

University of Southampton

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Bsc Oceanography



Investigating how UK coastal flooding between 1835-2015 varies
in time, spatially and in relation to storm tracks and the North
Atlantic Oscillation.

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Abstract

Coastal flooding is one of the most dangerous natural hazards, globally affecting 200-250 million people each year. By 2100, this could increase to 176-800 million under a high emissions scenario. The UK is especially vulnerable, with 6.3 million properties at risk. This thesis has three aims; to assess how UK coastal floods has varied spatially and temporally, identify meteorological and climatic drivers of change, and evaluate the North Atlantic Oscillation's (NAO) influence.

Objective 1 uses SurgeWatch V3 dataset to assess temporal and spatial changes across 549 flood events between 1835-2015. Results show flooding increases, particularly in Southwest and East England, where most flooding occurred. West England experienced a decrease, whilst Scotland observed no clear trend. Seasonally, flood events and categories experience a double peak in autumn and winter due to king tides. Floods are classified into six intensities, with Southwest and East England experiencing the highest frequency across all categories.

Objective 2 digitised and assessed storm tracks of the 105 most intense events. Southwest England storm tracks pass through the UK, West England and Scotland tracks pass north of the UK and East England tracks pass north but curves into the North Sea. Objective 3 examined the relationship between coastal flooding and NAO, with 68% of floods occurring during positive winter NAO, and 61.5% during annual positive NAO. Positive NAO storm tracks move linearly north of Scotland, whilst negative NAO curves around Scotland. These findings are valuable for coastal management, aiding areas vulnerable and predicting future flood frequency, especially under climate change.

1. Introduction

1.1. Motivation

Coastal flooding is one of the most dangerous natural hazards globally (Idier et al., 2020; Guha-Sapir et al., 2015; Mortensen et al., 2024; Pant et al., 2016). By 2050, coastal flooding is projected to double with a 10-20cm increase in sea level (USGS., 2022) driven by aging flood defences, an increase in coastal populations, the decline of natural habitats and climate change (Haigh et al., 2022). Aging defences fail to adequately protect communities (Pant et al., 2016). Urbanisation increases floodplain development (Stevens., 2017) putting more infrastructure at risk (Andreadis et al., 2022). The loss of natural buffers, like seagrasses which attenuate wave energy (Nelson., 2009), further heightens vulnerability (Zhu et al., 2019). Climate change exacerbates these threats through rising sea levels (Mackie et al., 2020).

In 2024, global sea level rose by 4.3mm (Masterson et al., 2025), consistent with the current 4.5mm/yr rate (Hamlington et al., 2024). Coastal flooding currently affects 200-250 million people annually (McMichael et al., 2020), many in low-elevation coastal zones (LECZs) and developing nations (MacManus et al., 2021; Rentschler et al., 2022). Communities are adapting by implementing early warning systems and enhancing natural buffers (Martyr-Koller et al., 2021). By 2100, sea levels could globally rise by 0.6-1.6m (Jevrejeva and Grinsted., 2010), annually affecting 176-800 million people under RCP8.5, a high emissions scenario (IPCC., 2022). Many current defences were designed on historic sea levels, becoming ineffective with a 0.5m rise, highlighting the urgency for improved defences and understanding future flooding trends (IPCC, chapter 9., 2022).

The UK has a long history of coastal flooding, predating anthropogenic climate change. The Great Storm of 1703, an early well-documented flood from a West Indian hurricane induced a depression (Hart., 2017), causing 8000 fatalities along the South, with seawalls built of sticks and stones (SurgeWatch., 2024a). The 1953 storm, originating off Greenland, coincided with spring tides (Hickey., 1997), causing 307 fatalities in East England and Scotland with 1,200 defence breaches (SurgeWatch., 2024b). It was the UK's most severe in the past 100 years (McRobie et al., 2005), leading to the construction of the Thames Barrier (Wadey et al., 2015). The winter 2013/14 floods occurred due to a series of successive storms (Met Office., 2017), breaching 50 defences across South and Northeast England, Wales and Scotland, but caused no UK fatalities (SurgeWatch., 2024c). The Thames barrier was key, relying on accurate forecasts for effective closure (Environment Agency., 2025; GOV.UK., 2025). This thesis seeks to determine flood trends to support future defence planning.

Since 1990, UK mean sea level has risen by 18.5cm (Kendon et al., 2023) putting 6.3 million properties in England at risk (GOV.UK., 2024). A 50cm rise puts 20% of England's flood defences at risk of failure (CCC., 2018). Historically, Bristol and London have faced the greatest flood risk and damage (Bates et al., 2022). By 2300, UK sea level could rise by 1.7-4.5m under RCP8.5 (Environment Agency., 2019), with a 1m rise endangering 1.5 million UK properties (CCC., 2018).

This thesis focuses on storm surges, using SurgeWatch, where low pressure systems raise sea levels and winds push water onshore (Needham and Keim., 2011). Multiple flood causes can combine in compound flooding (Hendry et al., 2019), these include tidal flooding, pluvial flooding, tsunami-induced flooding and seiches (Green et al.,

2025). The moon's orbit enhances flooding during spring tides (Murtiaji et al., 2022). Pluvial flooding from overland rainfall overwhelms watercourses and drainage systems (Falconer et al., 2009). UK tsunamis are rare, but the 1755 tsunami event occurred from a Lisbon earthquake (Santos and Rijo., 2022) and the 2011 meteotsunami occurred from small, rapid atmospheric pressure changes off Portugal (Tappin et al., 2011). Seiches can flood coastlines when there is sufficient forcing and topography to cause resonance (Wells et al., 2005; Airy., 1878; Pugh et al., 2020).

SurgeWatch, a UK coastal flood database, compiles tide gauge data with soft data, like newspapers (Haigh et al., 2017). Tide gauge flood events exceed a 1 in 5 year return threshold, meaning sea level surpasses this height once every 5 years. SurgeWatch V3 records 941 events from 7AD to 2019, categorised from 1 (nuisance) to 6 (disaster) (Haigh et al., 2017). Early data is biased towards densely populated areas which sufficiently record flooding events (Haigh et al., 2017). Considering events after 1835 reduces this bias due to widespread tide gauges and telecommunication.

NAO is a key source of natural variability on interannual timescales (Hurrell., 1995), influencing European winters (Wanner et al., 2001) through altering mean sea level pressure between Iceland and the Azores (Hurrell., 1995). A positive NAO phase from strengthened Azores pressure and deepened Iceland pressure (Chartrand and Pausata., 2020) strengthens the jet stream, enhances westerly winds and shifts storm tracks north, with the opposite occurring under negative NAO (Carbon Brief., 2019; Rogers., 1990; Hurrell and Van Loon., 1997; Chartrand and Pausata., 2020). Winter NAO shows the strongest seasonal cycle (Wanner et al., 2001), with these shifts influencing UK flood patterns.

1.2. Aims and objectives

The overall aim of this study is to assess how coastal floods impacting the UK have varied spatially and temporally, along with the meteorological and climate drivers driving this change. To address this aim there are three objectives, as follows:

1. To assess temporal and spatial changes in coastal flooding over the period 1835 to 2015;
2. To assess what meteorological conditions drive coastal flooding in different regions by looking at storm tracks; and
3. To assess NAO's effect on coastal flooding

1.3. Structure

The structure of this thesis is as follow: data and methodology are described in section 2, results with key findings are detailed in section 3, a discussion of results and literature is in section 4 and conclusions in section 5.

2. Data and Methodology

In this chapter, the origin of the data (Section 2.1) is discussed along with the steps taken to collect and analyse the data. The methods are then discussed (Section 2.2).

2.1. Data

2.1.1. Data Summary

This thesis has used three datasets, the first being SurgeWatch. This is a database of historical UK coastal flood events containing the date, location and severity of the flood. The second dataset is 20th Century Reanalysis (V3) mean sea level pressure and wind vectors. This was processed to be used in combination with SurgeWatch to track the origin and termination of each storm which induced UK coastal flooding. This dataset is often referred to herein as storm tracks. The third dataset is 20th Century Reanalysis (V3) NAO index. This was used with SurgeWatch to correlate NAO to coastal flood frequency. It was then used with storm tracks to correlate the NAO's relationship to the path each storm takes.

SurgeWatch has undergone three updates, to increase the amount of coastal flood events. SurgeWatch V1 considered Tidal gauge data after 1915 to find events exceeding a 1 in 5 year return thresholds (Haigh et al., 2015). These events were verified through newspapers which documented the event. V2 improved the database by including an extensive trawl of newspapers, but events were limited to after 1915 (Haigh et al., 2017). V3 was more extensive dating back 2000 years using soft data of written observations. This thesis collated data from SurgeWatch V3 database, extracting a 180 year period from

July 1835 to June 2015. This database of historic coastal floods allows data to be processed on the relevant days where flooding occurred. It also allowed for flood intensity to be analysed based on categories classified by Haigh et al. (2017) as follows:

- Nuisance (1)-localised flooding and no specific consequences,
- Minor (2)-extensive inundation with properties flooded or services disrupted;
- Moderate (3)-high quantity of flooded properties with wide service disruptions or agricultural flooding;
- Major (4)-extensive flooding with significant infrastructure damage and significant economic damage costs;
- Severe (5)-extensive flooding with significant infrastructure damage and significant economic damage costs. There must be loss of life from drowning or reliable evidence that flood warning responses mitigated fatalities; and
- Disaster (6)- large consequence events with multiple drownings.

The second dataset extracted wind vectors and mean sea level pressure from 20th Century Reanalysis (V3): ([NOAA/CIRES/DOE 20th Century Reanalysis \(V3\): NOAA Physical Sciences Laboratory NOAA/CIRES/DOE 20th Century Reanalysis \(V3\)](#)). The data consists of objectively analysed 4D weather maps on a spatial and temporal resolution of 1 degree by 1 degree on an hourly basis. This dataset ranges between 1981 to 2015, but this thesis will only consider data between 1835-2015.

The third dataset extracted NAO indexes from 20th Century Reanalysis (V3): ([psl.noaa.gov/data/20thC_Rean/timeseries/monthly/NAO/nao.20crv3.long.data](#)). The data consisted of sea level pressure between Azores and Iceland for each month of the

year. Anomalies are calculated and divided by standard deviation to obtain NAO. This dataset was from 1836 to 2015. As such, the whole dataset was used in this thesis.

2.1.2. Data Formatting

SurgeWatch V3 data was extracted from July 1835 to June 2015 in order to fall outside the storm season, preventing storm seasons from being cut in half, skewing data results. Additionally, the dataset had to be altered from a comma separated format to a column format to allow MATLAB to process the regions, and categories, that were impacted by coastal floods (Appendix a- Tables 1 and 2). Spatial footprints are labelled 1-4 (Figure 1) with Southwest England (1), West England and West Scotland (2), Highlands and East Scotland (3); and East England (4).

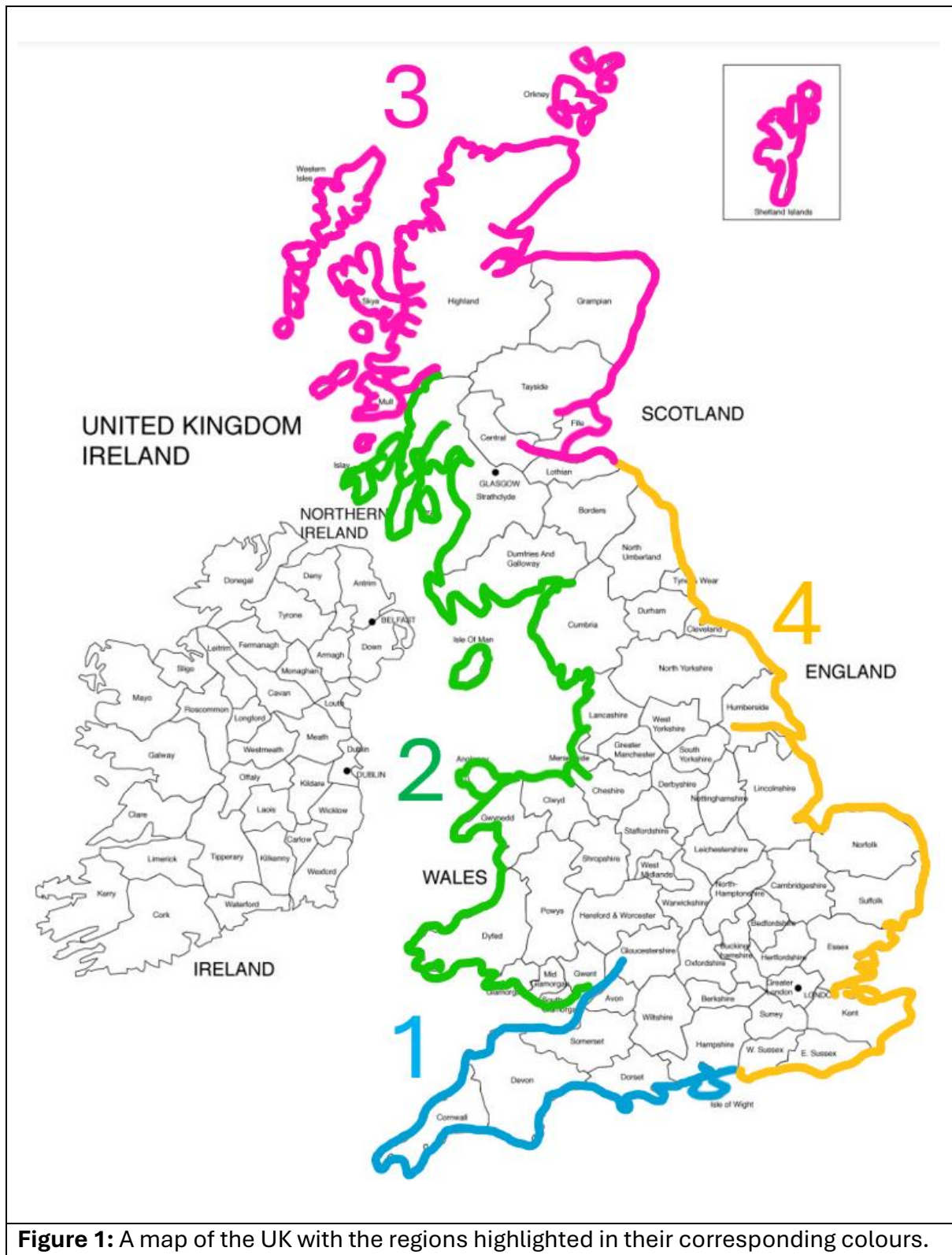


Figure 1: A map of the UK with the regions highlighted in their corresponding colours.

For the second objective, the 20th Century Reanalysis (V3) data was put into a grid format. Which was then filtered to 00:00, 06:00, 12:00 and 18:00, in order to save time when manually progressing through the storm track path over a series of days, evident in

Figures 14-17. This also meant MATLAB had less data to process for a single track. A total of 105 storm tracks were plotted, featuring all category 3-6 events but only 26 category 2 events. Once again as a result of time constraints, this is something for future studies to build on. The first track occurred on 12/10/1839 with the final track occurring on 14/02/2014. SurgeWatch data was combined with the storm tracks to identify the regions each track affected.

To address the third objective, the 20th Century Reanalysis (V3) NAO index was processed in 3 different ways. The first processed monthly NAO with SurgeWatch monthly coastal flood events, obtaining a percentage of events that occurred under a positive index compared to a negative index. The same was done for winter NAO by only considering coastal flood events within winter months. This was also done using storm tracks instead of coastal flood events. The next way data was processed was by averaging monthly NAO to produce an annual NAO. Once again, this was done for winter NAO by averaging only winter months NAO. The final way NAO data was process, was by obtaining an average NAO index across all months for 1, 3 and 5 years.

2.2. Methodology

The analysis was undertaken in three main stages, each addressing one of the three study objectives, and is described in the three sub-sections below.

2.2.1. Storm Surge

The first objective, to assess temporal and spatial changes in coastal flooding over the period 1835 to 2015, processed SurgeWatch V3 data into 7 main figures (Figures 2-8). This was done by filtering months, years, regions and categories in MATLAB. Figure 2 compares annual flood frequency, decadal flood frequency and 20 year flood frequency, obtained by grouping SurgeWatch V3 flood events by years, decades and 20 years. Figure 3 compares different regions decadal flood frequency. Figures 4 and 5 compare annual flood frequency by regions. Figure 6 compares regional frequency according to months. Figure 7 compares flood categories by regions. Figure 8 compares flood categories according to months.

2.2.2. Storm Tracks

The second objective is to assess what meteorological conditions drive coastal flooding in different regions by looking at storm tracks. Haigh et al. (2017) correlated each coastal flood to its associated single storm event. The 20th Century Reanalysis data used SurgeWatch V3 flood dates with a time of 00:00, to be when the storm hit the UK and caused flooding. The storms were identified based on areas of low pressure surrounded

by cyclonic winds (moving counterclockwise in the northern hemisphere (Marsh and Seville., 2012)). These storm events were tracked with an interactive interface in MATLAB (developed by Ivan Haigh) of mean sea level pressure and wind vectors over the North Atlantic Ocean and Northern Europe displayed in 6-hourly progressions (Figures 14-17).

Using the SurgeWatch coastal flood date for each event, the interface tracked back in time to identify the storms origin location. In some cases, the location the storm was generated in, could not be obtained; this was due to the interface preventing tracking past -75°E and 35°S . On 6 hour progressions, a coordinate was entered for the centre of the storm, the storm track was generated by interpolating between the coordinates. Tracking forward in time showed the storm's termination, with the limit of this study stopping at 15°E and 80°N . Manually tracking the storms relied on the user identifying the centre of low pressure and cyclonic winds as the centre of the storm. As such, this subjectivity will present bias and small anomalies in the storm tracks. Each track was processed to obtain a single path removing pressure and wind data, to produce 4 main figures (Figures 9-11, and 13). Figure 9 compiles all individual storm tracks from the interactive MATLAB interface, on a map across the North Atlantic. Figure 10 split the storm tracks by regions using the SurgeWatch V3 dataset. Figure 11 compares average storm tracks taken by each region. Figure 13 groups the storm tracks by 50 years, comparing storm track paths and frequency in 50 year periods. Examples of the interactive MATLAB interface are found in Figures 14-17.

2.2.3. NAO

The third objective is to assess NAO's effect on storm tracks between 1835-2015. The positive and negative NAO years from 20th Century Reanalysis data was combined with SurgeWatch V3 data and storm tracks (with data obtained from 20th Century Reanalysis) to produce 3 figures and 2 data tables. Table 1 calculates the proportion of coastal flooding, of a given category, that occur in positive verses negative annual NAO. It also calculates the proportion of coastal floods that occurred in positive vs negative winter NAO. Table 2 uses NAO index, averaged over 1,3 and 5 years, to obtain correlation coefficients to coastal floods. Figure 18 compares storm tracks with their corresponding positive/negative annual/winter NAO. Figure 19 plots an average of positive and negative annual NAO. Figure 20 compares average annual and winter NAO index by years.

3. Results

The results are described in the three sub-sections below. Each subsection addresses one of the three study objectives.

3.1. Storm Surge

The first objective is to assess temporal and spatial changes in coastal flooding.

Figure 2a analyses coastal flood frequency by year across the whole of the UK, showing an increasing trend in the 20th century compared to the 19th century. A maximum of 16 events occurred in 1954 and there is an annual average of 3.1 coastal floods. There are 21 individual years without any flood events. The earliest occurs in 1835 and the latest in 2009. The decades 1830, 1850 and 1940 have 3 years without floods, with the majority of years without floods occurring in the 19th century.

Figure 2b analyses coastal flooding per decade across the whole of the UK, showing an increasing trend which drops in the last few decades. A maximum of 46 events occurred in the decade 1950 and there is a decadal average of 28.9 coastal floods. The majority of flooding occurred in the 20th century with all but 2 decades being above the average. The 1830 and 2010 bars only contain 5 years of data. This is because this thesis restricts data to between 1835-2015, due to NAO data being between 1836-2015. Therefore, this data is lower than what was actually experienced.

Figure 2c analyses coastal flooding over a 20 year interval, across the whole of the UK, showing an increasing trend to 1950. A maximum of 91 events occurred between 1950-1970, and there is a 20 year average of 54.9 coastal floods. The majority of flooding occurred in the 20th century, where they are all above the average. Once again, data is

limitation means the 1830 bar is missing 5 years of data, whilst the 2010 bar is missing 15 years of data. This is likely to lower the average frequency and by including this data, (Figure 2) would be significantly improved, accurately reflecting flooding trends.

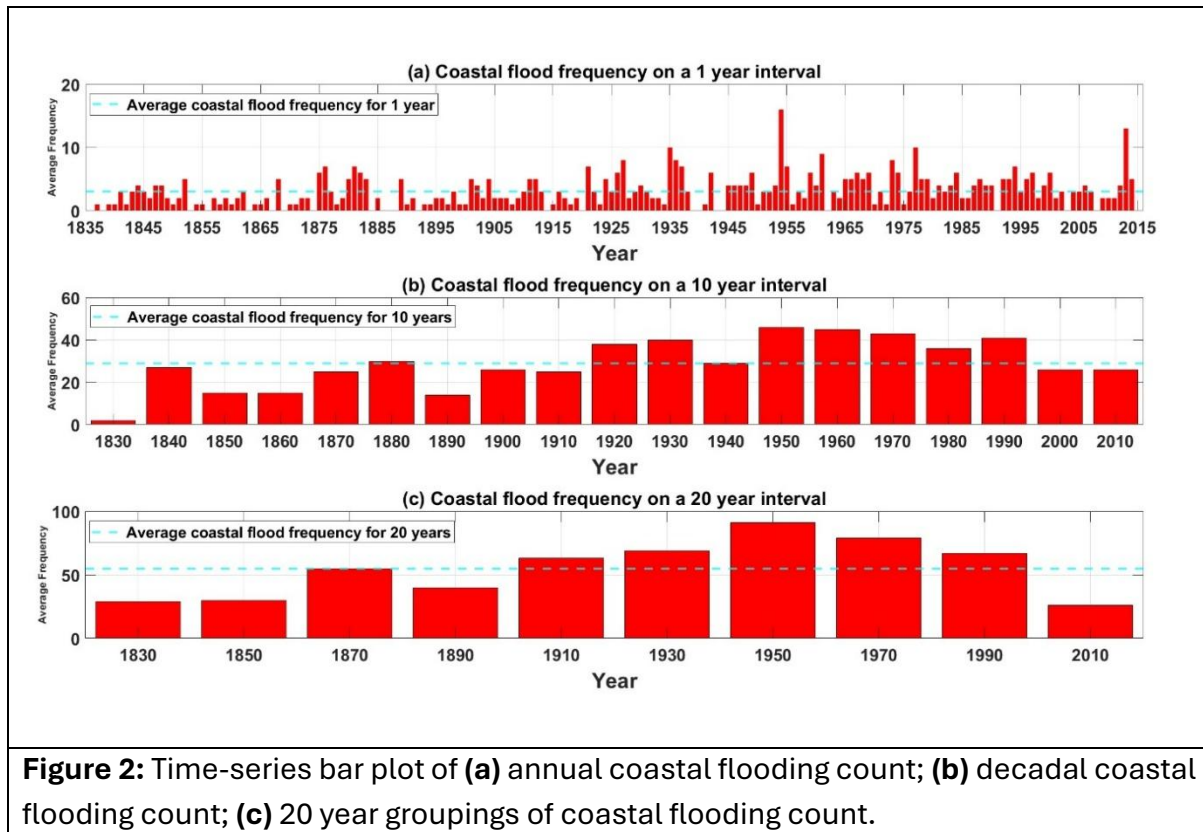


Figure 2: Time-series bar plot of **(a)** annual coastal flooding count; **(b)** decadal coastal flooding count; **(c)** 20 year groupings of coastal flooding count.

Figure 3a, is a repeat of Figure 2b which analyses coastal flooding by decade across all of the UK. It is not the sum of regional flooding, because a coastal flood event can affect multiple regions. Once again all of Figure 3 has 5 years of data in 1830 and 2010, resulting in a smaller flood frequency than what is likely to have occurred. Appendix b, Figure 5 repeats Figure 3 but by year.

Figure 3b, enlarged in Appendix b, Figure 1, analyses coastal flooding by decade across region 1, showing an increasing trend. A maximum of 29 events occurred in the decade 1960, with no events in the decade 1830.

Figure 3c, enlarged in Appendix b, Figure 2, analyses coastal flooding by decade across region 2, showing a decreasing trend. A maximum of 13 events occurred in the decade 1890, with no events in the decade 1990.

Figure 3d, enlarged in Appendix b, Figure 3, analyses coastal flooding by decade across region 3, showing a decreasing trend between 1860-1940, despite 1910 being anomalously high. After 1940, a long term trend is inconclusive. A maximum of 6 events occurred in the decade 1860, with no events in the decade 1990.

Figure 3e, enlarged in Appendix b, Figure 4, analyses coastal flooding by decade across region 4, showing an increasing trend. A maximum of 26 events occurred in the decade 1990, with no events in the decade 1830.

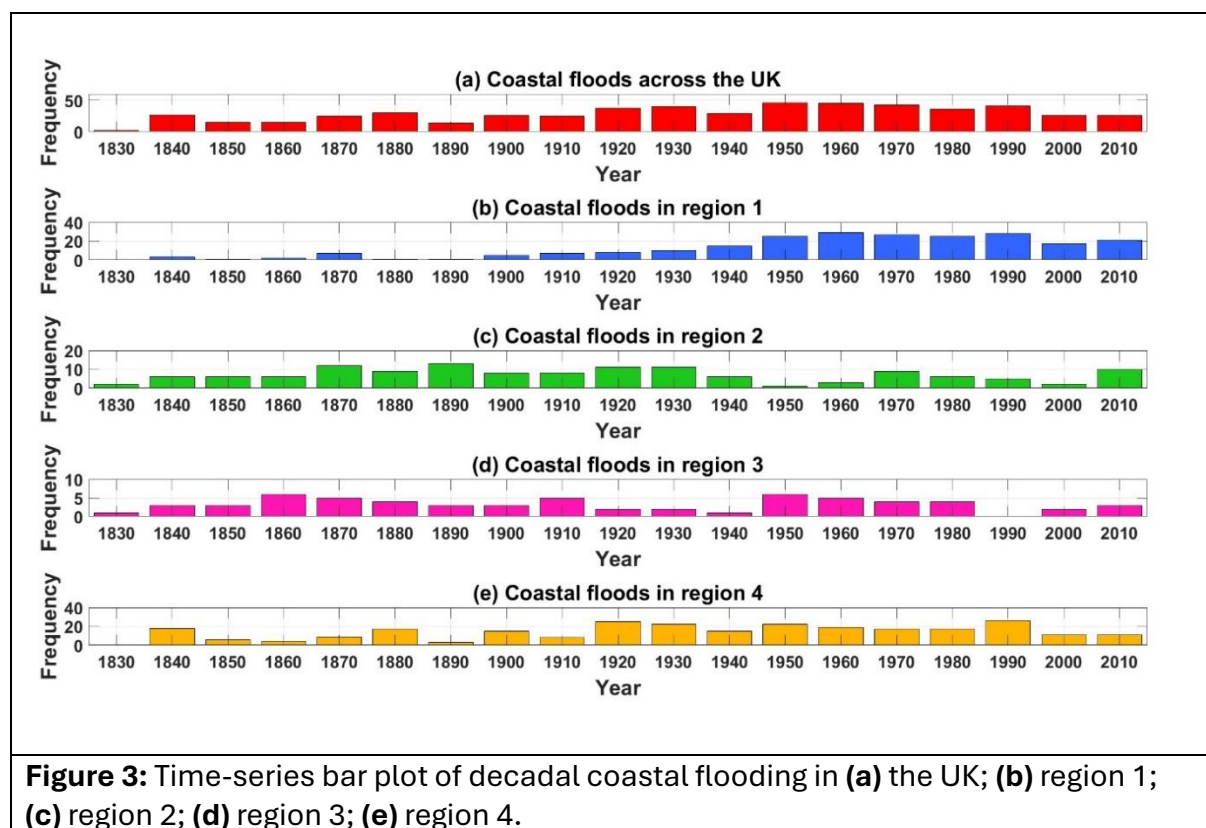


Figure 4 analyses coastal flood events annually by regions. Appendix b, Figure 6 repeats Figure 4 but by decade. Appendix b, Figures 7-12 examining only two regions at a time. The

most events within a year occur in region 1, with 10 events in 2014. Before 1940, region 1 is generally lower than other regions, lacking distinguishably large events. Region 4 contains considerable peaks throughout, with a maximum of 7 events in 1936 and 1954. Region 2 has most of its peaks occurring before 1940, with a maximum of 6 events in 2014. Region 3 has fewest and the lowest amount of peaks, with a maximum of 3 events in 1869.

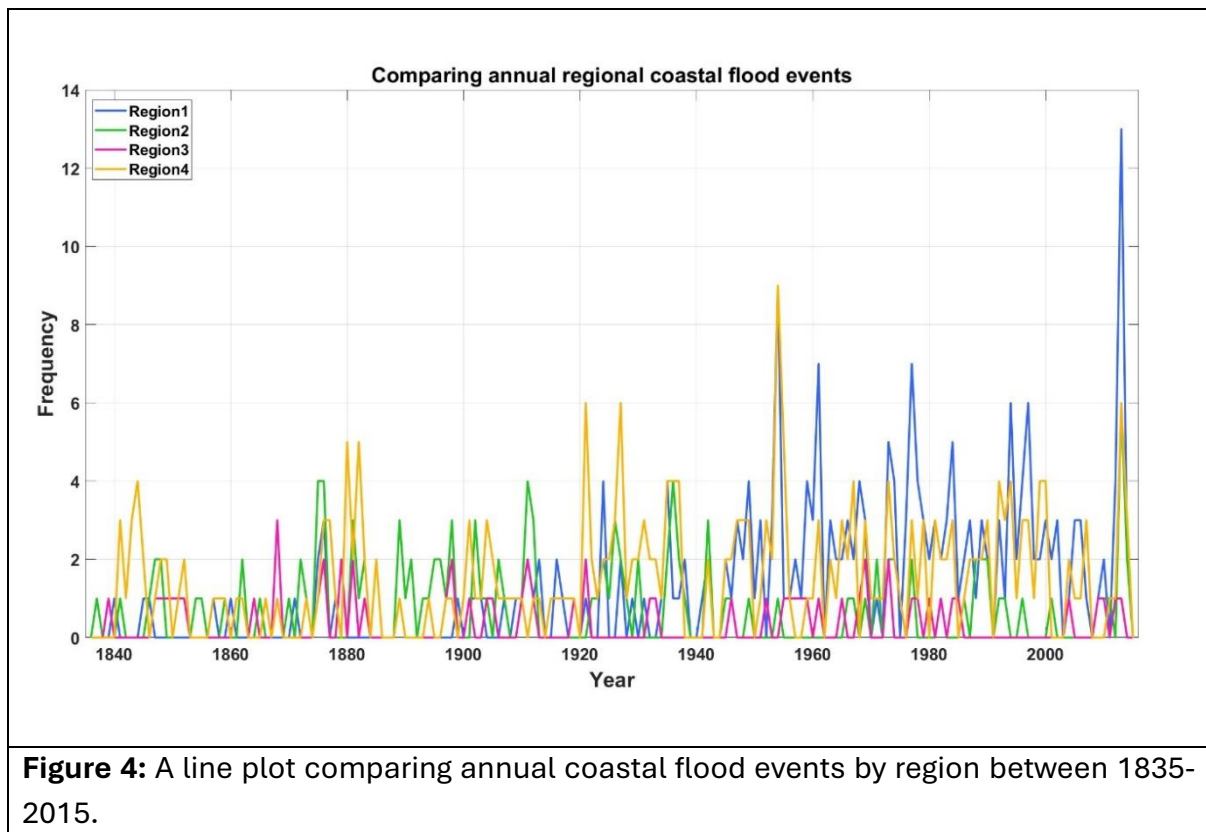


Figure 5 uses a colour bar to analyse the trend in coastal flood frequency over years by region. Region 1 shows a significant increase flooding after 1940. Region 2 shows a decrease in flooding after 1940, interestingly this shows an inverse relationship to region 1. Region 3 shows no observable trend, due to there being too few events. Region 4 shows a significant increase in flooding after 1920. Appendix b, Figure 13, repeats Figure 5, but by decade.

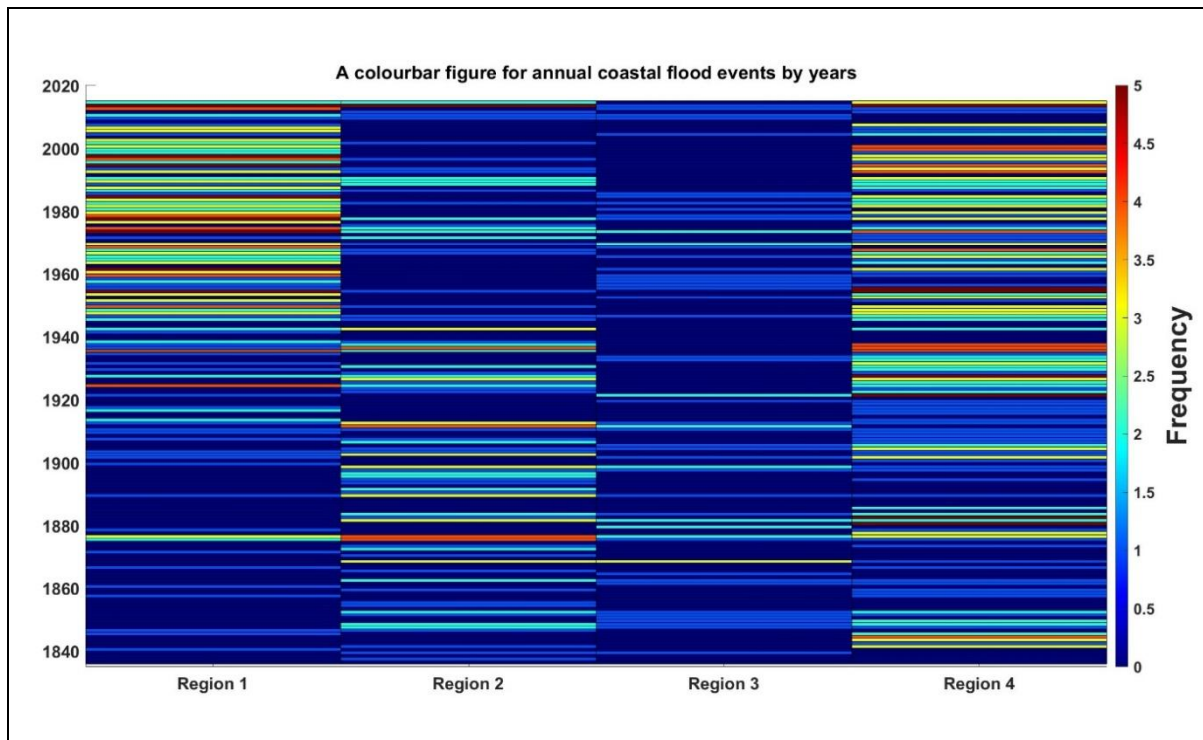


Figure 5: A colour bar plot of annual coastal flood events by region between 1835-2015.

Figure 6 analyses coastal flood frequency by region according to month. The x axis starts in July and ends in June, to capture the winter storm season in the centre of the figure. Appendix b, Figure 14 contains January-December on the x axis. There is a strong seasonal pattern with more coastal flood events in the winter months, for all four regions. January has the highest frequency of coastal flooding with 49 events in region 4, 19 in region 3, 35 in region 2 and 53 in region 1. Overall, regions 1 and 4 experience more coastal flooding than regions 2 and 3. There are two distinct peaks, in January and October, for regions 1-3. This corresponds to large equinox tides.

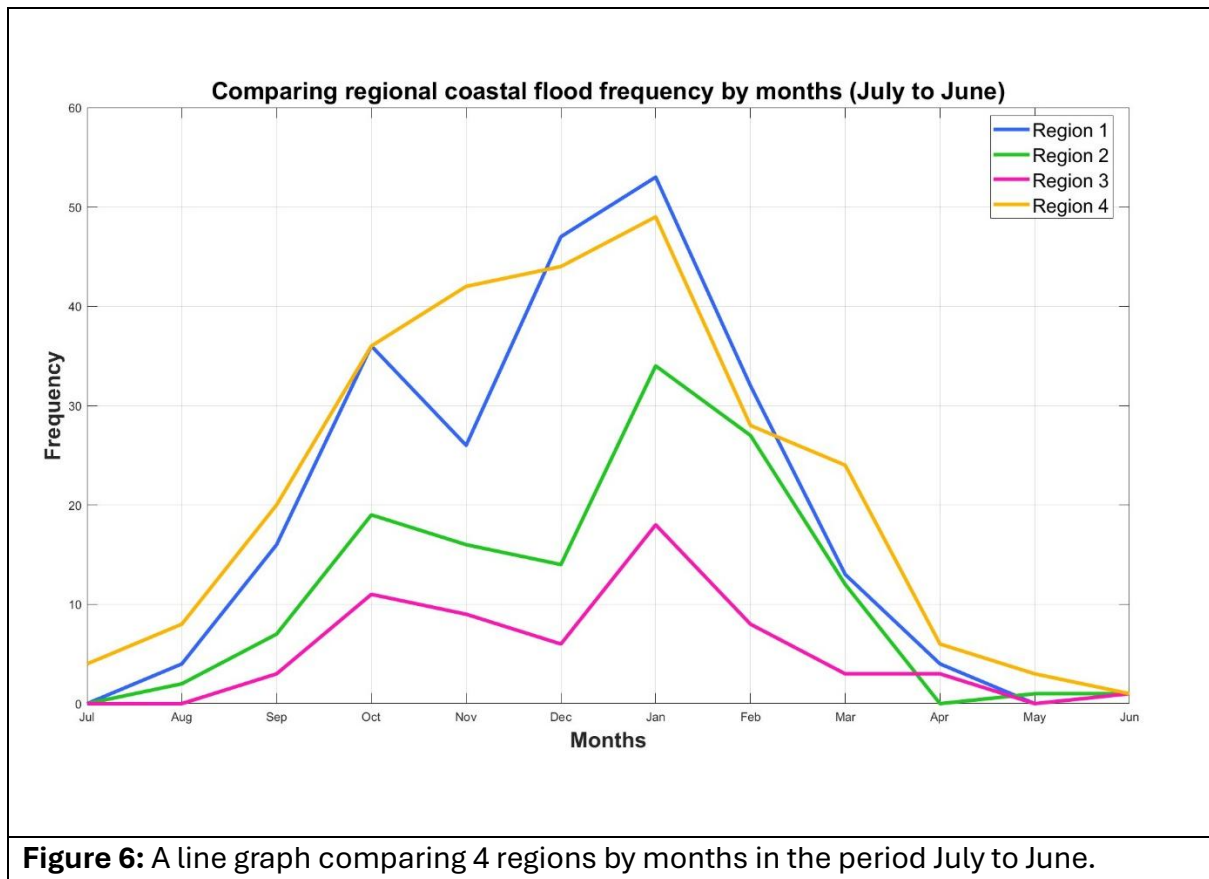


Figure 7 analyses coastal flood frequency by categories according to regions. Category 1 has the greatest amount flood events across all regions. This is due to category 1 events corresponding to the weak winds, which make these events more common. Whilst category 6 events require significantly strong storms to induce disastrous flooding, making these events rarer. Flood frequency decreases exponentially with increasing categories across all regions, except region 3 which experiences 4 flood events in both category 4 and 5. Region 4 experiences the greatest amount of category 1 (175), 4 (17) and 6 (2) events. Region 1 experiences the greatest amount of category 2 (65) and 3 (24) events. Region 2 and 4 experience the greatest amount of category 5 (7) events.

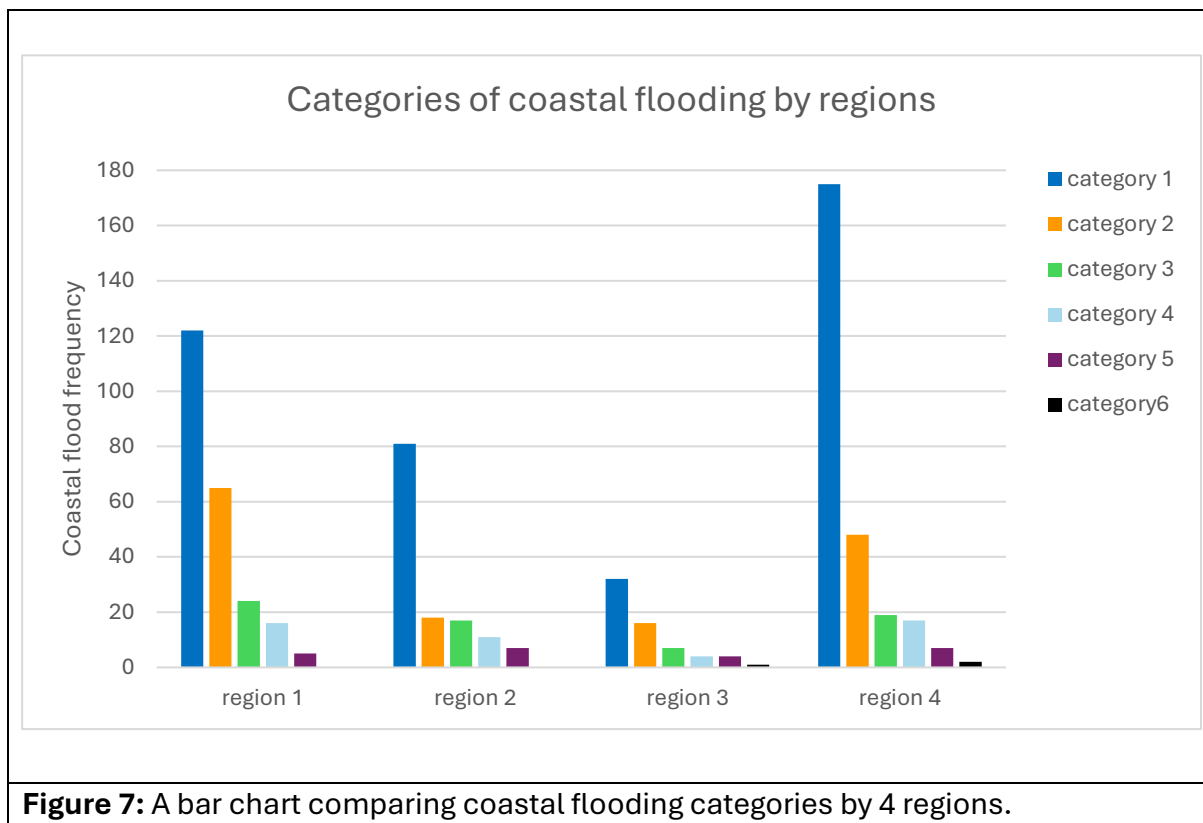


Figure 8 analyses coastal flood frequency by category according to month. The x axis starts in July and ends in June, to capture the winter storm season in the centre of the figure. Appendix b, Figure 15, contains January-December on the x axis. There is a strong seasonal pattern with more coastal flood events in the winter months, for all 6 categories. January has the highest frequency of coastal flooding for all categories except category 6 which has a secondary peak in August. This can be observed clearer in Appendix b, Figure 16. Categories 3 and 5 show a symmetrical distribution, whilst categories 1 and 2 have a double peak in October and January. Category 4 has the double peak in November and January. Once again, these correspond to large equinox tides.

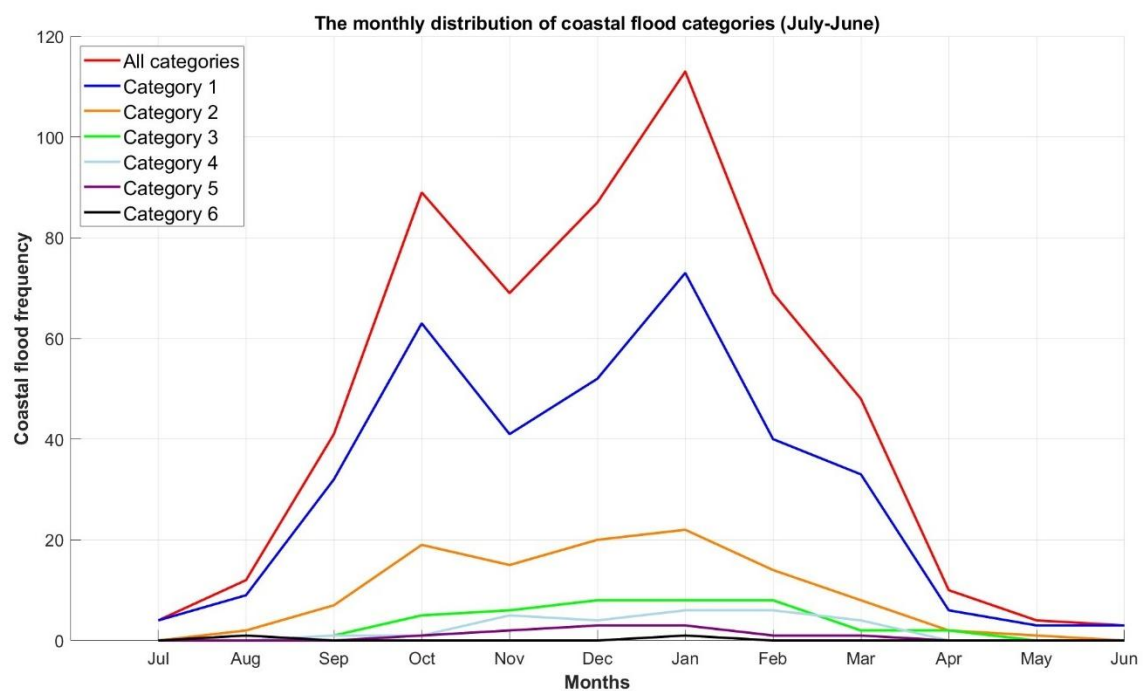


Figure 8: A line graph comparing 6 coastal flood categories by months in the period July to June.

3.2. Storm Tracks

The second objective is to assess the characteristics of the storms which drive coastal flooding around the UK.

Figure 9 compiles all the digitised storm tracks (red lines) across the North Atlantic and British Isles which produced coastal floods above category 3, and the 26 category 2 events. The majority of storms impacting the UK are generated in the region of northeast USA and south Canada, and move in a northeasterly direction towards the UK, crossing into Scandinavia. Storm tracks are widespread with the majority crossing the UK or passing north of the UK between latitudes 45 and 70. While most storms follow a relatively linear southwest to northwest direction, some storms are more chaotic, rotating back on themselves.

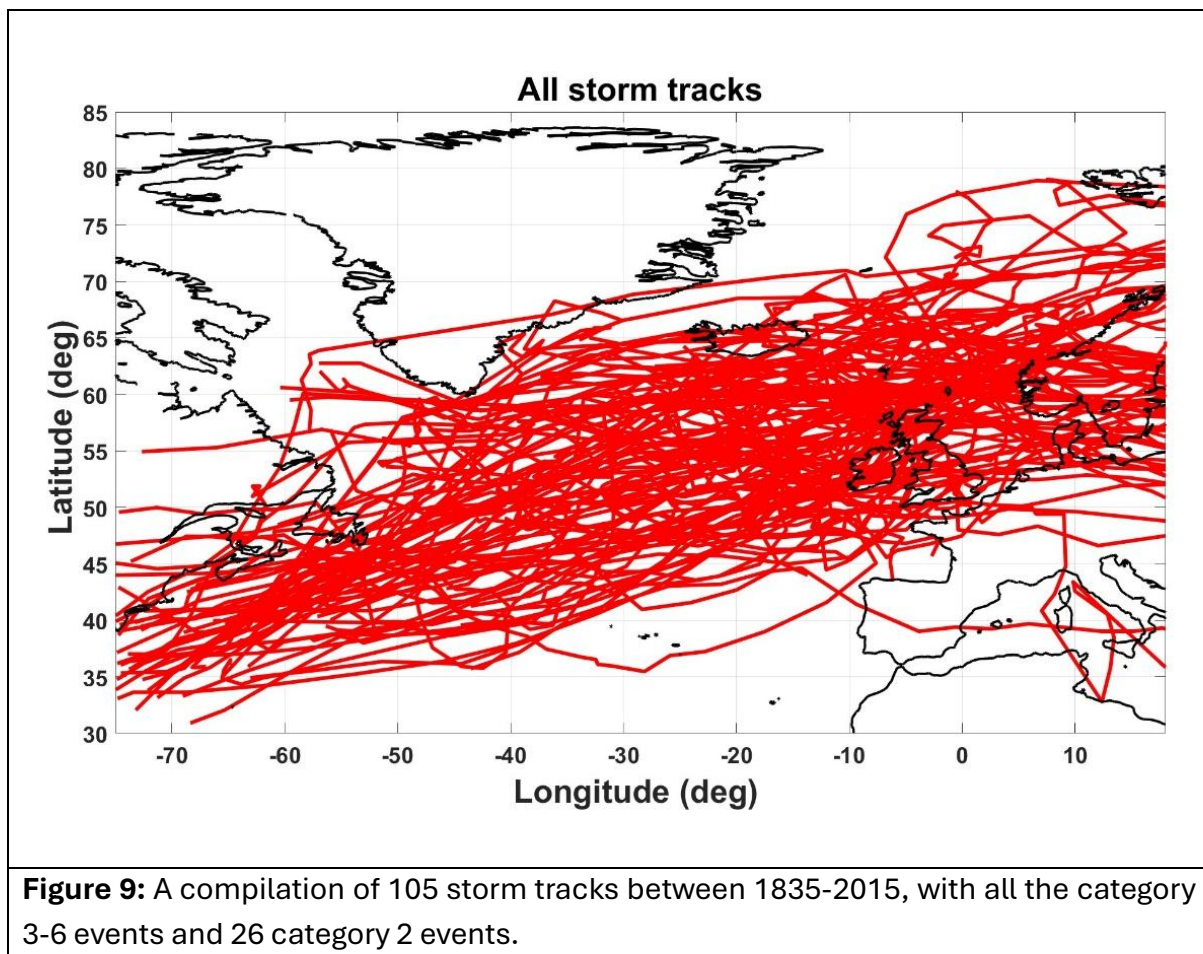


Figure 10 analyses storm tracks, that are above category 3 (with the exception of 26 category 2 events), by region.

Figure 10a analyses 52 storm tracks that caused coastal flooding in region 1. Figure 10b analyses 44 storm tracks that caused coastal flooding in region 2. Figure 10c analyses 22 storm tracks that caused coastal flooding in region 3. Figure 10d analyses 55 storm tracks that caused coastal flooding in region 4. The average storm track for each region, (Figure 11), is overlaid on each sub-plot. Appendix c, Figure 1 repeats Figure 10, without the average storm tracks. Some storm tracks are identical due to the same storm impacting more than one region.

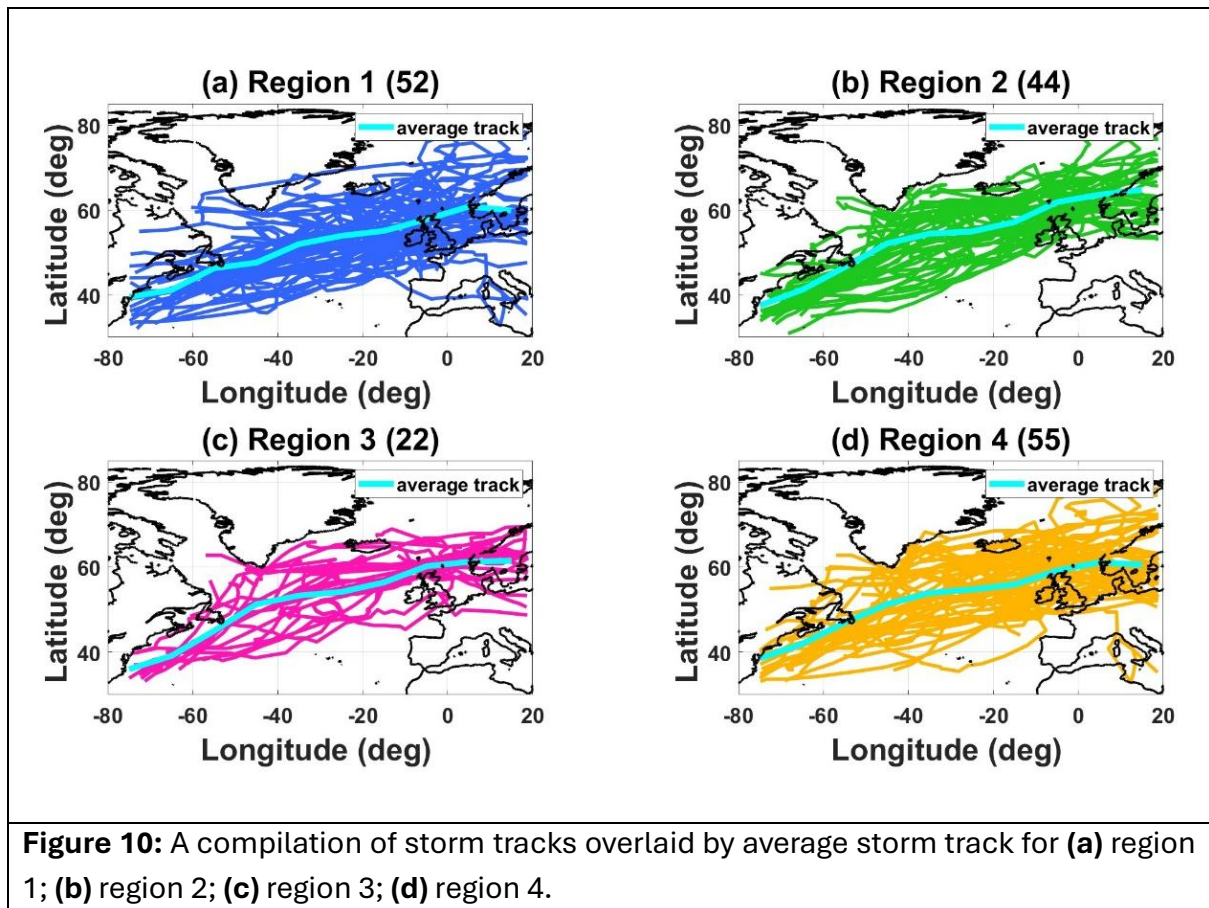


Figure 11 analyses the average storm track for each region. There is more variability in the western area of the track, because some storms originated around Iceland, instead of the US coast. Therefore, there are less storm tracks to average on the western part of the figure. The tracks have subtle differences by regions. Region 1 storm tracks are located further south. Region 3 tracks are more north with region 2 most north. Region 4 tracks curve around into the North Sea.

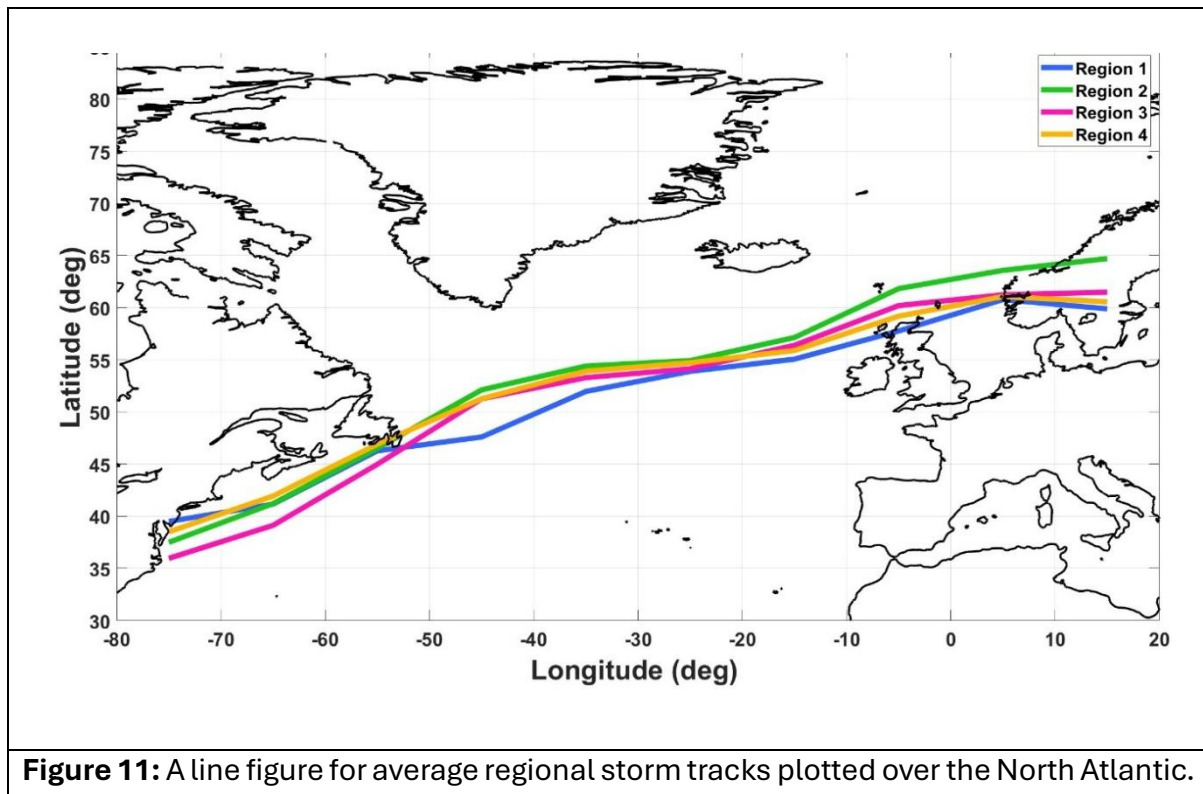


Figure 12 is a schematic of Figure 11 storm track paths by regions, showing the storm tracks which induced flooding in all four regions, with respected winds responsible for the coastal flooding.

Figure 12a shows the storm track passing through the centre of UK, with the pressure and wind positions pushing water up along the south coast. Figure 12b shows the storm track passing through north England, with winds and pressure pushing water up along the west coast. Figure 12c shows the storm track passing through Scotland, with winds and pressure pushing water up along the north coast. Figure 12d shows the storm track passing through Scotland and curving into the North Sea, with winds and pressure pushing water up along the East coast.

Storm pathways

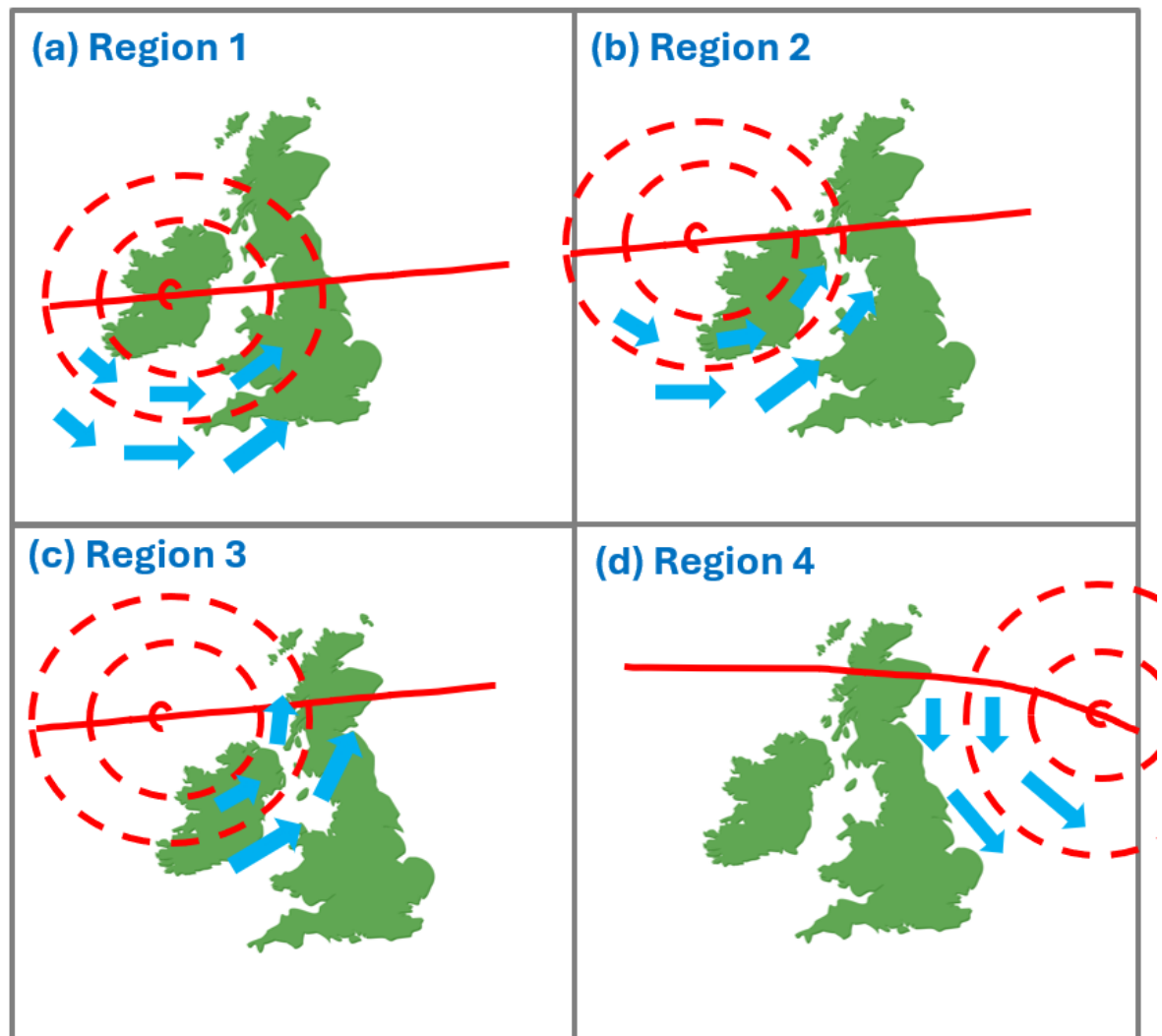
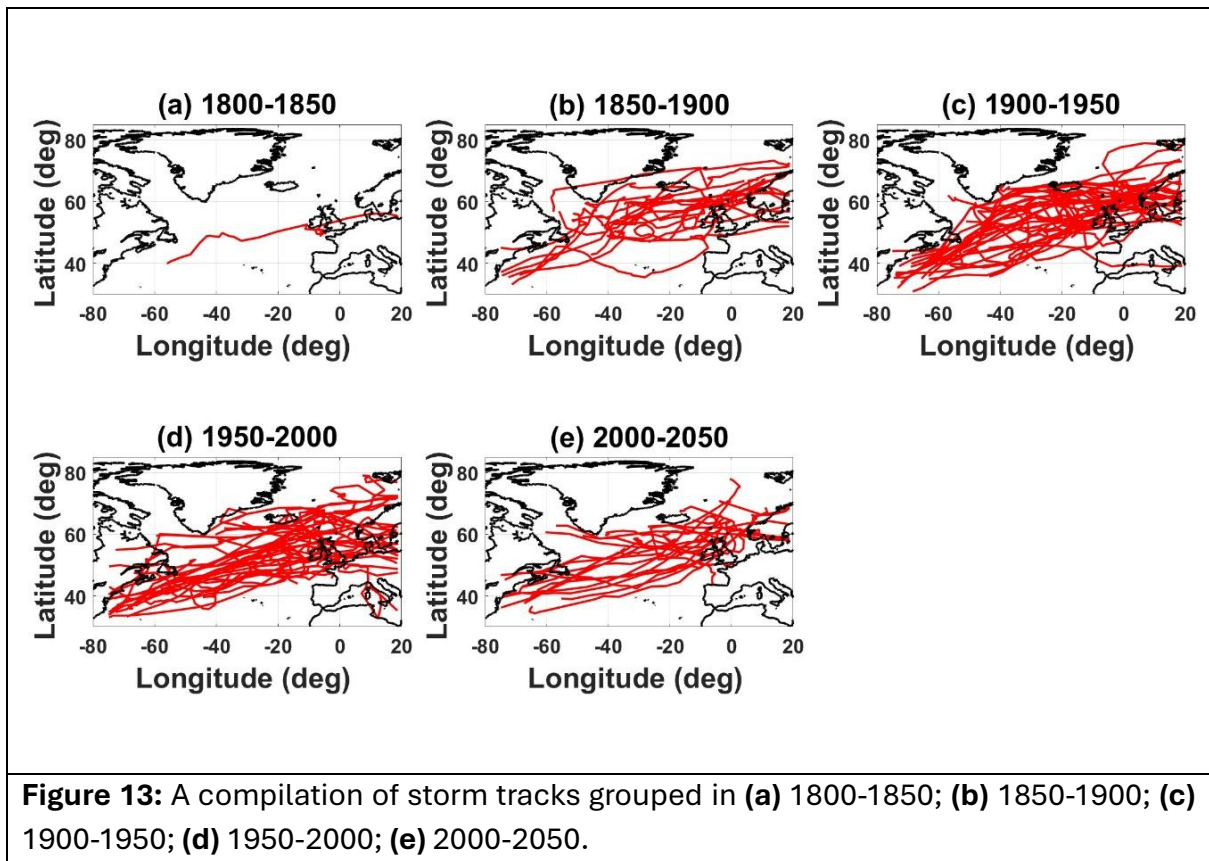


Figure 12: An infographic on the storm track pathways and area affected in **(a)** region 1; **(b)** region 2; **(c)** region 3; **(d)** region 4.

Figure 13 analyses storm track changes in a 50 year period. There were no obvious changes in paths, but it does illustrate the increase in coastal flooding over the years. 2000-2050 has less events due to data ending in 2015. 1800-1850 also only has data after 1830, making Figures 13a and 13e significantly lower than what is likely to have occurred. Appendix C, Figures 2-4 show storm tracks by decade.



Mean atmospheric pressure and wind fields are shown in Figures 14-17.

Figure 14 shows the 26/12/2012 category 3 storm flooding region 1. The storm first enters from the west at 12:00 25/12/12, moving across the Atlantic and dissipating at 00:00 27/12/12.

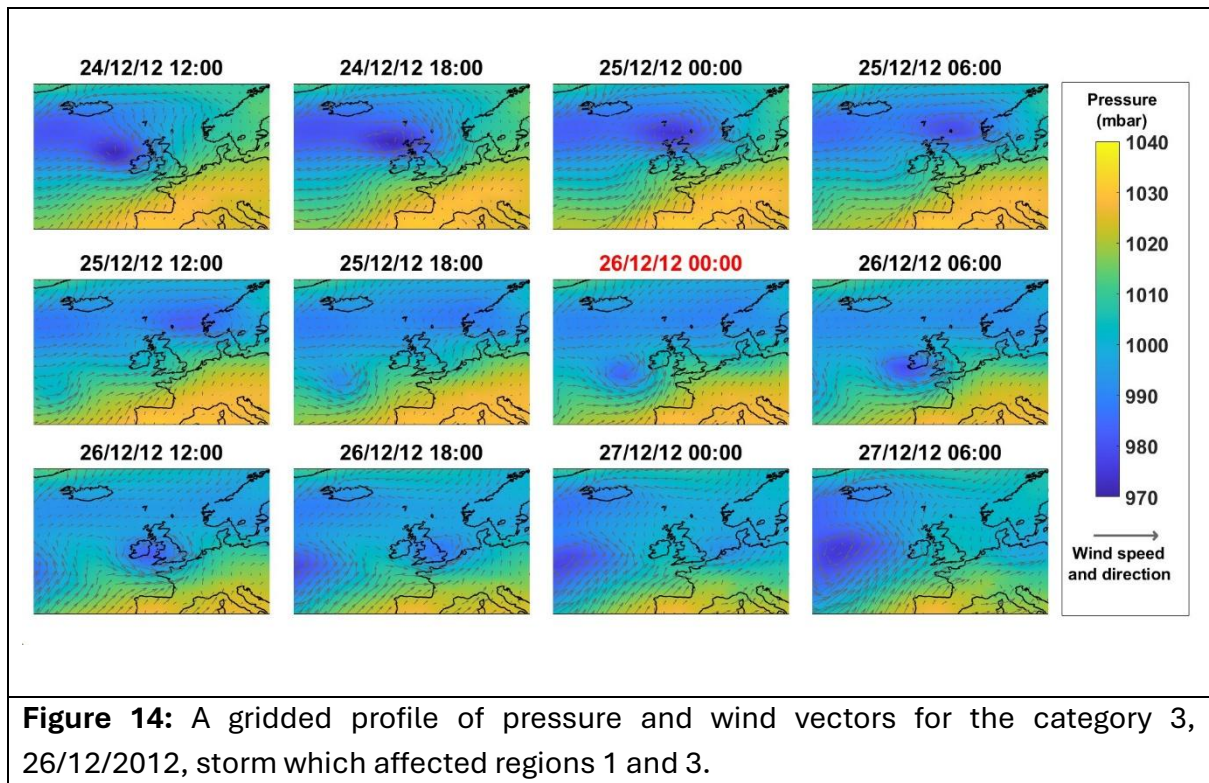


Figure 15 shows the 15/03/1905 category 5 storm impacting region. Low pressure fields are persistent between Iceland and the UK. As it condenses, it drops further generating strong winds and intense flooding.

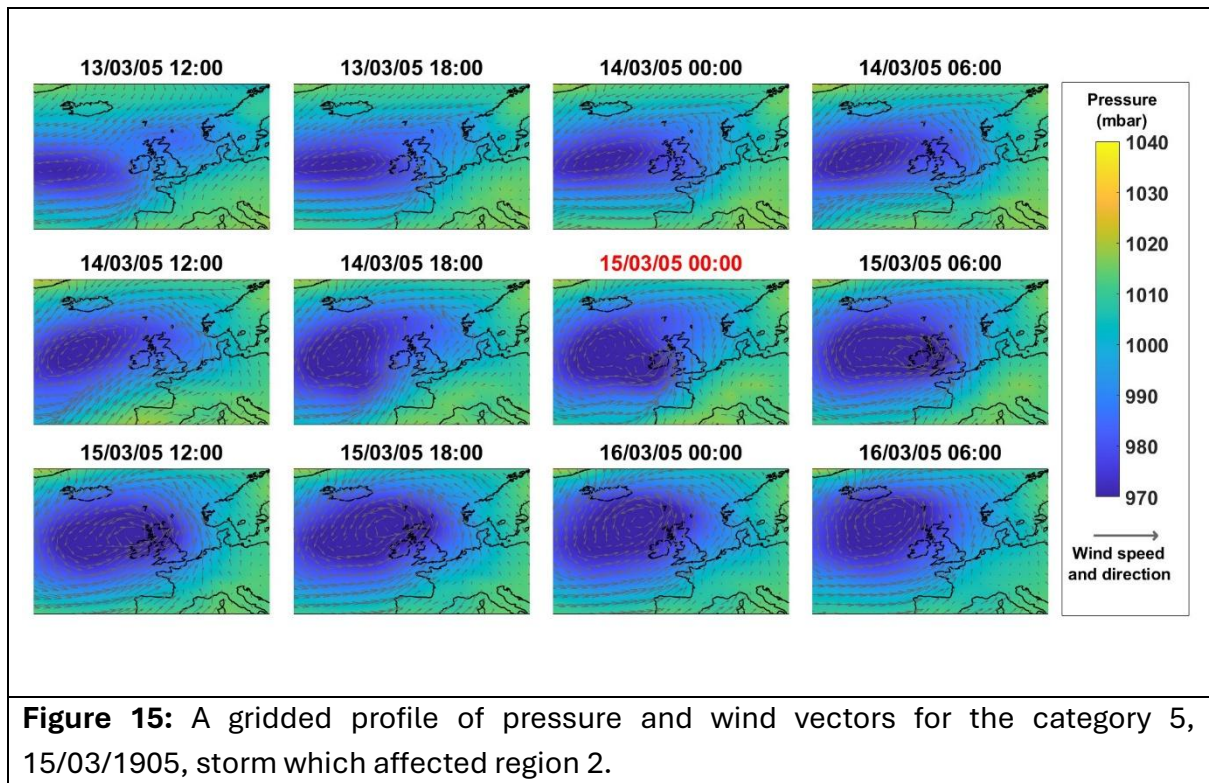


Figure 16 shows the 31/01/1953 category 6 storm impacting region 3. The arctic generates the storm, tracking pass North Sctoland. When it is over Denmark, winds at the back of the storm are southwards generating a large North Sea storm surge.

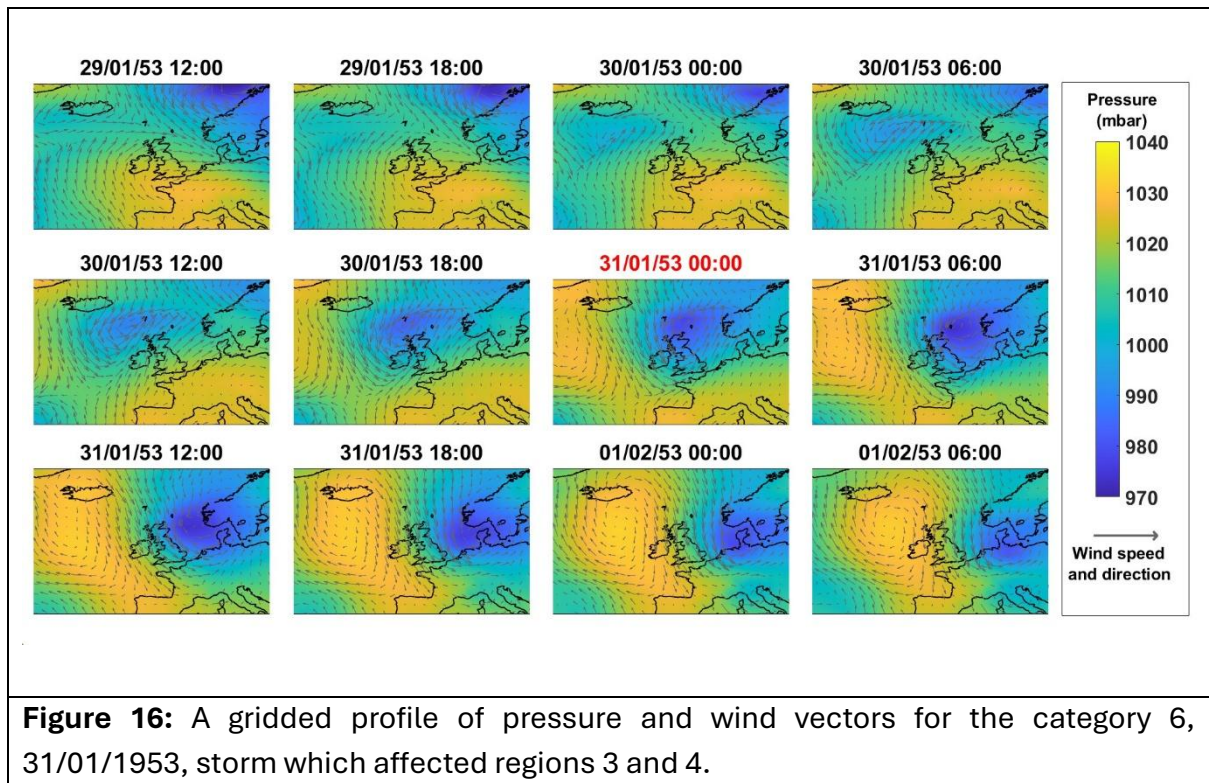


Figure 17 shows the 26/08/1912 category 6 storm impacting region 4. Low pressure moves slowly across the UK, generating lower pressure and stronger winds. Once the storm has passed over the UK, flooding occurs to region 4, late in the evening.

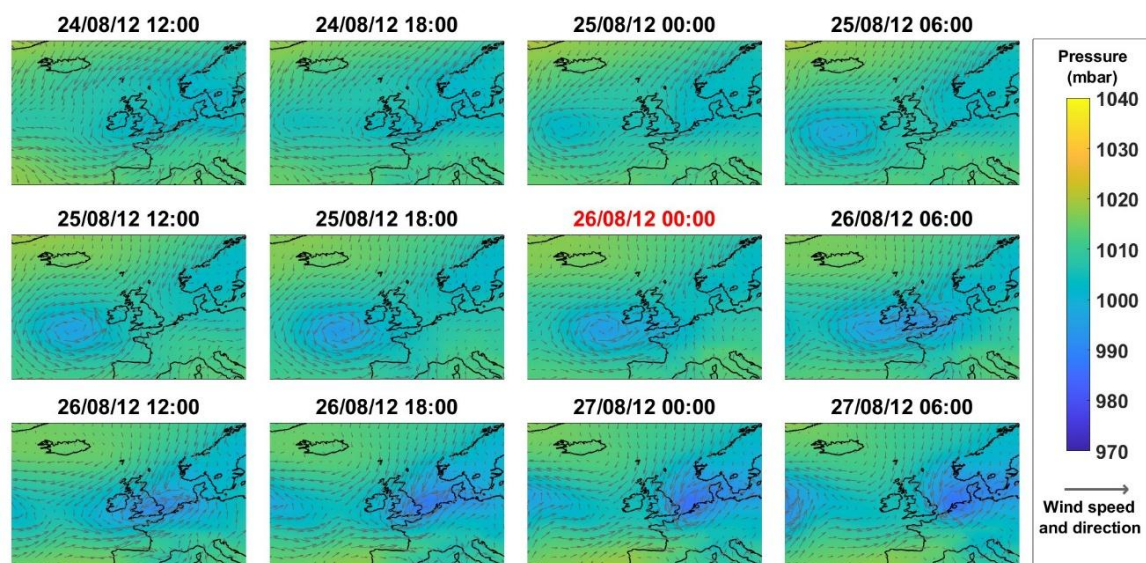


Figure 17: A gridded profile of pressure and wind vectors for the category 6, 26/08/1912, storm which affected region 4.

3.3. NAO

Table 1 compares the proportion of coastal floods that occurred in positive versus negative NAO phase, for both annual NAO and winter NAO.

Table 1a shows that 61.6% of all the annual coastal floods occurred in the positive NAO phase. There is a greater percentage of floods occurring in positive annual NAO for all categories. Table 1c shows that 67.9% of the winter coastal floods occurred in the positive winter NAO phase. As such, there is a stronger correlation between positive winter NAO and increased coastal floods, with the exception of category 4 which is most prominent under positive annual NAO.

Table 1: The percentage of coastal floods occurring in positive versus negative NAO under **(a)** positive annual NAO; **(b)** negative annual NAO; **(c)** positive winter NAO; **(d)** negative winter NAO.

Positive Annual NAO				Negative Annual NAO			
a	Category	Coastal flooding events	Positive NAO flood proportion (%)	b	Category	Coastal flooding events	Negative NAO flood proportion (%)
	1	213	59.33148		1	146	40.66852
	2	70	63.63636		2	40	36.36364
	3	23	57.50000		3	17	42.50000
	4	23	85.18519		4	4	14.81481
	5	7	63.63636		5	4	36.36364
	6	2	100.00000		6	0	0.00000
	All	338	61.56648		All	211	38.43352
Positive Winter NAO				Negative Winter NAO			
c	Category	Coastal flooding events	Positive NAO flood proportion (%)	d	Category	Coastal flooding events	Negative NAO flood proportion (%)
	1	250	69.63788		1	109	30.36212
	2	70	63.63636		2	40	36.36364
	3	26	65.00000		3	14	35.00000
	4	18	66.66667		4	9	33.33333
	5	7	63.63636		5	4	36.36364
	6	2	100.00000		6	0	0.00000
	All	373	67.94171		All	176	32.05829

Figure 18 collates all the storm tracks and sorts them by NAO phases. Figures 18a and 18c show a much higher density of storm tracks than Figures 18b and 18d. The storm tracks however, do not appear to shift position based on NAO condition.

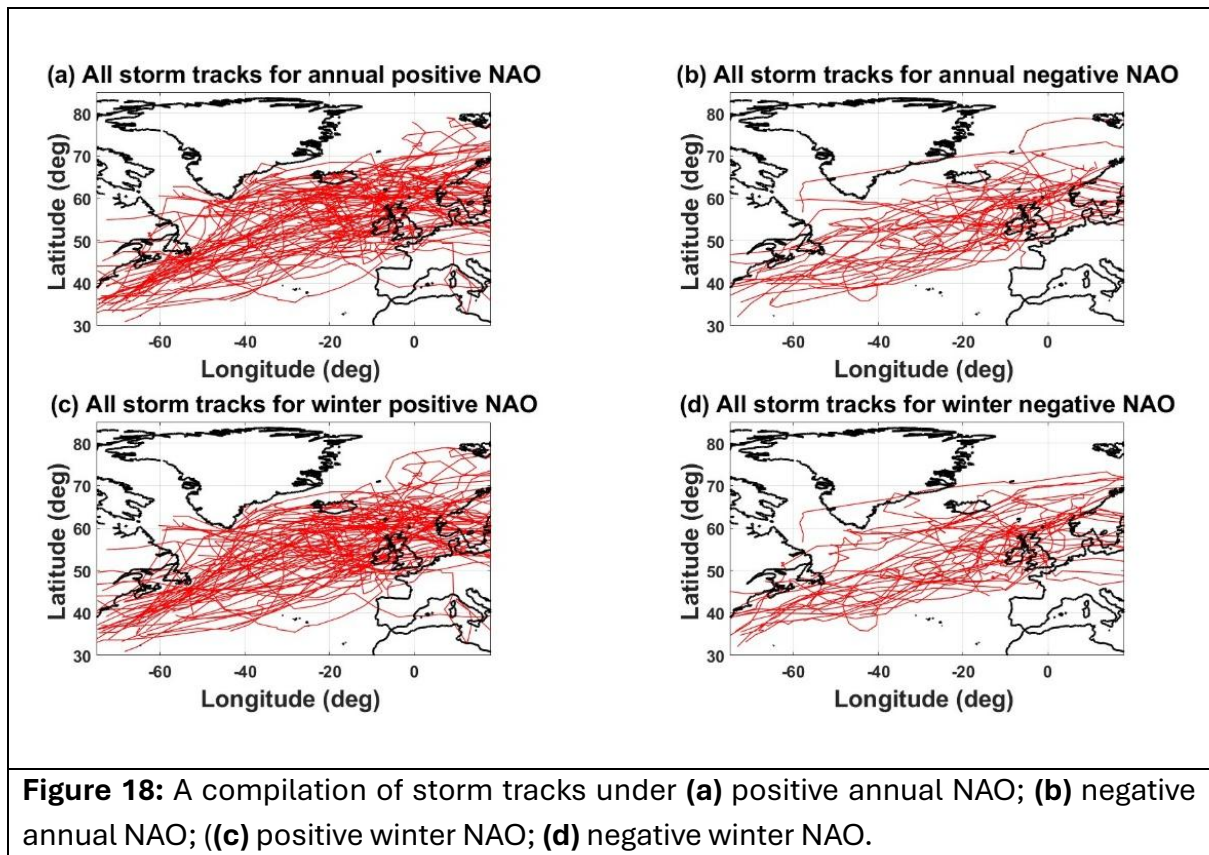


Figure 19 is the average positive (Figure 19a) and negative (Figure 19b) annual NAO storm track. Positive NAO causes storm tracks to be fairly linear. Negative NAO causes strong fluctuations in the storm track. This is likely due to there being less events to average. It does, however, causes storm tracks to curve north around Scotland.

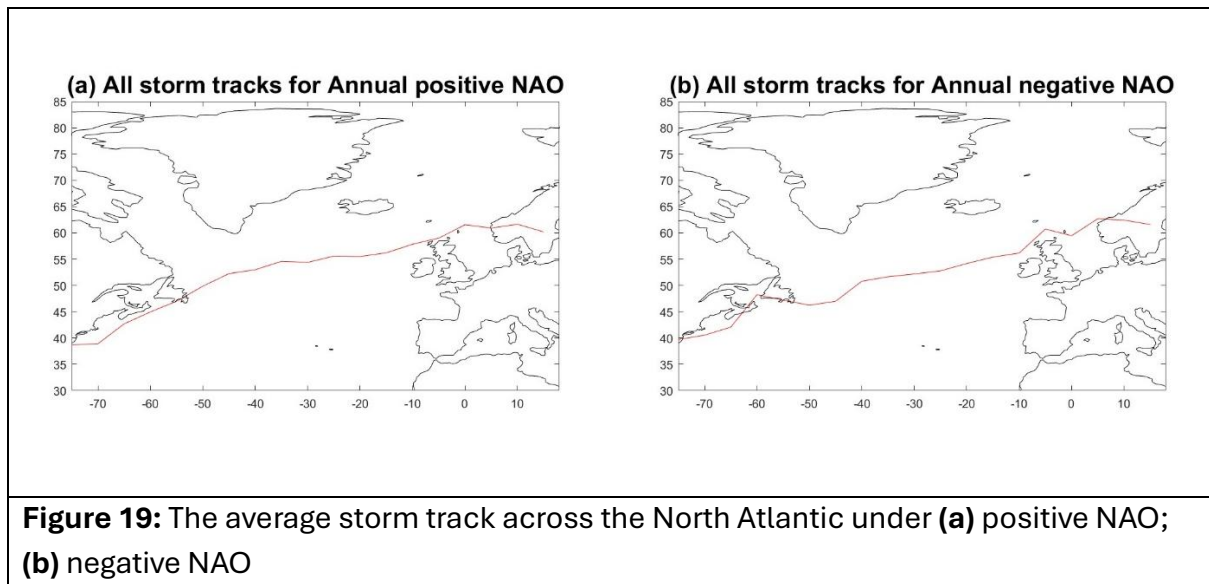


Figure 20 shows that there are a lot more positive NAO phases than negative phases. Figure 20a has a strong negative index before 1900 and after 2000. Figure 20b has a stronger positive index throughout.

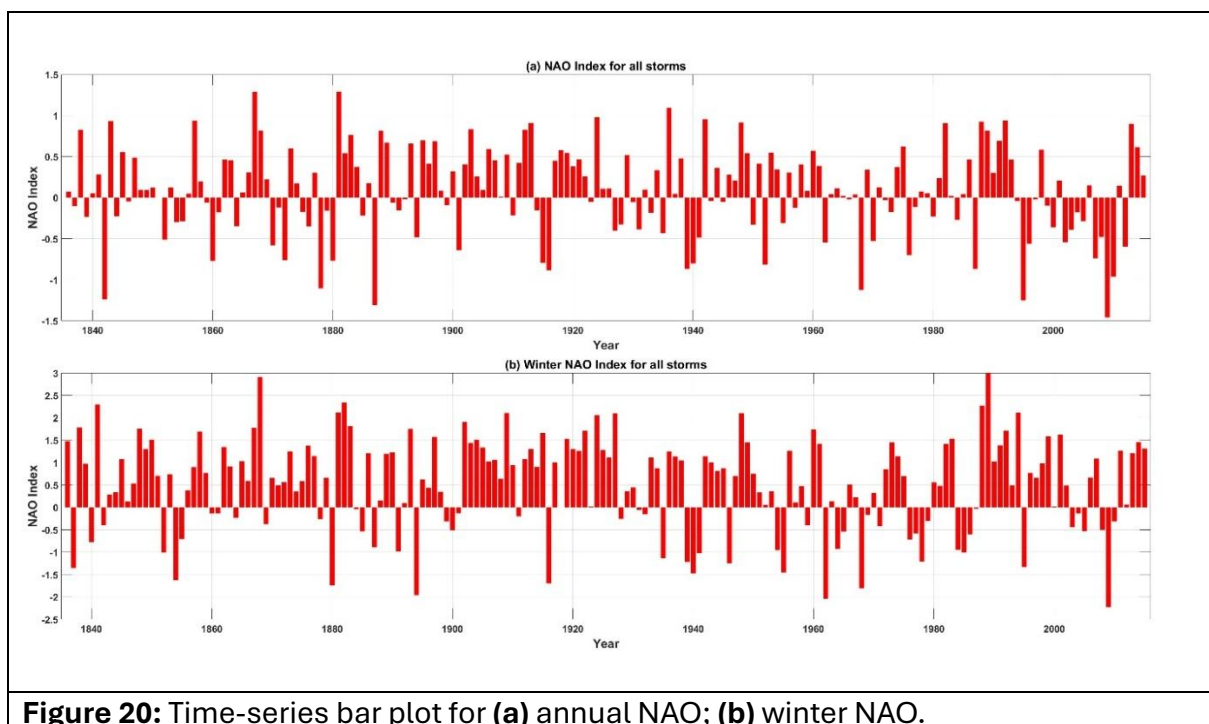


Table 2 shows correlation coefficients between regions and NAO averaged out over 1, 3 and 5 years. Region 1 experiences the strongest negative correlation over 3 averages. Region 2 experiences the strongest correlation of moderately positive. Region 3 is the most similar to all of the UK with positive correlation in 1 and 3 years, switching to a very weak negative correlation in 5 years. Overall, correlation coefficients are weak, showing little correlation between NAO and regional events.

Table 2: Table of NAO correlation coefficients by regions in 1, 3 and 5 years

NAO	1 year	3 year	5 year
All	0.09	0.08	-0.03
region 1	-0.02	-0.11	-0.17
region 2	0.24	0.41	0.26
region 3	0.04	0.06	-0.01
region 4	0.15	0.15	0.12

4. Discussion

The overall aim of the study is to investigate how UK coastal flooding has varied between 1835-2015 and the influence of storm tracks and NAO. The first objective of the study is to assess temporal and spatial changes in coastal flooding. In the three sub-sections below, the key findings of each objective are discussed, considering relevant literature.

4.1. Storm Surge

The first objective of this thesis is to investigate how coastal flooding varies spatially and temporally. To assess this, SurgeWatch was used, which considered storm surges as the main cause of coastal flooding (Haigh et al., 2017). Storm surges are caused by low pressures associated with hurricanes, cyclones and other sea storms which force water levels to rise with cyclonic or anticyclonic winds (Needham and Keim., 2011). When they hit the coast this band of localised high water can have severe consequences (Needham and Keim., 2011).

Many of other types of flooding exist: tidal, pluvial, tsunami flooding and storm surges can occur in combination, referred to as compound flooding (Hendry et al., 2019). Compound flooding amplifies the flood severity and is often associated with high category events in SurgeWatch (Hendry et al., 2019; Haigh et al., 2017).

Results show an increase in coastal flooding over the last 200 years. However, it is difficult to say whether this is due to climate change or bias in the data. A form of bias consists of West England publishing more newspapers, and therefore recording more events, whilst areas without publishing houses, north Scotland, inadequately record events (Beegan., 2008). This means that the majority of the flooding data is skewed to

show region 4 as receiving the most storm surges. Region 2 was also high in reporting events in the 19th century by being a newspaper hub (The Manchester Guardian established in 1821). These were highly populated regions, and due to insufficient defences, they are likely to have experienced more severe flooding impacts (Balaian et al., 2024).

Not only does this data have a positive historic skew to densely populated cities, but it has a bias against remote areas such as the coastline of region 3 (Stevens et al., 2016). There was little reporting in these regions, due to smaller and fewer settlements (Krueger et al., 2013). Not only that but in rural areas where there was no settlement, any mild to moderate flooding would not have been recorded, because there was no tide gauge or anyone reporting it. Additionally, in the early 19th century there were no telephones; this meant communication to a publishing house was not possible and as such many severe events are likely to have been neglected. Moreover, more urbanisation generally means building on flood plains, which means a greater consequence of severe flooding with loss of life. Additionally, a decrease in flooding over recent decades is due to better flood protection. As such, this data is not entirely reflective of the change in storm surge strength and occurrence.

To assess the objective of how coastal flooding varies spatially, the findings in this study will be analysed before comparing the results to literature. Flooding events have generally increased (Figure 2), clearest in Figure 2c. Stevens et al. (2016) found the same increase in flooding events, but when de-trending exposure to flood events, found no increase in flood events. Concluding that the increasing trend in coastal flooding event was due to exposure through population growth and urbanization (Stevens et al., 2016). What was

found was strong decadal variations, the causes of these variations will be explored in the following sections. Zong and Tooley (2003) did not detrend exposure, meaning they found that flooding is increasing over the UK generally, but is not the same in every region. (Zong and Tooley., 2006) found that flooding along South England increased but the west decreased. This thesis found (Figure 3-5) that region 1 (Southwest) and 4 (East) increased whilst region 2 (West) decreased, supporting Zong and Tooley's (2006) findings. Region 3 (Scotland) has so few and sporadic events that a clear trend is not present, this is potentially due to the remoteness of some of the coastline, where mild to moderate flooding events fail to be recorded, due to limited impact on humans.

To investigate how coastal flooding varies spatially, it is important to consider the causes of flooding to each region. Starting with the region 3 (Scotland), this region experiences flooding because of sea level rise, lack of defences in certain regions and the tendency of certain locations to have storm surges (Ball et al., 2013). Scotland generally has a very low risk due to the steep topography with there being on average 2 significant floods per year since 1849 (Ball et al., 2010; Hickey., 1997). As such, this affirms the findings that region 3 experiences the least amount of storm surges. This study found the most storm surges occurred in region 4 (East England) with 268 events over 80 years. (Haigh et al., 2016) affirmed that the East coast receives the most coastal flooding. The low lying geography means that it will only take a small sea level rise or storm surge to flood the region, whilst high topography will be unaffected (Gudde et al., 2024). This region also experiences storm surges from the North Sea which funnels water during storm surges increasing flood heights (Spencer et al., 2015). Region 1 (South England) has also experienced an increase in recent flooding (Figure 5) and the reason for this is because it is exposed to the Atlantic Ocean where storms originate from (Scott et al., 2015). In

contrast, region 2 (West England) experiences a decrease in flooding potentially because of the steep terrain, requiring stronger storm surges to cause flooding, or the increase in natural defences and management, such as the Severn in northwest England (Knight et al., 2015). Another possible reason is through the south-westerly winds hitting the west coast which cause wave actions which contribute to storm surges (Hendry et al., 2019). As such, changing wind patterns could result in decreasing storm surges, which will be further considered in the next section.

Overall, storm surges are linked to storm events (Figure 6 and 8) showing that the increase in flooding falls within the winter storm season (Allan et al., 2009). Regions also experience an exponential decrease in categories (Figure 7), with region 4 experiencing the most coastal flooding overall and generally the most in each category. The more flood events that occur in a given region, the increased chance that they will experience high categories. The higher categories link with more severe storms, requiring more strength to cause disaster. Therefore, both regions (Figure 6) and categories (Figure 8) show similar seasonal trends with a double peak pattern. This corresponds to periods of large tides around the equinoxes, called king tides (Roman-Rivera and Ellise., 2018). King tides are where the sun and moon gravitational forces align to amplify tidal ranges (Roman-Rivera and Ellise., 2018). These unusually high tides occur during spring and autumn equinoxes which play a significant role in storm surges (Hunter., 2020). As such, with climate change melting more land ice and rising sea levels, storm surges are likely to increase (Oddo et al., 2017). The following section will consider how storm tracks are changing, along with the impacts this has on flooding.

4.2. Storm Tracks

The second objective of this study; assess the meteorological conditions which drive coastal flooding in different regions. Key results are discussed and compared with findings from literature.

The first way this thesis analyses the UK storm tracks is through how they vary from region to region (Figure 10). Storm frequency increases by decade across the entire UK (Stewart et al., 2017). Region 1 (Southwest England) storm track crosses the UK at Scotland (Figure 10-12). Hendry et al. (2019) found that Devonport storm tracks moved north easterly crossing north Scotland. Zong and Tooley (2003) found that these pathways were along 55N travelling east into the English Channel generating onshore winds with surges along the south coast. In contrast, (Santos et al., 2017) found that the southwest tracks originated in the southwest Atlantic towards Scandinavia, where storms diagonally crossed the UK. The UK west coast (region 2) storm path passes north around the UK (Figure 10-12). Studies that find this include (Zong and Tooley., 2003) which found they were concentrated along 60N. Conversely, (Santos et al., 2017) found that the west storms originated in the central Atlantic, but followed the same path as the southwest, with Ireland shielding most of the storm surges. As such, any storm surges from this region are due to Irish Sea winds generating them, with winds generated from the storms that hit Ireland (Santos et al., 2017).

Figure 3 illustrates that region 2 has experienced a decrease in flood events, linking this to storm tracks (Figure 11 and 12). Ireland could potentially dissipate the storm's strength, having weaker winds enter the Irish Sea with weaker coastal flood occurring (Devoy., 2008). It is possible that region 2 storm tracks could have changed over the years

to cause this decrease. The thesis has not considered how regional tracks have changed throughout the years, as such an improvement would be to consider how regional storm tracks have changed by decade.

The north Scotland (region 3) storm path is the same as the west coast, but slightly further north (Figure 10-12). Studies that find this are (Santos et al., 2017) finding a similar path to the south and west, with storms passing below Iceland to hit the west of Scotland, but to hit the east of Scotland they present a different path, passing around the UK, instead of through it, the storm was dissipated. Finally, the East coast UK (region 4) path is very different, where it passes around Scotland (Figure 10-12) but then curves back around the UK. The cause of this variation is that the storms pass over northern UK and turn south-east into the North Sea (Zong and Tooley., 2003). The North Sea is able to create surges that affect the east coast with strong west winds (Zong and Tooley., 2003). However, (Santos et al., 2017) found that they occurred when the storm passed over northern Europe. The cause of the different paths will be explained in section 4.3.

Storm tracks do not appear to have varied across different time periods (Figure 13). This is reinforced in literature which found inconsistencies in long term variability trends (Krueger et al., 2012) but there is the presence of decadal variability, which will be examined in section 4.3. Inconsistencies occur from the lack of accurate UK regional data before the 19th century. As such, paleo records can help analyse how tracks have changed throughout the years (Orme et al., 2017). There was a southward shift of storm tracks in warm periods shifting to the north-east Atlantic (Hess et al., 2023). The calm conditions occur in the last ice age, where it is colder, illustrating how NAO is causing these variations (Hess et al., 2023; Stewart et al., 2017)

Another important point to consider in understanding how storm tracks have varied, is to consider how they have changed with categories. Comparing how storm tracks have varied over the years (Figures 14-17), illustrated that in 1953 it was generated from Iceland, whilst in 1912 it was generated across the Atlantic. This finding could be significant in understanding the change in severe storms. However, due to the limited amount of data, it is not possible to synthesise this result and would benefit from further investigation in future studies. Comparing a category 3 and 5 path found that there was little difference in storm tracks but a significant difference in pressure between the 107 years. This pressure difference leads nicely on to the third objective. No research has compared the variability of storm strength with years. However, Wadey et al. (2015) have compared the 2013 winter storm to the 1953 storm concluding that there were more high waters in 2013, indicating it could have been a more intense storm surge, despite the low flood category. SurgeWatch classed 1953 as category 6, whilst 2013/14 was category 5. This illustrates how flood severity is no longer correlating with storm severity, because of improved flood defences, often improved by combining natural infrastructure with hard infrastructure (Vuik et al., 2019).

4.3. NAO

The final objective of this study was to assess NAO's effect on storm tracks and coastal flooding. NAO is the sea level pressure difference between the Azores and Iceland (Kendon et al., 2022). The greater the pressure difference, the more positive the NAO (Hannachi and Stendel., 2016). The greater the pressure difference, the stronger the westerlies (Hannachi and Stendel., 2016; Marsh and Seville., 2021). These will push the jet stream northwards and as such the storm tracks more northward (Luo et al., 2010). Together these mean that more north UK areas will experience increased storm surge events under a positive NAO, whereas negative NAO will decrease storm surges within the north of the UK. The pressure difference has a seasonal cycle where the jet stream in northern hemisphere winter moves north, whilst in summer it moves south (Gillett et al., 2003).

Figures 6 and 8 reflect seasonal storm cycles, there is also long term variability (Ortega et al., 2015) with multidecadal timescales of 20-30 years due to the Atlantic meridional overturning circulation (AMOC) and 50-70 years due to atmospheric exchange with the Arctic (Frankcombe et al., 2010). AMOC closely correlates to NAO through NAO driving atmospheric exchange into the ocean which strengthens AMOC, under a positive NAO phase (Delworth and Zeng., 2016). Considering the past millennium, proxy records have shown that NAO exhibits regular fluctuations based on natural climate variability (Ortega et al., 2015). Visbeck et al. (2001) did not have this finding, concluding that NAO has been trending to the positive phase in the last 30 years. Considering longer timescales, the jet stream in glacial periods was accelerated and shifted southwards, likely causing more

storm surges in south England, whilst in interglacial show the opposite (Merz et al., 2015).

This emphasises the connection between past NAO variability and storm tracks.

The annual NAO coefficient of 0.09 for all regions (Table 2) confirms that there is a degree of correlation, but it is extremely weak. This weak correlation suggests a change in NAO will result in a change in storm tracks. Positive NAO links to more coastal flooding for all regions (Table 1 and Figure 20) verified by Economou et al. (2015) which found that extreme storms are intensifying due to NAO. As such Figure 20 shows that NAO has been most in the positive phase, with very strong positive indexes in winter NAO. Table 1a and 1c illustrates that the positive winter NAO has more coastal floods overall than the positive annual NAO. A reason for this is that winter NAO has a stronger storm season than annual NAO because including the summer/spring season with less storms, weakens the NAO correlation to flooding events, as such, extracting only the stormiest period (winter NAO) allows for a stronger correlation between UK storminess and NAO phase changes to be drawn (Krueger et al., 2019). This positive correlation identified between NAO and coastal flood frequency shows that NAO phase is important for UK storm season. There is also some significance in storm track position (Figures 18 and 19), shifting tracks seasonally and pushing tracks north under positive NAO (Luo et al., 2010).

In terms of storm tracks, NAO does shift the path (Figure 19) with a positive annual NAO resulting in a path crossing the north of Scotland, whilst a negative NAO sees the path just avoiding the UK. Literature finds that a positive NAO does mean more northerly and zonal tracks, with the reverse being the case for negative NAO (Rogers., 1990). These changes are connected to the jet stream position and storm landfall locations through

teleconnections (Rogers., 1990). In summary, NAO changes the paths of storms which contributes to the regional variability in storm impacts.

Although this study does not observe a clear trend in NAO and storm change throughout the years (Figure 19), literature also concludes that NAO change is inconclusive with models showing bias and no consensus (Woollings and Blackburn., 2012). The IPCC predicts, with low confidence, that with CMIP6, global surface air temperature will rise, increasing NAO index (IPCC., 2023). Considering future trends, with anthropogenic carbon dioxide inputs increasing, there will be more of a persistent positive NAO, causing the UK to experience greater winter storms, causing more storm surges and coastal flooding (Mitevski et al., 2025). In response to this, flood defences will have to be better designed to cope with the influx of greater storms (Wilbry and Keenan., 2012).

5. Conclusion

The overall aim of this study was to assess how coastal floods impacting the UK have varied spatially and temporally, along with the meteorological and climatic drivers of this change. 598 coastal flood events from the SurgeWatch V3 database were assessed over the period 1835 to 2015. The study was undertaken in three main stages, each addressing an objective.

The first objective was to assess temporal and spatial changes in coastal flooding over the period 1835 to 2015. Results show that the number of coastal floods has been increasing in recent years. In terms of regional flooding, East England has the greatest frequency of storm surges due to being in contact with the North Sea, Scotland has the lowest flooding frequency potentially due to topography and storm tracks. West England has a decrease in flooding for recent years. This is potentially because Ireland is dissipating more of the storm's strength, having weaker winds enter the Irish Sea. As such a weaker coastal flood occurs. This trend could be down to a change in West England storm tracks over the years. Seasonally, there is a double peak in the winter storm season which is due to King tides.

The second objective was to assess what meteorological conditions drive coastal flooding in different regions by looking at storm tracks. For storm tracks, results showed that when flooding occurs in Southwest England, the storm tracks are further south, but still cross Scotland. West England and Scotland tracks are similar but more north than Southwest England tracks, whilst East England storm tracks cross back into the North Sea. Therefore, regional storm tracks vary based on where coastal flooding occurs, but storm tracks have not varied historically.

The third and final objective was to assess NAO's effect on coastal flooding. Results showed that the positive NAO phase corresponds to more coastal floods than the negative NAO phase. The winter months have more positive NAO phases, corresponding to storm season. Positive NAO shifts storm tracks more northern regions through strong teleconnections. NAO varies on interdecadal timescales, but the addition of anthropogenic carbon dioxide is predicted to further alter storm tracks, despite literature being unable to quantify the extent.

To close, data shows that coastal flood frequency and severity has been increasing in almost all regions of the UK and is likely to further increase in the future. As such, this data can be used to inform future investment in coastal management.

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Appendix a

Table 1: The original SurgeWatch V3 dataset with comma separated spatial footprints.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
	No.	Year	Month	Day	Category (Low/Medium/High)	Spatial Footprint	Country	County	City, Town, Village	Road names	1. Met Office Report	2. Lamb (1991)	3. Eden (2008)	Zong and Tooley (2003)	5. Hickey (1997) Vol. 1	6. Britton (1937)	7. Lowe (1870)	8. Hickey (1997) Vol. 2	9. Davison (1993)	10. Student Projects
1																				
328	327	1848	12	12	1	4	1	2			0	0	0	1	0	0	0	0	0	0
329	328	1848	12	16	1	2	3	26	Glasgow		0	0	0	1	0	0	0	0	0	0
330	329	1849	1	10	1	2, 3	1, 3	29, 19, 20, 15	Milnthorpe, Peterhead, Buckie, Alloa		0	0	0	1	0	0	0	1	0	0
331	330	1849	12	27	1	4	1	6	River Yare, Waveney, Bure river valleys		0	0	0	1	0	0	0	0	0	0
332	331	1850				1	1	46	Scilly Isles		0	0	0	0	1	0	0	0	0	0
333	332	1850	1	29	2	3, 4	1, 3	2, 5, 8, 21	Fenland, Hull, Inverness	Bank Street, Douglas Row	0	0	0	1	0	0	0	1	0	0
334	333	1850	10	7	1	3	3	21	Aird		0	0	0	0	0	0	0	1	0	0
335	334	1851				3	3	19	Fraserburgh		0	0	0	0	0	0	0	1	0	0
336	335	1852	1	6	1	4	1	4	Ipswich		0	0	0	1	0	0	0	0	0	0
337	336	1852	1	8-10	3	2, 3	1, 2, 3	19, 28, 29	Stranraer, Kirkcolum, Whitehaven, Fraserburgh	Clayton Street, Fisher Street, North Strand Street, Harboot Streer, Cairmyran Road	0	0	0	0	0	0	0	1	0	0
338	337	1852	9	29	1	3	3	20	Lossiemouth		0	0	0	0	0	0	0	1	0	0
339	338	1852	11	12	1	4	1	2			0	0	0	1	0	0	0	0	0	0
340	339	1852	11	17	2	4	1	1, 2, 3	Thames Estuary, Maidenhead	Bath Road	0	0	0	0	1	0	0	0	0	0

Table 2: Formatted SurgeWatch V3 dataset with column separated spatial footprints.

No.	Year	Month	Day	Category (Low/Medium/High)	Spatial Footprint				Country	County	City, Town, Village	Road names	1. Met Office Report 2. Lamb (1991)	3. Eden (2008)	Zong and Tooley (2003)	5. Hickey (1997) Vol. 1	6. Britton (1937)	7. Lowe (1870)	8. Hickey (1997) Vol. 2	9. Davison (1993)	10. Student Projects
62	1872	11	1	1	2	0	0	0	1	30	Blackpool		0	0	0	1	0	0	0	0	0
63	1873	1	3	1	2	0	0	0	3	26, 27	Port Glasgow, Greenock		0	0	0	1	0	0	0	0	0
64	1874	3	4	1	4	0	0	0	1	2			0	0	0	1	0	0	0	0	0
65	1874	3	20	1	2	0	0	0	1	30	Morecambe, Fleetwood		0	0	0	1	0	0	0	0	0
66	1875	9	26	1	2	0	0	0	1	31	Liverpool		0	0	0	1	0	0	0	0	0
67	1875	10	14	1	4	0	0	0	1	10	Hartlepool		0	0	0	1	0	0	0	0	0
68	1875	10	18	1	2	0	0	0	2	37	Beaumaris		0	0	0	1	0	0	0	0	0
69	1875	10	19	1	1	0	0	0	1	45	Dawlish		0	0	0	1	0	0	0	0	0
70	1875	11	11	1	1	2	3	0	1	1, 2, 3, 9, 12, 46, 47, 49, 50, 51, 52	Berwick-upon-Tweed, White Southsea Castle	0	0	0	1	1	0	0	0	1	
71	1876	3	3	1	2	0	0	0	1	30	Blackpool		0	0	0	1	0	0	0	0	0
72	1876	12	5	1	1	0	0	0	1	49	Portsmouth, Southampton		0	0	0	1	0	0	0	0	1
73	1876	12	20	1	3	0	0	0	3	16	Dundee		0	0	0	1	0	0	0	0	0
74	1876	12	31	1	1	0	0	0	1	49	Portsmouth		0	0	0	1	0	0	0	0	1
75	1877	1	1	4	1	2	4	0	1, 3	2, 3, 12, 11, 9, 49, 47, 1, 52, 48, 14,	Maldon, Berwick-upon-Tweed, Portobello, Joppa	0	0	0	1	1	0	0	1	1	1
76	1877	1	30	1	2	3	0	0	2, 3	21, 22, 38	Aberystwyth, Caithness, Orkney	0	0	0	1	0	0	0	1	0	0
77	1877	1	31	1	2	4	0	0	1	1, 2, 5, 6, 8, 9, 25, 28	Sittingbourne, Fenland, Scar, Cairryan Road	0	0	0	1	0	0	0	1	0	0
78	1877	2	3	3	2	4	0	0	1	2, 30, 31, 32	Bootle, Widnes, Southport, Malden	0	0	0	0	0	0	0	0	0	0
79	1877	9	9	1	4	0	0	0	1	2			0	0	0	1	0	0	0	0	0

Appendix b

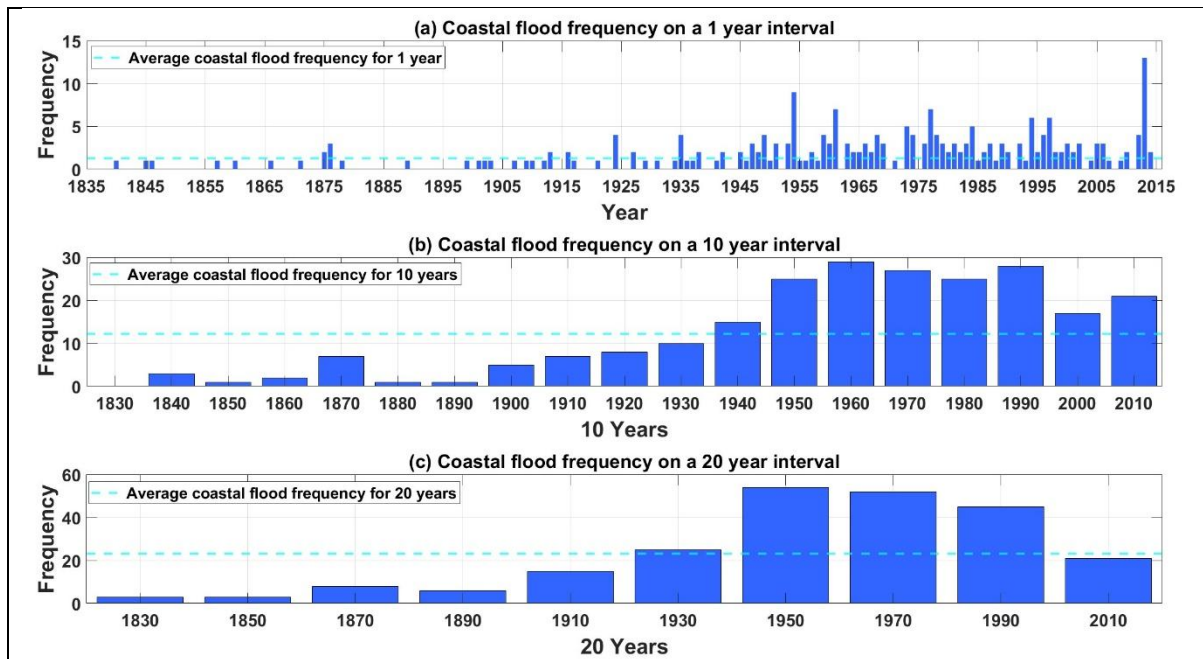


Figure 1: Time-series bar plot for region 1 of (a) annual coastal flooding count with an average of 1.3 events; (b) decadal coastal flooding count with an average of 12.2 events; (c) every 20 years coastal flooding count with an average of 23.2 events.

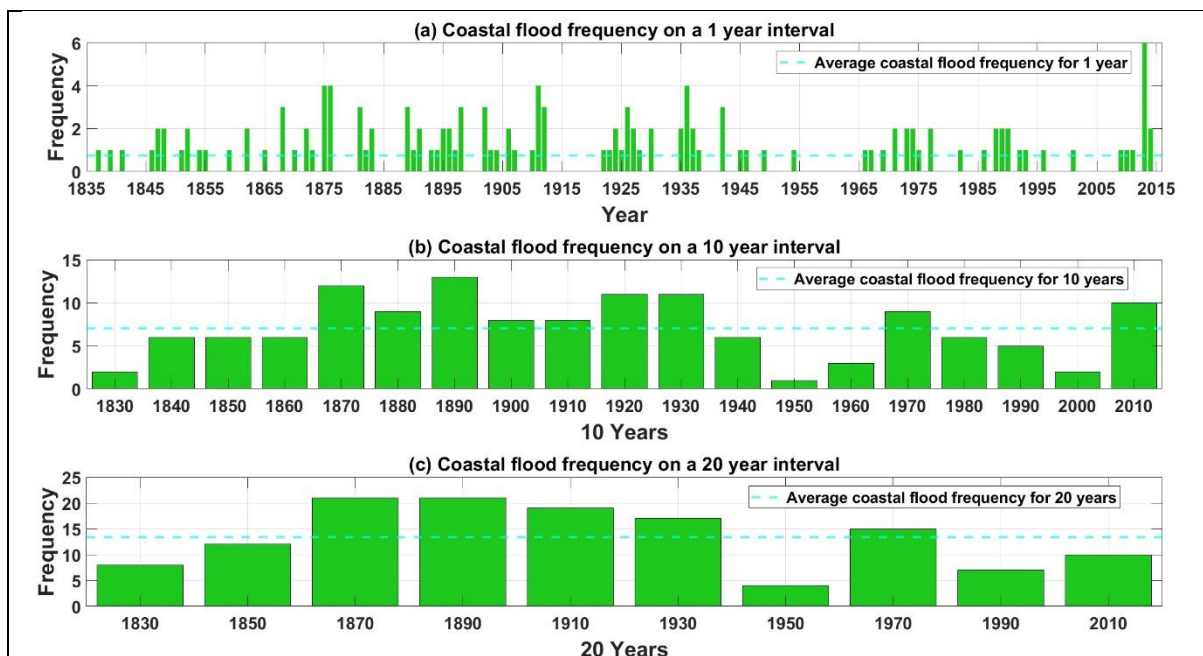


Figure 2: Time-series bar plot for region 2 of (a) annual coastal flooding count with an average of 0.7 events; (b) decadal coastal flooding count with an average of 7.1 events; (c) every 20 years coastal flooding count with an average of 13.4 events.

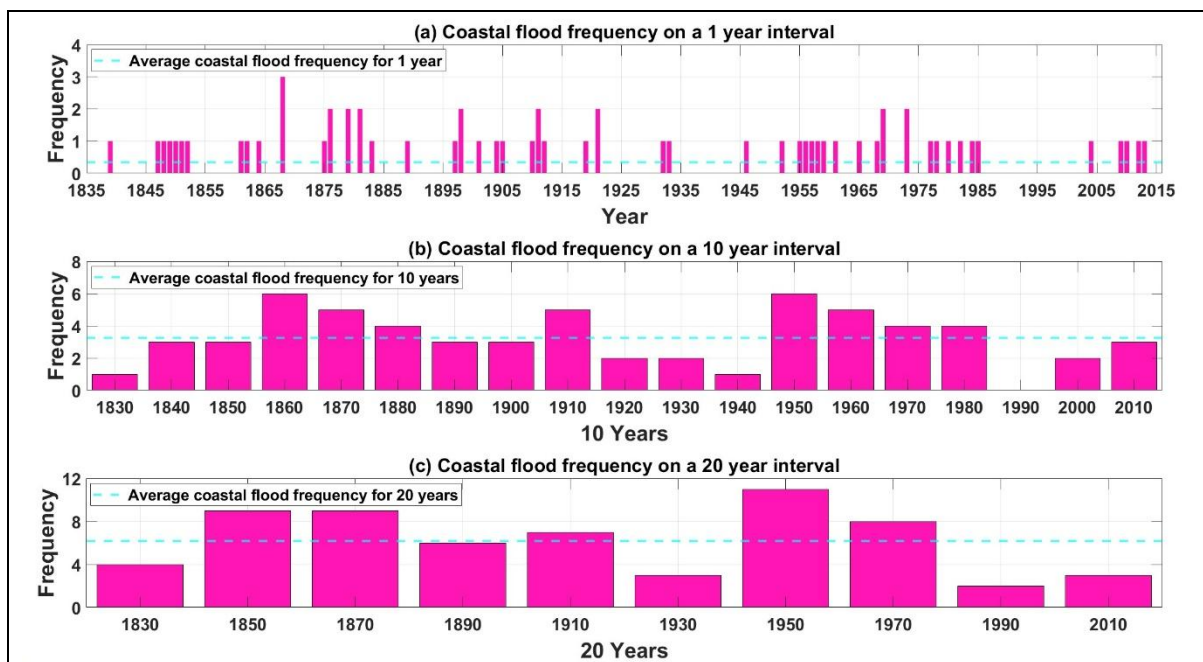


Figure 3: Time-series bar plot for region 3 of (a) annual coastal flooding count with an average of 0.3 events; (b) decadal coastal flooding count with an average of 3.3 events; (c) every 20 years coastal flooding count with an average of 6.2 events.

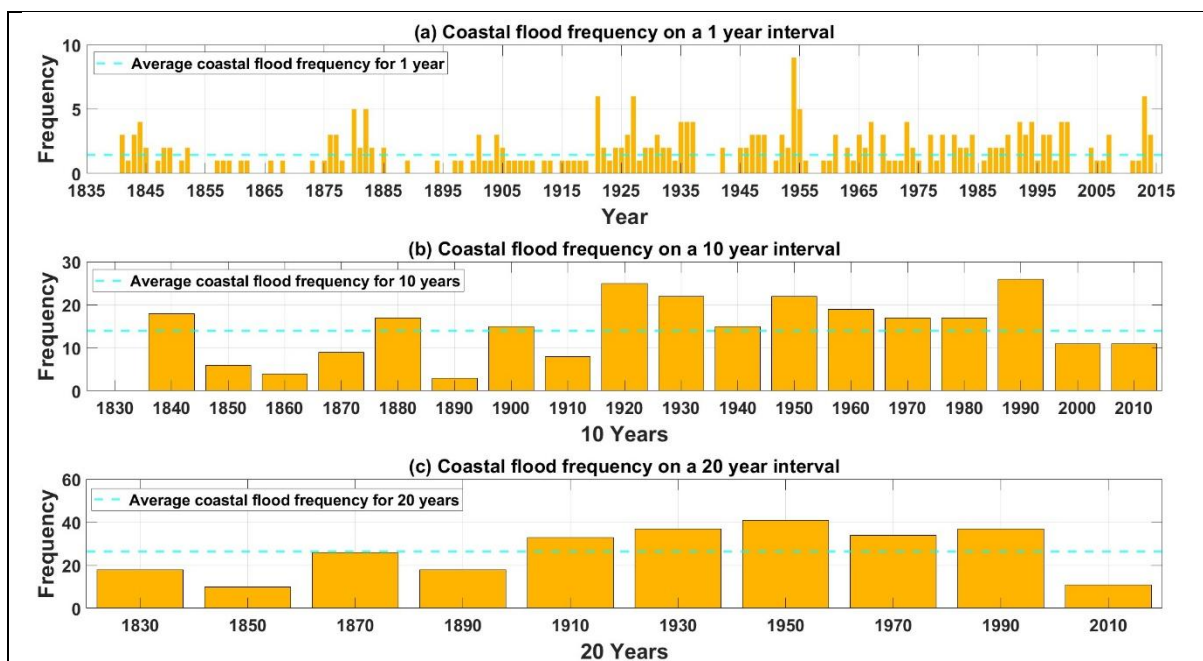


Figure 4: Time-series bar plot for region 4 of (a) annual coastal flooding count with an average of 1.5 events; (b) decadal coastal flooding count with an average of 13.9 events; (c) every 20 years coastal flooding count with an average of 26.5 events.

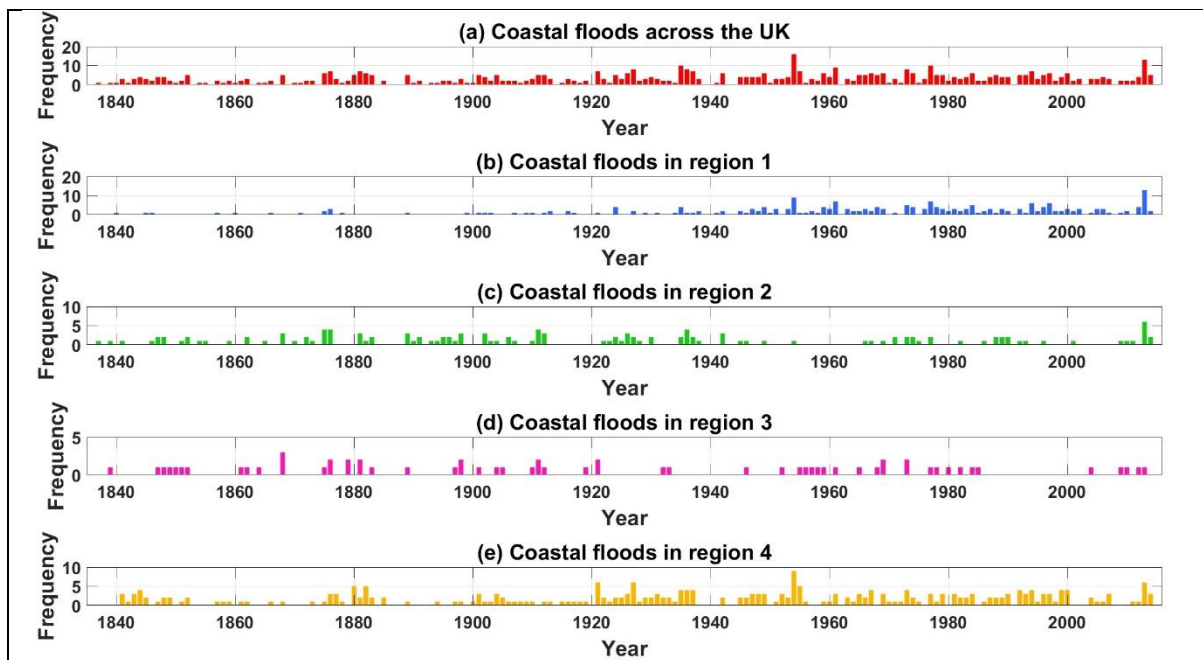


Figure 5: Time-series bar plot of annual coastal flooding in (a) the UK; (b) region 1; (c) region 2; (d) region 3; (e) region 4

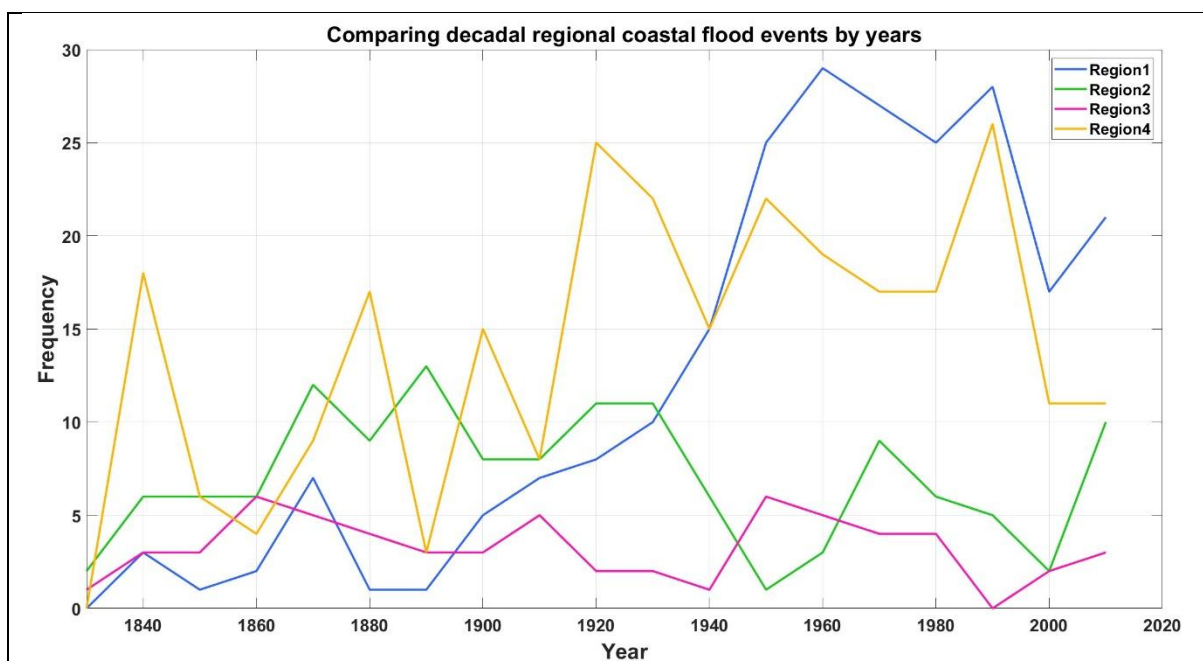


Figure 6: A line graph comparing decadal coastal flood events by regions over the years.

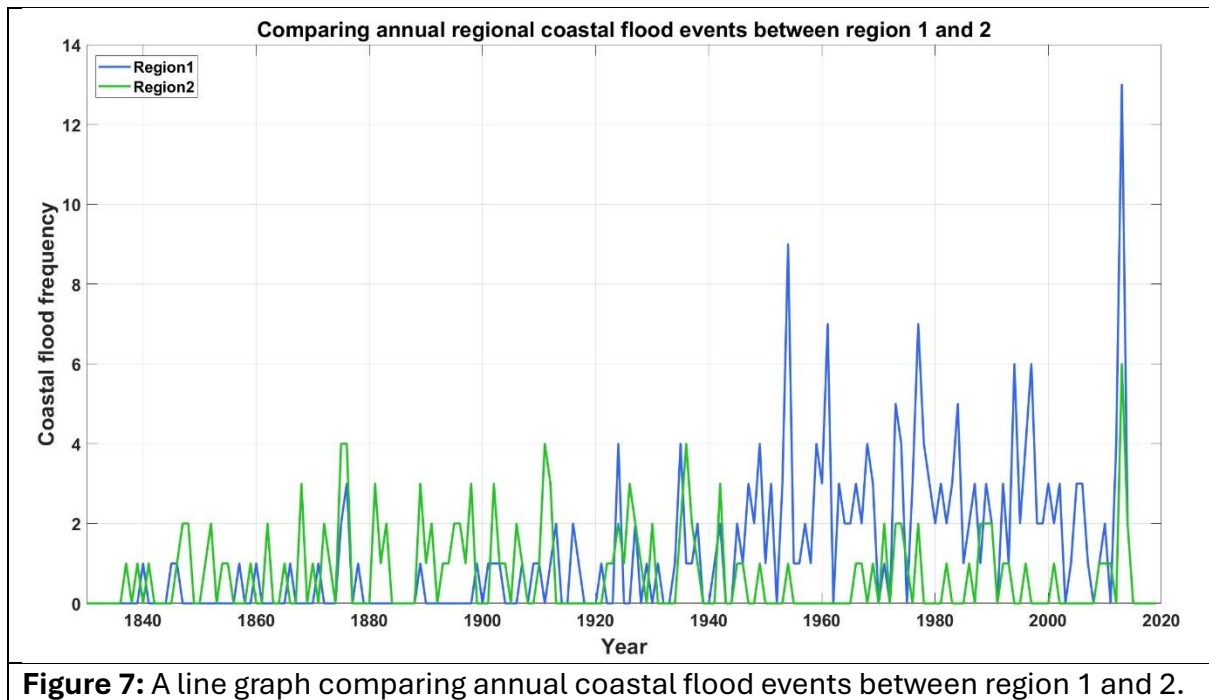


Figure 7: A line graph comparing annual coastal flood events between region 1 and 2.

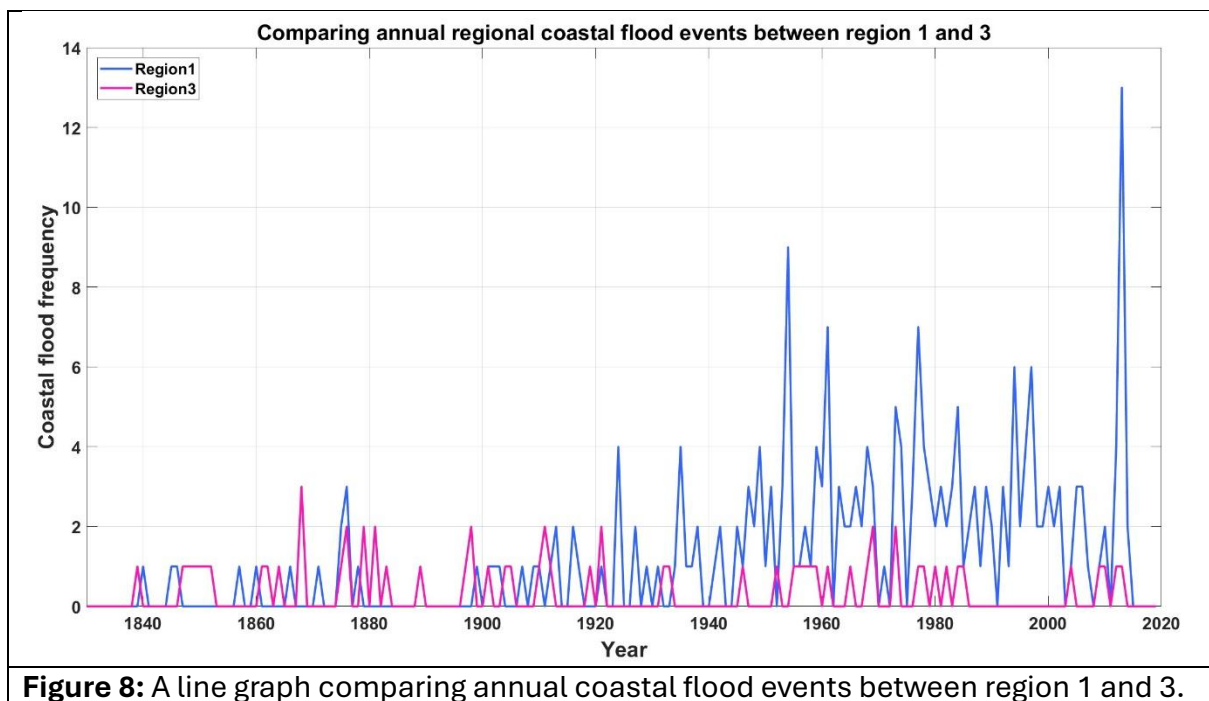


Figure 8: A line graph comparing annual coastal flood events between region 1 and 3.

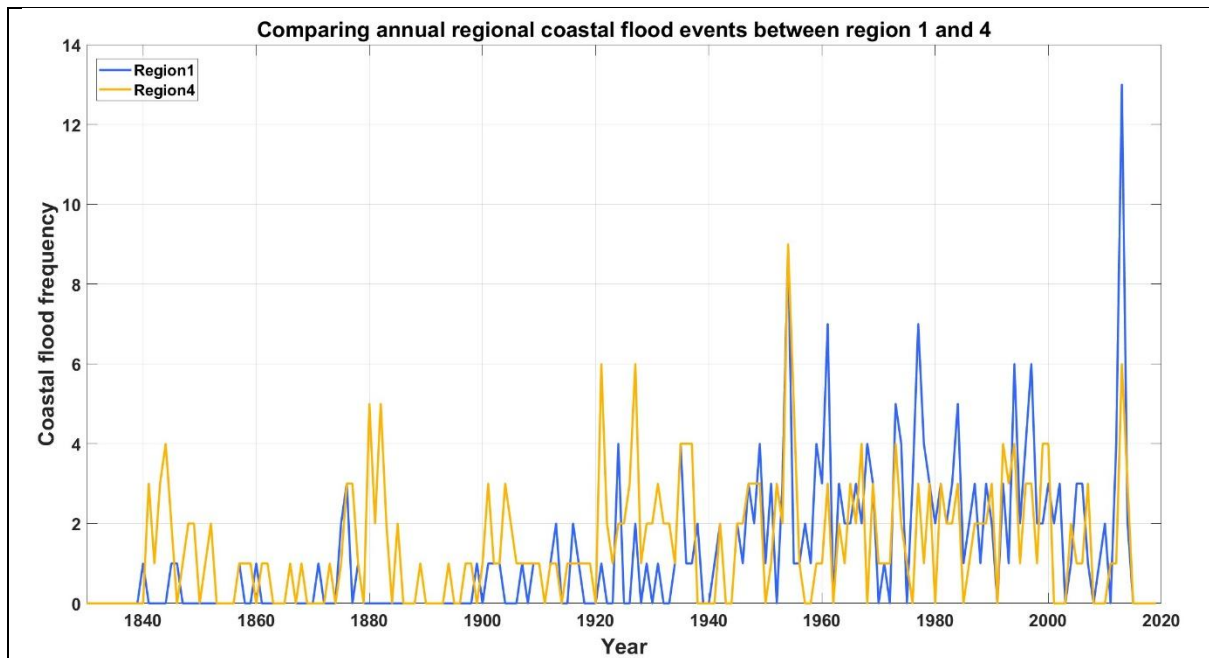


Figure 9: A line graph comparing annual coastal flood events between region 1 and 4.

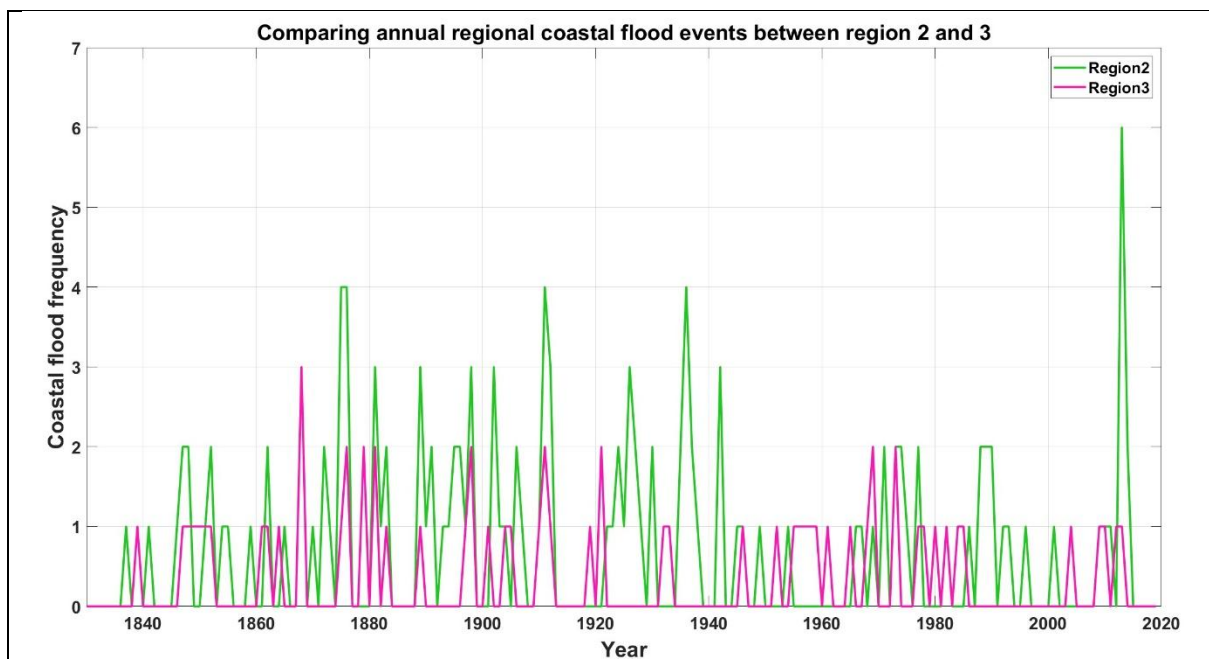


Figure 10: A line graph comparing annual coastal flood events between region 2 and 3.

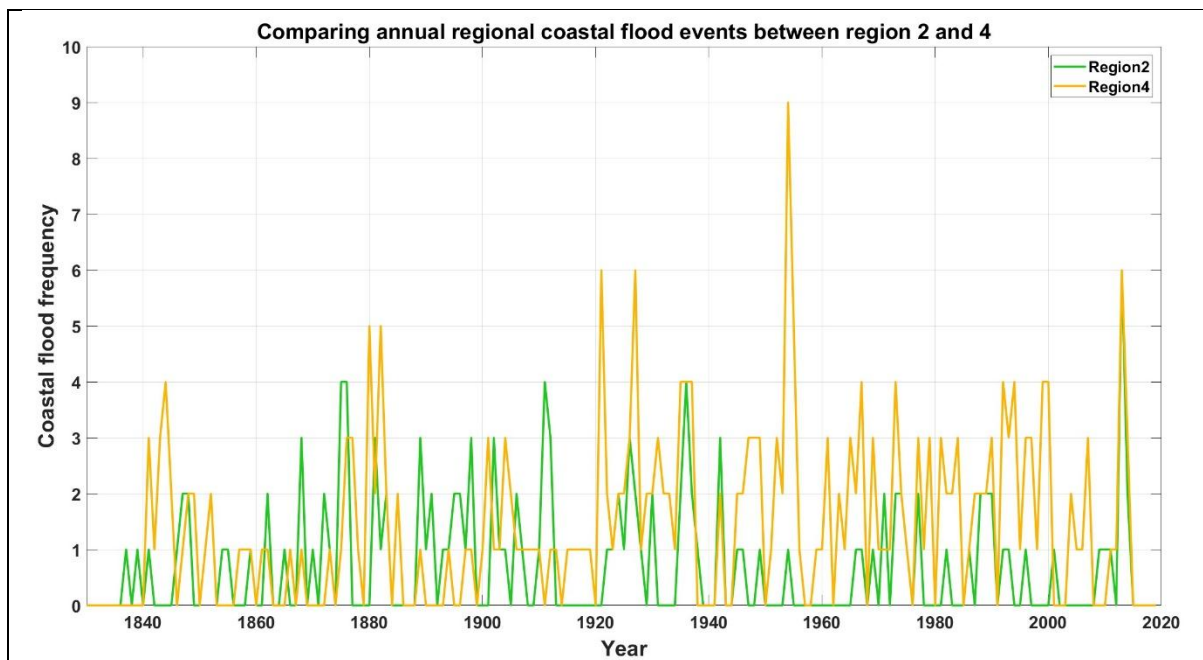


Figure 11: A line graph comparing annual coastal flood events between region 2 and 4.

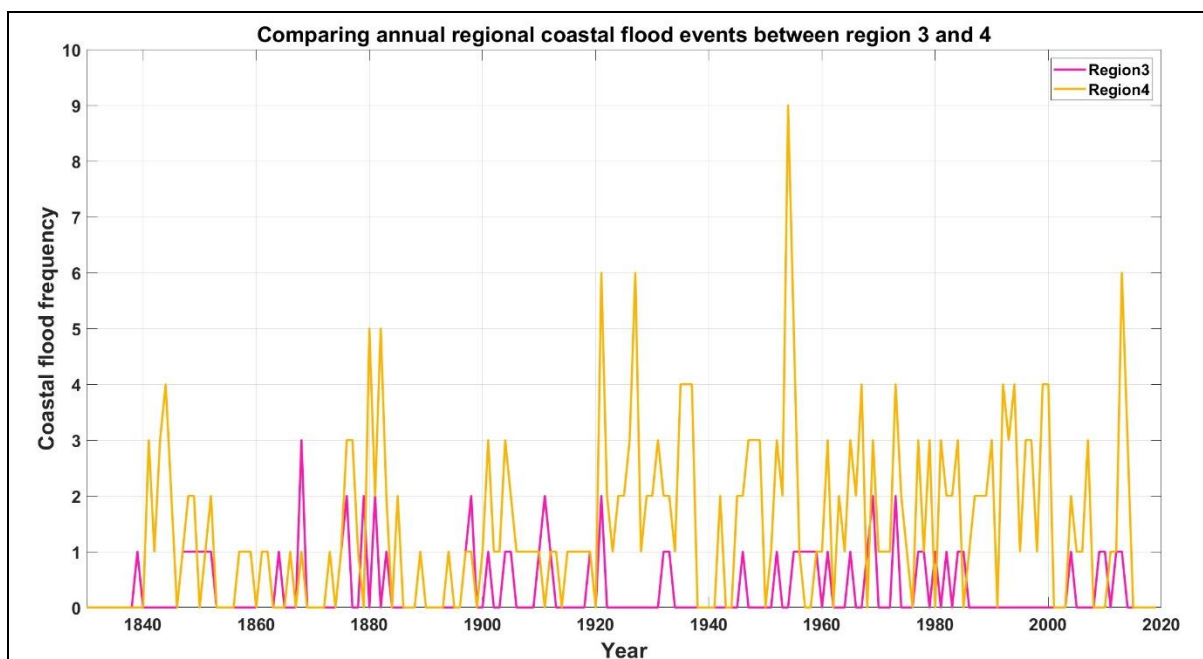


Figure 12: A line graph comparing annual coastal flood events between region 3 and 4.

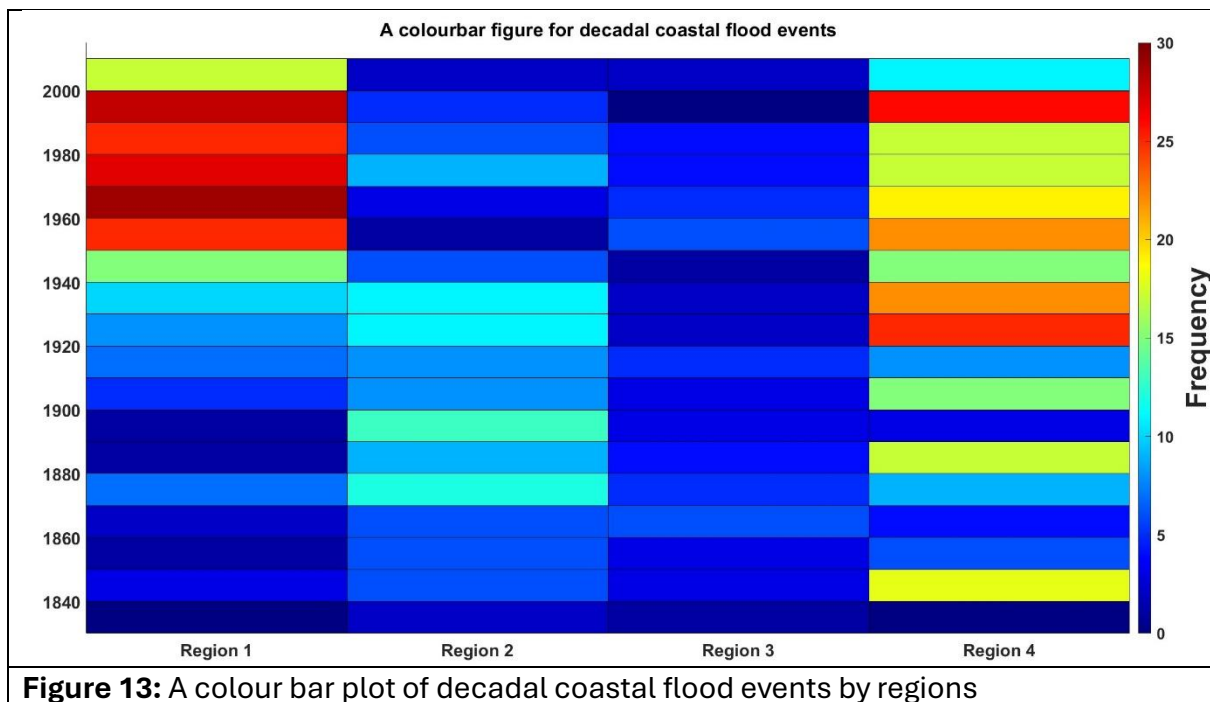


Figure 13: A colour bar plot of decadal coastal flood events by regions

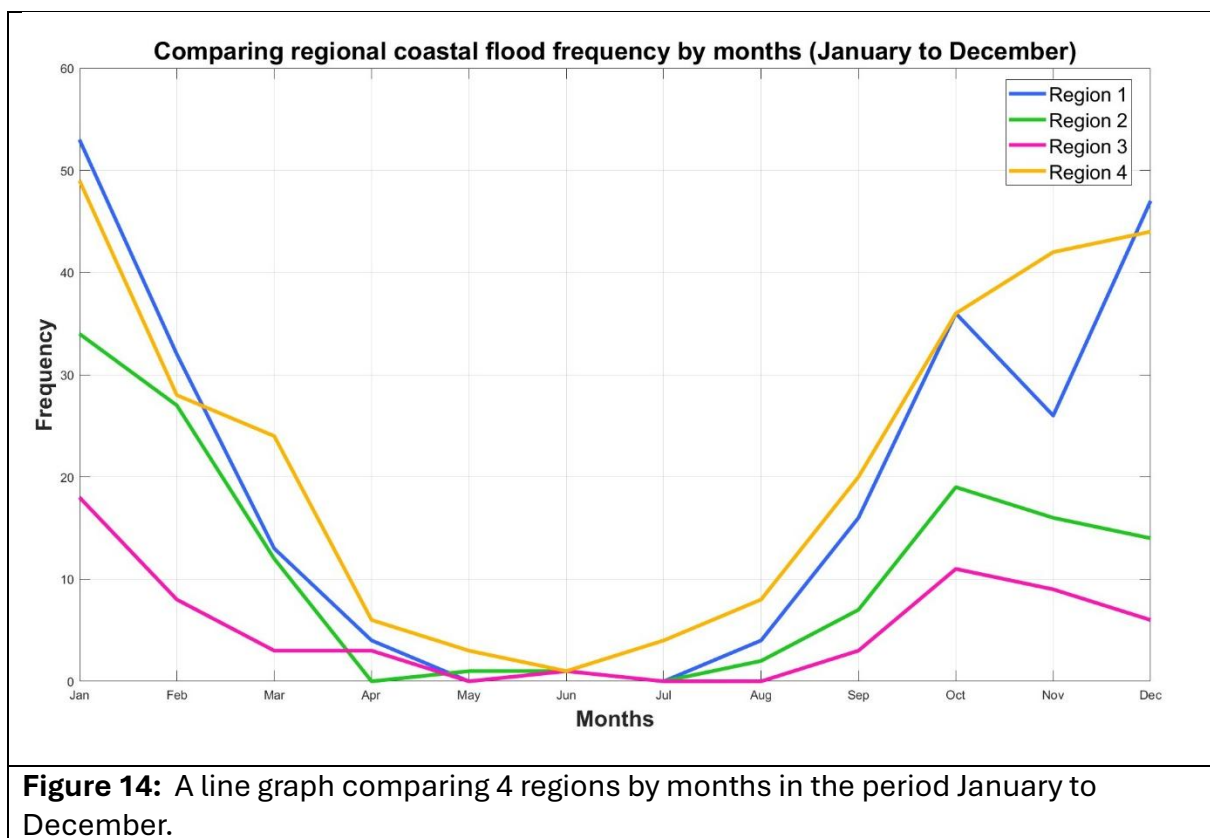


Figure 14: A line graph comparing 4 regions by months in the period January to December.

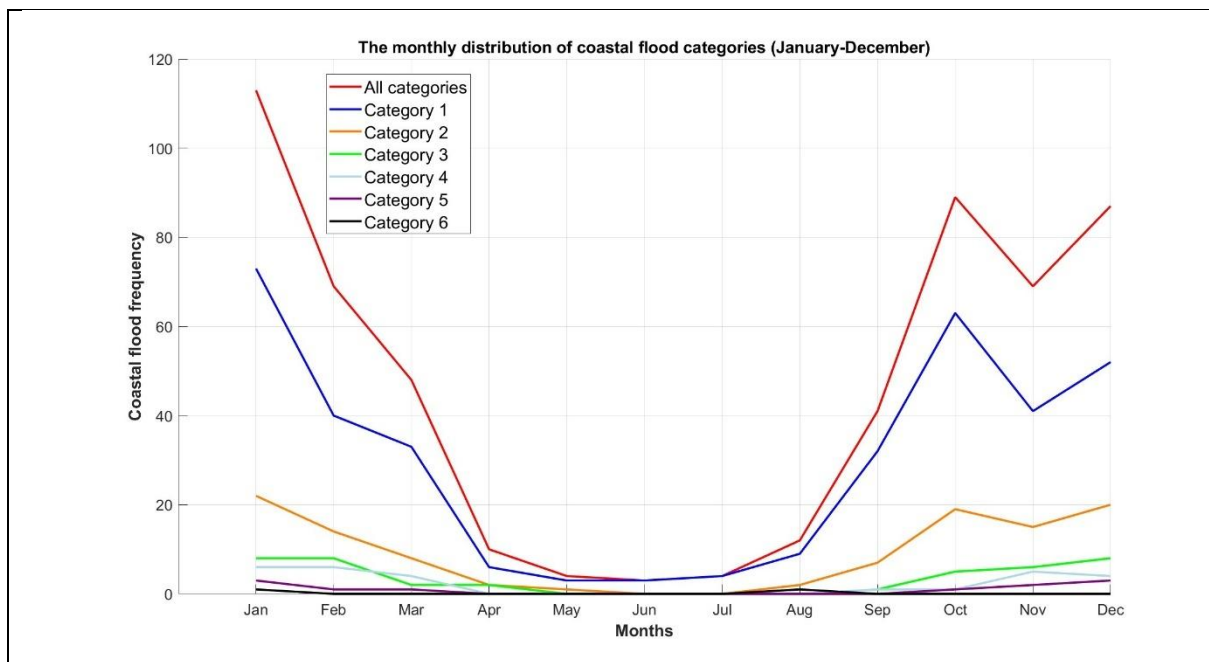


Figure 15: A line graph comparing categories by months in the period January to December.

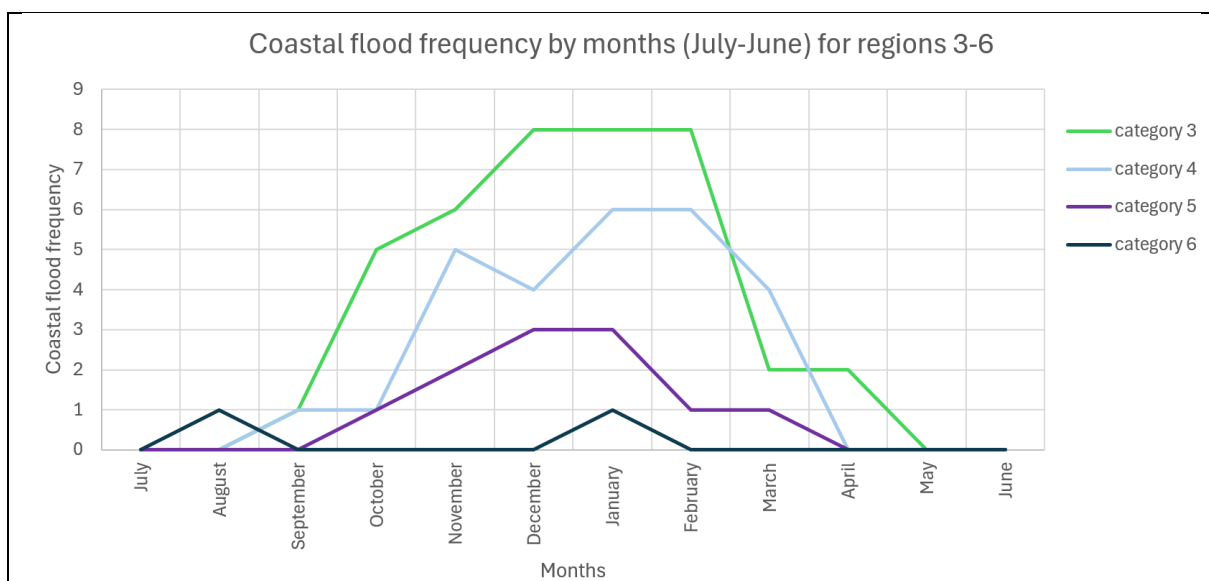
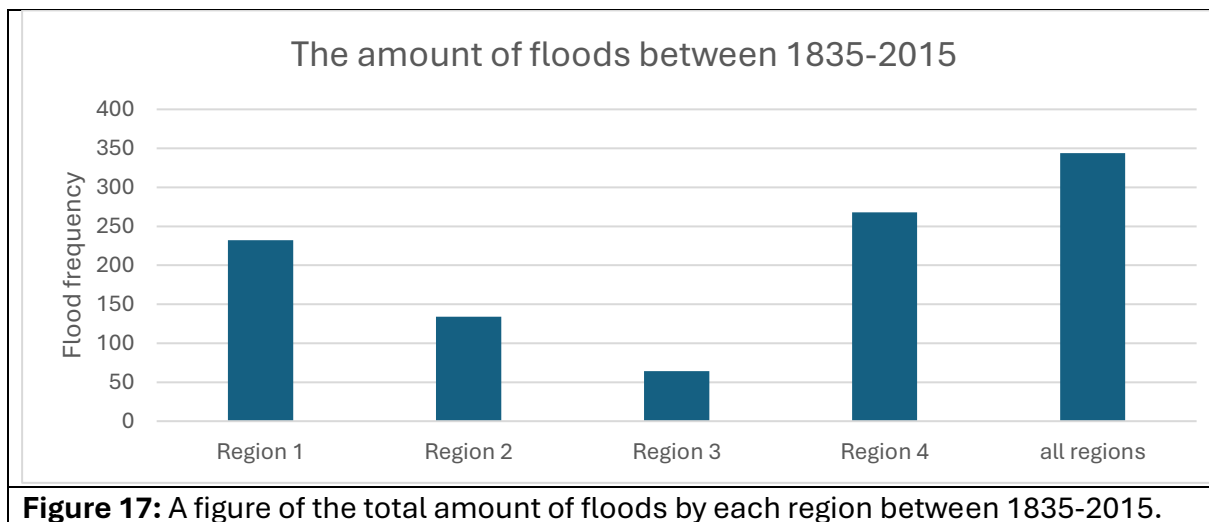
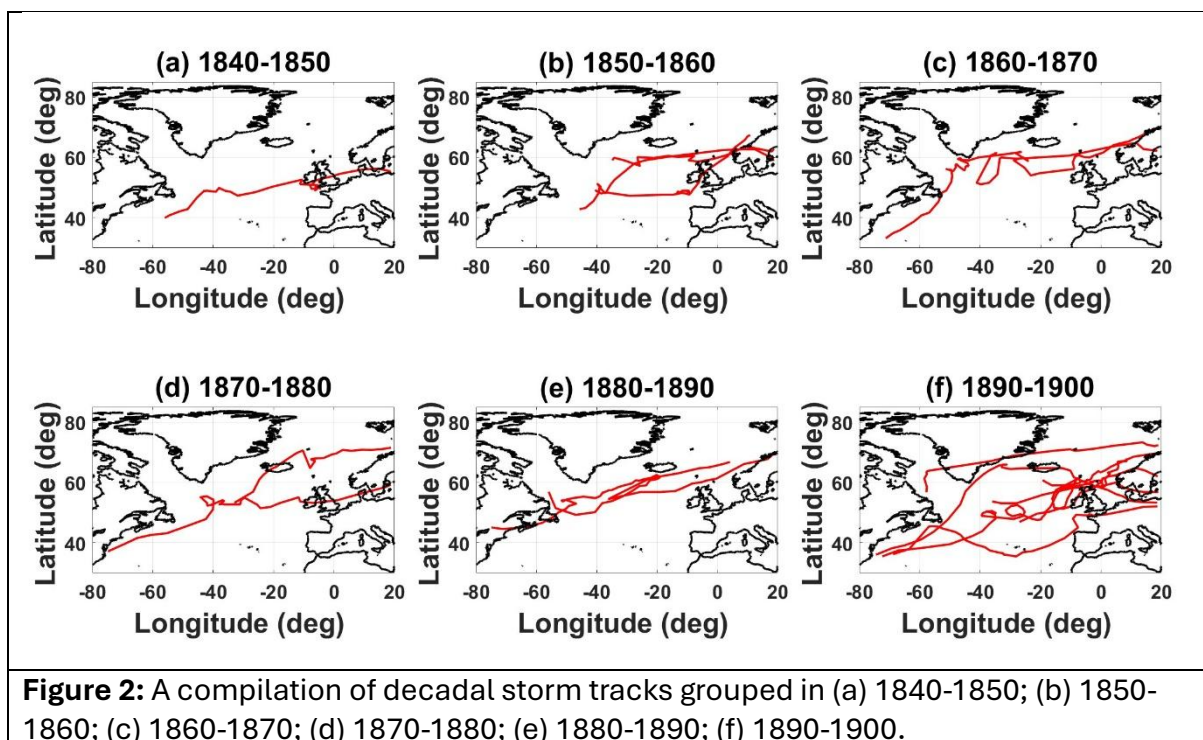
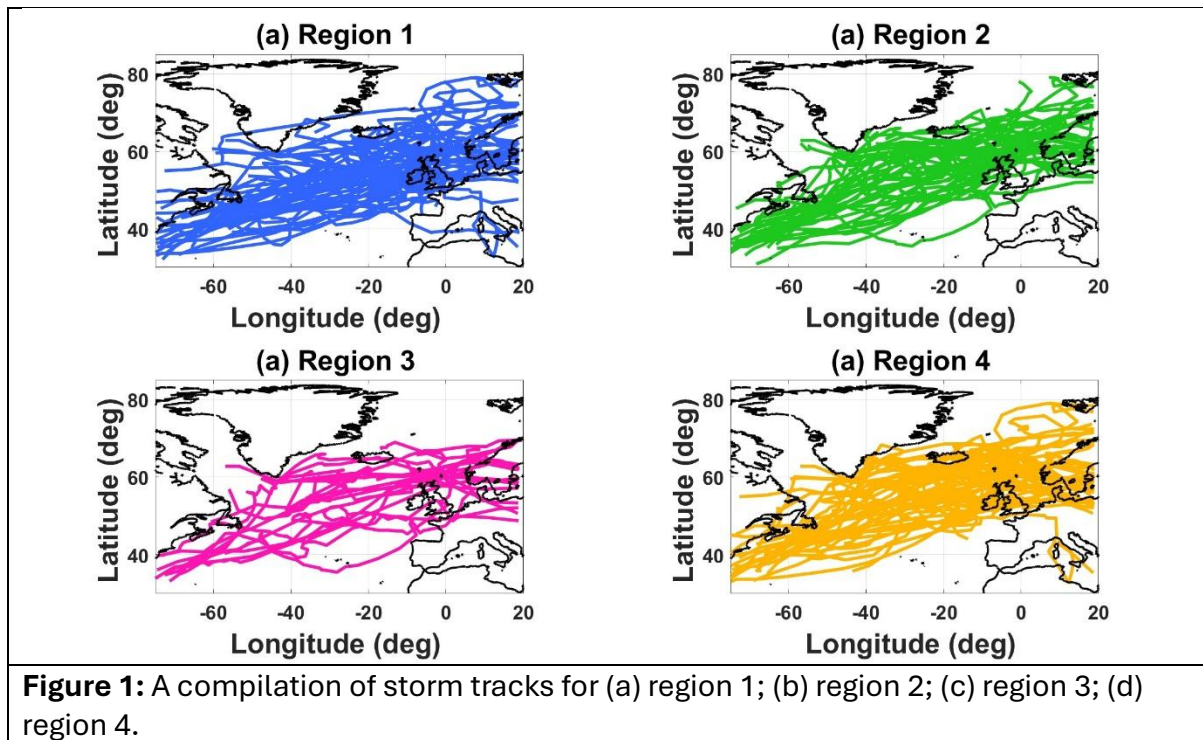
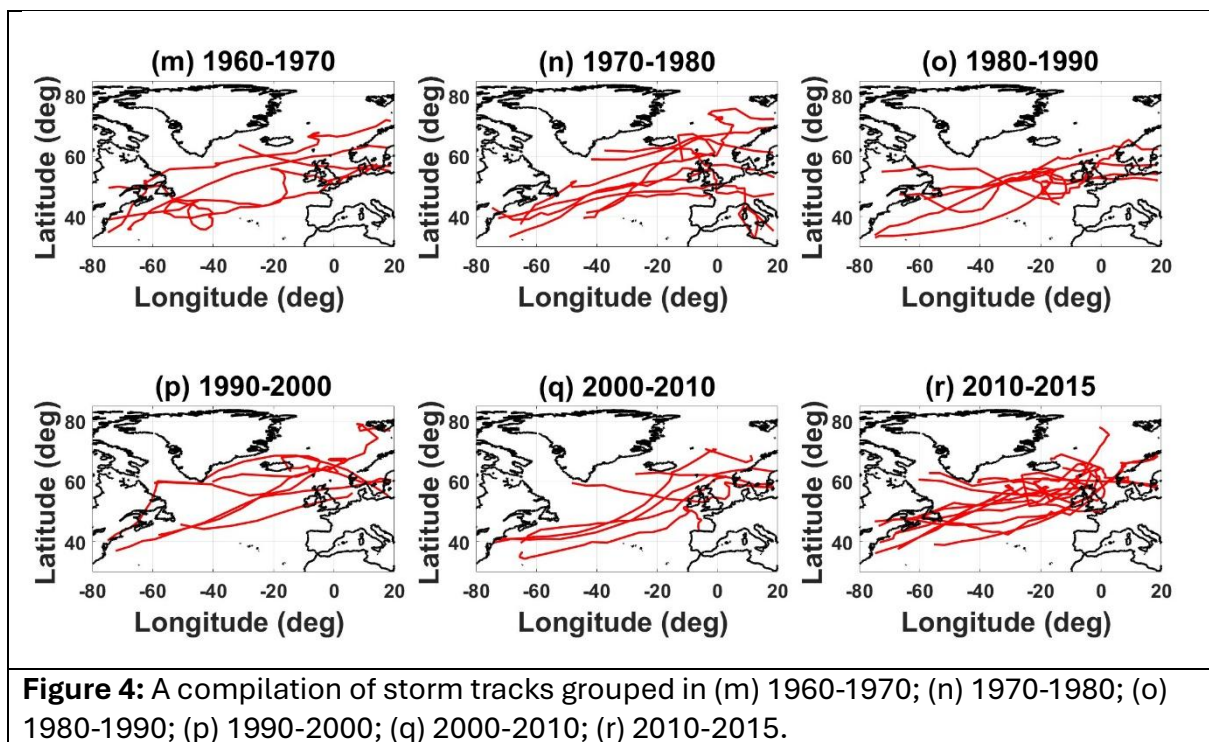
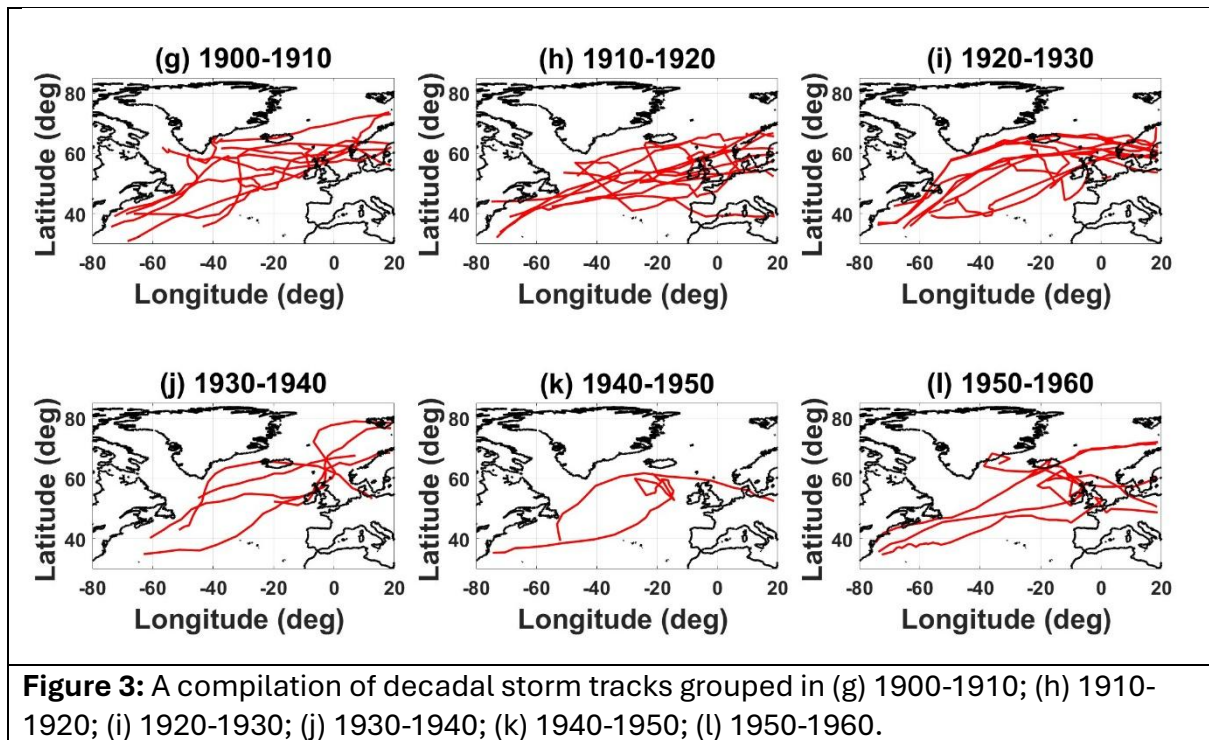


Figure 16: A line graph comparing monthly coastal flood frequency by categories 3-6.



Appendix c





Appendix d

(Figures 1-5) NAO for all of the UK

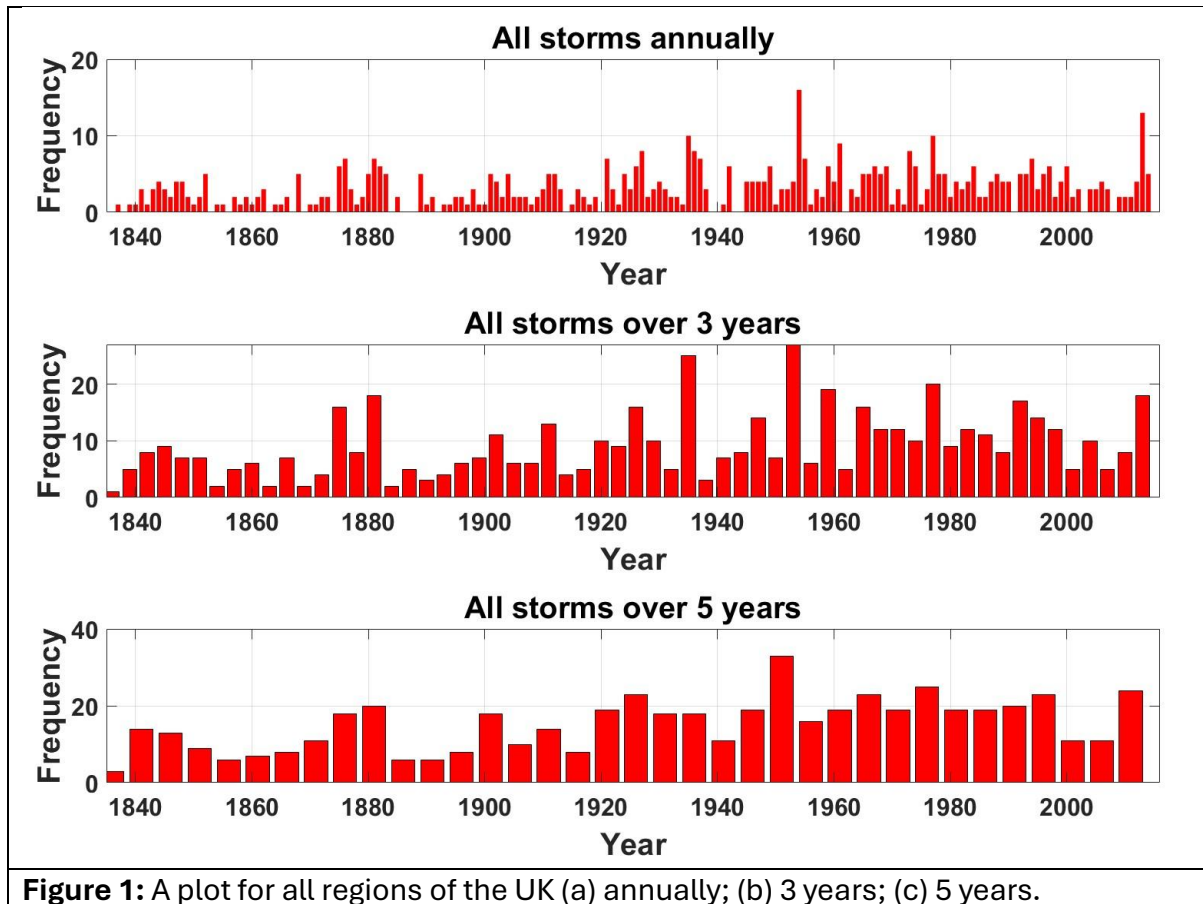


Figure 1: A plot for all regions of the UK (a) annually; (b) 3 years; (c) 5 years.

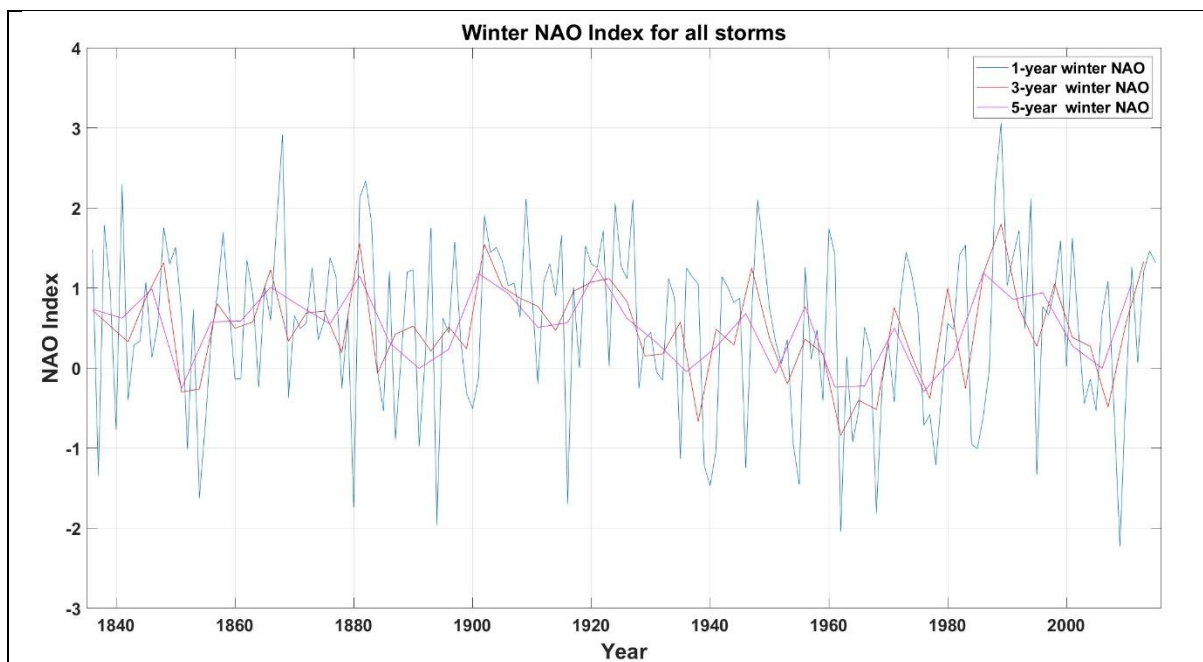


Figure 2: A figure for Winter NAO index, over all of the UK averaged over 1, 3 and 5 years.

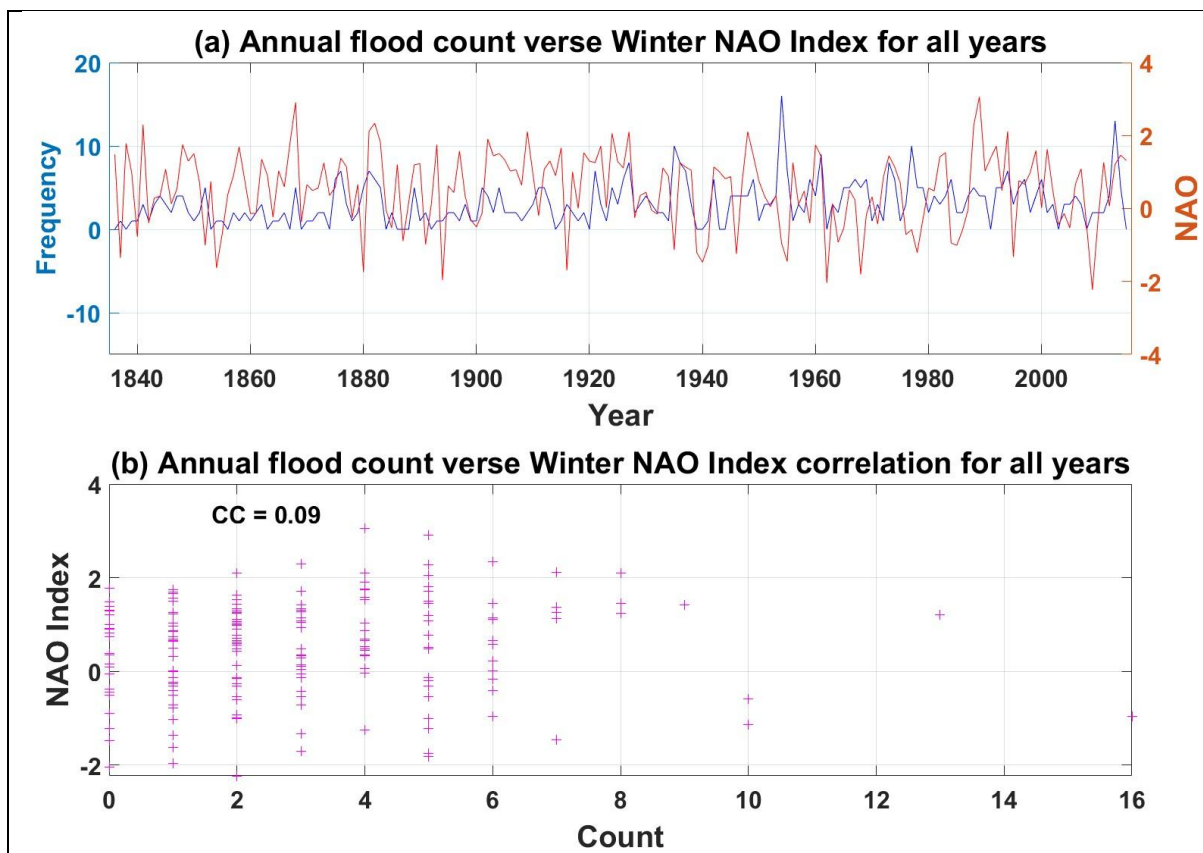


Figure 3: A figure for all of the UK in winter NAO over a 1 year (a) average winter NAO annually; (b) winter annual correlation coefficient.

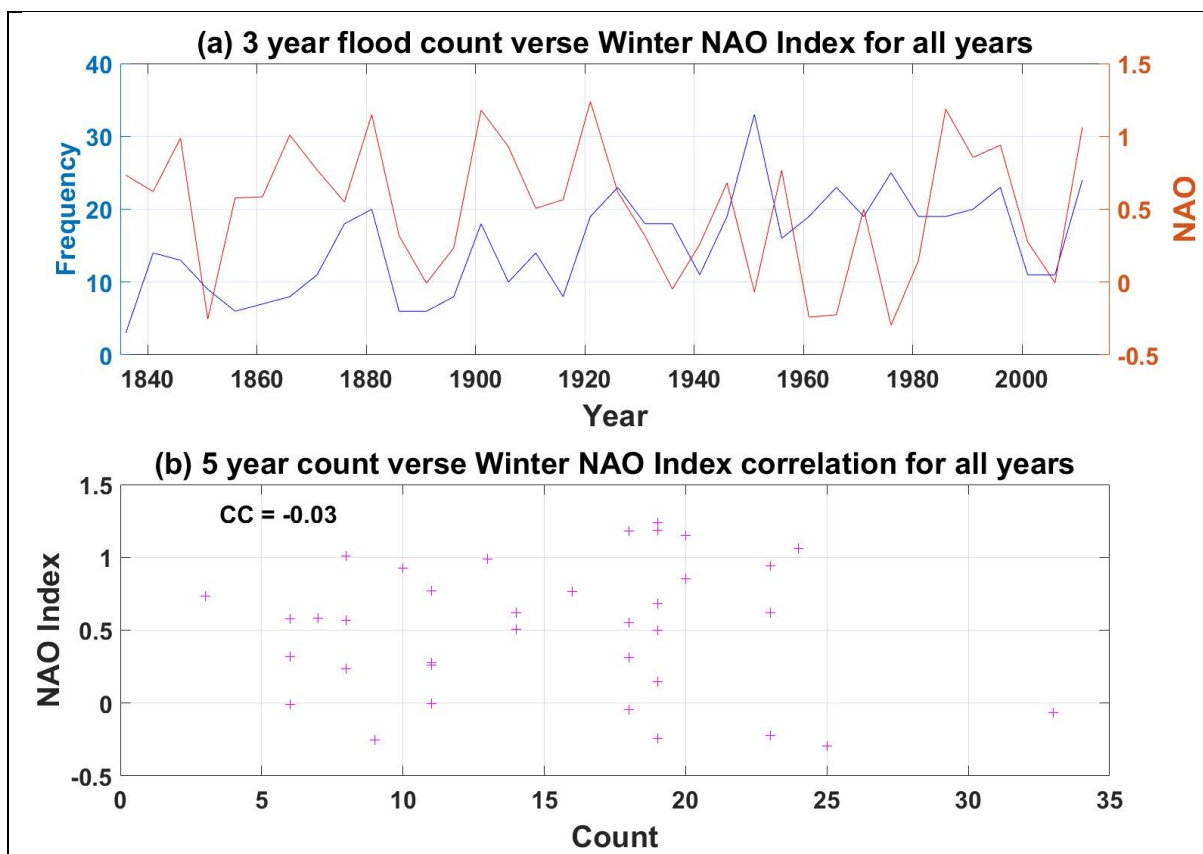
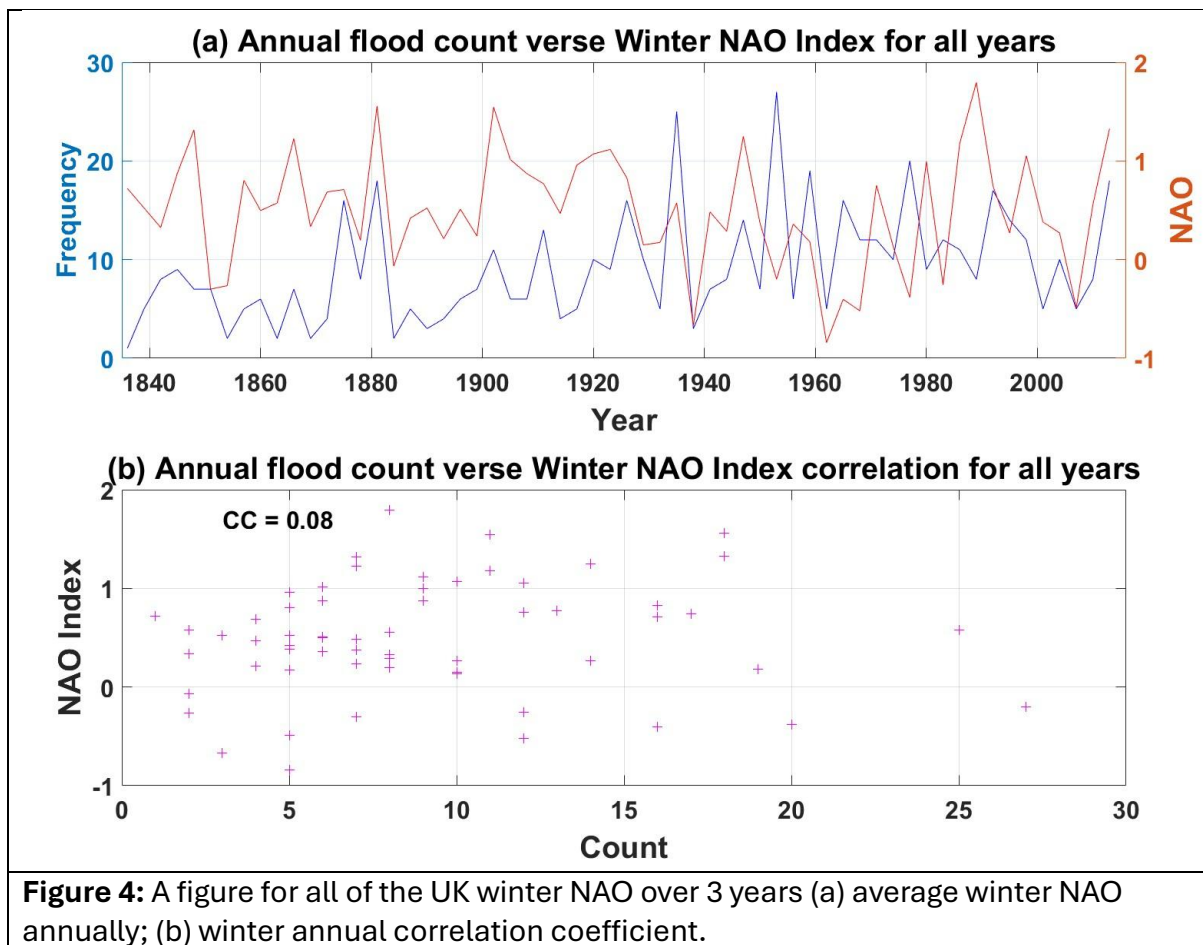


Figure 5: A figure for all of the UK winter NAO over 5 years (a) average winter NAO annually; (b) winter annual correlation coefficient.

(Figures 1-5) NAO for region 1

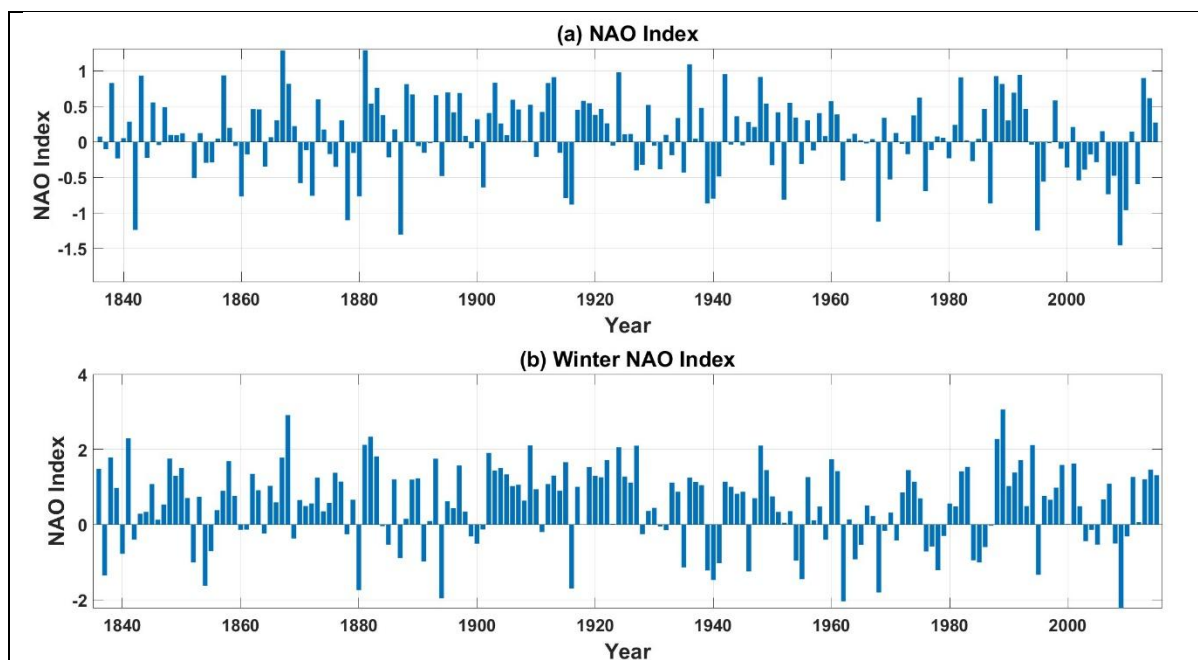


Figure 6: A plot for region 1 NAO index for each year (a) annually; (b) winter.

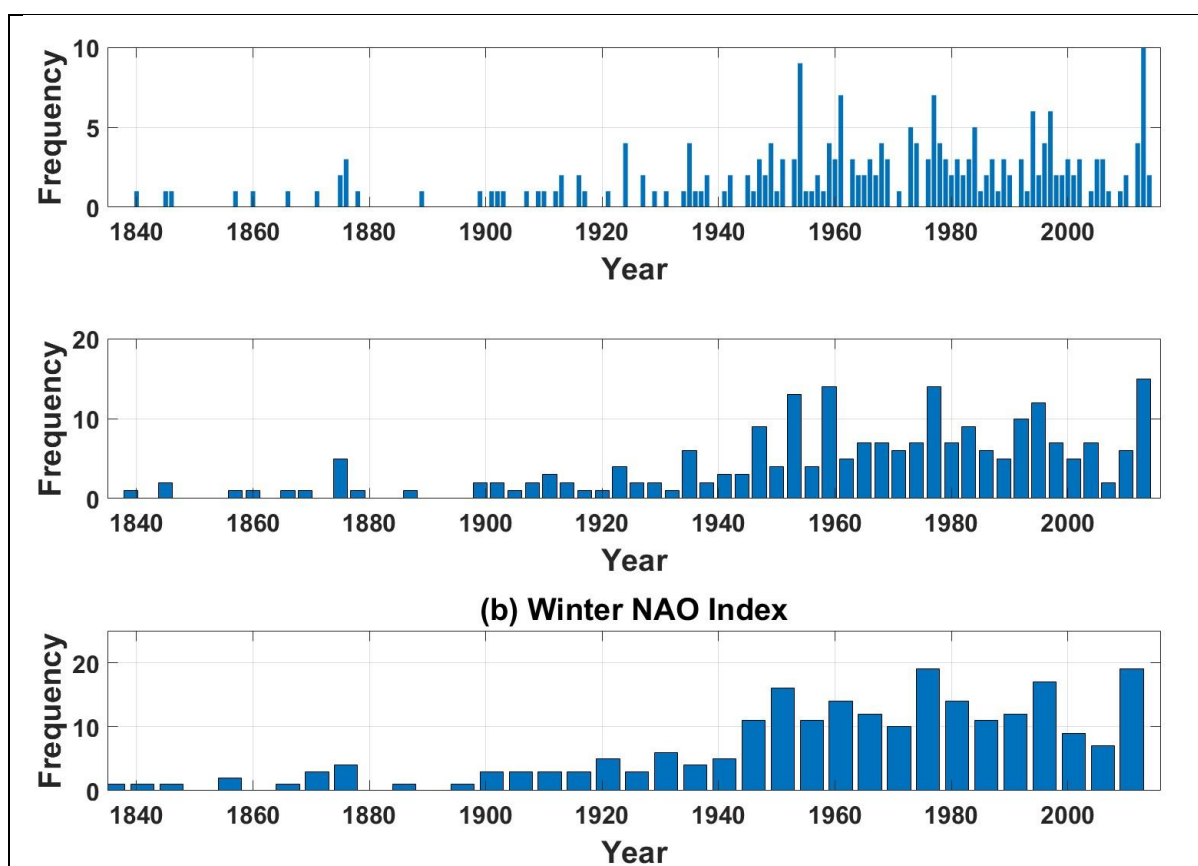


Figure 7: A plot for region 1 (a) annually; (b) 3 years; (c) 5 years.

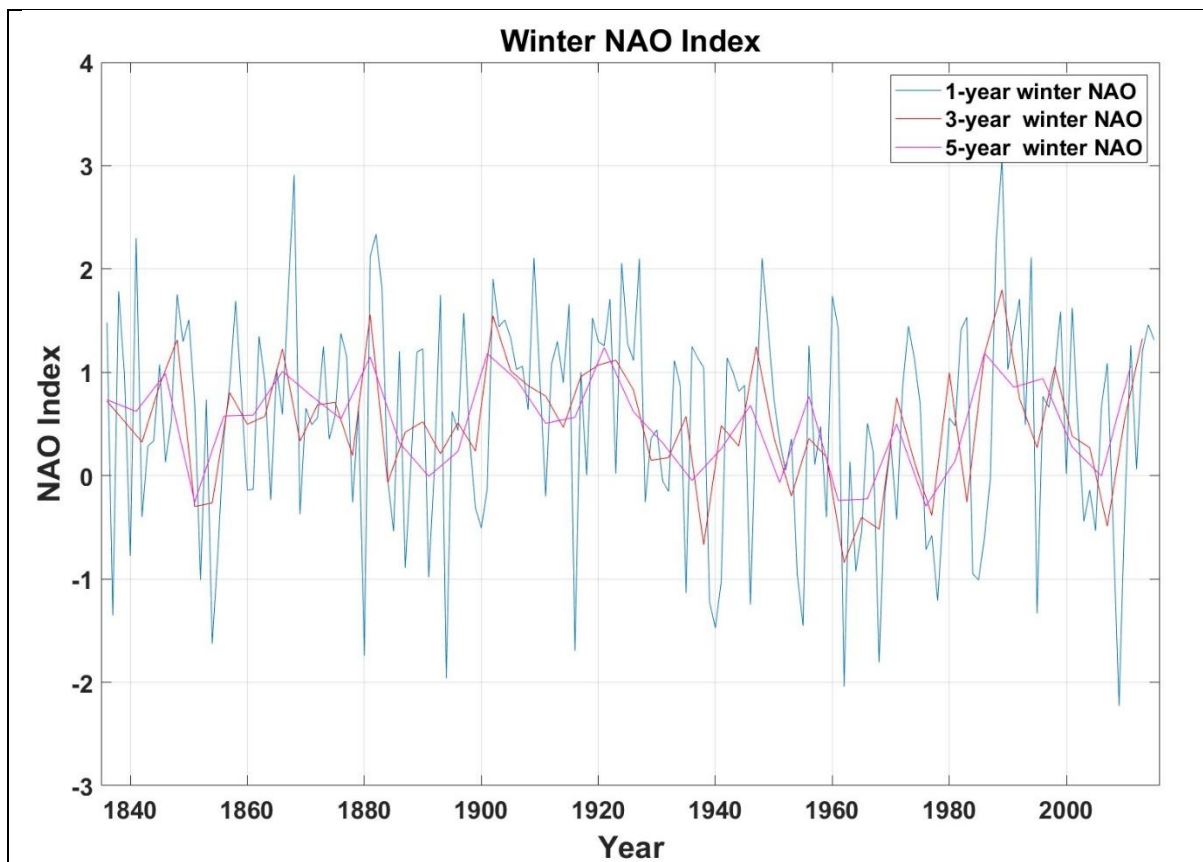


Figure 8: A figure for Winter NAO index, over region 1, averaged over 1, 3 and 5 years.

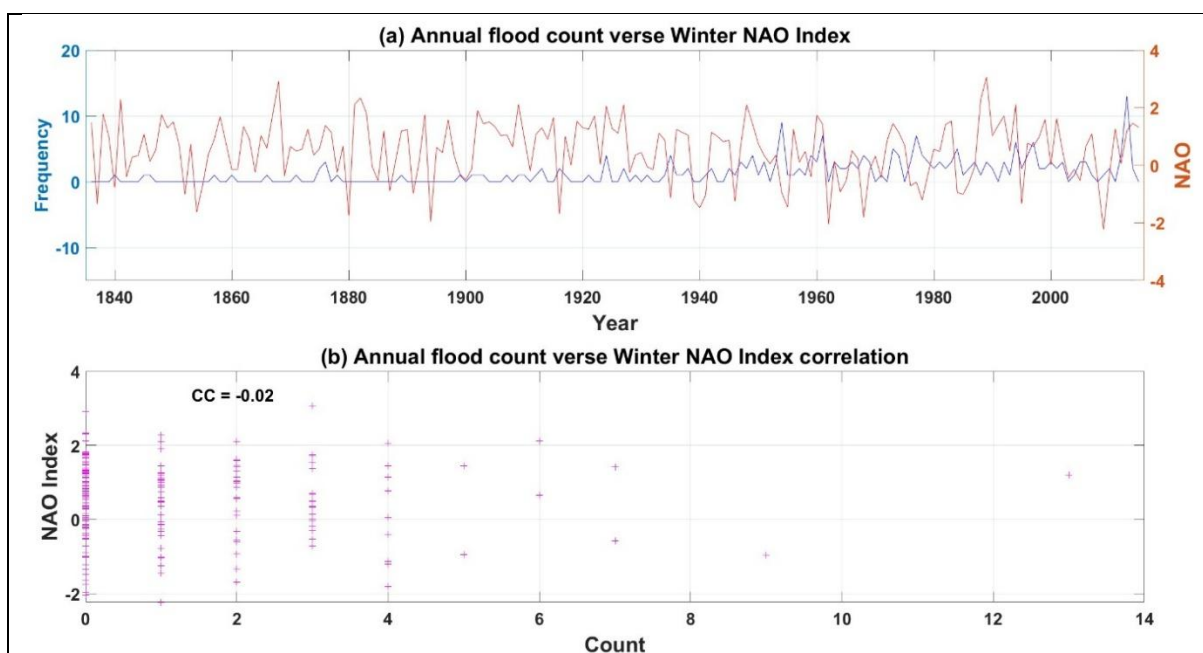
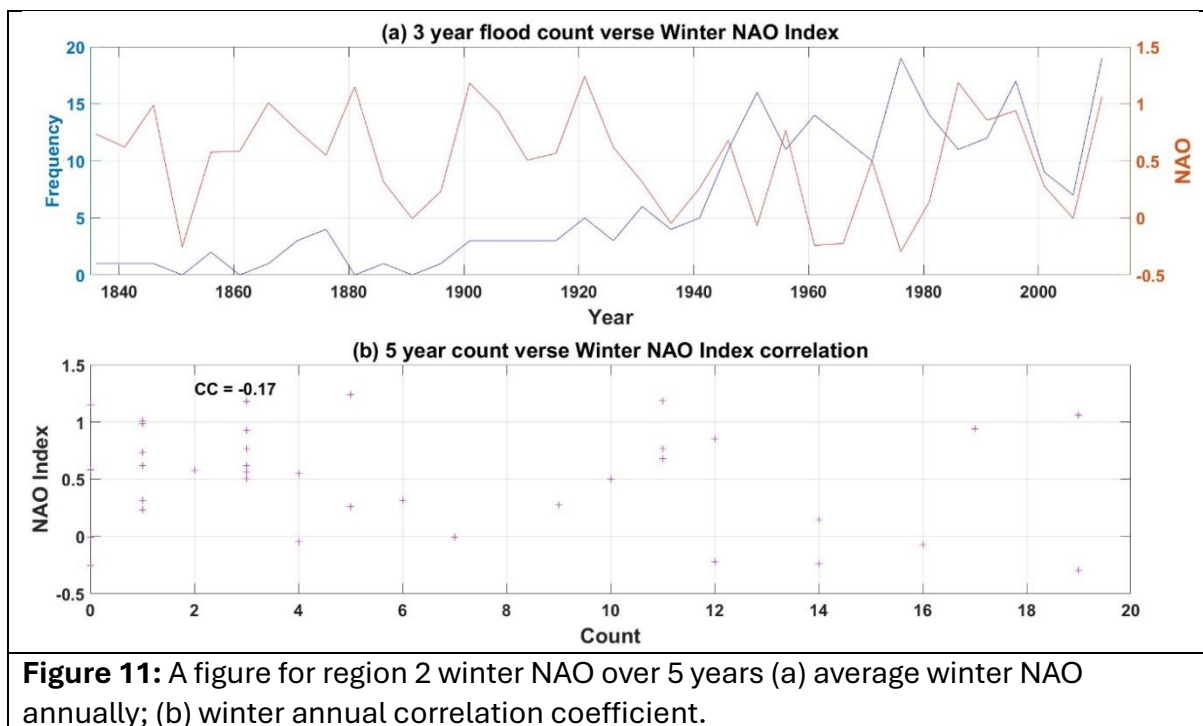
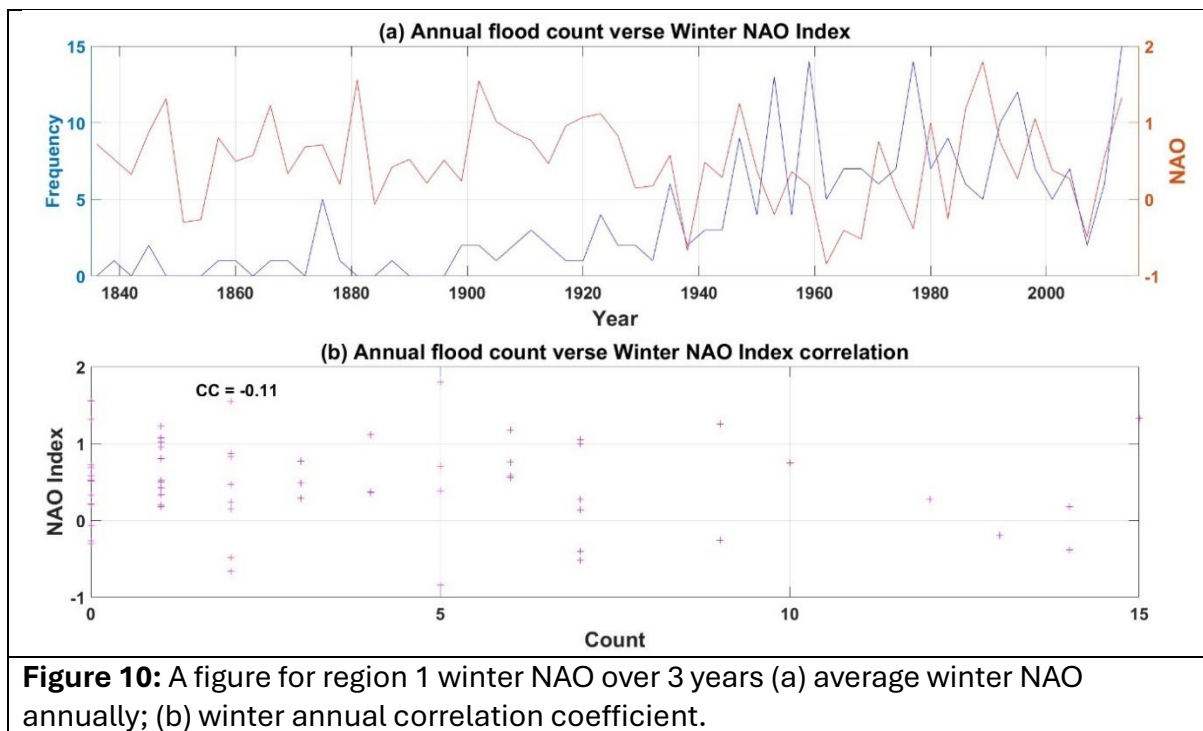


Figure 9: A figure for region 1 winter NAO over a 1 year (a) average winter NAO annually; (b) winter annual correlation coefficient.



(Figures 1-5) NAO for region 2

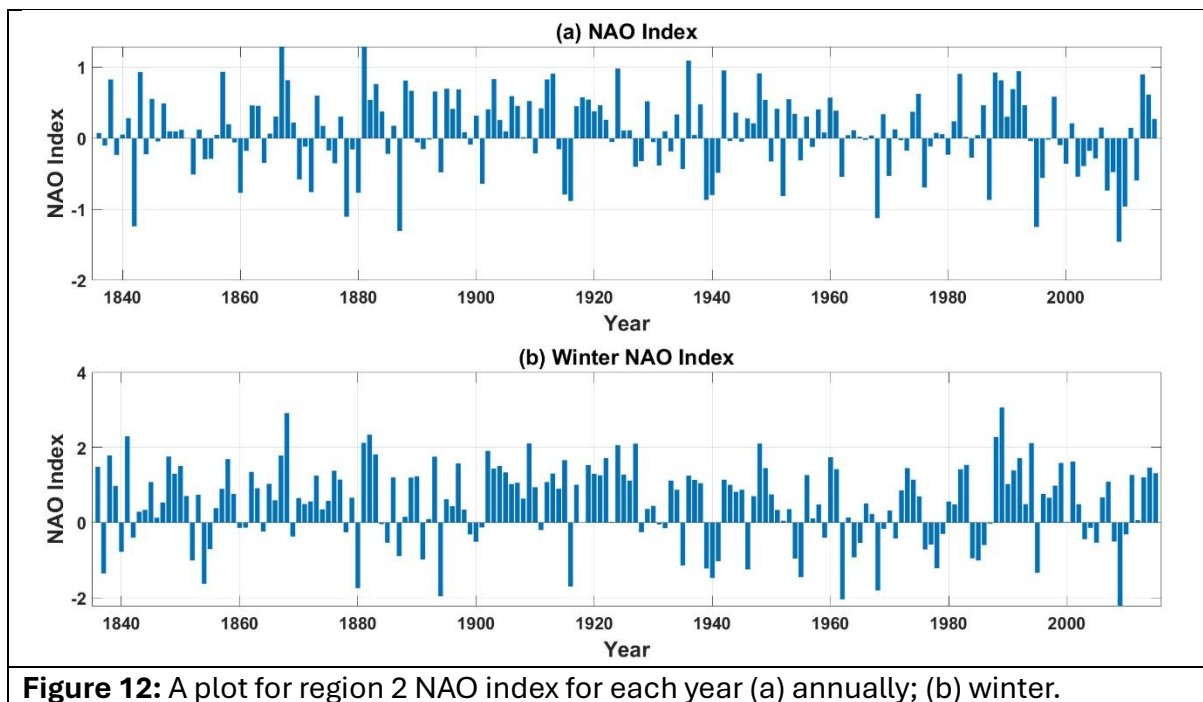


Figure 12: A plot for region 2 NAO index for each year (a) annually; (b) winter.

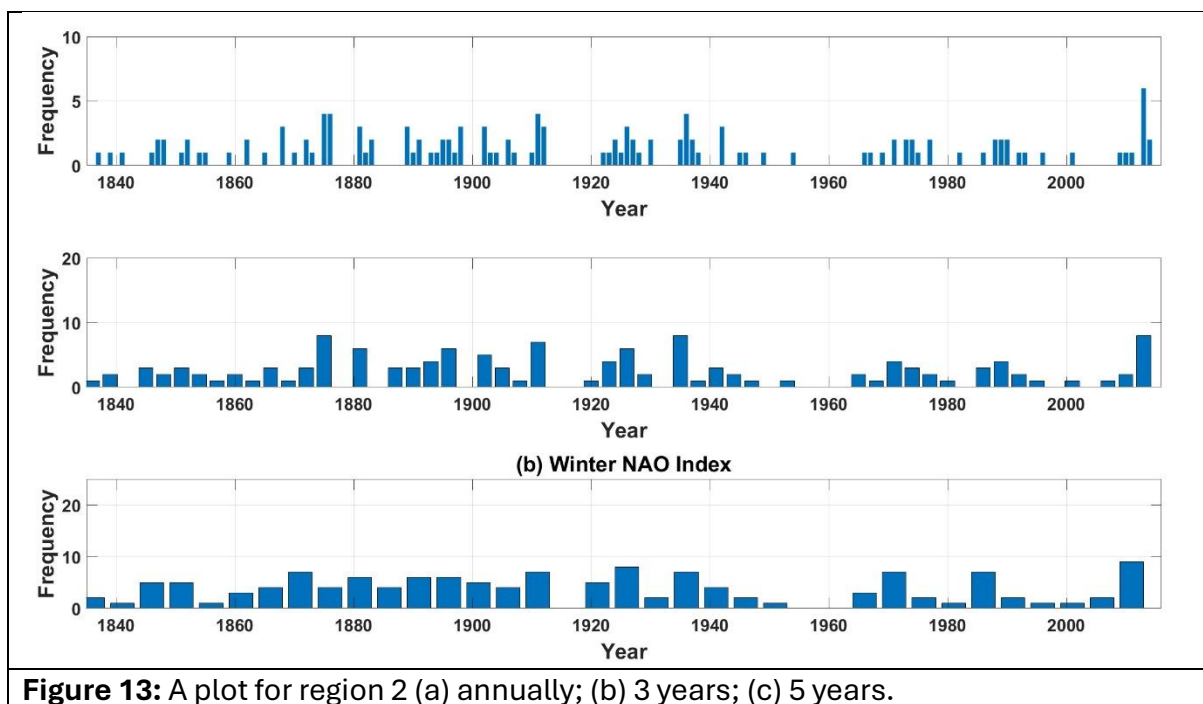


Figure 13: A plot for region 2 (a) annually; (b) 3 years; (c) 5 years.

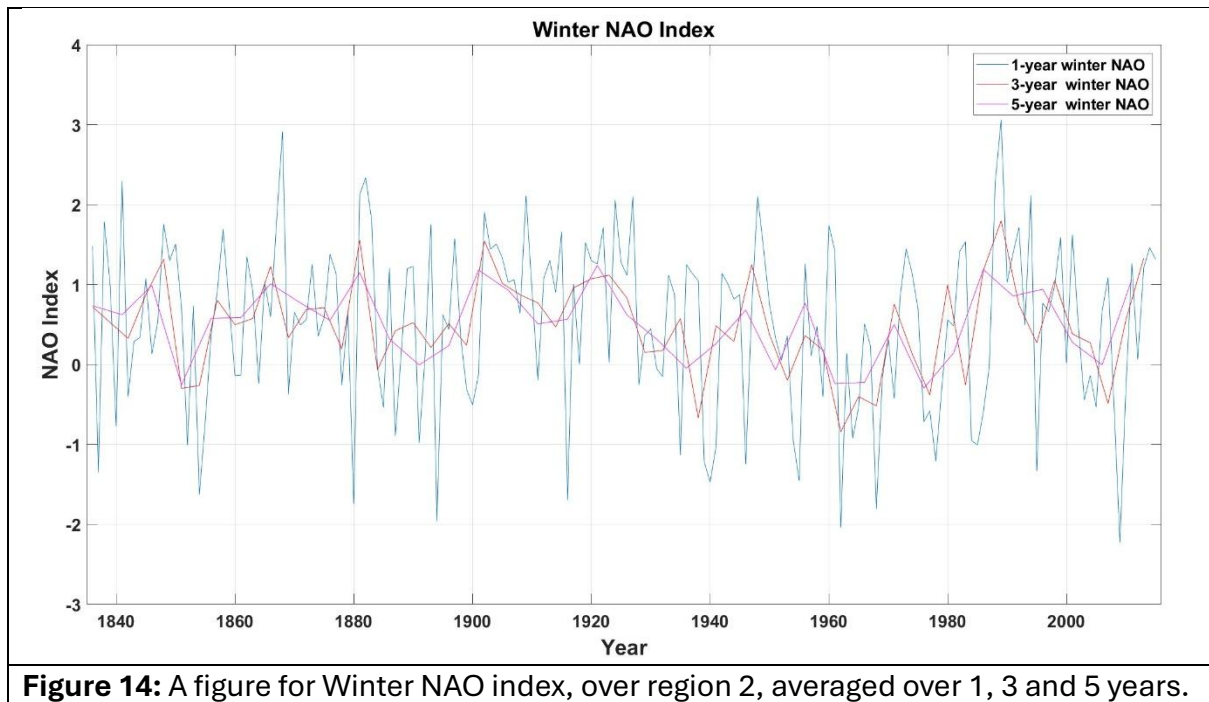


Figure 14: A figure for Winter NAO index, over region 2, averaged over 1, 3 and 5 years.

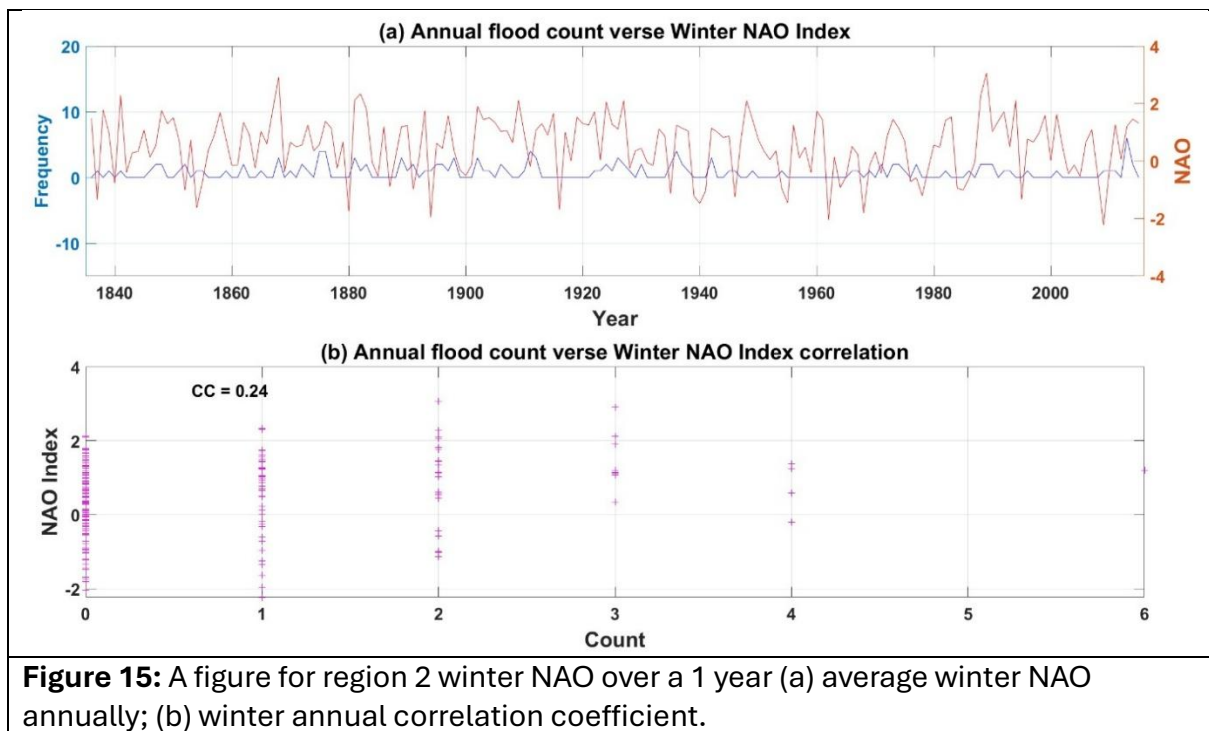


Figure 15: A figure for region 2 winter NAO over a 1 year (a) average winter NAO annually; (b) winter annual correlation coefficient.

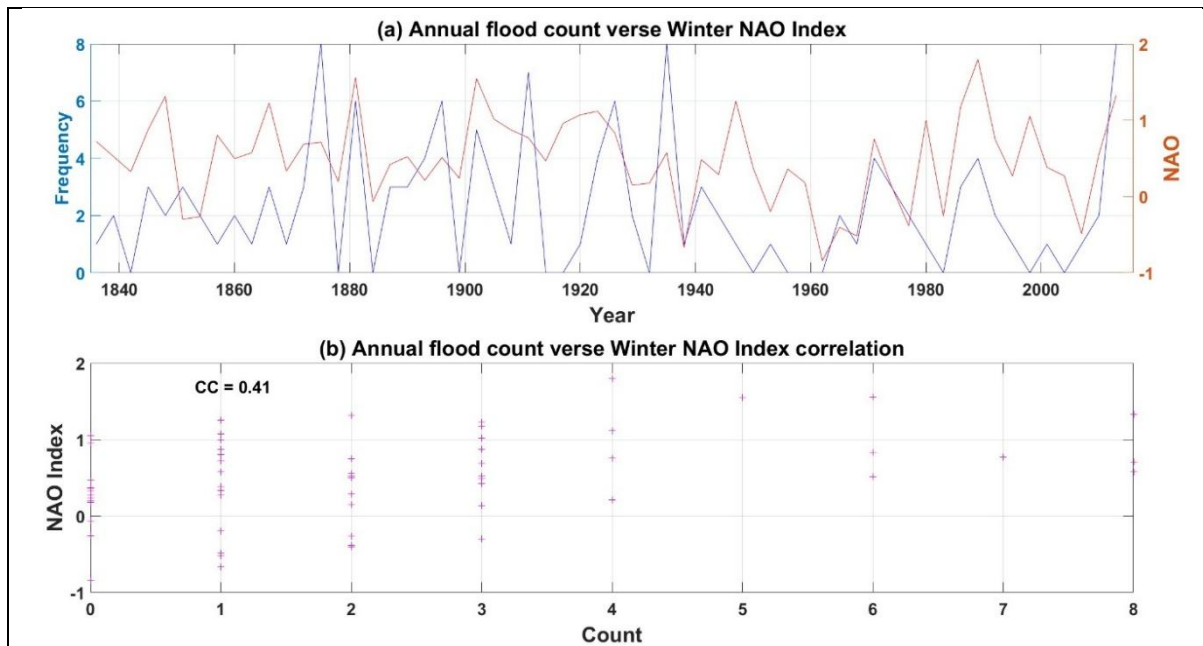


Figure 16: A figure for region 2 winter NAO over 3 years (a) average winter NAO annually; (b) winter annual correlation coefficient.

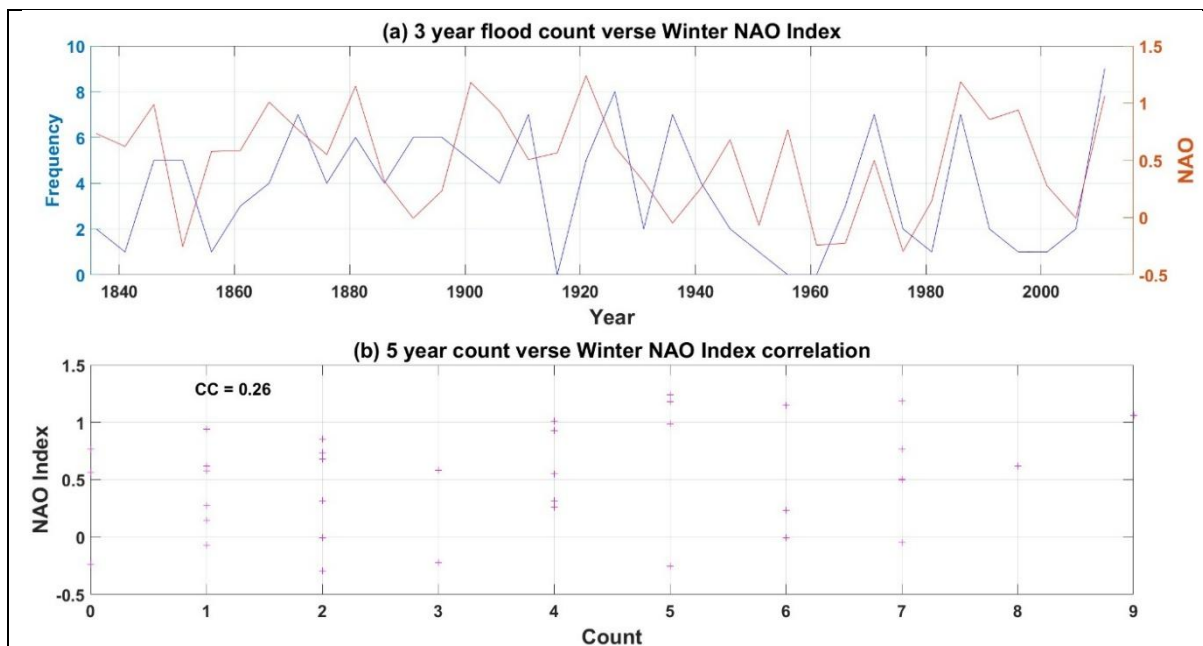


Figure 17: A figure for region 2 winter NAO over 5 years (a) average winter NAO annually; (b) winter annual correlation coefficient.

(Figures 1-5) NAO for region 3

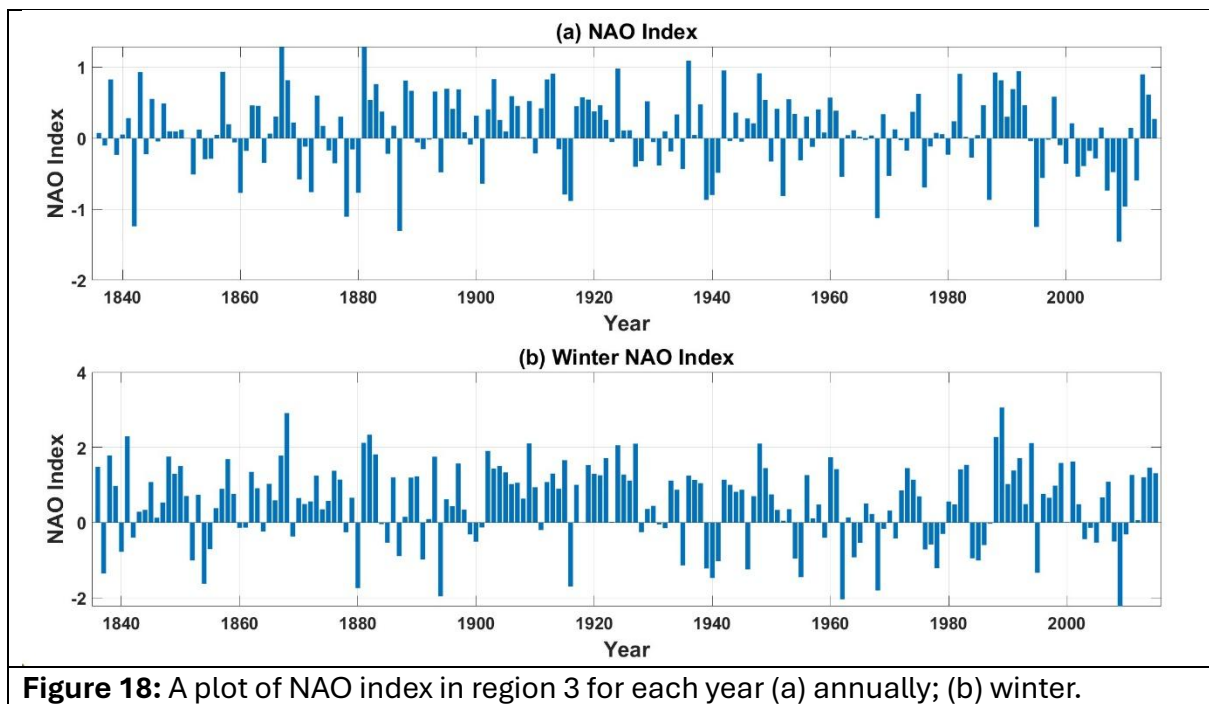


Figure 18: A plot of NAO index in region 3 for each year (a) annually; (b) winter.

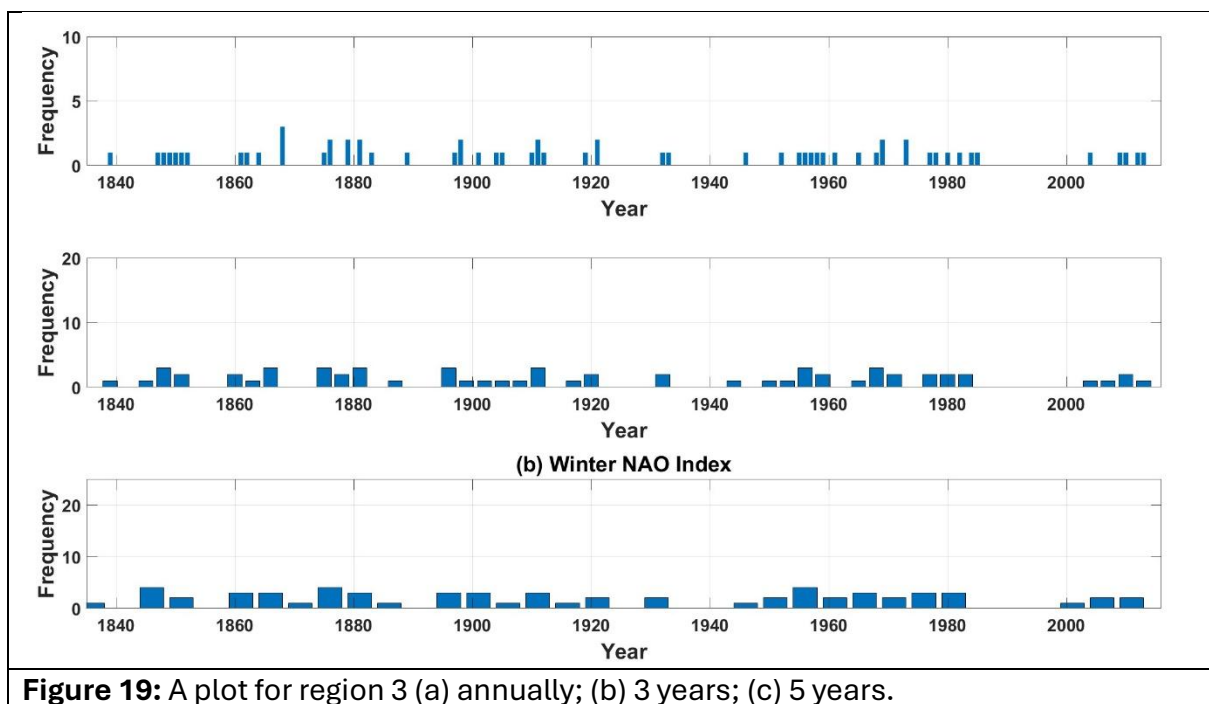


Figure 19: A plot for region 3 (a) annually; (b) 3 years; (c) 5 years.

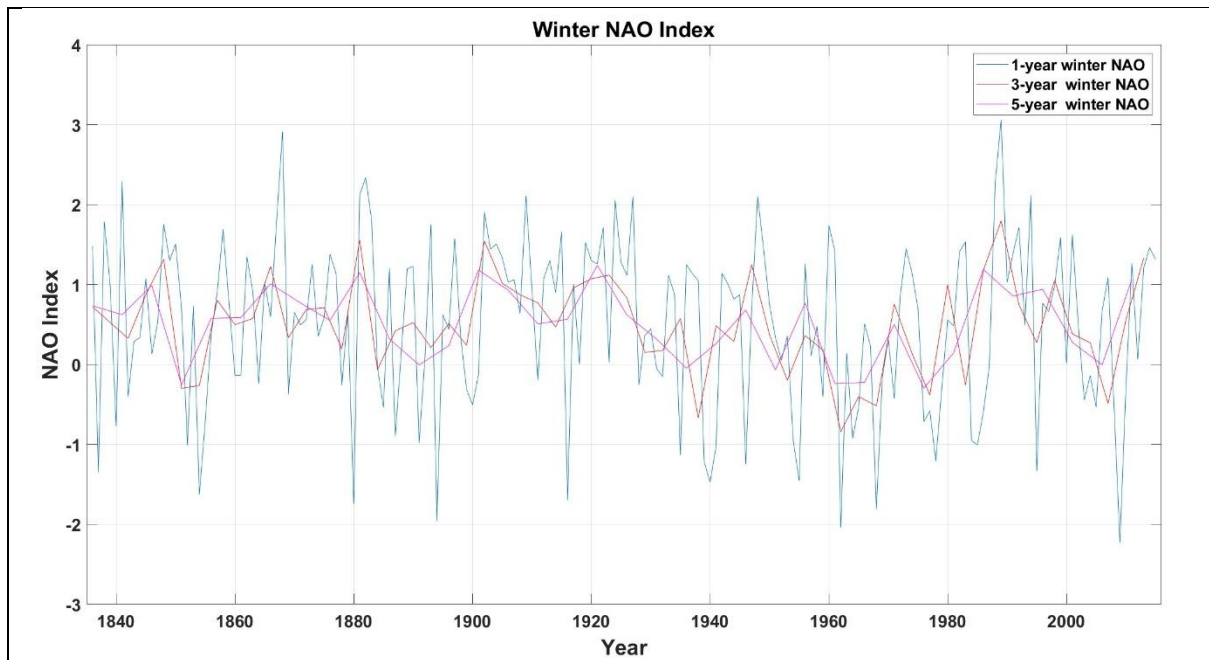


Figure 20: A figure for Winter NAO index, over region 3, averaged over 1, 3 and 5 years.

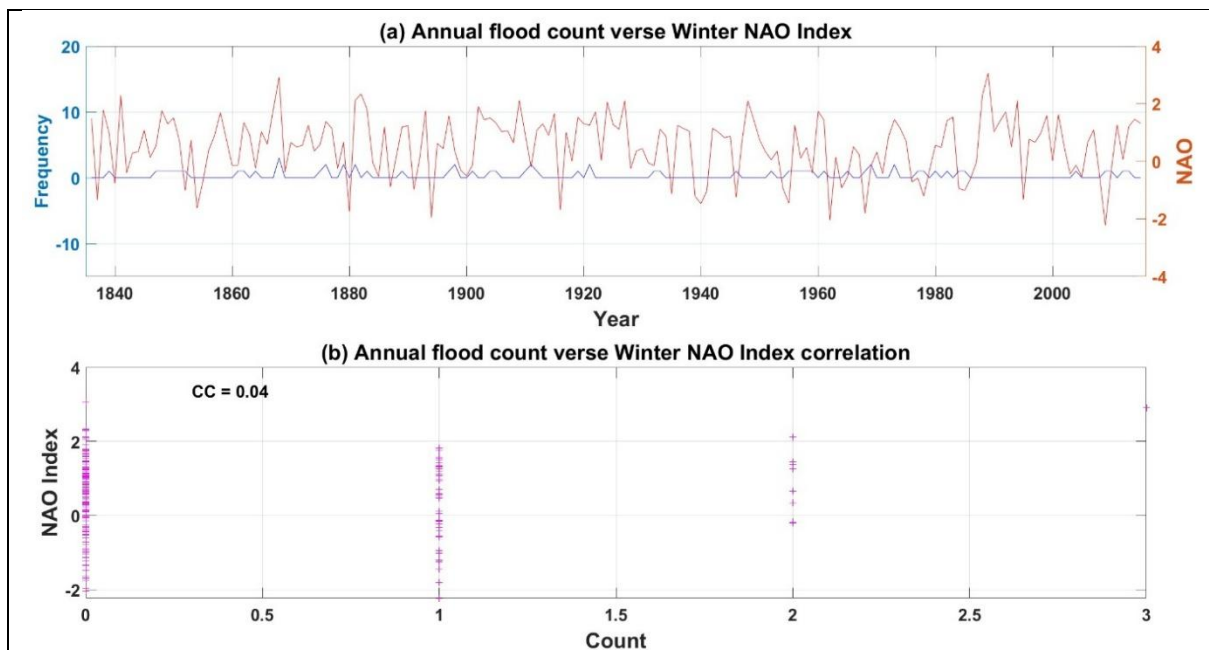
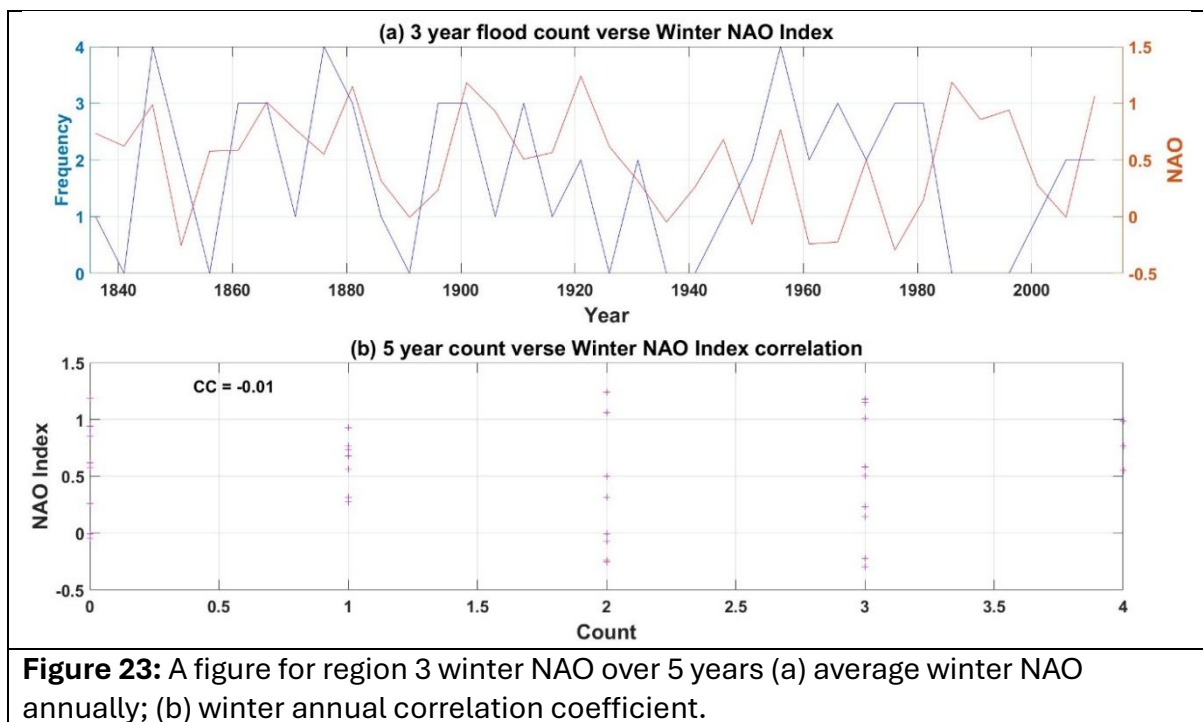
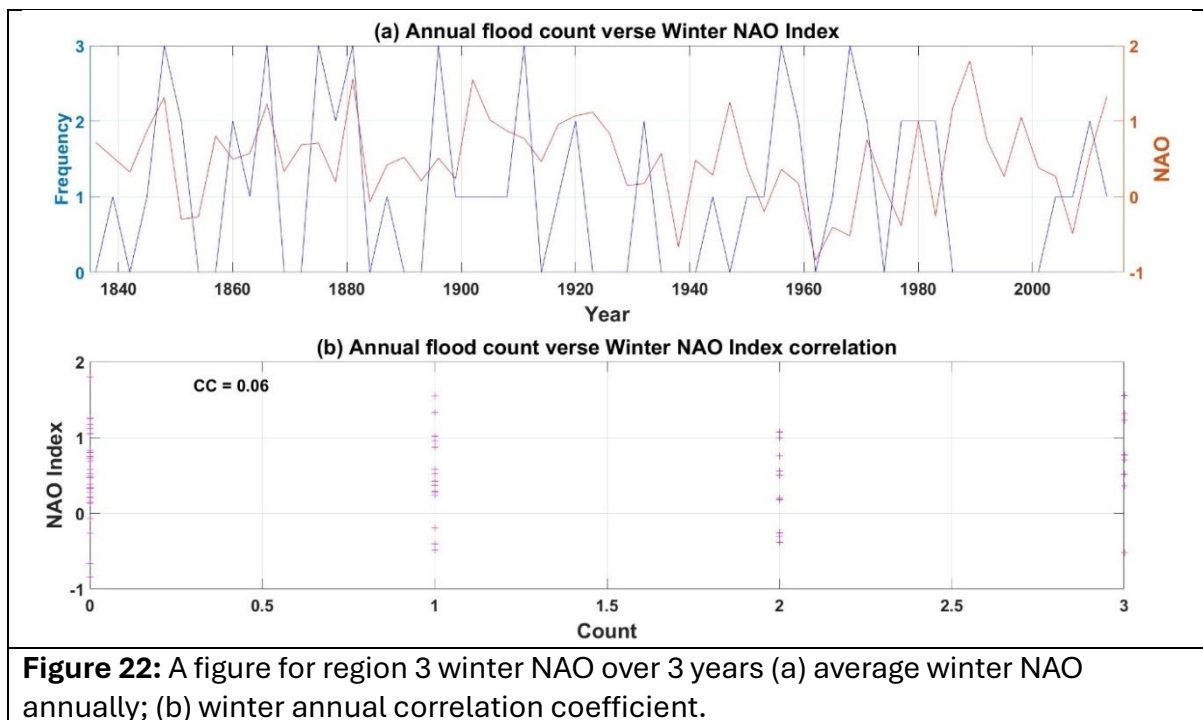


Figure 21: A figure for region 3 winter NAO over a 1 year (a) average winter NAO annually; (b) winter annual correlation coefficient.



(Figures 1-5) NAO for region 4

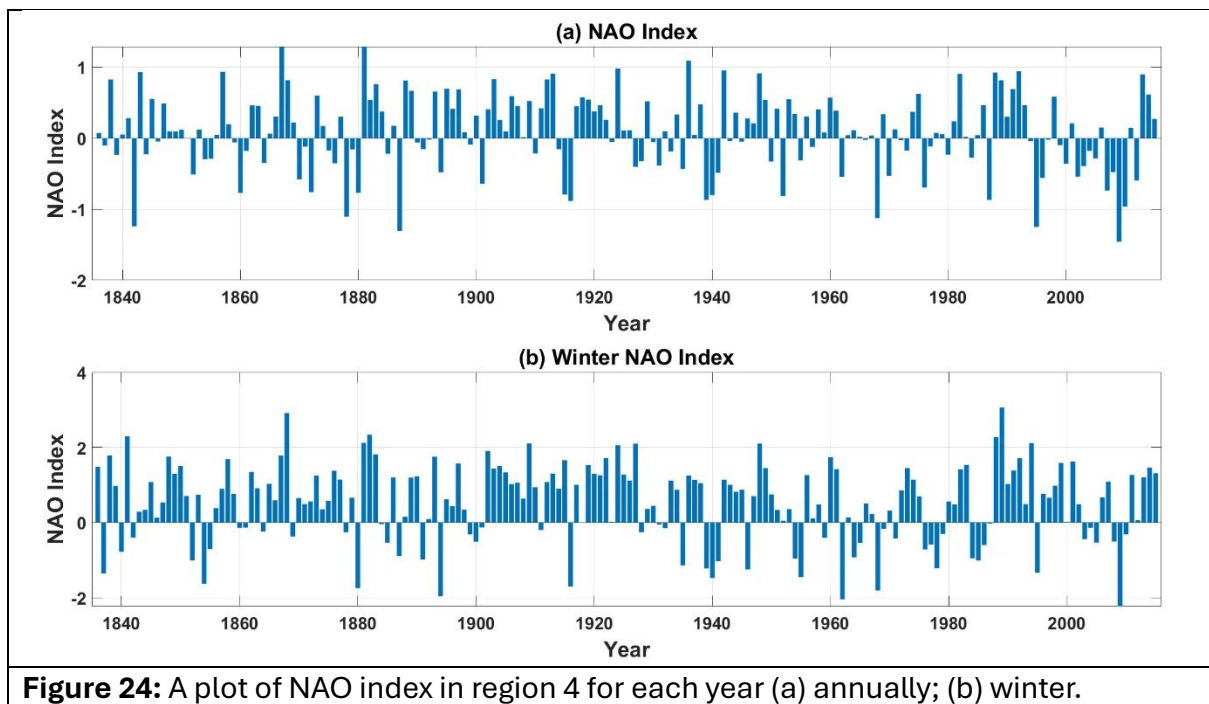


Figure 24: A plot of NAO index in region 4 for each year (a) annually; (b) winter.

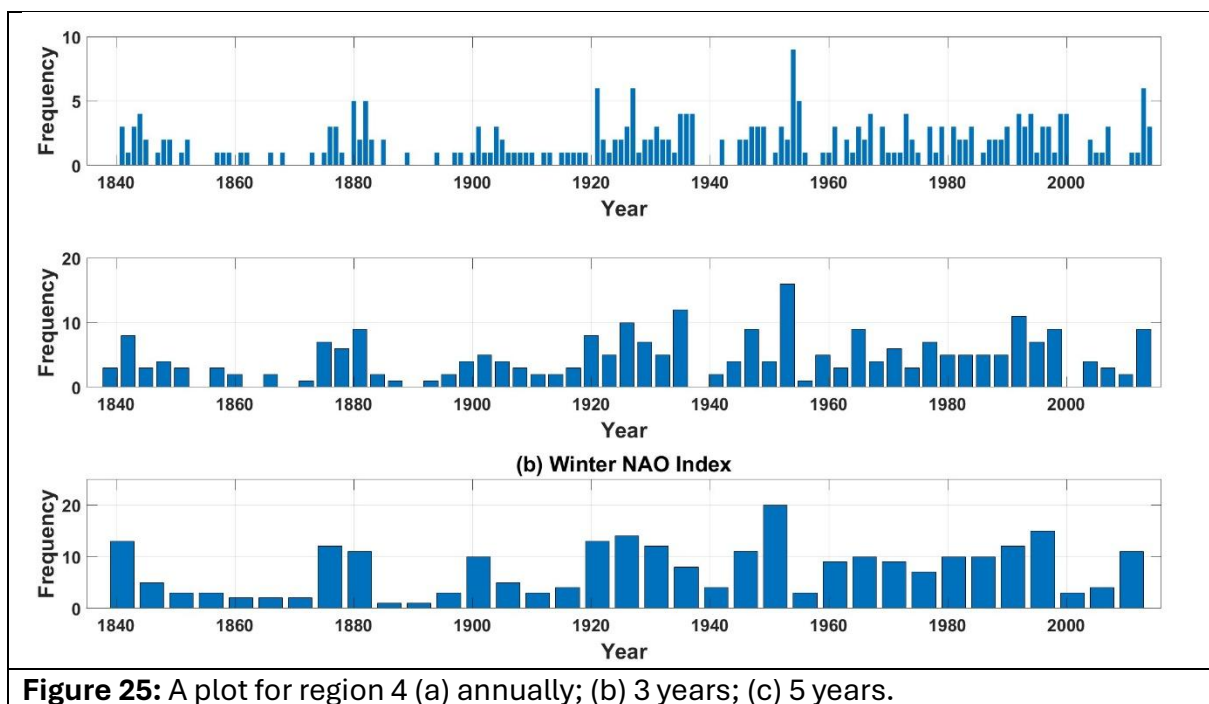


Figure 25: A plot for region 4 (a) annually; (b) 3 years; (c) 5 years.

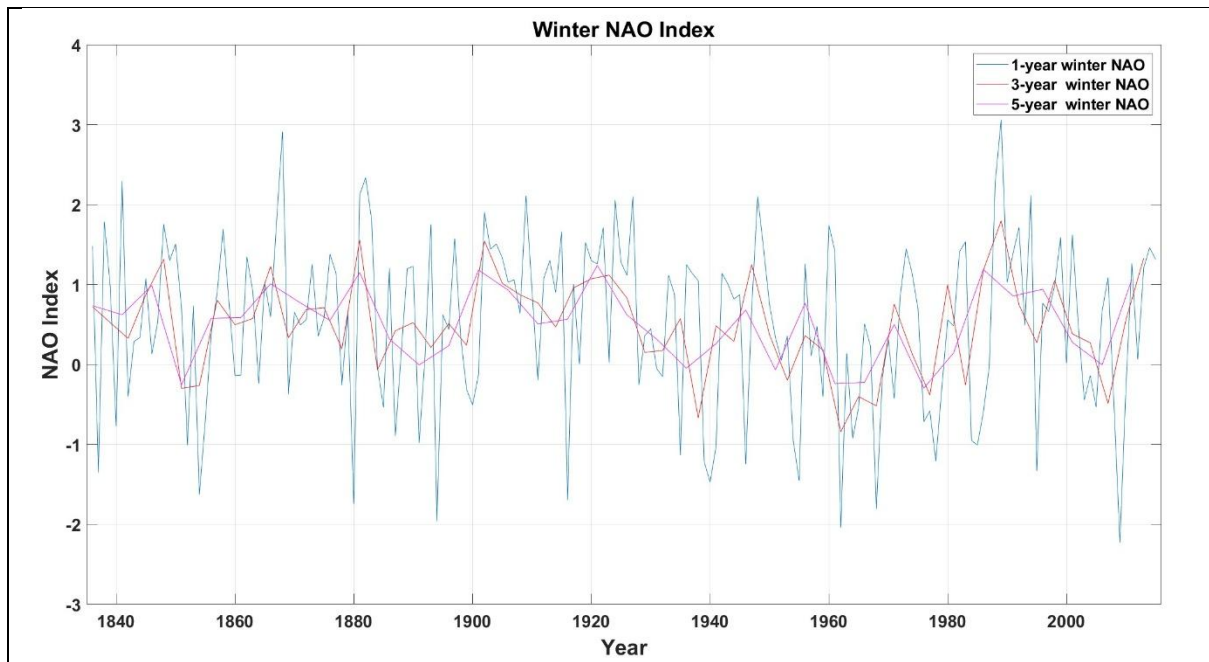


Figure 26: A figure for Winter NAO index, over region 4, averaged over 1, 3 and 5 years.

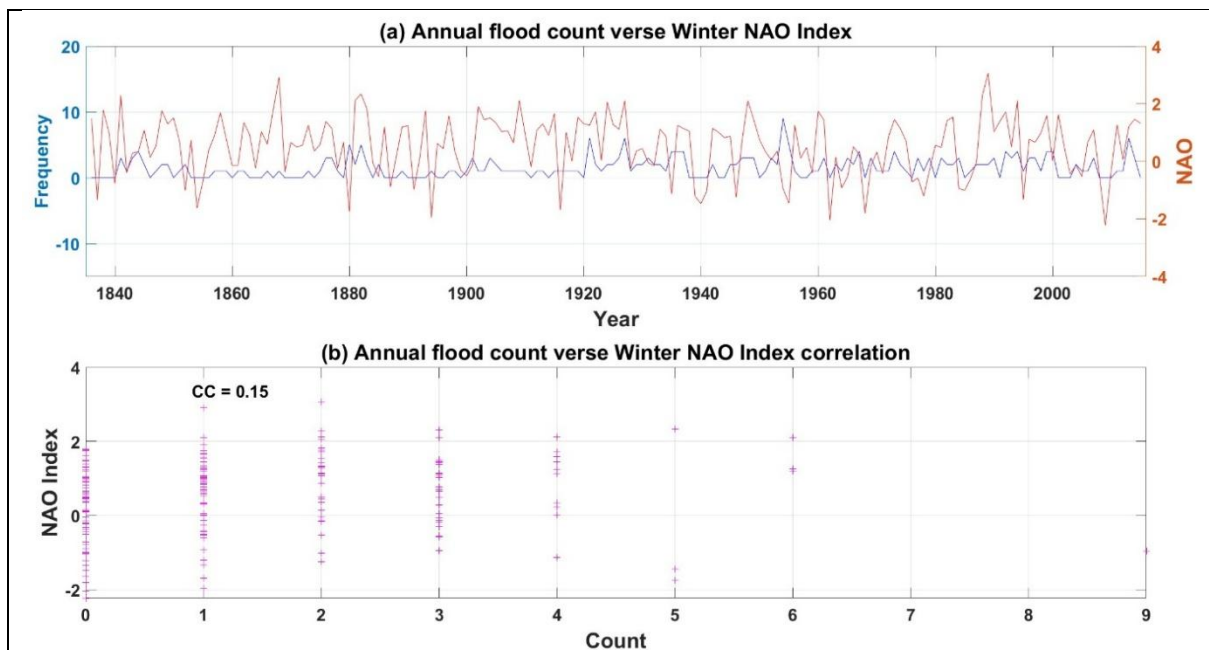


Figure 27: A figure for region 4 winter NAO over a 1 year (a) average winter NAO annually; (b) winter annual correlation coefficient.

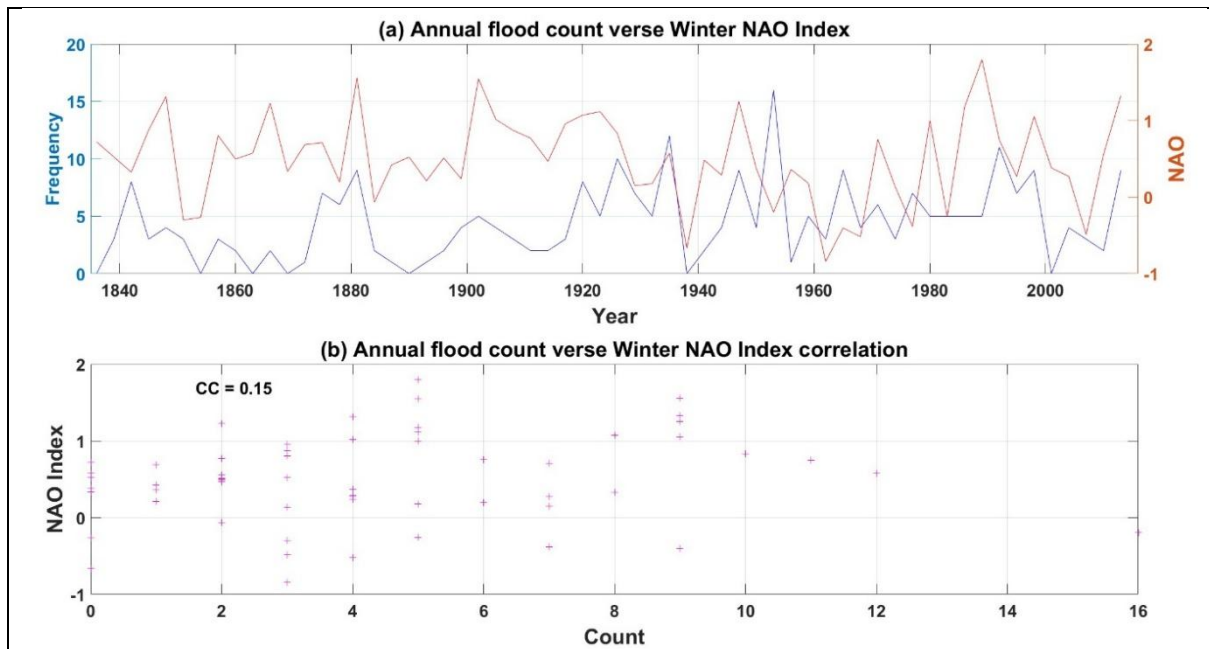


Figure 28: A figure for region 4 winter NAO over 3 years (a) average winter NAO annually; (b) winter annual correlation coefficient.

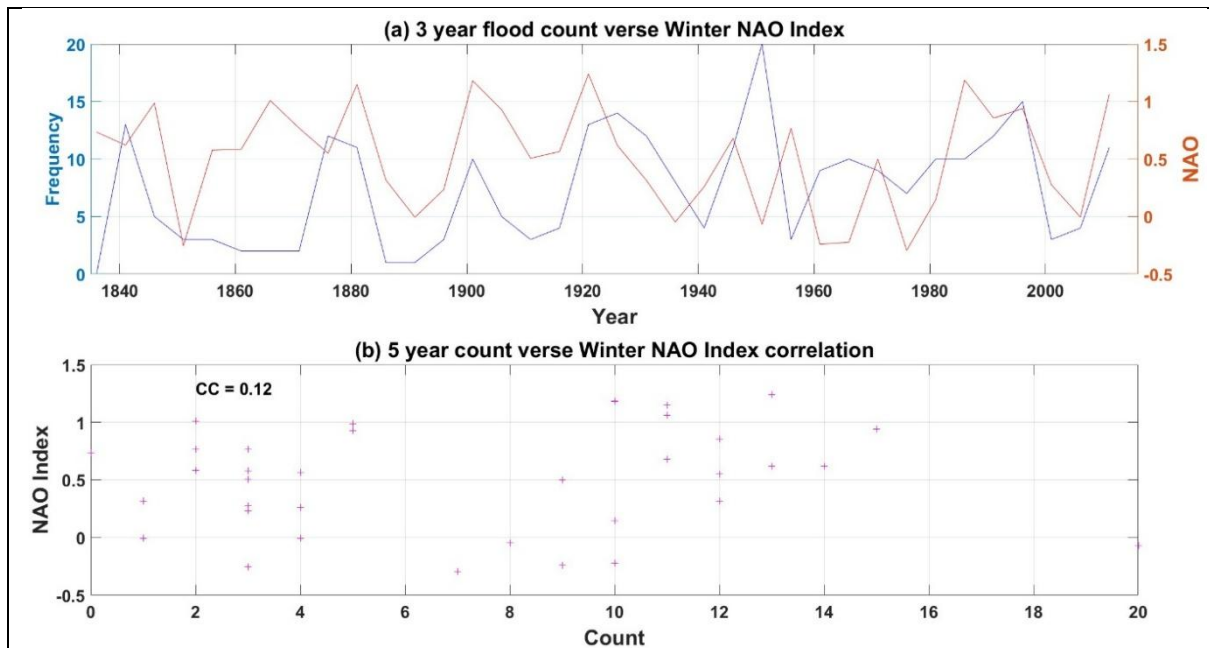


Figure 29: A figure for region 4 winter NAO over 5 years (a) average winter NAO annually; (b) winter annual correlation coefficient.