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Changes in freshwater content in the North Atlantic Ocean 1955–2006

Tim Boyer,[1] Syd Levitus,[1] John Antonov,[1] Ricardo Locarnini,[1] Alexey Mishonov,[1]
Hernan Garcia,[1] and Simon A. Josey[2]

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[1] Freshwater content changes (FW) for the North Atlantic Ocean (NA) are calculated from in situ salinity profiles for the period 1955–2006 from the surface to 2,000 meters. Heat content (HC) is also calculated from in situ temperature profiles for comparison. A decrease in FW between 1955 and 2006 of ~30,000 km^3 is found for the NA, despite an increase in FW of ~16,000 km^3 in the subpolar North Atlantic (SNA) and Nordic Seas between the late 1960s and the early 1990s. Over the last two decades there is a pattern of decreasing FW in the upper 400 meters and increasing FW below 1,300 meters for the NA. FW and HC are strongly negatively correlated for both the SNA (r = −0.93) and the NA (r = −0.79). Net precipitation, from NCEP/NCAR, is found to have a strong influence on FW changes in the SNA but this relation is weaker elsewhere. **Citation:** Boyer, T., S. Levitus, J. Antonov, R. Locarnini, A. Mishonov, H. Garcia, and S. A. Josey (2007), Changes in freshwater content in the North Atlantic Ocean 1955–2006, *Geophys. Res. Lett.*, *34*, L16603, doi:10.1029/2007GL030126.

1. Introduction

[2] Concerns about climate change, including sea level change due to reduction of continental glaciers, and possible abrupt changes caused by reduction in the Meridional Overturning Circulation, make it important to quantify the variability of the ocean's freshwater cycle. The ocean is a major component of the Earth's hydrological cycle. Addition and subtraction of freshwater in the ocean are due to many factors: precipitation and evaporation over the ocean, river runoff, sea-ice formation and melt, and storage of freshwater in continental glaciers are all major factors which can measurably affect the oceans freshwater budget. However, there remain significant uncertainties in observational estimates of the various factors affecting the freshwater budget. A way around this problem is to get an estimate of changes in the ocean's freshwater content by using measurements of salinity taken during oceanographic cruises. This can be done under the assumption that the salt content in the ocean is relatively constant over time periods on the order of 50 years and that any changes in salinity are due to the addition or subtraction of freshwater to the water column.

[3] When studying the ocean component of the Earth's freshwater cycle, it is also important to consider the role of ocean heat content. Temperature and salinity are two of the three variables (along with pressure) in the equation of state for seawater. Knowledge of changes to both is necessary to fully understand physical changes in the ocean. Freshwater content and heat content are the calculated quantities from these measured variables which define the oceans relation to the Earth's climate system.

[4] The salinity and temperature dataset used in this study is the World Ocean Database 2005 [*Boyer et al.*, 2006]. Figures S1a–S1d[1] show the geographic coverage for temperature and salinity data for years 1945–2006 down to 3,000 meters, compositing data by 1-year periods and 5-year periods (pentads). Here, geographic coverage is defined in terms of "sufficient coverage" for a one-degree square (henceforth ODSQ) based on data in and surrounding that ODSQ. Sufficient coverage is defined as ≥3 ODSQs within a 444 km radius around the midpoint of a given ODSQ containing at least one datum. This definition is closely tied to the objective analysis technique used to calculate the anomaly fields used in this study [see *Antonov et al.*, 2006]. The values are percentages of ODSQs in the ocean which meet the definition for sufficient coverage. Taking 70% coverage to be acceptable, this study will necessarily be limited to pentads for the North Atlantic for 1955–2006 (Figures S1a–S1d) for the upper 2,000 meters.

[5] A number of recent studies have addressed changes in salinity and/or freshwater in the North Atlantic [*Curry et al.*, 2003; *Curry and Mauritzen*, 2005; *Polyakov et al.*, 2005; *Peterson et al.*, 2006]. The present study will extend these studies by presenting equivalent freshwater content (FW) volume integrals and heat content (HC) for the entire North Atlantic 0° to 80°N (not including Hudson Bay, the Mediterranean and Baltic Seas), as well as sub-areas of the North Atlantic. It is important to note that FW is an anomaly from total freshwater content calculated from salinity anomalies as if all changes to salinity in the study region are due only to addition or subtraction of freshwater (hence the term equivalent). It is not possible in this calculation to separate out the effects of deepening or shoaling of isopycnal surfaces, or advection to/from the area of integration.

[6] One of the major factors influencing ocean freshwater content is variability in the air-sea freshwater flux, also termed net precipitation (i.e. precipitation minus evaporation, P-E) variations. Precipitation is very hard to accurately measure over the ocean, either from ship, buoy or satellite; evaporation is also difficult to determine. Here we use P-E fields from NCEP/NCAR reanalysis which were employed by *Josey and Marsh* [2005] to analyze sea surface salinity variations in the eastern subpolar gyre. In their analysis, interdecadal variations in NCEP/NCAR precipitation fields

[1]National Oceanographic Data Center, NOAA, Silver Spring, Maryland, USA.
[2]National Oceanography Centre, Southampton, Southampton, UK.

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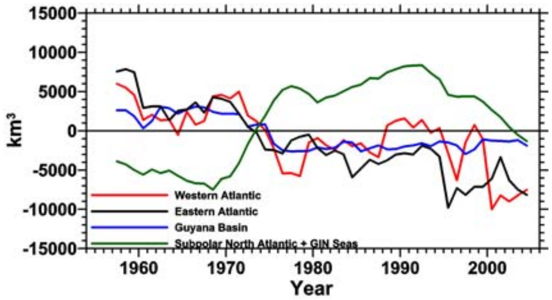

Figure 1. Equivalent freshwater content for different areas of the North Atlantic Ocean 0–2,000 meters (1955–1959) to (2002–2006).

for this region were shown to be in good agreement with independent rain gauge measurements. *Josey and Marsh* [2005] found a similar level of agreement with the ERA40 reanalysis dataset. However, the latter dataset is known to have problems at lower latitudes [*Uppala et al.*, 2005] and so we have not employed it here. Pentadal basin integrals of P-E, expressed as anomalies from 1957–1990 will be compared to FW. This will give a partial estimate of how much of the FW is due to actual addition or subtraction of freshwater as opposed to advection or changes in isopycnal surface depths. This is only a partial freshwater estimate which does not include river runoff or ice import/export.

2. Method

[7] All salinity data which passed the WOD05 quality control checks were used to calculate running pentadal salinity anomaly fields for years (1955–1959) through (2002–2006). Salinity anomalies were calculated by subtracting the appropriate monthly salinity climatology from each salinity profile after interpolation of the profile to 26 standard depth levels from the surface to 2,000 meters. The set of climatologies used is the World Ocean Atlas 2005 (WOA05) salinity climatologies [*Antonov et al.*, 2006]. Each standard level for each pentadal field was then objectively analyzed using a first-guess field of 0.0 (i.e. zero salinity anomaly assumed). The mean anomaly for years 1957–1990 is subtracted in each ODSQ, so the anomalies are relative to this time period.

[8] FW is calculated from the salinity anomaly fields using equation (1) for each ODSQ and depth interval and summing over all depth intervals.

$$FW_{i,j} = -a \int \frac{\rho(t,s,p)}{\rho(t,0,p)} \frac{\Delta s}{(s+\Delta s)} dz \quad (1)$$

$\boldsymbol{a}$ is the area of each ODSQ, $\boldsymbol{\rho}$ is the density of seawater, $\boldsymbol{z}$ is depth, $\boldsymbol{t}$ and $\boldsymbol{s}$ are WOA05 climatological annual temperature and salinity at the standard depth representing a depth interval, $\boldsymbol{p}$ is pressure at the same standard depth, $\boldsymbol{\Delta s}$ is the salinity anomaly at the standard depth, $\boldsymbol{i}$ and $\boldsymbol{j}$ are the geographic coordinates of the ODSQ. Text S1 gives a full derivation of FW. Heat content (HC) is calculated using pentadal temperature anomalies and equation (2).

$$HC_{i,j} = a \int \rho(t,s,p) c_p(t,s,p) \Delta t dz \quad (2)$$

$\boldsymbol{c_p}$ is the specific heat of seawater, and $\boldsymbol{\Delta t}$ is the temperature anomaly at the given standard depth.

[9] Objective analysis error statistics are computed using equation (3)

$$\sigma_{FW} = \sqrt{\sum_{n=1}^{N} \left(\frac{\partial FW}{\partial \Delta s_n} \sigma_{\Delta s_n} \right)^2} \quad (3)$$

$\boldsymbol{\sigma_{\Delta sn}}$ is the standard deviation of the salinity anomaly at depth level $\boldsymbol{n}$, and $\boldsymbol{N}$ is the total number of depth levels over which integration is performed. Error statistics for HC were computed in a similar manner.

3. Results

3.1. Equivalent Freshwater Content in the North Atlantic

[10] Figure S2 shows the North Atlantic divided into 6 areas. In addition to examining FW for the entire North Atlantic, these 6 areas (and the subpolar North Atlantic (SNA) and Greenland, Iceland and Norwegian (GIN) Seas together [SNA + GIN]) will be examined. The SNA and GIN are defined as *Curry and Mauritzen* [2005] defined them for comparison with their results, with the southern boundary of the SNA along 50°N latitude. The eastern and western North Atlantic areas are divided roughly along the mid-Atlantic ridge and denote the areas more directly affected by the Mediterranean outflow and the Gulf Stream respectively. The Guyana Basin is the area most directly affected by the Amazon River outflow. The FW change in four of the delineated areas is shown in Figure 1 (with the SNA and the GIN combined). The SNA + GIN shows an increase of ~13,000 km^3 in FW from (1966–1970) to (1975–1979), and a more gradual increase of 3,000 km^3 from there through (1990–1994). The initial increase in FW was due, at least in part, to the Great Salinity Anomaly, described by *Dickson et al.* [1988]. The maximum in (1990–1994) is followed by a period of decreasing FW extending through (2002–2006). In contrast, all other areas experienced large decreases in FW in the late-1960s through mid-1970s. In the western Atlantic a decrease of ~10,000 km^3 occurred between (1967–1971) and (1976–1980). For the eastern Atlantic, there was a decrease of ~7,000 km^3 between (1966–1970) and (1974–1978). The Guyana Basin saw a decrease of ~4,500 km^3 from (1969–1973) to (1974–1978). All areas outside the SNA + GIN and Gulf of Mexico/Caribbean Seas had relatively steady FW from the mid-1970s through the 1980s. The Guyana Basin continued with relatively little change in FW through the 1990s to the present. The western and eastern Atlantic areas experienced a large decrease in FW in the mid-1990s, with one pentad decreases of ~6,000 km^3 in the eastern Atlantic (1993–1997) and ~4,500 km^3 in the western Atlantic (1994–1998).

3.2. Equivalent Freshwater and Heat Content in the Subpolar North Atlantic + GIN Seas

[11] The SNA + GIN experienced a period of increasing FW, starting in (1966–1970) and peaked in (1990–1994). The total increase for this period found in the present study is approximately 16,000 km^3 (Figure 2, top). This is within

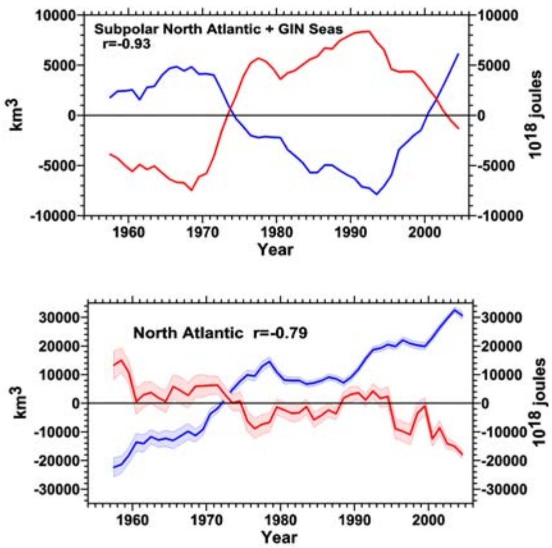

Figure 2. (top) Equivalent freshwater content (red) and heat content (blue) in the subpolar North Atlantic and GIN Seas 0–2,000 meters (1955–1959) to (2002–2006). (bottom) Equivalent freshwater content (red) and heat content (blue) for the North Atlantic (0–80°N) 0–2,000 meters (1955–1959) to (2002–2006) with error estimates (2 × standard error).

the error bars for the 19,000 ± 5000 km^3 increase in FW for the same area calculated by *Curry and Mauritzen* [2005]. Since the peak value in (1990–1994), the SNA + GIN FW decreased by ~9,500 km^3 by (2002–2006). The FW pattern for the SNA + GIN contrasts with the opposite pattern found in the HC of the SNA + GIN (Figure 2, top). The correlation between FW and HC for the SNA + GIN is r = −0.93. This high negative correlation shows that processes governing FW and HC are related, but how is not immediately apparent. If water is less saline at the surface in areas of deep convection, it will have to lose more heat to the atmosphere before deep convection can occur, and vice-versa. However, deep convection does not occur over the entire subpolar North Atlantic, so other processes must also account for the high negative correlation between FW and HC. The correlation for the GIN alone is r = −0.33 (Figure S3e), so processes acting on the GIN affect HC and FW differently. The close relation of FW and HC in the SNA is an area for further study.

3.3. Equivalent Freshwater and Heat Content for the North Atlantic

[12] While the SNA + GIN experienced an increase in FW from (1966–1970) to (1990–1994), all other areas of the North Atlantic experienced a decrease in FW from the late 1960s through the mid to late 1970s. When integrating over the NA, the increases in the SNA + GIN are more than compensated by the decreases elsewhere, resulting in a trend of decreasing FW content over the NA (Figure 2, bottom). The total FW change in the NA over the time period of this study is ~−30,000 km^3. The decrease in FW is mirrored by an increase in HC, although the correlation of r = −0.79 is lower than for the SNA + GIN. FW versus HC for all subareas of the North Atlantic (Figures S3a–3f) show that the lowest correlations (outside the GIN) are in the Western Atlantic and the Gulf of Mexico + Caribbean Sea. Error bars for FW are on the order of 4,000 km^3. Error bars for HC are on the order of 1,500 × 10^{18} joules. Error estimates are shown only on Figure 2

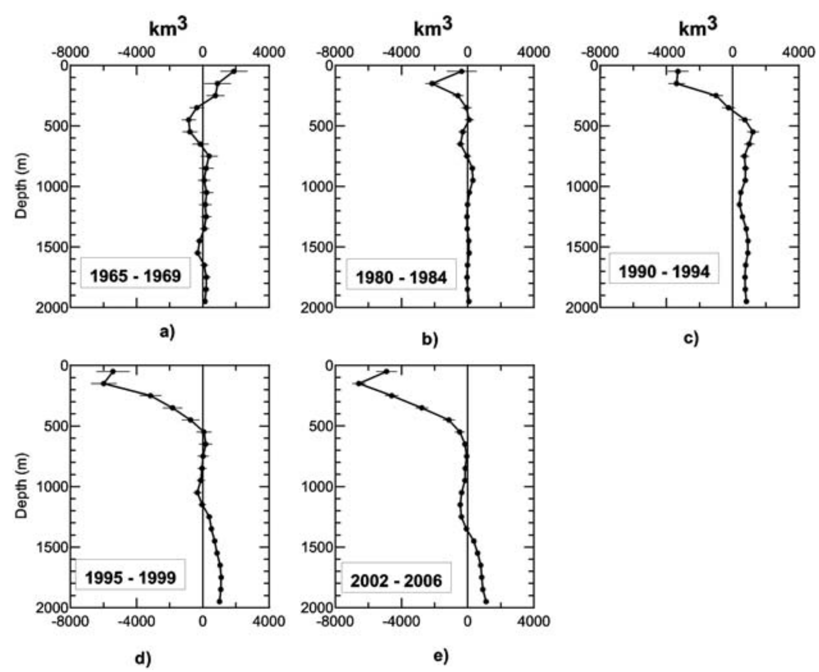

Figure 3. North Atlantic Ocean equivalent freshwater volume integrals by 100 meter ocean layers for (a) (1965–1969), (b) (1980–1984), (c) (1990–1994), (d) (1995–1999), and (e) (2002–2006) with error bars (standard error).

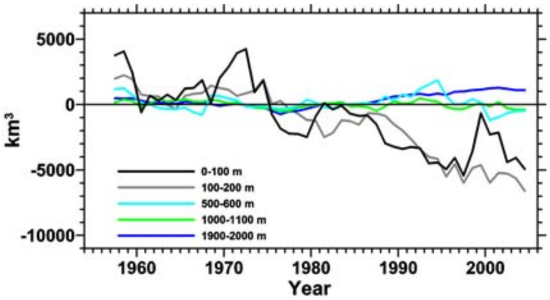

Figure 4. North Atlantic equivalent freshwater volume for selected ocean layers (1955–1959) to (2002–2006).

(bottom) to give an idea of the magnitude of the uncertainty in the FW and HC calculations.

3.4. Variability in Equivalent Freshwater Content by Depth for the North Atlantic

[13] It is important to examine the depth distribution of changes in FW to understand the relative contributions of surface-driven changes and advection forced changes to FW. Figure 3 shows depth distributions of FW. Integrating FW in 100 meter increments over the North Atlantic has the effect of integrating across multiple density surfaces, masking dynamic changes along these surfaces, but it is still instructive to investigate large-scale patterns on depth surfaces. In the pentad (1965–1969) (Figure 3a) freshening is apparent in the upper 300 meters, an opposite pattern between 300 and 700 meters, and little change below 700 meters. Pentad (1980–1984) (Figure 3b) again shows little change below 700 meters, but with negative FW in the upper 400 meters. This negative FW pattern in the upper 400 meters continues through all subsequent pentads shown, with the decreases in FW in the upper 400 meters much greater in the 1990s and 2000s. A freshening below 1,300 meters is evident in (1990–1994), (1995–1999), and (2002–2006) (Figures 3c–3e). This freshening roughly matches the 25– 30 year time frame of *Smethie et al.* [2000] for the southern advection of the fresh SNA water at depth throughout the deep western Atlantic and is consistent with a meridional overturning circulation. Intermediate depths (400 to 1400 meters) in (1990–1994) exhibit a freshening, while pentads (1995–1999) and (2002–2006) reveal no coherent change at these depths.

[14] An interesting feature of Figure 3 is that, excepting the (1965–1969) pentad, FW for the 100 to 200 meter layer has larger decreases in FW, in some pentads significantly larger, than in the 0–100 meter layer, despite being more isolated from surface processes. Looking at FW for selected 100 meter thick depth layers over the 1955–2006 period (Figure 4) shows why this may be so. The 0–100 meter layer exhibits large interdecadal variability in FW which overlay the long-term trend of decreasing FW for this layer over the course of the time period of this study. The 100–200 meter layer also exhibits some interdecadal variations, but not of as great a magnitude as the 0–100 meter layer. This may be because some processes which result in addition or subtraction of freshwater to the upper 100 meters of the North Atlantic do not completely penetrate to deeper layers before the process is ended or reversed. Looking at smaller layers in the top 100 meters (not shown) it is also evident that some intense but geographically limited changes, such as changes associated with the Amazon outflow, do not penetrate deeper than the top 20 or 30 meters and are often of the opposite sign of changes at deeper layers.

[15] At the 500–600 meter layer, there is very little change in FW until an increase in the early 1990s followed by a decrease in the FW of this layer. For the 1000–1100 meter layer, there is very little change in FW. At the 1900–2000 meters, the deepest layer in this study, FW has been increasing nearly linearly from the mid-1970s until the early 2000s. So a pattern of large FW decreases in the upper North Atlantic and smaller increases of FW in the deep North Atlantic (1,300–2,000 meters) is recognizable. A similar pattern was found by *Polyakov et al.* [2005] directly from salinity anomalies.

3.5. Equivalent Freshwater and Precipitation Minus Evaporation

[16] A comparison of FW and P-E (relative to years 1957–1990) for the SNA (Figure 5, top) shows that minimums and maximums for each occurred in the same pentads, (1965–1969) and (1990–1994) respectively. The FW and P-E have a correlation of r = 0.68 over the time period of this study. If only years 1959–2001 are included, the correlation is r = 0.84. If the SNA alone is considered from 1959–2001, the correlation is r = 0.91. Since the maximums in FW and P-E occurred in the 1990s, FW has decreased steadily, while P-E has only slightly decreased, so other factors are responsible for the FW decrease. The magnitude of FW is considerably larger than that for P-E for most pentads, implying that even though P-E is an important contributor to FW, other factors are also significant for changes in FW. Figure 5 (bottom) shows FW and P-E for the NA, Figures S4a–4f show the other 5 areas of the

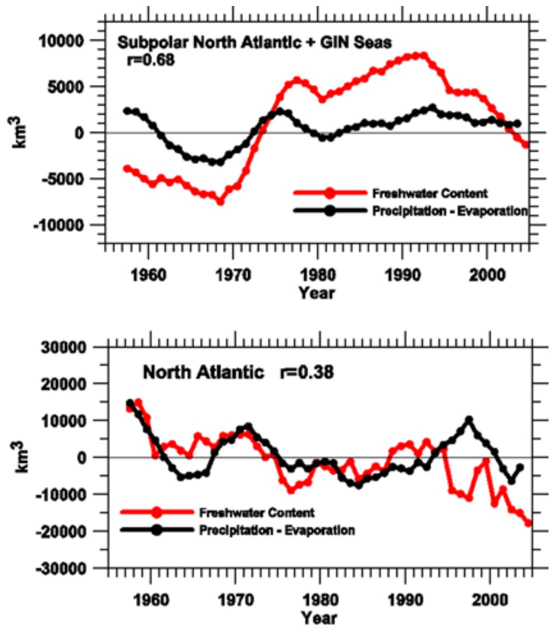

Figure 5. Equivalent freshwater content (red) versus Precipitation - Evaporation from NCEP/NCAR reanalysis (black) for the (top) subpolar North Atlantic and (bottom) North Atlantic (0–80°N).

North Atlantic. All other areas show less correlation than in the SNA.

4. Discussion

[17] This study gives first estimates of the freshwater content of the entire North Atlantic Ocean (NA) using salinity data from the surface to 2,000 meters over the last 50 years. We find, in agreement with previous work, freshening in the subpolar North Atlantic and Gin Seas (SNA + GIN) from the late 1960s to early 1990s. However, the North Atlantic as a whole has exhibited a decrease in freshwater content from 1955 to 2006. The increases in the freshwater content of the subpolar North Atlantic are smaller than the cumulative decreases in other regions of the North Atlantic. The subpolar North Atlantic itself has experienced decreases in fresh water in the last decade. The freshening period of the subpolar North Atlantic was highly correlated with variations in precipitation minus evaporation. However, this relationship is not as well correlated from the early 1990s to the present, the period over which the SNA has become more saline. This result is consistent with *Hátún et al.* [2005] who attribute the increased salinity to high salinity water advected through the eastern SNA. Analysis of the FW variation with depth indicates that the earlier SNA freshwater increase is being advected to the subtropical and tropical North Atlantic at depths greater than 1,300 meters. This freshening from 1,300 to 2,000 meters in the NA is smaller in magnitude than the reduction in FW content in the upper 400 meters of the water column. This exchange of fresh and salty water between the subpolar and subtropical North Atlantic is important for maintaining the haline balance of the NA. An imbalance in this exchange may have important implications for the ocean's thermohaline circulation.

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J. Antonov, T. Boyer, H. Garcia, S. Levitus, R. Locarnini, and A. Mishonov, National Oceanographic Data Center, NOAA, SSMC3, 4th Floor, 1315 East-West Highway, Silver Spring, MD 20910-3282, USA. (tim.boyer@noaa.gov)

S. A. Josey, National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK.