Observational Estimates of the Seasonal Cycle of North Atlantic Eighteen Degree Water Volume.

Gaël Forget, Guillaume Maze, Martha Buckley and John Marshall

Dept. of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge MA 02139 USA

December 16, 2009

E-mail address: gforget@mit.edu
ABSTRACT

The seasonal cycle in the volume and formation rate of Eighteen Degree Water (EDW) in the North Atlantic are quantified over the three-year period from 2004 to 2006. The EDW layer is defined as all waters which have a temperature between 17°C and 19°C. The study is facilitated by a synthesis of various observations — principally Argo profiles of temperature and salinity, sea surface temperature and altimetry — using a general circulation model as an interpolation tool. The winter increase in EDW volume occurs most intensively in February, peaking at about 8.6Sv, where 1Sv $\approx 3.15 \times 10^{13} m^3$ corresponding to a $1Sv = 10^6m^3s^{-1}$ flow sustained for one year. This largely reflects winter EDW formation due to air-sea heat fluxes. Over the remainder of the year, newly created EDW is consumed by air-sea heat fluxes and ocean mixing, which roughly contribute 2/3 and 1/3, respectively. We estimate a net annual volume increase of 1.4Sv per year, averaged over the three year period. It is small compared to the amplitude of the seasonal cycle (8.6Sv) and annual formation due to air-sea fluxes (4.6Sv). The overall EDW layer volume thus appears to fluctuate around a stable point during the study period. Our estimate of the full EDW volume budget is provided along with an uncertainty estimate of 1.8Sv, and largely resolves apparent conflicts between previous estimates.
1. Introduction

Mode waters are voluminous upper-ocean water masses characterized by near-homogeneous properties. The western subtropical North Atlantic contains a large volume of water with temperature close to 18°C, which has become known as Eighteen Degree Water (hereafter EDW). It is a characteristic feature that is typically found in the gyre recirculation to the south of the Gulf Stream. Attention was drawn to EDW by Worthington (1959), whose key contribution was to put EDW in the context of the large scale ocean circulation and climate. Understanding the cycle of EDW formation and consumption is important because this water mass mediates heat exchange between the ocean interior and the atmosphere. Wintertime convection induced by surface cooling is thought to be the primary formation process. However the precise nature of the formation/dissipation processes and their rates remain unclear and are the subject of vigorous research (for example, the CLIMODE field experiment — for CLivar MOde Water Dynamic Experiment, described in Marshall et al. 2009). In this context, the present study provides new insights into the seasonal fluctuation of EDW volume, based on the recent and extensive collection of Argo profiles.

Here, consistent with Worthington (1976), we simply define EDW as all fluid with a temperature between 17°C and 19°C found in the Atlantic Ocean north of 5°N. The North Atlantic temperature distribution shows a mode in this temperature range – the so defined EDW is therefore a mode water. A major advantage of such a simple definition is that the Walin (1982) framework can be applied to form a precise volume budget of the EDW layer. Let us emphasize, however, that there is no unique valid definition of EDW, and several flavors of EDW have been distinguished in the literature. We will therefore also discuss subsets of EDW which have low potential vorticity (PV=−(f/ρ0)∂ρ/∂z) and split EDW between the western basin and eastern basin (delimited by the 35°W line). The distinction of eastern and western EDW follows from Siedler et al. (1987), who designated eastern EDW as ‘The Madeira Mode Water’.
Two main approaches have been used to obtain observational insights into the volume budget of EDW: 1) volume census changes from in situ data (e.g. Worthington 1976; Kwon and Riser 2004); 2) formation rates computed from air-sea fluxes (e.g. Worthington 1976, Speer and Tziperman 1992, and Maze et al. 2009). Confusion has arisen because the two approaches yielded quantitatively different results, providing an important motivation for the CLIMODE project (see Marshall et al. 2009) and the present study. Errors associated with both approaches are likely to be very different, suggesting the utility of a combined methodology. One such is pursued here, allowing us to reconcile EDW volume and formation/dissipation rates by synthesizing the variety of available data sets within the dynamical framework of a General Circulation Model (hereafter GCM). Our broader goal is an improved dynamical and quantitative understanding of the seasonal cycle of EDW on the scale of the basin and its underlying mechanisms.

In Section 2 we present the methods used to synthesize and analyze the observations, and characterize the seasonal cycle of the EDW layer. Our reference estimate of the full EDW volume budget is presented and analyzed in Section 3. To place the full budget estimate in context and associate it with an uncertainty estimate, stand-alone estimates of a volume census based on Argo profiles and of surface formation rates from air-sea fluxes are assessed in Section 4. The results shed new light on previous estimates, which we attempt to reconcile in Section 5. Finally, Section 6 summarizes and discusses the results.
2. Observational Syntheses

a. Generalities

Our North Atlantic study exploits a recent near-global synthesis of the vast Argo, SST and altimetric data sets collected over the three-year period from 2004 to 2006 (Forget 2009). This data set — named OCCA for OCean Comprehensible Atlas — is obtained using GCM-interpolation and consists of a time-varying estimate of the full ocean state. The 2004-2006 period of analysis was chosen because of the unprecedented near-global in-situ data coverage provided by Argo floats. By virtue of this relatively dense data coverage, the 2004-2006 period ought to provide a good reference point to gauge past and future shifts in the ocean state.

Let us recall the motivation for using an Ocean General Circulation Model (OGCM) as a data synthesis tool. A purely statistical model of the ocean behavior, based e.g. on a spatial decorrelation model, may be used to map Argo observations and estimate EDW volumes. Yet there are at least three major advantages in using GCM-interpolation of the data, which are particularly relevant to EDW volume budget estimates. First GCM-interpolation is adequate to bring together the disparate variety of available observations, and exploit their synergy. Second GCM-interpolation immediately yields full estimates of ocean budgets. Third an OGCM is a convenient framework to carry out an extended interpretation of the observations, in terms of known dynamical principles.

It is clear that neither statistical models nor OGCMs can yield perfect representations of ocean dynamics. When used to synthesize observations, both are susceptible to overfitting or underfitting observations, which may lead to a mis-interpretation of the observations. To identify such occurrences, and assess errors more generally, it is useful to compare results of different data synthesis methods. We will therefore also provide extensive comparisons between the OCCA estimate and data syntheses that do not involve an OGCM.
A crucial aspect of the data synthesis problem is how to deal with ‘noise’ in the data due to aliasing of small-scale phenomena. Dynamical instabilities generating meso-scale or mixed-layer eddies may be a key process in mode water dynamics, and such processes are accounted for by OGCMs (albeit in an imperfect, parametric form). It is clear, however, that the Argo array, despite vastly improving the in-situ data coverage, cannot fully resolve the meso-scale and will alias eddy signals. It follows that the unresolved signals must be treated as data noise in the data synthesis process. In the syntheses presented below (whether using an OGCM or not) the data are accordingly smoothed in time and space. Let us now provide specifics on the data synthesis methods.

b. OCCA state estimate

The state estimation problem and methods that lead to the OCCA estimate are discussed in detail by Forget (2009). Briefly, a GCM-data synthesis is obtained as an approximate solution to a constrained non-linear least-squares estimation problem. The general circulation model employed is the MITgcm (Marshall et al. 1997; Adcroft et al. 2004) in the ECCO framework (Stammer et al. 2002; Wunsch and Heimbach 2007) with a grid resolution of one degree horizontally and with 50 levels in the vertical. The sub-grid-scale processes are parameterized as background vertical mixing \((K = 10^{-5} m^2 s^{-1})\), isopycnal mixing \((K = 1000 m^2 s^{-1})\), boundary layer vertical mixing (KPP scheme), and a bolus velocity representing advection by eddies (GM scheme; \(K = 1000 m^2 s^{-1}\)). Air-sea fluxes are computed (from the GCM) using the Large and Yeager (2004) algorithm, an adjusted version of NCEP atmospheric state variables, and the GCM fields of SST (see Forget 2009 for details).

In the GCM, time-evolving fields are made to fit to a variety of observations (including Argo profiles, SST, and altimetric data), by iteratively adjusting initial conditions and surface forcing fields, using the adjoint method. The aforementioned mixing parameters are held constant,
however, which would need to be refined. The three-year period from 2004 to 2006 is split into three 16-month overlapping time intervals. The choice of the estimation interval(s) of 16 months is a practical means to mitigate the effect of model error accumulation, and yields a close fit to the observations. Each 16-month solution is required to strictly satisfy the GCM dynamics but, when compiling the three-year time series, this strict constraint is relaxed over the periods when solutions overlap one another (see Forget 2009 for details).

The resulting estimate of the time-evolving ocean state (OCCA) closely matches Argo, SST, and altimetric observations over the three year period from 2004 to 2006, within random error bounds (see Figs. 3 to 8 of Forget 2009). OCCA thus potentially provides robust observational estimates of water mass properties and volumes, which indeed will be established below for EDW (see Sections 2d and 4a). In addition OCCA includes estimates of air-sea fluxes and interior ocean fluxes that are constrained by ocean observations within the GCM-interpolation framework. This yields a full EDW volume budget estimate (Section 3) which, along with the associated error estimate (Section 4c), is the main result of our study.

c. **EDW sample census method**

To assess the reliability of OCCA estimates of EDW volumes, we shall compare them with the results of a very different data synthesis method, which we refer to as sample census (SC). It is based on a simple statistical model rather than a GCM.

For a given control volume $V$, assume that $N$ observations of temperature are available, which are irregularly distributed within $V$. The EDW volume $V_{EDW}$ of fluid such that $17 < T < 19^\circ C$ in $V$ is to be estimated. The sample census method consists of: (1) computing the ratio $R_{EDW} = N_{EDW}/N$, where $N_{EDW}$ is the number of samples satisfying $17 < T < 19^\circ C$ in $V$; (2) computing $V_{EDW}$ as $R_{EDW} \times V$. The method can readily be generalized to any other water mass definition. As noted by Siedler et al. (1987), who used such a method, the
necessary assumption is that the data coverage of $V$ is sufficiently uniform to ensure that $R_{EDW}$ is representative of the probability of finding $EDW$ in $V$. It is clear that this is an imperfect statistical model in the case of Argo profiles, which are rather irregularly distributed in space and time.

In practice, when dealing with a vast domain in this fashion, one should aim to appropriately split $V$ into elementary control volumes $\{V^i\}$, and estimate $V_{EDW}$ as $\sum_i R_{EDW}^i \times V^i$, in order to minimize artifacts due to irregular sampling. Each $V^i$ should ideally be: (1) large enough to contain numerous observations; (2) homogeneous enough to minimize irregular sampling within $V^i$. In this study we use winter SST contours and depth levels to guide our choice of control volumes. The rationale is that the winter SST is representative of the mixed layer temperature at the peak of convection when mode waters are formed. In particular each $V^i$ is delimited in the horizontal by two contours (SST = $\Theta^i \pm \Delta \Theta$) of the three-year-mean RSS-Reynolds March SST map (see Fig.1; the top right panel shows a plan view of $V^i$ for $\Theta^i = 18^\circ C$). Setting $\Delta \Theta = 1 K$ we compute $V_{EDW}$ as $\sum_i R_{EDW}^i \times \delta \Theta$ where $\delta \Theta = \Theta^{i+1} - \Theta^i = 0.1 K$. The small $\delta \Theta / \Delta \Theta = 0.1$ ratio is designed to reduce the noise level in $V_{EDW}$ by smoothing the $R^i(\Theta^i)$ curves. We do no such smoothing in the vertical or in time. Section 4a discusses the resulting SC estimates of $V_{EDW}$. We first display the SC results in the form of $R_{EDW}^i$ sections (Figs.4-5-6-7). These are very useful for descriptive purposes.

d. Observed Evolution of the EDW Layer

Before turning to a more quantitative analysis, it is important to present the observed signals. The outcropping of the EDW layer and its seasonal variation are shown in Fig.1. Isotherms sweep back and forth over a $20^\circ$ latitudinal range, migrating northward under spring and summer warming, and southward again in fall and winter. The distances involved are very large (see Fig.1) and do not reflect migration of fluid parcels, but rather diabatic processes
changing the properties of surface water. A key feature associated with EDW formation is the opening up of a broad outcrop in February and March over the western part of the basin (top right panel). The EDW outcrop area typically peaks in March, as it reaches its southernmost location, at which point it is more than twice as large as the summer outcrop area.

Figs.2-3 show the time evolution of the temperature profile beneath this winter outcrop window. In both the western basin (Fig.2) and the eastern basin (Fig.3), the EDW layer rapidly thickens in winter as the mixed layer deepens and reaches the pre-existing sub-surface EDW reservoir. In summer, the EDW layer gradually thins as the water column restratifies from the surface downward. The main difference between the two regions is that the EDW layer is shallower and thinner in the eastern basin (Fig.3) than it is in the western basin (Fig.2). In the western basin, EDW typically occupies a depth range of 200-400m in summer and 0-400m in winter. The thickness of the EDW layer thus varies by a factor of two over the seasonal cycle, from 230m at the peak of stratification to 430m during winter convection. In the eastern basin these figures are typically smaller by a factor of two. The thickness of the EDW layer varies by a factor of three over the seasonal cycle, but only from 50m to 180m.

The evolution of the EDW layer below the surface is displayed in Fig.4. The figure shows the probability $R_{EDW}$ that an Argo observation of $T$ lies between 17 and 19°C, as a function of depth and ‘equivalent latitude’ (see legend of Fig.4 for more details). In each panel of Fig.4, for a given month of the year, the presence of EDW is indicated by $R_{EDW}$ approaching unity. Fig.4 thus shows the southward (in fall and winter; top panels) and northward (in spring and summer; bottom panels) sweep of the EDW layer below the surface. In summer, the EDW layer exhibits a northward tilt near the surface. In winter, the EDW layer slopes strongly up to the surface, reflecting the downward penetration of the mixed layer. In March, the subsurface EDW reservoir (in the 150-400m depth range) is connected directly to the surface through a well-mixed column. From March onwards (bottom panels), the lower part of this ‘umbilical
cord’ becomes extended and eroded, while its upper part sweeps northward.

In exactly the same way, Figs.5-6 show the evolution of two EDW subsets: EDW with potential vorticity $PV < 1.5 \times 10^{-10} m^{-1} s^{-1}$ (Fig.5), and EDW with $PV < 2 \times 10^{-11} m^{-1} s^{-1}$ (Fig.6). The low PV restriction ($PV < 1.5 \times 10^{-10} m^{-1} s^{-1}$) is guided by the literature on subtropical mode waters (see Hanawa and Talley 2001; Kwon and Riser 2004). The very low PV restriction ($PV < 2 \times 10^{-11} m^{-1} s^{-1}$) will also prove insightful (see below).

Fig.5 shows a surface mixed layer (ML) patch of low PV EDW and a large subsurface reservoir of low PV EDW that merge in winter. The ML patch appears to deepen and migrate southward during fall and winter (top panels). Kinematically, this behavior can be understood as follows. At any location, in winter, the ML cools down progressively as it deepens (reaching into colder layers beneath), and the ML fluid will temporarily qualify as EDW when the ML reaches the $18^\circ C$ isotherm at this location. The ML temperature simply crosses the $18^\circ C$ mark earlier at higher latitudes, where it was shallower in summer-time (see Fig.4). Hence we observe a southward migration of the ML patch in winter (Fig.5). In March the ML has reached the depth of the EDW reservoir, and the ML patch has reached its southernmost location. At this point, it cannot be distinguished from the EDW reservoir, which reaches right up to the surface. In spring and summer restratification proceeds downward from the surface (see Figs.2-3), increasing PV and causing the ML patch to progressively disappear, and the EDW reservoir returns to its pre-winter subsurface configuration (Fig.5). In the early fall, a new ML patch appears at the northernmost position of the EDW outcrop, initiating a new cycle.

Restricting attention to a very low PV subset of EDW allows one to focus on EDW that has recently been affected by convection in the ML (Fig.6). The winter deepening and southward migration of the ML patch is thus most evident in Fig.6. By March, the ML is seen to penetrate the EDW reservoir down to a depth of 400m, well into core of the EDW reservoir, which resides at a depth of about 300m (see Fig.4). In May, after restratification has begun, very low PV
EDW is left behind at the core of the EDW reservoir (Fig.6, bottom right panel). It then progressively disappears reflecting its dissolution within the EDW reservoir. This behavior is suggestive of mixed layer deepening driving the EDW reservoir towards low potential vorticity.

Aside from their descriptive purpose, Figs. 1 to 6 also serve to test the reliability of ocean data sets (GCM-interpolated or otherwise). Firstly the fact that individual data sets, prior to GCM-interpolation, readily allow clear representations of EDW layer fluctuations is indicative of a rather solid data base. In particular, the clear signals evident in Figs.4-5-6 suggest that Argo provides the bulk of the in situ information needed to estimate the seasonal cycle of the EDW layer. It should be kept in mind, however, that the observational syntheses shown in Figs.4-5-6 involve a stringent statistical model and a considerable amount of smoothing. Secondly there is good agreement between OCCA and the data sets prior to GCM-interpolation for both the time-varying surface outcrop (Fig.1) and the time-varying vertical structure (Figs.2-3) of the EDW layer. Differences in the area of the EDW outcrop (see Fig.1, bottom panel) between the OCCA, Reynolds and RSS SST maps have a standard deviation of $1.5 \times 10^5 \text{km}^2$, while the seasonal fluctuation is about 20 times larger. The correlation coefficients between the various estimates are close to 0.99. With regard to EDW layer thicknesses (see Figs.2-3, bottom panel), differences between OCCA and Argo estimates have a standard deviation of 40m (12m) for the western box (eastern box), while the seasonal fluctuation is 5 times (10 times) larger. The correlation coefficients between the various estimates are close to 0.95.

To further compare OCCA with Argo profiles, OCCA daily fields are sampled the same way as the Argo profiles, and a map of the fluctuating EDW layer is constructed using the SC method (see Fig.7). A comparison of Fig.7 (from OCCA profiles) and Fig.4 (from raw Argo profiles) shows that the two representations of the fluctuating EDW layer are very similar. In particular, the features that were evident in Argo profiles (Fig.4; prior to GCM-interpolation) are consistently found in OCCA profiles (Fig. 7; after GCM-interpolation). The same is
true for the EDW subsets that are displayed in Figs.5-6 (not shown). The most substantial inconsistency between OCCA profiles and raw Argo profiles is that the probability of finding EDW below 400m, at the very bottom of the EDW layer, shows a low bias in Fig.7 compared with Fig.4, for all months of the year. As a result, we judge that the OCCA estimate for the annual mean EDW volume (75Svy; as reported in Tab.1) could be too small by perhaps 10%.

It should be kept in mind, however, that the Argo and SST data sets were made use of in OCCA (see Forget 2009), so the above consistency checks (using Figs.1, 2, 3 and 4-7) should not be mistaken for comparisons of independent estimates. Rather they demonstrate that OCCA is a rather adequate synthesis of Argo and SST data, subject to the dynamical/thermodynamical constraints encoded in the GCM, and OCCA readily captures the signals of interest.

To complete this preliminary description, Fig.8 reveals the time mean and variability of the EDW layer thickness using OCCA. We see that the mean EDW layer thickness is a maximum over a broad region to the southeast of the March 17°C isotherm (denoting the Gulf Stream path). The seasonal cycle in thickness is a maximum over the same broad region but appears to be slightly shifted to the North West (right panel). Maxima in both thickness and thickness variation are well collocated with the opening of a broad winter outcrop, consistent with mode water being predominantly formed through a one-dimensional convective process. At lower latitudes, the EDW layer never outcrops and its thickness does not exhibit a strong seasonal cycle. The EDW layer remains relatively thick as far south as 20°N, however, which is more than 10° to the south of the winter outcrop region. This well-known feature of the EDW layer is suggestive of an influence of the EDW outcrop over a large fraction of the thermocline of the subtropical gyre. A secondary regional maximum in thickness variability is found in the eastern part of the basin, as first noted by Siedler et al. (1987). We now will quantify the seasonal cycle of EDW volume revealed in Figs.1 to 8.
3. Estimated EDW Volume Seasonal Cycle

a. Water Mass Transformation Framework

The problem at hand is precisely formulated in the Walin (1982) framework. The volume budget of the EDW layer at time $t$ within a control volume $\mathcal{V}$ (taken here as the North Atlantic north of $5^\circ$N) is written as

$$\frac{dV_{EDW}}{dt} = \Delta A_{EDW} - M_{EDW}$$

where $V_{EDW}(t)$ is the volume of EDW in $\mathcal{V}$, $\Delta A_{EDW}(t)$ is the ‘formation rate’ of EDW in $\mathcal{V}$, and $M_{EDW}(t)$ is the flow of EDW across $5^\circ$N (counted $>0$ out of $\mathcal{V}$, i.e southward). Advection by meso-scale eddies, which is parameterized using the GM scheme, is included in $M_{EDW}(t)$.

$$\Delta A_{EDW} = A_{19} - A_{17}$$

where $A_{17}$ and $A_{19}$ are the ‘transformation rates’ $A_\Theta$ for $\Theta = 17^\circ$C and $\Theta = 19^\circ$C, respectively. $A_{17}$ and $A_{19}$ are the volume fluxes through the $17^\circ$C and $19^\circ$C isotherms (counted $>0$ towards colder isotherms), respectively. Thus $\Delta A_{EDW}$ is the volume flux through the two (moving) isotherms that delimit the EDW layer (counted $>0$ entering the EDW layer). We recall from Walin (1982) and studies that followed that

$$A_\Theta = \frac{\partial}{\partial \Theta} \left( \iiint_{R(\Theta,t)} -\frac{DT}{Dt} \, d\mathcal{V} \right)$$

where $R(\Theta,t)$ is the three-dimensional ocean region within $\mathcal{V}$ where $T < \Theta$ (increasing with $\Theta$), and $\frac{DT}{Dt} = - \nabla \cdot N_T$ is the convergence of non-advective heat fluxes $N_T$ (see e.g. Marshall et al. 1999). $\Delta A_{EDW}$ may be further decomposed as

$$\Delta A_{EDW} = \Delta A_{EDW,ext} + \Delta A_{EDW,int}$$

where $\Delta A_{EDW,ext}$ are external contributions due to air-sea heat fluxes, and $\Delta A_{EDW,int}$ are internal contributions due to ocean mixing. $\Delta A_{EDW,int}$ is the combined effect of vertical, isopycnal,
and surface boundary layer diffusion. $ΔA_{EDW, ext}$ is not quite a sea surface term, because shortwave fluxes can penetrate the subsurface. Eq.1-4 states that EDW volume fluctuations ($\frac{dV_{EDW}}{dt}$) consist of not only water mass transformations due air-sea fluxes ($ΔA_{EDW, ext}$), but also water mass transformations due to mixing ($ΔA_{EDW, int}$), and water mass fluxes out of the control volume ($M_{EDW}$). Comprehensive estimates of EDW volume fluctuations must address all four terms in Eq.1-4, and be obtained in an integrated fashion to ensure Eq.1-4. Such an estimate, synthesizing the disparate variety of ocean data sets, is presented in Section 3b.

b. OCCA Reference Estimate

Here we focus on the OCCA estimate for the three-year-average seasonal cycle in EDW volume. First a three year daily time series of Eq.1-4 is computed (see appendix for details). Second the 2004, 2005 and 2006 daily rates are averaged together, leading to an average year daily time series (from $t_0 = Dec. 1^{st}$ to $t_1 = Nov. 30^{th}$). Third, integrating in time, leads to the average year daily time series of

\[ V_{EDW}(t) = \Delta A_{EDW, ext}^t + \Delta A_{EDW, int}^t - M_{EDW}^t \]  

(5)

where $V_{EDW}(t)$ is the EDW volume at time $t$ referenced to the EDW volume at time $t_0$ (i.e. Dec. 1st), and $\int_{t_0}^{t} \cdot dt$ denotes the time integral from $t_0$ to $t$. An equivalent notation for $V_{EDW}(t)$ is $\frac{dV_{EDW}}{dt}^t$. Results are presented in units of Sv (Sverdup-year), where $1Sv = 10^6 \times 365 \times 86400 \approx 3.15 \times 10^{13} m^3$ corresponding to a $1Sv = 10^6 m^3 s^{-1}$ of volume flux sustained for one year.

A key advantage of the OCCA data set is its representation of three dimensional budgets of volume and heat, which allow diagnostic computation of a full volume budget for the EDW layer through Eq.5. Nevertheless, numerical application of Eq.5 is a non-trivial matter, which led us to use two different numerical recipes (see Appendix). Using either recipe, the residual imbalances in Eq.5 are three orders of magnitude less than the balancing terms. In other words,
the EDW volume budget is ‘closed’ to three digits.

Our reference estimate is displayed in Fig.9. For each term in Eq.5 it plots the interval between the two numerical recipes (shading) and the average result (thick curves). In this section the estimates will be presented as $a \pm b$ where $b$ is half the interval width. $b$ quantifies uncertainties emerging from numerics alone, and should not be mistaken as a full error estimate, which must also account for observational uncertainties (see Section 4c and arrows in Fig.9). Numerical uncertainties in EDW volume change $\mathbb{V}_{EDW}$ amount to $2b = 0.5$Svy by year end. Numerical uncertainties in EDW export $\mathbb{M}_{EDW}$ amount to $2b = 1.1$Svy by year end. These two combine to yield a numerical uncertainty of $2b = 1.6$Svy in EDW formation $\Delta A_{EDW}^t$, which is split equally between $\Delta A_{EDW,int}^t$ and $\Delta A_{EDW,ext}^t$.

The EDW volume shows a rapid increase in winter to about $8.6 \pm 0.3$Svy (relative to the Dec. 1st value), achieving a maximum at the end of February. This mostly reflects the $9.3 \pm 0.4$Svy wintertime formation by air-sea heat fluxes $\Delta A_{EDW,ext}^t$ due to vigorous cooling of the ocean. Subsequently, air-sea heat fluxes consume $4.6 \pm 0.4$Svy of the newly formed EDW mostly from March through May. The net annual effect of air-sea heat fluxes is a $4.6 \pm 0.4$Svy formation of EDW. Mixing in the ocean interior $\Delta A_{EDW,int}^t$ consumes $2.6 \pm 0.4$Svy by year end. It consumes EDW over most of the year, except in February when convective mixing tends to reinforce formation by air-sea heat fluxes (as denoted by the increase in $\Delta A_{EDW,int}^t$). The net total EDW formation (due to air-sea fluxes and mixing) hence is $2 \pm 0.8$Svy. The EDW flux through $5^\circ$N is weakly southward throughout the year, only resulting in a $0.6 \pm 0.6$ EDW export $\mathbb{M}_{EDW}$ by year end. The net annual change in EDW volume $\mathbb{V}_{EDW}$ is a relatively small increase of $1.4 \pm 0.3$Svy, per year in the three year average. The bulk of the estimated $V_{EDW}$ interannual variability ($\pm 1.6$Svy, as reported in Tab.2; see also Section 4a) is due to this trend. The net total formation ($2 \pm 0.8$Svy) is balanced by volume change ($1.4 \pm 0.3$Svy) and, to a lesser extent, by a southward flow through $5^\circ$N ($0.6 \pm 0.6$Svy).
It is interesting to note that the net annual change in EDW volume (1.4 ± 0.3Svy) is small compared with the seasonal fluctuation (8.6 ± 0.3Svy). Gauging the EDW reservoir volume (75Svy) with respect to this rate of annual volume change (1.4Svy) implies a 50 year time scale. The relatively large seasonal fluctuation, however, suggests that 8 years may be sufficient to *ventilate* the EDW reservoir. The difference between these time-scales is largely due to the restratifying effects of air-sea heat fluxes and mixing that balance winter-time creation. Although we do not exclude the possibility that seasonal cycle imbalances could be larger during other periods, the EDW volume appears to fluctuate around a rather stable point during 2004 to 2006.

It should be emphasized that the annual formation by air-sea heat fluxes \( \Delta A_{EDW,ext}^t \) alone does not yield a good proxy for the annual volume change \( V_{EDW} \). Neglecting the contribution of ocean mixing \( \Delta A_{EDW,int}^t \) and, to a lesser extent, export \( M_{EDW}^t \), would lead to an overestimation of the net annual volume change \( V_{EDW} \) by a factor of 3 based on \( \Delta A_{EDW,ext}^t \) alone. Winter-time air-sea heat fluxes, however, do largely determine winter-time volume change.

4. Sensitivity Tests And Uncertainty Estimates

To put our reference estimate of the full EDW volume budget (Fig.9) into perspective, we now consider stand-alone estimates of \( V_{EDW}(t) \) and \( \Delta A_{EDW,ext}^t \). These sensitivity tests will provide insights into the different sources of uncertainty.

a. Sample Census of EDW in Argo Profiles

Stand-alone estimates of \( V_{EDW}(t) \) can be derived by a sample census (SC) of EDW in Argo profiles (see Section 2c). Volume estimates are obtained by computing volume weighted
integrals of the statistics shown in Fig.4. This approach can be carried out with any set of profiles and water mass definition (e.g. for Fig.5, 6 or 7). Monthly estimates of water mass volumes are thus shown in Fig.10 for EDW or EDW subsets, using Argo profiles or OCCA profiles (sampling OCCA fields as Argo did the real ocean). Thin lines denote individual year estimates (for 2004, 2005 or 2006), and thick lines denote three year average estimates. We define the ‘spread’ as the standard deviation of individual year monthly anomalies (from the corresponding three year monthly average). Interpretation of this metric will be clarified below. Spreads and seasonal cycle amplitudes are reported in Tab.2.

Let us start with the full EDW volume seasonal cycle, which is our main focus. The Argo SC estimate of EDW volumes (Fig.10; top left panel; thick blue curve) shows a 7.3Svy peak-to-peak seasonal cycle with a rapid volume increase in winter. This value is broadly consistent with the OCCA reference estimate (thick black curve; 8.6Svy) and the OCCA SC estimate (thick red curve; 7.7Svy). This encouraging consistency suggests that Argo does provide a fairly solid data base to estimate the EDW volume seasonal cycle over the period from 2004 to 2006, so that the result does not strongly depend on the choice of data synthesis method.

For SC estimates, the spread is relatively large, however: 2.9Svy for OCCA profiles, and 4.8Svy for Argo profiles (see Tab.2). It reflects systemic sampling errors (due to irregularities in data coverage) rather than robust signals of interannual variability. Indeed, when sampling OCCA as Argo does the real ocean, the spread in the OCCA SC estimate (2.9Svy) becomes much larger than the spread in the OCCA reference estimate (1.6Svy; based on full OCCA fields). Further evidence is given by the comparison of two OCCA SC results: (1) profiling daily fields that include interannual variability (Fig.10, top left panel; red curves); (2) profiling three-year-mean monthly fields that do not include interannual variability (not shown). The spread is the same in both cases (2.9Svy; see Tab.2), showing that the variation in data coverage suffices to explain this spread. Unsurprisingly, raw Argo profiles yield a larger spread (4.8Svy)
than do OCCA profiles (2.9 Svy). The former indeed include small/meso-scale signals that the float array cannot properly resolve, which is a large source of random noise. Hence, as expected, the smoothing provided by the coarse resolution OGCM implies a clear spread reduction in SC estimates (from 4.8 Svy to 2.9 Svy). Finally the OCCA reference estimate spread (1.6 Svy; based on full OCCA fields) is the small fraction (11% in terms of variance) of the Argo SC spread (4.8 Svy) that may be due to large-scale interannual variability. Of course it could also reflect an aliasing of ‘eddy noise’, even though one may hope otherwise. Whether such interannual variability can rigorously be distinguished from noise is less than clear.

Before we turn to EDW formation by air-sea fluxes, let us examine SC results for subsets of EDW. The above conclusions generally hold for the various EDW subsets. They show similar temporal patterns (Fig.10), and there is a satisfying quantitative agreement amongst the various estimates (Fig.10 and Tab.2), but SC results show a relatively large spread due to sampling errors (Tab.2). There are noticeable differences between the various EDW subsets, however, which are particularly relevant in the context of previous subtropical mode water studies which have sometimes favored more restrictive water mass definitions. First, low PV restrictions tend to increase the seasonal cycle amplitude (Tab.2; line 3 vs 2; line 4 vs 3). The underlying reason seems clear: part of the lower PV EDW that is created during winter convection actually consists of pre-existing EDW, whose PV gets reduced by convective mixing. This feature is most evident in Fig.5 in the upper 100m of the ocean, where EDW is accounted for in winter, but discarded in summer when its PV is more than $1.5 \times 10^{-10} m^{-1} s^{-1}$ (compare Fig.5 with Fig.4). Second, the $PV < 1.5 \times 10^{-10} m^{-1} s^{-1}$ restriction tends to exacerbate sampling errors. For example, sub-sampling OCCA (as Argo sampled the ocean) leads to a 4.4 Svy offset in the case of EDW with $PV < 1.5 \times 10^{-10} m^{-1} s^{-1}$ (Tab.2; line 2; column 3 vs 2). Also, the spread in the Argo SC estimate increases from 4.8 Svy to 5.8 Svy upon introducing this PV restriction (Tab.2; column 4; line 3 vs 2). The $PV < 2.0 \times 10^{-11} m^{-1} s^{-1}$ restriction seems more favorable in
this respect. For this case, however, the smoothing provided by the OGCM implies a significant
overestimation of the seasonal fluctuation (Tab.2; line 4; column 3 vs 4). A closer investigation
suggests that it is due to an offset in very low PV values (not shown). Finally, the seasonal
fluctuation in EDW volume for the eastern basin is ≈ 20% of the western basin value (Tab.2;
lines 5 and 6). While the western basin seasonal fluctuation is clearly predominant, the eastern
basin provides a sizeable fraction of the total fluctuation (≈ 15%, as noted by Siedler et al.
1987).

b. EDW Formation Due to Air-Sea Heat Fluxes

We recall that OCCA air-sea fluxes are computed (from the GCM) using the Large and
Yeager (2004) algorithm, an adjusted version of NCEP atmospheric state variables, and the
GCM fields of SST. The adjustment to NCEP fields is determined by the GCM-interpolation
procedure to best fit ocean observations (see Forget 2009 for details). The SST maps from
Reynolds and Smith (1994) are applied as constraints (along with other ocean data) in that
GCM-interpolation procedure. The OCCA estimate of surface EDW formation rates is derived
from the OCCA full temperature fields, along with the OCCA fluxes, using Eq.3-4.

Stand-alone estimates of surface EDW formation rates can be derived from atmospheric re-
analysis data sets and SST maps, while omitting the available sub-surface ocean observations.
This is done using a simplified version of Eq.3 for air-sea fluxes that is

\[ A_{\Theta, ext} = \frac{\partial}{\partial \Theta} \left( \int \int_{S(\Theta, t)} \frac{Q_{net}}{\rho_0 C_p} \, dS \right) \] (6)

where \( S(\Theta, t) \) is the sea surface within the control volume \( V \) where \( T < \Theta \), and \( \frac{Q_{net}}{\rho_0 C_p} \) is the net
air-sea temperature flux directed out of the ocean (i.e. \( Q_{net} > 0 \) is a cooling of the ocean) in
units of \( K m^{-1} \). The underlying simplification is that short-wave penetration is omitted, so
that computing Eq.6 only requires SST fields (rather than full temperature fields). As in Section
3b, the results are presented in the form of the time integrated EDW formation $\Delta A_{EDW,ext}^t$.

In Fig. 11 we thus show six stand-alone estimates of $\Delta A_{EDW,ext}^t$ that differ in the choice of re-analysis data sets (NCEP or ECMWF) and atmospheric surface layer parameterization. For each re-analysis, three sets of air-sea heat fluxes are considered, which correspond to three different atmospheric surface layer algorithms: (a) the re-analysis center algorithm; (b) the Large and Yeager (2004) algorithm; (c) the Fairall et al. (2003) algorithm. In case (a) re-analysis maps of net air-sea heat flux ($Q_{net}$) are used. For (b) and (c), re-analysis maps of 10m-height state variables are used, along with Reynolds and Smith (1994) SST maps, to compute $Q_{net}$ maps. Each of the six $Q_{net}$ data sets is then used to compute $\Delta A_{EDW,ext}^t$ using Eq.6 and Reynolds and Smith (1994) SST maps. Fig.11 is intended to complement the consideration of random errors presented by Maze et al. (2009) with an assessment of systematic errors. Since there is no clear consensus on the best combination of surface layer parameterization and re-analysis data set, it is a priori unclear whether one of the six stand-alone $\Delta A_{EDW,ext}^t$ estimates is to be preferred. The intention here is not to argue for a particular one, but to examine them as a group and assess the implied range of uncertainties.

It is encouraging that all estimates present the same overall temporal pattern in the seasonal cycle of EDW volume: winter formation followed by lesser spring consumption and almost no contribution in summer and fall. As pointed out by Maze et al. (2009), they also show good qualitative agreement in the spatial distribution of formation rates. Therefore, in these respects atmospheric re-analysis fields provide robust constraints on estimates of the full volume budget, such as the one discussed in Section 3b. However the stand-alone calculations imply wide ranges of estimates varying from 5 to 13 Svy for winter formation and from 2 to 11 Svy for net annual formation. Such wide ranges cannot be solely explained by the 1Svy uncertainty in net annual formation estimated by Maze et al. (2009) due to random errors of moderate spatio-temporal correlation scales in meteorological fields. Further systematic errors are likely to arise due to
uncertainties in bulk formulae coefficients and inconsistencies with chosen input fields. For example, we found that a $0.2 \times 10^{-3}$ (i.e. $\approx 15\%$) change in drag coefficient\(^1\) is sufficient to imply a 1 Svy increase in annual EDW formation. Such uncertainties in the drag coefficient are likely to occur (see e.g. Marshall et al. 2009).

Formation rates implied by OCCA air-sea fluxes happen to be in the center of the range of stand-alone estimates. We make no claim that OCCA air-sea fluxes are systematically more accurate than others. Unlike other data sets, however, they have been required to imply a seasonal fluctuation of the EDW layer that is consistent with ocean observations (as shown by Figs.1 to 7 and 10) and the GCM interior mixing rates.

c. Uncertainty Estimate

We now derive an approximate uncertainty estimate for the reference OCCA estimate (of Section 3b; Fig.9), which is thought to reflect the limited availability of in situ observations. The 2.9 Svy spread amongst OCCA atlas SC results for the full EDW volume (Tab.2; line 2; column 5) is taken as the uncertainty that prevails in individual-year monthly OCCA volume estimates. This value is regarded as quite a conservative estimate, since (1) it discounts any additional skill that may be provided by other data sets (e.g. SST data) and dynamical constraints (i.e. the GCM) and (2) it implies that all of the interannual variability in the reference estimate (1.6 Svy) is noise. For three-year-mean monthly OCCA volume estimates, the uncertainty is then computed as $2.9/\sqrt{3} \approx 1.8$ Svy. Here the factor of $1/\sqrt{3}$ reflects that three-year-mean estimates are based on roughly three times as many observations as individual-year estimates.

In theory, under an assumption of error independence, the error variance for $V_{EDW}(t)$ should equal the sum of error variances for the three terms on the right-hand-side of Eq.5. However

\(^1\)Turbulent, sensible and latent air-sea heat fluxes depend on the drag coefficient through the Stanton and Dalton transfer coefficients in the Large and Yeager (2004) bulk formulae algorithm.
we conservatively assume that any r-h-s term may be responsible for the full uncertainty in $V_{EDW}(t)$, rather than just a fraction of it. Hence in Fig.9, the arrows mark a $\pm 1.8$ Svy error margin for $V_{EDW}(t)$ and also $\Delta A_{EDW,ext}^{t}$, $\Delta A_{EDW,int}^{t}$ and $M_{EDW}^{t}$.

Our error budget for Eq.5 is conservative by design. Yet it is very approximate and will eventually need to be refined. Unfortunately, we lack a practical method to carry out a full error budget of Eq.5 at this stage. The crudeness of our present error estimate cannot be overstated, however, and should be kept in mind. First, there could be additional compensating errors on the right-hand-side of Eq.5. Second, there may be some seasonality in the error budget of Eq.5 due to, for example, parameterized mixing processes, which are likely to be quite imperfect.

5. A Discussion of Previous Estimates

a. Potential Sources of Inconsistencies

One of the main motivations for the CLIMODE observational program was the apparent conflict between previous stand-alone estimates of volume census changes (i.e. $V_{EDW}$) and formation by air-sea heat fluxes (i.e. $\Delta A_{EDW,ext}^{t}$). Table 1 summarizes estimates from three representative studies. Here we begin by assessing potential sources of apparent conflicts using our own results. We will then attempt to reconcile previous estimates with one another and with those presented here.

First, large differences between $V_{EDW}$ and $\Delta A_{EDW,ext}^{t}$ estimates may not necessarily imply that they are in conflict. Indeed Eq.5 involves mixing ($\Delta A_{EDW,int}^{t}$) and export ($M_{EDW}^{t}$) terms in addition to $V_{EDW}$ and $\Delta A_{EDW,ext}^{t}$. Comparisons between estimates of $V_{EDW}$ and $\Delta A_{EDW,ext}^{t}$ must take these contributions into account.\(^2\) According to our reference estimate

\(^2\)Of course if errors in stand-alone estimates of $V_{EDW}$ and $\Delta A_{EDW,ext}^{t}$ were well known and small, differences between them would readily lead to useful inferences of the combined contribution of mixing and export.
mixing and export can amount to 3.2 Sv. Neglect of these processes could thus lead one to wrongly conclude that estimates of formation by air-sea heat fluxes ($\Delta A_{EDW,ext}^t$) are, for example, three times too large compared with volume census change estimates ($V_{EDW}$).

Second, subjectivity in water mass definitions is a major potential source of confusion. There is never a single ‘best’ water mass definition, but a continuum of useful ones, and results can be very sensitive to subtle differences. For example we found that adding potential vorticity restrictions tends to increase the amplitude of the seasonal cycle by up to a factor of two (Tab. 2; from line 2, to 3, to 4). Such a sensitivity should be kept in mind when comparing estimates discussed in the literature.

Third, uncertainties in $V_{EDW}$ and $\Delta A_{EDW,ext}^t$ estimates can be large. In particular stand-alone estimates for $\Delta A_{EDW,ext}^t$ were found to differ by as much as a factor of 5. Such sensitivity can be translated to an error margin of $\pm (11 - 2)/2 = \pm 4.5$ Sv when a heat flux data set is simply selected from those available, without making use of additional constraints from ocean observations. This, by itself, could explain apparent conflicts amongst previous estimates.

Fourth, estimates from the literature often differ in the time period under consideration. Low frequency variability thus provides another potential source of apparent conflict amongst published estimates. Whether it is significant compared with the aforementioned issues is less than clear, however. Our estimates of EDW volumes (Section 4a) suggest that interannual variability is well below the noise level (due to sampling errors). In this respect, our results are in contrast to the optimism expressed in Kwon and Riser (2004).

Fifth, any data synthesis effort involves choices of methodology, each with its own source of systematic errors. The large range of stand-alone estimates for $\Delta A_{EDW,ext}^t$ is indicative of such systematic errors. The neglect of mixing and export terms in Eq.5 would also fall into this category of issues. More generally, the impact of statistical and/or dynamical model errors

---

But this is not the case at present.
is hard to evaluate. Comparing the results of different methods is the most practical, albeit approximate, approach, as carried out here in Section 4.

For our reference estimate (Section 3b) the first two concerns are largely resolved by using self-consistent approaches to data synthesis and volume budget analysis. In this sense estimates of volume census change ($V_{EDW}$) and formation by air-sea heat fluxes ($\Delta A_{EDW,ext}$) are readily reconciled by our reference estimate. Furthermore, the second concern is mitigated by the fact that water mass definitions were only introduced at the analysis stage, whereas the data synthesis step (leading to OCCA) did not assume any. Hence it is a simple matter to change our EDW definition in future studies and adjust our reference estimate accordingly. The third issue is addressed by attaching a reasonably conservative error estimate (Section 4c) to our reference estimate (Section 3b). Regarding the fourth concern, our results suggest that it is not a significant issue at this stage, as compared with the level of random errors. Finally, Section 4a shows that $V_{EDW}$ estimates for the 2004-2006 period do not strongly depend on the choice of data synthesis method, especially for those that do not involve PV restrictions (see Tab.2; lines 2-5-6), thus addressing the fifth concern, at least for water mass volumes.

b. Reconciling Previous Estimates

Regarding net annual EDW formation $\Delta A_{EDW,ext}$ inferred from air-sea fluxes, the estimates of Worthington (1976) (7.3±4.5Svy) and Speer and Tziperman (1992) (8±4.5Svy) are slightly larger than our reference value (4.6±1.8Svy), but are well within error margins. The 4.5Svy error margin we place on estimates of Worthington (1976) and Speer and Tziperman (1992) seems appropriate because they selected a heat flux data set from those available, and made no use of additional constraints from ocean observations. We note that Worthington (1976) did not quantify errors for his estimate, but envisioned that they would be very large. It may be fortunate that the Worthington (1976) estimate agrees so well with the other two.
Regarding Speer and Tziperman (1992), we note that their total estimate (14Svy) accounts for both freshwater and heat fluxes. To facilitate comparison with other estimates in Tab.1, which omit salinity and freshwater fluxes, we tabulated their estimate from heat fluxes alone (≈ 8Svy) based on their Fig.3. Finally, while the periods of the three estimates differ, there is no reason to invoke interannual variability to explain the differences between them, given the large systematic error margin (±4.5Sv; see Fig.11).

In respect to EDW volume fluctuations, Kwon and Riser (2004) estimate a seasonal cycle of 3.5 ± 0.5Svy whereas our reference estimate is 8.6 ± 1.8Svy. The comparison of these two estimates is complicated by several factors. First, it is striking that Kwon and Riser (2004) focus on a small fraction (≈ 1/5) of what Worthington (1976) and the present study refer to as EDW (see annual mean volumes in Tab.1). This likely explains why their estimate for the seasonal fluctuation in volume is a fraction (≈ 1/2) of ours. Trossman et al. (2009) put the same argument forward to explain why the Kwon and Riser (2004) is rather low. Second, the formal error estimate provided by Kwon and Riser (2004) seems rather small. Such a formal error estimate largely depends on the presumed uncertainties, which are not provided or discussed by Kwon and Riser (2004). The various sensitivity tests presented in Section 4a suggest that our 2004-2006 estimate of $V_{EDW}(t)$ does not strongly depend on the choice of data synthesis method. Whether the same is true for the 1961-2001 period and the statistical model that Kwon and Riser (2004) consider remains to be demonstrated. Finally, the extent to which estimates of weakly stratified EDW volumes (such as the one of Kwon and Riser (2004)) can be rationalized as part of a precise volume budget framework (such as the one Walin 1982) remains unclear.
6. Summary and Discussion

Based on observations and an observational synthesis (OCCA), a dynamical and quantitative analysis of the EDW layer (defined as all water between 17°C and 19°C in the North Atlantic) has been presented for the period from 2004 to 2006. The various observed EDW signals have been brought together using GCM-interpolation. We presented the observed signals and showed that they are well captured in the OCCA observational synthesis. A reference estimate of the volume budget of the EDW layer was presented over the seasonal cycle. Finally it was shown that this estimate, together with the associated uncertainty estimate, largely resolves apparent conflicts between previous estimates.

The North Atlantic EDW layer outcrop exhibits a pronounced seasonal cycle, covering a 20° latitude range, with isotherms sweeping southward in winter and northward in summer. The EDW layer thickness varies most markedly over a broad region to the south of the Gulf Stream, ranging from about 200m at the peak of stratification to about 400m at the peak of convection. This region corresponds to the region where the EDW layer outcrops in winter, and the region of large EDW formation rates due to air-sea fluxes, as shown by Maze et al. (2009). The EDW signals described above are consistently established from observations with or without GCM interpolation.

According to our estimates, winter-time increase in EDW volume occurs mostly in February and amounts to 8.6Svy. Winter formation by air-sea heat fluxes (9.3Svy) is the leading contribution to this winter EDW volume change. Subsequently, from March through May, air-sea heat fluxes consume 4.6Svy of the newly formed EDW. Mixing consumes another 2.6Svy over the year, so that net formation from air-sea fluxes and mixing combined is only 2.0Svy. It is balanced by EDW volume increase in the North Atlantic (1.4Svy) mostly, with export from the North Atlantic making a lesser contribution (0.6Svy). According to our reference estimate, EDW volume is 75Svy on average over the period from 2004 to 2006 and shows relatively large
seasonal fluctuations around this rather stable head of water.

Throughout our sensitivity studies, key quantitative aspects of the seasonal cycle of the EDW layer are found to transcend individual data synthesis approaches, reflecting a robust signal. It was estimated, however, that uncertainties of order $\pm 1.8$ Svy prevail in our best available observational estimates of EDW volume budgets based on Argo data. Our reference estimate presents a clear path forward, not only because it covers the full EDW volume budget, but also because we associate it with this reasonably conservative error estimate. Large discrepancies beyond $\pm 1.8$ Svy amongst previous estimates were also rationalized.

**Acknowledgments**

This work was supported by NSF (CLIMODE project), NASA (ECCO2 and ECCO-GODAE projects), and NOPP (ECCO-GODAE project).
The procedure used to diagnose the full EDW volume budget (Eq.1-4; Section 3a) for the OCCA reference estimate (Section 3b) comprises the following steps:

1. For each grid cell, compute the budget of fluid with $T < \Theta$, for $\Theta = 17^\circ$C and $19^\circ$C, as:

   $$\frac{dv_{\Theta}}{dt} = a_{\Theta} - m_{\Theta}$$  \hspace{1cm} (7)

   where $v_{\Theta}$, $a_{\Theta}$ and $m_{\Theta}$ are the volume of $T < \Theta$ fluid inside the grid cell, the grid cell transformation rate at $T = \Theta$, and the export rate of $T < \Theta$ fluid out of the grid cell, respectively.

2. Sum over grid cells in the Atlantic north of $5^\circ$N to get

   $$\frac{dV_{\Theta}}{dt} = A_{\Theta} - M_{\Theta}$$  \hspace{1cm} (8)

3. Subtract the volume budget of water with $T < \Theta = 17^\circ$C from the volume budget of water with $T < \Theta = 19^\circ$C, to form Eq.1, and then Eq.5.

To compute Eq.7, two different numerical recipes are used. Their analytical foundation, and practical limitations, will be discussed in detail elsewhere. Here we only outline the numerical recipes.

1. The Tracer equation method (TE-M) starts from the grid cell temperature equation

   $$\frac{\Delta T}{\Delta t} \times \Delta V = -\sum_k N_{\text{adv}}^k - \sum_k A_{\text{adv}}^k$$  \hspace{1cm} (9)

   where $\Delta V$ is the grid cell volume, $\Delta t$ is the time step, and $\Delta T$ is the temperature increment from time $t$ to time $t + \Delta t$. $\{N_{\text{adv}}^k\}$ and $\{A_{\text{adv}}^k\}$ are, respectively, the non-adveective and advective temperature fluxes through the grid cell faces $\{k\}$, counted $> 0$ outward. Eq.9 is simply converted to Eq.7 by multiplying it with

   $$\pi_{\Theta}(T) = \begin{cases} 
   1/\Delta \Theta & \text{if } \Theta^- < T < \Theta^+ \\
   0 & \text{otherwise}. \end{cases}$$  \hspace{1cm} (10)
where $T$ is the grid cell temperature, $\Theta^- = \Theta - \Delta\Theta/2$, $\Theta^+ = \Theta + \Delta\Theta/2$, and $\Delta\Theta$ is a temperature bin. $\pi_\Theta(T)$ is a parameterization for the local probability density that the fluid has $T = \Theta$. Hence $\pi_\Theta(T) \times (\Delta T / \Delta t \times \Delta)$, $\pi_\Theta(T) \times (-\sum_k N_{adv}^k)$, and $\pi_\Theta(T) \times (-\sum_k A_{adv}^k)$ correspond to $\frac{d\pi_\Theta}{dt}$, $a_\Theta$ and $-m_\Theta$, respectively.

2. The Volume census method (VC-M) starts from the grid cell continuity equation $\sum_k U^k = 0$, where $\{U^k\}$ are the volume fluxes through the grid cell faces $\{k\}$, counted $> 0$ outward. VC-M then uses

$$\Pi_\Theta(T) = \begin{cases} 
(\Theta^+ - T) / (\Theta^+ - \Theta^-) & \text{if } \Theta^- < T < \Theta^+ \\
0 & \text{if } T > \Theta^+ \\
1 & \text{if } T \leq \Theta^- 
\end{cases} \quad (11)$$

which is a parameterization of the local concentration of fluid such that $T < \Theta$, to compute $\frac{d\pi_\Theta}{dt}$ as $\Delta\Pi_\Theta / \Delta t \times \Delta V$, followed by $-m_\Theta$ as $-\sum_k U^k \Pi_\Theta^k$, and $a_\Theta$ as the residual of Eq.7.

Several computational details need elaboration. First, in computing $\pi_\Theta(T)$ and $\Pi_\Theta(T)$, the temperature bin $\Delta\Theta$ must be small compared with the EDW temperature range (19–17 = 2°C), so we use $\Delta\Theta = 0.25°C$. The EDW layer edge consists of grid cells where $\pi_{17} \neq 0$ or $\pi_{19} \neq 0$ (forming two discrete isotherms). To avoid scatter in the EDW layer edge we interpolate temperature fields on to a higher resolution grid, compute $\pi_\Theta$ and $\Pi_\Theta$ on the refined grid, and then average them back to the native GCM grid. Increasing the resolution by a factor of 12 (in the three directions) was found to be adequate. Second, Eq.7 is not computed with $\Delta t = 1$ hour (i.e. the GCM time step) in order to save storage. Since the temperature field undergoes rapid evolution (due e.g. to convective mixing), $\Delta t$ must be small enough to compute Eq.7 accurately, however. It was found that $\Delta t = 1$ day is adequate. Third, all fields necessary to ‘close’ the discrete temperature and volume budgets (needed for TE-M or VC-M) were readily diagnosed.
by the GCM. For TE-M, $-\sum_k \text{Adv}^k_T$ is the sum of Eulerian and parameterized eddy (GM term; see Section 2b) temperature advection terms. The term $-\sum_k \text{Nadv}^k_T$ is the sum of air-sea heat flux terms and parameterized mixing terms (as listed in Section 2b; except for the GM term). The sum of air-sea heat flux (mixing) terms leads to an explicit computation of $\Delta A_{EDW,ext}^t$ (resp. $\Delta A_{EDW,int}^t$). There are two ‘numerical terms’ involved: (1) the Adam-Bashforth time-stepping, which uses forward extrapolation by half a time-step; (2) the assimilation procedure underlying OCCA, which allows some compensation of model error accumulation (see Forget 2009). Neither one has a clear physical interpretation, but their contributions to Eq.5 are rather small ($< 0.3\text{Sv}$ by year end), so they are simply included as adjustments to $\Delta A_{EDW,int}^t$. For VC-M, $\sum_k U^k$ is the sum of Eulerian and bolus (GM term) velocity contributions. Finally, to go from Eq.1-4 to Eq.5, the procedure is: (1) compute the three-year daily time series of Eq.1-4, from Dec. 1st 2004 to Nov. 30th 2006; (2) compute the average year daily time series, from Dec.1st to Nov. 30th; (3) time integrate to form Eq.5.
REFERENCES


List of Figures

1 Top and middle panels: mean monthly Sea Surface Temperature (SST) from two estimates (color contours) for the period Dec. 2003 through Nov. 2006. Each of the six panels represents a month of the year, forming a clockwise sequence. Only the 17, 18 and 19°C isotherms are shown. Blue contours: average of mapped microwave SST data (Remote Sensing System product) and mapped infrared SST data (Reynolds product) (hereafter RSS-Reynolds SST). Red contours: OCCA mapped data (Forget 2009). The boxes used in Figs.2-3 are shown in black. Bottom panel: area of the 17 – 19°C outcrop (in km²) as a function of time in the OCCA (thick solid line), RSS (thick dash-dotted line), and Reynolds (thick dashed line) estimates. The corresponding thin lines show the differences between OCCA and the two other estimates. 37

2 Annual cycle of temperature observed by Argo floats (top) as a function of month and depth, averaged over the western box delimited by 62°W, 47°W, 34°N, and 38°N (see Fig.1), and averaged over the period from Dec. 2003 through Nov. 2006. A one-month running window is used to bin-average profiles. Middle: same but from OCCA fields sampled accordingly. EDW is defined as all fluid with temperature between 17 and 19°C. The thick black contours are the 17 and 19°C isotherms, marking the boundaries of the EDW layer. The bottom panel shows the EDW layer thickness estimates (in m) associated with the top panel (thick dashed line, from Argo profiles) and the middle panel (thick solid line, from OCCA profiles). The thin solid line shows the difference between the two estimates. 38

3 Same as Fig.2 but for the eastern box (delimited by 27°W, 12°W, 30°N, and 34°N; Fig.1). Note that the depth range is half that of Fig.2. 39
Monitoring of the average seasonal cycle of the EDW layer (over 2004 to 2006) by applying the sample census (SC) method to Argo profiles, as described in Section 2b. In each panel the probability $R^i_{EDW}$ that an Argo observation collected in a control volume $V^i$ reveals EDW is plotted for the month indicated, as a function of the depth and ‘equivalent latitude’ of $V^i$. $R^i_{EDW} = 1$ means that all observations collected in $V^i$ satisfy the definition of EDW ($17 < T < 19^\circ C$).

Each $V^i$ is delimited in the horizontal by two contours (SST= $\Theta^i \pm \Delta \Theta$) of the three-year-mean RSS-Reynolds March SST map (Fig.1, top right panel). Both ‘equivalent latitude’ $L(\Theta^i)$ and $\Theta^i$ are used as a horizontal axis. Equivalent latitude is defined as $L(\Theta) = A^{-1}(A(\Theta))$ where $A(\Theta)$ is the area between the equator and the SST= $\Theta$ contour, and $A(L)$ is the area between the equator and the latitude = $L$. The bar at the top of each panel plots RSS-Reynolds SST in the same manner.

Same as Fig.4 but for the subset of EDW with potential vorticity less than $1.5 \times 10^{-10} m^{-1} s^{-1}$ (and $17 < T < 19^\circ C$).

Same as Fig.4 but for the subset of EDW with potential vorticity less than $2 \times 10^{-11} m^{-1} s^{-1}$ (and $17 < T < 19^\circ C$).

Same as in Fig.4 but for OCCA profiles (sampling OCCA daily fields accordingly) rather than Argo profiles. The bar at the top is now computed from OCCA SST maps.

Time mean (left) and daily standard deviation (right) of EDW layer thickness (in m), for the three-year period from Dec. 2003 through Nov. 2006, using the OCCA data set. The overlaid white contours are: (1) mean March SST isotherms ($17$ and $19^\circ C$), using the OCCA data set; (2) the boxes used in Figs.2-3.
Seasonal cycle in EDW volume for the average year, as estimated in OCCA over the three-year period from Nov. 2003 through Oct. 2006. The OCCA estimate of Eq.1-4 is displayed in the form of Eq.5, the cumulative time integral from Dec 1st to Nov 30th of the average year. Blue: cumulated EDW volume change ($V_{EDW}$ in Eq.5). Green: cumulated northward flow through 5°N ($-M_{EDW}$). Red: cumulated formation due to air-sea heat fluxes ($\Delta A_{EDW,ext}$). Black: cumulated formation due to ocean mixing ($\Delta A_{EDW,int}$). Two different recipes were used to diagnose Eq.5 (see Appendix). For each term in Eq.5 the shading shows the interval between the two recipes, while the thick curve is the average of the two.

Units: $1 Sv \approx 3.15 \times 10^{13} m^3$ corresponds to $1 Sv = 10^6 m^3 s^{-1}$ sustained for one year. The uncertainty estimate of Section 4c is represented with arrows.

Seasonal fluctuation obtained by sample census (SC) of EDW (see Section 2b for methodological details) in irregularly distributed Argo profiles (blue curves) or similarly sampled OCCA profiles (red curves). In each panel, the thick black curve is the corresponding reference OCCA estimate, based on complete daily fields rather than irregularly distributed profiles. Thick curves are for the three year average and thin lines are for individual years. Top left: all EDW; top right: EDW such that $|PV| < 1.5 \times 10^{-10} m^{-1} s^{-1}$; bottom right: EDW such that $|PV| < 2 \times 10^{-11} m^{-1} s^{-1}$; bottom left: eastern basin EDW, located to the east of 35°W. For any curve of any panel, the median value has been subtracted.

Units: Sv.
Stand-alone estimates of cumulated EDW formation due to air-sea heat fluxes \((\overline{\Delta A_{EDW,ext}})\) derived from NCEP and ECMWF data. In the legend: ‘LY04’ ('Fal03') denotes that the Large and Yeager (2004) (Fairall et al. 2003) bulk formulae algorithm was used to compute fluxes driven by re-analysis atmospheric state estimates. See Section 4b for details. The reference estimate described in Section 3b is plotted in black. Units: Svy.
Fig. 1. Top and middle panels: mean monthly Sea Surface Temperature (SST) from two estimates (color contours) for the period Dec. 2003 through Nov. 2006. Each of the six panels represents a month of the year, forming a clockwise sequence. Only the 17, 18 and 19°C isotherms are shown. Blue contours: average of mapped microwave SST data (Remote Sensing System product) and mapped infrared SST data (Reynolds product) (hereafter RSS-Reynolds SST). Red contours: OCCA mapped data (Forget 2009). The boxes used in Figs.2-3 are shown in black. Bottom panel: area of the 17 – 19°C outcrop (in km$^2$) as a function of time in the OCCA (thick solid line), RSS (thick dash-dotted line), and Reynolds (thick dashed line) estimates. The corresponding thin lines show the differences between OCCA and the two other estimates.
Fig. 2. Annual cycle of temperature observed by Argo floats (top) as a function of month and depth, averaged over the western box delimited by 62°W, 47°W, 34°N, and 38°N (see Fig.1), and averaged over the period from Dec. 2003 through Nov. 2006. A one-month running window is used to bin-average profiles. Middle: same but from OCCA fields sampled accordingly. EDW is defined as all fluid with temperature between 17 and 19°C. The thick black contours are the 17 and 19°C isotherms, marking the boundaries of the EDW layer. The bottom panel shows the EDW layer thickness estimates (in m) associated with the top panel (thick dashed line, from Argo profiles) and the middle panel (thick solid line, from OCCA profiles). The thin solid line shows the difference between the two estimates.
Fig. 3. Same as Fig.2 but for the eastern box (delimited by 27°W, 12°W, 30°N, and 34°N; Fig.1). Note that the depth range is half that of Fig.2.
Fig. 4. Monitoring of the average seasonal cycle of the EDW layer (over 2004 to 2006) by applying the sample census (SC) method to Argo profiles, as described in Section 2b. In each panel the probability $R_{i}^{EDW}$ that an Argo observation collected in a control volume $V_{i}$ reveals EDW is plotted for the month indicated, as a function of the depth and ‘equivalent latitude’ of $V_{i}$. $R_{i}^{EDW} = 1$ means that all observations collected in $V_{i}$ satisfy the definition of EDW ($17 < T < 19^\circ C$). Each $V_{i}$ is delimited in the horizontal by two contours (SST= $\Theta_{i} \pm \Delta\Theta$) of the three-year-mean RSS-Reynolds March SST map (Fig.1, top right panel). Both ‘equivalent latitude’ $L(\Theta^{i})$ and $\Theta^{i}$ are used as a horizontal axis. Equivalent latitude is defined as $L(\Theta) = \mathcal{A}^{-1}(A(\Theta))$ where $A(\Theta)$ is the area between the equator and the SST= $\Theta$ contour, and $\mathcal{A}(\mathcal{L})$ is the area between the equator and the latitude = $\mathcal{L}$. The bar at the top of each panel plots RSS-Reynolds SST in the same manner.
Fig. 5. Same as Fig. 4 but for the subset of EDW with potential vorticity less than $1.5 \times 10^{-10} m^{-1}s^{-1}$ (and $17 < T < 19^\circ C$).
Fig. 6. Same as Fig. 4 but for the subset of EDW with potential vorticity less than $2 \times 10^{-11} \text{m}^{-1} \text{s}^{-1}$ (and $17 < T < 19^\circ \text{C}$).
Fig. 7. Same as in Fig. 4 but for OCCA profiles (sampling OCCA daily fields accordingly) rather than Argo profiles. The bar at the top is now computed from OCCA SST maps.
Fig. 8. Time mean (left) and daily standard deviation (right) of EDW layer thickness (in m), for the three-year period from Dec. 2003 through Nov. 2006, using the OCCA data set. The overlaid white contours are: (1) mean March SST isotherms (17 and 19°C), using the OCCA data set; (2) the boxes used in Figs. 2-3.
Fig. 9. Seasonal cycle in EDW volume for the average year, as estimated in OCCA over the three-year period from Nov. 2003 through Oct. 2006. The OCCA estimate of Eq.1-4 is displayed in the form of Eq.5, the cumulative time integral from Dec 1st to Nov 30th of the average year. Blue: cumulated EDW volume change ($V_{EDW}$ in Eq.5). Green: cumulated northward flow through 5°N ($-\overline{M_{EDW}}$). Red: cumulated formation due to air-sea heat fluxes ($\Delta A_{EDW,ext}^{t}$). Black: cumulated formation due to ocean mixing ($\Delta A_{EDW,int}^{t}$). Two different recipes were used to diagnose Eq.5 (see Appendix). For each term in Eq.5 the shading shows the interval between the two recipes, while the thick curve is the average of the two. Units: $1Sv y \approx 3.15 \times 10^{13} m^3$ corresponds to $1Sv = 10^6 m^3 s^{-1}$ sustained for one year. The uncertainty estimate of Section 4c is represented with arrows.
Fig. 10. Seasonal fluctuation obtained by sample census (SC) of EDW (see Section 2b for methodological details) in irregularly distributed Argo profiles (blue curves) or similarly sampled OCCA profiles (red curves). In each panel, the thick black curve is the corresponding reference OCCA estimate, based on complete daily fields rather than irregularly distributed profiles. Thick curves are for the three year average and thin lines are for individual years. Top left: all EDW; top right: EDW such that $|PV| < 1.5 \times 10^{-10} m^{-1}s^{-1}$; bottom right: EDW such that $|PV| < 2 \times 10^{-11} m^{-1}s^{-1}$; bottom left: eastern basin EDW, located to the east of 35°W. For any curve of any panel, the median value has been subtracted. Units: Svy.
Fig. 11. Stand-alone estimates of cumulated EDW formation due to air-sea heat fluxes ($\Delta A_{EDW,ext}$) derived from NCEP and ECMWF data. In the legend: ‘LY04’ (‘Fal03’) denotes that the Large and Yeager (2004) (Fairall et al. 2003) bulk formulae algorithm was used to compute fluxes driven by re-analysis atmospheric state estimates. See Section 4b for details. The reference estimate described in Section 3b is plotted in black. Units: Svy.
List of Tables

1. Previous and present estimates of EDW and subtropical mode water volumes, formation rates and amplitudes of the seasonal cycle. Note that the various studies differ in water mass definitions. The second column shows the water mass definition depending on the author. In Svy units ($1_{Svy} \approx 3.15 \times 10^{13} m^3$).

2. Reference OCCA estimates (second column) of the amplitude (peak to peak) of the average seasonal fluctuation in EDW volume (second line) and various subsets (subsequent lines). Sensitivity tests are reported in columns 3-4-5, based on the sample census (SC) method (see Section 2c; Fig.10). The spread (reported below each estimate) is computed as the standard deviation of individual year monthly anomalies (from the three-year monthly average). Differences between columns 2 and 3 reflect the irregular Argo data coverage. Differences between columns 3-4-5 reflect different choices of smoothing/averaging. Unlike column 3, column 4 involves no preliminary smoothing of Argo profiles. Unlike column 3, column 5 involves no interannual variability of temperature, and the spread can only result from inhomogeneities in data coverage. Estimates are presented in Svy units ($1_{Svy} \approx 3.15 \times 10^{13} m^3$).
<table>
<thead>
<tr>
<th>reference</th>
<th>EDW definition</th>
<th>specifications</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwon and Riser (2004)</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>volume</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial T}{\partial z} &lt; 0.006^\circ C m^{-1}$</td>
<td>(western basin, winter)</td>
<td></td>
</tr>
<tr>
<td>Worthington (1976)</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>volume</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(western basin, annual mean)</td>
<td></td>
</tr>
<tr>
<td>Worthington (1976)</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>volume</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(full North Atlantic, annual mean)</td>
<td></td>
</tr>
<tr>
<td>this study, OCCA</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>volume</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(full North Atlantic, annual mean)</td>
<td></td>
</tr>
<tr>
<td>Speer and Tziperman (1992)</td>
<td>$26 &lt; \sigma &lt; 27 \text{ kg.m}^{-3}$</td>
<td>formation rate due to buoyancy flux</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(full North Atlantic, annual mean)</td>
<td></td>
</tr>
<tr>
<td>Speer and Tziperman (1992)</td>
<td>$26 &lt; \sigma &lt; 27 \text{ kg.m}^{-3}$</td>
<td>formation rate due to heat flux</td>
<td>$\approx$ 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(full North Atlantic, annual mean)</td>
<td></td>
</tr>
<tr>
<td>Worthington (1976)</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>formation rate due to heat flux</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(box, annual mean)</td>
<td></td>
</tr>
<tr>
<td>this study, Maze et al. (2009), OCCA</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>formation rate due to heat flux</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(full North Atlantic, annual mean)</td>
<td></td>
</tr>
<tr>
<td>Kwon and Riser (2004)</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>volume fluctuation</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial T}{\partial z} &lt; 0.006^\circ C m^{-1}$</td>
<td>(western basin, winter vs autumn)</td>
<td></td>
</tr>
<tr>
<td>this study, OCCA</td>
<td>$17 &lt; T &lt; 19^\circ C$</td>
<td>volume fluctuation</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(full North Atlantic, March vs Dec.)</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.** Previous and present estimates of EDW and subtropical mode water volumes, formation rates and amplitudes of the seasonal cycle. Note that the various studies differ in water mass definitions. The second column shows the water mass definition depending on the author. In Svy units ($1 \text{Svy} \approx 3.15 \times 10^{13} \text{m}^3$).
<table>
<thead>
<tr>
<th></th>
<th>OCCA reference estimate</th>
<th>OCCA profiles</th>
<th>ARGO profiles</th>
<th>OCCA profiles (atlas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>all EDW</td>
<td>8.6</td>
<td>7.7</td>
<td>7.3</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>±1.6</td>
<td>±2.9</td>
<td>±4.8</td>
<td>±2.9</td>
</tr>
<tr>
<td>PV &lt; 1.5 × 10^{-10} m^{-1} s^{-1}</td>
<td>15.5</td>
<td>11.1</td>
<td>9.3</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>±2.0</td>
<td>±2.9</td>
<td>±5.8</td>
<td>±3.1</td>
</tr>
<tr>
<td>PV &lt; 2 × 10^{-11} m^{-1} s^{-1}</td>
<td>20.2</td>
<td>20.5</td>
<td>15.0</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>±1.3</td>
<td>±1.7</td>
<td>±2.1</td>
<td>±0.7</td>
</tr>
<tr>
<td>west of 35°W</td>
<td>7.6</td>
<td>7.1</td>
<td>7.3</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>±1.4</td>
<td>±3.0</td>
<td>±4.7</td>
<td>±3.0</td>
</tr>
<tr>
<td>east of 35°W</td>
<td>1.3</td>
<td>2.9</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>±0.3</td>
<td>±1.5</td>
<td>±1.4</td>
<td>±1.5</td>
</tr>
</tbody>
</table>

Table 2. Reference OCCA estimates (second column) of the amplitude (peak to peak) of the average seasonal fluctuation in EDW volume (second line) and various subsets (subsequent lines). Sensitivity tests are reported in columns 3-4-5, based on the sample census (SC) method (see Section 2c; Fig.10). The spread (reported below each estimate) is computed as the standard deviation of individual year monthly anomalies (from the three-year monthly average). Differences between columns 2 and 3 reflect the irregular Argo data coverage. Differences between columns 3-4-5 reflect different choices of smoothing/averaging. Unlike column 3, column 4 involves no preliminary smoothing of Argo profiles. Unlike column 3, column 5 involves no interannual variability of temperature, and the spread can only result from inhomogeneities in data coverage. Estimates are presented in Svy units (1Svy ≈ 3.15 × 10^{13} m^3).