Reversal of the 1960s - 1990s Freshening Trend in the North-east North Atlantic and Nordic Seas

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Abstract

Hydrographic time series in the north-east North Atlantic and Nordic Seas show that the freshening trend of the 1960s-1990s has completely reversed in the upper ocean. Since the 1990s temperature and salinity have rapidly increased in the Atlantic Inflow from the eastern subpolar gyre to the Fram Strait. In 2003-2006 salinity values reached the previous maximum last observed around 1960, and temperature values exceeded records.

The mean properties of the Atlantic Inflow decrease northwards, but variations seen in the eastern subpolar gyre at 57°N persist with the same amplitude and pattern along the pathways to Fram Strait. Time series correlations and extreme events suggest a time lag of 3-4 years over that distance. This estimate allows predictions to be made; the temperature of Atlantic water in the Fram Strait may start to decline in 2007 or 2008, salinity a year later, but both will remain high at least until 2010.

1. Introduction

A 30-year period of freshening of the North Atlantic and Nordic Seas has been documented by Curry et al (2003) and Curry and Mauritzen (2005). The 1960s to 1990s freshening occurred in surface, intermediate and deep water masses, and approximately half occurred during the Great Salinity Anomaly (GSA) in the 1970s (Dickson et al 1988). In the same 3 decades sub-tropical Atlantic salinity had been increasing, thought to be due to a change in the precipitation-evaporation balance (Curry et al, 2003). An investigation of the total freshwater budget of the North Atlantic and Arctic (subpolar and subtropical North Atlantic, Nordic Seas and Arctic Ocean) suggested that changes in freshwater content can be explained entirely in terms of changes in ice melt, river discharge and net precipitation (Peterson et al, 2006), while ocean circulation advects high or low salinity features within the basins.

Ten years on from the mid-1990s there exist sufficient new observations to demonstrate that the freshening trend ended in the upper ocean in the mid-1990s. There are a growing number of reports of increasing salinity at various separate locations within the upper ocean of the subpolar gyre and Nordic Seas, including the Labrador Sea (Avsic et al, 2006) and the Norwegian and Barents Seas (Skagseth et al, *in press*). Hátún et al (2005) showed increasing salinities up to 2003 in the eastern subpolar gyre, and increasing temperatures in the Atlantic water flowing into the Arctic Ocean have been reported (Polyakov et al, 2005, Walczowski and Piechura, 2006). Boyer et al (2007) provide a overview of basin-scale changes in freshwater content that include a recent (since 1993) decrease in the freshwater content of the 0-2000 m layer of the subpolar North Atlantic and Nordic Seas. Bethke et al (2006) use an atmosphere-ocean general circulation model to describe a scenario of increasing salinity at 0-1000m in the northern North Atlantic and Nordic Seas under global warming conditions.

In this synthesis of historical and new observations across an inter-basin region from the Rockall Trough to the Fram Strait, we will show that in the decade to 2006, the upper ocean freshening of the previous 30 years was reversed, until salinities of the Atlantic Inflow were as high as the maximum last observed around 1960. The coherence of the variability on annual to decadal time scales across the region is demonstrated by tracing anomalies along advection pathways.

2. Intense warming and increasing salinity in the northern seas

From the Rockall Trough to the Fram Strait there are several open-ocean hydrographic sections and stations that have been occupied regularly on timescales from monthly to yearly over a number of decades (Figure 1, and auxiliary material). The observations together form a picture of property changes over the inter-basin region and can be examined for large scale fluctuations with time. Data collection and analysis methods for each time series are given in Hansen et al (2003), Holliday et al (2000), Ingvaldsen et al (2003), Mork and Blindheim (2000), Osterhus and Gammelsrod (1999), Schauer et al (2004) and Turrell et al (1999).

The route by which Atlantic water flows towards the Arctic has been described as follows (Figure 1). The North Atlantic Current brings warm saline subtropical water into the eastern subpolar gyre by two main routes. An indirect route takes NAC water into an intergyre region where it is recirculated and modified before flowing northwards through the Rockall Trough (Eastern North Atlantic Water, ENAW), and a more direct route runs through the Iceland Basin (Western North Atlantic Water, WNAW), where it undergoes significant modification and mixing with subpolar water masses (Pollard et al, 1996, McCartney and Mauritzen, 2001, Pollard et al, 2004). There is mixing between the two branches; during some periods, part of the WNAW branch enters the southern Rockall Trough where it cools and freshens the eastern branch, and at other times the eastern branch spills into the Iceland Basin where conversely it increases temperature and salinity (Holliday, 2003). The two major branches travel northwards over the Iceland-Scotland ridge and they are observed in the deepest gap, the Faroe-Shetland Channel. There two water masses are described. The cooler fresher Modified North Atlantic Water (MNAW) originates mainly in the Iceland Basin and flows anticyclonically around the Faroe Plateau in the Faroe Current before being deflected southwards into the Channel. The warmer more saline North Atlantic Water (NAW) is carried from the Rockall Trough mainly in the shelf-edge current. There is some exchange between the two branches.

From the sill they continue into the Nordic Seas as the Norwegian Atlantic Current (NwAC, Hansen and Østerhus, 2000). The NwAC has two main cores which continue the poleward progression to the Fram Strait, a largely barotropic eastern current that follows the continental shelf break, and a largely baroclinic current that is steered along various submarine ridges (Orvik and Niiler, 2002). Some flow in the barotropic eastern NwAC separates off into the Barents Sea and forms one route of Atlantic inflow to the Arctic Ocean. The eastern NwAC becomes the West Spitsbergen Current (WSC). Walczowski et al (2005) suggest the topographically steered, baroclinic western branch rejoins the WSC in Fram Strait where a significant portion of the Atlantic inflow rapidly recirculates southwards (Schauer at al, 2004), while the rest enters the Arctic Ocean.

Figure 2 summarises the conditions along the pathway of the Atlantic Inflow in the form of annual upper ocean temperature and salinity anomalies at the hydrographic sections and stations. The anomalies are normalised with respect to the standard deviation from the long-term mean, defined as 1978-2006. For the two shortest time series (Faroe Current and Fram Strait) the mean period is 1988-2006. Tests showed that the results are not sensitive to the different mean period. The anomalies relate to slightly different parameters of the water column for each section, (within a depth range, or properties at the salinity maximum). Each parameter has been deliberately chosen to best represent the properties of the Atlantic inflow water at that location and full details are given in the auxiliary material.

The visual impression given by Figure 2 is of a cross-region, coherent multi-decadal evolution of temperature and salinity. This evolution is characterised by a maximum in the late 1950s, a minimum in the mid-1970s (the GSA), and increasingly high values in the most recent years (mid-2000s). Most notably the recent decade of 1996 to 2006 has been one of rapidly increasing temperature and salinity, reversing the earlier long term freshening trend. During the middle years of the 2000s decade, the salinity and temperature of the upper ocean at all locations across this vast area of the ocean (spanning over 20° of latitude) reached the highest recorded for 50 years. The longest time series emphasise minima in the 1970s, whereas the shorter time series emphasise the very rapid increase during 1996-2006.

3. The progression of Atlantic Inflow from the sub-polar gyre to the Fram Strait

The spatial distribution of the long-term time series allows an examination of the downstream progression of Atlantic inflow water. The sampling is imperfect; the sections are widely spaced, are of varying timespans, and usually under-sample the seasonal cycle. But despite these difficulties, co-ordinated patterns emerge from the data when taken as a whole, and when considering the interannual to decadal scale changes. The spatial coherence of patterns of interannual variability can be investigated both by calculating section-to-section correlations of annual averages of temperature and salinity for a range of time lags, and by examining the passage of extreme events. Of the statistics described, only relationships that are significant at 95% confidence level are accepted as probably meaningful.

The Atlantic Inflow origins in the eastern subpolar gyre take the form of the following water masses; the mix of ENAW and WNAW in the Rockall Trough, and the two types of Atlantic water (NAW and MNAW) as they pass into the Nordic Seas through the Faroe-Shetland Channel. Figure 3 illustrates the development of their properties over the last 4 decades. Concurrent changes in the Rockall Trough and Iceland Basin occur as a result of east-west movements of the subpolar front as follows. When the front moves westwards, it allows more of the warm saline ENAW water to enter the Iceland Basin, and less of the cooler fresher WNAW water to enter the Rockall Trough (Bersch, 1999, Holliday, 2003, Hátún et al, 2005). When the front moves eastwards it carries WNAW into the Rockall Trough and reduces the ENAW flux into the Iceland Basin making them both cooler and fresher. Figure 3 shows that in the short distance between the northern Rockall Trough and the Faroe-Shetland Channel the properties are changed very little.

North of the Iceland-Scotland sill, the Atlantic Inflow is heavily modified by heat and freshwater exchange with the atmosphere and by mixing with fresh coastal currents and recirculating Arctic waters. The overall reduction in mean temperature and salinity is clear (Figure 3), but the widescale coherence to the pattern of interannual to decadal salinity signal is also evident. The conditions in the southern Norwegian Sea co-vary with the Inflow at the sill (significant correlations at < 1 year time lag between MNAW and Ocean Weather Station Mike (OWS M), and at time lags of up to 2 years between NAW at the sill and the series at Svinøy and Gimsøy). The statistical relationship between the variability in the subpolar waters and the Nordic Seas seems to break down as the inflow passes into the Northern Norwegian Sea; there is no statistically significant correlation between the NAW in the Faroe Shetland Channel and the Atlantic Inflow at Sørkapp. Similarly there is a significant correlation between the salinity and temperature series in the Rockall Trough and Svinøy (up to 3 years) but none between Rockall Trough and Sørkapp. This probably reflects a change in mechanisms that dominate the year-to-year variations in properties. However the extreme events which dominate the multi-year variability (e.g. 1970s GSA, 1990s low salinity, 2000s high salinity) can be seen from Rockall Trough through the Norwegian Sea sections. The passing of the extrema is illustrated in Figure 4 which shows Hovmoeller diagrams of normalised salinity and temperature anomalies. The figure shows that the peaks of the extrema typically take around one year to get from the north-eastern subpolar gyre (Rockall Trough and Faroe-Shetland

Channel) to the southern Norwegian Sea (OWS M) and 2 more years to reach the northern Norwegian Sea (Sørkapp).

The eastern NwAC continues northwards and becomes the West Spitsbergen Current (WSC). South of the Fram Strait the western branch joins the WSC to form the Atlantic Inflow there. The time series of properties in the Fram Strait is short and sparse in the early years but the statistics show the expected results. There are statistically significant correlations between the southern Norwegian Sea and the WSC in the Fram Strait (up to 2 year lags). Of the extreme events, only the 1990s low salinity and the 2000s high salinity periods are easily visible in the Fram Strait time series. The lowest salinity was seen in 1997, one year after the extreme event passed through the northern Norwegian Sea, and 4 years after it passed through the Faroe-Shetland Channel.

Discussion and Conclusions

The correlations between temperature and salinity time series along the pathway of the Atlantic Inflow confirm the visual impression given by the figures; that interannual to decadal scale patterns of variability have a large-scale coherence. Time lags along the pathway can be explained by the net advective speed of the Atlantic Inflow. The statistics imply a total time lag from the north-eastern subpolar gyre to the Fram Strait of 3-4 years, a result supported by the estimated 4-year lag from the passage of extreme events. The result is in agreement with earlier conclusions from shorter time series (e.g. Dickson et al, 1988 and Furevik, 2001).

The time lag estimate allows us to make some short-term empirical predictions about conditions at the entrance to the Arctic Ocean. The Faroe-Shetland Channel salinity began to increase in 1996, reached a peak in 2004, and showed a slight decrease since then (2005-2006). Temperatures peaked in 2003 but remained high in 2005 and 2006. We can therefore predict that Fram Strait temperature may start to decline in 2007 or 2008, while salinity will peak a year later, but both will remain high at least until 2010.

It is no surprise that a longer time series will reveal lower frequency variations. The longest time series shown in Figure 2 show the multi-decadal evolution of Atlantic Inflow properties whereas the shorter time series emphasise the 1-5 year variations. With 10 years more data, the documented ~30 year freshening trend appears to be one part of the multi-decadal-scale pattern. The smoothed fits suggest that while the cooling/freshening took around 30 years (1960s to 1990s), the equivalent increase in salinity and temperature may have happened more quickly (1990s to 2000s). This is reflected in the steeply increasing properties in the shorter time series. However this conclusion is heavily dependent on the end points of the time series and the chosen fit, so should be treated with caution.

In general, the temperature and salinity properties of the upper ocean co-vary, but it is notable that while salinity has returned to high values previously recorded around 1960, temperature has exceeded values in all the time series. There is some evidence of a maximum in both properties being reached recently; temperatures and salinity have decreased slightly at the more southern locations since 2003 or 2004, but the interannual variability overlying the multi-decadal scale pattern means it will be several years before we can conclude whether a new maximum has passed.

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Figure Captions

Figure 1. Schematic of the major pathways of Atlantic Inflow Water from the eastern subpolar gyre through the Nordic Seas (adapted from Orvik and Niiler, 2002). Regularly occupied hydrographic sections and stations are shown in red.

Figure 2. Time series of upper ocean temperature anomalies (left panel) and salinity anomalies (right panel) from sustained ocean observations along the pathways of Atlantic Inflow from the Rockall Trough (bottom) to the Fram Strait (top). Locations of sections are shown in Figure 1. Data are presented as normalised anomalies from the long-term mean (1988-2006 for Faroe Current and Fram Strait, 1978-2006 for all others).

Figure 3. Time series of temperature (left panel) and salinity (right panel) in the Atlantic Inflow from the eastern sub-polar gyre to the Fram Strait.

Figure 4. Hovmoeller diagrams of normalised subsurface temperature and salinity anomalies from the sections and stations in Figure 1. Data are presented as normalised anomalies from the long-term mean (1988-2006 for Faroe Current and Fram Strait, 1978-2006 for all others). The latitude of the time series are given by the dashed lines.

Figures

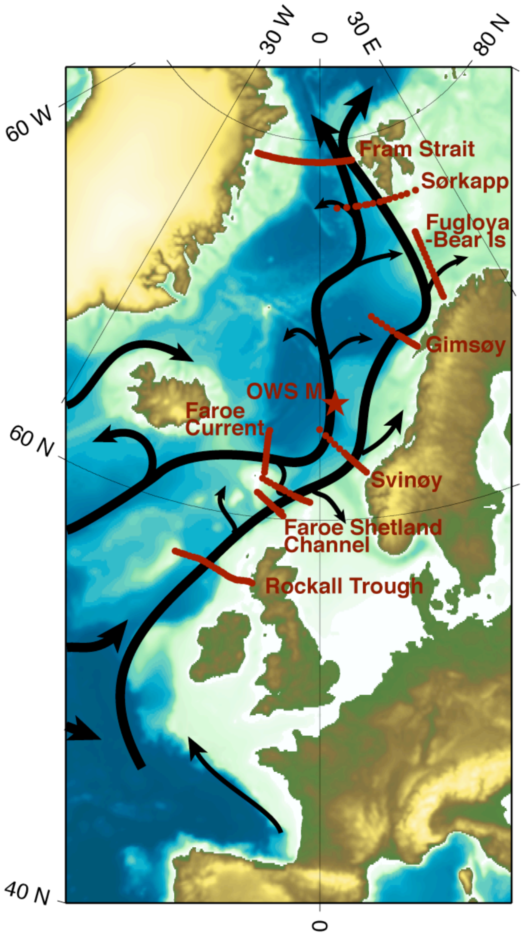

Figure 1.

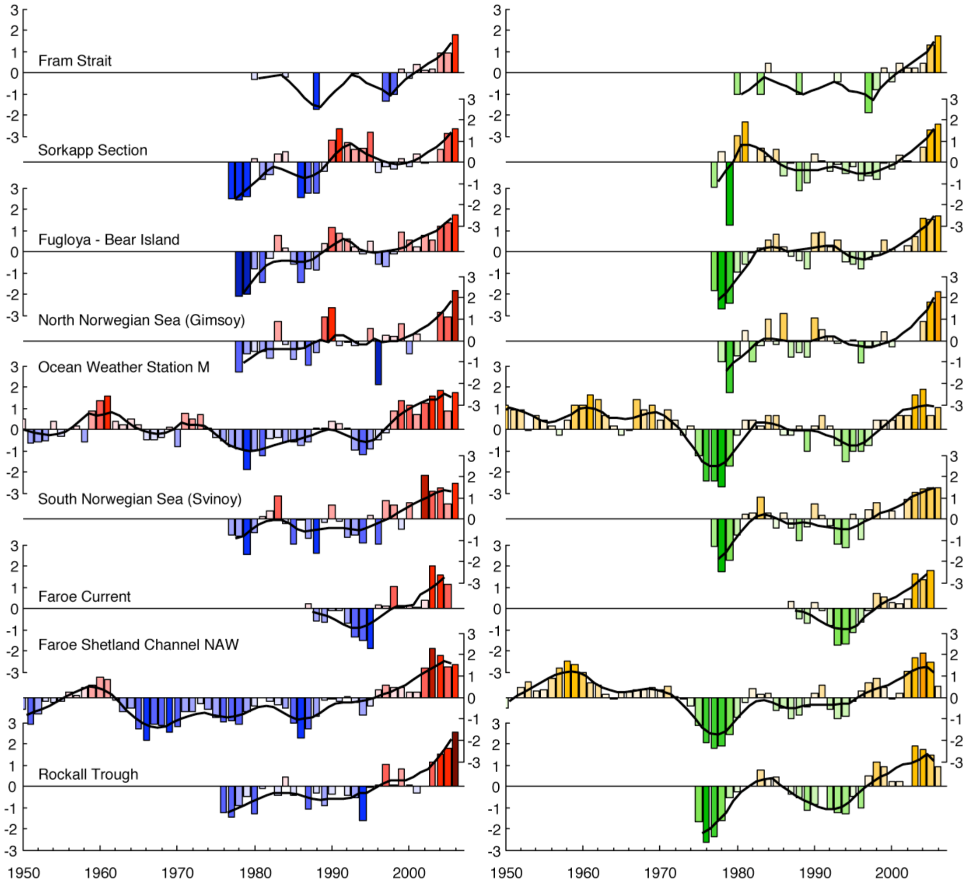

Figure 2.

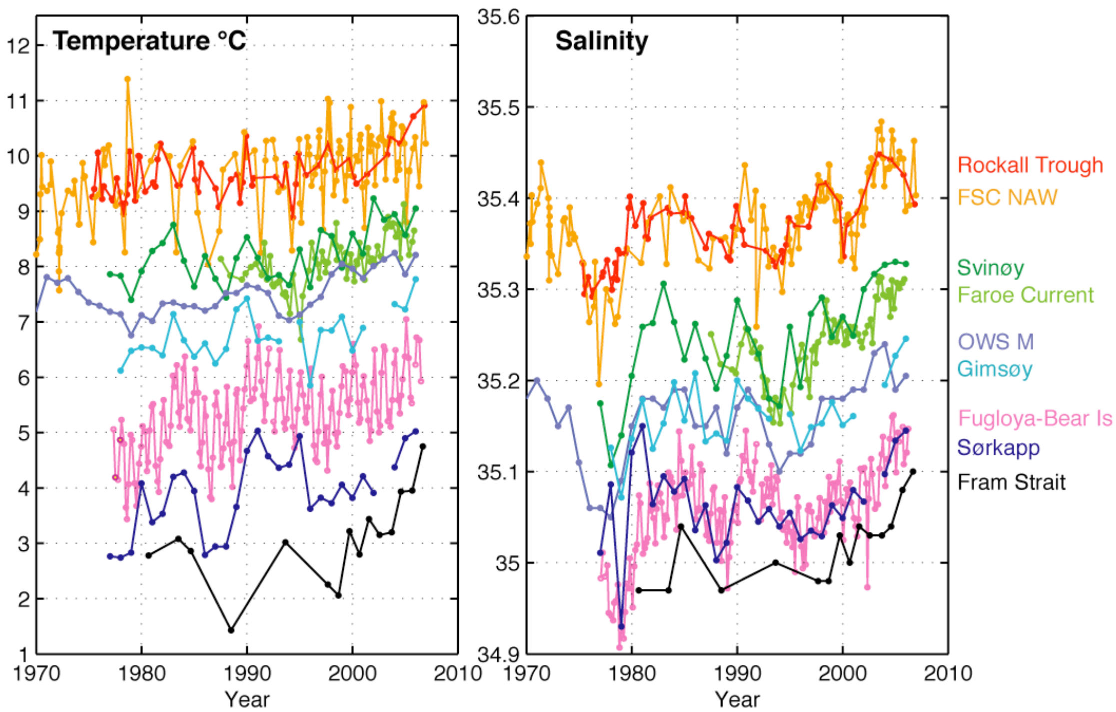

Figure 3.

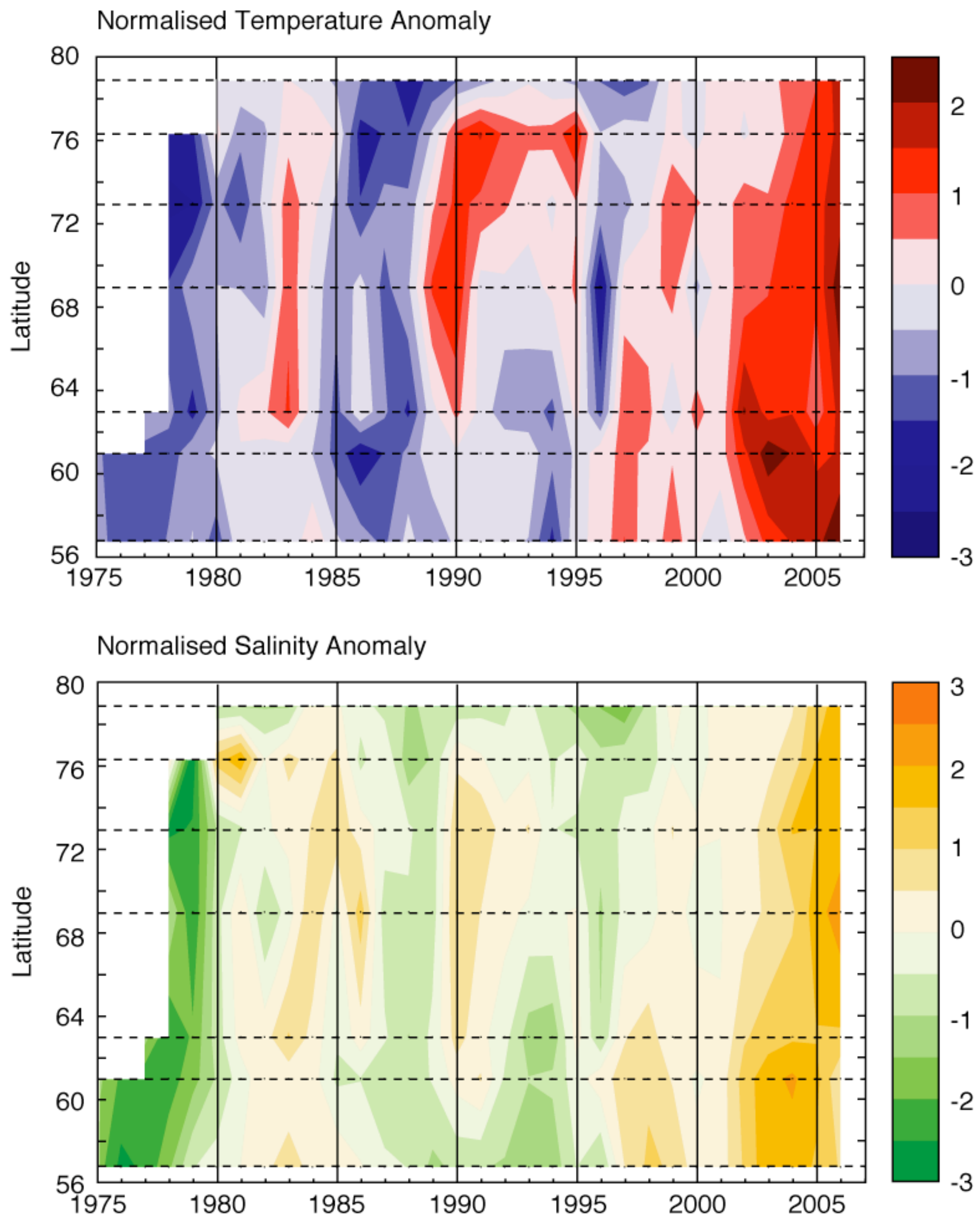
Normalised Temperature Anomaly
Latitude
80
76
72
68
64
60
56
1975
1980
1985
1990
1995
2000
2005
2
1
0
-1
-2
-3
Normalised Salinity Anomaly
Latitude
80
76
72
68
64
60
56
1975
1980
1985
1990
1995
2000
2005
3
2
1
0
-1
-2
-3

Figure 4