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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 saline. The decadal-scale pattern of change around the UK reflects the mean 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 have been stable 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 as 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, and recent years have been higher than average in salinity.

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.

In the future the shelf seas and adjacent ocean may be slightly fresher (less saline) than the present. On the shelf the oceanic influence will dominate the mean long-term salinity.

There remains uncertainty in the causes of 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.

FULL REVIEW

1. What is already happening?

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 to Shetland 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 is providing additional information in surface waters around the UK. Offshore observations in the North Atlantic and Nordic Seas are summarised annually in the International Council for the Exploration of the Seas (ICES) Report on Ocean Climate (IROC) (Holliday *et al.*, 2009). 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, Southampton, the Proudman Oceanographic Laboratory, the Plymouth Marine Laboratory, Marine Biological Association, and Centre for Environment, Fisheries and Aquaculture Science. ICES co-ordinate 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 (including Charting Progress Regions 7 and 8)

The northern North Atlantic and Nordic Seas exhibit multi-decadal-scale variability in mean ocean salinity cycle, with a maximum in the early 1960s and minimum in the mid-1990s (Peterson *et al.*, 2006, *Holliday et al.*, 2009). It is presently high in salinity. At each sampling site, imposed on that large-scale, long-term pattern are further levels of variability related 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 more variable than deep salinity. But the salinity 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. 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).

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 (Fig. 1). A further minimum occurred in the 1990s, and the present day conditions are relatively saline. 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 Charting Progress Region 8 influence the Nordic Seas and ultimately the Arctic Ocean (Holliday *et al.*, 2008; Polyakov *et al.*, 2007).

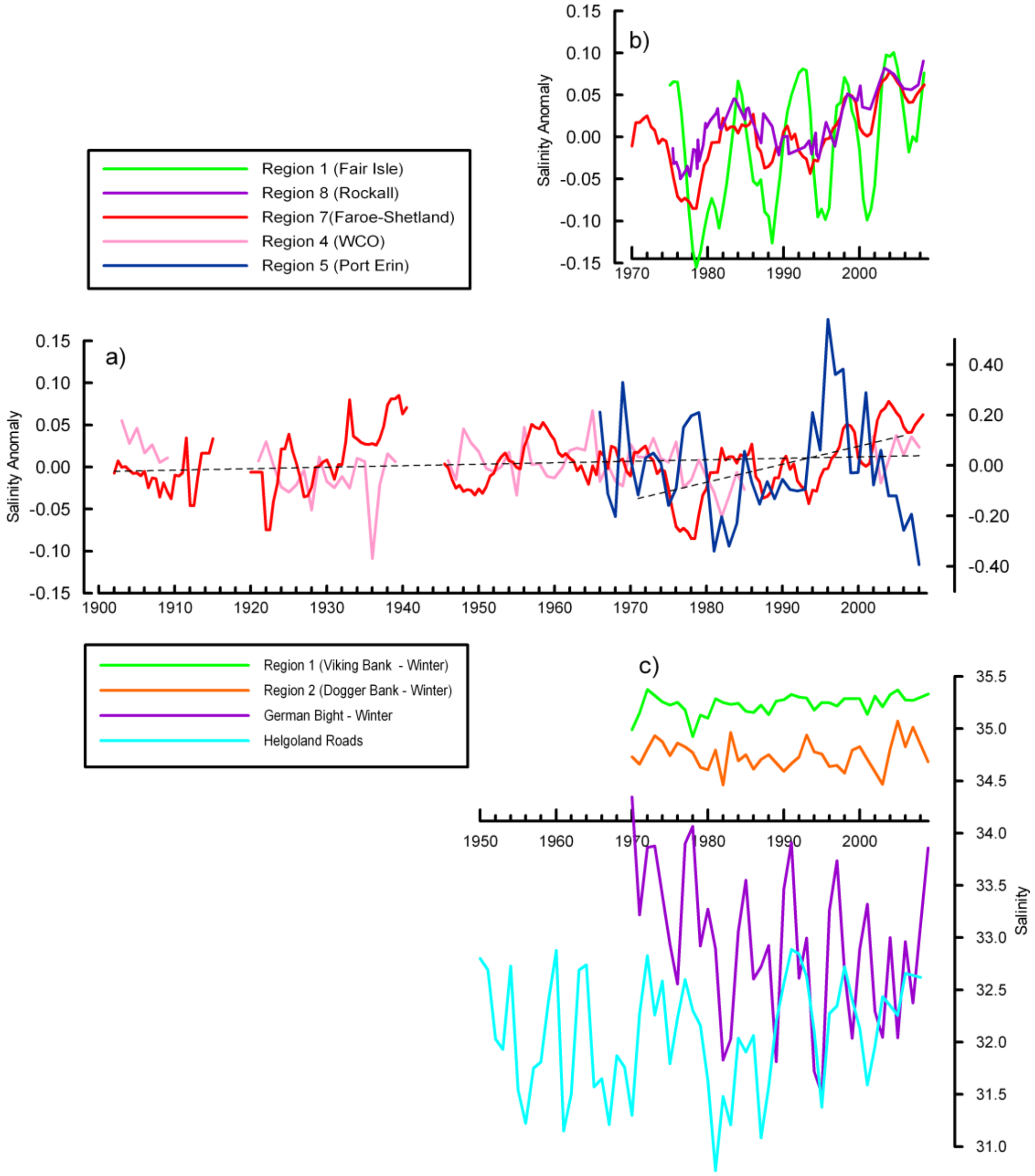


Figure 1 *Comparison of Salinity trends across regions.*

a) *Long salinity timeseries: left axis, Salinity anomaly of the Atlantic Water in the slope current (Region 7, North Atlantic Water in the Faroe Shetland Channel). Long term trends and trend since 1970 are indicated with dashed line (simple linear fit). Right axis, salinity in the Irish Sea (Region 5, Port Erin) and Western English Channel (Region 4, Western Channel Observatory Station E1 in the English Channel (50.03°N 4.37°W))*

b) *Comparison of salinity anomalies in Regions 1, 7 and 8. Region 1: Northern North Sea. Salinity anomaly in the Fair Isle current entering the North Sea from the North Atlantic, Region 7: North Atlantic Water in the Faroe Shetland Channel, Region 8: Rockall Trough. Salinity of the upper ocean (0-800 m).*

c) *Comparison of winter bottom salinity from ICES IBTS dataset at Viking Bank, Dogger Bank and German Bight. Annual mean salinity data from Helgoland Roads also included for comparison.*

Below 1000 m the deep ocean west of the UK has become fresher since 1975, reflecting a period of freshening in the Labrador Sea where the deep water originates (Fig. 2). The Labrador Sea has become more saline again since the late 1990s, and we expect the deep water west of the UK will also increase in salinity over the next few years. North of the UK, the deep waters (800 m) flow from the Nordic Seas and while they have also freshened since 1950, they have been stable for the last decade (Fig. 3).

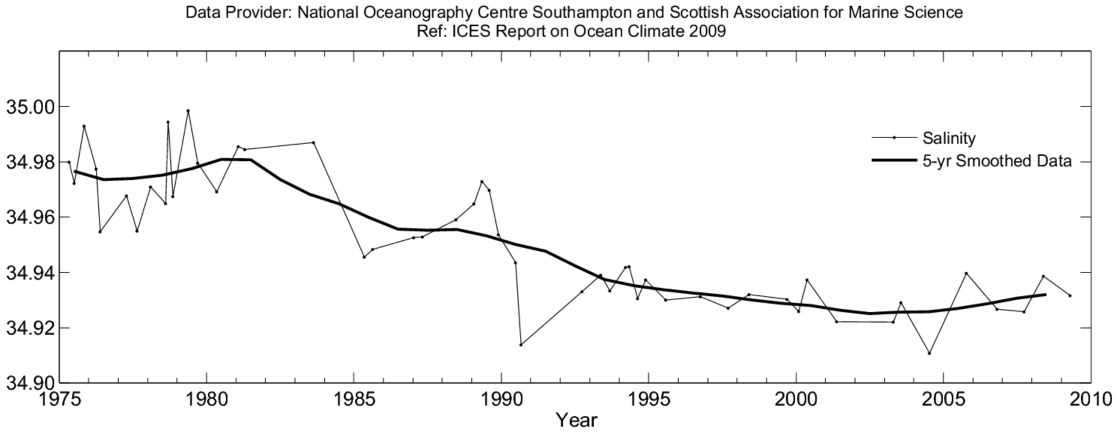


***Figure 2**. Rockall Trough . Salinity of the deep ocean (Labrador Sea Water, 1800 - 2000 m)*

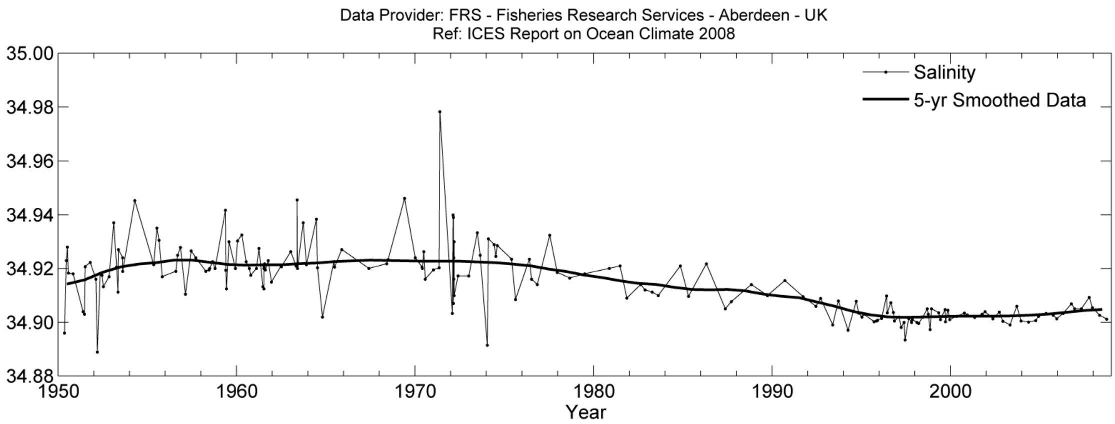


***Figure 3**. Faroe Shetland Channel. Salinity of overflow water at 800 m.*

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 but the increasing trend in salinity since the 1970s is less clear (Fig. 1). 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. There is no clear trend since the 1970s but multi-annual variations in this salinity appear to be similar to those in the northern North Sea and Atlantic waters of the Faroe Shetland Channel (Figs. 1, 4, 5).

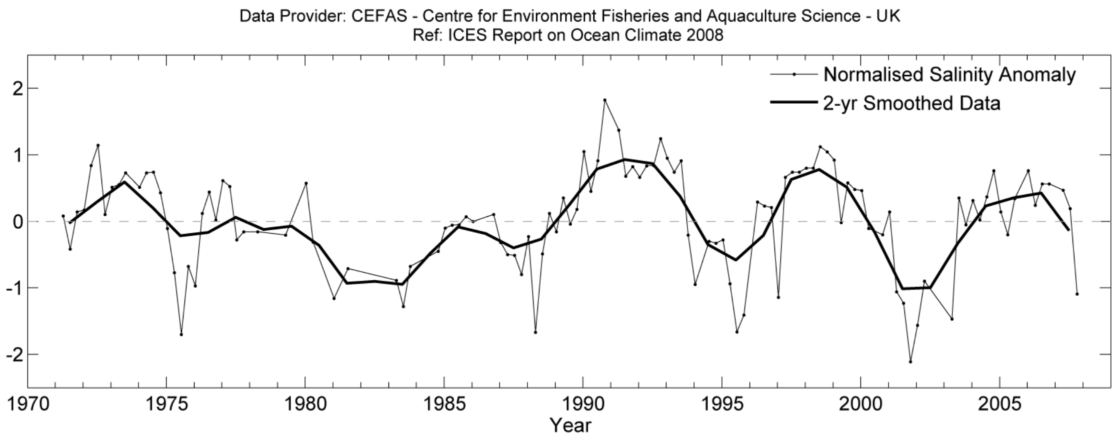


Figure 4: *Southern North Sea. Normalised sea surface salinity anomaly relative to the period 1971-2000 measured along 52°N, a regular ferry at six standard stations. The time series show the seasonal section average (DJF, MAM, JJA, SON) of the normalised variable.*

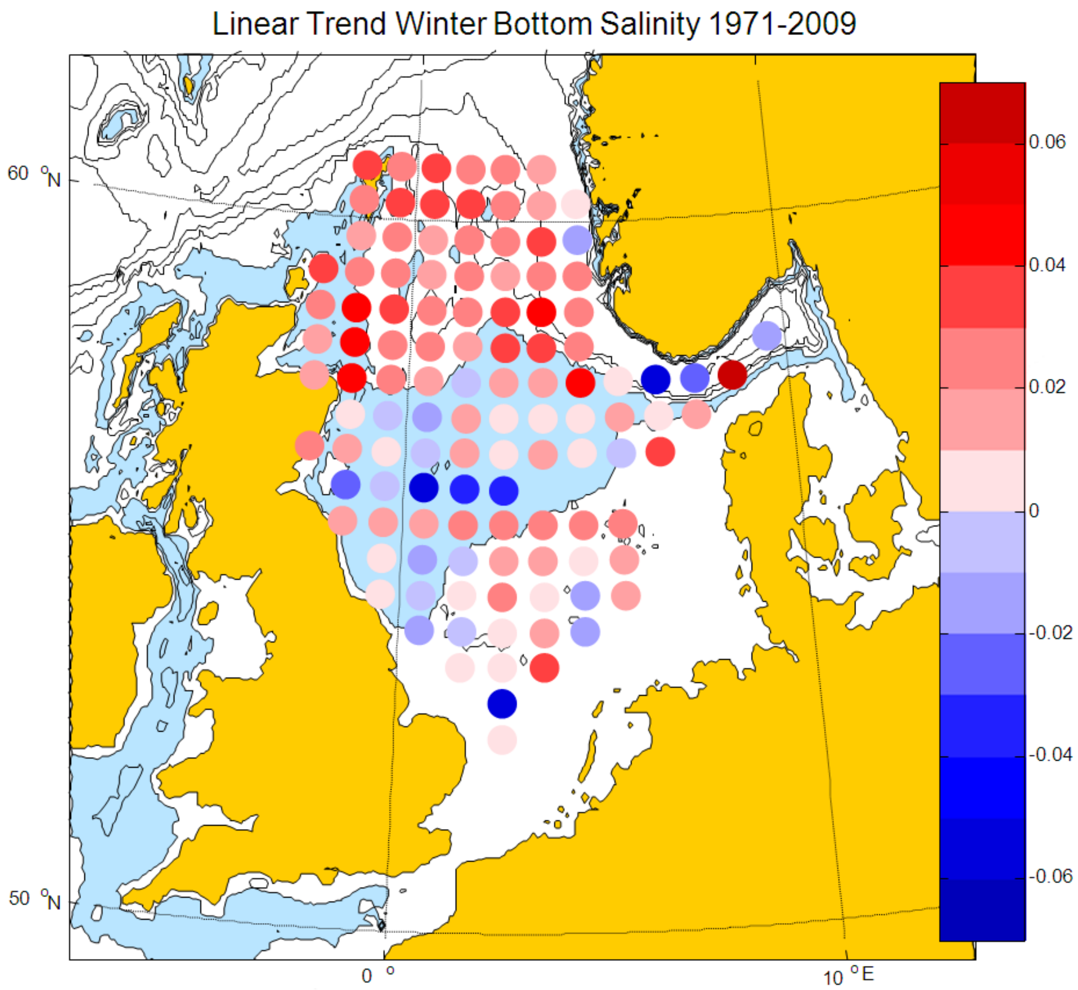


Figure 5. *Linear trend (per decade) in Winter Bottom salinity calculated from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1971-2009. Values calculated from linear fit to data in ICES rectangles with more than 30 years of data. Note that the high interannual variability in the coastal regions make a salinity trend difficult to determine with confidence, data have been rejected in coastal regions with high inter-annual variability.*

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 timeseries does not extend back far enough to offer an overview of long term variability.

Western English Channel (Charting Progress Region 4*)

The western English Channel, away from the coast, is mainly influenced by North Atlantic Water. 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. Station E1, sampled since 1903, lies in 75m of water and shows considerable inter-annual variability in salinity, with a much greater range of values than the open ocean (Fig. 1). There is no discernible long-term trend in over a century of observations, and recent years have been higher than average in salinity.

Irish Sea (Charting Progress Region 5)

Salinity in the Irish Sea can be represented by a time series in the coastal waters of the Isle of Man at Port Erin Bay (Fig. 1). No significant long-term trends have been established, though there are decadal fluctuations as follows. Salinity through the 1970s was relatively stable with little evidence of the Great Salinity Anomaly. There was a period of low salinities through the 1980s into the early 1990s. The 1990s was generally a period of higher salinity followed by a salinity decrease or freshening in the early 2000s and to date.

The North Atlantic is the source water for the Irish Sea, but salinity is not heterogeneous with all regions 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.

West Scotland (Charting Progress Region 6)

Reliable continuous measurements of salinity in the Tiree passage on the west coast of Scotland started in 2002 (Fig. 6). 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.

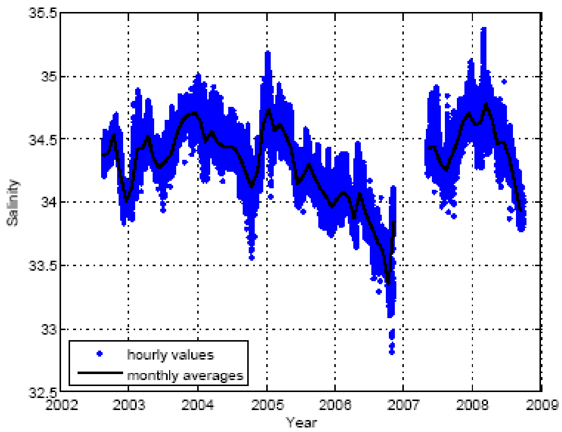


Figure 6. *Measured hourly and monthly averaged salinity in Tiree Passage*

2. What could happen in the future?

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 (Fig. 7). In contrast the Celtic and Irish Seas show a weaker change (~0.1). The open ocean salinity is mainly controlled by large scale ocean circulation driven by wind fields and the meridional overturning circulation. 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.

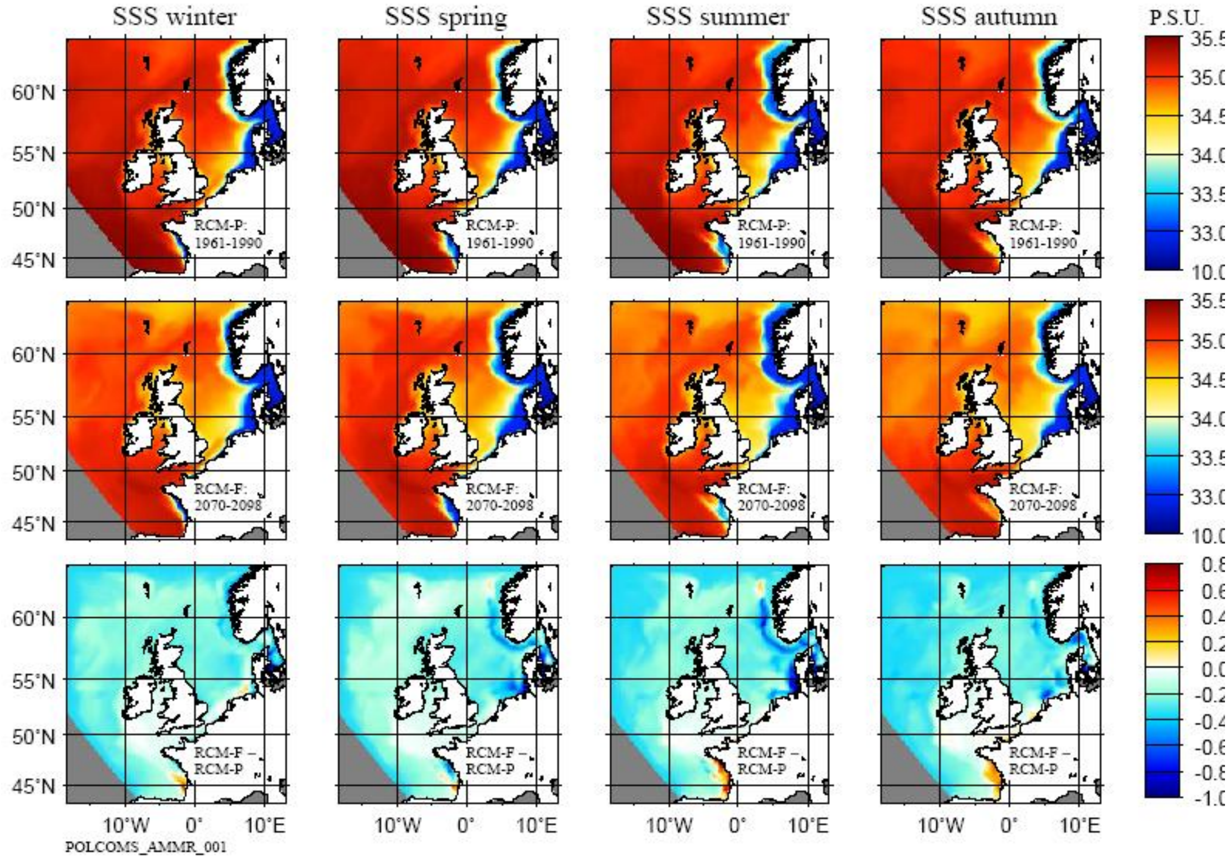
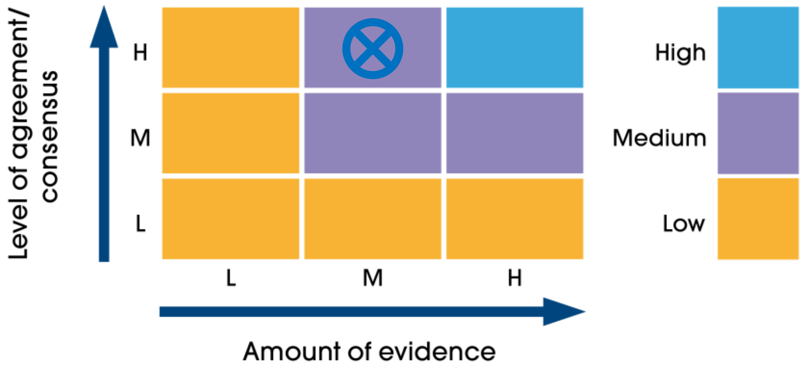


Figure 7. *Distribution of sea-surface salinity by season, modelled for 1961-1990 (Past, top row, 2070-2098 (Future, middle row), and the different (Future minus Past, bottom row). From UKCP09, Lowe et al., 2009.*

3. Confidence in the science

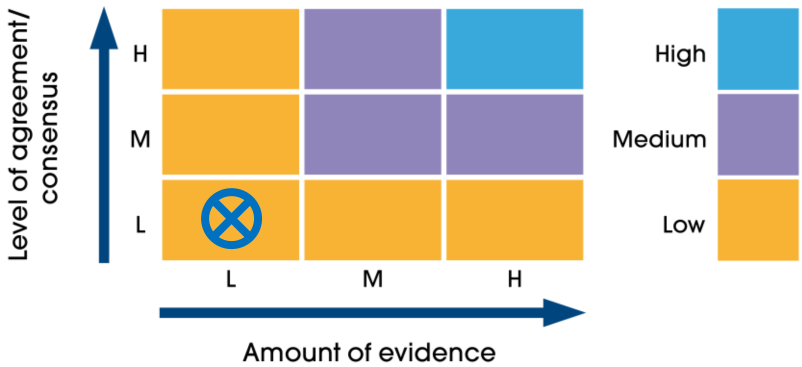
What is already happening: **Medium**



Measurements of salinity at offshore sites are made 1-3 times per year, under-sampling the seasonal cycle which may alias 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: **Low**



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 UKCP 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.

4. Knowledge gaps

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

1. *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.

2. *Under-sampling of the seasonal cycle* The surface and upper layers of the ocean exhibit a strong seasonal salinity cycle with an amplitude greater than longer-term changes. Usually surface salinity is higher in the winter in the open ocean. 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 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.

3. *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 either from the open ocean or from the river catchments that discharge onto the northwest European shelf.

5. 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 (Hatun *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 ARC Science Review 2010-11 Atlantic Heat Conveyor (Atlantic Meridional Overturning Circulation) (*Cunningham et al. 2010).

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