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ADVECTIVE HEAT FLUX AT THE BATS SITE (SARGASSO SEA)

АДВЕКТИВНЫЙ ПОТОК ТЕПЛА В САРГАССОВОМ МОРЕ (СТАНЦИЯ BATS)

Климчук Е.И. / Klimchuk E.I.

Инженер Федерального государственного бюджетного учреждения «Научно-исследовательский центр космической гидрометеорологии «Планета» / Research technician of State Research Center “Planeta”

e-mail: kuchmilk@gmail.com

Аннотация. Представлены результаты исследования горизонтального потока тепла в океане по метеорологическим данным и данным о вертикальном распределении температуры на станции BATS (Bermuda Atlantic Time Series project) в Саргассовом море. Приведены расчеты адвективного потока тепла с 1988 по 2008 год. Проанализированы причины поступления адвективного потока тепла на различных глубинах.

Ключевые слова: Адвективный поток тепла,профиль температуры,запас тесла в океане,межгодовая изменчивость.

Abstract. Results on advective heat flux analysis in open ocean based on meteorological and vertical temperature (CTD) profiles for the period1988-2008 from BATS site are presented. Method for horizontal heat flux calculation is explained in details. Main reasons of coming horizontal heat are given for different depth distribution.

Keywords: Advective heat flux, temperature profiles, ocean heat storage, heat flux ratios, interannual variability.

Introduction

One of the most important scientific problems nowadays is the global climate change. Processes which occur in the atmosphere and the ocean connected with each other and atmospheric fluctuations taken place in North Atlantic reflected in changing hydrological characteristics within the ocean. The nature of interaction between the ocean and atmosphere has been the subject of intense debate [2, 21]. Ocean’s great role in the climate system belongs to ability store and transport heat, fresh water (and carbon) over a wide range of time and space scales [9]. Nowadays scientists make attempts in understanding and quantifying ocean`s heat and freshwater transport for the reason to build reliable models of the climate system [22].

In heat redistribution between latitudes system of global oceanic gyres plays an important role. Recent studies [5,29] show that North Atlantic Subtropical Gyre during last several years was changing its position, slowing down and as a sequence carrying less heat. Data set from the Bermuda Atlantic Time series Study site (Sargasso Sea) located approximately in the middle of the North Atlantic Subtropical gyre can assist in understanding long term variability processes and identify the reasons of changes which taking place. Moreover the BATS site region is influenced by mesoscale eddy variability. Fig.1 shows distribution of sea level anomalies, measured by satellite Jason-1, Jason-2. Using these images we can easily recognize eddy persistence and give a brief characteristic of upper ocean layer. To analyze the quantity of heat and water that system transfers and store within the area components of heat balance and origin of advection processes on different depths should be estimated and clarified.

This study include estimation of depth-averaged heat storage and advection heat fluxes, net surface heat flux based on monthly CTD and meteorological hourly data for almost 20 years (1988-2008). In discussion main reasons for different depths is done including mesoscale eddy variability passing by the site; advection heat flux imbalance index estimated and analyzed.

Study area

The BATS site is located in the western North Atlantic subtropical gyre, in Sargasso Sea area, about 80 kilometers southeast of Bermuda. BATS – Bermuda Atlantic Time Series project was started in 1988 as a part of US Joint Global Ocean Flux Study (JGOFS) program. Monthly cruises collect data at the BATS site in deployment area of 31°40`N and 64°10`W (before July,1994 31°45`N and 64°10`W). Bottom depth at the BATS deployment area is ~ 4680 m. The BATS site is dominated by weak geostrophic recirculation, with net flow towards the southeastern coast of North America and high eddy energetic [24]. Mesoscale eddies between about 10 and 500 km in diameter with persistence for periods of days to months are common in Sargasso Sea [18].

These eddy phenomena include cold core rings dominated in Gulf Stream area and smaller cyclonic and anti-cyclonic eddies, associated with cold and warm temperature anomalies (fig.2). Anticyclonic eddies relatively poor in nutrients (i.e. nitrates, phosphates, and silicates), eddies rotating cyclonically due to subsequent intensification caused by interaction with surrounding features are reasonable for sporadic nutrient injections into the surface layer [16,28]. Processes of eddy pumping also provide flux of nutrients into the euphotic zone. Eddy pumping is a process by which mesoscale eddies induce isopycnal displacements that lift nutrient-replete waters into the euphotic zone, driving new primary production [23]. Thus freshly upwelled, cool, nutrient-rich waters in the center of a cold core eddy are a feast for phytoplankton. Ocean eddies provide an important role in displacement of water and heat masses, nutrients in the upper layer of the ocean. Eddy heat transport significantly influences the heat balance of strong currents and tropical areas [8, 19].

Data

Two types of data are used in this study: BATS station dataset and Bermuda Weather Service data, which are described below.

a. BATS data-hydrography

A long-term time series of hydrological data includes samples from CTD instrument and niskin bottles. A Sea Bird CTD instrument package is mounted on a 24-position General Oceanics Model SBE 32 rosette containing 12 Teflon-coated Niskin bottles [11]. The instrument package includes sensors for continuous measurement of pressure, temperature, conductivity, dissolved oxygen, and fluorescence. Continuous CTD data are calibrated by water collected in discrete Niskin bottle samples on the rosette. Data processing includes sensor corrections, empirical field calibrations and quality control analysis [24].

Monthly casts (fig.3) latitude and longitude, depth (h, m), pressure (P, mbar), temperature (Tsst,°C) and salinity (S,psu) data were used started October, 1988 to December, 2007; during that time 230 cruises were made.

The BATS site temperature profiles for the vicinity of 10 km from June, 1994 to December 2007 (fig.4) characterized by deep winter mixing (range ~200 m) and strong summer thermal stratification. Temperature distribution in the Sargasso Sea is characterized be presence of several layers: surface layer (100-150m.), where temperature varies from 28 to 19-20°C; then layer with weak vertical temperature gradient (temperature from 19-20 to 16,5-17°C),with a presence of a large body of nearly isothermal water (18°C) between 200-600m. Deeper there are main thermocline waters with temperature decreasing from 16,5/17,5-7,5°C at depth of 1000 - 1200 meters. Then temperature varies from 5 to 2°C [26]. Differences in the seasonal cycle of the Sargasso Sea relate to variability of winter mixing depth and 18°C mode water formation. The upper ocean layer at BATS site is highly variable on timescales ranging from diurnal to seasonal, annual, and interannual.

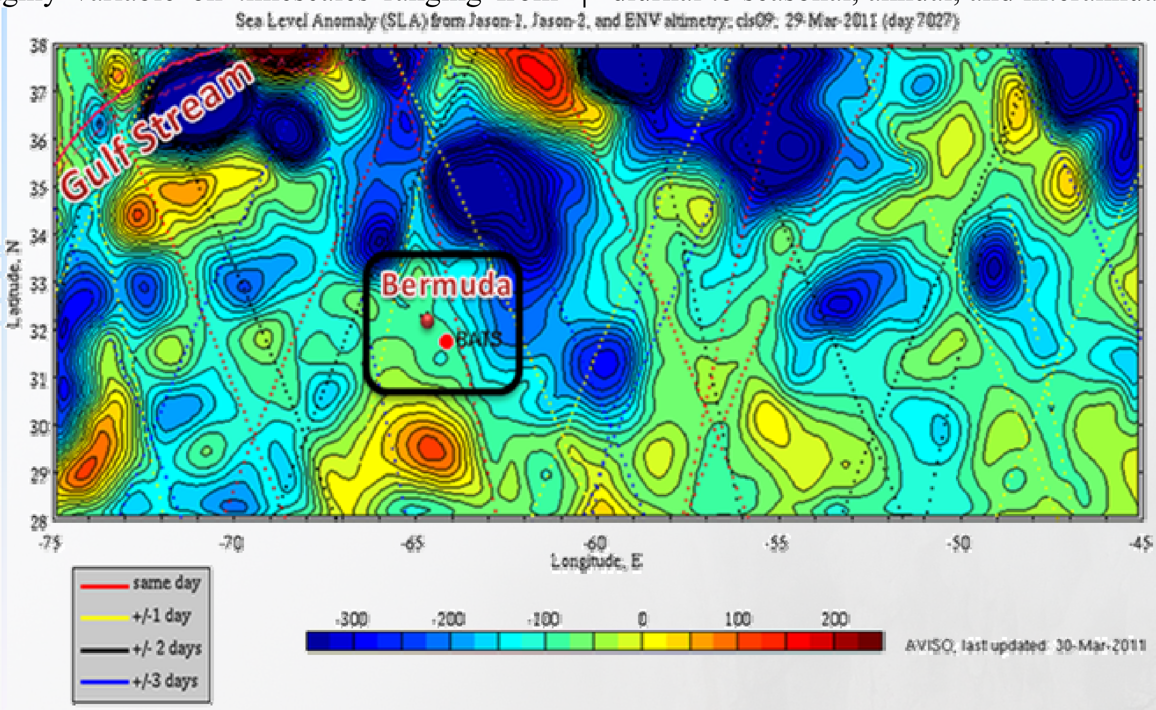

Fig.1. Sea level anomaly in the Sargasso Sea from Jason-1, Jason-2 for March, 29 2011 (http://science.whoi.edu/users/valery/altimetry)

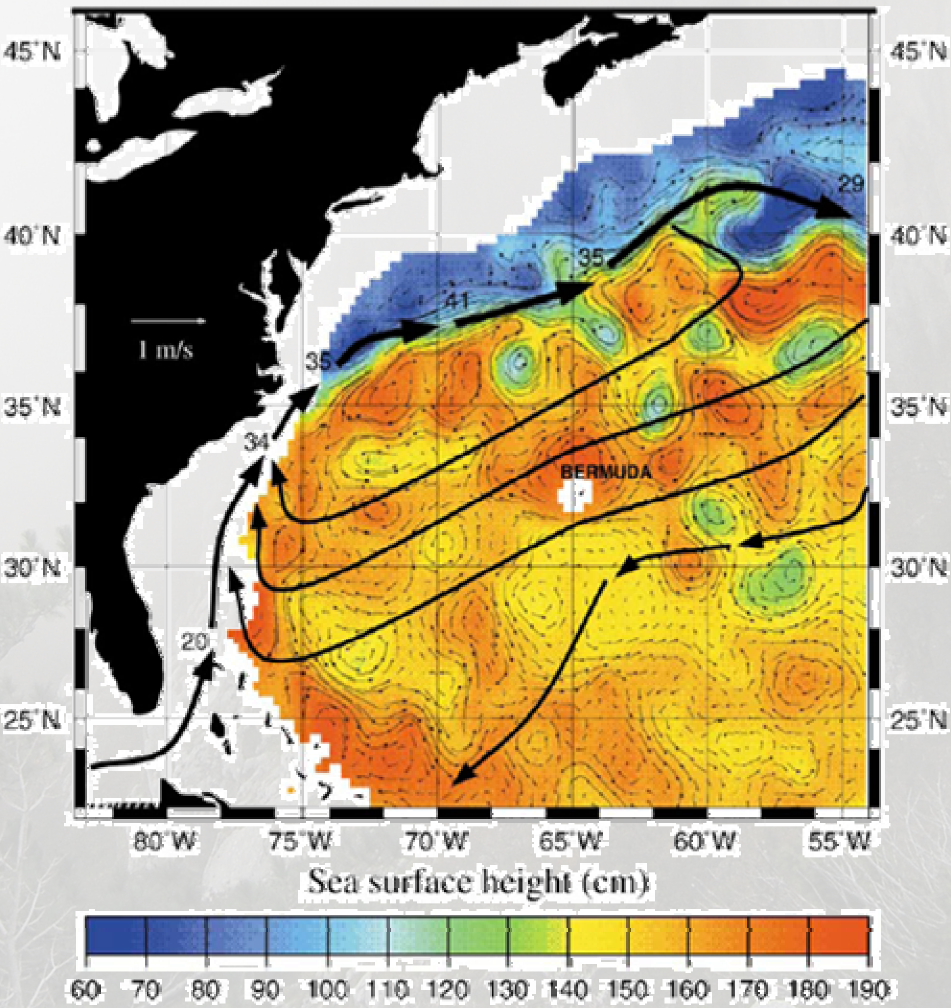

Fig.2. Sea surface height (SSH) satellite image of the Sargasso Sea area, illustrating typical mesoscale variability; thick black lines represent geostrophic velocities, from [23]

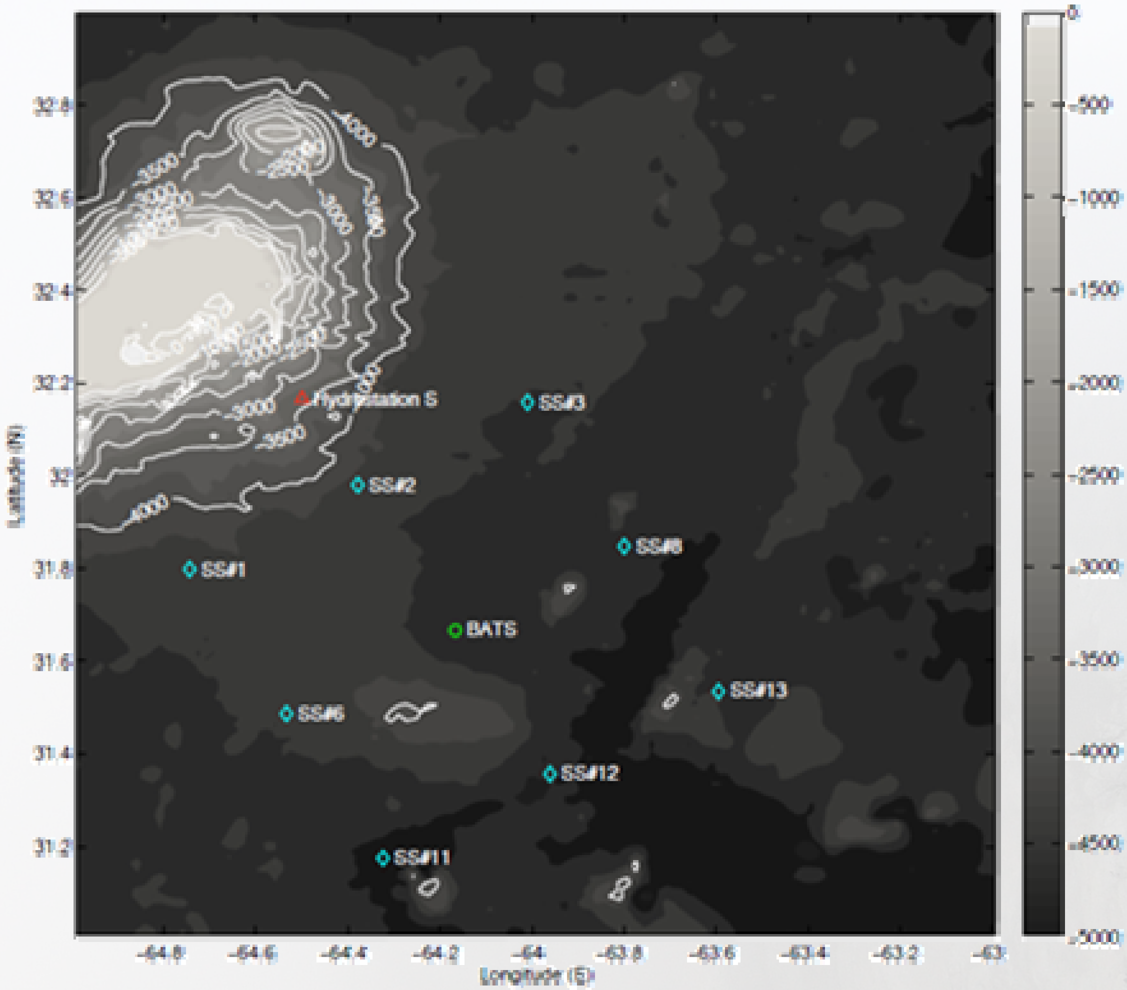

Fig.3. Monthly position for CTD casts (BATS site in the middle)

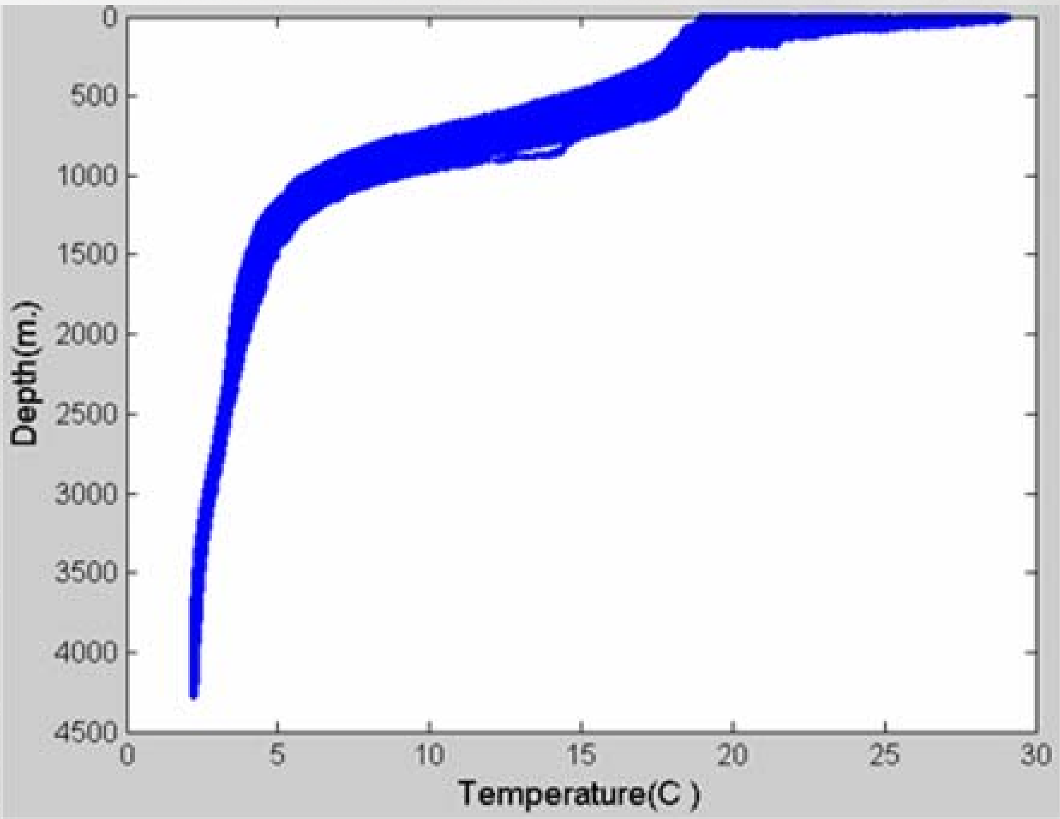

Fig.4. Temperature profiles from BATS dataset 1994-2007

b. Meteorological data

The Bermuda Weather Service is Bermuda's national meteorological service, provides public, marine, tropical and aviation weather forecasts as well as warnings and climate related services. Data obtained in collaboration with Bermuda International Airport include hourly air temperature, pressure, humidity, wind speed and direction. Hourly surface in-situ measurements by Weather Radar and Automated Weather Observing System (AWOS) for the period from 01 January 1988 to 31 December 2007 contain wind direction, wind speed (U, m/s), total cloud cover (N, tenths), air temperature (Ta,°C), dew point (Tdew,°C), atmospheric pressure (mbar), solar short wave radiation(Qsw, W/m^2) and rainfall (mm/hour). Total number of a measurement is 175321.

Method

Calculations of total and regional fluxes of energy across the ocean surface is a study for oceanographers and meteorologists in order to estimate and understand changing produced by the ocean and atmosphere resulting in global transport of energy. Near half of the solar energy reaching the Earth is absorbed by the ocean and land where it is temporarily remain stored. Around 1/5 of the obtained solar energy is directly absorbed by the atmosphere [1]. Within the energy acquired by the ocean most of it released to the atmosphere by evaporation, convection or long-wave radiation. Rest is transported by strong western boundary currents, mesoscale eddies especially in midlatitudes. Solar energy stored in the ocean makes Earth`s climate milder in summer. As ocean currents play significant role in transporting heat and freshwater masses within the latitudes, particularly in North Atlantic, and in this way affect climate change or sea level, it is important to estimate oceanic heat budgets, heat transports, analyze short and long term variability [25].

Imbalance between input and output of heat through the sea surface area or heat transport cause change of heat content within the ocean. A heat flux is a process of heat transfer across or through the surface. Heat budget is the sum of all heat fluxes. The main components of heat budget are following:

- Short wave solar radiation- the flux of solar energy into the sea (Qsw)
- Net long wave infrared radiation – the flux of infrared radiation from the sea (Qlong)

The turbulent exchange of heat between the ocean and atmosphere is due to sensible heat and latent heat flux.

- Sensible heat flux – the flux of energy carried due to conduction and convection (Qsens)
- Latent heat flux - the flux of energy carried by evaporation or condensation (Qlat)
- Advection heat flux – heat transported by currents, water masses, eddies etc.(Qadv)

Total surface heat flux can be described as:

$$Q_{total} = Q_{sw} + Q_{long} + Q_{sens} + Q_{lat} \pm Q_{adv}, \quad (1)$$

where Qtotal is the result from heat gain and loss. Units for heat fluxes are W/m^2.

Heat storage estimation

From the standpoint of heat budget calculation the heat storage is the important term and estimated as:

$$H = mC_p \Delta T_{sst}, \quad (2)$$

where $m=\rho V$ – mass of water column, $C_p \approx 4{,}0 \cdot 10^3 (J \cdot kg - 1^{*0} C - 1)$ - specific heat capacity of sea water at constant pressure, T_{sst} denote monthly values for the depth-integrated temperature [17].

According to Stainberg D. [24] mixed layer depths in Sargasso Sea near the BATS site observed as 150-300m. in winter and 20 m. in summer periods. Thus calculations of heat storage were made for the depths 0-200m, 0-500m and difference between layers in order to identify the signals of mode water and deep water convective mixing which are coming to the BATS site from the north-east part of North Atlantic ocean. Estimated values for depth averaged heat storage in J/ m^3 can be observed in results section.

Indirect calculation of fluxes

Sensible and latent heat fluxes can be estimated by bulk formulas. The bulk radiational exchange equations are empirical and the coefficients must be determined [4].

The sensible heat flux is

$$Q_{sens} = p_a C_p C_s U(T_{sst} - T_a), \qquad (3)$$

where ρ_a is the density of air, C_P is the specific heat of air at constant pressure, C_S is sensible heat transfer coefficient, T_{sst} and T_a – absolute sea surface (0-6m.) and air temperatures, respectively, U is the wind speed.

The bulk formula for evaporation is

$$Q_{lat} = p_a L C_L U(q_{sst} - q_a), \qquad (4)$$

where L is the latent heat of evaporation, C_L is latent heat transfer coefficient, q_{sst}-q_a – specific humidity difference between sea surface and air (10m above the sea surface); C_s and C_L coefficients taken from [25].

Latent heat of evaporation is estimated following Jacquet J. [10] in J/kg:

$$L = 4186.8(597.1 - 0.57T_{sst}). \qquad (5)$$

The infrared radiation Q_{long} has been computed from the equation used by Bunker A. [4]:

$$Q_{long} = -0.022 \cdot 0.96Ta^4(11.7 - \\ - 0.23E_a)(1 - CN) - 4 \cdot 0.96\sigma Ta^3(T_{sst} - T_a), \qquad (6)$$

where σ is the Stefan-Boltzmann constant, E_a is the water vapor pressure (at 10 m), C – variable cloud coefficient, N – cloud cover, taken from meteorological data set.

Advection flux calculus

Advection heat flux (W/m^2) was estimated based on above ocean heat content, radiation and turbulent flux terms:

$$Q_{adv} = (\Delta_{Heat\ storage} / \Delta_{total\ surface\ heat\ flux}) \cdot \Delta_{time} \cdot \\ \cdot 365.25 \cdot 25 \cdot 3600, \qquad (7)$$

where Δ_{Heat} storage is a difference in estimated heat content between BATS cruises (J/m^2), $\Delta_{total\ surface\ heat\ flux}$ (J/m^2) is *1*-dimensional surface heat flux change, Δ_{time} is a time interval in days between cruises in seconds.

Advection heat flux values estimated for 0-200 m., 0-500 m. and 200-500 m. were then averaged with depths (W/m^3) for further analysis.

Results

Heat storage and advection heat flux

Estimated values for heat storage and advection heat flux at the BATS site for the mixed layer and below in J/m^3 and W/m^3 (depth averaged) from October 1988 to December 2007 (fig. 5, 6) demonstrate irregular variations within time range. Graphs illustrate clear seasonality, especially for upper ocean layer. Two minimums occured nearly at 1995 and 2006, maximum denoted at 1998. Heat storage variability is characterized by low-frequency fluctuations with a 10 year periodicity, which is correlated with studies about multidecadal and decadal variability in North Atlantic [3,6,20]. Main cause for these variations is the Atlantic Meridional Overturning Circulation (AMOC), driven by density fluctuations in the convection regions. Mechanisms suggested for this relationship include variations in the meridional heat and salt transports causing basin scale fluctuations in surface temperatures (Tsst) known as the Atlantic Multidecadal Oscillation (AMO) [6,12,14]. Same distinct changing in variability for heat storage values in deeper ocean layers are not defined; some years show high frequent fluctuations in spring which can be a signal of deep convection occurred mostly in late winter-early spring.

Graphs of depth averaged advection heat flux measurements for 0-200m and 0-500m (fig.6) characterized by high frequency fluctuations, linear trends (at our methods of calculation) are not defined. However, low-frequency fluctuations within time scale can be observed.

Heat storage and horizontal advection for 300m depth (200-500m) (fig.7) repeat previous distribution of estimated values (fig.5,6) and do not represent any significant decadal or more variability. Heat storage estimated values have no any decadal variability. Since 1989 values increased within interannual scale and reached maximum around 2000 year then values declined till 2007. Depth averaged horizontal heat flux has no significant trends and seasonality, with mostly chaotic values distribution.

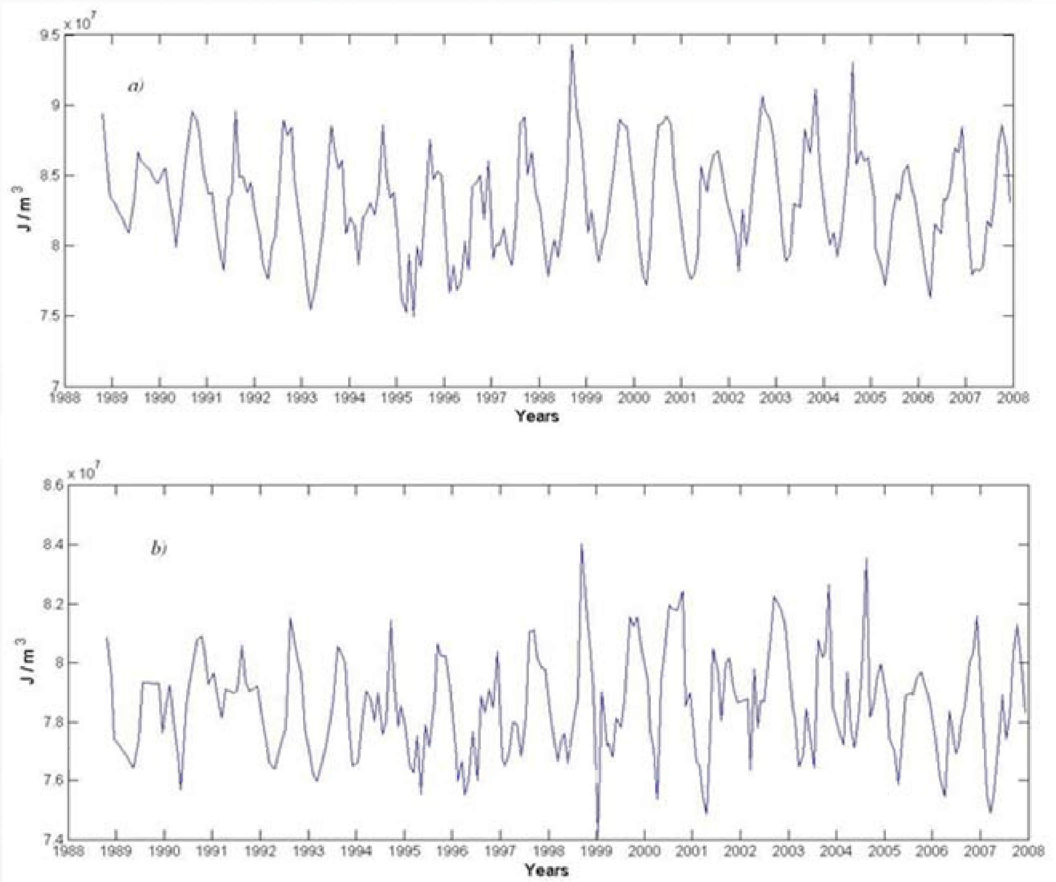

Fig.5 Depth-averaged values of heat storage (J/m^3): a) for upper 200m. b) for upper 500m

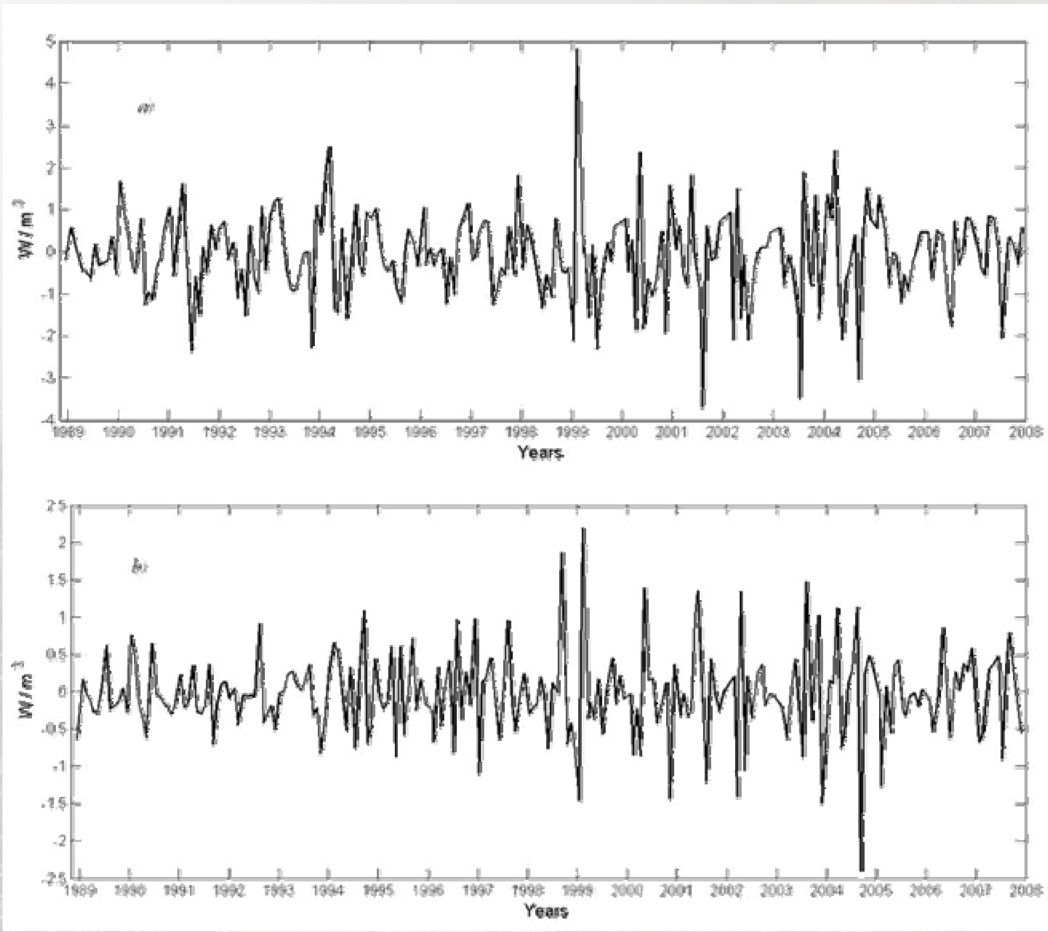

Fig.6 Depth-averaged advection heat flux (W/m^3): a) 0- 200m. b) 0- 500m

In comparison to fig.7 heat storage for 0-200m mostly depends on local (surface heating, advection-diffusion, the Ekman pumping response) [7] and non local (horizontal flux) supply, in deeper layers from 200-500m (lower mixed layer depth) mostly pure advection heat flux component supplies oceanic heat content. Quasi-advection from north-east of North Atlantic carries lenses of subtropical mode water (NA STMW) due to subduction at intermediate ocean depths and transport to the BATS site according to western intensification of STMW [15].

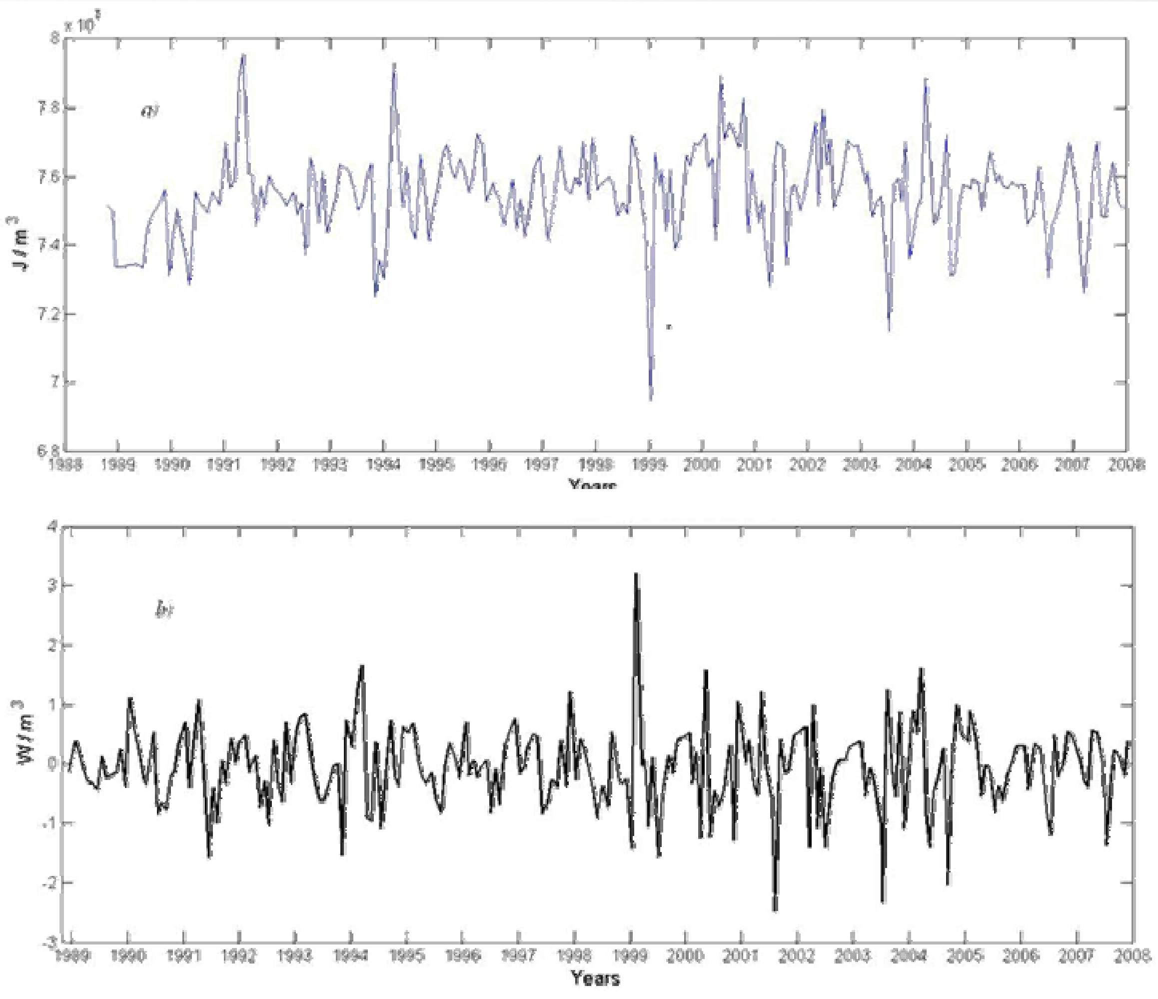

Fig.7 Depth-averaged (depth 200:500m) values for a) heat storage (J/m^3), b) advection heat (W/m^3)

Imbalance ratio

Heat sources which come, remain and leave the BATS site are detected by imbalance ratio parameter. Equation (8) allows estimate and analyze values for system balance/imbalance:

$$Ratio = Advection\,heat\;flux\,/\,/\,Mean(net\;surface\,heat\;flux). \quad (8)$$

Values of this parameter are in range from 0 to±10 and further. Index number 0 responsible for one dimensional system (BATS site) balance, ±1 – system is imbalanced due to local one dimensional supply and finally, values in range ±10 and more: system imbalance order of magnitude is greater than can be explained by local forcing. Imbalance ratios (fig.8) for 0-200, 0-500 and 200:500 meters depths lead to understanding inner ocean processes of heat origin coming to the BATS site. Index values within the time rate for 1989 to 2007 do not confirm seasonal variation of calculated parameters, eddy scale processes can be described as chaotic. Values below 0 (negative supply) detected not only in winter as was expected, but also in spring, summer and autumn (years 1995, 1997, 2004), conversely positive supply observed in winter months for years 1994, 1996, 1999.

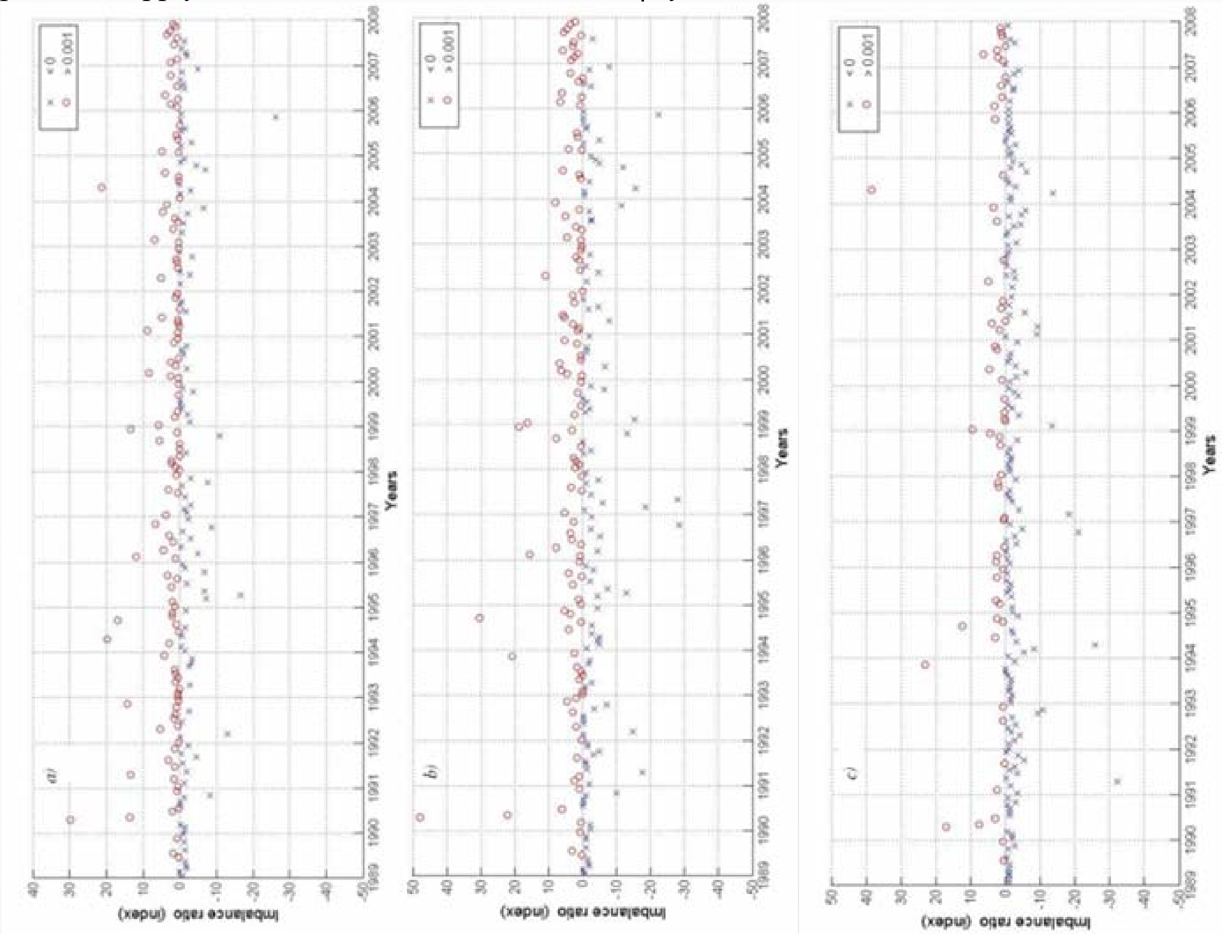

Fig.8 Imbalance ratios with positive and negative values for heat supply from 1989 to 2007 year for: 0-200m. b) 0-500m. c) 200:500m

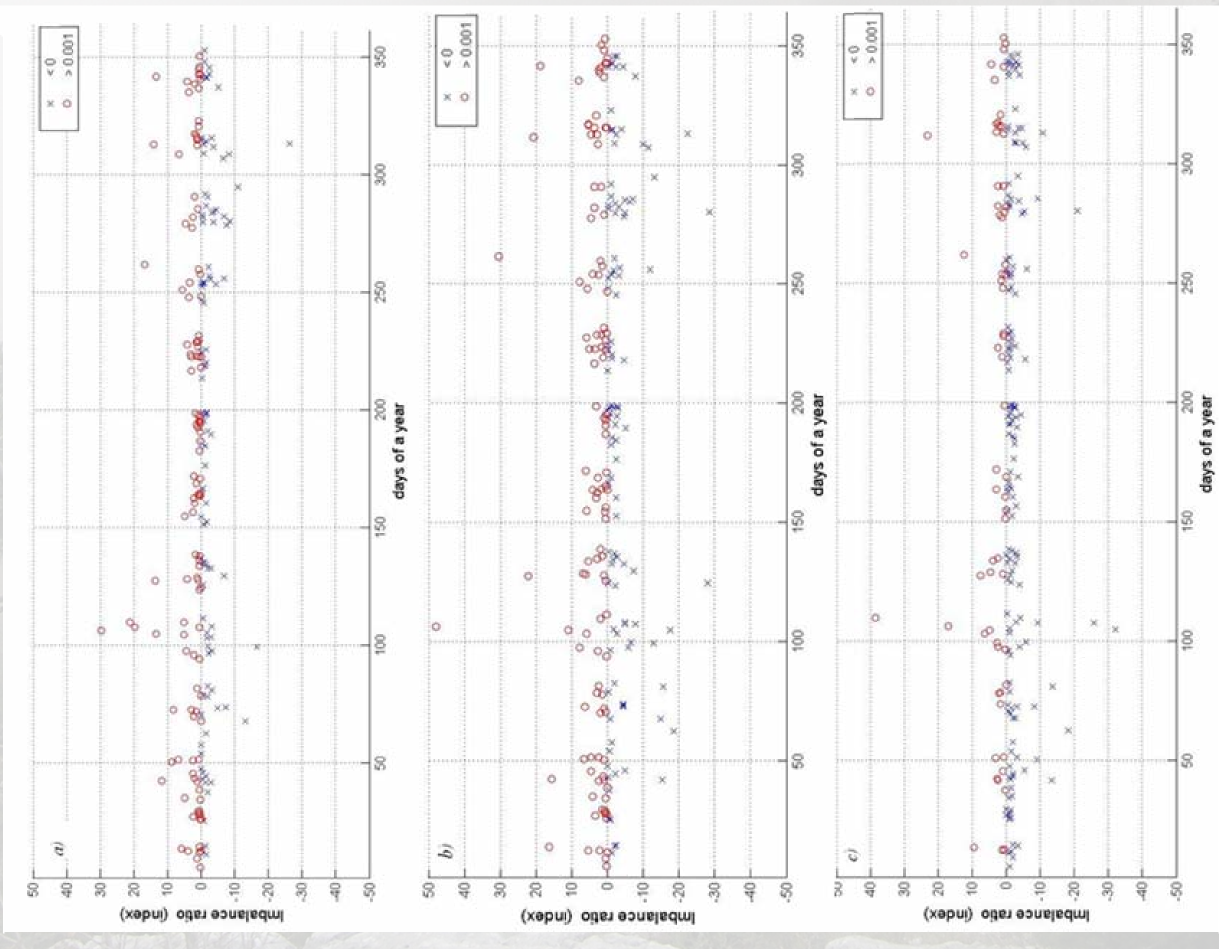

Fig.9 Heat supply imbalance ratio with positive and negative values for day of a year: a) 0-200m. b) 0-500m., c) 200:500m

In order to understand for which year period long-term isopycnal transport prevails, ratio distribution according to year-day fraction was done; values (fig. 9) represent distribution of positive and negative supply to the BATS site according to the day of the year.

Following previous results (fig.6-8) obtained results do not confirm seasonal distribution of characteristics. In winter–early spring due to the winter mixing processes negative values of imbalance index represent advection coming from north-east cold subtropical mode water lenses [13] – graphs (fig.9 b, c) time range form 0-110 confirm that with mostly negative index values for this period. In summer months (fig.9 a, b, c) measured values represent system balance. Index for 200-500m (fig.9 c) demonstrate subtle mode water supply in middle of March only.

Discussion

Heat storage, surface heat fluxes (solar radiation, latent and sensible heat) and advection component are widely known. However its role in system balance is unclear. Variability of heat storage values differ within the water column: for upper layer values show interannual variability with almost decadal period, for deeper layer measured values increasing from 1989 with maximum around 2000 year, because of weak solar influence. Surface total heat flux has seasonal cycle as it warms the ocean from April to August and cools from September to March. Warming by advection occur oppositely in winter months for upper layer (fig.6 a), deeper from 200 to 500 meters this tendency also exists but much weaker and starting from 1999 year (fig.7 b) greater amplitude of fluctuations observed.

Heat storage and horizontal heat flux long – term variability analysis is important for interpreting heat balance of a one dimensional system at the BATS site. Estimated imbalance ratios (fig.8) illustrate how different processes affect site supply on diverse ocean layers. Even though they do not show seasonality – we can conclude that processes responded for supply are chaotic within time range and besides during one particular year values distribution do not show any dominance for particular season. Sum of imbalance ratio values within a year should tend to zero. Table 1 displays ratio distribution for years 1989-2007; thus for a range of 20 years only 5 have positive year supply, negative supply observe for remain 15 years, minimum(max negative) denoted in 1989 and maximum(max positive) in 1999, with a difference of 10 years, which is correlated with decadal scale climate oscillations persistent in North Atlantic[27]. Kwon Y. and C. Riser [13] found that deep winter mixing events correspond also for changing in NAO index.

Table 1.

Imbalance ratio distribution for years 1989-2007, depth 200:500m.

1988	**0.22**	**1998**	**1.14**
1989	-9.25	**1999**	9.6
1990	0.21	**2000**	-1.22
1991	-0.14	**2001**	-0.07
1992	-0.86	**2002**	-2.03
1993	-1.49	**2003**	-0.63
1994	-0.64	**2004**	-1.53
1995	-1.82	**2005**	-0.96
1996	-1.29	**2006**	-1.045
1997	0.44	**2007**	-0.09

The imbalance index graphs (fig.8, 9) represent strong eddy variability within a year as was expected. Interestingly, according to plots in time of strong positive heat supply for example 1990, 1994 and 1995 equivalent changing e.g. commensurate loss of heat is not observed in time of subsequent cruises. Thus we can conclude that system while obtaining heat due advection stays in balance with obtained amount of heat for a long time period (~several months).

Conclusions

One dimensional system heat storage, net surface heat flux and horizontal advection were estimated based on Bermuda Atlantic Time-series and meteorological (Bermuda Weather Service) data sets for BATS site (31 40`N, 64 10`W). Interestingly that upper ocean heat storage shows significant interannual close to decadal variability, which connected to AMO (changing of Tsst) and other signals associated with climate change. Meanwhile advection heat flux has no any significant trend for almost 20 years of calculus, observed that obtained values have fluctuations of high frequency during the time range.

Heat budget im/balance analysis at the BATS site of was explained by imbalance ratio and revealed that system is imbalanced mostly by mesoscale eddies energetics coming from eastern part of North Atlantic and events that can`t be explained by local forcing: deep water formation in North Atlantic and water masses that ventilate shallower ocean depths such as subtropical mode water STMW of the subtropical gyres penetrate Sargasso Sea.

Distribution of positive and negative supply during the whole period illustrates that time series values for 20 years has only five years with positive supply, rest 15 years show negative supply. Ten years is the difference between year with maximum and minimum heat supply according to imbalance ratio distribution for depth deeper then mixed layer depth, according to seasons and year to year positive/negative supply have chaotic distribution.

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