Foras na Mara
Marine Institute

CHAPTER 3

PHYSICAL OCEANOGRAPHY

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3.1 NORTH ATLANTIC CIRCULATION

Circulation of the North Atlantic offshore of Ireland is dominated by the subpolar gyre circulation and the Atlantic Meridional Overturning Circulation (Figure 3.1(a)). Closer to the Irish shelf, the European Slope Current delineates the separation between the open Atlantic and the shelf seas, although the path of the Slope Current near Goban Spur is still debated (orange dashed line in Figure 3.1). The shelf seas around Ireland are home to a system of coastal currents (Figure 3.1(b))

3.1.1 NORTH ATLANTIC GYRE CIRCULATION

The North Atlantic consists of two gyres: the subtropical gyre, with warm western branches of the Gulf Stream recirculating through the Azores current, and the subpolar gyre with warm eastern inflow from a branch of the North Atlantic Current and cooler currents through the Iceland, Irminger, and Labrador Seas (Figure 3.1(a)).

A major mode of variability in the subpolar gyre is an expansion of the gyre associated with cool periods, and a contraction of the gyre during warmer periods. Cool periods in the Atlantic are associated with drier summers in northwest Europe and beyond; warmer periods are associated with increased hurricane frequency (Sutton *et al*., 2018). This was first described by Häkkinen and Rhines (2004) who showed the contraction of the subpolar gyre was co-incident with a rapid warming in the mid-1990s. Satellite-derived indices for subpolar gyre strength show that the subpolar gyre is in a cool, expanded state in recent years, consistent with observed cooling (Hátún and Chafik, 2018).

In the subtropical gyre, an expected change is a poleward expansion of the gyre due to the northward shift of the western boundary current, the Gulf Stream, in response to a poleward shift of the prevailing winds (Yang *et al*., 2016). Direct observations do not show this clearly, with the Gulf Stream extension showing a broadening rather than a poleward shift (Andres 2016).

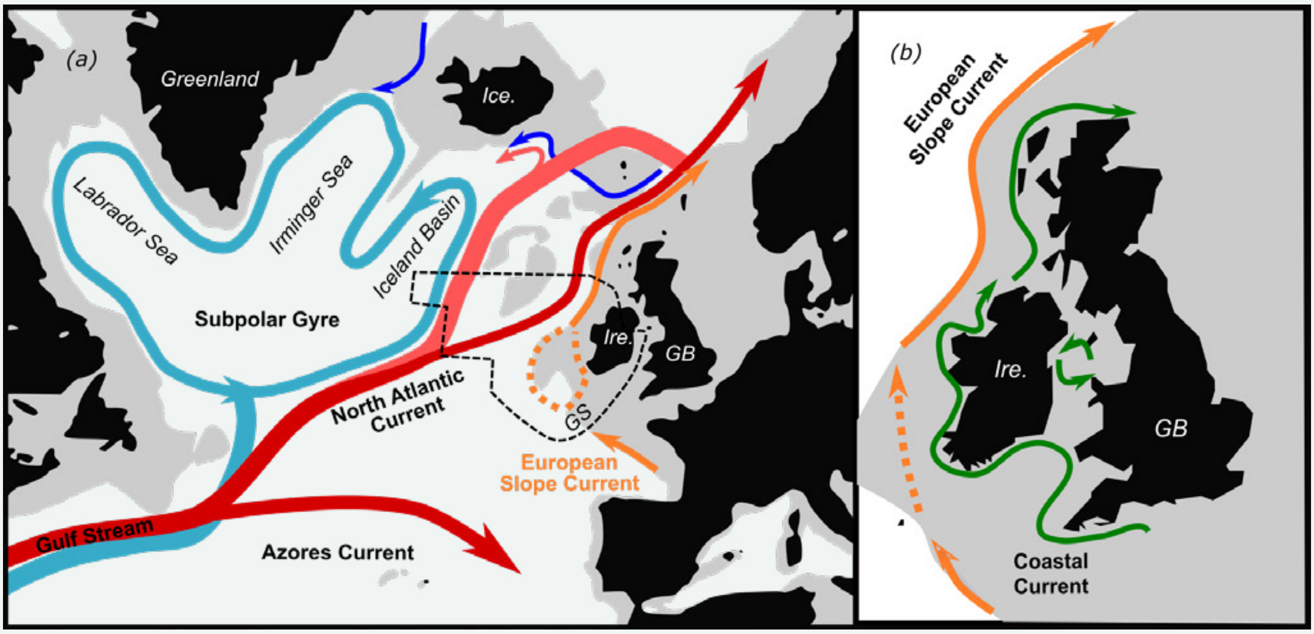


Figure 3.1 (a) Circulation of the North Atlantic showing the main ocean currents (bold text) and geographic features (italics). Warm currents, such as the Gulf Stream and North Atlantic Current, are shown in red. Cold currents, such as those of the subpolar gyre, are shown in blue (b) Slope (orange) and coastal (green) circulation around Britain and Ireland modified from Hill *et al*. (2008). Dashed orange line in (a) denotes the disputed path of the Slope Current near Goban Spur (GS). Dashed black line in (a) denotes the so-called 'Real Map of Ireland'—the limits of Irish waters used for calculations in Figure 3.3 Grey shaded areas indicate the continental shelf (depth < 200 m).

3.1.2 ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

The Atlantic Meridional Overturning Circulation (AMOC) is a system of ocean currents, including the Gulf Stream (the AMOC is sometimes referred to as the Gulf Stream System), which transports warm, shallow water northwards and returns, cold deep water to the south. The AMOC is a major factor in the maintenance of Ireland's mild climate (McCarthy *et al*., 2015), with Ireland potentially 10°C cooler if the AMOC were to collapse (Jackson *et al*., 2015). A collapse of the AMOC is not considered a likely scenario (Masson-Delmotte *et al*., 2021). However, a decline in the 21st century due to anthropogenic climate change is *very likely* (Masson-Delmotte *et al*., 2021). The trajectory of the AMOC in the 21st century is one of the largest sources of future uncertainty in climate models (Bellomo *et al*., 2018).

Prior to about the 1980s, AMOC estimates rely on proxy data such as sea surface temperature (SST) or changes in fossilised plankton distribution in marine cores (Figure 3.2, lower three lines). Taken on the centennial timescales, proxy reconstructions indicate that the AMOC is weaker now than it has been in 1000 years, showing two clear points of slowdown: one in the late 19th century and one in the mid-20th century (Caesar *et al*., 2021). The mid-20th century decline is not simulated by climate models (Menary *et al*., 2020). The question remains whether the proxies themselves could be in conflict (Kilbourne *et al*., 2022) or whether the unconstrained climate models are capable of reproducing the observed variability (Bonnet *et al*., 2021).

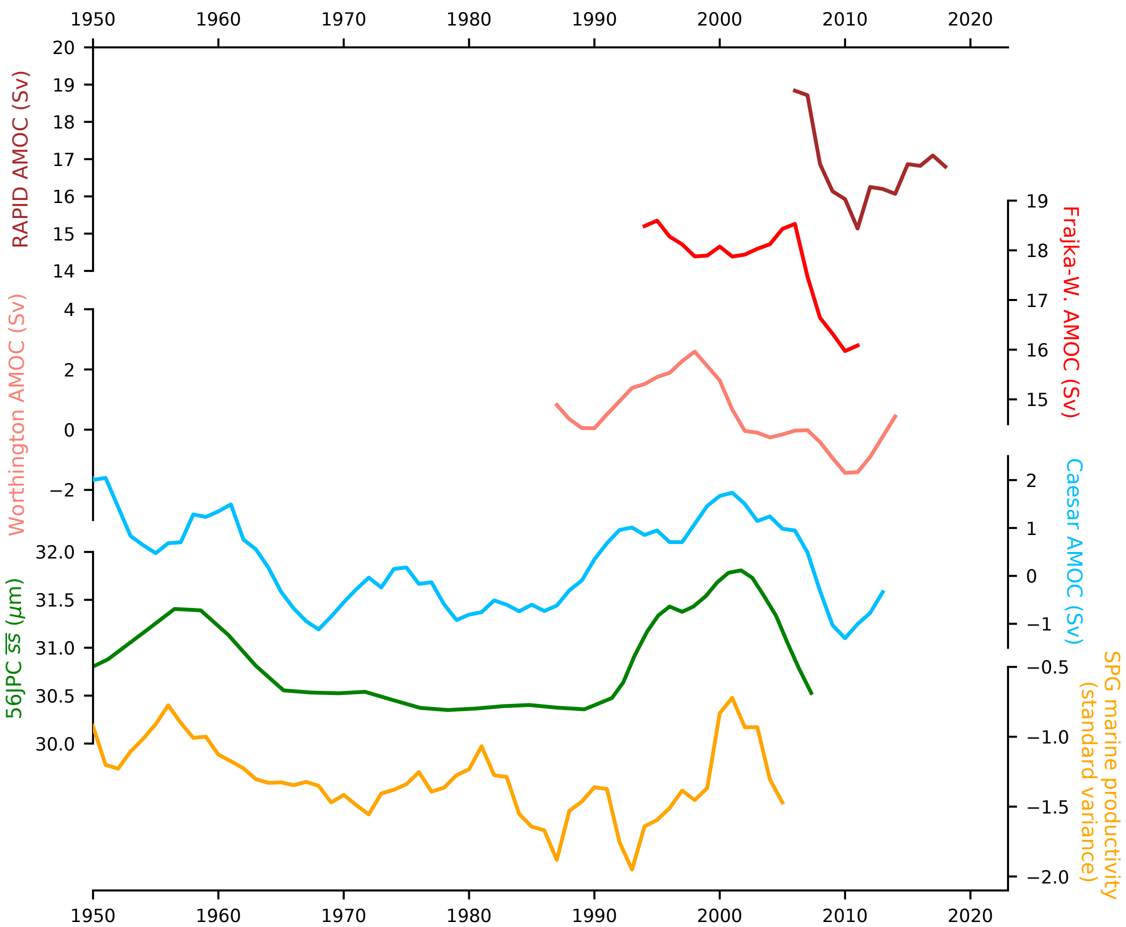


Figure 3.2 Figure taken from (Caesar *et al*., 2022) showing AMOC evolution since the mid-20th century. The top three lines are AMOC estimates based on high-quality hydrographic or satellite data. The lower three lines are proxy-based data. A mid-20th century decline, centered on 1960 is seen in the proxy data. All proxies show a strengthening of the AMOC through the 1990s and a weakening through to around 2010.

Photo credit: Tomasz Szumski

Reconstructions of the AMOC based on hydrographic data span a shorter time, with the longest reconstruction stretching from the 1980s (Figure 3.2, upper three lines). These show no evidence of a long-term decline in AMOC strength (Worthington *et al*., 2021; Fu *et al*., 2017). Direct observations from modern AMOC observing systems, such as the RAPID project, showed a decline from the mid-2000s but a recovery since around 2010 (Moat *et al*., 2020). None of these observations are necessarily in conflict, given their different timespan but their lack of agreement does show the difficulties in interpreting observed AMOC change.

3.1.3 LOCAL CIRCULATION AROUND IRELAND: THE EUROPEAN SLOPE CURRENT AND THE IRISH COASTAL CURRENT

Close to Ireland, the European Slope Current marks the separation of Irish shelf waters from the open ocean (Fig 3.1(b)). The Slope Current is a narrow (20–50 km) current along the continental shelf edge (in waters 500–1000 m depth), with its origins traceable to the Iberian Peninsula and extending all the way around the European shelf towards Scandinavia. The concept of a single continuous slope current is an oversimplification. For example, there is a known seasonal reversal of the current south of the Goban Spur, that is not replicated farther north (Porter *et al*., 2018). The strength of the Slope Current ranges from 1–2 Sv near Goban Spur up to 5–8 Sv in the Faroe-Shetland Channel (Xu *et al*., 2015) (1Sv=1 million cubic metres per second). The Slope Current has notable seasonality in general, being stronger in winter than summer—a seasonality that is exaggerated to the north, with the strong winter flow being associated with bringing heat and material to higher latitudes (Xu *et al*., 2015). North of the Porcupine Bank, the Slope Current is forced by the wider Atlantic, with a particular role for the North Atlantic Current (Marsh *et al*., 2017). Questions remain about the pathways of the Slope Current southwest of Ireland, with competing pathways suggesting offshore (Moritz *et al*., 2021) and onshore (Xu *et al*., 2015) pathways (Figure 3.1(b)).

Closer to the coast, the Irish coastal current winds its way around Ireland (Figure 3.1(b)). It is influenced by wind, tides, and thermohaline factors, which can each dominate at different times. For example, in a long-term study of the coastal circulation west of Scotland, Jones *et al.* (2018) noted times the longest-term variations were likely of thermohaline origin but that large contrasts existed if easterly or westerly wind forcing was the dominant factor. In summer, warm or salty bottom fronts contribute to a thermohaline driven circulation in addition to the regular tidal mixing factors (Hill *et al.*, 2008). The summertime coastal circulation is important to the transport of harmful algal material around the Irish coast and towards the important aquaculture regions of the southwest coast (Raine, 2014).

Irish waters warmed strongly from the 1980s to the mid-2000s, with the highest annual sea surface temperatures recorded in 2007 at over 0.8°C above the 1960–1990 average. Recent years have seen a cooling trend of over -0.3°C/decade, linked by some to a decline in the AMOC.

3.2 HEAT AND FRESHWATER

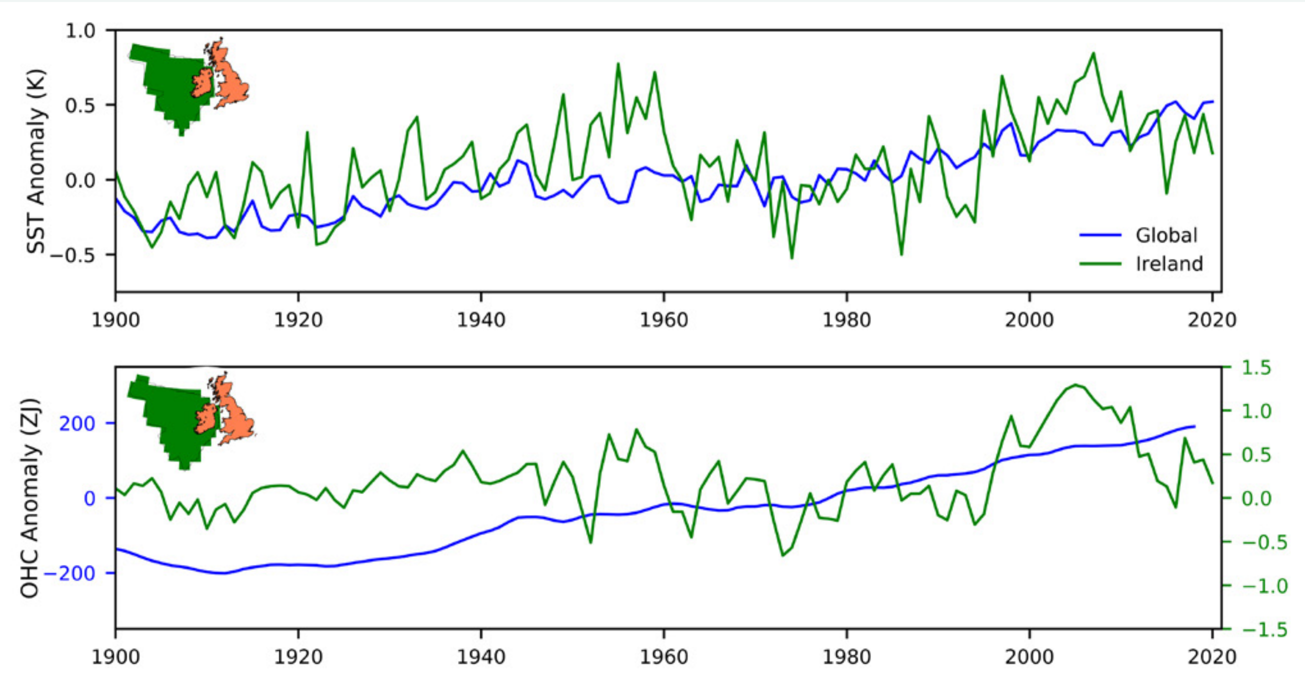


Figure 3.3 (top) Global (blue) and Irish waters (green) sea surface temperature anomaly. (bottom) Global (blue) and Irish waters (green) ocean heat content. Anomalies are calculated relative to the period 1960–1990. Inset hightlights in green the 'Real Map of Ireland'—the limits of Irish waters used here.

3.2.1 SEA SURFACE TEMPERATURE AND OCEAN HEAT CONTENT

Globally sea surface temperature (SST) and ocean heat content (OHC) are rising due to anthropogenic climate change (Masson-Delmotte *et al.*, 2021). In fact, OHC—the sum of the heat energy stored in the ocean—has taken over 90% of the excess heat trapped in the climate system due to anthropogenic climate change (Masson-Delmotte *et al.*, 2021). The same patterns are evident in Irish SST and OHC but with notable periods of deviation from the long-term trend (Figure 3.3). Anomalies are shown relative to the period 1960–1990. Specifically, Irish SST and OHC experienced warm periods from the 1940s to the late 1950s, and from the mid-1990s to the mid-2000s. The highest SSTs in Irish waters occurred in 2007, averaging over 0.8°C warmer than 1960–1990, and the highest heat content occurred in 2005. Cool periods interceded these warm periods. Through the 1970s and 1980s, a cooler period persisted with record low SST anomalies in Irish waters of -0.5°C occurring in 1974 and 1986. This decadal variability is well-known in the North Atlantic, most famously in the Atlantic Multidecadal Variability (AMV)—sometimes referred to as the Atlantic Multidecadal Oscillation. The drivers of AMV are disputed. External (to the ocean) forcing has been cited as dominant through volcanic or anthropogenic forcing (Mann *et al.*, 2020) or through anthropogenic aerosols (Booth *et al.*, 2012). An alternative perspective however, is that AMV is an internal oscillation linked with variations in the AMOC (Zhang *et al.*, 2019).

In recent years, Irish waters have been cooling. Since 2007, SSTs in Irish waters have cooled at a rate of -0.3°C/decade. The Atlantic SST south of Iceland exhibited record low temperatures in 2015. This cold anomaly has been linked with atmospheric heat loss (Josey *et al.*, 2018) or linked to a slowdown in the AMOC that occurred around 2009/10 (Bryden *et al.*, 2020). This cold anomaly had a direct impact on Irish waters with the coolest SST values in the 21st century occurring. Land temperatures in Ireland were also lower than average in 2015 because of the cool ocean—an almost unique record in a year that showed the highest global temperatures on record. Despite this recent cooling, SSTs in Irish waters are 0.4°C warmer in the 21st century, relative to 1960–1990.

The Atlantic Meridional Overturning Circulation (AMOC) or Gulf Stream System is key to Ireland's mild climate but is predicted to decline due to climate change, with some proxies indicating this may already have begun.

Photo credit: Christine Loughlin

3.2.2 SALINITY

Salinity in the ocean is frequently interpreted as an indicator for changes in the global hydrographic cycle with the precept that 'the wet gets wetter and the dry gets drier' translates to ocean salinity as the fresh areas get fresher—regions where precipitation dominates over evaporation—and the salty areas get saltier—regions where evaporation dominates (Masson-Delmotte *et al.*, 2021). In the subpolar gyre however the precipitation-evaporation exchange does not dominate the observed salinity changes. For example, in recent years, the eastern subpolar Atlantic has seen its freshest values in 120 years (Holliday *et al.*, 2020). This freshening was a result of a wind-driven change to ocean circulation where fresh waters from the western subpolar gyre were imported to the eastern basin.

3.2.3 SHELF SEAFLOOR PROPERTIES AND STRATIFICATION

Seafloor temperature and salinity are key quantities for fisheries and benthic ecosystems. Information on how the near seafloor is changing is however limited. A climatology compiled by Berx and Hughes (2009) is shown in Figure 3.4. Distribution of temperature follows a meridional (north-south) gradient with warmer temperatures to the south and colder to the north. Salinity reflects the competing influence of salty Atlantic waters and on shelf freshwater. The climatology of (Berx and Hughes 2009) provides a snapshot of seafloor conditions. Investigations of bottom temperature and salinity west of Ireland using the EN4 (https://www.metoffice.gov.uk/hadobs/en4/) found that cooler and fresher conditions occurred when Atlantic climate indices such as the NAO and AMOC were positive (Johnson *et al.*, 2020). Both studies are limited—temporally in the former study and spatially in the latter study (EN4 is a 1° product).

To address these gaps in our understanding, the NEOClime Product will provide 50-year climatology of temperature and salinity over the last half century (1971–2020), for the northwestern European continental region, encompassing the Celtic Sea, the continental margin west of Ireland and Scotland and the North Sea. NEOClime is co-developed between the Marine Institute and Marine Scotland Science and builds, in scope and

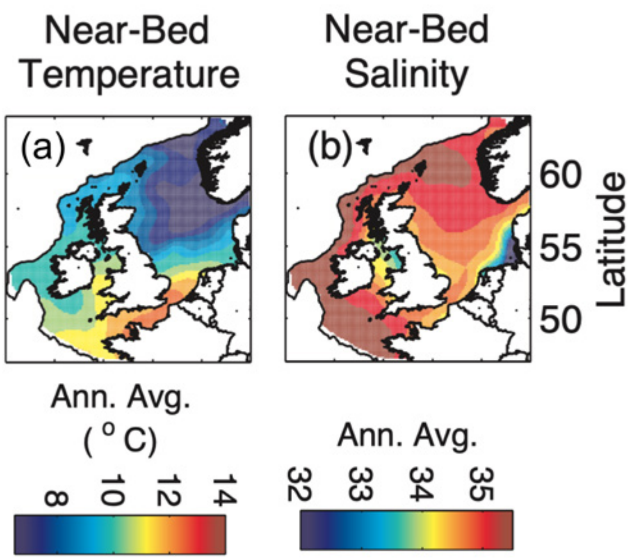


Figure 3.4 (a) Seafloor temperature and (b) salinity from (Berx and Hughes 2009).

methodology, on a previous product by Marine Scotland Science for the ICES standard 30-year climatology of 1971–2000 (Berx and Hughes, 2009).

Shelf stratification is another key quantity for ecosystems. Stratification occurs when less dense water lies above more dense water. Typical seasonal stratification occurs when a surface warmed layer lies on top of deeper, colder water during summer months. This type of stratification is key to ecosystems as it is a barrier to the replenishment of nutrients to the sunlit zone. Factors that act against stratification are tidal and wind-driven mixing. A trend towards earlier stratification has been noted in the European Shelf (Sharples *et al*., 2020), and stronger stratification has been noted in the western Irish Sea (Young and Holt 2007). Future projections are for earlier stratification by one week by the end of the century and stronger stratification. Both of these projections are based on projections of future warming. Where wind-driven factors are important, stratification projections are less confident due to lack of confidence in future wind projections (Sharples *et al*., 2020).

Sea levels continue to rise around Ireland. Larger local sea level rise has been observed in Cork and Dublin, with recent rates of relative sea level rise being twice the global average in Dublin.

3.3 SEA LEVEL

Sea level is a combination of mean sea level (the averaged sea level over a period, typically a month or a year), tides, storm surges, and waves.

3.3.1 MEAN SEA LEVEL

Sea levels around Ireland remained relatively constant from 5000 years ago until the anthropogenic influences began to cause global sea levels to rise in the 20th century (Kopp *et al*., 2016). Rising global temperature impacts sea level through thermosteric expansion of the water column and when land ice (glaciers, ice sheets, etc.) melts. While the former dominated sea level rise through the 20th century, the latter is set to dominate in the coming centuries to millennia (Masson-Delmotte *et al*., 2021).

In Ireland, mean sea level trends are in line with global trends (Cámaro García *et al*., 2021), with a number of important regional caveats. Prior to the early 1990s, observational evidence for sea-level rise is reliant on coastal tide gauge data. Ireland has a historical geographical bias in the location of these gauges, with long-term observations being confined northeast of an axis from Dublin to Malin Head. Sea-level rise from Dublin and Belfast was reported at <1 mm/year prior to the 1990s (Carter 1982; Woodworth *et al*., 1999), not dissimilar for recently revised global rates of rise for the same period (Dangendorf *et al*., 2017). Since the 1990s, satellites have shown increased rates of global mean sea level rise of 3 mm/year (Nerem *et al*., 2018). A comprehensive all-Ireland tide gauge network was established in the 2000s but is shorter than the necessary 40 years (Hogarth *et al*., 2021) for assessing mean sea level trends. Data archaeology (digitisation and observational-based statistical modelling) has successfully supplemented observations. In Cork, Pugh *et al*., (2021) found a 40 cm rise in mean sea level since 1842, equivalent to 2.2 mm/year, larger than would be expected from a combination of regional mean sea level rise and Glacial Isostatic Adjustment alone. A statistical reconstruction of recent trends in Dublin showed double the rates of global rise since 1997 (Shoari Nejad *et al*., 2022). Investigation into the regional differences in rates of sea level rise around Ireland is ongoing work. A new project, Retro, funded by the Marine Institute will contribute to this understanding through data archaeology southwest of the Dublin-Malin axis and offer a better picture of Irish sea level rise.

Local factors that need to be considered to understand Irish mean sea level deviations from regional trends include Glacial Isostatic Adjustment, local land level change, proximity to the Greenland Ice Sheet, and ocean circulation changes. For example, Figure 3.5 shows future projections for Cork from Palmer *et al.* (2018) relative to the global projections. Cork has a lower rate of relative sea-level rise than global estimates, primarily due to Ireland's proximity to the Greenland Ice Sheet. A complexity of the impacts of melting of Greenland Ice Sheet is that locations sufficiently close to Greenland, including Ireland, will experience a relative sea level fall due to the resultant change in the Earth's gravitational field. This relationship means that melting of the Antarctic ice sheet leads to greater than average sea level rise in regions far from Antarctica, including Ireland. Sea level rise in Ireland is projected to be 15–20% higher than global average rates in a scenario of the west Antarctic Ice Sheet alone melting (Mitrovica *et al.*, 2011). And in future scenarios dominated by Antarctic melt, Ireland's sea level rise is greater than the global average.

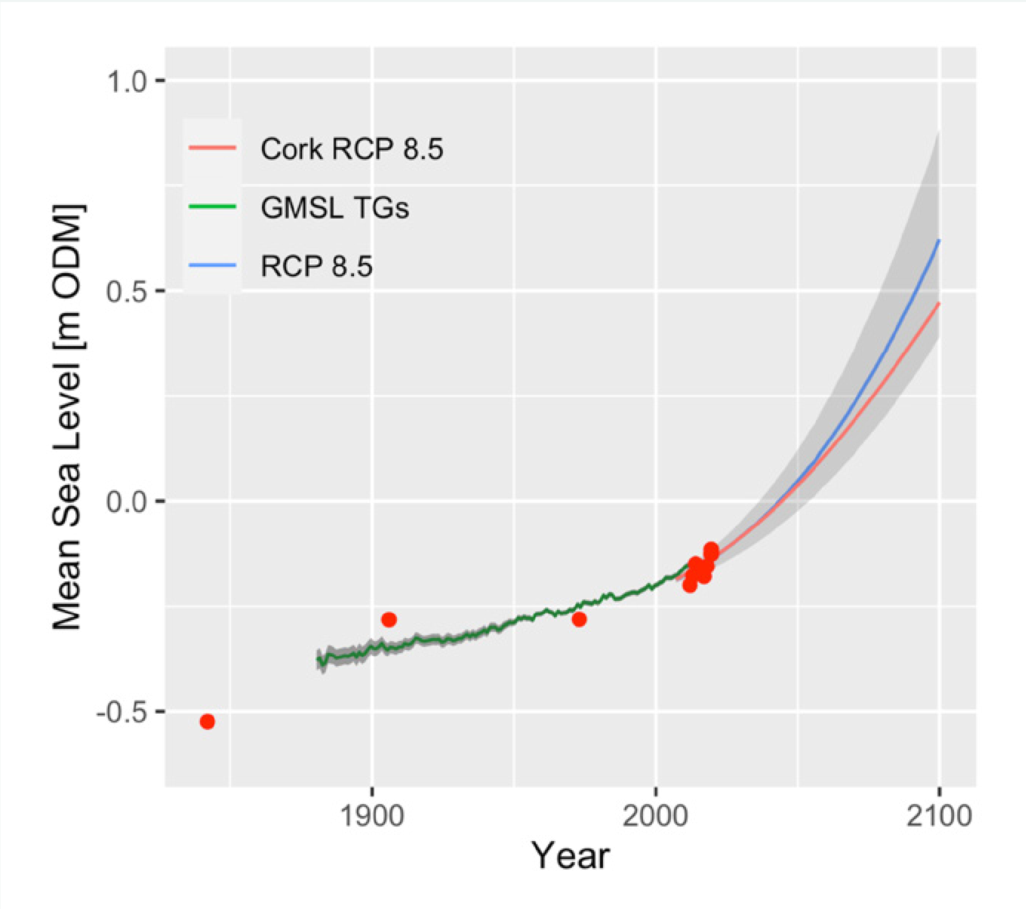


Figure 3.5 Mean sea level estimates from the Cork region from Pugh *et al.* (2021) (red dots) with future projections from UK Climate Projections (Palmer *et al.*, 2018) for Cork (red line). Observed global mean sea level (GMSL) rise through the 20th century (green line) from Church and White (2011) and future projections under RCP8.5 (blue line) from (IPCC 2019).

3.3.2 TIDES

Astronomical tides are driven by the regular transit of the sun and the moon. These drivers are not likely to change on any human timescale. Real tides, however, propagate as shallow water waves and are subject to the changing depth of water. The largest factor in this is modification of channels through dredging. Interest is growing in how sea level rise is potentially changing tides globally (Haigh *et al.*, 2020; Idier *et al.*, 2017) however, studies of tidal change in Ireland have not found changes to tidal parameters (Pugh *et al.*, 2021).

3.3.3 WAVE CLIMATE AND EXTREME SEA LEVELS

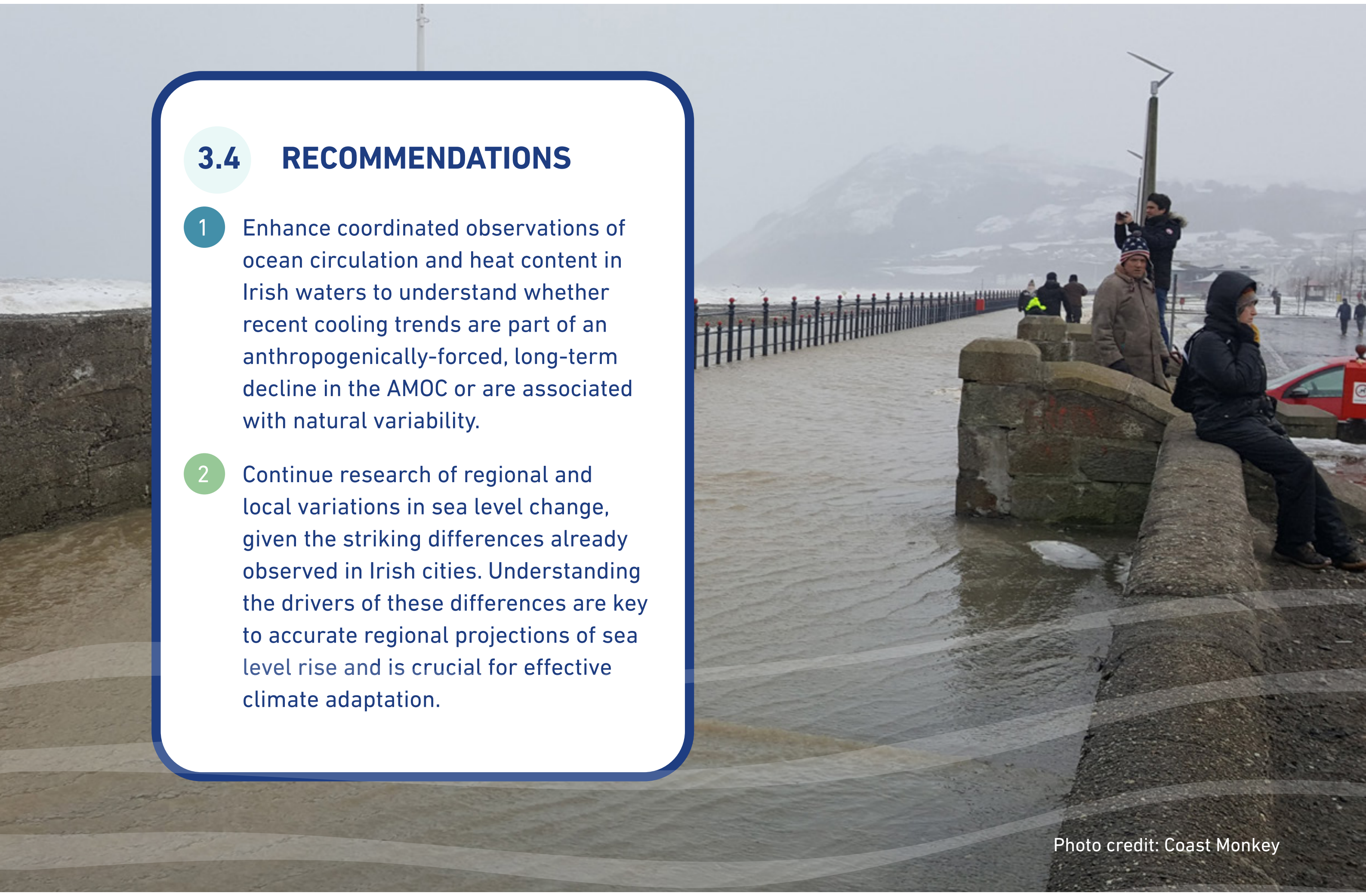
Significant variation in wave and wind climate is evident due to complicated geomorphology of the Irish coast (Gallagher *et al.*, 2014). Due to its location in the Northeast Atlantic, Ireland possesses one of the highest wave energy climates in the world (Tiron *et al.*, 2015). Ireland has a long history of large waves, from storm waves to destructive freak waves recorded in a variety of sources (O'Brien *et al.*, 2013).

Studies on future wave climate show an overall decrease in significant wave height around Ireland (Gallagher *et al.*, 2016; Tiron *et al.*, 2015). Tiron *et al.* (2015) compared the 30 year (2031–2060) wave climate projection with a 29 year (1981 to 2009) historical run and revealed annual decreases in both mean significant wave height and storm wave heights for the North Atlantic in general and Ireland in particular, and a decrease of maximum significant wave height in winter. Gallagher *et al.*, (2016) looked at future wave projection and found an overall decrease in annual and mean significant wave height around Ireland with largest decrease in summer.

Strong correlation between the North Atlantic Oscillation (NAO) and wave height, wave period and wave direction was found by Gallagher *et al.* (2014) from a 34 year (1979–2012) wave hindcast performed for Ireland. In addition to this, Gleeson *et al.* (2017) showed a strong correlation (>0.7) between NAO and significant wave height to the west and northwest of Ireland.

Extreme sea levels including waves and storm surges pose an ever-increasing threat to coastal communities due to changing patterns of storminess and rising mean sea levels. The coastal cities of Dublin and Galway have seen notable wave overtopping events in recent years. In February 2002, the coincidence of high astronomical tides and a storm surge led to a wave overtopping event in Clontarf, Co. Dublin when numerous houses and businesses were flooded. Subsequent improvement of flood defences in the Dublin area (Cooke *et al.*, 2005) meant that higher sea levels in 2014 resulted in less flooding and stands as a benchmark for adaptation measures in response to rising seas and extreme sea levels.

Ireland is vulnerable to changing extreme sea levels due to its location on the edge of the Atlantic, close to the mean position of the North Atlantic storm track. Storminess is closely associated with the NAO, which has been positive (increased storminess) in recent years. Future projections of storminess remain uncertain in climate projections (Masson-Delmotte *et al.*, 2021).



3.4 RECOMMENDATIONS

1. Enhance coordinated observations of ocean circulation and heat content in Irish waters to understand whether recent cooling trends are part of an anthropogenically-forced, long-term decline in the AMOC or are associated with natural variability.

2. Continue research of regional and local variations in sea level change, given the striking differences already observed in Irish cities. Understanding the drivers of these differences are key to accurate regional projections of sea level rise and is crucial for effective climate adaptation.

Photo credit: Coast Monkey

LIST OF FIGURES

Figure 3.1 a) Circulation of the North Atlantic showing the main ocean currents (bold text) and geographic features (italics). Warm currents, such as the Gulf Stream and North Atlantic Current, are shown in red. Cold currents, such as those of the subpolar gyre, are shown in blue (b) Slope (orange) and coastal (green) circulation around Britain and Ireland modified from Hill *et al*. (2008). Dashed orange line in (a) denotes the disputed path of the Slope Current near Goban Spur (GS). Dashed black line in (a) denotes the so-called 'Real Map of Ireland'—the limits of Irish waters used for calculations in Figure 3.3 Grey shaded areas indicate the continental shelf (depth < 200 m). 26

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CHAPTER 3 – PHYSICAL OCEANOGRAPHY

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