Master's thesis

Climate change in the Westfjords, Iceland

A local perspective of a global problem

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Declaration

I hereby confirm that I am the sole author of this thesis and it is a product of my own academic research.

Deirdre Bannan

Abstract

Climate change is one of the most pressing issues of our time. Climate has fluctuated considerably over Earth's history, however we seem to be now in a period of climate warming that is novel in its anthropogenic causes and impacts on human livelihoods in manifold ways. This warming is predicted to have many global consequences, including ecosystem damage, spread of disease and sea level rise, which gives rise to investigate the impact of these changes. Iceland, located in the middle of the North Atlantic Ocean just south of the Arctic Circle, is experiencing increasing risks to its physical, biological and social systems. This study aims to analyse and communicate climate change from a local perspective, focusing on the Westfjords region in north-western Iceland, by assessing the changes in air temperature and precipitation, and evaluate their potential impact on physical, biological, and social systems. Existing temperature and precipitation data were collected from weather stations located around the Westfjords. These were used to model trends of climate change in the region at an unprecedented resolution. The results show that the period 2001-2020 has been warmer than a 1961-1990 reference period for almost every month of every year. Furthermore, that warming has been more pronounced in the winter months. A pattern of seasonality that was detectable at the beginning of the twentieth century is notably reduced at the beginning of the twenty-first century. Precipitation analysis suggests that precipitation has increased during 1991-2020 compared to 1961-1990. These detected patterns mirror some of the major predictions about climate change but also highlight the importance of gaining further local perspectives. The Westfjords region should adopt careful management and adaptation strategies for the impacts of climate change going forward.

Útdráttur

Loftslagsbreytingar eru eitt af mest aðkallandi málefnum líðandi stundar. Loftslag hefur í gegnum jarðsöguna sveiflast töluvert, þær breytingar sem nú eiga sér stað virðast hins vegar ekki eiga sér hliðstæðu í sögunni. Núverandi loftlagsbreytingar eru þegar farnar að hafa mikil áhrif á lífsviðurværi jarðarbúa á ýmsan hátt, og því er spáð að áframhaldandi hlýnun loftlags muni hafi margvíslegar afleiðingar á heimsvísu, eins og til dæmis hnignun vistkerfa, útbreiðslu sjúkdóma og hækkun sjávarborðs. Svo umfangsmiklar breytingar kalla á auknar rannsóknir á mögulegum áhrifum þeirra. Ísland, staðsett í miðju Norður Atlantshafi rétt sunnan við heimskautsbaug, hefur ekki farið varhluta af auknum loftlagsbreytingum og áhætta vegna loftslagstengdra breytingar á náttúrufar, lífríki og samfélag landsins virðist aukast ár frá ári. Markmið þessarar rannsóknar er að greina loftslagsbreytingar á Vestfjörðum og meta möguleg áhrif þeirra á náttúrufar og lífsviðurværi íbúa á svæðinu. Upplýsingum um hitastig og úrkomu var safnað frá öllum veðurstöðvum á Vestfjörðum eins langt aftur og tiltæk gögn ná, og gögnin greind og kortlögð í hárri upplausn. Niðurstöður sýna að tímabilið 2001-2020 er hlýrra en viðmiðunartímabilið 1961-1990, og á það við um næstum alla mánuði hvers árs. Jafnframt sýna niðurstöður að hlýnunin er mest yfir vetrarmánuðina. Eftirtektarvert er að mynstur árstíðarsveiflu sem greinanleg er í upphafi síðustu aldar, minnkar í upphafi þessarar aldar. Úrkomugreining bendir enn fremur til þess að úrkoma hafi aukist á árunum 1991-2020 miðað við 1961-1990. Þessi mynstur endurspegla nokkrar af helstu spám um loftslagsbreytingar og undirstrika jafnframt mikilvægi aukinna rannsókna á staðbundnum áhrifum loftlagsbreytinga til að auka skilning á áhrifum breytinganna á náttúruvá og samfélagslega innviði á hverju svæði fyrir sig.

I would like to dedicate this thesis to my Dad, who is not well at the moment. Thank you for always supporting my education.

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Acronyms and abbreviations

AMAP: Arctic Monitoring and Assessment Programme

AMO: Atlantic Multidecadal Oscillation

AMOC: Atlantic Meridional Overturning Circulation

a.s.l.: Above sea level

CO_2: Carbon dioxide

COP: United Nations Climate Change Conference

Corine: Coordination of information on the environment

DEM: Digital Elevation Model

DJF: December, January and February

FAO: Food and Agriculture Organisation of the United Nations

GHGs: greenhouse gases

GDD: growing degree days

H^+: Hydrogen ion

IDW: inverse distance weighted

IMO: Icelandic Meteorological Office

IPCC: International Panel on Climate Change

JJA: June, July and August

ka: thousand years before present

LMÍ: The National Land Survey of Iceland

Ma: million years before present

NAO: North Atlantic Oscillation

ppm: parts per million

SST: sea surface temperatures

WHO: World Health Organisation

WMO: World Meteorological Organisation

Acknowledgements

I would like to thank my advisors, Ben and Rannveig for all their valuable input and help throughout this project. I would like to acknowledge the Arctic Hubs project for providing some funding to do the work. I would also like to thank my family and friends for always being there for me, and especially Conor who has been supportive and provided me with lots of cups of tea while I worked.

1 Introduction

1.1 Study foundations

“It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.” (IPCC, 2021, p.4)

Climate change has become one of the most pressing issues of our time. In 2021, governments from around the world made pledges to try and reduce the impacts of climate change at the United Nations Climate Change Conference (COP) 26 meeting. However, it is not unusual for the global climate to change. The earth has fluctuated between various temperature states over the last billion years, sometimes with vast quantities of ice covering most of the continents, to periods with little to no ice cover (Williams, 2007). The warming that is occurring today is distinguished by the fact that it has anthropogenic causes - it is attributed to (at least in part) the increase in atmospheric carbon dioxide (CO_2) that has occurred globally since the beginning of the industrial revolution (El-Montasser & Ben-Salha, 2019; IPCC, 2021). CO_2 is a greenhouse gas that traps heat within the earth’s atmosphere, and levels of are currently higher than any period in the last 800,000 years (Ritchie & Roser, 2020). This combination of rising temperatures and rising CO_2 is predicted to have a multitude of potential implications including sea level rise, ocean acidification, ecosystem disruption, changes to weather patterns and impacts on human life (AMAP, 2021; Doney et al., 2009; IPCC, 2021; Perner et al., 2019; Rocklöv & Dubrow, 2020). The IPCC uses climate computer models to make predictions with varying degrees of certainty about how the world might change – the changes depend on the quantity of CO_2 humans continue to emit (IPCC, 2021).

Arctic regions are reported to be feeling climate change acutely, with sea ice retreating and land ice melting (Overland et al., 2019). Temperatures are rising fast in the Arctic with the Arctic Monitoring and Assessment Programme (AMAP) reporting in 2021 that annual mean surface temperature rise was three times higher than the global average for the period 1971-

2019 (AMAP, 2021). AMAP also reports an increase in precipitation, particularly during the colder months - listed as October-May. Changes in air temperature and precipitation are seen as key indicators for Arctic climate change (Box et al., 2019).

Iceland lies just beneath the Arctic circle and is likely to feel the effects of these changes. Studies have shown that Iceland has warmed in recent decades. Crochet & Jóhannesson (2011) created temperature anomaly maps of the whole of Iceland and showed that the decades 1991-2000 and 2001-2010 to be warmer on average, by up to 1.25 degrees, compared to the 1961-90 mean temperatures. Similarly the Icelandic Meteorological Office (IMO, 2018) reported that between 1980-2016 there was a warming trend of 0.47°C per decade for the country. Most published data from Iceland does not include the most recent complete decade, 2011-20.

Climate change is often presented in a global or national context. Studies have shown that many people in western societies view the impacts of climate change as problems that are somehow far away, either in space or in time (Ballew et al., 2019; Whitmarsh & Capstick, 2018). This disconnect from the problem means there is scope for continued and improved climate change communication. Several studies therefore recommend including a local perspective on climate change as a means of making the public more engaged (Chadwick, 2017; Sheppard et al., 2011).

This study brings a local perspective by focusing on the high-latitude region of the Westfjords, in north-west Iceland. The Westfjords is a rural region scattered with small coastal communities that faces many potential challenges - from rising temperatures changing pollination patterns to freshwater input from precipitation and melting ice altering soil content and marine environments (AMAP, 2019). The Westfjords region is characterised by steep mountains and is prone to both avalanches and landslides which are heavily influenced by climatic patterns, particularly precipitation (Decaulne & Saemundsson, 2006). Some of the main industries in the Westfjords include fisheries, tourism and aquaculture which are all likely to experience changes with a change in climate.

1.2 Aim and Objectives

The aim of this study is to analyse and communicate climate change from a local perspective, focusing on the Westfjords region in Iceland. It will assess the changes in air temperature and precipitation that are occurring in the Westfjords and produce an evaluation of what impact they might have on physical, biological, and social systems.

To achieve its aim the study has the following objectives

1. Identify how climate change may affect the Westfjords region using the available literature. This will include examples of physical systems, ecosystems and industries that are specific to the Westfjords that may be impacted by climate change.

2. Analyse the available weather observations to see what changes in air temperature can be detected in the Westfjords over the period 1901-2020 and what changes in precipitation can be detected from 1961-2020.

3. Assess how the local climate observations compare with regional and global climate trends.

4. Use visualisation through graphics and maps to make the findings accessible and easy to read to communicate these changes and resulting potential impacts of climate change in the Westfjords region.

1.3 Thesis Structure

This thesis is divided into seven chapters. Chapter 1 (this introduction) gives a brief overview of the foundations for the study and describes the aims and objectives of the study. The literature review in chapter 2 is divided into five key sections. The first section describes climate fluctuations and how they occur. The second section focuses more specifically on climate changes that are occurring in the Arctic. The third section discusses some of the global implications of climate change and the fourth section puts the focus on Iceland and its climate. The fifth and final section talks about climate change communication. Chapter 3 is dedicated to the study site and describes the geography and climate of the Westfjords, as well as highlighting some systems in the Westfjords region that are at particular risk of being affected by climate change. Chapter 4 describes the methods used and gives summaries of data type and availability. The results are presented in the chapter 5, with graphics and written descriptions. The results are summarised with the annual, winter and summer trends, with additional details provided in the appendix. They are grouped into three sections – temporal analysis, spatiotemporal analysis and the climate change impact map which combines results and implications. Chapter 6, the discussion, is divided into two sections. The first discusses the results tie in the context of national and global observations and projections and addresses some of the limitations of this study. The second section of the discussion focuses on the impacts of climate change, and what measures could be taken in response to them. The thesis ends with a conclusion in chapter 7.

2 Background

2.1 Climate fluctuations

Throughout its history Earth has fluctuated between icehouse and greenhouse states. Icehouse states are characterised by waxing and waning ice caps at high latitudes and greenhouse states by warmer temperatures and small or no ice caps (Council et al., 2011). This definition means that Earth is currently in an icehouse state and has been so since the evolution of humans and for the previous 30 million years (Ma)[1] (Council et al., 2011). Much has been learned about past climate from fossil records, submarine glacial deposits and analysis of ice cores (Andrews et al., 2000; Denk et al., 2011; T. Einarsson & Albertsson, 1988; Steffensen et al., 2008).

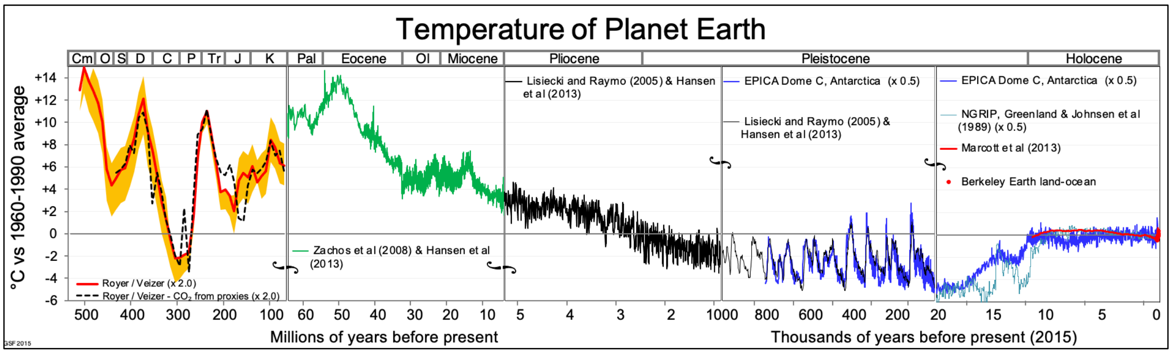

Figure 2.1 Earth's temperature over the previous 500 million years (Modified from Fergus, 2014)

Earth has gone from having surface temperatures above 100°C around the time of formation (Sleep et al., 2001) to having ice caps potentially as far reaching as 30° north and south of the equator 750–580 Ma (Schrag et al., 2002). The Paleocene-Eocene Thermal Maximum (PETM), ~56 Ma, is associated with a 5-8°C rise in global air temperature (McInerney &

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[1] Ages of past events are given as millions of years before present (Ma) or thousands of years before present (ka)

Wing, 2011) as well as ocean temperature rise and acidification (Zachos et al., 2005). Earth has undergone a cooling trend for the last 50 Ma (Figure 2.1), with continental scale icing of Antarctica occurring just over 30 Ma (Fernández et al., 2021). The Pleistocene epoch is characterised by alternating glacial and interglacial periods, the penultimate interglacial being the Eemian period and the emergence from the last glacial maximum into our present interglacial Holocene epoch (Pages, 2016).

The Holocene epoch began ~11.7 ka and is warm relative to the preceding Pleistocene glacial periods (Steffensen et al., 2008). The data from the Greenland Ice Sheet drilling projects is clear for this period, as the ice can be viewed in annual rings (Dansgaard et al., 1993). The ice core samples show that climatic instability is prevalent (Dansgaard et al., 1993; Steffensen et al., 2008) and that abrupt changes in climate patterns can be detected over a very short period of time, as little as a year (Steffensen et al., 2008). Particularly in the north Atlantic region, ice core records and timings of climate change have been validated with marine sediment and glacial fluctuation records (Mayewski et al., 2004). The Holocene epoch has been subject to climate variability, with Mayewski et al., (2004) discussing up to 6 periods of rapid climate change, defined as change happening in the space of a few centuries or shorter. The Holocene climatic optimum occurred around 8-6 ka with summer temperatures being warmer than they are today in northern latitudes (IMO, 2018). The previous millennium began during what is sometimes referred to as “the medieval warm period”, a relatively warm period for at least the north Atlantic region during approximately the years 950-1250 (Cronin et al., 2003; Mann et al., 2009). Reconstructions of sea-surface temperatures in the northeast Atlantic show a variable cooling trend and declining sea-surface temperatures from the 12th-19th century (IMO, 2018). This is also associated with glacial advance in Europe, between roughly 1500-1900, sometimes referred to as the “Little Ice Age” (Cronin et al., 2003; Free & Robock, 1999). This has been followed with a warmer twentieth and early twenty-first century, which has coincided with an increase in atmospheric CO_2 concentration (Figure 2.2) (Cronin et al., 2003; IPCC, 2021; NOAA, 2020). The average rate of global surface temperature increase has been 0.07°C per decade between 1880 – 2019 and this rate has increased to 0.18°C per decade since 1971 (Blunden & Arndt, 2020).

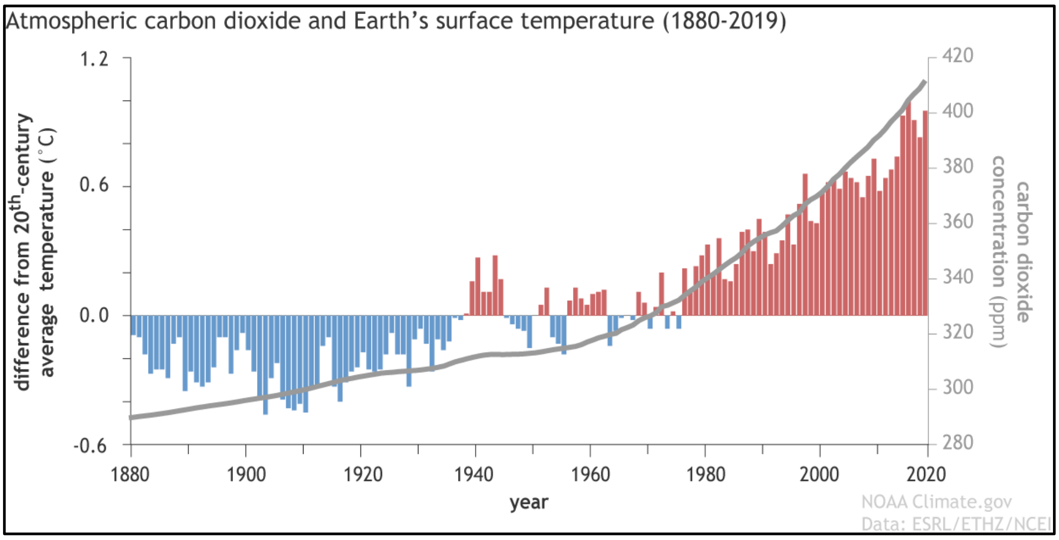

Figure 2.2 Global average temperatures and atmospheric CO2 concentration from 1880-2019. Temperatures are displayed relative to a twentieth century mean (coloured bars), with atmospheric CO_2 concentration overlaid (grey line) (NOAA, 2020).

There are multiple potential causes for the dramatic shifts in global climate. These include changes in solar radiation, changes in the concentration of greenhouse gases or blocking of the sun by volcanic aerosols (Crowley, 2000; Miller et al., 2010). Changes in the quantity of solar radiation reaching earth are brought about by cyclical changes in the properties of the earth's orbit, such as its orbital eccentricity and axial tilt (Ritchie & Roser, 2020). These fluctuations, known as Milankovitch cycles after the scientist who proposed them, are thought to be a dominant driver of the major ice ages of the past (Spiegel et al., 2010). Changes to the climate can be amplified or altered by modifications to ocean currents, which help to transport global heat from the equator (Reid et al., 2009) and the albedo effect, by which more heat is absorbed by dark surfaces, and reflected by light surfaces (Nuttall, 2005).

CO_2 and other gases, such as methane, nitrous oxide and water vapour are known as greenhouse gases due to their ability to trap heat in a similar manner to greenhouses (Kweku et al., 2018). Solar irradiance arrives to the earth as ultraviolet radiation, and some of this heat is emitted from the earth as infra-red or long wave radiation. Greenhouse gases act by absorbing and re-emitting this heat, essentially trapping some of it within the earth's atmosphere as opposed to it being lost to space (Kweku et al., 2018; Ramanathan & Feng, 2009). This effect contributes to keeping the world at a habitable temperature for life as we know it - the world is 33°C warmer than it would be without the greenhouse effect (Tuckett, 2018) - but it also is contributing to the warming of the planet we see today (IPCC, 2021;

Karl, 2003; Spiegel et al., 2010). This warming trend involves global temperatures increasing faster since 1970 than any other 50-year period in the last 2000 years and ocean temperatures warming faster than any period since the last deglacial transition, approx. 11 ka (IPCC, 2021).

What distinguishes the climate warming seen today is that it is almost certainly caused by *human emissions* of greenhouse gases, particularly CO_2 (Crowley, 2000; IPCC, 2021; Ritchie & Roser, 2020). Atmospheric CO_2 concentrations fluctuated in the past but the burning of fossil fuels and land use change by humans has caused the quantity of CO_2 in the atmosphere to increase to levels greater than the previous 800 ka (Ritchie & Roser, 2020). Methane and nitrous oxide levels are also higher than any time during this period (IPCC, 2021).

In the past 270 years, atmospheric CO_2 has risen from 280ppm by volume to a current level of around 400ppm by volume (Tuckett, 2018). This rate of change has been much faster than previous fluctuations in CO_2. Whereas historic changes could take millennia to occur, this change has been much more rapid -about 100 times faster than increases that occurred at the onset of the Holocene (NOAA, 2020; Ritchie & Roser, 2020). This fast rate of change leaves little time for biological systems to react and adapt. The lifetime of a molecule of CO_2 in the atmosphere is in the region of a century or more (Ramanathan & Feng, 2009). This means the effects of CO_2 will be felt for some time even if emissions were to slow down or stop. Without a reduction in emissions, it is projected that atmospheric CO_2 could increase to levels not seen in the last 30 Ma (Council et al., 2011).

Rising CO_2 levels are not only having an atmospheric effect, they are also making an impact on global oceans, by influencing both the temperature and acidity of the ocean. The oceans have absorbed over 90% of the excess heat generated by anthropogenic activities (Cheng et al., 2021). Atmospheric CO_2 is dissolved by the ocean, with surface levels reaching an equilibrium with the atmosphere after a period of approximately a year (Doney et al., 2009). The ocean is estimated to have absorbed some 20-30% of anthropogenic CO_2 from the atmosphere (IPCC, 2021). CO_2 and water form carbonic acid, which can then dissociate to form bicarbonate ions, with the release of hydrogen ions (H^+). The increase in H^+ leads to a decrease in pH, ($pH = -log10[H+]$) causing ocean acidification. This could impact any organism that is sensitive to pH but it is of particular concern to calcifying organisms, as increasing acidity causes the dissolution of calcium carbonate, which is the structural component of many shells and skeletons for many species such as corals, echinoderms and molluscs (Doney et al., 2009; García-Ibáñez et al., 2021).

2.2 Climate in the Arctic

The Greenland ice sheet has been of particular importance to understanding the climate of the 250 thousand years before present (ka). Here, drilling projects have allowed records of past climates kept in its ice to be viewed. Analysing the extracted ice for changes in isotope ratios, trapped gas and dust allows for assumptions to be made about past climate – for example the ratio of stable oxygen isotopes can be used as a proxy for air temperature (Dansgaard et al., 1993; Steffensen et al., 2008). For time periods beyond the scope of ice-cores, information about the earth's climate must be reconstructed from rocks (Council et al., 2011).

Iceland was formed in the Miocene epoch, around 15 Ma with warmer global temperatures than today. There has been a cooling trend since its formation, with the northern hemisphere ice sheets forming around 5 Ma (J. E. Hansen & Sato, 2012). 2.6 Ma marks the beginning of the Quaternary period and the cold Pleistocene epoch with glacial and interglacial periods over the Northern hemisphere (Símonarson & Eiríksson, 2008). The interglacial periods sometimes show substantial warming, with temperatures reaching as much as 5°C higher than today during the Eemian interglacial (the penultimate interglacial, ~124 ka) (Andersen et al., 2004; Miller et al., 2010). At the peak of the last glacial maximum in the Arctic, around 21 ka, air temperatures were as much as 20°C colder than they are today (Miller et al., 2010). Today, most Arctic regions experience below freezing temperatures from October-May (Box et al., 2019) and Arctic lands have seasonally varying snow and ice cover, and ocean areas may experience seasonal or year-round sea ice (Nuttall, 2005). The Arctic today is experiencing diminishing sea ice extent, rising air temperatures and rising sea surface temperatures (AMAP, 2021; Box et al., 2019; Overland et al., 2019)

A particularly important climate driver in the Arctic is the albedo effect, where solar radiation is reflected by white surfaces and absorbed by darker ones (Nuttall, 2005). Clean sea ice reflects more solar heat, whereas sea ice darkened by pollutants, sea ice melted to expose the darker ocean, or the expansion of dark boreal forests will allow for more heat to be absorbed (Jeffries et al., 2013; Meredith et al., 2019; Miller et al., 2010; Previdi et al., 2021). Low albedo creates a positive feedback loop of warming. Conversely high albedo - characterised in the Arctic by larger areas covered by older sea ice - will cause cooling, and is thought to have been a contributing factor to the little ice age (Geirsdóttir et al., 2009). Low albedo in the Arctic is a contributor to the phenomenon of Arctic amplification, where the Arctic air temperatures are warming faster than lower latitudes (Cohen et al., 2020; Previdi et al., 2021). Arctic amplification is concentrated in the winter months (Box et al., 2019; Cohen et al., 2020; Newton, 2007; Rantanen et al., 2021)

Arctic amplification today is so pronounced that the increase in mean surface temperature (land and ocean) between 1971 and 2019 was three times higher than the increase in the global average during the same period (AMAP, 2021). Box et al. (2019), showed that air temperature warming in winter was 1.3°C higher than it is in summer over the period 1971-2017. This means the amplitude of the seasonal cycle has decreased over this time (Box et al., 2019). It has also been observed that warm temperature extremes are increasing and cold temperature extremes are decreasing (AMAP, 2019). In 2016, surface temperatures in the Arctic averaged 5°C above expected during October-December with daily anomalies being as much as +16°C in some areas (Simpkins, 2017). Cold spells lasting more than 15 days are very rare since the beginning of the twenty first century (AMAP, 2021). The IPCC states that this change in extremes is a global trend and it is “virtually certain” that it will continue (Pachauri et al., 2014).

While the evidence for rising temperatures is clear, evidence for changes in precipitation in the Arctic are reported with more uncertainty. It is estimated that annual precipitation has increased 1.5-2% per decade from 1971-2017, with the strongest increase during October-May (AMAP, 2019; Box et al., 2019). The nature of precipitation has been changing too, with an increase of rain on snow events, and a shift to precipitation falling as rain instead of snow - especially in Scandinavia and Baltic regions. This is coupled with an observed decrease in snow extent in the Arctic, particularly in the spring (Box et al., 2019; Overland et al., 2019).

It is projected that the Arctic will continue to warm faster than the global average, and that warming will be greater in the winter months than in the summer months (AMAP, 2021; Meredith et al., 2019; Pachauri et al., 2014). This means the observed decrease in the amplitude of the seasonal cycle may continue. Projections about Arctic warming are unanimous for the near future, but in the second half of the 21st century projections about warming vary depending on the amount of greenhouse gases humanity continues to emit (Overland et al., 2019).

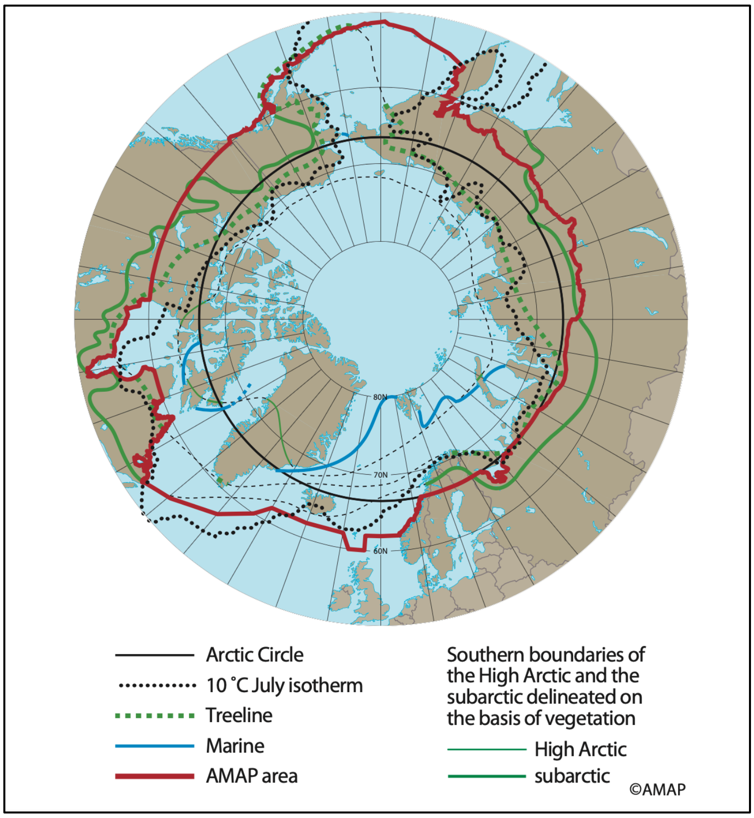

Figure 2.3 High latitudes of the Northern Hemisphere with various Arctic boundaries. Modified from the Arctic Monitoring and Assessment Program/AMAP, 2010.

Depending on the definition used, Iceland may be considered part of the Arctic (Figure 2.3). The Arctic circle includes the northern regions where there is at least one day a year the sun does not set. Mainland Iceland is just south of this boundary (Nuttall, 2005). Another way define the Arctic is to use the 10°C isotherm, where the warmest month averages at or below 10°C. This would include part of, but not all of Iceland (Nuttall, 2005). However Iceland is a member of the Arctic Council, and the Arctic Council working groups, which publish a lot of reports on the people and environment in the Arctic include Iceland in their publications (AMAP, 2019; CAFF, 2021). Many papers which are published on th subject of the Arctic define the Arctic on their own terms. The southern boundary may be set at 60°N (Box et al., 2019; Overland et al., 2019; Previdi et al., 2021), 65°N (Ivanov et al., 2019) or 70°N (Davy et al., 2018).

2.3 Global Implications of Climate Change

There is a vast amount of literature discussing how the warming climate trend we are seeing today is going to affect physical, biological and social systems worldwide. There are varying degrees of certainty about each speculation. The IPCC attempts to bring clarity by grading its statements based on how certain the research is (IPCC, 2021). Of particular concern are tipping points (Lenton et al., 2019). Initially responses to climate change may be proportional and reversible. If a certain threshold - a tipping point - is passed, this could lead to large and likely irreversible changes to the whole climate system.

Crossing tipping points could lead to an unstoppable melting of sea and land ice or cause changes to global sea currents, particularly the Atlantic Meridional Overturning Circulation (AMOC), which is of crucial importance in the transfer of heat to the poles (Lenton et al., 2019). If certain climate thresholds are crossed there could be dire consequences for ecosystems, in particular, tropical forests, boreal forests and coral reefs are deemed to be at high risk (Lenton et al., 2019; Thostrup & Rasmussen, 2009; Venäläinen et al., 2020). This could lead to the extinction of many existing species, and the loss of global forests could both release carbon and decrease our potential for carbon capture.

Even though crossing some tipping points may be inevitable, the rate at which the consequences play out could still be controlled. For example, the melting of the Greenland ice sheet, which is occurring at an accelerating rate (M. D. King et al., 2020) could be nearing a tipping point which would mean future sea-level rise for generations to come. However, the rate of melting - and sea level rise - will depend on how much warming occurs beyond the tipping point. Predictions suggest that at 1.5°C rise it could take 10,000 years to melt, but above 2°C, it could take less than 1,000 years (Lenton et al., 2019). This is why the IPCC recommends to keep emissions and warming to a minimum and why government pledges at the COP 26 conference in Glasgow in 2021 were meant to be made in the spirit of “keep 1.5 alive” meaning to keep warming to below 1.5°C (COP UK website, 2021).

As mentioned above, the ocean has been absorbing the vast majority of the heat generated in recent decades. Global ocean heat content with respect to a 1981-2010 mean has shown an increasing trend from 1958-2020, with 2020 setting a new record for total heat content in this time series (Cheng et al., 2021). As heat content rises in the ocean, this causes a reduction in the density, and a rise in the volume of seawater. This is called thermal expansion and it is contributing to a rise in global sea level. Global mean sea level has increased by 1.56 ± 0.33 mm/year from 1900-2018, with multidecadal variability. The thermosteric component of this has been greater since 2000 (to 2018) than any time in the twentieth century, however during 1900-2018 input of water from land (primarily through glacier melting) has always been the dominant contributor to global mean sea level rise (Frederikse et al., 2020). While this input from ice melting is currently increasing, it is currently comparable to rates that occurred during the 1930s. Human activities can also lead to sea level drop, with a rise in dam construction, particularly during the 1970s, leading to a sea level drop of 26 ± 9 mm between 1900-2003 (Frederikse et al., 2020). The present rate of sea level rise is expected to increase as temperatures continue to rise and land ice continues to melt (Council et al., 2011)

Global mean sea level change is different to relative sea level change, which takes into account local conditions, and vertical land movement such as subsidence or rising (Gregory et al., 2019). For example, relative sea level rise in the western tropical Pacific has been up to three times higher than the global rate from the early 1990s, while in the same period in the eastern tropical Pacific, relative sea level has declined (Martínez-Asensio et al., 2019). Tropical Pacific islands are considered to be especially vulnerable to sea level rise, as some are low lying and susceptible to coastal erosion, especially if they are sandy in nature (Martínez-Asensio et al., 2019). Subsidence in the Torres Islands in Vanuatu resulted in a relative sea level rise of ~20mm/year and flooding of coastal areas (Martínez-Asensio et al., 2019). Conversely some other areas of the globe, such as high latitudes in the northern hemisphere are experiencing vertical uplift due to glacial isostatic adjustment - a slow rebound in response to the thinning and retreat of ice caps (Compton et al., 2015).

Climate change is predicted to be damaging to human health and way of life. Sea level rise from land ice melt and thermal expansion of seawater not only threatens to cover coastal settlements, it also poses a risk to coastal freshwater sources and storm and sewerage drainage (Hummel et al., 2018; McKenzie et al., 2021; Patz & Olson, 2006). The IPCC reports with “medium confidence” that anthropogenic climate change has already caused an increase agricultural and ecological droughts in some areas of the globe (IPCC, 2021) and there are a projection for an increase in droughts, especially in semi-arid areas, depending on the rate of continuation of warming (Cook et al., 2018; IPCC, 2021). Droughts can lead to drinking water and food shortages, as agricultural production is hampered, and also to greater indirect effects like migration and conflict (Mukherjee et al., 2018).

There are concerns about how the current climate shift might negatively impact human health. Certain vector borne diseases are a cause for concern, particularly in tropical and sub-tropical climates. Many vector borne diseases are carried by ectothermic insects which can be very sensitive to changes in weather and climate (Ogden, 2017; Rocklöv & Dubrow, 2020). In a very simple, direct effect, cutting fossil fuel consumption would improve human health through increased air quality (WHO, 2021). Rapid global climate change has been associated with the collapse of human systems in the past. For example, droughts brought on by climate change are theorised to have contributed to the collapse of the Maya 1.2-1 ka and the little ice age (~600 years ago) to have contributed to the collapse of Norse colonies in Greenland (Mayewski et al., 2004).

The warming climate has led to a poleward shift of certain species (Chen et al., 2011) (Chen et al., 2011; Virkkala & Lehikoinen, 2014). This is due to species tracking their optimum thermal environment and is predicted to continue, with one study placing the observed median latitudinal shift at 16.9 km/decade, with greater shifts associated with greater warming (Chen et al., 2011). A noted limitation of this study was that most species included lived in ecosystems that were not precipitation limited. Studies in Europe have shown a northern shift corresponding with temperature increase in the range of many species, including some birds (Massimino et al., 2015; Virkkala & Lehikoinen, 2014), butterflies (Hällfors et al., 2021; Parmesan et al., 1999), certain species of trees (S. Berger et al., 2007; Dyderski et al., 2018) and foxes (Elmhagen et al., 2017). In most of these studies, the change involved an expansion of the northern range, rather than a decrease of the southern range.

However, temperature is not the only driver of distribution, and the situation is more complicated, particularly at lower latitudes. VanDerWal et al. (2013) examined the ranges of 464 bird species in Australia and found movements in response to climate change were much more complex than poleward, and even included equatorial shifts. This study estimated that focusing on poleward shifts alone, would underestimate the impact of climate change on species distribution by 26% in temperate regions of Australia, and by 95% in tropical regions. It is likely that some species are tracking precipitation, or some temperature-precipitation interaction (VanDerWal et al., 2013).

A relevant limiter of species distribution in polar and subpolar regions is the photoperiod, that is the amount of light per day. At higher latitudes, the difference between the maximum (summer solstice) and minimum (winter solstice) photoperiod rises, and the rate of change between maximum and minimum photoperiods becomes faster. Most organisms are affected by a circadian rhythm and polar organisms have developed adaptive measures to the changing photoperiod, such as low-light vision in animals, or regulation of photosynthesis in plants (Huffeldt, 2020). A poleward shift of some species may lead to circadian mismatch or a competitive weakness due to the photic conditions. So while some species may track optimal temperatures as they move north, it is possible that they will encounter a photic barrier along the way.

The threats to current life on Earth caused by climate change are being compounded by other human actions, such as habitat destruction, resource depletion and pollution in many forms - such as plastics, oil spills and other persistent organic pollutants.

2.4 Climate in Iceland

Iceland is an island located in the North-Atlantic and at the divergent boundary between the North American and Eurasian continental plates (P. Einarsson, 2008). It is situated roughly midway between Europe and North America, its closest neighbour being the country of Greenland. Geologically speaking, Iceland is a young volcanic island, with the oldest rocks being around 16 Ma (Denk et al., 2011). It has seen great fluctuations in its climate since formation, from being both warmer than the present day on formation to being completely covered by an ice sheet during the last glacial maximum. Sedimentary rocks containing fossilised flora indicate that Iceland initially had a warm humid climate with evidence of tall trees and warmth loving flowering plants from 15 Ma to 12 Ma (Denk et al., 2011). Around 3 Ma the climate showed rapid deterioration and the fossil record begins to show evidence of boreal species (T. Einarsson & Albertsson, 1988). At the peak of the last glacial maximum, around 21 ka, Iceland was completely covered in an icesheet (T. Einarsson & Albertsson, 1988; Geirsdóttir et al., 2009). This began to break up around 15 ka. By the onset of the Holocene epoch, the Icelandic ice sheet was in rapid retreat. At the Holocene thermal maximum (~8 ka), temperatures were as high as 3°C above the 1961-90 reference period (Geirsdóttir et al., 2009). Since settlement in the 9th century, Iceland has experienced the medieval warm period and the little ice age, in line with the rest of north Atlantic (Geirsdóttir et al., 2009; Thostrup & Rasmussen, 2009).

The current day climate of Iceland is kept mild for its latitude by the transfer of heat from lower latitudes via atmospheric and ocean currents (M. A. Einarsson, 1984). The glaciers in Iceland today are temperate glaciers and are more sensitive to temperature fluctuations than frozen bed glaciers (Hanna et al., 2004). Two prominent modes of climatic variability that affect the Icelandic climate are the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (also described as Atlantic Multidecadal Variability/AMV) (Börgel et al., 2020; Ministry for Environment and Natural Resources, 2018).

The North Atlantic Oscillation index (NAO) is a measurement of the difference of pressure between two semi-permanent areas of atmospheric pressure, the Icelandic low and the Azores high. If the difference between the two is great, the NAO is said to be in a positive phase, and if it is less, it is said to be in a negative phase (Iles & Hegerl, 2017; Lindsey & Dahlman, 2009). During positive NAO phases, the increased difference in pressure results in a stronger Atlantic jet stream and a northward shift of the storm track. Consequently, northern Europe (and southeast North America) experience increased storminess and precipitation, and warmer-than-average temperatures that are associated with the air masses that arrive from lower latitudes (Lindsey & Dahlman, 2009; Smith et al., 2020). Conversely during negative NAO phases, northern European regions and southeast North America experience colder and drier weather, with increased storminess and temperatures occurring in Southern Europe and north east North America.

Warm and saline water from the Atlantic is brought to the south and west via the Irminger current and this travels clockwise around the country (Figure 2,3) (Astthorsson et al., 2007; Eiríksson & Símonarson, 2021). The Irminger current is a branch of the North Atlantic Current (or North Atlantic Drift), which itself is an extension of the Gulf Stream (Krauss, 1995). The North Atlantic Current is unique in transporting warm waters much further north than in any other ocean (Rossby, 1996). It plays a crucial role in moderating the climates of the North Atlantic and Europe, and it is estimated that if it were its poleward path was diverted or reduced, North Atlantic and European land masses would see a dramatic drop in temperatures (Rossby, 1996). Colder, fresher water arrives from the Arctic and the north. There is considerable variation in the water to the north of the country, where sometimes the

Atlantic water dominates and sometimes it is negligible (Gudmundsson, 1998). The meeting of the warm salty Atlantic and colder, fresher northern waters in the Denmark strait between Iceland and Greenland is part of the formation of North Atlantic Deepwater which is a crucial contributor to the Atlantic Meridional Overturning Circulation (AMOC) and the greater global thermohaline circulation (Eiríksson & Símonarson, 2021; Saberi et al., 2020). Global thermohaline circulation refers to a massive continuous flow of seawater based on density through the earth's oceans that is important for distributing heat through the oceans and also redistributes oxygen and nutrients within the water to support life. Many climate models predict that the AMOC could weaken or alter in some way with global warming (Jackson et al., 2020). There is also a clockwise coastal current around Iceland (Eiríksson & Símonarson, 2021).

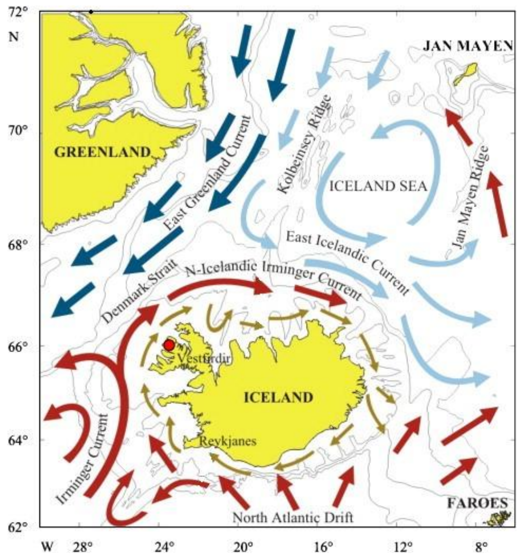

Figure 2.4 Ocean currents around Iceland. Red arrows: relatively warm Atlantic water; Dark blue arrows: cold, polar water of low salinity; Light blue arrows: Arctic water; Dark yellow arrows: Icelandic coastal current. Grey lines show 200, 500 and 1000 m depth contours. Red dot = Westfjords Peninsula. (Modified from Astthorsson et al., 2007)

The AMO is a variability in sea-surface temperatures in the North Atlantic that changes on a multi-decadal time scale and affects the climate in its vicinity, with a positive AMO usually associated with warmer temperatures in the North Atlantic and a negative AMO associated with colder temperatures (Nye et al., 2014; Wang et al., 2017). It is thought to be driven, at least in part, by the strength of the AMOC (Drinkwater et al., 2014). These natural variations can amplify or mask anthropogenic climate change (Iles & Hegerl, 2017; Nye et al., 2014).

Fluctuations in the NAO and AMO have been associated with changes in biological organisms, including zooplankton, fish, birds and arctic foxes (Báez et al., 2021; Haest et al., 2018; Hátún et al., 2016; Hersteinsson et al., 2009; Nye et al., 2014). This gives a precedent to assume human induced climate change will alter ecosystems, although perhaps adds difficulty to separate natural population fluctuations from those that are anthropogenically forced.

The longest continuous collection of climate data in Iceland is from Stykkishólmur, which dates to 1845, and in 1872 the Danish meteorological society founded a network of stations in Iceland (Bjornsson et al., 2007). Data from the pre-1900 period of this record shows greater temperature variations which is thought to be a product of irregular sea ice influence (Hanna et al., 2006). Icelandic glaciers reached their maximum Holocene extent towards the end of the 19th century (IMO, 2018). Iceland had an unusually cold winter at the end of 1917 and beginning of 1918. This is known as the "great frost winter" of Iceland. Thick sea ice formed in Reykjavík harbour and approximately 30 polar bears were spotted in northern Iceland, suggesting heavier than usual sea ice in the north as well. This is thought to have been driven by an extreme negative NAO (Moore & Babij, 2017).

While the late 19th and early 20th century were relatively cold, the 1920s brought a warmer period lasting to the 1950s. This was in line with a global pattern of warming, but it was particularly pronounced at high northern latitudes and in the Arctic (Bengtsson et al., 2004; Hegerl et al., 2018). Hanna et al., (2006) propose that the loss of sea ice and its climatic forcing abilities contributed to early twentieth century warming around Iceland. Colder conditions set in from the 1960s lasting until the 1990s and is associated with a period of glacial advance in Iceland (IMO, 2018). Ozone depletion by human activities is thought to have contributed to a cooling of the stratosphere during some of this time (IPCC, 2021).

A warming trend began in Iceland near the end of the 21st century, with the Icelandic Meteorological Office (IMO) reporting that between 1980-2016 there was a warming trend of 0.47°C per decade. (Björnsson & Jónsson, 2009; IMO, 2018). This is over twice the global average, and consistent with the accelerated warming that has been observed in the Arctic as a whole. A third of the glacial retreat that has occurred since the late 1800s happened since 2000 (IMO, 2018). It is reported with some uncertainty that some of the warmer periods throughout the twentieth and twenty-first century in Iceland have corresponded with increased precipitation (Hanna et al., 2004).

The IMO made an effort to separate the influence of natural variation cycles, such as the AMO, and anthropogenic effects on temperature rise. By comparing the observed trend to the predictions of the IPCCs model (CMIP5) they determined that half of the observed warming may be attributed to natural variation and half can be attributed to anthropogenic forced warming (IMO, 2018). This warming trend is projected to continue as global CO_2 emissions arise (IPCC, 2021). Warming in Iceland is expected to be greater during the winter months than the summer months, which will reduce the amplitude of the seasonal cycle (IMO, 2018).

With this observed and projected warmer weather, there is also a projection for an increase in precipitation at high latitudes (Pachauri et al., 2014). The IMO states that climate models for Iceland predict an increase of about 1.5% in precipitation for each degree of warming but it may be masked by natural variability. Climate models also indicate a tendency for an increase in precipitation during late summer and autumn with less of a tendency for an increase earlier in the year (IMO, 2018).

The marine environment in Iceland is also observed and projected to be altered by anthropogenic climate change. The melting of the Greenland ice sheet and other Arctic and sub-Arctic glaciers is predicted to cause freshening in the subpolar north Atlantic, which could in turn influence the AMOC (Dukhovskoy et al., 2019). While disruption to the AMOC may ultimately lead to cooling of the subpolar north Atlantic (Keil et al., 2020), the issues that the Icelandic marine system is facing today is a rise in sea surface temperatures (SST) and ocean acidification (García-Ibáñez et al., 2021; Lapointe et al., 2020). A reconstruction of SST in the north Atlantic suggests the warming today is unmatched on a decadal scale throughout the past 2900 years (Lapointe et al., 2020) Throughout the twentieth century, Icelandic SST have broadly followed the pattern of the atmospheric temperatures, which consists a warming during the 1920s and a cooling in the 1970s, followed by a warming in the 1990s (Hanna et al., 2006). Ocean acidification has been observed around Iceland. pH levels are declining faster than the global average, and this is particularly pronounced in the colder waters to the northeast compared to the warmer, Atlantic surface waters in the southwest (IMO, 2018). Polar and sub-polar waters have lower buffering capacity and lower natural pH than warmer waters, making them more vulnerable to acidification (Pérez et al., 2021).

Different areas of Iceland do not face the same challenges from sea level rise. Vertical uplift has been put as high as 30mm/year with a 1mm/year acceleration in areas of central Iceland near the larger glaciers (Compton et al., 2015). There is subsidence occurring on the Reykjanes peninsula and little movement in areas in the North and East (IMO, 2018). Another consideration for relative sea level is the gravitational pull of an ice sheet. As large masses such as the Greenland or Antarctic ice sheets melt, they lose their gravitational pull on the local sea water and sea levels decline in their vicinity. This is in part the reason that projections for sea level rise in the subpolar north-Atlantic in the twenty first century are 50% of the global mean (Slangen et al., 2014). The IMO suggest, with uncertainty, that a 1m rise in global mean sea level by the end of the twenty-first century would result in relative sea level change for Iceland of 40-60cm in subsidence areas, and a 10-180cm decrease in areas of fast uplift (IMO, 2018).

2.5 Climate Change Communication

"On the surface, climate change communication is about educating, informing, warning, persuading, mobilizing and solving this critical problem. At a deeper level, climate change communication is shaped by our different experiences, mental and cultural models, and underlying values and worldviews." (Yale Program on Climate Change Communication, n.d., para. 1)

Conveying the complexities and importance of climate change is a relatively recent occupation. Analysis of the effectiveness of climate change communication, and of the understanding of the general public began in the mid 1990s (Chadwick, 2017; Nerlich et al., 2010). The field has developed since then, and in some ways has been successful, with studies showing that over 70% of Americans in 2017 believed that climate change is happening (Ballew et al., 2019). Canada, many European countries and China are also reported to have a high awareness of climate change, while some populous regions of the globe such as India, Indonesia and parts of sub-Saharan Africa have been shown to have low awareness of the issue (Whitmarsh & Capstick, 2018).

However, despite awareness being fairly high in some western societies, there is disconnect from the complexities and the seriousness of the problem. Nearly half of Americans think climate change does not have human causes, and over half see the problem as something that will not affect them personally, but rather something that will affect people in the future, or people that are far away (Ballew et al., 2019).

For Iceland, a European Social Survey indicated that over 90% of Icelanders believed that climate change was happening and was at least in part caused by humans (Poortinga et al., 2018), however, a separate survey conducting interviews with Icelanders, found that almost all participants viewed climate change as a problem for future generations, rather than themselves (Jalbert et al., 2018). In spite of this high awareness, Iceland has only shown very modest decreases in total CO_2 equivalent emissions from 2009-2019, with emissions from industrial processes increasing over this time (Statistics Iceland, 2020). Whitmarsh and Capstick's review on perceptions of climate change mentions several studies that show how members of the public have a limited understanding about the relative contributions of different activities to climate change. In particular, people underestimate the influence of meat and food production, food transport and food waste (Whitmarsh & Capstick, 2018). These misunderstandings, and the disconnect between awareness of climate change and action on climate change, means there is still scope for the continuation and improvement of communication on climate change. Rahimi (2020) argues that Covid-19 levels of awareness and engagement from the public are necessary to drive "bottom up" change and really tackle the climate issue (Rahimi, 2020).

Imagery and graphics are an important means of communicating complex or wordy issues. Moser (2016) discusses how the sometimes abstract nature of climate change lends itself to be communicated through visualisation and imagery rather than text and spoken word. O'Neill et al., (2013) cite the example of imagery being key to raising public engagement about the Deepwater Horizon Oil Spill. Maps are commonly used to communicate issues about climate change, and can be seen frequently in the IPCC reports, government agency websites and newspaper articles. Fish describes the goal of maps used in these instances "to make climate change relatable, tangible, and understandable" (Fish, 2020, p.1). They are also an appropriate means of expressing climate information due to spatial heterogeneity of the subject. Fish assesses climate maps for vividness - essentially on how engaging they are to the reader. She summarises that vivid maps follow good cartographic principles and include some sort of novel design, perhaps through the use of colour or symbolisation (Fish, 2020).

One way to make climate change issues more tangible is to keep it local. The use of images of polar bears on melting ice to represent climate change has been shown to increase the perception that climate change is a distant problem (Schroth et al., 2014). Jones et al., (2017), found that the psychological distance of climate change could be reduced using messages about the proximal impact of climate change. Reduction of this psychological distance also increased intentions to engage in carbon mitigation activities (Jones et al., 2017). Sheppard et al. (2011) discuss the importance of bringing climate change information down to the local level as a means of engaging stakeholders. He mentions local community involvement as being key to implementing GHG emission targets or adaptation measures and recommends visual tools for maximum engagement and education of local stakeholders (Sheppard et al., 2011). Other review papers and the National Academy of Sciences recommend real, local events in climate change communication and citizen involvement as a way of increasing personal engagement with the issues (Chadwick, 2017; Maktoufi, 2021; Nicolosi & Corbett, 2018). This all goes to suggest that novel climate change maps and graphics of areas that people are familiar with and have a personal connection to may be a way to increase community recognition and action in the face of climate change.

2.6 Summary

Chapter 2 presents and contextualises the problem of climate change. It discusses some of the major global consequences of climate change and how warming is pronounced in the Arctic and other high latitude regions. Among those high latitude regions is the country of Iceland, and an overview of its current climate is presented. Finally, the need for effective climate change communication is emphasised. Visualisations and local perspectives are discussed as ways to increase the reach of climate change information. The following chapter leaves the global and national scale behind and focuses in on a coastal area in northwest Iceland to see what climate and climate change look like on a smaller scale. It presents the current climate and geography of the Westfjords region. It looks at the systems in place in this high latitude region to see what the implications of climate change might be for the people and ecosystems in this area.

3 Study area – The Westfjords

3.1 Geography and climate in the Westfjords region

Iceland is situated in the North Atlantic over the geological border between the Eurasian and North American tectonic plates. The Westfjords region is in its most north-westerly corner at approximately 66◦ N–23◦ W (Figure 3.1). It is a highly indented peninsula that is connected to the rest of Iceland by a 7km wide isthmus (Seyfrit et al., 2010). The Westfjords region contains over a third of Iceland's coastline (Visit Westfjords, n.d.-c) and is highly mountainous

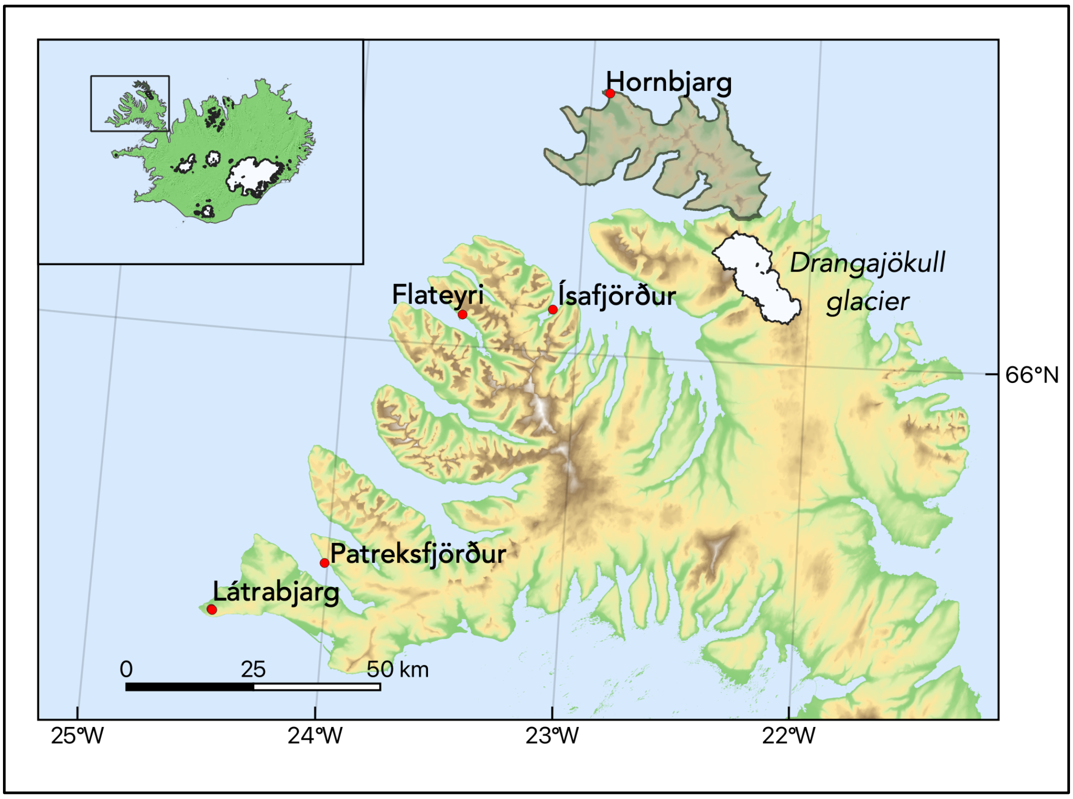

Figure 3.1 Map of Westfjords. Areas of interest discussed in this thesis are marked on the map. Shaded area = Hornstrandir Nature Reserve

It is home to approximately 7000 residents (Statistics Iceland, 2021). Most settlements and activities are at or near the coast, and the land is not ideal for agriculture (Seyfrit et al., 2010). The fjords, however, provide good conditions for natural harbours, and with fertile fishing grounds surrounding the region most towns are rooted in the fishing industry (Seyfrit et al., 2010). Ísafjörður is the largest town in the region with approximately 2700 residents in 2019 and acts as a service centre for many of the other smaller towns (Seyfrit et al., 2010; Statistics Iceland, 2021).

Due to its high northern latitude, there is a large disparity between summer and winter daylight hours. The town of Ísafjörður, for example, experiences 24 hours of daylight during the summer solstice, and only 2 hours and 43 minutes of daylight at the winter solstice (timeanddate.com, n.d.).

The climate is a subpolar oceanic climate which is relatively mild for such a high latitude and is subject to high winds and frequent precipitation (Decaulne & Saemundsson, 2006). In 2007, the reported mean temperature range for Iceland for areas below 400 m was – 2 to 9°C, and the warmest month being July and the coldest being January (Bjornsson et al., 2007). In the same year, specifically for the Westfjords, the mean annual temperature was published as 2.9°C and precipitation as 969 mm per annum at sea level (data compiled from the meteorological stations of Lambavatn, Galtarviti, Hornstrandir and Aedey) (Decaulne, 2007). There is little published about temperature and precipitation specifically in the Westfjords, and often it could be considered out of date. The IMO report that Iceland's temperatures are increasing at a rate of 0.47°C per decade, so mean figures from 2007 can quickly lose their relevance (IMO, 2018). There is a need for updated figures, and there is a lack of detail with regards the climate situation in the Westfjords region specifically.

Large scale cyclonic storm systems occur in the Westfjords, particularly in the winter. These bring heavy snowfall and strong winds – the same conditions that generally occur during or immediately preceding the release of large avalanches (Nawri, 2013). Accessibility to the Westfjords region is hampered in the winter, as winter storms often close the roads and airports (Icelandic Road Administration, n.d.).

The Irminger current has the biggest influence on the seawater in the Westfjords (Eskafi et al., 2019), however there is local variation within the fjords. For example, salinity gradients exist within fjords due to freshwater input and their restrictive shape (Munda, 1978). Eskfai (2019) showed that the water in the fjord in Önundarfjörður rarely dropped below 1°C or rose above 10°C. However, localised freezing, particularly in the mouths of the fjords, does occur during winter (Valdimarsson, 2010). The tidal range in Ísafjörður is 3.2m (Eiríksson & Símonarson, 2021).

The geology of the Westfjords consists of basaltic rocks intercalated with sedimentary layers which have been shaped by glaciation and deglaciation (Decaulne & Saemundsson, 2006; Peras et al., 2016). It is a mountainous region with most mountains peaking with flat summit areas between 600-900m a.s.l. The mountains are characterised by steep slopes, and often have rock walls in their upper sections (Figure 3.2) (Decaulne, 2005). The mountains not only give the Westfjords a distinctive shape, but also influence human activity in the area, as there is minimal accessible flat land for infrastructure and agriculture.

Figure 3.2 Steep slopes in the Westfjords. A+B: Skutulsfjörður, C: Súgandafjörður, D: Önundarfjörður [all from 2021] (Photographs Deirdre Bannan)

The mountains contribute to variability in the weather within localised regions (Ólafsson et al., 2007). Snow cover is high during the winter months, particularly in the northern part of the Westfjords (M. A. Einarsson, 1984). The topography and climate leave residents and infrastructure vulnerable to a variety of slope-processes including avalanches, landslides, slush flows, rock falls and debris flows (Conway et al., 2010; Decaulne, 2005). Deep snow on these steep slopes allows for snow avalanche formation, and large quantities of available debris on the mountains allow for debris flows. The changeable weather which includes heavy snow, rapid snowmelt and long-duration and high intensity rainfall enhances the likelihood of these processes (Decaulne, 2007). The Westfjords region has experienced severe avalanche incidents in inhabited areas in recent history, with the loss of 34 lives in two separate avalanches in 1995 (Jóhannesson, 2019; Decaulne, 2007). Much has been done in the wake of this to try and reduce the risk of slope processes, including the construction of large defences in many towns in the Westfjords and a monitoring centre in Ísafjörður (personal observation). The Westfjords however remains at risk, with an avalanche surmounting the defences in Flateyri in 2020. Ísafjörður is vulnerable to debris flows, as well as avalanches. Certain slopes above the town are limited from debris flows only by the number of triggering events (in other locations in Iceland, debris flows are supply limited) (Conway et al., 2010).

While glaciers cover around 10% of the land area in Iceland, there is only one glacier in the Westfjords, Drangajökull. It is located in the north-eastern part of the Westfjords. It is 143km^2 (in 2014) and is unusual among Icelandic glaciers in that it is entirely below 1000m elevation (Belart et al., 2017).

There are 399 bird species identified in Iceland (Petersen & Olsen, 2021) and 340 fish species within Icelandic marine waters (Valtysson & Jonsson, 2018). The only native land mammal is the arctic fox. Other mammals that have been introduced and are present in the Westfjords are domestic pets, such as dogs and cats, farmed animals such as sheep, cattle and horses and various wild species of rodents. The life in the ocean supports an important and profitable fishing industry. Wild fishing is complemented with aquaculture which is a new and growing industry in Iceland, with salmon having been farmed in the Westfjords for less than ten years (Karbowski et al., 2019).

The Westfjords receives around 20% of Iceland‘s summer tourists and 8% of its winter tourists. (Hale, 2018). Approximately 137,000 visitors arrived by plane or ship in 2017 (Vestfjarðastofa, 2018). The majority of summer tourists arrive on cruise ships, which typically dock in Ísafjörður, which is the third most popular cruise ship destination in Iceland (Hale, 2018).

3.2 Potential impacts of climate change

This section discusses some of the systems that exist in the Westfjords that may be affected by climate change. It is broken up into physical impacts, biological impacts and socio-economic impacts. Latin names of biological species are given the first time they are mentioned, and common names used thereafter.

3.2.1 Physical impacts

Physical processes can be sensitive to changes in temperature and precipitation. The physical systems at risk from a changing climate chosen for discussion are slope processes and glacial melt leading to marine freshening. These were chosen as sheer mountains and the glacier make up the Westfjords region's unique topography.

Slope processes

Weather conditions and topography in the Westfjords region are already favourable to slope processes. The main triggering conditions for avalanches in the Westfjords are strong northerly winds and heavy precipitation which create large snow accumulations on unstable slopes (Haraldsdóttir et al., 2004; Nawri, 2013). The climate predictions of warmer weather and increased precipitation could influence the number of avalanches. It is possible to draw analogies from studies on climate change outside Iceland that may apply to the Westfjords. A study from Europe suggests that warming weather may decrease avalanches at low elevations but increase the number of wet snow avalanches at higher elevations. It also notes that wet snow avalanches contain denser snow, and are therefore more difficult to preform rescues in (Strapazzon et al., 2021). AMAP (2017) describe two examples of physical processes in other Arctic regions that have been triggered by changing weather. An extreme rain-on-snow event took place in Svalbard in February 2012. The resulting ice layer increased permafrost temperatures and triggered slush avalanches which not only damaged human infrastructure but caused starvation of reindeer due to a blocked food source (AMAP, 2017). This report also describes heavier than average precipitation followed by warm spring weather which caused extensive flooding and damage in Alaska in 2015 (AMAP, 2017, p. 20). These case studies could have relevance to the Westfjords with its sub-Arctic climate and its susceptibility to land movements.

Trigger events for debris flows in Ísafjörður are rapid snowmelt or prolonged rainfall. These work by saturating the sediment stack, enhancing the instability of the sediment (Conway et al., 2010). The debris flow occurs when the sediments are undercut by water at the interface with the bedrock. Increased precipitation, or changes in precipitation patterns could affect the amount of triggering events. The mean interval between large flows for this slope in Ísafjörður is 5 years, which is more frequent than elsewhere in Iceland (Conway et al., 2010).

Increased slope processes in the Westfjords due to climate change could lead to damage to infrastructure, evacuations, road closures and increased expenditure on protection and in the worst case, loss of life

Glacial melt and marine freshening

Figure 3.3 Drangajökull glacier viewed from Kaldalón, in August 2021 (Photograph: Deirdre Bannan)

Glaciers in Iceland such as Vatnajökull and Snæfellsjökull have shown to be retreating (Ministry for the Environment and Natural Resources, 2018). Drangajökull may be impacted by future warming. Glacial melting contributes to local freshening of marine water and sea level rise (AMAP, 2019). There may be local freshening if Drangajökull is to melt but Iceland's (and the Westfjords') proximity to Greenland needs to be considered as well. The Greenland ice sheet has been losing mass for several decades and the rate of discharge has increased 14% between 1985-1999 and 2007-2018 means (King et al., 2020).

The retreat of the Greenland ice sheet in the 21st century has been attributed to some extent to anthropogenic climate forcing (Fyke et al., 2014; Perner et al., 2019). The freshwater input from the Greenland ice sheet and other Arctic glaciers is predicted to cause freshening of the subpolar north Atlantic (Dukhovskoy et al., 2019). Freshening due to glacial melt or increased precipitation will have knock on effects to both terrestrial and marine ecosystems. Increase in river discharges has led to a corresponding increase in the delivery of carbon and nutrients near Arctic coastlines (AMAP, 2019). Increased primary production in the upper portion of the Icelandic sea has been associated with increased nutrient rich freshwater discharge from the Greenland ice sheet (Perner et al., 2019).

A freshening of the marine system around Iceland would have further ecological effects. It could affect biological organisms, and again it is possible to look at studies from elsewhere that may apply to Iceland. Dickey et al., (2021) examined effects of salinity on *Asterias rubens,* the common sea star, which is present in the waters around Iceland and is a keystone predator. They found reduced incidences of predation and feeding at lower salinities as well as lower larval recruitment (Dickey et al., 2021). This was done in the Baltic Sea which is a low salinity sea, however analogies may be drawn with the Westfjords due to the range of salinities that may be present in Icelandic fjords (Munda, 1978). Pteropods are small marine organisms that are an important food source for many larger species found around Iceland, including herring, salmon, whales and birds. Their survival is negatively impacted when seawater freshening is combined with a reduction in pH (ocean acidification). Decreases in salinity combined with pH increased overall mortality and reduced swimming ability of certain species (Manno et al., 2012). Larger commercial fish can be affected by salinity too. North Atlantic cod (*Gadus morhua*) stocks collapsed in the 1990s, primarily due to overfishing but it is hypothesised that their recovery was hampered by cold and low salinity conditions in their northern range (Greene et al., 2008).

Similar to temperature, background and natural variations in salinity need to be considered. The amount of freshwater discharge from the Greenland Ice sheet and subsequent freshening of the Icelandic shelf is also dependent on the NAO and AMO phases (Perner et al., 2019)

As well as causing freshening of the marine system, glacial retreat may lead to the destabilisation of slopes due to the loss of the physical pressure of the glacier on the slope. This, compounded by the thawing of permafrost, could increase the risk of landslides (IMO, 2018). Between 2000 and 2006, land cover changes in south west Iceland were mostly attributed to the melting of glaciers and the change of course to glacial rivers (National Land Survey of Iceland, 2009).

3.2.2 Biological impacts

This subsection discusses some of the biological systems that are at risk from climate change in the Westfjords region. These are vegetation, birds, arctic foxes and marine life.

Vegetation

A classification of land type using the European Union coordination of information on the environment (Corine) classification system shows that the Westfjords is primarily "moors and heathland", "sparsely vegetated areas" and "bare rocks". Covering much smaller areas are the types "glaciers and perpetual snow", "coastal lagoons", "intertidal flats'' and "continuous urban fabric" (Figure 3.4) (National Land Survey of Iceland, 2018).

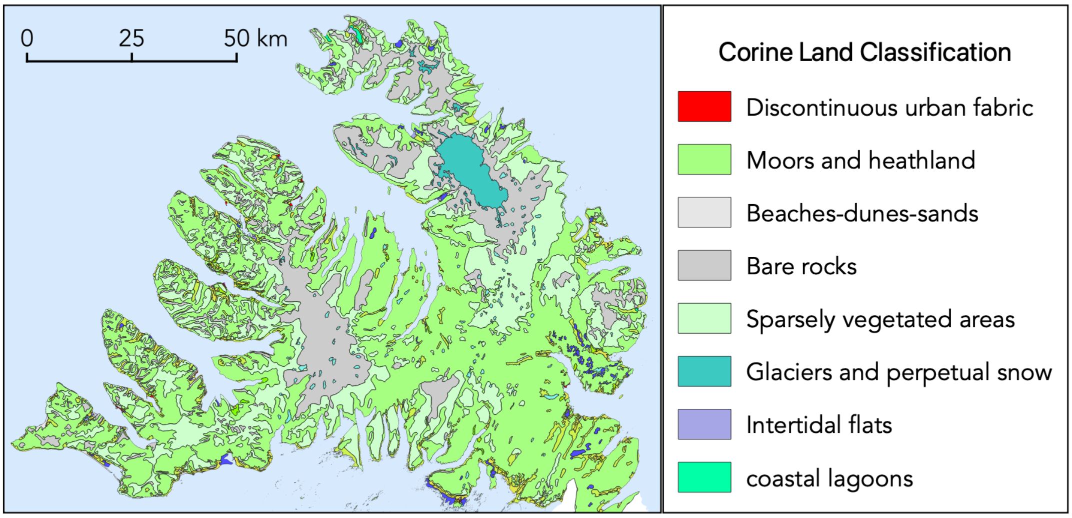

Figure 3.4 Land cover in the Westfjords. (Data source: National Land Survey of Iceland, 2018)

The Westfjords contain very little "urban fabric", but a perception of unspoiled nature is misleading. At the time of settlement, in the ninth century, Iceland had forest cover of 25-40%, mainly concentrated in low land areas (Eysteinsson, 2009). This has been destroyed over the last millennium for various anthropogenic uses, and now less than 2% of the natural woodland remains. It is not just trees that have been lost, soil erosion and desertification have contributed to the disappearance of more than half of the vegetation cover since settlement (Ministry for Environment and Natural Resources, 2018).

Modelling by Ólafsdóttir et al. (2001), suggests that Icelandic vegetation was in a period of decline at the time of settlement and would have continued to decline to some extent despite anthropogenic influences. The driving factor in this scenario would have been a cool climate, and this suggests that not all land degradation present in Iceland today is due to human influence (Ólafsdóttir et al., 2001). Conversely, the warming climate today is already contributing to increased plant productivity and a rising of the tree limit to higher altitudes (Björnsson et al., 2011).

Satellite data shows that Iceland, like a lot of the circumpolar region, has become greener in recent decades, with a particular rise in greenness in the west and north-western parts of the country, where a rise in summer temperatures has been detected (IMO, 2018). Plant abundance is closely linked to summer temperatures in Arctic regions (CAFF, 2021). Remote sensing also indicates an earlier start to the growing season in lower and middle latitudes of the Arctic (CAFF, 2021).

The Icelandic government has put forward in its climate action plan that reforestation and afforestation, as well as revegetation will be afforded a "substantial increase in funding", as a means of both carbon sequestration and reducing land degradation (Ministry for Environment and Natural Resources, 2020). This human action, combined with a warmer climate and longer growing season could see a more vegetated and forested Westfjords in the future.

Agricultural land makes up 2.4% of the land in Iceland. In the Westfjords this primarily consists of pastoral areas that are near the coast (National Land Survey of Iceland, 2009). While in 2011, an increase in grain production was reported (Björnsson et al., 2011) there is also a fear that warmer conditions might bring new pests and insects that could be detrimental to yields (IMO, 2018).

King et al., (2018) looked at how the amount of green growing days (GDD) might change over the global boreal region until the end of the next century. GDD is an index of how suitable plant growing conditions are, based on temperature. While this study predicted suitable agriculture areas in the boreal zone could treble by the end of the century, it only predicted modest increases for Iceland. This paper cautioned that some crops that grow well at lower latitudes might be hindered by the photoperiod further north, and suggested local crop variations may need to be bred (M. King et al., 2018).

Benefits to some forms of plants are at the expense of others. An increase in vascular plants and grasses may lead to a decrease in native mosses and lichens in Iceland (IMO, 2018). Temperature and altitude above sea level were shown to the most important determinants of alien plant distribution in Iceland. Wasowicz et al. (2013) showed that by 2050 the warming climate would leave several areas of Iceland more vulnerable to invasion by alien plant species, and the southern Westfjords region was especially likely to see an increase in abundance of alien species (Wasowicz et al., 2013).

There is also a limit to how much warming can benefit plant productivity, with experiments showing an increase above 5°C causing system collapse (IMO, 2018). High latitude areas that receive more favourable growing temperatures in the future may be limited by reduced precipitation, or increased evapotranspiration leading to periods of drought (Box et al., 2019; M. King et al., 2018). Modelling by King et al. suggested the west of Iceland would have a slight negative climatic water balance during summer months in 2099 (M. King et al., 2018). Changing winter precipitation may affect plant growth as well. Snow can insulate and protect plants from cold extremes, warm winters causing snow melt may leave plants vulnerable to cold snaps. Rain on snow events can lead to thick ground ice which could also hinder plant growth (Box et al., 2019).

Birds

The Westfjords region is home to many species of endemic and migratory birds. The west-coast of Iceland is particularly important for the breeding of sea birds, including 3-4 million auks, that primarily use the cliffs in the northwest. There are also large amounts of puffins (*Fratercula arctica*), fulmars (*Fulmarus glacialis*), kittiwakes (*Rissa tridactyla*), arctic terns (*Sterna paradisaea*) and eider ducks (*Somateria mollissima*), (Gardarsson, 2021). Some of its bird cliffs are major tourist attractions, including Látrabjarg in the southern Westfjords - where many people come to view puffins but which is also a nesting site for razorbills (*Alca torda*), fulmars and guillemots (*Uria spp.*). Hornbjarg in the Hornstrandir Nature Reserve in the northern Westfjords receives visitors for its spectacular height and distinctive shape and also contains many breeding pairs of fulmar, kittiwake and auks during the summer months (Gardarsson, 2021).

Figure 3.5 Razorbills and a puffin at Látrabjarg, May 2021 (Photographs: Deirdre Bannan)

Important food sources for Icelandic seabirds are capelin (*Mallotus villosus*), sandeels (*Ammodytes spp.*) and euphausiid crustaceans (Astthorsson et al., 2007; Gardarsson, 2021). The populations of various sea birds have declined considerably, probably as a result of changes in food stocks, which may be related to warming (IMO, 2018). For example, sand eels show lower recruitment and smaller body size during warmer ocean conditions, partially due to the development of smaller gonads under warmer winter conditions (E. S. Hansen et al., 2021). Sand eels are the main food source for arctic terns, and recent population declines of arctic terns in Iceland have been linked to sand eel collapse (Petersen et al., 2020).

Puffin populations in Iceland are also declining and recent study has correlated this decline with high sea surface temperatures. This study showed that a previous period of puffin decline coincided with the early twentieth century warming in the Arctic, and again attributed these declines to warmer sea surface temperatures affecting sand eel populations (E. S. Hansen et al., 2021). Some birds are benefiting from alterations to their food sources due to warmer conditions. Populations of the Greenland barnacle goose (*Branta leucopsis)* which uses Iceland as a staging ground have been increasing over the past 50 years. This has been correlated with warmer, wetter conditions in Iceland which are proposed to improve the productivity of their forage grounds (Doyle et al., 2020).

Many of the seabirds discussed here are vulnerable to winter cyclones in the north Atlantic. While predictions of storms are uncertain, the frequency of the strongest cyclones are predicted to increase under global warming, combined with a northern shift of the storm track. North Atlantic seabirds experience starvation and fatalities during north Atlantic winter cyclones, positively correlated to the magnitude of the storm. Climate related alterations to the frequency or severity of storms leaves these birds vulnerable to mass wrecks (Clairbaux et al., 2021).

Arrival times for some migratory birds have been altered. For example, the black-tailed godwit, *(Limosa limosa),* which winters in Europe, now arrives on average about 10 days earlier than it did in 1990 (IMO, 2018). A study of spring arrival times of migratory birds to southern Iceland between 1988 and 2009 found that 9 out of 17 species studied arrived significantly earlier in warmer springs. Species with longer migrations were less likely to arrive earlier in response to favourable conditions (Gunnarsson & Tómasson, 2011). The consequences of earlier migration times are not unanimous, but the concern is a trophic mismatch at breeding grounds, particularly in relation to food sources, as species who arrive too early or too late may miss optimum feeding times (Knudsen et al., 2011).

A study of 100 European migratory birds has shown that birds that did not advance their spring arrival times preformed worse than those who did (Møller et al., 2008). Other studies caution how early arrival, especially at high and mid-latitudes leaves birds vulnerable to low food supplies and cold weather spells (Newton, 2007). As migration and climate patterns change, it is likely that some birds will succeed through adaptive behaviour or a more favourable environment, and others will lose out. It is not just the climate in Iceland that must be considered for these birds. For those that winter in Africa, rainfall during this period is a major determinant of success. Changes in precipitation patterns or an increase in droughts in these areas could affect Icelandic migratory bird populations (Knudsen et al., 2011)

Over the course of the twentieth and twenty-first century, new bird species have arrived in Iceland. In the period 1980-2010, at least 7 different species became new breeders in Iceland. The arrival of these species is thought to be at least in part driven by favourable climate, with other factors, such as habitat formation at play as well. For example, the establishment of the Goldcrest (*Regulus regulus*) is thought to have been aided by the planting of non-native trees (Petersen & Olsen, 2021). A northern shift of birds not only means the arrival of southern species, but also the loss of some to the north. The Little Auk (*Alle alle*), a high arctic species, is no longer seen in Iceland (the north of which was the southern end of its range) (IMO, 2018). This is attributed to the warming climate, but it is uncertain if it was due to physiological stress on the bird or due to the northern shift of its food sources (Astthorsson et al., 2007).

Arctic Fox

The arctic fox (*Vulpes lagopus*) is the only land mammal native to Iceland and the highest density population in Europe is found in the Westfjords, in the Hornstrandir Nature Reserve, where foxes have been protected since 1994 (Botková & Unnsteinsdóttir, 2015). Arctic foxes in inland areas of the Arctic tundra typically eat lemmings and other small rodents but in coastal Iceland they eat seabirds, eggs, marine and tidal invertebrates and berries (Botková & Unnsteinsdóttir, 2015; Hersteinsson & Macdonald, 1996; Pálsson et al., 2016).

Figure 3.6 An arctic fox in Hornstrandir, August 2021. The feathers in the foreground are likely remains of seabird prey. (Photograph: Deirdre Bannan)

The arctic fox survives the cold winter with reduced access to food with its thick coat, fat layer and the ability to alter its metabolic rate (Fuglei & Oritsland, 1999). Fuglei and Ims (2008) do not anticipate a warmer summer to cause physiological stress to the arctic fox due to these adaptive mechanisms and because it begins to shed its thick winter coat in May (Fuglei & Ims, 2008). A warming climate provides a threat of competition from the red fox (*Vulpes vulpes*) in other parts of the world. It is a superior predator compared to the arctic fox and its northward expansion has been documented (Fuglei & Ims, 2008). As the arctic fox is the only species of fox in Iceland, it does not suffer this threat of increased competition due to climate change (Botková & Unnsteinsdóttir, 2015).

It is possible that the foxes' food sources will be disrupted with a change in climate. A range of impacts on bird populations due to climate change are predicted including timing of migration and breeding; breeding performance (egg size, nesting success); and changes in population size and distribution (Crick, 2004). Sea birds are important in the diet of Westfjords foxes, with fulmars, eiders and alcids all shown to make up significant proportions of their food intake (Hersteinsson & Macdonald, 1996; Pálsson et al., 2016). There are varying predictions about how climate will affect seabirds found in the Westfjords - these are discussed in the bird section - it seems likely that bird populations will be modified in some way (E. S. Hansen et al., 2021; Virkkala & Lehikoinen, 2014).

However, the opportunistic nature of arctic fox feeding means it may be able to adapt to changes in available food sources. Pálsson et al., (2016) document how a decline in arctic fox population in Iceland due to decreased numbers of rock ptarmigan recovered by modifying their diet to eat increased numbers of pink-footed geese.

Arctic foxes have historically travelled on the arctic pack ice, and connection and reconnection via ice of certain populations in the arctic has allowed for genetic mixing and recolonisation of islands (Fuglei & Ims, 2008). For example, genetic mixing has been shown to occur between the arctic fox populations of Svalbard and North America. (Norén et al., 2009) Iceland is not regularly connected to the arctic sea ice and thus it has an isolated population of foxes. A genetic study shows that arctic foxes within Iceland have sub-populations - there is a particular genetic difference between the population in the North-West compared to Central and Eastern populations (Norén et al., 2009). It is hypothesised that there is little mixing between the populations due to the narrow isthmus that connects the Westfjords to the rest of Iceland reducing the scope for travel and is possibly compounded by sheep-proof fences. This means that the Westfjords population of arctic foxes is isolated and shows relative homogeneity (Norén et al., 2009).

Arctic foxes are also important for the tourist industry in the Westfjords. Of note there is the Arctic fox centre in Súdavík and the foxes serve as an attraction for visitors to the

Hornstrandir nature reserve, where they are easily spotted in the summer months, providing a chance for visitors to connect with Icelandic nature (Botková & Unnsteinsdóttir, 2015).

Marine Species and Fisheries

The oceans around Iceland are currently being impacted by warming SST and ocean acidification (García-Ibáñez et al., 2021; Lapointe et al., 2020; Pérez et al., 2021). The continental shelf of Iceland is considered to be moderately productive (Jaworski & Ragnarsson, 2006). The marine fauna of Iceland consists of boreal and subarctic boreal species, with some arctic species (Eiríksson & Símonarson, 2021). Some of the commercially important species include cod, haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), redfish (*Sebastes spp.*), halibut (*Reinhardtius hippoglossoides*), and capelin (Jaworski & Ragnarsson, 2006). Fish are ectotherms, and have evolved to have an optimal thermal window for physiological functions, so can be particularly sensitive to changes in temperature (Freitas et al., 2015).

Cod is the most valuable commercial fish in Iceland, representing on average 35% of the catch value of the country's fishing fleet and being one of the most expensive per tonne (Gunnlaugsson & Valtysson, 2022). Cod have been shown to adapt their behaviour in response to warmer sea surface temperatures, vertically migrating to colder, deeper waters in response to warm sea surface temperatures (Freitas et al., 2015). Cod stocks are dependent on another commercially important species, capelin. Adult cod feed primarily on capelin, and their weight depends on capelin abundance (Astthorsson et al., 2007).

In 2002, Icelandic capelin stocks displayed a major shift in abundance and distribution. They were no longer found in their typical nursery grounds along the north coast of Iceland and were subsequently found further west on the Greenlandic shelf. Recruitment to the fishery has declined dramatically since 2003 (figures until 2016) (T. Jansen et al., 2021). Jansen et al. propose that the change in distribution could be attributed to both current dynamics and temperature change while the marked decrease in abundance has corresponded in time with an increase in temperature and is likely the cause of this (T. Jansen et al., 2021). In 2007, Assthorsson reported that cod weights were poor and attributed it to the change in distribution of capelin. A northern shift of capelin (from south to north Iceland) has been seen before during the warm period 1920-1930 (Astthorsson et al., 2007).

Other fish stocks are showing a tendency for a northern shift in distribution with warming temperatures. Monkfish (*Lophius piscatorius)*, prior to 1985 were only found in waters off the south coast. Now its abundance and range have increased, and it is also found along the western coast and northern shelf of Iceland (Astthorsson et al., 2007). Similarly haddock and blue whiting (*Micromesistius poutassou*) have also moved their distributions further north (T. Jansen et al., 2021). Atlantic mackerel (*Scomber scombrus)* has become more abundant in Icelandic waters since 2007. Some papers have suggested this is due to warmer conditions (IMO, 2018; Valtysson & Jonsson, 2018), however Ólafsdóttir et al., suggest that this is not the case, as temperatures have been within the mackerel's preferred range since prior to 2007, and it is more likely due to increased stock abundance (Olafsdottir et al., 2019). Valtysson & Jonsson cite an example of an indirect effect of temperature on species abundance, whereby the Icelandic scallop (*Chlamys islandica)* has seen population declines due to an outbreak of disease which was probably brought on by warmer waters. This review discusses that while there is some tendency for northern marine stocks to decline and southern stocks to increase with warmer temperatures, these changes appear to be non-linear and in the case of declines, difficult to separate from overfishing (Valtysson & Jonsson, 2018). It is possible that the northern shift of certain mesopelagic fish could be hampered by the photoperiod, especially if they rely on visual feeding, or the cover of darkness for safe nocturnal feeding (Kaartvedt & Titelman, 2018).

Calcifying organisms are deemed to be most at risk from ocean acidification. In the subpolar north Atlantic, cold water corals reefs form biodiversity hot spots. These orgaisms use calcium carbonate in the form of aragonite. Aragonite saturation levels showed significant decline in the Irminger and Icelanic basins from 1991-2018 due to the increase in anthropgenic CO_2 (García-Ibáñez et al., 2021). Aragonite understuration would ultimately leave the corals exposed to corrosion. Molluscs are also at risk of corrosion due to ocean acidification, however a meta analyses of studies suggested that under realistic pH decreases, shell growth is not necessarily impacted. This paper concluded that acidification has clearer negative trends on mollusc larval survival and development (Gazeau et al., 2013). The IMO climate report states that no *in situ* affects on calcifying organisms in Iceland have been observed (IMO, 2018) but papers state undersaturation for argonite in subpolar waters could occur by the turn of the century if the current CO_2 emission trend continues (García-Ibáñez et al., 2021; Pérez et al., 2021). Acidification is likely to affect the physiological functions of both calcifying and non-calcifying marine organisms (Le Quesne & Pinnegar, 2012). A lab experiment on cod larvae survival showed increased mortality under ocean acidification conditions that could be achieved by the end of the century (Stiasny et al., 2016). Some experiments suggest a tolerance or compensation ability for acidic conditions by certain subpolar plankton. Hoppe et al., showed that no decreases in primary producutivity were observed in arctic and subarctic phytoplankton under a range of acidity, light and temperature conditions (Hoppe et al., 2018). Another study on copepods found the fitst generation was subject to stress and reduced preformance from acidification, however the following gerneration had developed a tolerance for acidic conditions and did not display the same negative effects (Thor & Dupont, 2015).

There is a concern that the melting of the Arctic sea ice will allow for the migration of species from the Pacific to the Atlantic and vice-versa, as we head for ice for ice free summers in the Arctic. (Chan et al., 2019). One study predicts an exchange of approximately 40 species each way by 2100 (Wisz et al., 2015).

Summary

For all the biological factors, there is some uncertainty about the specific impact of changing climate. What seems to be certain is that there will be trade-offs, some species will do well out of climate change, but at the expense of others (vascular plants outcompeting mosses, bird populations displacing each other). It is also difficult to say if a species truly benefits from a change, for example, some species might perform better physiologically at warmer temperatures, but this will not be an advantage if their prey does not. The interconnectivity of ecosystems is a major factor too, one change or loss of a species may have numerous and/or unimagined knock-on effects.

3.2.3 Socio-economic impacts

The biological and physical impacts discussed above have knock-on socio-economic impacts. These could be increased expenditure, or loss of infrastructure and life, due to slope processes. Changes to bird or arctic fox populations may influence nature based tourism. Undoubtably, changes to the marine realm will alter the important fishing industry in the Westfjords. Some of the impacts on fisheries, tourism and aquaculture are discussed below.

Fisheries

Until the 20th century, fisheries and agriculture were the primary industries of Iceland (Government of Iceland, n.d.-c). While the economy has diversified, fish are still Iceland's second biggest export, constituting 22% of exports. The seafood and fishing industries together employ 6% of workers (Østhagen et al., 2020). The fishing industry is still an important provider of employment in the Westfjords, however modern fishing technology and the introduction of the quota system mean that some small fishing towns can no longer fish commercially (Edvardsson et al., 2018).

Figure 3.7 Demersal fish caught on a research vessel in the Westfjords (Photograph: Deirdre Bannan)

Models predict an increase in available fish biomass in the northern north Atlantic, particularly over 60° latitude over the coming century (Bryndum-Buchholz et al., 2020; Peck & Pinnegar, 2019). This is contrast to a biomass decline in temperature and subtropical areas of the Atlantic (Bryndum-Buchholz et al., 2020). Changes in species distribution and increased primary productivity (including in the Arctic the open water season extends) are thought to contribute to increases in available biomass over the next century (Lam et al., 2016)

A study by Lam et al., assessed the economic consequences of climate change on Icelandic and other northern fisheries. This study predicted that warmer conditions would have a positive economic effect, but ocean acidification would have a negative economic effect, resulting in net positive economic effects. This study acknowledged many uncertainties, including trophic interactions and the fact that new countries may begin fishing in Arctic regions (Lam et al., 2016). The finding is in keeping with a previous study, that also predicted modest rise in GDP from fisheries under warming circumstances. This second paper also acknowledges large uncertainties, does not consider ocean acidification and only had data that was available in 2006 with regards climate projections and fish stocks (Arnason, 2008). Arnason assumes cod stocks will increase with warmth, but other literature suggests the future of cod stocks is less certain – that it may not experience much net change (Oostdijk et al., 2021) or that it will vary depending on the sublocation (Peck & Pinnegar, 2019).

It is interesting that the expanding mackerel stock mentioned in the previous section is already causing management disputes between north-Atlantic countries. As the stock expands into Greenlandic and Icelandic waters who previously had no share of the catch, quotas have become difficult to agree on, and the lack of shared management is potentially leading to overfishing (Boyd et al., 2020). This has been dubbed the mackerel wars and is possible that similar disputes could arise in the future as commercially important fish change their behaviour and distribution due to climate (Boyd et al., 2020; Østhagen et al., 2020). Careful management of all fish stocks is needed going forward, as the uncertainties of climate change play out. Some key points for climate informed management are highlighted in a book published by the FAO, these include advance monitoring of climate driven impacts on fish and habitats, reduction of non-climate stressors and temporarily closing fisheries when necessary (Peck & Pinnegar, 2019).

Tourism

Tourism is an important industry in Iceland, and number of overnight stays in the Westfjords region increased by 64% from 2012-2017. The vast majority are foreigners arriving by cruise ship, however there are festivals throughout the year that attract Icelanders to the Westfjords as well (Vestfjarðastofa, 2018). For example, every year (non-pandemic), Ísafjörður hosts a music festival, *Aldrei fór ég suður (I never went south),* This held at Easter and coincides with *Skíðavikan*, or Ski-week which is an activity festival with skiing and cultural events (Visit Westfjords, n.d.-a). *Fossavatnsgangan* is a cross country ski race also held in Ísafjörður that also attracts skiers from around Iceland and abroad (fossavatn.is, n.d.).

There are two ski areas in Ísafjörður, a downhill and a cross country area. They allow for the hosting of the two above events but are also widely used by locals (personal observations). It could be argued that they play an important role in the physical and mental health of the local community, providing a means for outdoor exercise during dark and cold days. Skiing is one industry that is viewed as being particularly under threat from climate change. A European modelling study predicts that Iceland could see a reduction of 50-75 days per year (from 200-250) where snow above 800m is at least 30cm deep by the turn of the century (Morin et al., 2021).

In the eastern European Alps, it is suggested that only 69% of ski resorts could survive past 2050, even allowing for snowmaking capabilities (Demiroglu et al., 2019). Many ski areas were set up in the 1960s and 1970s when climate conditions were colder in Europe, and are now the altitudes they begin at are suboptimal for today's warmer climate (Steiger et al., 2019). The downhill ski area in Ísafjörður may be a victim of this phenomenon, as its lowest point is at 120m a.s.l. A comparable cross ski country race to *Fossavatnsgangan* takes place in Sweden, where a study has shown that increased cancellations are already occurring due to natural snow conditions, and they expect this to continue into the future (Falk & Hagsten, 2017). In fact, the timing of *Fossavatnsgangan* has recently been permanently rescheduled which allows it to take place consistently earlier than it has done since 1980 (fossavatn.is, n.d.). The website does not specifically mention climate change as the reason for this change. There are numerous potential socio-economic consequences to a reduction in the ski season. Firstly, it may be detrimental to the physical and mental health of regular users, as they lose a form of outdoor exercise, one that is potentially a social activity as well. There are also economic consequences, directly to the ski field, which may become non-viable and lead to a loss of jobs, but also to other businesses in the area if major ski events are cancelled and cease to bring visitors to the town.

Aquaculture

Aquaculture is a new and growing industry in Iceland, with Atlantic salmon (*Salmo salar*) having been farmed in the Westfjords for less than ten years (Karbowski et al., 2019). The total aquaculture production in 2019 in Iceland was 34,000 tonnes, 27,000 of which salmon (Solås et al., 2020). The Government of Iceland expect salmon to remain the most of important farmed species in Iceland and for production to grow, however the Marine and

Freshwater Institute of Iceland recommends that no more than 50,000 tonnes of salmon be farmed in the Westfjords region (Government of Iceland, n.d.-b).

Salmon is a temperature sensitive fish, and shows increased stress and reduced growth performance at temperatures above 16°C (Islam et al., 2021). However sea temperatures within the fjords in the Westfjords region currently reach a maximum of around 10°C (Eskafi et al., 2019) so even with increases in SST, farmed salmon are unlikely to experience physiological stress in these waters. In fact research by Klinger et al., (2017) indicated that the temperature projections for waters around Iceland will be beneficial for salmon growth until 2050.

Rising ocean temperatures may leave salmon more susceptible to disease. Salmon lice (*Lepeophtheirus salmonis* and *Caligus* spp.) are parasitic copepods that feed on the mucus and surface tissue of their hosts, causing lesions and inducing a stress response. (Godwin et al., 2021). They are an economic concern, being the most costly of all parasites affecting aquaculture, and a fish welfare concern. Outbreaks in salmon lice in salmon farms may also affect wild populations (Overton et al., 2019). Sea lice infestations in a farm on the Westfjords region were shown to be relatively low, and this was in part attributed to relatively low intensity farming but also the cold waters, which were frequently below 10°C, a temperature that is reported to negatively impact sea louse hatching success (Karbowski et al., 2019). In Canada, Godwin et al., (2021) found that sea louse infestation in farms increased during a warm year (1.27°C above average, average not given) and rendered the parasite control policy of the farm ineffective. A study from Norway showed how increased temperatures decreased development time and increased infectivity of copepods. A modelling exercise showed that infection pressure from farmed to wild salmon increased with rising temperatures, with an estimated twofold increase in infection pressure if temperatures rose from 9°C to 11°C. The increase in infection pressure was greater at rises from lower temperatures (i.e. 6°Cto 8°C) and lower at rises in higher temperatures (i.e. 12°C-14°C) (Sandvik et al., 2021). These temperature rises are comparable to what may happen in the Westfjords region, and it is possible that salmon aquaculture (and wild salmon) will see greater pressure from salmon lice infestations in the future. Sea lice from farmed salmon have been shown to be a cause of infection in wild populations (P. A. Jansen et al., 2012; Karbowski et al., 2019). Various wild salmonids are found in the rivers of Iceland and there is some tourism based on wild salmon fishing (Jóhannesdóttir & Pálsson, 2016; Visit

Westfjords, n.d.-b). Karbowski et al. (2019), predict that if salmon production increases in the Westfjords, so does the risk of sea lice epidemics and recommends environmental monitoring and coastal zone management.

3.3 Summary

Chapter 3 introduces the reader to the Westfjords region and highlights some areas that are at risk due to climate change. The following analysis stage uses data collected at weather stations in the Westfjords to see if the climate patterns identified globally and at a national level can be detected on a local level. Average temperature and precipitation will be analysed. Climate on this local scale has not been reported in the literature, nor has much been published on Iceland that covers the last complete decade (2011-20). The graphics produced to illustrate the changes aim to be simple and effective climate communicators. They will benefit from having data until 2020. These graphics will frame a large global problem in the context of a small coastal region, in an effort to make the issue more tangible and relatable for residents of the Westfjords.

4 Methods

4.1 Data acquisition

To analyse climate change for the Westfjords region data on average temperatures and precipitation was obtained from the Icelandic Meteorological Office (Icelandic : Veðurstofa Íslands,). Some of it was published on their website, www.vedur.is, and some was obtained through email request. The data came in the form of long table sheets of daily or monthly collections and had to be carefully examined for missing values and parameters. Data was obtained from 37 different stations around the Westfjords region, with different time spans and different parameters measured at each station. The stations are primarily coastal and low lying, rather than mountainous (Figure 4.1). A total of 90.92% of land in the Westfjords is above 50m elevation. This was calculated from the Digital Elevation Model (DEM), obtained from the National Land Survey of Iceland, resolution 10 x 10m. However, only four of the weather stations used in this study are above 50m.

While the stations are not fairly representing the topographical distribution of the Westfjords, they are representative of the habited areas of the Westfjords, with most towns located and activities taking place at or near sea level. There is a particularly dense network of stations in the vicinity of the main town of Ísafjörður and in the south-western part of the Westfjords region, in the vicinity of Patreksfjörður. These two areas house the majority of the residents of the Westfjords region (Statistics Iceland, 2021). The stations with elevations above 50m are Gemlufallsheiði (250m), Steingrímsfjarðarheiði (440m), Þverfjall (741m) (all of which are proximate to roads going over mountain passes) and Seljalandsdalur (550m) (which is situated near the cross country ski area in Ísafjörður). There is only temperature data available for these stations, the earliest available data from any of these stations is from 1994 (Table 4.1).

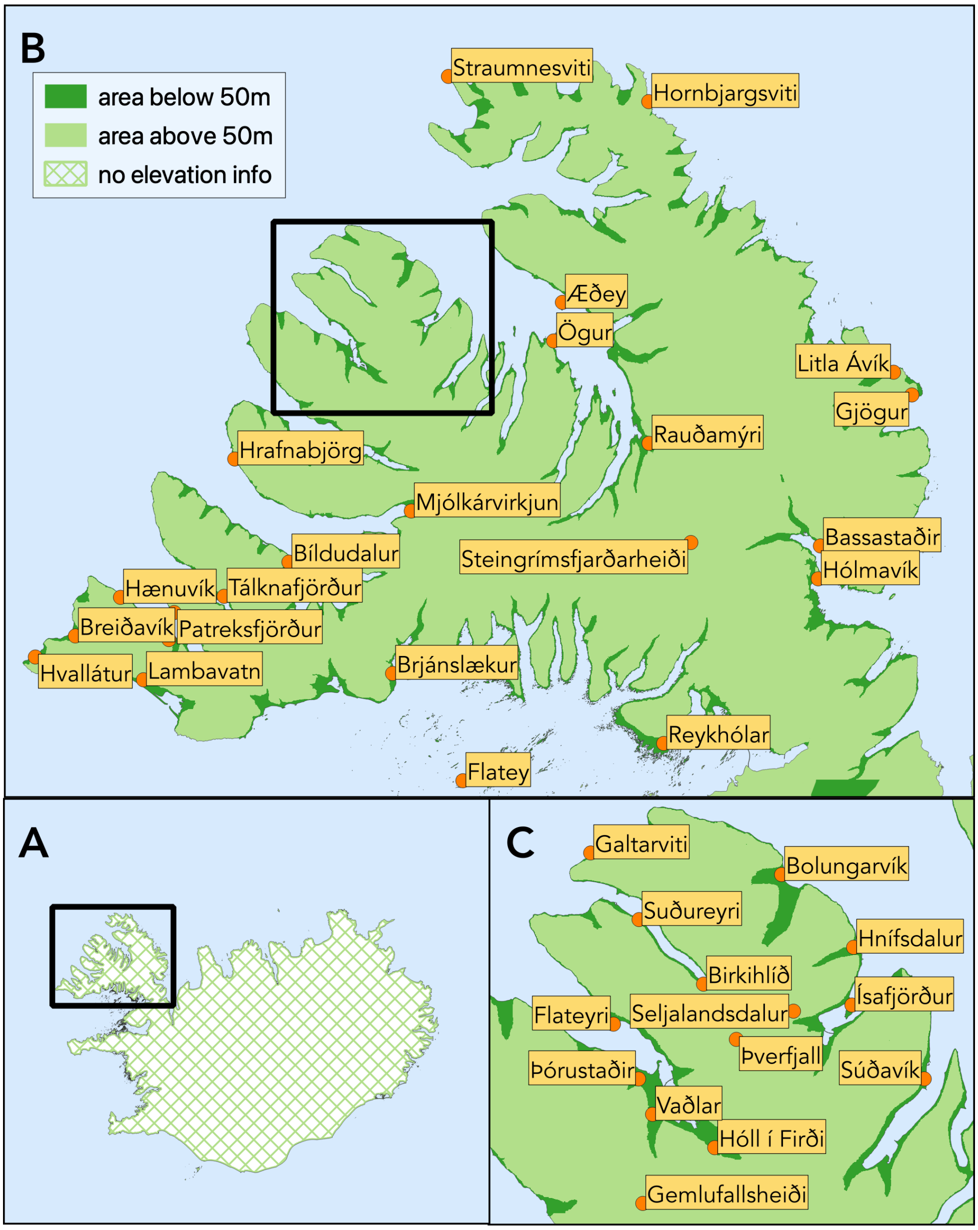

Figure 4.1 Locations of weather stations used in this study. A = The Westfjords region within Iceland, B = weather station used in this study C = dense network of stations around the most populous region of the Westfjords.

The stations collected data for varying time periods, some collecting temperature data, some precipitation, and some both. There was a lack of long term continuous data. Bolungarvík alone collected temperature data from 1898 until 2020. Five stations had at least sixty years of temperature data - Hornbjargsviti, Gjögur, Reykhólar, Lambavatn and Æðey. For all the aforementioned stations it was possible to create a 1961-90 reference figure to compare recorded temperatures to. Overall, temperature data was used from 28 different stations and precipitation from 27 different stations (Table 4.1).

A station was considered to have covered a full decade if 8 out of 10 years of recordings were available. This is in keeping with World Meteorological Organisation (WMO) guidelines that data should be available for 80% of the years of the averaging period, before creating a mean (WMO, 2017). More temperature data was available for the most recent two decades, with 18 and 21 stations collecting temperature data for the periods 2001-10 and 2011-20 respectively. There are 12 or less stations with a complete decade of temperature recordings for each decade between 1951-2000. There was less variability in numbers of stations for each decade collecting precipitation, with between 10 and 15 stations available for each decade 1961-2020. Only two stations, Lambavatn and Mjólkárvirkjun, had continuous recordings of precipitation for sixty years. For these stations it was possible to create a 1961-90 mean to compare precipitation recordings against.

If a station had changed altitude but remained in a similar location, all measurements were converted to sea level estimation and considered to be the same station. To give an example, Æðey station took recordings at 5m a.s.l. from 1961-2012 and then at 21m a.s.l from 2012-2020, these recordings were combined as 0m a.s.l estimations (see section 4.2.2 for conversion methods). A representative temperature for the Westfjords was calculated by combining the sea level estimates from all stations with 60 years of continuous temperature data collection. These were Bolungarvík, Gjögur, Hornbjargsviti. Æðey, Reykhólar and Lambavatn.

Table 4.1 Summary of temperature and precipitation data availability

Summary of data availability *Timespan of data collection for each station of mean monthly temperatures and precipitation*											
#	Station	1951-60	1961-70	1971-80	1981-90	1991-00	2001-10	2011-20	1961-90	Temp	Precip
1	Bolungarvík	T[1]	T	T	T	T	X	X	T	1898-2020	1995-2018
2	Gjögur	X	X	X	X	T	T	T	X	1949-2020	1949-1993
3	Hornbjargsviti	X	X	X	X	T	T	T	X	1949-2020	1949-1995
4	Kvígindisdalur	X	X	X	X	X	NA	NA	X	1949-2004	1949-2004
5	Flatey	T	X	X	X	NA	NA	NA	X	1952-1989	1956-1989
6	Reykhólar	NA	X	X	X	X	T	T	X	1961-2020	1961-2004
7	Æðey	NA	X	X	X	X	X	T	X	1954-2020	1954-2012
8	Lambavatn	NA	X	X	X	X	X	X	X	1961-2020	1961-2020
9	Mjólkárvirkjun	NA	P	P	P	P	P	P	P	NA	1959-2020
10	Þórustaðir	NA	X	X	X	X	NA	NA	X	1961-1998	1961-1998
11	Suðureyri	NA	X	X	X	NA	NA	NA	X	1961-1989	1961-1989
12	Galtarviti	NA	X	X	X	NA	NA	NA	X	1953-1994	1953-1994
13	Hvallátur	NA	X	X	X	NA	NA	NA	X	1953-1989	1953-1989
14	Ísafjörður	NA	NA	NA	P	P	X	X	NA	1999-2020	1981-2020
15	Brjánslækur	NA	NA	NA	P	P	P	P	NA	NA	1997-2020
16	Rauðamýri	NA	NA	NA	P	NA	NA	NA	NA	NA	1978-1989
17	Hóll í Firði	NA	NA	NA	NA	X	X	X	NA	1983-2020	1983-2020
18	Breiðavík	NA	NA	NA	NA	X	NA	NA	NA	1990-2003	1990-2003
19	Litla Ávík	NA	NA	NA	NA	NA	X	X	NA	1996-2020	1996-2020
20	Bíldudalur	NA	NA	NA	NA	NA	X	X	NA	1998-2020	1998-2020
21	Súðavík	NA	NA	NA	NA	NA	X	X	NA	1996-2020	1999-2020
22	Hnífsdalur	NA	NA	NA	NA	NA	P	P	NA	NA	1995-2020
23	Flateyri	NA	NA	NA	NA	NA	T	T	NA	1997-2020	NA
24	Þverfjall	NA	NA	NA	NA	NA	T	T	NA	1994-2020	NA
25	Ögur	NA	NA	NA	NA	NA	T	T	NA	1997-2020	NA
26	Straumnesviti	NA	NA	NA	NA	NA	T	T	NA	1996-2020	NA
27	Seljalandsdalur	NA	NA	NA	NA	NA	T	T	NA	2001-2020	NA
28	Steingrímsfjarðarheiði	NA	NA	NA	NA	NA	T	T	NA	1995-2020	NA
29	Patreksfjörður	NA	NA	NA	NA	NA	T	T	NA	1996-2020	NA
30	Birkihlíð	NA	NA	NA	NA	NA	P	NA	NA	NA	1998-2014
31	Vaðlar	NA	NA	NA	NA	NA	P	NA	NA	NA	2000-2011
32	Hrafnabjörg	NA	NA	NA	NA	NA	P	NA	NA	NA	1995-2012
33	Gemlufallsheiði	NA	NA	NA	NA	NA	NA	T	NA	2010-2020	NA
34	Tálknafjörður	NA	NA	NA	NA	NA	NA	T	NA	2009-2020	NA
35	Hólmavík	NA	NA	NA	NA	NA	NA	T	NA	2008-2020	NA
36	Bassastaðir	NA	NA	NA	NA	NA	NA	P	NA	NA	2005-2020
37	Hænuvík	NA	NA	NA	NA	NA	NA	P	NA	NA	2005-2020
NA	TOTAL T	5	12	12	12	10	18	21	12	28	NA
NA	TOTAL P	3	12	12	15	10	14	12	12	NA	27

[1] T = temperature data available, P = precipitaion data available, X = both temperature and precipitation data available

4.2 Data Analysis

4.2.1 Point graphs

Analysis of yearly and decadal trends in temperature were performed on all stations that had at least sixty years of data. The temperature anomaly for a particular period was calculated by subtracting the mean temperature for that period from 1961-90. A thirty year mean to compare data against is an accepted standard promoted by the WMO (Minaei & Irannezhad, 2018; Sluiter, 2009). While the WMO recommends updating the mean to the most recent 30 years (i.e. 1991-2020) for some decision making purposes, for historical comparisons and climate change monitoring it recommends "the continuation of the 1961-1990 period for computation and tracking global climate anomalies relative to a fixed and common reference period" (WMO, 2021a, para 6.). Temperature anomalies are expressed in degrees Celsius (°C) compared to the mean. Precipitation anomalies are expressed as a percentage of the mean. This is also accepted by the WMO (WMO, 2017), and was selected so results would be relative to seasonal variations in precipitation. Anomalies were calculated for each month and year and for a winter period defined as December, January and February (DJF) and a summer period defined as June, July and August (JJA). These are the typical meteorological winter and summer months in the Northern hemisphere (Trenberth, 1983). These definitions of winter and summer have been used in many papers discussing different climatic variables in Iceland, including wind (Rögnvaldsson & Ólafsson, 2005), precipitation (Jónsdóttir et al., 2006; Rögnvaldsson et al., 2004), atmospheric pressure (Hanna et al., 2006) and temperature (Jónsdóttir et al., 2006).

R studio software (version 1.4.1106) was used to create graphs and charts to illustrate changes observed compared to the reference period. These were then visualised as 'temperature circles' and 'precipitation circles' for decadal anomalies, and as 'temperature stripes' and 'precipitation stripes' for yearly anomalies. The temperature stripes visualisation takes inspiration from the 'warming stripes' designed by Prof Hawkins, a UK climate scientist and an author for the IPCC sixth assessment report (WMO, 2021b). This model was chosen as the visualisation is simple and clear and also in common use, featuring on the cover of the Bulletin of the American Meteorological Society's State of the Climate 2019 (Blunden & Arndt, 2020) and used in a campaign to promote climate change awareness supported by the UN, the WMO and the IPCC (WMO, 2021b). Diverging colour schemes were used which are considered appropriate when visualising dichotomies, such as cooler versus warmer than average, or drier versus wetter. Blue-red (cold to hot) and brown to blue-green (dry to wet) are considered to have intuitive associations and were used to represent temperature and precipitation anomalies respectively (Kaye et al., 2012).

4.2.2 Spatially interpolated maps

QGIS software (version 3.18.2) was used to create spatially interpolated maps. Interpolation techniques allow for point data (measurements from individual stations) to be applied to a 2-dimensional face such as the surface of a map. Base maps of Iceland and a digital elevation model (DEM) were obtained from *Landmælingar Íslands* - The National Land Survey of Iceland (LMÍ). Prior to interpolation, all temperature data was converted to a sea level estimate using a constant lapse rate of -6.5°C/1000m.

This was calculated in the form:

$$T_s = T_0 + (h \times 0.0065)$$

where

T_s is Sea level temperature

T_0 is Recorded temperature at the station

h is the altitude of the station in metres

0.0065 is the lapse rate per metre.

The rate at which air cools due to elevation depends on its moisture content but an average range of -0.6 to -0.7°C /100m is often applied for moist air (Gardner et al., 2009; Rolland, 2003). This current study used a rate of -0.65/100m which was also employed in a study by Crochet & Jóhannesson (2011) where they validated methods for gridded temperature maps of Iceland. Crochet & Jóhannesson tested this constant lapse against a variable lapse rate with a seasonal pattern and concluded that "overall, estimates made with a variable lapse rate are not better than those made with a constant lapse rate of 6.5 ◦C/km." (Crochet & Jóhannesson, 2011).

A limit of the lapse rate is that it only takes the effects of elevation into account and ignores other parameters that influence the rate of temperature change such as distance from the coast and local topography. It was noted that stations with especially high altitudes such as

Þverfjall (741m) Steingrímsfjarðarheiði (440m), Seljalandsdalur (550m) come in with temperatures slightly colder than the stations nearer to sea level after being adjusted with the constant lapse rate. This is likely due to neglect of other factors besides elevation on temperature and this source of error is noted in the discussion chapter.

Temperature and precipitation data were interpolated using Inverse Distance Weighted (IDW) interpolation. IDW predicts a value for an unknown point, with the known values closest to the unknown point having the most influence on the predicted value. Thus the influence of a measurement decreases with increased distance from the unknown location - hence the name inverse distance weighted (Samanta et al., 2012). Multiple other methods of interpolation are available, including Nearest Neighbour, Splines, Linear regression and several types of kriging. There are many papers published which discuss the strengths and limitations of each method (Hofstra et al., 2008; Kurtzman & Kadmon, 1999; Perry & Hollis, 2005; Samanta et al., 2012; Sluiter, 2009). Different methods are found to work better in different situations, for example Kurtzman & Kadmon found that IDW outperformed splining in the winter but not in the summer months in Israel (Kurtzman & Kadmon, 1999). Kriging is sometimes found to be more accurate (Kim et al., 2010; Sluiter, 2009). but is also more complicated and involves heavier computer use (Crochet & Jóhannesson, 2011). IDW was used in this study partly because it is "fast, easy to implement" (Sluiter el al., 2009) but also because it is widely accepted and used in climate interpolation. It has been used by the UK Met Office to make climactic datasets (Perry & Hollis, 2005) and by the country of Spain to produce monthly climate anomaly maps of temperature, precipitation and insolation (Sluiter et al., 2009). IDW is also deemed appropriate for a low number (less than 30) of stations (Sluiter et al., 2009).

The sea-level temperatures were attached to their geographic locations on a vector file within QGIS. The interpolation was then performed using inbuilt IDW interpolation processing in QGIS and a distance coefficient of 2. This produces a file with an interpolated temperature for every point within a defined area (in this case, the Westfjords region). Temperature data was readjusted to terrain level from sea level after interpolation using the constant lapse rate and the elevations from the DEM obtained from the National Land Survey of Iceland.

Precipitation point data was interpolated using the same approach as for the temperature data. However no adjustments were made for elevation as precipitation does not have a simple relationship with elevation (Lloyd, 2005).

IDW can be tested by using cross validation methods, where one station's measurement is omitted and then its estimated temperature from IDW compared to the actual measurement (Sluiter, 2009). This was performed and a sample of the tests done on some temperature recordings can be seen in Table 4.2.

Table 4.2 Inverse Distance Weighted Cross Validation

IDW Cross Validation *IDW predicted values for omitted stations*				
Omitted station	Date	Actual value	IDW value	Error
Kvígindisdalur	October 1971-80	4.3385	4.3701	0.0316
Þverfjall	February 2001-10	-1.2091	-0.5718	0.6373
Æðey	May 2011-20	4.8996	5.0407	0.1411
Reykhólar	January 1981-90	-1.4245	-1.7595	-0.3350
Seljalandsdalur	February 2001-10	-0.6229	-0.8698	-0.2469

Temperature and precipitation were displayed using colour scales, with the minimum and maximum ends of the scale being the minimum and maximum temperature from the interpolation over the 60-year time scale (for the relevant month). Relative temperature maps were created as well, comparing the total change in the most recent decade (2011-20) compared to the 1961-90 mean. This was done by subtracting the 1961-90 interpolated surface from the 2011-20 surface.

4.2.3 Climate change impact map

The climate change impact map was created using QGIS software and base maps from the National Land Survey of Iceland. It combines a map of the Westfjords and illustrations and text describing some of the temperature changes that are occurring in the Westfjords and what the potential impacts of climate change might be. An effort was made to describe the impacts at their associated geographic location, for example, impacts on Arctic foxes at Hornstrandir, impact on birds at Látrabjarg.

Graphics were designed by the author or from open sources. Temperature changes were illustrated using the original analysis from this study. The literature building the background to this study was used to make decisions about what areas of potential change to highlight on the map. Areas of change with low uncertainty or that had already been observed were chosen to include. Space was also a limiting factor. The map takes inspiration from similar educational maps produced by the UK Met Office (Edward, 2014; Gray, 2009). Colour and simple text and graphics were chosen to make it accessible to a general reader.

5 Results

5.1 Temporal changes in temperature & precipitation

This section looks at the changes in temperature and precipitation that were gathered at stations that had at least 60 years of continuous data collection.

5.1.1 Temperature changes 1901-2020

Decadal temperature anomalies 1901-2020

An analysis of the average temperature anomaly per decade at Bolungarvík (the longest continuous time series, 1898-2020) compared to the 1961-90 mean shows that each decade varies differently from the reference period. The periods 1901-20, 1961-70 and 1981-90 are colder than the reference period. The periods from 1921-60, 1971-80 and 1991-2020 are warmer than the reference period. The winter months during the period 1901-20 are particularly cold compared to the reference period, while the summer months are warmer. Every month from 2001-20 is warmer than the reference period. The greatest negative difference from the reference period was seen in February 1910-20, which was on average 2.94°C less than the average temperature February 1961-90, and the greatest positive difference was seen in June 2001-10, where temperatures averaged 1.97°C greater than the reference period.

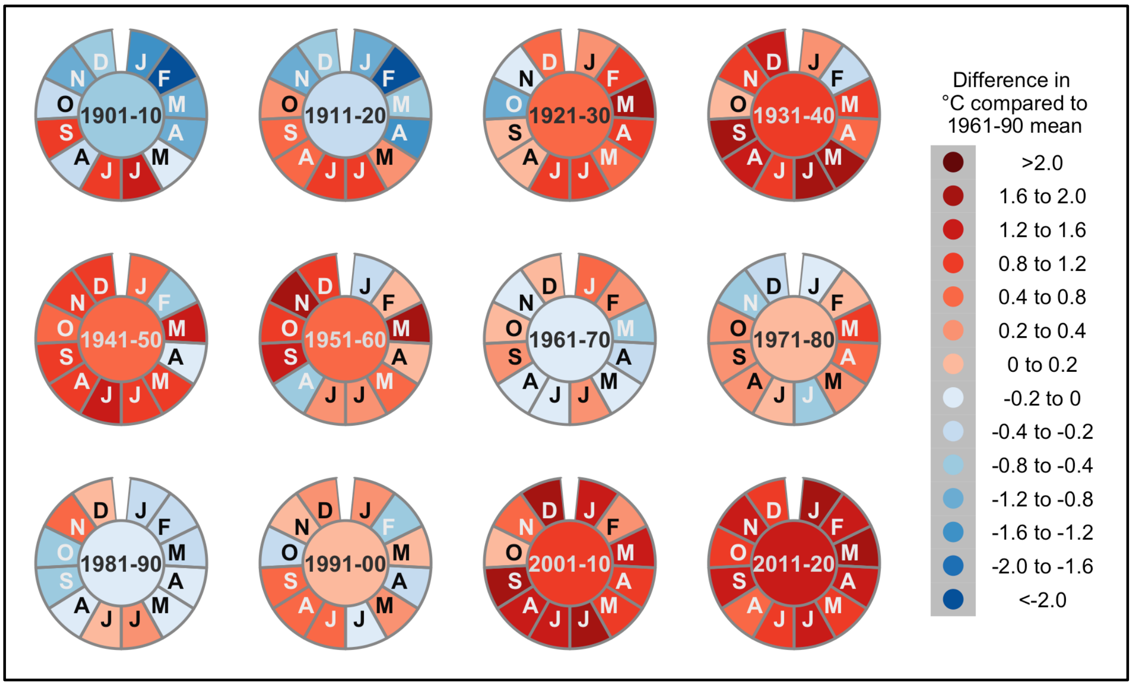

Figure 5.1 Average temperature anomalies for each decade 1901-2020, Bolungarvík. There is a "temperature circle" for each decade. There are 12 outer segments for each month, labelled chronologically and clockwise - The uppermost and righthand "J", is January, the "F" to the right is February, and so on. Each colour represents the difference in degrees Celsius compared to a 1961-90 reference period. The colour in the centre represents the annual average temperature anomaly for the decade.

Yearly temperature anomalies 1898-2020

An analysis of each individual year recorded at Bolungarvík compared to the 1961-90 reference period shows that the years are mostly colder than the reference period from 1898-1924 and warmer than the reference period from 1925-1964 (Figure 5.2 A). There was a cold period from 1965-1971 and from 1972-1999 the temperature alternated between being colder and warmer than average. Every year from 2000-2020 is warmer than the reference period. The warmest year is 2016, with an anomaly of +2.17°C and the coldest year was 1981 with an anomaly of -1.14°C.

DJF and JJA anomalies 1898-2020

An analysis of the December, January and February temperatures and June, July and August temperatures shows seasonal differences (Figure 5.2 B + C). From 1898-2020, winters tended to be colder than average, and summers tended to be warmer than average. Winter anomalies show greater deviation from the mean than summer anomalies (1.37°C vs 0.84°C standard deviation). The winter of 1918 was -5.64°C compared to the 1961-90 reference period (the January anomaly for 1918 is -11.80°C.) Summer temperatures tend to be warmer than the reference period from 1923 until 1951, then show a period of fluctuation until 1994. Winter temperatures fluctuate more than summer but are generally warmer than the reference period between 1923 to 1951 period, and generally colder from 1966-1995. Since 2000 all but one winter (2004) has been warmer than average. Since 1994, all but one summer (2015) has been warmer than average.

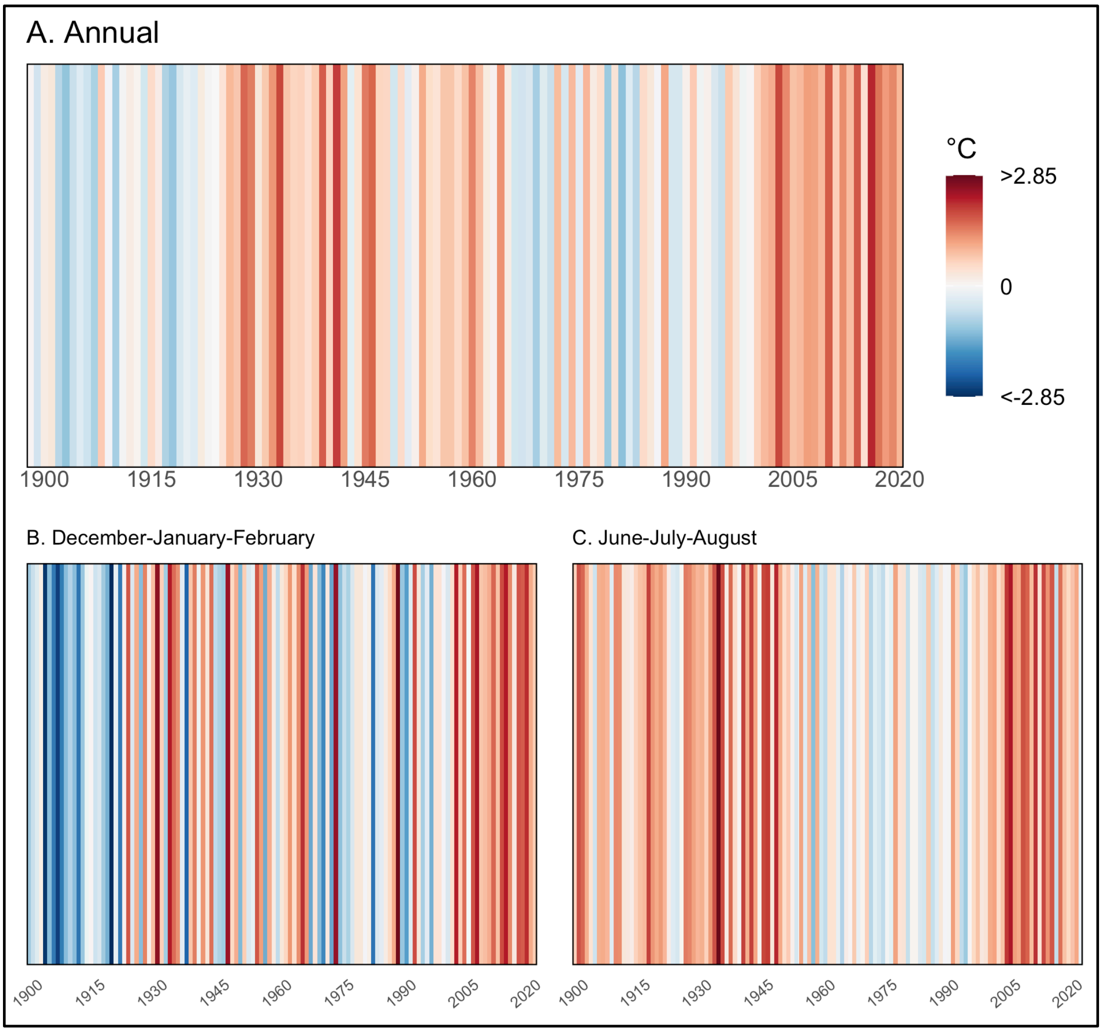

Figure 5.2 Average annual, winter and summer temperature anomaly for each year 1898-2020, Bolungarvík. There is a coloured stripe for each year from 1898-2020. The colour of the stripe represents the annual temperature difference in °C for the year compared to the 1961-90 mean.

Rate of air temperature change 1901-2020

Analysis of the total change in temperature between each decade at Bolungarvík from 1901 to 2020 shows a net rise for annual, winter and summer temperatures (Figure 5.3). Winter temperatures show the most total change and summer temperatures the least. Winter components show high fluctuations, the greatest being 1.94°C increase between 1911-10 and 1921-30. Winter temperatures fall slightly between 1921-30 and 1991-2000, while summer fall steeply between 1941-50 and 1951-60, and remain below 1901-10 temperatures until 1981-90. All three components rise from 1981-90, until 2001-10, when summer temperatures fall over the last decade. Winter temperatures show the greatest total change. Between 1901-10 and 2011-20, annual warming has been at a rate of 0.15°C per decade, winter 0.27°C per decade and summer 0.03 °C per decade.

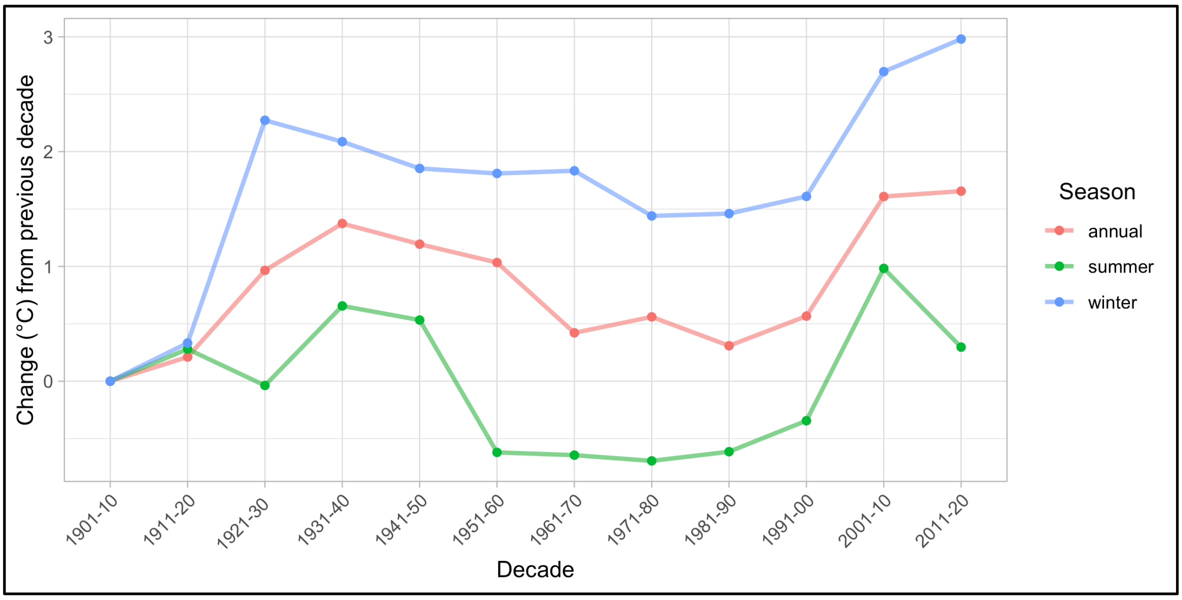

Figure 5.3 Change in mean temperature between each decade, 1901-2020, Bolungarvík.

Decadal anomalies 1950-2020

Decadal analysis of five stations with long term continuous temperature collections [Gjögur (1949-2020), Hornbjargsviti (1949-2020), Æðey (1954-2020), Reykhólar (1961-2020) and Lambavatn (1961-2020)] shows that temperature anomalies follow a similar pattern at each station (Figure 5.4). The stations, rarely differ in whether a month was colder or warmer than the 1961-90 reference period. Gjögur and Hornbjargsviti show that 1951-60 was warmer than the reference period. The temperatures during 1961-90 do not show large deviation from the mean, aside from the month of March being around 1°C higher than average during the decade 1971-80. Monthly temperatures for the decade 1991-00 fluctuated between being above and below the reference period, but average annual temperatures were higher. Every month of the decades 2001-10 and 2011-20 was warmer than the reference period for all stations.

Yearly anomaly 1949-2020.

Yearly analysis of average annual temperatures in the Westfjords (data combined from Bolungarvík, Gjögur, Hornbjargsviti, Æðey, Reykhólar and Lambavatn) shows a warmer than average period from 1951-62, a period of fluctuating warm and cold years from 1963-99 and all years warmer than average from 2000-2020 (Figure 5.5 A). Temperatures deviated as much as +2.16°C from the reference period, with the warmest years being 2003, 2014 and 2016. The coldest year was 1981 with an anomaly of -1.21°C.

DJF and JJA anomaly 1949-2020

An analysis of the December, January and February temperatures compared to the June, July and August temperatures shows seasonal differences (Figure 5.5 B+C). Both years show fluctuations in being hotter or colder than average until 1996. Since 1996 all winters, and all but one summer (2015) have been warmer than average. Winters show a greater deviation from the mean, with temperatures ranging from -2.08°C below and 2.7°C above the 1961-90 reference period (total range 4.79°C) while summers dip -1.17°C below and rise 2.21°C above the reference period (total range 3.39°C). Since the year 2000, winter temperatures have been on average 1.54°C warmer than the reference period and summer temperatures have been on average 1.10°C warmer than the reference period.

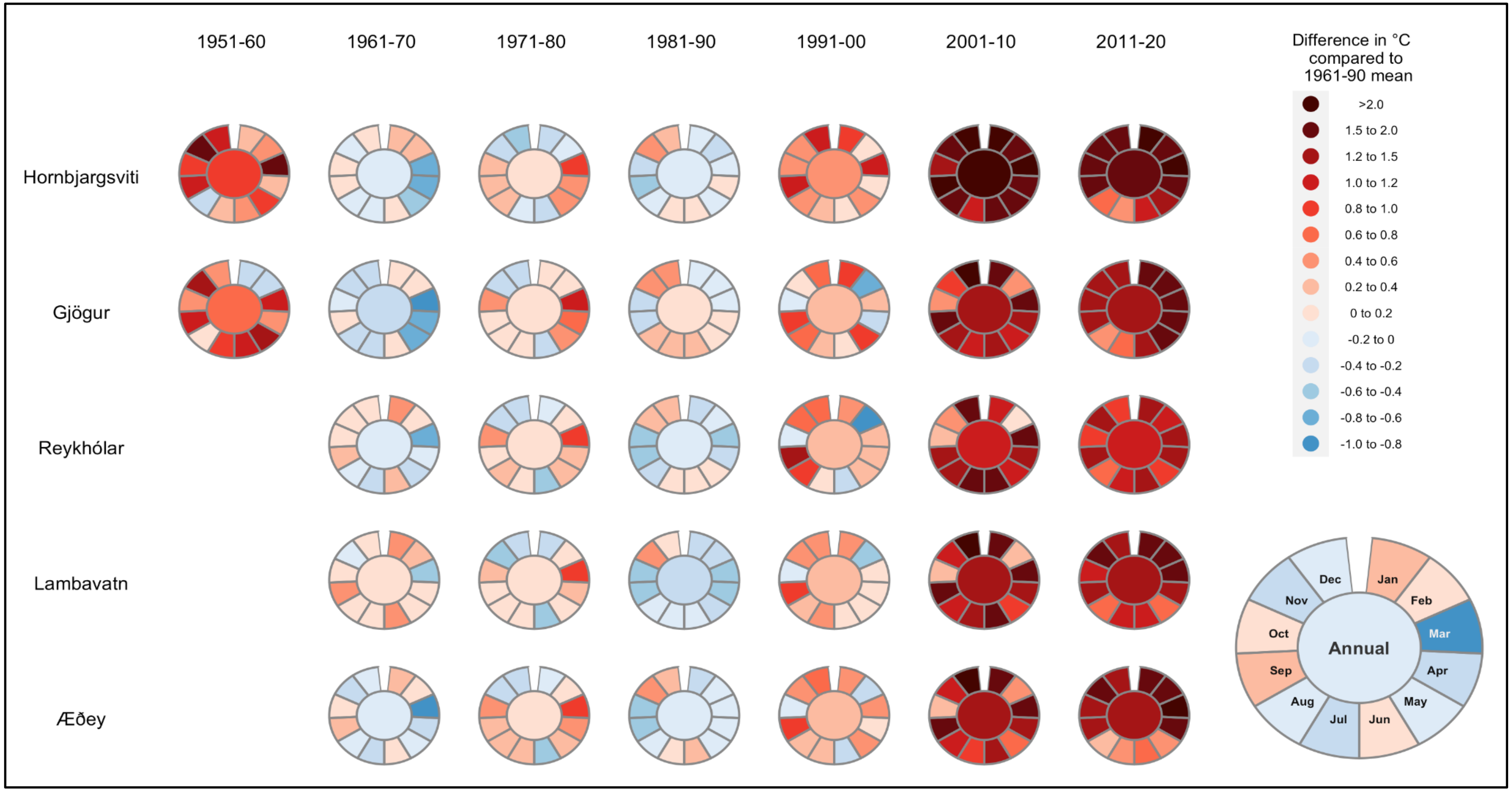

Figure 5.4 Average temperature anomalies for each decade 1950-2020, Hornbjargsviti, Gjögur and 1960-2020 Reykhólar, Lambavatn and Æðey. There are 12 outer segments in a circle for each month, labelled according to the larger sample circle in the right-hand corner. The colour of each segment represents the difference in °C compared to a 1961-90 reference period. The colour in the centre represents the annual average temperature anomaly for the decade.

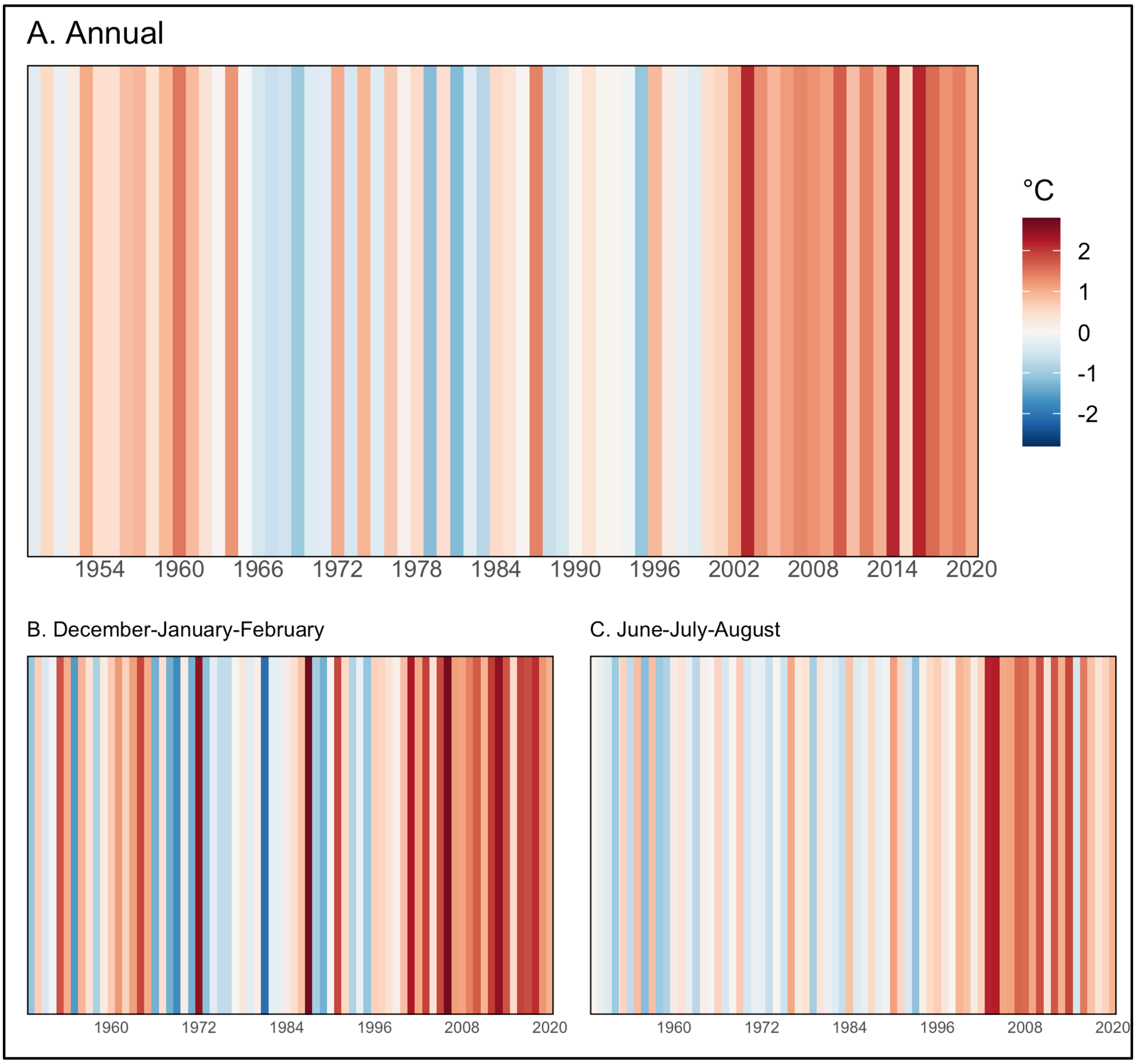

Figure 5.5 Average annual, winter and summer temperature anomaly for each year 1949-2020, Westfjords. There is a coloured stripe for each year from 1949-2020. The colour of the stripe represents the annual temperature difference in °C for the year compared to the 1961-90 mean. The data used in the figure is an average of the anomalies from Bolungarvík (1949-2020), Gjögur (1949-2020), Hornbjargsviti (1949-2020), Æðey (1954-2020), Reykhólar (1961-2020) and Lambavatn (1961-2020).

Rate of air temperature change 1951-2020

Analysis of the change in air temperature anomaly for annual, summer (June-July-August) and winter (December-January-February) shows that three components follow a similar pattern (Figure 5.6). Each shows little deviation from the mean from 1951-1990. All three components rise from 1981-90, with the greatest change occurring between 1991-2000 and 2001-10 anomalies. Between these two decades annual temperatures jump 1.05°C, summer 1.11°C and winter 1.26°C. Annual and summer anomalies decrease slightly between 2001-

10 and 2011-20, while winter continue to rise. The winter component shows the greatest change. Between 1981-90 and 2011-20, annual warming has been at a rate of 0.47°C/ decade, winter warming 0.55°C/decade and summer 0.28°C/decade.

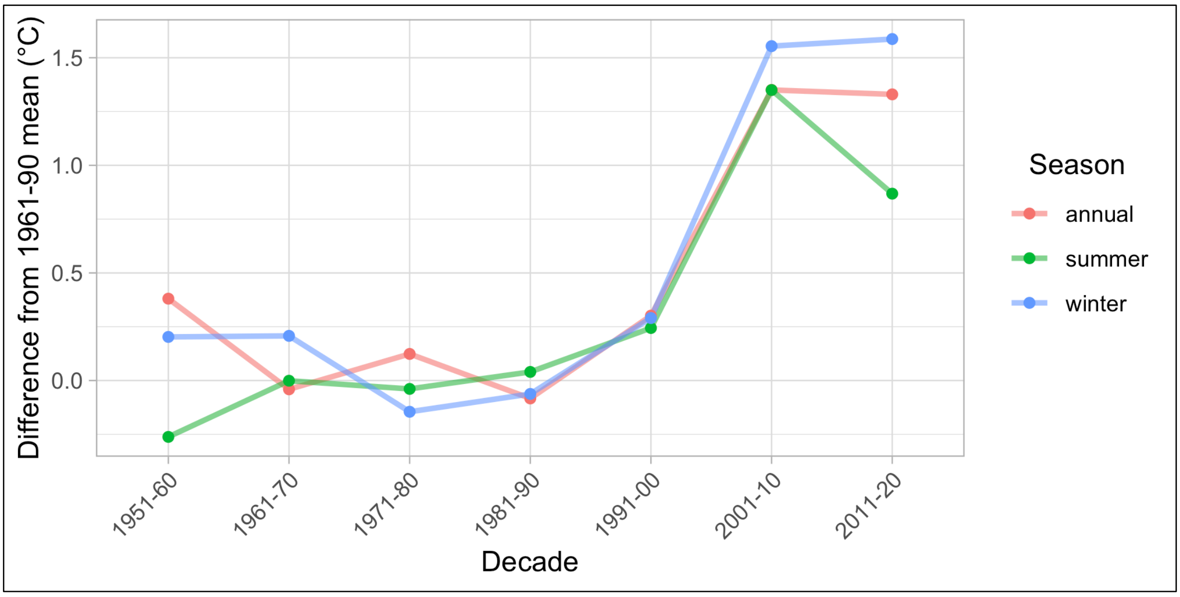

Figure 5.6 Change in temperature anomoly between each decade, 1951-2020, Westfjords. Change is in °C relative to the 1961-90 reference period (0 line on Y axis). The data used in the figure is an average of the anomalies from Bolungarvík (1949-2020), Gjögur (1949-2020), Hornbjargsviti (1949-2020), Æðey (1954-2020), Reykhólar (1961-2020) and Lambavatn (1961-2020).

5.1.2 Precipitation changes 1961-2020

Decadal precipitation trend 1961-2020

Analysis of the precipitation anomaly (expressed as a percentage) between Lambavatn and Mjólkárvirkjun shows that the two stations do not necessarily follow the same pattern (Figure 5.7). The decades from 1991-2020 experienced more precipitation than the reference period in Mjólkárvirkjun. However, at Lambavatn, these decades experienced precipitation that was within 5% of the reference period during 1991-2020. The stations correspond for some months though, for example that from 1991-2020 June was drier than the reference period and September was wetter. Mjólkárvirkjun experienced a wetter month than the reference period for every month except June and August in the decade 2011-20.

The greatest positive difference in rainfall was May 1991-00 in Lambavatn with 167.26% rainfall and December 2001-10 in Mjólkárvirkjun with 208.98% rainfall compared to the

1961-90 reference period. Conversely the greatest negative difference in rainfall was June 2001-10 in Lambavatn with 54.63% rainfall and April 2001-10 in Mjólkárvirkjun with 66.28% rainfall compared to the 1961-90 reference period.

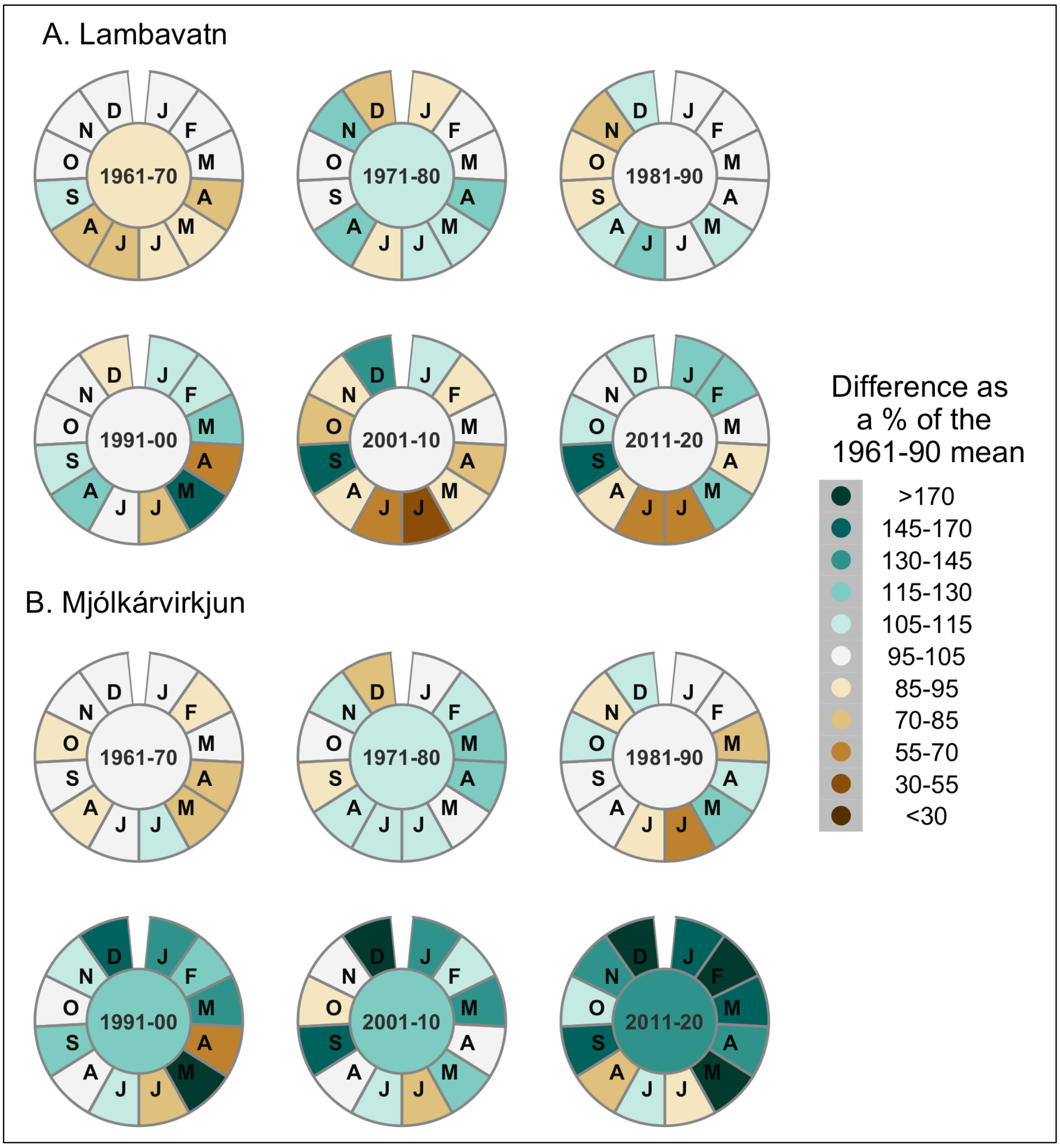

Figure 5.7 Average precipitation anomalies for each decade 1960-2020, Lambavatn and Mjólkárvirkjun. There are "precipitation circles", created for each decade for two stations, Lambavatn (A) and Mjólkárvirkjun (B). In each circle there are 12 outer segments for each month, labelled chronologically and clockwise - The uppermost and righthand "J", is January, the "F" to the right is February, and so on. The colour of the segments represents the monthly precipitation as a percentage of the 1961-90 mean precipitation. The colour in the centre of the circle represents the annual precipitation anomaly.

Yearly Precipitation Trend (Annual, DJF and JJA)

The yearly annual precipitation trend was for Lambavatn (1961-2020) and Mjólkárvirkjun (1959-2020) does not necessarily show homogeneity between the stations (Figure 5.8). Mjólkárvirkjun analysis shows every year but three have been wetter than average since the year 2000, but Lambavatn shows only 8 years as being wetter than average and displays less deviation from the mean. Both stations have a trend for winters to be wetter than the reference period from the year 2001, however this seems to be more pronounced in Mjólkárvirkjun where 19/20 winters were wetter and the deviation from the mean was greater, compared to 17/20 at Lambavatn. There also seems to be a trend for summers to be dryer than the reference period from 2001 onwards, however this seems to be more pronounced in Lambavatn where 17/20 summers were dryer than the reference period, compared to 13/20 at Mjólkárvirkjun.

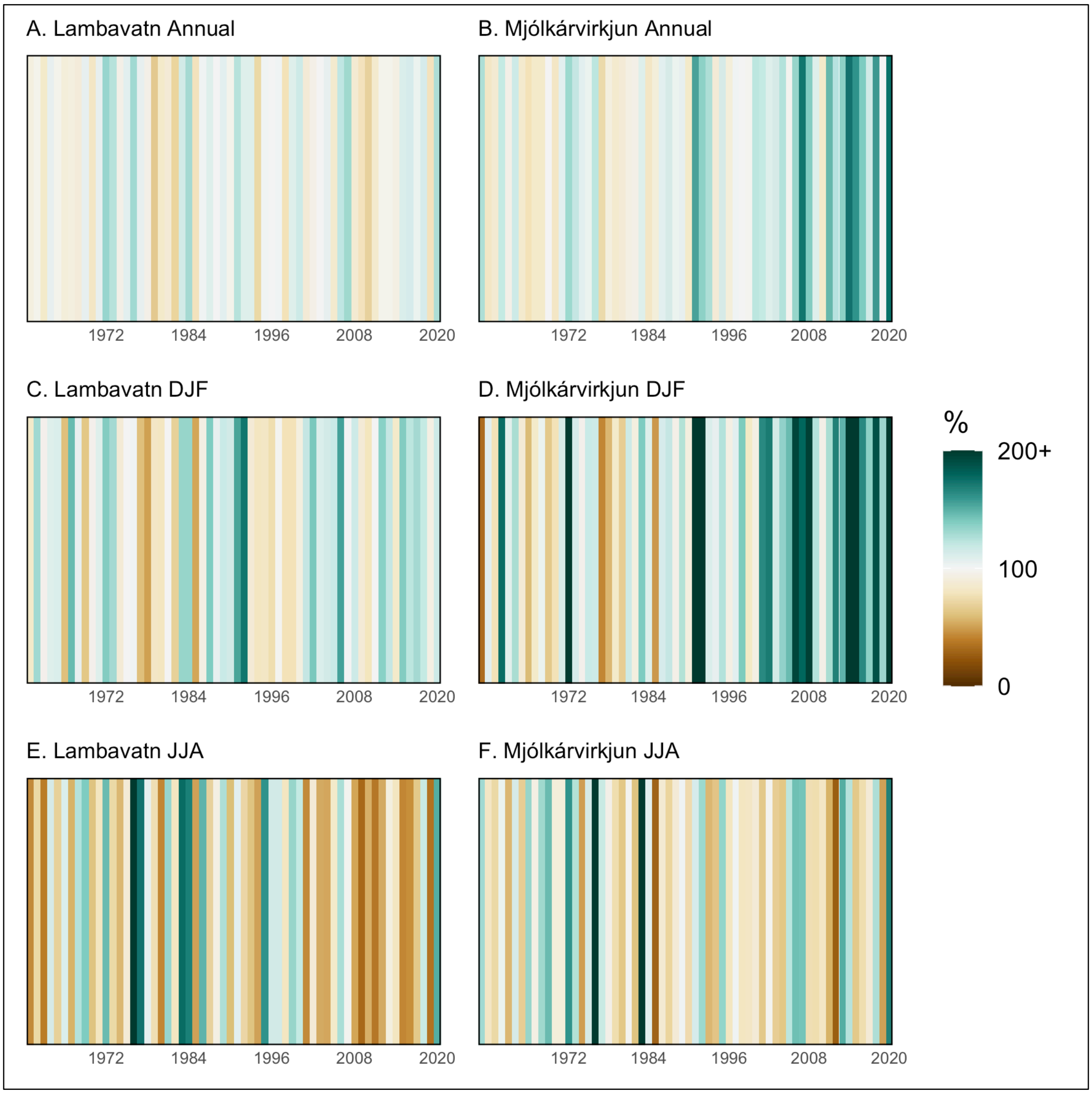

Figure 5.8 Average annual, winter and summer precipitation anomaly for Lambavatn, 1961-2020 and Mjólkárvirkjun, 1959-2020. These figures show a coloured stripe for each year of data. The colour of the stripe represents the annual average precipitation as a percentage of the 1961-90 reference period.

5.2 Spatial changes of temperature and precipitation

5.2.1 Temperature changes 1961-2020

Spatial analysis of absolute annual temperatures

Spatial analysis of absolute annual temperatures shows that temperatures in the decades 2001-10 and 2011-20 tended to be hotter than each decade 1961-2000 (Figure 5.9). Annual temperatures in 2001-10 and 2011-20 were warmer across all elevations compared to 1961-70 and 1981-90.

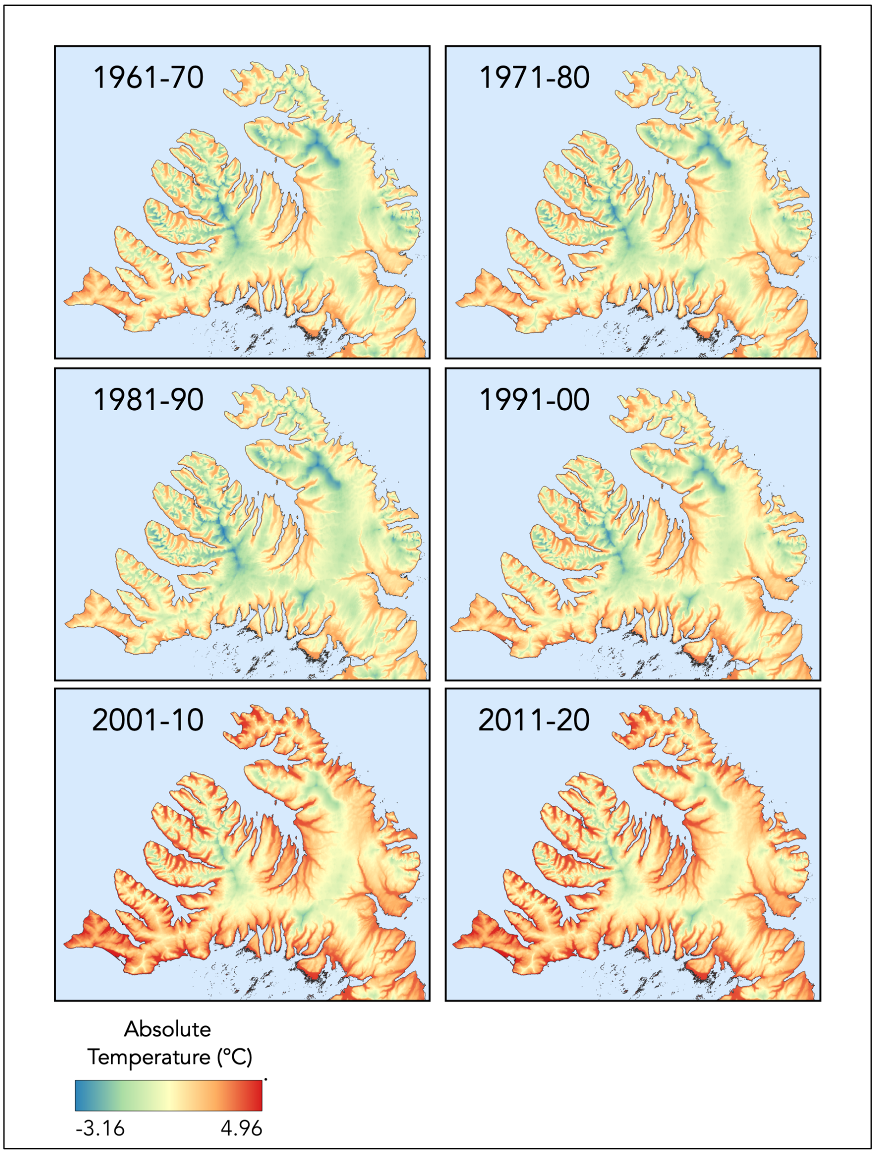

Figure 5.9 Spatial maps of absolute average annual temperatures in the Westfjords for each decade, 1961-2020.

Spatial analysis of absolute DJF and JJA temperatures

Spatial analysis of the average winter (DJF) and summer (JJA) absolute temperatures shows that 2001-10 and 2011-20 also tended to be hotter than each decade 1961-2000 (Figure 5.10). Winter temperatures in 2011-20 were warmer across all elevations compared to 1981-90 and 1971-80. Summer temperatures in 2011-20 were warmer across all elevations compared to each decade 1961-1990 but were cooler across all elevations compared to 2001-10.

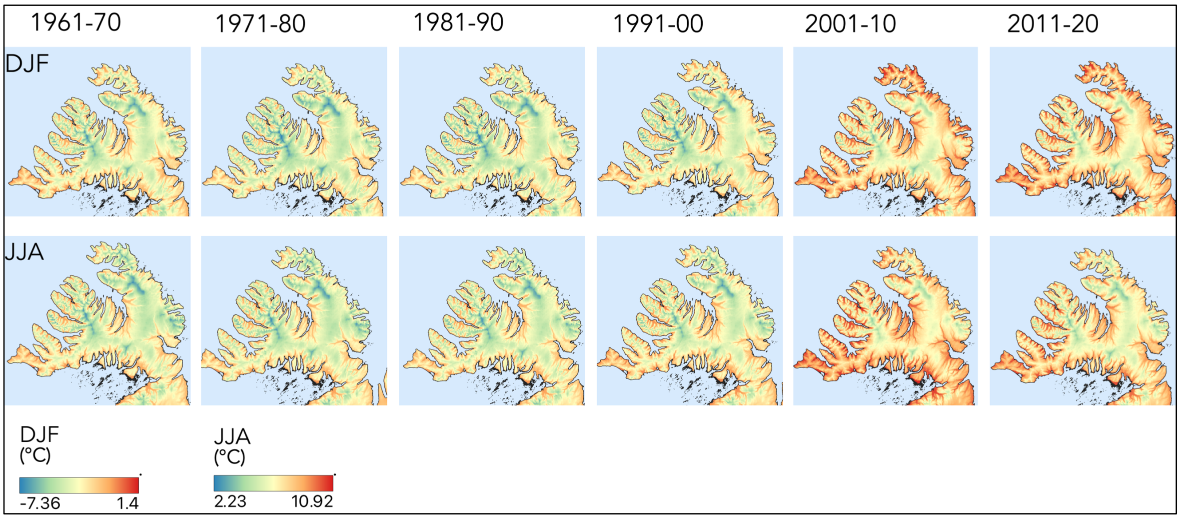

Figure 5.10 Spatial maps of absolute temperature for winter and summer 1961-2020, Westfjords. DJF = December, January and February. JJA = June, July and August.

Spatial analysis of anomaly for 2011-20

Maps of the annual, winter (DJF) and summer (JJA) anomaly for 2011-20 compared to 1961-90 reference show no negative anomaly was detected across the whole Westfjords region (Figure 5.11). Greater anomalies were generally detected in the DJF component compared to the annual or JJA component, particularly in the northernmost part of the Westfjords. The annual temperature shows a maximum of 1.67°C difference. The maximum change in the winter months is found to be 2.25°C while in the summer months it is 1.66°C. The annual and winter temperature differences seem to be stronger in the northern part of the Westfjords while summer differences seem to be most pronounced in the south west. An area of low anomaly is detected in all maps in the southeast quadrant.

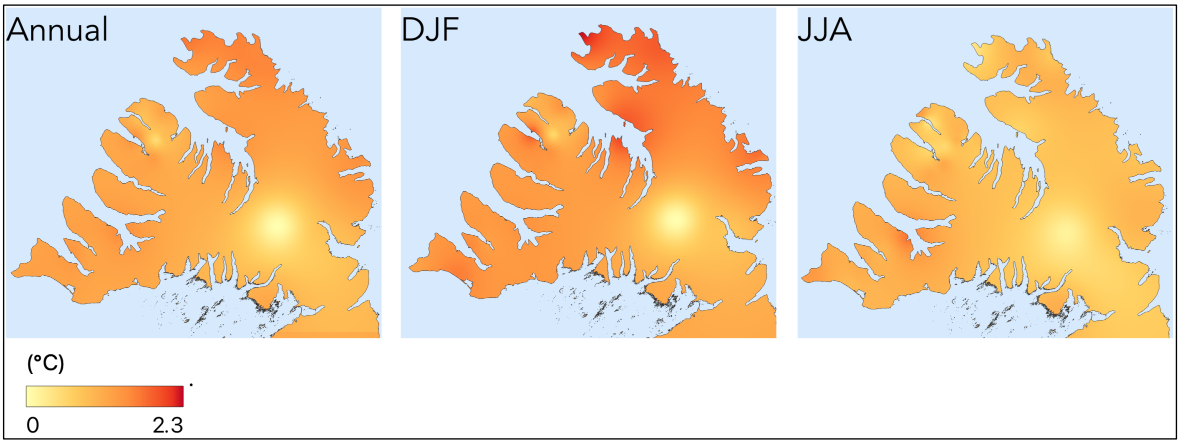

Figure 5.11 Spatial maps of temperature anomaly, 2011-20, annual, summer and winter. DJF = December, January and February. JJA = June, July and August. All anomalies were positive.

5.2.2 Precipitation changes 1961-2020

Spatial Decadal trend 1961-2020

Spatial analysis of absolute average annual precipitation for each decade 1961-2020 shows that annual precipitation appears to be heavier across the Westfjords region during 1991-2020 compared to 1961-90 (Figure 5.12). The winter trend follows a similar pattern of heavier precipitation in the most recent thirty years, especially in the central western part of the Westfjords region. The summer component shows a trend of decreasing precipitation. In the summer, the northernmost region of the Westfjords shows less precipitation during 1991-2020 compared to 1961-90 and the southwestern part of the Westfjords show less precipitation in the period 2001-20 than 1961-2000.

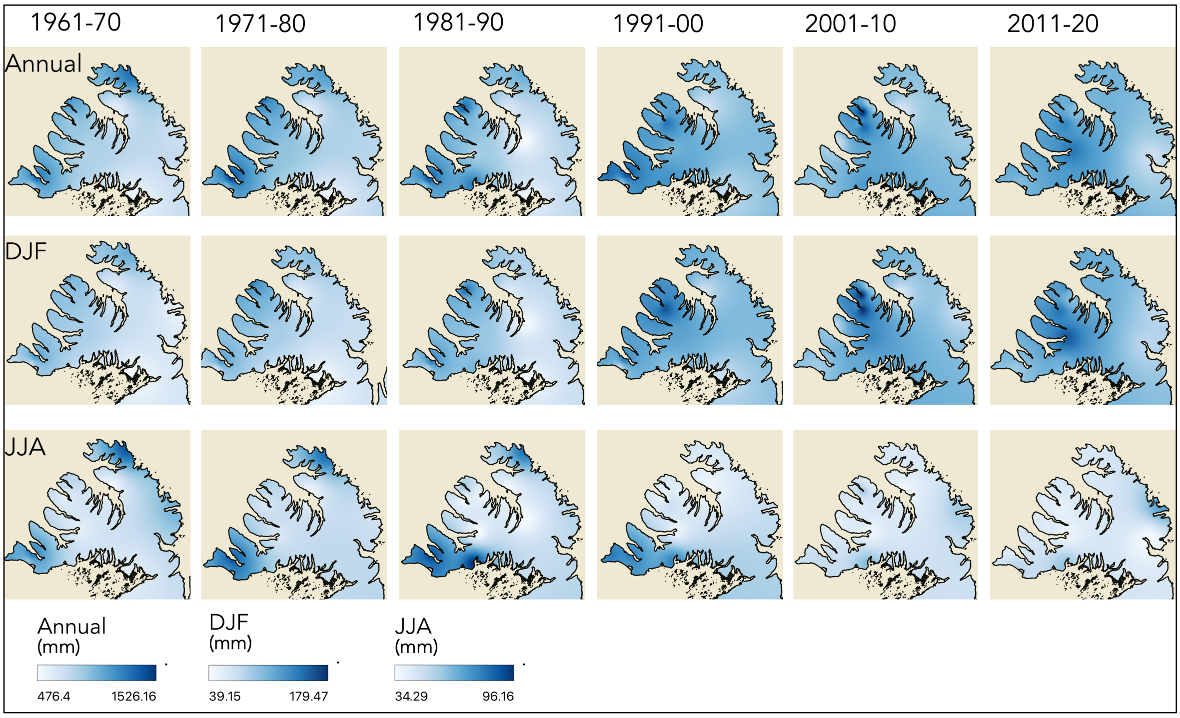

Figure 5.12 Absolute annual, winter and summer precipitation maps for the Westfjords region, for each decade, 1961-2020. DJF = December, January and February, JJA = June, July and August. Each time series is coloured to its own scale, with the maximum and minimum interpolated values at each end.

5.3 Climate Change Impact Map

The climate change impact map presents some of the key findings in this study. One of the main messages is that the Westfjords is warming, and this is illustrated using the original analysis from this study (Figure 5.13). The findings from the literature review that were chosen to include are the potential impacts of climate change on Westfjords Arctic foxes, which are genetically isolated (Norén et al., 2009), changing fisheries (IMO, 2018; Valtysson & Jonsson, 2018), changing precipitation potentially affecting slope processes and ski tourism (Conway et al., 2010; Morin et al., 2021), retreat of Drangajökull and the Greenland ice sheet (IMO, 2018; M. D. King et al., 2020), declining bird populations due to changing food stocks (E. S. Hansen et al., 2021; Petersen & Olsen, 2021), increased plant growth that may be associated with environmental trade-offs (CAFF, 2021; IMO, 2018) and the vulnerability of salmon to sea lice at warmer ocean temperatures (Godwin et al., 2021).

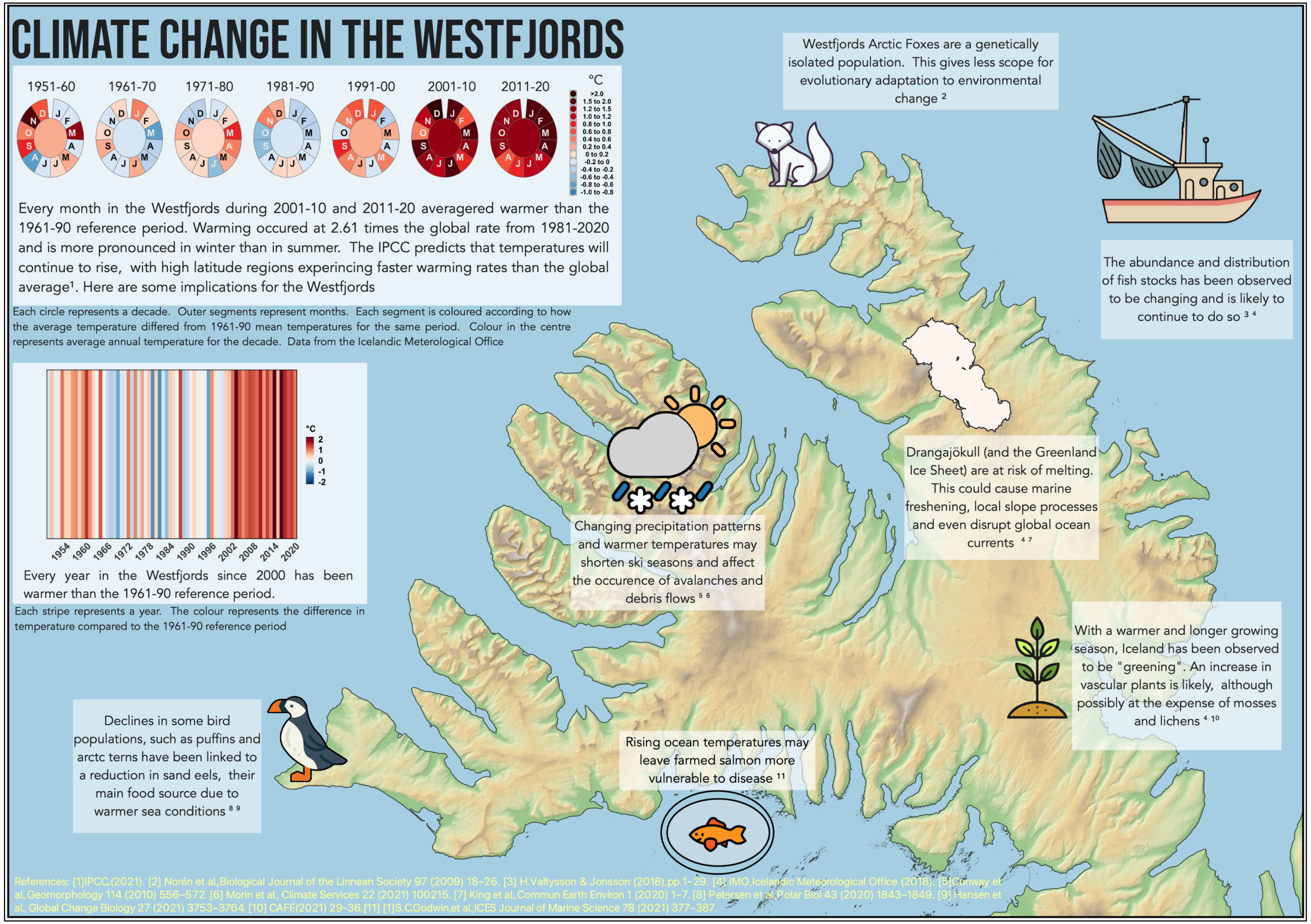

Figure 5.13 Overview map of climate change impacts in the Westfjords of Iceland

6 Discussion

6.1 Global climate change in the Westfjords

The first section of this chapter discusses how the patterns in the results section line up with global observations about climate change. It also brings in some of the limitations of the results obtained in this study. The second section discusses what the impacts of the trends detected might be, and actions the Westfjords region could take to prepare for these impacts. The third and final section discusses future research.

6.1.1 Temperature trends in the Westfjords

Observed temperature trends

Homogeneity between the relative recorded temperatures can be seen when the five stations, Hornbjargsviti, Gjögur, Reykhólar, Lambavatn and Æðey are compared (see Figure 5.3). This is perhaps not surprising given the small geographical area the Westfjords region occupies and that all the stations are at comparable altitudes (all situated below 30m a.s.l.). This suggests that the long-term temperatures recorded at Bolungarvík (1898-2020) may be a reasonable representation of relative temperatures in the Westfjords throughout the twentieth century.

In the temporal analysis of temperature trends in Bolungarvík it is possible to see some of the national climate trends for Iceland. For example, at the turn of the twentieth century, for the first two decades, winters are colder than average and summers are warmer than average, suggesting strong seasonality. One year that stands out is the colder winter of 1918, where the January anomaly is -11.80°C. This is the "great frost winter" of Iceland, and is associated with thick sea ice forming in Reykjavík harbour and an unusually high number of polar bears arriving in northern Iceland (Moore & Babij, 2017). Then it is possible to see annual warming from 1921-40, with temperatures relatively elevated until 1950. A warmer period from 1920-1950 has previously been reported by the IMO for the whole of Iceland (IMO, 2018). The warm period during 1920-1950 is likely part of the global trend of early twentieth century warming, which was particularly pronounced in the Arctic (Bengtsson et al., 2004; Brönnimann, 2009). The most dramatic change during this period is shown in the rate of change graph for Bolungarvík where average winter temperatures jumped 1.94°C from 1911-20 and the 1921-30 period. Temperatures deviate less from the mean during 1961-90, with 1961-70 and 1981-90 being colder than average. This colder period has also been reported by the IMO and glacial advance occurred in Iceland from approximately 1960-1980 (IMO, 2018).

All temperature representations indicate that the Westfjords is warming. The trend can be seen from 1981-90 in the decadal trend, but it is particularly pronounced since the turn of the century, with sustained positive anomalies under almost all conditions. The largest change occurs between 1991-00 temperatures and 2001-10. This pronounced warming at the turn of the century can also be seen on the absolute temperature spatial maps (see Figures 5.9 and 5.10). The warming is not unprecedented, as a similar jump occurred (at least in Bolungarvík) between 1911-10 and 1921-30 temperatures. However natural forces are thought to play a bigger role in early twentieth century warming that anthropogenic forces (Bengtsson et al., 2004; Brönnimann, 2009). This late twentieth and early twenty-first century warming that is being seen globally (and in the Westfjords) is thought to be driven by anthropogenic release of greenhouse gases (Blunden & Arndt, 2020; IPCC, 2021).

Reported global temperature rises between 1980 and 2019 are 0.18°C/decade (Blunden & Arndt, 2020). Westfjords temperatures rose 0.47°C/decade from 1981-90 to 2011-20, which is 2.61 times the global rate. Reported global temperature rise between 1880-2019 is 0.07-8°C/decade (Blunden & Arndt, 2020) while in Bolungarvík from 1901-10 and 2011-2020, the rate was 0.15°C/decade. In both timelines (1981-90 to 2011-20 and 1901-2020) the rate of warming is slower in the summer and higher in the winter. Depending on the definition of Arctic used, this could be seen as an example of Arctic amplification.

Evidence for stronger seasonality is seen in the early part of the twentieth century. The yearly graphs for Bolungarvík (see Figure 5.2) show that before 1920, winters tended to be colder than average and summers warmer than average. This contrasts strongly with the first twenty years of the twentieth century, where nearly all summer and winter periods have been warmer than the reference period. In both periods, 1901-2020 and 1951-2020 winters show a greater total difference from reference temperatures, and summers the least. All this indicates a reduction in the amplitude of the seasonal cycle, and that warming is stronger in winter. This is in line with what has been observed above 60°N latitude, where for this area as a whole a reduction in the amplitude of the seasonal cycle has been reported (Box et al., 2019).

The spatial maps indicate that the decades 2001-10 and 2011-20 tended by warmer than the preceding four decades, which is in keeping with what is seen in the temporal analysis. Maps of the total anomaly during the most recent decade, 2011-20 compared to the 1961-90 mean show that all areas experienced a positive temperature rise. The northern parts of the annual and the winter maps of anomaly indicate a greater change in temperature in the north. The southwest appears to have warmed more in the summer. These maps are novel in both the data range used, and the resolution provided.

Limitations of temperature analysis

The importance of a longer time scale in which to view climate variations can be emphasised in the temperature results. Looking at the decadal trend from stations from 1961 onwards and extrapolating makes the warming look more extreme than it does in the context of the trend from 1901-2020, where a previous warm period can be seen. It was noted in the research for this study that climate conditions are often placed in a very short-term context. For example, one paper headlined "Upper Ocean Temperatures Hit Record High in 2020", reported on data from 1958 onwards (Cheng et al., 2021). Similarly, record temperatures in Siberia are reported by Copernicus from a record that begins in 1950 (Copernicus, 2020). The Arctic sea ice extent reported by the National Snow and Ice Data centre is a record from 1979 onwards (NSIDC, n.d.). These records are limited because of a lack of available data and consist of some data that was impossible to collect prior to the invention of satellites. Climate data collection has become more precise and abundant in recent years. However, the short term nature of the presentation of these data sets gives it almost no context. There is no scope to view natural variability or to understand how usual or unusual the current situation is. This is not an attempt to downplay the seriousness or actuality of the warming of the oceans and Siberia, or the melting of the sea ice but an emphasis on looking at attention grabbing headlines with a critical eye.

The disparity in data availability between decades may have affected the spatial analysis. For example, there were 21 stations with temperature collections for the period 2011-20, but only 10 for the period 1991-2000 (see Table 4.1). There was also no available data from stations above 50m from 1961-2000. While cross validation of the IDW indicated relatively low errors (see Table 4.2), this disparity should be considered when viewing the results.

In all maps of the temperature anomaly of 2011-20, an area of low anomaly was detected in the southeast. This radiates from the high elevation station of Steingrímsfjarðarheiði. These temperatures were adjusted to sea level estimation using a constant lapse rate, which assumes only elevation affects temperature. It was noted during analysis that the higher altitude stations were giving slightly lower than expected temperatures when adjusted to sea level. As Steingrímsfjarðarheiði is relatively far from other stations, it leaves its mark on a greater distance when the IDW interpolation is performed. It was concluded that this cold spot is a relic of error from the constant lapse rate adjustment, rather than an actual area of less change in temperature.

6.1.2 Precipitation trends in the Westfjords

Observed precipitation trends

The two long term (1961-2020) datasets on precipitation do not show the same homogeneity that can be seen from the stations collecting temperature data for the same period of time. Lambavatn shows less deviation from the reference period and does not show the same increase in precipitation over the most recent 25 years. These stations are separated geographically, and the mountainous terrain of the Westfjords region could be contributing to localised differences in precipitation patterns (Ólafsson et al., 2007).

Evidence of drier summers and wetter winters in the last 20-30 years can be seen in both the temporal and spatial analysis of precipitation. In the decadal trend and, Mjólkárvirkjun shows wetter winter months during the period 1991-2020 and both Mjólkárvirkjun and Lambavatn show a dryer than average June for the same period. The spatial trend is also for a wetter winter period from 1991-2020 and a dryer summer period in the north of the Westfjords from 1991-2020 and dryer in the southwest from 2001-2020 (see Figure 5.12). Wetter winters at higher latitudes are predicted to be a feature of our changing climate (IPCC, 2021). It was observed that increased precipitation above 50° latitude was greater during the colder months (there defined as October-May) from the period 1971-2017, and the extent of the increase was greatest after the mid 1980s (Box et al., 2019). Increased winter precipitation combined with the warmer winter weather indicated by the temperature analysis could mean the Westfjords region is now experiencing more precipitation falling as rain instead of snow during the winter months. Drier and warmer summers could leave the Westfjords at risk of periods of drought.

The spatial analysis in this instance allowed what could be considered sporadic data collection to be useful. The available data on precipitation was less likely to be continuous than the temperature data, making it difficult to judge how it was changing from temporal analysis alone. The interpolation methods allowed data from stations that had only collected for a single decade to be used and to produce a comprehensive picture of precipitation in the Westfjords over the last 60 years. Like the temperature spatial maps, these maps are unique in both the time range that they cover and the local detail they provide.

Limitations of precipitation analysis

Einarsson, in his summary of Icelandic climate in 1984, discusses how Icelandic rain gauges are liable to underestimate the amount of precipitation, particularly if it is accompanied by high winds or falling as snow, by as much as 25% (M. A. Einarsson, 1984). While there has likely been some improvement in data collection since 1984 (although errors prior to 1984 still impact the results of this study), a report by the IMO in 2020 still acknowledges error in precipitation measurements. It specifically mentions two stations in the Westfjords region, Ísafjörður and Súðavík, for their complex terrain leading to a difficulty in collecting accurate data (Massad et al., 2020). It is possible that both actual differences and measurement errors account for the disparity between the two stations.

The precipitation data had on average less available data per decade than the temperature data, however there was not the same disparity in the number of stations available, with between 10 and 15 stations available for each decade (see Table 4.1). The weaknesses of a 60 year time scale are mentioned in the temperature section. These apply here also. The short time span of the precipitation analysis, as well as the potential errors in measuring precipitation mean that caution should be exercised when extrapolating from these results.

6.2 Impact of climate change in the Westfjords

The results presented show warming air temperatures over the last century, which has accelerated since 1981. Warming is greater in winter than in summer. Precipitation appears to have increased annually and in winter from 1961-90, compared to 1991-2020, while decreasing in the summer, although there is more uncertainty in this pattern. Sea surface temperatures in Iceland have broadly followed atmospheric patterns throughout the twentieth century (Hanna et al., 2004) and rising SSTs have been reported for the North Atlantic (Lapointe et al., 2020) so it is likely that SSTs in the Westfjords region have been increasing as well. The background chapters highlighted some systems in the Westfjords region that are vulnerable to temperature rise, SST rise and precipitation changes and the climate change impact map summarised some of the key findings (see Figure 5.13). The climate change impact map makes use of some of the climate change communication tools described in the chapter 2, such as using novel information (in the form of the original research from this study), imagery and framing information about climate change in a local context. It is hoped it could be used outside this study as an effective means of climate change communication.

The impacts of climate change that have been described are a mixture of consequences that could be viewed as positive or negative. The most serious consequences would be increased avalanches or debris flows, posing a direct risk to human life, as well as bring costly to prevent or recover from. In contrast, the Westfjords region might benefit, for example, from a longer growing season, or new species of fish may thrive in the coastal waters under warmer conditions. With any benefits there are trade-offs, particularly in ecological systems, one species usually benefits at the expense of another. It can also be seen in socio-economic terms, income from summer tourism may increase with warmer summers, but ski tourism may decline with warmer winters. Aquaculture salmon may grow better in moderately warmer conditions, but also be more vulnerable to salmon lice.

The Westfjords is likely to experience a changing environment well into this century. However the magnitude of climate change impacts depend on the quantity of emissions released, so there is still a strong case for reducing emissions locally and globally (IPCC, 2021; Overland et al., 2019). Iceland has committed to cutting carbon emissions by 40% by 2030 and become carbon neutral by 2040 (Government of Iceland, n.d.-a). While this is admirable, carbon emissions globally will continue past this point, and the long life of a CO_2 molecule and the thermal inertia of the oceans mean the effects of emissions will be felt into the future. As such there is a level of committed warming, that will occur even if all fossil fuel emissions were to stop (Mauritsen & Pincus, 2017). A limit to the amount of mitigation that can be done leaves room for adaptation and planning.

The changes that do occur as a result of rising temperatures may pose threats to fragile ecosystems, important economic systems and infrastructure and human life. As such, careful planning, management, and adaptation strategies to protect these systems should be implemented. Indicators should be chosen carefully to assess how effective any measures taken are (Kenney & Janetos, 2020). Effective management and adaptation measures may limit the negative impacts of climate change in the area and allow the area to benefit from any positive impacts (for example, increased fish stocks or agricultural growth) in a sustainable way.

Fisheries management is one area that could help the Westfjords prepare for the changes in store. There have already been failures in this area, as in the case with the expanding mackerel fishery, where the states involved failed at co-operative international management, which has possibly already led to overfishing (Boyd et al., 2020; Østhagen et al., 2020). As it is quite possible fish stocks will continue to change with no respect for international boundaries, learning from the "mackerel wars" is imperative. As fishing encompasses a large part of the Westfjords and Iceland's economy it is in its interest to come to international agreements and to set quotas that are sustainable. It is likely that fisheries will have to diversify and catch new fish species, or possibly expend more fuel chasing established fishing stocks, such as capelin, as they change their distribution.

Salmon aquaculture has the potential to expand in the Westfjords. The current trend is for production to increase and the current production in the Westfjords is below the recommendations from the Marine and Freshwater Institute (Government of Iceland, n.d.-b). Klinger et al., predict that water temperature in Iceland will be beneficial for salmon growth until 2050, so the climate may aid production. This could be good for employment and the economy within the Westfjords, but it does come with increased risk of disease among farmed salmon (Godwin et al., 2021; Sandvik et al., 2021). Managing and treating sea lice infestations will bring greater costs to aquaculture in the Westfjords, and raise concerns about animal welfare, which could impact public opinion on salmon aquaculture. Infections spread from farmed to wild salmon populations could anger local wild salmon fishers and damage wild salmon fishing tourism.

Management of plant species will be important too. While warmer temperatures are already leading to more favourable growing conditions in Iceland (IMO, 2018), it has been shown that the warming climate may lead the Westfjords region to experience invasion by alien plant species (Wasowicz et al., 2013). New crops or plants to grow should be chosen carefully, to make sure that they are not likely to become invasive. King et al., also stresses the importance of choosing plants to grow that are local variants or specifically adapted to the photoperiod at high latitudes (M. King et al., 2018)

As the climate changes, particularly in relation to ecosystems (and ecosystem-dependent economies such as nature tourism and fisheries) it is important to limit non-climate stressors. Humans are threatening various life forms by releasing greenhouse gases but they could limit these threats to life by reducing pollution incidents and having stricter pollutant controls for things other than CO_2. Improved waste management, waste reduction, water treatment and tighter control of toxic substances could mean that while species have to adapt to warmer climates or different precipitation patterns, they are not also being stressed by other human influences.

There is evidence that species in Iceland are being affected by non-climate stressors. There are currently no wastewater treatment facilities in the Westfjords region (Veitur, n.d.). A survey of the seafloor near waste water outflows in Ísafjörður found evidence of hypoxic conditions and plastic pollution (Thompson, 2020). Dissections of 25 fulmars in 2020 (19 of which were from the Westfjords) found plastic in the gastrointestinal tracts in 68% of the birds (Snæþórsson, 2021). Oil in the water in Reykjavík harbour was shown to be causing considerable physiological stress to blue mussels (*Mytilus edulis* L.) (Halldórsson et al., 2005), it is possible conditions could be similar in harbours in the Westfjords region. Improved systems for wastewater treatment and waste management could ameliorate these conditions.

There is also scope to increase protected areas, particularly in the marine environment. Protected areas, on land or at sea, could help reduce stress on ecosystems going forward.

Currently less than 1% of Iceland's waters are protected (MPA Atlas, n.d.). The largest protected marine area is in Breiðafjörður, to the south of the Westfjords, but this is a multi-use area and still permits fishing activities (Muir et al., 2003). While a fully protected marine protected area would not offer protection from ocean acidification or warming waters, it could help protect against these non-climate stressors, such as pollution and overfishing. A fully protected marine protected area would also make a good controlled environment in which to monitor the effects of climate change. Changing SSTs, salinity and pH are all posing threat to life in the ocean as a result of climate change (Astthorsson et al., 2007; Dickey et al., 2021; Gazeau et al., 2013).

Arctic foxes in the Westfjords are already offered protection in the Hornstrandir Nature Reserve (Botková & Unnsteinsdóttir, 2015), however they are genetically isolated from both global and other Icelandic fox populations (Norén et al., 2009). Low genetic diversity is predicted to leave a species with less evolutionary adaptive capacity to environmental change (Matocq & Villablanca, 2001). This means the Westfjords sub-population of foxes could be particularly vulnerable to environmental changes brought about by climate change. Monitoring of the fox populations within the protected area would help to manage this risk.

Investing in alternative winter recreation sports or relocating ski centres to higher locations could be a way to adapt to a decreasing ski season. Exercise has been shown to alleviate symptoms of seasonally affective disorder (Drew et al., 2021) as well as being important for physical health. It is vital for the communities in the Westfjords to have areas for physical recreation and socialising throughout the winter. While alternatives to skiing do exist in towns in the Westfjords (swimming, indoor hall sports), compensation for the potential loss of skiing areas should be considered.

6.3 Future Research

The graphics produced may be used outside of this thesis to show to Westfjords residents how climate change is affecting where they live. It might be possible to display them at the University Centre of the Westfjords in Ísafjörður or in local cafés. The graphics display the changes that have already occurred in the region, and could perhaps communicate the proximity of a problem that people often view as being far away (Ballew et al., 2019; Jalbert et al., 2018). Testing on whether these images or similar images influence the psychological distance of climate change for Westfjords residents could be performed as a follow up study.

Climate stripes can already be produced online for many countries at a national scale (WMO, 2021b), but these ones with local data for the Westfjords are unique. These, or the other images in this study could be replicated in other areas if individuals have access to regional scale data. Having local statistics could engage residents with climate change in their area. Increased engagement with the issues could lead to increased action and mitigation policies (Jones et al., 2017; Sheppard et al., 2011) bringing benefits to both the local area and across the globe. The climate change impact map could be expanded upon to include more information and have better visual balance if it was produced on a larger scale outside this thesis.

The analysis done in this study could be repeated annually. As discussed, the longer the time scale, the more robust and contextualised the analysis will be. It is important to keep monitoring the changes at a local level, as it will help to predict what impacts might be felt, and how dramatic they might be. Of particular interest will be the rate at which change is occurring. Was the large difference detected between 1991-00 and 2001-10 temperatures an outlier, or can we expect a similar rate of change into the future? Frequent updates of this analysis will keep the output relevant and more engaging to the reader. The trend seems to be for increased data availability – i.e. the most temperature data points were available for the most recent decade. This means subsequent analysis could be more robust, and lead to less errors in procedures such as spatial interpolation.

Temperature and precipitation are useful climate change indicators, but they are not the only ones available. A future similar study would benefit from collecting other data. Of particular interest would be in-situ measurements of SST and ocean pH to observe how these are changing in this coastal region. A lot of the impacts discussed in this study not only depend on air temperature and precipitation changes but are intrinsically tied up with SST change and ocean acidification. Including these two variables would give a more holistic view of how the Westfjords environment is changing in response to climate change and what impacts might be expected.

Any of the proposed impacts of climate change on the Westfjords would make an interesting longitudinal study. For example, how a certain species of bird, or the fishing economy is impacted over the next ten years by climate change. This information could then be used to better inform how high latitude coastal areas can expect to be affected by climate change. It would also be possible to retrospectively correlate the temperature and precipitation trends in this study with observed changes, for example changes to ecosystems.

7 Conclusion

In conclusion, the analysis from this study shows that the Westfjords region of Iceland is experiencing some of the global and national trends associated with climate change. This includes warming at a rate that is faster than the global mean. Annual, winter and summer temperatures have been above the 1961-90 mean for almost every year since 2000. The degree of warming is greater in winter than in summer months, resulting in a reduction in seasonality. A single station collection of temperature data shows that the Westfjords experienced a comparable period of warming in the early twentieth century. Precipitation shows an increasing trend annually and in winter months, but decreasing in summer months, when 1961-90 and 1991-2020 are compared.

These trends mean that the Westfjords region might be impacted by climate change. There are many physical, biological, and socio-economic systems that could be affected. The degree of impact depends on how global emissions continue to change. The Westfjords should adopt climate change mitigation strategies but also put in place adaptation and management strategies, as some changes may be unavoidable. These strategies could include environmental protection and investment in alternative practices (such as for fishing or tourism).

Graphs and maps were produced to illustrate the findings of this study. These images are unique in the resolution they provide of the Westfjords region and put climate change in the context of this rural coastal area. Having a local context may improve the quality of climate change communication and may reduce the perceived distance of climate change.

The analysis done in this study lends itself to repetition. This could be done annually, or at longer scale. Due to the changing nature of the data, there will be novel findings each year. It is important to keep monitoring the changes at a local level, as it will help to predict what impacts might be felt, and how dramatic they might be. The study could be repeated to include different variables, for example SST or ocean pH. Long term monitoring of any of the systems highlighted as at risk of change due to climate change in this project could make a valuable contribution to how climate change can be expected to impact high latitude coastal areas.

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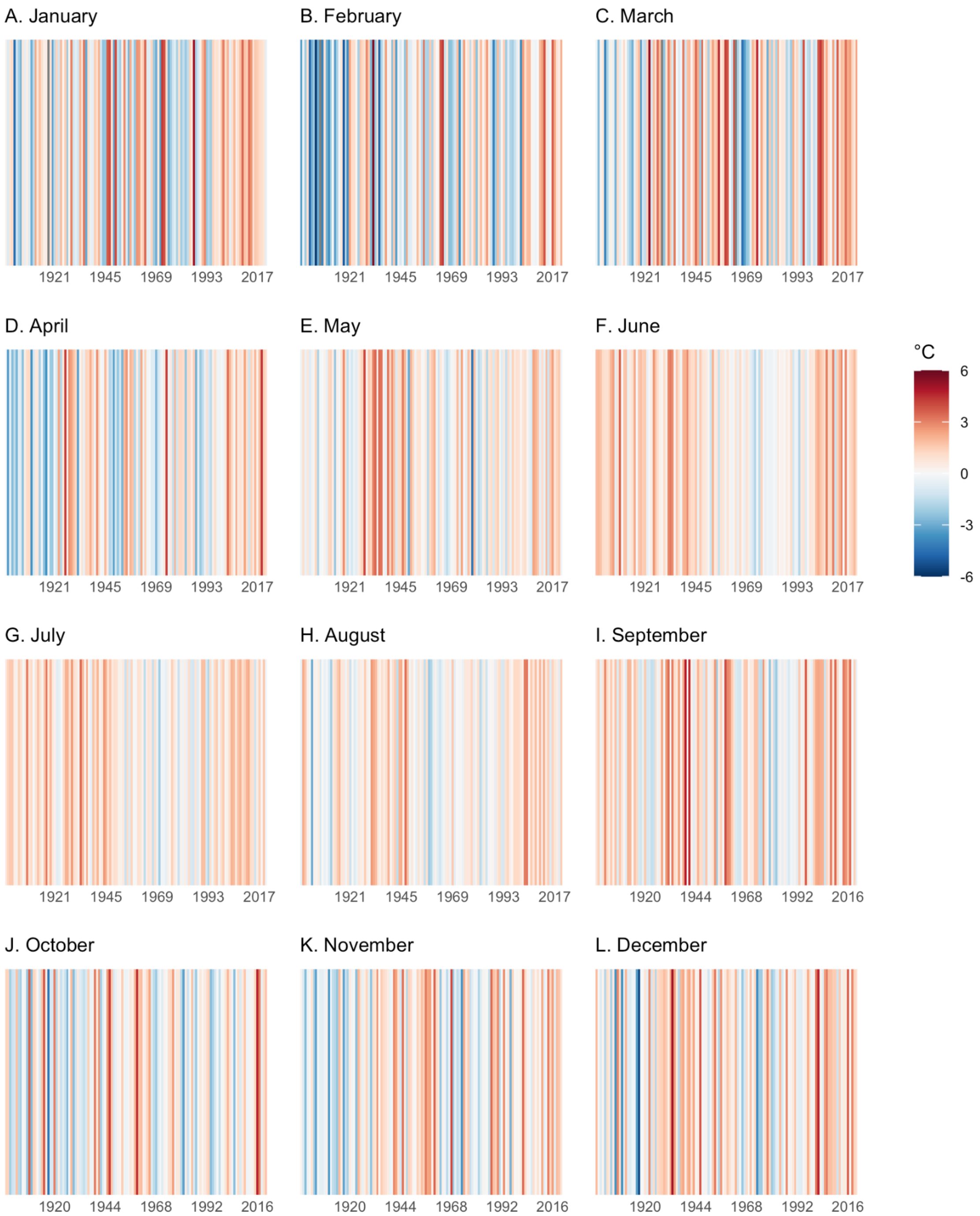
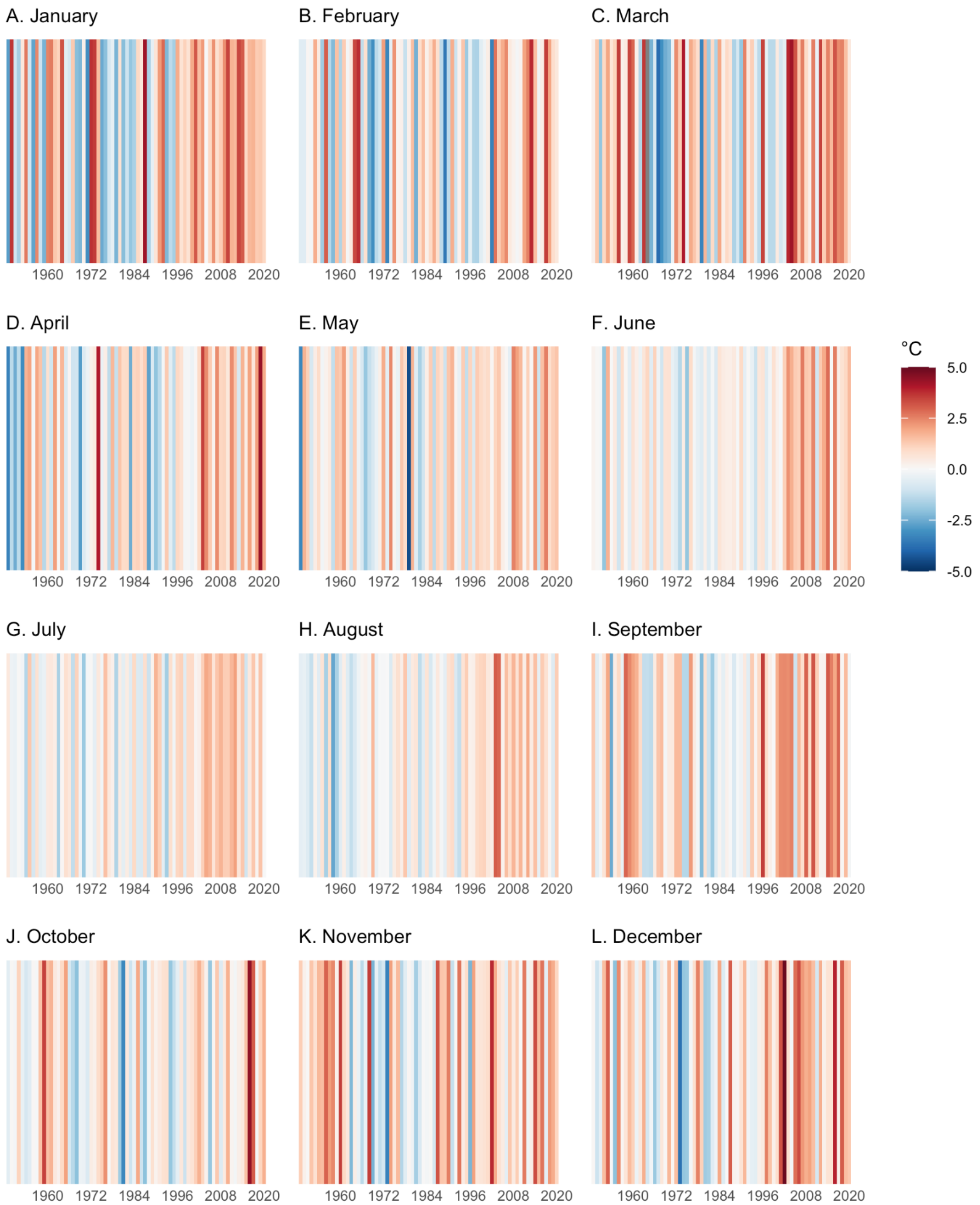
APPENDIX A



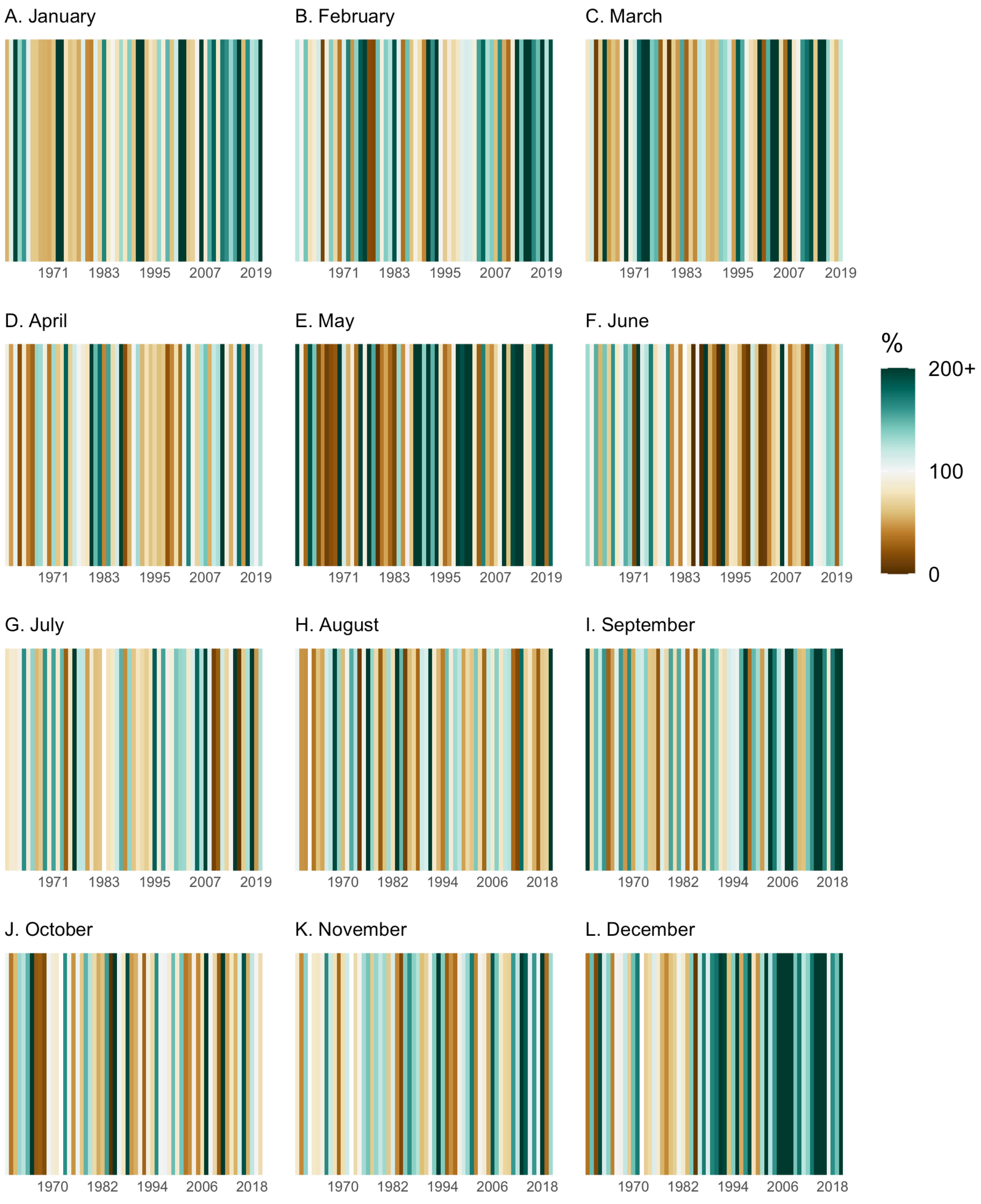
Temperature stripes for each month, Bolungarvík 1898-2020

APPENDIX B



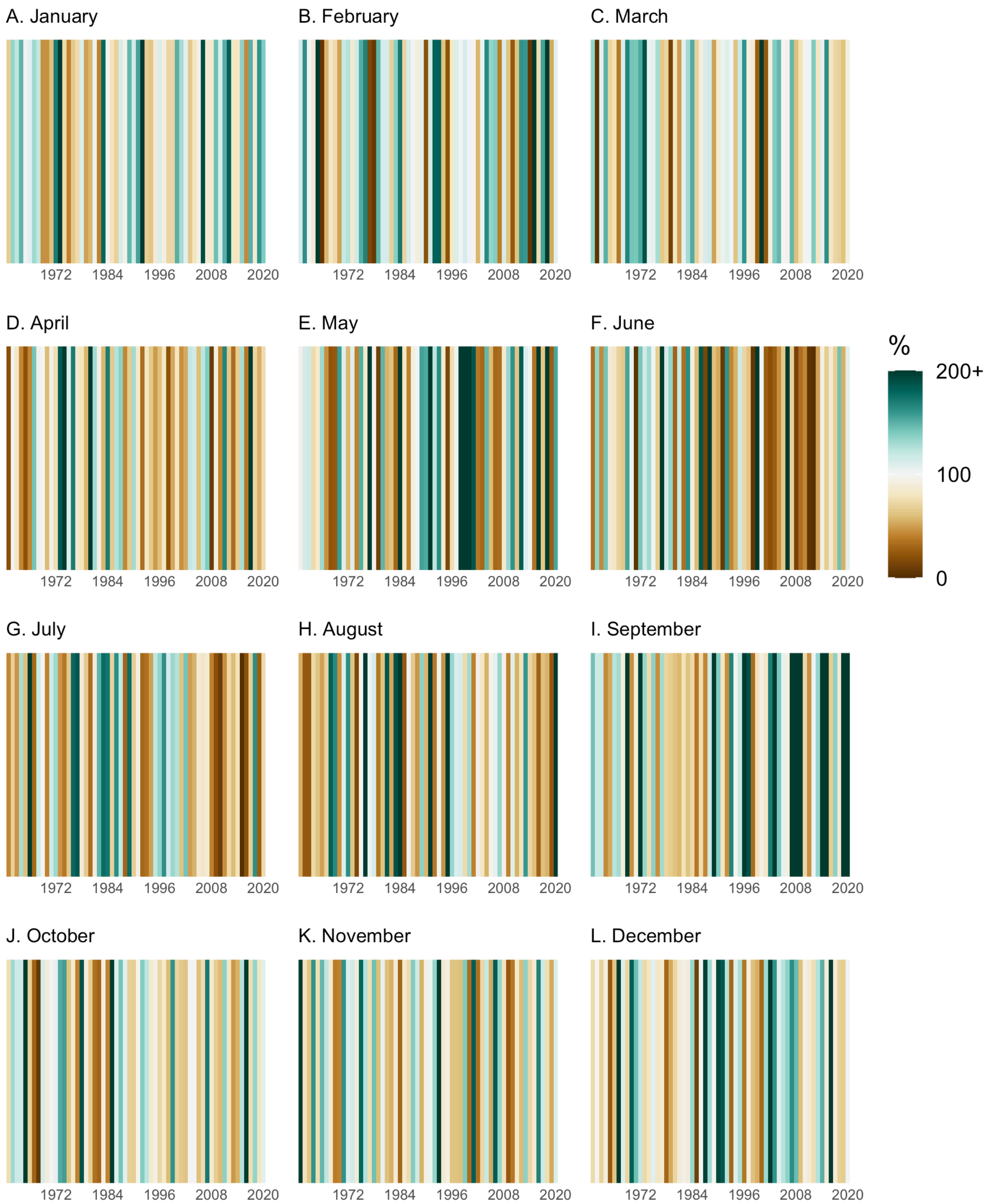
Temperature stripes for each month, Westfjords average, 1949-2020

APPENDIX C



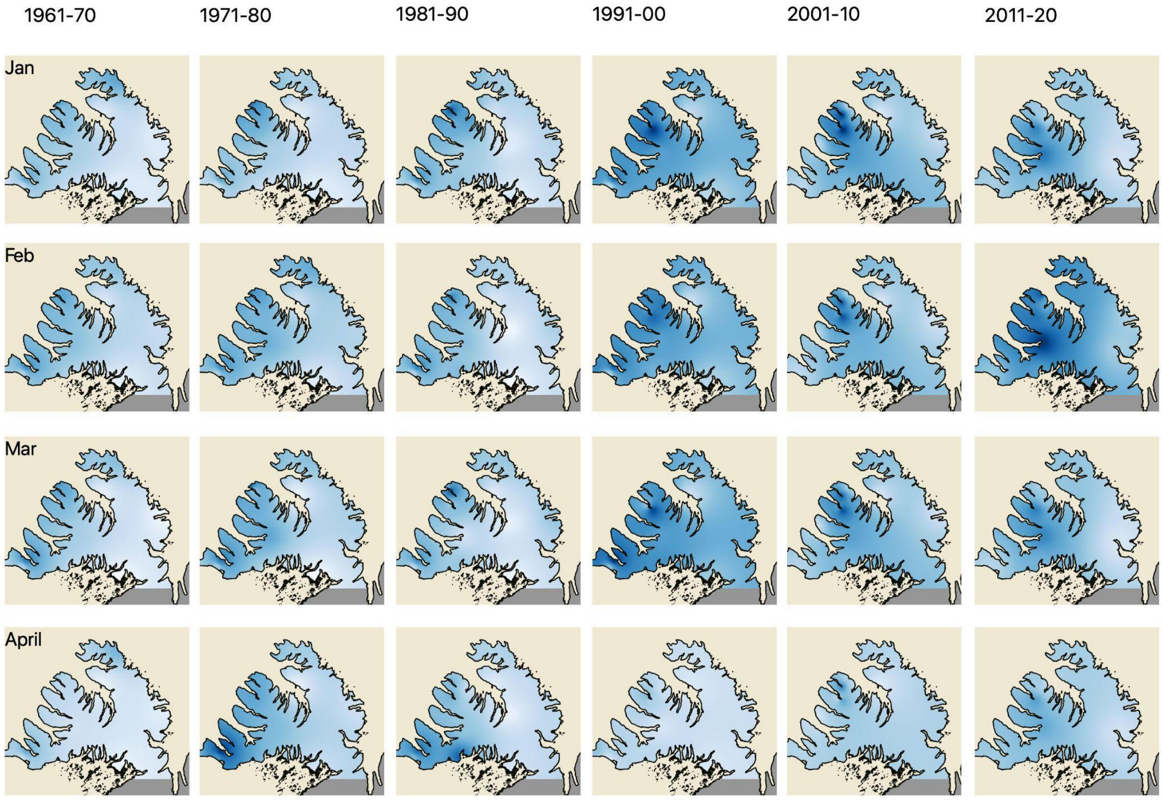
Precipitation stripes for Mjólkárvirkjun 1960-2020

APPENDIX D

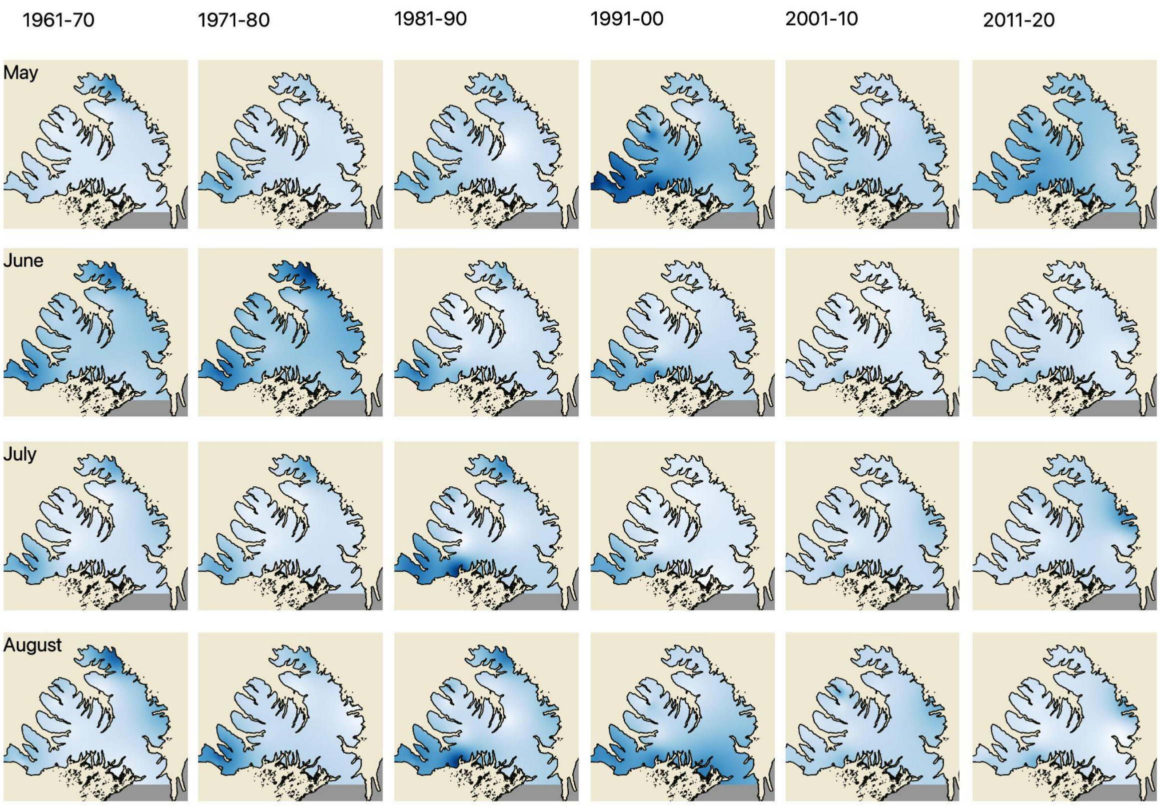


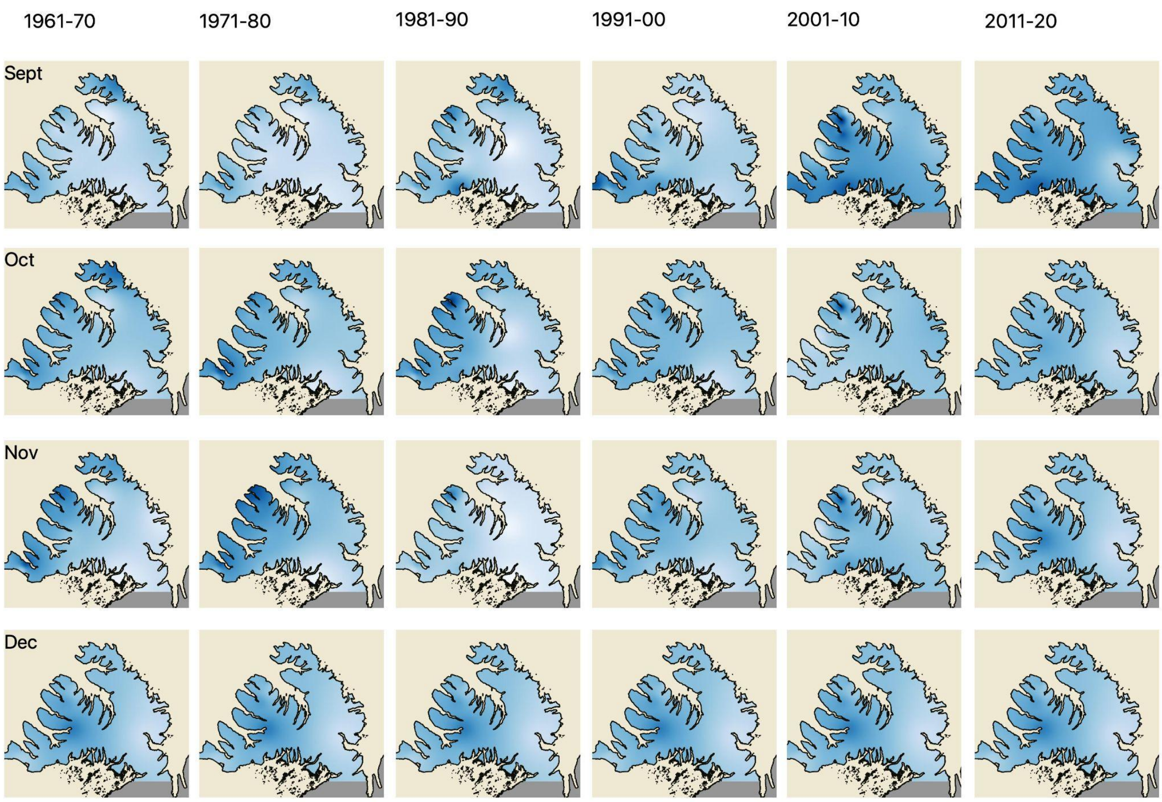
Precipitation stripes for Lambavatn, 1960-2020

APPENDIX E



Absolute Precipitation for each month in the Westfjords.


1961-70
1971-80
1981-90
1991-00
2001-10
2011-20
May
June
July
August


1961-70
1971-80
1981-90
1991-00
2001-10
2011-20
Sept
Oct
Nov
Dec

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