North Atlantic Subtropical Mode Water: A history of ocean-atmosphere interaction 1961–2000

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[1] Water masses that ventilate intermediate ocean depth, such as the North Atlantic Subtropical Mode Water (NASTMW), play important roles in various aspects of climate, but their basic properties and space-time variability need to be better quantified. Herein we examine the mean annual cycle and long-term variability of NASTMW for the 40-year period 1961–2000. Integrated NASTMW properties such as water mass volume, temperature, and heat content show a consistent annual cycle superimposed over a much larger interannual-to-decadal cycle that is strongly correlated to the North Atlantic Oscillation index. The 40-year record clearly shows the ocean's ability to integrate atmospheric forcing over several years and to exhibit an interannual memory of wintertime forcing by the atmosphere. *INDEX TERMS:* 4283 Oceanography: General: Water masses; 4215 Oceanography: General: Climate and interannual variability (3309); 4504 Oceanography: Physical: Air/sea interactions (0312); 4572 Oceanography: Physical: Upper ocean processes; 1635 Global Change: Oceans (4203). **Citation:** Kwon, Y.-O., and S. C. Riser (2004), North Atlantic Subtropical Mode Water: A history of ocean-atmosphere interaction 1961–2000, *Geophys. Res. Lett.*, *31*, L19307, doi:10.1029/2004GL021116.

1. Introduction

[2] Mode waters are upper ocean water masses with nearly uniform temperature over a thickness of a few hundred meters. Their ubiquity over the world's ocean, strong property correlations with atmospheric indices, and relatively short renewal time scales have drawn considerable attention in climate studies [*Bates et al.*, 2002]. The NASTMW, also often called the Eighteen Degree Water (EDW), is one of the most studied mode waters [*Thompson*, 1877]. This water mass is of uniform temperature close to 18°C and is typically 250 m thick; it is widely spread over the western subtropical North Atlantic [*Worthington*, 1959] (Figure 1). Despite the long interest and potential importance of EDW, most of the observational analyses related to EDW have relied on one time hydrographic surveys or long time series at single points in space inside the EDW region. The properties of the upper ocean layer near the potential vorticity (PV) minimum, estimated from the time series of biweekly observations collected at Station S (1954–present) near Bermuda, have been the most extensively used dataset for studying EDW variability [*Talley and Raymer*, 1982; *Talley*, 1996; *Dickson et al.*, 1996; *Joyce et al.*, 2000]. As Station S is located near the center of the EDW distribution and is downstream from the EDW formation region, the data have generally been considered to provide a reasonable representation of the mean characteristics of the EDW water mass. In reality, since Station S is just a single point in a vast region that contains EDW (Figure 1b), the data collected there can only serve as a proxy of the entire range of EDW properties, despite the excellent temporal resolution.

[3] In this study we present a space/time reconstruction of the EDW field over the 40-year period from 1961–2000 based on historical data; the reconstructions allow the resolution of seasonal variability, providing a unique glimpse of the average characteristics and variability of EDW with relatively good spatial coverage and relatively high temporal resolution.

2. Data

[4] As a first step, the temperature field for individual season at each standard depth for the upper 800 m was objectively mapped [*Bretherton et al.*, 1976; *Le Traon*, 1990] using all temperature data for the corresponding period and depth from the World Ocean Database 2001 (WOD2001) [*Conkright et al.*, 2002] archive and from profiling floats in the region (the floats were deployed as part of the World Ocean Circulation Experiment (WOCE) [*Siedler et al.*, 2001] and the Argo project [*Roemmich et al.*, 2001]). More than 1 million temperature profiles from the region were examined for the 40-year analysis period, 1961–2000. Each season corresponds to a 3-month period starting from February (i.e., February–April is winter, and so on). In all, 160 independent temperature fields were mapped from winter 1961 through autumn 2000.

[5] The next step was to identify the EDW from each temperature profile of the objectively mapped fields. The following two criteria were applied to determine whether or not the profile contains the EDW layer: (1) the temperature must be in the range of 17–19°C; and (2) vertical temperature gradient should be less than 0.006°C/m. The first criterion loosely follows Worthington's original EDW definition [*Worthington*, 1959], and the second one has been added to restrict the result to a thermostad [*Klein and Hogg*, 1996; *Alfultis and Cornillon*, 2001]. The portion of each temperature profile that satisfied both criteria was identified as EDW, and the thickness and mean temperature of that portion were calculated. At that juncture, the objective mapping was repeated, in order to map the EDW thickness and temperature field for individual seasons over the 40 years (Figures 1c–1f).

[6] The final step in the procedure was to calculate the total volume, mean temperature, and total heat content of

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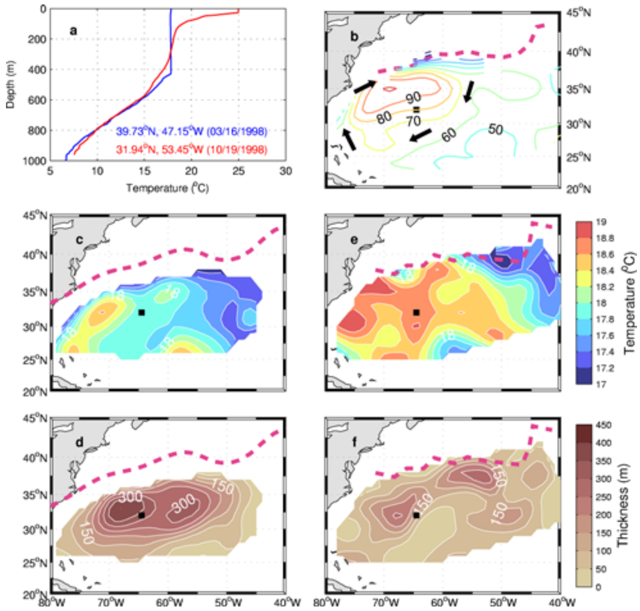

Figure 1. (a) Typical EDW temperature profiles. The blue is a typical profile in the formation region in late winter, and the red is one for summer. (b) Geostrophic pressure on the 26.5 σ_θ surface (in centimeters of water) for April, 1998–2002, estimated from WOCE and the Argo profiling float temperature, salinity and velocity data. Clockwise gyre circulation around the high pressure center is indicated with arrows. (c) EDW temperature for May–July, 1981, reconstructed from WOD2001. The dashed line is the Gulf Stream position for the corresponding period, defined by the 15°C isotherm at 200 m. The black square is the location of Station S. (d) EDW thickness for May–July, 1981. (e) EDW temperature for May–July, 2000, observed by profiling floats deployed in the WOCE and Argo. The Gulf Stream position is identified using TOPEX/POSEIDON altimeter data (Courtesy of K. Kelly and S. Dong). (f) EDW thickness for May–July, 2000.

each 3 month EDW field, then to combine these estimates to create the EDW time series (Figure 2). The EDW volume was calculated by integrating thickness over the area covered by EDW in each period. The EDW temperature was derived by thickness-weighted averaging of the mapped EDW temperature field for each period. To calculate the heat content, temperature and thickness at each grid point were multiplied together (and scaled by the density and heat capacity), then area-integrated over the region. Note that our EDW temperature time series is highly correlated with the temperature of the PV minimum layer at Station S [*Talley and Raymer*, 1982; *Talley*, 1996], with a correlation coefficient of 0.64 (significant at 98% level) (Figure 2c). The correlation is 0.77 when the annual cycles are filtered out. This high correlation between our derived fields and the directly measured temperature at Station S provides confidence in the utility of our method.

3. Annual Cycle

[7] It has been conjectured that EDW forms in late winter by convective mixing adjacent to the Gulf Stream [*Worthington*, 1972]. Since the winter mixed layer temperature is generally relatively warm in the northwestern corner of the Sargasso Sea and relatively cold in the northeastern corner, the typical distribution of EDW temperature shows water with temperature warmer than 18°C spreading eastward from the northwestern corner of the subtropical Atlantic and colder water flowing southwestward from the northeastern corner, following the mean advection path [*Talley and Raymer*, 1982; *Klein and Hogg*, 1996] (Figures 1b–1f). The spreading of EDW along the Gulf Stream recirculation gyre is also reflected in the distributions of the thickness and the center of mass of the EDW. The maximum thickness is generally greater than 300 m in the region close to the northern formation area in late winter and early spring, and moves in a southwestward direction during following seasons. The center of mass of the EDW distribution in the winter (February–April), averaged over the 40 year period, is at 33.09°N, 58.37°W, and gradually moves southwestward as the seasons progress, reaching 31.99°N, 62.02°W in the autumn (November–January).

[8] The annual cycles of EDW volume, temperature, and heat content over the 40-year period were superimposed over energetic lower frequency fluctuations (Figure 2). The EDW volume is greatest in winter, owing to renewal of the water mass along the outcrops, and gradually decreases throughout the year to a minimum value in autumn. The average volume of EDW in winter was found to be 3.93 ± 0.20 × 10^{14} m^3 (error bounds denote the standard error), with an autumn volume of 2.84 ± 0.16 × 10^{14} m^3. The mean annual production of EDW was then estimated as the

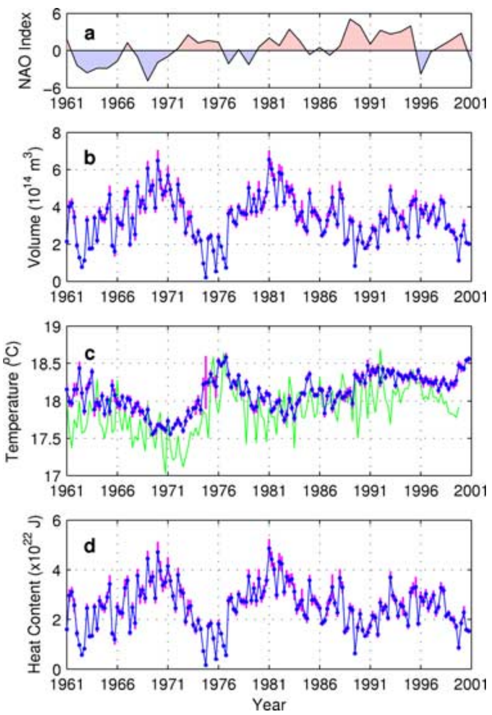

Figure 2. The 40-year EDW time series. (a) Winter NAO index. (b) Seasonal EDW volume reconstructed based on WOD2001. (c) Seasonal EDW temperature (blue) and temperature of the PV minimum layer at Station S (green). (d) Seasonal EDW heat content. Pink vertical bars are uncertainty based on the estimation of the variance of the error in each objective mapping.

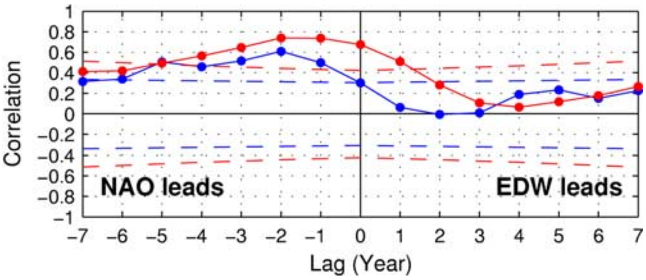

Figure 3. Lag-correlation between the winter EDW temperature and the winter NAO index. Lag is negative when NAO leads EDW. The blue line is the correlation between the original NAO index and EDW temperature. The red line is the correlation between 4-year integrated NAO and EDW temperature. Correlations are significant at 95% level when they lie outside the dashed lines, respectively.

difference between the volumes of each winter and the preceding autumn to be $1.10 \pm 0.16 \times 10^{14}$ m^3. Dividing the volume in each year by annual production yields a mean turnover time of 3.57 ± 0.54 years for the EDW, consistent with the previous work based on isopycnal salinity and apparent oxygen utilization [*Jenkins*, 1982]. Similarly, the difference between the volume of EDW present during each winter, and the volume present during the *following* autumn, can be used as an estimate of average quantity of annual EDW destruction. The average annual destruction of EDW over the 40-year period was found to be $1.09 \pm 0.16 \times 10^{14}$ m^3, statistically identical with the annual production. On a year-to-year basis, the differences between these two values were much greater, as reflected in the large low frequency variability of the time series for the volume. The lagged correlation between EDW volume and production was found to be a maximum (and significant at the 95% level) when EDW production leads the total volume by a 0–1 year, and for EDW volume and destruction when the destruction lags the total volume by 0–2 year, respectively.

[9] The EDW temperature was colder in winter than other seasons by about 0.06°C, but this difference was not statistically significant. Since the annual cycle of EDW volume was much more pronounced than that of EDW temperature, the annual cycle of the EDW heat content (essentially volume × temperature) was dominantly controlled by the cycle of EDW volume. Thus, the EDW heat content was a maximum in winter and minimum in autumn, despite the fact the EDW temperature was colder in winter. The average difference in the EDW heat content between winter and autumn was $8.20 \pm 1.20 \times 10^{21}$ J.

[10] The average heat given up by the ocean to the atmosphere during each winter (presumably the heat responsible for the annual production of the EDW) was estimated, assuming the region of EDW formation in winter to be bounded by 50° and 75°W longitudinally, and extending from the path of the Gulf Stream to a line 3° south of the Stream in the latitudinal direction. This region corresponds to the region of maximum flux of heat from the ocean surface to the atmosphere in the North Atlantic [*Worthington*, 1972]. A mean autumn temperature profile for this region was constructed from the WOD2001 data, and the heat required to cool the temperature profile to 18°C uniformly from the surface to the estimated average mixed layer depth was calculated. Using this method, the estimated heat loss associated with EDW production was $7.43 \pm 0.14 \times 10^{20}$ J, which explains about 67% of the total surface heat lost to the atmosphere in winter in this region [*Da Silva et al.*, 1994]. This estimate also represents about 42% of the surface heat lost between 20°N and 40°N in winter, where the total N. Atlantic meridional heat transport decreases by half and its atmospheric counterpart doubles [*Trenberth and Caron*, 2001].

4. Interannual Variability

[11] Probably the most striking feature in the time series is the apparent interannual to decadal variability, which is clearly much stronger than the annual cycle. In the case of EDW volume, the interannual to decadal variance is about 54% larger than annual variance, and for the EDW temperature the difference is even larger. The most obvious characteristic of this long-term variability is the strong negative correlation between EDW volume and EDW temperature (their correlation coefficient is −0.8 and is significant at the 99% level). This clear anti-correlation would appear to support previous studies, which have suggested that active EDW formation years have more and colder EDW because the newly formed EDW is colder than residuals from the previous years [*Talley and Raymer*, 1982]. However, it is equally possible that in the years of active production, relatively more EDW is formed near the northeastern reaches of the formation region where the coldest EDW water is formed (and vice versa for lower production years). This second possibility was actually observed using profiling float data in winters from 1998–2001 [*Kwon*, 2003].

[12] A number of investigators have suggested that the North Atlantic Oscillation (NAO) is a likely source of EDW variability, based on both observations and numerical models [*Talley*, 1996; *Dickson et al.*, 1996; *Paiva and Chassignet*, 2002]. The lag correlation between our winter EDW temperature time series and the winter NAO index [*Hurrell*, 1995] shows a broad peak (significant at the 95% level) when NAO leads EDW temperature by 1–6 years (Figure 3). The maximum correlation coefficient was 0.61, with a 2-year lead; the correlation at zero lag was not significant and was mostly due to the long-term trend. When both time series were detrended, the correlation coefficient at zero lag became 0.01. This lag correlation with a broad peak implies that EDW has a memory of atmospheric forcing over several years, and that EDW is effectively integrating the atmospheric forcing represented by NAO over times of up to 6 years. The EDW's ability to integrate the atmospheric forcing was further demonstrated by the fact that significant instantaneous correlation can be obtained when winter EDW temperature was correlated with values of the NAO integrated over 3–5 years (Figure 3). Note that in this case the integration was not carried out using a centered moving average of NAO, but was instead integrated by assigning the integrated value to the last year of integrating window [*Curry and McCartney*, 2001]. The resulting 3–5 year time scale agrees well with the estimated average turnover timescale of 3.57 years from the mean annual production and the annual destruction. The oceanic integrating process and associated lag correlation with the NAO index can also be found in the correlation between the winter surface heat flux and the EDW properties. A regression of the March surface

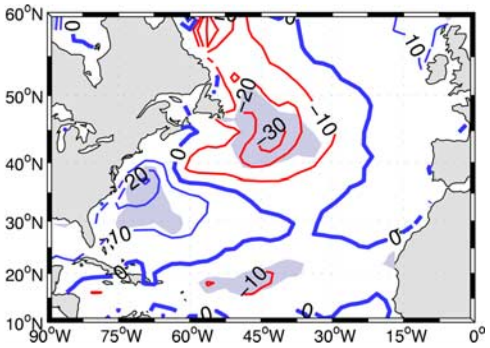

Figure 4. Regression of March surface heat flux anomaly onto winter EDW volume when heat flux leads EDW volume by 1 year. The surface heat flux is taken from NCEP reanalysis [*Kalnay et al.*, 1996]. Values are normalized to show that the anomaly corresponds to one standard deviation of the EDW volume time series. A positive sign corresponds to heat flux from the ocean to the atmosphere. Blue contours are for positive and red contours are for negative values. Units for the contour labels are W/m^2. The shaded region denotes that the correlation is significant at the 95% level.

heat flux onto the winter EDW volume time series indicates a significant anomalous heat loss of about 20 W/m^2 over the EDW formation region when the surface heat flux leads EDW by 0–2 years (Figure 4). Previous studies have had difficulties in establishing a significant correlation between the local heat loss and EDW properties near Bermuda [*Talley and Raymer*, 1982; *Jenkins*, 1982]; however, here, when the oceanic memory is taken into account, the correlation appears to be significant. The spatial pattern of the regression when NAO leads by 1 year is similar to the N. Atlantic tripole pattern in anomalous sea surface temperature [*Cayan*, 1992; *Deser and Blackmon*, 1993].

[13] All three time series of EDW properties reveal a well-defined 10–14 year cycle for the first 20 years of the dataset, with no obvious cycle for the second half of the period (Figure 2). Prior to the early 1980s, the sign of the NAO index alternated over periods of 4–6 years, with negative NAO years seemingly more prevalent. In the later portion of the record, the NAO index has been predominantly positive. The average turnover time of EDW was 3.23 ± 0.75 years for the first half of the 40-year period and 4.00 ± 0.77 years for the second half. Additionally, during the first 20 years, the winter EDW temperature and NAO index showed significant negative correlation when EDW temperature leads NAO by 3 years (and a positive peak when NAO leads), which was missing in the correlation for the whole 40 years. This could be due to the strong periodicity of the EDW time series in the first 20 years, but could also indicate a signature of a negative feedback between the NAO and the upper ocean properties in the N. Atlantic [*Frankignoul et al.*, 2001]. For the latter 20-year portion of the record, no significant correlation can be found at any lag. The detailed causes for the asymmetric characteristic between the positive and negative NAO years are subject of further study.

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