NEPTUNUS
PROJECT

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Abstract

The aim of this deliverable is to outline the pattern of climate change in the selected fishing areas in the Atlantic. This technical report details several key climatic variables and analyses their pattern of changes since the 1950s.

This project is co-financed by the Interreg Atlantic Area Programme through the European Regional Development Fund (EAPA_576/2018 –NEPTUNUS).

Version History

Version	Date	Author partner	Description
1	October 2022	UoL	First internal draft
2	November 2022	UoL	Second internal draft
3	December 2022	UoL	Final draft

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Executive summary

This report is crucial deliverable for Work Package 8 Action 2 – Threats and challenges fisheries in the Atlantic area from the Interreg Atlantic Area project NEPTUNUS (EAPA_576/2018). Specifically, Task 8.2.2. will provide an overview of recent climatic variability patterns in selected regions of the NE Atlantic. NEPTUNUS aims to facilitate the sustainable development of the seafood sector in the Atlantic area through the provision of a consistent methodology for products eco-labeling and defining eco-innovation strategies for production and consumption under a circular economy approach. Key actions: The project will provide key actions for resource efficiency, informed by life cycle thinking and involving producers, policymakers, and consumers in the decision-making process, will be provided.

One area of focus for NEPTUNUS is how fisheries in the Atlantic area can adapt effectively to the impacts of climate change. Climate change affects fisheries in several ways, including species reproduction and migration, operational aspects during harvesting, likely impacts along the supply change, and particularly at the production stage but also at structural levels , as well as policy developments.

This document focuses on the harvesting stage that is

In Section 1 provides an overview of emerging evidence regarding climate impacts on fish populations and the fishing industry in recent years, and the general trend of selected climatic variables in the north-east Atlantic Ocean frequently visited by UK and EU registered fishing vessels.

In Section 2, the report explains the criteria uses for data selection and introduces the study area. This part also describes the methodology employed in this report.

Section 3 presents the analytic results of the climate change pattern in the NE Atlantic area from 2008 to 2020. Additionally, the section discusses the climate impact on the fishing industry.

1. Introduction

In this section, we introduce the emerging evidence of climate impact on fish populations and the fishing industry in recent years, and the general trend of selected climatic variables in the north-east Atlantic Ocean.

Scientific evidence regarding how climatic conditions can affect fishing stocks has been built for over 100 years (Hjort, 1914). Since then, a vast number of documented studies related to climatic influence on fishery have emerged from marine, limnological, and experimental sources (Parmesan and Yohe, 2003, Edwards and Richardson, 2004). Generally, the warming trend in climate is predicted to drive fish poleward in range, which could lead to mass extinction or threat to survival when suitable habitats are unavailable, or the species lack the ability to disperse in time (Edwards and Richardson, 2004). In the marine environment, climate change may strongly influence fish distribution and abundance (Cheung et al., 2009) through changes in growth, community composition (Genner et al., 2004), survival (Fogarty et al., 2008) and reproduction rate (Pankhurst and Munday, 2011). Moreover, other climatic variables such as cloud cover, precipitation, and salinity may significantly impact the distribution and productivity of the marine ecosystem (Stenseth et al., 2004, Bakun, 1997).

However, climatic influences on ecology are usually scale-sensitive and species-sensitive, which means that the situation in the northeast part of the Atlantic Ocean may differ from other areas. Several studies provide us with a region-specific picture of this relationship.

Under a warming scenario, fish species that spawn in the shallow water areas of the Atlantic (e.g. capelin, herring, mackerel) will be most affected and are subject to a northward migration in response to climate change (Ottersen et al., 2013). Ter Hofstede et al. (2010) found that fish species richness could increase in the North Sea and Celtic Sea (an area of the Atlantic south of Ireland) but decrease in the Atlantic area west of Scotland due to climate change, rather than fishing efforts. The impact of temperature on physiological change is inconclusive, with simulation models built by Holt and Jørgensen (2014) predicting increased growth rates and a larger asymptotic size for Atlantic cod, while a recent study by Lindmark et al. (2022) suggested a warming trend could lead to faster growth but smaller fish sizes and yields.

Climatic fluctuations also pose uncertainty to fishing activity. Long-term changes in the frequency and magnitude of storminess could directly affect UK fisheries (Pinnegar et al., 2020), disrupting fishing efforts and endangering fishermen, gear and fishing infrastructure. In 2013 and 2014, the winter storms in the UK generated an estimated USD 11.0 million (€13.4 million in 2018) in fishery income lost and almost USD 2.5 million (€3.0million in 2018) in fishing gear and infrastructure lost to the fishing industry (Sainsbury et al., 2018). The frequency of extreme weather conditions, as characterized by windspeed, precipitation, air, and sea surface temperature, posed a strong relationship with commercial fishing activities in the Atlantic (Rezaee et al., 2016).

According to the Intergovernmental Panel on Climate Change (IPCC) reports (Barros et al., 2014), the warming trend in the Atlantic Ocean from 1950–2009 was significant (0.07°C per decade) in the surface layers. This is consistent with the suboceanic heat content measured in depth average of 0-700m as observed from 1971 to 2010 and an increase in sea surface temperature of 0.44°C between 1950 and 2009. A regional study by Taboada and Anadón (2012) indicated the greatest change in sea surface temperature across the North Atlantic Basin occurred at northern latitudes and near land regions.

Although the projection of long-term precipitation changes in the Atlantic is still in low confidence due to the complexity of interannual, decadal, and multidecadal climatic variation and uneven spatial sampling (Barros et al., 2014), studies over the change in the recent past have indicated an emerging winter precipitation pattern in Europe – with more (fewer) winters with wet conditions in Northern (Southern) Europe observed in the multi-decadal scale (Ummenhofer et al., 2017). This pattern coincides with changes in storminess over the Central/Eastern North Atlantic towards the Northern British Isles and local simulation results indicating a decrease in precipitation over the Iberian Peninsula in the 21st century (Rodríguez-Puebla and Nieto, 2010).

Storminess, as agents of extreme precipitation and windiness, will not only remix suboceanic nutrients from the deep sea to stimulate ocean productivity but also affect fishery and coastal infrastructure. Robust evidence provided by Lee et al. (2012) indicated an increasing trend of storm frequency in the Atlantic at the inter-decadal scale. However, the relationship between warming and storminess is not one way. A warmer ocean can support more storm activity but close observation of Hurricane Harvey in 2017 revealed that the storm significantly cooled the ocean in the short term, despite solar radiation replenishing the heat quickly in shallow water (Trenberth et al., 2018). In general, suboceanic heat content in the upper layer of most ocean regions has increased by 4% over the past 40 years (Barros et al., 2014).

This report presents the latest findings on climate changes in sea surface temperature, precipitation, near-surface windspeed, and suboceanic heat content in selected key fishing regions, and discusses some of their implications for the fishing sector.

2. Climatic variables and characteristics of selected fishery sites

Section 2 provides detailed information on the climate/fishery data used in this study, the guidelines used to select study areas and the methods employed in this report.

2.1 Data acquisition

To describe the climatic variations that affect Atlantic fisheries, we first identify key fishing areas based on the fishery statistics obtained from Marine Management Office (MMO) in the UK. The MMO provides a summary of fishing activities for UK commercial fishing vessels by month since 2008[1]. The data were spatially aggregated by the International Council for the Exploration of the Sea (ICES) division and 'Rectangle' fishing activity took place in. The 'Rectangle' refers to sub-divisions of the sea surface area under ICES with approximately 30 nautical miles by 30 nautical miles in size. We further rank the UK fishing activity based on the total live weight of fish caught in each 'Rectangle' and extract the top 50 fishing rectangles (Table 1). The rectangles are aggregated into key fishing areas if there are more than three rectangles adjacent to each other in the Atlantic area. A total of four key fishing areas (Figure 1) are identified for further analysis with respect to climate change.

Rank	Rectangle	Rank	Rectangle	Rank	Rectangle	Rank	Rectangle	Rank	Rectangle
1	49E9	11	46E2	21	37E4	31	29F0	41	36F0
2	47E8	12	47E9	22	45E9	32	45E1	42	48F6
3	49E8	13	46F3	23	37E5	33	45E8	43	37D7
4	48E8	14	48E4	24	30F0	34	41E1	44	28E6
5	48E5	15	50E9	25	36D6	35	29E9	45	51E9
6	48E9	16	47E3	26	49E6	36	50E8	46	46F0
7	47E4	17	29E6	27	43E0	37	36E4	47	49F0
8	47E7	18	29E4	28	37D6	38	45F0	48	47E5
9	48E7	19	49E7	29	42E0	39	46E3	49	44E0
10	46E8	20	29E5	30	40E0	40	31F1	50	49E5

Table 1. *Top 50 fishing rectangles of the UK fishery based on live weights of catch in tonnage from 2016 to 2020*

[1] https://www.gov.uk/government/collections/uk-sea-fisheries-annual-statistics

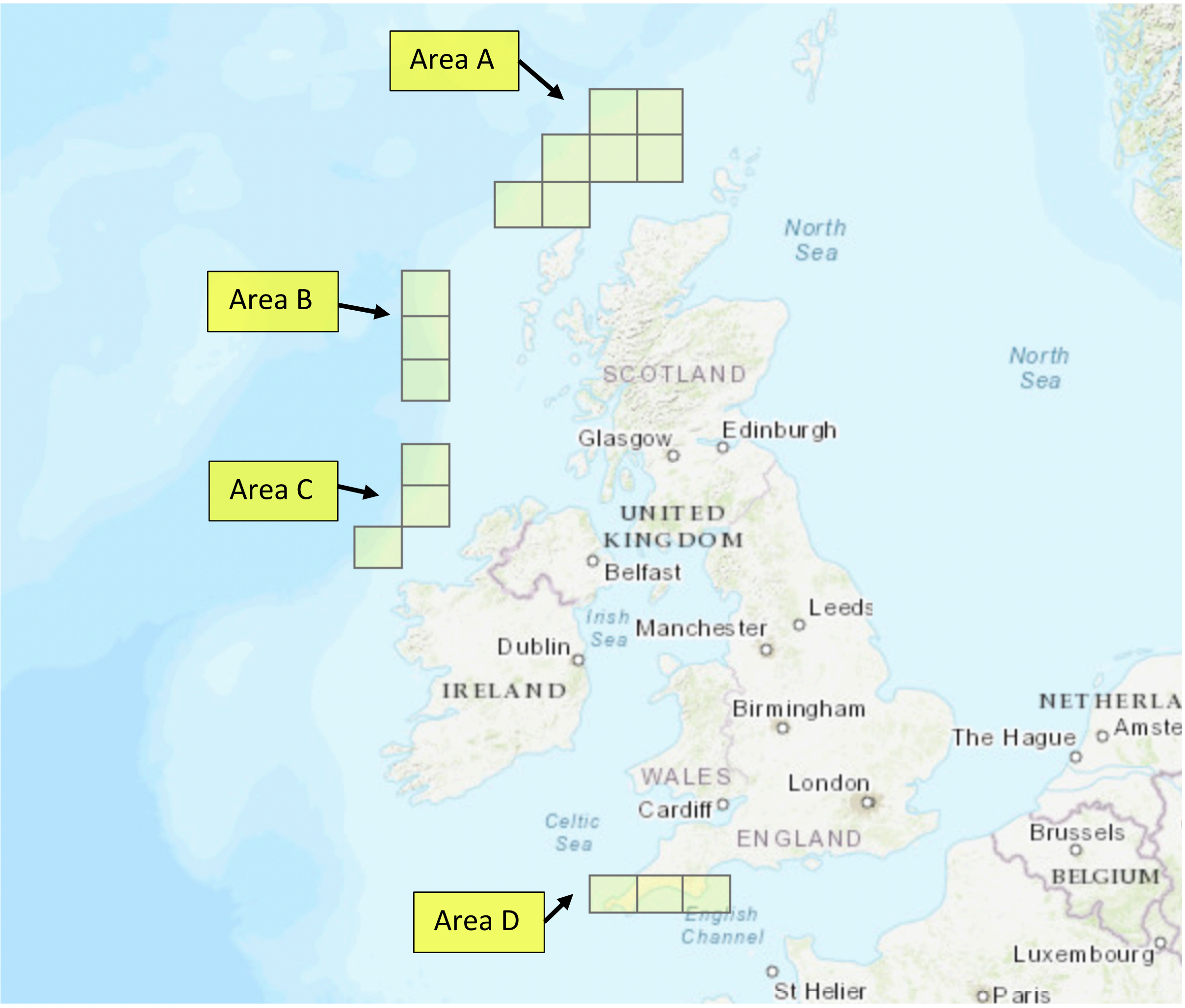

Figure 1. *Map showing the four key fishing areas for the UK fishery in the Atlantic region*

The ERA5 reanalysis (Hersbach et al., 2020) is a climate dataset that combines global climate model with in situ and satellite observations (Urban et al., 2021). It provides gridded estimates, up to hourly, of a large number of atmospheric, terrestrial, and oceanic climate variables with various spatial resolutions. For this report, we adopt the monthly updates of ERA5 sea surface temperature at 0.25° x 0.25° grid size and precipitation reanalysis data at 0.25° x 0.25° grid size from 1950 onwards, and the daily updates of ERA5 near-surface wind speed at 0.50° x 0.50° grid size from 1950 onwards. We also include suboceanic heat content at 0-400m at 1.00° x 1.00° grid size from the EN4 database (Good et al., 2013) from 1900 onwards. Climatic data are extracted from the centre point of each key fishing area for further analysis.

2.2 Characteristics of key fishing areas

We summarize the basic characteristics of the four key fishing areas in Table 2 and present the monthly fishing activity based on live weight from 2008–2020 in Figure 2. Different fishing grounds would have different fishing seasons. In Area A, the major catch comes from mackerel in January and herring in July and August. In Area B, mackerel comes in January in the study period but the catch gradually moves to February since 2013, the Whiting season arrives in March or April. In Area C, Mackerel season shifts from January to February from 2014 onwards while the blue whiting usually harvests in March or April. Area D is unlike other offshore fisheries, as it is located near the shoreline in the Southwestern part of England. The major species harvested in this region are mainly sprats and sardines throughout the year, along with shellfish, especially crabs.

	Area A	**Area B**	**Area B**	**Area D**
Location	Northwest of Scotland	West of Scotland	Northwest of Ireland	Near Cornwall
Number of ICES Rectangles	7	3	3	3
Type of fishing	Offshore	Offshore	Offshore	Nearshore
Major species	Mackerel, Herring	Mackerel, Blue Whiting	Mackerel, Blue Whiting	Sprats, Sardine
Total live weight (Tonnes)	735,987	185,873	175,622	297,373
Total value of fish caught (£)	703 million	139 million	127 million	482 million

Table 2. *Characteristics of the four UK key fishing areas in the Atlantic region based on fishery data from 2008–2020*

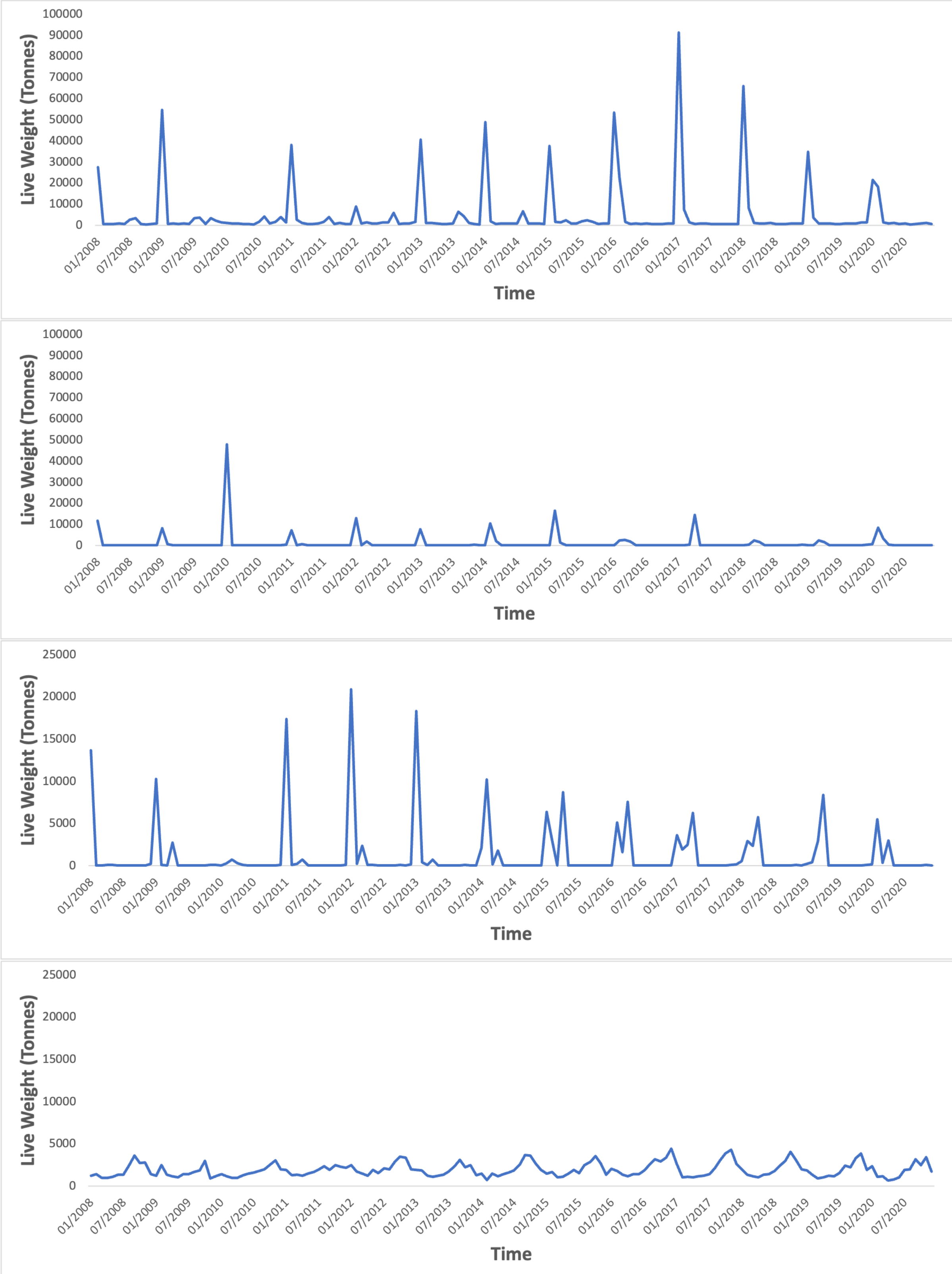

Figure 2. *Time series of total monthly live weight of catch in (A). Area A; (B). Area B; (C). Area C; (D). Area D from 2008 to 2020. The Y-axes for (A) and (B) are set the same and (C) and (D) are identical for visualization.*

3. Statistical analyses

Several statistical analyses were conducted on the four climatic variables selected in each key fishing area. For each area, climatic data from 1991 to 2020 (1989–2018 for suboceanic heat content) were extracted as a 30-year time block to compare with the 1961–1990 time block (1951 – 1980 for suboceanic heat content) to obtain basic descriptive statistical results. To better understand the changes in pattern and distribution of each climatic variable, we further produced the Box and Whisker plots, anomaly graphs, and histograms from the two 30-year blocks. We also conducted T-test and Kolmogorov-Smirnov two-way Test (KS two-way test) to determine whether there was a significant change in the means and distribution of climatic variables between the past and the present. For surface windspeed, we calculated the 5-day average from the daily data to smoothen the data resolution for the box and whisker plots. In addition, we calculated the annual frequency of extreme windiness for surface windspeed with reference to the Beaufort wind scale.

4. Climatic variation

4.1 Sea surface temperature change

Analysis of the sea surface temperature record shows that there was a significant increase in the annual average temperature in all four fishing regions from 1961-1990 to 1991-2020 (Table 3). The range of warming spans from 0.14°C per decade to 0.20°C per decade.

Time block	Area A	Area B	Area C	Area D
1961-1990	8.89°C	9.74°C	10.33°C	11.29°C
1991-2020	9.36°C	10.20°C	10.75°C	11.88°C
Difference	+0.47°C	+0.46°C	+0.42°C	+0.59°C

Table 3. *Comparison of average annual sea surface temperature in the four fishing regions*

Box and Whisker plot provides a closer look at the warming trend at a monthly resolution. Figure 3 shows the plots of the two 30-year blocks in the four selected fishing areas. In fact, warming occurs in all the months from 1961-1990 to 1991-2020. In particular, more dispersed temperature conditions are seen in the summer months (June, July, and August) according to the Box Interquartile Range (BIR) hinting that temperature variability increases with warming.

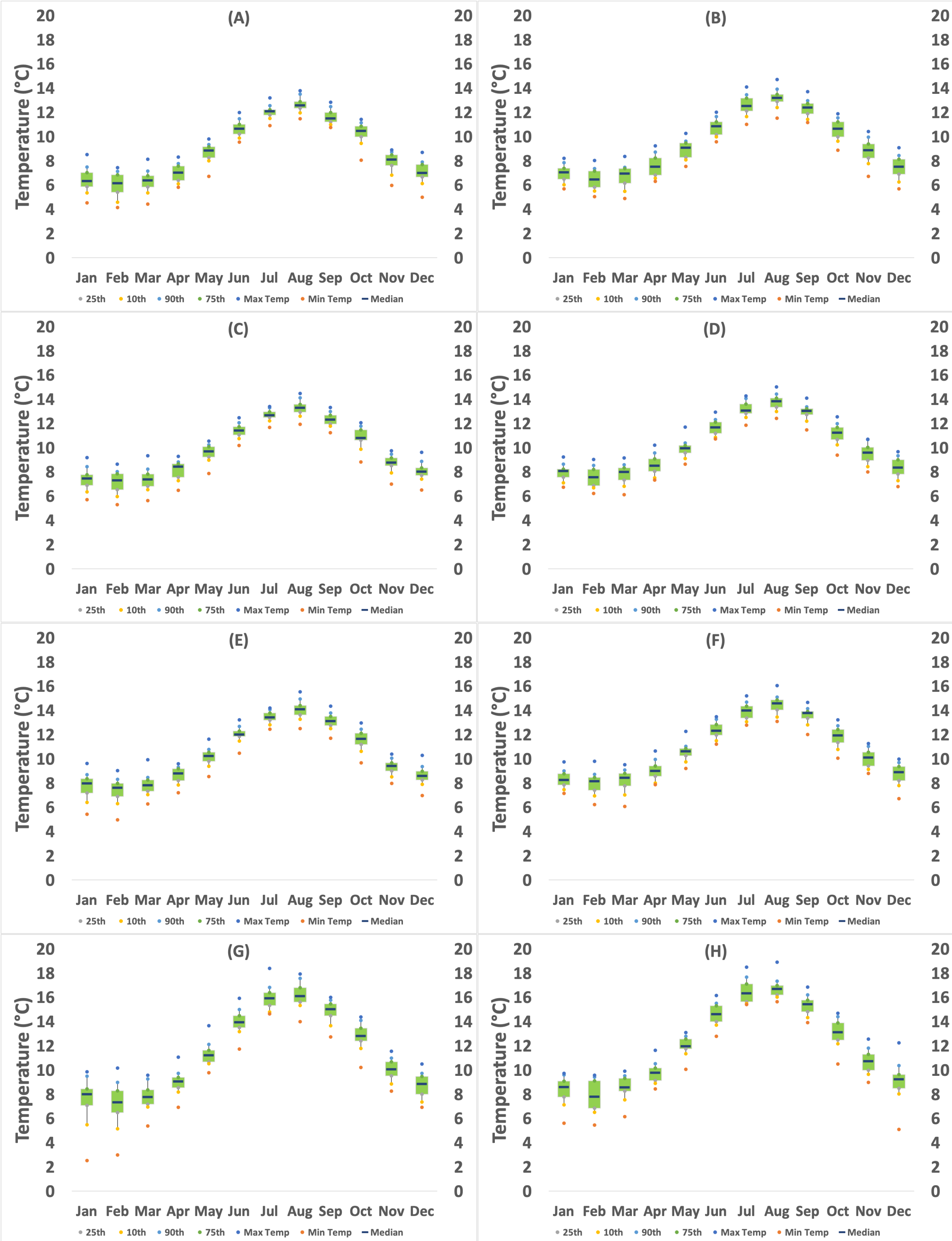

Figure 3. *Box and Whisker plot for average monthly sea surface temperature for (A) Area A in 1961–1990; (B) Area A in 1991–2020; (C) Area B in 1961–1990; (D) Area B in 1991–2020; (E) Area C in 1961–1990; (F) Area C in 1991–2020; (G) Area D in 1961–1990; (H) Area*

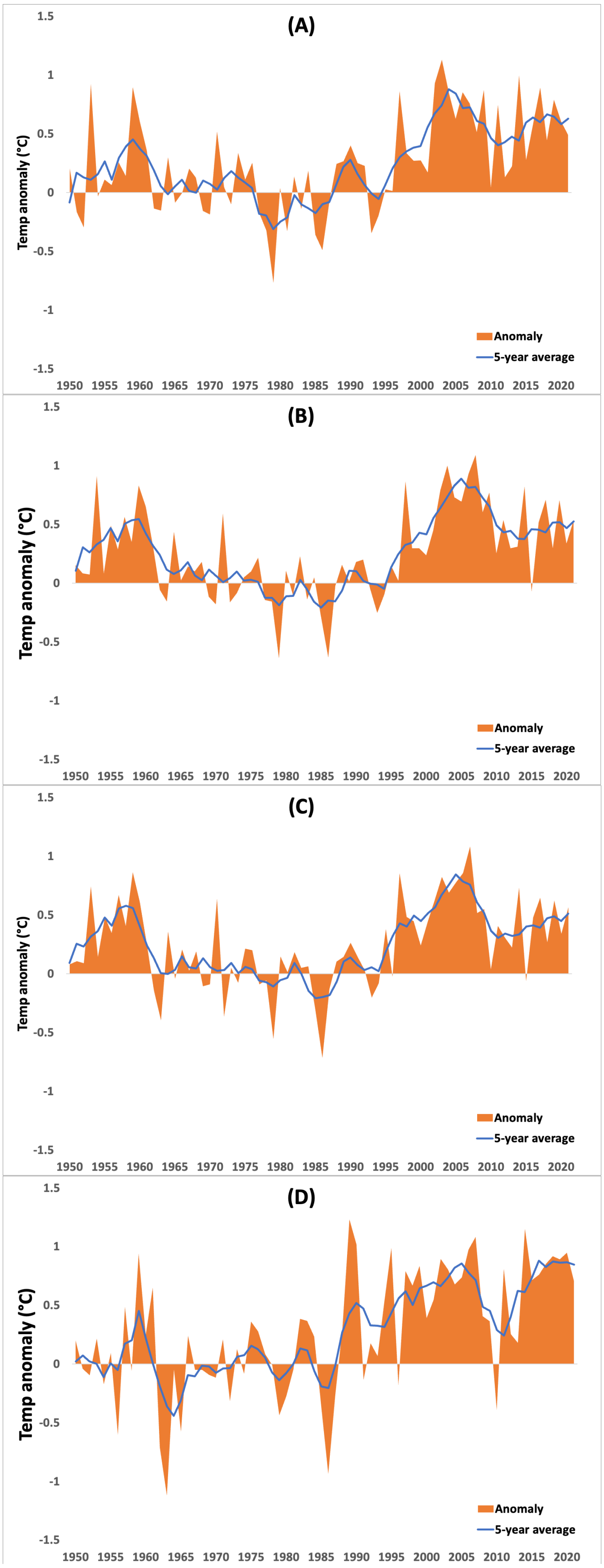

***Figure 4** Sea surface temperature anomaly with reference to 1961–1990 in (A) Area A; (B) Area B; (C) Area C and (D) Area D*

Based on the anomaly graph in Figure 4, compared to the period of 1961-1990, the increase in temperature was more significant between 1990–2005, and fluctuated at a plateau since then. T-test and KS 2-sample test results between the two 30-year blocks in the study areas are reported in Table 4. The T-test results suggests means of the two 30-year blocks are statistically different (p>0.005) in both summer and winter in all four regions. The t-value suggested the warming is stronger in wintertime. The K-S results reject the null hypotheses, indicating that both summer and winter between the two 30-year blocks in all four regions are drawn from different continuous distributions.

	Area A	**Area B**	**Area C**	**Area D**
		Summer		
t-value	-2.47***	-2.72***	-2.45***	-2.78***
KS value	1.86***	1.71***	1.56***	1.42***
		Winter		
t-value	-5.96***	-3.45***	-3.26***	-2.85***
KS value	2.24***	1.94***	1.42***	1.64***

Table 4. *Student's t-test and Kolmogorov-Smirnov two-way test applied to compare the mean and distributions of summer temperatures and winter temperatures between 1961–1990 and 1991–2020 in each selected fishing area. ***p<0.005, **p<0.01, *<0.05*

The histograms depicting temperature distribution (Figure 5) indicate that there are now more warm months in both summer and winter. In particular, the number of cold months in winter dropped significantly across all four fishing areas.

Although there are slight variations in the magnitude of warming among all four key fishing areas, the pattern of sea surface temperature change and the distribution of temperature change is consistent across these fishing areas.

The rising temperature trend poses new challenges for fisheries including shifts of habitat, migration of species, and the spread and increase of diseases and invading species. Based on the IPCC report (Barros et al., 2014), there is medium evidence and agreement that these changes could potentially jeopardize current fisheries as well as the provision of food and protein to millions of people. Moreover, the increase in temperature will result in more extreme weather events. A recent study has shown that the heat wave in June 2021 in Canada has caused widespread and multiyear negative impacts on nearshore ecologies and fisheries (Raymond et al., 2022).

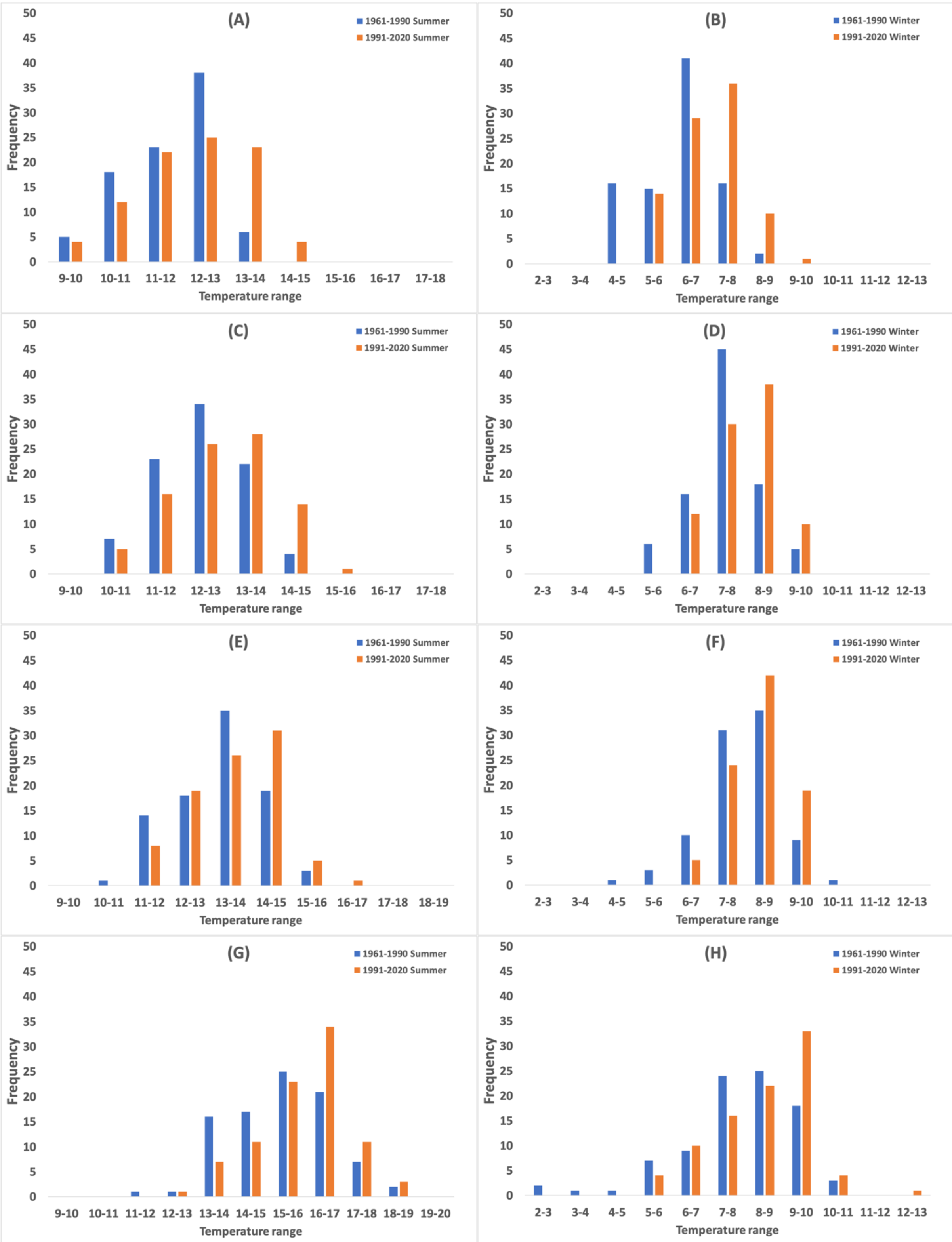

Figure 5 *Histogram for comparing the shift in average monthly sea surface temperature distribution between 1961–1990 and 1991–2020 in (A) summer of Area A; (B) winter of Area B; (C) summer of Area B; (D) winter of Area B; (E) summer of Area C; (F) winter of Area C; (G) summer of Area D; (H) winter of Area D*

4.2 Precipitation change

The average daily rainfall recorded at four key fishing areas show that rainfall generally increase from the 1961–1990 time block to the 1991–2020 time block. The range of increase spans from 0.11mm/day to 0.23mm/day.

Time block	Area A	Area B	Area C	Area D
1961-1990	3.53mm/day	3.46mm/day	3.56mm/day	2.28mm/day
1991-2020	3.64mm/day	3.64mm/day	3.79mm/day	2.44mm/day
Difference	+0.11mm/day	0.18mm/day	0.23mm/day	0.16mm/day

Table 5. *Comparison of average annual precipitation in the four fishing regions*

A closer breakdown of precipitation by box and whisker plot indicates inconsistent rainfall variation patterns across different months. In Area A, precipitation is concentrated from September to March, with most of the increase in rainfall in the period 1991–2020 focusing on winter, while there is no significant change in rainfall in summer. In Area B and Area C, the rainy season typically occurs in winter, with increases in precipitation observed both in the summer and winter months. The BIR indicates precipitation variability increases in winter. In Area D, the rainfall pattern is relatively even all year round, with slightly more rainfall that can be seen in winter. In comparison to the 1961–1990 time block, the increase in precipitation is mainly found in summer, with no obvious change in rainfall in winter.

Precipitation anomaly graphs (Figure 7) show a general increasing trend in precipitation since 1950 in all four fishing areas with reference to the period 1961–1990. However, there was a small decrease in the early 2000s in Area A, Area B and Area C but in Area D, the rainfall was exceptionally high during a similar period. Despite the overall increase in precipitation, there are regional variation in rainfall patterns in the northeast Atlantic for the past seven decades.

Table 6 presents the results of t-test and KS 2-sample test for the precipitation change between the two 30-year blocks. T-test results suggest a change in mean precipitation significantly in wintertime and in the summer in Area A. Interestingly, the results of the KS 2-sample test largely support the t-test results and accepted the null hypothesis that distribution between the two 30-year blocks in winter of fishing grounds and summer in Area A has significantly changed. KS two-sample test only indicates the change in distribution – it does not tell whether there is an increase or decrease in the mean or whether there is a change in the variance. The patterns of rainfall in summer elsewhere, as evidenced by the KS test results, have no significant difference in distribution.

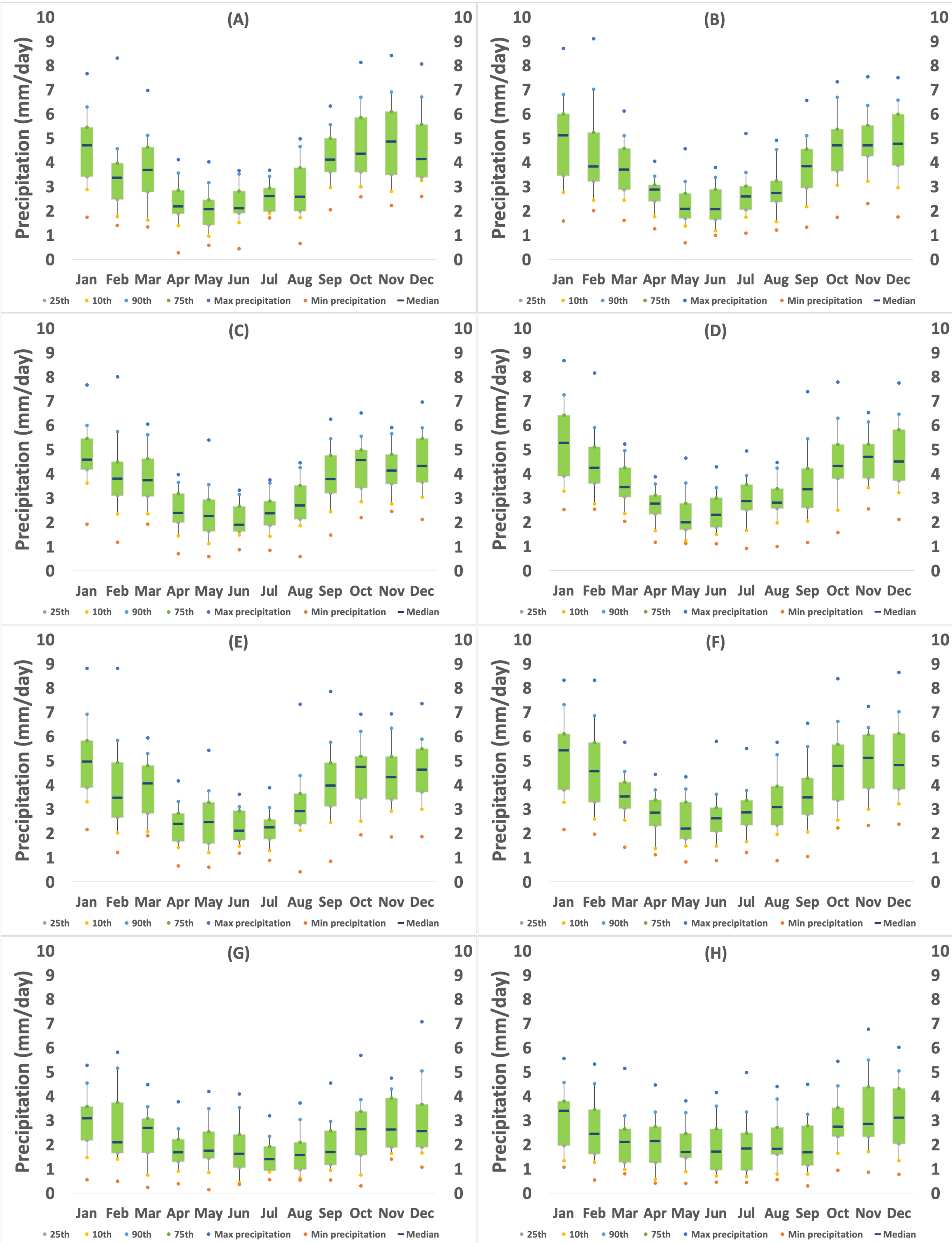

Figure 6. *Box and Whisker plot for average monthly precipitation for (A) Area A in 1961–1990; (B) Area A in 1991–2020; (C) Area B in 1961–1990; (D) Area B in 1991–2020; (E) Area C in 1961–1990; (F) Area C in 1991–2020; (G) Area D in 1961–1990; (H) Area D in 1991–2020*

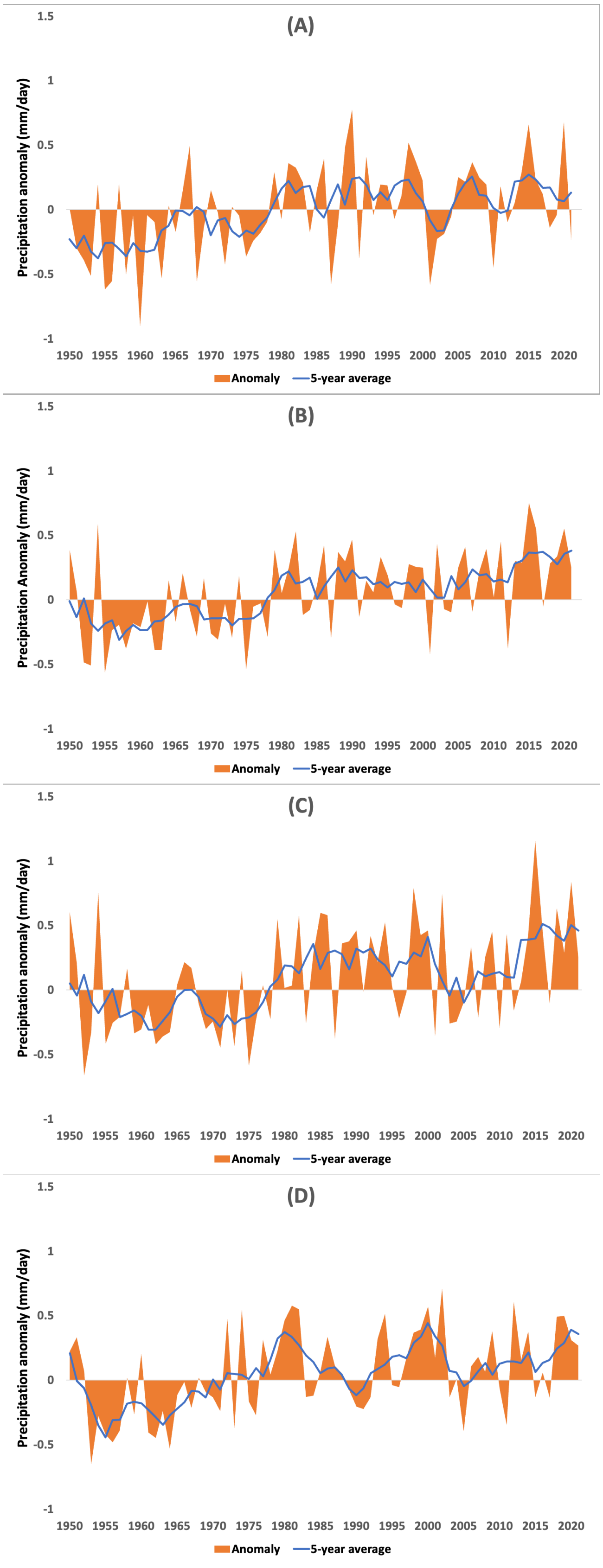

Figure 7. *Precipitation anomaly with reference to 1961–1990 in (A) Area A; (B) Area B; (C) Area C and (D) Area D*

	Area A	Area B	Area C	Area D
		Summer		
T-value	0.13	-2.1*	-2.08*	-2.11*
KS value	0.60	1.42*	1.42*	1.42*
		Winter		
T-value	-1.96	-1.83	-1.99*	-0.13
KS value	1.56	0.97	1.12	0.60

Table 6. *T-test and Kolmogorov-Smirnov two-way test applied to compare the data distribution of summer precipitation and winter precipitation between 1961–1990 and 1991–2020 in each selected fishing area. ***p<0.005, **p<0.01, *<0.05*

The histograms for precipitation distribution **(Figure 8)** also showed a general shift to a wetter climate in the 1991–2020 time period. In particular, the shift is more significant in winter of Area B and Area C, where frequency of high rainfall events is doubled from before.

At present, it is uncertain whether rainfall has a significant impact on fishery or marine life (Barros et al., 2014). However, the rise in rainfall observed in recent decades corresponds to the predictions that global warming will increase precipitation in most regions of the world (Trenberth, 2011). This shift in rainfall intensity could lead to more frequent extreme rainfall events, posing a serious threat to the safety of crews. Despite we have established the general information for precipitation changing patterns over the last few decades, the inconsistency in these patterns across the four fishing areas has yet to be explained. This discrepancy may indicate the complexity in precipitation variability across the northeast part of the Atlantic. In commercial fishing, understanding precipitation patterns at a local scale could be crucial in helping fishermen plan their trips ahead.

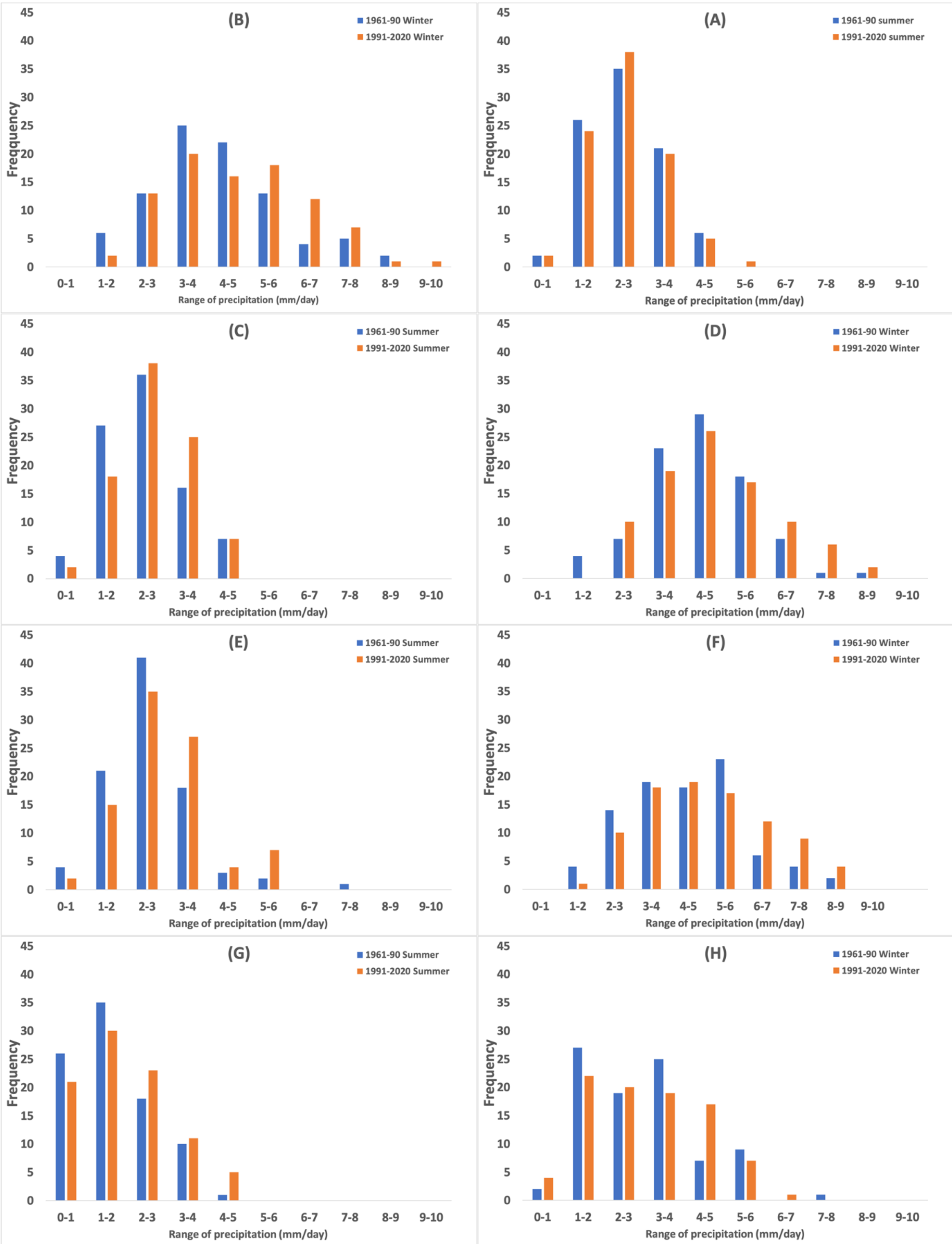

Figure 8*. Histogram for comparing the shift in average monthly precipitation distribution between 1961–1990 and 1991–2020 in (A) summer of Area A; (B) winter of Area B; (C) summer of Area B; (D) winter of Area B; (E)summer of Area C; (F) winter of Area C; (G) summer of Area D; (H) winter of the Area D.*

4.3 Suboceanic heat content

For suboceanic (0-400m) heat content we analyzed data from 1900–2018. By comparing the time block 1989–2018 to 1951–1980 **(Table 7)**, there is an increase in suboceanic heat content with a similar magnitude (0.003^{11} J/m2 to 0.004^{11} J/m2) in all four key fishing areas.

Time block	Area A	Area B	Area C	Area D
1951-1980	3.061^{11} J/m^2	4.875^{11} J/m^2	4.881^{11} J/m^2	1.417^{11} J/m^2
1989-2018	3.065^{11} J/m^2	4.878^{11} J/m^2	4.877^{11} J/m^2	1.420^{11} J/m^2
Difference	$+0.004^{11}$ J/m^2	$+0.003^{11}$ J/m^2	$+0.004^{11}$ J/m^2	$+0.003^{11}$ J/m^2

Table 7. *Comparison of average annual suboceanic heat content in the four fishing regions*

Box and whisker plots (Figure 9) indicate a warming trend across all months in the four study areas. The warming is particularly noticeable from March to May, but less pronounced from September to October in Areas B and C, indicating a differential warming rate in summer and winter. It should be noted that the plots show the peak of suboceanic heat content typically occurs in September/October, while the trough arrives in March/April. This reflects a 3-month delay in transforming the solar energy from summer into suboceanic heat content in summer, or in losing the suboceanic heat content to the subsurface in winter.

Anomaly graphs (Figure 10) for suboceanic heat content, dating back to 1900, reveal a century-scale change in climate under the ocean. With reference to the period 1951–1980, there is a clear increasing trend in suboceanic heat content in the northeast Atlantic since the 1990s. The warming trends in Areas A, B, and C are similar, with the peak of suboceanic heat content reaching around 2010 and fluctuating since then. However, in Area D, suboceanic heat content reached its peak in 2018, with an increasing trend.

Figure 9. *Box and Whisker plot for average monthly heat content for (A) Area A in 1951–1980; (B) Area A in 1989–2018; (C) Area B in 1951–1980; (D) Area B in 1989–2018; (E) Area C in 1951–1980; (F) Area C in 1989–2018; (G) Area D in 1951–1980; (H) Area D in 1989–2018. The y-axis is set comparable in each area due to the large variety of suboceanic heat content across different areas.*

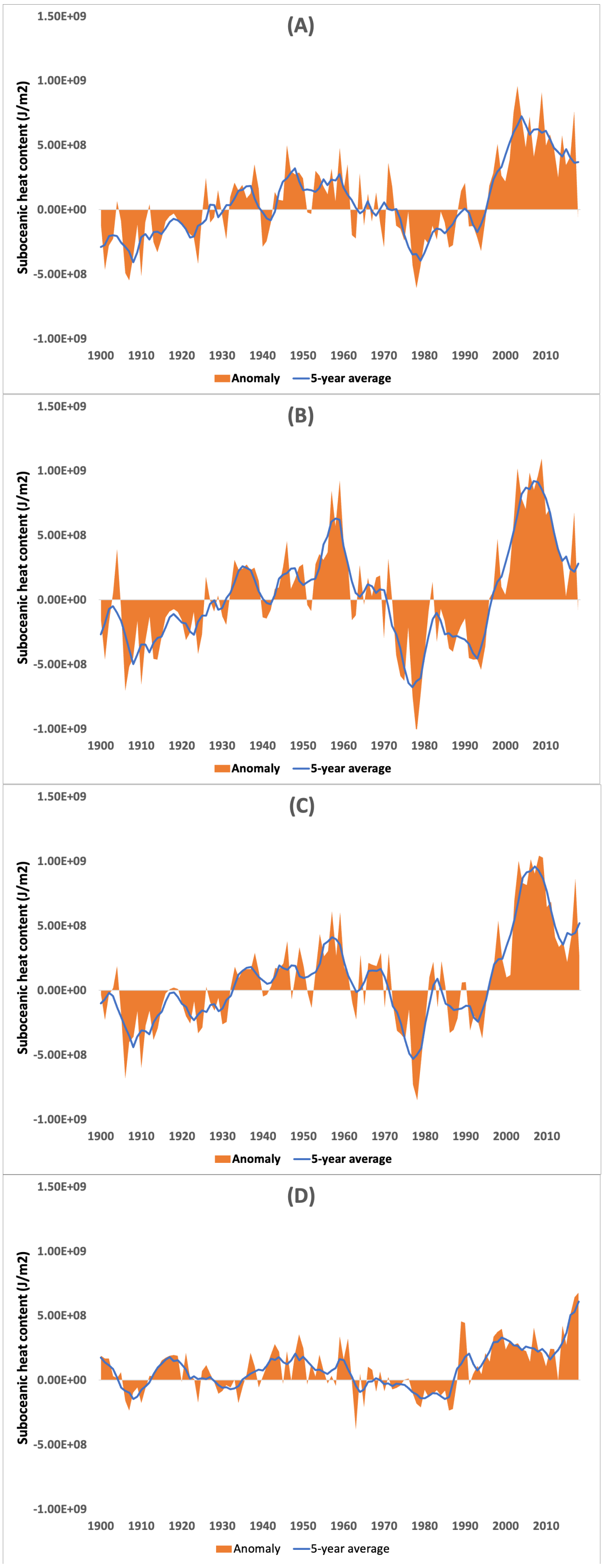

Figure 10. *Suboceanic heat content anomaly with reference to 1951–1980 in (A) Area A; (B) Area B; (C) Area C and (D) Area D*

The T-test results indicated significant differences in means in both summer and winter in all four study areas except for summer in Area B. The t-values suggested the warming is more significant in winter across the four study areas. Results from the KS two-sample test point to the null hypothesis that the data distributions between the two 30-year blocks (1951–1980 and 1989–2018) in summer and winter are drawn from different distributions, with the exception in Area B. In the Area B, KS two-sample test supported the hypothesis that both data in two-time blocks were sampled from populations with identical distributions.

	Area A	**Area B**	**Area C**	**Area D**
		Sept to Nov		
T-value	-4.05***	-1.85	-2.95***	-5.74***
KS value	1.57***	1.04	1.42*	2.68***
		Mar to May		
T-value	-7.40***	-4.66***	-7.82***	-10.06***
KS value	2.83***	2.01***	3.06***	3.80***

Table 8. *T-Test and Kolmogorov-Smirnov two-way test applied to compare the data distribution of suboceanic heat content from September to November (The warmest 3 months) and from March to May (the coldest 3 months) between 1961–1990 and 1991–2020 in each selected fishing area. ***p<0.005, **p<0.01, *<0.05*

The histogram plots **(Figure 11)** show that the suboceanic heat content has increased in the study period for all four key fishing grounds. Again, the magnitude of this increasing trend is more significant in wintertime of Area B and Area C, with more months skewed to the right sides of histogram. The histogram results suggest a different degree of suboceanic warming across different months in the Atlantic at the local scale.

The increasing trend in suboceanic heat content over the last decade indicates the marine heatwave – a rapidly rising topic emerging in recent decades that is defined as a discrete period of prolonged anomalously warm water at a particular location. In 2012, the marine heatwave in northwest Atlantic caused an extended fishing season with record high landings of lobsters, but it also led to a paradoxical economic crisis in the fishery when it contradicted market demand (Mills et al., 2013). With the supply outstripping the processing capacity and the demand of the market in a short period of time, the lobster price eventually collapsed. Ex-vessel prices (price received by lobsterman at the pier) of lobsters fell to 70% below normal, threatening the economic viability of fishermen. In 2018, the severe marine heatwave in North Atlantic led to high kelp mortality and the loss of marine habitat (Filbee-Dexter et al., 2020). Substantial evidence has shown that marine heatwave is posing new challenges and uncertainty to commercial fishery (Jacox, 2019, Caputi et al., 2016).

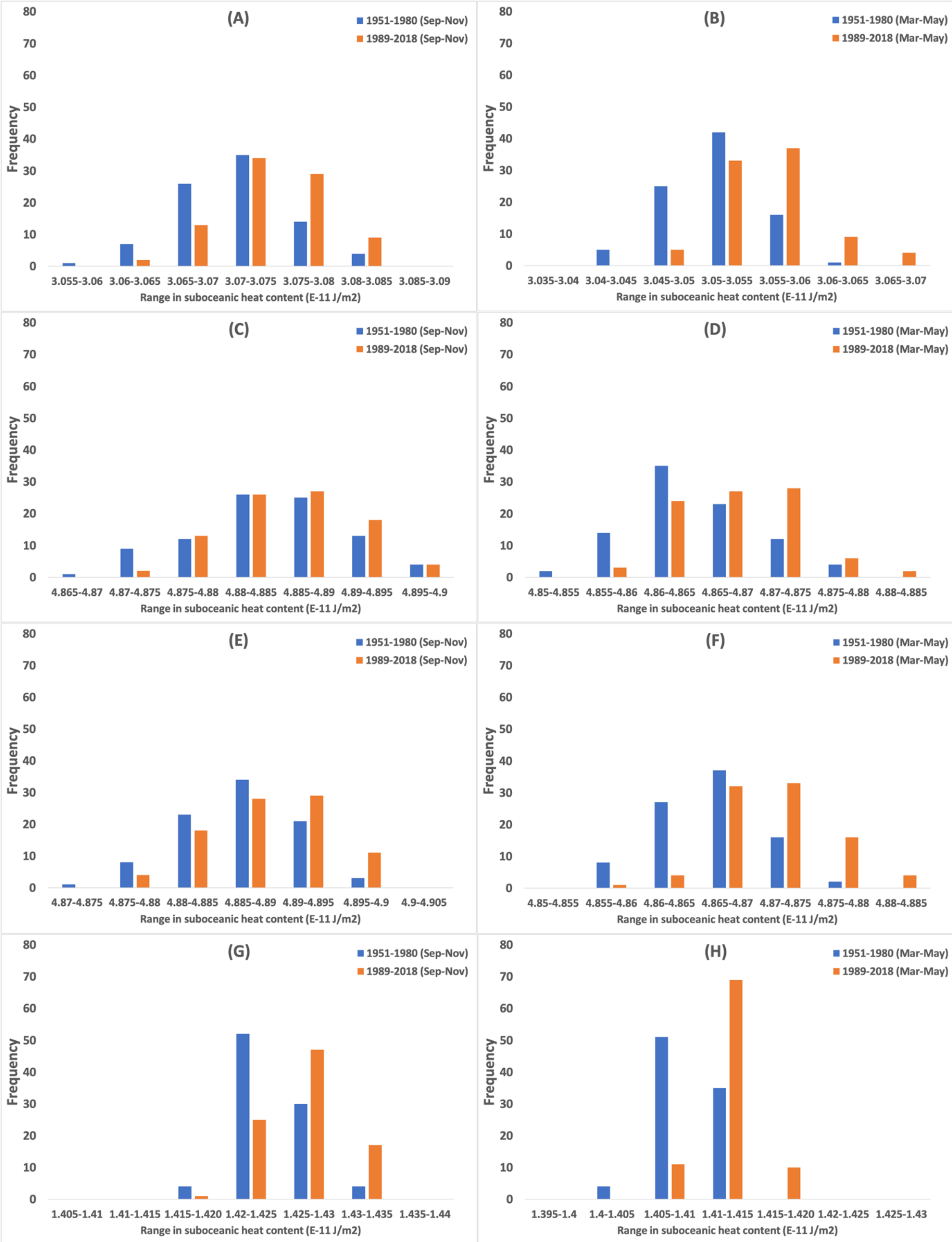

***Figure 11**. Histogram for comparing the shift in average monthly suboceanic heat content distribution between 1951–1980 and 1989–2018 in (A) summer of Area A; (B) winter of Area B; (C) summer of Area B; (D) winter of Area B; (E)summer of Area C; (F) winter of Area C; (G) summer of Area D; (H) winter of Area D. The x-axis is set individually for each setting due to the large variety of suboceanic heat content across different areas in different seasons.*

4.4 Surface wind speed

In addition to temperature and precipitation, climate change can affect pressure systems, which can lead to changes in wind pattern or an increase in the frequency of extreme wind speed events. The surface windspeed data **(Table 9)** shows that average daily wind speed had increased in Area A and Area D but stayed the same in the Area B and Area C.

Time block	Area A	Area B	Area C	Area D
1961-1990	8.68m/s	9.17m/s	9.03m/s	7.08m/s
1991-2020	8.74m/s	9.16m/s	9.03m/s	7.26m/s
Difference	+0.06m/s	-0.01m/s	0	+0.18m/s

Table 9. *Comparison of average surface windspeed in the four fishing regions*

Further breakdown of wind speed change by box and whisker plots **(Figure 12)** with a five-day average data clustering shows inconclusive results, indicating no consistent seasonality or monthly shift in wind speed under the impact of climate change.

Graphs of wind speed anomaly **(Figure 13)** show no significant increase in windspeed with reference to the period 1961–1990 in the Area A, Area B and Area C. However, there is seemingly an increasing trend in wind speed since the 1970s in Area D, with the increased wind speed fluctuating at the plateau since then.

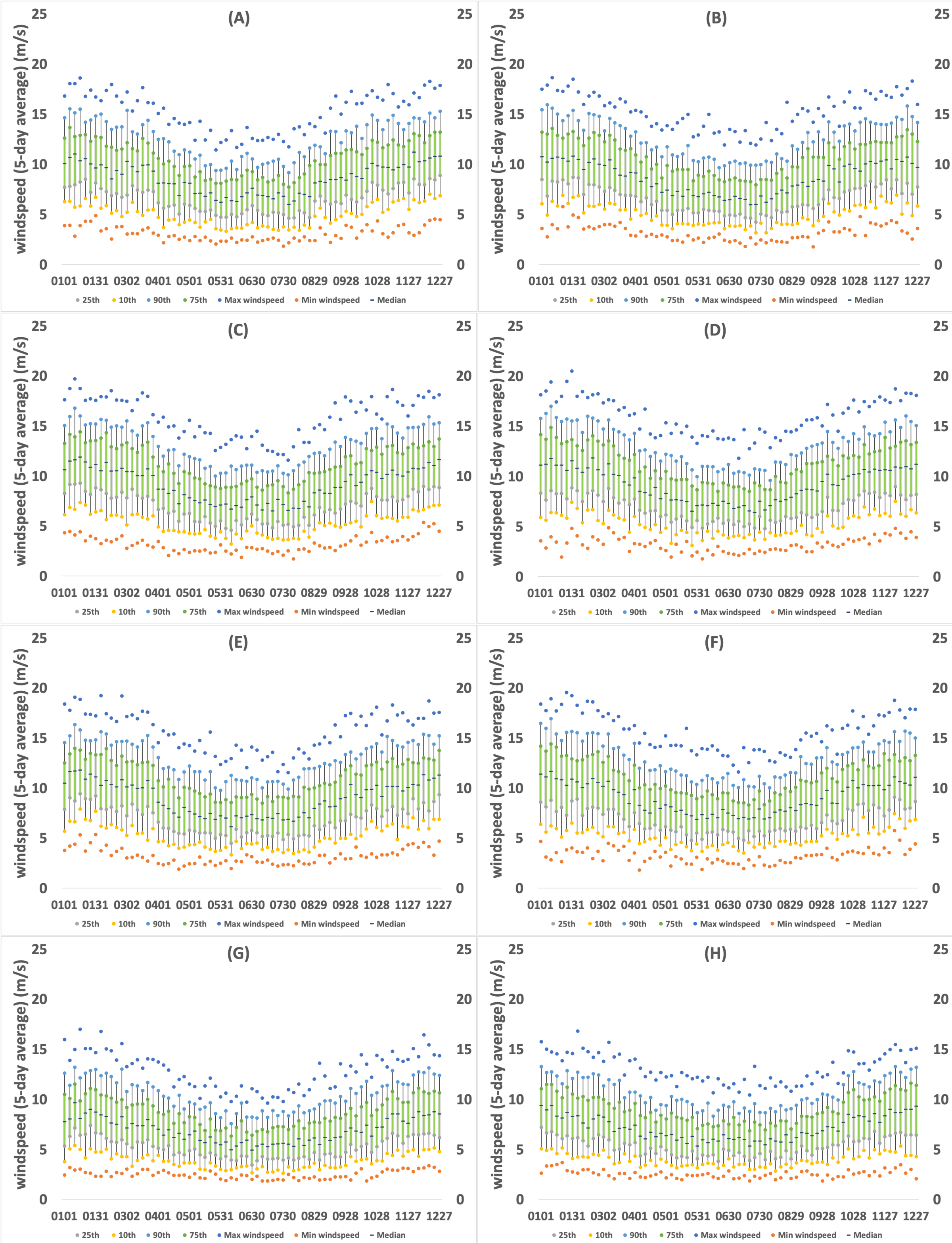

Figure 12. *Box and Whisker plot for average daily windspeed (5-day average) for (A) Area A in 1951–1980; (B) Area A in 1991–2020; (C) Area B in 1951–1980; (D) Area B in 1991–2020; (E) Area C in 1951–1980; (F) Area C in 1991–2020; (G) Area D in 1951–1980; (H) Area D in 1991–2020*

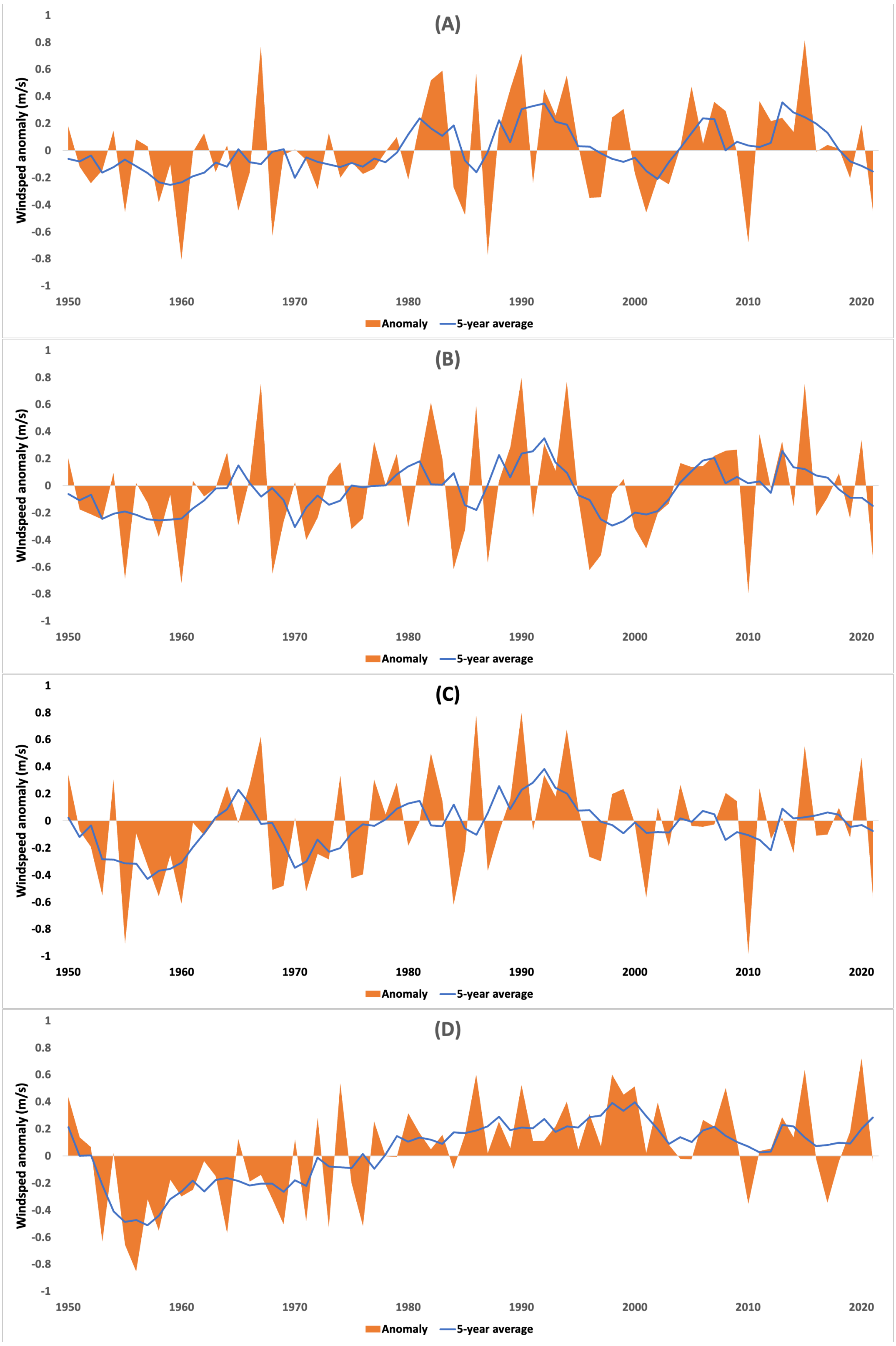

Figure 13. *Average daily windspeed with reference to 1951–1980 in (A) Area A; (B) Area B; (C) Area C and (D) Area D*

To explore the change in frequency of extreme windspeed events, we compared the number of dates with average windspeed in 1950–2021 to Beaufort Windscale 6 and 7 – the former refers to a mean windspeed of 12m/s and the latter refers to a mean windspeed of 15m/s. **Figure 14** indicates that the frequency of occurrence of windy days, in terms of Beaufort Windscale 6 and 7, has a generally rising trend in the four key fishing areas based on the ERA5 reanlaysis data,. **Table 10** summarizes the average number of dates with high windspeed in the 1961–1990 and 1991–2020 time blocks, showing an increase in the number of dates with an average windspeed higher than Beaufort Scale 6 in Area A and Area D. In Area A, there are now fewer days with an average windspeed higher than Beaufort Scale 6 but more days with an average windspeed higher than Beaufort Scale 7, indicating a potential shift to extreme climate. **Tables 11** and **12** further break down the shift in extreme windspeed events by seasons, suggesting that there are generally more extreme wind speed events than before , with increasing events concentrated in wintertime.

The increase in extreme windiness events is of immediate concern, as it is set against the safety of fishermen and fishery utility. According to the latest study by Sainsbury et al. (2021), windspeed at Beaufort scale 6 could lead to a 20% increase in fishermen's aversion to their fishing trip, and at Beaufort scale 7, their aversion would double. This aversion refers to whether fishermen are likely to take a fishing trip in consideration of the risk they face under certain weather conditions. The growing aversion to higher wind speed may have originated from the risk of at-sea vessel accidents (Rezaee et al., 2016, Jin and Thunberg, 2005), escalating physical risks (Smith and Wilen, 2005), and increasing fuel costs (Abernethy et al., 2010).

However, fishermen's decision to sail is not only risk-dependent – fishery is also an economic decision. With the current downturn in the economy and the competitive fishing environment, fishermen, especially those who desperately need income, are likely to take greater risk for their return if other options at lower risks are absent. Vessel owners, who may not sail out with the crews hired, may likely ignore the elevating risk posed by extreme weather events to carry out fishing activities. With climate variability indicating a growing frequency of extreme windiness in the major fishing areas in the Atlantic, disruption to fishing activities and the safety of fishermen should now be on the watch list.

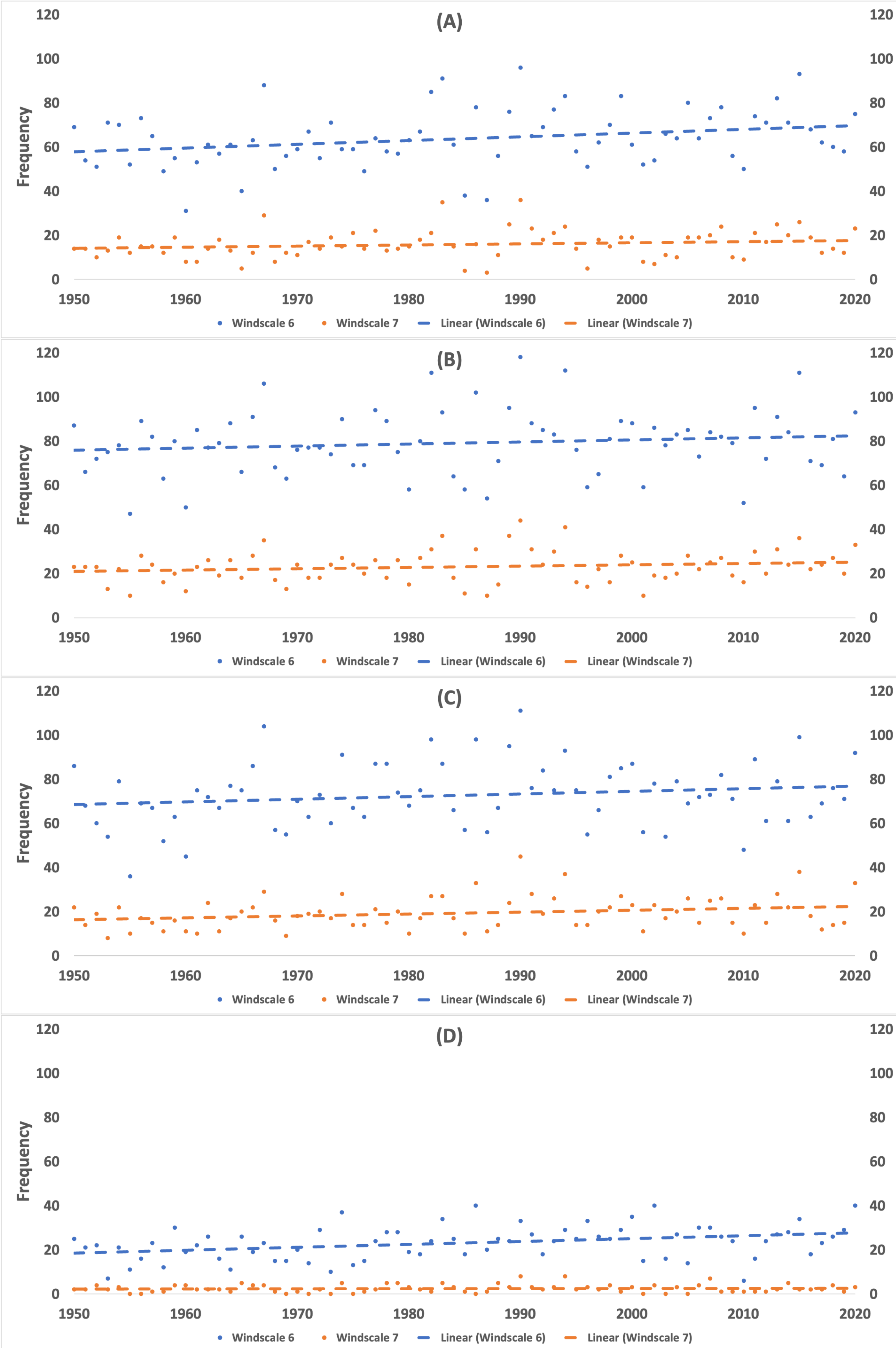

Figure 14. *Scatter plot that indicates the trend in frequency of dates exceeding Beaufort Windscale 6 (as indicated in blue) and 7 (as indicated in orange) in 1950-2021 in (A) Area A; (B) Area B; (C) Area C and (D) Area D*

	Area A	Area B	Area C	Area D
		Beaufort Scale 6		
1961-1990	62.5 days	80.6 days	76.0 days	22.4 days
1991-2020	67.7 days	80.6	74.0 days	25.5 days
Difference	+5.2	0	-2.0	+3.1
		Beaufort Scale 7		
1961-1990	15.9 days	23.5 days	19.3 days	2.5 days
1991-2020	16.7 days	23.9 days	21.2 days	2.5 days
Difference	+0.8	+0.4	+1.9	0

Table 10. *Change in frequency of windy days in 1961–1990 and 1991–2020 with reference to the 1951–2020 based on Beaufort Windscale*

	Area A	Area B	Area C	Area D
		Beaufort Scale 6		
1961-1990	3.7 days	5.5 days	5.1 days	0.4 days
1991-2020	3.9 days	5.2 days	4.5 days	1.3 days
Difference	+0.2	-0.3	-0.6	+0.9
		Beaufort Scale 7		
1961-1990	0.2 days	0.4 days	0.4 days	0 days
1991-2020	0.5 days	0.8 days	0.4 days	0.1 days
Difference	+0.3	+0.4	0	+0.1

Table 11. *Change in frequency of summer windy days in 1961–1990 and 1991–2020 with reference to the 1951–2020 based on Beaufort Windscale*

	Area A	Area B	Area C	Area D
		Beaufort Scale 6		
1961-1990	27.9 days	36.4 days	34.4 days	13.3 days
1991-2020	30.5 days	36.1 days	34.1 days	14.3 days
Difference	+2.6	-0.3	-0.3	+1.0
		Beaufort Scale 7		
1961-1990	8.6 days	12.7 days	10.6 days	1.9 days
1991-2020	9.4 days	13.6 days	12.8 days	1.7 days
Difference	+0.8	+0.9	+1.8	-0.2

Table 12. *Change in frequency of winter windy days in 1961–1990 and 1991–2020 with reference to the 1951–2020 based on Beaufort Windscale*

5. Summary

Against the background of global warming, the four UK major fishing regions in the Atlantic have experienced raised temperatures, enhanced rainfall, suboceanic warming, and intensified surface windiness over the last few decades. Our results indicate that the changes in temperature and suboceanic heat content are consistent across four study areas, while precipitation and windiness exhibit more regional/local variations in northeast Atlantic. Studies of the past have shown that climatic variation could negatively impact the ecology of fishery and the safety of crews on their trip, eventually harming the fishing industry. All in all, the climatic factors this study investigated all display different degrees of variations and their impact should be taken into consideration during the future planning of the food industry.

References

ABERNETHY, K. E., TREBILCOCK, P., KEBEDE, B., ALLISON, E. H. & DULVY, N. K. 2010. Fuelling the decline in UK fishing communities? *ICES Journal of Marine Science,* 67**,** 1076-1085.

BAKUN, A. 1997. Patterns in the ocean: ocean processes and marine population dynamics. *Oceanographic Literature Review,* 5**,** 530.

BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O. & GENOVA, R. C. 2014. Climate change 2014 impacts, adaptation, and vulnerability Part B: regional aspects: working group II contribution to the fifth assessment report of the intergovernmental panel on climate change. *Climate Change 2014: Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

CAPUTI, N., KANGAS, M., DENHAM, A., FENG, M., PEARCE, A., HETZEL, Y. & CHANDRAPAVAN, A. 2016. Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot. *Ecology and Evolution,* 6**,** 3583-3593.

CHEUNG, W. W., LAM, V. W., SARMIENTO, J. L., KEARNEY, K., WATSON, R. & PAULY, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and fisheries,* 10**,** 235-251.

EDWARDS, M. & RICHARDSON, A. J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature,* 430**,** 881-884.

FILBEE-DEXTER, K., WERNBERG, T., GRACE, S., THORMAR, J., FREDRIKSEN, S., NARVAEZ, C., FEEHAN, C. & NORDERHAUG, K. 2020. Marine heatwaves and the collapse of marginal North Atlantic kelp forests. *Scientific Reports,* 10**,** 1-11.

FOGARTY, M., INCZE, L., HAYHOE, K., MOUNTAIN, D. & MANNING, J. 2008. Potential climate change impacts on Atlantic cod (Gadus morhua) off the northeastern USA. *Mitigation and Adaptation Strategies for Global Change,* 13**,** 453-466.

GENNER, M. J., SIMS, D. W., WEARMOUTH, V. J., SOUTHALL, E. J., SOUTHWARD, A. J., HENDERSON, P. A. & HAWKINS, S. J. 2004. Regional climatic warming drives long–term community changes of British marine fish. *Proceedings of the Royal Society of London. Series B: Biological Sciences,* 271**,** 655-661.

GOOD, S. A., MARTIN, M. J. & RAYNER, N. A. 2013. EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *Journal of Geophysical Research: Oceans,* 118**,** 6704-6716.

HERSBACH, H., BELL, B., BERRISFORD, P., HIRAHARA, S., HORÁNYI, A., MUÑOZ-SABATER, J., NICOLAS, J., PEUBEY, C., RADU, R. & SCHEPERS, D. 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society,* 146**,** 1999-2049.

HJORT, J. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. 1914. ICES.

HOLT, R. E. & JØRGENSEN, C. 2014. Climate warming causes life-history evolution in a model for Atlantic cod (Gadus morhua). *Conservation Physiology,* 2**,** cou050.

JACOX, M. G. 2019. Marine heatwaves in a changing climate. Nature Publishing Group.

JIN, D. & THUNBERG, E. 2005. An analysis of fishing vessel accidents in fishing areas off the northeastern United States. *Safety Science,* 43**,** 523-540.

LEE, S.-S., LEE, J.-Y., WANG, B., HA, K.-J., HEO, K.-Y., JIN, F.-F., STRAUS, D. M. & SHUKLA, J. 2012. Interdecadal changes in the storm track activity over the North Pacific and North Atlantic. *Climate Dynamics,* 39**,** 313-327.

LINDMARK, M., AUDZIJONYTE, A., BLANCHARD, J. & GÅRDMARK, A. 2022. Temperature impacts on fish physiology and resource abundance lead to faster growth but smaller fish sizes and yields under warming. *Global Change Biology*.

MILLS, K. E., PERSHING, A. J., BROWN, C. J., CHEN, Y., CHIANG, F.-S., HOLLAND, D. S., LEHUTA, S., NYE, J. A., SUN, J. C. & THOMAS, A. C. 2013. Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography,* 26**,** 191-195.

OTTERSEN, G., STIGE, L. C., DURANT, J. M., CHAN, K.-S., ROUYER, T. A., DRINKWATER, K. F. & STENSETH, N. C. 2013. Temporal shifts in recruitment dynamics of North Atlantic fish stocks: effects of spawning stock and temperature. *Marine Ecology Progress Series,* 480**,** 205-225.

PANKHURST, N. W. & MUNDAY, P. L. 2011. Effects of climate change on fish reproduction and early life history stages. *Marine and Freshwater Research,* 62**,** 1015-1026.

PARMESAN, C. & YOHE, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *nature,* 421**,** 37-42.

PINNEGAR, J., WRIGHT, P., MALTBY, K. & GARRETT, A. 2020. The impacts of climate change on fisheries, relevant to the coastal and marine environment around the UK. *MCCIP Sci. Rev,* 2020**,** 456-581.

RAYMOND, W. W., BARBER, J. S., DETHIER, M. N., HAYFORD, H. A., HARLEY, C. D., KING, T. L., PAUL, B., SPECK, C. A., TOBIN, E. D. & RAYMOND, A. E. 2022. Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea.

REZAEE, S., PELOT, R. & GHASEMI, A. 2016. The effect of extreme weather conditions on commercial fishing activities and vessel incidents in Atlantic Canada. *Ocean & Coastal Management,* 130**,** 115-127.

RODRÍGUEZ-PUEBLA, C. & NIETO, S. 2010. Trends of precipitation over the Iberian Peninsula and the North Atlantic Oscillation under climate change conditions. *International Journal of Climatology,* 30**,** 1807-1815.

SAINSBURY, N. C., GENNER, M. J., SAVILLE, G. R., PINNEGAR, J. K., O'NEILL, C. K., SIMPSON, S. D. & TURNER, R. A. 2018. Changing storminess and global capture fisheries. *Nature Climate Change,* 8**,** 655-659.

SAINSBURY, N. C., SCHUHMANN, P. W., TURNER, R. A., GRILLI, G., PINNEGAR, J. K., GENNER, M. J. & SIMPSON, S. D. 2021. Trade-offs between physical risk and economic reward affect fishers' vulnerability to changing storminess. *Global Environmental Change,* 69**,** 102228.

SMITH, M. D. & WILEN, J. E. 2005. Heterogeneous and correlated risk preferences in commercial fishermen: The perfect storm dilemma. *Journal of Risk and Uncertainty,* 31**,** 53-71.

STENSETH, N. C., OTTERSEN, G., HURRELL, J. W. & BELGRANO, A. 2004. *Marine ecosystems and climate variation: The North Atlantic-A comparative perspective*, Oxford University Press.

TABOADA, F. G. & ANADÓN, R. 2012. Patterns of change in sea surface temperature in the North Atlantic during the last three decades: beyond mean trends. *Climatic Change,* 115**,** 419-431.

TER HOFSTEDE, R., HIDDINK, J. G. & RIJNSDORP, A. D. 2010. Regional warming changes fish species richness in the eastern North Atlantic Ocean. *Marine Ecology Progress Series,* 414**,** 1-9.
TRENBERTH, K. E. 2011. Changes in precipitation with climate change. *Climate research,* 47**,** 123-138.
TRENBERTH, K. E., CHENG, L., JACOBS, P., ZHANG, Y. & FASULLO, J. 2018. Hurricane Harvey links to ocean heat content and climate change adaptation. *Earth's Future,* 6**,** 730-744.
UMMENHOFER, C. C., SEO, H., KWON, Y. O., PARFITT, R., BRANDS, S. & JOYCE, T. M. 2017. Emerging European winter precipitation pattern linked to atmospheric circulation changes over the North Atlantic region in recent decades. *Geophysical Research Letters,* 44**,** 8557-8566.
URBAN, A., DI NAPOLI, C., CLOKE, H. L., KYSELÝ, J., PAPPENBERGER, F., SERA, F., SCHNEIDER, R., VICEDO-CABRERA, A. M., ACQUAOTTA, F. & RAGETTLI, M. S. 2021. Evaluation of the ERA5 reanalysis-based Universal Thermal Climate Index on mortality data in Europe. *Environmental research,* 198**,** 111227.