

Climate change impacts on the waters around the UK and Ireland: Salinity

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EXECUTIVE SUMMARY

The salinity of the upper ocean (0-800 m) to the west and north of the UK (Region 8) has been generally increasing since a fresh period in the 1970s. A minimum occurred in the mid 1990s, and present day conditions are relatively saline. The decadal-scale pattern of change around the UK reflects the conditions of the North Atlantic.

West of the UK the water of the deep ocean (>1000 m) comes from the Labrador Sea and has freshened since 1975. North of the UK, the deep water (800 m) flows from the Nordic Seas; they have freshened since 1950 but salinity has been steady for the last decade.

In the northern North Sea (Region 1) the salinity is heavily influenced by inflowing North Atlantic water and has become more saline since the 1970s, though the trend is not clear. The salinity of the southern North Sea (Region 2) is dominated by river run-off balanced with flow through the Dover Strait and there is no clear trend since the 1970s.

The western English Channel (Region 4) is influenced by North Atlantic Water, tidal currents and local weather conditions. There is no discernible long-term trend in over a century of observations, but in recent years salinity has been higher than average.

Since the mid-1960s the salinity of the Irish Sea (Region 5) shows no significant long-term trend. The decadal pattern is different to the deep offshore water; maxima occurred in the late 1970s and late 1990s; present conditions are close to the long-term mean.

There is no clear trend in the shelf waters off the west coast of Scotland (Region 6); observed changes in salinity are due to an east-west migration of salinity gradients, with warm periods being associated with higher inshore salinities.

There is considerable uncertainty regarding future salinity. The projections currently available weakly suggest that the shelf seas and adjacent ocean may be slightly fresher (less saline) in the future than at present. On the shelf the oceanic influence will dominate the mean long-term salinity.

There remains uncertainty in quantifying large-scale, long-term changes in salinity as there are considerable uncertainties on the effects of climate-driven changes in precipitation, evaporation, ocean circulation and ice-melt.

1. WHAT IS ALREADY HAPPENING?

The evidence base

Observational evidence for long-term changes in salinity is relatively sparse. There are few long-term measurements of shelf or deep waters in the North Atlantic, though two of the

longest (Faroe - Shetland Channel since 1900, and Rockall Trough since 1948) are maintained by UK agencies. The Argo programme of profiling floats has been significantly increasing the data resource since the early 2000s and data collected from 'ferrybox' systems are providing additional information in surface waters around the UK.

Long term observations of salinity in the North Atlantic and Nordic Seas and for some NW European shelf sites are summarised by the Working Group on Oceanic Hydrography (www.ices.dk/community/groups/Pages/WGOH.aspx) annually in the International Council for the Exploration of the Seas (ICES) Report on Ocean Climate (IROC). Here we use the IROC (Dye *et al.*(eds.), 2012) that covers the period up to the end of 2011 and is hereafter referred to as IROC2011. Coastal and shelf sea monitoring stations are maintained around Scotland by Marine Scotland, Marine Laboratory Aberdeen and the Scottish Association for Marine Science, Oban. Other long-term observations are maintained by the Government Laboratory of the Isle of Man, the National Oceanography Centre, the Plymouth Marine Laboratory, Marine Biological Association, and Cefas. ICES coordinate an annual winter survey (IBTS – International Bottom Trawl Survey) which provides an annual snapshot of conditions over the whole of the North Sea.

Deep Ocean around the UK and Ireland (including Charting Progress Regions 7, 8, and Irish Atlantic)

The northern North Atlantic and Nordic Seas exhibit multi-decadal-scale variability in ocean salinity, with a maximum in the early 1960s and minimum in the mid-1990s (Peterson *et al.*, 2006, IROC2011). It is presently high in salinity. At each sampling site, the large-scale, long-term pattern has further levels of variability imposed upon them, relating to locally important processes such as changing positions of fronts, passing of eddies, river run-off, the changing inflow of different water masses, and the exchange of freshwater with the atmosphere. Sampling of salinity is often too sparse to accurately define the smaller scale influences.

The surface layer of the ocean (the top 100 m) is heavily influenced by changes in precipitation and evaporation (Josey and Marsh, 2005) and is therefore more variable than salinity below the surface layer. However, the salinity of the upper waters of the deep ocean around the UK is most strongly influenced by changes in ocean circulation, which in turn is affected by large-scale atmospheric conditions (Holliday, 2003; Hátún *et al.*, 2005; Hakkinen and Rhines, 2009). At present the relationship between changes in the hydrological cycle and ocean circulation, and the impact on regional and large-scale salinity is unclear.

The salinity of the upper ocean (0-800 m) to the west and north of the UK has been increasing since a fresh period (the Great Salinity Anomaly) in the 1970s (Figure 1). A further minimum occurred in the 1990s, and the present day conditions are the most saline since the late 1950s and have remained stable at this level since about 2003. The pattern reflects the changing balance of the inflow of subtropical (salty) versus subpolar (fresh) water into the area (Holliday, 2003). When more subtropical water is drawn into the waters around the UK, the upper ocean becomes warmer and more saline. The relative impact of variations in the salinity of subtropical water has not yet been quantified. Northward advection of the upper ocean waters mean that conditions in this region influence the Nordic Seas and ultimately the Arctic Ocean (Polyakov *et al.*, 2007; Holliday *et al.*, 2008).

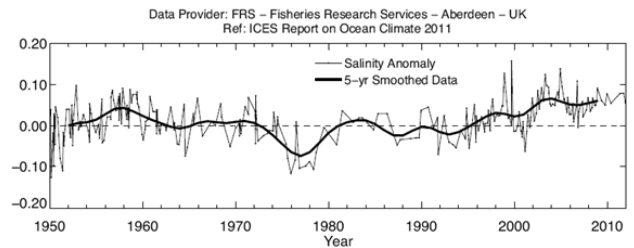


Figure 1a: Charting Progress Region 7 Faroe - Shetland Channel (61.00°N 3.00°W). Salinity anomaly (base period 1971-2000) of the Atlantic Water in the slope current in the Faroe Shetland Channel for the period 1950 to 2011. [Image sourced from IROC2011 Figure 52]

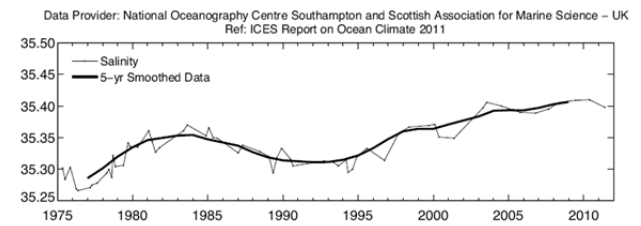


Figure 1b: Charting Progress Region 8 Rockall Trough (56.75 °N 11.00°W). Salinity of the upper ocean (0-800 m) for the period 1975 to 2011. [Image sourced from IROC2011 Figure 45]

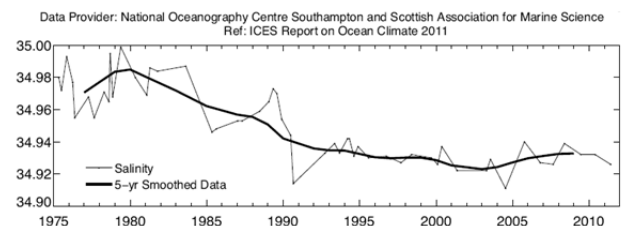


Figure 2a: Charting Progress Region 8 Rockall Trough (56.75 °N 11.00°W). Salinity in the Labrador Sea Water layer (1800 - 2000 m) for the period 1975 to 2011. [Image sourced from IROC2011 Figure 83]

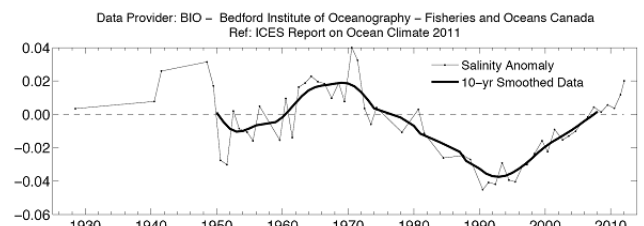


Figure 2b: Labrador Sea. Salinity anomaly in the Labrador Sea Water layer (1800 - 2000 m) for the period 1929 to 2011. [Image sourced from IROC2011 Figure 81]

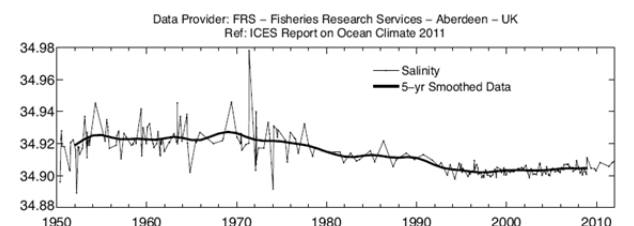


Figure 3: Charting Progress Region 7 Faroe - Shetland Channel. Salinity of overflow water at 800 m for the period 1950 to 2011. [Image sourced from IROC2011 Figure 78]

Surface conditions in a few key locations remote to the UK (e.g. Labrador Sea, Nordic Seas), where surface water sinks into the deep ocean, affect the salinity of UK deep waters (Dickson, *et al.*, 2002; Yashayaev *et al.*, 2007). Below 1000 m the deep ocean west of the UK and Ireland has become fresher since 1975 (Figure 2a), reflecting a lagged response to a period of freshening in the Labrador Sea where this deep water originates (Figure 2b). In the Rockall Trough this water mass appears to have reached its salinity minimum in 2003-2004 with a slight increase towards the end of the last decade (Figure 2a). This fits, but is too early to confirm, our expectation that the deep water west of the UK will respond to changes in the originating waters of the Labrador Sea that has become more saline since the late 1990s (Figure 2b). North of the UK, and separated from the main North Atlantic by the Greenland Scotland Ridge, deep waters (800 m) flow from the Nordic Seas. They overflow the ridge into the Atlantic via the Wyville Thomson Ridge and Faroe Bank Channel. These waters had a fairly stable high salinity in the 1950s and 60s, then freshened until the about the mid-1990s and have since been stable at relatively low salinity (Figure 3).

Shelf Seas

North Sea (Charting Progress Regions 1 and 2)

In the northern North Sea the salinity is heavily influenced by inflowing North Atlantic water from the north (Figure 1a) but the year to year variability here is higher. Since the 1970s salinity has no clear trend in the near-shore Fair-Isle current (Figure 4) but evidently increased in deeper waters to the east (IROC2011, Figure 53). The salinity of the southern North Sea is controlled by a balance of freshwater supply from the surrounding catchments in the UK and Northern Europe and by changes in the transport of Atlantic origin water through the Dover Strait and from the north (Figure 5a). There is no clear trend since the 1970s but multi-annual variations in this salinity appear to have features in common with some in the northern North Sea (Figure 4), in the Atlantic waters of the Faroe-Shetland Channel (Figure 1a) and also in the salinity at Helgoland in the south-eastern part of the North Sea heavily influenced by the outflow of major European rivers (Figure 5b).

Examining the spatial pattern of long-term trends in wintertime bottom salinity in the North Sea from ICES International Bottom Trawl Survey data (Figure 6) suggests

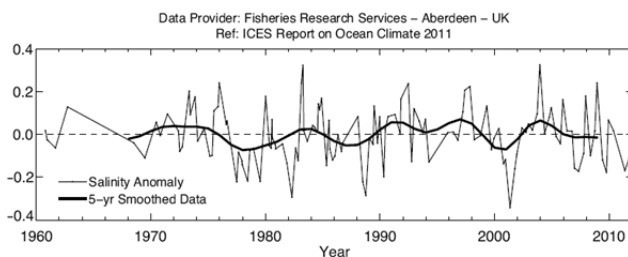


Figure 4: Charting Progress Region 1 Northern North Sea (59.00°N 2.00°W). Salinity anomaly in the Fair-Isle Current for the period 1960 to 2011. [Image sourced from IROC2011 Figure 54]

that the positive trend identified in North Atlantic waters to the north of the area is evident in the very northern part of the North Sea but this trend weakens and becomes variable further south.

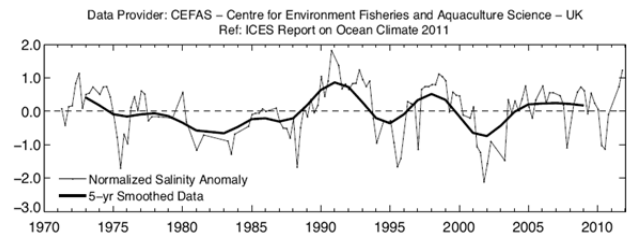


Figure 5a: Charting Progress Region 2 Southern North Sea. Normalised sea surface salinity anomaly relative to the period 1971-2000 measured along 52°N between Harwich and Rotterdam, a regular ferry at six standard stations. The time series show the seasonal section average (DJF, MAM, JJA, SON) of the normalised variable. [Image sourced from IROC2011 Figure 58]

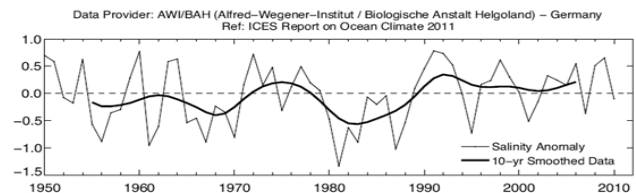


Figure 5b: Charting Progress Region 2 Southern North Sea. Annual sea surface salinity anomaly at Helgoland (base period 1971-2000) for the period 1950-2010. [Image sourced from IROC2011 Figure 55]

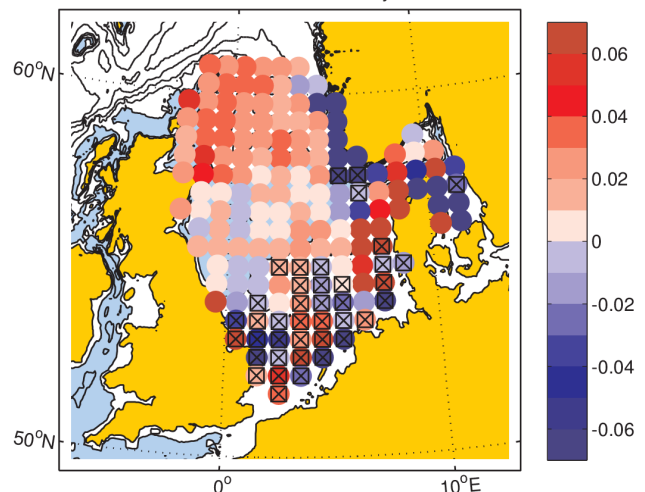


Figure 6: Charting Progress Region 1 and 2 North Sea. Linear trend (per decade) in Winter Bottom salinity calculated from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1971-2012. Values calculated from linear fit to data in ICES rectangles with more than 30 years of data. Hatched areas have a slope which is not significant at the 95% confidence level ($\alpha=0.05$) using Mann-Kendall non-parametric test for a trend. [Image updated from UKMMAS (2010), Figure 3.31, courtesy S. Hughes, Marine Scotland Science]

Eastern English Channel (Charting progress Region 3)

There are few available salinity records for Charting Progress Region 3. Ferrybox measurements have been made but the time-series do not extend back far enough to offer an overview of long term variability.

Celtic Sea and Western English Channel (includes Charting Progress Region 4)

The western English Channel, away from the coast, is mainly influenced by North Atlantic Water from the west. It is heavily influenced by tidal currents and local weather conditions which induce stratification in the spring and summer, and deep mixing in the autumn and winter. The Western Channel Observatory (www.westernchannelobservatory.org.uk) station E1 (about 25 miles SSW of Plymouth), sampled since 1903 (Figure 7), lies in 75 m of water and shows considerable inter-annual variability in salinity, with a much greater range of values than the open ocean (compare with Figure 1-3). There is no discernible long-term trend in over a century of observations but there appears to have been an increase in salinity between the early 1980s and recent years which have been higher than average in salinity. This pattern of fresh conditions in the early 1980s and saline conditions in the late 2000s appears similar to that in the southern North Sea (Figure 5) but the data gap at E1 makes a full comparison of the variability difficult.

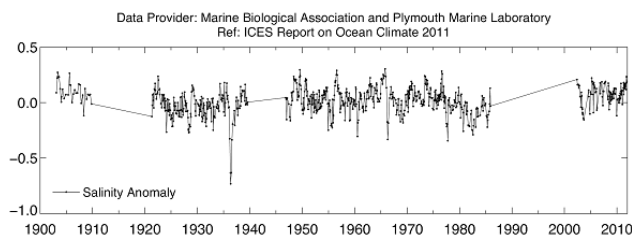


Figure 7: Charting Progress Region 4 Western English Channel – Western Channel Observatory Station E1 (50.03°N 4.37°W). Sea surface salinity anomaly (base period 1971-2000) for the period 1903-2011. [Image sourced from IROC2011 Figure 41]

Irish Sea (includes Charting Progress Region 5)

The North Atlantic is the saline source water for the Irish Sea, but salinity is heterogeneous and all regions are, to some extent, influenced by freshwater. Low salinity waters are largely confined to the north-eastern Irish Sea corresponding to high riverine freshwater loadings, with highest salinities being observed in offshore western Irish Sea waters.

Salinity in the Irish Sea can be represented by a time series in the coastal waters of the southern Isle of Man (IoM) at the Cypris Station near Port Erin Bay (Figure 8). No significant long-term trends have been established, though there are decadal scale variations. Salinity through the 1970s was relatively stable with little evidence of the Great Salinity Anomaly. There was a period of low salinity through the 1980s into the early 1990s. The late 1990s was generally a period of higher salinity and was followed by a freshening in the early 2000s. Salinity has been lower in the first part of the 21st century than the long term average (1966-2010)

with a small positive anomaly evident in 2010. A negative correlation between the winter North Atlantic Oscillation index (NAO_{DJFM}) and winter salinity has been identified here working through the influence of NAO on precipitation. In the IoM NAO negative (positive) winters tend to have lower (higher) rainfall generating more saline (fresher) waters around the IoM in these years (Kennington, 2012).

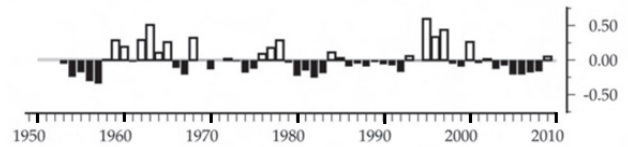


Figure 8: Charting Progress Region 5 IrishSea Cypris station. Salinity anomaly (base period 1966-2010). [Data source, Department of Environment, Food, and Agriculture Isle of Man Government. Image sourced from Kennington (2012) Figure 7.4.2]

West Scotland (Charting Progress Region 6)

Reliable continuous measurements of salinity in the Tiree Passage on the west coast of Scotland started in 2002 (Figure 9). Observations made between 1975 and 1996 indicate that intra-annual changes from warm high salinity water to cool low salinity water are, in general, associated with the across shelf migration of isohalines rather than a broad scale change over the whole shelf (Inall *et al.*, 2009). However, it has not been possible to detect any link between this movement and local climate, such as rainfall patterns, or the North Atlantic Oscillation.

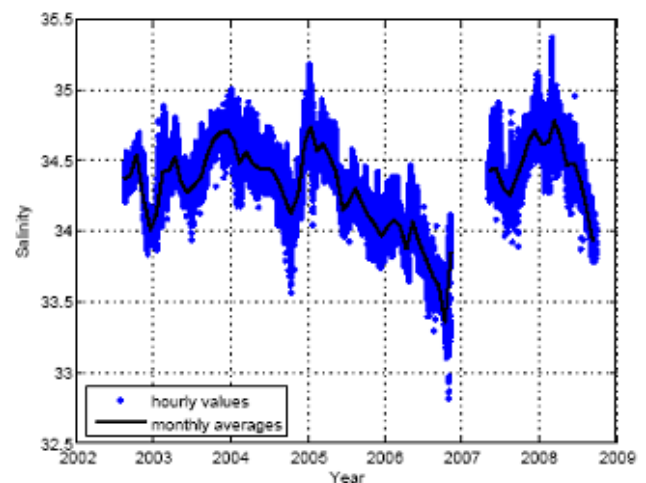


Figure 9: Charting Progress Region 6. Measured hourly and monthly averaged salinity in Tiree Passage. [Image sourced from UKMMAS (2010), Figure 3.79, courtesy M.Inall, SAMS]

2. WHAT COULD HAPPEN?

The UK Climate Projections 2009 (Lowe *et al.*, 2009) indicate that in the future (2070-2098) the shelf seas and adjacent ocean may be slightly fresher than the present, by ~0.2 (Figure 10). In contrast the Celtic and Irish Seas show a weaker change (~0.1). This freshening in the UKCP09 projection has also been evident to some degree in two further projections (Friocourt *et al.*, 2012, Gröger *et al.*, 2012). The open ocean

salinity is mainly controlled by large scale ocean circulation driven by wind fields, the meridional overturning circulation and the large scale balance of precipitation and evaporation. Those conditions then affect the shelf seas through transport of oceanic water on to the shelf. The on-shelf salinity is modified by changes in precipitation, evaporation and river run-off, but the oceanic control dominates the mean long-term salinity.

A limitation of the regional model UKCP09 projection is the representation of ocean salinity changes from its driving global scale model. Future ocean salinity forcing for the regional model was created by adding a salinity change anomaly (from the driving global climate model) to the present day climatology, effectively limiting aspects of change in salinity (e.g. interannual or spatial variability) that could be observed on the European shelf (Holt *et al.*, 2010). Furthermore, the location of the anomaly may have led to an underestimate of projected freshening (pers. comm. J. Tinker). Further runs of the same model with a fully varying open ocean boundary, and estimates of uncertainty, are being produced by the UK Met Office and hope to be reported in 2014.

3. KNOWLEDGE GAPS

a. Sparse availability of data

The number of deep ocean sites for which long term measurements have been made are small. This problem is being addressed in the deep ocean by the Argo float programme which has been greatly increasing the amount of global subsurface data since the early 2000s. This new data source is helping to reduce some of the difficulties due to sparse observations, but it is important that new floats continue to be deployed in order to maintain the level of sampling required as older floats cease to function. The installation of thermo-salinographs on a number of ferries and voluntary observing ships using UK waters will help to redress the shortfall of surface salinity observations in shelf waters.

b. Under-sampling of the seasonal cycle

When looking at long term variability in time series that are sampled only 1-3 times per year, we need to take account of the season in which the measurements were made. The under-sampling of the open ocean seasonal cycle and how

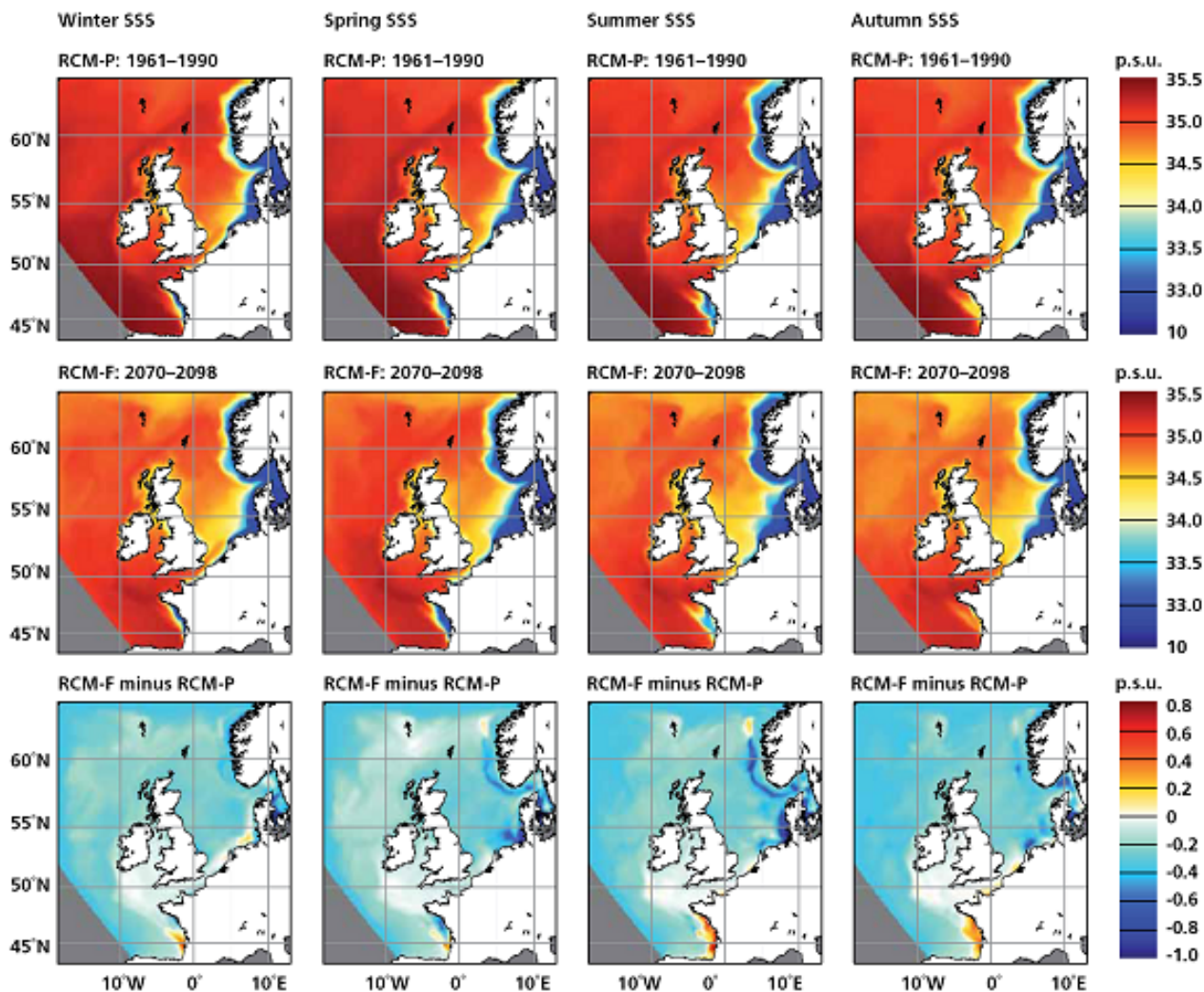


Figure 10: Distribution of sea-surface salinity by season, modelled for 1961-1990 (Past, top row, 2070-2098 (Future, middle row), and the different (Future minus Past, bottom row). [Image sourced from UKCP09, Lowe *et al.*, 2009 Figure 6.8].

it may be changing over time is a major uncertainty for interpreting long term changes. The key to resolving the open ocean signal cycle lies in assimilating temperature and salinity from profiling floats and other devices into numerical models. The models can fill the gaps between the data points, and the data can keep the model close to reality. Progress is being made with developing this technique.

c. The hydrological cycle

We know that the North Atlantic ocean undergoes large-scale, long-term changes in salinity, and so freshwater content, at all depths. But at present there remains uncertainty in the causes of those changes and their relationship with anthropogenic climate change. Climate models are not able to predict future evolution of the salinity fields with confidence. In particular it is unclear how changes in the hydrological cycle relate to changes in ocean circulation and what the feedback mechanisms might be. Modelling of salinity trends in the UK shelf seas is still being developed, and the accuracy of such models is very much dependent on boundary inputs both from the open ocean (generally long-term) and from the river catchments that discharge onto the north-west European shelf (generally shorter term but often large magnitude salinity change).

4. SOCIO-ECONOMIC IMPACTS

There has been little research into the direct socio-economic impacts of variations in salinity around the UK; rather, the main focus has been on temperature and sea-level rise. However a recent study has shown that phytoplankton, zooplankton and some commercial fisheries are affected by changes in the circulation of the subpolar gyre (Hátúnét *et al.*, 2009). Periods of high salinity in the northern North East Atlantic are associated with higher temperatures, while periods of low salinity tend to have cooler temperatures. These opposing scenarios are linked to the strength of the subpolar gyre circulation which determines the balance between subtropical and subarctic water flowing into the region. It has been shown that when the Rockall Trough is more strongly influenced by warm saline subtropical water due to a weak subpolar gyre (as it is presently), phytoplankton abundance is high, the abundance of warm-water zooplankton is high, and the density of blue whiting and pilot whales in the Iceland-Faroe region is high.

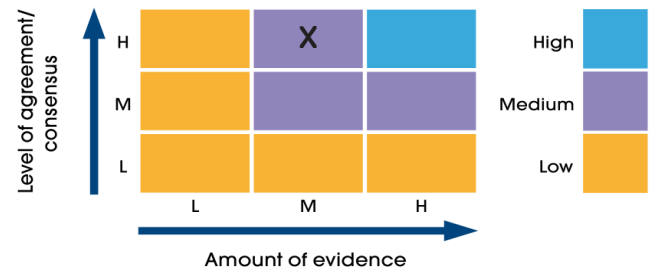
As a key component of the ocean climate and dynamics (through its control of density) salinity is partly responsible for driving ocean circulation. The potential socio-economic impacts of large-scale circulation change are considered in the MCCIP report on Atlantic Circulation and Heat Transport (Smeed *et al.*, 2013).

5. CONFIDENCE ASSESSMENT

What is already happening?

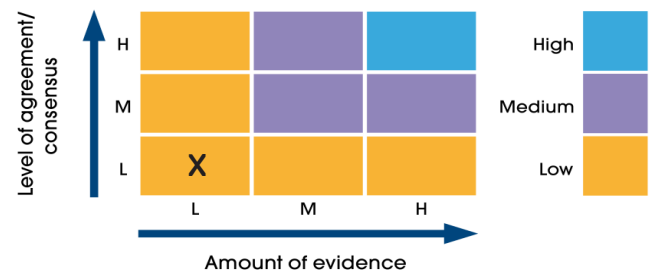
Measurements of salinity at offshore sites are made 1-3 times per year, under-sampling the seasonal cycle which may bias the results. Shelf sea and coastal stations are sampled more frequently (up to daily), so the seasonal cycle is usually better resolved. Calibration is good (although data prior to 1970 are less reliable), so high confidence can be put on actual measurements.

The number of sites for which long-term records exist are limited, so it can be difficult to make an overall assessment of changes in salinity around the UK. However, the variability at the deep ocean sites on time scales of years to decades are consistent across the region and with the North Atlantic region, giving us overall moderate confidence in the results.



What could happen?

There is less confidence in regional climate-change prediction than in global predictions, and less confidence for the hydrological cycle (for salinity) than for temperature. Note that the UKCP09 projections for salinity present a single run under one climate scenario (medium - Lowe *et al.*, 2009) and they note a lower confidence in salinity in the model.



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