Climate change and salinity of the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

What is already happening

- Salinity of eastern North Atlantic waters west of the UK has dramatically decreased over the last five years, probably in response to changes in the atmosphere in the western North Atlantic in the first years of the decade.
- This dramatic freshening in ocean waters is not evident on the shelf beyond the northern North Sea waters east of Scotland with changes that appear within the bounds of typical interannual variability.
- North of the UK, where the deep water (>800 m) flows from the Nordic Seas, the water freshened for five decades up until the late 1990s but has gradually become more saline over the last 20 years.
- In the deep Rockall Trough where waters are thought to have originated in the North-West Atlantic, the salinity has remained stable over the last decade without the increases expected to have been passed on to it from changes in the Labrador Sea.
- Some sustained observations are no longer available, but new models merged with data are just becoming available that may fill gaps in coverage.
- Large interannual to decadal variability makes simple linear trends of salinity in the shelf seas less useful than assessments of identification of periods of fresh and saline anomalies.

What could happen in the future?

- There is considerable uncertainty regarding future salinity.
- Most 21st Century projections suggest UK shelf seas, and the adjacent Atlantic Ocean, will be less saline than present, driven by ocean circulation changes in response to climate change.

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- Centennial-scale salinity decreases in UK shelf seas are likely to be driven by ocean circulation change. Reduced inflow across the ocean-to-shelf boundary is thought to be the main driver of the salinity decrease.
- Greater salinity decreases are projected for the North Sea, than the Irish and Celtic Seas.

Readers are referred to previous reports for MCCIP that have described the drivers, evidence base and decadal evolution of salinity in the seas around the UK (Gommenginger, 2006; Holliday *et al*., 2008, 2010; Dye *et al*., 2013). Here we update the time–series observations and describe how our knowledge has changed over the last five years.

1. WHAT IS ALREADY HAPPENING?

Sustained observations

A key source of the information presented here is the set of long-term observations of salinity in the North Atlantic, Nordic Seas and North-West European Shelf sites summarised annually by the International Council for the Exploration of the Seas (ICES) Working Group on Oceanic Hydrography (www.ices.dk/community/groups/Pages/WGOH.aspx) in the ICES Report on Ocean Climate (IROC – https://ocean.ices.dk/iroc/). The most recent IROC (IROC2017: González-Pola *et al*., 2018) was published in September 2018 covering the period up to the end of 2017, and it is hereafter referred to as 'IROC2017'. For the seas around Scotland this information is further enhanced by the latest Scottish Ocean Climate Status Report 2016 (Hughes *et al*., 2018) and includes analysis of salinity for the nearshore environment using a new Ocean Data Tool (ODaT) developed by the Scottish Association for Marine Science (SAMS) as well as information drawn from regular trawl surveys.

Sustained multidecadal observations are vulnerable to changes in programmes, funding and scientific interest. Since the last relevant MCCIP report card (Dye *et al*., 2013) two of the underlying time–series studies have changed: information from Port Erin, in the Irish Sea, is no longer available, and the regular ferry samples in the southern North Sea are no longer collected with the time–series extended by use of nearby moorings.

Copernicus Re-analysis

Alongside well-established, sustained observation programmes, a new development since the last MCCIP report in 2013 has been in the field of re-analysis. Re-analyses can be simply described as models that are driven by the atmosphere, ocean boundary- and freshwater-forcing over past decades that are also constrained by the observations of some of the properties being modelled over those decades. Re-analyses have been used for many years in the atmospheric community as a best estimate of state over past decades. They allow us to understand how conditions varied in places where no observations were made and can give the broader spatial dimension of regional variability. The first re-analyses are now available for the ocean and seas in our region through the Copernicus programme, and they underlie part of its first Copernicus Ocean Status Report (COSR; von Schuckmann *et al*., 2016) that was updated with information through to 2016 (COSR18; von Schuckmann *et al*., 2018) and was updated again in September 2019 (COSR19; von Schuckmann *et al*., 2019).

In its reporting on global salinity the COSR18 (von Schuckmann *et al*., 2018) used a mixture of observations and re-analysis. The North-West Shelf salinity assessment is based on a re-analysis alone over the period 1993–2016 that uses the NEMO coastal ocean model (Nucleus for European Modelling of the Ocean - Madec, 2008) on a 7 km grid that covers the whole of the North-West European Shelf seas. It is forced by historical atmospheric conditions, ocean boundaries and riverine fluxes for that period and is further constrained to observed conditions by assimilation of satellite-based Sea-Surface Temperature (SST) (Wakelin *et al*., 2016; Tinker *et al*., 2018) with assimilation of in-situ surface temperatures, profiles of temperature and profiles of salinity added for the newest reanalysis used in COSR19 (Renshaw *et al*., 2019).

Each of the Copernicus products has a published validation in the form of a Quality Information Document (QUID). The QUID for the North-West European Shelf product used in COSR18 (Wakelin *et al*., 2016) found that the magnitude of the salinity bias in the re-analysis is generally less than 0.5 psu. Wakelin *et al.* (2016) note that this bias (an average offset) can be fresh by ~2 psu, in some coastal areas of the Southern North Sea, or saline, by ~0.5 psu in the Irish Sea surface. Some of the validation has used the same sustained observations that we also use in this and previous MCCIP reports. For observations south of the Isle of Man, Wakelin *et al.* (2016) found a good correlation of re-analysis monthly mean salinity in the Irish Sea (r^2 ~0.5). Tinker *et al.* (2018), using an earlier version of the re-analysis (V2) also examined multi-annual variations and found some correlation (r^2 <0.25) in the Western English Channel (Western Channel Observatory below) but strong correlation (r^2 ~0.8) in the Southern North Sea (Figure 1; Harwich Ferry time–series) The QUID for the updated North-West Shelf re-analysis (V4) used for COSR19 (Renshaw et al. 2019) salinity shows a notable improvement in the bias west of Scotland, Southern North Sea, Irish Sea and also in the Norwegian Trench. In this 2019 update the output is now too saline in the Southern North Sea, but with a smaller bias magnitude, and the overall summary statement remains that: “Biases are generally of magnitude less than ±0.5 PSU”.

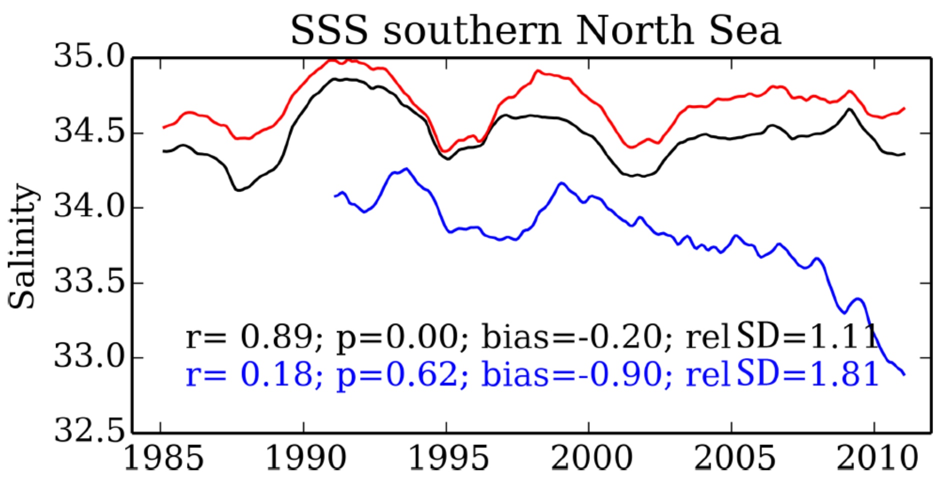


Figure 1: Sea-Surface Salinity (SSS), reproduced from Tinker et al. *2018 (CCBY4.0 licence). Comparison between observed surface salinity (red), the NEMO based North-West Shelf re-analysis (black) and a global re-analysis. Where relSD is the ratio of the model to observation standard deviation, bias is the average offset between the model and observations, r is the correlation coefficient which is statistically significant (95% confidence) where p <0.05. Data smoothed on a two-year running mean.*

These validations of the re-analysis highlight some of the limitations in the products, but ensure that we are aware of their uncertainty as we begin to use this new information source. They are developing products and must be used with care and in conjunction with other assessments. It is clear, however, that in the future, reanalyses will play an increasingly important role in our understanding and description of the development of the climate of the marine environment in the North Atlantic and UK Shelf seas. We include here a brief summary of its findings for the period up to 2016.

The Copernicus Ocean Status Report 2018 section on salinity (Mulet *et al.*, 2018) reports that global sea surface is currently more saline than average, but that the North Atlantic surface is one of the few areas that is relatively fresh compared to the long-term average. The re-analysis for the North-West Shelf surface in COSR18 highlights significant freshening over the period 1993–2016 (Figure 2; Mulet *et al.*, 2018).

The latest report COSR19 does not update these metrics of salinity change, instead replacement analyses will be made available as part of the Copernicus Ocean Monitoring indicators (OMI) at http://marine.copernicus.eu/science-learning/ocean-monitoring-indicators/. In Figure 3, we show the latest update of the OMI for North-West Shelf salinity highlighting the degree of multiannual variability around any trend (Figure 2). They identify that shelf average water column was particularly fresh from 2013 until the end of the re-analysis in 2018.

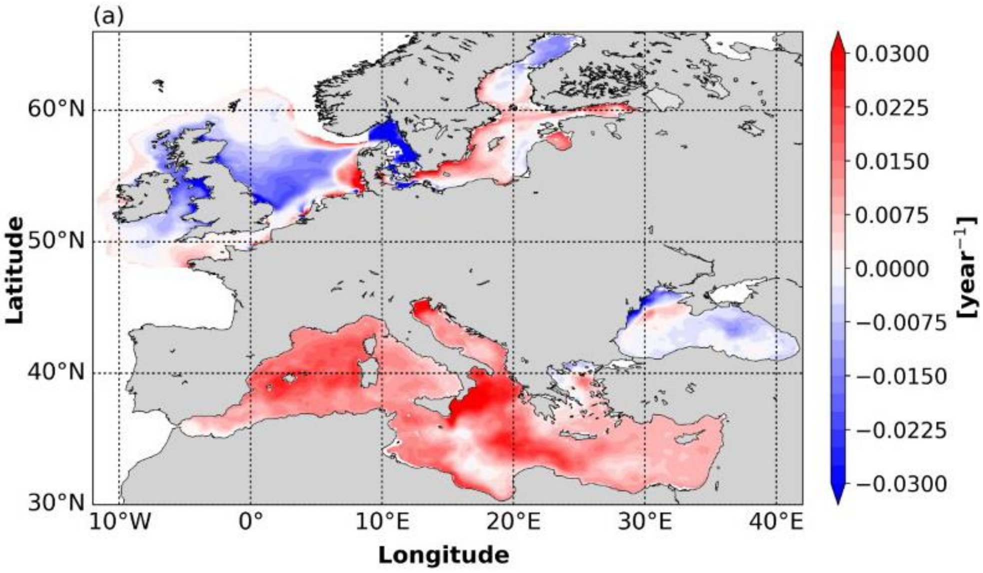


Figure 2: Modified from Figure 1.1.7 in Mulet et al. *(2018; CCBY4.0 licence). Re-analysis estimate for 1993–2016 of surface salinity trend.*

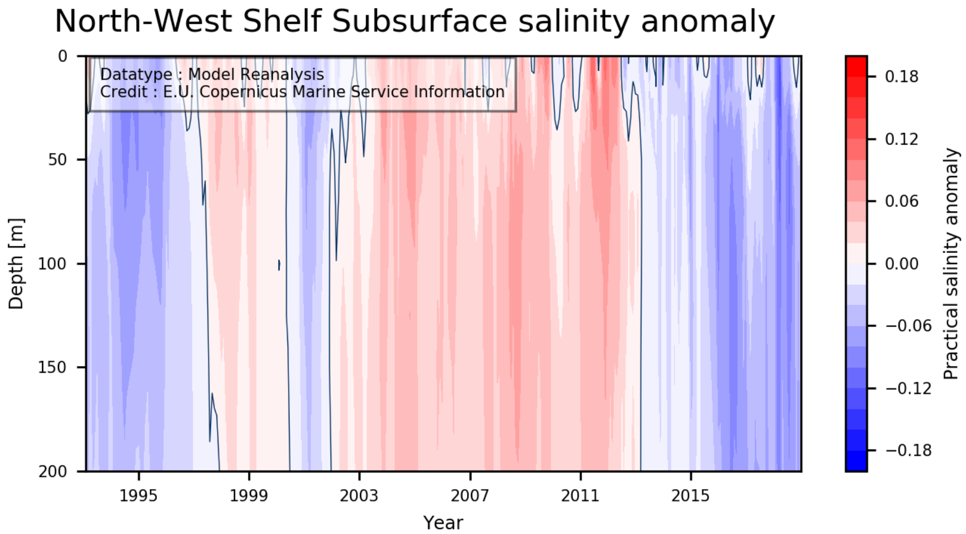


Figure 3: Modified from Figure 1.1.7 in Mulet et al. *(2018) from Copernicus Ocean Monitoring Indicator (CCBY4.0 licence) re-analysis estimate for 1993–2018 of shelf-wide, average water-column salinity anomaly relative to the base period 1993–2017.*

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

In the last MCCIP report (Dye *et al.*, 2013) using data available up to the year 2011, we reported that the upper ocean salinity in this region had "*generally increased 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". High salinity conditions had persisted through most of the preceding 10 years in both the Rockall Trough and the Faroe–Shetland Channel.

Since 2011 the salinity in this region has decreased dramatically and the waters at this Atlantic boundary are now as fresh as they were in the mid-1970s (Figure 4a, b) during a period known as the 'Great Salinity Anomaly' (Dickson *et al.*, 1988). The source of the recent freshening signal is the North Atlantic where a large fresh anomaly (relative to 1981–2010 conditions) has developed since 2013 (Figure 4c; IROC2017). The IROC2017 notes that the near-surface Atlantic is about 0.4 psu fresher than average, and this anomaly has been present at the same time as a relatively cool period in the Sub-Polar Gyre (cf. the accompanying MCCIP temperature report, Tinker *et al*., 2020). The fresh anomaly appears to have developed in the west of the Atlantic spreading into the eastern and northern North Atlantic over the next five years (Figure 4c). The IROC2017 does not identify a cause but only that it could be due to an "*increase in the freshwater flux from the atmosphere, ocean, or Greenland ice sheet melt*".

In an update to work on the progression of previous positive salinity anomalies west and north of the UK (Holliday *et al*., 2008b), the *Scottish Ocean Climate Status Report 2016* (Hughes *et al.*, 2018) illustrates that, by 2015, the signal of freshening had passed along the pathway of the North Atlantic Current, from Rockall Trough along the coast of Norway reaching the Barents Sea (Figure 1d).

Understanding the causes of these anomalous Atlantic conditions has recently taken a step forward. Firstly, a new analysis (Reverdin *et al*., 2018; data available from doi:10.6096/tsd-bins-naspg) has collated and binned salinity observations from repeat oceanographic sections, Argo floats, and ships of opportunity into regions of the open subpolar North Atlantic an annual sea surface salinity over the 1896–2015 period. Secondly, this new data product has been analysed by Holliday and co-authors (in review) to demonstrate that the recent fresh period is unprecedented over the entire 120-year period. They further find that the cause of the freshening is through a period of anomalous atmospheric conditions in the early years of the decade that changed the flux of fresh waters from the Arctic into the west of the North Atlantic which then propagates eastward via the North Atlantic Current/Subpolar Gyre. Interestingly the drivers of this extreme anomaly were different from those associated with the earlier *Great Salinity Anomaly* of the 1970s (Dickson *et al.*, 1988).

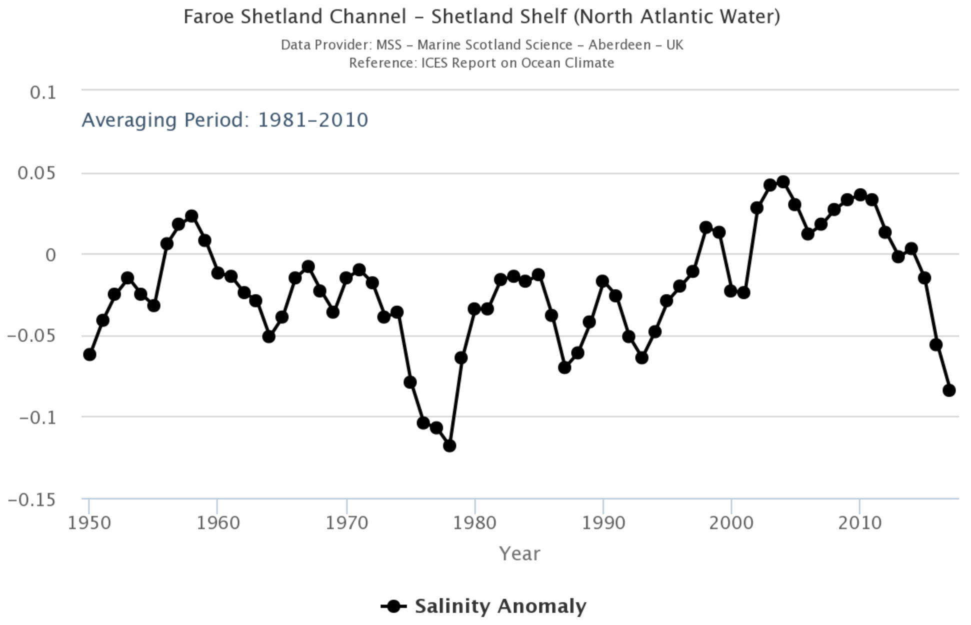


Figure 4a: Charting Progress Region 7 – Faroe Shetland Channel (61.00°N 3.00°W). Annual salinity anomaly (base period 1981–2010) of the Atlantic Water in the slope current in the Faroe Shetland Channel for the period 1950–2017. (Image sourced from IROC2017.)

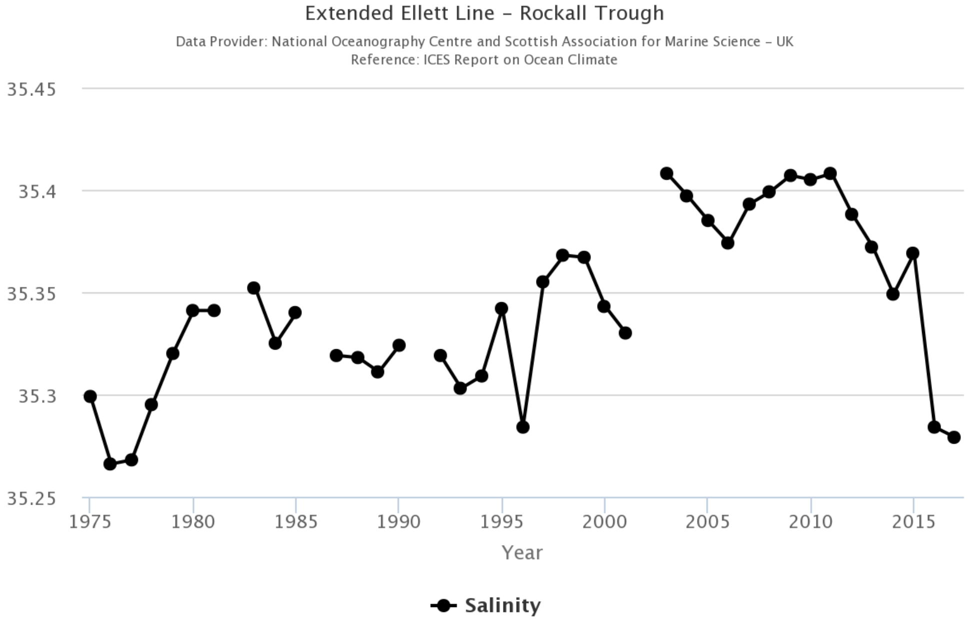


Figure 4b: Charting Progress Region 8 – Rockall Trough (56.75 °N 11.00°W). Salinity of the upper ocean (0–800 m) for the period 1975 to 2017. (Image sourced from IROC2017.)

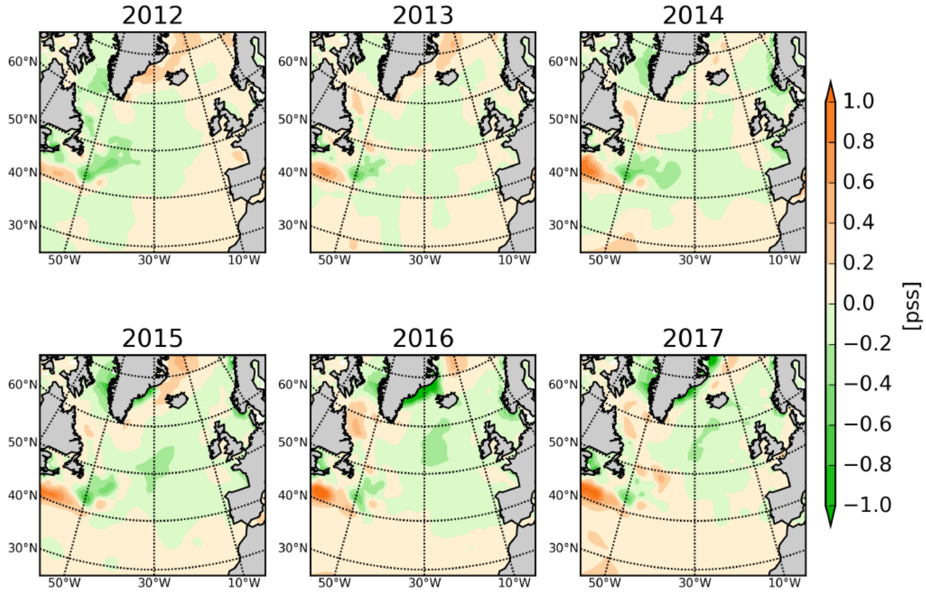


Figure 4c: Atlantic Salinity: The In Situ *Analysis System (ISAS; Gaillard* et al.*, 2016) merges available data from ARGO floats, moorings, CTDs and other* in-situ *measurements to calculate a 0.5° gridded annual salinity anomaly for the surface North Atlantic for the period 2012–2017. The baseline climatology to calculate anomalies is the World Ocean Atlas 2005 Climatology (Antonov* et al.*, 2006). (Image sourced from IROC2017 – Figure 8, Data from Coriolis.)*

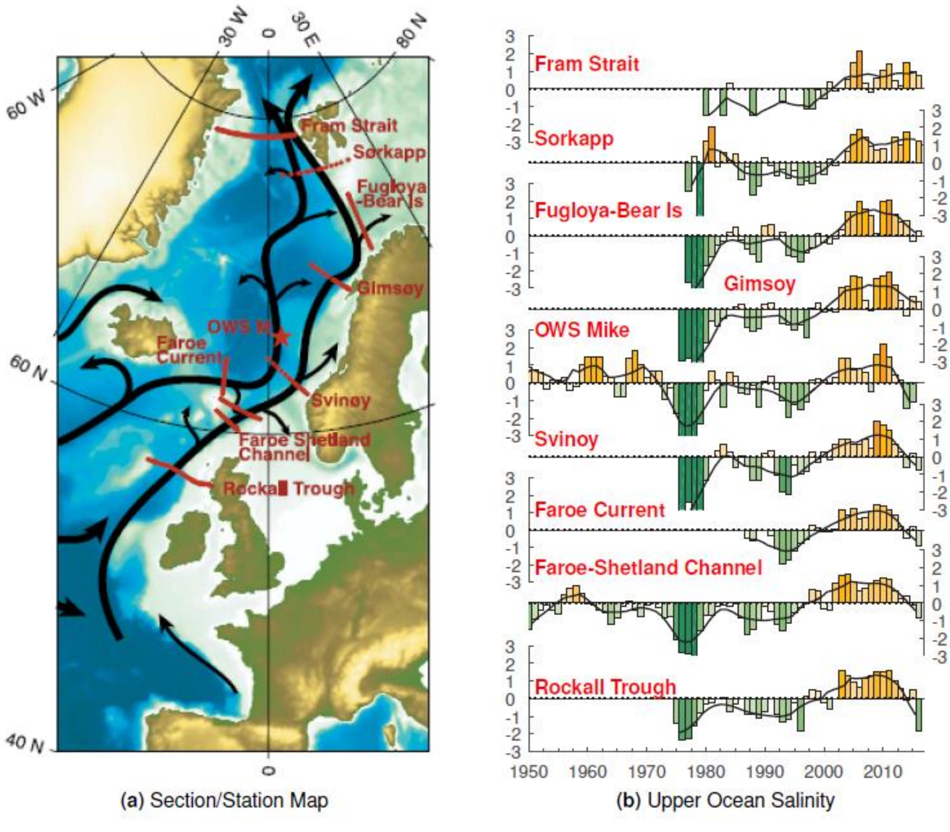


Figure 4d: Atlantic Salinity: Circulation in the eastern North Atlantic showing the pathway along the UK Shelf Edge towards the Arctic (adapted from Orvik and Niiler, 2002). The regular IROC sections are shown in red. Salinity (right) as annual normalised anomalies from the long-term mean 1981–2010. (Reproduced from Hughes et al.*, 2018, under Open Government Licence.)*

When MCCIP last reported on salinity in 2013 "*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.*"

Below 1000 m the deep ocean west of the UK and Ireland in Rockall Trough has become fresher since 1975 (Figure 5a), and Dye *et al.* (2013) suggested that this reflected a lagged response to a period of freshening in the Labrador Sea where this deep water originates (Figure 5b). Our weak expectation was that the deep water west of the UK would respond to changes in the originating waters of the Labrador Sea that has become more saline since the late 1990s (Figure 5b). This has not been borne out over the subsequent years and this layer of water has maintained a relatively stable salinity for the last seven years.

In the Faroe–Shetland Channel, deep waters (800 m) that flow from the Nordic Seas become the source for overflow of the Greenland Scotland Ridge that go on to contribute to the deep limb of the Atlantic overturning circulation (cf. accompanying MCCIP Atlantic heat conveyor (AMOC) report McCarthy *et al.*, 2020). In 2013, we reported that these waters had had a fairly stable high salinity in the 1950s and 60s, then freshened until the about the mid1990s and had since been stable at relatively low salinity. With a further seven years of data we can now see that a minimum salinity was reached in 1997 and it has since steadily increased (Figure 6).

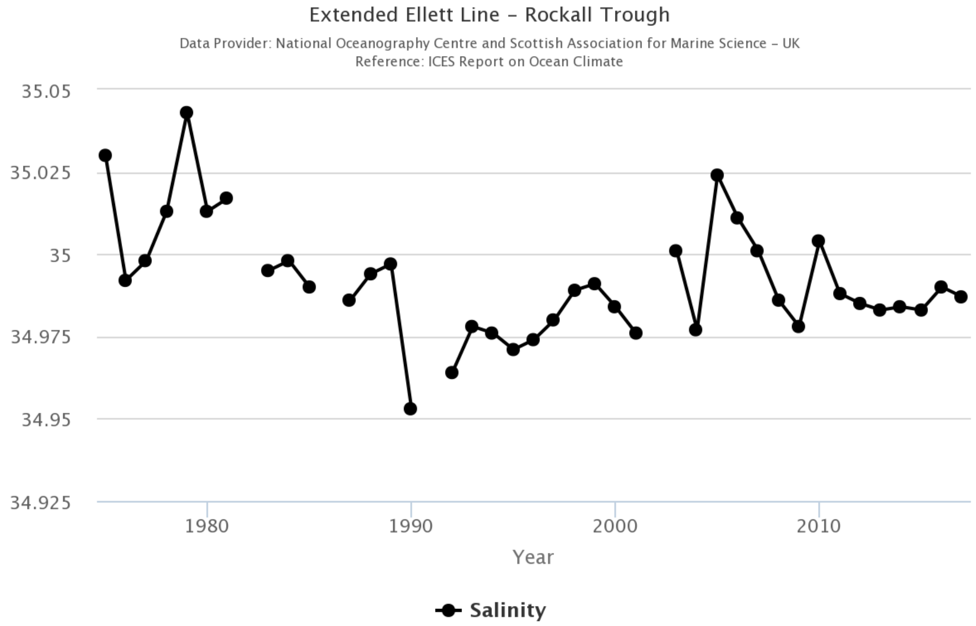


Figure 5a: Charting Progress Region 8 – Rockall Trough (56.75 °N 11.00°W). Salinity in the Labrador Sea Water layer (1800–2000 m) for the period 1975 to 2017. (Image sourced from IROC2017.)

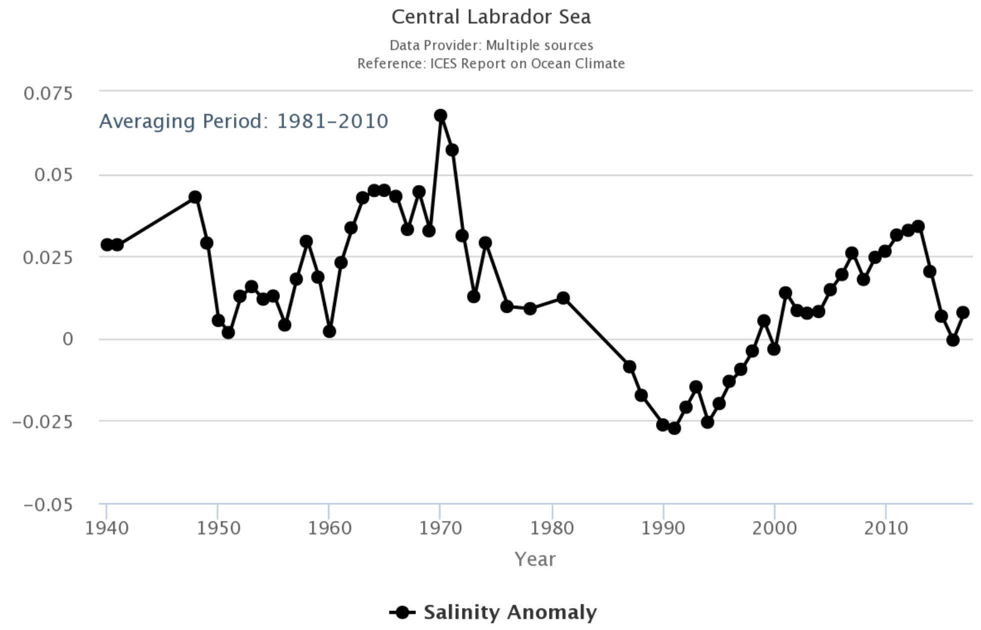


Figure 5b: Labrador Sea – Salinity anomaly in the Labrador Sea Water layer (1800–2000 m) for the period 1929 to 2017 relative to base period 1981–2010. (Image sourced from IROC2017.)

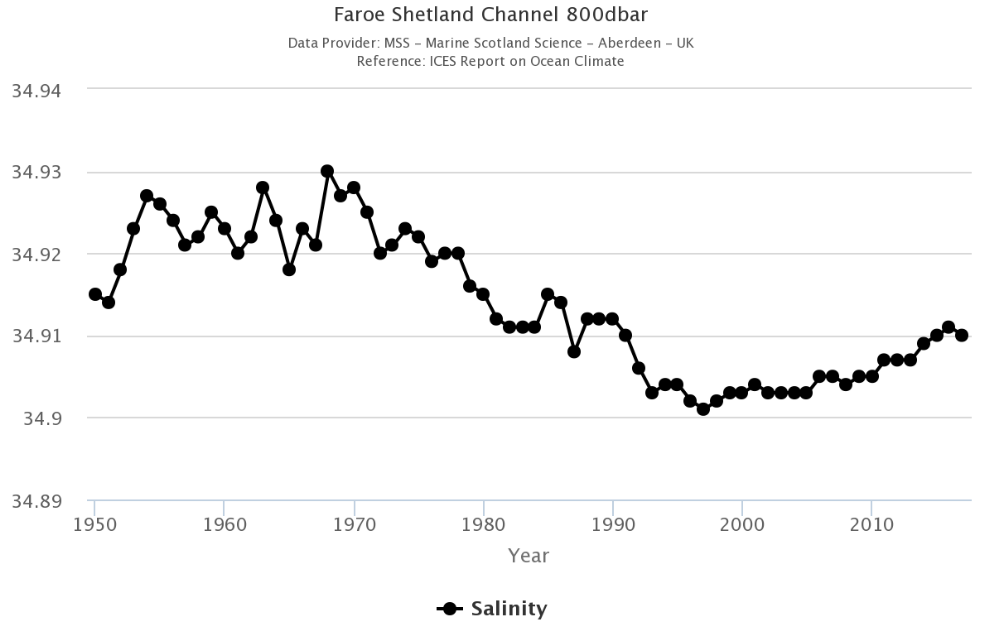


Figure 6: Charting Progress Region 7 – Faroe Shetland Channel. Salinity of overflow water at 800 m for the period 1950 to 2017. (Image sourced from IROC2017.)

Shelf Seas

North Sea (Charting Progress Regions 1 and 2)

When MCCIP last reported on salinity in 2013 the executive summary for Salinity stated: *"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."*

Despite proximity to the waters of the Faroe–Shetland Channel (Figure 4a) there are no clear multidecadal trends evident in the near-shore Fair Isle Current water (Figure 6). Over the last five years it has been fresh in character, but these years fall in line with other fresh years where the salinity is close to 34.8 rather than a clear response to the extreme decrease observed in the Atlantic's salinity. Further east, Cooled Atlantic Water enters the North Sea from the area north-east of the Shetland Islands and does show an evolution in salinity that is more similar to that seen in the Faroe–Shetland Channel (Hughes *et al*., 2018).

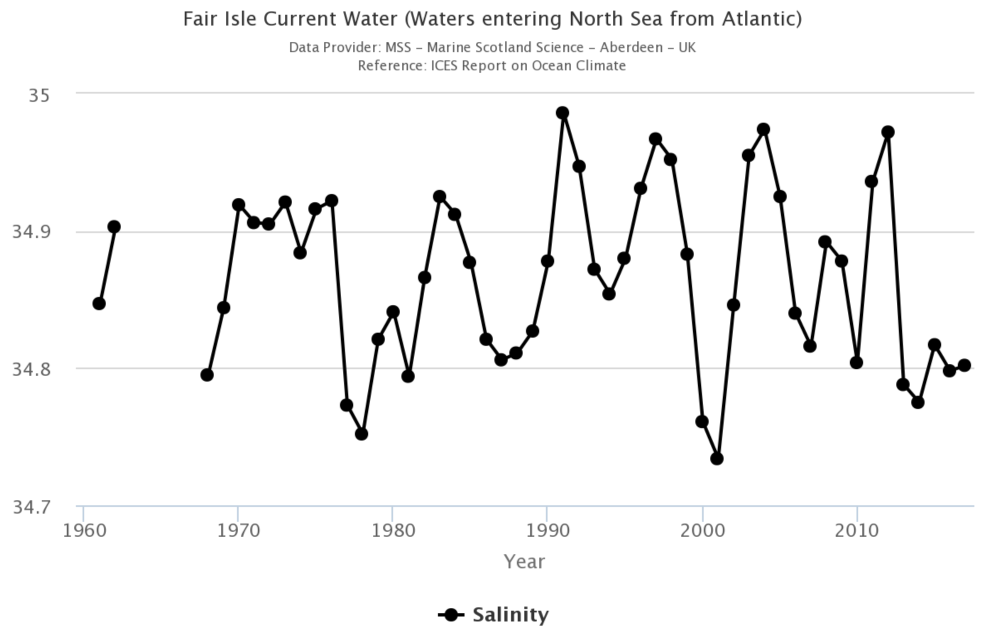


Figure 6: Charting Progress Region 1 – Northern North Sea (59.00°N 2.00°W). Salinity in the Fair Isle Current for the period 1960 to 2017. (Image sourced from IROC2017.)

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 7a, b). Here again there appears no clear long-term trend in salinity but some evidence of a low salinity period in the early 1980s.

There is coherence in the multi-annual variations between the two Southern North Sea stations (compare the fresh years in Figure 7a and b) and there are some shared features with observations in the Northern North Sea (Figure 6).

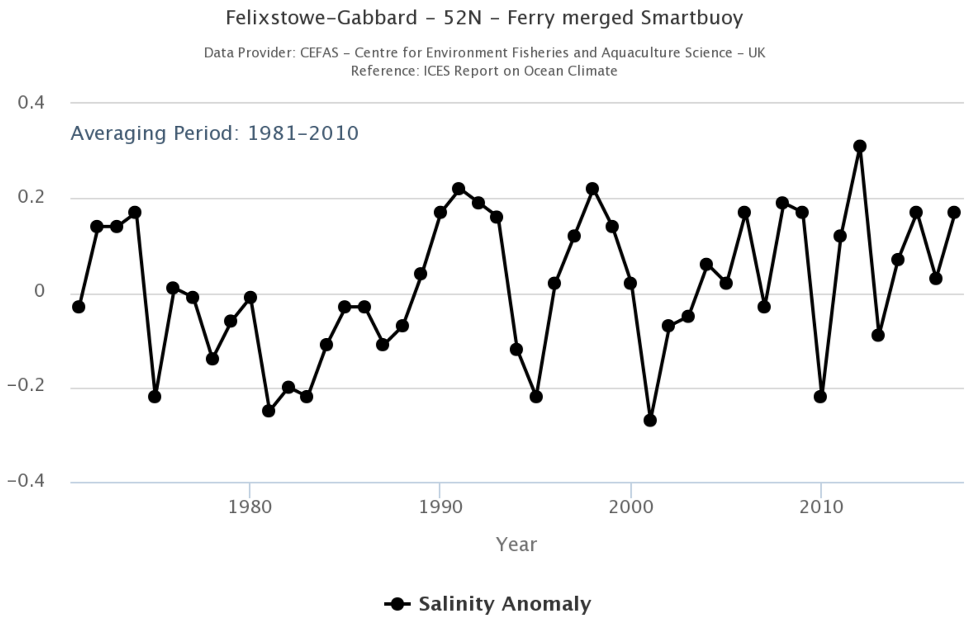


Figure 7a: Charting Progress Region 2 Southern North Sea. Sea surface salinity anomaly 1971–2017 (relative to the period 1981–2010) measured at 52°N by merging Ferry (Harwich–Rotterdam) and Smartbuoy (moored) measurements. (Image sourced from IROC2017.)

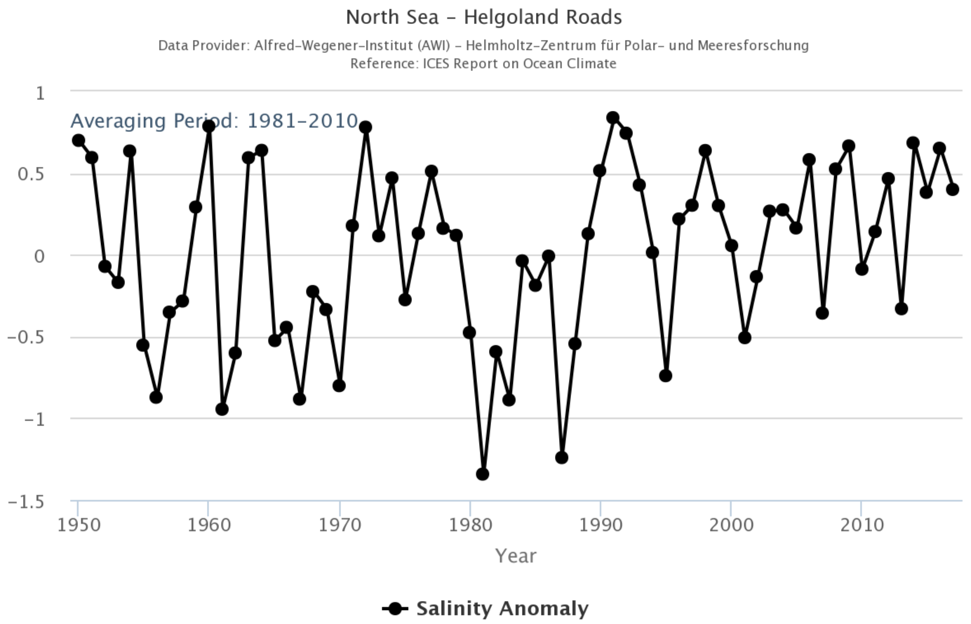
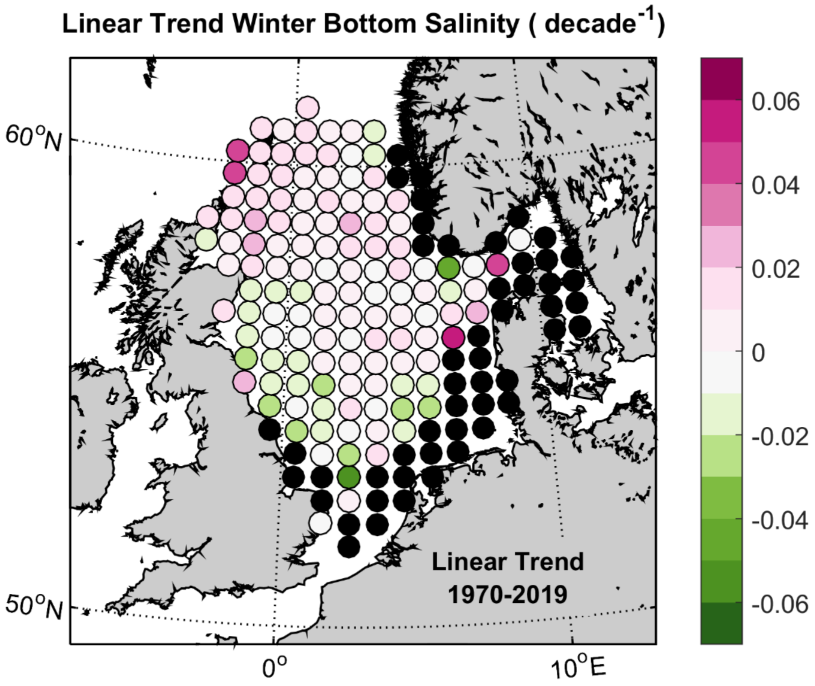


Figure 7b: Southern North Sea–Helgoland. Annual sea surface salinity anomaly at Helgoland (base period 1981–2010) for the period 1950–2017. (Image sourced from IROC2017.)

All three of the time–series datasets from the North Sea show a minimum in salinity either in the late 1970s (in Region 1, Figure 6) or early 1980s (Region 2, Figure 7a, b) as part of the Great Salinity Anomaly (Dickson *et al.*, 1988). For these data, available through 2017, there is no clear response in these shelf waters to the fresh conditions evident in the North Atlantic (Figure 4). On first inspection there also appears to be little to confirm the widespread freshening trend identified in the Copernicus re-analysis (Mulet *et al.,* 2018, Figure 2). However, the re-analysis trend is calculated over the period since 1993 a time where salinity was evidently high in the north and south of the North Sea (Figures 6, 7a, b). Furthermore, the Copernicus OMI showing average shelf salinity appears to capture the fresh-salty cycle seen in the early part of the 2000s (compare fresh conditions around 2000 with salty conditions around 2005 in Figures 3, 6 and 7).

A regular grid of wintertime bottom salinity in the North Sea is constructed from ICES International Bottom Trawl Survey data for the *Scottish Ocean Climate Status Report* (Hughes *et al*., 2018) and updated here using data up to and including 2019 (Figure 8a). This analysis does find some evidence of a freshening trend since 1970 in the Southern North Sea, but confirms the lack of any robust trend in the German Bight and Southern Bight. The early 1970s was a period of relatively high salinity in the Southern North Sea (Figure 6a, b) prior to the arrival of the Great Salinity, and this may be part of the explanation for an overall freshening trend between 1970 and 2019. The area of increasing salinity at the north-west of the North Sea is surprising given results shown in Figure 4 but may be reflecting the long-term increase in Atlantic Ocean salinity that had been evident prior to 2012–13 (Figure 4a, b, d). The salinity observed on this survey in 2019 (Figure 8a, lower panel) shows an area of particularly fresh surface water in the central Northern North Sea, in an area where the trends identified are weak and mainly positive. This fresher water may be an indication of the recent freshening that is not picked up by a simplistic trend analysis particularly for salinity where 5-year to decadal variability appears greater than the linear trend.



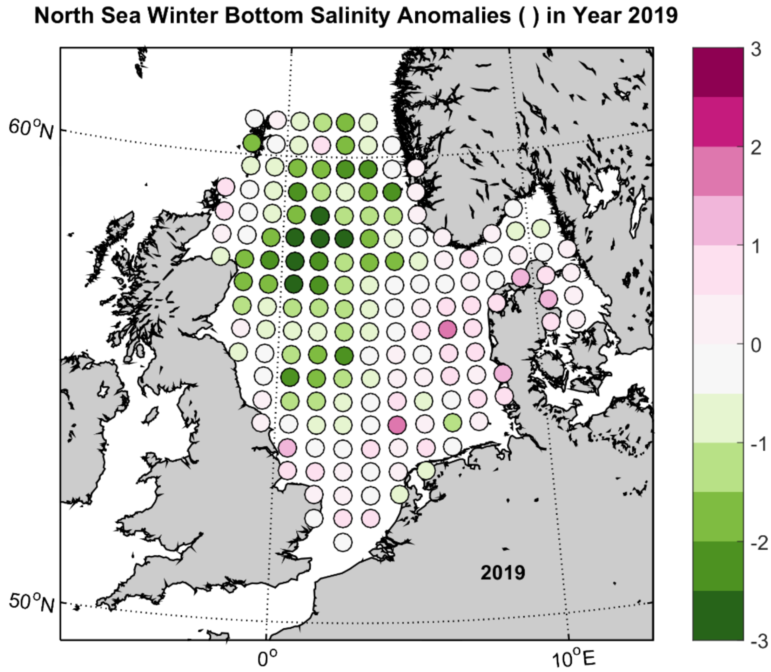


Figure 8a. Charting Progress Regions 1 and 2: North Sea Linear trend (per decade) in Winter Bottom salinity calculated from the ICES International Bottom Trawl Survey Quarter 1 data for the period 1971–2019. Values calculated from linear fit to data in ICES rectangles with more than 30 years of data. Blacked-out circles have a slope which is not significant at the 95% confidence level using Mann-Kendall non-parametric test for a trend. Bottom Panel: Normalised salinity anomaly in 2019 (1981–2010 base period). (Updated from Hughes et al.*, 2018, courtesy B. Berx, MSS.)*

The *Scottish Ocean Climate Status Report* (Hughes *et al*., 2018) presents a salinity analysis for near-shore regions around the Scottish coastline (Figure 8b). For the North Sea coastal regions variability is high, but low-pass filtering uncovers a remarkably consistent set of changes that reinforce those seen in the offshore sustained observations (Figures 6, 7). For all regions from Shetland southward along the North Sea coast to the Forth and Tay, the progression of local salinity can be characterised as: (1) early 1970s high salinity period, (2) dramatic drops in salinity in the late 1970s/early 1980s, (3) increased or increasing salinity through the late 1980s and 1990s, and (4) sustained high salinity through the 2000s into the early 2010s. All of the regions apart from the Moray Firth show salinity over the last five years reducing to levels similar to the late 1970s fresh period.

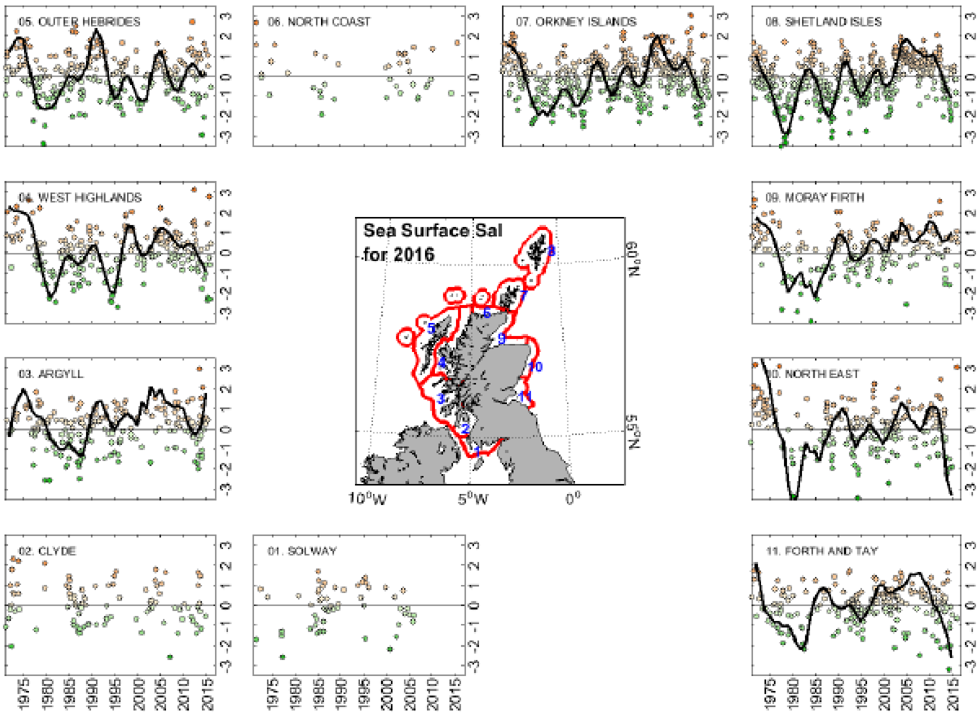


Figure 8b: Time–series of normalised annual anomalies of sea surface salinity up to 2016 (relative to 1981–2010 base period from the Ocean Data Tool (ODaT), Scottish Association of Marine Science (SAMS), Oban, UK). (Reproduced from SOCSR 2016 (Hughes et al.*, 2018) under Open Government Licence http://www.nationalarchives.gov.uk/doc/open-governmentlicence/version/3/)*

English Channel (Charting Progress Regions 3 and 4)

There are few available salinity records for Charting Progress Region 3, the eastern English Channel. Ferrybox measurements have been made, but the time–series does not extend back far enough to offer an overview of long-term variability. There are no available publications that summarise multidecadal changes in salinity for the eastern English Channel, but it would be expected to share some of the characteristics of the series in the Southern Bight of the North Sea as well as the western Channel. The COSR18 report shows this region as having no significant trend in salinity since 1993. It is difficult to know how robust the long-term variability of the reanalysis would be here as it lies between areas that Tinker *et al.* (2018) identified as performing well against observations (Southern North Sea) and less well (Western Channel). In the future as reanalyses develop, information here is likely to improve and give some estimate of long-term changes in the absence of sustained observations.

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. As part of the Western Channel Observatory (www.westernchannelobservatory.org.uk, Smyth *et al*., 2015a, b) station E1 (about 25 miles SSW of Plymouth), has been sampled since 1903 (Figure 9a) but with a large gap between the 1980s and 2000. With the latest data available since MCCIP 2013 there is no change to our main message of "no discernible long-term trend in over a century of observations". Salinity here appears to vary over multidecadal timescales and conditions since the early 2000s were of a higher than average in salinity (as previously seen in the 1910s, 50s and 70s). Until the run of 13 consecutive 'high' salinity years was ended in 2018 (Figure 9a) there was no suggestion that the freshening of the subpolar North Atlantic was having an influence.

The re-analysis (COSR18) finds a positive trend in salinity in this region between 1993–2016 which cannot be confirmed by the WCO observations due to the data gap in the 1990s, however the sustained high saline conditions between 2005 and 2016 would not dismiss this possibility. Further support is found in the comparison between the re-analysis and WCO observations shown in Tinker *et al.*, (2018, Figure 9b). The re-analysis may not reproduce all of the interannual variability (R^2<0.25) but does appear capture the relatively low salinity years in the 2003 and 2004 observations versus the high salinity years for the remainder of the 2000s.

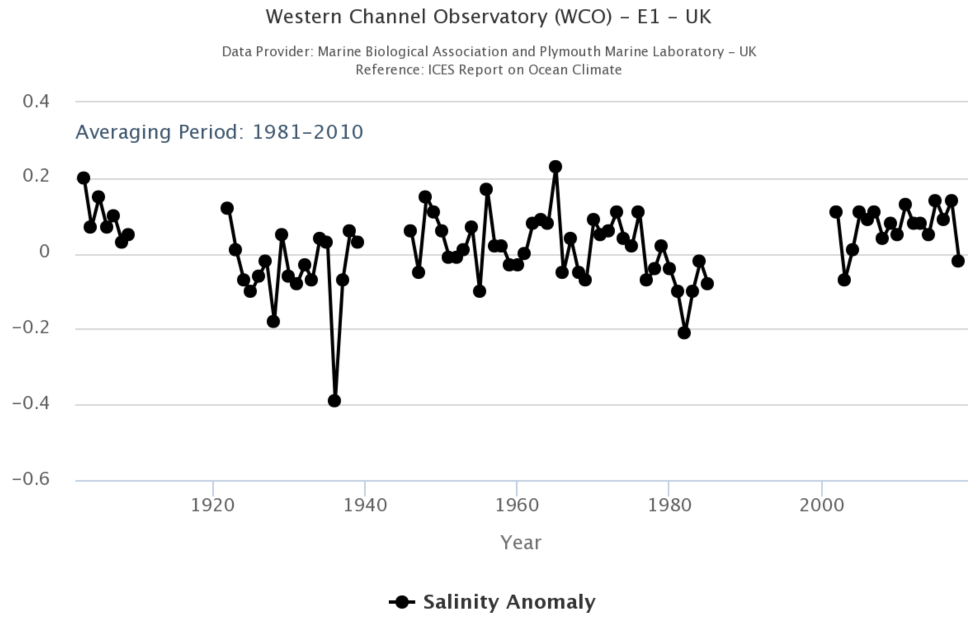


Figure 9a: Charting Progress Region 4 Western English Channel – Western Channel Observatory Station E1 (50.03°N 4.37°W). Sea surface salinity anomaly (base period 1981–2000) for the period 1903–2018. (Image sourced from IROC2017.)

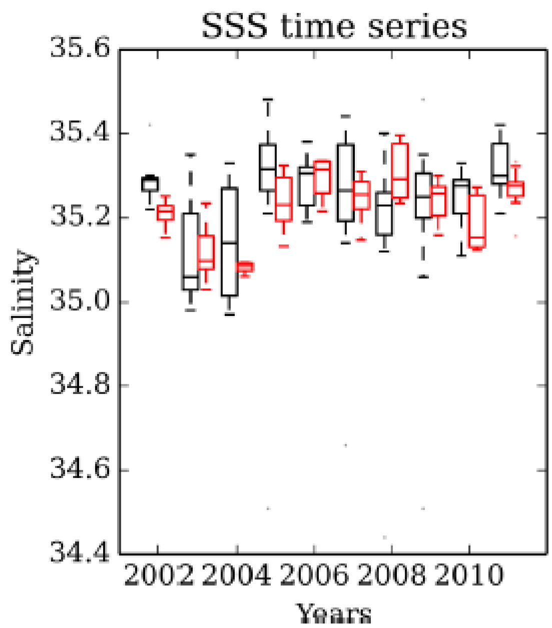


Figure 9b: Comparison of Western Channel Observatory sea surface salinity (SSS, black) with the NWS Reanalysis salinity at the same location (red). (Reproduced from Tinker et al. *(2018) under the Creative Commons Attribution 4.0 License.)*

Irish Sea (includes Charting Progress Region 5)

In the last MCCIP Salinity report in 2013, we were able to use information from the sustained observations made by the Isle of Man Government at the Cypris Station south of the Isle of Man and reported by Kennington (2012). We stated that "*No significant long-term trends have been established, though there are decadal scale variations*" picking up on a period of low salinity over the previous decade. We noted that Kennington (2012) had demonstrated a link between the winter salinity here and the winter North Atlantic Oscillation index (NAO_{DJFM}): *"… 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.)

The data and time–series for the Cypris Station are no longer available and there is no updated report on the long-term development of salinity in the Irish Sea. In the absence of new or ongoing observations then it may, in the future, be possible to use re-analysis output for the Irish Sea. Wakelin *et al.* (2016) find that the re-analysis is about 0.5 more saline than observations at Cypris Station and that at a monthly mean timescale they share almost 50% of their variability (r=0.7). Examining the trend from the re-analysis over the period 1993–2016 (Figure 2) for the region would suggest generally fresher than average conditions in the 2010s. We can infer, with limited confidence, from the reanalysis that the surface Irish Sea has not returned to conditions similar to the mid-1990s or 1960s when salinity anomalies were strongly positive at Cypris Station (as shown in the last MCCIP salinity report, Dye *et al*., 2013).

West Scotland (Charting Progress Region 6)

In 2013 we reported on the findings of Inall *et al.* (2009) which included "*Reliable continuous measurements of salinity in the Tiree passage on the west coast of Scotland started in 2002*". The short time–series study presented then did not allow any clear summary of multidecadal variability. Recently Jones and co-authors (2018) have merged the mooring based time–series with other measurements in the region to construct a Tiree Passage salinity time–series that covers the period 1976–2014 (Figure 10). The variability of this coastal time-series is high, particularly in winter but for the average salinity they find "*little seasonality and no significant decadal trend*". The important driver appears to be wind direction where they find that westerly (easterly) winds tend to bring a greater proportion of Atlantic (coastal) water making surface water here more (less) saline. They conclude that the high degree of variability is so much greater than that evident in the Atlantic surface salinity (Figure 4) that these waters are unlikely to be significantly affected.

As for the North Sea, the *Scottish Ocean Climate Status Report* (Hughes *et al*., 2018) presents a salinity analysis for near-shore regions around the western Scottish coastline (Figure 8b). The 3 regions Argyll, West Highlands and Outer Hebrides all exhibit a high variability from measurement to measurement. Hughes *et al.* (2018) does show periods of high and low salinity across the regions but without the consistency shown in the North Sea regions. There is some similarity between the west coast regions and even across to the east coast with a low salinity period in the late 1970s to early 1980s followed by relatively high salinities around 2000.

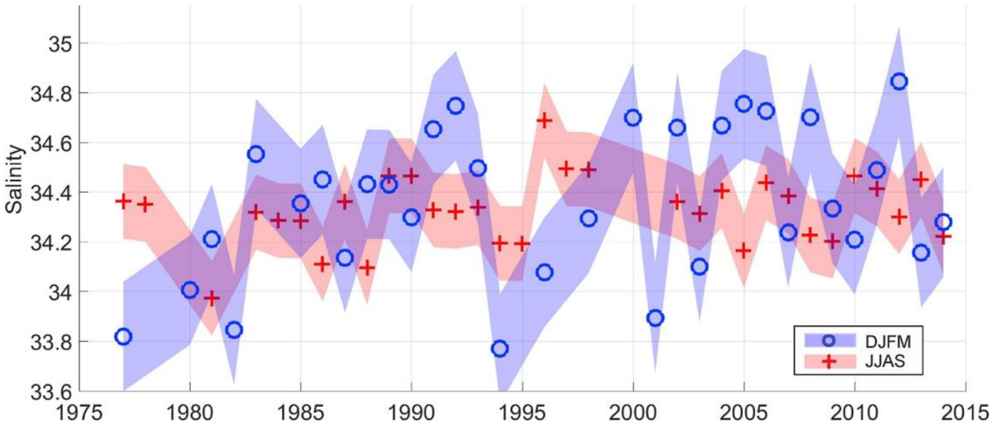


Figure 10: Tiree Passage salinity composite time–series (1976–2014) using moored instruments (post 2002) merged with CTDs (Conductivity, Temperature and Depth profiles 1976-2014). Winter (Dec-Mar) versus summer (June–Sept) shaded by standard deviation. (Image modified from figure 4 of Jones et al.*, 2018 under licence CC BY 4.0 https://creativecommons.org/licenses/by/4.0/)*

2. WHAT COULD HAPPEN IN THE FUTURE?

The last MCCIP salinity report (Dye *et al*., 2013) summarised the situation then:

"*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.*"

These results were based on the UK Climate Projections 2009 (Lowe *et al*., 2009; Holt *et al*., 2010) with some support for the finding freshening over the coming century from other studies (Friocourt *et al*., 2012; Gröger *et al*., 2013). The findings were hard to judge as the UKCP09 projections used a single model run and this run had limited variability in the ocean boundary forcing, effectively maintaining the inflowing salinity at present and future average conditions (Holt *et al.*, 2010).

An updated model was published and validated in 2015 (Tinker *et al*., 2015) with much improved representation of the boundary forcings (Figure 11). In this system a regional climate model (HadRM3) is driven by HadCM3, one of the Met Office Hadley Centre's global climate models. A river routing model (TRIP) is in turn driven by the regional model. These three models then provide a consistent climate that drives the shelf-sea climate model (POLCOMS) from the ocean boundary, atmosphere and rivers (freshwater). They concluded that the modelling system's representation of salinity was "*fit for the purpose of providing centennial climate projections for the northwest European shelf seas*". This confidence had two caveats for salinity as the authors identified that the Norwegian Trench and Skagerrak were poorly represented and that the absolute mean salinity should be interpreted with care.

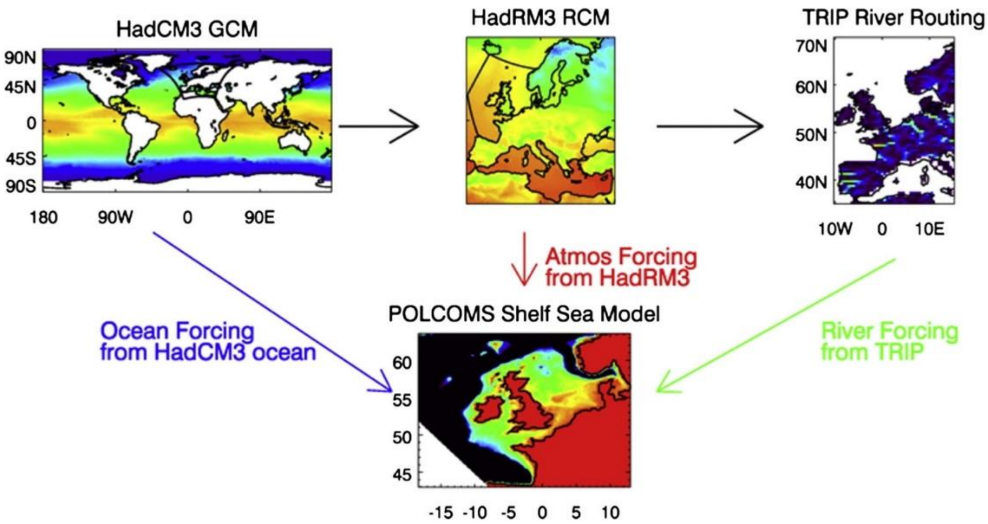


Figure 11: Consistent forcing for the shelf-sea climate models. (Reproduced from Tinker et al., 2015 under licence CC BY-NC-ND 4.0 https://creativecommons.org/licenses/by-nc-nd/4.0/)

This model system was then used to generate an updated projection in the form of an 11-member ensemble (11 separate runs) under the medium emissions (SRES -A1B) climate scenario (Tinker *et al*., 2016). The ensemble approach allowed them to assess two of the key statistical uncertainties in the projections. Firstly, the ensemble variability gives an indication of the uncertainty associated with model parameters in the driving global climate model. Secondly, the multiple transient runs lead to much improved understanding of the interannual variability in the modelled parameters. The salinity projections are summarised in Figure 12 and Table 1, and overall demonstrate that the suggestion of freshening for UK shelf seas found in the earlier studies (Holt *et al.*, 2010) is reproduced and strengthened (a change in the annual mean of –0.41 psu rather than –0.19 psu). The freshening is generally stronger in the North Sea and for Atlantic waters off-shelf to the north and west of Scotland. Off-shelf waters also tend to exhibit the greater uncertainties, both in ensemble variance and in interannual variability. In an additional analysis of the significance of the change versus interannual to multiannual variability (Figure 13) Tinker *et al.* (2016) illustrate that the changes in the western shelf (Channel, Celtic Sea, Irish Sea) are less clear than in the North Sea. This differs from their findings for SST where temperature changes are more similar across the whole shelf, and this is because salinity is more dependent on advective changes.

Examining the causes of the change across the ensemble, Tinker *et al.* (2016) could not find evidence that the freshening was associated with changes in regional climate drivers such as the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Atlantic Meridional Overturning Circulation (AMOC), precipitation–evaporation balance (P-Ev), stormtrack strength or location. The projected changes were most closely linked to the Equilibrium Climate Sensitivity (ECS) of the global model, the members of the ensemble with highest ECS showed the strongest projected freshening. These members of the ensemble exhibited changes in the ocean circulation and strongest freshening in the open Atlantic to the north-west of the UK Shelf. A further projection (also medium emissions scenario SRES A1B) using a different model (Mathis and Pohlman, 2014) also finds significant century scale freshening in the North Sea (–0.6 psu) and also associates this with changes in the salinity of the Atlantic alongside changes in Baltic discharge and increased precipitation.

The dominance of the Atlantic circulation as the cause for the general freshening of the shelf seen in the projections has recently been explained by Holt and co-authors (2018). They run experiments on model projections that show the decrease in salinity (e.g. reaching –1 psu in the North Sea the run shown in Figure 15). The projections show a "*shutdown of the exchange between the Atlantic and the North Sea and a substantial decrease in the circulation of the North Sea in the second half of the 21st century*" (Holt *et al.*, 2018). They diagnose this as positive (but not runaway) feedback whereby ocean scale circulation changes and a fresher North Atlantic decreases the salinity of the surface water at the northern boundary of the North Sea and reduces the density driven flow of oceanic water onto the shelf. The overall result for the shelf is reduced salinity as the circulation becomes more estuarine.

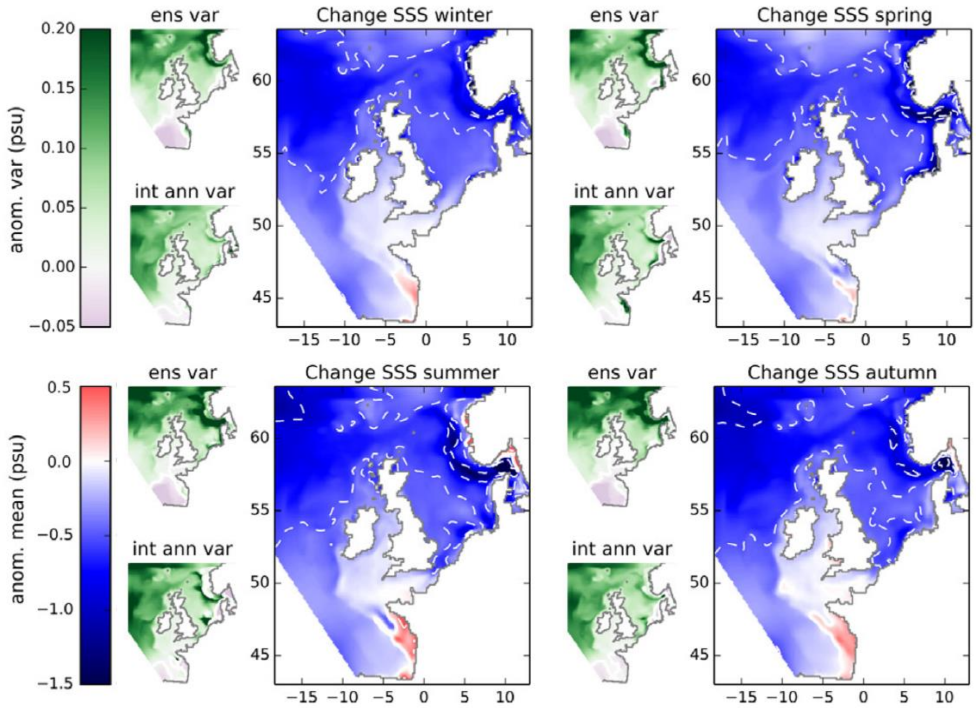


Figure 12: Projections of seasonal change in Sea Surface Salinity (SSS) between the period 1960–1989 and 2070–2098. Ensemble mean change in the main panels, blue-red colour-scale. Small panels show the ensemble variance and the interannual variance, white-green colour-scale (modified from Tinker et al., 2016 under Open Government Licence http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/)

Table 1. Ensemble mean change (±2 std) in annual SSS and NBS by the end of century (2069–2098 relative to 1960–1989) by region. (Tinker et al.*, 2016.)*

Change in Annual	Shelf	Southern North Sea (Region 2)	Central North Sea (Region 2)	Northern North Sea (Region 1)	English Channel (Regions 3 and 4)	Celtic Sea (Region 4)	Irish Sea (Region 5)
Surface Salinity (SSS)	-0.41 (±0.47)	-0.51 (±0.61)	-0.48 (±0.53)	-0.62 (±0.65)	-0.08 (±0.25)	-0.18 (±0.27)	-0.11 (±0.23)
Near Bottom Salinity (NBS)	-0.33 (±0.38)	-0.49 (±0.58)	-0.47 (±0.48)	-0.52 (±0.52)	-0.08 (±0.24)	-0.18 (±0.26)	-0.03 (±0.19)

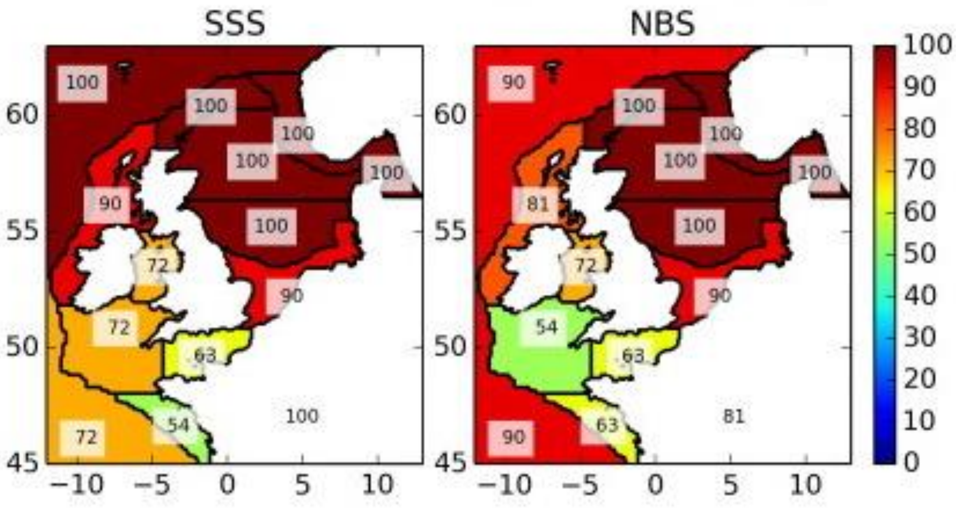


Figure 13: Percentage of the ensemble for which the change in SSS and NBS over the 1960–1989 and 2070–2098 is significant (95 percentile) versus the interannual variability (Modified from Tinker et al.*, 2016 under Open Government Licence http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/)*

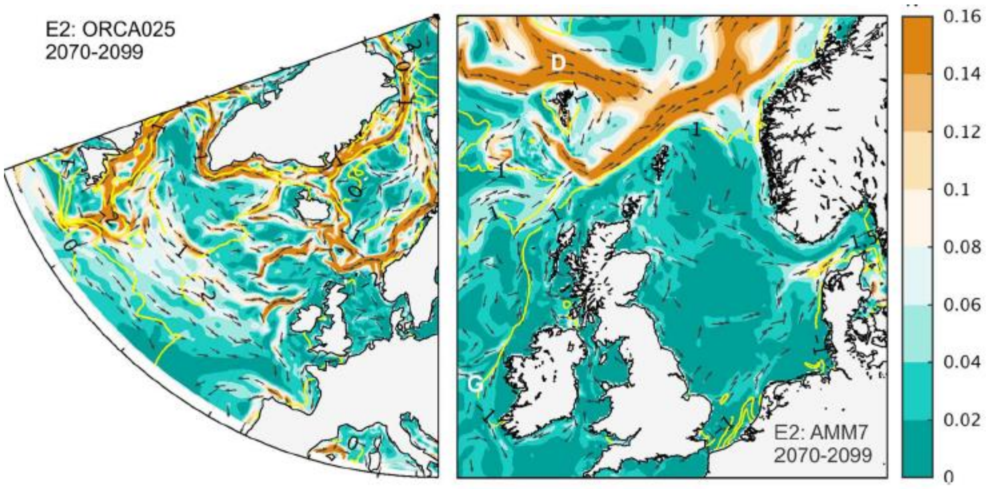
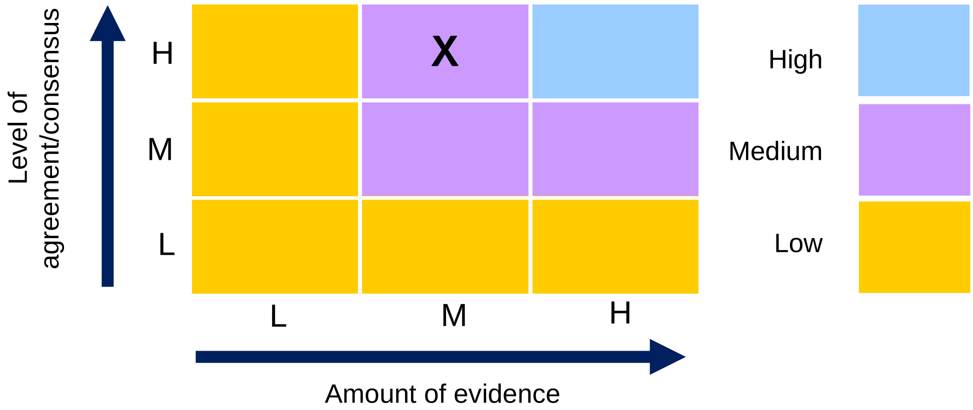


Figure 14: Example of future upper 200 m currents in global climate model (left panel) that drives the boundaries of a regional shelf sea model (right panel) and change in surface salinity (yellow contours). Reproduced from Holt et al.*, 2018. under licence CC BY 4.0 https://creativecommons.org/licenses/by-nc-nd/4.0/*

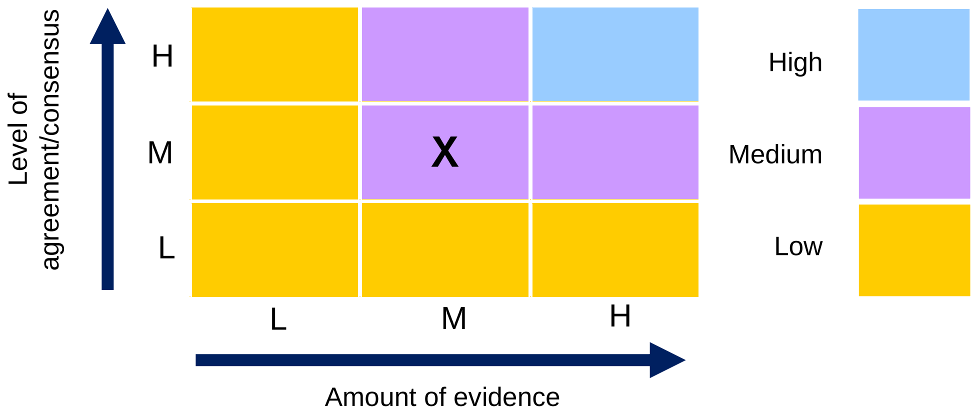
3. CONFIDENCE ASSESSMENT

What is already happening



The assessment here remains similar to that made in 2013. There are some places where there are fewer observations than were previously available, but this loss of confidence is made up by additional new sources of information, whether that be availability of status summaries and re-analysis (Hughes *et al*., 2018; Mulet *et al*., 2018), new time–series construction (e.g. Jones *et al*., 2018, Reverdin *et al*., 2018) or new tools (e.g. ODaT). In general, there is a high level of consistency between the different sources, with apparent differences mainly associated with linear trend calculations over different periods in the presence of high multi annual to decadal variability.

What could happen in the future?



The assessment here reflects an increase in confidence in the projection of change in salinity. What was a weak diagnosis of centennial-scale freshening has been reproduced in multiple and more-detailed studies. The scale of the freshening also appears to be stronger and our understanding of the driver of this change has been improved.

4. KEY CHALLENGES AND EMERGING ISSUES

1. Understanding the Atlantic–Shelf sea connection. The projection models consistently identify a link between UK shelf sea salinity change and the circulation of the North Atlantic. Recent observations of changes in North Atlantic salinity are not so clearly affecting the conditions on the shelf. A much clearer picture of the ocean-shelf exchange processes that drive multiannual variability and long-term trends in the shelf seas is needed.
2. Some areas of the shelf seas remain under reported. It is likely that more data is available from sustained observations but not analysed for multidecadal salinity change.
3. Analysis tools and data hindcast re-analysis – the re-analysis products (Copernicus) and data analysis tools (e.g. ODaT) have demonstrated their potential utility in assessing change. The communication of change through key metrics will also have to be improved so that the assessments can be used by decision makers. For example, salinity simple linear trend analysis over multiple decades is not always the best way to illustrate change. More, and improved, reanalysis information will become available and we need the tools in place to use them. It is likely that by next MCCIP report a new reanalysis based on the higher resolution Met Office AMM15 will be available.

ACKNOWLEDGEMENTS

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