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

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24 **Abstract**

25

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

32

33 The mean properties of the Atlantic Inflow decrease northwards, but variations seen
34 in the eastern subpolar gyre at 57°N persist with the same amplitude and pattern along
35 the pathways to Fram Strait. Time series correlations and extreme events suggest a
36 time lag of 3-4 years over that distance. This estimate allows predictions to be made;
37 the temperature of Atlantic water in the Fram Strait may start to decline in 2007 or
38 2008, salinity a year later, but both will remain high at least until 2010.

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40

40 **1. Introduction**

41

42 A 30-year period of freshening of the North Atlantic and Nordic Seas has been
43 documented by Curry et al (2003) and Curry and Mauritzen (2005). The 1960s to
44 1990s freshening occurred in surface, intermediate and deep water masses, and
45 approximately half occurred during the Great Salinity Anomaly (GSA) in the 1970s
46 (Dickson et al 1988). In the same 3 decades sub-tropical Atlantic salinity had been
47 increasing, thought to be due to a change in the precipitation-evaporation balance
48 (Curry et al, 2003). An investigation of the total freshwater budget of the North
49 Atlantic and Arctic (subpolar and subtropical North Atlantic, Nordic Seas and Arctic
50 Ocean) suggested that changes in freshwater content can be explained entirely in
51 terms of changes in ice melt, river discharge and net precipitation (Peterson et al,
52 2006), while ocean circulation advects high or low salinity features within the basins.

53

54 Ten years on from the mid-1990s there exist sufficient new observations to
55 demonstrate that the freshening trend ended in the upper ocean in the mid-1990s.
56 There are a growing number of reports of increasing salinity at various separate
57 locations within the upper ocean of the subpolar gyre and Nordic Seas, including the
58 Labrador Sea (Avsic et al, 2006) and the Norwegian and Barents Seas (Skagseth et al,
59 *in press*). Hátún et al (2005) showed increasing salinities up to 2003 in the eastern
60 subpolar gyre, and increasing temperatures in the Atlantic water flowing into the
61 Arctic Ocean have been reported (Polyakov et al, 2005, Walczowski and Piechura,
62 2006). Boyer et al (2007) provide a overview of basin-scale changes in freshwater
63 content that include a recent (since 1993) decrease in the freshwater content of the 0-
64 2000 m layer of the subpolar North Atlantic and Nordic Seas. Bethke et al (2006) use

65 an atmosphere-ocean general circulation model to describe a scenario of increasing
66 salinity at 0-1000m in the northern North Atlantic and Nordic Seas under global
67 warming conditions.

68

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

75

76 **2. Intense warming and increasing salinity in the northern seas**

77

78 From the Rockall Trough to the Fram Strait there are several open-ocean
79 hydrographic sections and stations that have been occupied regularly on timescales
80 from monthly to yearly over a number of decades (Figure 1, and auxiliary material).
81 The observations together form a picture of property changes over the inter-basin
82 region and can be examined for large scale fluctuations with time. Data collection and
83 analysis methods for each time series are given in Hansen et al (2003), Holliday et al
84 (2000), Ingvaldsen et al (2003), Mork and Blindheim (2000), Osterhus and
85 Gammelsrod (1999), Schauer et al (2004) and Turrell et al (1999).

86

87 The route by which Atlantic water flows towards the Arctic has been described as
88 follows (Figure 1). The North Atlantic Current brings warm saline subtropical water
89 into the eastern subpolar gyre by two main routes. An indirect route takes NAC water

90 into an intergyre region where it is recirculated and modified before flowing
91 northwards through the Rockall Trough (Eastern North Atlantic Water, ENAW), and
92 a more direct route runs through the Iceland Basin (Western North Atlantic Water,
93 WNAW), where it undergoes significant modification and mixing with subpolar water
94 masses (Pollard et al, 1996, McCartney and Mauritzen, 2001, Pollard et al, 2004).
95 There is mixing between the two branches; during some periods, part of the WNAW
96 branch enters the southern Rockall Trough where it cools and freshens the eastern
97 branch, and at other times the eastern branch spills into the Iceland Basin where
98 conversely it increases temperature and salinity (Holliday, 2003). The two major
99 branches travel northwards over the Iceland-Scotland ridge and they are observed in
100 the deepest gap, the Faroe-Shetland Channel. There two water masses are described.
101 The cooler fresher Modified North Atlantic Water (MNAW) originates mainly in the
102 Iceland Basin and flows anticyclonically around the Faroe Plateau in the Faroe
103 Current before being deflected southwards into the Channel. The warmer more saline
104 North Atlantic Water (NAW) is carried from the Rockall Trough mainly in the shelf-
105 edge current. There is some exchange between the two branches.
106
107 From the sill they continue into the Nordic Seas as the Norwegian Atlantic Current
108 (NwAC, Hansen and Østerhus, 2000). The NwAC has two main cores which continue
109 the poleward progression to the Fram Strait, a largely barotropic eastern current that
110 follows the continental shelf break, and a largely baroclinic current that is steered
111 along various submarine ridges (Orvik and Niiler, 2002). Some flow in the barotropic
112 eastern NwAC separates off into the Barents Sea and forms one route of Atlantic
113 inflow to the Arctic Ocean. The eastern NwAC becomes the West Spitsbergen
114 Current (WSC). Walczowski et al (2005) suggest the topographically steered,

115 baroclinic western branch rejoins the WSC in Fram Strait where a significant portion
116 of the Atlantic inflow rapidly recirculates southwards (Schauer et al, 2004), while the
117 rest enters the Arctic Ocean.

118

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

129

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

140

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

142

143 The spatial distribution of the long-term time series allows an examination of the
144 downstream progression of Atlantic inflow water. The sampling is imperfect; the
145 sections are widely spaced, are of varying timespans, and usually under-sample the
146 seasonal cycle. But despite these difficulties, co-ordinated patterns emerge from the
147 data when taken as a whole, and when considering the interannual to decadal scale
148 changes. The spatial coherence of patterns of interannual variability can be
149 investigated both by calculating section-to-section correlations of annual averages of
150 temperature and salinity for a range of time lags, and by examining the passage of
151 extreme events. Of the statistics described, only relationships that are significant at
152 95% confidence level are accepted as probably meaningful.

153

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

165 short distance between the northern Rockall Trough and the Faroe-Shetland Channel
166 the properties are changed very little.
167
168 North of the Iceland-Scotland sill, the Atlantic Inflow is heavily modified by heat and
169 freshwater exchange with the atmosphere and by mixing with fresh coastal currents
170 and recirculating Arctic waters. The overall reduction in mean temperature and
171 salinity is clear (Figure 3), but the widescale coherence to the pattern of interannual to
172 decadal salinity signal is also evident. The conditions in the southern Norwegian Sea
173 co-vary with the Inflow at the sill (significant correlations at < 1 year time lag
174 between MNAW and Ocean Weather Station Mike (OWS M), and at time lags of up
175 to 2 years between NAW at the sill and the series at Svinøy and Gimsøy). The
176 statistical relationship between the variability in the subpolar waters and the Nordic
177 Seas seems to break down as the inflow passes into the Northern Norwegian Sea;
178 there is no statistically significant correlation between the NAW in the Faroe Shetland
179 Channel and the Atlantic Inflow at Sørkapp. Similarly there is a significant correlation
180 between the salinity and temperature series in the Rockall Trough and Svinøy (up to 3
181 years) but none between Rockall Trough and Sørkapp. This probably reflects a
182 change in mechanisms that dominate the year-to-year variations in properties.
183 However the extreme events which dominate the multi-year variability (e.g. 1970s
184 GSA, 1990s low salinity, 2000s high salinity) can be seen from Rockall Trough
185 through the Norwegian Sea sections. The passing of the extrema is illustrated in
186 Figure 4 which shows Hovmoeller diagrams of normalised salinity and temperature
187 anomalies. The figure shows that the peaks of the extrema typically take around one
188 year to get from the north-eastern subpolar gyre (Rockall Trough and Faroe-Shetland

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

191

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

202

203 **Discussion and Conclusions**

204

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

213

214 The time lag estimate allows us to make some short-term empirical predictions about
215 conditions at the entrance to the Arctic Ocean. The Faroe-Shetland Channel salinity
216 began to increase in 1996, reached a peak in 2004, and showed a slight decrease since
217 then (2005-2006). Temperatures peaked in 2003 but remained high in 2005 and 2006.
218 We can therefore predict that Fram Strait temperature may start to decline in 2007 or
219 2008, while salinity will peak a year later, but both will remain high at least until
220 2010.

221

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

232

233 In general, the temperature and salinity properties of the upper ocean co-vary, but it is
234 notable that while salinity has returned to high values previously recorded around
235 1960, temperature has exceeded values in all the time series. There is some evidence
236 of a maximum in both properties being reached recently; temperatures and salinity
237 have decreased slightly at the more southern locations since 2003 or 2004, but the

238 interannual variability overlying the multi-decadal scale pattern means it will be

239 several years before we can conclude whether a new maximum has passed.

240

240 **References**

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343 **Figure Captions**

344

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

348

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

355

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

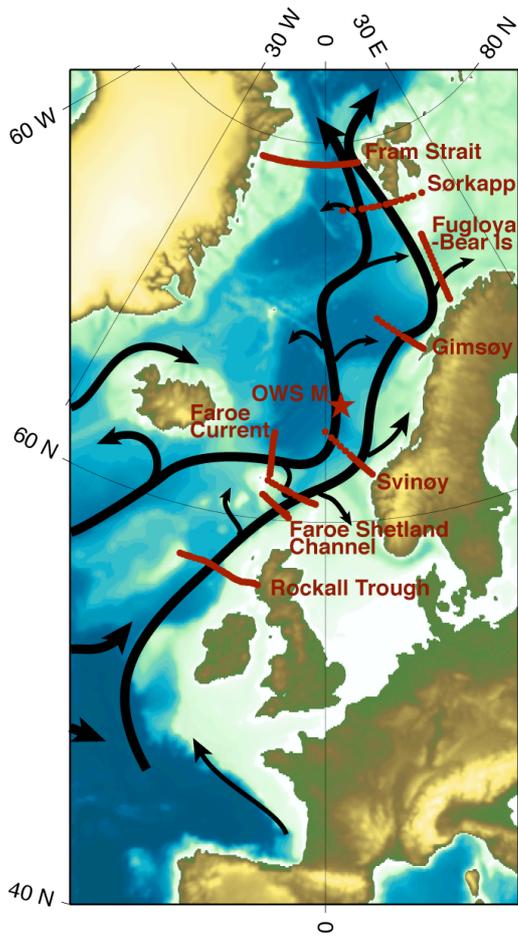
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359 Figure 4. Hovmoeller diagrams of normalised subsurface temperature and salinity
360 anomalies from the sections and stations in Figure 1. Data are presented as normalised
361 anomalies from the long-term mean (1988-2006 for Faroe Current and Fram Strait,
362 1978-2006 for all others). The latitude of the time series are given by the dashed lines.

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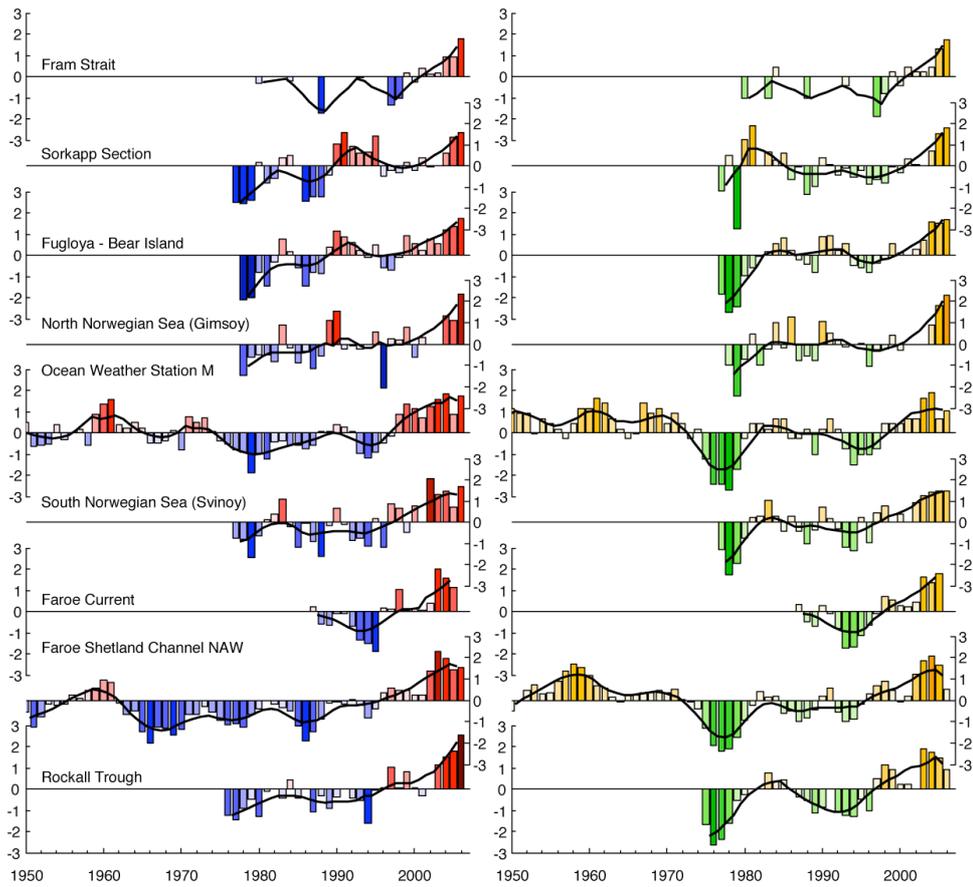
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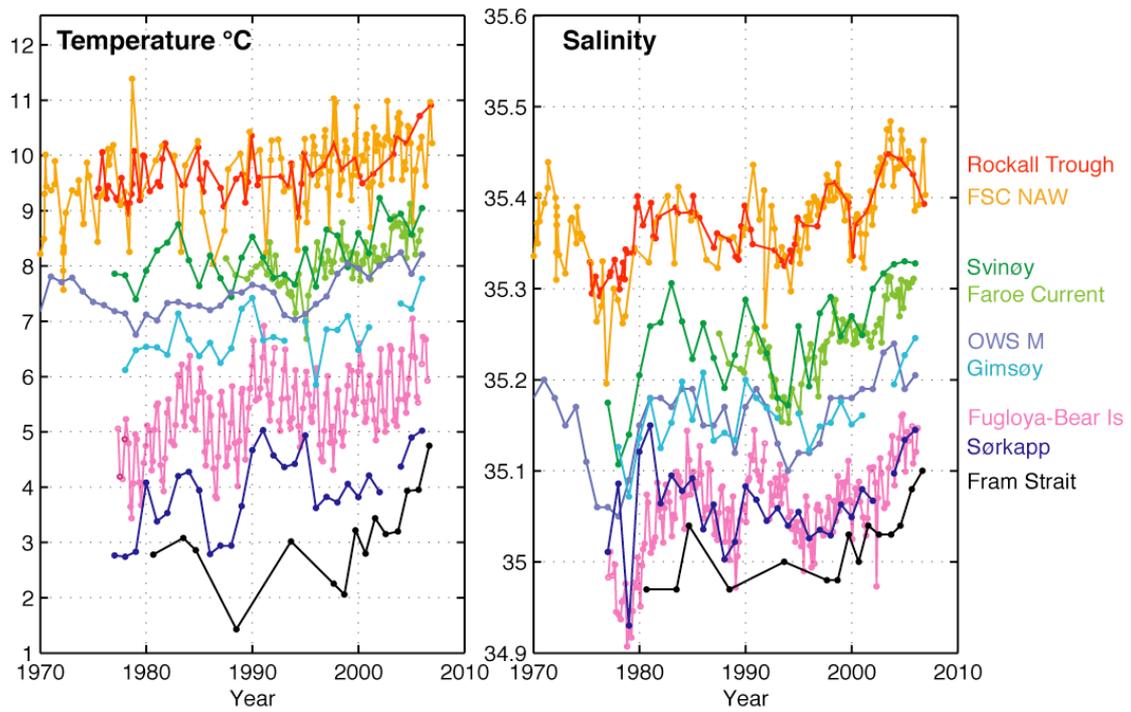
367 Figure 1.

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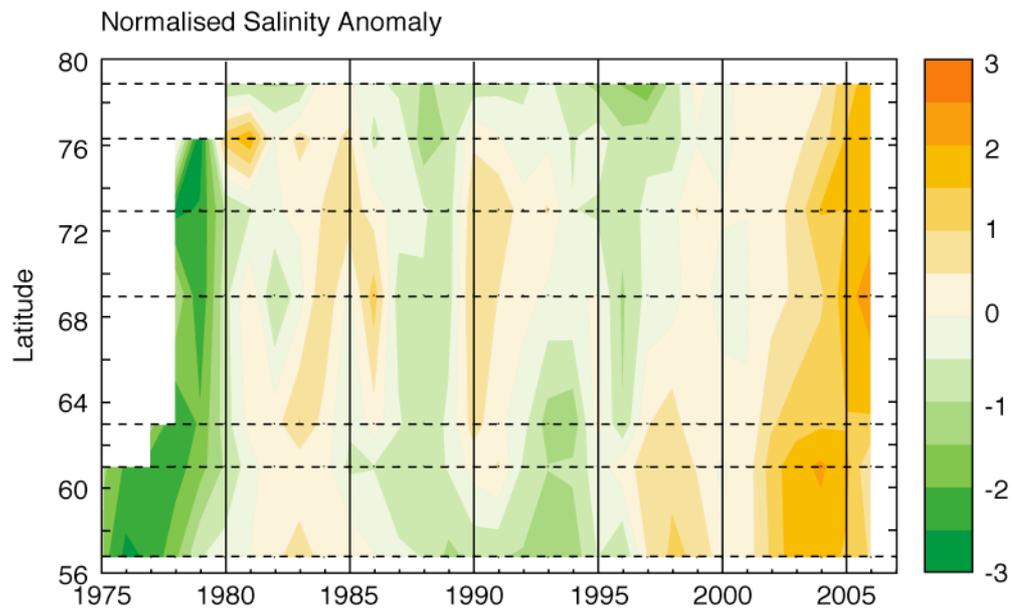
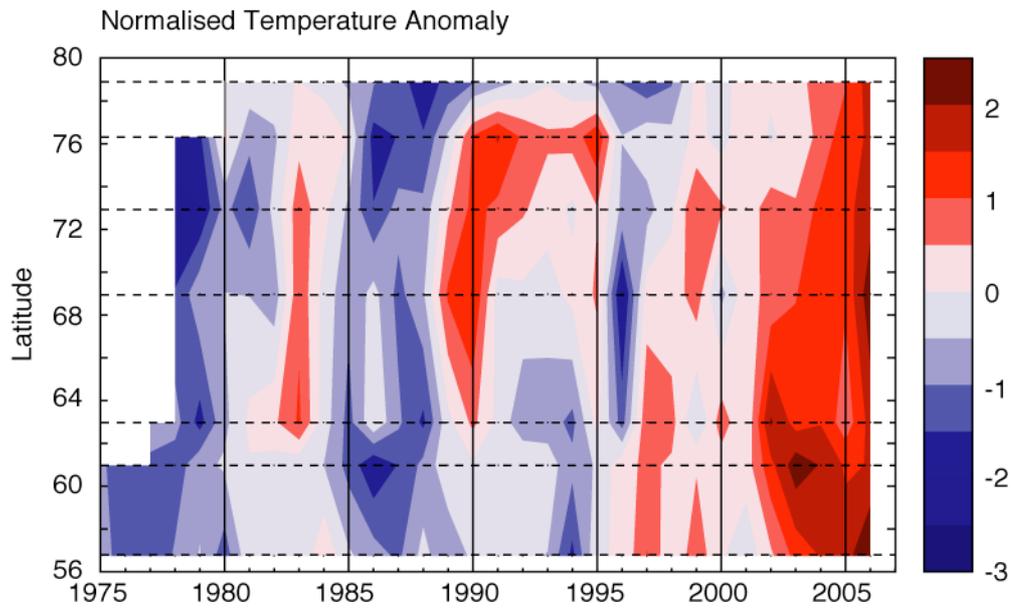
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370 Figure 2.



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372 Figure 3.



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375 Figure 4