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Climate change and adaptation in the coastal areas of Europe's Northern Periphery Region

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ABSTRACT

Adaptation to climate change in coastal regions of northern and western Norway, Scotland and Ireland and the coasts of Iceland must respond to trends and variability in a number of physical parameters that affect the regional life and economy. Historical trends and variability are apparent in historical data over several decades in temperature, precipitation and winds. Associated changes in waves, sea level and sea surges are also implied. Predictions of future climate change imply further trends in the same parameters. Those physical parameters act according to the local characteristics of various locations producing predictable impacts (both positive and negative) to which local communities will need to adapt.

1. Introduction

The CoastAdapt project is a European Union InterReg Northern Periphery Programme (NPP) sponsored project investigating climate change adaptation within the coastal regions of the Northern Periphery (NP) region. This paper aims to provide an introduction to a special issue of this journal by considering observed and projected climate changes in the region and to highlight some specific examples of what adaptation is already being done within the region.

The recent IPCC (2013) report of Working Group I which replaces the previous version (IPCC, 2007a,b) notes that:

> "The report confirms that warming in the climate system is unequivocal, with many of the observed changes unprecedented over decades to millennia: warming of the atmosphere and the ocean, diminishing snow and ice, rising sea levels…" (Foreward p v)

Rohde et al. (2012) noted that since the 1880s the Earth's coupled Atmospheric–Oceanic System has warmed with a linear trend of +0.74 °C over the 100 years from 1906 to 2005 (IPCC, 2007a) and that:

> "If all of the residual evolution during the last 150 years is assumed to be natural, then it places an upper 95% confidence bound on the scale of decadal natural variability at ±0.17 °C. Though non-trivial, this number is small compared to what our correlation analysis suggests may be anthropogenic changes that occurred during the last century."

The IPCC (2013) gave a higher figure for globally averaged combined land and ocean temperature warming (as calculated by a linear trend) of 0.85 °C, over the period 1880–2012 (with a range between 0.65 and 1.06 °C). Importantly it was also noted that observed Global Mean Surface Temperatures (GMST) anomalies relative to 1880–1919 in recent years lie well outside the range of GMST anomalies in Coupled Modelling Inter-comparison Project Phase 5 (CMIP5) simulations with natural forcing only. Model results including anthropogenic forcing were consistent with the observed trend.

Both land and sea surface temperatures (SSTs) have risen, with the former increasing by 0.065 °C per decade (1880–2012) and the latter by 0.054 °C per decade (1900–2012). The rate of warming of the oceans is faster closer to the surface than at depth and the transfer of energy deeper into the ocean will reduce the transient rate of increase of SSTs as compared to the overall global change.

This paper reviews the key climate and linked environmental changes that have been observed and those that are expected in the

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future in some of the coastal areas of Iceland, Ireland, Norway and Scotland, which lie within the Europe's Northern Periphery Region (Fig. 1). Given that the long predicted effects of anthropogenically induced climate warming (as noted by Hansen et al., 1981) are now confirmed (IPCC, 2013), we describe the observed climate change and predicted future trends for the Northern Periphery (NP) region. Further, the key climate parameters that affect communities are described and explained, and thus the issues that need to be addressed by adaptation are introduced (further discussion of *adaptation* is covered in other papers in this Special Issue volume).

2. Observed global climate change trends and links to the Northern Periphery Region

2.1. Temperature

For the Northern Hemisphere Trenberth et al. (2007) give the temperature increase (1901–2005) as either 0.075 °C per decade using the UEA Climate Research Unit/UKMO (CRU/UKMO) data with a r^2 value of 0.63, or 0.063 °C per decade, using the National Climatic Data Center (NCDC) data with an r^2 value of 0.55. Over the more recent period of 1979–2005, a steeper increase of 0.234 °C per decade (r^2 0.69 CRU/UKMO data) or 0.245 °C per decade (r^2 0.72, NCDC data) was noted.

Although both series show increases, the differences illustrate that there is some uncertainty and as noted earlier the IPCC (2013) gives a range for the observed change. The temperature increase are higher over the land than the oceans and the figures above (both from the IPCC and Trenberth) are for combined land and ocean changes as this seems more appropriate as a comparison for the coastal parts of the NP region.

While these temperature trends cover the whole of the Northern Hemisphere, there are regional differences in the observed changes across the hemisphere an individual stations do not always reflect the overall trend.

As an illustration a number of stations were selected across the NP region using different freely available data series. For example within the Northern Periphery Region data for Iceland stations from 1949 are available from the Icelandic Met Office, for Irish stations for 1958 onwards from the Irish Central Statistical Office (more recent years from the Irish Meteorological Service), from the Norwegian Meteorological Institute which provides the full length of individual stations records and from the British Atmospheric Data Centre (BADC) for stations in the United Kingdom. In addition, the UK Meteorological Office's Hadley Centre provides the CRUTEM4 data which has individual station temperature data from across the world and the European Climate Assessment and Dataset (ECD&A) which has data from stations across Europe.

For temperatures, the monthly data from CRUTEM4 were chosen as that dataset had more long records from stations in the coastal areas of the NP of interest to the CoastAdapt project. As a check inter-comparisons were made between the above different datasets and in general differences were within ±0.1 °C.

All of the stations chosen had observations from 1890 onwards in the CRUTEM4 series and in the rare cases where records were not complete it proved possible to include data from the other data series listed above to provide a complete series. As both Trenberth et al. (2007) and the IPCC (2013) used a linear trend in estimating changes over time, the increases for the stations listed (Table 1) are also linear trends found using regression.

These stations, with the exception of the most southerly (Valentia), show a greater increase in temperature per decade than the wider Northern Hemisphere figures and greater than the global change 0f 0.065 °C per decade based on the total change from 1880 to 2012 given by the IPCC (2013). However, the adjusted *r*-squared values for statistically significant regressions are poorer than that

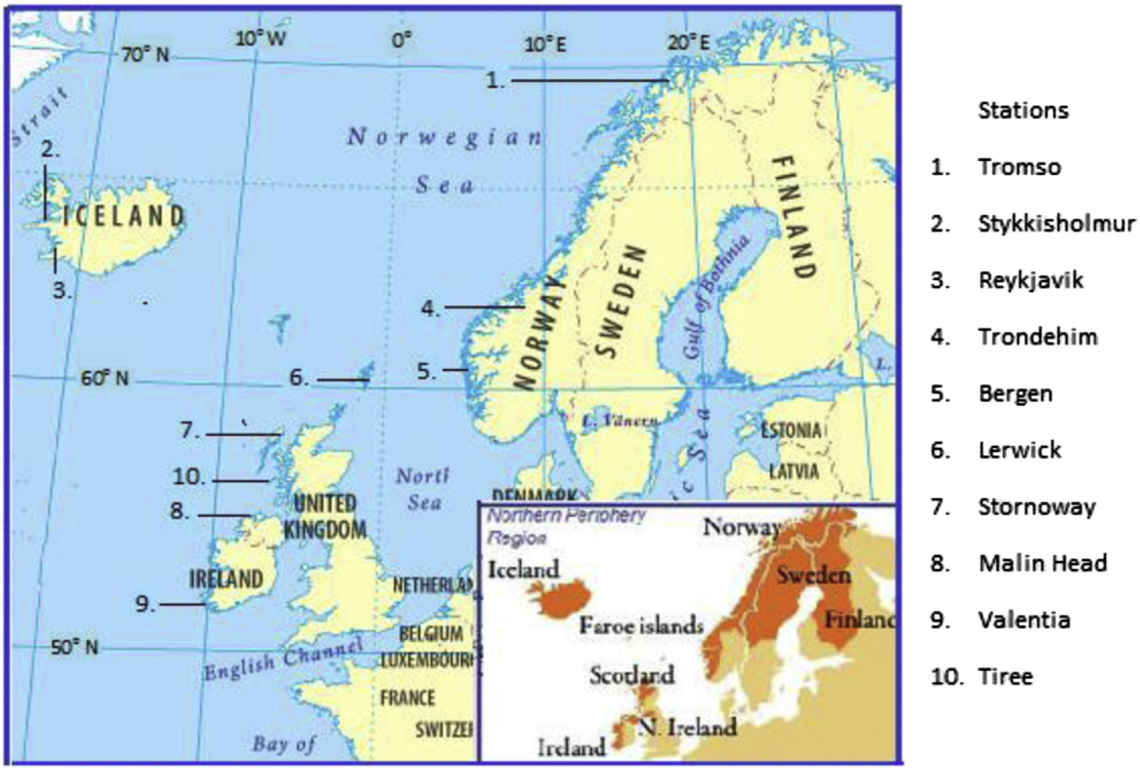

Fig. 1. The Northern Periphery (NP) Region and selected meteorological stations. (Source: http://www.mapsofworld.com/lat_long/europe.html and NP region insert from http://www.northernperiphery.eu/en/home/).

Table 1
Temperature increase per decade at selected stations in the NP region.

Station	Latitude	1890–2013		1979–2013	
		ΔT (°C)	r^2 (adj%)	ΔT (°C)	r^2 (adj%)
Tromso	69.7	0.086	13.6	0.248	13.8**
Tromso, Langnes	69.7	0.081	13.1	0.359	26.1*
Stykkisholmur	65.1	0.087	16.4	0.378	47.2
Reykjavik	64.1	0.079	16.3	0.337	62.3
Trondehim	63.5	0.104	17.0	0.232	4.8 NS
Bergen	60.4	0.090	20.3	0.312	16.3*
Lerwick	60.2	0.079	27.4	0.602	36.7
Stornoway	58.2	0.075	27.6	0.577	57.8
Malin Head	55.4	0.079	33.3	0.258	29.4*
Valentia	51.9	0.044	12.4	0.213	22.0*
Northern Hemisphere (NH)	–	0.073	69.1	0.219	76.1

All adjusted r^2 values are significant at better than 0.1%, except * (1%), **(5%) and NS not significant. NH and CRUTEM4 data from: http://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html.

given for the Northern Hemisphere, typically between 13 and 33% of the variance explained for the 1890–2013 period and 13–62% for the later 1979–2013 period. This poorer variance explained is to be expected, as there is considerable inter-annual variation at individual stations which is smoothed out to some extent when a figure for the whole northern hemisphere is used.

It is also possible to smooth the individual station data by using a 10 year running mean. Using those 10 year means at 10 year intervals gives 12 observations over the 1890 to 2013 period. The decadal rate of temperature increase for the stations for 10 year periods starting in 1900, 1901, 1902 and 1903 are given in Table 2. The results show improved r-squared values although the statistical significance is lower (simply due to the reduced number of observations). The results show that although there is some variation between the different start years they are within ±11% of the rates for the whole 1890–2013 period.

The lower rate of increase for Valentia over the period 1890–2013 (and relatively lower rate for 1979–2013) is interesting as it highlights that individual stations may not follow the general trend. The overall change in Ireland for 1890–2004 was given by Sweeney et al. (2008) as 0.7 °C and the change for Malin Head and Valentia over a similar period would have been 0.9 °C and 0.5 °C respectively. With regard to Valentia, the report by McElwain and Sweeney (2007) published tables of recent climate changes at a number of Irish stations including Valentia and their figures also indicated a slower rate of increase at Valentia, although they did not comment on that.

Valentia may be affected by its location in the far southwest perhaps reflecting more than most stations in Ireland, the maritime nature of the Irish climate (Sweeney et al., 2002; Sweeney et al., 2008), although as Lerwick and Stornoway (both island stations with a maritime climate) have larger temperature increases, it may simply be part of the variability between stations.

The steeper increase in temperatures shown by the majority of these stations, as compared to the values for the Northern Hemisphere as a whole, fits with the expectation that higher latitudes are warming more than lower latitudes.

These results suggest that in the case of temperature, the coastal regions of the Northern Periphery region show increases at or above the rate for the hemisphere. The implications of this change are discussed later.

2.2. Precipitation

Trenberth et al. (2007) and IPCC (2012) note that there are quite distinct upward trends evident in many world regions, including central North America, eastern North America and northern Europe, which have experienced increases in precipitation of between 6 and 8% between 1900 and 2005.

While there are good sets of long term temperature data for the stations listed in Table 1, precipitation data are generally only available over shorter periods and there are more frequent occurrences of missing values in the data sets (Table 3). The principal data records used for the precipitation were those from the ECD&A as it generally had the longest series.

Trondheim has 40% of data missing over the period of records and Stornoway has missing data from December 2011. Daily precipitation data for 2011–2013 for Stornoway were not available from BADC.

Some stations had missing values in individual months but monthly values were obtained from the other datasets listed earlier to infill those missing values. It should be noted that precipitation data are also prone to errors as strong winds can lead to undercatch due to flow over the gauge, as can very heavy precipitation and hail which can bounce out of the gauge. The largest errors are with snowfall as not only can it be difficult to ensure that the correct amount of snow is melted, but snow is redistributed by wind and hence the typical open area of a meteorological observatory in windy conditions can have much less lying snow than the amount that actually fell.

As with the temperature data, a comparison was made between the different datasets and if was found that while the average monthly differences were less than 0.3%, there was a range of up to ± 48% in individual months. This highlights again that caution needs to be taken when using precipitation data. However give the small average percentage differences, it was felt the ECD&A data were acceptable.

As the records were of variable length it was decided to use only the six stations that had a complete record from 1957. Fortunately these stations did provide a good geographic spread over the region. In addition, an examination was made of the Northern and

Table 2
Temperature increases per decade for 10 year smoothed values.

Station	Start year of smoothed values					
	1900	1901	1902	1903	Significance	R^2 (adj%)
	ΔT (°C)	ΔT (°C)	ΔT (°C)	ΔT (°C)	Better than	
Tromso	0.084	0.089	0.083	0.077	0.10%	80
Tromso, Langnes	0.079	0.086	0.083	0.077	5%	39
Stykkisholmur	0.085	0.087	0.082	0.083	5%	46
Reykjavik	0.077	0.077	0.074	0.074	10%	25
Trondehim	0.108	0.117	0.112	0.109	10%	21
Bergen	0.092	0.096	0.092	0.091	1%	65
Lerwick	0.079	0.081	0.078	0.077	1%	55
Stornoway	0.074	0.074	0.069	0.069	1%	48
Malin Head	0.081	0.081	0.079	0.081	1%	65
Valentia	0.043	0.043	0.041	0.044	5%	28

Table 3
Length of precipitation records at selected NP stations.

Station	Period of records
Tromso	1932–2013
Tromso, Langnes	1965–2013
Stykkisholmur	1951–2013
Reykjavik	1951–2013
Trondehim	1951–Feb 1967; Jan 1999–Nov 2000; Jan 2002–Dec 2013
Bergen	1983–2013
Lerwick	1946–2013
Stornoway	1932–Nov 2011
Malin Head	1957–2013
Valentia	1941–2013

Western Scotland data series (available from the UK Meteorological Office) as those data are regional series (less prone to error than individual stations) and are available from 1910.

The European Environment Agency (2012) noted that annual precipitation trends since 1950 show an increase by up to 70 mm per decade in north-western Europe. The figures for the stations and regions given in Table 4 all show an increase in annual precipitation over time and even exceed 70 mm per decade in one case.

It should be noted that precipitation in the Northern Periphery coastal regions does have some relationship with large scale atmospheric modes, such as the North Atlantic Oscillation (NAO), essentially an index of the pressure difference between the Portugal and Iceland, and this affects seasonal and inter-annual variability. The effect of the NAO is particularly evident in winter when a negative index leads to cold winters in northwest Europe whereas a positive index leads to mild and wet winters. In addition there can be considerable differences across regions in the NP as illustrated by the UK figures for 2012 which showed that 2012 was the wettest year on record for England (since 1910) and the third wettest on record for the England and Wales series from 1766 but was below average for the Northern Scotland region. Although there are periods when the NAO is higher or lower than normal there is no trend evident in either the annual or winter NAO (based on data from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based1899–2013).

Despite these trends, a recent report on a very wet period (Slingo et al., 2014) noted that:

> “As yet, there is no definitive answer on the possible contribution of climate change to the recent storminess, rainfall amounts and the consequent flooding. This is in part due to the highly variable nature of UK weather and climate.”

2.3. Wind speed

Wind speed records (hourly data) were not readily available (in a downloadable form) from across the whole NP Region. The ECD&A data do have daily wind records but only in the NP region for stations in Norway and average monthly winds speed for stations in Iceland are available from the Icelandic Met Office. Hourly wind data are available for UK stations from the British Atmospheric Data Centre.

As an illustration, data for five stations, Tromso, Reykjavik, Bergen, Lerwick and Tiree (about 450 km to the SW of Lerwick) were obtained for the period 1981 to 2010. Figs. 2 and 3 show the mean wind speed (m/s) for those stations for January and July (based on the average of hourly wind speeds for Lerwick and Tiree, ECD&A daily data for Tromso and Bergen and Icelandic Met Office monthly averages for Reykjavik). An estimate was made of the linear trend and none of the stations except Reykjavik showed any statistically significant trend. In the case of Reykjavik the trend was a decline of about 0.8 m/s per decade (statistically significant at better than 0.1%). With regard to the Norwegian stations, Revheim and Beyer (2013) also noted no apparent trends in wind speed in southern Norway.

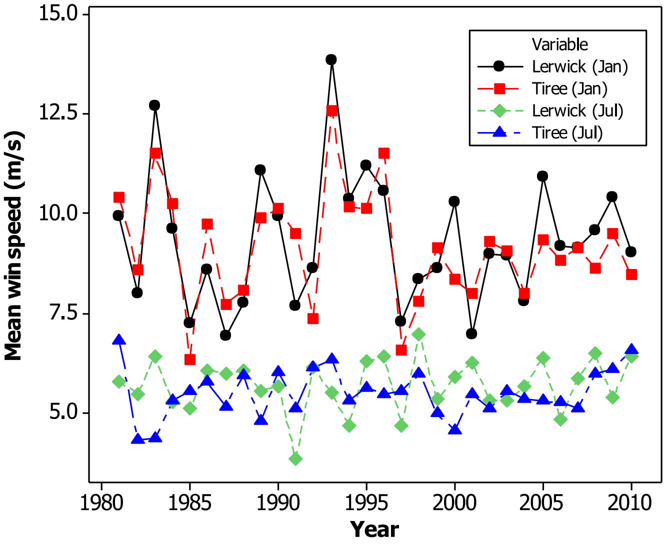

Fig. 2. Mean wind speed (m/s) in January and July for Lerwick and Tiree.

Table 4
Precipitation changes 1957–2013 at selected stations and regions in the NP region.

Station	Increase per decade (mm)	Statistical significance better than (%)	Equivalent change (%) 1957–2013
Tromso	22.2	5%	13%
Stykkisholmur	5.9	NS	5%
Reykjavik	15.3	NS	11%
Lerwick	31.1	1%	16%
Malin Head	17.0	5%	9%
Valentia	53.6	0.10%	22%
Northern Scotland[a]	67.2	0.10%	26%
Western Scotland[a]	75.7	0.10%	28%

[a] Data for Northern and Western Scotland are from the UK Met Office regional climate summaries regional values (http://www.metoffice.gov.uk/climate/uk/summaries/datasets) which have Northern, Western and Eastern Scotland whereas the Hadley Centre regional data are for Northern, Southern and Eastern Scotland (http://www.metoffice.gov.uk/hadobs/hadukp/) which all have different boundaries from those in the Met Office regional Summaries.

In Ireland reported the trends generally show increased wind speeds for the last 30 yrs over the coastal regions of western Ireland (Lozano et al., 2004; Sweeney et al., 2002, 2008; McGrath and Lynch, 2008; Dwyer, 2012). This was particularly true over the northwest of Ireland and increases in averaged wind speed values reduce southwards to southwest Ireland.

It is not just mean wind speeds that are important but the frequency of severe storm associated with high wind speeds, as they can cause major disruption to coastal system functioning (morphodynamic changes), loss of life and the wide impacts on people

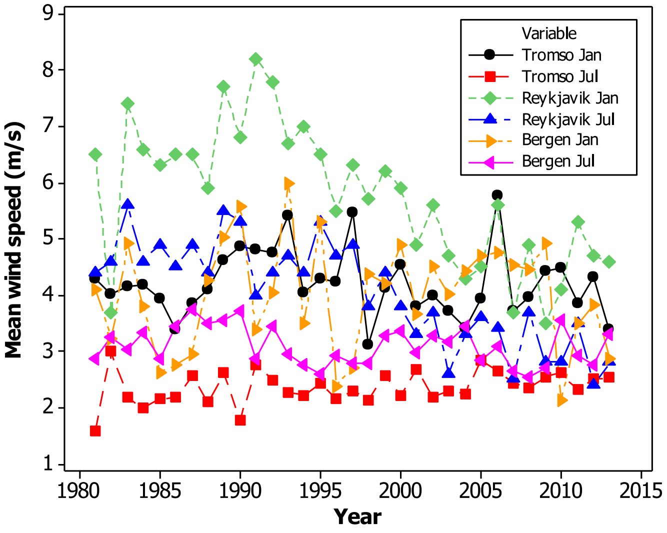

Fig. 3. Mean wind speed (m/s) in January and July for Tromso, Reykjavik and Bergen.

and coastal infrastructures (Stone and Orford, 2004; Coll et al., 2013; Clarke and Rendell, 2009; Delaney et al., 2012).

Jenkins et al. (2009), as part of the UK climate impacts programme, noted that severe windstorms around the UK to the end of the 1990s had become more frequent, although not above that seen in the 1920s. However, Woolf and Wolf (2013) note that there has been no noticeable trend since that time.

As noted by Woolf and Wolf (2013), gale day frequency is significantly correlated to the NAO and Corbel et al. (2007) and Lozano et al. (2004) found that strong south-westerly winds for the Atlantic coasts of Europe, and particularly for sites around the Scottish coasts are closely linked to the behaviour of the NAO. Allan et al. (2009) note that the frequency of both October to December and January to March severe storms have increased from the period 1960–1970 to the period 1990–2000. However, the frequency of more positive NAO increased over the same time and Woolf and Wolf (2013) noted there is a strong trend in the NAO and storminess from the early 1960s to the early 1990s. Osborn (2004) found that it was uncertain whether this was a response to greenhouse forcing and a study by Hanna et al. (2008) of storminess using meteorological stations in Denmark, the Faroe Islands, Greenland, Iceland, UK, and Ireland, found no evidence to suggest a long-term increase in storminess in these regions, despite increasing temperature.

Woolf and Wolf (2013) note that since the 1990s the warming of the Arctic may be related to a reduction in the latitudinal gradient of sea-level pressure leading to a lower, or negative, NAO Index and thus a weakening in the delivery of the number storm systems. This in turn may have resulted from the substantial retreat of Arctic sea ice since the 1990's (as illustrated by the data from the Japan Aerospace Exploration Agency's Arctic Sea-ice Monitor, http://www.ijis.iarc.uaf.edu/en/home/seaice_extent.htm),halting the upward trend in storm frequency and the more frequent occurrence of "NAO negative" winters. However, the magnitude of individual storm events for the NP region has increased generally since the 1990s, together with an eastwards, European on-land shift in the position of storm-peak centres consistent with modelled projections for climate warming effects (Lozano et al., 2004; McGrath and Lynch, 2008; Lowe et al., 2009). However, as noted by Slingo et al. (2014) there is no definitive confirmation that recent storminess is a result of climate change.

3. Future climate changes

3.1. Understanding climate

The IPCC (2013) notes that in terms of scientific understanding, it provides a qualitative level of confidence (from very low to very high) and, when possible, includes a probabilistic assessment of likelihood of outcome ranging from exceptionally unlikely to virtually certain.

The following terms have been used by the IPCC (2013) to indicate the assessed likelihood (Table 5).

Table 5
IPCC definition of likelihood of outcome of model projections.

Term[a]	Likelihood of the outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

[a] Additional terms (extremely likely: 95–100% probability, more likely than not: >50–100% probability, and extremely unlikely: 0–5% probability) may also be used when appropriate.

3.2. Radiative forcing of climate

In terms of future changes, the IPCC (2013) makes use of four Representative Concentration Pathways (RCPs) for greenhouse gases that replace the emissions scenarios used in the IPCC (2007) a,b report and subsequent modifications included in IPCC (2012), These updated RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) provide a range of possible outcomes and confidence levels for scientific understanding and likelihood probabilities for outcomes are given when each is used.

At present, global emissions of greenhouse gases, particularly carbon dioxide appear to be following the RCP8.5 scenario of high emissions (for example Anderson and Alice, 2011; IEA, 2013) and therefore future climate changes are likely to follow modelling based on the RCP8.5 scenario.

3.3. Modelling future climate

The IPCC (2013) notes that Earth Systems Models (ESMs) are the current state-of-the-art which expand on the previously used Atmosphere Ocean General Circulation Models (AOGCMs) to include representation of biogeochemical cycles such as those involved in the carbon cycle, the sulphur cycle, or ozone.

Although models have improved there are still areas of uncertainty. Flato et al. (2013) note that atmosphere, cloud processes, including convection and its interaction with boundary layer and larger-scale circulation, remain major sources of uncertainty and as are parameterizations of vertical and horizontal mixing and convection in ocean modelling.

As well as ESMs and AOGCMs, in order to provide more information at a regional scale more limited-area regional climate models (RCMs) have been developed which can be used to dynamically 'downscale' global model simulations. As an alternative to RCMs empirical and statistical downscaling methods constitute a range of techniques to provide similar regional or local detail.

In Europe very high resolution regional climate models have been developed as part of the ENSEMBLES project (van der Linden and Mitchell, 2009) and these have informed regional climate change projections.

Although uncertainties remain at both global and regional scale modelling, the IPCC (2013) report provides a probabilistic assessment of likely changes noted below in the discussion of temperature, precipitation and sea level.

3.4. Global changes

3.4.1. Temperature

Collins et al. (2013) noted that global mean surface temperatures for 2081–2100, relative to 1986–2005 will likely be within the range 2.6 °C–4.8 °C using RCP8.5 (which at present seems the most likely scenario) and there is high confidence that warming will exceed 2 °C above 1850–1900. The range quoted is from the 5th to 95th percentile in terms of the likely change. They also noted that warming above 4 °C by 2081–2 100 using RCP8.5 is about as likely as not (medium confidence).

Sea-surface temperatures will also change but the largest errors in modelling SSTs occur at mid and high latitudes. SSTs play an important role in atmospheric circulation and introduce uncertainty about changes in weather patterns. While a marginal improvement in projections of SSTs has been noted in the most recent IPCC report (Collins et al., 2013), as compared to the previous report, with fewer individual models exhibiting serious bias. Collins et al. (2013) also noted that there had been a significant reduction in the model zonal mean SST error standard deviation in many areas but the multi-model mean was only slightly improved. In addition it was noted that the projected increase of SST and heat content over the next two decades is relatively insensitive to the emissions trajectory but that outcomes for different emission scenarios diverge as the 21st century progresses.

3.4.2. *Precipitation*

With regard to precipitation, Collins et al. (2013) noted that the modelling output appears to suggest that high latitude land masses are likely to experience greater amounts of precipitation. They note that this will be a result of the increased specific humidity of the warmer troposphere and increased transport of water vapour from the tropics by the end of this century under the RCP8.5 scenario. They also note that projected changes, as compared to natural variability, suggest that there is high confidence that the changes will be greater than natural variation.

However compared to projected temperature changes, there is considerable variation is projected precipitation changes between different models. Collins et al. (2013) suggest that this is due to differences in models' ability to replicate observed precipitation patterns but an important issue is the small ensemble size from each model.

3.4.3. *Sea level changes*

Although sea-level change is not a climate element, it is driven by climate changes. Sea-level changes will have important implications for coastal communities as, for example, it increases risk from flooding. Church et al. (2013) provided the review of the IPCC projections of sea level changes. They noted that compared to 1986–2005, global mean sea level rise by 2081–2100 under the RCP8.5 scenario ranges from 0.52 to 0.98 m (5th to 95th percentile), with a rate during 2081–2100 of 8–16 mm/yr. Their results also indicated variations in sea level rise in different parts of the world and that the rises in the north Atlantic (where the NP region is situated) are at the higher end of those variations.

Church et al. (2013) also noted that semi-empirical models mostly suggest a change that is greater than process based models which could suggest that sea level changes may be larger than those noted above. However, they commented that there is no scientific consensus about the reliability of semi-empirical models and therefore confidence in their output is low.

3.5. *Regional climate changes*

Although there are now new RCP scenarios given by IPCC (2013) the published regional projections given here are based on the previous emissions scenarios (IPCC, 2000, 2007a,b, 2012). However, the general direction of changes of climate and sea level has not changed between IPCC (2007a,b, 2013), although changes are slightly greater, and the previous high emissions scenarios are to some extent comparable to the RCP8.5 scenario. The regional projections in Western Europe are based on Regional Climate Models (e.g., Lowe et al., 2009; McGrath and Lynch, 2008) and some of those projected changes are given in the following Figures (Figs. 4–11) based on regional climate analyses undertaken in Iceland, Ireland, Norway and the UK.

Unfortunately the results are not directly comparable as each country produces their results in a different way and for slightly different future time periods. In Norway, change by 2050 and 2100 is given (Norway Ministry of the Environment, 2010) whilst in Iceland it is averaged for the periods 2016–2025, 2046–2055 and 2091–2100 (Iceland Ministry for the Norway Ministry of the Environment, 2010). The changes shown are also from different standard periods. In the Norway and the UK it is from the standard 1961–1990 means, in Ireland it is from a 1961–2000 mean and in Iceland it is from an estimated 2001–2015 mean. In the UK (UKCP09, 2009) and Ireland (McGrath and Lynch, 2008) there are also estimates for different periods with the latter period being, 2070–2099 for the UK and 2060–2099 for Ireland. In the case of the UK the UKCP09 (2009) maps also have probabilities shown for a range of IPCC scenarios of greenhouse gas emission changes. The figures presented here maps are for the 50% probability (an equal probability that future climate will be warmer or colder or wetter or drier than the projections) under a high emissions scenario.

In summary, all of these projections show similar sorts of changes, with most regions experiencing the development of a warmer climate, which is generally wetter in Winter but may be a little drier in Summer in some regions.

It is important to realise that these projected changes are large. The temperature changes are potentially >50% of the global change that has taken place since the last Ice Age over 10 000 years ago. The precipitation changes, in particular, may well pose serious challenges for the coastal regions in the countries in the NP region. In parts of western Scotland the predicted winter increases at high levels in the mountains (a 40% increase on winter precipitation of as much as 1600 mm) would be more than the present average annual precipitation in much of eastern England.

The illustrations shown here provide only the projections for temperature and precipitation, as there is no clear consensus about likely changes in wind speeds. Studies for European Atlantic and linked coastal regions (e.g., Lozano et al., 2004; McGrath and Lynch, 2008; Lowe et al., 2009) show modelled projections for slight increases in Winter wind speeds (1–2%) and decreases in Summer (2–3%) for 2021–2060, both of which are much less than the standard deviation of monthly wind speeds recorded at the stations listed in Section 3. As regards storminess, future natural climate variability effects on storminess could overwhelm any anthropogenic signal there might be (Allan et al., 2009) and as yet there is no confirmation that usual events are related to climate change (Slingo et al., 2014).

3.5.1. *Temperature changes by 2050 and 2100*

In all of the CoastAdapt regions temperatures are predicted to rise by the end of the century. In Norway the winter range for low to high emissions is between +1.5 and +3.3 °C (by 2050) and +2.8 to +6.0 °C for 2100, with an expected probable temperature change of +4.3 °C (Fig. 4). In summer the range is 0.8–1.9 °C (low to high emissions) with 1.3 °C expected (2050) and +1.4 to +3.5 °C, with an expected value of +2.4 °C (2100). The Atlantic coastal regions will not warm as much as the far north.

In Iceland the predicted warming for the different emissions scenarios are shown in Fig. 5 and in all cases the warming appears to be lower than in the other CoastAdapt areas. For high emissions there is a range of +0.9–1.6 °C with a median of 1.2 °C (2046–2055) and +2.1 to +2.8 °C with a median of +2.4 °C (2091–2100). However, the projected changes are based on the change from an estimate 2000–2015 mean and if the 1961–1990 means for Reykjavik and Stykkisholmur are used and compared with the 2000–2013 means (which approximate to the estimated 200–2015 means) there would be an additional 1.1 °C of warming. Only annual figures are given for Iceland (Iceland Ministry for the Environment, 2010).

In Scotland North (as defined by UKCP09, 2009) for a high emissions scenario summer temperatures changes may range

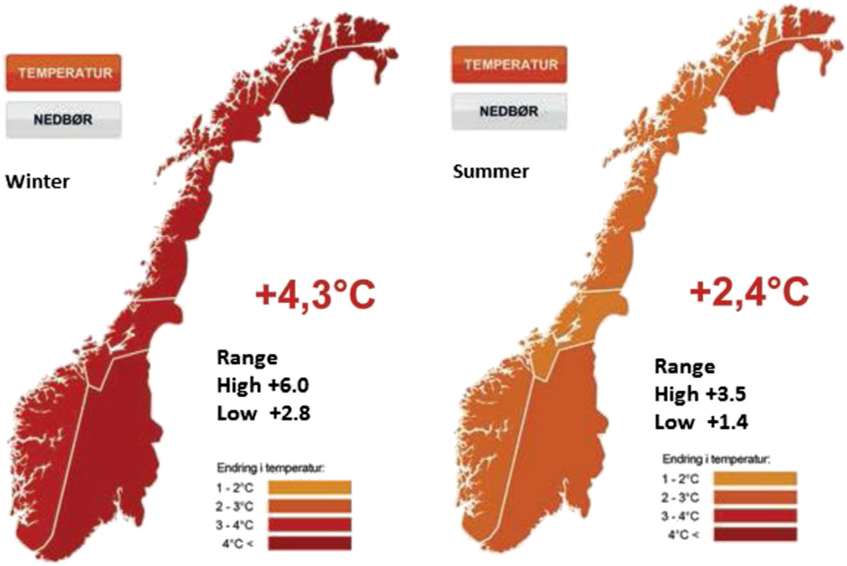

Fig. 4. Predicted Winter and Summer temperature changes in Norway by 2100 (Source: http://www.regjeringen.no/pages/36782608/pdfs/nou201020100010000en_pdfs.pdf).

from +1.1 to +3.9 °C with a central estimate of +2.4 °C (2050s) and +1.9 to +6.0 °C with the central estimate of 3.7 °C (2080s, Fig. 6). Unlike Norway warming is less in winter than in summer (+0.7–3.0 °C) with a central estimate of +1.8 °C in the 2050s and +1.2 to +4.1 °C with a central estimate +2.5 °C in the 2080s). The western coastal regions and Northern Isles (the CoastAdapt area) being at the lower end of that normal range.

The maps produced for Ireland cover the whole of the British Isles and show that in western Ireland the warming in the Atlantic coastal regions is less than in the south and east of the country. Across Ireland for a high emissions scenario the greatest warming is in summer and autumn and ranges from +1.2 to +2.4 °C in 2021–2060 to +3.0 to +3.4 °C in 2060–2099 (Fig. 7). As with Scotland, the summer warming is somewhat greater than in winter with the Atlantic coasts predicted to warm by over +3.0 °C in the far southwest (a little more in autumn). An interesting point is that the Irish maps covering the whole British Isles suggest that northern Scotland will warm more in winter than in summer which contrasts with the UKCP09 (2009) findings. It is important to note that the Irish results were based on a different set of models from that used by UKCP09 and this highlights the need for careful interpretation of model output at regional level.

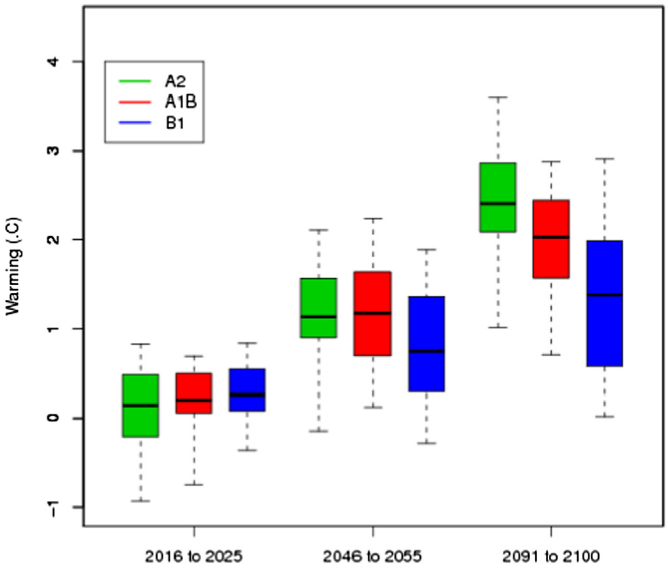

Fig. 5. Annual projected temperature changes from present conditions in Iceland showing results from a range of emission scenarios for the periods 2016 to 2025, 2046 to 2065 and 2091–2100 (Source: http://unfccc.int/resource/docs/natc/isl_nc5_resubmit.pdf).

Overall, the modelled projections indicate substantial changes in temperature, but in general the coastal regions may warm a little less than inland areas, with the smallest rises being in Iceland.

3.5.2. Precipitation changes by 2100

While temperature changes are expected to be considerable the impact of precipitation changes has the potential to cause greater disruption, either through more frequent floods or longer and more frequent periods of drought (IPCC, 2012). In Norway winter changes by 2050 are expected to range from +3.8 to +18.4% and in 2100 (Fig. 8) from +8.5 to +39.9%, lower in the northern coastal areas and greatest in southeast Norway. In summer the changes are smaller being in the range −1.6 to +9.7% (2050) and −3.2 to +17.4% (2100) with the greater increase being in the north and Atlantic coastal regions and least in southeast Norway. In Iceland (Fig. 9) changes are expected to be between +1 and +5% (2046–2055) and +3 and +12% (2091–2100) but these are annual values so it is not possible to make a direct comparison with the other countries.

For Scotland North winter precipitation is expected to increase by +3 to +26% with a central estimate of 2.5% in the 2050s and 9–45% with a central estimate of +24% in the 2080s (Fig. 10). In both periods the increase in the western coastal regions and Northern Isles is greater than the central estimate for Scotland North (and is a somewhat larger increase than in Norway). In summer there is expected to be a change of −24 to +3% with a central estimate of −10% in the 2050s and −36 to +4% with a central estimate of −16% in the 2080s (with a smaller reduction in Shetland), increasing the contrast between summer and winter. Changes in Ireland (Fig. 11) are expected to be in the order of +5 to +10% (2021–2060) +15 to +25% (2060–2099) in (at the lower end in the northwest coastal regions) and showing a reduction in precipitation in Summer, from −5 to −10% (2021–2060) and −10 to −18% (2060–2099). With

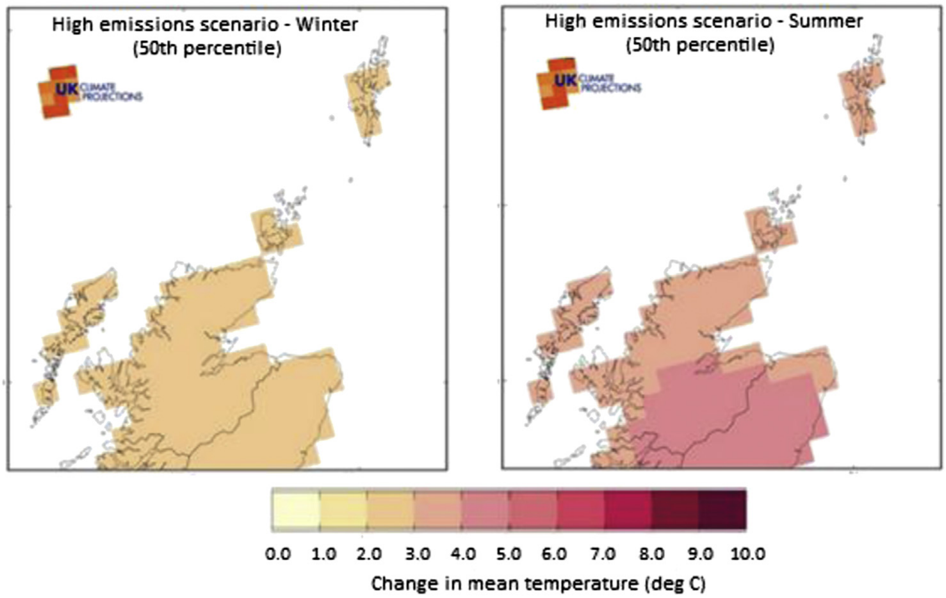

Fig. 6. Projected temperature changes northern Scotland for 2070–2099 (Source: http://ukclimateprojections.defra.gov.uk/21759.

smaller changes in the northwest coastal regions and greater reductions predicted in the south.

In summary, it appears that winter precipitation, which is generally already substantial in all the coastal regions within the CoastAdapt project, is likely to increase particularly in western Scotland. In the summer, substantial reductions are predicted for Scotland and southwest Ireland, but Norway may have a summer increase in precipitation.

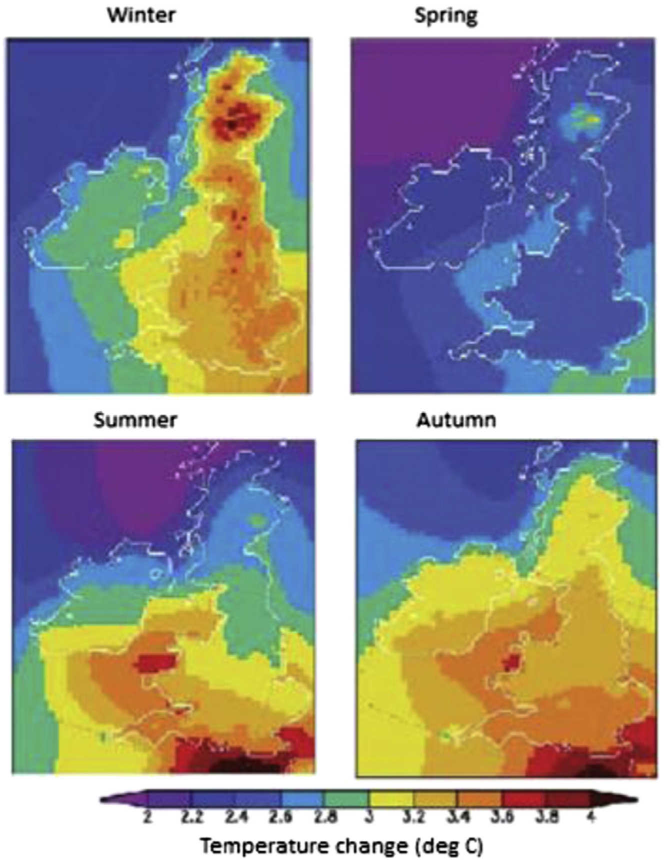

Fig. 7. Projected temperature changes (°C change) for the British Isles by 2060–2099. (Source: McGrath and Lynch, 2008 http://www.c4i.ie/docs/IrelandinaWarmerWorld.pdf).

3.5.3. *Sea-level rise by 2100*

For the Northern Periphery regions an important impact of climate warming will be the projected rise in sea-level, driving particularly changes in the incidences of coastal flooding, erosion, damage to infrastructures and impacts on coastal aquifers and groundwater (Alcamo et al., 2007; IPCC, 2012).

The projections of sea level rises have increased between the earlier IPCC report (IPCC, 2007a) and the most recent one (Church et al., 2013) and are given in Table 6. Recent studies indicate that the real value of sea-level rise is most likely for many regions to be close to, or above the upper end of projections. Results from satellite-based survey of the NP region indicates a current increase in the approximate rate of background of sea-level rise here from 1–2 mm/yr to c.3.2 mm/yr (e.g., Colorado University Sea-level Research Group, 2014; Woodworth et al., 2009, 2010), consistent with the expected wider trends of climate warming.

As noted by Rahmstorf et al. (2012), while temperature changes appear to match projections quite well, sea-level rises are faster than anticipated. Rignot et al. (2011) have shown that both the Greenland and Antarctic ice sheets are losing mass (the IPCC predicted the Antarctic ice sheet would gain mass). Further, quantification of the feedback effects from a warming atmosphere on the oceans still remain broad, in terms of the impact of the steric effects, or of effective wave and storm surge levels on sea levels at the coast. These considerations would suggest that the IPCC projections may be conservative.

Nicholls et al. (2011) quote a range of sea-level rises per century ranging from 0.5 m to 2.0 m, with their more recent ones having ranges of 0.75–1.90 m (Vermeer and Rahmstorf, 2009) and 0.72–1.60 m (Grinsted et al., 2009) both of which were produced by semi-empirical methods. There is a lack of scientific confidence in such methods (Church et al., 2013) although Bittermann et al. (2013) in assessing the predictability of sea-level rise noted that their results gave support to the use of semi-empirical methods for future sea-level projections.

Overall, given that the current climate change trends suggest that the world is following a high emissions scenario it would

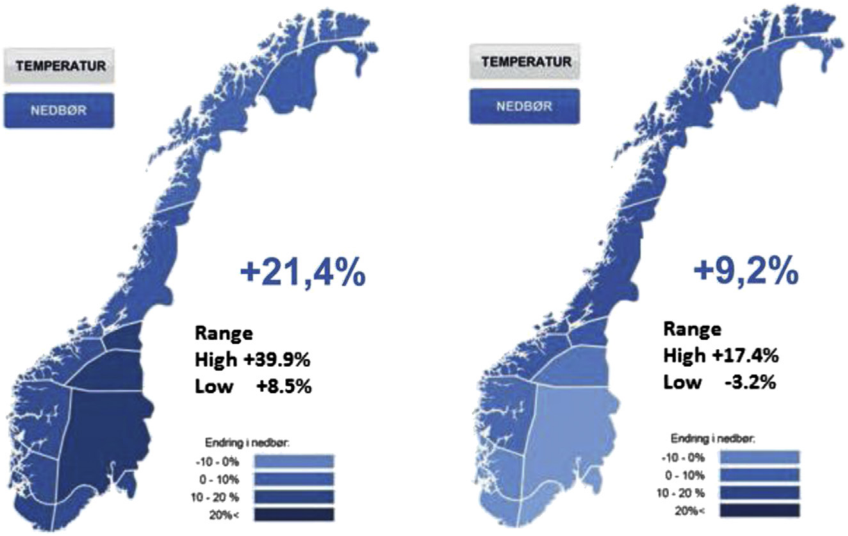

Fig. 8. Predicted winter and summer changes in precipitation in Norway by 2100 (Source: http://www.regjeringen.no/pages/36782608/pdfs/nou201020100010000en_pdfs.pdf).

appear likely that the sea-level rise by 2100 may well be over 1.0 m (and more in some places) which will pose serious problems for low-lying coastal areas including parts of the CoastAdapt region. However, in some parts of the CoastAadpt region, particularly Scotland, there is the counterbalancing effect of isostatic rebound as a result of the removal of the burden of ice present at the end of the last ice age. Lowe et al. (2009) note that including such effects gives larger sea level rise projections relative to the land in the southern UK (where land is subsiding) and somewhat lower increases in relative sea level for the north. They note that the projected relative sea level rises to the end of the 21st century to be 21–68 cm for London and 7–54 cm for Edinburgh. It should be noted that the Scottish Islands (Western and Northern Isles) which are within the CoastAdapt region are not greatly affected by isostatic changes and so sea level rises in those areas will be closer to the average UK value.

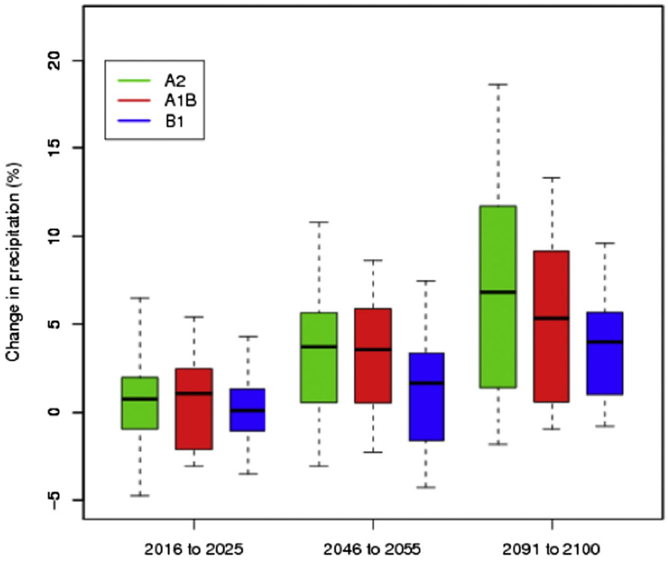

Fig. 9. Predicted precipitation changes from present conditions in Iceland showing results from a range of emission scenarios (Source: http://unfccc.int/resource/docs/natc/isl_nc5_resubmit.pdf).

4. Implications of climate warming for communities of the NP region

4.1. Community concerns

As part of the CoastAdapt project, coastal stakeholder workshops were held in each of the study areas (northern Norway, Hammerfest; Iceland, Vik; the Western Isles, Benbecula and South Uist, and southwest Ireland, Tralee). At those meetings the potential impacts resulting from climate warming on the infrastructure and the people living in these coastal communities were discussed in depth (Gray et al., 2014). Key impacts recognised by people in particular study areas are noted (but many are of wider regional significance such as adverse weather, erosion, storminess and sea-level rise) included:

- More rain –less snow leading to pressure on the drainage system and on roads (Hammerfest)
- Oscillating temperatures (between from above and below 0 °C) leading to more icy and slippery surfaces (Hammerfest)
- Isolation of island communities during extreme weather (Hammerfest)
- Adverse winter weather and increased rainfall leading to poor road conditions/restrictions on access (Tralee Bay)
- Coastal erosion–land loss, threats to roads and houses (Tralee Bay)
- Coastal erosion – loss of land (Western Isles)
- Increased storminess/high winds and flooding – damage to infrastructure and communications, closure of roads, loss of agricultural lands (Western Isles)
- More frequent freeze-thaw events which lead to faster deterioration of roads (Iceland)
- Sea-level rise coinciding with land subsidence could lead to an increase in coastal floods (SW Iceland)

Notwithstanding the concern about coastal flooding, the concern about climate change in Iceland appears to be less than in other parts of the CoastAdapt region. Jónsdóttir (2012) noted that climate change is not likely to have severe economic impacts in Iceland in the short term.. In fact, the short-term effects are likely to be favourable for agriculture and hydro-electric energy production.

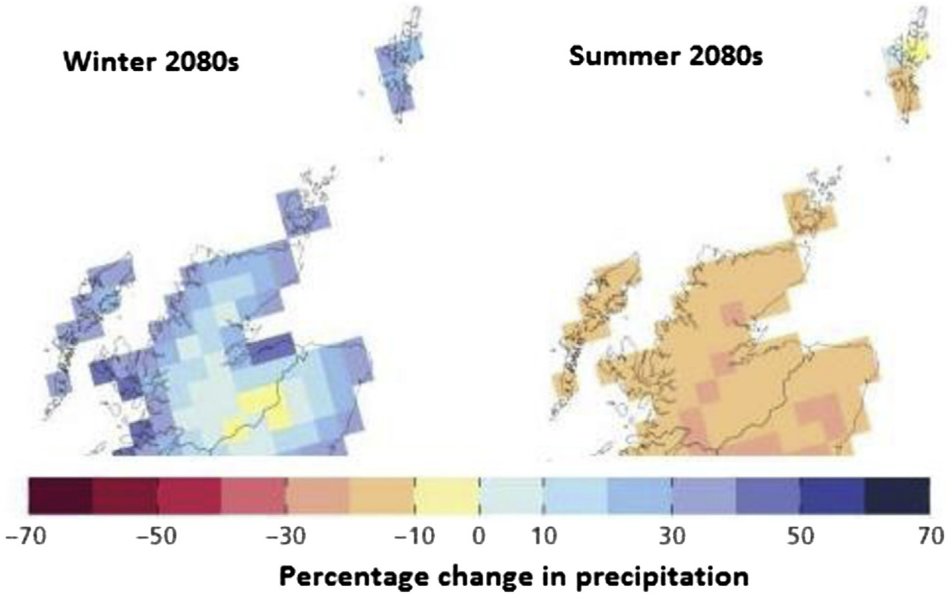

Fig. 10. Predicted precipitation changes from present conditions in northern and northwest Scotland showing results for a high emission scenario (50% probability level). (Source: http://ukclimateprojections.metoffice.gov.uk/21759).

Air temperature has risen in Iceland in the past 15 years, causing noticeable increase in plant growth with species found in new areas and at higher altitudes. If the climate continues to warm by 1.5 °C–2 °C, new crops and commercial plants may be able to grow in Iceland, including oats, wheat and berries. Higher temperatures were also thought to be potentially beneficial to agriculture in Scotland and Norway.

Together with rising sea levels, changes in precipitation (less snow – more rain) are the most likely to cause problems for local communities, particularly increased flooding intensity and frequency.

4.2. *Sea level rise*

In a forthcoming spatial strategy for Hammerfest (northern Norway), building restrictions will be introduced in the coastal zones to prevent houses being built any lower than 3 m above the high tide level. The municipality of Hammerfest is working to identify all areas that might be affected by sea-level rise. This appears to be a sensible precaution given the higher increases in sea levels that are now expected.

In the Western Isles, the implications for severe weather including stormy seas and tidal surges of climate change concern the community. Participants identified that the traditional industries of crofting and fishing, also aquaculture, would be the most vulnerable to sea level rise and climate change.

According to Angus and Hansom (2004), climate change scenarios for the Western Isles envisage a combination of rising sea-level, increased winter precipitation, and increased frequency and severity of winter storms. The flat low-lying machair lands of Uists are thus particularly vulnerable, not only from marine overtopping of coastal dune ridges but also from inland flooding and restricted drainage. The conservation importance of machair is significantly augmented by a pattern of rotational cultivation that largely employs traditional methods and provides species-rich fallow. This tradition is already under economic threat and increased flooding could have far–reaching consequences for both agriculture and wildlife.

Fishing and aquaculture are also vulnerable because of potential damage to slipways, moors and fish farms, as well as the actual impact of changing environmental conditions on fish stocks.

4.3. *Precipitation*

More widely, many coastal communities are already feeling the effects of increased flooding. Solutions include re-instating flood plains or natural soaks, introducing floodplain woodlands and increasing drainage capacity (Nordregio, 2010). These different management techniques to climate impacts on coastal changes form part of the recommended adoption of an integrated approach in coastal management (Alcamo et al., 2007). Cooper and McKenna (2008), Devoy (2008), Cooper and Cummins. (2009), Cummins and Kopke (2011) and Falaleeva et al. (2011) review and highlight the coastal geomorphological and wider community management benefits and also draw-backs of using such an approach in addressing the future issues for coastal zone management and in the newer linked approaches in the EU of Marine Spatial (EU Atlantic Strategy, 2011).

Any change in precipitation is important as rain is one of the most important factors affecting the design and operation of the road network. It affects the design of drainage systems to collect and discharge surface water, these systems being designed to accommodate the 1 in 1 year storm, without system storage being required and to store the 1 in 5 year storm without flooding of the road surface. It also affects the sizing of river bridges/culverts, which are designed to accommodate a much larger rainfall event, typically the 1 in 100 year storm for the catchment concerned. Rain also creates a hazard to road users when it is not shed sufficiently quickly from the carriageway, resulting in loss of visibility and skid resistance, both of which are frequent contributing factors in road accidents.

Rain also has the potential to cause significant landslide events, for example those witnessed in Scotland in August 2004. These occur through large volumes of surface water eroding the land surface and/or through changes in groundwater levels reducing the stability of cuttings. In addition, rain, together with temperature,

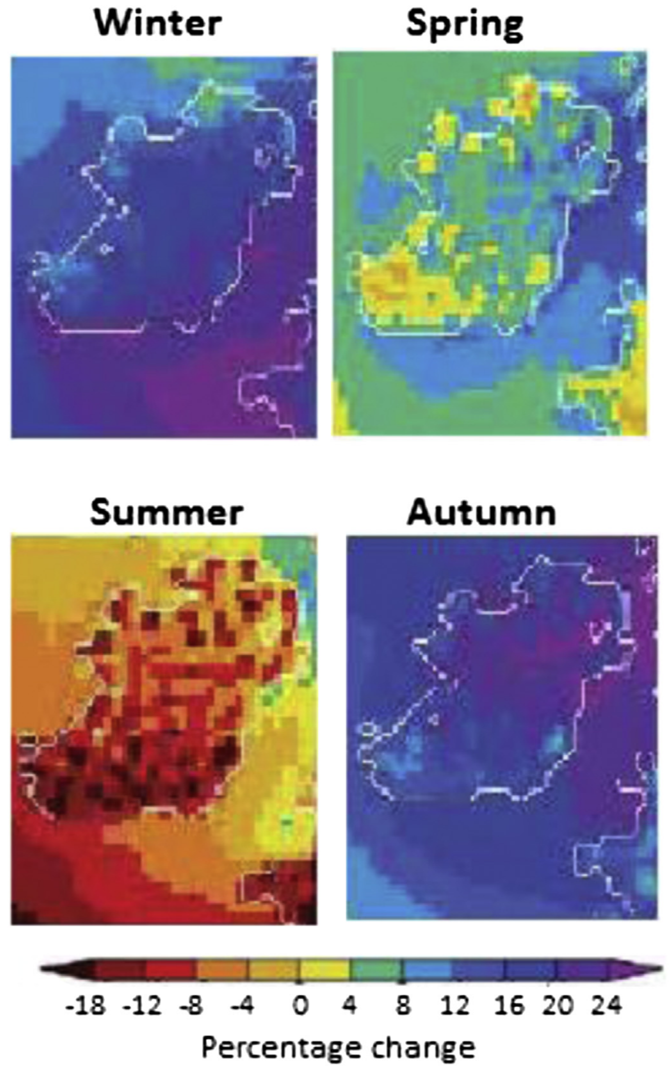

Fig. 11. Projected precipitation changes in Ireland by 2060–2099, as percentage change. (Source: adapted from McGrath and Lynch, 2008 http://www.c4i.ie/docs/IrelandinaWarmerWorld.pdf).

can significantly alter the soil moisture condition within a catchment, creating a situation where the volume of water that the catchment sheds may be much higher than the 15%–50% currently used in the design of drainage systems. This issue will also be of relevance in Norway and Ireland where like Scotland there are substantial projected increases in precipitation.

The rainfall events currently used in road design in Scotland are based on historical records of rainfall events, and therefore a particular concern is that given the predicted increases in winter rainfall, these records may no longer correctly describe the design storm event. Galbraith et al. (2005) identify some of the potential impacts and Winter et al. (2005) provide a number of potential options which could be applied to the management of debris flows caused by heavy periods of rain.

Table 6
Sea-level rise by 2100 for different emissions scenarios (IPCC, 2007a; Church et al., 2013).

Sea level rise (m) 2090–2099 relative to 1980–1999 (IPCC, 2007a)		Sea level rise (m) 2081–2100 relative to 1986–2005 (Church et al., 2013)	
Case		Case	
B1 Scenario	0.18–0.38		
A1T scenario	0.20–0.45	RCP2.6	0.26–0.55
B2 Scenario	0.20–0.43	RCP4.5	0.32–0.63
A1B scenario	0.21–0.48	RCP6.0	0.33–0.63
A2 scenario	0.23–0.51	RCP8.5	0.42–0.82
A1FI scenario	0.26–0.59		

5. Discussion and conclusions

Communities across the CoastAdapt Northern Periphery region have significant concerns about the impacts of climate change. Many have begun to develop adaptation strategies and it is interesting to note that sea-level rise and increases in the amount and/or intensity of precipitation (and whether it falls as rain or snow) appear to be the features of climate change which pose the most concern (see Gray et al., 2014). Higher temperatures are thought of as bringing potential agricultural benefits but would not be welcomed by the skiing industry, particularly in Scotland (although ski areas are mostly inland and not in the coastal areas of the CoastAdapt project).

The projections from the modelling of future climate changes appear to suggest that as well as considerable temperature changes there will be significant increases in winter precipitation in Ireland, Norway and Scotland and that more will fall as rain rather than snow (although there may be more snow at high levels). While the projections are clear about the direction of change, it is not clear whether the scale of mountain/uplands (orographic) enhancement will remain the same. This will be important especially in the western Highlands of Scotland, where orographic enhancement can give over a fourfold increase in precipitation over 1000 m as compared to values at sea level (Ballentyne, 1983; McClatchey, 1996), and also in southwest Ireland and western Norway.

In addition, as noted by Woolf and Wolf (2013), a possible future weakening of the North Atlantic storm track may be related to the warming of the Arctic. This could lead to greater uncertainty in projections, as a weakening could lead to larger waves in the upper westerlies and consequently a more meridional air flow that could lead to longer periods of unusually wet or dry periods in north western Europe, particularly the CoastAdapt regions. For example, the winters of 2009/10, 2010/11 and 2012/13 were dry in western and northern Scotland and were generally much wetter further south (2012 was the wettest on record for England and Ireland). These years were all periods with a negative NAO index, which is associated with a weaker upper westerly airflow. Such changes will not affect overall global warming but across the NP region some areas may be colder and drier while others may be wetter and milder. This will pose challenges for climate modellers and for those implementing schemes for adaptation to climate change.

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