Freshening of the Labrador Sea surface waters in the 1990s: Another great salinity anomaly ?

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Both the observed and simulated time series of the Labrador Sea surface salinities show a major freshening event since the mid-1990s. It continues the series of decadal events of the 1970s and 1980s from which the freshening in the early 1970's was named as the Great Salinity Anomaly (GSA) by Dickson et al. 1988). These events are especially distinguishable in the late summer (August and September) time series. The observed data suggests that the 1990's freshening may equal the GSA in magnitude. This recent event is associated with a large reduction in the overturning rate between the early and latter part of the 1990s (Häkkinen, 2001). Both the observations and model results indicate that the surface salinity conditions appear to be returning towards normal during 1999 and 2000 in the coastal area, but offshore, the model predicts the freshening to linger on after peaking 1997.

1. Background

Sea surface salinity serves as an indicator of convective conditions in the high latitude North Atlantic Ocean: fresher than normal conditions mark a cessation of deep convection. Because deep convection is part of the maintenance of the thermohaline circulation, the lack of convection could imply a weakening of overturning. Even though the observational data base for salinity is more sparse than for sea surface temperatures, several wide spread fresh anomalies in the northern North Atlantic surface salinity have been captured by the existing data base.

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These fresh conditions have been occurring nearly once a decade (Belkin et al. 1998) and seem to be associated with numerous icebergs which survive to the latitudes south of 48N. In this respect the 1990s represent a decade with the highest incidence of iceberg crossings at 48N since the beginning of the record keeping by the International Ice Patrol (from 1901).

There are considerable variations between freshening events both in their intensity and location (Reverdin et al. 1997), but by far the largest occurrence was the GSA at the end of 1960's and early 1970's (Dickson et al 1988). This event was associated with a multi-year cessation of convection in the Labrador Sea as recorded at Station Bravo (Lazier, 1980) (Fig. 1). Another large event took place in the early 1980's (Belkin et al. 1998). The first signs of the 1990's freshening from the Gulf of Maine and Georges Bank have been reported in Smith et al. (2001) among others. The large fresh events like GSA can have widespread influence on the hydrography of the N. Atlantic as documented in the observational study of the pentads 1955-1959 and 1970-1974 by Levitus (1989). The fresh periods are often associated by significant changes in the index of the North Atlantic Oscillation (NAO) (Fig. 2a) (Dickson et al. 1996) and in the meridional overturning as suggested by the model simulations (Häkkinen, 1999, 2001).

2. Salinity Data

The dynamic impact of the fresh events (on convection) is limited to the winter season, but observations are more abundant for the summer season because of the local weather and ice conditions. The time series of all salinity observations in the upper 5meters from the ocean weather station Bravo [52W, 56N] suggests that there exists a stronger signal in summer than in winter. This stratification of Bravo upper ocean salinities between the winter (March) and summer (August and September) values is shown in Fig. 1. Thus, the summer salinity values can be considered a valuable signal of the lack of deep convection. This relationship relies on the timing of the major fresh water input (precipitation, ice melt sources etc.) which occurs during spring and summer Any leftover stratification (from a lack of convection) from the previous winter is enhanced by the normally occurring spring-summer fresh water input.

This study focuses on two overlapping areas, a coastal area (55W to 45W) and an off-shore area (50W-40W) which are limited by 45N and 55N. The observational data from these two areas are taken at irregular intervals with very few annually surveyed stations. By selecting surface salinities from August and September one can display the envelope of SSS values and its modulation as an efficient way to distinguish relatively fresh periods from the typical SSS conditions. The overlap is necessary because of the sparseness of offshore observations, but also to give a glimpse of the offshore SSS evolution. At present the surface salinity observations in the coastal box from NOAA Oceanographic data Center (NODC) has no data in 1997 and 1998 and several years of the early 1990's have only a few observations. The data gaps of 1997-1998 and 2000-2001 are filled with the observations from the Bedford Institute of Oceanography (BIO) data base along with additional data in the beginning of the 1990's. All data are shown in Fig. 2b and 2c for the coastal and further offshore areas respectively. Below the SSS values, the distribution of the longitudes of the observations is depicted. The areas closest to the shore (55W to 50W) are sampled quite well with only a few years of poor data coverage (e.g. 1966-1968, 1982, 1984-1985, and 1989-1990). In the offshore region, the sampling is sparse and years of no data are common in the early record.

3. Model

To support the conclusions from the sparse observations, numerical model results are presented here. This model is discussed in detail in Häkkinen (1999) and (2001). The model is forced by appending atmospheric anomalies from NCEP/NCAR Reanalysis to a monthly climatology adopted earlier in the model (Mauritzen and Häkkinen, 1997). The analysis of the simulation covers years 1958 to 2001. The model surface salinities are influenced by only 3 factors: mixing, advection and sea ice melt because precipitation minus evaporation (P-E) is kept at monthly climatology throughout the simulations. The contribution from interanually varying P-E is not important for the formation of the decadal subpolar fresh anomalies as also concluded by Houghton and Visbeck (2002) in their study of propagation of the Labrador Sea salinity anomalies.

4. Results

4.1 SSS variability

The minimum observed SSS values during any given year, Fig 2b, show that radically fresher surface conditions have prevailed during the 1990s compared to the four earlier decades. This coastal freshening started 1991 and lasted until 1998 with some recovery during 1996 and 1997. The data from 1999 and 2000 suggest return of more typical minimum summer salinities along the coast. GSA related fresh salinities appear in 1970 and 1974, but these events at the coast are short-lived. The 1980s show several high frequency freshening events relative to the years immediately before or after them. Another interesting aspect is the envelope of the maximum observed salinities where again the 1990s appear fresher than any of the four other decades. In the 1950's and 1960's the maximum salinities were close to 35psu, but in the 1970's and up to 1987, the maximum (available) observations show values of 34.5 or less. In the end of the 1980's the maximum values briefly approach 35psu, but plummet in the early 1990's. No recovery to high salinities had occurred as of 1996 which is the only year with data near 45W.

Away from the coastal area, Figs. 2c, both GSA and the 1980's dominate the picture in the lower range of SSS values, the latter freshening is more apparent than in Fig. 2b, and this event is competing in strength with GSA. This strengthening of the signal may be because the offshore observations were more abundant than the near-shore ones for the years of the 1980's freshening. The signal of the 1990's freshening is present but the stations carrying the signal were mostly included in the coastal box. However, the maximum salinity during the 1990s as recorded near 41W (1999) is far less than the upper range of salinities in the mid 1980's or even in 1989-1990. The crucial observations for years the 1990's are still missing from the data banks to confirm the spread of the freshening away from the coast.

The same areas are selected from the model simulations and consist of about 100 grid points. The simulated SSS values are more saline than the observations, but the simulated SSS variations (Figs. 2d) from the near-shore region reproduce the freshenings of the 1970's, 1980's and 1990's. The simulated 1990's freshening is competing in strength with GSA. A recovery is apparent during 1999 and 2000 as in the observations. The evolution at the offshore box (Fig. 2e) is very similar with the largest fresh events taking place in the 1970s and 1990s, but the peak of the latter event is shifted to 1997 from 1994 in the coastal box. The 1980's event is weaker than in the observations. In the Figs. 2d-e, the upper range of SSS values shows a distinct low-frequency variability and could be used also to define the fresh events. The upper range freshenings tend occur slightly earlier (off-shore origin !) than those of the lower range values.

Both observed and simulated salinities suggest the 1990s event to be significant in amplitude and rivaling GSA. Not only the surface is fresh, but the sea surface temperatures (SST) (from NOAA/CPC) are also anomalously warm. The fresh and warm surface is a signal of weak production of the subpolar water masses which occupy the mid-depths of the Atlantic. The warm temperatures and fresh waters at the surface amount to an increased sea surface height. TOPEX/Poseidon altimeter data show that in the off-shore box, the sea surface height has an increasing trend during the 1990s up to the end of the record (October 2001) (Fig. 3) suggesting the persistence of the fresh and warm conditions in the subpolar gyre. The subpolar SSTs represent a return to the warm temperatures of the early 1950s (not shown).

4.2 Relationship of SSS anomalies to NAO and oceanic dynamics

The fresh surface conditions in the subpolar gyre tend to occur in conjunction with weak heat loss (Dickson et al. 1996). The weak heat loss is typical of years with the negative phase of the North Atlantic Oscillation (NAO) which describes a weak Icelandic Low and a weak Azores High. Thus the heat loss associated with NAO modulates deep convection in the Labrador Sea with the Labrador Sea Water as the end product. Comparison of Figs. 2b-c and the NAO index averaged over the winter months (November through April) (Fig. 2a) does not indicate a well-defined relationship. The fresh conditions tend to appear during negative NAO, due to the lack of deep convection as suggested by Dickson et al. (1996), but there are time periods with positive NAO and very fresh conditions as in the beginning of the 1980's and 1990's.

Comparison of the timing of the fresh events and the variations of the meridional heat transport at mid-latitudes (e.g. in Häkkinen (2001)) gives an impression of a close linkage. The relationship between surface salinity and overturning is shown through correlations between the (annual values of) SSS and meridional heat transport at 45N (MHT45) (Fig.4a-b) for lags 0 and 1 years. The correlations preceding the MHT45 maximum are limited and barely significant (not shown). The main MHT45 signal in SSS occur in the central subpolar gyre and with a widening spatial extent after MHT45 has reached maximum. The positive correlations refer to saline (fresh) conditions associated with stronger (weakened) overturning. The salinity anomalies spread to all directions so that they occupy most of the subpolar gyre within two years. After the two years the anomalies rapidly dissipate. The offshore box overlaps (both study regions are shown in Fig. 4a) the initial appearance of the SSS anomalies as seen in the Figs. 4a,b, so the observations in Fig. 2c should sample the overturning associated SSS variations.

Now we can return to the ambivalent role of the NAO in the coastal SSS anomalies: a positive NAO and stronger overturning should lead to more saline conditions even in the coastal area. As a result from the intensification of the overturning, as shown by a simultaneous correlation in Fig 5, a cyclonic gyre (anomaly) exists along the Labrador coast. The cyclonic gyre implies stronger southward coastal currents and transport of more fresh water resulting in fresh SSS anomalies at the coast during the positive NAO phase. Off-shore the transports of course favor increased salt transport. The impact of NAO through wind stress curl also influences the vertically integrated transport in the coastal Labrador Sea as was shown in Häkkinen (2001) (its Fig. 8) so that a negative NAO phase enhances southward coastal transport and thus fresh water transport. Now the impact of NAO on the coastal SSS variability can be put into a new light: NAO can influence the coastal currents by (1) wind stress curl, whereby the positive NAO results in a decreased (vertically integrated) coastal transport, and by (2) the positive NAO enhancing the meridional overturning which strengthens the cyclonic subpolar gyre (Fig.5). As a result of these two opposing forces determining the strength of the coastal transports, the coastal SSS variability is not strongly tied to the sign of NAO. These considerations related to the coastal SSS also apply to the icebergs crossing 48N which is why the coastal fresh conditions seem to be associated with a southward invasion of icebergs.

5. Conclusions

Both the observed and simulated SSS data suggest that a strong North Atlantic freshening occurred in the mid to late 1990's. This fresh anomaly continues the decadal events in the N.

Atlantic. It is expected that this freshening will linger on in the subpolar into the early years of the 21st century. Model simulations indicate that this freshening is associated with the largest change in the meridional overturning of the simulated record which occurred at the mid-1990s (Häkkinen, 2001). Based on the observed and simulated surface salinity anomalies along the coast alone, the 1990's freshening is likely the largest event since 1950's even surpassing the GSA. The global thermohaline cell can be impacted further because the slower overturning reduces the transport of saline waters from lower latitudes creating even more buoyant surface and upper ocean waters at the high latitudes, i.e. there is a positive feedback. It is difficult to speculate what mechanisms can counteract this positive salinity feedback, but one possibility is a return of extremely cold and stormy winters to the Labrador Sea to disperse the fresh water.

Acknowledgements

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Figure Captions

Figure 1: Salinities from the top 5 meters at the Ocean Weather Ship Bravo in March (blue) and in August and September (red). Units are ppt.

Figure 2: a) Winter (November to April) average NAO index from the standardized table of NOAA/CPC. (b-c) All August and September surface salinity observations from NOAA/NODC

and BIO data base for regions [45W-55W,45N-55N] (b) and [40W-50W,45N-55N] (c) (the top distribution in blue dots; the axis in units of ppt on left). The longitudinal distribution of each point shown at the bottom in red, axis on the right.

(d-e) All simulated August and September SSS values for regions [45W-55W,45N-55N] (d) and [40W-50W,45N-55N] (e) in units of ppt.

Figure 3: Monthly average sea surface temperature (black line, in Celsius; axis on left) from NOAA and the sea surface height from the TOPEX/Poseidon altimeter (red line, in cm; axis on right) for the region [40W-50W,45N-55N].

Figure 4: Correlation of the annual averages of the meridional heat transport at 45N and surface salinity at lag 0 (a) and lag 1 year (b) after the maximum heat transport. The coastal (blue) and the offshore (red) study regions are also shown. Correlations above 0.5 are significant at 95% level. All values were linearly detrended before computing correlations.

Figure 5: Correlation of the annual averages of the vertically integrated transport stream function and the meridional heat transport at 45N at lag 0. Correlations above 0.5 are significant at 95% level. Positive (negative) correlations imply an anomalous cyclonic (anticyclonic) gyre. All values were linearly detrended before computing correlations.

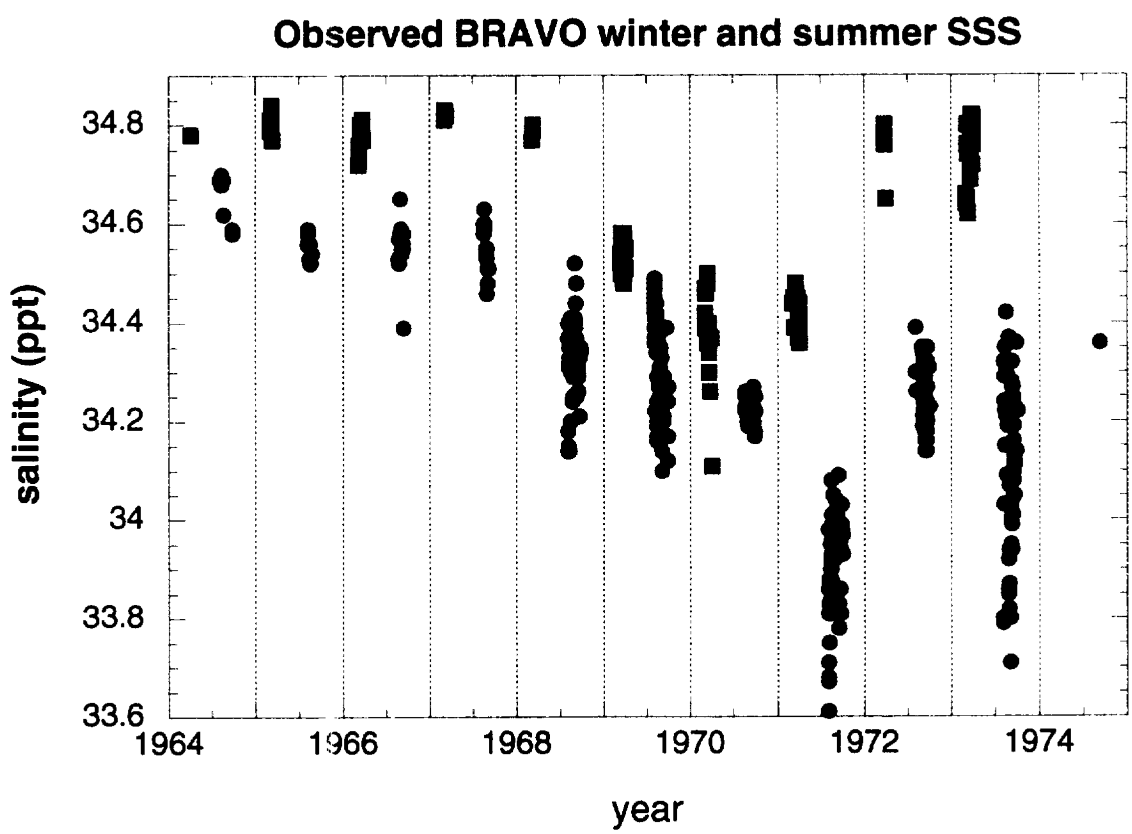
Observed BRAVO winter and summer SSS
salinity (ppt)
34.8
34.6
34.4
34.2
34
33.8
33.6
1964
1966
1968
1970
1972
1974
year

Figure 1

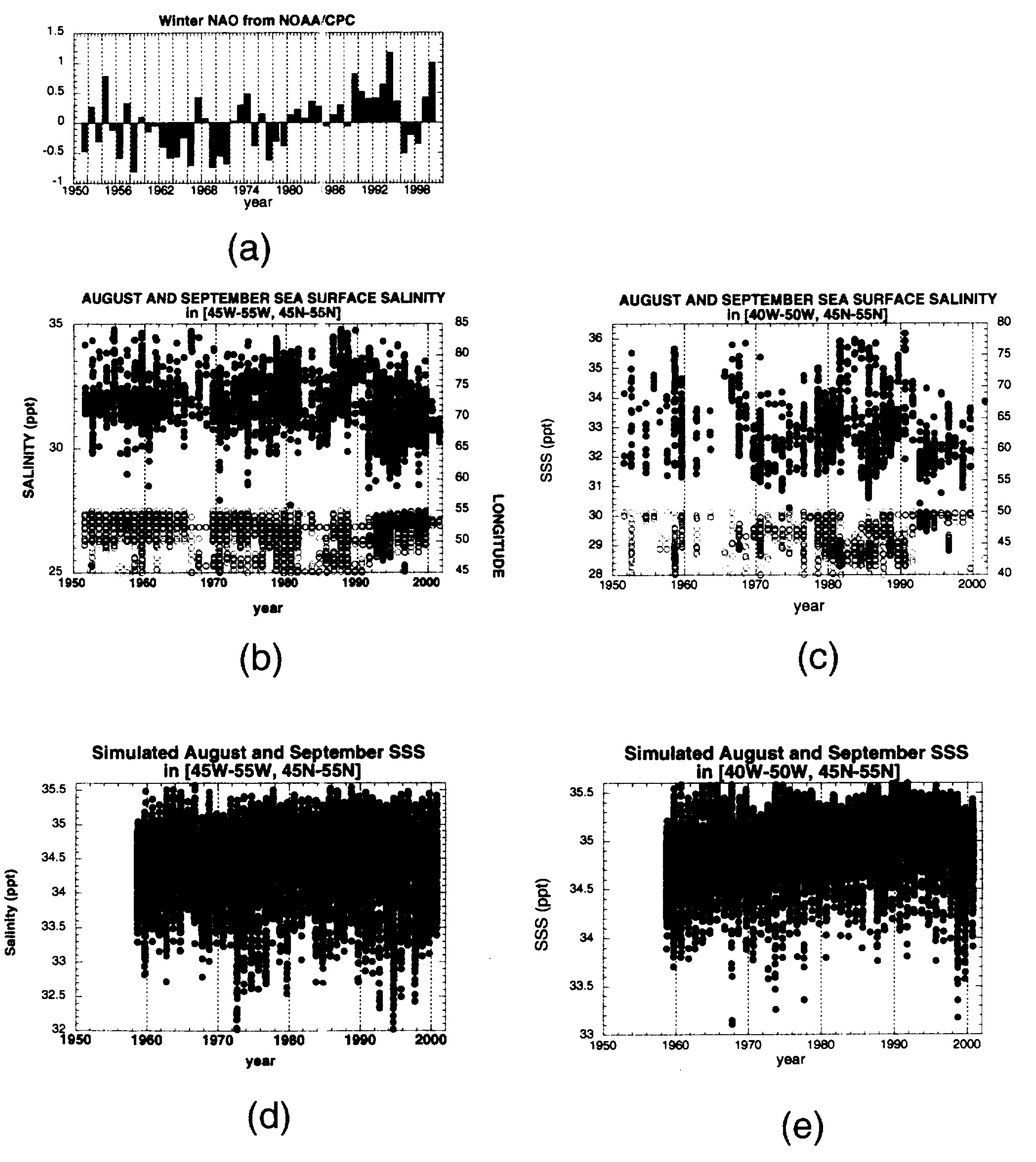
Winter NAO from NOAA/CPC
year
(a)
AUGUST AND SEPTEMBER SEA SURFACE SALINITY
in [45W-55W, 45N-55N]
SALINITY (ppt)
LONGITUDE
year
(b)
AUGUST AND SEPTEMBER SEA SURFACE SALINITY
in [40W-50W, 45N-55N]
SSS (ppt)
longitude
year
(c)
Simulated August and September SSS
in [45W-55W, 45N-55N]
Salinity (ppt)
year
(d)
Simulated August and September SSS
in [40W-50W, 45N-55N]
SSS (ppt)
year
(e)

Figure 2

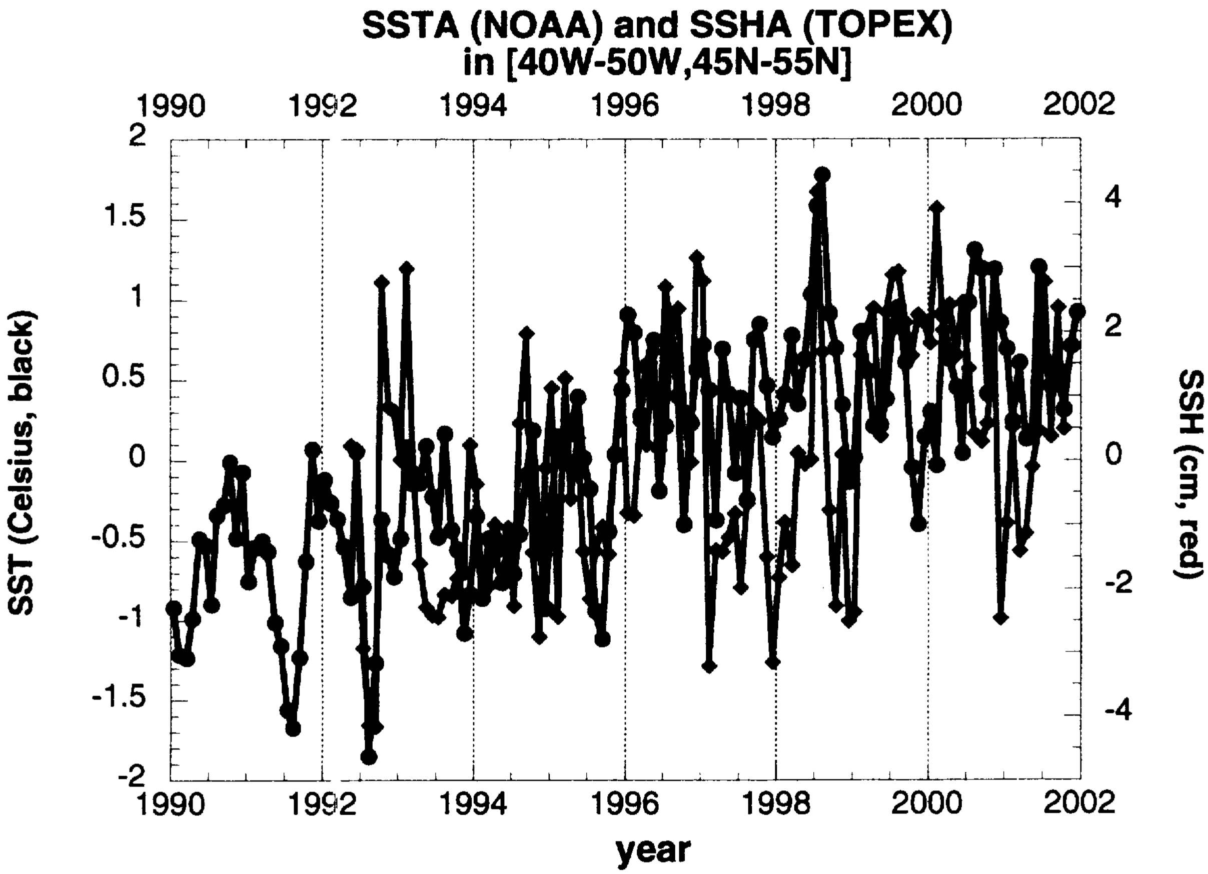
SSTA (NOAA) and SSHA (TOPEX)
in [40W-50W,45N-55N]
1990
1992
1994
1996
1998
2000
2002
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
4
2
0
-2
-4
SST (Celsius, black)
SSH (cm, red)
year

Figure 3

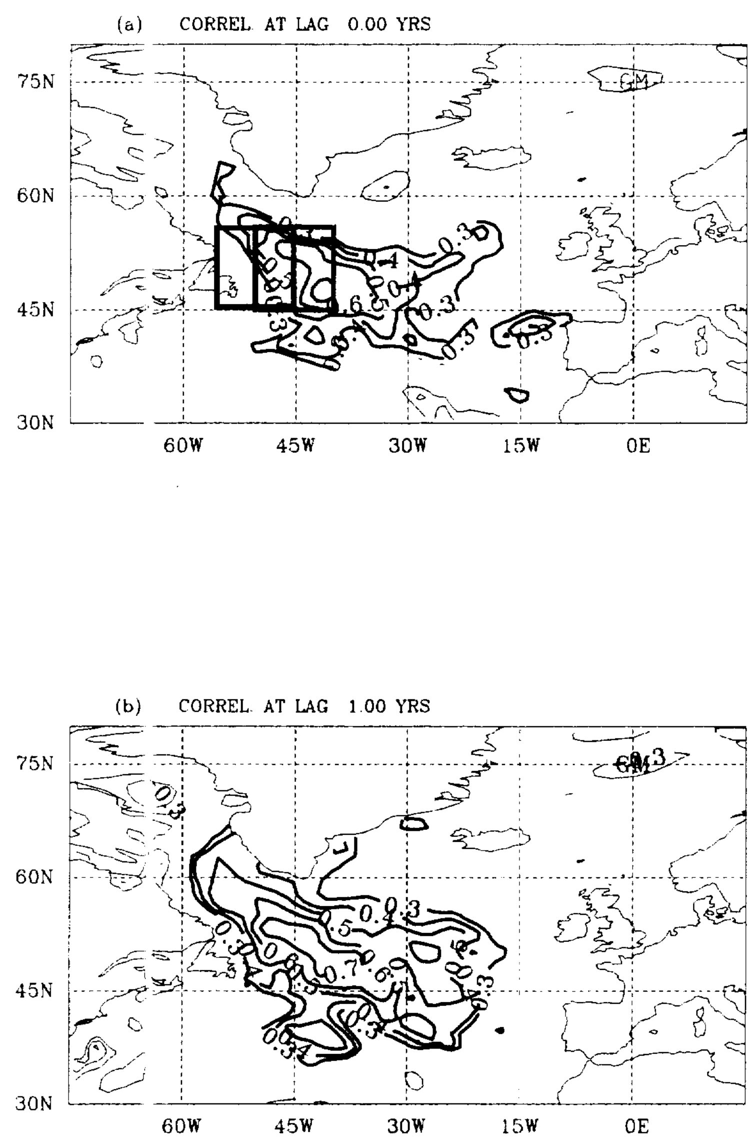
(a) CORREL. AT LAG 0.00 YRS
75N
60N
45N
30N
60W
45W
30W
15W
0E
(b) CORREL. AT LAG 1.00 YRS
75N
60N
45N
30N
60W
45W
30W
15W
0E

Figure 4

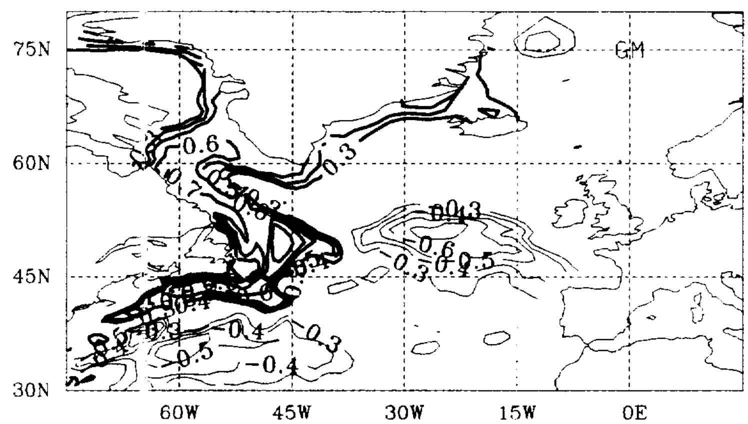

Figure 5