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NMPi Future Climate Change Data Layers

Scottish Marine and Freshwater Science Vol 8 No 11

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Marine Scotland Science is the directorate of the Scottish Government responsible for the integrated management of Scotland's seas. Marine Scotland Science (formerly Fisheries Research Services) provides expert scientific and technical advice on marine and fisheries issues. Scottish Marine and Freshwater Science is a series of reports that publish results of research and monitoring carried out by Marine Scotland Science. It also publishes the results of marine and freshwater scientific work that has been carried out for Marine Scotland under external commission. These reports are no subject to formal external peer review.

This report presents the results of marine and freshwater scientific work carried out by Marine Scotland Science.

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NMPi Future Climate Change Data Layers

Report to Accompany Marine Scotland MAPS NMPi Data Layers

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Executive Summary

This report has been prepared to accompany the UK Climate Projections 2009 (UK CP09) layers added to 'Marine Scotland MAPS NMPi'. NMPi is Marine Scotland's on-line portal to provide spatial information and data to support national and regional marine planning and the state of the sea assessments required to support national and regional planning. This report briefly summarises the climate change data layers selected.

A variety of time baselines are used in the climate change future projections (although all are generally for about 100 years in the future). Unfortunately the different time periods reflect how the source information was published, and this cannot be rectified in this report. Users can convert changes over the period published here to relative change per year, or per decade, and then estimate the size of changes for any specific year of their interest.

When multiple emission scenarios have been used to give a range of future climate variable possibilities, the 50% probability solution has been used. For projections when only one emissions scenario is available, a medium emissions scenario of future societal change has been used in this report, although other emissions scenarios are available in the information sources listed.

Storminess: Currently there is no clear understanding of the future of storminess (i.e. storm intensity and frequency) over Scottish seas. UKCP09 makes no projections as to whether storminess will increase or decrease in the future. Different models predict different outcomes. Hence there is no NMPi Data Layer on Storminess.

Winds: The models used in the UKCP09 project suggested that by 2080 there may be a slight decrease in winds over Scottish seas, by about 3%. There are small chances that this decrease could be double, or winds could increase by about 3%. These changes are small compared to natural variability, and regional differences

across Scottish seas are not clearly evident, hence no NMPi Data Layer is presented for wind.

Rainfall: The central estimate projections for the 2080s, using the medium emissions scenario as the most likely outcome of climate change, indicates that over Scotland summers will become up to 20% drier, and winters 20% wetter. Overall, the central estimate is for the annual average rainfall to be about 10% less in the 2080s. There are some regional differences, hence NMPi data layers for rainfall (precipitation) are presented.

NMPi Data Layer – Percent change in annual mean precipitation, 2080s compared to 1970s (Figure 1).
NMPi Data Layer – Percent change in summer precipitation, 2080s compared to 1970s (Figure 2).
NMPi Data Layer – Percent change in winter precipitation, 2080s compared to 1970s (Figure 3).

Air Temperature: For winter air temperatures, for the medium emissions scenario, the central estimate (50% probability) is for air temperatures to increase by between 1.1 and 2.4ºC by the 2080s. Increases are projected to be greater on the east coast than on the west coast. Increases are very unlikely to be greater than 4ºC, but also very unlikely to be less than 0.5 ºC. Very similar values are projected for summer air temperature increases. As there is some regional differences in the projections, NMPi data layers are presented for air temperature.

NMPi Data Layer – Increase (°C) in summer air temperature, 2080s compared to 1970s (Figure 4).
NMPi Data Layer – Increase (°C) in winter air temperature, 2080s compared to 1970s (Figure 5).

Relative Sea Level: Currently it is estimated that the average sea level around the UK has risen at a rate of about 1 mm per year over the past century[5] (if this rate of increase carried on to the year 2095, sea level around the UK will increase by about 86 cm).

To help contingency planning in the UK, a prediction has been given of a “low probability, high impact” relative sea level rise, i.e. a “worst case” scenario. This prediction does not have any regional variation, and hence is not presented in the form of an NMPi Data Layer. It states that the sea level around our coast will rise by between 93 cm and 190 cm by 2095. These levels depend on worst case ice melting around the globe.

For the medium emissions scenario, the least predicted rise in relative sea level occurs in the Clyde to Skye coastal waters, as well as the inner Firth of Forth and Moray Firth, with predicted rises of about 30 cm by 2095. The remainder of mainland Scottish coasts experience approximately 35 cm rise over the same period, while the Hebrides and Orkney experience a rise of 40 cm. The greatest predicted relative sea level rise by 2095 occurs in Shetland, with a rise of about 50 cm by 2095. An NMPi data layer for relative sea level rise is presented.

NMPi Data Layer – Rise in Relative Sea Level (cm), 2090s compared to 1980s, medium emissions scenario, central estimate (Figure 6).

Storm Surges: As described above, the current estimates of future climates do not suggest storminess will increase significantly over Scotland. Hence the predictions of increases in storm surge heights over the next 100 years is small. For most of Scotland the increases in extreme storm surges with return periods of 2, 10, 20 and 50 years are between about 1 and 3 cm by 2095. There is some regional variation, and hence an NMPi Data Layer for the increase in storm surge height is presented.

NMPi Data Layer – Increase in extreme storm surge water level (cm) by 2100, compared to 2000, for the 50-year return surge, medium emissions scenario (Figure 7).

Extreme Water Levels: Currently, the highest storm surge that may occur in a 50-year period raises the sea surface by between 90 and 180 cm. The effect is least on the east coast and in Shetland, and greatest on the west coast. The central estimate predicts that by 2095, these extreme water level events will have changed very little.

However, the worst case projections suggest that the 50-year return extreme water levels will have risen to between 300 and 500 cm, again with the highest levels on the west coast, and lowest on the east. As there is some regional variation, NMPi data layers are presented for extreme water levels.

NMPi Data Layer – Extreme water level (cm) - Present day baseline - 50-year return extreme water level above the highest astronomical tide (due to storm surge) (Figure 8).
NMPi Data Layer – Extreme water level (cm) - 2095 projection - 50-year return extreme water level above the highest astronomical tide (due to storm surge + medium emissions relative sea level rise) (Figure 9).
NMPi Data Layer – Extreme water level (cm) - 2095 projection - 50-year return extreme water level above the highest astronomical tide (due to storm surge + worst case relative sea level rise) (Figure 10).

Waves: Climate change projections suggest that by 2085, significant wave heights north of Scotland will decrease by about 30 cm in the winter while they will slightly increase around the southern UK. The other seasons have different patterns of change, although changes are quite small. Four NMPi data layers are given, each one showing the change in wave height for a different season.

NMPi Data Layer – Change (m) in significant wave height by 2085, compared to 1975, medium emissions scenario – winter (Figure 11).
NMPi Data Layer – Change (m) in significant wave height by 2085, compared to 1975, medium emissions scenario – spring (Figure 12).
NMPi Data Layer – Change (m) in significant wave height by 2085, compared to 1975, medium emissions scenario – summer (Figure 13).
NMPi Data Layer – Change (m) in significant wave height by 2085, compared to 1975, medium emissions scenario – autumn (Figure 14).

Hydrography – Temperature: By 2085, sea surface temperatures around Scotland are projected to be between 2 and 2.5ºC warmer. Further south around the UK sea surface temperatures may rise even more, by up to 3.5 or 4ºC. An exception occurs in summer, when surface temperatures north and west of Scotland may be only 1ºC warmer. The autumn seems to be when most warming will be evident. At the sea bed, warming is similar as at the surface, but only on the shallow continental shelf. In the deep waters surrounding Scotland, off the shelf, temperatures are projected to change very little.

As there is quite a lot of both regional and seasonal variation in temperature change, and as sea temperatures may be of importance to many users of the NMPi, eight NMPi data layers are presented, one for each of the four seasons, for surface and near-bed temperatures.

NMPi Data Layer – Increase in sea surface temperature (ºC) by 2085, compared to 1975 – winter (Figure 15).
NMPi Data Layer – Increase in sea surface temperature (ºC) by 2085, compared to 1975 – spring (Figure 16).
NMPi Data Layer – Increase in sea surface temperature (ºC) by 2085, compared to 1975 – summer (Figure 17).
NMPi Data Layer – Increase in sea surface temperature (ºC) by 2085, compared to 1975 – autumn (Figure 18).
NMPi Data Layer – Increase in sea bed temperature (ºC) by 2085, compared to 1975 – winter (Figure 19).
NMPi Data Layer – Increase in sea bed temperature (ºC) by 2085, compared to 1975 – spring (Figure 20).
NMPi Data Layer – Increase in sea bed temperature (ºC) by 2085, compared to 1975 – summer (Figure 21).
NMPi Data Layer – Increase in sea bed temperature (ºC) by 2085, compared to 1975 – autumn (Figure 22).

Hydrography – Salinity: Surface salinity is projected to decrease everywhere around Scotland, and in fact around the entire north east Atlantic, by about 0.2 salinity units. This decrease is mainly due to wide scale changes in the ocean rather than the local effect of rivers. As there is very little regional or seasonal variability in the change in surface salinity, only one NMPi data layer is presented, for winter surface salinity.

NMPi Data Layer – Change in sea surface salinity (psu) by 2085, compared to 1975 – winter (Figure 23.)

Hydrography – Stratification: It is projected that stratification will start earlier around Scotland by 2085, possibly by as much as 5 to 10 days. However, there are exceptions to this pattern, such as in the Tay/Forth area, west of the Hebrides, and some other local inshore areas. In the offshore waters around Scotland, stratification will end later in the year, by possibly as much as 10 to 15 days. In inshore waters again there is quite a complex pattern in the projected changes, with some inshore waters possibly having earlier breakdown in stratification, by up to 5 days. Thus the length of the stratified period in offshore waters is generally 10-15 days longer than currently, with some local, inshore variation. Three NMPi data layers are presented; change in start date of stratification, change in end date of stratification; and change in total number of stratified days.

NMPi Data Layer - Change in start date of stratification (days), by 2085, compared to 1975, medium emissions scenario (Figure 24).
NMPi Data Layer - Change in total number of stratified (days), by 2085, compared to 1975, medium emissions scenario (Figure 25).

Introduction

Climate change in the seas around Scotland may can be considered in two different ways, one looking at what has happened to our seas in the past and comparing past conditions to those of the present day, principally using observations, and another describing possible future marine climates principally using computer models of the connected ocean-atmosphere system coupled with “best guesses” of how human society will develop in the future. The “Future Climate Change” NMPi data layers focus on the second view of climate change in our seas.

The latest set (as at the publication of this report in 2017) of UK government climate change projections for the seas around the UK were published in 2009, and referred to as the UKCP09 projections. The projections and the models and data used to derive them are described in this report, along with all relevant supporting calculations, references and figures.

Here we go through different marine climate parameters and describe the principal possible features of Scottish seas in the future based on the best currently available science.

Weather above the sea, and conditions below the sea are treated differently in UKCP09. For atmospheric weather conditions, the UKCP09 team used multiple types of model, and three different scenarios of the future (high, medium and low greenhouse gas emissions) in order to show us the range of possibilities there were, given today’s best science.

For conditions under the sea, the team felt that the scientific understanding was not advanced enough to give estimates of uncertainty, and hence just one model and one future scenario (medium emissions) were used.

For sea level, storm surges and waves, the team used a middle ground approach between these two different methods in order to give some feel of potential worst case.

A variety of time baselines are used in the climate change future projections. Unfortunately, this is how the source information was published, and this cannot be rectified in this report. Users can convert changes over the period published here to relative change per year, or per decade, and then estimate the size of changes for any specific year of their interest.

Marine Weather

Weather above the surface of the sea, principally wind but also sunshine (and hence cloudiness) and rainfall (both over the sea, and over land which comes to the sea as runoff from rivers) affect conditions in the sea. Wind drives waves, currents and mixing in the sea. Storms in particular have significant impacts, not only through the effects of local wind and rain, but also in the far distance through storm surges and ocean swell. Hence we need to understand the potential changes in maritime weather as well as in conditions under the water.

Marine Weather – Storms

In a previous set of UK government climate change projections (UKCIP02) there was a headline statement that winter storminess over the UK was set to increase, although this statement was flagged as low in confidence[1].

The UKCP09 projections come to a different conclusion concerning UK storminess[1]. They found no clear consistent evidence of an increase in the frequency or intensity of storms. Different models, and different emissions scenarios, resulted in subtle positional shifts in the tracks of storms over the UK, but there was no discernible pattern to these.

NMPi Data Layers - Storminess

Currently there is no clear understanding of the future of storminess (i.e. storm intensity and frequency) over Scottish seas. UKCP09 makes no projections as to whether storminess will increase or decrease in the future. Different models predict different outcomes. Hence there is no NMPi Data Layer on Storminess.

Before leaving the subject of storminess, it is worthwhile to consider current observations rather than future projections. The winter of 2013/2014 was characterised by intense winter storms, causing coastal damage in the UK and Scotland. The UK Met Office assessment of these storms[2] concluded that for the period 1871 to 2010 there has been an increase in the number, duration and intensity of winter storms passing over the northern North Atlantic[3], including at our latitude, but for the southern UK the results are not so certain and are characterised by much natural variability. Current climate models cannot say for certain whether the observed changes are driven by man-made global warming or by natural variability. Intense research is underway globally to try to determine this. This research will hopefully allow more confident projections of future change in storminess over Scotland.

Marine Weather - Wind

While storms influence extreme winds, wind strength and direction throughout the year are important for our seas, driving part of the circulation and resulting in waves and mixing in the sea.

For all three emissions scenarios (low, medium and high) and for all coastal areas of Scotland, including the islands, the central estimate (50% probability) is that summer wind speeds will slightly decrease by the 2080s, by up to about 0.5 mph. The models suggest that it will be very unlikely the decrease will be more than 1 mph, and there is a small possibility that winds will actually increase, but not by more than 0.5 mph. These are very small changes, remembering how naturally variable the winds are, and that average summer winds are about 8 to 16 mph[4].

For winter winds there is some difference between emissions scenarios, and across Scotland, but in general the central estimate is for winds by the 2080s to have decreased by up to 0.2 mph, with it being very unlikely the decrease will be as much as 1 mph, and there is a small possibility winds will increase, but no more than by 1 mph. Again, these are very small changes, remembering how naturally variable the winds are, and that average winter winds[4] are about 10 to 16 mph.

NMPi Data Layers - Winds

The models used in the UKCP09 project suggested that by 2080 there may be a slight decrease in winds over Scottish seas, by about 3%. There are small chances that this decrease could be double, or winds could increase by about 3%.

These changes are small compared to natural variability, and regional differences across Scottish seas are not clearly evident, hence no NMPi Data Layer is presented for wind.

Marine Weather – Rainfall

Changes in rainfall (or more correctly precipitation) are most meaningful over land, as this impacts river runoff into coastal seas. Freshwater entering coastal waters can affect the density of those waters, thereby influencing circulation and mixing, especially in enclosed water bodies such as sea lochs, estuaries or Firths. Freshwater inputs can also introduce nutrients, sediment, urban waste water and contaminants from the land. Hence it is important to consider likely changes in rainfall, and indirectly river runoff into coastal waters.

The central estimate projections for the 2080s, using the medium emissions scenario as the most likely outcome of climate change, indicates that over Scotland summers will become up to 20% drier, and winters 20% wetter[5]. Overall, the central estimate is for the annual average rainfall to be about 10% less in the 2080s. There are some potential regional difference, hence NMPi data layers for rainfall (precipitation) are presented.

NMPi Data Layers – Rainfall (Precipitation)

NMPi Data Layers are presented for % precipitation change over land across the UK, 2080s compared to 1970s. Hence units are % change over the 110 year period 1975 to 2085 (approximately). A medium emissions scenario has been used to derive the estimates along with a central estimate of probability (50%).

Three layers are presented:

Figure 1 – Percent change in annual mean precipitation, 50% probability level.

Figure 2 – Percent change in summer precipitation, 50% probability level.

Figure 3 – Percent change in winter precipitation, 50% probability level.

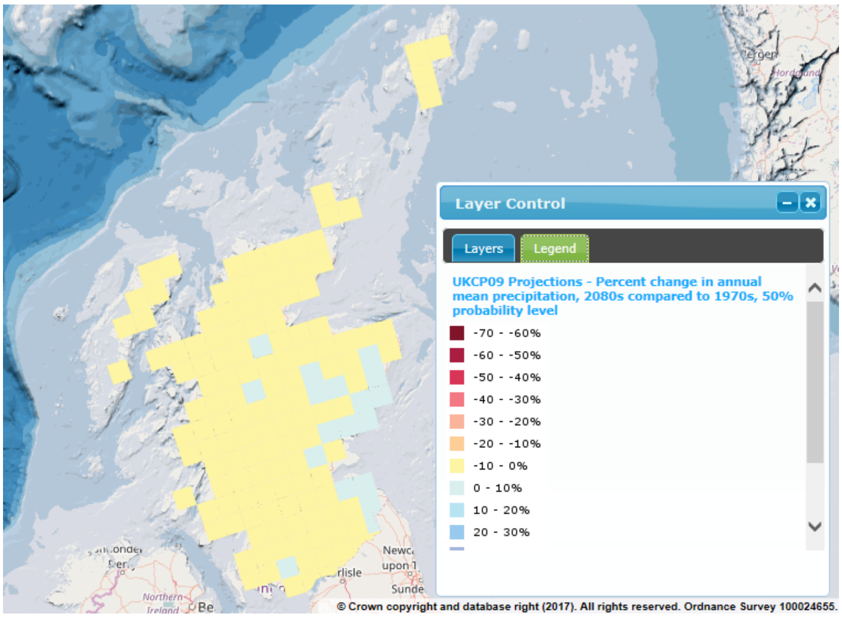


Figure 1: Percent change in annual mean precipitation, 2080s compared to 1970s, 50% probability level MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi]).

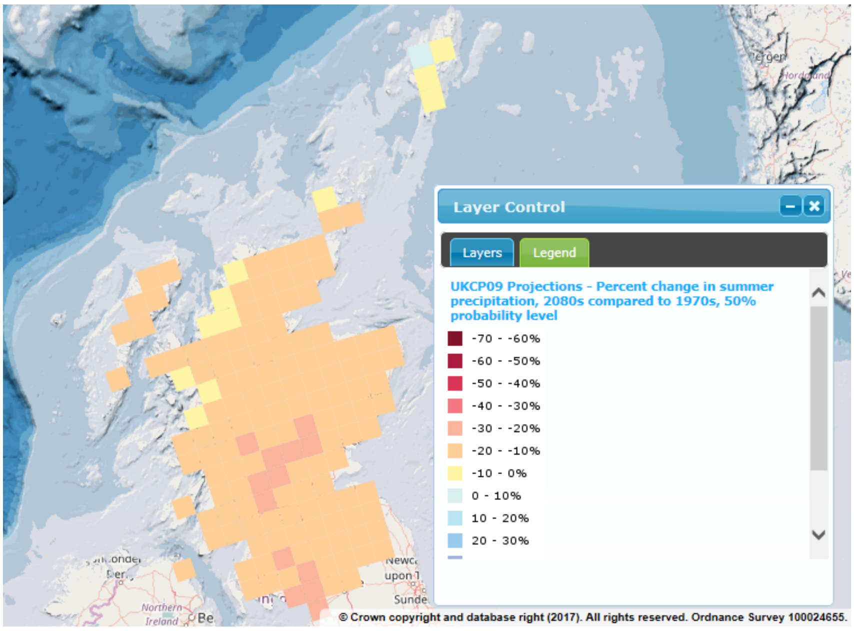


Figure 2: Percent change in summer precipitation, 2080s compared to 1970s, 50% probability level (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi).

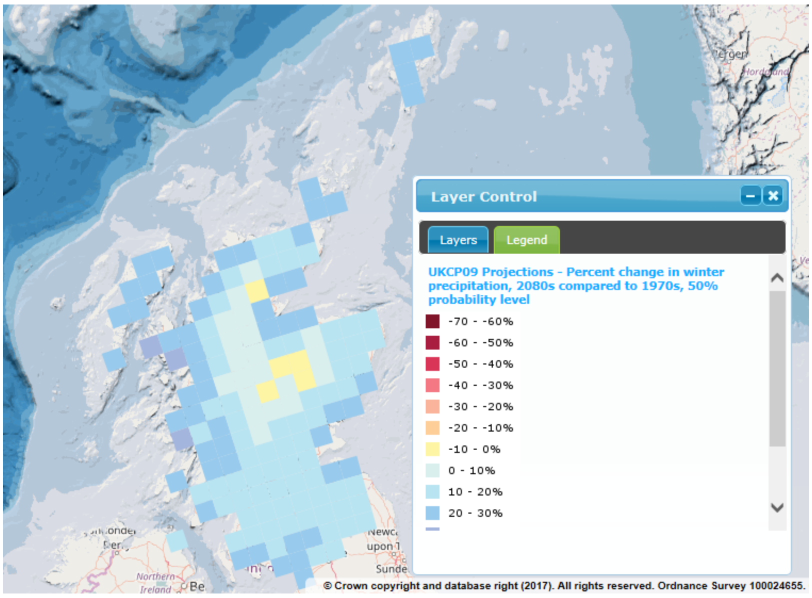


Figure 3: Percent change in winter precipitation, 2080s compared to 1970s, 50% probability level (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi).

Marine Weather – Air Temperature

Air temperature, as opposed to water temperature, has little direct relevance to marine studies. However, it may be of relevance to certain marine operations, and hence to planners, and so air temperature has been included as NMPi data layers.

For winter air temperatures, for the medium emissions scenario, the central estimate (50% probability) is for air temperatures to increase by between 1.1 and 2.4ºC by the 2080s[5]. Increases are projected to be greater on the east coast than on the west coast. Increases are very unlikely to be greater than 4ºC, but also very unlikely to be less than 0.5 ºC.

Very similar values are projected for summer air temperature increases. As there is some regional differences in the projections, NMPi data layers are presented for air temperature.

NMPi Data Layers – Air Temperature

NMPi Data Layers are presented for air temperature change over sea and land across the UK, 2080s compared to 1970s. Hence units are ºC change over the 110 year period 1975 to 2085 (approximately). A medium emissions scenario has been used to derive the estimates, along with a central estimate of probability.

Two layers are presented:

Figure 4 – Increase (°C) in summer air temperature, 50% probability level.
Figure 5 – Increase (°C) in winter air temperature, 50% probability level.

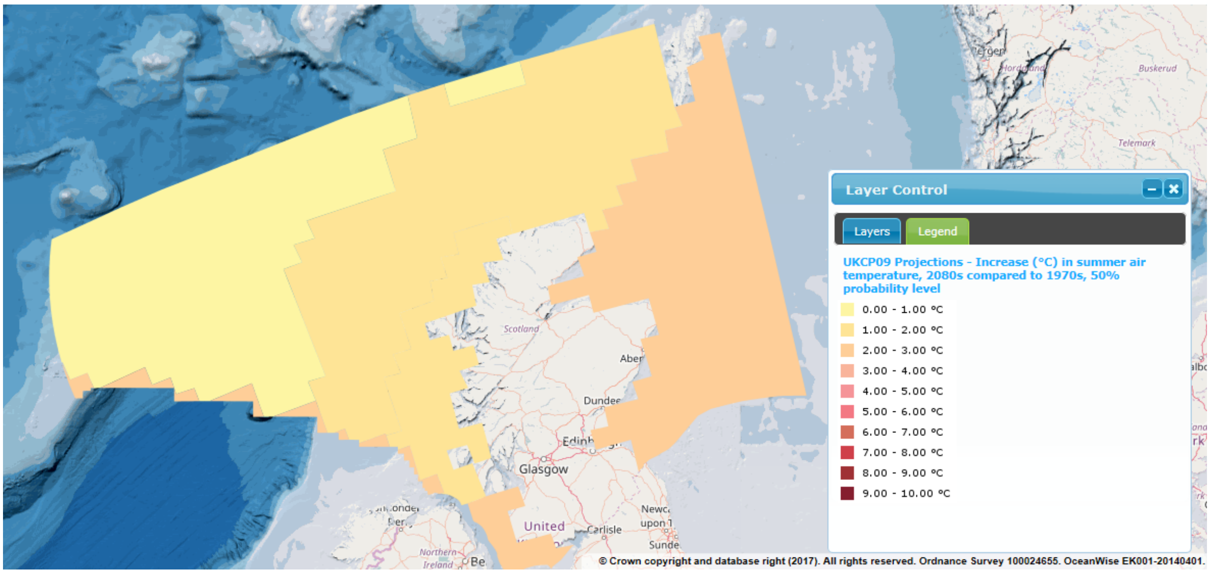


Figure 4: Increase (°C) in summer air temperature, 2080s compared to 1970s, 50% probability level (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi).

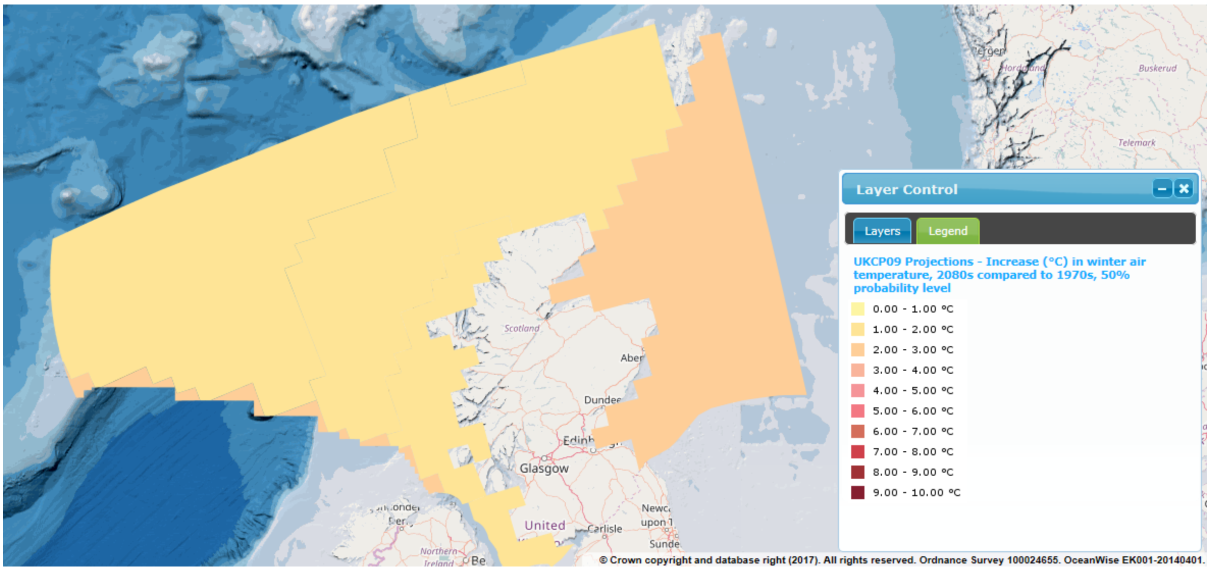


Figure 5: Increase (°C) in winter air temperature, 2080s compared to 1970s, 50% probability level (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi).

Sea Level

Currently it is estimated that the average sea level around the UK has risen at a rate of about 1 mm per year over the past century[5] (if this rate of increase carried on to the year 2095, sea level around the UK will increase by about 86 cm).

Predicting what the future of sea level rise will be is obviously of the utmost importance for coastal communities and for coastal planners. For this purpose, the figure we are most interested in is not the absolute rise of sea level, but the rise of sea level relative to the land, as the land itself is slowly moving vertically.

In the UK, the vertical movement of the land is primarily the result of the last ice age. The weight of ice pressed parts of the UK, particularly Scotland, down into the underlying molten earth, and now it is slowly coming back up. In response, other parts of the UK are sinking downwards, and this is particularly true in the south of the country.

In the sea, sea level rise is due to the expansion of sea water as it becomes warmer, as well as increases in sea level due to the addition of water from melting ice sheets and glaciers. Regionally, relative sea level rise can alter owing to local oceanographic effects, as well as the regional pattern of land movement.

Relative Sea level Rise - Worst Case Scenario

To help contingency planning in the UK, a prediction has been given of a "low probability, high impact" relative sea level rise, i.e. a "worst case" scenario. This prediction does not have any regional variation, and hence is not presented in the form of an NMPi Data Layer. It states that the sea level around our coast will rise by between 93 cm and 190 cm by 2095. These levels depend on worst case ice melting around the globe.

Relative Sea Level Rise – Regional Variation

To give perhaps more realistic pictures of possible relative sea level rise, an NMPi Data Layer is presented for the medium emissions scenario.

For this scenario, the least predicted rise in relative sea level occurs in the Clyde to Skye coastal waters, as well as the inner Firth of Forth and Moray Firth, with predicted rises of about 30 cm by 2095. The remainder of the mainland Scottish coast experiences approximately 35 cm rise over the same period, while the

Hebrides and Orkney experience a rise of 40 cm. The greatest predicted relative sea level rise by 2095 occurs in Shetland, with a rise of about 50 cm by 2095.

NMPi Data Layers – Relative Sea Level

An NMPi Data Layer is presented for relative sea level change, 2090s compared to 1980s. Hence units are cm change over the 110 year period 1985 to 2095 (approximately). Three emissions scenarios are used to derive the estimates; low, medium and high. However, here just the medium emissions scenario is presented.

One layer is presented:

Figure 6 – Rise in relative sea level (cm), medium emissions scenario, central estimate.

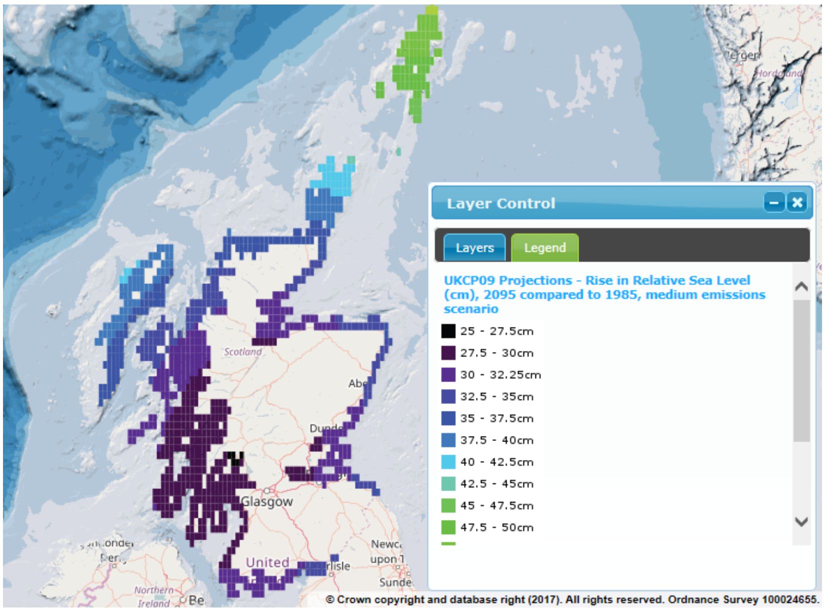


Figure 6: Rise in Relative Sea Level (cm), 2095 compared to 1985, medium emissions scenario (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi).

Storm Surges, Extreme Water Levels and Waves

When considering coastal flooding, as well as coastal and offshore engineering projects, a question often asked is what will be the highest possible level the sea will reach at a particular location? This question is most often phrased as, what is the highest possible water level that will be experienced at this location in a 10 year period? Or a 20 year period, or a 50 year period. The longer the period, we might expect a more extreme water level, as over that period a more extreme event is likely to happen. Hence this section considers the future projections of extreme water levels.

To consider coastal flooding at a point in the future, we should consider the effect of tide and of the rise in relative sea level. Tidal ranges will not change with climate change, and so we can add the height of the highest high tide to the predicted increase in relative sea level, to give us an idea of maximum sea flood levels in any future year.

Storm Surges

However, one more term needs to be added – that of the predicted maximum height of storm surges. Storm surges are, as their name suggests, temporary increases in sea levels caused by the passage of high winds over Scotland. A high tide which coincides with the passage of a storm surge is the most common cause of coastal flooding.

As described above, the current estimates of future climates do not suggest storminess will increase significantly over Scotland. Hence the predictions of increases in storm surge heights over the next 100 years is small. For most of Scotland the increases in extreme storm surges with return periods of 2, 10, 20 and 50 years are between about 1 and 3 cm by 2100. There is a little regional variation, and hence an NMPi Data Layer for the increase in storm surge height is presented.

NMPi Data Layers – Storm Surge Increase

An NMPi Data Layer is presented for the increase in the extreme additional water level due to storm surge in 2100 compared to 2000. One emissions scenario is used; the medium emissions scenario. The change presented is the increase in the 50-year return extreme surge height.

One layer is presented:

Figure 7 – Increase in extreme storm surge water level (cm) by 2100, compared to 2000, for the 50-year return surge, medium emissions scenario

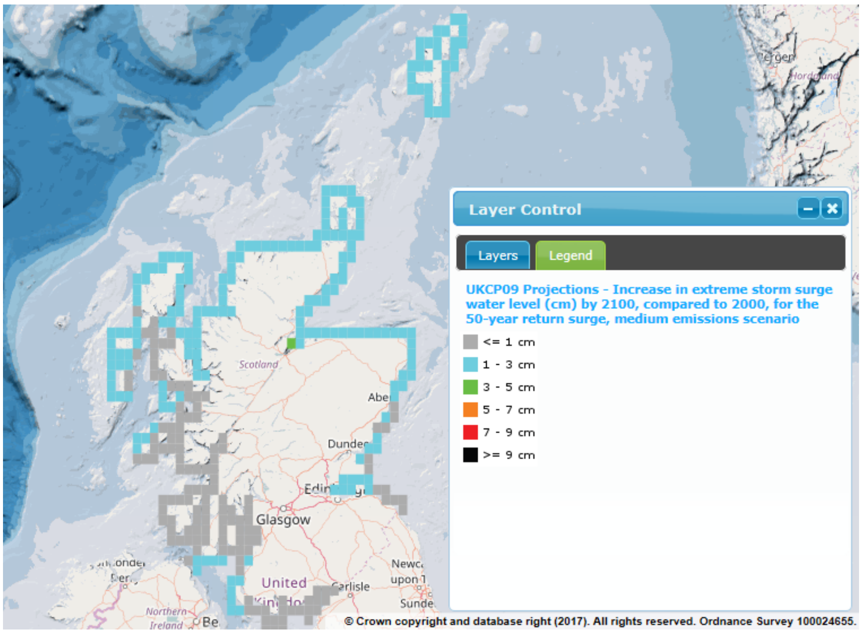


Figure 7: Increase in extreme storm surge water level (cm) by 2100, compared to 2000, for the 50-year return surge, medium emissions scenario (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi).

Extreme Water Levels

The change in storm surge height is now added to the change in relative sea level to give estimates of the change in extreme water levels. Extreme water levels are explained in terms of how high the sea surface may reach above the highest "astronomical" high tide. (Here "astronomical" means the tides produced by the interaction of the moon, sun and other planets, and hence entirely predictable and not affected by climate change).

Currently, the highest storm surge that may occur in a 50-year period raises the sea surface by between 90 and 180 cm. The effect is least on the east coast and in Shetland, and greatest on the west coast. The central estimate predicts that by 2095, these extreme water levels will have changed very little. However, the worst case projections suggest that the 50-year return extreme water levels will have risen to between 300 and 500 cm, again with the highest levels on the west coast, and lowest on the east. As there is some regional variation, NMPi data layers are presented for extreme water levels.

NMPi Data Layers – Extreme Water Levels

Three NMPi Data Layers are presented for extreme water levels. One presents the present day picture of how the highest astronomical tides are exceeded by storm surges in a 50-year return period. The second shows the same picture, but projected to 2095 using a central estimate of predicted changes of storm surge and relative sea level rise. The third gives the same picture as the second, but for the extreme worst case, assuming, for example, highest possible ice melt affecting relative sea level rise.

Three layers are presented:

Figure 8 – Extreme water level (cm) - Present day baseline - 50-year return extreme water level above the highest astronomical tide (due to storm surge).

Figure 9 – Extreme water level (cm) - 2095 projection - 50-year return extreme water level above the highest astronomical tide (due to storm surge + medium emissions relative sea level rise).

Figure 10 – Extreme water level (cm) - 2095 projection - 50-year return extreme water level above the highest astronomical tide (due to storm surge + worst case relative sea level rise).

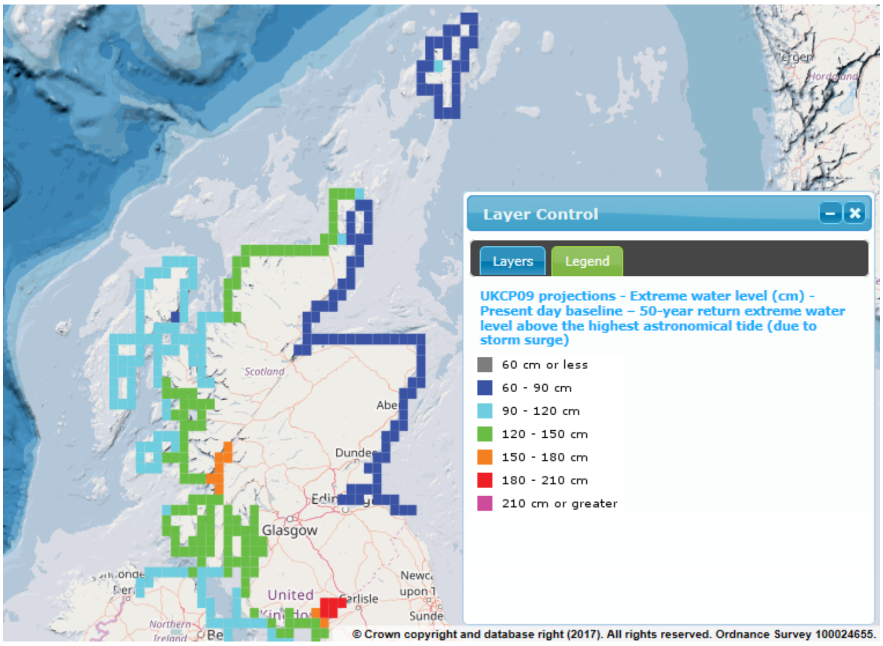


Figure 8: Extreme water level (cm) - Present day baseline – 50-year return extreme water level above the highest astronomical tide (due to storm surge) (MS MAPS NMPi link - [UKCP09 projections - Link to NMPi]).

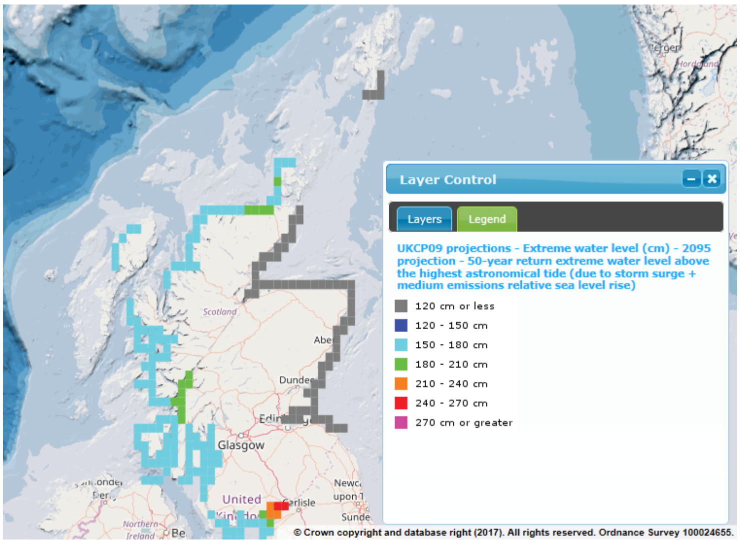


Figure 9: Extreme water level (cm) - 2095 projection - 50-year return extreme water level above the highest astronomical tide (due to storm surge + medium emissions relative sea level rise) (MS MAPS NMPi link - [UKCP09 projections - Link to NMPi](#)).

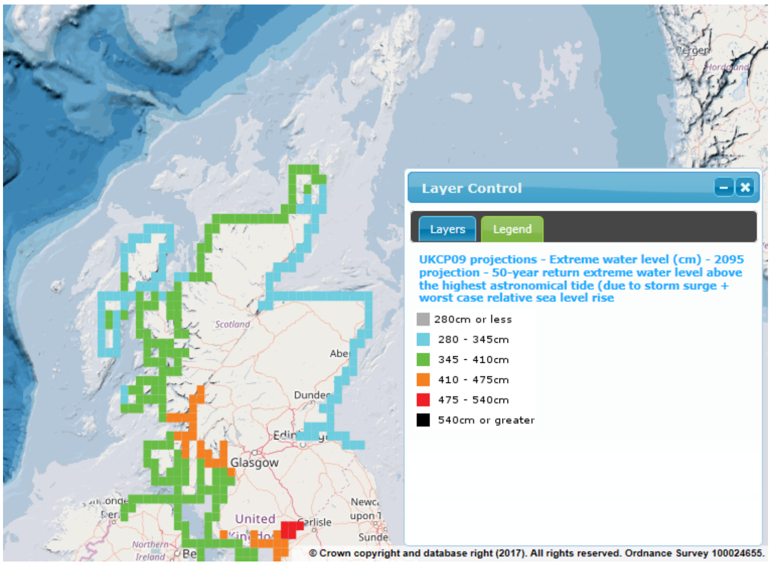


Figure 10: Extreme water level (cm) - 2095 projection - 50-year return extreme water level above the highest astronomical tide (due to storm surge + worst case relative sea level rise) (MS MAPS NMPi link - [UKCP09 projections - Link to NMPi](#)).

Waves

Waves on the surface of the sea, generated by the wind, are another feature marine users wish to know about. Waves can be useful when we consider the generation of renewable energy, or leisure activities such as surfing, or they can be destructive in terms of coastal erosion, damage to harbours and danger to shipping.

Climate change projections suggest that by 2085, significant wave heights north of Scotland will decrease by about 30cm in the winter while they will slightly increase around the southern UK. The other seasons have different patterns of change, although changes are quite small. Four NMPi data layers are given, each one showing a different season.

NMPi Data Layers – Waves

Four NMPi Data Layers are presented for waves, for the central year 2085 compared to the central year 1975. The medium emissions scenario is used.

Four layers are presented:

Figure 11 – Change (m) in significant wave height – winter.
Figure 12 – Change (m) in significant wave height – spring.
Figure 13 – Change (m) in significant wave height – summer.
Figure 14 – Change (m) in significant wave height – autumn.

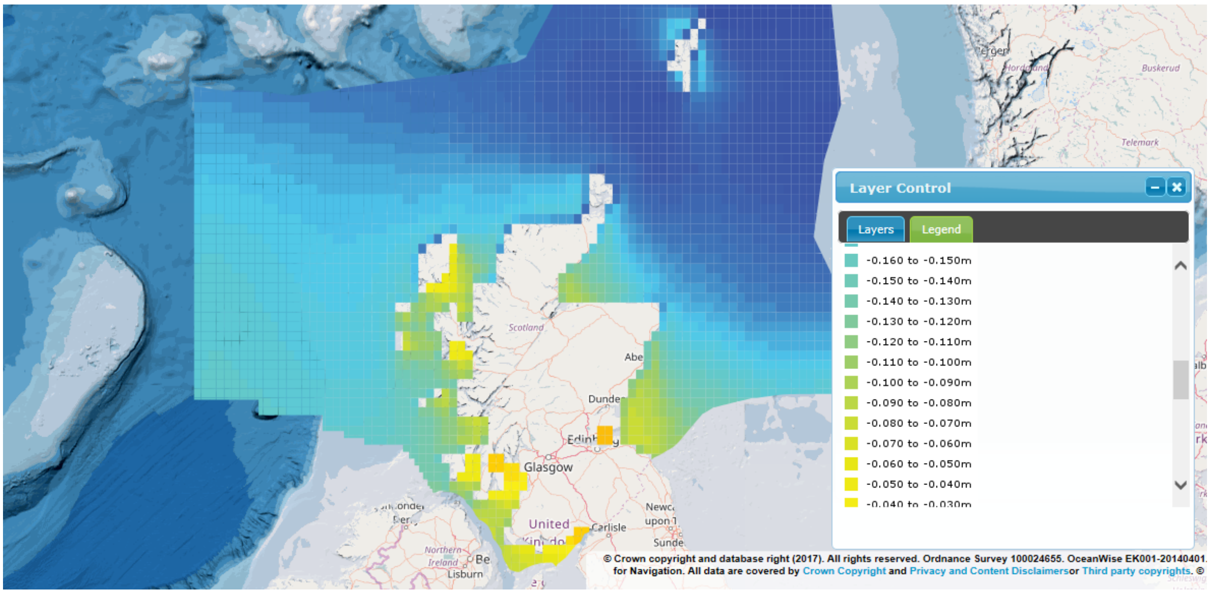


Figure 11: Change in significant wave height (m) by 2085, compared to 1975, medium emissions scenario – winter (MS MAPS NMPi link - [UKCP09 projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

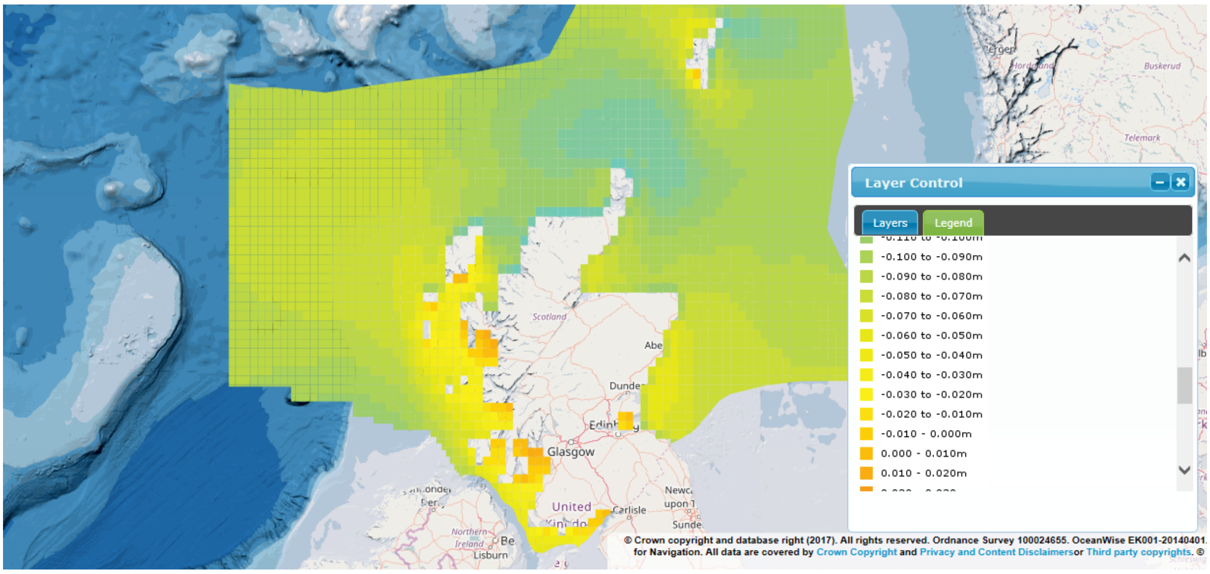


Figure 12: Change in significant wave height (m) by 2085, compared to 1975, medium emissions scenario – spring (MS MAPS NMPi link - [UKCP09 projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

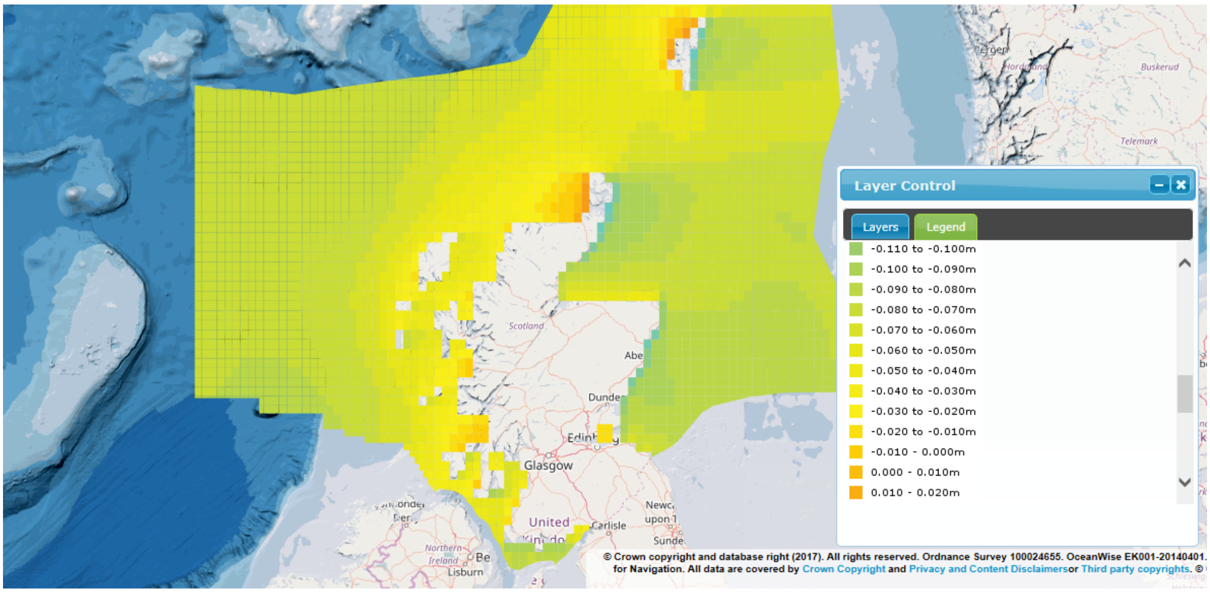


Figure 13: Change in significant wave height (m) by 2085, compared to 1975, medium emissions scenario – summer (MS MAPS NMPi link - [UKCP09 projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

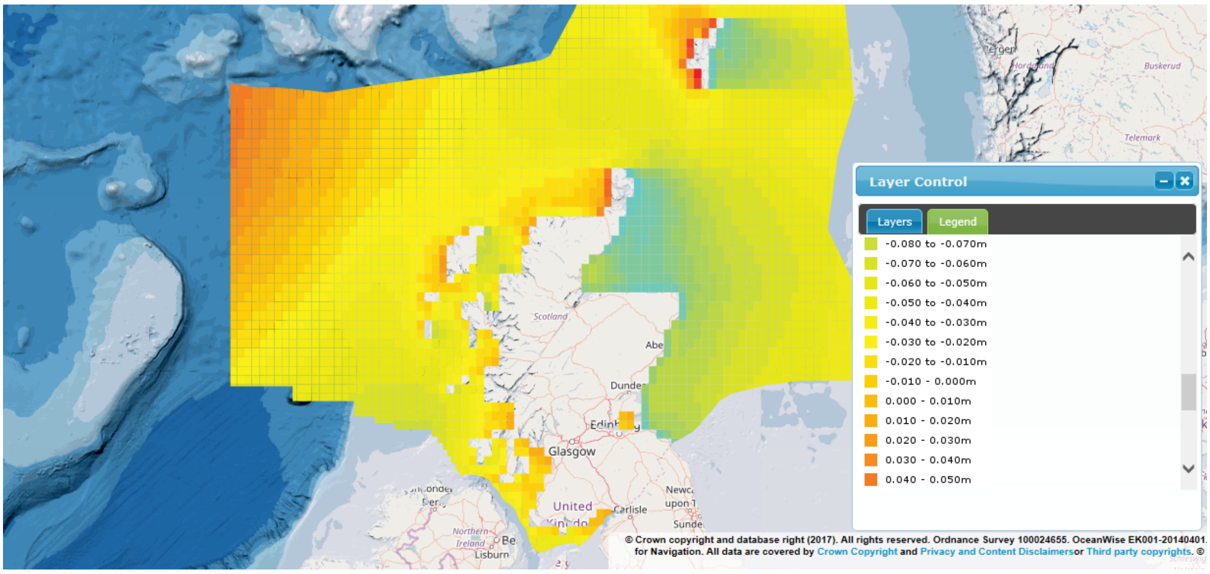


Figure 14: Change in significant wave height (m) by 2085, compared to 1975, medium emissions scenario – autumn (MS MAPS NMPi link – [UKCP09 projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

Hydrography and Circulation

As oceanographic modelling has not yet advanced as far as climate modelling, there are no estimates of uncertainty available for the projections of changes in the characteristics of the seas around Scotland. Projections are available, but they should be treated as tentative.

Hydrography - Temperature

By 2085, sea surface temperatures around Scotland are projected to be between 2 and 2.5ºC warmer. Further south around the UK sea surface temperatures may rise even more, up to 3.5 or 4ºC. An exception occurs in summer, when surface temperatures north and west of Scotland may be only 1ºC warmer. The autumn seems to be when most warming will be evident.

At the sea bed, warming is similar as at the surface, but only on the shallow continental shelf. In the deep waters surrounding Scotland, off the shelf, temperatures are projected to change very little.

As there is quite a lot of both regional and seasonal variation in temperature change, and as sea temperatures may be of importance to many users of the NMPi, eight NMPi data layers are presented, one for each of the four seasons, for surface and near-bed temperatures.

NMPi Data Layers – Temperature

Eight NMPi Data Layers are presented for sea temperatures. All use a medium emissions scenario. Change in temperature (ºC) from 1961-1990 (central year 1975) to 2070-2098 (central year 2085), i.e. over 110 years.

Figure 15 – Increase in sea surface temperature (ºC) – winter.
Figure 16 – Increase in sea surface temperature (ºC) – spring.
Figure 17 – Increase in sea surface temperature (ºC) – summer.
Figure 18 – Increase in sea surface temperature (ºC) – autumn.

Figure 19 – Increase in sea bed temperature (ºC) – winter.
Figure 20 – Increase in sea bed temperature (ºC) – spring.
Figure 21 – Increase in sea bed temperature (ºC) – summer.
Figure 22 – Increase in sea bed temperature (ºC) – autumn.

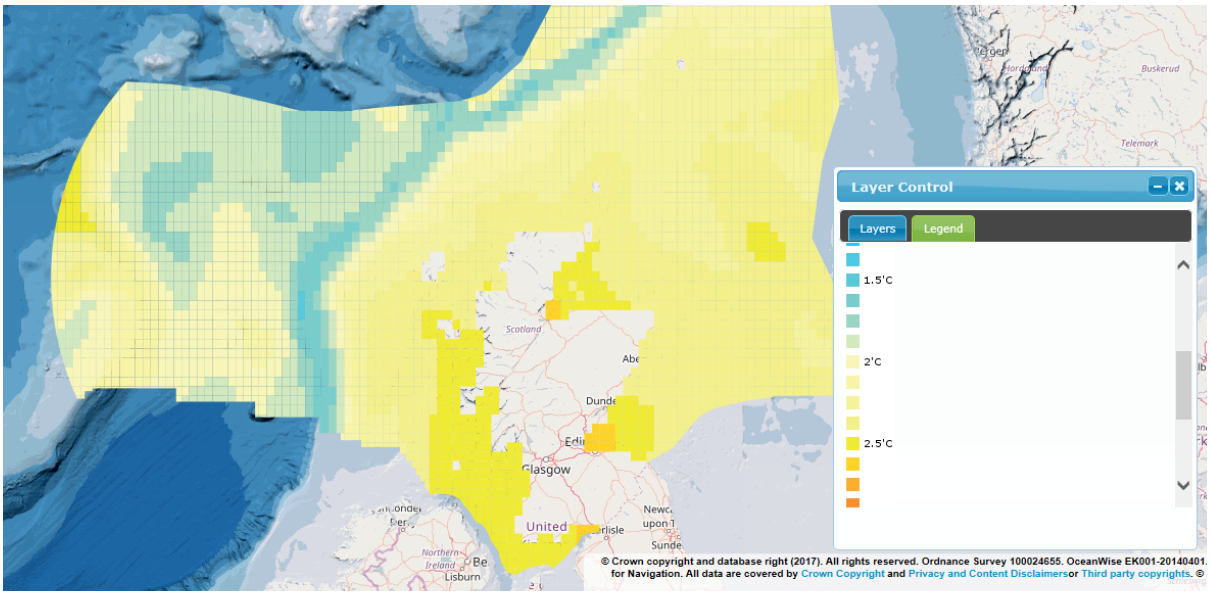


Figure 15: Increase in sea surface temperature (ºC) by 2085, compared to 1975, medium emissions scenario – winter (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)] Note: More scale colours available on the on line version).

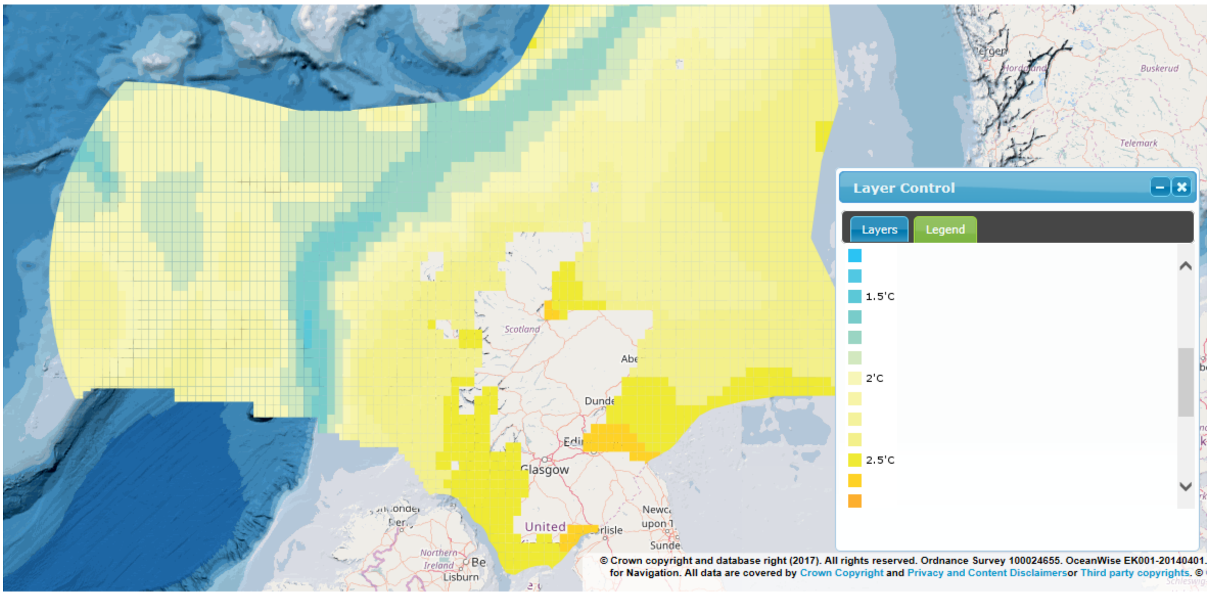


Figure 16: Change in sea surface temperature (ºC) by 2085, compared to 1975, medium emissions scenario – spring (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)] Note: More scale colours available on the on line version).

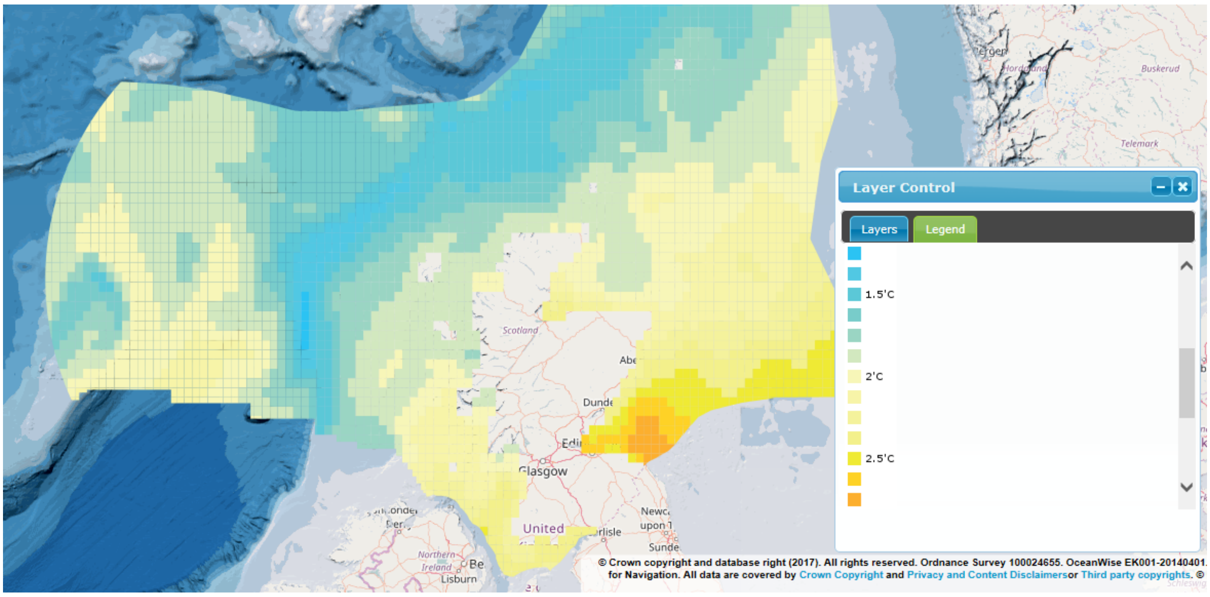


Figure 17: Change in sea surface temperature (ºC) by 2085, compared to 1975, medium emissions scenario – summer (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi] Note: More scale colours available on the on line version).

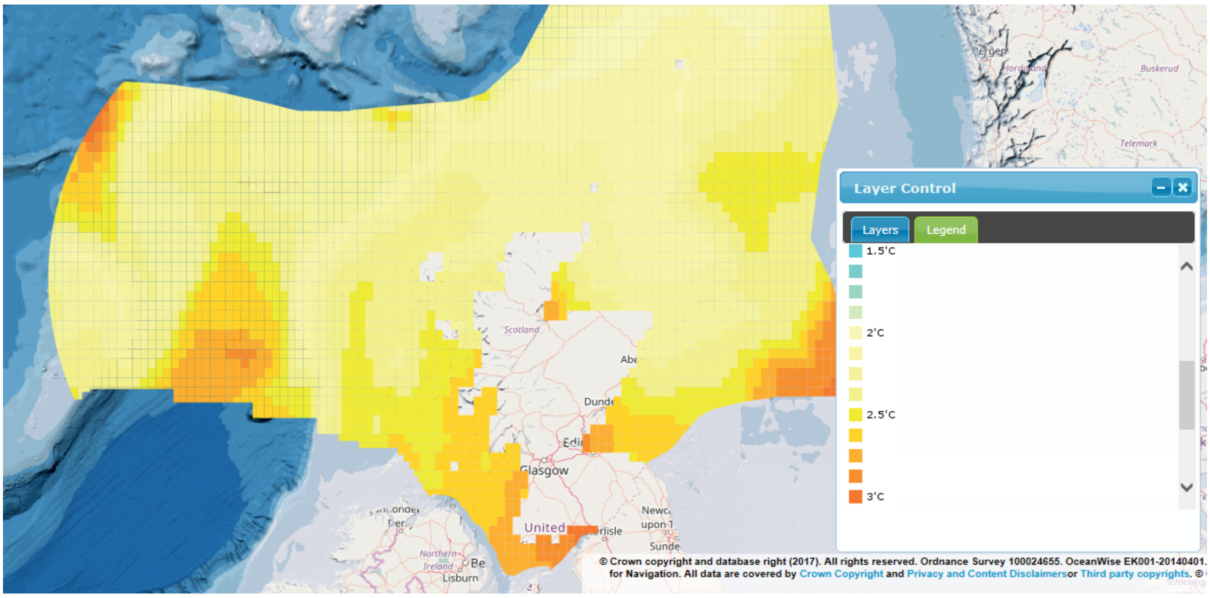


Figure 18: Change in sea surface temperature (ºC) by 2085, compared to 1975, medium emissions scenario – autumn (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)] Note: More scale colours available on the on line version).

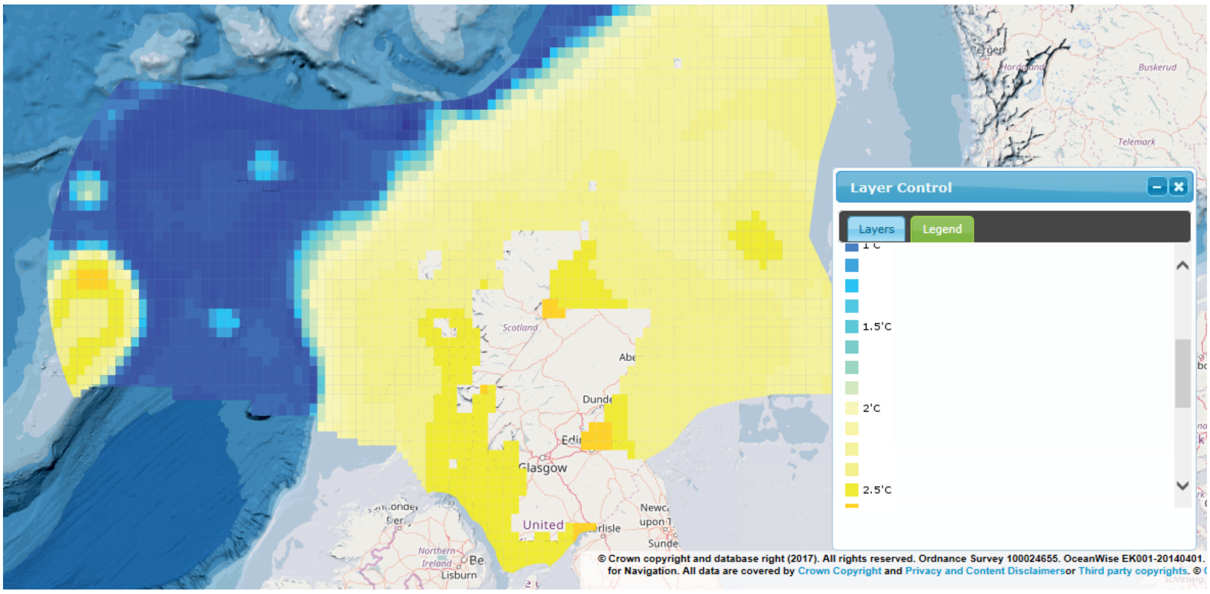


Figure 19: Change in near bed temperature (ºC) by 2085, compared to 1975, medium emissions scenario – winter (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

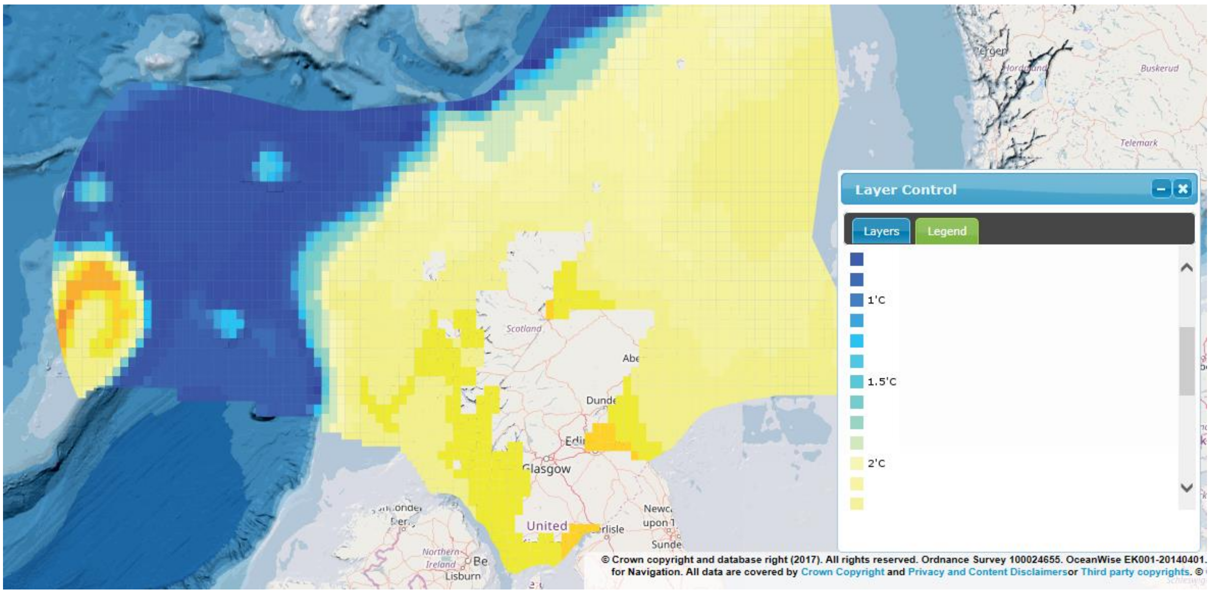


Figure 20: Change in near bed temperature (ºC) by 2085, compared to 1975, medium emissions scenario – spring (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

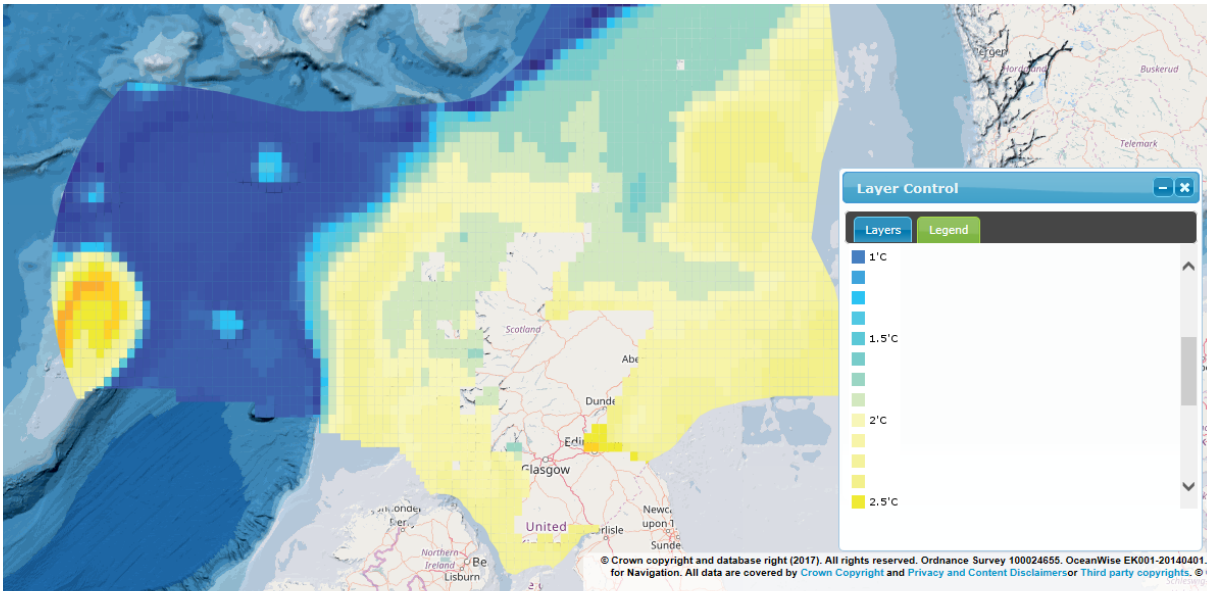


Figure 21: Change in near bed temperature (ºC) by 2085, compared to 1975, medium emissions scenario – summer (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)](UKCP09 Projections - Link to NMPi) Note: More scale colours available on the on line version).

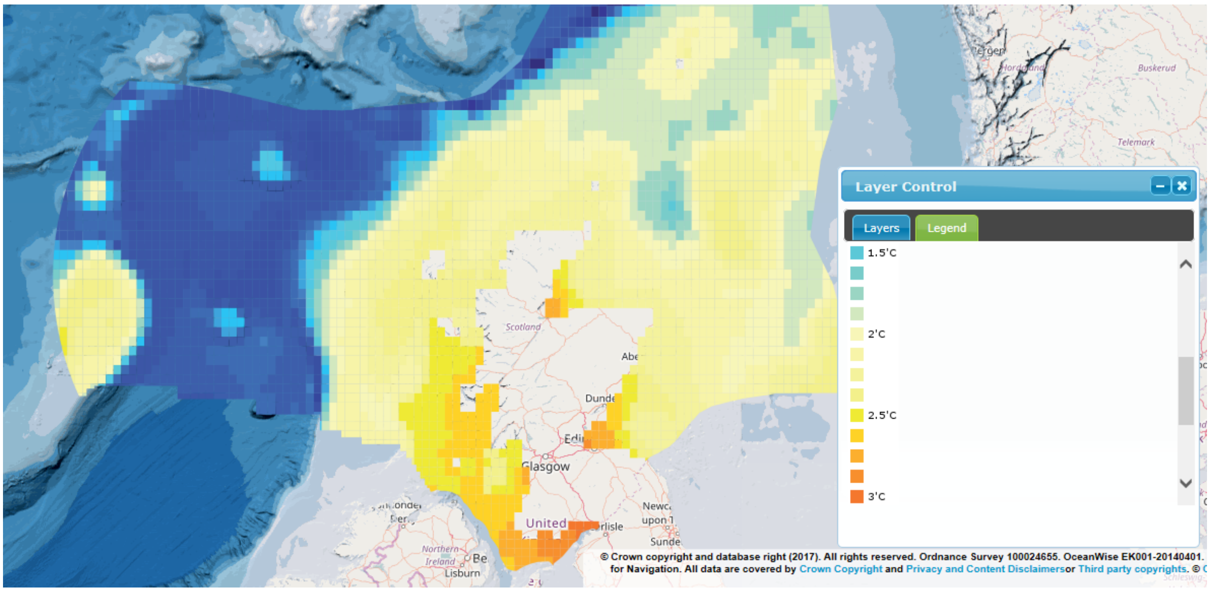


Figure 22: Change in near bed temperature (ºC) by 2085, compared to 1975, medium emissions scenario – autumn (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi) Note: More scale colours available on the on line version).

Hydrography - Salinity

Surface salinity is projected to decrease everywhere around Scotland, and in fact around the entire north east Atlantic, by about 0.2 salinity units by 2085. This decrease is mainly due to wide scale changes in the ocean rather than the local effect of rivers. As there is very little regional or seasonal variability in the change in surface salinity, only one NMPi data layer is presented, for winter surface salinity.

NMPi Data Layers – Salinity

One NMPi Data Layer is presented for salinity. Salinity change is in salinity units from 1961-1990 (central year 1975) to 2070-2098 (central year 2085), medium emissions scenario.

Figure 23 – Change in surface salinity (practical salinity units) by 2085, compared to 1975 – winter.

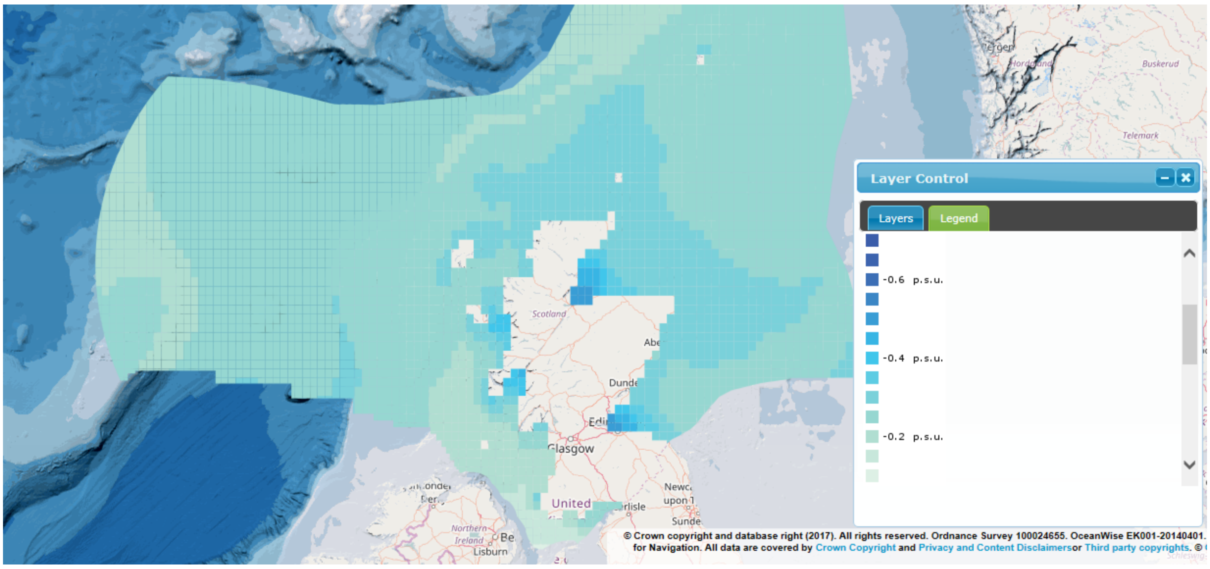


Figure 23: Change in surface salinity (practical salinity units) by 2085, compared to 1975, medium emissions scenario – winter (MS MAPS NMPi link - UKCP09 Projections - Link to NMPi) Note: More scale colours available on the on line version).

Hydrography - Stratification

In the winter, storms mix up the water on the continental shelf around Scotland so that there is very little difference between the sea surface and the sea bed in terms of the characteristics of the water. It is a constant mixture from surface to bed. However, as the winter winds reduce in strength in the spring, and the sun becomes stronger during the day and day length increases, so the surface waters become warmer, and hence lighter than the underlying water. Layering can start, with light, warm surface water lying on top of cold, heavy bottom water. This is called stratification. This layering has great importance to biological processes. If stratification occurs earlier or ends later in the year, then there is a longer “growing season” from the microscopic ocean plants called phytoplankton. This in turn can affect the food web which is dependent on this “primary production”. Hence stratification is an important aspect of the sea, and as it depends on the strength of the wind, the heating from the sun, cooling at the surface and also sometimes the run off of rivers, it will vary with future climate change.

It is projected that stratification will start earlier around Scotland by 2085, possibly by as much as 5 to 10 days. However, there are exceptions to this pattern, such as in the Tay/Forth area, west of the Hebrides, and some other local inshore areas. In the offshore waters around Scotland, stratification will end later in the year, by possibly as much as 10 to 15 days. In inshore waters again there is quite a complex pattern in the projected changes, with some inshore waters possibly having earlier breakdown in stratification, by up to 5 days. Thus the length of the stratified period in offshore waters is generally 10-15 days longer than currently, with some local, inshore variation. Two NMPi data layers are presented; change in start date of stratification, and change in total number of stratified days.

NMPi Data Layers – Stratification

Three NMPi Data Layers are presented for stratification. Change in days from 1961-1990 (central year 1975) to 2070-2098 (central year 2085), i.e. over 110 years. Negative days indicate the date moves earlier in the year. Medium emissions scenario used for both projections.

Figure 24 - Change in start date of stratification by 2085, compared to 1975.
Figure 25 - Change in total number of stratified days by 2085, compared to 1975.

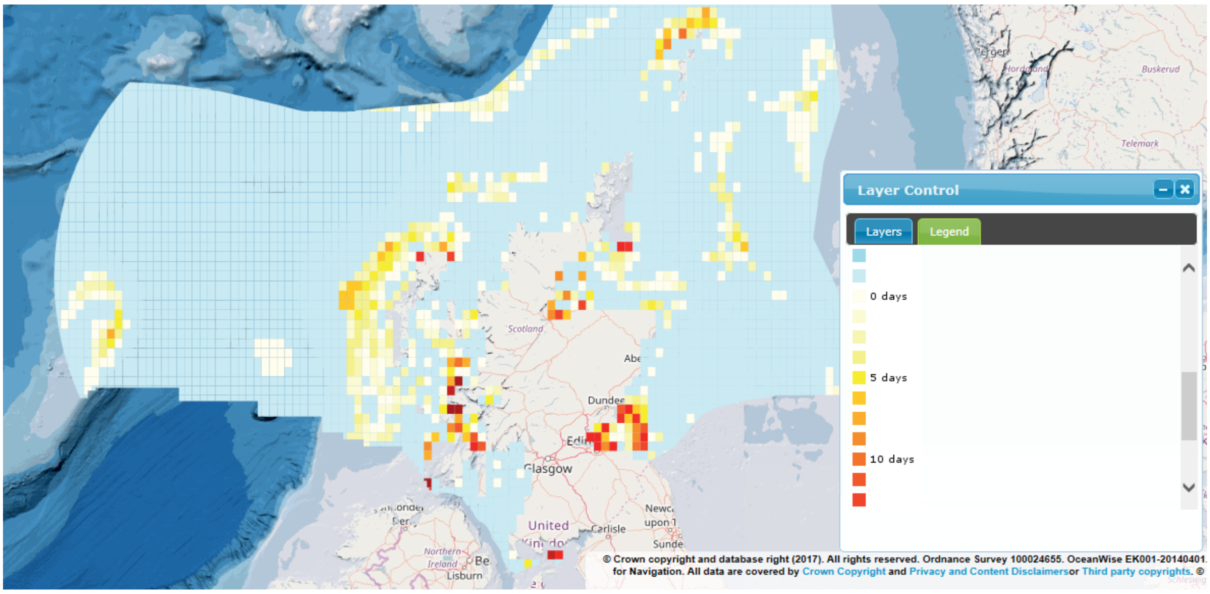


Figure 24: Change in start date of stratification (in days) by 2085, compared to 1975, medium emissions scenario. Negative days mean date moves earlier. (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)](#) Note: More scale colours available on the on line version).

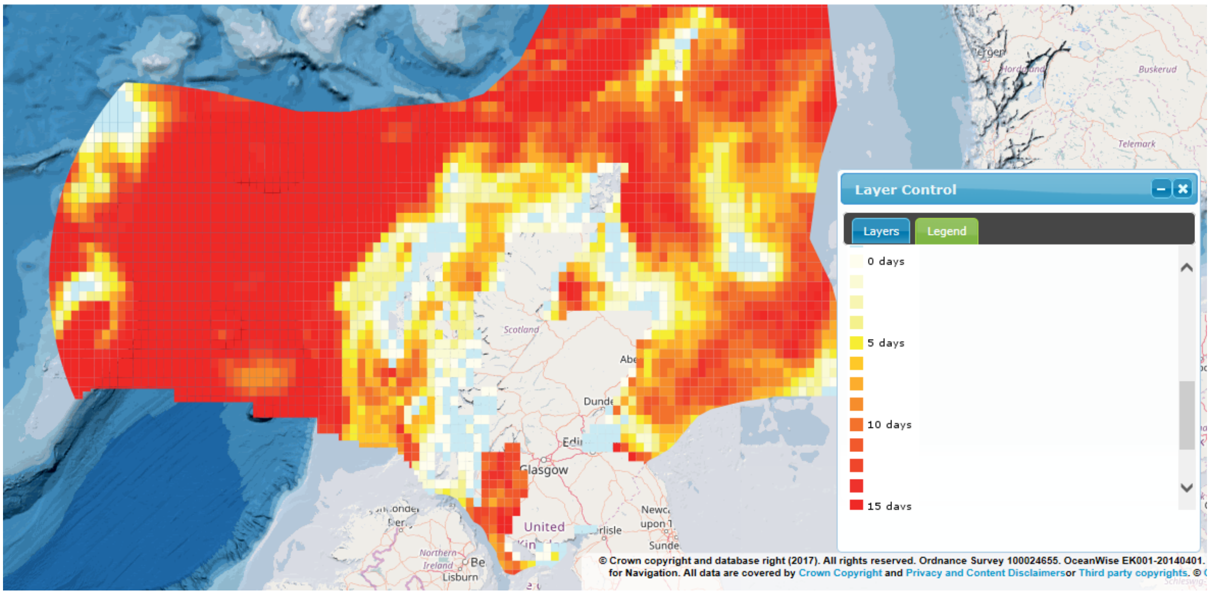


Figure 25: Change in number of days of stratification (in days) by 2085, compared to 1975, medium emissions scenario. Negative days mean date moves earlier. (MS MAPS NMPi link - [UKCP09 Projections - Link to NMPi)](UKCP09 Projections - Link to NMPi) Note: More scale colours available on the on line version).

Information Sources

1. UKCP09 Technical Note – UKCP09 Storm Projections
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87875&filetype=pdf

2. “The recent storms and floods in the UK”, UK Met Office, February 2014.
http://www.metoffice.gov.uk/media/pdf/n/i/Recent_Storms_Briefing_Final_07023.pdf

3. “Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of twentieth century reanalysis”. Wang, Xiaolan L; Feng, Y; Compo, G P; Swail, V R; Zwiers, F W; et al. Climate Dynamics; 40, 11-12 (Jun 2013): 2775-2800.

4. UKCP09: Probabilistic Projections of Wind Speed (David Sexton and James Murphy, UK Met Office)
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87845&filetype=pdf

5. Jenkins, G.J., Murphy, J.M., Sexton, D.M.H., Lowe, J.A., Jones, P. and Kilsby C.G. (2009). UK Climate Projections: Briefing report. Met Office Hadley Centre, Exeter, UK.
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87867&filetype=pdf

Annex - Technical Details

Introduction

Climate change in the seas around Scotland may can be considered in two different ways, one describing what has happened to our seas in the past and comparing past conditions to those of the present day, principally using observations, and another describing possible future marine climates principally using computer models of the connected ocean-atmosphere system coupled with "best guesses" of how human society will develop in the future. The "Future Climate Change" NMPi layers focus on the second view of climate change in our seas.

In order to visualise what the results of future climate change may look like in the seas around Scotland, it is necessary to use computer simulations of the physical processes that control conditions in the sea.

The UKCP09 Project

For the UK, a project which published its results in 2009 pulled together the best sources of information, and the best available models currently used in the UK, in order to present a "best estimate" set of climate change impact predictions that planners, government and the public could use.

This project, referred to as UKCP09[1], published summary reports describing climate change projections[2,3,4], assessments of observed trends[5], and on-line data describing projected changes[6] that includes the principle atmospheric weather parameters, as well as parameters describing different aspects of the seas around the UK. The UKCP09 project was part funded by the Scottish Government, and forms the basis of current governmental planning for future climate change scenarios.

Projected Changes in Weather - A Probabilistic Approach

When predicting changes in regional weather patterns, climate change modellers in UKCP09 used several different scenarios of how the world will develop in the future, each different scenario having a different level of greenhouse gas emissions (low, medium and high), and hence a different human impact on the climate. By using a variety of estimates of the future, and a variety of models (referred to as an ensemble), the UKCP09 project gave estimates of the range of possible outcomes for the weather. The estimates of variability, expressed as how probable projected changes may be, try to include estimates of natural variability as well as model imperfections.

Time Periods and Baselines

Probabilistic climate projections were given for seven overlapping 30-year periods. For example the "2080s" were characterised by projected data for the period 2070 to 2099. When regional scale projections are given, they are often on a grid with a resolution of 25km. "Change" is often calculated by reference to average conditions for the 30-year period 1961 to 1990, based on observations.

In order to relate the values of change given by the UKCP09 approach, to change in terms of units per year, we could take the central point of each of the time periods 2070 to 2099, and 1961 to 1990. These are (approximately and for convenience of calculation) 2085 and 1975. Hence the intervening time period is 110 years.

Projected Changes in the Sea – A Simple Approach

For marine projections, the UKCP09 team took a simpler approach than for atmospheric weather, and just used one emissions scenario (medium) and one model. This was because the science of ocean modelling is not yet as well developed as atmospheric modelling, and hence the team felt that the range of variability indicated by ocean models would not be useful.

There were two exceptions, and these were for predictions of sea level rise and predictions of storm surges. For these variables, because of their importance to planners and because the underlying physics is better understood, different climate change scenarios and different atmospheric models were considered in order to provide an estimate of the range of possible outcomes.

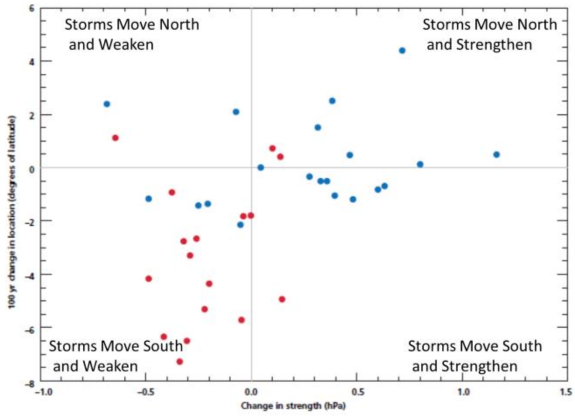
For more details concerning the methods and models used by UKCP09, refer to their web page[1].

For the rest of this report, we go though each type of parameter and discuss how the future projections were arrived at.

Marine Weather – Storminess

In order to assess future changes in storminess, UKCP09 used 17 variants of the principal Met Office model, and 20 similar climate models from around the world[2].

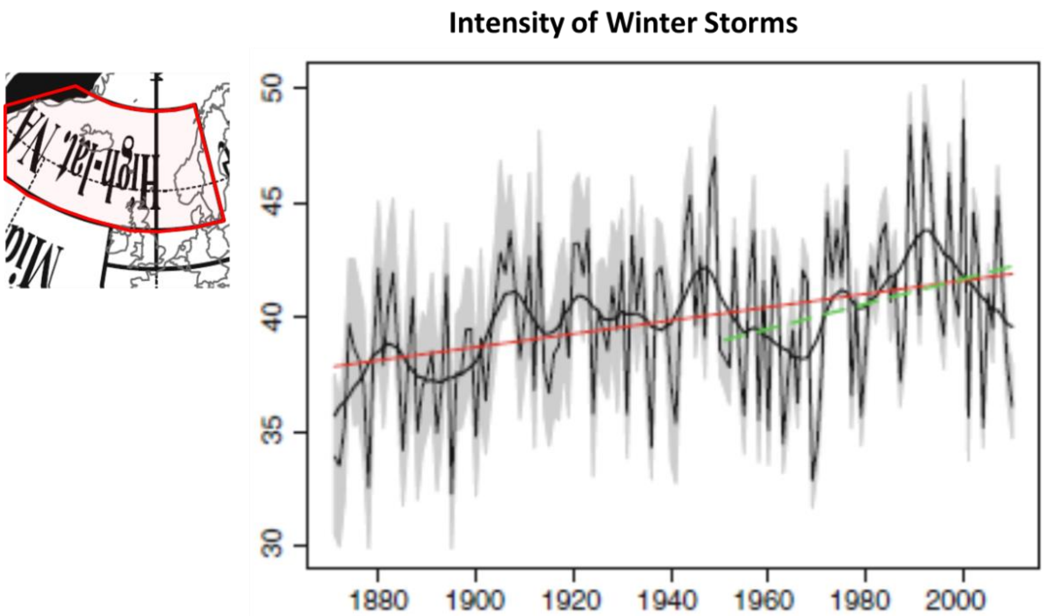
The figure below summarises the variation in what these models predicted for the 2080's, based on the medium emissions future scenario:



Change in strength (horizontal axis) and track in terms of latitude (vertical axis) of storms in the 2080's for 37 different models of future climate, all assuming the same medium-emissions scenario[2]. Red dots indicate the 17 variants of the Met Office model.

As can be seen from this figure, there was no consensus between the different models concerning what would happen to storminess over the UK. More research is needed in this area to improve the modelling.

From existing data sets, we can say that it looks as if storminess is currently increasing, at least in the northern North Atlantic within which Scotland lies. The figure below shows the intensity of winter storms estimated from climate models of the past[7], which also use observed conditions to improve their accuracy.



Intensity of winter storms over the High Latitude North Atlantic, 1871-2010[7]

However, we do not know if this trend is due to continue, nor whether it is caused by a natural process or man-made climate change.

In summary, for future projections of storminess in the UKCP09 project:

Marine Weather - Storminess	37 models (17 Met Office model variants, 20 other models) 1 emissions scenario (medium) Projections not probabilistic Projections for 2080s, compared to 1961-1990 baseline No trend discernible – hence no NMPi Data Layer

Marine Weather - Wind

Initially, owing to the uncertainties in predicting changes in wind strength, and the lack of wind data from some of the climate models used in the UKCP09 process, wind was not included as one of the projections in the UKCP09 project[2]. However, it was added as a supplementary study[8].

After some detailed analysis of how the different models performed, the following model projections are available for wind over the marine regions of Scotland:

Marine Weather - Wind	>20 models (11-17 Met Office model variants, 12 other models) 3 emissions scenarios (low, medium, high) Projections probabilistic Projections for 2050s, 2080s, compared to 1961-1990 baseline (110 year period 1975 to 2085) No regional differences across Scotland evident, hence no NMPi Data Layer Figure 5 from reference 8 is used to provide descriptive estimates of wind speed changes

Marine Weather – Rainfall (Precipitation) and Air Temperature

Rainfall and air temperature future projections were developed in the UKCP09 using the full set of Met Office model variants and 12 international models in order to encompass the uncertainties introduced by natural variability, model error and gaps in scientific understanding.

Marine Weather – Rainfall	Full UKCP09 probabilistic projections (multiple UK Met office model variants + 12 international models) 3 emissions scenarios (low, medium, high) Projections for 2080s, compared to 1961-1990 baseline (110 year period 1975 to 2085) NMPi Data Layers for rainfall (Figures 1 to 3) are derived from Figure 13 of reference 2, for 50% probability and medium emissions Probabilities at 10% and 90% are also available. High and low emissions scenarios also available. Units - % change in total precipitation over 110 year period 1975 to 2085

Marine Weather – Air Temperature	Full UKCP09 probabilistic projections (multiple UK Met office model variants + 12 international models) 3 emissions scenarios (low, medium, high) Projections for 2080s, compared to 1961-1990 baseline (110 year period 1975 to 2085) NMPi Data Layers for temperature (Figures 4 and 5) are derived from Figure 10 of reference 2, 50% probability and medium emissions. Probabilities at 10% and 90% are also available. High and low emissions scenarios also available. Units - ºC change over 110 year period 1975 to 2085

Relative Sea Level

Estimating future changes in *relative* sea level rise requires two sets of predictions[4]:

- the change in *absolute* sea level
- the change in land levels

Relative sea level change is then given by the addition of the absolute sea level rise, and the movement of the land.

Absolute global sea level rise has two principal causes; the thermal expansion of sea water as it gets warmer, and the effects of melting ice sheets, ice caps and glaciers. The global change is then modified regionally through more local responses of the ocean to warming and changes in circulation, for example.

The UKCP09 predictions of regional absolute sea level rise uses 11 different models in order to provide an estimate of possible uncertainty in the predictions. The models simulate the rise of sea level due to thermal expansion. A constant term is then added for the change in global absolute sea level due to ice melt.

A further complication in the UKCP09 predictions is that a different time frame is used for the presentation of sea level change. The baseline used is not the 1961-1990 one used for other climate parameters, but is 1980 to 1999. The predictions are given for several periods, but the one selected for the NMPi data layers is 2090-2099. Hence mid-period years are 1990 for the baseline and 2095 for the predictions, an intervening period of 105 years.

The *absolute* global sea level change, in cm, over the 105 year period (i.e. 2090-2099 compared to 1980-1999) is given in the table below:

	5th percentile	Central Estimate	95th percentile
High Emissions	15.4	45.6	75.8
Medium Emissions	13.1	36.9	60.7
Low Emissions	11.6	29.8	48.0

(Table 3.3, Reference 4)

Note that the figures given, i.e. cm rise in 105 years, are approximately the same as mm rise per year. Thus the central estimate, assuming medium emissions, is more than 30 times as great a rise rate as currently observed, i.e. 37 mm/year compared to 1 mm/year currently[2].

The next step in the process of deriving relative sea level change is to estimate the future movement of the land. This is done in UKCP09 using a combination of models and observations. The resulting map of movement of the land shows that much of Scotland is rising at a rate of approximately 1 mm/year, whereas England, Wales, southern Ireland, the outer Hebrides, and Orkney are sinking at about 0.5 mm/year. Shetland is sinking by about 1 mm/year (Figure 3.5, Reference 4).

Absolute Worst Case

UKCP09 provides users with an “absolute worst case” scenario for planning purposes. This worst case, described as a “low probability, high impact” scenario (the H^{++} scenario), for relative sea level has no regional pattern. One set of figures is given for the whole of the UK, and these are a minimum “worst case” relative sea level rise of 93 cm by 2095, and a maximum “worst case” relative sea level rise of 190 cm by 2095, compared to the baseline of 1990. These give rates of about 90 mm/year to 180 mm/year.

NMPi Data Layers

The NMPi data layer for relative sea level rise has been presented for low, medium and high emissions scenario, for the period 2090-2099, and the values of sea level rise are given in cm relative to the baseline of 1980-1991.

Relative Sea Level	11 international MME models of absolute sea level rise (no ice) IPCC estimate of ice-related sea level rise 1 model of land rise/fall (Bradley *et al.*, 2008 – reference 9) 3 emissions scenarios (low, medium, high) Projections for 2090-2099, compared to 1980-1991 baseline (110 year period 1985 to 2095) NMPi Data Layer (Figure 6) Relative Sea Level Rise from UKCP09 User Interface, medium emissions, central estimate 50th percentile. From Figure 3.7, reference 4. Units - cm change over 110 year period 1985 to 2095

Storm Surges and Extreme Water Levels

Extreme water levels are the sum of tide, storm surge and mean sea level. We need to project changes of all three into the future in order to estimate changes in extreme water levels. The UKCP09 project took several routes to do this:

Storm Surge Projections

UKCP09 used 11 different Met Office models, forced by the medium emissions scenario, to estimate future changes in storms over UK waters. They then coupled these models to the Proudman Oceanographic Laboratory's 12km storm surge model, which simulates both storm surges and tide around the UK. Thus the model includes interactions between tide and surge. Mean sea level rise was simply added linearly as experiments with the model showed little interaction between tide and surge and mean sea level.

The parameter used to quantify surge is the difference in sea water level from the predicted high tide, to the actual extreme water level, i.e. the height of the water level added on by the storm surge (as the most recent high tide is used, the technical term for this additional height is *skew surge*). A statistical model is used to determine frequency of extreme water levels at different locations, which obtains its information from a run of the coupled ocean-atmosphere models from 1951 to 2099. The projection selected for the NMPi Data Layer for storm surge is the mean trend in the 50-year return period surge height.

Storm Surge	Surge: 11 Met Office atmospheric models (PPE ensemble) 12km x 12km POLC3 tide and surge model Statistical model for return period analysis Medium emissions scenario Mean trend over a 149 year period (1951 – 2099) NMPi Data Layer (Figure 7) gives trend in 50-year return extreme level. From Figure 4.6, reference 4. Note this has to be added to change in relative sea level for absolute extreme heights. Units – in original source figure - mm change per year. However, for consistency this is changed in the NMPi Data Layer to cm in 100 years (1 mm/year = 10 cm/century). Hence Figure 7 units is change in cm by 2100 compared to 2000.

Extreme Water Level Projections

Two estimates of extreme water levels are presented from the UKCP09 projections. Extreme water level projections include changes in relative sea level and in storm surge heights. The extreme water levels are presented as the exceedance of present-day astronomical high tides by projected future extreme water 50-year return levels for the year 2095. Two scenarios are used; the medium emissions, central estimate; and the H++ "low probability, high impact" scenario (i.e. the worst case scenario). These two scenarios must be compared to the present day estimated 50-year exceedance of astronomical high tides.

Extreme Water Level – 2095 Projected 50-year Return Exceedance – Central Estimate	Surge: 11 Met Office atmospheric models (PPE ensemble) 12km x 12km POLC3 tide and surge model Statistical model for return period analysis Relative Sea Level: 11 international MME models of absolute sea level rise (no ice) IPCC estimate of ice-related sea level rise 1 model of land rise/fall (Bradley *et al.*, 2008 – reference 9) Medium emissions scenario NMPi Data Layer (Figure 9) gives 2095 values for 50-year return extreme water level. From Figure 4.9, reference 4, central estimate. Units – m exceedance above highest astronomical high tide.

Extreme Water Level – 2095 Projected 50-year Return Exceedance – Worst Case Scenario	Surge: Global MME atmospheric model worst case projections – downscaled to drive POLC3 model 12km x 12km POLC3 tide and surge model Statistical model for return period analysis Relative Sea Level: Upper value of H++ worst case scenario High emissions scenario NMPi Data Layer (Figure 10) gives 2095 values for 50-year return extreme water level. From Figure 4.11 (right panel), reference 4. Units – cm exceedance above highest astronomical high tide.

Waves

There are many ways of assessing waves. For example, we can consider their average height and their maximum height, and we can do this for all waves, or waves of a particular period or frequency, such as long-wave swell or short-wave "chop". The UKCP09 report[4] discusses several different aspects of waves around the UK. Here we have only used "significant wave height".

The UKCP09 report[4] discusses uncertainty in the projections of changes to waves around the UK, and also the degree of natural variability. On the whole, it is felt that the results presented in the NMPi data layers for waves are statistically significant. The NMPi data layer uses an atmospheric model with medium sensitivity. The results from a low sensitivity model, and a high sensitivity model are also presented in Reference 4. Although the distribution patterns of change do alter slightly, the general results described by the medium sensitivity model hold true.

Waves	3 Met Office atmospheric models (low, medium and high climate sensitivity). 3rd generation PROWAM wave model. 1 degree grid for whole Atlantic, and 12km grid for NW European shelf. Medium emissions scenario From Figure 5.8, reference 4 – medium sensitivity atmospheric forcing NMPi Data Layer (Figure 11) – change in significant wave height - winter NMPi Data Layer (Figure 12) – change in significant wave height - spring NMPi Data Layer (Figure 13) – change in significant wave height - summer NMPi Data Layer (Figure 14) – change in significant wave height - autumn Units – m change in significant wave height from 1960-1990 (central year 1975) to 2070-2100 (central year 2085), i.e. over 110 years.

Hydrography

The UKCP09 predictions emphasise that the projections of change in hydrography and circulation in the shelf seas around the UK are at an early stage of development, and are hence "tentative". No attempt is made to estimate uncertainty through using ensemble model runs, or by using different oceanographic models.

The UKCP09 projections provide estimates of many oceanographic variables (see section below). However, a small sub-set has been selected for presentation as NMPi data layers. The parameters selected are those that can be easily understood by a general user of the NMPi. Specialists should go directly to the UKCP09 web site for access to the full set of ocean parameters.

Hydrography	1 Met Office atmospheric model (RCM) Forced by mid-sensitivity unperturbed member of PPE Medium emissions scenario Atlantic Margin (AMM) application of POLCOMS oceanographic model, 12 km resolution, 34 layers 15 tidal constituents from North Atlantic tidal model River flows from CEH hydrological model *Temperature* Figure 6.4, reference 4 – RCM-F minus RCM-P NMPi Data Layer (Figure 15) – change in sea surface temperature -

	winter NMPi Data Layer (Figure 16) – change in sea surface temperature - spring NMPi Data Layer (Figure 17) – change in sea surface temperature - summer NMPi Data Layer (Figure 18) – change in sea surface temperature - autumn Figure 6.5, reference 4 - RCM-F minus RCM-P NMPi Data Layer (Figure 19) – change in near bed temperature - winter NMPi Data Layer (Figure 20) – change in near bed temperature - spring NMPi Data Layer (Figure 21) – change in near bed temperature - summer NMPi Data Layer (Figure 22) – change in near bed temperature - autumn Units – change in temperature ºC from 1961-1990 (central year 1975) to 2070-2098 (central year 2085), i.e. over 110 years. *Salinity* Figure 6.8, reference 4 - RCM-F minus RCM-P NMPi Data Layer (Figure 23) – change in surface salinity - winter Units – change in salinity units from 1961-1990 (central year 1975) to 2070-2098 (central year 2085), i.e. over 110 years. *Stratification* Figure 6.10, reference 4 - RCM-F minus RCM-P NMPi Data Layer (Figure 24) – change in start date of stratification NMPi Data Layer (Figure 25) – change in number of days of stratification Units – change in days from 1961-1990 (central year 1975) to 2070-2098 (central year 2085), i.e. over 110 years. Negative days indicate the date moves earlier in the year.

Marine Projections – Additional Available Variables

The following variables are available as data downloads from the UKCP09 website, from the “past and future multi-level ocean model simulations for UK waters”:

VARIABLE	Absolute Value			Climate Change Difference		
	S	B	F	S	B	F
Maximum daily mean sea water potential temperature	X	X		X	X	
Mean sea water potential temperature	X	X		X	X	
Minimum daily mean sea water potential temperature	X	X		X	X	
Standard deviation of mean sea water potential temperature	X	X		X	X	
Maximum daily mean salinity	X	X		X	X	
Mean salinity	X	X		X	X	
Minimum daily mean salinity	X	X		X	X	
Standard deviation of mean salinity	X	X		X	X	
Maximum daily mean total kinetic energy through water column			X			X
Mean total kinetic energy through water column			X			X
Minimum daily mean total kinetic energy through water column			X			X
Standard deviation of mean total kinetic energy through water column			X			X
Maximum daily mean mixed layer depth			X			X
Mean mixed layer depth			X			X
Minimum daily mean mixed layer depth			X			X
Standard deviation of mean mixed layer depth			X			X
Maximum daily mean potential energy anomaly per unit depth			X			X
Mean potential energy anomaly per unit depth			X			X
Minimum daily mean potential energy anomaly per unit depth			X			X
Standard deviation of mean potential energy anomaly per unit depth			X			X
Day of breakdown of seasonal stratification			X			X
Average number of seasonally stratified days			X			X
Day of onset of seasonal stratification			X			X
Day of peak seasonal stratification			X			X

(S=surface layer, B=near-bottom layer, F=a value only available for the full water column).

The future predictions are presented for the period of the 2080s (2070 to 2099).

The climate change difference values are given compared to baseline values calculated for the period December 1960 to November 1990.

Thus for the basic oceanographic variables, there are 64 possible data sets to examine.

Data is given for averages over different time periods. Annual averages are given, as are seasonal ones (Winter – DJF, Spring – MAM, Summer – JJA, Autumn – SON) and monthly averages. This means that for each data set, 17 different time-period averages are presented.

Thus there are 1088 possible data sets for the basic oceanographic properties.

Technical Details - Data Sources

1. The UKCP09 web site
http://ukclimateprojections.metoffice.gov.uk/

2. UKCP09 Briefing Report - Jenkins, G. J., Murphy, J. M., Sexton, D. M. H., Lowe, J. A., Jones, P. and Kilsby, C. G. (2009). UK Climate Projections: Briefing report. Met Office Hadley Centre, Exeter, UK.
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87868&filetype=pdf

3. UKCP09 Climate Projections – Summary Report
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87894&filetype=pdf

4. UKCP09 Marine and Coastal Projections - Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S. (2009), UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK.
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87906&filetype=pdf

5. UKCP09 The Climate of The UK and Recent Trends

http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87933&filetype=pdf
6. UKCP09 On-line User Interface
http://ukclimateprojections-ui.metoffice.gov.uk/ui/admin/login.php

7. “Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of twentieth century reanalysis”. Wang, Xiaolan L; Feng, Y; Compo, G P; Swail, V R; Zwiers, F W; et al. Climate Dynamics; 40, 11-12 (Jun 2013): 2775-2800.

8. UKCP09: Probabilistic Projections of Wind Speed (David Sexton and James Murphy, UK Met Office)
http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87845&filetype=pdf

9. Bradley *et al.*, 2008. Glacial isostatic adjustment of the British Isles: new constraints from GPS measurements of crustal motion. Geophysical Journal International, doi:10.1111/j.1365-246x.2008.04033.x..