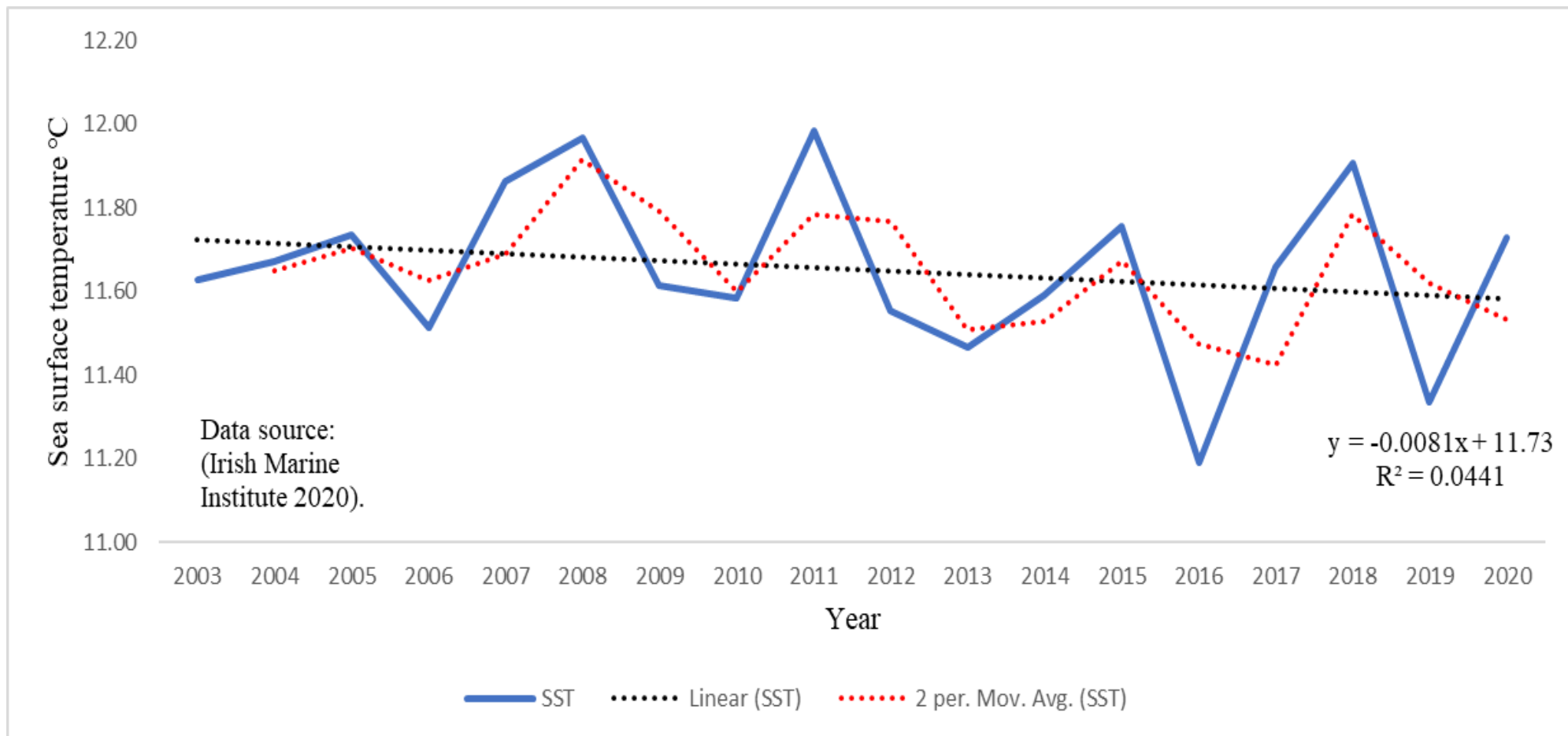


Figure 7 Restored sea surface temperature annual averages M2.

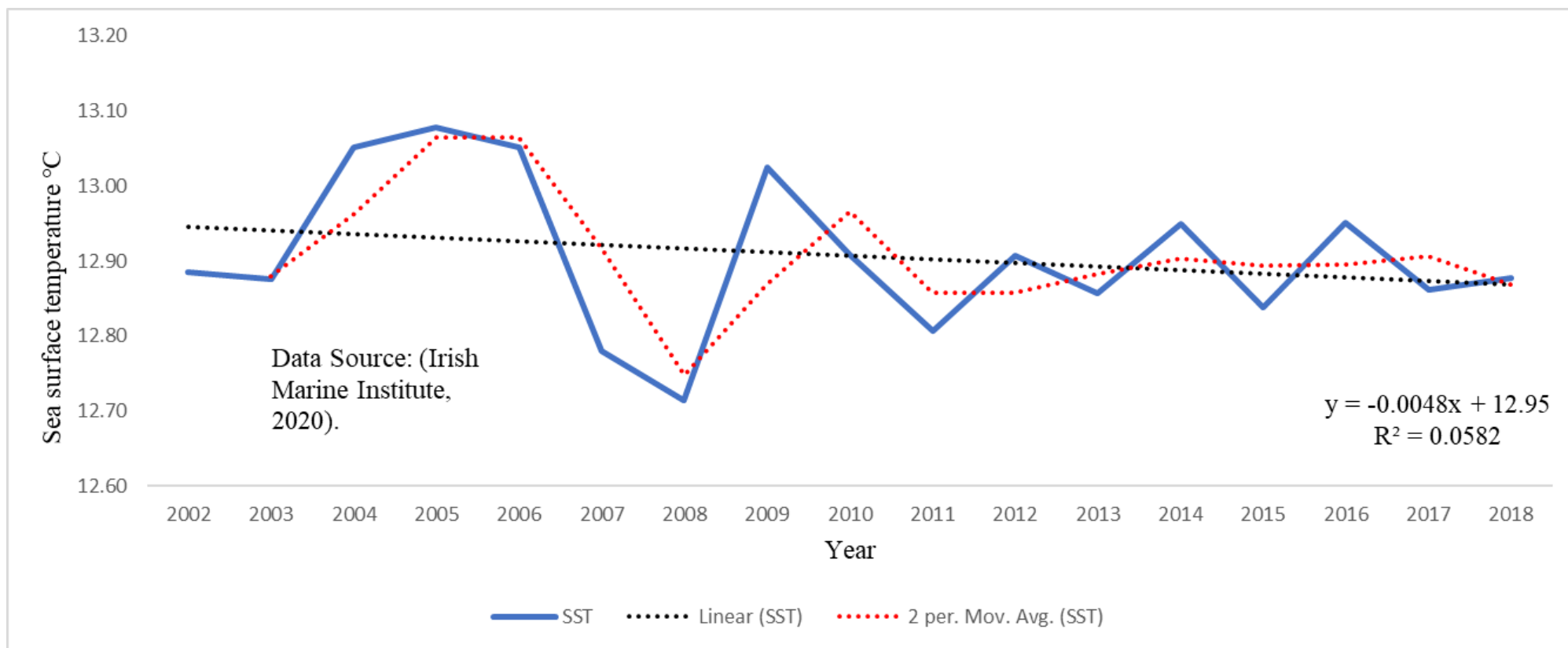


Figure 8 Restored sea surface temperature annual averages M3.

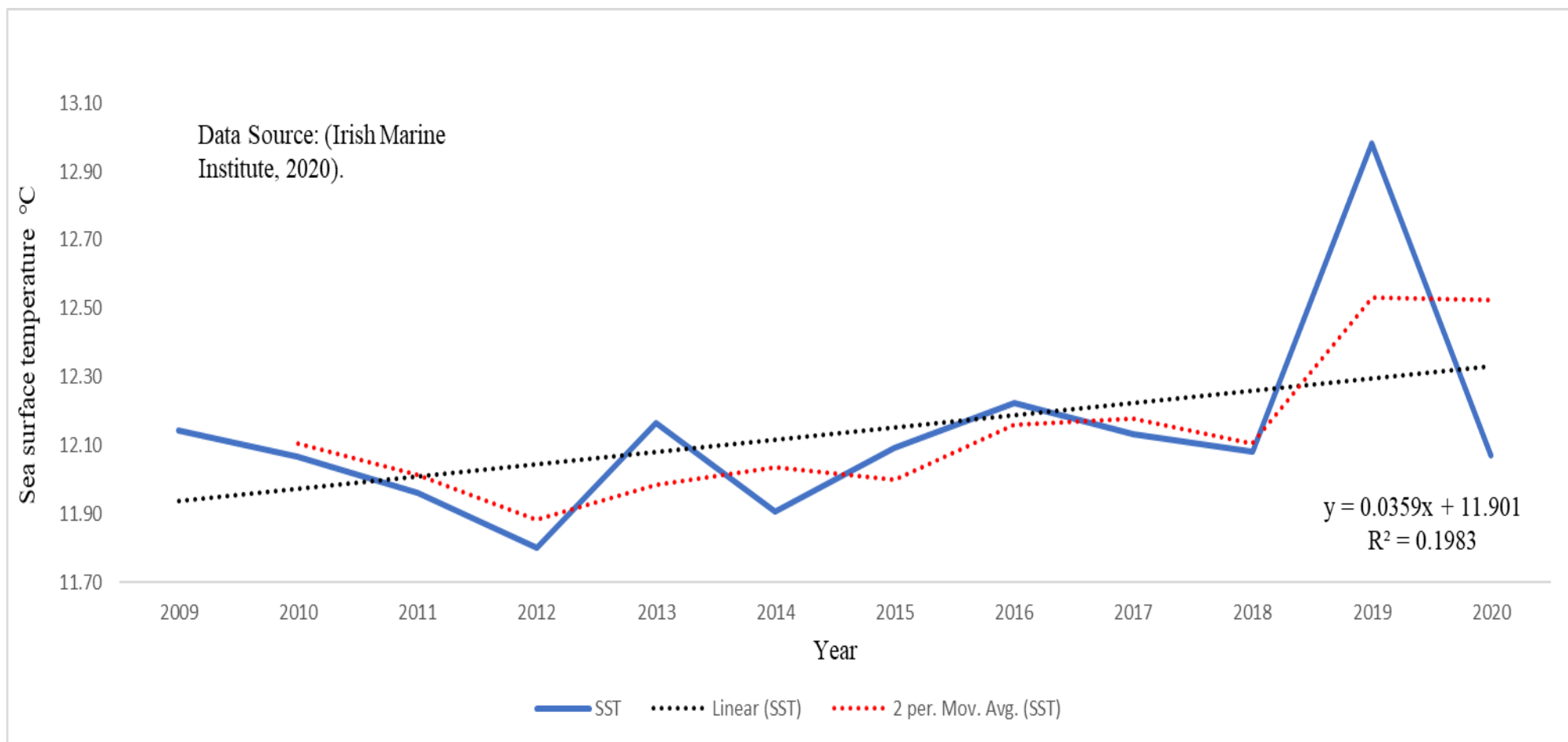


Figure 9 Restored sea surface temperature annual averages M4.

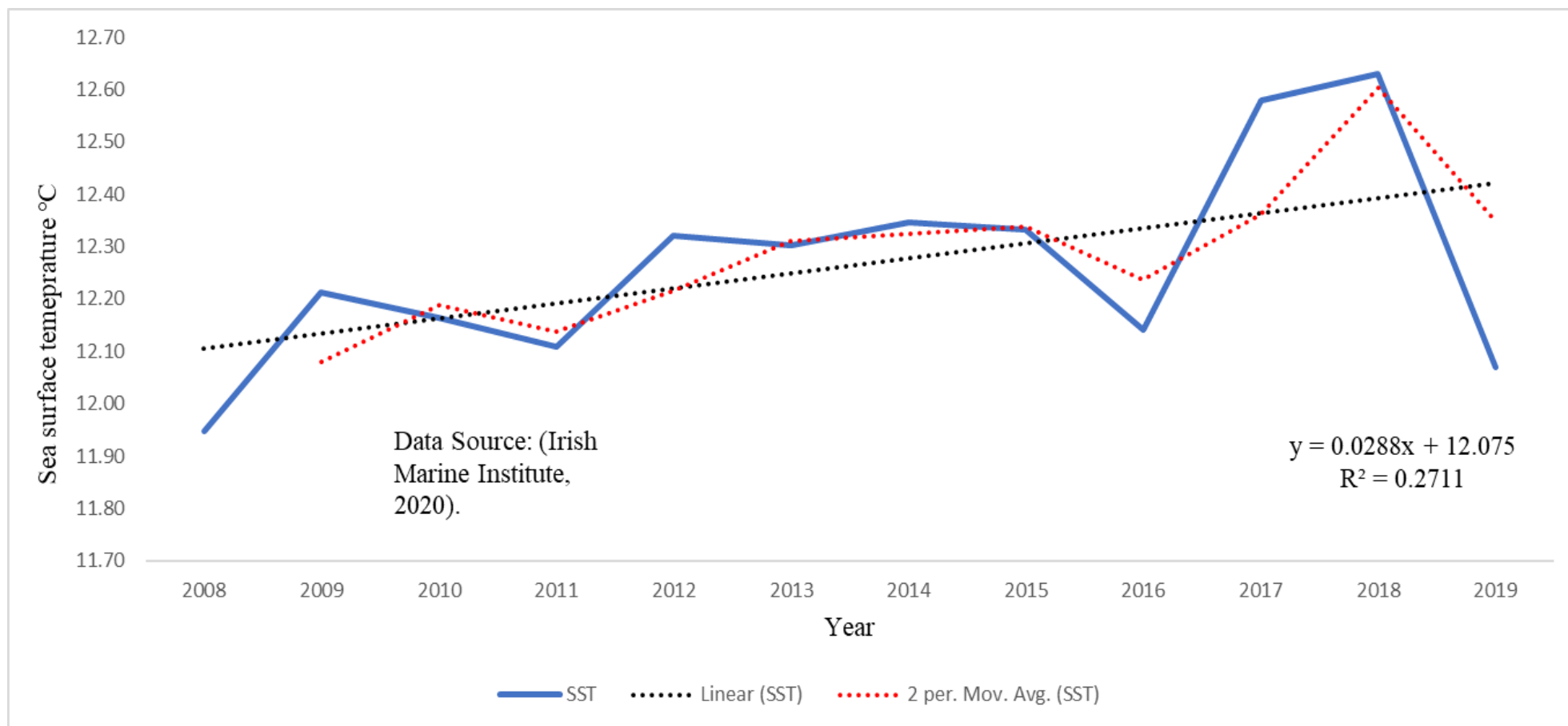


Figure 10 Restored sea surface temperature annual averages M5

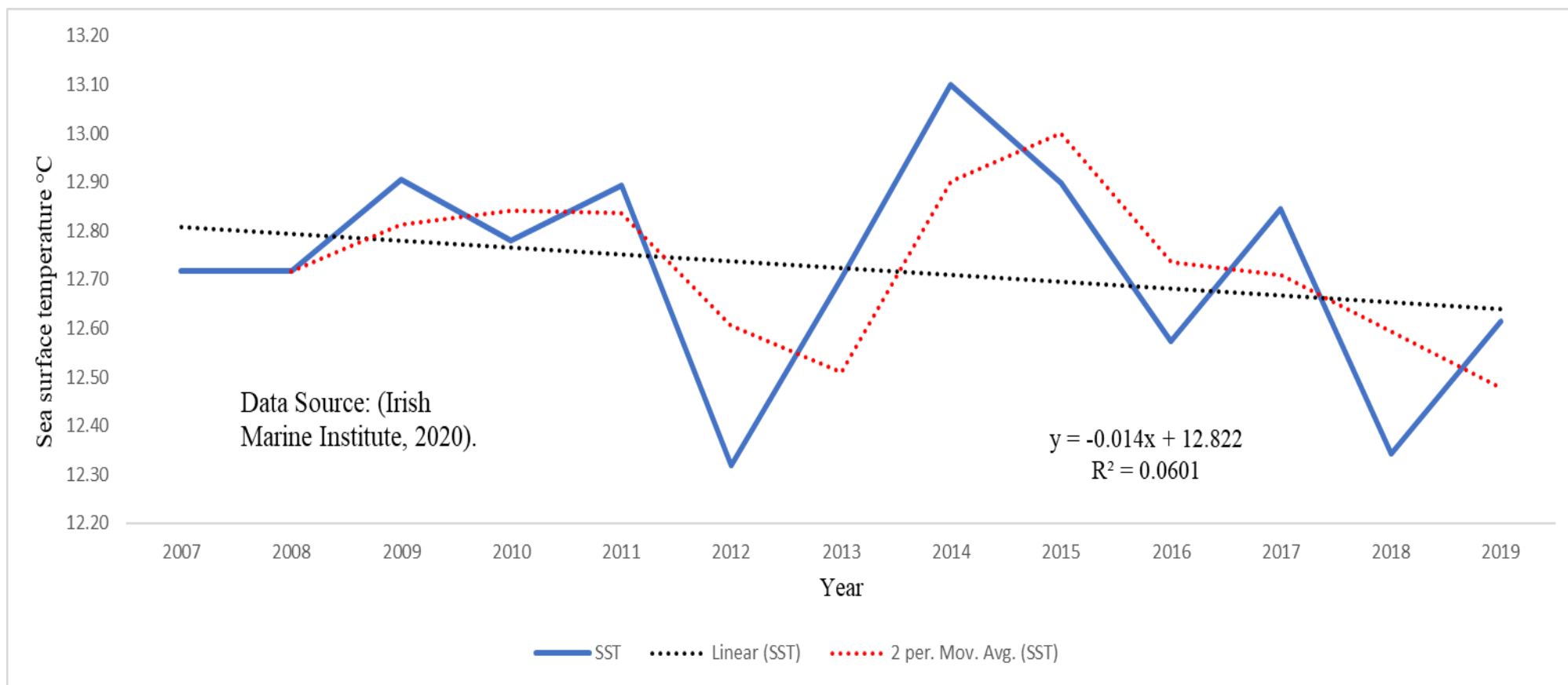


Figure 11 Restored sea surface temperature annual averages M6

4.2 Reconstituted data seasonal SST analysis

M2

M2 March SST analysis

The linear trend shows an overall decrease in March mean SST from 2001-2020. Overall, there were oscillations in SST for March, from 2001-2020, which is within the range of uncertainty. From 2001-2020 there was a sharp decrease in mean SST. There are oscillations of SST from 2002-2015. From 2015-2020 SST continues to oscillate, but these SST are higher than previous oscillations.

The maximum recorded SST for March, was recorded in 2001, of 11.3°C. The minimum SST recorded for March was recorded in 2015, of 7.7°C. Based on this there was an overall high variation in the range of March SST of 3.6°C, from 2001-2020.

From 2001-2002 there was a sharp decrease in March SST of 3°C, from 11.3°C to 8.3°C. From 2002-2006 there were oscillations in SST, within the range of uncertainty. 2007 recorded an increase in March SST of 0.4°C, from 8.3°C to 8.7°C. Following this increase, there was a subsequent decrease in March SST from 2007-2008, forming the first pronounced oscillation in SST. SST decreased by 0.6°C, from 8.7°C to 8.1°C, between 2007-2008. From 2008-2012 there were oscillations in SST, recording increases and decreases, but remaining relatively stable between these years.

From 2012-2013 there was a decrease in SST of 0.5°C, from 8.4°C-7.9°C, forming another pronounced oscillation. Between 2013-2014 there was a subsequent increase in SST of 0.7°C, from 7.9°C to 8.6°C. Another pronounced oscillation was recorded between 2014-2015, showing a decrease in March SST of 0.9°C, from 8.6°C to 7.7°C. A subsequent SST increase was recorded in 2015-2016, of 1.5°C, from 7.7°C to 9.2°C. This oscillation was the most pronounced for March SST variations.

From 2016-2017 there was a stabilisation in SST, with only a decrease of 0.1°C between these years from 9.2°C to 9.1°C. From 2017-2018 there was a decrease in SST of 0.6°C, from 9.1°C to 8.5°C, forming another pronounced oscillation. Between 2018-2019 there was a subsequent increase in SST, of 0.7°C, from 8.5°C to 9.2°C. From 2019-2020 there was another decrease in SST, of 1°C, from 9.2°C to 8.2°C, forming another oscillation in SST. These variations in the restored March SST for M2 are seen in figure 12.

M2 June SST analysis

From 2001-2020 there was an overall increase in mean June SST, based on the linear trendline. Overall, there were significant oscillations in SST from 2001-2020. The minimum SST for June was recorded in 2012 of 11.4°C. The maximum recorded SST for June was recorded in 2016 of 15.4°C. Between the minimum and maximum SST, there was a range of SST variations of 4.1°C, resulting in a high range of variability.

From 2001-2002 there was a sharp decrease in mean June SST of 2.1°C, from 13.8°C to 11.7°C. Between 2002-2003 there was a increase in SST of 0.2°C, from 11.7°C to 11.9°C. This SST increase continued between 2003-2004, showing an increase of 0.7°C, from 11.9°C to 12.6°C. There was an oscillation in SST between 2004-2005, showing a decrease in SST of 0.5°C, from 12.6°C to 12.1°C. Following this, there was a subsequent increase in mean June SST from 2005- 2006, of 0.5°C, from 12.1°C to 12.6°C. Following this there was another decrease in SST, between 2006-2007, of 0.2°C, from 12.6°C to 12.4°C. Between the years 2004-2006 there was oscillating increasing and decreasing SST of the same range, between the same mean SST values.

From 2007-2008 there was an increase in SST of 1.3°C, from 12.4°C to 13.7°C, forming a pronounced oscillation in SST. From 2008-2009 there was a decrease in SST, of 0.4°C, from 13.7°C to 13.3°C. Between 2009-2010 there was another pronounced oscillation in SST for June, showing a pronounced increase of 1.2°C, from 13.3°C to 14.5°C. Following this, there was a significant decrease in mean SST for June between 2010-2011 of 2.8°C, from 14.5°C to 11.7°C. Between 2011-2012 there was a decrease in SST of 0.3°C, from 11.7°C to 11.4°C, showing a stabilisation in mean June SST. From 2012-2013 there was a continued increase in SST, of 0.5°C, from 11.4°C to 11.9°C. This increase in mean June SST continued from 2013-2014, showing a increase of 0.5°C, from 11.9°C to 12.4°C.

From 2014-2015 there was a decrease in mean June SST of 0.9°C, from 12.4°C to 11.5°C, forming another SST oscillation. Between 2015-2016 there was a significant increase in mean June SST, of 3.9°C, from 11.5°C to 15.4°C. This was the most significant SST oscillation recorded for mean June SST for M2 from 2001-2020. Following this significant oscillation there was a subsequent decrease in SST from 2016- 2017, of 2.9°C. Between 2017-2018 there was another oscillation in SST, showing an increase in mean June SST of 1.3°C, from 12.5°C to 13.8°C. Between 2018-2019 there was a decrease in SST, of 0.7°C, from 13.8°C to 13.1°C. SST continued to decrease from 2019-2020, on a more pronounced

scale, showing a decrease of 1.2°C. These variations in resorted June SST from M2 are seen in figure 13.

M2 September SST analysis

The reconstituted data shows an overall decrease in SST for mean September SST from 2001-2020 based on the linear trend. Overall, there were SST oscillations from 2001-2020, which are within the range of uncertainty. 2001 recorded the minimum mean September SST of 11.4°C. 2008 recorded the maximum mean September SST of 15°C. The range of SST variations between the minimum and maximum SST was 3.6°C, showing a high variation in SST of 2001-2020. From 2001-2002 there was a significant SST oscillation, followed by stabilised oscillations until 2010. From 2010- 2020 there was oscillations of a larger SST variance.

From 2001-2002 there was a significant mean SST increase for the months of September of 4.2°C, from 11.4°C to 14.6°C. from 2002-2004 there was a stabilisation in SST with minor SST increases and decreases. Between 2004- 2005 there was a decrease in SST of 0.2°C, from 14.5°C to 14.3°C, forming the beginning of an oscillation in SST. From 2005-2006 there was a subsequent increase in SST, which was directly proportional to the previous year's SST decrease, of 0.2°C, from 14.3°C to 14.5°C. From 2006-2008 there was a continued gradual increase in mean September SST. Between 2008-2009 there was another SST oscillation recorded, showing a decrease in SST of 0.8°C, from 15°C to 14.2°C. SST increases ly between 2009-2010, by 0.5°C, from 14.2°C to 14.7°C.

Between 2010-2011 another SST oscillation was recorded, showing a decrease in SST of 0.4°C, from 14.7°C to 14.3°C. This was followed by a subsequent increase in SST, between 2011-2012, of 0.6°C, from 14.3°C to 14.9°C. From 2012-2013 there was only a decrease in SST, of 0.2°C, from 14.9°C to 14.7°C. There was another notable decrease in mean September SST between 2013- 2014, of 0.9°C, from 14.7°C to 13.8°C. From 2014-2015 there was a increase in SST of 0.1°C, from 13.8°C to 13.9°C.

From 2015-2016 there was a significant decrease in the mean SST for September, of 2.2°C, from 13.9°C to 11.7°C, forming a significant oscillation in SST. Following this there was a subsequent significant increase in SST of, 2.9°C, from 14.6°C to 11.7°C between 2016-2017. From 2017- 2018 there was a decrease in SST of 0.5°C, from 14.6°C to 13.9°C. This decrease in SST continued from 2018-2019, recording a decrease in SST of 0.3°C, from

13.9°C to 13.6°C. From 2019-2020 there was an increase in SST of 1.1°C, from 13.6°C to 14.7°C. These variations in restored September SST for M2 are seen in figure 14.

M2 December SST analysis

There was an overall decrease in mean SST for December from 2002-2020 based on the linear trendline. Overall, there was oscillating SST from 2002-2020, which is within the range of uncertainty. The minimum mean SST was recorded in 2008, of 10.7°C. The maximum SST was recorded in both 2006 and 2014, of 12.2°C. The SST variation range between the minimum and maximum recorded SST was 1.5°C.

From 2002-2003 there was an increase in SST of, 0.5°C, from 11.2°C to 11.7°C. From 2003-2005 there was a stabilisation in SST, with no variation in mean December SST for these years, with the SST remaining at 11.7°C. From 2005-2006 there was an oscillation in SST, showing an increase in SST of 0.5°C, from 11.7°C to 12.2°C. There was a subsequent decrease in SST, from 2006-2007, of 0.8°C, from 12.2°C to 11.4°C. SST continued to decrease, further pronouncing the significance of the SST oscillation, between 2007-2008. Between 2007-2008 there was a SST decrease of 0.7°C, from 11.4°C to 10.7°C. Between 2008-2009 there was a increase in SST, of 0.1°C, from 10.7°C to 10.8°C.

From 2009-2010 there was a continued increase in SST, of 0.3°C, from 10.8°C to 11.1°C. SST continued to increase from 2010-2011, by 0.5°C, from 11.1°C to 11.6°C. 2011-2012 marked another oscillation in SST, showing a decrease in SST of 0.7°C, from 11.6°C to 10.9°C. SST recovered to the temperature before this oscillation, by recording an increase in SST of 0.7°C, from 10.9°C to 11.6°C, between 2012-2013. Between 2013-2014, SST continued to increase, showing an increase of 0.6°C, from 11.6°C to 12.2°C.

From 2014-2015 there was another marked SST oscillation, showing a decrease in SST of 0.3°C, from 12.2°C to 11.9°C. SST continued to decrease from 2015- 2016, showing a decrease in SST of 0.8°C, from 11.9°C to 11.1°C. Between 2016- 2017 there was a increase in SST, of 0.2°C, from 11.1°C to 11.3°C. From 2017-2018 there was a decrease in SST of 0.9°C, from 11.3°C to 10.4°C. SST stabilised between 2018-2019, maintaining a mean SST of 10.4°C. These variations in restored December SST for M2 are seen in figure 15.

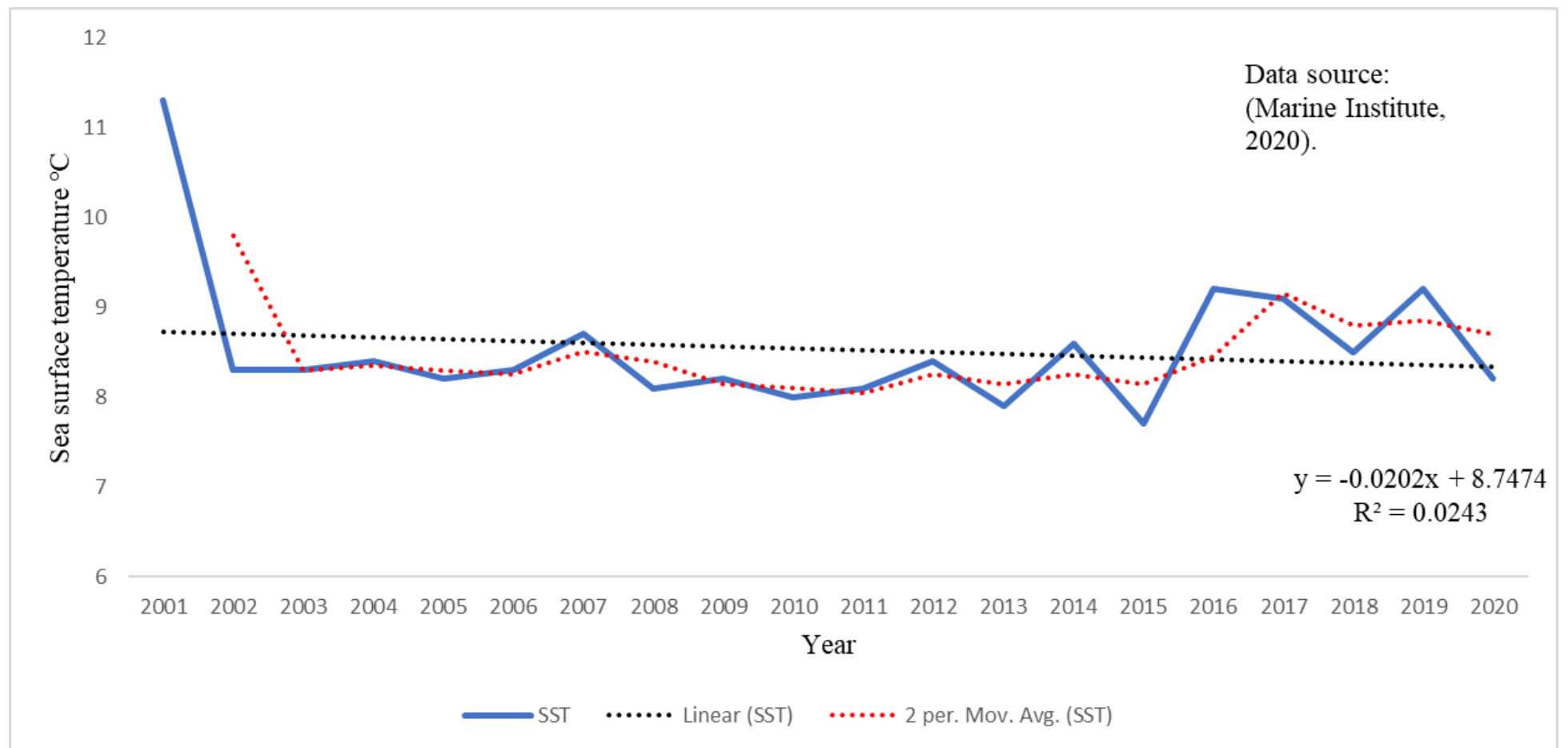


Figure 12 Restored March SST variations M2.

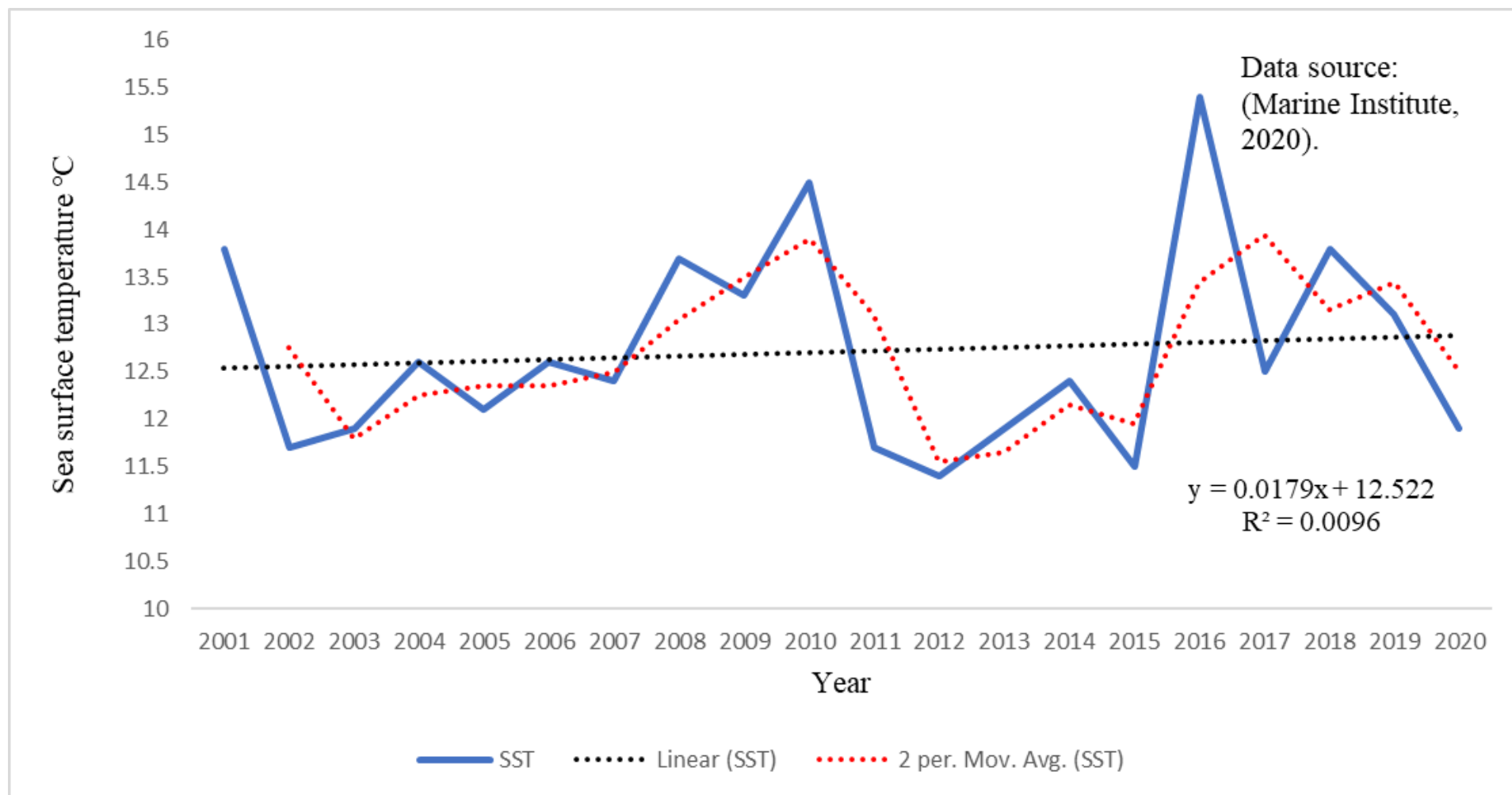


Figure 13 Restored June SST variations M2.

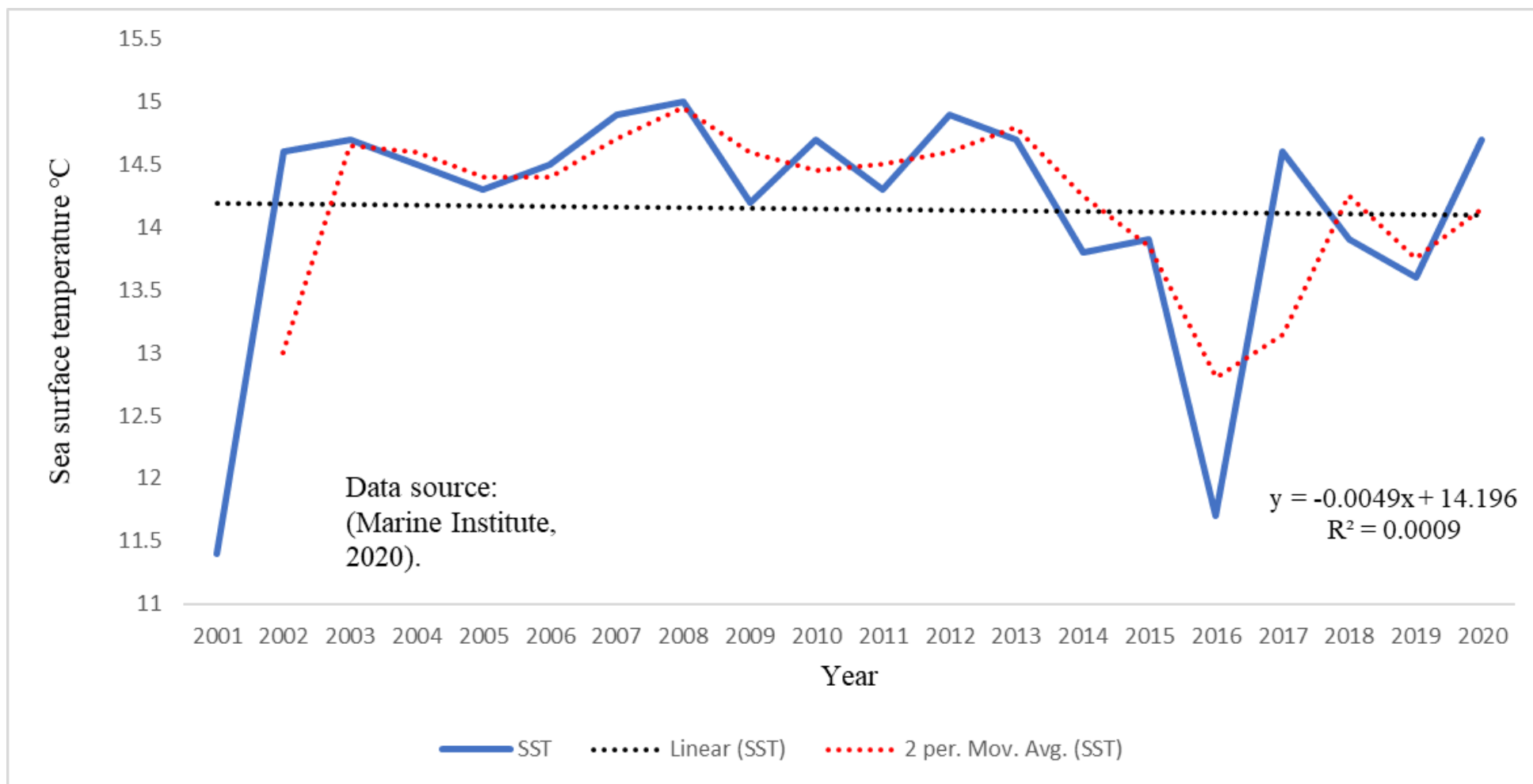


Figure 14 Restored September SST variations M2.

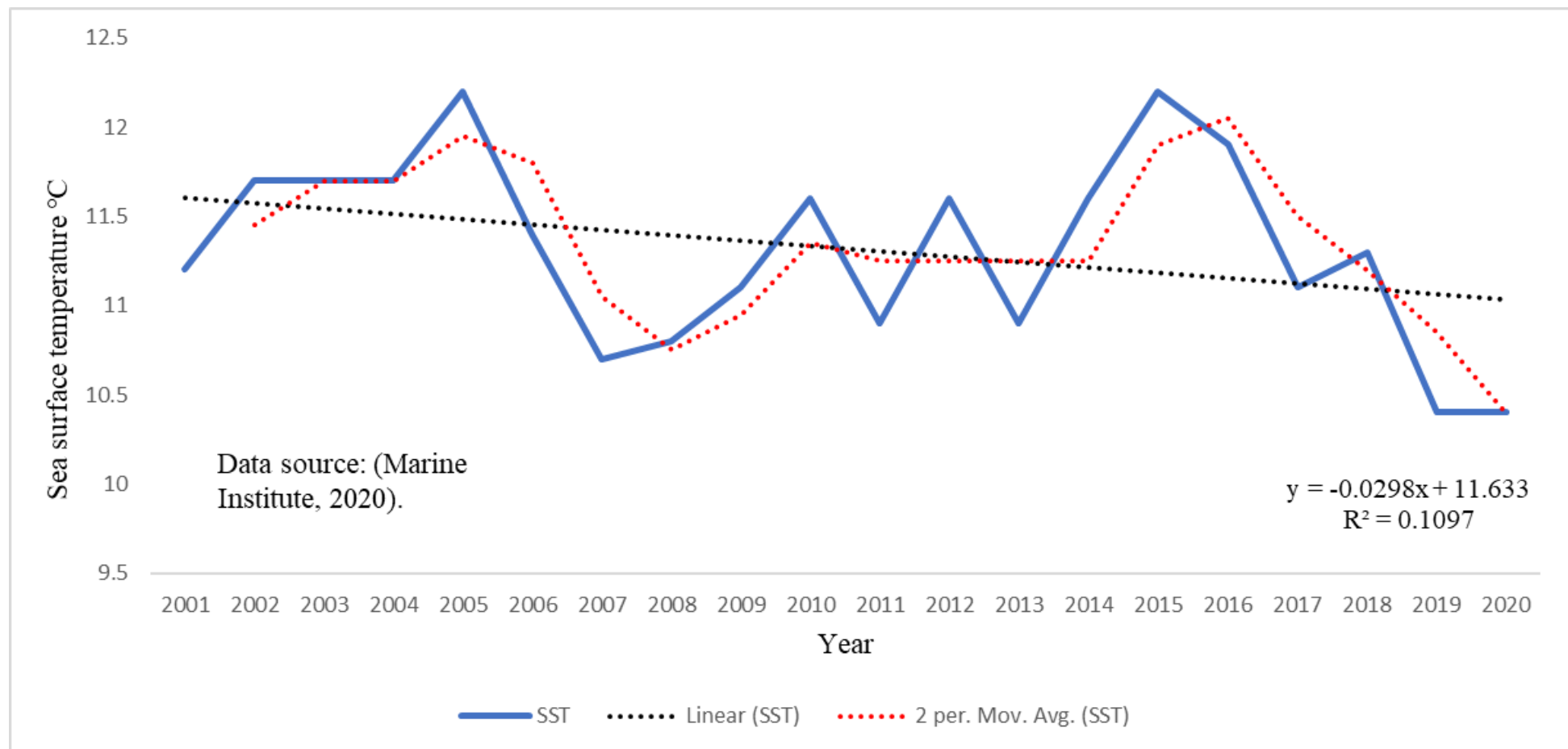


Figure 15 Restored December SST variations M2.

M3

M3 March SST analysis

Both 2008 and 2011 recorded the maximum SST of 11°C. 2020 recorded the minimum mean March SST, of 8.3°C. There was an overall decrease in mean March SST from 2003-2020 for M3, based on the linear trendline. Overall, there was oscillating SST from 2003-2020. The range of SST variations between the minimum and maximum SST was 2.7°C.

Between 2003-2004 there was a increase in mean March SST, of 0.3°C, from 10.6°C to 10.9°C, to form the beginning of the first SST oscillation. From 2004-2005 there was a subsequent decrease in SST, of 0.3°C, to return back to 10.6°C. From 2005-2006 there was a continued decrease in SST, of 0.5°C, from 10.6°C to 10.1°C. From 2006-2007 there was a increase in SST of 0.4°C, from 10.1°C to 10.5°C. SST continued to increase from 2007-2008, by 0.5°C, from 10.5°C to 11°C.

Another SST oscillation was recorded between 2008-2009, showing a decrease of 0.6°C, from 11°C to 10.4°C. SST stabilised between 2009-2010, recording no change in the mean SST of 10.4°C. From 2010-2011 there was an increase in SST of 0.6°C, from 10.4°C to 11°C. From 2011 to 2012 there was a significant decrease in SST of 1.6°C, from 11°C to 9.4°C, forming another oscillation in SST. There was a subsequent increase in mean March SST, from 2012-2013, of 1°C, from 9.4°C to 10.4°C.

2013-2014 recorded another SST oscillation, showing a decrease in mean March SST, of 0.7°C, from 10.4°C to 9.7°C. Following this there was a subsequent increase in SST of 1°C, from 9.7°C to 10.7°C, from 2014-2015. From 2015-2016 there was a decrease in SST, of 0.4°C, from 10.7°C to 10.3°C. This was followed by a increase in SST, of 0.2°C, from 10.3°C to 10.5°C, between 2016-2017. Between 2017-2018 there was a significant decrease in SST of 1.9°C, from 10.5°C to 8.6°C. This marks the beginning of the largest recorded oscillation for mean March SST variations. Following this significant decrease there was a subsequent SST increase of 2.2°C, from 8.6°C to 10.8°C, between 2018-2019. In 2019-2020 there was another significant decrease in SST of 2.5°C, from 10.8°C to 8.3°C. This was the largest variation in mean March SST from 2003-2020. These variations in restored March SST for M3 are seen in figure 16.

M3 June SST analysis

2018 recorded the maximum SST of 16.3°C. 2015 recorded the minimum SST of 12.9°C. From 2003-2020 there was an overall increase in mean June SST for M3 based on the linear trendline. Between 2006-2009 there was a relative stabilisation in SST, with the other years showing oscillating SST values. Between the minimum and maximum SST, there was a SST range of 3.4°C.

From 2003-2004 there was a mean SST increase of 1.4°C, from 13.5°C to 14.9°C, forming the first oscillation in SST. From 2004-2005 there was a subsequent decrease in SST of 0.9°C, from 14.9°C to 14°C. Between 2005-2006 there was an increase in SST of 0.5°C, from 14°C to 14.5°C. Following these SST oscillations, there was a stabilisation in SST from 2006-2009 with only increases and decreases of SST, ranging from 0.1°C and 0.2°C.

From 2009-2010 there was another oscillation in SST, showing an increase in SST of 0.8°C, from 14.5°C to 15.3°C. From 2010-2011 there was a significant decrease in mean June SST of 2.2°C, from 15.3°C to 13.1°C, continuing the oscillation in SST. From 2011-2012 there was a subsequent increase in mean June SST, of 2.1°C, from 13.1°C to 15.2°C, returning to a similar SST recorded for the previous year.

Between 2012-2013 there was another SST oscillation, recording a decrease in mean June SST of 1.1°C, from 15.2°C to 14.1°C. From 2013-2014 there was a decrease in SST of 0.1°C, from 14.1°C to 14°C, showing a stabilisation in SST. Between 2014-2015 there was another decrease in mean June SST, forming another oscillation in SST, recording a decrease in SST of 1.1°C, from 14°C to 12.9°C. A subsequent SST increase was recorded between 2015-2016, following the previous SST oscillation, recording a SST increase of 2.1°C, from 12.9°C to 15°C.

Between 2016-2017 there was a SST decrease of 0.8°C, from 15°C to 14.2°C, forming another SST oscillation. Between 2017-2018 there was a subsequent SST increase of 2.1°C, from 14.2°C to 16.3°C. From 2018-2019 there was a decrease in mean June SST, forming another SST oscillation, recording a decrease of 2.5°C, from 16.3°C to 13.8°C. From 2019-2020 there was a SST decrease of 0.2°C, from 13.8°C to 13.6°C. These variations in restored June SST for M3 are seen in figure 17.

M3 September SST analysis

The maximum mean September SST was recorded in 2012 of 16.9°C. The minimum mean September SST was recorded in both 2008 and 2020, of 14.6°C. From 2002-2020 there was an overall decrease in mean September SST, based on the linear trendline. There was an overall mean September SST variation range of 2.3°C.

Between 2002-2003 there was a mean SST increase of 0.6°C, from 15.8°C to 16.4°C. A SST oscillation was recorded between 2003-2004 there was a decrease in SST, of 1.2°C, from 16.4°C to 15.2°C. SST increased between 2004-2005, to recover to similar mean September SST as the previous year, showing an increase of 1.1°C, from 15.2°C to 16.3°C. Between 2005-2006 there was a stabilisation in mean September SST, showing only a decrease in SST of 0.1°C from 16.3°C to 16.2°C. From 2006-2007 there was a continued decrease in SST of 0.3°C, from 16.2°C to 15.9°C.

From 2007-2008 there was a SST oscillation recorded, showing a decrease in SST of 1.3°C, from 15.9°C to 14.6°C. Between 2008-2009 there was a increase in mean September SST, showing a increase of 0.1°C from 14.6°C to 14.7°C. From 2009-2010 there was another SST oscillation recorded, showing an increase in mean September SST, of 1.6°C, from 14.7°C to 16.3°C. The SST oscillation continued between 2010-2011, recording a decrease in SST of 1.5°C, from 16.3°C to 14.8°C.

From 2011-2012 there was another SST oscillation, showing an increase in mean September SST of 2.1°C, from 14.8°C to 16.9°C. From 2012-2013 there was another significant SST oscillation recording a decrease in mean September SST, of 2.2°C, from 16.9°C to 14.7°C. Between 2013-2014 there was a SST increase of 0.5°C, from 14.7°C to 15.4°C, forming another SST oscillation. From 2014-2015 there was a SST decrease of 0.5°C, from 15.4°C to 14.9°C, continuing the SST oscillation.

From 2015-2016 there was a SST increase of 0.5°C, from 14.9°C to 15.4°C. Between 2016-2018 there was a stabilisation in SST variations, with only a decrease of 0.2°C between 2016-2017, and no variation in SST between 2017-2018. From 2018-2019 there was a increase in SST of 0.5°C, from 15.2°C to 15.7°C, forming an oscillation in SST. Between 2019-2020 there was a significant decrease in mean September SST of 1.1°C, from 15.7°C to 14.6°C. These variations in restored September SST for M3 are seen in figure 18.

M3 December SST analysis

The maximum recorded mean SST for December was recorded in 2015, of 12.3°C. The minimum recorded mean SST for December was recorded in 2008, of 10.4°C. From 2002-2020 there was an overall decrease in mean December SST, based on the linear trendline. Overall, there was a variation in the range of SST, between the minimum and maximum SST, of 1.9°C.

From 2002-2003 there was a mean SST decrease of 0.6°C, from 11.9°C to 11.3°C. Between 2003-2005 there were variations in SST. From 2003-2004 there was a increase in SST of, 0.1°C, from 11.3°C to 11.4°C. From 2004-2005 there was a decrease in mean December SST, of 0.2°C, from 11.4°C to 11.2°C. Between 2005-2006 there was a increase in SST of 0.4°C, from 11.2°C to 11.6°C, forming a SST oscillation. Between 2006-2007 there was only a increase in mean December SST of 0.1°C, from 11.6°C to 11.7°C.

From 2007-2008 there was a decrease in mean December SST of 1.3°C, from 11.8°C to 10.5°C, continuing the SST oscillations. Between 2012-2013 there was an increase in mean December SST of 1.2°C, from 10.5°C to 11.7°C, continuing the oscillations in SST. From 2013-2014, there was another oscillation in SST showing a decrease in mean SST of 0.8°C, from 11.7°C to 10.9°C. Between 2014-2015 there was another oscillation in SST, showing an increase in SST of 1.4°C, from 10.9°C to 12.3°C.

From 2015-2016 there was a decrease in mean December SST, showing a decrease of 0.5°C from 12.3°C to 11.8°C. This SST decrease continued between 2016-2017, showing a decrease of 0.7°C, from 11.8°C to 11.1°C, forming another SST oscillation. From 2017-2018 there was an increase in SST of 0.6°C, from 11.1°C to 11.7°C, forming another SST oscillation. From 2018-2019 there was a significant decrease in mean December SST of 1°C, from 11.7°C to 10.7°C. These variations in restored December SST for M3 are seen in figure 19.

M4

M4 March SST analysis

The maximum mean March SST was recorded in 2008 of 10.4°C. The minimum mean March SST was recorded in 2012, of 8.9°C. From 2008-2020 there was an overall decrease in mean March SST, based on the linear trendline. From 2008-2011 there were variations in SST,

followed by oscillating SST from 2012-2020. Overall, there was a range of 1.5°C, between the minimum and maximum SST.

From 2008-2009 there was a decrease in mean March SST, showing a decrease of 0.4°C, from 10.4°C to 10°C. Between 2009-2010 there was a decrease in SST of 0.1°C, from 10°C to 9.9°C. Following this, there was an increase in SST, between 2010-2011, of 0.2°C, from 9.9°C to 10.1°C.

From 2011-2012 there was an oscillation in SST, recording a decrease in SST of 1.2°C, from 10.1°C to 8.9°C. From 2012-2013 there was an increase in SST, of 0.5°C, from 8.9°C to 9.4°C, showing a continuation of this SST oscillation. Between 2013-2014 there was a decrease in SST, showing an oscillation in SST, recording a decrease of 0.4°C, from 9.4°C to 9°C. Between 2014-2015 there was another SST oscillation recorded, showing an increase in SST of 1.1°C, from 9°C to 10.1°C. From 2015-2016, there was a decrease in SST of 0.4°C, from 10.1°C to 9.7°C, forming another SST oscillation. From 2016-2017 there was an increase in SST of 0.5°C, from 9.7°C to 10.2°C.

From 2017-2018 there was another oscillation in SST, showing a decrease in SST of 0.8°C, from 10.2°C to 9.4°C. Between 2018-2019 there was an increase in SST of 0.7°C, from 9.4°C to 10.1°C, continuing the oscillation in SST. From 2019-2020 there was a decrease in SST, of 0.4°C, from 10.1°C to 9.7°C. These variations in restored March SST for M4 are seen in figure 20.

M4 June SST analysis

The maximum SST was recorded in 2018. The minimum SST for mean June SST, was 12°C, in 2011. From 2007-2020 there was an overall decrease in mean June SST for M4, based on the linear trendline. Overall, there was oscillating SST between 2007-2020. There was an overall SST variation range of 3.5°C.

Between 2007-2008 there was a decrease in SST, recording a decrease of 0.1°C, from 14°C to 13.9°C. An oscillation in SST was recorded between 2008-2009, recording a SST decrease of 0.9°C, from 13.9°C to 13°C. SST subsequently increased from 2009-2010, recovering from the previous oscillation. Between these years SST increased by 1.1°C, from 13°C to 14.1°C. Another SST oscillation was recorded between 2010-2011, recording a decrease of 1.9°C, from 14.1°C to 12°C. There was a subsequent SST increase recorded from 2011-2012, showing an increase of 2.5°C, from 12°C to 14.5°C.

From 2012-2013 there was another oscillation in SST, recording a SST decrease of 1.4°C, from 14.5°C to 13.1°C. SST stabilised between 2013-2014, recording a increase of 0.1°C, from 13.1°C to 13.2°C. From 2014-2015 there was a decrease in SST of 1°C, from 13.2°C to 12.2°C. From 2015-2016 there was a subsequent increase in SST of 2°C, from 12.2°C to 14.2°C. Between 2016-2017 there was another SST oscillation recorded, showing a decrease of 1.3°C, from 14.2°C to 12.9°C.

From 2017-2018 there was another oscillation in SST, recording an increase of 2.6°C, from 12.9°C to 15.5°C. There was a subsequent decrease in SST between 2018-2019 of 2.8°C, from 15.5°C to 12.7°C, being the largest variation in SST. From 2019-2020 there was a stabilisation in SST, with no change in mean June SST between these years, with SST remaining at 12.7°C. These variations in restored June SST for M4 are seen in figure 21.

M4 September SST analysis

The maximum mean September SST was recorded in 2012 of 16.1°C. The minimum mean September SST, was recorded in 2011 of 13.3°C. From 2007-2020 there was an overall increase in mean September SST based on the linear trendline. Between 2008-2010 and 2014-2016 there were relatively variations in SST, with larger oscillations present in the other years. Between the minimum and maximum SST, there was an overall SST range of 2.8°C.

From 2007-2008 there was a decrease in mean September SST of 0.8°C, from 14.7°C to 13.9°C, forming the first oscillation in SST. Between 2008-2009 there was a stabilisation in SST, recording a increase of 0.2°C, from 13.9°C to 14.1°C. The stabilisation in SST continued between 2009-2010, recording a but gradual increase of 0.1°C, from 14.1°C to 14.2°C.

From 2010-2011 there was another oscillation in SST, recording a decrease of 0.9°C, from 14.2°C to 13.3°C. From 2011-2012 another oscillation in SST was recorded, showing an increase of 2.8°C, from 13.3°C to 16.1°C. A further SST oscillation was recorded between 2012-2013, showing a decrease of 2.4°C, from 16.1°C to 13.7°C. Between 2013-2014 there was another oscillation, recording an increase of 0.9°C, from 13.7°C to 14.6°C.

From 2014-2016 there was an overall stabilisation in SST. From 2014-2015 there was a decrease in SST of, 0.3°C, from 14.6°C to 14.3°C. Between 2015-2016 there was a subsequent increase in SST, of 0.3°C, from 14.3°C to 14.6°C. From 2016-2017 there was a decrease of 0.5°C, from 14.6°C to 14.1°C. Between 2017-2018 there was an increase of

1.7°C, from 14.1°C to 15.8°C, forming a SST oscillation. There was a subsequent decrease in SST, continuing the oscillation in SST, of 1.7°C, from 15.8°C to 14.1°C. From 2019-2020 there was a increase of 0.4°C, from 14.1°C to 14.4°C. These variations in restored September SST for M4 are seen in figure 22.

M4 December SST analysis

The maximum mean December SST was recorded in 2018 of 12°C. The minimum mean December SST was recorded in 2008, of 9.9°C. From 2007-2020 there was an overall increase in mean December SST, based on the linear trendline. Overall, there was a SST range of 1.1°C, between the minimum and maximum SST.

Between 2007-2008 there was a decrease in SST of 1.3°C, from 11.2°C to 9.9°C. Between 2008-2009 there was an increase in SST of 0.8°C, from 9.9°C to 10.7°C, forming a SST oscillation. Another SST oscillation was recorded between 2009-2010, showing a decrease of 0.4°C, from 10.7°C to 10.3°C. From 2010-2011 there was a subsequent increase in mean December SST of 0.5°C, to continue the oscillation in SST.

From 2011-2012 another SST oscillation was recorded, showing a decrease of 0.8°C, from 10.8°C to 10°C. The SST oscillation was continued between 2012-2013, showing an increase of 0.7°C, from 10°C to 10.7°C. Another oscillation in SST was recorded, showing a decrease in mean December SST of 0.4°C, from 10.7°C to 10.3°C, between 2013-2014.

Between 2014-2015 there was another oscillation in SST, recording an increase of 1.4°C, from 10.3°C to 11.7°C. From 2015-2016 there was a decrease in SST of 0.6°C, from 11.7°C to 11.1°C. SST continued to decrease between 2016-2017, recording a decrease of 0.3°C, from 11.1°C to 10.8°C. Another SST oscillation was recorded, showing an increase in mean December SST of 1.2°C, from 10.8°C to 12°C. Another oscillation was recorded between 2019-2020, recording a decrease in mean December SST of 1.5°C, from 12°C to 10.5°C. These variations in restored December SST for M4 are seen in figure 23.

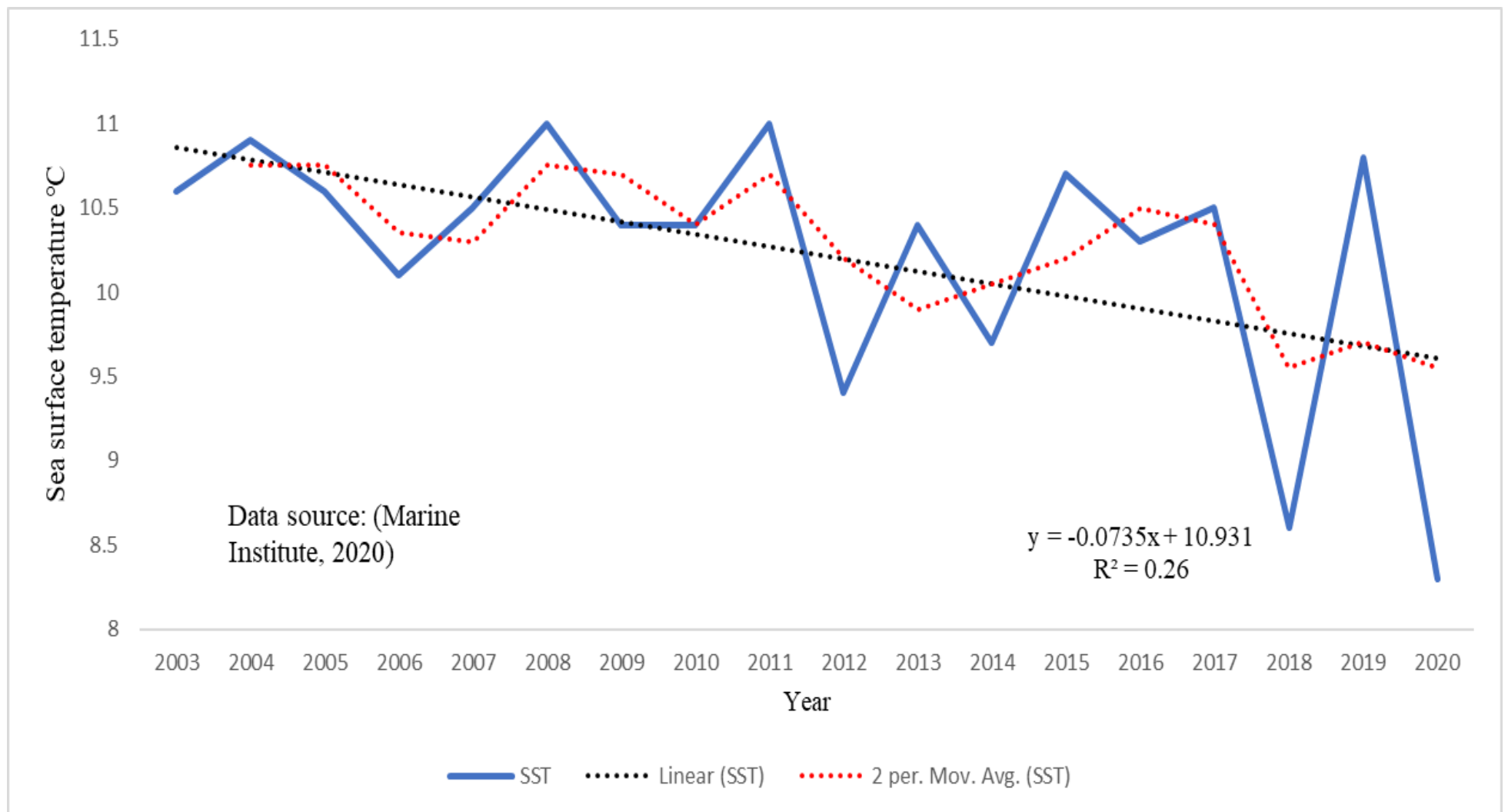


Figure 16 Restored March SST variations M3.

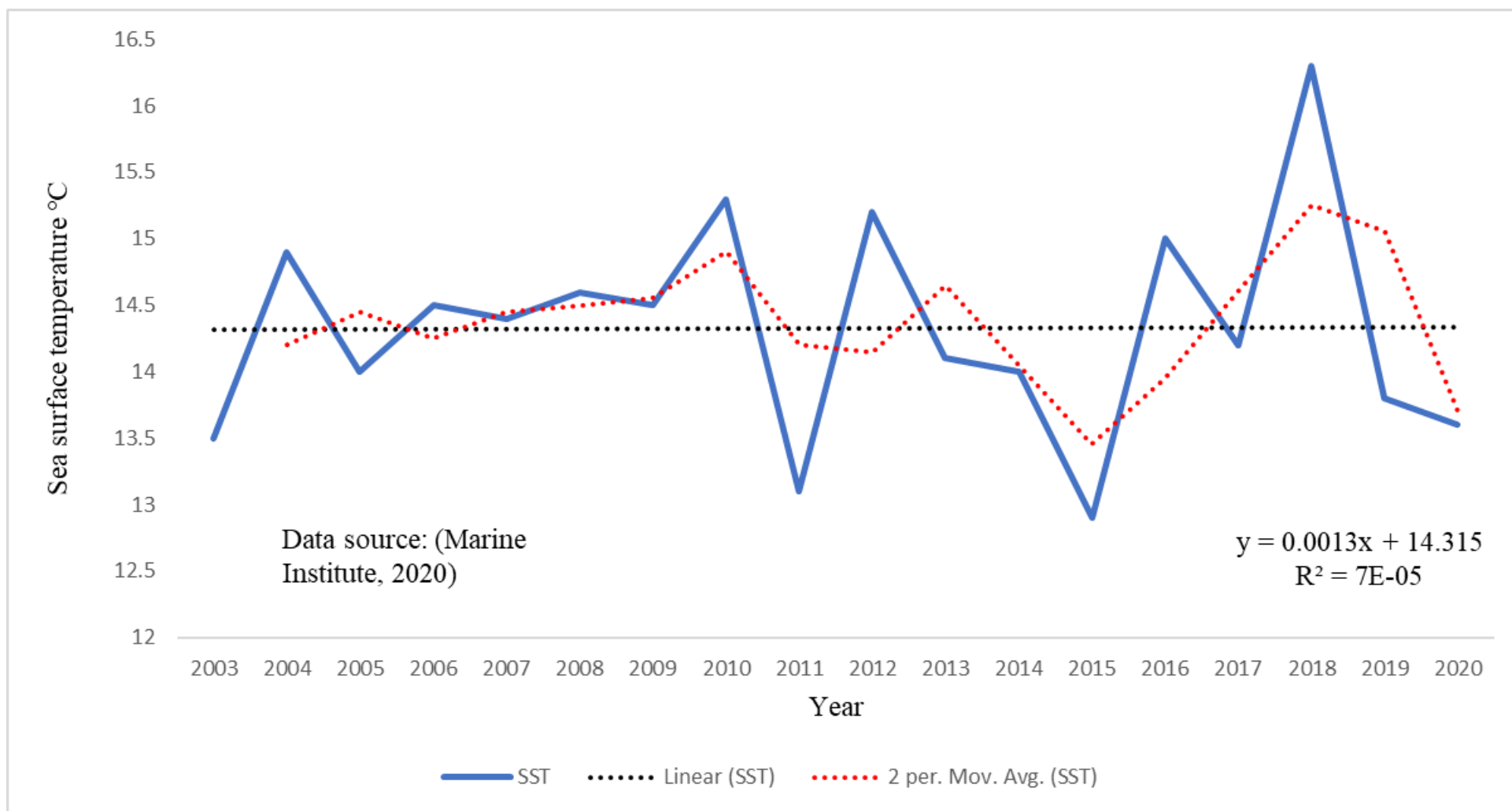


Figure 17 Restored June SST variations M3.

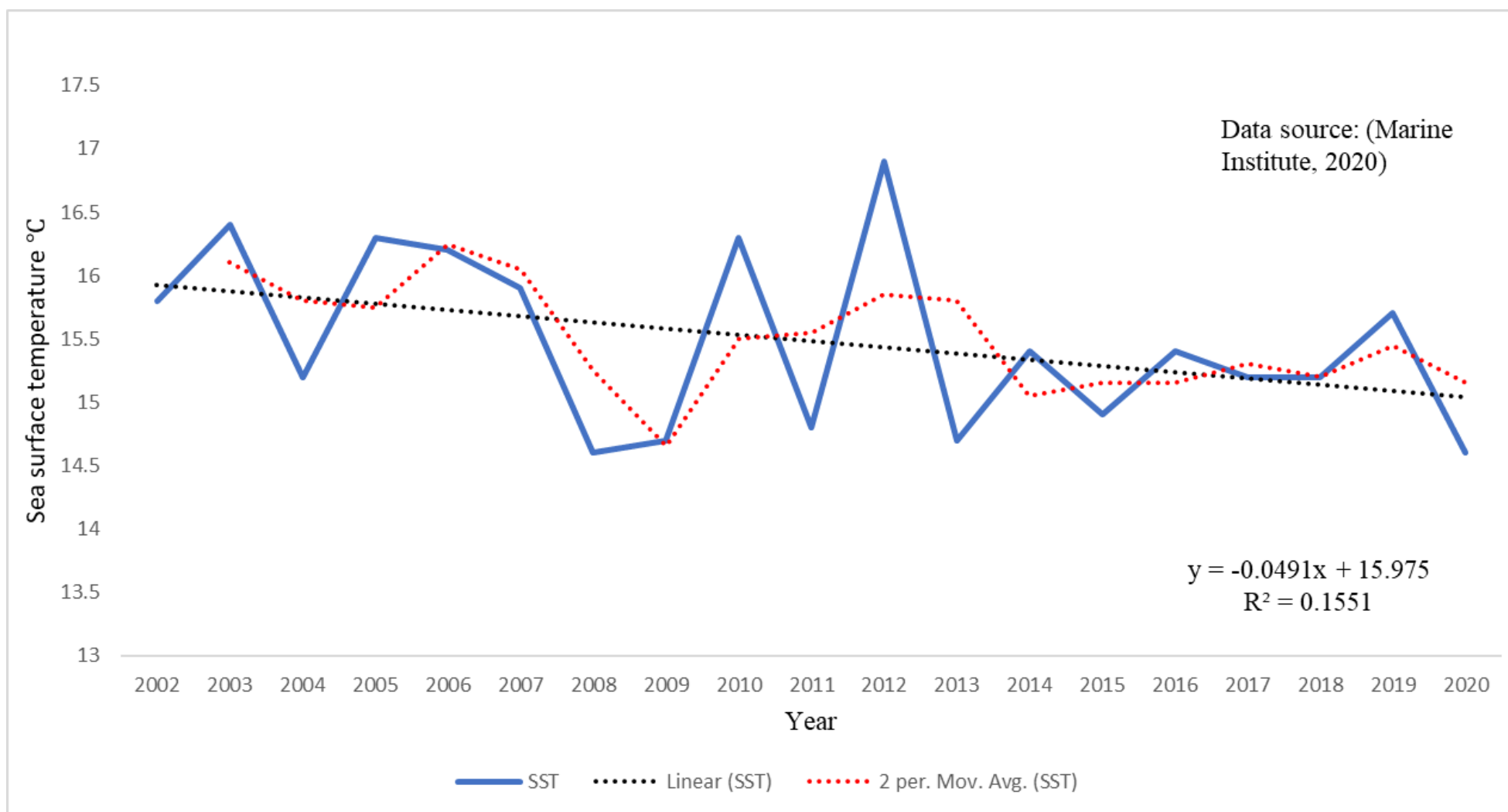


Figure 18 Restored September SST variations M3.

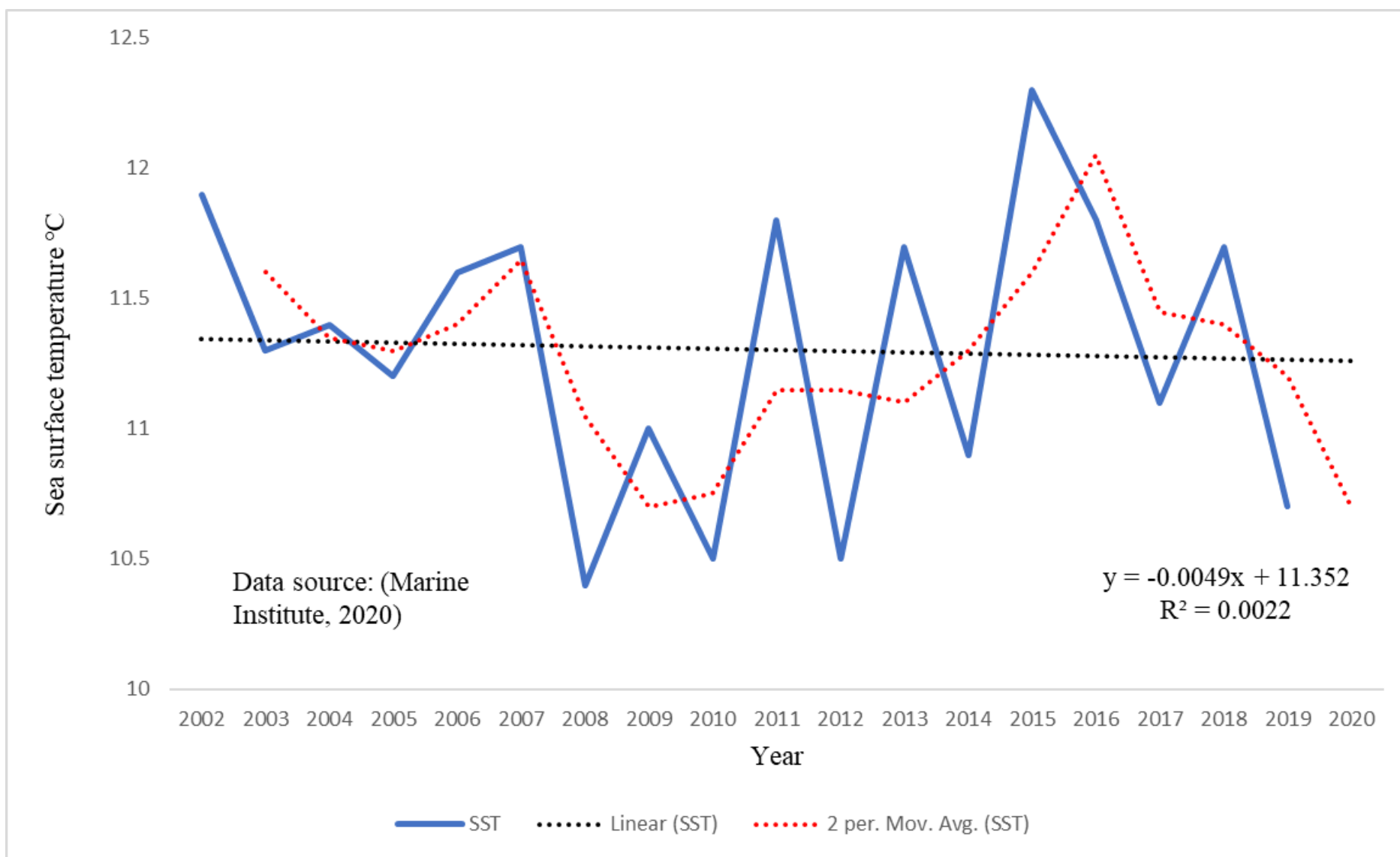


Figure 19 Restored December SST variations M3.

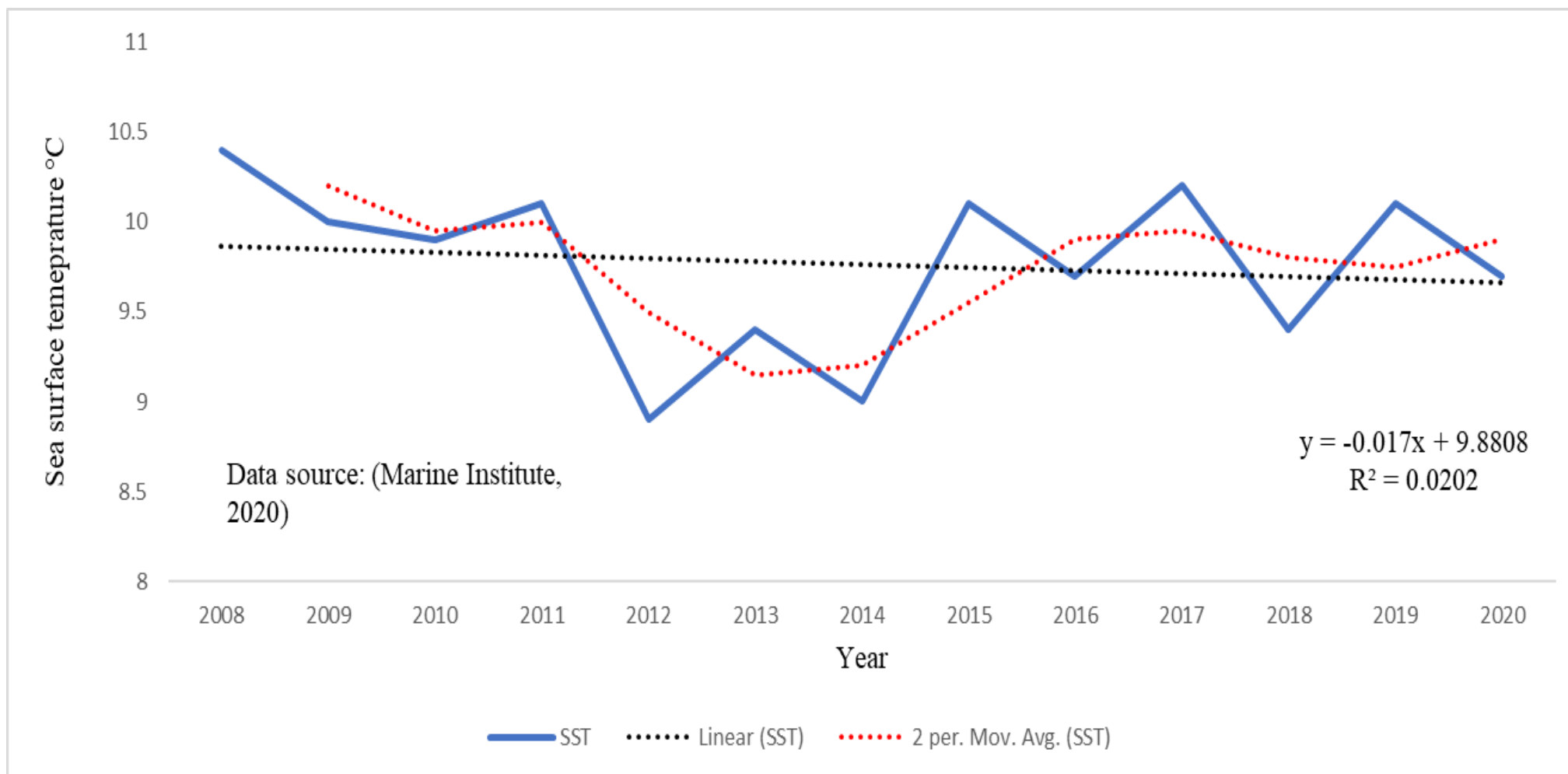


Figure 20 Restored March SST variations M4.

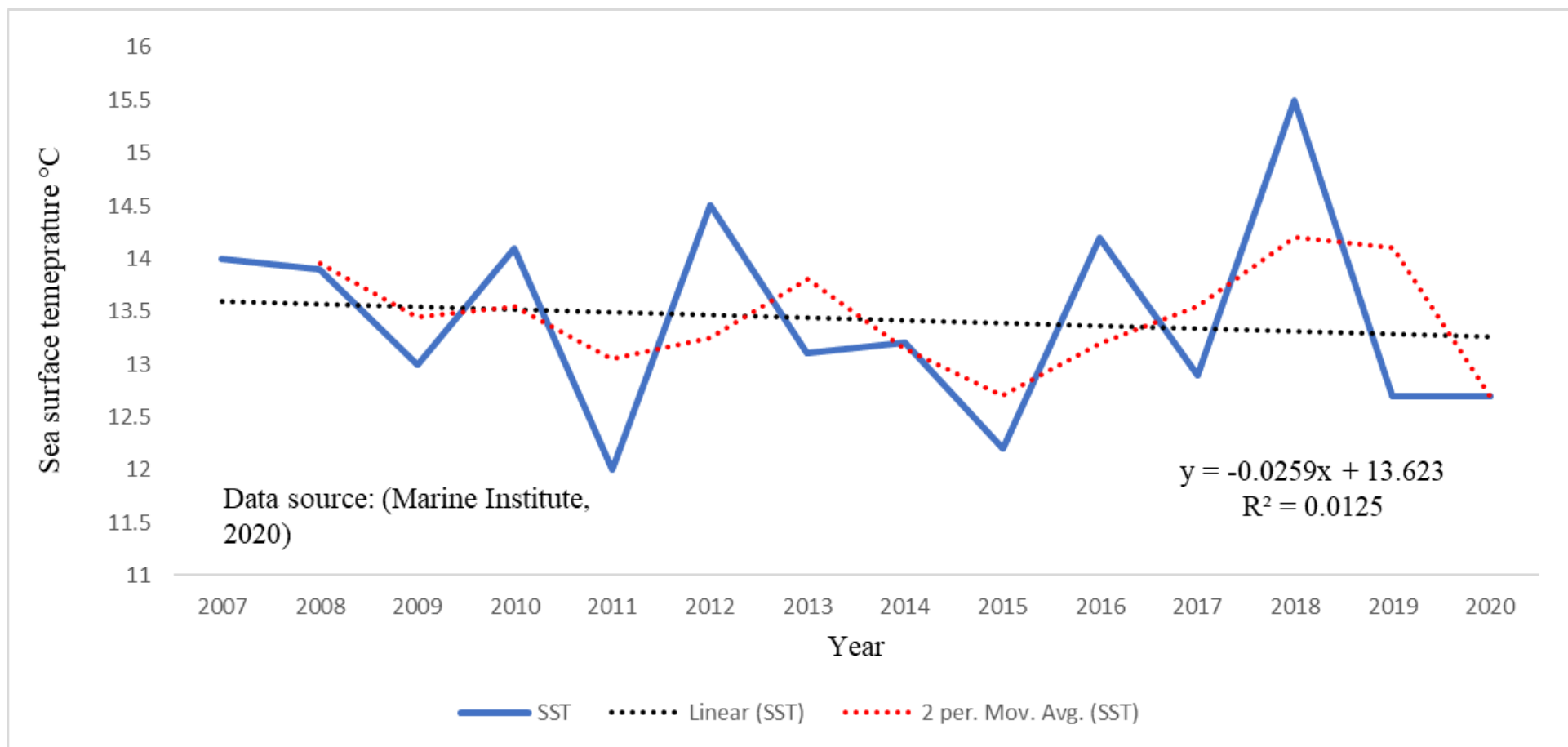


Figure 21 Restored June SST variations M4.

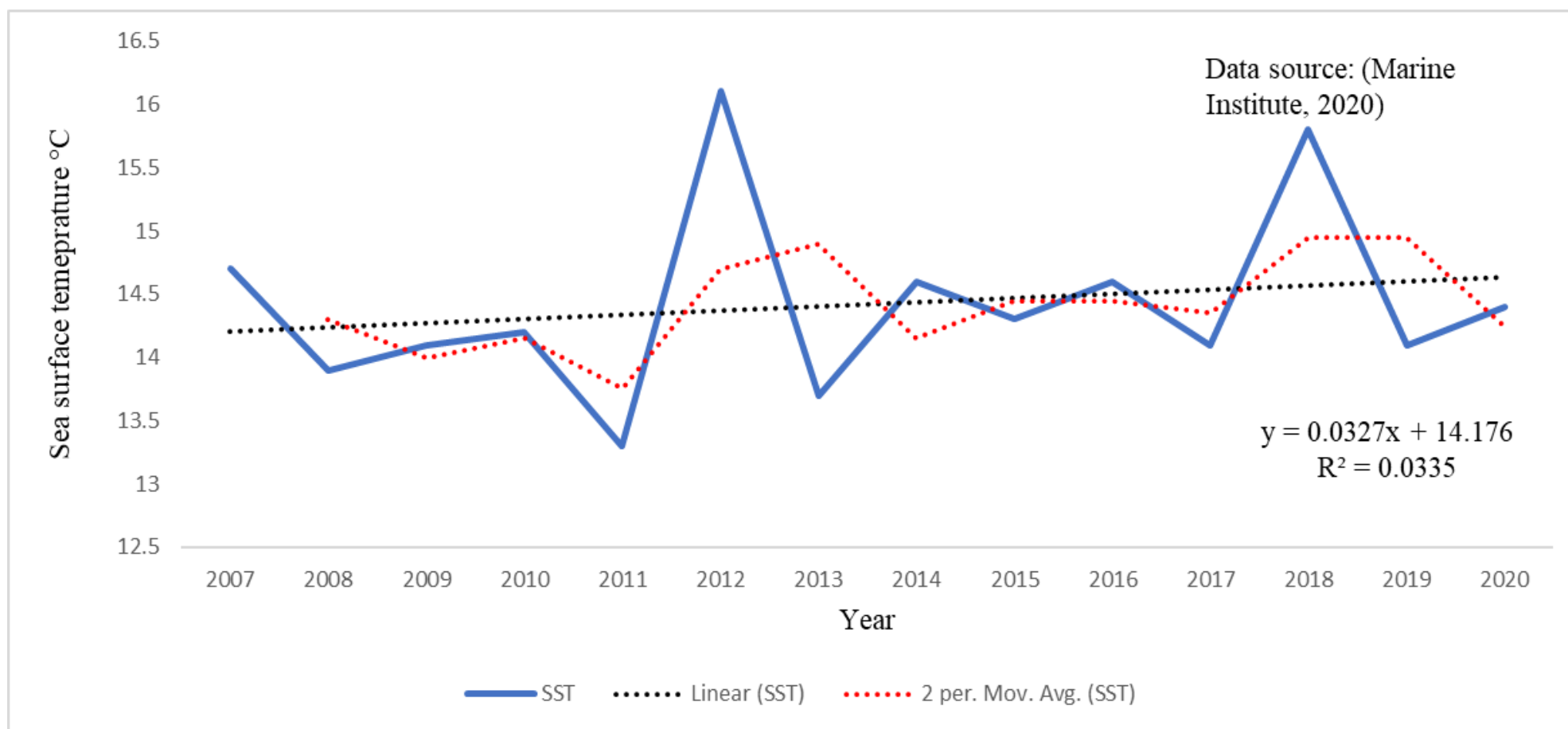


Figure 22 Restored September SST variations M4.

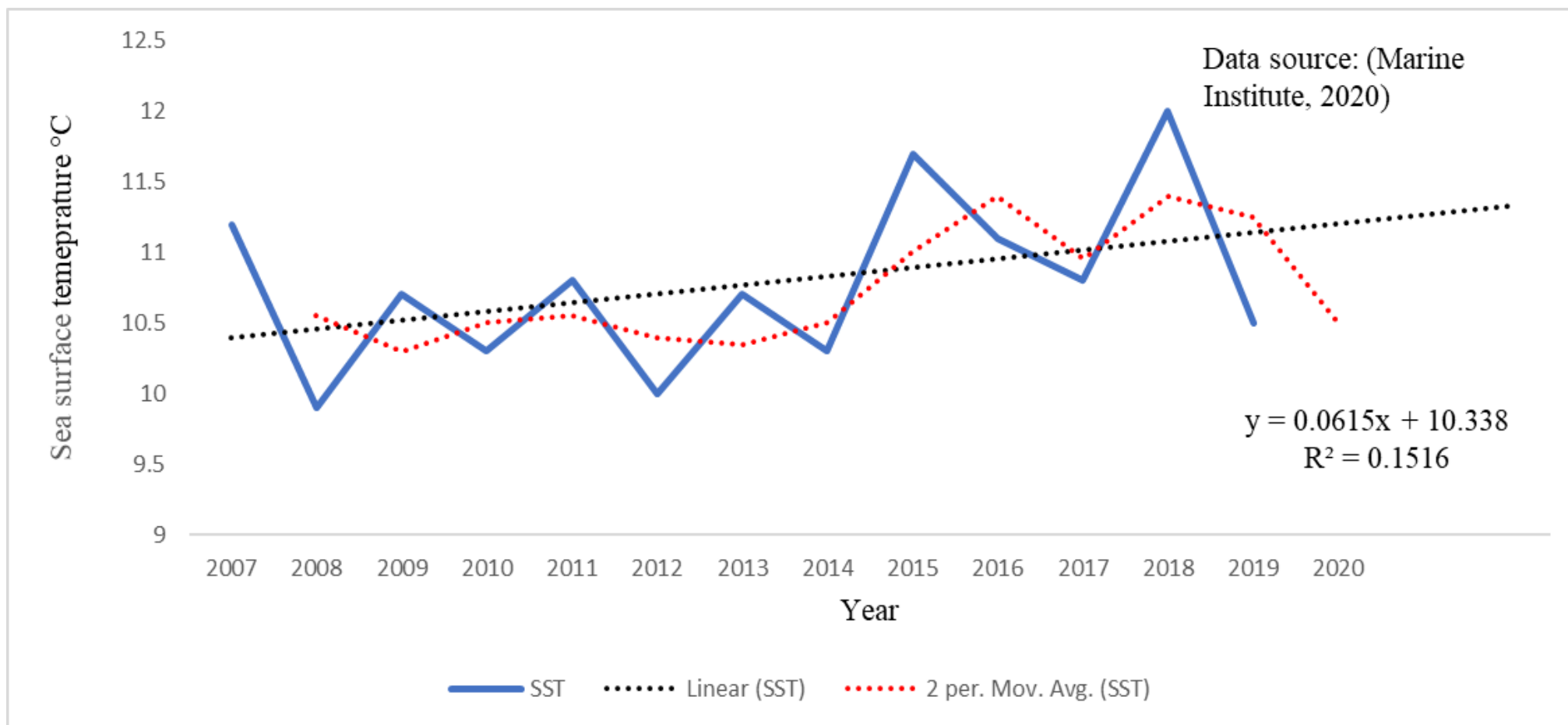


Figure 23 Restored December SST variations M4.

M5

M5 March SST variations

The maximum mean March SST was recorded in 2015, of 10.3°C. The minimum mean March SST was recorded in 2014, of 7.8°C. From 2005-2020 there was an overall increase in mean SST, based on the linear trendline. There were oscillating SST between 2005-2020. Between the minimum and maximum SST, there was an overall range in SST of, 2.5°C.

From 2005-2006 there was a decrease in mean March SST of 0.2°C, from 9°C to 8.8°C. Between 2006-2007 there was a increase in mean March SST, forming a oscillation, showing an increase of 0.6°C, from 8.8°C to 9.4°C. There was a stabilisation in SST between 2007-2008, showing a increase of 0.1°C, from 9.4°C to 9.5°C. Between 2008-2009 there was an oscillation in mean March SST, showing a decrease in SST of 0.8°C, from 9.5°C to 8.7°C. The oscillation in SST continued between 2009-2010, showing a continued decrease in SST, from 8.7°C to 8.3°C. From 2010-2011 SST increased to return to the mean SST prior to the oscillation. Between 2010-2011 there was a increase in SST of 0.3°C, from 8.3°C to 8.6°C. SST continued to increase from 2011-2012, showing an increase of 1.1°C, from 8.6°C to 9.7°C.

Between 2012-2013, there was another oscillation in SST showing a decrease of 1.1°C, to return to the SST of the previous year, prior to the oscillation in SST, from 9.7°C to 8.6°C. 2013-2014 recorded another oscillation in SST, showing a decrease of 0.8°C, from 8.6°C to 7.8°C. Between 2014-2015 the largest oscillation in SST was recorded showing an overall increase in mean SST of 2.5°C, from 7.8°C to 10.3°C.

From 2015-2016 there was a stabilisation in SST, recording a decrease in mean March SST of 0.4°C, from 10.3°C to 9.9°C. Between 2016-2017 there was a continued decrease in mean March SST of 0.3°C, from 9.9°C to 9.6°C. From 2017-2018 another SST oscillation was recorded, showing a decrease of 1.1°C, from 9.6°C to 8.5°C. From 2018-2019 there was another oscillation in SST, showing an increase of 0.6°C, from 8.5°C to 9.1°C. 2019-2020 there was a decrease in mean March SST of 0.4°C, from 9.1°C to 8.7°C. These variations in restored March SST for M5 are seen in figure 24.

M5 June SST variations

The maximum mean June SST was recorded in 2006 and 2018, of 15.1°C. The minimum mean SST for June, was recorded in 2015, of 12.3°C. From 2005-2020 there was an overall decrease in mean June SST, based on the linear trendline. There was a SST range of 2.8°C, between the minimum and maximum recorded SST. Overall, there was a high range of SST oscillations, apart from 2011-2014, which showed a stabilisation in SST.

From 2005-2006 there was a increase in mean June SST of 0.6°C, from 14.5°C to 15.1°C, forming the first oscillation in SST. Between 2006-2007 there was a decrease in mean June SST of, 0.3°C, from 15.1°C to 14.8°C. From 2007-2008 there was another oscillation in SST of 1.1°C, from 14.8°C to 13.7°C. Following this SST oscillation, there was a increase in mean June SST of 0.4°C, from 13.7°C to 14.1°C, between 2008-2009. SST continued to ly increase from 2009-2010, showing an increase of 0.7°C, from 14.1°C to 14.8°C.

From 2010-2011 there was another SST oscillation, showing a decrease of 1.4°C, from 14.8°C to 13.4°C. Between 2011-2014 there was a stabilisation in SST, recording no variation in SST from 2011-2012, with mean June SST remaining at 13.4°C. There was another decrease of 0.1°C, from 13.4°C to 13.3°C, continuing the stabilisation in SST.

From 2013-2014 there was a increase in mean June SST of 0.3°C, from 13.3°C to 13.6°C. Another SST oscillation was recorded between 2014-2015, recording a decrease in mean June SST of 1.3°C, from 13.6°C to 12.3°C. Following this oscillation, there was a subsequent increase in SST of 1.8°C, from 12.3°C to 14.1°C, between 2015-2016. From 2016-2017 there was a stabilisation in SST, recording a decrease in mean June SST of 0.1°C, from 14.1°C to 14°C.

From 2017-2018 there was another oscillation in mean June SST of 1.1°C, from 14°C to 15.1°C. Following this oscillation, there was a subsequent decrease in mean June SST of 2°C, from 15.1°C to 13.1°C, recording the largest oscillation in SST. From 2019-2020 there was a increase in mean June SST of 0.7°C, from 13.1°C to 13.8°C. These variations in restored June SST for M5 are seen in figure 25.

M5 September SST variations

The maximum mean September SST was recorded in 2014 of 15.9°C. The minimum mean September SST was recorded in 2015, of 14.3°C. From 2005-2020 there was an overall decrease in mean September SST for M5, based on the linear trendline. Overall, there was

oscillating mean SST from 2005-2020. Overall, there was a range of 1.6°C, between the minimum and maximum SST.

From 2005-2006 there was a decrease in mean September SST of 0.3°C, from 15.8°C to 15.5°C. There was a stabilisation in SST between 2006-2007, recording no change from 15.3°C mean SST between these years. Between 2007-2008 there was a decrease in mean September SST of 0.5°C, from 15.5°C to 15°C, forming the first notable oscillation in SST. Following this there was a increase of 0.1°C, from 2008-2009, of 0.1°C, from 15°C to 15.1°C. From 2009-2010 there was a decrease in mean SST of 0.1°C, from 15.1°C to 15°C. Between 2010-2011 there was another oscillation in SST, recording a decrease of 0.4°C, from 15°C to 14.5°C.

From 2011-2012 there was another oscillation in SST, recording an increase of 0.8°C, from 14.6°C to 15.4°C. Between 2012-2013 there was a stabilisation in SST, recording a increase of 0.1°C, from 15.4°C to 15.5°C. From 2013-2014 there was a increase of 0.4°C, from 15.5°C to 15.9°C.

From 2014-2015 there was another oscillation in SST, showing a decrease in mean September SST of 1.6°C, from 15.9°C to 14.3°C. Following this there was a subsequent increase in mean September SST of 0.5°C, from 14.3°C to 14.8°C. SST continued to increase from 2016-2017, recording an increase of 0.4°C, from 14.8°C to 15.2°C. From 2017-2018 there was a continued increase in mean September SST of 0.2°C, from 15.2°C to 15.4°C. Between 2018-2019 there was another oscillation in SST, showing a decrease in mean September SST of 0.7°C, from 15.4°C to 14.7°C. Another oscillation in SST was recorded between 2019-2020 of 0.6°C, from 14.7°C to 15.3°C. These variations in restored September SST for M5 are seen in figure 26.

M5 December SST variations

The maximum mean December SST was recorded in 2015 of 11.8°C. The minimum mean December SST was recorded in 2008 and 2010 of 10.2°C. There was an overall decrease in mean December SST, for M5 based on the linear trendline. Between the minimum and maximum SST, there was an overall range in SST of 1.6°C.

Between 2004-2005 there was a decrease in mean December SST of 0.1°C, from 11.5°C to 11.4°C. From 2005-2006 there was a increase of 0.3°C, from 11.4°C to 11.7°C. Between 2006-2007 there was a decrease of 0.1°C, from 11.7°C to 11.6°C. From 2007-2008 the first

notable oscillation in SST was recorded, showing a decrease in mean December SST of 1.4°C, from 11.6°C to 10.2°C. Following this oscillation there was a subsequent increase in SST of 0.8°C, from 10.2°C to 11°C, between 2008-2009.

From 2009-2010 there was another oscillation in SST, recording a decrease in mean December SST of 0.8°C, from 2009-2010 mirroring the previous oscillation in SST. From 2010-2011 there was another subsequent oscillation in SST, recording an increase of 0.9°C, from 10.2°C to 11.1°C. From 2011-2012 there was another oscillation in SST, recording a decrease of 0.6°C, from 11.1°C to 10.5°C.

Between 2012-2013 there was another oscillation in SST, recording an increase of 0.7°C, from 10.5°C to 11.2°C. This SST increase was continued between 2013-2014, recording an increase of 0.3°C, from 11.2°C to 11.5°C. This gradual increase was continued between 2014-2015, recording an increase of 0.3°C, from 11.5°C to 11.8°C.

Between 2015-2016 there was a decrease in mean December SST of 0.8°C, from 11.8°C to 11°C, forming another oscillation in SST. Following this, there was a stabilisation in SST between 2016-2017, recording no change in mean December SST, with SST remaining at 11°C. From 2017-2018 there was another oscillation in SST, recording an increase of 0.6°C, from 11°C to 11.6°C. From 2019-2020 there was another oscillation in SST, recording a decrease in mean December SST of 1.3°C, from 11.6°C to 10.3°C. These variations in restored December SST for M5 are seen in figure 27.

M6

M6 March SST variations

The maximum mean March SST was recorded in 2011 of 11.6°C. The minimum mean March SST was recorded in 2014 of 8.5°C. From 2007-2020 there was an overall decrease in mean March SST for M6, based on the linear trendline. Between the minimum and maximum mean March SST, there was an overall SST range of 3.1°C.

From 2007-2008 there was an increase in mean March SST of 0.4°C, from 10.4°C to 10.8°C. There was a continued increase in mean March SST of 0.5°C, from 2008-2009. In 2009-2010 there was an oscillation in SST, recording a decrease in SST of 0.7°C, from 11.3°C to 10.6°C. Following this oscillation, there was a subsequent increase in mean March SST, of 1°C, from 10.6°C to 11.6°C, from 2010-2011.

From 2011-2012 there was a decrease in mean March SST of 0.7°C, from 11.6°C to 10.9°C. There was a continued decrease in SST from 2012-2013 of 0.3°C, from 10.9°C to 10.6°C. Between 2013-2014 there was a significant oscillation in SST, recording a decrease of 2.1°C, from 10.6°C to 8.5°C. Following this oscillation, there was a subsequent increase in mean March SST, to recover to a similar SST of the previous year, recording an increase of 1.9°C, from 8.5°C to 10.4°C, between 2014-2015.

From 2015-2016 there was another oscillation in SST, recording a decrease in mean March SST of 0.7°C, from 10.4°C to 9.7°C. Between 2016-2017 there was a subsequent increase in SST of 1.1°C, from 9.7°C to 10.8°C. From 2017-2018 there was a decrease in mean SST of 0.2°C, from 10.8°C to 10.6°C. Between 2018-2019 there was a continued decrease of 0.3°C, from 10.6°C to 10.3°C. From 2019-2020 there was an increase in mean March SST of 0.2°C, from 10.3°C to 10.5°C. Between 2017-2020 there was a relative stabilisation in mean March SST, compared to the oscillating SST of 2007-2017. These variations in restored March SST for M6 are seen in figure 28.

M6 June SST variations

The maximum mean June SST was recorded in 2010 of 14.2°C. The minimum mean June SST was recorded in 2011, of 12.4°C. From 2007-2020 there was an overall decrease in mean June SST, based on the linear trendline. Between the minimum and maximum mean June SST, there was an SST range of 1.8°C.

From 2007-2008 there was an oscillation in SST, recording an increase in mean June SST of 0.9°C between these years, from 13°C to 13.9°C. Between 2008-2009 there was a subsequent oscillation, recording a decrease in mean June SST of 0.6°C, from 13.9°C to 13.3°C. From 2009-2010 there was another oscillation in SST, recording an increase in mean June SST of 0.9°C, from 13.3°C to 14.2°C.

Between 2010 there was another SST oscillation, recording a mean June SST decrease of 1.8°C, from 14.2°C to 12.4°C making this the largest oscillation in mean June SST. From 2011-2012 there was another oscillation in SST, recording an increase of 0.9°C, from 12.4°C to 13.3°C. A subsequent decrease in mean June SST was recorded between 2012-2013, of 0.7°C, from 13.3°C to 12.6°C.

From 2013-2014 there was another oscillation in SST, recording an increase in mean June SST of 0.9°C, from 12.6°C to 13.5°C. From 2014-2015 there was a decrease in mean June

SST of 0.3°C, from 13.5°C to 13.2°C. From 2015-2016 there was a increase in mean June SST of 0.4°C, from 13.2°C to 13.6°C, recovering to a similar SST of the previous year.

From 2016-2017 there was a decrease in mean June SST of 0.5°C, from 13.6°C to 13.1°C, forming another oscillation in SST. From 2017-2018 there was an oscillation in SST, recording an increase of 0.9°C, from 13.1°C to 14°C. From 2018-2019 there was another oscillation in SST, recording a decrease in mean June SST of 1.1°C, from 14°C to 12.9°C. Between 2019-2020 there was a increase in mean June SST of 0.1°C, from 12.9°C to 13°C. These variations in restored June SST for M6 are seen in figure 29.

M6 September SST variations

The maximum mean September SST was recorded in 2014 of 17.4°C. The minimum mean SST was recorded in 2018 of 13.9°C. From 2007-2020 there was an overall decrease in mean September SST, based on the linear trendline. There were oscillations in SST recorded, between 2007-2020, however, there was a stabilisation of SST between 2011-2012, with no change recorded in the mean September SST. Between the minimum and maximum SST, there was an overall SST range of 3.5°C.

Between 2007-2008 there was an oscillation in SST, showing a decrease of 1.2°C, from 15.5°C to 14.3°C. Between 2008-2009 there was a increase in mean September SST, recording an increase of 0.3°C to 14.3°C to 14.6°C. There was a continued increase of mean September SST between 2009-2010, recording an increase of 1.3°C, from 14.6°C to 15.9°C, marking another oscillation in SST. From 2010-2011 there was another oscillation in SST, recording a decrease of 1.3°C, from 15.9°C to 14.6°C, to return to the previous year's mean September SST.

From 2011-2012 there was a stabilisation in SST, recording no variation in SST, remaining at 14.6°C. From 2012-2013 there was another oscillation in SST, recording an increase of 0.7°C, from 14.6°C to 15.3°C. Between 2013-2014 there was another oscillation in SST, recording a significant increase in SST of 2.1°C, from 15.3°C to 17.4°C. From 2014-2015 there was a subsequent significant decrease in mean September SST, similar to the previous oscillation of 2.4°C, from 17.4°C to 15°C.

From 2015-2016 there was a increase in mean September SST, recording a increase of 0.5°C, from 15°C to 15.5°C. Between 2016-2017 there was a increase of 0.6°C, from 15.5°C to 14.9°C, resulting in a oscillation in SST. From 2017-2018 there was a continued decrease of

mean September SST, recording a decrease of 1°C, from 14.9°C to 13.9°C. Between 2018-2019 there was another oscillation in SST, recording an increase of 1.6°C, from 13.9°C to 15.5°C. From 2019-2020 there was a decrease in mean September SST of 0.6°C, from 15.5°C to 14.9°C. These variations in restored September SST for M6 are seen in figure 30.

M6 December SST variations

The maximum mean March SST was recorded in 2014 of 12.9°C. The minimum mean March SST was recorded in 2012 of 11.1°C. From 2006-2020 there was an overall decrease in mean March SST, based on the linear trendline. Between the minimum and maximum mean annual SST variations there was an overall range of 1.8°C.

From 2006-2007 there was a increase in mean SST of 0.6°C, from 11.6°C to 12.2°C, forming the first oscillation in SST. There was a subsequent decrease in SST following the oscillation in SST, between 2007-2008, of 0.5°C, from 12.2°C to 11.7°C. Between 2008-2009 there was a increase in mean SST of 0.1°C, from 11.7°C to 11.8°C.

From 2009-2010 there was another oscillation in SST, recording a decrease of 0.4°C from 11.8°C to 11.4°C. Following this oscillation, there was a subsequent increase in mean March SST of 0.8°C, from 11.4°C to 12.2°C, between 2010-2011. There was a subsequent SST decrease following this, between 2011-2012, recording a decrease of 1.1°C, from 12.2°C to 11.1°C.

Between 2012-2013 there was a increase in mean March SST of 0.2°C, from 11.1°C to 11.3°C. Between 2013-2014 there was a significant oscillation, recording an increase in mean March SST of 1.6°C, from 11.4°C to 12.9°C. From 2014-2015 there was a subsequent decrease in mean March SST of 0.7°C, from 12.9°C to 12.2°C. SST continued to decrease between 2015-2016, of 0.7°C, from 12.2°C to 11.5°C. From 2016-2017 there was another oscillation in SST, recording an increase in mean March SST of 0.7°C, from 11.5°C to 12.2°C, recovering to the previous oscillations mean SST value. From 2017-2018 there was another oscillation in SST, recording a decrease in mean March SST of 1°C, from 12.2°C to 11.2°C. Between 2019-2020 there was a increase in mean March SST of 0.2°C, from 11.2°C to 11.4°C. These variations in restored December SST for M6 are seen in figure 31.

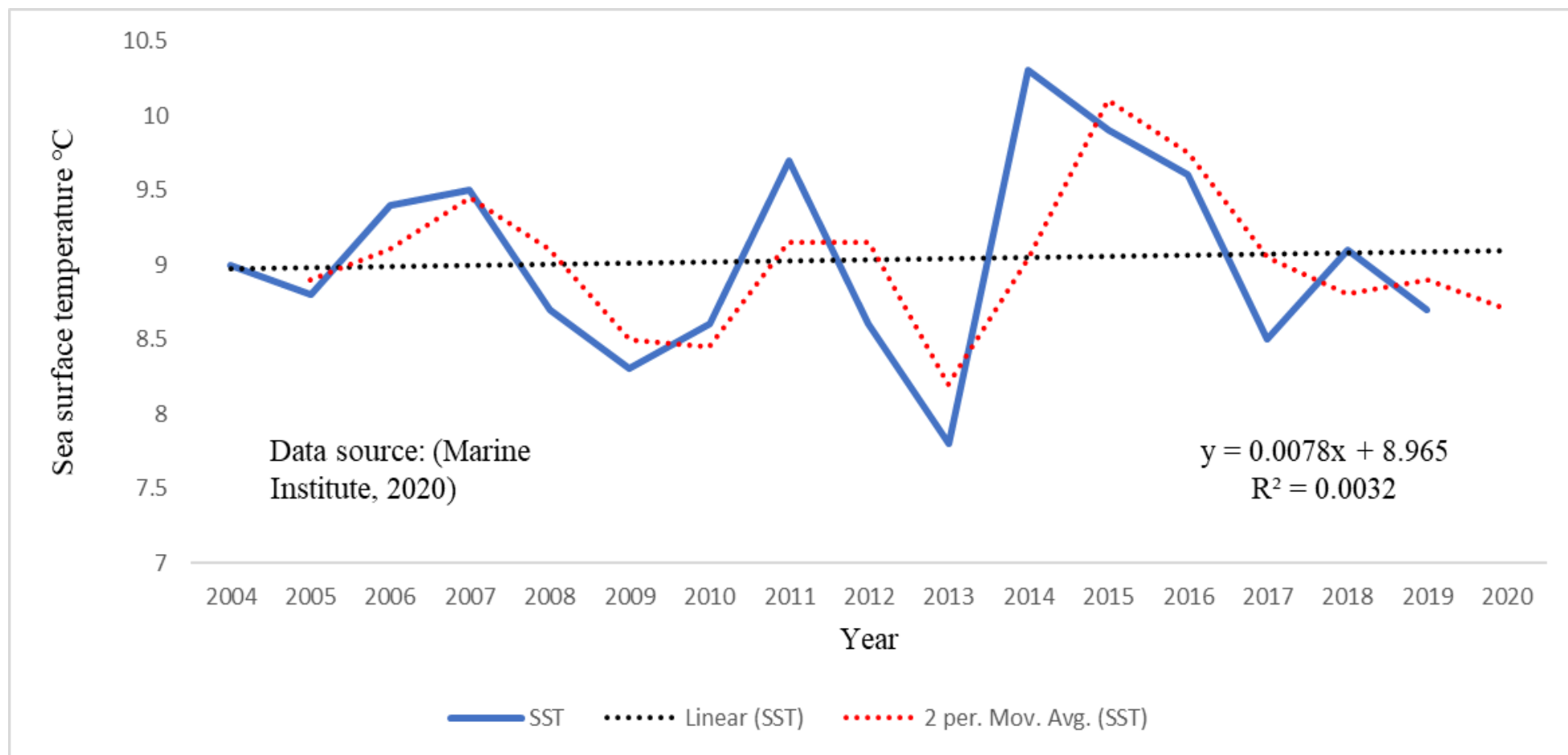


Figure 24 Restored March SST variations M5.

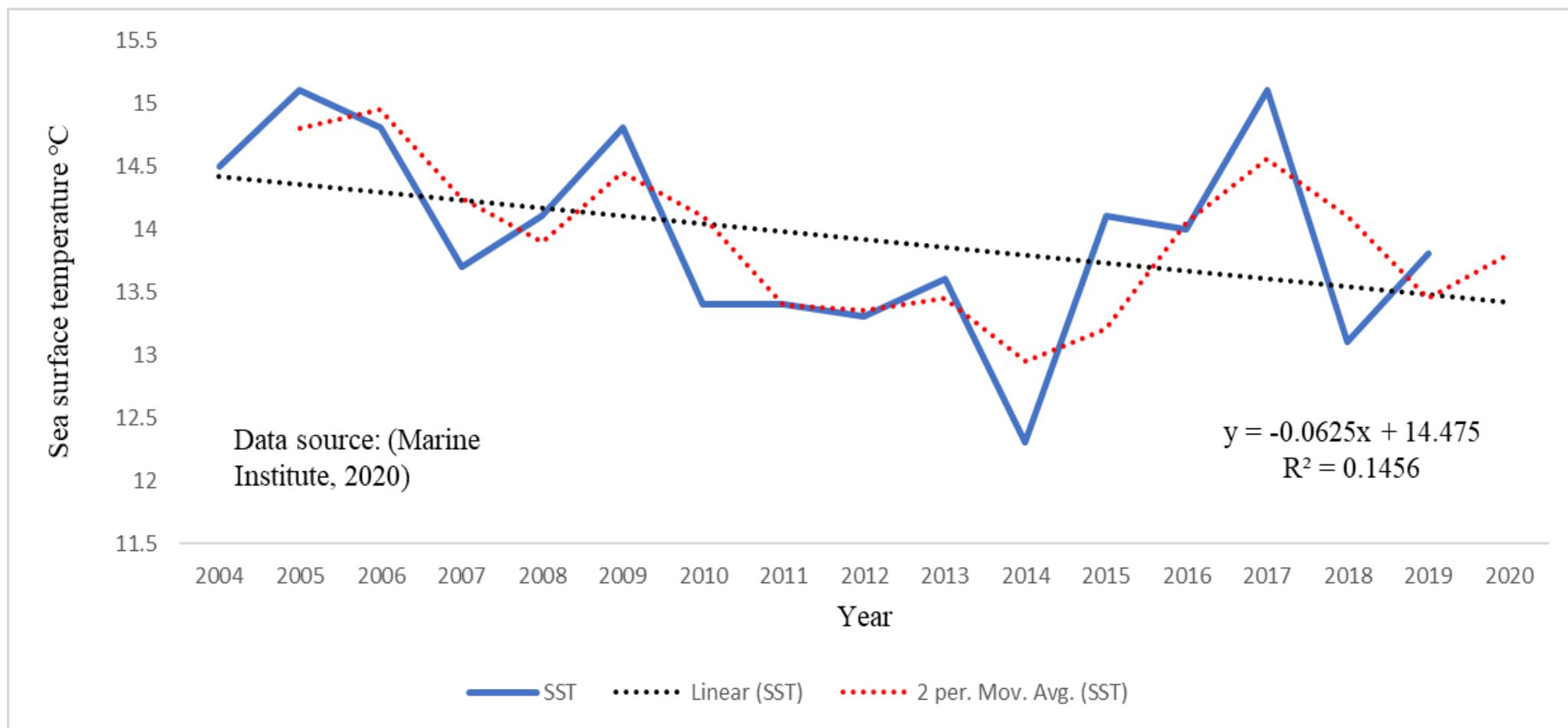


Figure 25 Restored June SST variations M5.

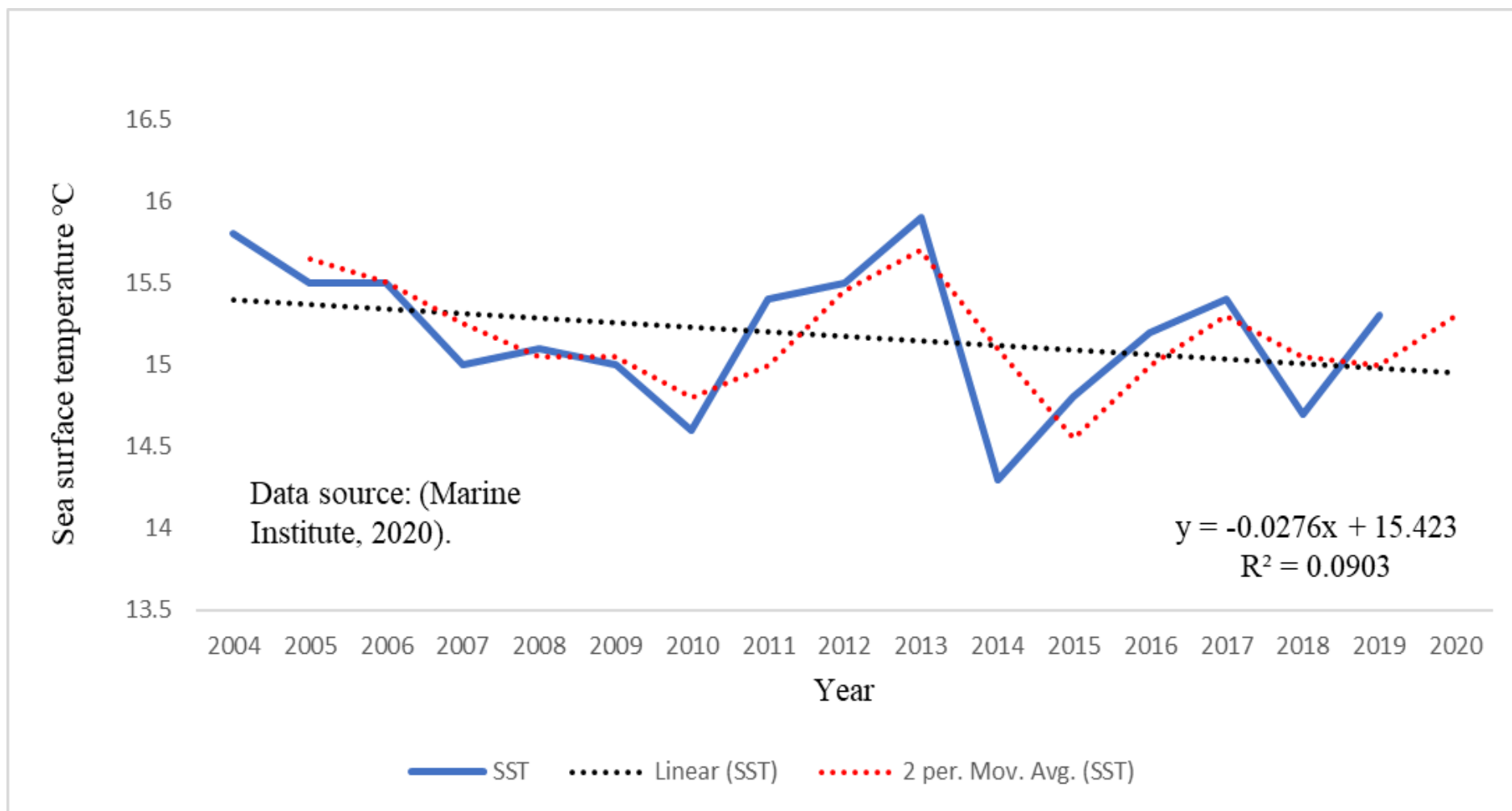


Figure 26 Restored September SST variations M5.

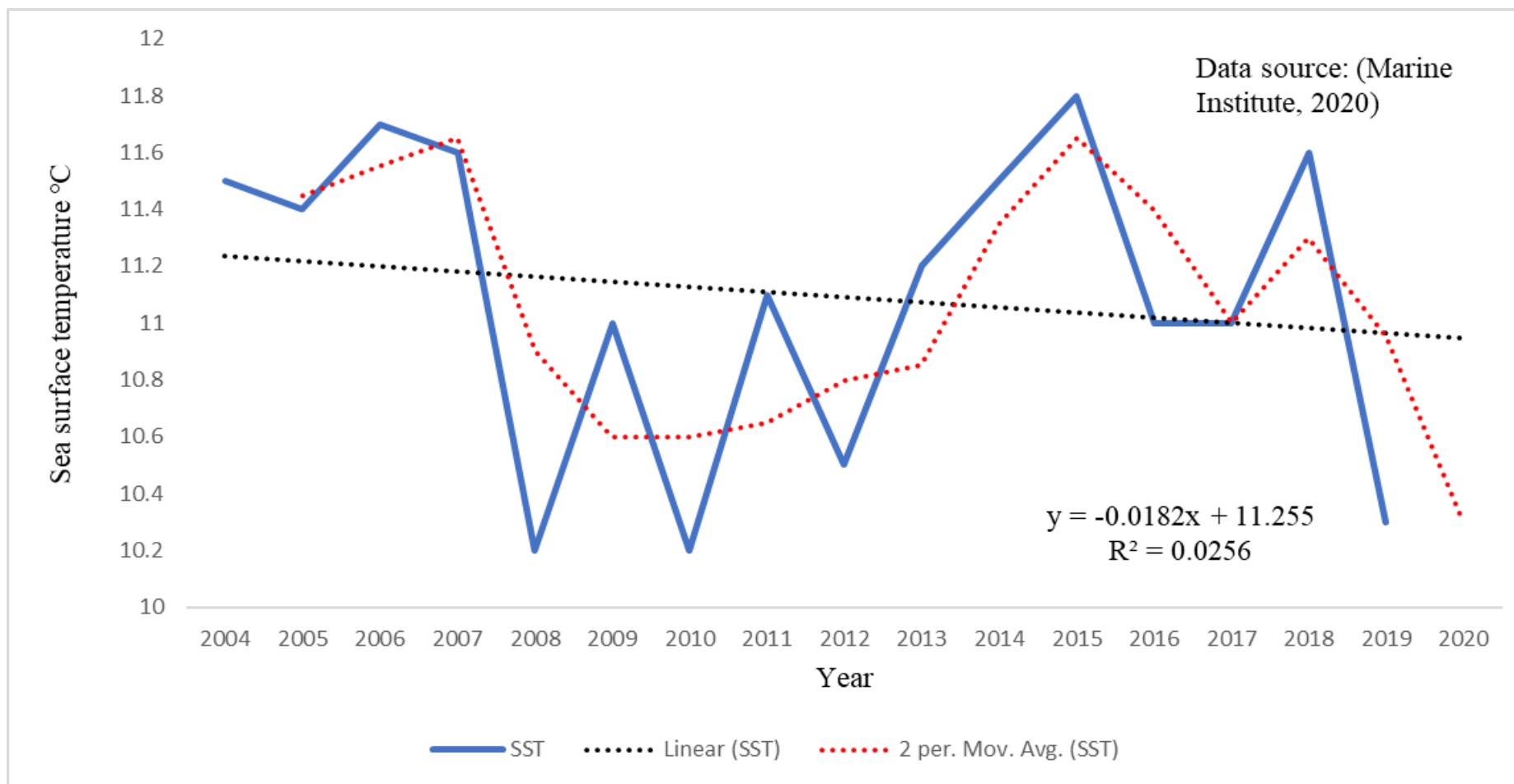


Figure 27 Restored December SST variations M5.

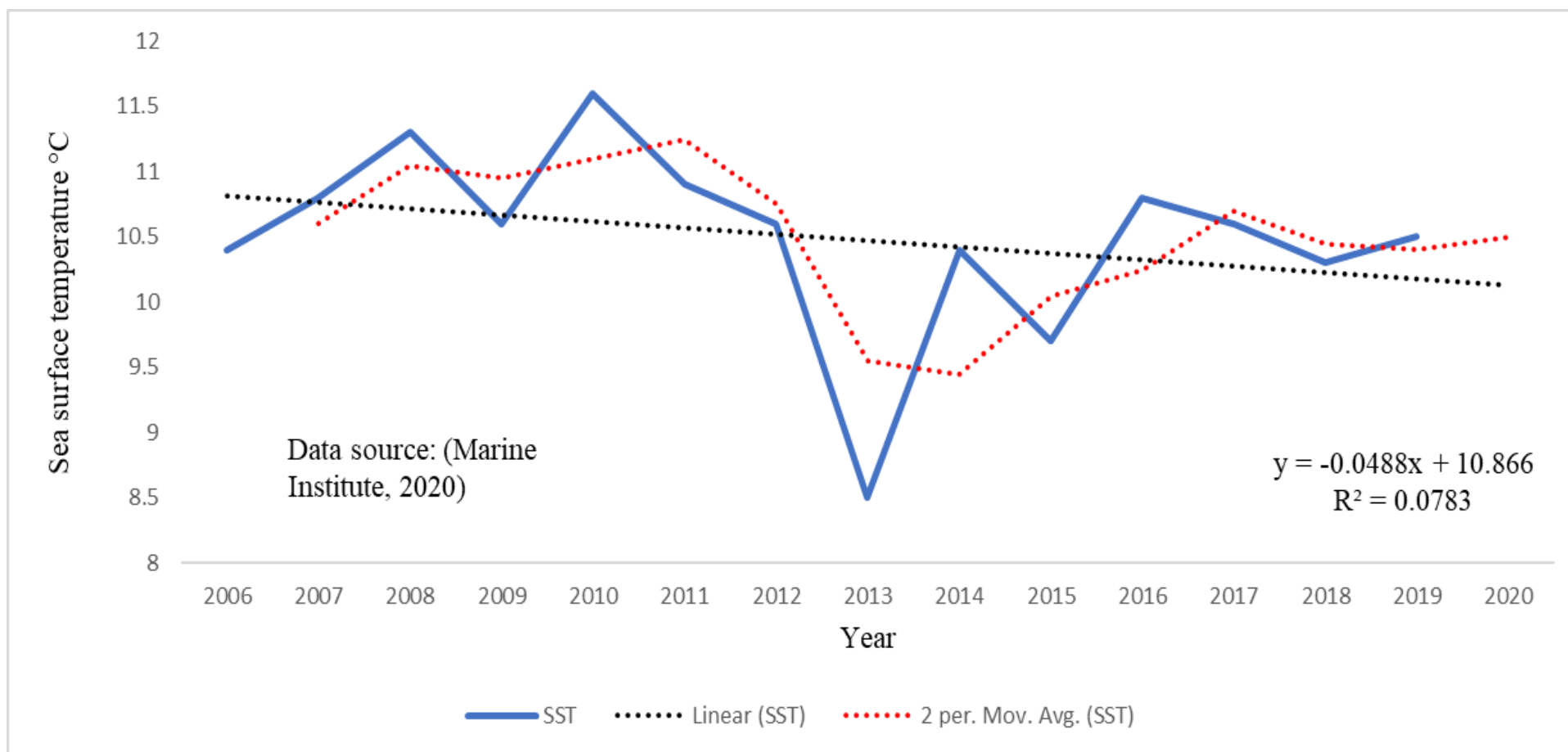


Figure 28 Restored March SST variations M6.

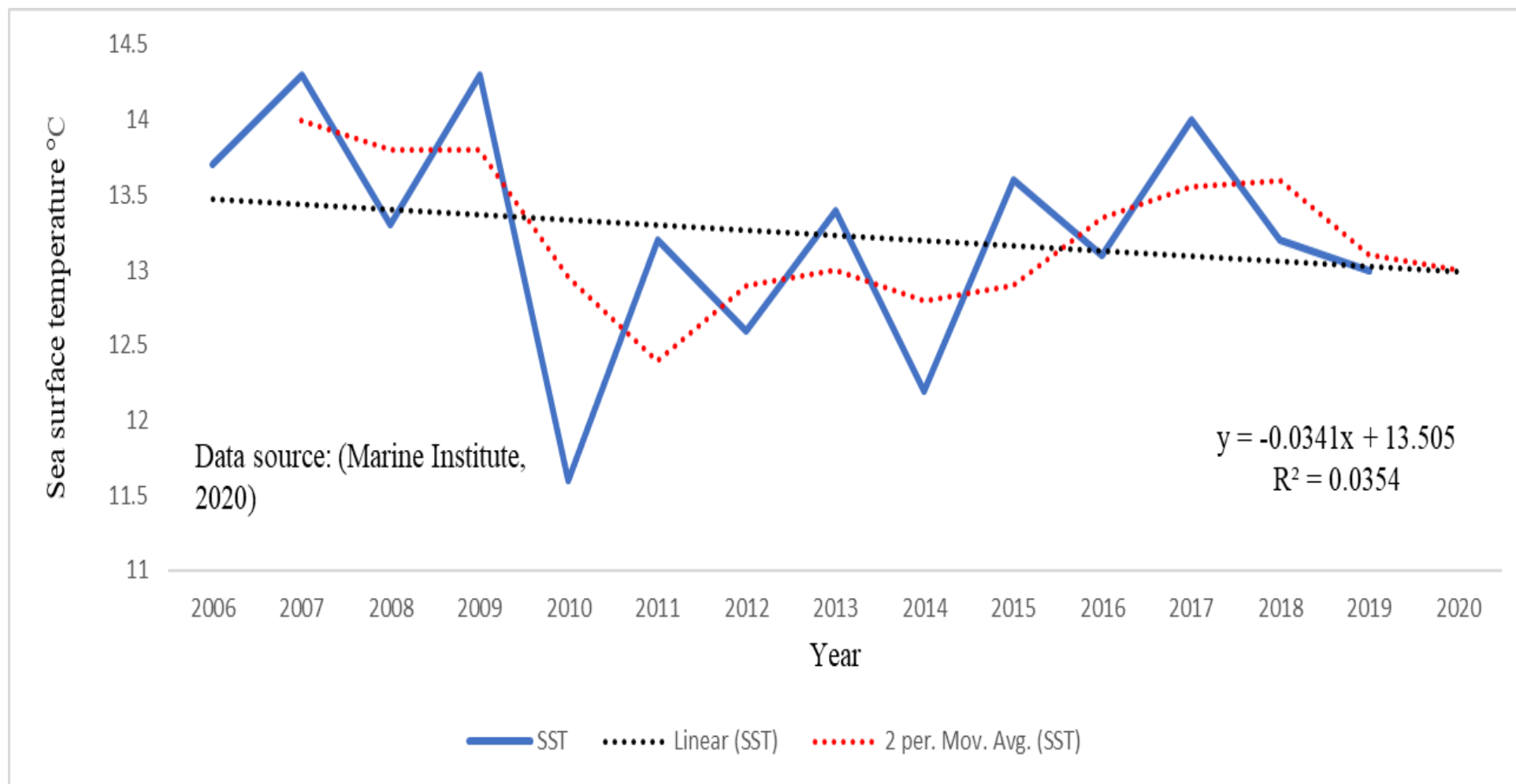


Figure 29 Restored June SST variations M6.

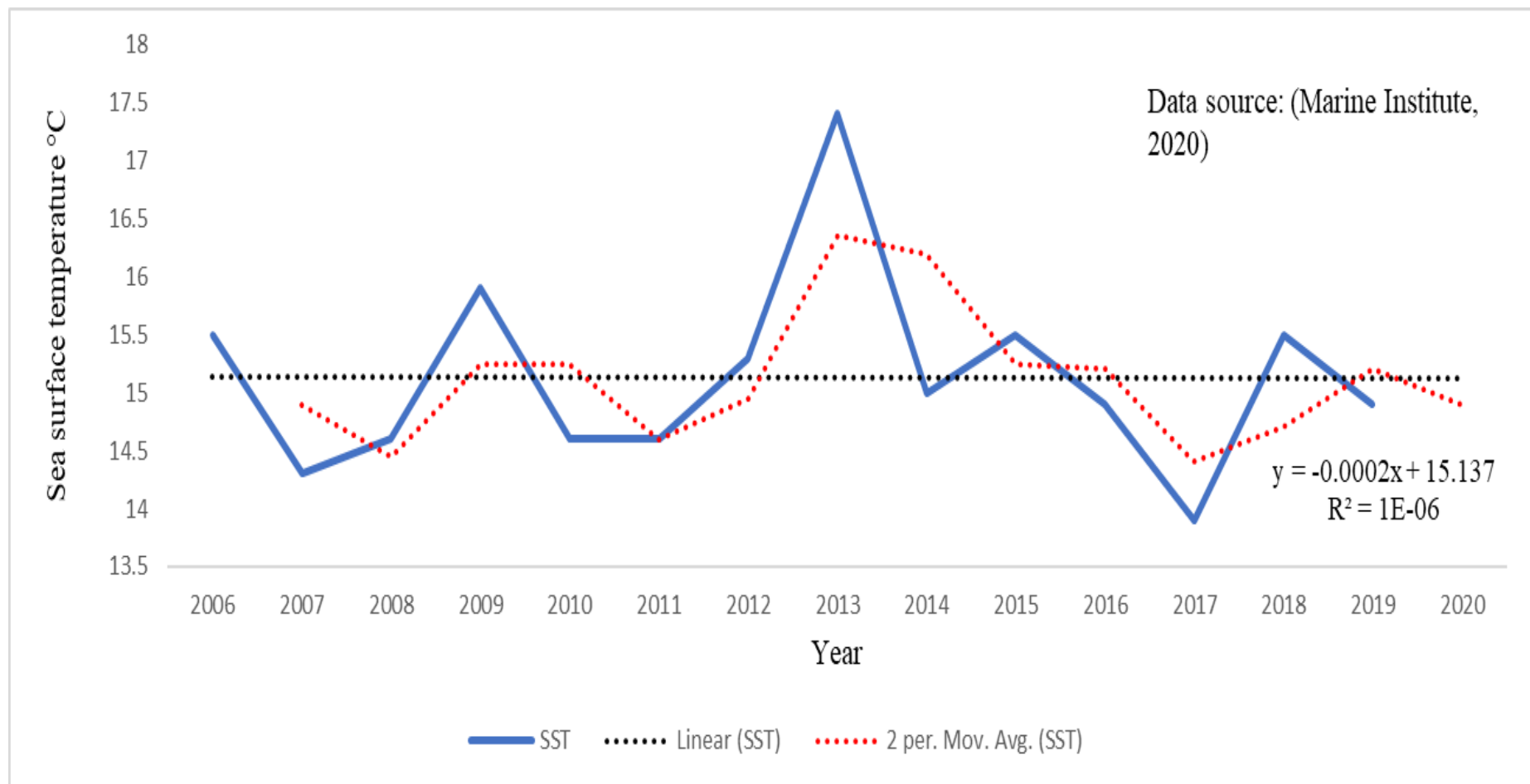


Figure 30 Restored September SST variations M6.

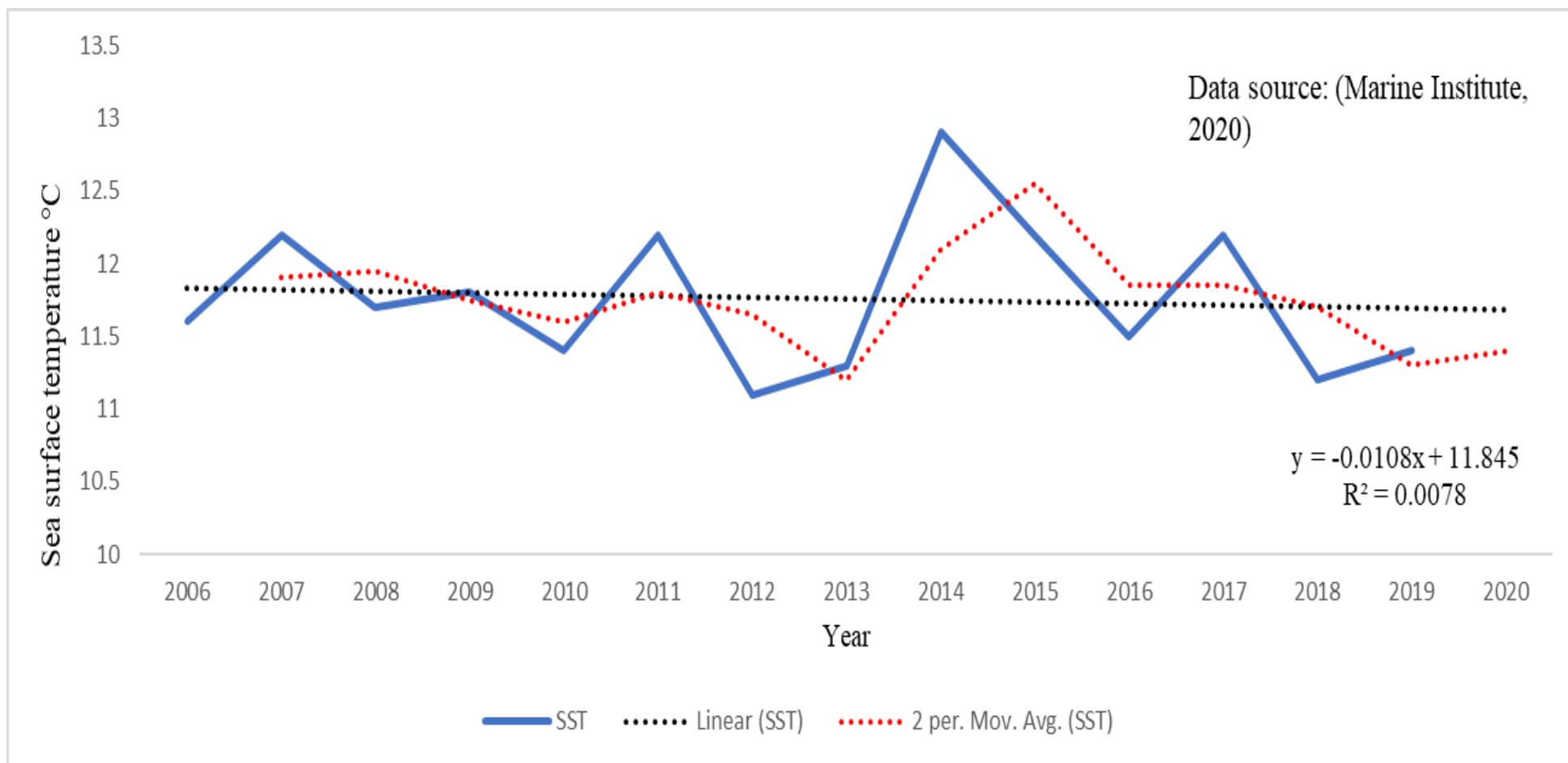


Figure 31 Restored December SST variations M6.

Chapter 5 Analysis

5.1 Extreme annual SST events

M2

From 2002-2010 there were oscillations in SST that were of a higher SST than the oscillations in SST from 2010-2020. The oscillations in SST from 2002-2010 show a lower range of SST increases and decreases compared to the oscillations from 2011-2020, which displayed more pronounced SST increases and decreases. From 2014-2015 the joint largest oscillation in SST was recorded showing a decrease in SST of 0.6°C, from 11.7°C to 11.1°C. Following this oscillation there was a subsequent increase in SST from 2015-2016 of 0.5°C, from 11.1°C to 11.6°C. Another oscillation was recorded between 2017-2018, showing a SST decrease of 0.6°C, from 11.9°C to 11.3°C, making this the same oscillation variation as the 2014-2015 oscillation. Overall, compared to the other buoys, there was a relatively low range in SST variations, see figure 7

Analysis of the mean air temperature for 2014-2015 showed that no air temperature data was recorded from 01/01/2014 until the 28/10/21 for 2014. From the 28/10/14 until the 31/12/14, the mean average air temperature was 10.5°C. The mean air temperature for 2015, was 10.6°C. 2015 is missing less than 10% of air temperature data, resulting in an accurate representation of the actual mean air temperature. There is little variation in annual mean air temperature between 2014-2015 however the missing air temperature for 2014 would need to be assessed to accurately conclude this. The little variation in air temperature could not solely have influenced the variations in mean SST witnessed. As part of the analysis, the maximum and minimum SST for M2 were identified. Table 12 shows the ten maximum SST recorded for M2 from 2002-2020, with the date and time that these maximum SST occurred.

Date and Time	SST in °C
17/07/2013 20:00	19.1
17/07/2013 19:00	19.0
17/07/2013 13:00	19.0
17/07/2013 16:00	19.0
17/07/2013 17:00	18.9
18/07/2013 15:00	18.9
17/07/2013 18:00	18.9
17/07/2013 22:00	18.9
17/07/2013 23:00	18.9
18/07/2013 16:00	18.9

Table 12 The maximum hourly recorded SST values for M2.

Table 13 shows the ten minimum SST recorded for M2 and the date and time at which they occurred.

Date and Time	SST in °C
27/12/2009 07:00	6.7
30/03/2013 06:00	6.7
31/03/2013 08:00	6.6
31/03/2013 09:00	6.6
31/03/2013 10:00	6.6
31/03/2013 11:00	6.6
31/03/2013 19:00	6.6
31/03/2013 23:00	6.6
31/03/2013 06:00	6.5
31/03/2013 07:00	6.5

Table 13 The minimum hourly recorded SST values for M2

Analysis was conducted for M2, of the variations in annual SST trends from one year to the next. Table 14 shows the SST values for each year, and the respective change in SST between one year to the next.

Years	SST Values	SST Variation in °C
2004-2005	11.7°C - 11.5°C	Decrease of 0.2°C.
2005-2006	11.6°C - 11.8°C	Increase of 0.2°C.
2007- 2008	11.9°C-11.6°C	Decrease of 0.3°C.
2009- 2010	11.5°C – 11.9°C	Increase of 0.4°C.
2010- 2011	11.9°C – 11.5°C	Decrease of 0.4°C.
2014-2015	11.7°C- 11.1°C	Decrease of 0.6°C.
2015- 2016	11.1°C – 11.6°C	Increase of 0.5°C.
2016- 2017	11.6°C- 11.9°C	Increase of 0.3°C.
2017-2018	11.9°C- 11.3°C	Decrease of 0.6°C.
2018-2019	11.3°C – 11.7°C	Increase of 0.4°C.

Table 14 The 10 largest annual SST changes for M2

M3

From 2002-2010 there were greater oscillations in SST, than from 2011-2020. The years 2004-2012 showed the greatest range of SST oscillations, showing more pronounced

increases and decreases than the oscillations from 2012-2020. From 2005-2008 there were only variations in SST, with the SST remaining relatively stable for these years. Following the stabilisation of SST there was a decrease in SST of 0.3°C, from 13°C to 12.7°C between 2007-2008. This decrease was the largest oscillation in SST recorded for M3 annual mean SST, see figure 8.

The annual mean air temperature for 2007 was 12.6°C. Overall, 2007 was missing 115 hours of air temperature data, totalling 1.3% of air temperature data missing for the year of 2007. The annual mean air temperature for 2008 was recorded at 12°C. Overall, M3 was missing 64 hours of recorded air temperature data, accounting for 0.7% of the overall air temperature data. As the most pronounced oscillation in SST was recorded between the years 2007-2008, the annual mean air temperature for these years was analysed to establish any correlation between air temperature and SST. As both the years 2007 and 2008 were missing less than 10% of air temperature data, the annual mean air temperatures can be used as an accurate parameter to assess any correlation between air temperature and SST. There was a decrease of 0.3°C in SST from 2007-2008. There was a decrease in the annual mean air temperature of 0.6°C. The decrease in SST could be associated with a corresponding decrease in mean annual air temperature. As part of the analysis, the maximum and minimum SST for M3 were identified. Table 15 shows the ten maximum SST recorded for M3 from 2003-2020, with the date and time that these maximum SST occurred.

Date and Time	SST in °C
26/07/2014 17:00	21.0
25/07/2014 17:00	21.0
25/07/2014 16:00	20.9
25/07/2014 20:00	20.9
25/07/2014 21:00	20.9
26/07/2014 20:00	20.9
26/07/2014 21:00	20.9
25/07/2014 22:00	20.9
25/07/2014 19:00	20.8
26/07/2014 19:00	20.8

Table 15 The maximum hourly recorded SST values for M3

Table 16 shows the ten minimum SST recorded for M3 and the date and time at which they occurred.

Date and Time	SST in °C
19/03/2020 02:00	7.9
19/03/2020 03:00	7.9
19/03/2020 04:00	7.9
19/03/2020 05:00	7.9
18/03/2020 01:00	7.9
19/03/2020 00:00	7.9
19/03/2020 01:00	7.9
19/03/2020 06:00	7.9
20/03/2020 00:00	7.9
20/03/2020 01:00	7.9

Table 16 The minimum hourly recorded SST values for M3

Analysis was conducted for M3, of the variations in annual SST trends from one year to the next. Table 17 shows the SST values for each year, and the respective change in SST between one year to the next.

Years	SST Values	SST Variation in °C
2004- 2005	12.8°C-13°C	Increase of 0.2°C.
2007- 2008	13°C- 12.7°C	Decrease of 0.3°C.
2009-2010	12.7°C- 13°C	Increase of 0.3°C.
2010- 2011	13°C- 12.9°C	Decrease of 0.1°C.
2011-2012	12.9°C- 12.8°C	Decrease of 0.1°C.
2012-2013	12.8°C – 12.9°C	Increase of 0.1°C.
2013-2014	12.9°C – 12.8°C	Decrease of 0.1°C.
2014-2015	12.8°C – 12.9°C	Increase of 0.1°C.
2015- 2016	12.9°C- 12.8°C	Decrease of 0.1°C.
2016-2017	12.8°C- 12.9°C	Increase of 0.1°C.

Table 17 The 10 largest annual SST changes for M3

M4

From 2008-2017 there were oscillations in SST. Between 2018-2020 there was a more pronounced oscillation in SST, showing an increase and subsequent decrease in SST. The largest SST oscillation recorded for M4 was recorded between 2017-2018 there was a SST increase of 0.9°C, see figure 9. As part of the analysis, the maximum and minimum SST for M4 were identified. Table 18 shows the ten maximum SST recorded for M4 from 2003-2020, with the date and time that these maximum SST occurred.

Date and Time	SST in °C
25/07/2014 22:00	20.2
26/07/2014 17:00	20.2
25/07/2014 17:00	20.2
25/07/2014 19:00	20.1
26/07/2014 19:00	20.1
25/07/2014 16:00	20.1
25/07/2014 20:00	20.1
25/07/2014 21:00	20.1
26/07/2014 20:00	20.1
26/07/2014 21:00	20.1

Table 18 The maximum hourly recorded SST values for M4

Table 19 shows the ten minimum SST recorded for M4 and the date and time at which they occurred.

Date and Time	SST in °C
20/03/2018 01:00	8.2
20/03/2018 02:00	8.2
13/06/2009 08:00	8.2
13/06/2009 09:00	8.2
15/02/2016 11:00	8.2
15/02/2016 12:00	8.2
08/03/2018 11:00	8.2
08/03/2018 12:00	8.2
13/06/2009 10:00	8.1
13/06/2009 07:00	7.8

Table 19 The minimum hourly recorded SST values for M4

Years	SST Values	SST Variation in °C
2011- 2012	11.8°C- 12.1°C	Increase of 0.3°C.
2012- 2013	12.1°C – 11.9°C	Decrease of 0.2°C.
2013- 2014	11.9°C- 12°C	Increase of 0.1°C.
2014- 2015	12°C- 12.2°C	Increase of 0.2°C.
2015-2016	12.2°C- 12.1°C	Decrease of 0.1°C.
2016- 2017	12.1°C- 12°C	Decrease of 0.1°C.

2017- 2018	12°C- 12.9°C	Increase of 0.9°C.
2018-2019	12.9°C- 12°C	Decrease of 0.1°C.

Table 20 The 8 largest annual SST changes for M4

Analysis was conducted for M4, of the variations in annual SST trends from one year to the next. Table 20 shows the SST values for each year, and the respective change in SST between one year to the next.

M5

Overall, there were oscillations in SST from 2008-2020. From 2008-2011 there were oscillations in SST, followed by a stabilisation in SST from 2012-2015. From 2016-2020 there were greater oscillations in SST, compared to the oscillations recorded in 2008-2011. The most pronounced annual mean SST decrease for M5 was recorded between 2018-2019. For these years, SST decreased by 0.6°C, see figure 10. As part of the analysis, the maximum and minimum SST for M5 were identified. Table 21 shows the ten maximum SST recorded for M5 from 2005-2020, with the date and time that these maximum SST occurred.

Date and Time	SST in °C
17/07/2014 22:00	19.6
17/07/2014 20:00	19.6
17/07/2014 19:00	19.6
17/07/2014 21:00	19.6
17/07/2014 18:00	19.6
17/07/2014 17:00	19.6
28/07/2014 19:00	19.5
28/07/2014 21:00	19.5
17/07/2014 23:00	19.5
28/07/2014 20:00	19.5

Table 21 The maximum hourly recorded SST values for M5

Table 22 shows the ten minimum SST recorded for M5 and the date and time at which they occurred.

Date and Time	SST in °C
27/02/2014 05:00	7.4
27/02/2014 06:00	7.4
27/02/2014 07:00	7.4
27/02/2014 08:00	7.4
27/02/2014 09:00	7.4
27/02/2014 10:00	7.4
26/02/2014 07:00	7.4
26/02/2014 08:00	7.4
26/02/2014 09:00	7.4
27/02/2014 02:00	7.4

Table 22 The minimum hourly recorded SST values for M5

Years	SST Values	SST Variation in °C
2008- 2009	11.9°C – 12.2°C	Increase of 0.3°C.
2011- 2012	12.1°C – 12.3°C	Increase of 0.2°C.

2015- 2016	12.3°C – 12.1°C	Decrease of 0.2°C.
2016- 2017	12.1°C – 12.5°C	Increase of 0.4°C.
2017- 2018	12.5°C – 12.6°C	Increase of 0.1°C.
2018-2019	12.6°C - 12°C	Decrease of 0.6°C.

Table 23 The 6 largest annual SST changes M5

Analysis was conducted for M5, of the variations in annual SST trends from one year to the next. Table 23 shows the SST values for each year, and the respective change in SST between one year to the next.

M6

Overall, there was oscillating SST from 2007-2020. Compared to M4 and M5 there were greater SST oscillations recorded. The joint largest oscillation in SST recorded a decrease of 0.5°C between 2011-2012. From 2017-2018 there was another SST oscillation, showing a decrease in SST of 0.5°C between these years, see figure 11. As part of the analysis, the maximum and minimum SST for M6 were identified. Table 24 shows the ten maximum SST recorded for M6 from 2007-2020, with the date and time that these maximum SST occurred.

Date and Time	SST in °C
01/10/2014 08:00	18.2
01/10/2014 09:00	18.2
01/10/2014 10:00	18.2
01/10/2014 11:00	18.2
27/07/2013 17:00	18.2
21/07/2014 21:00	18.2
21/08/2014 13:00	18.2
21/08/2014 15:00	18.2
17/07/2014 15:00	18.2
07/08/2014 01:00	18.2

Table 24 The maximum hourly recorded SST values for M6

Table 25 shows the ten minimum SST recorded for M6 and the date and time at which they occurred.

Date and Time	SST in °C
27/02/2014 05:00	8.0
27/02/2014 06:00	8.0
27/02/2014 07:00	8.0
27/02/2014 08:00	8.0
27/02/2014 09:00	8.0
27/02/2014 10:00	8.0
26/02/2014 07:00	8.0
26/02/2014 08:00	8.0
26/02/2014 09:00	8.0
27/02/2014 02:00	8.0

Table 25 The minimum hourly recorded SST values M6

Years	SST Values	SST Variation in °C
2008- 2009	12.7°C – 12.9°C	Increase of 0.2°C.
2009- 2010	12.9°C – 12.7°C	Decrease of 0.2°C.
2011- 2012	12.8°C – 12.3°C	Decrease of 0.5°C.
2012- 2013	12.3°C – 12.7°C	Increase of 0.4°C.
2013- 2014	12.7°C - 13°C	Increase of 0.3°C.
2014- 2015	13°C- 12.9°C	Decrease of 0.1°C.
2015- 2016	12.9°C- 12.5°C	Decrease of 0.4°C.
2016- 2017	12.5°C – 12.8°C	Increase of 0.3°C.
2017- 2018	12.8°C- 12.3°C	Decrease of 0.5°C.
2018-2019	12.3°C- 12.6°C	Increase of 0.3°C.

Table 26 The 10 largest annual SST changes for M6

Analysis was conducted for M6, of the variations in annual SST trends from one year to the next. Table 26 shows the SST values for each year, and the respective change in SST between one year to the next.

5.2 Analysis of spells in SST variations

M2

From 2002-2010 there were oscillations in SST that were of a higher SST than the oscillations in SST from 2011-2020. The oscillations in SST from 2002-2010 show a lower range of SST increases and decreases compared to the oscillations from 2011-2020, which displayed more pronounced SST increases and decreases. From 2014-2015 the joint largest variation in SST was recorded showing a decrease in SST of 0.6°C, from 11.7°C to 11.1°C. Following this, there was a subsequent increase in SST from 2015-2016 of 0.5°C, from 11.1°C to 11.6°C. Another oscillation was recorded between 2017-2018, showing a SST decrease of 0.6°C, from 11.9°C to 11.3°C, making this the same oscillation variation as the 2014-2015 oscillation. Overall, compared to the other buoys, there was a relatively low range in SST variations.

Analysis of the mean air temperature for 2014-2015 showed that no air temperature data was recorded from 01/01/2014 until the 28/10/21 for 2014. From the 28/10/14 until the 31/12/14, the mean average air temperature was 10.5°C. The mean air temperature for 2015, was 10.6°C. 2015 is missing less than 10% of air temperature data, resulting in an accurate representation of the actual mean air temperature. There is little variation in annual mean air temperature between 2014-2015 however the missing air temperature for 2014 would need to be assessed to accurately conclude this. The little variation in air temperature could not solely have influenced the variations in mean SST witnessed, see figure 7. To assess the impact of

the NAO on maximum and minimum recorded SST for M2, tables were created to determine the NAO Index value at that time of the maximum and minimum SST for M2. Table 27 shows that date and time of the maximum SST for M2 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
17/07/2013 20:00	19.1	0.67
17/07/2013 19:00	19.0	0.67
17/07/2013 13:00	19.0	0.67
17/07/2013 16:00	19.0	0.67
17/07/2013 17:00	18.9	0.67
18/07/2013 15:00	18.9	0.67
17/07/2013 18:00	18.9	0.67
17/07/2013 22:00	18.9	0.67
17/07/2013 23:00	18.9	0.67
18/07/2013 16:00	18.9	0.67

Table 27 The maximum hourly recorded SST values and corresponding NAO Index values for M2

Table 28 shows that date and time of the minimum SST for M2 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
27/12/2009 07:00	6.7	0.95
30/03/2013 06:00	6.7	-1.61
31/03/2013 08:00	6.6	-1.61
31/03/2013 09:00	6.6	-1.61
31/03/2013 10:00	6.6	-1.61
31/03/2013 11:00	6.6	-1.61
31/03/2013 19:00	6.6	-1.61
31/03/2013 23:00	6.6	-1.61
31/03/2013 06:00	6.5	-1.61
31/03/2013 07:00	6.5	-1.61

Table 28 The minimum hourly recorded SST values and corresponding NAO Index values for M2

Years	SST Values	SST Variation in °C	NAO Index
2004-2005	11.7°C - 11.5°C	Decrease of 0.2°C.	(0.24) - (-0.27)
2005-2006	11.6°C - 11.8°C	Increase of 0.2°C.	(-0.27) - (-0.21)
2007- 2008	11.9°C-11.6°C	Decrease of 0.3°C.	(0.17) - (-0.37)
2009- 2010	11.5°C - 11.9°C	Increase of 0.4°C.	(-0.24) - (-1.15)
2010- 2011	11.9°C - 11.5°C	Decrease of 0.4°C.	(-1.15) - (0.29)
2014-2015	11.7°C- 11.1°C	Decrease of 0.6°C.	(0.18) - (0.43)
2015- 2016	11.1°C - 11.6°C	Increase of 0.5°C.	(0.43) - (-0.03)
2016- 2017	11.6°C- 11.9°C	Increase of 0.3°C.	(-0.03) - (0.40)
2017-2018	11.9°C- 11.3°C	Decrease of 0.6°C.	(0.40) - (1.08)
2018-2019	11.3°C - 11.7°C	Increase of 0.4°C.	(1.08) - (-0.31)

Table 29 The 10 largest annual SST changes and corresponding NAO Index values for M2

Table 29 shows the 10 greatest annual SST changes and corresponding NAO Index values for M2. This table analysed the mean annual NAO Index value for each of the annual variations

in SST for M2. The relatively low and consistent NAO Index values suggest there was a distinct signal, showing that there was little storm activity around the time of the maximum and minimum SST values for M2. This suggests that there was a consistent and undisturbed block of water surrounding Ireland, that was not mixed due to storm activity. To confirm this, analysis of the other atmospheric processes that influence SST were examined.

Analysis of two days before and two days after the maximum recorded SST from M2 were conducted, and the results are displayed in table 30. The maximum recorded SST for M2 were recorded on the 17/07/2013 and the 18/07/2013. Two days before the 17/07/2013, there was an increase in the wind speed and gust speed as shown below, however this would not be categorised as storm level gusts. The air temperature was lower in the two days preceding the 17th and 18th of March 2013. Atmospheric pressure was also lower, preceding the 17th and 18th. The two days after the maximum recorded SST for M2 on the 17th and 18th of March 2013 shows a decrease in both wind and gust speed, and a increase in mean air temperature, as seen in tables 31 and 32 . There was a decrease in mean atmospheric pressure in the two days following the 17th and 18th.

Analysis of two days before and two days after the minimum recorded SST from M2 was also conducted and the results are displayed in table 33. The minimum SST for M2 were recorded on 27/12/2009, 30/03/2013 and the 31/03/2013. There was an overall increase in the daily mean gust speed in the two days before and after the minimum recorded SST. There was also a increase in the daily mean atmospheric pressure for the two days before and after the 30th and 31st of March 2013, but not for the 27/12/2009. There was a decrease in daily mean air temperature for the two days before and after the minimum SST dates as seen in table 34. Overall, there appears to be a relationship with increased wind and gust speed, and air temperature on the maximum and minimum SST around Ireland's coastline, consistent with the NAO Index values. To assess this further, analysis of the location of the air mass and movement of the jet stream location, related to the NAO Index are assessed, coupled with the possible influence of tropical storm events and this analysis is discussed in chapter 6.

Date	Atmospheric pressure	Wind direction	Wind speed	Gust	Air temperature
15/07/13	1002.34 Pa	222°	6 m s ⁻¹	8 m s ⁻¹	11.2°C
16/07/13	1010.97 Pa	254°	4 m s ⁻¹	5 m s ⁻¹	11.3°C

17/07/13	1016.29 Pa	47°	4 m s ⁻¹	4 m s ⁻¹	11.6°C
18/07/13	1015.43 Pa	198°	1 m s ⁻¹	1 m s ⁻¹	12.9°C
19/07/13	1017.94 Pa	229°	2 m s ⁻¹	3 m s ⁻¹	12.7°C
20/07/13	1012.80 Pa	148°	2 m s ⁻¹	Not recorded	12.8°C

Table 30 The mean daily values for two days before and two days after the maximum SST values for M2

Date and Time	SST °C	Air temp °C
17/07/2013 20:00	19.1	11.8
17/07/2013 19:00	19.0	12.0
17/07/2013 13:00	19.0	12.1
17/07/2013 16:00	19.0	12.1
17/07/2013 17:00	18.9	12.1
17/07/2013 18:00	18.9	12.0
17/07/2013 22:00	18.9	12.6
17/07/2013 23:00	18.9	12.3

Table 31 The maximum SST and corresponding air temperature values for 17/07/2013 M2

Time	SST °C	Air Temp °C
15:00	18.9	14.9
16:00	18.9	14.7

Table 32 The maximum SST and corresponding air temperature values for 18/07/2013 M2

Date	Atmospheric pressure	Wind direction	Wind speed	Gust	Air temperature
25/12/2009	994.70 Pa	215°	5 m s ⁻¹	8 m s ⁻¹	6.7°C
26/12/2009	992.58 Pa	206°	7 m s ⁻¹	9 m s ⁻¹	8.2°C
27/12/2009	997.46 Pa	273°	9 m s ⁻¹	12 m s ⁻¹	4.7°C
28/03/2013	1015.81 Pa	100°	6 m s ⁻¹	8 m s ⁻¹	3.5°C
29/03/2013	1012.60 Pa	106°	6 m s ⁻¹	8 m s ⁻¹	3.2°C
30/03/2013	1014.27 Pa	108°	5 m s ⁻¹	7 m s ⁻¹	3.8°C
31/03/2013	1013.28 Pa	138°	6 m s ⁻¹	8 m s ⁻¹	4.4°C

01/04/2013	1012.82 Pa	114°	7 m s ⁻¹	9 m s ⁻¹	3.8°C
02/04/2013	1018.41 Pa	99°	7 m s ⁻¹	9 m s ⁻¹	4.5°C

Table 33 The mean daily values for two days before and two days after the minimum recorded SST values for M2

Date and Time	SST in °C	Air Temp °C
27/12/2009 07:00	6.7	5.8
30/03/2013 06:00	6.7	3.1
31/03/2013 08:00	6.6	3.8
31/03/2013 09:00	6.6	3.6
31/03/2013 10:00	6.6	3.5
31/03/2013 11:00	6.6	3.6
31/03/2013 19:00	6.6	5.2
31/03/2013 23:00	6.6	4.4
31/03/2013 06:00	6.5	4.1
31/03/2013 07:00	6.5	3.9

Table 34 The minimum SST and corresponding air temperature values for M2

M3

From 2002-2010 there were greater oscillations in SST, than from 2011-2020. The years 2004-2012 showed the greatest range of SST oscillations, showing more pronounced increases and decreases than the oscillations from 2012-2020. From 2005-2008 there were only variations in SST, with the SST remaining relatively stable for these years. Following the stabilisation of SST there was a decrease in SST of 0.3°C, from 13°C to 12.7°C between 2007-2008. This decrease was the largest oscillation in SST recorded for M3 annual mean SST.

The annual mean air temperature for 2007 was 12.6°C. Overall, 2007 was missing 115 hours of air temperature data, totalling 1.3% of air temperature data missing for the year of 2007. The annual mean air temperature for 2008 was recorded at 12°C. Overall, M3 was missing 64 hours of recorded air temperature data, accounting for 0.7% of the overall air temperature data. As the most pronounced oscillation in SST was recorded between the years 2007-2008, the annual mean air temperature for these years was analysed to establish any correlation between air temperature and SST. As both the years 2007 and 2008 were missing less than 10% of air temperature data, the annual mean air temperatures can be used as an accurate

parameter to assess any correlation between air temperature and SST. There was a decrease of 0.3°C in SST from 2007-2008. There was a decrease in the annual mean air temperature of 0.6°C. The decrease in SST could be associated with a corresponding decrease in mean annual air temperature, see figure 8. To assess the impact of the NAO on maximum and minimum recorded SST for M3, tables were created to determine the NAO Index value at that time of the maximum and minimum SST for M3. Table 35 shows that date and time of the maximum SST for M3 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
26/07/2014 17:00	21.0	0.18
25/07/2014 17:00	21.0	0.18
25/07/2014 16:00	20.9	0.18
25/07/2014 20:00	20.9	0.18
25/07/2014 21:00	20.9	0.18
26/07/2014 20:00	20.9	0.18
26/07/2014 21:00	20.9	0.18
25/07/2014 22:00	20.9	0.18
25/07/2014 19:00	20.8	0.18
26/07/2014 19:00	20.8	0.18

Table 35 The maximum hourly recorded SST values and corresponding NAO Index values for M3

Table 36 shows that date and time of the minimum SST for M3 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
19/03/2020 02:00	7.9	1.01
19/03/2020 03:00	7.9	1.01
19/03/2020 04:00	7.9	1.01
19/03/2020 05:00	7.9	1.01
18/03/2020 01:00	7.9	1.01
19/03/2020 00:00	7.9	1.01
19/03/2020 01:00	7.9	1.01
19/03/2020 06:00	7.9	1.01
20/03/2020 00:00	7.9	1.01
20/03/2020 01:00	7.9	1.01

Table 36 The minimum hourly recorded SST values and corresponding NAO Index values for M3

Years	SST Values	SST Variation in °C	NAO Index
2004- 2005	12.8°C-13°C	Increase of 0.2°C.	(0.24) – (-0.26)
2007- 2008	13°C- 12.7°C	Decrease of 0.3°C.	(0.17) – (-0.37)
2009-2010	12.7°C- 13°C	Increase of 0.3°C.	(-0.24) – (-1.15)
2010- 2011	13°C- 12.9°C	Decrease of 0.1°C.	(-1.15) – (0.29)
2011-2012	12.9°C- 12.8°C	Decrease of 0.1°C.	(0.29) – (-0.45)
2012-2013	12.8°C – 12.9°C	Increase of 0.1°C.	(-0.45) – (0.21)

2013-2014	12.9°C – 12.8°C	Decrease of 0.1°C.	(0.21) – (0.18)
2014-2015	12.8°C – 12.9°C	Increase of 0.1°C.	(0.18) - (0.43)
2015- 2016	12.9°C- 12.8°C	Decrease of 0.1°C.	(0.43) – (-0.03)
2016-2017	12.8°C- 12.9°C	Increase of 0.1°C.	(-0.03) – (0.22)

Table 37 The 10 largest annual SST changes and corresponding NAO Index values for M3

Table 37 shows the 10 greatest annual SST changes and corresponding NAO Index values for M3. This table analysed the mean annual NAO Index value for each of the annual variations in SST for M3.

The relatively low and consistent NAO Index values suggest there was a distinct signal, showing that there was little storm activity around the time of the maximum and minimum SST values for M2. This suggests that there was a consistent and undisturbed block of water surrounding Ireland, that was not mixed due to storm activity. To confirm this, analysis of the other atmospheric processes that influence SST would need to be examined however M3 was undergoing maintenance at the time and did not record the atmospheric data such as wind speed and gust speed at this time and therefore cannot be used in the analysis, however the influence of the NAO Index values on the SST around Ireland's coastline are discussed further in chapter 6.

M4

From 2008-2017 there were oscillations in SST. Between 2018-2020 there was a more pronounced oscillation in SST, showing an increase and subsequent decrease in SST. The largest SST oscillation recorded for M4 was recorded between 2017-2018 there was a SST increase of 0.9°C, see figure 9. To assess the impact of the NAO on maximum and minimum recorded SST for M4, tables were created to determine the NAO Index value at that time of the maximum and minimum SST for M4. Table 38 shows that date and time of the maximum SST for M4 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
25/07/2014 22:00	20.2	0.18
26/07/2014 17:00	20.2	0.18
25/07/2014 17:00	20.2	0.18
25/07/2014 19:00	20.1	0.18
26/07/2014 19:00	20.1	0.18
25/07/2014 16:00	20.1	0.18
25/07/2014 20:00	20.1	0.18
25/07/2014 21:00	20.1	0.18
26/07/2014 20:00	20.1	0.18
26/07/2014 21:00	20.1	0.18

Table 38 The maximum hourly recorded SST values and corresponding NAO Index values for M4

Table 39 shows that date and time of the minimum SST for M4 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
20/03/2018 01:00	8.2	-0.93
20/03/2018 02:00	8.2	-0.93
13/06/2009 08:00	8.2	-1.21
13/06/2009 09:00	8.2	-1.21
15/02/2016 11:00	8.2	1.58
15/02/2016 12:00	8.2	1.58
08/03/2018 11:00	8.2	-0.93
08/03/2018 12:00	8.2	-0.93
13/06/2009 10:00	8.1	-1.21
13/06/2009 07:00	7.8	-1.21

Table 39 The minimum hourly recorded SST values and corresponding NAO Index values for M4

Years	SST Values	SST Variation in °C	NAO Index
2011- 2012	11.8°C- 12.1°C	Increase of 0.3°C.	(0.29) – (-0.45)
2012- 2013	12.1°C – 11.9°C	Decrease of 0.2°C.	(-0.45) – (0.21)
2013- 2014	11.9°C- 12°C	Increase of 0.1°C.	(0.21) – (0.18)
2014- 2015	12°C- 12.2°C	Increase of 0.2°C.	(0.18) – (0.43)
2015-2016	12.2°C- 12.1°C	Decrease of 0.1°C.	(0.43) – (-0.03)
2016- 2017	12.1°C- 12°C	Decrease of 0.1°C.	(-0.03) – (0.22)
2017- 2018	12°C- 12.9°C	Increase of 0.9°C.	(0.22) – (1.08)
2018-2019	12.9°C- 12°C	Decrease of 0.1°C.	(1.08) – (-0.31)

Table 40 The 8 largest annual SST changes and the corresponding NAO Index values for M4

Table 40 shows the 10 greatest annual SST changes and corresponding NAO Index values for M4. This table analysed the mean annual NAO Index value for each of the annual variations in SST for M4. Analysis of the atmospheric parameters for the two days before and two days after the spells of maximum and minimum SST could not be assessed due to M4 not recording the atmospheric data at the respective times due to maintenance and repair issues, however other influencing factors and the influence of the NAO Index on these SST variations are discussed in Chapter 6.

M5

Overall, there were oscillations in SST from 2008-2020. From 2008-2011 there were oscillations in SST, followed by a stabilisation in SST from 2012-2015. From 2016-2020 there were greater oscillations in SST, compared to the oscillations recorded in 2008-2011. The most pronounced annual mean SST decrease for M5 was recorded between 2018-2019. For these years, SST decreased by 0.6°C, see figure 10. To assess the impact of the NAO on maximum and minimum recorded SST for M5, tables were created to determine the NAO

Index value at that time of the maximum and minimum SST for M5. Table 41 shows that date and time of the maximum SST for M5 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
17/07/2014 22:00	19.6	0.18
17/07/2014 20:00	19.6	0.18
17/07/2014 19:00	19.6	0.18
17/07/2014 21:00	19.6	0.18
17/07/2014 18:00	19.6	0.18
17/07/2014 17:00	19.6	0.18
28/07/2014 19:00	19.5	0.18
28/07/2014 21:00	19.5	0.18
17/07/2014 23:00	19.5	0.18
28/07/2014 20:00	19.5	0.18

Table 41 The maximum hourly recorded SST values and corresponding NAO Index values for M5

Table 42 shows that date and time of the minimum SST for M5 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
27/02/2014 05:00	7.4	1.34
27/02/2014 06:00	7.4	1.34
27/02/2014 07:00	7.4	1.34
27/02/2014 08:00	7.4	1.34
27/02/2014 09:00	7.4	1.34
27/02/2014 10:00	7.4	1.34
26/02/2014 07:00	7.4	1.34
26/02/2014 08:00	7.4	1.34
26/02/2014 09:00	7.4	1.34
27/02/2014 02:00	7.4	1.34

Table 42 The minimum hourly recorded SST values and corresponding NAO Index values for M5

Years	SST Values	SST Variation in °C	NAO Index Change
2008- 2009	11.9°C – 12.2°C	Increase of 0.3°C.	(-0.37) – (-0.24)
2011- 2012	12.1°C – 12.3°C	Increase of 0.2°C.	(0.29) – (-0.45)
2015- 2016	12.3°C – 12.1°C	Decrease of 0.2°C.	(0.43) – (-0.03)
2016- 2017	12.1°C – 12.5°C	Increase of 0.4°C.	(-0.03) – (0.22)
2017- 2018	12.5°C – 12.6°C	Increase of 0.1°C.	(0.22) – (1.08)
2018-2019	12.6°C - 12°C	Decrease of 0.6°C.	(1.08) – (-0.31)

Table 43 The 6 largest annual SST changes and corresponding NAO Index values for M5.

Table 43 shows the 10 greatest annual SST changes and corresponding NAO Index values for M5. This table analysed the mean annual NAO Index value for each of the annual variations in SST for M5.

Analysis of the atmospheric parameters that could have influenced the spell of maximum SST for M5 could not be assessed due to buoy repairs, but other influencing factors are discussed in chapter 6. Analysis of two days before and two days after the spell of minimum SST for M5 could be analysed.. Table 44 shows the mean daily values for the atmospheric processes that occurred two days before and after the minimum SST values for M5.

Date	Atmospheric pressure	Wind direction	Wind speed	Gust	Air temperature	SST
24/02/2014	995 Pa	203°	8 m s ⁻¹	12 m s ⁻¹	9°C	8.4°C
25/02/2014	993 Pa	232°	9 m s ⁻¹	13 m s ⁻¹	9°C	8.4°C
26/02/2014	1008 Pa	234°	8 m s ⁻¹	11 m s ⁻¹	9°C	8.2°C
27/02/2014	1003 Pa	245°	7 m s ⁻¹	10 m s ⁻¹	8°C	8.2°C
28/02/2014	1001 Pa	310°	7 m s ⁻¹	10 m s ⁻¹	7°C	8.3°C
29/02/2014	1000 Pa	310°	8 m s ⁻¹	11 m s ⁻¹	9°C	8.3°C

Table 44 The mean daily values for two days before and two days after the minimum recorded SST values for M5

Analysis of these atmospheric processes shows that before the spell of minimum SST for M5 the atmospheric pressure was lower, with an elevated wind speed and gust speed. Air temperature was higher in the two days before the spell of minimum SST, and the wind was originating from a south-westerly direction as seen in table 44. Further analysis of the factors that influenced both the spell of maximum and minimum SST variations for M5 are discussed in chapter 6.

M6

Overall, there was oscillating SST from 2007-2020. Compared to M4 and M5 there were greater SST oscillations recorded. The joint largest oscillation in SST recorded a decrease of 0.5°C between 2011-2012. From 2017-2018 there was another SST oscillation, showing a decrease in SST of 0.5°C between these years, see figure 11. To assess the impact of the NAO on maximum and minimum recorded SST for M6, tables were created to determine the NAO Index value at that time of the maximum and minimum SST for M6. Table 45 shows that date and time of the maximum SST for M6 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
01/10/2014 08:00	18.2	-1.27
01/10/2014 09:00	18.2	-1.27
01/10/2014 10:00	18.2	-1.27
01/10/2014 11:00	18.2	-1.27
27/07/2013 17:00	18.2	0.67
21/07/2014 21:00	18.2	0.18
21/08/2014 13:00	18.2	-1.68
21/08/2014 15:00	18.2	-1.68
17/07/2014 15:00	18.2	0.18
07/08/2014 01:00	18.2	-1.68

Table 45 The maximum hourly recorded SST values and corresponding NAO Index values for M6.

Table 46 shows that date and time of the minimum SST for M6 and the corresponding NAO Index value.

Date and Time	SST in °C	NAO Index
27/02/2014 05:00	8.0	1.34
27/02/2014 06:00	8.0	1.34
27/02/2014 07:00	8.0	1.34
27/02/2014 08:00	8.0	1.34
27/02/2014 09:00	8.0	1.34
27/02/2014 10:00	8.0	1.34
26/02/2014 07:00	8.0	1.34
26/02/2014 08:00	8.0	1.34
26/02/2014 09:00	8.0	1.34
27/02/2014 02:00	8.0	1.34

Table 46 The minimum hourly recorded SST values and corresponding NAO Index values for M6

Years	SST Values	SST Variation in °C	NAO Index Changes
2008- 2009	12.7°C – 12.9°C	Increase of 0.2°C.	(-0.37) – (-0.24)
2009- 2010	12.9°C – 12.7°C	Decrease of 0.2°C.	(-0.24) – (-1.15)
2011- 2012	12.8°C – 12.3°C	Decrease of 0.5°C.	(0.29) – (-0.45)
2012- 2013	12.3°C – 12.7°C	Increase of 0.4°C.	(-0.45) – (0.21)
2013- 2014	12.7°C - 13°C	Increase of 0.3°C.	(0.21) – (0.18)
2014- 2015	13°C- 12.9°C	Decrease of 0.1°C.	(0.18) – (0.43)
2015- 2016	12.9°C- 12.5°C	Decrease of 0.4°C.	(0.43) – (-0.03)
2016- 2017	12.5°C – 12.8°C	Increase of 0.3°C.	(-0.03) – (0.22)
2017- 2018	12.8°C- 12.3°C	Decrease of 0.5°C.	(0.22) – (1.08)
2018-2019	12.3°C- 12.6°C	Increase of 0.3°C.	(1.08) – (-0.31)

Table 47 The 10 largest annual SST changes and corresponding NAO Index values for M6.

Table 47 shows the 10 greatest annual SST changes and corresponding NAO Index values for M6. This table analysed the mean annual NAO Index value for each of the annual variations in SST for M6.

Analysis of the atmospheric parameters for the two days before and two days after both the spells of maximum and minimum SST could not be assessed for M6 due to the buoy being repaired on those dates, however further in-depth analysis of the causations to these SST variations are discussed in Chapter 6.

5.3 Top ten spells of maximum SST analysis for each buoy

M2

July 2013 contributed greatly to the maximum SST spells recorded for M2. July 2006 was also characterised by warm spells in SST. August of 2003 also contributed to spells of high SST (but lower NAO Index compared to Julys of 2013 and 2006). A warm spell was recorded in August 2010 but had a lower NAO Index compared to the August warm spell of 2003. August 2003 and 2010 had considerable spells of maximum SST. Another, warm spell was recorded in August 2008.

A warm spell was recorded in June 2010, which is interesting as it displays the second lowest NAO Index value for M2 and is relatively early seasonality wise to experience such a warm spell based on the land/sea heat absorption and retention rates. July 2008 recorded another warm spell, with a low Index value of -1.27. July 2016 recorded warm spell, which interestingly has the lowest NAO Index value for M2 of -1.76 and is relatively early to experience such a pronounced warm spell. Interestingly, September or October did not have the ten most pronounced spells of maximum SST for M2, which is interesting based on the land/sea rule of heat absorption and retention.

M3

Similar to M2, July 2014 recorded a pronounced spell of maximum SST. A warm spell in SST was recorded in August 2020, which was not seen in the ten maximum SST spells for M2 but had a similar NAO Index value to the July warm spell in 2014. Similar to M2, a spell of maximum SST was recorded in July 2013. June 2018 also recorded a spell of maximum SST similar to M2, showing an overall consistency in the pronounced spells of maximum SST between M2 and M3, however shorter spells tended to vary between the buoys such as August 2012 recorded a spell of maximum SST, which was not present in the ten most pronounced spells in maximum SST for M2. Interestingly, September or October did not

have the ten most pronounced spells of maximum SST for M3, which is interesting based on the land/sea rule of heat absorption and retention.

M4

Corresponding with M2 and M3, M4 recorded a pronounced spell in maximum recorded SST in July 2014, showing a consistency in the pronounced spells of maximum SST across M2, M3 and M4. June 2018 a recorded spell of maximum SST for M4, which is consistent with M2 and M3. July 2013 recorded a spell of maximum recorded SST, consistent with M2 and M3. July and August 2018 recorded spells of maximum recorded SST, which was not recorded in the ten spells of maximum SST values for M2 or M3. Interestingly, September or October did not have the ten most pronounced spells of maximum SST for M4, which is interesting based on the land/sea rule of heat absorption and retention.

M5

July 2014 recorded a pronounced spell in maximum recorded SST. This spell was more pronounced for M5 but still present in M2, M3 and M4. July 2006 recorded a spell of maximum SST, which again was more pronounced in M5 compared to other buoys. June 2018 recorded a spell of maximum SST similar to M2, M3 and M4. July 2013 also recorded a spell of maximum SST as seen in M2, M3 and M4, showing consistent pronounced spells in the buoys. Similar to M2, M3, and M4, M5, September or October did not have the ten most pronounced spells of maximum SST for M4, which is interesting based on the land/sea rule of heat absorption and retention.

M6

July 2014, consistent with all the other buoys displayed a pronounced spell in maximum SST. August 2014 showed a continuation of the spell in maximum SST in 2014 for M6. (pronounced). Interestingly, M6 was the first buoy to record a spell in maximum SST in September 2014, which continued into October 2014. M6 Only recorded 2014, as having the ten spells of maximum SST, but shows pronounced and significant warm periods during this time.

5.4 Top ten spells of minimum SST analysis for each buoy

M2

March 2013 recorded a pronounced spell of minimum SST for M2, accompanied with a negative NAO Index. April 2013 showed a continuation of the spell of minimum SST accompanied by a positive NAO Index. The 2013 March and April minimum spells were

prolonged and pronounced. December 2009 recorded a spell of minimum SST, with a negative NAO Index at this time. March 2010 recorded a brief spell of minimum recorded SST, with a positive NAO Index value at this time.

January and February of 2010 recorded a pronounced cold spell for M2, with a negative NAO Index value at this time. April 2008 recorded a brief spell of minimum SST, with a negative NAO Index. March 2015 also recorded a brief spell of minimum SST for M2 but had a positive NAO Index value. February and March 2011 recorded a pronounced spell in minimum SST, accompanied by a positive NAO Index value.

M3

M3 recorded a pronounced spell of minimum SST in February 2020 which continued into March 2020. A positive NAO Index was recorded during this time; however, this spell of minimum SST was not recorded in M2. Another pronounced spell of minimum SST was recorded in March 2018, with a negative NAO Index value at this time. This spell was also not recorded in M2. February and March 2016 recorded another pronounced spell in minimum SST, which was not seen in M2.

February 2017 and April 2018 both had brief spells of minimum SST, and both had a positive NAO Index.

M4

M4 recorded an interesting spell of minimum recorded SST in June 2009. June 2009 recorded a negative NAO Index at this time. This brief spell in minimum recorded SST is interesting as they were recorded in June and this would not be typical based on the time of year and the SST was recorded to be between 7.8 °C and 8.1 °C. March 2018 recorded a spell of minimum SST, recording a negative NAO Index value during this time, which was earlier than the spell in 2018 in M3. February 2016 recorded a pronounced spell in minimum SST, which is consistent with M3, and had a positive NAO Index. March 2014 recorded a spell of minimum SST, which was not seen in M2 and M3, and had a positive NAO Index.

March 2010 recorded a spell of minimum SST, which was later than the 2010 spell recorded for M3. A negative NAO Index value was recorded during this time. March 2012 recorded a pronounced spell of minimum SST cold spell, accompanied by a positive NAO Index. April 2012 showed a continuation of this spell of minimum SST for M5.

M5

M5 recorded a pronounced spell in minimum SST for January, February, March, and April 2014, which was earlier than 2014 spell recorded for M4. The spell recorded in April 2014 for M5 was less pronounced than the spells recorded in January, February and March. March 2010 recorded a pronounced spell of minimum SST values, consistent with M4.

M6

February and March 2014 recorded a pronounced spell in minimum SST values, consistent with M4 and M5. Spells of minimum SST values were also recorded in January and April, but consistent with M4 and M5, these spells were less pronounced than February and March. November 2018 recorded a spell of minimum SST values, which was interesting as this was the only minimum SST spell recorded, not in the months January, February, March or April, which would be expected. There was a negative NAO Index recorded at this time. March 2016 recorded a pronounced spell in minimum SST not seen in M5. April 2020 recorded a brief spell in minimum SST, accompanied with a negative NAO Index at this time.

5.5 Summary of the top ten spells in SST and NAO comparison.

M2 Summary

The sea surface temperatures between 2002-2010 were higher than the sea surface temperatures between 2011-2020 overall. The sea surface temperatures from 2002-2010 were more stable than the sea surface temperatures between 2011-2020, which showed greater variations in SST between years. The years 2014-2015 and 2017-2018 displayed the largest variations in SST, both recording a decrease in SST of 0.6°C.

Analysis of the mean air temperature for 2014-2015 showed that no air temperature data was recorded from 01/01/2014 until the 28/10/21 for 2014. From the 28/10/14 until the 31/12/14, the mean average air temperature was 10.5°C. The mean air temperature for 2015, was 10.6°C. 2015 is missing less than 10% of air temperature data, resulting in an accurate representation of the actual mean air temperature. There is little variation in annual mean air temperature between 2014-2015 however the missing air temperature for 2014 would need to be assessed to accurately conclude this. The little variation in air temperature could not solely have influenced the variations in mean SST witnessed.

The top ten maximum SST were recorded in July 2013. For the top ten maximum SST values for M2, the NAO Index remained stable at 0.67°C, showing a stationary and stable NAO. This suggests that there was a consistent and undisturbed block of water surrounding Ireland,

that was not mixed due to storm activity. The top ten minimum SST from M2 were recorded in December 2009 and March 2013. In December 2009, the NAO Index was 0.95°C, showing stationary and stable conditions. However, the NAO Index was -1.61°C in March 2013, showing unstable conditions with the possibility of mixing water contributing to the minimum SST recorded.

Analysis of two days before and two days after the maximum recorded SST from M2 were conducted. The maximum recorded SST for M2 were recorded on the 17/07/2013 and the 18/07/2013. Two days before the 17/07/2013, there was an increase in the wind speed and gust speed as shown below, however this would not be categorised as storm level gusts. The air temperature was lower in the two days preceding the 17th July and 18th July of March 2013. Atmospheric pressure was also lower, preceding the 17th July and 18th July. The two days after the maximum recorded SST for M2 on the 17th and 18th of July 2013 shows a decrease in both wind and gust speed, and a increase in mean air temperature. There was a decrease in mean atmospheric pressure in the two days following the 17th July and 18th July.

Analysis of two days before and two days after the minimum recorded SST from M2 was also conducted. The minimum SST for M2 were recorded on 27/12/2009, 30/03/2013 and the 31/03/2013. There was an overall increase in the daily mean gust speed in the two days before and after the minimum recorded SST. There was also a increase in the daily mean atmospheric pressure for the two days before and after the 30th and 31st of March 2013, but not for the 27/12/2009. There was a decrease in daily mean air temperature for the two days before and after the minimum SST dates. Overall, there appears to be a relationship with increased wind and gust speed, and air temperature on the maximum and minimum SST around Ireland's coastline, consistent with the NAO Index values. To assess this further, analysis of the location of the air mass and movement of the jet stream location, related to the NAO Index will be assessed, coupled with the possible influence of tropical storm events.

Analysis of gust speeds shows that March 2013 had a mean gust speed of 19.9 mph. The maximum gust speed recorded for March 2013 for M2 was 42 mph. This relatively high gust speeds could be a contributing factor to the minimum SST values recorded for M2.

M3 Summary

Between 2002-2010 there was a greater range of sea surface temperature variations, than from 2011-2020. This shows unstable conditions between 2002-2010, and a stabilisation in sea surface temperatures from 2011-2020. This being said, the most pronounced oscillation in

SST was recorded between 2007-2008, showing a decrease in mean annual SST of 0.3°C, from 13°C to 12.7°C, which is not a significant deviation in mean annual SST overall. As this variation in SST is relatively small, this means that overall, there was stable mean annual SST conditions recorded by M3.

Considering 2007-2008 had the most pronounced change in annual mean SST, the annual mean air temperature was assessed as a possible contributing factor to this change in mean SST. The annual mean air temperature for 2007 was 12.6°C. Overall, 2007 was missing 115 hours of air temperature data, totalling 1.3% of air temperature data missing for the year of 2007. The annual mean air temperature for 2008 was recorded at 12°C. Overall, M3 was missing 64 hours of recorded air temperature data, accounting for 0.7% of the overall air temperature data. As the most pronounced oscillation in SST was recorded between the years 2007-2008, the annual mean air temperature for these years was analysed to establish any correlation between air temperature and SST. As both the years 2007 and 2008 were missing less than 10% of air temperature data, the annual mean air temperatures can be used as an accurate parameter to assess any correlation between air temperature and SST. There was a decrease of 0.3°C in SST from 2007-2008. There was a decrease in the annual mean air temperature of 0.6°C. The decrease in SST could be associated with a corresponding decrease in mean annual air temperature, but not solely due to this change in air temperature.

The top ten maximum SST for M3 were in July 2014. The corresponding NAO Index value at this time was 0.18°C, showing stable conditions with little mixing of water, providing conditions suitable to accumulate SST. The top ten minimum SST for M3 were recorded in March 2020. The corresponding NAO Index value at this time was 1.01°C, showing stable conditions and little mixing of water. The relatively low and consistent NAO Index values suggest there was a distinct signal, showing that there was little storm activity around the time of both the maximum and minimum SST values for M2. This suggests that there was a consistent and undisturbed block of water surrounding Ireland, that was not mixed due to storm activity. This reinforces the stability of SST and conditions for the years 2002-2020 as seen by the minor variations in annual SST.

M4 Summary

There was variations in annual mean SST between 2008 (when recording began) and 2016. From 2017-2020 there were greater variations of annual mean SST increases and decreases. The largest SST oscillation recorded for M4 was recorded between 2017-2018 where there

was a SST increase of 0.9°C. To assess the causes of this variation in annual mean SST between 2017-2018, analysis of the mean annual air temperature was completed. In 2017 the annual mean air temperature was 11.3°C, while the annual mean air temperature for 2018 was 11.6°C. This temperature for 2018 may however be higher, as 13% of air temperature data was missing or not recorded, compared to 2017 which had less than 10% missing data.

In 2012 the NAO Index value corresponding with the maximum SST values for M4 was recorded at -0.9°C. There was a subsequent increase and stabilisation in NAO values in the following year 2013, recording an NAO value of positive 0.6°C. There was a decrease in NAO Index value between 2013-2014, with an NAO Index value of 0.1°C being recorded in 2014. In 2018 there was a significant increase in NAO Index values, with mixing of temperatures between two months in the year 2018. In June 2018, the NAO Index was recorded at 1°C, and in August 2018 there was a continued increase in NAO values to 1.9°C, which is high. This would indicate stable conditions, consistent with the maximum recorded SST for M4.

As the largest variation in SST occurred in 2017- 2018 the mean annual gust speed for both years was assessed as a possible contributing factor. For 2017 the mean annual gust speed was 8 ms⁻¹, and the mean annual gust speed for 2018 was 9 ms⁻¹, 2017 is missing less than 5% of the gust data, while 2018 is missing 8% of the data. The maximum gust speed was recorded on 08/01/2008, and was a speed of 76 mph and had a corresponding air temperature of 4°C. The minimum gust speed was recorded on 18/06/2012, and was a speed of 1ms⁻¹, and had a corresponding air temperature of 10°C. Based on this, it seems that air temperature was a more significant factor contributing to variations in annual mean SST, compared to gust speed.

M5 Summary

From 2008 (when recording began) to 2011 there were fluctuations in SST, followed by a stabilisation in SST from 2012-2015. From 2016-2020 there were more pronounced increases and decreases in SST, compared to the SST fluctuations recorded in 2008-2011. The most pronounced annual mean SST decrease for M5 was recorded between 2018-2019, where a mean annual SST decrease of 0.6°C occurred.

There were overall stable NAO conditions recorded for M5, corresponding with the top ten spells of maximum SST for M5. At the time of the maximum SST spells, the corresponding NAO Index values were all positive showing stable conditions with little mixing of water, the

only mixing of SST water occurred in 2018 as there was a mixing of NAO Index values between two months, showing nonstationary conditions between these two months, within the same year. In June 2018 the NAO Index value was recorded at 1°C, and in July 2018 there was a increase in NAO Index to 1.3°C, showing a mixing of NAO Index temperatures. The NAO Index values corresponding with the dates of recorded minimum SST values were relatively stable but consisted of both positive and negative NAO Index values.

As the most pronounced annual mean SST decrease for M5 was recorded between 2018-2019, where a SST decrease of 0.6°C occurred, the mean annual gust speed for these years was assessed. For 2018 the mean annual gust speed was 18 mph. For 2019 the mean annual gust speed was 19 mph. The mean annual air temperature for 2018 was 11°C. The mean annual air temperature for 2019 was 13°C. The maximum gust speed was recorded in 22/12/2006 of 67 mph. The minimum gust speed was recorded on 25/10/2020 of 1 mph. The decrease in mean annual SST of 0.6°C between 2018-2019 could have been influenced by an increase in the mean annual gust speed and of 1 mph and an increase in air temperature by 2°C.

M6 Summary

Overall, there were oscillating SST from 2007 (when recording began) to 2020. Compared to M4 and M5 there were greater SST oscillations recorded. The joint largest oscillation in SST recorded a decrease of 0.5°C between 2011-2012. From 2017-2018 there was another SST oscillation, showing a decrease in SST of 0.5°C between these years.

The NAO Index values corresponding with the maximum SST values recorded for M6 were recorded in only 2013 and 2014. In 2013 there was a stable NAO Index value of 0.6°C recorded. In 2014 however there was a large range of NAO Index values, indicating mixing of temperatures and non- stationary conditions. In July 2014 the NAO Index value was recorded at 0.1°C. In August 2014, there was a decrease in NAO Index values to -1.6°C. There was a subsequent increase in NAO Index values in September 2014, which recorded the NAO Index value at positive 1.6°C. In October there was a decrease in NAO Index value to -1.2°C. This high variation between July, August, September and October shows mixing of SST and non-stationary NAO values at this time, corresponding to the times that the maximum SST values were recorded for M6.

As the years 2011-2012 and 2017-2018 both had the largest mean annual oscillation in SST, the mean annual wind gust speeds for these years were analysed, to assess the impact of gust

speed on influencing SST variations. The mean annual gust speed for 2011 was 10 ms^{-1} , and the mean gust speed for 2012 was 9 ms^{-1} . The mean annual gust speed for 2017 was 10 ms^{-1} the mean annual gust speed for 2018 was 25 mph. The maximum gust speed was recorded on 12/01/2017 at a speed of 33 ms^{-1} . The minimum gust speed for M6 was recorded on 16/08/2020 at a speed of 1 ms^{-1} .

To assess the impact of air temperature on the variations in SST between 2011-2012 and 2017-2018, the annual mean air temperature values were assessed. The mean annual air temperature for 2011 and 2012 was 11°C . The mean annual air temperature for 2017 was 11°C and the mean annual air temperature was 10°C . As there was little variation between the mean annual air temperatures, during the years of significant SST variations, air temperature is likely to have had limited influence on SST variations. It is possible that increased wind gust speed combined with local variations in air temperature could have contributed to the higher degree of SST variations experienced by M6 compared to M4 and M5. That being said, the location of M6 on the periphery of the west coast of Ireland is likely to have contributed to the variations in SST experienced at M6 compared to M4 and M5. Local and regional tide patterns as well as a shift in the position of the NAD North Atlantic Drift are likely contributors to the variations witnessed, this will be assessed further.

Chapter 6 Sea surface temperature causations

6.1 Introduction

The sea surface temperatures of the North Atlantic vary on an interannual to interdecadal timescale. A range of complex and dynamic processes interact with and govern the patterns of sea surface temperature fluctuations in the North Atlantic. Coupled atmospheric and oceanic processes, operate and oscillate on varying time scales, which contributes to long- and short-term fluctuations in SST in the North Atlantic Region. Long term, broader causations for SST fluctuations in the North Atlantic, will be discussed firstly in section 1, followed secondly by more specific and short-term causations for SST fluctuations in the North Atlantic, with specific focus on Ireland's sea surface temperatures will be examined in section 2.

6.2 Section 1

6.3 ENSO

El Niño is a climatic pattern that is characterised by the warming of sea surface temperatures in the Eastern Tropical Pacific Ocean. El Niño is characterised as a warm phase of a larger system called the El Niño – Southern Oscillation (ENSO). La Niña is characterised as a cool phase of ENSO, responsible for the cooling of the sea surface temperatures of the Eastern Tropical Pacific Region (Philander, 1985). El Niño and La Niña are considered to be the oceanic processes of ENSO, while the Southern Oscillation is responsible for the atmospheric responses associated with ENSO.

El Niño affects the sea surface temperatures, the velocity of ocean currents, and local weather patterns from Australia to South America, with subsequent effects on other regions. The cycle of El Niño is not regular and can be described as irregular and intense climate changes (Philander, 1985).

Following the work of Walker, (1930), Katz, (2002) El Niño was discovered to occur simultaneously with the Southern Oscillation. The Southern Oscillation is defined as “change in air pressure over the tropical Pacific Ocean” (Toniazzo, Scaife, 2006, 12). When sea surface temperatures become warmer in the Eastern Tropical Pacific due to El Niño, the atmospheric pressure above the ocean decreases.

The Ocean Niño Index (ONI) is used to measure deviations from the normal sea surface temperature. El Niño events are characterised by sea surface temperature increases of more than 0.5°C for at least five successive three-month seasons (Hoerling, et al, 1997). The

intensity of El Niño events varies from weak temperature increases (about 0–0.5°C) with only moderate local effects on weather and climate in the Pacific region to very strong increases (0.5 – 3°C) associated with worldwide climatic changes.

Normally, strong trade winds blow westward across the tropical Pacific, the region of the Pacific Ocean located between the Tropic of Cancer and the Tropic of Capricorn. These winds push warm surface water towards the western Pacific, where it borders Asia and Australia. As a result of this, the sea surface is normally about 0.5 meters higher and 7°C warmer in Indonesia than Ecuador. Upwelling of the ocean water results in the elevation of cold water and the submergence of warm surface water, supplying nutrient rich water to the euphotic zone. This upwelling process influences global climate patterns as the warm sea surface temperatures in the Western Pacific contributes to increased precipitation around the Western Pacific. Dong, et al, (2006) investigated a possible connection between the Atlantic Multidecadal Oscillation (AMO) and El Niño- Southern Oscillation (ENSO) variability, with the warm AMO phase being associated with weaker ENSO variability. Anomalous SST associated with the positive AMO lead to changes in the basic state in the tropical Pacific Ocean, (Dong, et al, 2006). The change in the basic state of the tropical Pacific Ocean is associated with a deepened thermocline and reduced vertical stratification of the equatorial Pacific Ocean, which results in a weakened ENSO variability. Dong, et al, (2006) suggests the role for an atmospheric bridge that rapidly conveys the influence of the Atlantic Ocean to the tropical Pacific. Results showed that anomalous Atlantic Ocean SST can modulate both mean climate and climate variability over the Pacific. Mean sea surface temperatures in the Atlantic were analysed between the AMO positive and negative phases which showed a dipolar in the Atlantic. Precipitation anomalies also showed a northward shift of the intertropical convergence zone over the tropical Atlantic which is a direct response to the underlying SST variations.

El Niño events are characterised by their wide-ranging teleconnections. Teleconnections are large-scale, long-lasting climate anomalies or patterns that are related to each other and can affect much of the globe. During an El Niño event, westward-blowing trade winds weaken along the Equator. These changes in air pressure and wind speed result in forcing warm surface water to move eastward along the Equator, from the western Pacific to the coast of northern South America, which is important for influencing the North Atlantic SST variations. These warm surface waters deepen due to the thermocline effect, as the level of ocean depth that separates warm surface water from the colder water below is altered. During

an El Niño event, the thermocline can dip as far as 152 meters (Hoerling, et al, 1997). This thick layer of warm water does not allow normal upwelling to occur. El Niño also produces widespread and sometimes severe changes in the climate. Convection above warmer surface waters bring increased precipitation, in the Pacific Region, indirectly causing changes to local SST and climatic patterns in the North Atlantic.

Stronger El Niño events also disrupt global atmospheric circulation. Global atmospheric circulation is the large-scale movement of air that distributes thermal energy across the surface of the Earth. The eastward movement of oceanic and atmospheric heat sources cause unusually severe winter weather at the higher latitudes of North and South America. Regions as far north as the U.S. states of California and Washington may experience longer, colder winters because of El Niño (Hoerling, et al, 1997).

El Niño events of 1982-1983 and 1997-1998 were the most intense of the 20th century. During the 1982-1983 event, sea surface temperatures in the eastern tropical Pacific were between 1°C to 5°C above normal. These strong temperature increases caused severe climatic changes. The El Niño event of 1997-1998 was the first El Niño event to be scientifically monitored from beginning to end. El Niño-related disruption of global atmospheric circulation extends beyond Pacific Rim nations, with both direct and indirect implications and effects on the North Atlantic SST variations.

6.4 La Niña

The first recorded occurrence of unusual desert rainfall was in 1525, when the Spanish conquistador Francisco Pizzaro landed in northern Peru. The intensity of El Niño episodes varies from weak thermal anomalies (2–3 °C) with only moderate local effects to very strong anomalies (8–10 °C) associated with worldwide climatic perturbations. El Niño events occur irregularly at two- to seven-year intervals, and the strong events are less common. The intermittency varies widely, however, and the phenomenon is neither periodic nor predictable in the sense that ocean tides are.

La Niña is a climate pattern that is characterised by the cooling of sea surface temperatures along the tropical west coast of South America. La Nina is considered to be the counterpart to El Nino, which is characterized by unusually warm ocean temperatures in the equatorial region of the Pacific Ocean (Katz, 2002). La Niña events sometimes follow El Niño events, which occur at irregular intervals of about two to seven years (Katz, 2002). The

local effects on weather caused by La Niña are generally the opposite of those associated with El Niño.

The Oceanic Niño Index is used to measure the deviations from normal sea surface temperatures that El Niño and La Niña produce in the east-central Pacific Ocean. La Niña events are indicated by sea-surface temperature decreases of more than 0.5 °C at least five successive three-month seasons. La Niña events may last between one and three years, unlike El Niño, which usually lasts no more than a year. Both phenomena tend to peak during the Northern Hemisphere winter.

La Niña is caused by a build-up of cooler-than-normal waters in the tropical Pacific, the area of the Pacific Ocean between the Tropic of Cancer and the Tropic of Capricorn. Unusually strong, eastward-moving trade winds and ocean currents bring this cold water to the surface, a process known as upwelling. Upwelling can cause a drastic drop in sea-surface temperature. Coastal sea-surface temperatures near Ecuador and Peru dropped nearly 4°C during the 1988-1989 La Niña event (Katz, 2002).

Both El Niño and La Niña affect patterns of precipitation, atmospheric pressure, and global atmospheric circulation. Atmospheric circulation is the large-scale movement of air that, together with ocean currents, distributes thermal energy on the surface of the Earth. These changes are the main sources of variability in climate, and subsequent sea surface temperature variations for many areas worldwide (Hoerling, et al, 1997). La Niña is characterized by lower-than-normal air pressure over the western Pacific. These low-pressure zones contribute to increased rainfall.

La Niña is also characterized by higher-than-normal pressure over the central and eastern Pacific. This results in decreased cloud production and rainfall in that region with subsequent effects on other local, regional, and global synoptic patterns. Drier-than-normal conditions are observed along the west coast of tropical South America, the Gulf Coast of the United States (Katz, 2002). During a La Niña year, winter temperatures are warmer than normal in the South Pacific and cooler than normal in the North Pacific. La Niña can also lead to an increase in the frequency and intensity of hurricanes in the North Atlantic Sea, causing subsequent effects on local and regional SST in the North Atlantic Region.

El Niño and the Southern Oscillation appear to be the oceanic and atmospheric components of a single large-scale, coupled interaction—the El Niño/Southern Oscillation (ENSO).

During the warm phase of ENSO, the South Pacific trade wind system undergoes a change of

state, or “seesaw,” in which the westward-blowing trades weaken along the Equator as the normally high pressure in the eastern South Pacific decreases and the low pressure over northern Australia and Indonesia rises. The El Niño–Southern Oscillation has a large impact on January–February North Atlantic mean sea level pressure (MSLP). The pressure changes and diminished trade winds cause warm surface water to move eastward along the Equator from the western Pacific, while the warm surface layer in the east becomes thicker.

El Niño–Southern Oscillation impacts the North Atlantic via two routes—one through the tropical Atlantic in the lower atmosphere (troposphere) and one through the middle atmosphere (stratosphere) in polar latitudes. It is found that the tropospheric pathway dominates for El Niño events, leading to a wavelike response in North Atlantic MSLP, characterized by a high pressure west of Ireland. However, the stratospheric pathway dominates for La Niña events leading to a different MSLP pattern, characterized by high pressure over the Azores and low pressure over Iceland. Therefore, if a really strong La Niña event were ever to occur, Northern Europe is likely to experience an increase volume of precipitation during the winter months (Katz, 2002).

In the case of El Niño events, the stratospheric pathway is influenced by an intensification and eastward shift of the Aleutian low which causes an increased planetary wave flux into the stratosphere (Pyle, Braesicke, Zeng, 2005), leading to a weaker than average December–January–February (DJF) stratospheric polar vortex strength and the downward projection of this onto an anomalously negative North Atlantic Oscillation. The tropospheric pathways of El Niño events are influenced by energy of Rossby Wave trains in the North Pacific which traverse North America and by Rossby Wave energy in the tropical Atlantic which propagate northward and eastward to impact on the North Atlantic (Toniazzo, Scaife, 2006).

6.5 North Atlantic Atmospheric- Oceanic interaction, and Greenland (GISP2) ice core and historical indicators of complex North Atlantic climate changes during the fourteenth century.

The coupled atmosphere-ocean climate system in the North Atlantic exhibits variability on seasonal and longer time scales. The turbulent latent and sensible heat flux, which plays a key role in the interaction between the atmosphere and the ocean, is dependent on local values of the air-sea temperature differences and low-level wind speed and humidity. The largest climatological values of the turbulent heat flux are found east of the North American and Eurasian continents. Qualitatively, this can be explained by outbreaks of cold and dry air

from the continents over the relatively warm ocean. In addition, sea ice covering the ocean modulates the turbulent heat fluxes quite significantly, depending on the type of sea ice, as discussed in Barry, et al, (1993). Therefore, places like the Labrador and Greenland Seas, where the variability of the sea-ice coverage is large to be important regions in terms of air-sea interaction.

Atmospheric circulation anomalies can exert a strong impact on SSTs and sea ice through heat-, momentum-, and fresh water forcing. Therefore, a two-way dynamic interaction exists between the oceanic conditions and the atmospheric circulation. However, the two mechanisms act on different time scales. An SST/SIE (sea ice extent) anomaly causes a local thermal forcing on the atmosphere, which in turn induces a local modification of the geopotential height field. Geostrophic adjustment implies the development of an anomaly of the vorticity field within one day or so. This vorticity anomaly is then propagated through the dispersion of stationary Rossby wave, which takes place on a time scale of ten days (Hoskins, Karoly, 1981), after which the atmosphere may be considered to be in statistical equilibrium with the forcing. On the other hand, atmospheric circulation anomalies act on the SSTs and sea-ice concentration on time scales ranging from a month to several years.

One of the strongest impacts of SST changes on the surface heat fluxes can be expected at places where those SST changes induce some modifications of the sea ice cover. There is a local response in the turbulent heat flux to changes in SST and/or SIE (sea ice extent). Thickening of the troposphere can be considered as the equivalent barotropic response to the heating anomaly associated with the prescribed SST change. Thickening of the troposphere can be considered as the equivalent barotropic response to the heating anomaly associated with the prescribed SST change (Hoskins, Karoly.,1981).

Dawson, et al, (2007) analysed Greenland GISP2 ice core data combined with historical data to investigate the climate changes recorded between AD 1270 and 1450 across the North Atlantic region. Detailed Deuterium and deuterium excess time series resolved to c. 8-10 samples per year were used to reconstruct relative changes in Greenland air temperature and past changes in sea surface temperature across the western North Atlantic. The data revealed that sea surface temperatures during the late thirteenth century and the majority of the fourteenth century were characterised by relatively high amplitude warming and cooling “events”. These oscillations preceded a notable reduction in the amplitude of the sea surface temperature changes around thirty to forty years before the

change in the Northern Hemisphere tropospheric circulation characterised by an increase in regional storminess that began around AD 1400 and 1420.

The time interval between AD 1270 and 1450 featured several short-lived phases of marked air temperature lowering that were rarely ever equalled to such a magnitude of air temperature lowering in sucking centuries over Greenland. Dawson, et al, (2007) emphasise that these climatic changes are of considerable importance in understanding the climate dynamics of the North Atlantic region, and subsequent influences, as they occurred at a time when the North Atlantic Oscillation (NAO) may have been weak. Results from Dawson, et al, (2006) show that the change in atmospheric circulation coincided with a significant increase in the North Atlantic storminess at around AD 1400- 1420, took place after the strong perturbations in North Atlantic Sea surface temperature, both the warming and changes in the NAO Index, which is an Index of winter surface air pressure differences between Iceland and the Azores have been used to understand historical changes in the frequency and intensity of North Atlantic storminess. Dawson, et al, (2007) describe the North Atlantic as a “see-saw”, exemplifying the dynamic interaction between climatic, synoptic and oceanic processes.

Oscillation in climate over the North Atlantic region are largely dominated by a major change in atmospheric circulation, as seen around AD 1400-1420. Prior to his oscillation, the Northern Hemisphere was dominated by both a weakly developed winter Icelandic Low and a weak winter and spring Siberian anticyclone (Meeker, Mayewski, 2002). After AD1400-1420, atmospheric circulation patterns and processes were intensified across the Northern Hemisphere coinciding with an increase in the frequency and intensity of storminess in the region.

From AD 1400-1420 until present, Icelandic tropospheric low pressure was strongly developed during winters, this time also coincided with a vigorous North Atlantic Oscillation. The NAO must have been weakly developed during the centuries before the start of the fifteenth century because if the existence of a poorly developed Icelandic low during winter.

A governing premise of the concept of the North Atlantic Oscillation (NAO) is that the collision of cold polar air with warmer air from lower latitudes, leads, during winter, to the development of cells of low pressure across the North Atlantic region. The juxtaposition of deep low pressure over Iceland during winter with the subtropical Azores high pressure cells to the South, resulting in positive monthly NAO Index.

In this mode of atmospheric circulation, both the Iceland low, the Azores high and the Siberian anticyclone have the combined effect of the development of a zonal (east–west) cyclonic air flow linked to a relatively sharp north–south thermal gradient over the North Atlantic. Meeker, Mayewski (2002) showed from analysis of the GISP2 ice core chemistry data that the increased vigour of tropospheric circulation only began around AD 1400–1420 and has continued until present.

By contrast, the period from AD 700 until c. AD 1400–1420 was characterized by relatively idle tropospheric circulation, within which the Iceland low and the Azores high were weakly developed while zonal cyclonic (west to east) air flow as well as the north–south thermal gradient over the North Atlantic were weak. During this time interval, the NAO must therefore always have been weak.

Barlow (1994) envisaged Atlantic SST fluctuations as part of the NAO temperature ‘seesaw’. Thus, she considered that warmer than average SSTs across the western Atlantic were frequently (though not always) associated with lower-than-average air temperatures across Greenland (and vice versa). However, this explanation cannot be used to account for the high magnitude fluctuations in weather and climate that appear to have taken place between AD 1270 and 1420 prior to the dramatic increase in North Atlantic storminess.

6.6 Multidecadal variability of the sea surface temperature gradient across the Subpolar North Atlantic, and influence of local and regional currents.

Variability of sea surface temperature in the North Atlantic and the Nordic Seas has a profound effect on climate in Europe and adjacent areas due to heat release to the atmosphere from the North Atlantic Current (NAC) (Bjerknes, 1964). The NAC itself is a surface expression of the Atlantic meridional overturning circulation (AMOC), which is an essential component of the global climate system which is responsible for transporting heat northward via the NAC and ventilating the surrounding ocean basins through North Atlantic Deep Water (NADW) formation. The sea surface temperature of the ocean reflects both the history of interactions with the overlying atmosphere and the influence of variations in the ocean circulation. A diverse range of processes are associated with sea surface temperature variations, including air-sea exchange, horizontal ocean heat transport divergence and ocean upwelling and mixed-layer entrainment (Josey, et al, 2018).

The AMOC and regional climate are dynamically interlinked and known to vary in the broad range of time scales from interannual (Cunningham et al., 2007) to interdecadal (Bianchi,

McCave, 1999); (Thornalley et al.,2009). The interannual variability is primarily governed by atmospheric processes (Marshall et al.,2001), whereas at longer time scales, dynamic oceanic processes, coupled with atmospheric processes become governing factors (Bjerknes, 1964); (Knight, et al. 2005). Variations in the advection of sea ice and polar water from the Arctic reduce the vigour of the AMOC and, hence, regional SST experienced in the North Atlantic Region (Mauritzen, Hakkinen 1997); (Greene, et al. 2008). The increased freshwater fluxes may reduce or cease deep convection, which forms North Atlantic deep-water masses in the Labrador and Nordic Seas, leading to a slowing of the AMOC and regional SST cooling (Dahl et al. 2005); (Greene et al, 2008). These variations have occurred on widely different time scales from decadal to millennial and have had major impacts on the North Atlantic climate, and sea surface temperatures (Bond, et al, 1997); (Andrews, Giraudeau, 2003).

The subpolar North Atlantic is an oceanographically dynamic area. The surface limb of the AMOC transports warm and saline Atlantic waters (the Atlantic inflow) north-eastward via the surface NAC across the North Atlantic into the Nordic Seas (Greenland, Iceland, and Norwegian Seas), passing between the subpolar (SPG) and subtropical (STG) gyres, from which it draws water. SPG and STG govern on the location, intensity, and composition of the NAC in the subpolar North Atlantic (Hatun, et al. 2005); (Thornalley et al. 2009). The NAC has two major north-eastward flowing surface branches, which form the major northward pathways of the Atlantic inflow in the subpolar North Atlantic; the western branch through the Iceland Basin, and the eastern branch through the Rockall Trough as the Continental Slope Current (CSC) (Fratantoni, 2001). The western branch of the NAC separates south of Iceland into the southwest flowing Irminger Current (IC) and the northeast flowing Faroe Current (FC), which forms north of the Faroe Islands the western branch of the Norwegian Atlantic Current. Most of the IC consists of a strong current southward along the eastern slope and subsequently north-eastward flow along the western slope of the Reykjanes Ridge (Orvik, Niiler,2002). It continues westward, turns south, flows parallel to the cold East Greenland Current (EGC) down to Cape Farewell on the southern Greenland tip, and is finally incorporated into the West Greenland Current (WGC). Part of the IC flows anticyclonically around Iceland to the North Icelandic Shelf as seen in figure 32. (Hansen, Østerhus 2000).

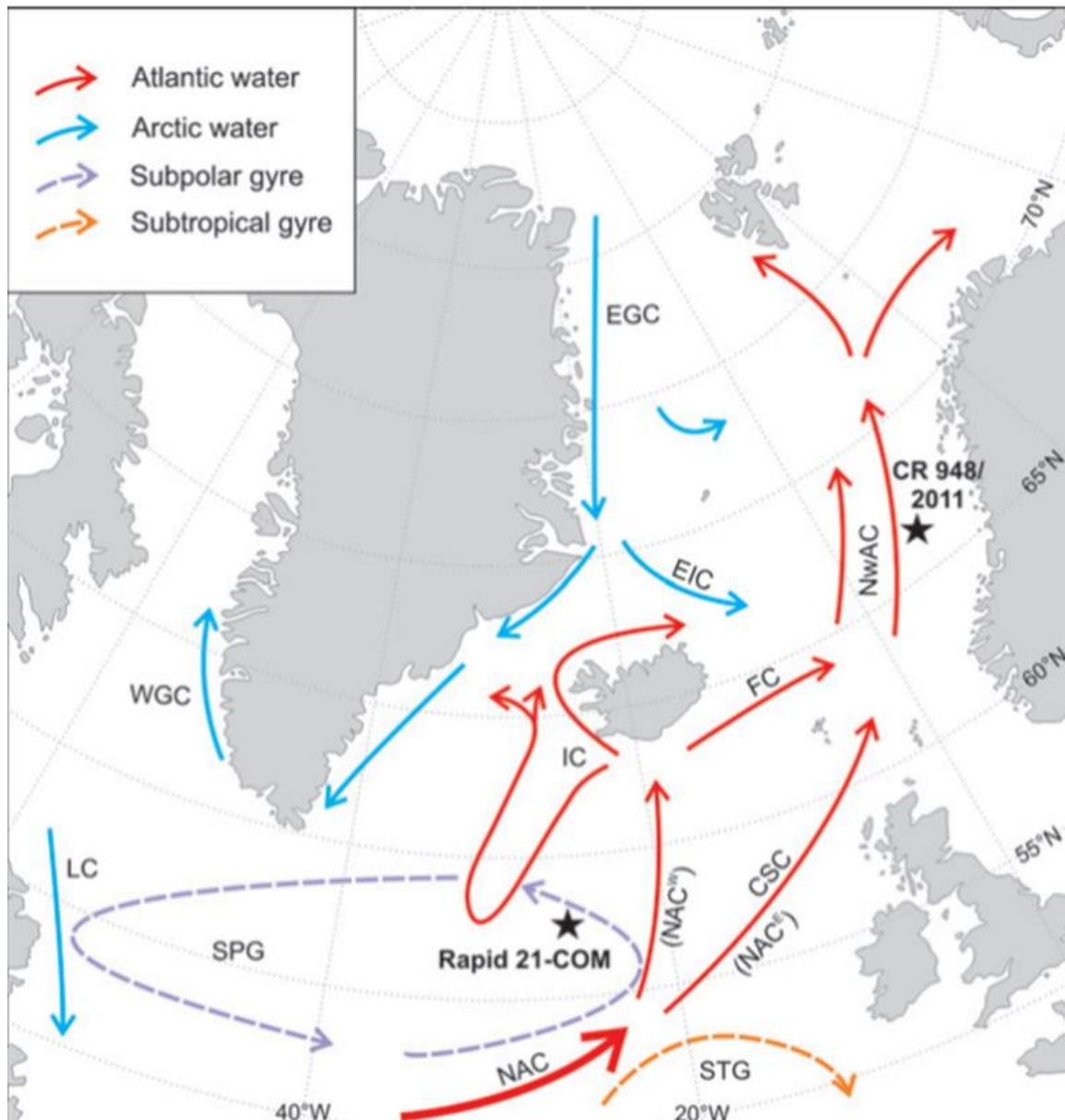


Figure 32 The ocean currents surrounding the west coast of Ireland (Hansen, Østerhus 2000).

Josey et al, (2018) discusses a record cold sea surface temperature anomaly that developed in the subpolar North Atlantic from the winter of 2013/2014 to 2016, that extended to a depth of 700 meters. This event prompted analysis of the likely forcing agents, including a possible link with a weakening of the Atlantic meridional overturning circulation (AMOC). The cold surface anomaly peaked in the summer of 2015 and is widely referred to as the “Big Blue Blob” (Josey, et al, 2018, 2). The anomaly occurred against a history of decadal variability and a centennial timescale cooling of the North Atlantic, termed the warming hole. At interannual timescales, the influence of the North Atlantic sea surface temperature anomalies, affect atmospheric circulation and European weather patterns. Josey, et al, (2018) identifies

the contributing factors to this cold sea surface temperature event, as these processes directly affect the temperature evolution of the mixed layer; extreme ocean surface heat loss, reduced northward ocean heat transport, and enhanced upwelling of cold water. Indirect contributing factors were identified as anomalous airflows and variations in the freshwater supply to the North Atlantic from the Arctic and Greenland, including the effects of enhanced glacial melt. Anomalous air flows in 2015 originated from the north and northwest and had the potential to enhance surface heat loss and modify wind-driven upwelling (Josey, et al, 2018). Increased freshwater supply has been suggested as a long-term influence on the strength of the AMOC via a reduction in the meridional density gradient, (Rahmstorf, et al, 2015), leading to a fall in poleward heat transport and a colder mid- to high- latitude North Atlantic. Results from, Josey, et al, (2018) show that the record-breaking cold sea surface temperature in the North Atlantic were caused largely by extreme surface heat loss, coupled with other oceanic and atmospheric processes. Josey, et al, (2018) identifies an earlier, weaker cold SST anomaly that occurred in 2009-2010, which was driven primarily by a reduction in the Atlantic meridional overturning circulation. This shows that both the ocean and atmospheric processes of the coupled climate system can generate strong interannual variability in SST in the North Atlantic.

6.7 The North Atlantic Oscillation (NAO):

The North Atlantic Oscillation (NAO) Index is based on the surface sea-level pressure difference between the Subtropical (Azores) High and the Subpolar Low. The positive phase of the NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport, which in turn results in changes in both air and sea surface temperatures, and precipitation patterns across the North Atlantic Region. The NAO exhibits considerable inter-seasonal and interannual variability, and prolonged periods (several months) of both positive and negative phases of the pattern are typical.

6.8 The relationship between the North Atlantic Oscillation and SSTs in the North Atlantic Basin.

The NAO is strongly correlated with large-scale changes in sea surface temperatures across the basin of the North Atlantic (Bjerknes 1964). The role that air–sea interactions play in the dynamics of the NAO is not fully understood; however, the two processes are dynamically interlinked. It is generally believed that atmospheric forcing dominates interactions over the North Atlantic basin and generates SST anomalies through turbulent heat fluxes or anomalous wind stress (Frankignoul, 1985); (Cayan, 1992). The ocean also contributes to the dynamics of air sea interactions via the influence of SST anomalies. The well-mixed ocean upper layer has a large heat capacity, resulting in an oceanic thermal signal that can persist for several months, which allows for a persistent thermal forcing of the overlying atmosphere (Frankignoul, 1985); (Kushnir et al. 2002).

Evidence for oceanic forcing of the NAO is suggested by studies of climate models (e.g., Rodwell et al. (1999), showing a significant relationship between the wintertime NAO and the leading mode of anomalous SSTs from the previous summer. The link between ocean and atmosphere at such long leads seems to be a result of the long persistence of the North Atlantic SST anomalies and thus serves as evidence for the oceanic forcing of the NAO (Kushnir et al.,2002). The link between ocean and atmosphere at such long leads seems to be a result of the long persistence of the North Atlantic SST anomalies and thus serves as evidence for the oceanic forcing of the NAO (Kushnir et al.,2002).

To further examine the correlations between the NAO and SST anomalies, Wang, et al, (2004) introduced the notion of the Granger causality Granger, (1969). Granger causality has been used to investigate physical systems (Kaufmann and Stern 1997); (Kaufmann et al. 2003) and is based on the notion of predictability.

Using this method, Wang, et al, (2004) regressed the detrended winter NAO Index onto the concurrent (winter) SST field and discovered the well-known tripolar pattern over the North Atlantic basin. Near the southeast of Greenland, and in the subtropics the SST is negatively correlated with the NAO. Between these two negative centres is an area of positive correlations located over the extension of the Gulf Stream. The results from Wang, et al, (2004) also show that the NAO is closely related to the Arctic Oscillation (AO).

Although Wang, et al, (2004) confirms that the wintertime NAO and SSTs shows the well-known tripolar pattern, the influence of the preceding seasons' NAO anomalies on the wintertime SST field are very limited. Instead, the preceding state of the ocean shows a significant causal relation with the dominant wintertime atmospheric circulation pattern (Wang, et al, 2004). This influence is mainly centred over the Gulf Stream area. Wang, et al, (2004) also states that only the Gulf Stream SST Index shows significant lead correlations with the winter NAO, and not Greenland or the subtropics SST's. These results suggest that the anomalous Gulf Stream SSTs are important in initiating disturbances of the atmospheric circulation over the wintertime North Atlantic.

Wang, et al, (2004) also maintains that the anomalous SSTs around the Gulf Stream may be more important in initiating disturbances of the atmospheric circulation over wintertime North Atlantic, while the tripolar pattern may be generated by positive feedbacks between two fields.

6.9 The North Atlantic Oscillation, surface current velocities, and SST changes in the Subpolar North Atlantic

Flatau, et al, (2003) investigated the changes in the ocean surface circulation in the subpolar North Atlantic associated with the interannual switch in the North Atlantic Oscillation (NAO) pattern from positive in the early 1990s to negative in the Autumn of 1995/1996. As a part of this investigation, the mean surface circulation was derived using surface drifter data and the anomalous circulation from drifters which was compared with that from altimetry.

The NAO is a major component of interannual to interdecadal variability in the North Atlantic area. Its atmospheric component is characterized by a sea level pressure (SLP) dipole between the Icelandic low and Bermuda high. Thompson, et al, (2000) suggested that the NAO is part of the more general Arctic zonally symmetric seesaw in the atmospheric mass over the polar cap and midlatitude zonal ring centred around 45°N and is related to the strength of the stratospheric polar vortex. While the NAO Index is usually based on the local SLP difference between Iceland and Portugal, the AO state is defined by the leading mode empirical orthogonal function of the monthly mean surface pressure north of 25°N (Thompson, Wallace 1998).

In the North Atlantic the high Index NAO and Arctic Oscillation (AO) are characterized by a larger meridional pressure gradient, stronger westerlies, and north-eastward displacement of the storm track compared with a low Index. The SST pattern that accompanies the positive

NAO regime is characterised by low temperatures in the polar regions, and higher SSTs between 25°N and 45°N.

Observations indicate that the midlatitude ocean responds to the surface flux anomalies created by an atmospheric circulation related to the NAO (Cayan, 1992). Joyce, et al, (2000) observed the changes in the Subtropical Mode Water (STMW) related to atmospheric buoyancy fluxes and hypothesized that a north–south shift of the Gulf Stream position associated with STMW modification could influence the midlatitude storms in the atmosphere and lead to a coupled oscillation in the North Atlantic Basin.

There is also evidence Sutton, Allen, (1997) that the SST anomalies forced by atmospheric circulation can propagate along the Gulf Stream and the North Atlantic Current, influencing the sea surface temperature in the North Atlantic about 7 years after their forcing by the original atmospheric disturbance. Forcing of the atmosphere by the ocean is more challenging to observe. Nevertheless, Czaja, Frankignoul, (1999) in their analysis of the covariance between atmospheric circulation and SST anomalies in the North Atlantic show maximum covariance at a 6-month lag (SST leading the atmospheric circulation). They suggest that the anomalous tropospheric circulation is driven by the anomalous heat flux related to SST in the North Atlantic. Observations of ice cover in the Arctic (Mysak and Venegas, 1998) show that fluctuation of sea ice extent can also contribute to changes in the atmospheric pressure and NAO pattern by influencing the surface heat flux.

Generally, the ocean–atmosphere coupling mechanism may involve the generation of the SST–ocean circulation anomaly by atmospheric anomalies, advection of anomalous SST by the ocean currents, or triggering the anomalous SST pattern by anomalous circulation and response of the atmosphere to the new anomalous SST field. Because of all the processes involved, the description of anomalous ocean currents related to NAO variability is important.

In 1995 there was a switch in the NAO Index. Using data from a World Ocean Circulation Experiment (WOCE) hydrographic section between Greenland and Ireland, Bersch, et al, (1999) noticed that relaxation of the NAO positive phase in 1995/96 was accompanied by decreased density in the Subpolar Mode Water, westward retreat of the subpolar front in the Iceland Basin, and suppressed spreading of the Labrador Sea Water. Reverdin, et al, (1999) documented the changes in ocean temperature between Iceland and Newfoundland. They noticed that interannual changes observed between 1994 and 1998 were larger than the

seasonal cycle. They concluded that although there was a strong correlation between the heat fluxes and temperature variability, not all the heat content change observed during this time could result from air–sea heat fluxes, and some other processes contributed to the heating observed after 1996.

Flatau, et al, (2003) defined the state of the NAO using the value of this Index averaged for the winter months (December to February). The NAO Index defined in this manner was predominantly positive in the 1990s following the trend that started in the 1980s. However, a short period of reversal occurred between 1995 and 1998, when the Index suddenly switched from a high positive value in the winter of 1994-1995 to a low value the following winter. In 1996-1997 the Index increased but remained negative and decreased again in 1997-1998. The positive NAO phase returned in winter 1998-1999.

A single-variable NAO Index, based on the pressure difference between Lisbon, Portugal, and southwest Iceland, (Hurrell, 1995), showed a different temporal pattern. It became negative in 1995-1996, but positive values returned in the two following years. The large positive values appeared again in 1998-1999.

Wang, et al, (2004) examined data from 687 drifting buoy's from the years 1992-1998, in the North Atlantic. Wang, et al, (2004) examined the mean circulation currents and assessed the variability of the circulation associated with changing NAO forcing. Analysis showed (Wang, et al, 2004) that the Ekman flow is strongest and south-eastward in the central North Atlantic between 50°N and 55°N, in the region of maximum wind speed, causing cooling due to southward Ekman advection in these areas. Ekman transport occurs when ocean surface waters are influenced by the friction force acting on them via the wind. Wang, et al, (2004) suggests that the stronger velocity of circulation that develops in winter becomes even more pronounced during the NAO positive years. This is consistent with the atmospheric circulation patterns, where strong westerlies and low pressure in the Icelandic low present during winter become more pronounced in positive NAO years.

Wang, et al, (2004) also considered the possible role of advection in NAO associated changes in sea surface temperature (SST) in the subpolar North Atlantic, as compared with surface heat fluxes. Hansen, Bezdek. (1996) showed that SST anomalies created by the surface fluxes can be advected by the surface currents. Wang, et al, (2004) analysis of North Atlantic SST for the years 1992–1999 indicates that a cold SST anomaly at 50°N was associated with

positive NAO developed in 1993 around 40°N and propagated eastward, until it was replaced by the warm anomaly in the winter of 1999-2002, as shown previously by Deser, et al, (2002).

Wang, et al, (2004) analysis of SST advection, showed that SST advection tends to cool most of the central subpolar region. Examining the zonal and meridional components of the advective flux indicates that this is mainly due to the eastward advection of cold water across the subpolar front. The northward advection of the warmer waters tends to oppose this cooling but since the meridional component of advective flux has smaller magnitude, the total advection is dominated by the zonal effects. In both NAO phases, the axis of cooling is centred just north of 50°N, stretching northward to about 60°N. Maximum cooling is observed where the geostrophic flow of the North Atlantic Current is almost perpendicular to the surface isotherms. The maximum cooling rate is large: more than 3°C month per month.

Wang, et al, (2004) concludes that the interannual changes observed in the drifter data were similar in pattern to the seasonal variability, with the enhanced winter characteristics of the flow observed during the NAO positive years. The most pronounced circulation changes observed in the North Atlantic basin showed the intensification of the north-eastward flow of water throughout the basin, coupled with the intensification of the cyclonic circulation in the Irminger Basin during the positive phase of NAO. These changes, coupled with SST temperature anomalies influence the SST distribution and could thus affect air-sea interaction in the North Atlantic Region.

More recently, Josey, et al, (2018) examined the role of the NAO and midlatitude SST variability during the cold anomaly SST period of 2001/2002 – 2016, with the peak of this cold anomaly experienced in 2015, known as the Big Blue Blob, in the North Atlantic. Josey, et al, (2018) identified that over long timescales, the NAO has been linked to causing a characteristic SST tripole pattern in the North Atlantic, primarily through heat surface exchange. This tripole exerts a positive feedback on the NAO through a rapid adjustment of the atmosphere. Josey, et al, (2018) identified a relationship between a horseshoe shaped pattern in North Atlantic SST and the winter NAO Index, with SST leading by up to six months. These results indicate a complex and dynamic relationship between the NAO and SST in the North Atlantic, with the first winter NAO initially generating a tripole SST pattern, through modified air-sea heat exchange, which has the potential to feed back at weekly timescales on the atmosphere, reinforcing the NAO in the first winter. Subsequently, the SST tripole evolves into the horseshoe pattern, which favours the development of further

positive NAO conditions in the second winter. This is likely to be caused by modifications in the ocean- atmosphere heat flux that affect atmospheric dynamics. Other recent works on the seasonal to annual prediction of winter NAO Index variation indicates that the climate system retains a memory of initial conditions for up to a year in advance (Dunstone, et al, 2016).

6.10 Section 2

6.11 The Gulf Stream and its influence on wintertime North Atlantic jet variability.

The ocean is an integral part of the climate system, but its impact on the atmosphere varies greatly from one region of the globe to another. Variations in midlatitude SST anomalies are readily balanced by small changes in the horizontal wind field, and thus the linear atmospheric response to midlatitude SST anomalies may be relatively shallow and weak. The most robust effects of midlatitude SSTs on the large-scale atmospheric circulation have been found in the context of the climatological-mean circulation (Kushnir, et al, 2002). Analyses of high-resolution SST and surface wind stress observations reveal that the climatological-mean near surface wind field is strongly influenced by large horizontal gradients in the SST field, such as those associated with the major western boundary currents. Results from numerical experiments run with and without sharp gradients in the SST field suggest that the climatological-mean ocean fronts play a key role in determining the location and amplitude of the extratropical storm tracks (Nakamura, et al, 2008), (Sampe, et al, 2010), (Small, et al, 2014), (Piazza, et al, 2016).

Observational analyses suggest that variations in SSTs in the vicinity of the Northern Hemisphere western boundary currents are linked to significant changes in the largescale atmospheric circulation (Czaja, Frankignoul, 1999) , (Ciasto, Thompson, 2004), (Frankignoul, et al, 2011).

Variations in SSTs in the Gulf Stream region and its extension can arise from forcing by the atmospheric flow, particularly in association with temperature advection from the cold continental regions to the west (Frankignoul, 1985), (Haney, 1985), (Kushnir, et al, 2002). They can also arise from forcing by the ocean circulation itself, especially near western boundary currents. (Frankignoul, 1985), (Reynolds, 2002), (Smirnov, et al, 2014).

To investigate the linkages between the atmospheric circulation and SSTs in the Gulf Stream extension, Thompson, (2016) generated a time series analysis of daily mean SST anomalies averaged over the region 37.5°–45°N, 72°–42°W. The Index (hereafter GSST) showed that positive values of the Index correspond to warmer-than-normal SSTs in the Gulf Stream

extension, and vice versa. Thompson, (2014) computed lag relationships between various fields and the GSST Index using daily mean data. Negative lags indicate results where the SLP (sea level pressure) and SST fields precede peak amplitude in the GSST Index, and vice versa for positive lags.

Results from Thompson, et al, (2016) showed that the most pronounced circulation anomalies are found at negative lags (i.e., the atmosphere leading variations in GSST), when positive SLP anomalies span much of the North Atlantic basin. Previous analysis of Deser, Timlin, (1997), Ciasto, Thompson, (2004) confirmed that the SLP anomalies at negative lags are consistent with forcing of the SST field by anomalies in the atmospheric circulation. In regions of large SST gradients, periods of anomalously warm SSTs over the Gulf Stream extension are consistent with anomalously southerly flow.

The regressions performed by Deser, Timlin, (1997) suggest that the several week period following anomalously warm conditions in the Gulf Stream extension is marked by anomalously low SLP over the Gulf Stream region and anomalously high SLP centred to the south of Iceland. Results from Wills, et al, (2016) show that SST variability in the Gulf Stream extension is associated with two distinct patterns of tropospheric circulation anomalies: Firstly, a pattern that peaks in amplitude several weeks before the largest anomalies in Gulf Stream extension SSTs, and is consistent with forcing of the SST field by the anomalous atmospheric circulation; and secondly a very different atmospheric circulation pattern that peaks in amplitude several weeks after the largest anomalies in Gulf Stream extension SSTs.

Kang, et al, (2013) investigated the influence of the Gulf Stream sea surface temperature (SST) front on the North Atlantic eddy driven jet and its variability by analysing the NCEP (National centres for Environmental Prediction) – CFSR (Climate Forecast System Reanalysis) dataset and a pair of AGCM (Atmospheric Global Circulation Model) simulations forced with realistic and smoothed Gulf Stream SST boundary conditions.

The Gulf Stream SST front acts to generate stronger meridional eddy heat flux in the lower troposphere and an eddy-driven jet over the eastern North Atlantic. The strong Gulf Stream SST gradient is found to be crucial in more accurately capturing the trimodal distribution of the eddy-driven jet latitude, with the more poleward climatological jet being the result of the jet occupying the northern jet position more frequently in the simulation forced with observed SSTs. The more frequent occurrence of the northern jet location is associated with periods of

high eddy heat flux over the Gulf Stream region. Composite analysis of high eddy heat flux events reveals that the significantly higher heat flux is followed by larger and more persistent poleward jet excursions, with upper-tropospheric eddy momentum fluxes acting to maintain the more poleward eddy-driven jet. Periods of high eddy heat flux over the Gulf Stream region are also shown to be associated with increased blocking frequency over Europe.

Jet streams contribute to determining the weather and climate of the midlatitudes. Jet streams are generally characterised according to the mechanisms by which they arise. A westerly jet occurs due to the angular momentum conservation of the poleward moving air (Held, Hou, 1980). Eddy-driven jets occur along the midlatitude storm tracks, where synoptic-scale eddies generate momentum flux convergence (Waterman, et al, 2013). Whereas subtropical jets are confined to the upper troposphere, eddy-driven jets extend through the entire depth of the troposphere and are responsible for the prevailing surface westerlies. Whilst subtropical and eddy-driven jets are usually not clearly separated, they tend to be well separated over the North Atlantic in winter, where thermal forcing of the subtropical jet is relatively weak (Li, Wettstein, 2012) and intense storm track activity generates a strong eddy-driven jet in the extra tropics.

Wintertime variability of the eddy-driven jet over the North Atlantic and Europe is strongly related to the North Atlantic Oscillation (NAO). Woollings, et al, (2010) analysed the nature of the eddy-driven jet to understand the wintertime variability. Woollings, et al, (2010) found that the North Atlantic eddy-driven jet exhibits three preferred latitudinal positions during winter, closely related to the variability of the NAO and East Atlantic patterns. The tri-modal distribution of the eddy-driven jet was found to be a robust characteristic of the variability throughout the twentieth century (Woollings, et al, 2010). Analysis demonstrated that the most common transitions between the three eddy-driven jet regimes involve consistent Rossby wave-breaking and associated momentum convergence, and to that associated with the different phases of the NAO (Rivière, Orlanski, Martius et al, 2007).

Recently, the dominant transitions of the North Atlantic eddy-driven jet position have been linked to variability of storm-track activity in the upstream region. Frame, et al, (2013) suggest that the storm track activity in the western North Atlantic is similar to a nonlinear oscillator. Frame, et al, (2013) showed that periods of intense storm track activity are often followed by periods of lower activity, during which the baroclinicity increases, leading to another period of intense storm track activity, creating a recurring cycle. Frame, et al, (2013)

showed that the storm track cycle upstream is closely linked to the preferred transitions of the eddy-driven jet. Periods of intense storm track activity upstream tend to shift the jet to the northern position, followed by a period of lower storm track activity and increasing baroclinicity when the jet tends to be located first in the southern regime and then the middle jet regime, where the baroclinicity peaks.

During winter, the restoration of the strong baroclinicity in the western North Atlantic can primarily be attributed to upstream orography and land–sea temperature contrast, but the sharp Gulf Stream sea-surface temperature gradient is also important contributing factor (Minobe, et al., 2008, 2010). The strong Gulf Stream SST gradient acts to increase the local baroclinicity through intense sensible and latent heat fluxes, and also anchors an intense precipitation band (Minobe, et al., 2008, 2010),(Kuwano-Yoshida, et al, 2010).

Minobe, et al, (2016) investigated the influence of the Gulf Stream on The North Atlantic eddy driven jet and its variability. Analysis of a pair of atmospheric general circulation model (AGCM) simulations, forced with realistic and smoothed Gulf Stream SST boundary conditions, and found that the response of the mean jet to the Gulf Stream SST small-scale features consists of a weakening of the westerly winds over Europe, a strengthening of the North Atlantic eddy-driven jet on the poleward flank.

Minobe, et al, (2016) found that at 850hPa, the eddy-driven jet is well separated from the subtropical jet, which is strongest in the upper troposphere. Analysis suggests the presence of the sharp Gulf Stream SST front results in both a northward shift in the mean eddy-driven jet and intensified local meridional eddy heat transport. Novak, et al, (2015) has shown that, during periods when the meridional eddy heat transport over the Gulf Stream is strong, the eddy-driven jet tends to be in a more northern position in the Atlantic Basin. This would suggest that the presence of the Gulf Stream SST front could generate a more northern mean eddy-driven jet through increased meridional eddy heat transport.

The North Atlantic Eddy driven jet operates in a tri-modal distribution, however, has been shown (Woolings, et al, 2010) to skew to a more pronounced degree towards the northern Atlantic, see figure 33. Based on maps of the mean meridional eddy heat transport, (Minobe, et al, 2016) hypothesised that the increase in frequency of northern jet occurrence may be as a result of the increased upstream storm track activity, consistent with the findings of Novak, et al, (2015), Madonna, et al, (2017).

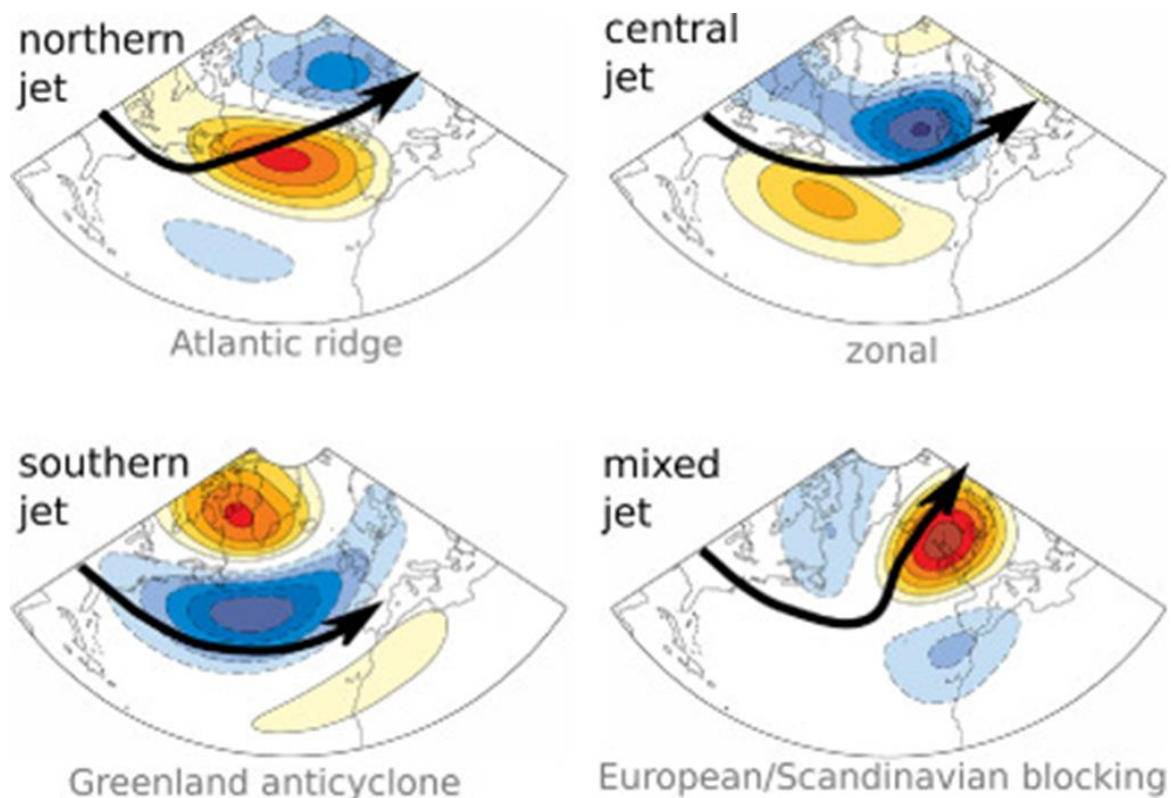


Figure 33 The Eddy driven jet positions (Woolings, et al, 2010).

6.12 The North Atlantic Drift Current

The North Atlantic Drift Current (NADC) is a slow-moving body of water located between about 50°-64°N and 10°-30°W (Drozdiak, 2005). NADC is also considered to be an extension of the North Atlantic Current. It is recognized as a shallow, widespread and variable wind-driven surface movement of warm water that covers a large part of the eastern subpolar North Atlantic and slowly spills into the Nordic Seas. It is also sometimes included as the Subarctic or Subpolar Front as it is thought of as the boundary between the cold, subpolar region and the warm, subtropical gyre of the North-eastern Atlantic. Generally, the NADC originates from the Gulf Stream-North Atlantic Current system and from the northern Sargasso Sea. These waters then slowly flow northward into the Labrador and European basins (Veron, et.al, 1999), eventually becoming the NADC as it enters the Iceland Basin.

The current is unique in that it transports warm waters to latitudes higher than in any other ocean, thereby producing the moderate climate of Europe, and influencing local sea surface temperatures in the North Atlantic region. Because of the rapid advection of the North Atlantic gyre, the temperature of the surface waters of the NADC almost always exceeds that of both surrounding waters and the overlying atmosphere (Rossby, 1996). Water temperatures in March are at around 8°C in the NADC while ranging from 2°C to 6°C in surrounding waters (Rossby, et. al., 1998).

The region that is occupied by the NADC is bounded by the cool Irminger Current to its west, while its southern and eastern border is weakly constrained by the extension of the North Atlantic Current that bends north-eastward, flanking the western edge of the Rockall Plateau. Eventually, the NADC feeds into the Norwegian Current to the north, past Iceland. The loop of the East Iceland Current acts as a boundary along the northern extent of the NADC (Rossby, 1996).

Mostly warm surface water trapped between cooler, faster flowing subpolar currents to its east, and the Rockall Plateau to its west, the NADC in the Iceland Basin can extend to a depth of about 1000 meters (Bower et. al., 2002), creating warmer sea surface temperatures than the surrounding ocean.

According to Krauss, Käse,(1984), the North Atlantic Current, is the main source of eddy energy in the North Atlantic. In the upper ocean, eddy kinetic energy decreases from about $1000 \text{ cm}^2\text{s}^{-2}$ (near Newfoundland) to about $300 \text{ cm}^2\text{s}^{-2}$ in the NAD near western Scotland. Krauss, Käse,(1984), maintains that the NADC exists as a region, rather than an actual stream-like current, where the main thermocline shoals to the surface along which a stronger baroclinic transport is sustained compared to the surrounding Atlantic Ocean. The NADC feeds two well-defined currents, transporting warm, saline water to both the northward-flowing Norwegian Current and to the southward-flowing Canary Current (Rossby, 1996). The southern-most extent of the NADC is marked by the northernmost boundary of the subtropical circulation system, (the eastward flowing NAC along 52°N). The zonal flow across the Mid-Atlantic Ridge seem to occur in the form of various branches (Krauss, 1996), some of which turn northwards into the subpolar region, feeding the thermohaline circulation; and others turning south and entering the recirculation of the wind-driven subtropical gyre (Rossby et. al., 1998).

The NADC is characterised by the contribution of warm waters from the North Atlantic Drift current that is now understood to be the main moderating force of the climate over western

Europe (Giraudeau et. al., 2006). The path of the NADC is clearly seen in the warming of the air over the western North Atlantic extending eastwards-and intensifying-into the Norwegian Sea (Rossby, 1996). A positive link exists between the NADC penetration into the Norwegian Sea and the North Atlantic Ocean Index, defined as the difference in sea-level pressure between two stations close to the low over Iceland and the high over the Azores, (Blindheim et. al, 2000). High NAO indices imply that only a narrow flow extends northward of the Faeroe-Iceland Strait, resulting in a sea-surface temperature (SST) cooling at the scale of the Greenland and Norwegian basins, owing to the spread of polar waters eastward, in the North Atlantic. The strong westerlies caused by the high winter/spring indices bring in warm, moist air over the European continent and leads to a rather mild, maritime winter, and increased local sea surface temperatures in the North Atlantic. Conversely, a low winter/spring index reflects weaker mean westerlies over the NAO, which in turn corresponds to colder European winters, and decreased local sea surface temperatures in the North Atlantic (Eynaud, et. al., 2002).

Overall, a 13-15 year see-saw pattern oscillation between the Gulf Stream and the NADC was observed by Eynaud, et al, (2002), which showed that at times of increased trade wind strength, tropical and subtropical waters are forced across the equator, enhancing the pool of warm water to be transferred to the high latitudes of the North Atlantic via the Gulf Stream and North Atlantic Drift, thereby increasing the pull of the thermohaline convective conveyor, see figure 34,(Hurrell, 1995).



Figure 34 The location of the North Atlantic Drift (Eynaud, et al, 2002).

6.13 Atmosphere-Ocean interaction

Air-sea feedbacks have been hypothesized to be an important contributing factor to tropical Atlantic variability. Positive feedback means that the atmosphere and oceans are mutually reinforcing each other and thereby the two media are coupled. Negative feedback usually indicates that the atmosphere is merely forcing the oceans. Analysis of the relationship between North Atlantic SSTs and large-scale atmospheric circulations, have shown that over longer time scales (seasonal/annual) the SST patterns in the North Atlantic can be strongly influenced by the large-scale atmospheric circulation, through both anomalous heat fluxes and wind stresses (Frankignoul, 1985).

6.14 Response of the Atlantic Ocean circulation to Greenland Ice Sheet melting.

Stommel, (1961) highlights that the Atlantic Meridional Overturning Circulation (AMOC) may be sensitive to changes in the freshwater balance of the northern North Atlantic. Freshening of the surface waters in the Nordic and Labrador Seas inhibits deep convection and hence the production of North Atlantic Deep Water (NADW), which feeds the deep southward branch of the AMOC. One of the potential sources of freshwater that might affect the AMOC is enhanced freshwater discharge from the Greenland Ice Sheet (GrIS). It has become increasingly clear that the mass balance of the GrIS is negative (Wu, et al, 2010), with the mass deficit continuing to increase.

The sensitivity of the AMOC with respect to freshwater fluxes has been studied using both Ocean General Circulation Models (OGCMs) and fully coupled climate models. The freshwater input and associated surface freshening has a strong impact on the deep-water formation process in the Labrador and Nordic Seas. The strongest discharges from there are within, and upstream of the Labrador Sea, and here sea surface salinities (SSS) are impacted most strongly, showing an overall decrease.

To demonstrate the impact the meltwater from the Greenland ice sheet can have on sea surface temperature, Cortijo, et al, (1997) examined the changes in distribution of sea surface temperature and salinity in the North Atlantic between 40°N and 60°N, during the time interval between 40 and 30 Kyr BP. This time period is associated with a large iceberg discharge event, associated with the deposition of Heinrich layer 4. Analysis showed that the meltwater input during the deposition of Heinrich layer 4 resulted in a 1-2 Kyr temperature decrease of about 2°C and a salinity decrease in the range of 1.5%-3.5% between 40°N and 50°N. Sites above 50°N did not experience significant salinity variations, however a much

larger area was affected by the reduction in sea surface temperature. Analysis concluded that the decrease in SST of around 2°C was probably sufficient to stop significant deep convection in the central North Atlantic. Cortijo, et al, (1997) also highlights that in higher latitudes, and Greenland in particular, are much more sensitive to climatic variations, and changes therefore in sea surface temperatures that lower latitudes.

6.15 Labrador Sea ice cover and North Atlantic SST.

Sea ice is an integral component of the physical climate system, modulating surface albedo, turbulent air-sea energy exchange, and upper ocean stratification. Ice cover in the Labrador Sea exhibits substantial year-to-year variability, particularly during the winter season, as shown by Parkinson, et al, (1999). The prevailing positive polarity of the NAO in recent decades has contributed to the retreat of the winter ice edge in the Greenland-Barents-Norwegian Seas and to an advance in the Labrador Sea, according to Deser, et al, (2002).

In addition to longer trends, decadal timescale fluctuations are prominent in many physical variables within the Labrador Sea, including upper ocean salinity, sea surface temperature, and sea ice extent. A lag association between decadal fluctuations in ice and sea surface temperature (SST) was reported by Deser, Blackman, (1993). They found that periods of enhanced winter ice cover in the northern Labrador Sea tend to precede colder than normal SSTs east of Newfoundland, to the North Atlantic by 1–2 years. Anomalous advection of cold, fresh water by the Labrador Current was suggested as a possible mechanism linking the ice and SST variations.

Subsequent studies by Reverdin, et al, (1999) and Belkin, et al, (1998) investigated the horizontal and vertical structure of decadal-scale salinity and temperature fluctuations in the northern North Atlantic and slope currents of the Labrador Sea. Their results confirmed a propagating signal of cold, fresh anomalies from the Labrador Sea to the north-eastern subpolar Atlantic in sea surface water.

Deser, et al, (2002) investigated the link between sea ice variations in the Labrador Sea and subsequent SST fluctuations in the subpolar North Atlantic. Deser, et al, (2002) concluded that three periods of anomalously high winter ice cover are identifiable in the Labrador Sea after 1953: 1972–1974, 1983–1985, and 1990–1994 (a weaker episode occurs in 1957–1959). Positive ice cover anomalies are consistently accompanied by below-normal SSTs in the subpolar Atlantic and less consistently by positive SST anomalies in the western subtropical gyre. The subpolar Atlantic SST anomalies persist 1–3 years after the decay of the ice cover

anomalies and in some cases exhibit a tendency for eastward movement. There is also a concurrent association between ice cover anomalies in the Davis Strait and SST anomalies over the North Atlantic, suggesting that the joint ice/SST anomaly patterns are due to a common large-scale atmospheric forcing.

6.16 Currents

Strong tidal currents are common along the north and east coast of Ireland and play a vital role in the transportation and distribution of sea surface temperature heat. The tidal current flow is particularly energetic entering the Irish Sea from the St. Georges Channel and the North Channel. Tidal current flows are relatively low along the west and south coasts. The bathymetry and hydrography of Ireland's coastline influences the local tidal currents. The large tidal currents are commonly located between land masses or adjacent to headlands. These narrow straits, relative to Ireland's close proximity to the Scottish and English coastline cause a funnelling effect, increasing the velocity of the tidal current flow. (Elliott, 2002).

The spring tidal ranges experienced over the Celtic Seas region are shown in Figure 35 A. In the open Atlantic tidal waves are generally small but they increase as they move eastwards across the shelf and are further enhanced by the funnelling effect of bays and estuaries. The general flow of tidal waves in Irish waters is shown in Figure 35 B. These propagate from both north and south, meeting just south-west of the Isle of Man at an amphidromic point (a point at which there is no variability in depth due to tidal activity). There is another amphidromic point south of Islay on the Malin Shelf. Tidal ranges on the Malin Shelf from 0.5m on a neap tide (1m on a spring tide) in the Sound of Jura just south of the amphidromic point south of Islay, to 1.6m on a neap tide (4.5m on a spring). Further offshore and north of Skye the tidal range is reduced. Within the Irish Sea maximum tidal ranges occur on the Lancashire and Cumbria coasts where the mean spring tides have a range of 8m, contrasting with Carnsore Point on the south-eastern Irish coast where the range is only 1.75m, (Elliott, 2002).

Surface tidal currents reach a speed of more than 4 knots in St. George's Channel, near the Irish coast, and are locally strong elsewhere. Currents are weakest in the west-central Irish Sea. The greatest ranges of tide occur on the northwest English coast. Tidal streams enter the Irish Sea from both the north and the south, meeting near latitude 54° N, just south of the Isle of Man, (Elliott, 2002).

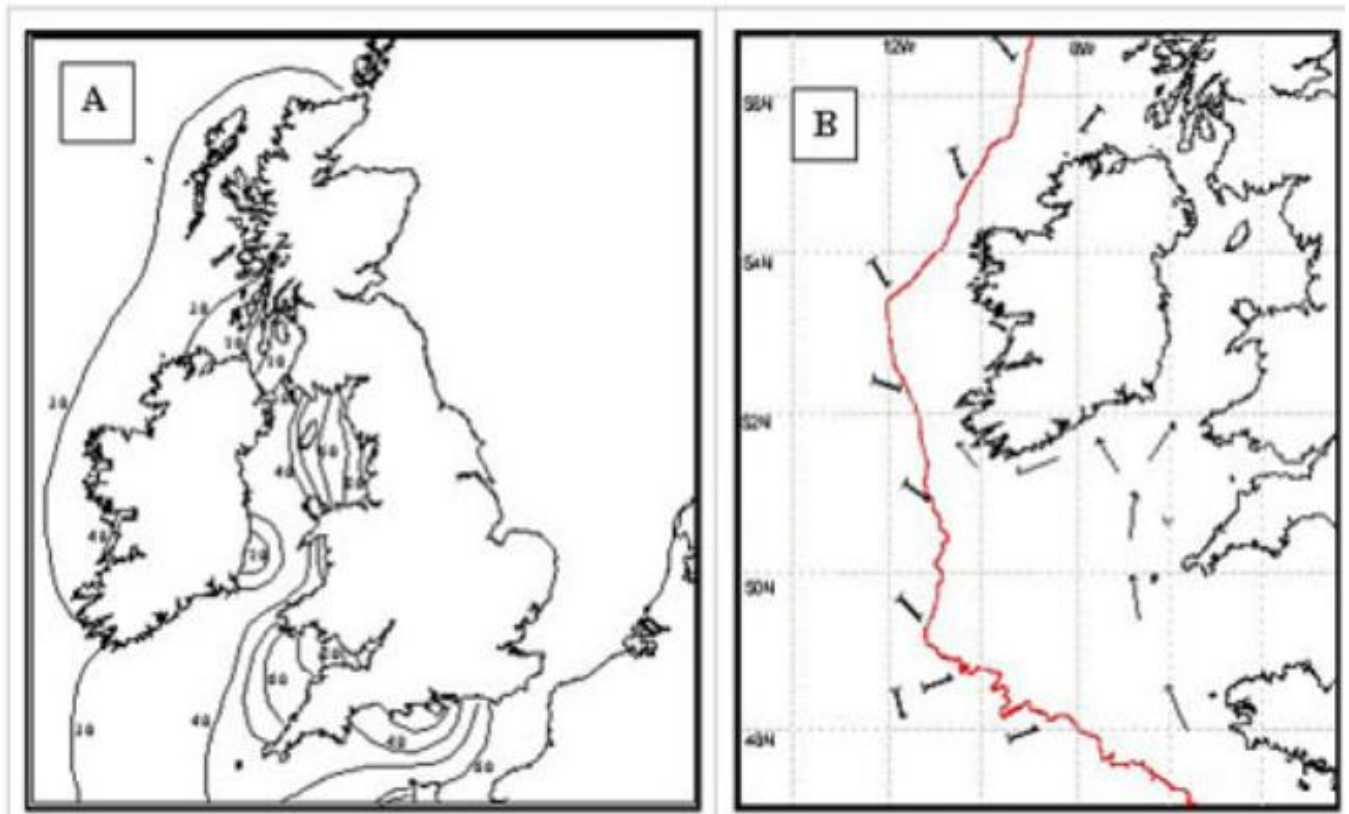


Figure 35 The Spring tidal ranges experienced over the Celtic Sea (Elliott, 2002).

6.17 Analysis of wave heights in the North Atlantic that impacted Ireland.

Analysis of wave heights during the periods of frequent storm events around Ireland's coastline shows a relationship between the identified clusters of storm events and increase in global wave heights. Both the increase in the frequency of storm events and a general global increase in wave height have a direct influence on SST around Ireland's coastline, as these processes contribute to increase mixing of water, with subsequent effects on SST variations (Cao, et al, 2021).

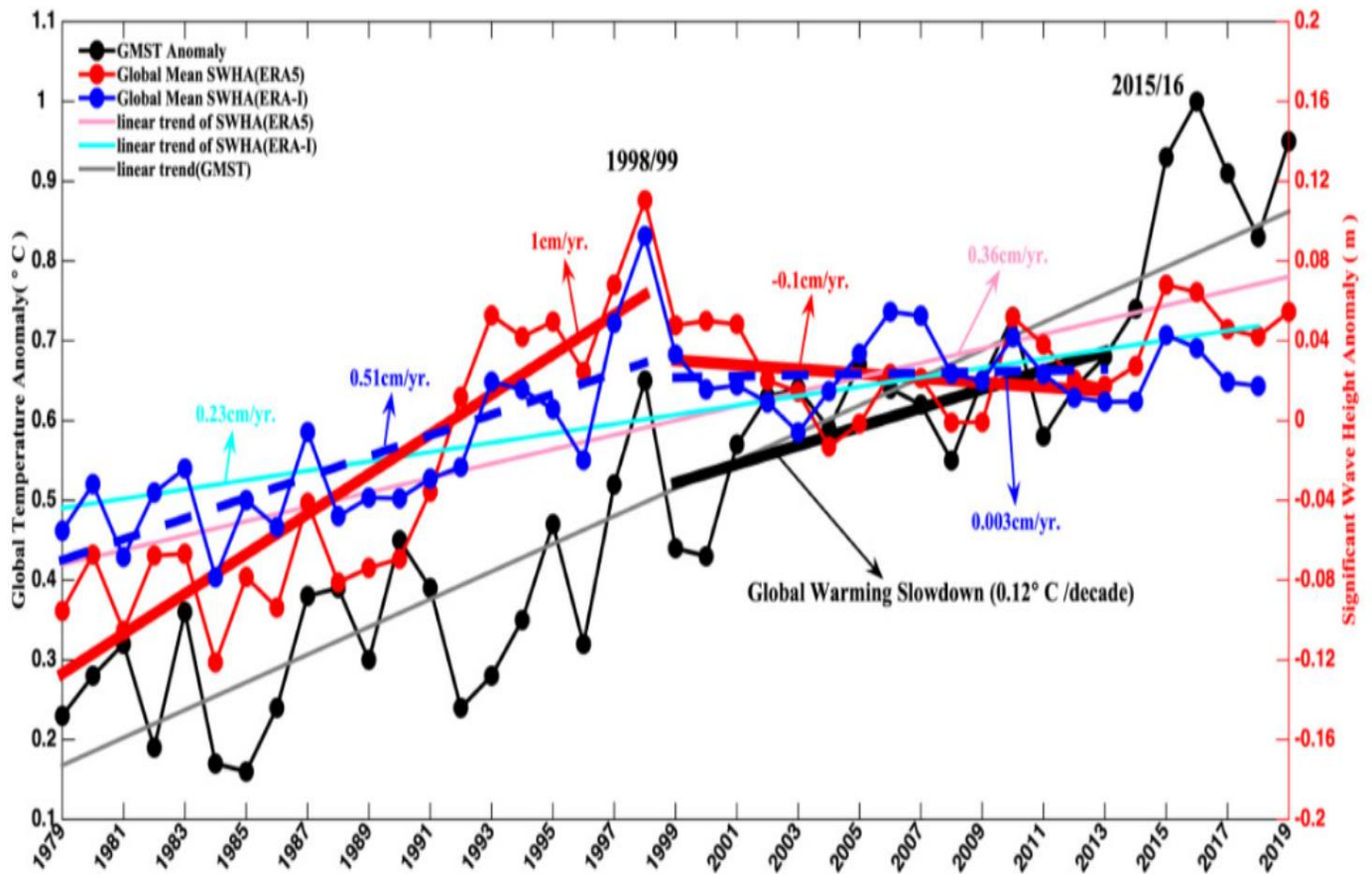


Figure 36 Trends in global wave heights from 1979-2019 (Cao, et al, 2021).

Analysis of Lozano, Swail, (2002) demonstrates the relationship of storm activity in the North Atlantic and wave height variability between 1979-2010. The increase in wave heights in the North Atlantic can be attributed to the northward displacement of the storm tracks in the North Atlantic. This results in an increase in wave heights approaching Ireland's coastline (Lozano, Swail, 2002). Analysis showed that the most significant factor in influencing an increase in wave heights in the North Atlantic is the northward shift in the trajectory of storms across the North Atlantic. Changes in the position of the jet stream previously discussed are responsible for the transportation of storm tracks towards Ireland, and can contribute to the transportation of colder waters from the Labrador Current being transported towards Ireland.

6.18 Conclusion

The processes mentioned above are highly important for governing the local sea surface temperature variations around Ireland's coastline. As the above causation is sea surface temperature variations, are located either directly in the North Atlantic, such as the North Atlantic Drift current, or indirectly influence the currents, constitution, and the sea surface temperatures of the North Atlantic, such as the Gulf Stream, these processes govern the

patterns of sea surface temperature variations around Ireland, on a monthly, seasonal and annual basis.

The first four topics mentioned relate to the broader oceanic and atmospheric processes that influence the Atlantic, and North Atlantic sea surface temperatures, and subsequent atmospheric processes. The following four topics discussed relate specifically to the North Atlantic and in particular Irish sea surface temperature variations, as these oceanic and atmospheric processes are directly responsible for governing changes in the sea surface temperatures and subsequent atmospheric conditions experienced around Ireland's coastline.

Chapter 7 Discussion

7.1 Introduction

Previous analysis of the mean annual and seasonal sea surface temperature variations revealed that there were spells of maximum and minimum sea surface temperature recorded for each buoy. In this section, the various influencing factors that contributed to the annual variation of sea surface temperature for each buoy, and the top spells of maximum and minimum SST were assessed. Both atmospheric and oceanic processes were assessed as possible contributing factors to the variations in sea surface temperature. In particular, processes such as atmospheric pressure, air temperature, the NAO Index and the North Atlantic hurricane season tracks were assessed to determine any correlation with these processes and a variation in sea surface temperature around Ireland's coastline.

7.2 M2

Significant variations in annual SST

As the years 2014-2015 recorded the joint largest variation in SST, showing a decrease in mean annual SST of 0.6°C, various parameters were assessed to determine the contributing factors and influences of this decrease in SST. Analysis of air temperatures shows a variation in the mean annual air temperature between 2014-2015 of 0.1°C, which would not solely contribute to the decrease in SST.

NAO Index value analysis for 2014 showed that there were unstable NAO Index conditions, showing a non-stationary body of water around M2 during the months of May, June, August and October, all of these months recording negative NAO Index values ranging from -0.9 to -1.6. Analysis of the North Atlantic hurricane season track shows that in August 2014, the tail end of Hurricane Bertha, reducing to an extratropical storm, tracked towards Ireland. This may have largely contributed to disturbing the body of water surrounding M2, leading to a reduction in SST. The NAO Index value at this time of the extratropical storm was -1.6, confirming a mixed signal.

NAO Index value analysis for 2015 showed that there were significantly unstable NAO Index conditions, similar to 2014, showing a non-stationary body of water around M2 during the months July, August and September. The NAO Index value was particularly unstable in July 2015 with a value of -3.1. Analysis of the North Atlantic hurricane season for 2015, does not

show any predominant tropical storm or depression in July 2015, that would have contributed to the significantly unstable NAO Index value.



Figure 37 The track of Hurricane Bertha 2014 (NOAA, 2020)

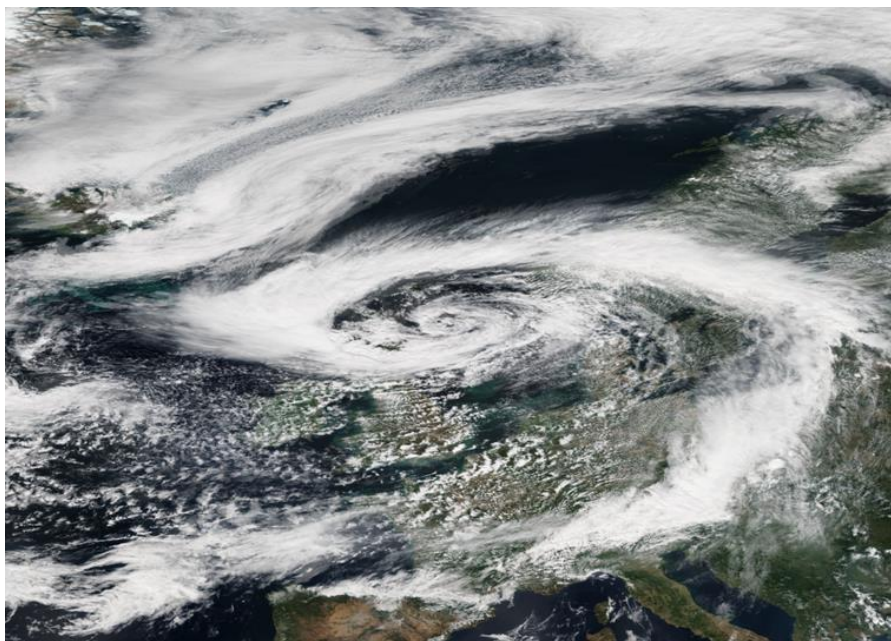


Figure 38 Satellite image of Hurricane Bertha over the North Sea 2014 (NOAA, 2020).

Spell analysis

The top ten spells of maximum SST for M2 were July 2013. For the top ten maximum SST values for M2, the NAO Index remained stable at 0.67, showing a stationary and stable NAO. This suggests that there was a consistent and undisturbed block of water surrounding Ireland, that was not mixed due to storm activity. The top ten minimum SST from M2 were recorded in December 2009 and March 2013. In December 2009, the NAO Index was 0.95, showing stationary and stable conditions. However, the NAO Index was -1.61 in March 2013, showing unstable conditions with the possibility of mixing water contributing to the minimum SST recorded.

Analysis of two days before and two days after the maximum recorded SST from M2 were conducted. The maximum SST for M2 were recorded on the 17/07/2013 and the 18/07/2013. Two days before the 17/07/2013, there was an increase in the wind speed and gust speed, however this would not be categorised as storm level gusts. The air temperature was lower in the two days preceding the 17th July and 18th July of March 2013. Atmospheric pressure was also lower, preceding the 17th July and 18th July. The two days after the maximum recorded SST for M2 on the 17th and 18th of July 2013 shows a decrease in both wind and gust speed, and a increase in mean air temperature. There was a decrease in mean atmospheric pressure in the two days following the 17th July and 18th July.

As there was an increase in wind speed and gust speed, this contributed to the transportation of atmospheric systems towards Ireland. There was however a decrease in atmospheric pressure which would typically be associated with unsettled weather conditions. These atmospheric parameters would usually be associated with a decrease in SST however the opposite is witnessed. The only consistent and stable influencing factor in governing the maintenance of maximum SST recorded in July 2013 was a stable and stationary NAO Index. Analysis of the North Atlantic hurricane season tracks shows that there was no hurricane activity that occurred at the same time as the spell of maximum SST. The NAO Index coupled with the land-sea heat absorption and retention rates are the only consistent factors governing the spells of maximum recorded SST for M2, which occurred in July 2013.

There were two spells of minimum SST recorded for M2, which occurred in December 2009 and March 2013. Analysis of two days before and two days after the minimum recorded SST from M2 was conducted. There was an overall increase in the daily mean gust speed in the

two days before and after the minimum recorded SST. There was also a increase in the daily mean atmospheric pressure for the two days before and after the 30th and 31st of March 2013, but not for the 27/12/2009. There was a decrease in daily mean air temperature for the two days before and after the minimum SST dates. Overall, there appears to be a relationship with increased wind and gust speed, and a decrease in air temperature on the minimum SST for M2. The NAO Index values for these two spells of minimum SST, showed that for December 2009, the NAO Index value was -1.9, showing unstable conditions and a non-stationary body of water surrounding M2 at this time. Similarly for the spell of minimum SST in March 2013, the NAO Index value at the time was unstable, recording a value of -1.6 and showed a non-stationary body of water around M2 during this time.

Analysis of the North Atlantic hurricane season tracks showed that in August and October the remnants of an extratropical storm tracked towards Ireland. In August 2009 before its dissipation near Ireland, the hurricane was classified as a major hurricane, Bill, and tracked along the North Atlantic before dissipating to an extratropical storm that tracked along the south, and southwest of Ireland. Due to the month and the position in which it struck the south and southwest coast of Ireland, it is unlikely that Hurricane Bill had a significant impact on influencing the spell of minimum SST witnessed in December 2009 for M2. In October 2009, tropical storm Grace, which originated in the Northeast Atlantic Region, tracked towards Ireland before dissipating to an extratropical storm, impacting the southeast and east coast of Ireland. 48mm of precipitation was recorded in Wexford on the East coast of Ireland, with gales of up to 18m s^{-1} being recorded during the storm. As this weather event occurred in October, it is possible that the extratropical storm Grace, could have contributed to the spell of minimum SST that occurred in December 2009, due to a mixing of water as a result of wind gusts and precipitation volumes.

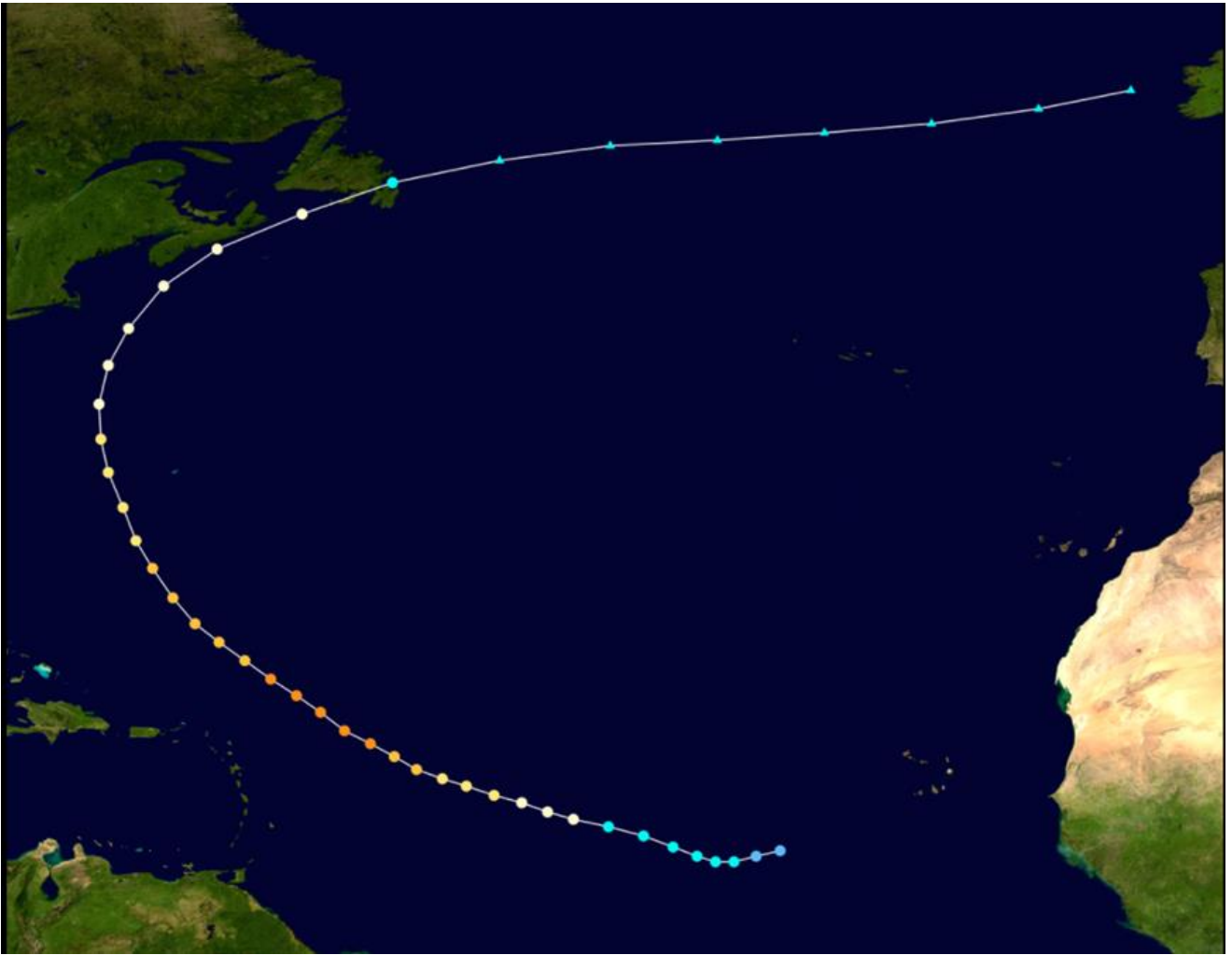


Figure 39 The track of Hurricane Bill 2009 (NOAA, 2020).

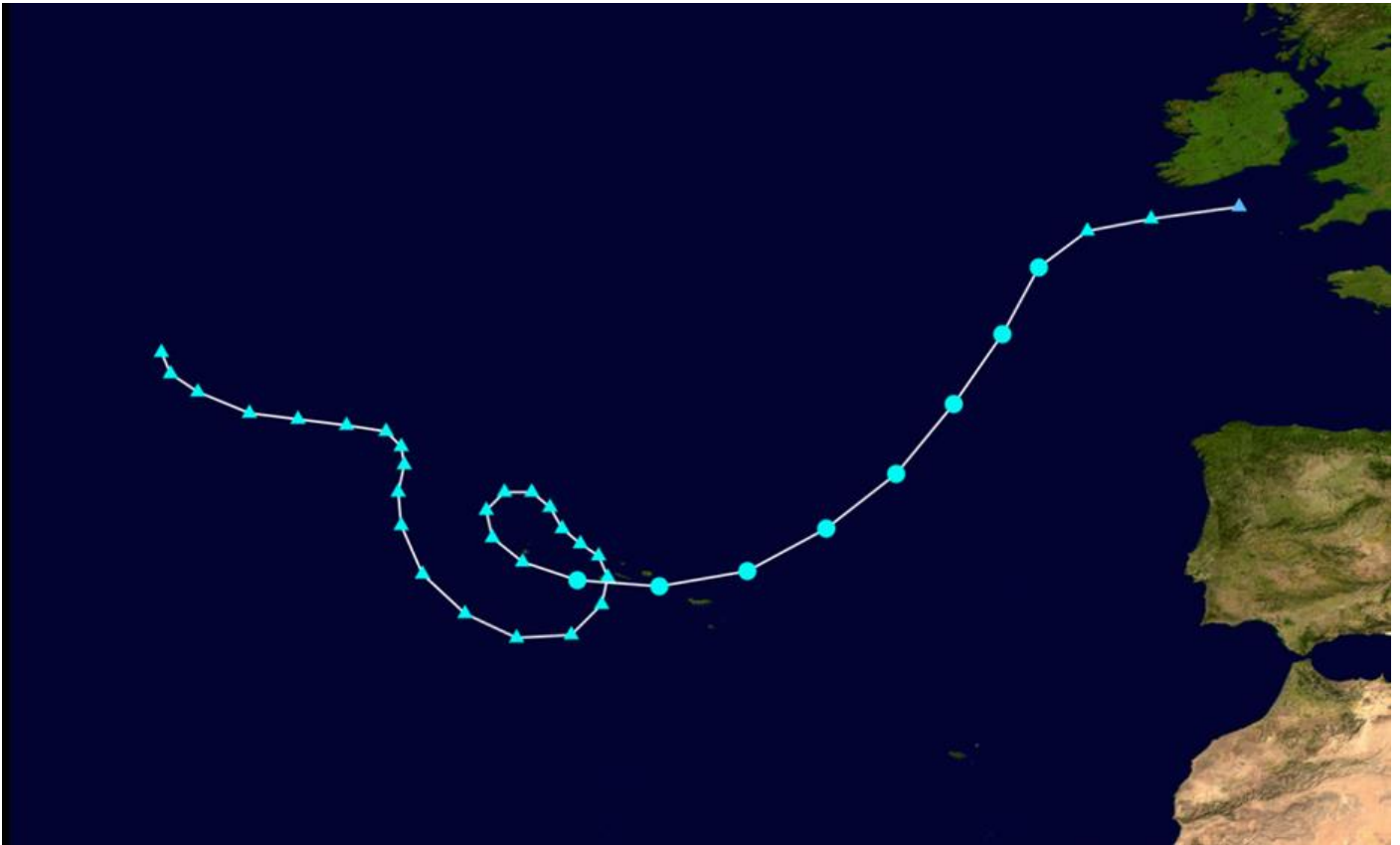


Figure 40 The track of Tropical Storm Grace 2009 (NOAA, 2020)

NAO Index value analysis for 2015 showed that there were significantly unstable NAO Index conditions, similar to 2014, showing a non-stationary body of water around M2 during the months July, August and September. The NAO Index value was particularly unstable in July 2015 with a value of -3.1. Analysis of the North Atlantic hurricane season for 2015, does not show any predominant tropical storm or depression in July 2015, that would have contributed to the significantly unstable NAO Index value.

7.3 M3

Significant variations in annual SST

The most pronounced mean annual variation in SST was recorded between 2007-2008, showing a decrease in mean annual SST of 0.3°C, from 13°C to 12.7°C. As this variation in SST is relatively small, this means that overall, there was stable mean annual SST conditions recorded by M3. Various parameters were assessed to determine the contributing factors and influences of this decrease in SST.

The annual mean air temperature was assessed as a possible contributing factor to this change in mean SST. The annual mean air temperature for 2007 was 12.6°C. Assessment of the missing air temperature data revealed that 1.3% of air temperature data was missing for the year of 2007, but despite this missing data, the mean annual air temperature can accurately represent the true mean annual data, as there was less than 10% of the total data. The annual mean air temperature for 2008 was 12°C. Analysis of the mean air temperature for 2008 showed that there was less than 1% missing data, also creating an accurate representation of the true annual air temperature. This data was used to establish any correlation between air temperature and SST. Between 2007-2008, there was a decrease in SST of 0.3°C. This corresponded with a decrease in mean annual air temperature of 0.6°C. The decrease in SST could be associated with a corresponding decrease in mean annual air temperature but cannot be attributed solely to this change in air temperature, but likely coupled with other parameters.

Spell analysis

The top ten spells of maximum SST were analysed for M3 to assess the other parameters influencing SST. The top ten maximum SST for M3 were in July 2014. The corresponding NAO Index value at this time was 0.18. The relatively low and consistent NAO Index values suggest there was a distinct signal, showing that there was little storm activity around the time of the maximum SST values for M3. This suggests that there was a consistent and undisturbed block of water surrounding Ireland, that was not mixed due to storm activity. However, in the following month, August 2014, there is a significant decrease in NAO Index values to -1.6, either showing the presence of a disturbance to the SST as the result of storm activity or other atmospheric processes, or however that the NAO Index value for July 2014 which recorded the top ten spells of maximum SST as the result of a transportation of a warm block of water during this time or the influence of other atmospheric and hydrological processes. To assess this, analysis of the other atmospheric processes that influence SST were examined.

Air temperature data, gust speed and atmospheric pressure was not recorded for the period of maximum SST values for M3. Local weather observation stations did not have records of air temperature data available prior to the 16/10/2015, so these could also not be used to ascertain air temperature data. Analysis of the North Atlantic hurricane storm track showed that although there was a hurricane event that occurred on the 28th June 2014, Hurricane Arthur which originally developed from a non-tropical area of low pressure over the South-

eastern United States that emerged into the western Atlantic on the 28th June (Berg, 2015). Hurricane Arthur tracked north north-eastward before eventually dissipating to an extra tropical cyclone, reaching the coast of Nova Scotia on the 5th July 2014 (Berg, 2015). Due to the location of the origin of this hurricane and in particular the direction of its track north north-eastward along the American and Canadian coastline, although this hurricane event occurred at the same time as spells of maximum SST around M3, it is unlikely that this hurricane event could have been a significant contributing factor to these spells.

The top ten minimum SST for M3 were recorded in March 2020. The corresponding NAO Index value at this time was 1.01. The minimum spells of SST were recorded on the 19th and 20th of March 2020. Analysis was firstly conducted on the mean air temperature values to establish any correlation between changes in air temperature and corresponding SST. M3 was missing the air temperature data for March 2020, so the air temperature data was calculated using data from Cork Airport weather station. Analysis was conducted of various parameters such as atmospheric pressure, wind direction, wind speed, and air temperature for two days before the spell of minimum SST (17/03/2020 and 18/03/2020), the spells of minimum SST (19/03/2020 and 20/03/2020), and two days after the spell of minimum SST (21/03/2020 and 22/03/2020).

In the two days before the spell of minimum SST for M3, atmospheric pressure was lower than the atmospheric pressure during the spell of minimum SST. There was a significant reduction in wind speed on the 18/03/2020 which is the day before the spell of minimum SST recordings. This reduction was from 17mph on the 17/03/2020 to 8mph on the 18/03/2020. Similarly, there was a significant reduction in air temperature from the 17/03/2020 which the mean air temperature was 8.4°C compared to the 18/03/2020 which recorded a mean air temperature of 5.6°C. Based on this analysis, in the two days before the spell of minimum SST, an increase in atmospheric pressure, coupled with a decrease in both wind speed and air temperature, contributed to a reduction in SST of 0.1°C.

On the days of the spells of minimum SST, there was an increase in atmospheric pressure compared to the two days before the minimum SST spells. There was also an increase in mean wind speed, following the low wind speed recorded on the 18/03/2020 of 3 m s⁻¹. There was a decrease in air temperature on the days of minimum SST, compared to two days prior. The increase in atmospheric pressure, increase in wind speed and a decrease in air temperature contributed to the spell of minimum SST recorded on the 19/03/2020 and 20/03/2020.

In the two days following the spell of minimum SST, there was a decrease in atmospheric pressure compared to the spell of minimum SST. There was a decrease in mean wind speed and there was a increase in mean air temperature in the two days following the spell.

Analysis of the NAO Index value for the period of the spells of minimum SST recorded in March 2020, showed that the NAO Index value was 1.01. The relatively low and consistent NAO Index values suggest there was a distinct signal, suggesting that there was little storm activity around the time of both the maximum and minimum SST values for M3. This suggests that there was a consistent and undisturbed block of water surrounding Ireland, that was not mixed due to storm activity. This reinforces the stability of SST and conditions for the years 2002-2020 as seen by the minor variations in annual SST, however analysis of the North Atlantic Hurricane season will be assessed to determine if this undisturbed block of water was due to the lack of storms in the Atlantic or from other causes.

Analysis of the North Atlantic hurricane season and tracks, confirms the previous statement that there was a consistent and undisturbed block of water around Ireland during the period of minimum SST, resulting in a low and stable NAO Index value of 1.01, as the first significant hurricane or tropical cyclone event only occurred on the 16th May 2020, showing that hurricane or tropical cyclone events did not contribute to the minimum SST values for M3.

Based on analysis of the maximum and minimum SST analysis for M3, it seems that atmospheric pressure, wind speed and air temperature, coupled with NAO Index values and North Atlantic hurricane activity contribute to influencing the patterns of SST variations around M3. As M3 overall had a relatively consistent and stable mean SST variations, it seems that for minor variations in SST, atmospheric pressure, wind speed, air temperature and a stable NAO Index value were the most significant contributing factors to the stable SST witnessed. Although the NAO Index value can be affected by the North Atlantic hurricane activity, it seems that the position and track of hurricane or tropical cyclones, is the most significant factor when determining the impact or lack of impact these events have on Ireland. The North Atlantic hurricane season can have significant impacts on SST variations as seen in M2, however the degree of impact depends largely on the position and track of these hurricane or tropical cyclone events, as seen in M3.

7.4 M4:

Significant variations in annual SST

From 2008-2017 there were oscillations in SST. Between 2018-2020 there was a more pronounced oscillation in SST, showing an increase and subsequent decrease in SST. The largest SST oscillation recorded for M4 was recorded between 2017-2018 there was a SST increase of 0.9°C . Various parameters were assessed to determine the contributing factors and influences of this decrease in SST.

As the largest variation in SST occurred in 2017- 2018 the mean annual gust speed for both years was assessed as a possible contributing factor. For 2017 the mean annual gust speed was 8 m s^{-1} and the mean annual gust speed for 2018 was 9 m s^{-1} , 2017 is missing less than 5% of the gust data, while 2018 is missing 8% of the data. As the missing data accounts for less than 10% of the data, the gust speed accurately represents the true patterns of actual gust speed. As there is only a increase in mean annual gust speed for the years 2017-2018 which had the largest annual variation in SST, it seems that gust speed is not a significant contributing factor in the influence of annual SST variations.

Analysis of the mean annual air temperature for 2017 and 2018 was also conducted to establish any correlation between changes in mean annual air temperature and corresponding changes in SST. Analysis of the air temperature for 2017, showed that 8.4% of the air temperature data was missing or not recorded due to buoy maintenance, however the 91.6% of actual data available can be used to accurately represent the true value of mean air temperature for 2017. The mean annual air temperature for 2017 was 11.3°C . Analysis of the mean air temperature data for 2018 however showed that 40% of the air temperature data was not recorded due to buoy operational issues. Therefore, the mean annual air temperature value for 2018 can only be used as an indication, rather than a true representation of the actual data. The annual mean air temperature based on the available data for 2018 was 11.6°C . As mentioned the missing data for 2018 means that it can only be used as an indication for the true mean annual air temperature, however based on the results shown, it is likely that there was a increase in mean annual air temperature from 2017 to 2018, as the data for 2017 renders the results to be a true representation of the actual air temperature, and the mean air temperature for 2018 recorded an increase of 0.3°C , whilst missing the data elements discussed. Based on this analysis it seems there may be a interconnectedness with an increase in air temperature and an increase in SST for M4.

The mean NAO Index value for 2017 was 0.22 and the mean NAO Index value for 2018 was 1.08. The influence of the NAO Index value on SST on a monthly rather than an annual basis will be discussed in the spell analysis to assess the impact of monthly variations rather than long term annual of the NAO Index, but as per the previous parameters, the years 2017-2018 will be used to assess the annual variations in NAO Index values and establish any correlation between these variations and variations in SST values, as the greatest variations in mean annual SST values was between these years. Between 2017 and 2018 there was an increase in mean NAO Index values from 0.22 to 1.08 respectively. As both of these NAO Index values are positive and relatively stable, this factor alone could have contributed to the increase in mean SST recorded for 2017-2018. The increase in NAO Index values themselves from 0.22 in 2017 to 1.08 in 2018 correlates with an increase in mean annual SST from 2017-2018 of 0.9°C.

Spell analysis

The top ten spells of maximum SST were analysed for M4 to assess the impact of various parameters influencing spells of maximum SST, as opposed to the previous section which analysed data over a longer period of time, so the analysis of spells of maximum SST and the factors that influenced these variations in SST over short periods of time were analysed. A spell occurred in 2014 that recorded the top ten maximum SST values for M4. The maximum SST and spell of SST for M4 occurred on 25/07/2014 and 26/07/2014. Atmospheric data such as air temperature, wind speed, wind direction and atmospheric pressure could not be assessed as possible contributing factors that influenced this spell of maximum SST, as the buoy had N/A readings recorded for this period of time and Met Eireann weather observation stations do not have available data for these parameters that is accessible before 2015.

Analysis of the NAO Index values for 2014 was conducted as this was one of the spells of maximum SST for M4. The mean NAO Index value for 2014 was 0.18. This shows a positive and stable NAO Index at this time. The stable NAO Index value for 2014 suggests that there was a stationary body of water surrounding Ireland with little mixing of water. This is consistent with the spell of maximum SST recorded in 2014 for M4. Further analysis of the mean annual NAO Index values and corresponding SST values, suggests that there is a strong link between the NAO Index value and variations in SST value. It seems that the degree of impact that the NAO Index value has on determining the patterns of SST changes, is coupled with the influence of other atmospheric processes, and in particular, based on previous analysis, air temperature. As the other atmospheric parameters could not be accurately

assessed as a possible contributing factor to the influence of SST, due to data unavailability, the degree of influence on and with the NAO Index to contribute as influencing factors in SST variations.

Analysis of the North Atlantic hurricane track for 2014 was also conducted to assess whether any tropical cyclone or hurricane events occurred around the time of maximum SST and establish any correlation between these two processes. Analysis of the North Atlantic hurricane storm track showed that although there was a hurricane event that occurred in the North Atlantic, Hurricane Arthur, as mentioned for the M3 discussion, the origin and track of Hurricane Arthur north north-eastward along the North American and Canadian coastline, it is unlikely that this hurricane even could have significantly contributed to the spells of maximum SST around M4 at this time.

The top ten spells of minimum SST were analysed for M4 to assess the impact of various parameters influencing spells of minimum SST. Analysis showed that there were three notable spells of minimum SST values for M4. These spells of minimum SST for M4 were recorded on 13/06/2009, 15/02/2016, and 18/03/2018.

Analysis of two days before and two days after the three spells of minimum SST mentioned above, was conducted to examine the atmospheric processes that occurred at the time of the spells of minimum SST. Table 48 summarises the main atmospheric processes involved with the influence of SST variations. Wind speed and wind speed could not be assessed because the buoy recorded N/A values for these dates and Met Éireann do not have accessible data for these processes prior to 2015.

Date	Atmospheric pressure (Pa)	Wind Direction (°)	Air Temperature °C
11/06/2009	1019	94° (E)	11.2°C
12/06/2009	1015	126° (ESE)	12.1°C
13/06/2009	1013	163° (SSE)	12.9°C
14/06/2009	1015	148°(SE)	13°C
15/06/2009	1016	50°(NE)	13.4°C

Table 48 The changes in atmospheric processes before and after the spell of minimum SST for M4

Analysis of these processes shows that there was a decrease in atmospheric pressure on the 13/06/2009 which recorded the minimum SST values. The daily mean atmospheric pressure for the two days before and two days after the day that recorded the minimum SST value,

suggests that the reduction in atmospheric pressure on the day that recorded the minimum is likely to have been a contributing factor to the reduction in SST.

The wind direction during the two days before the minimum recorded SST which occurred on the 13/06/2009, showed that the wind direction originated from the East and East-Southeast respectively. On the 13/06/2009 there was a change in wind direction, with the wind originating from the South-South-East. This change in wind direction could have influenced the increase in the daily mean air temperature for the 13/06/2009, compared to the two days beforehand. In the two days after the 13/06/2009 there was another change in wind direction, with wind originating from the South-East and North-East. This change in wind direction could have contributed to the continued rise of daily air temperature values recorded in the two days following the spell of minimum SST.

The NAO Index value recorded for the 13/06/2009 was -1.21. This shows that there were unstable conditions around Ireland at this time, indicating that there was a non-stationary body of water, with a high degree of mixing surrounding Ireland. This is consistent with the spell of minimum SST experienced at this time. Based on analysis for the spell of minimum SST on 13/06/2009, it seems that the NAO Index and atmospheric pressure were the most significant factors contributing to the spell of minimum SST.

Analysis of the North Atlantic Hurricane Tracks for 2009 was also assessed to determine if any hurricane or tropical cyclone events occurred that could have influenced this spell of minimum SST on 13/06/2009. Analysis of the North Atlantic hurricane tracks did not show any hurricane events that occurred prior to August 2009, so therefore it would be unlikely that a hurricane or tropical cyclone from the North Atlantic influenced this spell of minimum SST.

Another spell of minimum SST for M4 was recorded on the 15/02/2016. The same atmospheric processes mentioned above, were assessed as seen in table 49, to establish any correlation with changes in these atmospheric process that could have contributed to the spell of minimum SST recoded at this time.

Date	Atmospheric pressure (Pa)	Wind Direction (°)	Wind Speed m s ⁻¹	Gust Speed	Air Temperature (°C)	SST (°C)
13/02/2016	N/A	102 (ESE)	6	11	6.1	8.4
14/02/2016	N/A	57 (NE)	6	10	6	8.2
15/02/2016	N/A	131 (SE)	6	8	6.5	8.1

16/02/2016	N/A	212 (SW)	6	16	8	8.7
17/02/2016	N/A	239 (SW)	6	6	6.2	9

Table 49 The changes in atmospheric processes before and after the spell of minimum SST for M4

Based on this analysis, the two days before the spell of minimum SST recorded on the 15/02/2016, had higher SST, but lower air temperature. The mean daily gust speed was also higher on the two days before the spell of minimum SST, but the mean daily wind speed remained consistent. The day before the minimum SST, however there was a change in wind direction, with wind originating from the Northeast.

On the 15/02/2016, the minimum SST value, there as a reduction in gust speed compared to the two previous days. There was a increase in daily mean air temperature but a reduction in SST. There was also a change in the wind direction, compared to the previous day which originated from the Northeast, on the day of minimum SST, the wind direction originated from the South East.

Analysis of the two days after the minimum SST showed that there was a significant increase in SST, correlating with a significant increase in air temperature. There was also an increase in the daily mean gust speed in the two days following the minimum SST. There was also a change in wind direction with wind originating from the Southwest. Based on analysis of these parameters, air temperature, wind direction and gust speed were significant factors contributing to this spell of minimum SST.

The NAO Index value was also assessed to examine any correlation between the NAO Index value and the spell of minimum SST experienced on the 15/02/2016. The NAO Index recorded a value of 1.58. This shows a relatively high but stable NAO Index, indicating that there was a stable and stationary body of water around M4 on the day of minimum SST.

Analysis of the North Atlantic hurricane season tracks was conducted to establish any correlation with hurricane or tropical cyclone events that occurred in the North Atlantic in 2016 and any subsequent effect on M4 SST. Analysis shows that a hurricane event occurred on the 12th to the 15th January 2016, which could have impacted SST that contributed to the spell of minimum SST experienced on the 15/02/2016.

Hurricane Alex originated as a non tropical low near the Bahamas on the 7th January 2016. Hurricane Alex originally tracked northeast and passed Bermuda on the 8th January before turning southeast and deepening. The system transitioned into a subtropical cyclone south of

the Azores on the 12th January. Alex weakened to a high-end tropical storm before making landfall on Terceira Island on 15th January. Alex merged with another cyclone over the Labrador Sea on 17th January. Although this hurricane event occurred one month before the month of the minimum spell of SST for M4 on the 15/02/2016, due to the area of the North Atlantic, this time period would have possibly allowed time for the transportation of unsettled waters following this hurricane event to travel towards Ireland due to the direction of transportation of water from the Gulf Stream current.

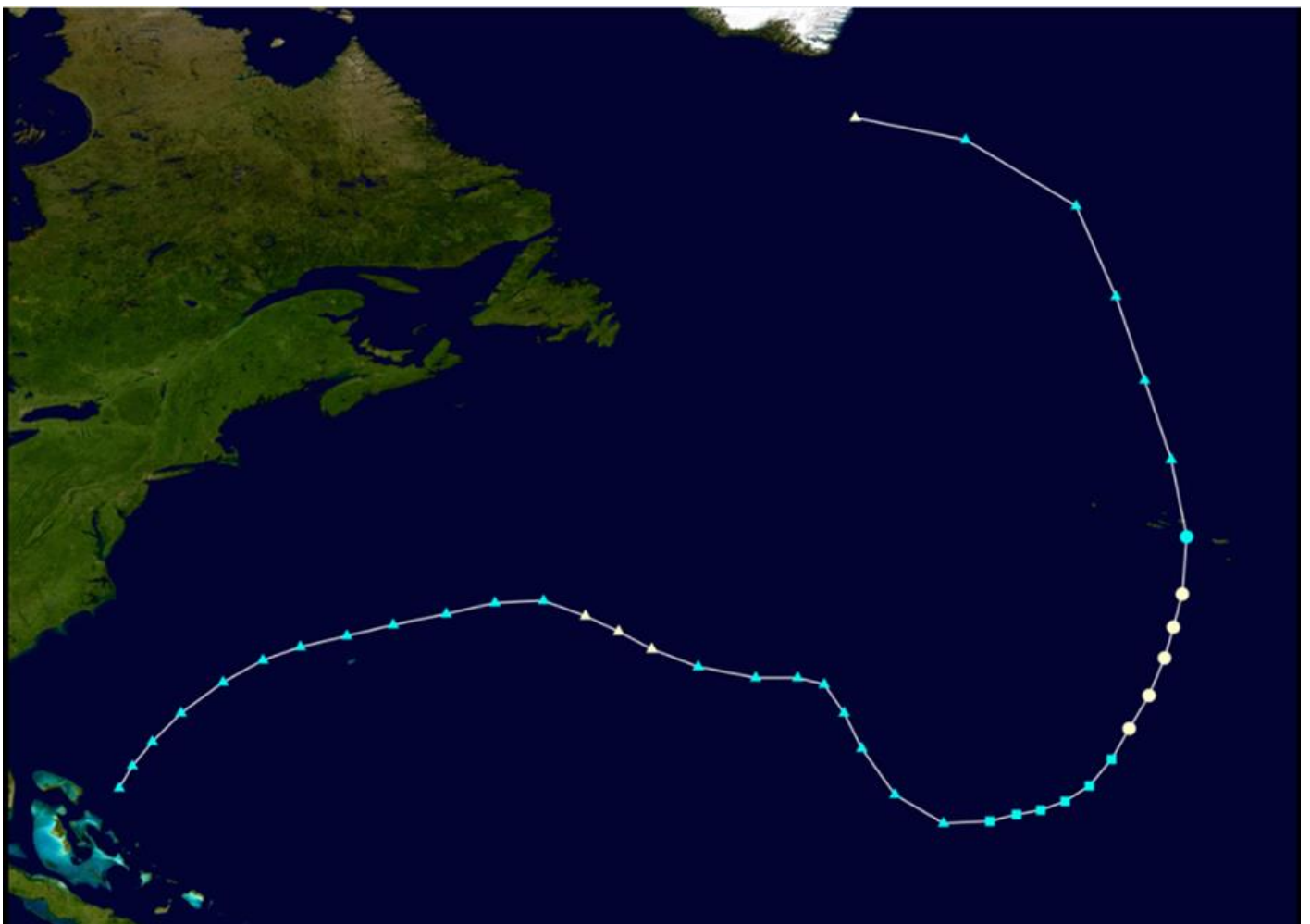


Figure 41 The track of Hurricane Alex 2016 (NOAA, 2020).

Another spell of minimum SST for M4 was recorded on the 18/03/18. The same atmospheric processes mentioned above, were assessed, see table 50, to establish any correlation with changes in these atmospheric process that could have contributed to the spell of minimum SST recoded at this time.

Date	Atmospheric Pressure (Pa)	Wind Direction	Wind Speed m s^{-1}	Gust Speed m s^{-1}	Air Temperature $^{\circ}\text{C}$	SST $^{\circ}\text{C}$
16/03/18	993	120 (SE)	4	10	6.5	9.2
17/03/18	1011	109 (ESE)	4	12	2.1	9.4
18/03/18	1020	85 (E)	4	12	-0.9	8.9
19/03/18	1026	85 (E)	4	8	2.1	9.3
20/03/18	1032	211(SW)	4	6	3.2	9.2

Table 50 The changes in atmospheric processes before and after the spell of minimum SST for M4

Based on this analysis, The two days before the minimum spell of SST recorded on 18/03/18, had slower atmospheric pressure than the 18/03/18. The wind direction for the two days before the 18/03/18 showed that the wind originated from a more south easterly direction compared to the 18/03/18. The mean daily wind speed remained unchanged throughout the days examined so this could be eliminated as a factor that influenced the spell of minimum SST on the 18/03/18. There was a gradual increase in the mean daily gust speed in the two days before the minimum SST. The SST was obviously higher than the 18/03/18. Analysis of the daily mean air temperature shows that there were significant variations in air temperature that could have contributed to the spell of minimum SST. From the 16/03/18 to the 17/03/18 there was a significant reduction in daily mean air temperature with a decrease from 6.5°C to 2.1°C respectively. From the 17/03/18 there was a continued reduction in air temperature, as the 18/03/18 recorded a daily mean air temperature of -0.9°C. This significant reduction in air temperature is likely to correlate and contribute to the spell of minimum SST on the 18/03/18.

Analysis of two days after the spell of minimum SST on 18/03/18 shows that there was a gradual increase in atmospheric pressure following the spell of minimum SST. There was also a change in wind direction with the wind direction changing from Easterly on the 18/03/18 to South-westerly on the 20/03/18. This change in atmospheric pressure and wind direction after the spell of minimum SST shows that these processes could have contributed to the spell of minimum SST. There was a gradual reduction in gust speed following the 18/03/18 showing that this factor could also have contributed to the spell of minimum SST. Air temperature gradually increased following the significant reduction on and before the 18/03/18, also confirming that air temperature was a significant contributing factor on the

variations in SST. Based on analysis of this spell of minimum SST for M4, the most significant atmospheric processes that influenced the spell of minimum were air temperature, atmospheric pressure, wind direction and gust speed.

Analysis of the NAO Index value for the spell of minimum SST recorded on the 18/03/18 shows that the NAO Index value at that time was -0.93. This shows that there were unstable and non-stationary conditions surrounding M4 at this time. This is consistent with the spell of minimum SST experienced on the 18/03/18, indicating that there were unsettled waters surrounding Ireland at this time.

Analysis of the North Atlantic hurricane season tracks were examined to establish any correlation with hurricane or tropical cyclone events that occurred in the North Atlantic and any penitential impact this had on effecting the variations in Irish SST. Analysis showed that there was no hurricane or tropical cyclone events that would have contributed to this particular spell of minimum SST on 18/03/2018, as the first tropical cyclone event occurred on the 25th May 2018.

7.5 M5

Annual analysis

The most pronounced annual mean SST decrease for M5 was recorded between 2018-2019. For these years, SST decreased by 0.6°C. Various parameters were assessed to determine the contributing factors and influences of this decrease in SST. To assess the causes of this variation in annual mean SST between 2018-2019, analysis of the mean annual air temperature for these years was completed. Analysis of the air mean air temperature for 2018 showed that there was 22% missing air temperature data for this year. Therefore, the mean annual air temperature for 2018 for M5 can only be used as an indication of the true actual mean air temperature. Based on this data the mean annual air temperature for 2018 was 12.2°C. Analysis of the mean annual air temperature for 2019 showed that 52% of the air temperature data was missing, and therefore the calculated mean annual air temperature can only be used as an indication of the true mean annual air temperature. Based on this data the mean annual air temperature for 2019 was 13.2°C. Due to the volume of missing air temperature data these results can not be deemed a true representation of the actual mean annual air temperature, however, it is likely that there was an increase in mean annual air temperature from 2018-2019 based on this analysis.

Other atmospheric processes that could influence the variations in SST for M5 are examined in the spell analysis, as these spells occur over a shorter period of time than the annual analysis, and therefore the influencing factors are more easily determined compared to annual analysis. The mean annual NAO Index values however for 2018 and 2019 were examined to assess any changes in mean annual NAO Index values for 2018-2019 as these years contained that largest annual variation in SST and examine any relationship between changes in the mean annual NAO Index value and changes in annual SST. Analysis of the NAO Index values for 2018 overall showed relatively stable and positive NAO Index values throughout the year. The mean annual NAO Index value was 1.08, reinforcing the positive, stable and stationary conditions for 2018. Analysis of the mean NAO Index value for 2019 however was in contrast to 2019, showing unstable, negative and non-stationary conditions overall, with a large majority of NAO Index values for 2019 being negative. The mean annual NAO Index value for 2019 was -0.29. These contrasts between NAO Index from 2018-2019 is therefore likely to have had significant impact on the reduction in mean annual SST from 2018-2019 of 0.6°C.

Spell analysis

The top spells of maximum SST were analysed for M5 to assess the impact of various parameters influencing spells of maximum SST, as opposed to the previous section which analysed data over a longer period of time, so the analysis of spells of maximum SST and the factors that influenced these variations in SST over short periods of time were analysed. A spell occurred on 17/07/2014 that recorded the top ten maximum SST values for M5. The maximum SST and spell of SST for M4 occurred on 17/07/2014. Atmospheric data such as air temperature, wind speed, wind direction and atmospheric pressure could not be assessed as possible contributing factors that influenced this spell of maximum SST, as the buoy had N/A readings recorded for this period of time and Met Éireann weather observation stations do not have available data for these parameters that is accessible before 2015.

The NAO Index for July 2014 was assessed however to establish any correlation between the NAO Index value and the spell of maximum SST recorded in July 2014. The NAO Index value for July 2014 was 0.18. This shows that the NAO Index at the time of the spell of maximum SST was positive, stable, and showed stationary conditions around M5, with little mixing of water. This is consistent with the environment required to enable the spell of maximum SST to occur. Based on this it is likely that the NAO Index played a significant role in the influence of the spell of maximum SST for M5 recorded in July 2014.

Analysis of the North Atlantic hurricane season tracks was also conducted to establish any correlation with hurricane or tropical cyclone events that occurred in the North Atlantic, and any impact this may have had on the spell of maximum SST for M5 recorded in July 2014. Analysis of the North Atlantic hurricane storm track showed that although a hurricane event, Hurricane Arthur occurred at the same time as spells of maximum SST for M5, as mentioned for M3 and M4 discussions, it is unlikely that this hurricane event could have significantly contributed to the spells of maximum SST for M5, due to the location of the origin and track of this hurricane event.

The top spells of minimum SST were analysed for M5 to assess the impact of various parameters influencing spells of minimum SST. The top spells of minimum SST for M5 occurred on the 27/02/2014.

Analysis of two days before and two days after the spell of minimum SST mentioned above, was conducted to examine the atmospheric processes that occurred at the time of the spells of minimum SST. The table below summarises the main atmospheric processes involved with the influence of SST variations.

The atmospheric pressure was lower on the two days before the spell of minimum SST on the 27/02/2014. The wind direction originated from a more south westerly compared to the date of the minimum SST which was more west south westerly. The wind speed was higher on the two days before the minimum SST on 27/02/14. The mean gust speed remained consistent throughout the period analysed so this can be removed as a possible contributing factor to the influence of the spell of minimum SST on 27/02/14. The mean air temperature was also higher on the two days before the spell of minimum SST.

On the date of the spell of minimum SST, there was a reduction in atmospheric pressure, as well as a change in wind direction compared to the previous two days. There was a reduction in daily mean wind speed on the 27/02/14, as well as a reduction in mean daily air temperature. Based on this analysis, atmospheric pressure, wind direction, wind speed and air temperature were the most significant factors contributing to the spell of minimum SST on 27/02/14.

During the two days after the spell of minimum SST there was a continued reduction in atmospheric pressure. There was a change in wind direction, from West south westerly on the 27/02/14 to North westerly on the following day. There was a continued gradual reduction in wind speed and air temperature in the two days following the spell of minimum SST, as

displayed in table 51. Based on this analysis it is likely that changes in atmospheric pressure, wind direction, wind speed and air temperature influenced the spell of minimum SST for M5 recorded on the 27/02/14.

The NAO Index value was also assessed to examine any relationship between changes in the NAO Index values and the spell of minimum SST on the 27/02/14. The NAO Index recorded a value of 1.34. This shows a relatively high but stable NAO Index, indicating that there was a stable and stationary body of water around M5 on the day of minimum SST. This could have contributed to the spell of minimum SST experienced at this time as there was little to no mixing of waters, preventing an influx of warmer water, leading to the spell of minimum SST experienced.

Date	Atmospheric Pressure (Pa)	Wind Direction	Wind Speed m s^{-1}	Gust Speed m s^{-1}	Air Temperature $^{\circ}\text{C}$	SST $^{\circ}\text{C}$
25/02/2014	993	232 (SW)	9	8	9.3	8.4
26/02/2014	1008	236 (SW)	8	8	9.1	8.2
27/02/2014	1003	245 (WSW)	7	8	8.9	8.2
28/02/2014	1001	310 (NW)	7	8	7.8	8.3
01/03/2014	1001	214 (SW)	4	8	8.4	8.3

Table 51 The changes in atmospheric processes before and after the spell of minimum SST for M5

Analysis of the North Atlantic hurricane season tracks was conducted to establish any correlation with hurricane or tropical cyclone events that occurred in the North Atlantic in February 2014 and any subsequent effect on M5 SST. Analysis showed that there were no major hurricane or tropical cyclone events in the North Atlantic before the month of July in 2014, excluding this as a possible contributing factor to the spell of minimum SST for M5 recorded on the 27/02/14.

7.6 M6

Annual analysis

The joint largest oscillation in SST for M6 recorded a decrease of 0.5°C between 2011-2012. From 2017-2018 there was another SST oscillation, showing a decrease in SST of 0.5°C between these years. To assess the contributing factors to both of these mean annual decreases in SST, various atmospheric parameters were assessed to establish any relationship between variations in atmospheric processes and the subsequent annual decreases in SST.

The mean annual air temperature and NAO Index value for each of these years was assessed to determine any relationship between variations in these processes and the respective mean annual SST decrease between the years 2011-2012 and 2017-2018. Other atmospheric processes such as atmospheric pressure and wind direction are assessed during spells of maximum and minimum SST to ensure maximum accuracy and ascertain the short-term influencing factors in spells of SST fluctuations.

Analysis of the mean annual air temperature for 2011-2012 was conducted to establish any correlation between changes in mean annual air temperature and the subsequent decrease in mean annual SST. In total M6 was missing 4% of the total annual air temperature data, allowing for a highly accurate representation of the true annual air temperature. The mean annual air temperature for 2011 was 11.2°C. Analysis of the annual air temperature for 2012 for M6 showed that 5% of the total air temperature data was missing, however this enables an accurate representation of the true annual air temperature. Based on these calculations, the annual mean air temperature for 2012 was 11.4°C. Based on the analysis of mean annual air temperature variations between 2011-2012 there was an overall increase in mean annual air temperature of 0.2°C. Based on this analysis variations in annual air temperature between 2011-2012 are unlikely to have significantly contributed to the decrease in mean annual SST between these years.

Analysis was also conducted on the mean annual air temperature variations between 2017-2018 to assess whether variations in the mean annual air temperature could have contributed to the decrease in mean annual SST of 0.5°C. Analysis shows that 2017 was missing a total of 12% of the annual air temperature data, however this data can still provide an accurate representation of the true variations in annual air temperature due to the volume of data. The mean annual air temperature for 2017 was 11.8°C. Analysis shows that 2018 was missing a total of 31% of the annual air temperature data. This means that the calculations can only be used as an indication of the annual air temperature and cannot be deemed a true representation. Based on this, the mean annual air temperature for 2018 was 10.9°C.

Although the missing data for these years can impact the accuracy of these results, it is likely that there was an overall decrease in the mean annual air temperature between 2017-2018. This decrease in annual mean air temperature could have contributed to the decrease in mean annual SST of 0.5°C between these years.

The NAO Index value for the years 2011-2012 and 2017-2018 respectively was assessed to examine any relationship between variations in the mean annual NAO Index and variations in SST. The mean annual NAO Index value for 2011 was 0.29. This shows positive and stable conditions around M6 at this time. This means there was little mixing of waters and a stationary body of water surrounding M6 at this time. Analysis of the NAO Index value for 2012 however showed unstable conditions as a value of -0.45 was recorded. Although this is not an extremely low value, analysis showed that there were months of continued negative NAO Index values, showing disturbed waters and non-stationary conditions. Evaluation of the NAO Index value between these years shows that the variations in NAO Index values could have significantly contributed to the decrease in mean annual SST from 2011-2012 of 0.5°C.

Analysis of the NAO Index value for 2017-2018 was also conducted as these years had the same largest variation in annual mean SST as 2011-2012. The NAO Index value for 2017 was 0.20 showing stable and stationary conditions surrounding M6 at this time. This indicates there was little mixing of water. Analysis of the NAO Index value for 2018 recorded a higher NAO Index of 1.08. Although this NAO Index is higher than 2017, it shows stable conditions also with little mixing of water. Based on this analysis, the NAO Index value for 2017-2018 did not seem to have a significant impact of the mean annual SST decrease of 0.5°C recorded in these years.

Spell analysis.

To assess the impact of other atmospheric processes, the top spells of maximum and minimum SST were assessed to establish any correlation with variations in different atmospheric processes and their impact on creating spells of maximum and minimum SST values.

This approach was problematic when conducting analysis of the spells of maximum SST for M6 as July, August and October all recorded the top spells of maximum SST for M6, but the atmospheric data was not recorded by the buoy, and this information cannot be accessed on Met Eireann prior to 2015.

The NAO Index values therefore were the primary parameter used to assess the impact of this process on the spells of maximum SST. Table 52 displays the variations in NAO Index values for the top spells of maximum SST for M6.

Date	SST °C	NAO Index Value
July 2014	18.2	0.18
August 2014	18	-1.68
September 2014	17.8	1.62
October 2014	17.6	-1.27

Table 52 The variations in NAO Index values for the top spells of maximum SST for M6

July 2014 recorded the top spell of maximum SST and had a NAO Index value of 0.18. This shows a positive, stable and stationary body of water surrounding M6 which is likely to have contributed to this spell of maximum SST. August 2014 recorded the next spell of maximum SST but had a negative and unstable NAO Index value of -1.68. This would imply that there were unstable conditions and a non-stationary body of water surrounding M6 at this time. This would usually not be associated with conditions favourable to influence spells of maximum SST, however the North Atlantic hurricane Season is assessed later to examine if a hurricane event could have contributed to this unsettled body of water but high SST. September 2014 recorded the next spell of maximum SST and had a corresponding NAO Index value of 1.62. This is in stark contrast to the previous month as it recorded a positive value and indicated that there were stable conditions surrounding M6 at this time which would be conducive to the conditions required for the spell of maximum SST recorded. October recorded the last spell of maximum SST, and the NAO Index value was -1.27, which is in stark contrast to the previous month again. This NAO Index value suggests unstable conditions that would not typically be favourable to influence a spell of maximum SST recorded. Analysis of the North Atlantic hurricane season is assessed in the next section to examine if a hurricane or tropical cyclone even could have contributed to this unsettles water indicated by the NAO Index but have transported warm waters which contributed to the spell of maximum SST.

Analysis of the North Atlantic hurricane season was conducted to examine if any hurricane or tropical cyclone events occurred around the months of the spells of maximum SST for M6 and could have contributed to the fluctuating NAO Index values recorded between months. As July, August, September and October recorded the spells of maximum SST for M6, it is extremely evident that hurricane events that occurred in the North Atlantic contributed greatly to the spells of maximum SST for M6, as a tropical cyclone or hurricane or major hurricane event occurred in every month that recorded spells of maximum SST. Similar to

M3, M4, and M5 discussions, Hurricane Arthur occurred at the same time as a spell of maximum SST for M6, but it is unlikely that this hurricane event significantly contributed to this spell of maximum SST due to the location of the origin and track of this hurricane event.

Hurricane Bertha occurred in early August 2014 and originated from a tropical wave south of the Cape Verde Islands. It acquired gale force winds and enough convection to be categorised as a tropical storm on 1st August. On 3rd August it moved over the south-eastern Bahamas and intensified to a hurricane on 4th August. Hurricane Bertha then tracked north and then north eastwards and was later declared an extratropical storm. The remnant system tracked across the Atlantic and struck Ireland on the 10th August. This would have directly influenced the unstable NAO Index of -1.68. The origins of the hurricane however could have attributed to the spell of maximum SST in August if a body of warm water had been transported from the origin of the hurricane across the Atlantic following the hurricane track.

Hurricane Cristobel was an Atlantic tropical cyclone that formed on 23rd August from a long tracked tropical wave, and gradually tracked north. On the 28th August Cristobel tracked north-eastward and struck Iceland on 1st September. Although this hurricane event may not have directly contributed to the spell of maximum SST recorded by M6, it contributed significantly to the unstable NAO Index values experienced in August and September 2014.

Hurricane Edouard originated as a tropical wave accompanied by a broad area of low pressure on the West coast of Africa on 6th September. On the 11th September the depression intensified into Tropical Storm Edouard. The cyclone tracked northwest and intensified to hurricane status on 14th September. The location of this hurricane over the Atlantic reduces the potential impact of this hurricane event to directly contribute to the spell of maximum SST recorded by M6 in September 2014, however the origin location, through convection and transportation mechanisms have transported a warm body of water towards Ireland. This hurricane event is also likely to have contributed to the fluctuations in NAO Index value for September 2014, which would subsequently effect SST.

Lastly, Hurricane Gonzalo originated from a tropical wave on October 12th while located east of the Lesser Antilles. Gonzalo accelerated towards the waters of the North Atlantic, passing close to south-eastern Newfoundland before dissipating to an extratropical storm on 19th October. A large storm system with the remnants of Gonzalo struck Ireland and Great Britain on 21st October. The origins of this hurricane event could also have resulted in the transportation of warmer waters towards Ireland, contributing to the spells of maximum SST.

This event also would have contributed to the fluctuating and unstable NAO Index experienced in October 2014, which would also impact SST.

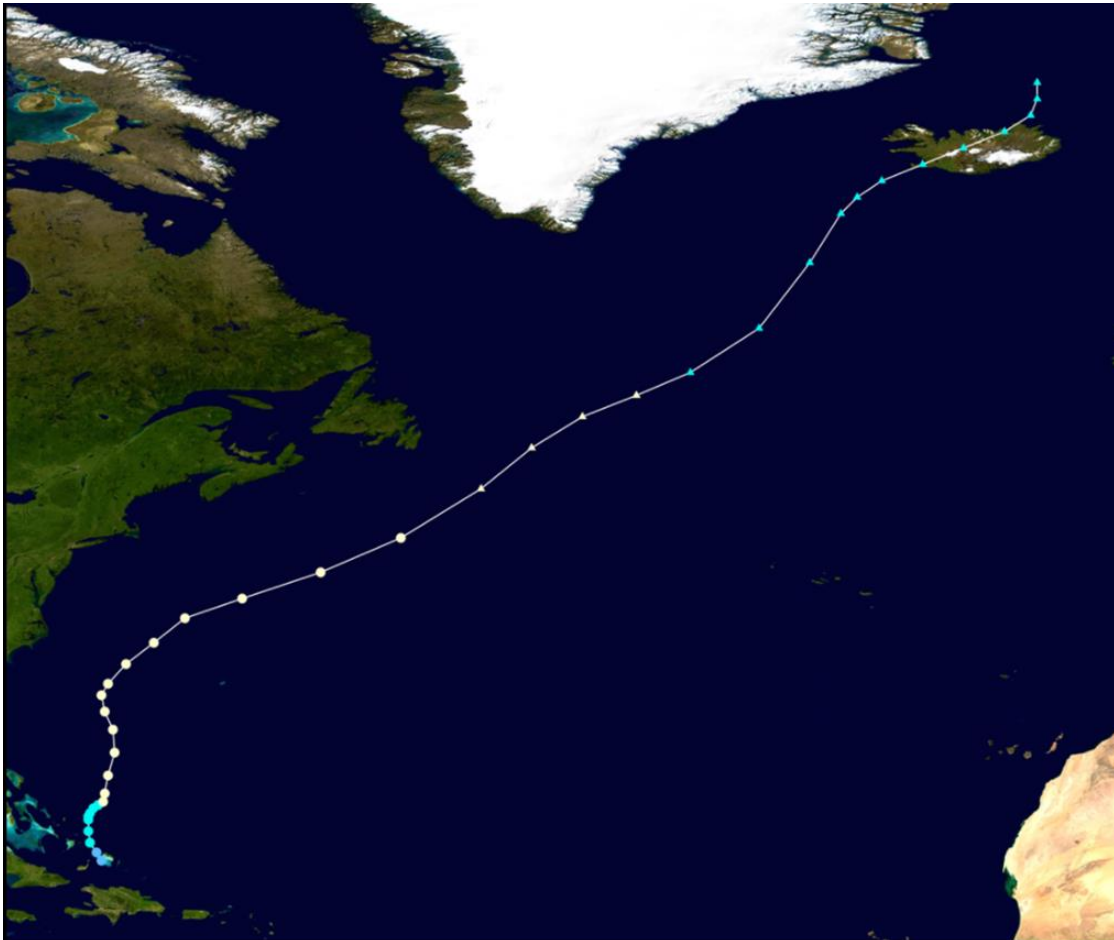


Figure 42 The track of Hurricane Cristobel 2014 (NOAA, 2020).

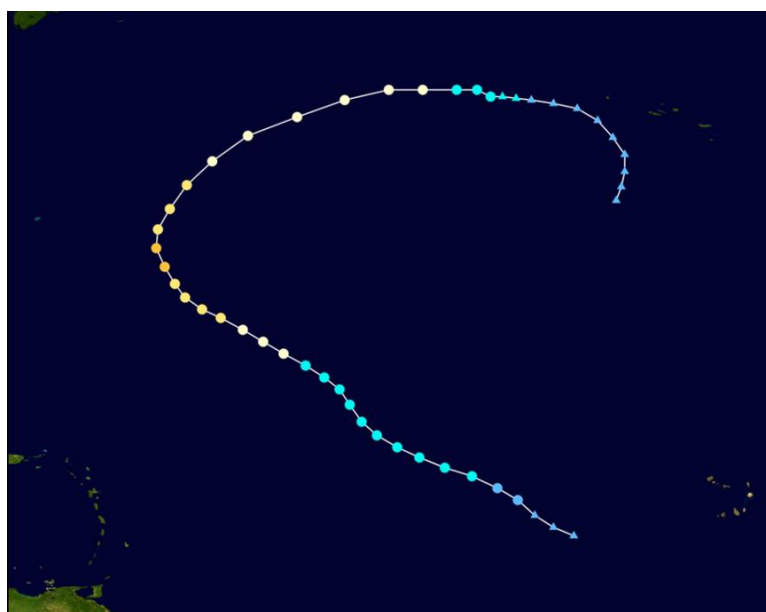


Figure 43 The track of Hurricane Edouard 2014 (NOAA, 2020).

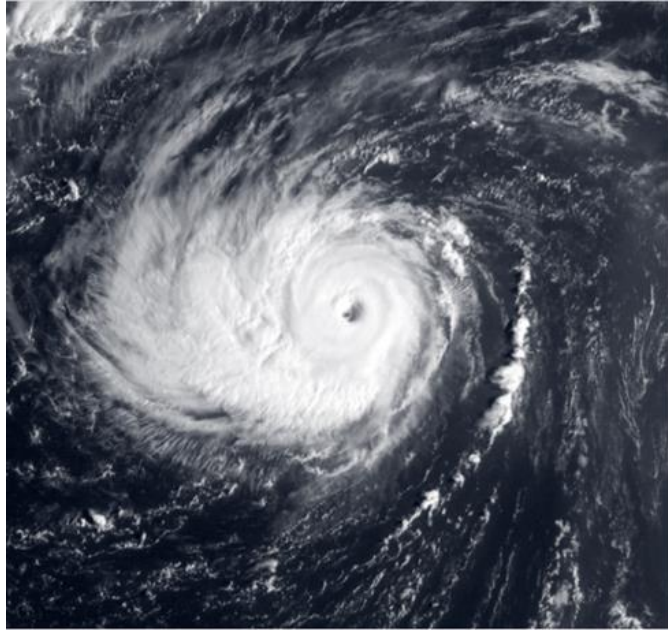


Figure 44 Satellite image of Hurricane Edouard 2014 (NOAA, 2020).

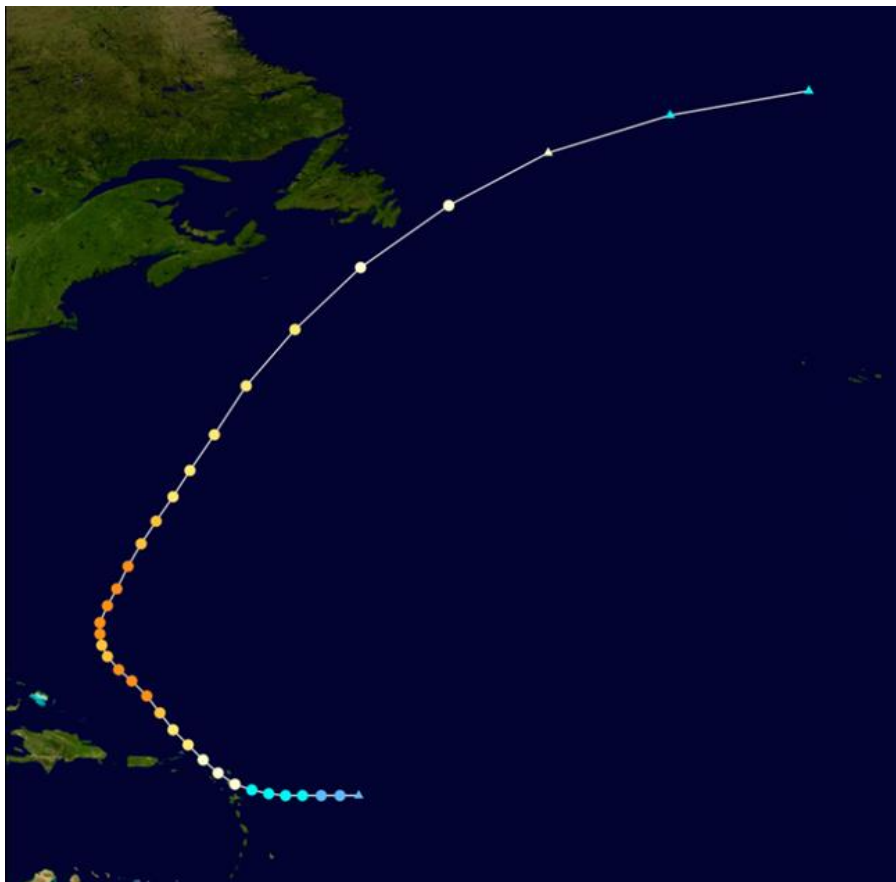


Figure 45 The track of Hurricane Gonzalo 2014 (NOAA, 2020).

The top spell of minimum SST for M6 was recorded on 26/02/2014. This again was problematic as M6 did not record atmospheric data for this spell either and this data is not accessible from Met Eireann prior to 2015. Similar to the spells of maximum SST, the NAO Index value will therefore be used to assess the impact of this on the spell of minimum SST for M6 on the 26/02/2014. The NAO Index value for February 2014 was recorded at 1.34. This shows positive, stable, and stationary conditions surrounding M6 during the spell of minimum SST. As seen in the analysis of the North Atlantic Hurricane Season for 2014, the first hurricane event occurs in July 2014, so can therefore be eliminated as a contributing factor to the top spell of minimum SST for M6 in February 2014.

7.7 Jet stream position and the NAO Index impact on SST.

As seen in the above analysis, hurricane events in the North Atlantic have impacted SST around Ireland's coastline, contributing to both spells of maximum and minimum SST, however based on the analysis, the North Atlantic hurricane events occurred more frequently at the times of spells of maximum SST. The position of the jet stream around the time of the hurricane events in the North Atlantic is significant as the jet stream transports cyclonic weather systems towards Ireland, and therefore variations in the jet stream position is a direct factor contributing to the degree of intensity in which Ireland is impacted by hurricane events in the North Atlantic.

NOAA, (2021) defines jet stream as “a strong narrow current concentrated along quasi-horizontal axis in the upper troposphere or in the stratosphere and is characterised by strong vertical and lateral wind shear and featuring one or more velocity maxima.” Polar front jet streams are formed above the convergence zone (40°N-60°N) of the surface polar cold air mass and tropical warm air mass. The thermal gradient is steepened because of convergence of two contrasting air masses. These move in an easterly direction but are irregular. Polar front jet stream variability is responsible for instances of extreme weather and is crucial for regional climate change. The North Atlantic Polar Front jet is of particular significance to Ireland's storm track variability, atmospheric models of variability such as the NAO, temperature, sea surface temperature and precipitation patterns are interconnected with jet stream changes (Hall, et al, 2015). The polar front jet is also known as the eddy driven jet as it is driven by momentum and heat fluxes from transient eddies or cyclones in the mid latitudes, (Panetta, Held, 1988). Experiments by Williams, (1979), Panetta, (1993), Lae, Kim, (2003) indicate that eddies can perturb a baroclinic zone and spontaneously generate a jet. The Atlantic sector shows particularly clear separation of the subtropical jet stream and the

polar front jet stream, and the presence of a double jet structure makes the North Atlantic unique in the Northern Hemisphere.

Blackmon, (1976) showed that variability and mean flow of jet streams increases over the oceans. Summer jet streams are weaker than in winter and are displaced poleward. These seasonal changes are the result of a reduced poleward shift in meridional temperature gradient (Hall, et al, 2015). The atmospheric circulation and therefore the jet streams are subject to internal unforced variability as a result of a chaotic internal dynamical process.

Analysis.

Trends in the speed and probability of winter jet stream cores over the Northern Hemisphere were measured for 1958-2007 (Strong, Davis, 2007). Analysis Strong, Davis, (2007) showed that eddy driven jet (EDJ) core speeds and probabilities increased over the mid latitudes (40°N - 60°N) with changes as large as 15% (speed) and 30% (probability). These increasing trends are collocated with increases in baroclinicity, driven by a spatially heterogeneous patterns of height change consistent of large-scale warming with cooling centres embedded poleward of 60°N. Analysis of the subtropical jet stream core probabilities (Strong, Davis, 2007) remained relatively consistent but core speeds increased by as much as 1.75 m/second per decade in association with Hadley cell intensification.

The subtropical jet stream shifted poleward over the east pacific and Middle East, and an equatorward shift and intensification of the subtropical jet stream were found over the Atlantic Basin (Strong, Davis, 2007), contributing to an increased separation of the eddy driven jet and the subtropical jet stream.

Minor changes in the jet streams position and strength can impact midlatitude storm tracks (Nakamura, 2004), weather extremes, (Clark, Schaffer, Gallus and Johnson-O'Mara, 2009) stratosphere- troposphere exchange, circulation regimes and sea surface temperatures (Ruti, et al, 2006). Examination (Strong, Davis, 2007) of projections by fifteen coupled global climate models predict intensification and poleward shifts throughout the 21st century of storms tracks, implying a poleward shift in the jet streams of both hemispheres (Yin, 2005).

Strong, Davis, (2007) examined patterns in the historical record which showed a poleward trend in surface cyclone frequency (Macabe, et al, 2001), contracting and strengthening of the circumpolar vortex since 1970 (Frauenfeld, Davis, 2003), increasing the strength of the winter Hadley circulation since the 1950's (Mitas, Clement, 2005), and an approximate one

degree poleward shift in the position of tropospheric jet streams during 1979-2005 implied by satellite derived radiances (Fu, et al, 2006). Analysis of the winter tropospheric height, pressure and temperature trends over the Euro-Atlantic area project onto the Arctic Oscillation (AO) (Wu, Straus, 2004),(Thompson, Wallace, 2000).

Strong. Davis, (2007) showed that increasing frequency and strength of eddy jet stream cores is physically consistent with baroclinicity enhancement, indicated by the collocated corridor of increasing geopotential height gradient and the increasing is consistent with the circumpolar vortex's poleward trend toward the region of the eddy jet stream core intensification.

Lattanzio, et al, (2021) conducted a time series analysis of Atmospheric Motion Vectors (AMV) to detect changes in the position and intensity of the polar jet stream. Changes in the location and intensity of the polar jet stream are influenced by interannual variations of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). Lattanzio, et al, (2021) states that a positive NAO directs the polar jet towards northern Europe see figure 46, while a negative NAO directs it southward, shown in figure 47.

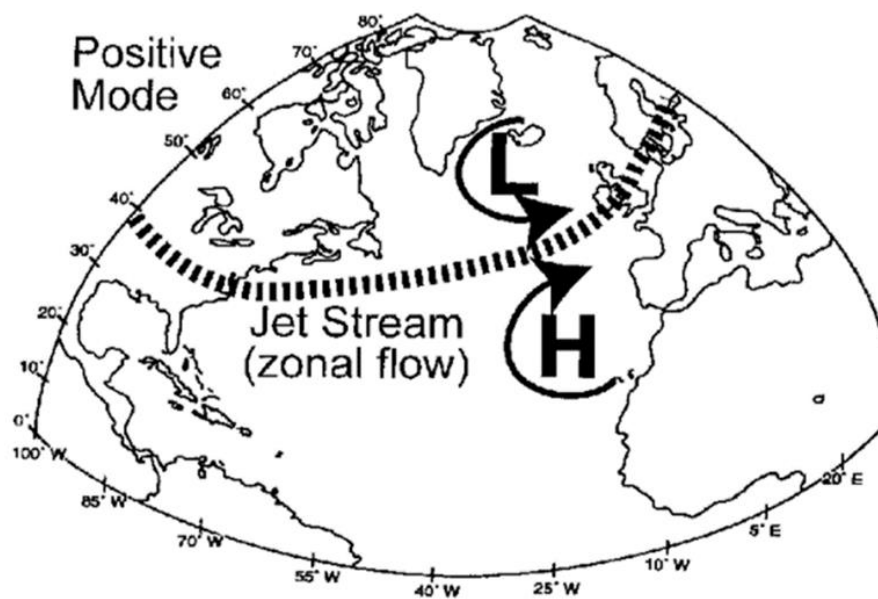


Figure 46 A positive NAO Index which directs the polar jet stream Northwards (Lattanzio, et al, 2021)

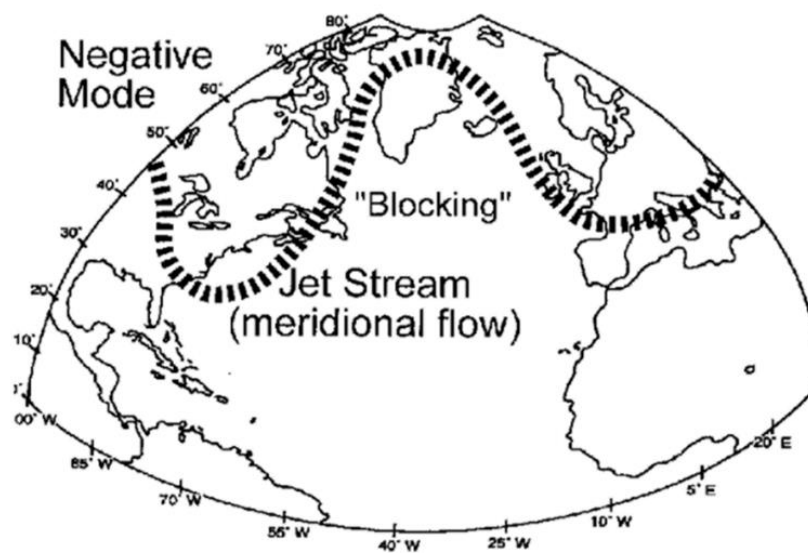


Figure 47 A negative NAO Index which shifts the polar jet stream Southwards (Lattanzio, et al, 2021)

7.8 Jet stream and NAO Index analysis.

Lattanzio, et al, (2021) noted that the winter of 2009-2010 was particularly longer and colder than normal in Western and North Europe. This was evident around Ireland's coastline through analysis of the mean NAO Index values, confirmed an unusually cold NAO Index value over a prolonged period of time during the majority of months in 2010. NAO variations have a direct impact on the polar jet or jet stream. Jet streams are geostrophic winds. Which their strength is governed by the pressure gradient and the Coriolis force, this is demonstrated in figure 48

Doutriaux-Boucher, et al., (2016) first attempted to analyse the relationship between the NAO and jet stream using Meteosat observations comparing two single days: 1st December 2010 and 1st December 2011. Lattanzio, et al, (2021) furthered this analysis by extending the comparison for a complete December, January and February (DJF) season. Lattanzio, et al, (2021) compared AMV patterns for a day during a season with a strong negative NAO phase (20 December 2009) and a day during a season with a strong positive NAO phase (20 December 2011). Analysis showed that during the day with a negative NAO phase (20 Dec 2009), the median latitude of the detected AMVs was about 14 degrees lower and their corresponding median speed is about 5 m s^{-1} slower, compared to the day with a positive NAO phase (20th December 2011).

Lattanzio, et al, (2021) also completed analysis of the seasonal anomaly of AMV latitude and AMV wind speed for the winter (DJF) with mostly negative NAO indices (2009-2010), and the winter with mostly positive NAO indices (2011-2012). Analysis showed that AMV latitudes during the winter with negative NAO indices (2009-2010) are about 15 degrees lower than during the winter with positive NAO indices (2011-2012). Similarly, a difference in AMV wind speeds is observed, with about 5 m s^{-1} slower wind speeds during periods with negative NAO indices. Lattanzio, et al, (2021) concluded that the patterns in AMV latitude and wind speed are consistent with the expected behaviour due to changes in NAO and may serve as proxy for observing NOA changes related to shifts in the polar jet.

Based on this analysis, the position of the jet stream is impacting Ireland significantly during both positive and negative phases of NAO Index's, however the direction of movement is significant in either transporting warm water from the Gulf Stream towards Ireland, or colder water from near the coast of Greenland towards Ireland. Analysis of the NAO Index at the time of hurricane events in the North Atlantic that impacted sea surface temperatures around

Ireland's coastline was completed to use the NAO Index at the time of the hurricane event to attempt to ascertain the direction of movement of the jet stream over Ireland, as seen in table 53.

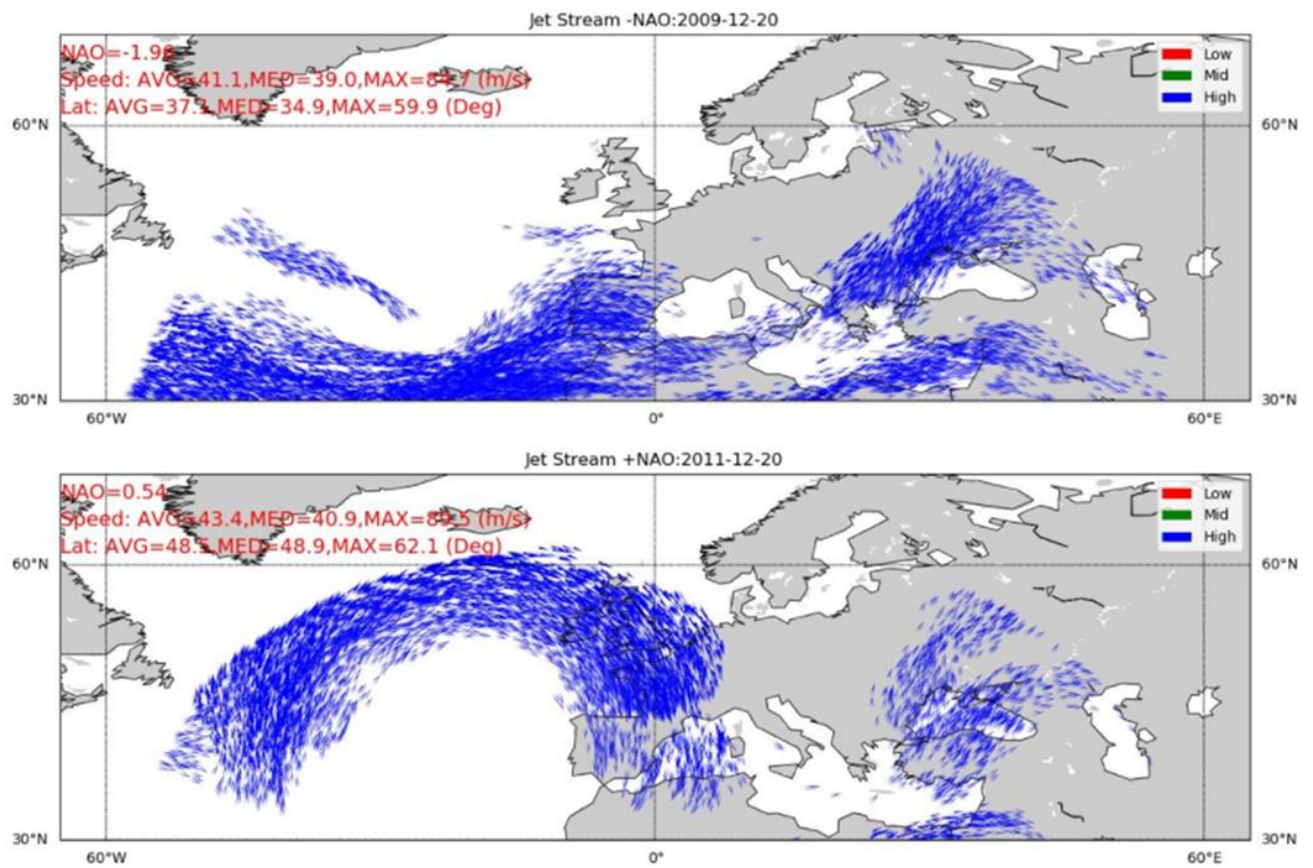


Figure 48 The position of the jet stream on 20th December 2009 (positive NAO Index phase) and on the 20th December 2011 (negative NAO Index phase) (Lattanzio, et al, 2021)

Buoy	Hurricane Event (max SST)	NAO Index	Hurricane Event (Min SST)	NAO Index
M2	No Hurricane Activity.		Hurricane Bill – August 2009. Extratropical Storm Grace – October 2009.	-0.19 -1.03
M3	No Hurricane Activity.		No Hurricane Activity.	
M4	No Hurricane Activity		No Hurricane Activity. Hurricane Alex – January 2016. No Hurricane Activity.	0.12
M5	No Hurricane Activity.		No Hurricane Activity.	
M6	Hurricane Bertha – August 2014. Hurricane Cristobel – August 2014. Hurricane Edouard – September 2014. Hurricane Gonzalo – October 2014.	-1.68 -1.68 1.62 -1.27	No Hurricane Activity.	

Table 53 The hurricane events corresponding with spells of maximum and minimum SST for each buoy

As seen in table 53, M6 was the only buoy that could have been potentially influenced by hurricane activity in the North Atlantic during the spells of maximum SST. No other buoy had the potential to be influenced by hurricane activity during the spells of maximum SST for each buoy respectively. The spells of maximum SST for M6 correspond with hurricane events in the North Atlantic, possibly resulting in the transportation of a warm body of water from the North Atlantic around Ireland's coastline resulting in the spells of warm SST experienced by M6.

For the spells of minimum SST, only two buoys had hurricane events that occurred at the same time as the spells of minimum SST. During the spells of minimum SST for M2, a hurricane event and an extratropical storm occurred at the same time. M4 had three top spells of minimum SST, however only one hurricane event occurred at the same time as one of the three spells of minimum SST. Based on this analysis, it is likely that hurricane events have a

more significant influencing factor on spells of maximum SST around Ireland, compared to spells of minimum SST.

7.8 Conclusion

Of the various processes assessed, atmospheric pressure, wind direction, air temperature, the NAO Index, the North Atlantic hurricane tracks, and the position of the jet stream are all significant factors in determining the variations in SST around Ireland's coastline. These processes are interlinked with each other and have a domino effect on influencing sea surface temperatures around Ireland's coastline. Although hurricane events occurred during both spells of maximum and minimum SST, hurricane events were more frequent during spells of maximum SST around Ireland's coastline. The location of the jet stream could be an important factor in determining the degree of impact that these North Atlantic hurricane events have on Ireland. This is due to the changing position of the jet stream during positive and negative phases of the NAO Index respectively. Changes in the location and intensity of the polar jet stream are influenced by interannual variations of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). Lattanzio, et al, (2021) states that a positive NAO directs the polar jet towards northern Europe, while a negative NAO directs it southward. The NAO Index contributes to the degree of mixing of waters around Ireland's coastline, thus, potentially influencing variations in SST.

Chapter 8 Conclusions

8.1 Introduction

Assessment of the annual trends of SST variations for each buoy, showed varying results of either an overall increase or decrease in SST from 2002-2020 for each buoy. Table 54 shows the annual trend of SST variations for each buoy form 2002-2020.

Buoy	Annual SST from 2002-2020
M2	Decrease
M3	Decrease
M4	Increase
M5	Increase
M6	Decrease

Table 54 The annual SST trends for each buoy for 2002-2020

8.2 Causes in the short-term variations in SST variations around Ireland's coastline

Analysis has shown that there are atmospheric and oceanic processes that cause both short term and long-term variations in SST fluctuations around Ireland's coastline. Firstly, short term variations in SST changes around Ireland's coastline are influenced primarily but not exclusively by changes in local air temperatures, changes in atmospheric pressure, changes in local currents and tides and by wave heights and incidence rates. Short periods of warmer SST around Ireland's coastline usually but not exclusively correlated with periods of higher local air temperatures and higher atmospheric pressure, and a lower wave incidence rate and wave height than periods of colder SST. Short periods of lower SST around Ireland's coastline usually but not exclusively correlated with lower local air temperatures, and lower atmospheric pressure, coupled with a higher wave incidence rate and higher wave height. Local currents and tidal patterns also influence short term variations in SST changes around

Ireland's coastline, causing the mixing of waters based on the current direction and tidal frequency.

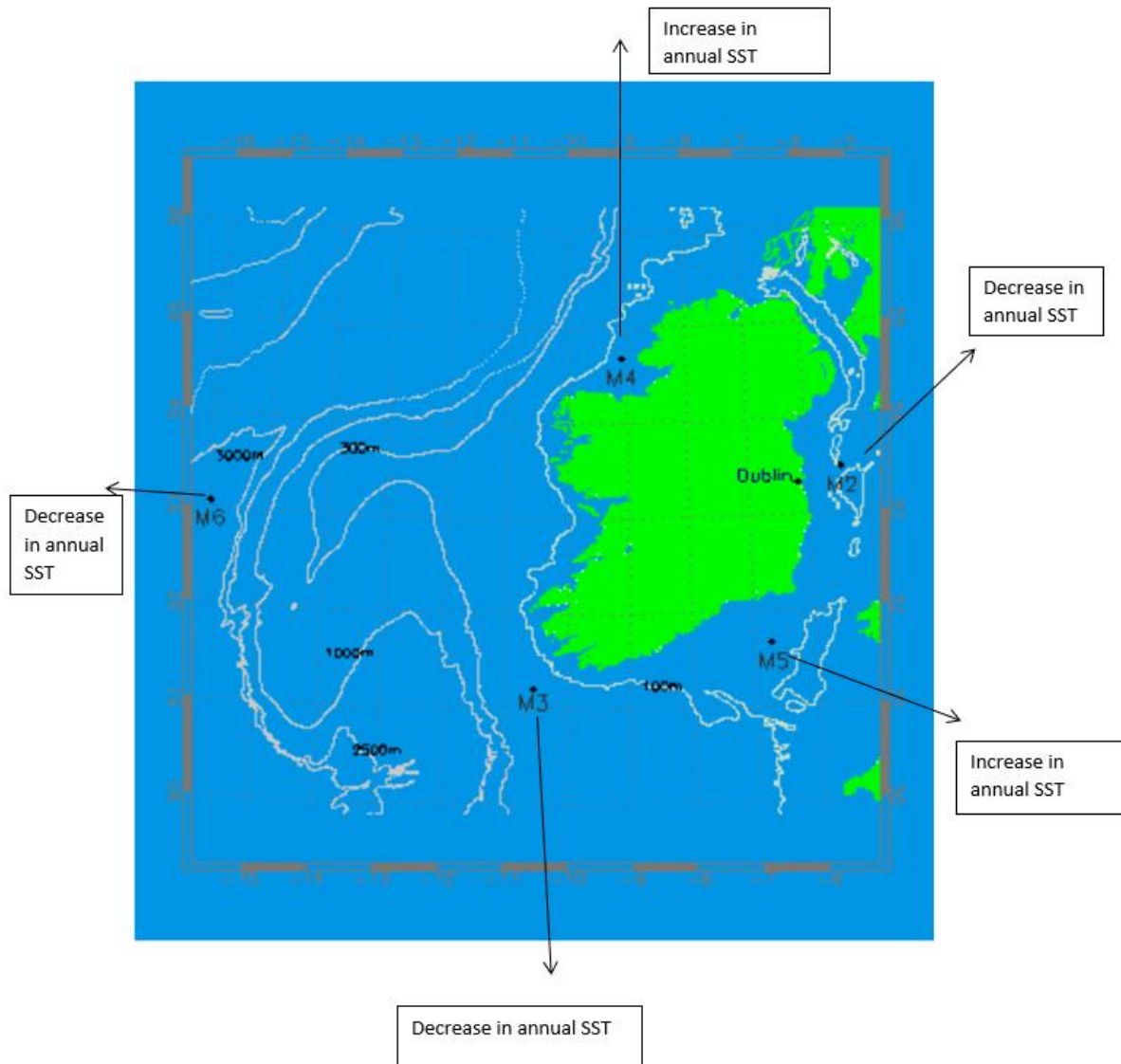


Figure 49 Overall trends in annual SST variations for each buoy from 2002-2020.

8.3 Causes of long-term variations in SST changes around Ireland's coastline.

The AMV signal impacts on air temperature, causing an increase of the effect and frequency of hurricane events in the North Atlantic which influence SST around Ireland's coastline. The AMV causes fluctuations in air temperature variations which contributes to influencing the frequency and intensity of hurricane events in the North Atlantic. Depending on the location and track of the hurricane event in the North Atlantic, the occurrence of hurricane events can influence variations in the NAO Index. The NAO Index indicates states of either stable or unstable water conditions around Ireland's coastline. The hurricane events contribute to the

mixing of waters around Ireland's coastline, causing unstable conditions and a high level of mixing waters during negative NAO Index occurrences.

The increase in the frequency and intensity of both storm and hurricane events is a significant contributing to the long term or prolonged variations in SST changes around Ireland's coastline. Hurricane events occurred in both the spells of maximum and minimum SST around Ireland's coastline. For this reason, the location of the origin, and the track of the hurricane itself is important for determining the effect on Irish SST variations. The location and track of the hurricane relative to the Gulf Stream is a significant factor in the transportation of warm water to and around Ireland's coastline. This is supported by the relatively stable NAO Index conditions around Ireland's coastline during the time of these hurricane events for spells of maximum SST. Although the NAO Index is negative during this time, that shows that there is a degree of mixing of waters, however the NAO Index value itself is stable. The origin and track of hurricanes in the North Atlantic are responsible for the transportation of cooler waters to and around Ireland's coastline, contributing to the spells of minimum SST around Ireland's coastline. An important factor to the influence of hurricane events on Ireland's SST, is the position and changing position of the Jet stream.

The position of the jet stream impacts Ireland's SST significantly during both positive and negative phases of NAO Index, however the direction of movement is significant in either transporting warm water from the Gulf Stream towards Ireland, or colder water from near the coast of Greenland, and the Labrador Current towards Ireland. Analysis of Lattanzio, et al, (2021) showed that during positive phases of the NAO Index, the Polar Jet Stream is shifted Northwards, which transports warmer waters from the Gulf Stream region towards Ireland, and contributes to stable conditions in Irish SST, with little mixing of waters. During negative phases of NAO Index, the polar Jet stream is shifted Southwards. This creates a high level of mixing waters and contributes to the transportation of cooler waters from the Labrador Current and Greenland ice sheet meltwater towards Ireland, and this was confirmed in the analysis of spells of maximum and minimum SST for each buoy.

The most influential factors for contributing to significant and long-term variations in SST around Ireland's coastline are the AMV, the increase in the frequency and intensity of storm and hurricane events in the North Atlantic, the position of the Jet stream, and the NAO Index. All of these processes are interconnected and correlate with each other showing a

proportionate relationship between these processes, that not only significantly influence SST around Ireland's coastline, but also influence each other.

8.4 The variations in SST between the buoys M2-M6

The location of buoys M2-M6 respectively, relative to the continental shelf and coastline of Ireland has influenced whether they have recorded an overall increase or decrease in mean annual SST from 2002-2020. Both M3 and M6 are located off the continental shelf and recorded an overall decrease in annual SST from 2002-2020. The location of M3 is off of the continental shelf to the southwest of Ireland. Its outlying location relative to the continental shelf, renders M3 susceptible to the full effects of the Atlantic Ocean, and the short- and long-term causations to SST variations. M3 is the closest buoy off the coast of Ireland to the effects of the Subtropical gyre. This area of anticyclonic ocean circulation, which could contribute to the mixing of waters in the Ekman layer around the area of M3, potentially causing the decrease in mean annual SST from 2002-2020. M6 is the most outlying location of all the buoys, relative to the continental shelf. M6 is located in the deep waters of the Atlantic Ocean and is the most susceptible buoy to the effects of the Atlantic Ocean, such as the North Atlantic current and cannot be influenced by the land-sea retention rates associated with the continental shelf unlike buoys M2, M4 and M5. As seen in Chapter 7, during negative phases of the NAO Index, the position of the polar jet stream southward, which would be on the direct path of where M6 is located off the east coast of Ireland. This could be a potential factor in the overall decrease in mean annual SST for M6.

M2 is the only buoy located on the continental shelf that also recorded an overall decrease in annual SST from 2002-2020, however this can be attributed to the funnelling effect of the current in the North Sea between the English channel which creates a high velocity of moving water around M2, contributing to the overall decrease in annual SST, as the water is not remaining on the continental shelf long enough to be influenced by the land-sea heat retention rates, as the currents and tides transport the water down the English channel. Tidal streams enter the English channel from the north and south of buoy M2, The Irish sea maximum spring tidal ranges are up to eight meters, not only causing a high level of mixing waters, which could possibly contribute to the decrease in overall mean annual SST for M2, but renders M2 the most susceptible buoy to the effects of local tides and currents compared to M3, M4, M5, and M6.

M4 and M5 are the only two buoys that recorded an overall increase in mean annual SST from 2002-2020. Although these two buoys are influenced by the short- and long-term changes in SST previously discussed, their location relative to the continental shelf is a significant factor contributing to the recorded overall increase in mean annual SST for M4 and M5. Their location on the continental shelf allows the land-sea heat retention process to take effect. The shallow waters of the continental shelf allow for the prolonged retention of heat energy and provide shelter from the harsh conditions of the open Atlantic waters. M4 located on the northeast coast of Ireland, could be more susceptible to the influence of the northward position of the jet stream during positive phases of the NAO Index. This could attribute to the transportation of warmer waters from the Gulf stream being transported northward, as increased cyclone frequency is associated with impacting storm tracks in the North Atlantic. A connection between M4 and M5, as they were the only two buoys to record an overall increase in annual mean SST, is their location. Both M4 and M5 are located around Ireland's coastline, within the boundaries of the continental shelf. Their locations within the continental shelf are more sheltered than M2, which is directly on the continental shelf, and M3 and M6 which are located off the continental shelf. The location of M4 and M5, provides some shelter from the effects of local tides and currents experienced by M2, and greater oceanic and atmospheric processes associated with M3 and M6 off the continental shelf.

Thus not only are the complex ocean-atmosphere interactions a significant factor in determining the variations in SST around Ireland's coastline, the varying or inconsistent locations of the buoys themselves all contribute to the complex and dynamic SST around Ireland's coastline. Limited knowledge on the constantly changing position of the jet stream, is an aspect that future research would benefit from, as this is a crucial process between the ocean-atmosphere interaction, and changes in this influence the NAO Index, and atmospheric circulation patterns experienced on a global, regional and local scale. Future works should be carried out to ensure that the marine buoys are maintained, and fully operational to ensure complete accuracy. Lastly, the influence of the position of each buoy around Ireland's coastline in relation to the continental shelf, would need to be further assessed to ascertain the degree of influence that this has on SST variations.

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Appendices

Table of the annual average sea surface temperature comparisons.

Year.	Observations.
2001	only M1 and M2 have recorded temperatures. M1 recorded a mean temperature of 12.74°C and M2 recorded a mean temperature of 12.56°C. There was a temperature difference of 0.18°C between the two buoys. This could be due to the different locations of the buoys, and the influence of the continental shelf in relation to the buoys will be examined.
2002	had recorded mean sea surface temperatures for buoys M1, M2, and M3. M1 recorded a mean temperature of 12.10°C. M2 recorded a mean temperature of 11.63°C. M3 recorded a mean temperature of 14.74°C. Between M1 and M2 there is a temperature difference of 0.47°C. Between M1 and M3 there is a temperature difference of 2.64°C. Between M2 and M3 there is a temperature difference of 3.11°C. There is a high temperature variance between the buoys. The causes for this will be examined further based on the location of the buoys, their location in relation to the continental shelf and the depth of the water in which the buoys are located.
2003	had recorded mean sea surface temperature values for M1, M2 and M3. M1 recorded a mean sea surface temperature of 12.85°C. M2 recorded a mean sea surface temperature of 11.67°C. M3 recorded a mean sea surface temperature of 13.37°C. Between M1 and M2 there is a temperature difference of 1.18°C. Between M1 and M3 there is a temperature difference of 0.52°C. Between M2 and M3 there is a temperature difference of 1.7°C. There is a high temperature variance between the buoys. The causes for this will be examined further based on the location of the buoys, their location in relation to the continental shelf and the depth of the water in which the buoys are located.
2004	recorded mean sea surface temperature values for M1, M2, M3, and M5. M1 recorded a mean sea surface temperature of 12.02°C. M2 recorded a mean sea

	surface temperature of 11.62°C. M3 recorded a mean sea surface temperature of 12.95°C. M5 recorded a mean sea surface temperature of 12.21°C. Between M1 and M2 there is a temperature difference of 0.4°C. Between M2 and M3 there is a temperature difference of 1.33°C, which is significant due to their close location. The causes for this will be further assessed. Between M3 and M5 there is a temperature difference of 0.74°C. There is a high temperature variance between the buoys. The causes for this will be examined further based on the location of the buoys, their location in relation to the continental shelf and the depth of the water in which the buoys are located.
2005	recorded mean sea surface temperature values for M1, M2, M3 and M5. M1 recorded a mean sea surface temperature of 12.51°C. M2 recorded a mean sea surface temperature of 11.62°C. M3 recorded a mean sea surface temperature of 13.03°C. M5 recorded a mean sea surface temperature of 12.50°C. Between M1 and M2 there was a temperature difference of 0.89°C. Between M2 and M3 there was a temperature difference of 1.41°C, which is high given their close proximity to each other and the causes for this will be assessed. Between M3 and M5 there was a temperature difference of 0.53°C. Between M2 and M5 there was a temperature difference of 0.88°C. There is a high temperature variance between the buoys. The causes for this will be examined further based on the location of the buoys, their location in relation to the continental shelf and the depth of the water in which the buoys are located.
2006	recorded mean sea surface temperature values for M1, M2, M3, M5 and M6. M1 recorded a mean sea surface temperature of 12.40°C. M2 recorded a mean sea surface temperature of 11.35°C. M3 recorded a mean sea surface temperature of 13.07°C. M5 recorded a mean sea surface temperature of 12.57°C. M6 recorded a mean sea surface temperature of 12.98°C. Between M1 and M2 there was a temperature difference of 1.05°C. Between M2 and M3 there was a temperature difference of 1.72°C which is significantly high considering their close proximity to each other. Between M3 and M5 there was a temperature difference of 0.5°C. Between M5 and M6 there was a temperature difference of 0.41°C. There is a high temperature variance between the buoys and the causes for this will be assessed.
2007	recorded the mean sea surface temperature variations for M1, M2, M3, M4, M5 and M6. M1 recorded a temperature of 12.41°C. M2 recorded a temperature of 11.95°C. M3 recorded a temperature of 13.33°C. M4 recorded a temperature of 13.35°C. M5 recorded a temperature of 12.81°C. M6 recorded a temperature of 13.38°C. Between M1 and M2 there was a temperature variation of 0.46°C. Between M2 and M3 there was a temperature variation of 1.38°C. Between M3 and M4 there was a temperature variation of 0.02°C. Between M4 and M5 there was a temperature variation of 0.54°C. Between M5 and M6 there was a temperature variation of 0.57°C. Between M4 and M6 there was a temperature variation of 0.05°C. The temperature variation between M2 and M5 showed a temperature difference of 0.86°C. There is a high temperature variation between the buoys and the causes for this will be examined.
2008	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a mean sea surface temperature of 9.08°C which was significantly low. M3 recorded a mean sea surface temperature of 12.78°C. M4 recorded a mean sea surface temperature of 12.07°C. M5 recorded a mean

	sea surface temperature of 13.10°C. M6 recorded a mean sea surface temperature of 13.09°C. Between M2 and M3 there was a significant temperature variation of 3.7°C. This is a significant variation based on their close proximity to each other. There is a high temperature variation between the buoys and the causes for this will be examined.
2009	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 11.41°C. M3 recorded a mean temperature of 12.71°C. M4 recorded a mean temperature of 12.05°C. M5 recorded a mean sea surface temperature of 12.16°C. M6 recorded a mean sea surface temperature of 12.85°C. Between M2 and M3 there was a temperature difference of 1.3°C. Between M3 and M4 there was a temperature difference of 0.66°C. Between M4 and M5 there was a temperature difference of 0.11°C. Between M5 and M6 there was a temperature difference of 0.69°C. Considering the close proximity of M2 and M3 there is a significant difference between the mean annual sea surface temperature values. The causes for this will be assessed further.
2010	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a mean temperature of 10.40°C. M3 recorded a mean temperature of 12.92°C. M4 recorded a mean temperature of 11.98°C. M5 recorded a mean temperature of 12.06°C. M6 recorded a mean temperature of 12.83°C. Between M2 and M3 there was a temperature difference of 2.52°C, which is a significant difference given their close proximity to each other. Between M3 and M4 there was a temperature difference of 0.94°C, which is also a significant difference given their close proximity to each other. Between M4 and M5 there was a temperature difference of 0.08°C, which is significantly low, but this could be attributed to their location on the west coast of Ireland. Between M5 and M6 there was a temperature difference of 0.77°C. The causes of the temperature variations between the buoys will be examined further in the analysis.
2011	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 12.05°C. M3 recorded a temperature of 12.61°C. M4 recorded a temperature of 11.81°C. M5 recorded a temperature of 12.06°C. M6 recorded a temperature of 12.05°C. Between M2 and M3 there was a temperature difference of 0.56°C. Between M3 and M4 there was a temperature difference of 0.80°C. Between M4 and M5 there was a temperature difference of 0.25°C. Between M5 and M6 there was a temperature difference of 0.01°C which is significantly low. Overall, 2011 had relatively low temperature variations compared to previous years. The causes for the variations in sea surface temperature will be analysed further.
2012	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 11.49°C. M3 recorded a temperature of 13.37°C. M4 recorded a temperature of 11.75°C. M5 recorded a temperature of 12.05°C. M6 recorded a temperature of 12.30°C. Between M2 and M3 there was a temperature difference of 1.88°C, this is a significant difference due to their close proximity to each other and the causes for this variation will be further assessed. Between M3 and M4 there was a temperature difference of 1.62°C, which is also a significant variation based on their close proximity to each other and the causes for this variation will be

	further assessed. Between M4 and M5 there was a temperature difference of 0.30°C which is a low variation. Between M5 and M6 there was a temperature difference of 0.25°C which is also a low variation in temperatures. Between M4 and M6 there was a temperature variation of 0.55°C. The causes for the variations in sea surface temperature will be analysed further.
2013	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 9.66°C, which was significantly low and the causes for this will be examined further. M3 recorded a temperature of 10.62°C. M4 recorded a temperature of 12.83°C. M5 recorded a temperature of 12.31°C. M6 recorded a temperature of 12.75°C. Between M2 and M3 there was a temperature difference of 0.92°C. Between M3 and M4 there was a temperature difference of 2.21°C, which was significantly high considering their close proximity to each other, and the causes for this will be further examined. Between M4 and M5 there was a temperature difference of 0.52°C. Between M5 and M6 there was a temperature difference of 0.44°C. Between M4 and M6 there was a temperature difference of only 0.08°C, which is significantly low. The causes for these temperature differences will be further assessed.
2014	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 13.15°C. M3 recorded a temperature of 12.08°C. M4 recorded a temperature of 11.08°C. M5 recorded a temperature of 10.64°C. M6 recorded a temperature of 11.38°C. Between M2 and M3 there was a temperature difference of 1.07°C, which is a significant difference given their close proximity to each other. Between M3 and M4 there was a temperature difference of 1°C, which is a significant variation given their close proximity to each other. Between M4 and M5 there was a temperature difference of 0.44°C. Between M5 and M6 there was a temperature difference of 0.74°C. The causes of the variations in sea surface temperature recordings between the buoys will be examined.
2015	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 11.20°C. M3 recorded a temperature of 10.89°C. M4 recorded a temperature of 11.54°C. M5 recorded a temperature of 8.72°C, which was significantly low. M6 recorded a temperature of 12.71°C. Between M2 and M3 there was a temperature difference of 0.31°C. Between M3 and M4 there was a temperature difference of 0.65°C. Between M4 and M5 there was a temperature difference of 2.82°C, which is a significant difference based to the location of the two buoys on the west coast. Between M5 and M6 there was a temperature difference of 3.99°C, which is a significant difference. The causes for these temperature variations will be examined further.
2016	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 9.50°C, which was significantly low, and the causes for this will be examined further. M3 recorded a temperature of 14.55°C. M4 recorded a temperature of 12.15°C. M5 recorded a temperature of 13.99°C. M6 recorded a temperature of 13.36°C. Between M2 and M3 there was a temperature difference of 5.05°C, which was significant difference based on their close proximity to each other. Between M3 and M4 there was a temperature difference of 2.4°C, which is a significant difference

	based on their close proximity to each other. Between M4 and M5 there was a temperature difference of 1.84°C which again is a significant difference. Between M5 and M6 there was a temperature difference of 0.63°C. The causes for these temperature variations between the buoys will be examined further.
2017	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 11.91°C. M3 recorded a temperature of 12.76°C. M4 recorded a temperature of 12.22°C. M5 recorded a temperature of 13.26°C. M6 recorded a temperature of 12.09°C. Between M2 and M3 there was a temperature difference of 0.85°C. Between M3 and M4 there was a temperature difference of 0.54°C. Between M4 and M5 there was a temperature difference of 1.04°C, which is a significant difference. Between M5 and M6 there was a temperature difference of 0.17°C, which is only a variation. The causes of the temperature variations will be examined further.
2018	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 13.19°C. M3 recorded a temperature of 13.88°C. M4 recorded a temperature of 10.10, which was significantly lower than the other buoys. M5 recorded a temperature of 13.03°C. M6 recorded a temperature of 12.37°C. Between M2 and M3 there was a temperature difference of 0.69°C. Between M3 and M4 there was a temperature difference of 3.78°C, which is a significant difference based on their close proximity to each other. The causes for this temperature variation will be assessed further. Between M4 and M5 there was a temperature difference of 2.93°C, which again is a significant temperature difference, and the causes for this will be assessed further. Between M5 and M6 there was a temperature difference of 0.66°C. The causes for the variations in temperature will be assessed further.
2019	recorded the mean sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 13.92°C. M3 recorded a temperature of 13.42°C. M4 recorded a temperature of 12.82°C. M5 recorded a temperature of 12.85°C. M6 recorded a temperature of 12.68°C. Between M2 and M3 there was a temperature difference of 0.5°C. Between M3 and M4 there was a temperature difference of 0.6°C. Between M4 and M5 there was a temperature difference of 0.03°C. Between M5 and M6 there was a temperature difference of 0.17°C. Overall, there was a low variation in temperature changes for this year, compared to previous years and the causes for this will be assessed further.
2020	recorded sea surface temperature variations for M2, M3, M4, M5 and M6. M2 recorded a temperature of 11.52°C. M3 recorded a temperature of 13.47°C. M4 recorded a temperature of 11.98°C. M5 recorded a temperature of 12.38°C. M6 recorded a temperature of 13.40°C. Between M2 and M3 there was a temperature difference of 1.95°C, which is a significant difference given their close proximity to each other. Between M3 and M4 there was a temperature difference of 1.49°C, which is a significant difference based on their close proximity to each other. Between M4 and M5 there was a temperature difference of 0.40°C, which is a low variation. Between M5 and M6 there is a temperature difference of 1.02°C. Between M4 and M6 there

	was a temperature difference of 1.42°C. The variations between M4, M5 and M6 are greater than previous years, and the causes for these temperature variations will be examined further.
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Spells in SST and the corresponding comparison to the NAO Index.

Table of the Maximum Hourly Recorded SST Values for M2 (Spell 1)

Date and Time	SST in °C	NAO Index
17/07/2013 20:00	19.1	0.67
17/07/2013 19:00	19.0	0.67
17/07/2013 13:00	19.0	0.67
17/07/2013 16:00	19.0	0.67
17/07/2013 17:00	18.9	0.67
18/07/2013 15:00	18.9	0.67
17/07/2013 18:00	18.9	0.67
17/07/2013 22:00	18.9	0.67
17/07/2013 23:00	18.9	0.67
18/07/2013 16:00	18.9	0.67

M2 (Spell 2)

Date and Time	SST in °C	NAO Index
12/07/2013 15:00	17.5	0.67
17/07/2013 00:00	17.5	0.67
22/07/2013 02:00	17.5	0.67
14/08/2003 17:00	17.5	-0.07
28/07/2006 09:00	17.5	0.67
28/07/2006 10:00	17.5	0.67
20/07/2013 10:00	17.5	0.67
22/07/2013 14:00	17.5	0.67
22/07/2013 15:00	17.5	0.67
23/07/2013 03:00	17.4	0.67

M2 (Spell 3)

Date and Time	SST in °C	NAO Index
08/08/2003 14:00	17.3	-0.07
08/08/2003 15:00	17.3	-0.07
09/08/2003 17:00	17.3	-0.07
10/08/2003 15:00	17.3	-0.07
10/08/2003 19:00	17.3	-0.07
12/08/2003 16:00	17.3	-0.07
27/07/2006 09:00	17.3	0.90
28/07/2006 22:00	17.3	0.90
27/07/2008 17:00	17.3	-1.27
12/07/2013 21:00	17.3	0.67

M2 (Spell 4)

Date and Time	SST in °C	NAO Index
28/07/2006 06:00	17.2	0.90
28/07/2006 18:00	17.2	0.90
28/07/2006 19:00	17.2	0.90
27/07/2008 18:00	17.2	-1.27
27/07/2008 20:00	17.2	-1.27
27/07/2008 22:00	17.2	-1.27
28/07/2008 01:00	17.2	-1.27
15/08/2010 16:00	17.2	-1.22
15/08/2010 17:00	17.2	-1.22
15/08/2010 18:00	17.2	-1.22

M2 (Spell 5)

Date and Time	SST in °C	NAO Index
08/08/2003 09:00	17.2	-0.07
08/08/2003 18:00	17.2	-0.07
09/08/2003 18:00	17.2	-0.07
09/08/2003 20:00	17.2	-0.07
10/08/2003 16:00	17.2	-0.07
13/08/2003 17:00	17.2	-0.07
13/08/2003 16:00	17.2	-0.07
13/08/2003 17:00	17.2	-0.07
13/08/2003 18:00	17.2	-0.07
14/08/2003 16:00	17.2	-0.07

M2 (Spell 6)

Date and Time	SST in °C	NAO Index
08/08/2003 09:00	17.2	-0.07
08/08/2003 18:00	17.2	-0.07
09/08/2003 18:00	17.2	-0.07
09/08/2003 20:00	17.2	-0.07
10/08/2003 16:00	17.2	-0.07
10/08/2003 17:00	17.2	-0.07
13/08/2003 16:00	17.2	-0.07
13/08/2003 17:00	17.2	-0.07
13/08/2003 18:00	17.2	-0.07
14/08/2003 16:00	17.2	-0.07

M2 (Spell 7)

Date and Time	SST in °C	NAO Index
26/06/2010 17:00	17.1	-0.82
15/08/2010 15:00	17.1	-1.22
15/08/2010 19:00	17.1	-1.22
15/08/2010 21:00	17.1	-1.22
15/08/2010 22:00	17.1	-1.22
15/08/2010 23:00	17.1	-1.22
16/08/2010 00:00	17.1	-1.22
16/08/2010 14:00	17.1	-1.22
16/08/2010 17:00	17.1	-1.22
16/08/2010 18:00	17.1	-1.22

M2 (Spell 8)

Date and Time	SST in °C	NAO Index
08/08/2008 13:00	17	-1.16
08/08/2008 19:00	17	-1.16
09/08/2008 00:00	17	-1.16
25/06/2010 18:00	17	-1.39
25/06/2010 19:00	17	-1.39
25/06/2010 21:00	17	-1.39
25/06/2010 22:00	17	-1.39
26/06/2010 15:00	17	-1.39
26/06/2010 16:00	17	-1.39
26/06/2010 18:00	17	-1.39

M2 (Spell 9)

Date and Time	SST in °C	NAO Index
13/08/2003 21:00	17	-0.07
15/08/2003 17:00	17	-0.07
15/08/2003 18:00	17	-0.07
24/08/2003 14:00	17	-0.07
24/08/2003 15:00	17	-0.07
26/07/2006 08:00	17	0.90
27/07/2008 13:00	17	-1.27
28/07/2008 04:00	17	-1.27
28/07/2008 17:00	17	-1.27
29/07/2008 13:00	17	-1.27

M2 (Spell 10)

Date and Time	SST in °C	NAO Index
16/08/2010 12:00	16.9	-1.22
16/08/2010 13:00	16.9	-1.22
01/07/2016 09:00	16.9	-1.76
01/07/2016 10:00	16.9	-1.76
01/07/2016 11:00	16.9	-1.76
01/07/2016 12:00	16.9	-1.76
02/07/2016 19:00	16.9	-1.76
01/07/2016 00:00	16.9	-1.76
20/07/2013 02:00	16.8	0.67
21/07/2013 20:00	16.8	0.67

Table of the Maximum Hourly Recorded SST Values for M3. (Spell 1)

Date and Time	SST in °C	NAO Index
26/07/2014 17:00	21.0	0.18
25/07/2014 17:00	21.0	0.18
25/07/2014 16:00	20.9	0.18
25/07/2014 20:00	20.9	0.18
25/07/2014 21:00	20.9	0.18
26/07/2014 20:00	20.9	0.18
26/07/2014 21:00	20.9	0.18
25/07/2014 22:00	20.9	0.18
25/07/2014 19:00	20.8	0.18
26/07/2014 19:00	20.8	0.18

M3 (Spell 2)

Date and Time	SST in °C	NAO Index
26/07/2014 16:00	20.8	0.18
27/07/2014 19:00	20.7	0.18
27/07/2014 20:00	20.7	0.18
25/07/2014 15:00	20.7	0.18
26/07/2014 15:00	20.7	0.18
27/07/2014 21:00	20.6	0.18
27/07/2014 18:00	20.6	0.18
27/07/2014 17:00	20.6	0.18
26/07/2014 14:00	20.5	0.18
08/08/2020 15:00	20.4	0.12

M3 (Spell 3)

Date and Time	SST in °C	NAO Index
25/07/2014 23:00	20.4	0.18
27/07/2014 16:00	20.3	0.18
28/07/2014 00:00	20.3	0.18
27/07/2014 02:00	20.2	0.18
27/07/2014 15:00	20.2	0.18
27/07/2014 23:00	20.2	0.18
28/07/2014 18:00	20.2	0.18
26/07/2014 01:00	20.2	0.18
26/07/2014 22:00	20.2	0.18
28/07/2014 01:00	20.2	0.18

M3 (Spell 4)

Date and Time	SST in °C	NAO Index
26/07/2013 15:00	20.1	0.67
27/07/2014 03:00	20.1	0.18
28/07/2014 19:00	20.1	0.18
25/07/2013 15:00	20.1	0.67
25/07/2014 18:00	20.1	0.18
26/07/2014 18:00	20.1	0.18
27/07/2014 14:00	20.1	0.18
28/07/2014 14:00	20.1	0.18
28/07/2014 15:00	20.1	0.18
28/07/2014 17:00	20.1	0.18

M3 (Spell 5)

Date and Time	SST in °C	NAO Index
28/07/2014 23:00	20	0.18
25/07/2013 18:00	20	0.67
25/07/2013 19:00	20	0.67
26/06/2013 18:00	20	0.52
26/07/2013 19:00	20	0.67
25/06/2018 17:00	20	1.09
26/06/2018 17:00	20	1.09
27/06/2018 17:00	20	1.09
28/06/2018 17:00	20	1.09
29/06/2018 17:00	20	1.09

M3 (Spell 6)

Date and Time	SST in °C	NAO Index
26/07/2014 00:00	19.9	0.18
26/07/2014 13:00	19.9	0.18
29/07/2014 00:00	19.9	0.18
25/06/2018 14:00	19.9	1.09
26/06/2018 14:00	19.9	1.09
27/06/2018 14:00	19.9	1.09
28/06/2018 14:00	19.9	1.09
29/06/2018 14:00	19.9	1.09
20/06/2018 14:00	19.9	1.09
26/07/2013 13:00	19.8	0.67

M3 (Spell 7)

Date and Time	SST in °C	NAO Index
23/07/2014 21:00	19.4	0.18
25/07/2013 23:00	19.4	0.67
26/07/2013 20:00	19.4	0.67
27/07/2013 23:00	19.4	0.67
24/06/2018 16:00	19.4	1.09
27/07/2013 14:00	19.4	0.67
25/07/2014 12:00	19.3	0.18
27/07/2013 21:00	19.3	0.67
28/07/2013 16:00	19.3	0.67
08/08/2012 19:00	19.3	-0.98

M3 (Spell 8)

Date and Time	SST in °C	NAO Index
24/07/2014 01:00	19.2	0.18
24/07/2014 02:00	19.2	0.18
25/07/2014 00:00	19.2	0.18
29/07/2014 17:00	19.2	0.18
29/07/2014 18:00	19.2	0.18
29/07/2014 21:00	19.2	0.18
29/07/2014 23:00	19.2	0.18
26/07/2013 23:00	19.2	0.67
28/07/2013 10:00	19.2	0.67
08/08/2012 18:00	19.2	-0.98

M3 (Spell 9)

Date and Time	SST in °C	NAO Index
30/06/2018 23:00	18.9	1.09
01/07/2018 00:00	18.9	1.39
28/07/2013 05:00	18.8	0.67
21/07/2014 20:00	18.8	0.18
24/07/2014 20:00	18.8	0.18
30/07/2014 17:00	18.8	0.18
30/07/2014 20:00	18.8	0.18
30/07/2014 21:00	18.8	0.18
01/08/2014 19:00	18.8	-1.68
01/08/2014 21:00	18.8	-1.68

M3 (Spell 10)

Date and Time	SST in °C	NAO Index
01/07/2018 01:00	18.8	1.39
23/07/2013 12:00	18.8	0.67
23/07/2013 13:00	18.8	0.67
23/07/2013 16:00	18.8	0.67
26/07/2013 02:00	18.8	0.67
26/07/2013 10:00	18.8	0.67
27/07/2013 08:00	18.8	0.67
31/07/2014 14:00	18.7	0.18
01/08/2014 12:00	18.7	-1.68
01/08/2014 15:00	18.7	-1.68

Table of the Maximum Hourly Recorded SST Values for M4 (Spell 1).

Date and Time	SST in °C	NAO Index
25/07/2014 22:00	20.2	0.18
26/07/2014 17:00	20.2	0.18
25/07/2014 17:00	20.2	0.18
25/07/2014 19:00	20.1	0.18
26/07/2014 19:00	20.1	0.18
25/07/2014 16:00	20.1	0.18
25/07/2014 20:00	20.1	0.18
25/07/2014 21:00	20.1	0.18
26/07/2014 20:00	20.1	0.18
26/07/2014 21:00	20.1	0.18

M4 (Spell 2)

Date and Time	SST in °C	NAO Index
27/07/2014 17:00	19.9	0.18
27/07/2014 19:00	19.9	0.18
27/07/2014 20:00	19.9	0.18
27/07/2014 21:00	19.8	0.18
27/07/2014 18:00	19.8	0.18
26/07/2014 14:00	19.7	0.18
27/06/2018 15:00	19.6	1.09
28/06/2018 15:00	19.6	1.09
29/06/2018 15:00	19.6	1.09
30/06/2018 15:00	19.6	1.09

M4 (Spell 3)

Date and Time	SST in °C	NAO Index
25/07/2014 18:00	19.4	0.18
15/07/2018 16:00	19.3	1.39
10/07/2018 16:00	19.3	1.39
13/07/2018 16:00	19.3	1.39
11/07/2018 16:00	19.3	1.39
12/07/2018 16:00	19.3	1.39
08/07/2018 16:00	19.3	1.39
27/07/2014 03:00	19.3	0.18
28/07/2014 19:00	19.3	0.18
15/07/2014 01:00	19.3	0.18

M4 (Spell 4)

Date and Time	SST in °C	NAO Index
27/07/2013 16:00	18.6	0.67
09/08/2018 21:00	18.5	1.97
09/08/2018 17:00	18.5	1.97
17/07/2018 00:00	18.5	1.39
10/07/2018 23:00	18.5	1.39
27/07/2013 19:00	18.5	0.67
09/07/2018 05:00	18.5	1.39
22/07/2014 16:00	18.5	0.18
23/07/2014 11:00	18.5	0.18
25/07/2014 12:00	18.5	0.18

M4 (Spell 5)

Date and Time	SST in °C	NAO Index
26/07/2013 12:00	18.5	0.67
22/07/2014 15:00	18.5	0.18
29/07/2014 11:00	18.4	0.18
29/07/2014 15:00	18.4	0.18
29/07/2014 16:00	18.4	0.18
29/07/2014 19:00	18.4	0.18
29/07/2014 22:00	18.4	0.18
09/08/2018 20:00	18.4	1.97
09/08/2018 22:00	18.4	1.97
10/07/2018 00:00	18.4	1.39

M4 (Spell 6)

Date and Time	SST in °C	NAO Index
25/07/2013 21:00	18.4	1.39
23/07/2014 07:00	18.4	1.39
11/07/2018 06:00	18.3	1.39
08/07/2018 00:00	18.3	1.39
12/07/2018 08:00	18.3	1.39
14/07/2018 04:00	18.3	1.39
14/07/2018 21:00	18.3	1.39
12/07/2018 21:00	18.3	1.39
15/07/2018 21:00	18.3	1.39
13/07/2018 21:00	18.3	1.39

M4 (Spell 7)

Date and Time	SST in °C	NAO Index
13/07/2018 14:00	18.2	1.39
11/07/2018 14:00	18.2	1.39
12/07/2018 14:00	18.2	1.39
11/07/2018 13:00	18.2	1.39
08/08/2012 18:00	18.2	-0.98
10/08/2018 00:00	18.2	1.97
05/08/2018 22:00	18.2	1.97
11/07/2018 05:00	18.2	1.97
13/07/2018 00:00	18.2	1.39
10/07/2018 04:00	18.2	1.39

M4 (Spell 8)

Date and Time	SST in °C	NAO Index
10/07/2018 12:00	18.1	1.39
14/07/2018 06:00	18.1	1.39
20/07/2018 22:00	18.1	1.39
21/07/2014 21:00	18.1	0.18
22/07/2014 02:00	18.1	0.18
22/07/2014 12:00	18.1	0.18
25/07/2014 03:00	18.1	0.18
01/08/2014 20:00	18.1	-1.68
27/07/2013 00:00	18.1	0.67
27/07/2013 13:00	18.1	0.67

M4 (Spell 9)

Date and Time	SST in °C	NAO Index
22/07/2014 04:00	18	0.18
22/07/2014 05:00	18	0.18
22/07/2014 06:00	18	0.18
22/07/2014 08:00	18	0.18
13/07/2018 11:00	17.9	1.39
14/07/2018 11:00	17.9	1.39
15/07/2018 11:00	17.9	1.39
11/07/2018 11:00	17.9	1.39
27/07/2013 10:00	17.9	0.67
27/07/2013 20:00	17.9	0.67

M4 (Spell 10)

Date and Time	SST in °C	NAO Index
15/08/2018 05:00	17.8	1.97
20/07/2013 20:00	17.8	0.67
27/07/2013 03:00	17.8	0.67
28/07/2013 18:00	17.8	0.67
29/07/2013 00:00	17.8	0.67
29/07/2013 01:00	17.8	0.67
29/07/2013 02:00	17.8	0.67
29/07/2013 03:00	17.8	0.67
12/07/2014 16:00	17.8	0.18
30/07/2014 05:00	17.8	0.18

Table of the Maximum Hourly Recorded SST Values for M5 (Spell 1)

Date and Time	SST in °C	NAO Index
17/07/2014 22:00	19.6	0.18
17/07/2014 20:00	19.6	0.18
17/07/2014 19:00	19.6	0.18
17/07/2014 21:00	19.6	0.18
17/07/2014 18:00	19.6	0.18
17/07/2014 17:00	19.6	0.18
26/07/2014 20:00	19.5	0.18
26/07/2014 21:00	19.5	0.18
17/07/2014 23:00	19.5	0.18
28/07/2014 20:00	19.5	0.18

M5 (Spell 2)

Date and Time	SST in °C	NAO Index
18/07/2014 00:00	19.3	0.18
29/07/2014 01:00	19.3	0.18
28/07/2014 12:00	19.3	0.18
26/07/2014 23:00	19.3	0.18
27/07/2014 23:00	19.3	0.18
26/07/2014 18:00	19.2	0.18
28/07/2014 17:00	19.2	0.18
28/07/2014 00:00	19.2	0.18
27/07/2014 18:00	19.2	0.18
26/07/2014 17:00	19.2	0.18

M5 (Spell 3)

Date and Time	SST in °C	NAO Index
28/07/2014 09:00	19.2	0.18
29/07/2014 02:00	19.2	0.18
28/07/2014 16:00	19.2	0.18
28/07/2014 13:00	19.2	0.18
28/07/2014 15:00	19.2	0.18
26/07/2006 17:00	19.2	0.90
26/07/2006 18:00	19.2	0.90
26/07/2006 19:00	19.2	0.90
26/07/2006 16:00	19.2	0.90
17/07/2013 15:00	19.2	0.67

M5 (Spell 4)

Date and Time	SST in °C	NAO Index
27/07/2014 02:00	19	0.18
25/07/2014 15:00	19	0.18
26/07/2014 15:00	19	0.18
25/07/2014 16:00	19	0.18
25/07/2014 18:00	19	0.18
25/07/2006 21:00	19	0.90
25/07/2006 22:00	19	0.90
26/07/2006 13:00	19	0.90
27/07/2013 17:00	19	0.67
27/07/2013 18:00	19	0.67

M5 (Spell 5)

Date and Time	SST in °C	NAO Index
28/07/2013 15:00	18.8	0.67
27/07/2013 22:00	18.8	0.67
27/07/2013 16:00	18.8	0.67
26/07/2013 15:00	18.8	0.67
25/06/2018 17:00	18.8	1.09
26/06/2018 17:00	18.8	1.09
27/06/2018 17:00	18.8	1.09
28/06/2018 17:00	18.8	1.09
29/06/2018 17:00	18.8	1.09
20/06/2018 17:00	18.8	1.09

M5 (Spell 6)

Date and Time	SST in °C	NAO Index
17/07/2013 23:00	18.7	0.67
29/07/2013 08:00	18.7	0.67
29/07/2013 11:00	18.7	0.67
29/07/2013 07:00	18.7	0.67
29/07/2013 06:00	18.7	0.67
29/07/2013 05:00	18.7	0.67
29/07/2013 04:00	18.7	0.67
29/07/2013 02:00	18.7	0.67
29/07/2013 03:00	18.7	0.67
28/07/2013 12:00	18.7	0.67

M5 (Spell 7)

Date and Time	SST in °C	NAO Index
30/07/2013 12:00	18.6	0.67
29/07/2013 19:00	18.6	0.67
27/07/2013 08:00	18.6	0.67
27/07/2013 07:00	18.6	0.67
27/07/2013 06:00	18.6	0.67
26/07/2013 23:00	18.6	0.67
27/07/2013 00:00	18.6	0.67
25/07/2013 13:00	18.6	0.67
26/07/2013 13:00	18.6	0.67
25/07/2013 14:00	18.6	0.67

M5 (Spell 8)

Date and Time	SST in °C	NAO Index
26/07/2013 12:00	18.5	0.67
27/07/2013 15:00	18.5	0.67
16/07/2018 00:00	18.5	1.39
15/07/2018 23:00	18.5	1.39
16/07/2018 20:00	18.5	1.39
15/07/2018 22:00	18.5	1.39
15/07/2014 01:00	18.5	0.18
13/07/2014 18:00	18.5	0.18
31/07/2014 09:00	18.5	0.18
31/07/2014 21:00	18.5	0.18

M5 (Spell 9)

Date and Time	SST in °C	NAO Index
30/07/2013 05:00	18.4	0.67
30/07/2013 07:00	18.4	0.67
30/07/2013 08:00	18.4	0.67
30/07/2013 06:00	18.4	0.67
30/07/2013 10:00	18.4	0.67
30/07/2013 20:00	18.4	0.67
24/07/2013 22:00	18.4	0.67
26/07/2013 03:00	18.4	0.67
26/07/2013 02:00	18.4	0.67
25/07/2013 11:00	18.4	0.67

M5 (Spell 10)

Date and Time	SST in °C	NAO Index
27/07/2006 03:00	18.3	0.90
29/07/2006 16:00	18.3	0.90
29/07/2006 15:00	18.3	0.90
29/07/2006 14:00	18.3	0.90
29/07/2006 12:00	18.3	0.90
29/07/2006 13:00	18.3	0.90
19/07/2006 16:00	18.3	0.90
19/07/2006 17:00	18.3	0.90
19/07/2006 18:00	18.3	0.90
19/07/2006 22:00	18.3	0.90

Table of the Maximum Hourly Recorded SST Values for M6 (Spell 1)

Date and Time	SST in °C	NAO Index
12/07/2014 20:00	18.2	0.18
17/07/2014 13:00	18.2	0.18
13/07/2014 00:00	18.2	0.18
17/07/2014 14:00	18.2	0.18
27/07/2013 17:00	18.2	0.67
21/07/2014 21:00	18.2	0.18
21/08/2014 13:00	18.2	0.18
21/08/2014 15:00	18.2	0.18
07/08/2014 01:00	18.2	0.18
17/07/2014 15:00	18.2	0.18

M6 (Spell 2)

Date and Time	SST in °C	NAO Index
23/07/2014 07:00	18.1	0.18
23/07/2014 09:00	18.1	0.18
22/07/2014 00:00	18.1	0.18
31/07/2014 09:00	18.1	0.18
23/07/2014 06:00	18.1	0.18
31/07/2014 07:00	18.1	0.18
21/07/2014 19:00	18.1	0.18
27/07/2013 16:00	18.1	0.67
30/07/2014 11:00	18.1	0.18
30/07/2014 09:00	18.1	0.18

M6 (Spell 3)

Date and Time	SST in °C	NAO Index
20/08/2014 01:00	18	-1.68
25/08/2014 05:00	18	-1.68
23/08/2014 04:00	18	-1.68
23/08/2014 03:00	18	-1.68
24/08/2014 01:00	18	-1.68
24/08/2014 00:00	18	-1.68
23/08/2014 09:00	18	-1.68
23/08/2014 10:00	18	-1.68
23/08/2014 11:00	18	-1.68
23/08/2014 17:00	18	-1.68

M6 (Spell 4)

Date and Time	SST in °C	NAO Index
04/09/2014 22:00	17.8	1.62
05/09/2014 00:00	17.8	1.62
05/09/2014 01:00	17.8	1.62
26/08/2014 05:00	17.8	-1.68
26/08/2014 04:00	17.8	-1.68
25/08/2014 16:00	17.8	-1.68
25/08/2014 18:00	17.8	-1.68
04/09/2014 20:00	17.8	1.62
04/09/2014 23:00	17.8	1.62
26/08/2014 03:00	17.8	-1.68

M6 (Spell 5)

Date and Time	SST in °C	NAO Index
30/09/2014 13:00	17.7	1.62
04/10/2014 23:00	17.7	-1.27
05/10/2014 00:00	17.7	-1.27
07/09/2014 13:00	17.7	1.62
01/09/2014 01:00	17.7	1.62
01/09/2014 20:00	17.7	1.62
01/09/2014 00:00	17.7	1.62
19/07/2014 08:00	17.7	0.18
19/07/2014 13:00	17.7	0.18
19/07/2014 14:00	17.7	0.18

M6 (Spell 6)

Date and Time	SST in °C	NAO Index
08/09/2014 15:00	17.6	1.62
07/09/2014 12:00	17.6	1.62
12/07/2014 12:00	17.6	0.18
08/09/2014 01:00	17.6	1.62
08/09/2014 02:00	17.6	1.62
08/09/2014 16:00	17.6	1.62
08/09/2014 21:00	17.6	1.62
08/09/2014 17:00	17.6	1.62
08/09/2014 18:00	17.6	1.62
08/09/2014 20:00	17.6	1.62

M6 (Spell 7)

Date and Time	SST in °C	NAO Index
10/09/2014 17:00	17.6	1.62
14/09/2014 16:00	17.6	1.62
05/10/2014 16:00	17.6	-1.27
29/09/2014 18:00	17.6	1.62
09/09/2014 01:00	17.6	1.62
13/09/2014 15:00	17.6	1.62
10/09/2014 18:00	17.6	1.62
14/09/2014 20:00	17.6	1.62
05/10/2014 03:00	17.6	-1.27
05/10/2014 11:00	17.6	-1.27

M6 (Spell 8)

Date and Time	SST in °C	NAO Index
10/09/2014 22:00	17.5	1.62
10/09/2014 11:00	17.5	1.62
10/09/2014 12:00	17.5	1.62
10/09/2014 16:00	17.5	1.62
12/09/2014 07:00	17.5	1.62
09/09/2014 22:00	17.5	1.62
11/09/2014 16:00	17.5	1.62
12/09/2014 11:00	17.5	1.62
29/09/2014 10:00	17.5	1.62
12/09/2014 00:00	17.5	1.62

M6 (Spell 9)

Date and Time	SST in °C	NAO Index
18/07/2014 06:00	17.4	0.18
16/07/2014 21:00	17.4	0.18
15/07/2014 14:00	17.4	0.18
15/07/2014 15:00	17.4	0.18
16/07/2014 20:00	17.4	0.18
15/07/2014 18:00	17.4	0.18
16/07/2014 19:00	17.4	0.18
18/07/2014 05:00	17.4	0.18
16/07/2014 18:00	17.4	0.18
16/07/2014 17:00	17.4	0.18

M6 (Spell 10)

Date and Time	SST in °C	NAO Index
11/10/2014 00:00	17.4	-1.27
11/10/2014 01:00	17.4	-1.27
11/10/2014 05:00	17.4	-1.27
10/10/2014 19:00	17.4	-1.27
23/10/2014 08:00	17.4	-1.27
23/10/2014 07:00	17.4	-1.27
23/10/2014 06:00	17.4	-1.27
10/10/2014 21:00	17.4	-1.27
23/10/2014 04:00	17.4	-1.27
10/10/2014 23:00	17.4	-1.27

Table of the Minimum Hourly Recorded SST Values for M2 (Spell 1)

Date and Time	SST in °C	NAO Index
27/12/2009 07:00	6.7	-1.93
30/03/2013 06:00	6.7	-1.61
31/03/2013 08:00	6.6	-1.61
31/03/2013 23:00	6.6	-1.61
31/03/2013 09:00	6.6	-1.61
31/03/2013 10:00	6.6	-1.61
31/03/2013 11:00	6.6	-1.61
31/03/2013 19:00	6.6	-1.61
31/03/2013 06:00	6.5	-1.61
31/03/2013 07:00	6.5	-1.61

M2 (Spell 2)

Date and Time	SST in °C	NAO Index
30/03/2013 18:00	6.9	-1.61
30/03/2013 19:00	6.9	-1.61
01/04/2013 10:00	6.8	0.69
01/04/2013 08:00	6.8	0.69
31/03/2013 18:00	6.8	-1.61
01/04/2013 07:00	6.8	0.69
01/04/2013 11:00	6.8	0.69
01/04/2013 00:00	6.7	0.69
01/04/2013 09:00	6.7	0.69
31/03/2013 12:00	6.7	0.69

M2 (Spell 3)

Date and Time	SST in °C	NAO Index
07/03/2011 08:00	7.4	0.61
07/04/2013 08:00	7.3	0.69
16/04/2013 08:00	7.3	0.69
08/04/2013 03:00	7.3	0.69
08/04/2013 07:00	7.3	0.69
06/04/2013 20:00	7.3	0.69
06/04/2013 19:00	7.3	0.69
12/04/2013 04:00	7.3	0.69
14/03/2013 04:00	7.3	-1.61
07/04/2013 10:00	7.3	0.69

M2 (Spell 4)

Date and Time	SST in °C	NAO Index
26/02/2010 02:00	7.4	-1.98
24/02/2010 07:00	7.4	-1.98
26/02/2010 01:00	7.4	-1.98

24/02/2010 08:00	7.4	-1.98
24/02/2010 09:00	7.4	-1.98
26/02/2010 03:00	7.4	-1.98
26/02/2010 00:00	7.4	-1.98
26/02/2010 04:00	7.4	-1.98
24/02/2010 10:00	7.4	-1.98
25/02/2010 00:00	7.4	-1.98

M2 (Spell 5)

Date and Time	SST in °C	NAO Index
08/04/2013 01:00	7.5	0.69
05/04/2013 15:00	7.5	0.69
18/04/2013 21:00	7.5	0.69
06/04/2013 05:00	7.5	0.69
08/04/2013 05:00	7.5	0.69
05/04/2013 14:00	7.5	0.69
07/04/2013 12:00	7.5	0.69
11/04/2013 03:00	7.5	0.69
19/04/2013 09:00	7.5	0.69
19/04/2013 01:00	7.5	0.69

M2 (Spell 6)

Date and Time	SST in °C	NAO Index
06/04/2008 20:00	7.5	-1.07
07/04/2008 09:00	7.5	-1.07
07/04/2008 10:00	7.5	-1.07
08/04/2008 08:00	7.5	-1.07
07/04/2008 20:00	7.5	-1.07
07/04/2008 21:00	7.5	-1.07
07/04/2008 22:00	7.5	-1.07
08/04/2008 06:00	7.5	-1.07
09/04/2008 21:00	7.5	-1.07
27/10/2010 08:00	7.5	-0.93

M2 (Spell 7)

Date and Time	SST in °C	NAO Index
22/02/2010 07:00	7.5	-1.98
29/01/2010 06:00	7.5	-1.11
30/01/2010 01:00	7.5	-1.11
25/01/2010 16:00	7.5	-1.11
06/03/2011 20:00	7.5	0.61
06/03/2011 18:00	7.5	0.61
22/02/2011 07:00	7.5	0.70
21/02/2011 22:00	7.5	0.70
21/02/2011 23:00	7.5	0.70

21/02/2011 07:00	7.5	0.70
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M2 (Spell 8)

Date and Time	SST in °C	NAO Index
10/04/2014 00:00	7.5	0.69
07/04/2013 13:00	7.5	0.69
07/04/2013 20:00	7.5	0.69
08/04/2013 17:00	7.5	0.69
09/04/2013 23:00	7.5	0.69
11/04/2013 02:00	7.5	0.69
10/04/2013 13:00	7.5	0.69
10/04/2013 22:00	7.5	0.69
10/04/2013 23:00	7.5	0.69
10/04/2013 18:00	7.5	0.69

M2 (Spell 9)

Date and Time	SST in °C	NAO Index
14/03/2015 11:00	7.5	1.45
14/03/2015 08:00	7.5	1.45
15/03/2015 08:00	7.5	1.45
15/05/2015 09:00	7.5	1.45
15/03/2015 07:00	7.5	1.45
15/03/2015 05:00	7.5	1.45
15/03/2015 06:00	7.5	1.45
15/03/2015 03:00	7.5	1.45
16/03/2015 10:00	7.5	1.45
14/03/2015 21:00	7.5	1.45

M2 (Spell 10)

Date and Time	SST in °C	NAO Index
02/04/2013 00:00	7.6	0.69
02/04/2013 06:00	7.6	0.69
03/04/2013 01:00	7.6	0.69
01/04/2013 19:00	7.6	0.69
03/04/2013 21:00	7.6	0.69
01/04/2013 02:00	7.6	0.69
10/04/2013 10:00	7.6	0.69
13/04/2013 16:00	7.6	0.69
13/04/2013 17:00	7.6	0.69
13/04/2013 18:00	7.6	0.69

Table of the Minimum Hourly Recorded SST Values for M3 (Spell 1)

Date and Time	SST in °C	NAO Index
19/03/2020 04:00	7.9	1.01
19/03/2020 05:00	7.9	1.01
19/03/2020 02:00	7.9	1.01
19/03/2020 03:00	7.9	1.01
20/03/2020 00:00	7.9	1.01
20/03/2020 02:00	7.9	1.01
20/03/2020 01:00	7.9	1.01
19/03/2020 06:00	7.9	1.01
18/03/2020 01:00	7.9	1.01
19/03/2020 00:00	7.9	1.01

M3 (Spell 2)

Date and Time	SST in °C	NAO Index
18/03/2020 22:00	8	1.01
18/03/2020 13:00	8	1.01
18/03/2020 15:00	8	1.01
18/03/2020 16:00	8	1.01
18/03/2020 14:00	8	1.01
31/03/2020 04:00	8	1.01
21/03/2020 16:00	8	1.01
21/03/2020 15:00	8	1.01
21/03/2020 17:00	8	1.01
21/03/2020 18:00	8	1.01

M3 (Spell 3)

Date and Time	SST in °C	NAO Index
23/03/2020 18:00	8.2	1.01
30/03/2020 02:00	8.2	1.01
30/03/2020 00:00	8.2	1.01
29/03/2020 17:00	8.2	1.01
20/02/2020 13:00	8.2	1.01
29/03/2020 02:00	8.2	1.01
29/03/2020 01:00	8.2	1.01
29/03/2020 03:00	8.2	1.01
29/03/2020 04:00	8.2	1.01
27/03/2020 21:00	8.2	1.01

M3 (Spell 4)

Date and Time	SST in °C	NAO Index
08/03/2018 10:00	8.2	-0.93
08/03/2018 09:00	8.2	-0.93
08/03/2020 08:00	8.2	1.01
08/03/2018 20:00	8.2	-0.93
08/03/2018 21:00	8.2	-0.93
08/03/2018 22:00	8.2	-0.93
08/03/2018 23:00	8.2	-0.93
07/03/2018 20:00	8.2	-0.93
30/03/2020 11:00	8.2	1.01
30/03/2020 14:00	8.2	1.01

M3 (Spell 5)

Date and Time	SST in °C	NAO Index
08/03/2018 13:00	8.3	-0.93
08/03/2018 14:00	8.3	-0.93
08/03/2018 16:00	8.3	-0.93
08/03/2018 17:00	8.3	-0.93
09/03/2018 18:00	8.3	-0.93
18/03/2018 14:00	8.3	-0.93
09/03/2018 19:00	8.3	-0.93
09/03/2018 20:00	8.3	-0.93
18/03/2018 15:00	8.3	-0.93
09/03/2018 21:00	8.3	-0.93

M3 (Spell 6)

Date and Time	SST in °C	NAO Index
29/02/2020 22:00	8.4	1.26
26/02/2020 02:00	8.4	1.26
21/02/2020 01:00	8.4	1.26
24/02/2020 11:00	8.4	1.26
08/03/2020 14:00	8.4	1.26
29/02/2020 07:00	8.4	1.26
26/02/2020 01:00	8.4	1.26
25/02/2020 02:00	8.4	1.26
25/02/2020 03:00	8.4	1.26
28/02/2020 20:00	8.4	1.26

M3 (Spell 7)

Date and Time	SST in °C	NAO Index
25/03/2016 18:00	8.7	1.58
25/02/2016 10:00	8.7	1.58
25/02/2016 14:00	8.7	1.58
25/02/2016 15:00	8.7	1.58
15/02/2016 17:00	8.7	1.58
15/02/2016 19:00	8.7	1.58
15/02/2016 09:00	8.7	1.58
15/02/2016 10:00	8.7	1.58
15/02/2016 16:00	8.7	1.58
15/02/2016 13:00	8.7	1.58

M3 (Spell 8)

Date and Time	SST in °C	NAO Index
03/04/2018 21:00	8.7	1.24
03/04/2018 22:00	8.7	1.24
04/04/2018 03:00	8.7	1.24
04/04/2018 02:00	8.7	1.24
03/04/2018 16:00	8.7	1.24
07/04/2018 12:00	8.7	1.24
17/02/2020 21:00	8.8	1.26
04/03/2018 13:00	8.8	-0.93
25/02/2016 11:00	8.8	1.58
15/02/2016 18:00	8.8	1.58

M3 (Spell 9)

Date and Time	SST in °C	NAO Index
17/02/2020 19:00	8.9	1.26
17/02/2020 18:00	8.9	1.26
13/02/2020 07:00	8.9	1.26
17/02/2020 17:00	8.9	1.26
12/02/2020 10:00	8.9	1.26
12/02/2018 22:00	8.9	1.58
03/03/2018 02:00	8.9	-0.93
03/03/2018 12:00	8.9	-0.93
04/03/2018 08:00	8.9	-0.93
04/03/2018 07:00	8.9	-0.93

M3 (Spell 10)

Date and Time	SST in °C	NAO Index
25/02/2017 15:00	8.9	1.00
25/02/2017 10:00	8.9	1.00
25/02/2017 14:00	8.9	1.00
15/02/2017 09:00	8.9	1.00
15/02/2017 10:00	8.9	1.00
15/02/2017 19:00	8.9	1.00
15/02/2017 16:00	8.9	1.00
15/02/2017 17:00	8.9	1.00
15/02/2017 13:00	8.9	1.00
08/04/2018 04:00	8.9	1.00

Table of the Minimum Hourly Recorded SST Values for M4 (Spell 1)

Date and Time	SST in °C	NAO Index
20/03/2018 02:00	8.2	-0.93
20/03/2018 01:00	8.2	-0.93
13/06/2009 09:00	8.2	-1.21
13/06/2009 08:00	8.2	-1.21
15/02/2016 11:00	8.2	1.58
15/02/2016 12:00	8.2	1.58
08/03/2018 11:00	8.2	-0.93
08/03/2018 12:00	8.2	-0.93
13/06/2009 10:00	8.1	-1.21
13/06/2009 07:00	7.8	-1.21

M4 (Spell 2)

Date and Time	SST in °C	NAO Index
25/02/2016 10:00	8.3	1.58
25/02/2016 14:00	8.3	1.58
25/02/2016 15:00	8.3	1.58
15/02/2016 17:00	8.3	1.58
15/02/2016 19:00	8.3	1.58
15/02/2016 09:00	8.3	1.58
15/02/2016 10:00	8.3	1.58
15/02/2016 16:00	8.3	1.58
15/02/2016 13:00	8.3	1.58
08/03/2018 13:00	8.3	-0.93

M4 (Spell 3)

Date and Time	SST in °C	NAO Index
17/03/2014 02:00	8.3	0.80
17/03/2014 01:00	8.3	0.80
17/03/2014 03:00	8.3	0.80
17/03/2014 07:00	8.3	0.80
16/03/2014 23:00	8.3	0.80
17/03/2014 00:00	8.3	0.80
17/03/2014 08:00	8.3	0.80
17/03/2014 09:00	8.3	0.80
17/03/2014 10:00	8.3	0.80
17/03/2014 11:00	8.3	0.80

M4 (Spell 4)

Date and Time	SST in °C	NAO Index
24/02/2016 09:00	8.4	1.58
11/02/2016 09:00	8.4	1.58
15/02/2016 23:00	8.4	1.58
11/02/2016 10:00	8.4	1.58
11/02/2016 18:00	8.4	1.58
14/02/2016 00:00	8.4	1.58
14/02/2016 01:00	8.4	1.58
14/02/2016 09:00	8.4	1.58
14/02/2016 10:00	8.4	1.58
12/02/2016 11:00	8.4	1.58

M4 (Spell 5)

Date and Time	SST in °C	NAO Index
24/02/2016 13:00	8.5	1.58
24/02/2016 14:00	8.5	1.58
11/02/2016 20:00	8.5	1.58
16/02/2016 12:00	8.5	1.58
13/02/2016 17:00	8.5	1.58
13/02/2016 18:00	8.5	1.58
12/02/2016 13:00	8.5	1.58
12/02/2016 15:00	8.5	1.58
12/02/2016 19:00	8.5	1.58
11/02/2016 15:00	8.5	1.58

M4 (Spell 6)

Date and Time	SST in °C	NAO Index
15/03/2010 21:00	8.6	-0.88
15/03/2010 23:00	8.6	-0.88
15/03/2010 19:00	8.6	-0.88
15/03/2010 20:00	8.6	-0.88
15/03/2010 18:00	8.6	-0.88
15/03/2010 14:00	8.6	-0.88
09/03/2010 21:00	8.6	-0.88
15/03/2010 22:00	8.6	-0.88
15/03/2010 17:00	8.6	-0.88
15/03/2010 15:00	8.6	-0.88

M4 (Spell 7)

Date and Time	SST in °C	NAO Index
09/03/2012 17:00	8.7	1.27
11/03/2012 09:00	8.7	1.27
11/03/2012 10:00	8.7	1.27
10/03/2012 22:00	8.7	1.27
11/03/2012 22:00	8.7	1.27
07/03/2012 20:00	8.7	1.27
08/03/2012 21:00	8.7	1.27
07/03/2012 18:00	8.7	1.27
07/03/2012 19:00	8.7	1.27
08/03/2012 03:00	8.7	1.27

M4 (Spell 8)

Date and Time	SST in °C	NAO Index
16/03/2012 22:00	8.8	1.27
17/03/2012 00:00	8.8	1.27
17/03/2012 02:00	8.8	1.27
11/03/2012 00:00	8.8	1.27
14/03/2012 13:00	8.8	1.27
14/03/2012 14:00	8.8	1.27
23/03/2012 05:00	8.8	1.27
07/03/2012 08:00	8.8	1.27
06/03/2012 20:00	8.8	1.27
07/03/2012 23:00	8.8	1.27

M4 (Spell 9)

Date and Time	SST in °C	NAO Index
04/04/2020 03:00	8.8	-1.02
02/04/2020 03:00	8.8	-1.02
02/04/2020 01:00	8.8	-1.02
02/04/2020 02:00	8.8	-1.02
01/04/2020 13:00	8.8	-1.02
14/03/2014 02:00	8.8	0.31
14/03/2014 03:00	8.8	0.31
13/03/2014 23:00	8.8	0.31
14/03/2014 00:00	8.8	0.31
13/03/2014 22:00	8.8	0.31

M4 (Spell 10)

Date and Time	SST in °C	NAO Index
15/03/2010 12:00	8.8	-0.88
14/03/2010 13:00	8.8	-0.88
15/03/2010 04:00	8.8	-0.88
15/03/2010 11:00	8.8	-0.88
06/04/2010 06:00	8.8	-0.72
15/03/2010 10:00	8.8	-0.88
15/03/2010 07:00	8.8	-0.88
16/03/2010 00:00	8.8	-0.88
06/04/2010 05:00	8.8	-0.72
06/04/2010 03:00	8.8	-0.72

Table of the Minimum Hourly Recorded SST Values for M5 (Spell 1)

Date and Time	SST in °C	NAO Index
27/02/2014 08:00	7.4	1.34
27/02/2014 09:00	7.4	1.34
27/02/2014 06:00	7.4	1.34
27/02/2014 07:00	7.4	1.34
27/02/2014 10:00	7.4	1.34
27/02/2014 05:00	7.4	1.34
27/02/2014 22:00	7.4	1.34
27/02/2014 11:00	7.4	1.34
27/02/2014 02:00	7.4	1.34
27/02/2014 03:00	7.4	1.34

M5 (Spell 2)

Date and Time	SST in °C	NAO Index
03/03/2014 17:00	7.5	1.34
03/03/2014 18:00	7.5	1.34
04/03/2014 06:00	7.5	1.34
26/02/2014 12:00	7.5	1.34
26/02/2014 18:00	7.5	1.34
26/02/2014 19:00	7.5	1.34
03/03/2014 20:00	7.5	1.34
05/03/2014 07:00	7.5	1.34
05/03/2014 09:00	7.5	1.34
26/02/2014 16:00	7.5	1.34

M5 (Spell 3)

Date and Time	SST in °C	NAO Index
01/04/2014 06:00	7.9	0.31
15/03/2014 12:00	7.9	0.80
30/03/2014 21:00	7.9	0.80
30/03/2014 22:00	7.9	0.80
15/03/2014 21:00	7.9	0.80
26/03/2014 10:00	7.9	0.80
02/04/2014 01:00	7.9	0.31
01/04/2014 10:00	7.9	0.31
28/03/2014 18:00	7.9	0.80
01/04/2014 03:00	7.9	0.31

M5 (Spell 4)

Date and Time	SST in °C	NAO Index
31/03/2014 20:00	8	0.31
01/04/2014 22:00	8	0.31
01/04/2014 23:00	8	0.31
01/04/2014 13:00	8	0.31
18/02/2014 17:00	8	1.34
04/02/2014 04:00	8	1.34
02/02/2014 12:00	8	1.34
01/04/2014 21:00	8	0.31
02/02/2014 10:00	8	1.34
02/02/2014 11:00	8	1.34

M5 (Spell 5)

Date and Time	SST in °C	NAO Index
14/03/2010 04:00	8.1	-0.88
17/03/2010 06:00	8.1	-0.88
18/03/2010 19:00	8.1	-0.88
18/03/2010 21:00	8.1	-0.88
18/03/2010 20:00	8.1	-0.88
17/03/2010 15:00	8.1	-0.88
17/03/2010 16:00	8.1	-0.88
18/03/2010 16:00	8.1	-0.88
18/03/2010 18:00	8.1	-0.88
19/03/2010 01:00	8.1	-0.88

M5 (Spell 6)

Date and Time	SST in °C	NAO Index
31/01/2014 03:00	8.1	0.29
31/01/2014 04:00	8.1	0.29
29/01/2014 13:00	8.1	0.29
29/01/2014 14:00	8.1	0.29
29/01/2014 15:00	8.1	0.29
29/01/2014 22:00	8.1	0.29
30/01/2014 20:00	8.1	0.29
31/01/2014 05:00	8.1	0.29
02/02/2014 06:00	8.1	1.34
01/02/2014 20:00	8.1	1.34

M5 (Spell 7)

Date and Time	SST in °C	NAO Index
08/03/2018 11:00	8.1	-0.93
07/03/2018 19:00	8.1	-0.93
08/03/2018 06:00	8.1	-0.93
09/03/2018 10:00	8.1	-0.93
08/03/2018 19:00	8.1	-0.93
09/03/2018 00:00	8.1	-0.93
01/04/2013 22:00	8.1	1.24
01/04/2013 23:00	8.1	1.24
08/03/2013 03:00	8.1	-0.93
08/04/2013 07:00	8.1	1.24

M5 (Spell 8)

Date and Time	SST in °C	NAO Index
08/04/2013 06:00	8.1	0.69
06/04/2013 01:00	8.1	0.69
06/04/2013 06:00	8.1	0.69
06/04/2013 02:00	8.1	0.69
08/04/2013 04:00	8.1	0.69
03/04/2013 07:00	8.1	0.69
06/04/2013 09:00	8.1	0.69
05/04/2013 01:00	8.1	0.69
06/04/2013 04:00	8.1	0.69
02/04/2013 04:00	8.1	0.69

M5 (Spell 9)

Date and Time	SST in °C	NAO Index
07/03/2018 18:00	8.2	-0.93
09/03/2018 02:00	8.2	-0.93
09/03/2018 05:00	8.2	-0.93
09/03/2018 01:00	8.2	-0.93
09/03/2018 13:00	8.2	-0.93
09/03/2018 14:00	8.2	-0.93
09/03/2018 03:00	8.2	-0.93
08/03/2018 18:00	8.2	-0.93
09/03/2018 12:00	8.2	-0.93
09/03/2018 15:00	8.2	-0.93

M5 (Spell 10)

Date and Time	SST in °C	NAO Index
01/04/2013 10:00	8.2	0.69
01/04/2013 11:00	8.2	0.69
01/04/2013 12:00	8.2	0.69
01/04/2013 09:00	8.2	0.69
01/04/2013 10:00	8.2	0.69
01/04/2013 11:00	8.2	0.69
01/04/2013 08:00	8.2	0.69
01/04/2013 10:00	8.2	0.69
01/04/2013 21:00	8.2	0.69
02/04/2013 09:00	8.2	0.69

Table of the Minimum Hourly Recorded SST Values for M6 (Spell 1)

Date and Time	SST in °C	NAO Index
27/02/2014 09:00	8	1.34
27/02/2014 08:00	8	1.34
27/02/2014 06:00	8	1.34
27/02/2014 07:00	8	1.34
27/02/2014 10:00	8	1.34
27/02/2014 05:00	8	1.34
27/02/2014 22:00	8	1.34
27/02/2014 11:00	8	1.34
27/02/2014 02:00	8	1.34
27/02/2014 03:00	8	1.34

M6 (Spell 2)

Date and Time	SST in °C	NAO Index
04/03/2014 08:00	8.1	0.80
04/03/2014 09:00	8.1	0.80
05/03/2014 06:00	8.1	1.34
26/02/2014 10:00	8.1	1.34
26/02/2014 11:00	8.1	1.34
26/02/2014 20:00	8.1	1.34
26/02/2014 21:00	8.1	1.34
27/02/2014 19:00	8.1	1.34
05/03/2014 08:00	8.1	0.80
26/02/2014 06:00	8.1	1.34

M6 (Spell 3)

Date and Time	SST in °C	NAO Index
07/03/2014 01:00	8.2	0.80
07/03/2014 02:00	8.2	0.80
07/03/2014 03:00	8.2	0.80
07/03/2014 04:00	8.2	0.80
01/03/2014 08:00	8.2	0.80
28/02/2014 22:00	8.2	0.80
28/02/2014 23:00	8.2	0.80
02/03/2014 20:00	8.2	0.80
05/03/2014 11:00	8.2	0.80
06/03/2014 06:00	8.2	0.80

M6 (Spell 4)

Date and Time	SST in °C	NAO Index
01/04/2014 11:00	8.6	0.31
01/04/2014 12:00	8.6	0.31
15/03/2014 20:00	8.6	0.80
19/03/2014 07:00	8.6	0.80
13/02/2014 01:00	8.6	1.34
13/02/2014 02:00	8.6	1.34
13/02/2014 03:00	8.6	1.34
13/02/2014 09:00	8.6	1.34
13/02/2014 08:00	8.6	1.34
30/03/2014 19:00	8.6	0.80

M6 (Spell 5)

Date and Time	SST in °C	NAO Index
30/01/2014 11:00	8.8	0.29
30/01/2014 12:00	8.8	0.29
31/01/2014 02:00	8.8	0.29
02/02/2014 16:00	8.8	1.34
04/02/2014 22:00	8.8	1.34
01/04/2014 15:00	8.8	0.31
30/01/2014 00:00	8.8	0.29
30/01/2014 05:00	8.8	0.29
30/01/2014 06:00	8.8	0.29
30/01/2014 07:00	8.8	0.29

M6 (Spell 6)

Date and Time	SST in °C	NAO Index
05/04/2014 07:00	9	0.31
06/04/2014 05:00	9	0.31
07/04/2014 02:00	9	0.31
05/02/2014 19:00	9	1.34
05/04/2014 09:00	9	0.31
07/04/2014 07:00	9	0.31
05/02/2014 21:00	9	1.34
06/02/2014 17:00	9	1.34
06/02/2014 06:00	9	1.34
06/02/2014 07:00	9	1.34

M6 (Spell 7)

Date and Time	SST in °C	NAO Index
23/11/2018 11:00	9.2	-0.11
04/04/2014 13:00	9.2	0.31
04/04/2014 16:00	9.2	0.31
04/04/2014 17:00	9.2	0.31
23/01/2014 18:00	9.2	0.29
25/01/2014 15:00	9.2	0.29
05/03/2016 10:00	9.2	0.73
04/03/2016 10:00	9.2	0.73
03/03/2016 08:00	9.2	0.73
04/03/2016 05:00	9.2	0.73
04/03/2016 06:00	9.2	0.73

M6 (Spell 8)

Date and Time	SST in °C	NAO Index
06/03/2016 17:00	9.4	0.73
04/03/2016 13:00	9.4	0.73
04/03/2016 22:00	9.4	0.73
05/03/2016 12:00	9.4	0.73
05/03/2016 20:00	9.4	0.73
05/03/2016 19:00	9.4	0.73
05/03/2016 13:00	9.4	0.73
02/03/2016 22:00	9.4	0.73
03/03/2016 01:00	9.4	0.73
03/03/2016 02:00	9.4	0.73

M6 (Spell 9)

Date and Time	SST in °C	NAO Index
20/01/2014 00:00	9.4	0.29
20/01/2014 01:00	9.4	0.29
20/01/2014 12:00	9.4	0.29
23/01/2014 07:00	9.4	0.29
19/01/2014 05:00	9.4	0.29
19/01/2014 22:00	9.4	0.29
19/01/2014 23:00	9.4	0.29
22/01/2014 05:00	9.4	0.29
20/01/2014 13:00	9.4	0.29
20/01/2014 14:00	9.4	0.29

M6 (Spell 10)

Date and Time	SST in °C	NAO Index
01/04/2020 09:00	9.5	-1.02
01/04/2020 06:00	9.5	-1.02
01/04/2020 10:00	9.5	-1.02
12/04/2014 07:00	9.5	0.31
12/04/2014 08:00	9.5	0.31
13/04/2014 07:00	9.5	0.31
13/04/2014 08:00	9.5	0.31
13/04/2014 09:00	9.5	0.31
13/04/2014 23:00	9.5	0.31
11/04/2014 04:00	9.5	0.31