Climatological annual cycle of ocean heat content

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[1] Ocean heat content is a major component of earth's energy budget. This paper presents estimates of the climatological annual cycle of upper (0–250 m layer) ocean heat content based on *World Ocean Atlas 2001*. The land-ocean ratio is responsible for the geographical distribution of the annual cycle of ocean heat content. Globally, the amplitude of annual harmonic of upper ocean heat content is 3.7×10^{22} J for the World Ocean, 10.2×10^{22}J for the Southern Hemisphere, and 6.5×10^{22}J for the Northern Hemisphere. *INDEX TERMS:* 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 4223 Oceanography: General: Descriptive and regional oceanography; 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Antonov, J. I., S. Levitus, and T. P. Boyer (2004), Climatological annual cycle of ocean heat content, *Geophys. Res. Lett.*, *31*, L04304, doi:10.1029/2003GL018851.

1. Introduction

[2] The heat content of the global ocean plays a critical role in the earth's heat balance for the climatological annual cycle [*Ellis et al.*, 1978] and for interannual-to-decadal scales [*Levitus et al.*, 2001]. One of the uses of heat content estimates is to verify Atmosphere-Ocean General Circulation Models (AOGCMs) that attempt to simulate the earth's climate system. In fact, the climatological cycle of ocean heat content [*Levitus*, 1982] was used to verify the first AOGCM that incorporated realistic land-sea, land topography, and ocean bathymetry distributions [*Manabe et al.*, 1979]. Indeed, the success of an AOGCM model to reasonably simulate this cycle is a crucial test of the model's ability to simulate the earth's climate system. *Bryan and Schroeder* [1960], *Merle* [1980], and *Lamb and Bunker* [1982] published estimates of ocean heat content for limited regions of the oceans. Near-global (20°S to 60°N) analysis of heat content annual cycle was presented by *Hsiung et al.* [1989]. Our work updates previous global and basin estimates by *Levitus* [1984, 1987] and *Levitus and Antonov* [1997, hereafter referred to as LA97]. LA97 was based on the data contained in the *World Ocean Atlas 1994* (WOA94) [*Levitus and Boyer*, 1994]. The latest version of this climatological ocean atlas series, *World Ocean Atlas 2001* (WOA01) [*Stephens et al.*, 2002], contains about 2.5 million temperature profiles not available for the WOA94 analyses. Some of these data are from traditionally data sparse regions such as the southern hemisphere.

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[3] In this paper we update earlier estimates of the climatological annual cycle of ocean heat content for the oceans using WOA01 climatological monthly temperature fields. The global gridded fields and the zonal and basin integrals of the climatological monthly mean heat content used in this paper are available from the NOAA National Oceanographic Data Center web site at http://www.nodc.noaa.gov.

2. Method

[4] Monthly mean objectively analyzed temperature fields on a one-degree grid at standard depth levels have been used to compute the monthly heat content (HC_{month}) for each one-degree square with vertical thickness defined by the difference between adjacent standard depth levels as follows;

$$HC_{month} = \int_{\lambda_1}^{\lambda_2} \int_{\varphi_1}^{\varphi_2} \int_{z1}^{z2} \rho_0 c_p (T_{month} - T_{annual}) a^2 \cos\varphi dz d\varphi d\lambda$$

in which: T_{month} is the climatological monthly mean temperature (°C), T_{annual} is the climatological annual mean temperature (°C), $\rho_0 = 1020$ is sea-water density (kg m^{-3}) that we take to be a constant value for the purpose of this computation, $a = 6372$ is the earth's radius (10^3 m), $c_p = 4187$ is specific heat of water (J kg^{-1} K^{-1}), ϕ is the earth's latitude, λ is the earth's longitude, z is depth and z_1 and z_2 are the lower and upper boundaries of the layer (0–250 m in this work). Zonal and basin heat content are defined as spatial integrals of one-degree square heat content estimates.

3. Basin Zonal Annual Cycle of Heat Content of the 0–250 m Layer for the Atlantic, Indian, Pacific and World Oceans

[5] Basin zonal integrals by one-degree latitude belts of monthly heat content of the 0–250 m layer for the Atlantic, Indian and Pacific oceans are shown in Figure 1. In each ocean basin a maximum in the seasonal change of heat content occurs in the 30°–45° latitude belt of each hemisphere. Seasonal changes in heat content from 60° of latitude toward the poles are relatively small since the heat content estimates shown in Figure 1 are volume integrals. In the tropics, the annual cycle of heat content is out of phase with the mid-latitudes of both hemispheres by about 3 months. The range of the seasonal cycle of the tropical Pacific is approximately 28×10^{20}J thus exceeding the range of any other latitude belt in an individual ocean. Overall, the magnitudes of monthly heat content in tropics and for most of the Southern hemisphere in Figure 1 are slightly (up to 10–15%) larger than in similar figures presented in LA97. The seasonal cycle of zonally integrated

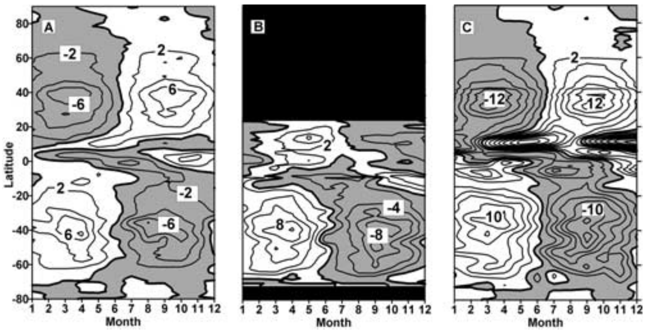

Figure 1. Zonally integrated heat content (10^{20}J) of the 0–250 m layer for the Atlantic Ocean (A), the Indian Ocean (B), and the Pacific Ocean (C). Contour interval: 2×10^{20}J. Shading denotes negative values.

heat content for the World Ocean is shown in Figure 2. and is dominated by the Pacific Ocean contribution.

[6] To quantify the seasonal cycle of zonal heat content by ocean basins we performed fourier analyses of this quantity. We present the annual harmonic as a function of latitude for the three major ocean basins and the World Ocean in Figure 3a. Note again that the contribution of the Pacific Ocean is dominant. For instance, the annual amplitude around 35°S in Pacific Ocean is more than 40 percent of the magnitude of the annual amplitude for the World Ocean. Figure 3b shows the results of a fourier analysis of zonal heat content per unit area. We note that all three oceans exhibit very similar estimates of this quantity at all latitudes except the tropics and subtropics where heat content is governed in part by dynamical processes that effect heat content through variations in the depth of the thermocline. Thus poleward of the subtropics (>20° of latitude), the differences between Figures 3a and 3b show the effect of the geographical distribution of the ocean-land ratio by latitude. This is so despite the observation that seasonal changes in the mean temperature of the 0–250 m layer are larger in the Northern Hemisphere compared to the Southern Hemisphere (LA97).

[7] In the latitude belt 20°–60° of each hemisphere, the annual harmonic accounts for more than 95% of the

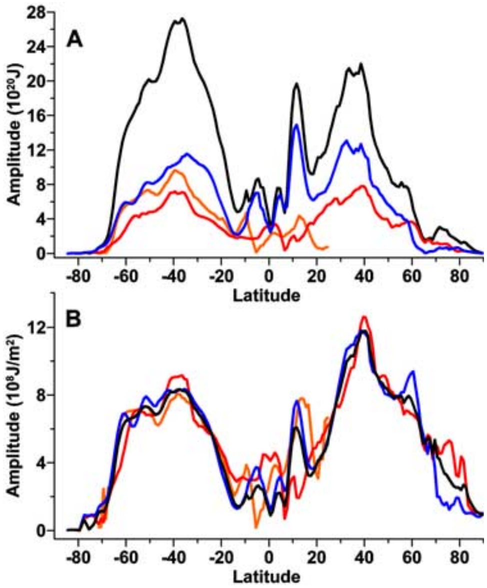

Figure 3. Amplitude of the annual harmonic of the seasonal cycle of zonal heat content (10^{20}J) (A) and zonal heat content per unit area (10^8J/m^2) (B) for the 0–250 m layer for the Atlantic (red), the Indian (yellow), and the Pacific (blue) oceans, and the World Ocean (black).

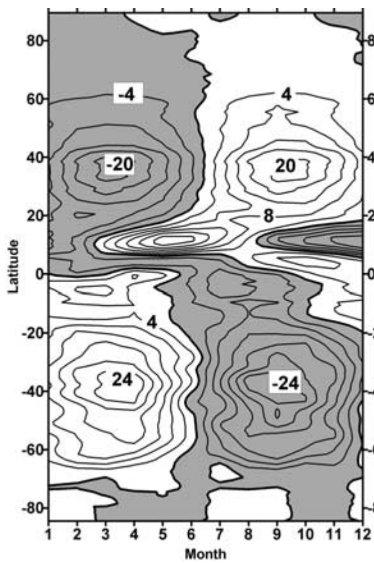

Figure 2. Zonally integrated heat content (10^{20}J) of the 0–250 m layer for the World Ocean. Contour interval: 4×10^{20}J. Shading denotes negative values.

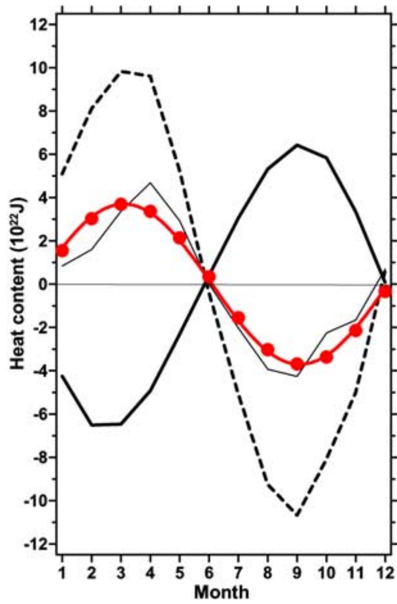

Figure 4. Heat content (10^{22}J) of the 0–250 m layer for the Southern (dashed line) (SH), and the Northern (heavy solid line) (NH) Hemispheres, and the World Ocean (thin solid line) (WO). Reconstructed heat content for WO: red line - annual harmonic of heat content for WO, red dots - sum of SH and NH annual harmonics.

Table 1. Fourier Parameters, Amplitude (10^{22}J), Phase (Months) and Percent Variance, of the Annual and Semiannual Harmonics of the Seasonal Cycle of Heat Content for the 0–250 m Layer for Major Ocean Basins

	Annual harmonic			Semiannual harmonic				
	Amplitude	Phase	Variance	Amplitude	Phase	Variance	Area	Volume
North Atlantic	2.65	9.2	99.7	0.12	1.8	0.2	0.45	1.08
South Atlantic	2.46	3.0	98.9	0.10	1.7	0.2	0.46	1.12
North Indian	0.52	4.9	89.7	0.15	1.5	7.3	0.11	0.26
South Indian	3.10	3.0	99.4	0.18	1.2	0.3	0.63	1.55
North Pacific	3.82	8.8	98.9	0.35	1.7	0.8	0.85	2.02
South Pacific	4.62	2.9	99.1	0.26	2.4	0.3	0.95	2.33
Northern Hemisphere	6.50	8.9	99.0	0.63	1.7	0.9	1.46	3.47
Southern Hemisphere	10.18	3.0	99.6	0.45	1.9	0.2	2.04	5.01
World Ocean	3.70	3.1	90.2	1.07	1.7	7.6	3.50	8.48

Note that data from the Mediterranean and Baltic Seas were included in computation for the Northern Hemisphere and the World Ocean only. The Caspian Sea, the Black Sea, the Red Sea and the Persian Gulf data were excluded from any zonal or basin integration in this paper. Also shown are the area (10^{14}m^2) of each basin and the volume (10^{16}m^3) of the 0–250 m layer of each basin.

variance of the seasonal cycle (see Supplementary Figure S1)[1]. Poleward of 60° in each hemisphere (especially in the Southern Hemisphere) the contribution of the semiannual harmonic becomes important but these are data sparse, in some cases ice-covered regions. Thus, it is not clear how well our climatological analyses represent actual conditions in these high latitudes, in particular during the data sparse winter periods. However, our results indicate that in the tropics the semiannual harmonic must be taken into account in addition to the annual harmonic to achieve the same 95% threshold as in the midlatitudes. For example, the semiannual harmonic accounts for more than 45% of the variance around 11°N in the Atlantic and at the equator for both the Indian and Pacific oceans. Around 5°S in the Indian ocean, the semiannual harmonic dominates the seasonal cycle of heat content (65% compared to 10% due to the annual harmonic). The amplitude of the semiannual cycle for both zonally integrated heat content and zonally integrated heat content per unit area for each basin and the world ocean is shown in Supplementary Figure S2[1].

[8] Monthly heat content estimates for the Northern and Southern Hemispheres and the World Ocean are shown in Figure 4. About 99% of seasonal changes in heat content of both hemispheres is accounted for by the annual harmonic (Table 1). For both hemispheres, the magnitude of seasonal changes defined as a half of the range of monthly heat content estimates differs from the annual amplitude by less than 1%. Thus, a sum of annual harmonics of heat content for both hemispheres is expected to be the best fit for seasonal changes in heat content for the World Ocean. Indeed, their sum practically coincides with annual harmonic computed from monthly heat content for the World Ocean (Figure 4). Based on this fact we conclude that the annual harmonic alone describes adequately the annual cycle of heat content for the World Ocean. Overall, these amplitudes are in a good agreement with results presented previously by *Levitus* [1984] and LA97. The largest differences between the present study and *Levitus* [1984] is seen for May and June heat content of the Southern Hemisphere (being about 30–40% of the annual amplitude for the Southern Hemisphere). This is most likely due to the increase of data coverage for the Southern Hemisphere in this study as compared to previous analyses.

4. Summary

[9] It is encouraging that our current estimates of annual cycle of heat content for major ocean basins are generally consistent with results presented previously by *Levitus* [1984] and LA97 despite a significant increase of data available for this analysis. This data increase mostly resulted in 10–15% increase in magnitude of seasonal changes in heat content in tropics and in the Southern hemisphere. Our results suggest that in addition to the annual harmonic, the semiannual harmonic plays a significant role in accounting for the seasonal changes of the upper ocean heat content in the tropics of all three major ocean basins and its contribution to the global integrals is negligibly small. Because the ocean-land ratio for the Southern hemisphere is larger than for the Northern hemisphere, the annual harmonic of the World ocean heat content peaks in March with amplitude that is about one-third of the annual amplitude of the Southern Hemisphere ocean heat content.

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References

Bryan, K., and E. Schroeder (1960), Seasonal heat storage in the North Atlantic Ocean, *J. Meteorol.*, *17*, 670–674.

Ellis, J. S., T. H. Vonder Haar, S. Levitus, and A. H. Oort (1978), The annual variation in the global heat balance of the earth, *J. Geophys. Res.*, *83*, 1958–1962.

Hsiung, J., R. E. Newell, and T. Houghtby (1989), The annual cycle of oceanic heat storage and oceanic meridional heat transport, *Q. J. R. Meteorol. Soc.*, *115*, 1–28.

Lamb, P. J., and A. F. Bunker (1982), The annual march of the heat budget of the North and tropical Atlantic, *J. Phys. Oceanogr.*, 1388–1410.

Levitus, S., and J. Antonov (1997), *Climatological and Interannual Variability of Temperature, Heat Storage, and Rate of Heat Storage in the World Ocean*, NOAA Atlas NESDIS 16, U.S. Govt. Printing Office, Washington, D. C.

Levitus, S., and T. P. Boyer (1994), *World Ocean Atlas 1994, Vol. 4: Temperature*, NOAA Atlas NESDIS 4, U.S. Govt. Printing Office, Washington, D. C.

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL018851.

Levitus, S. (1984), Annual cycle of temperature and heat storage in the World Ocean, *J. Phys. Oceanogr.*, *14*, 727–746.
Levitus, S. (1982), *Climatological Atlas of the World Ocean*, NOAA Professional Paper No. 13, U.S. Govt. Printing Office, Washington, D. C.
Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli (2001), Anthropogenic warming of earth's climate system, *Science*, *292*, 267–270.
Levitus, S. (1987), Rate of change of heat storage in the World Ocean, *J. Phys. Oceanogr.*, *17*, 518–528.
Manabe, S., K. Bryan, and M. J. Spelman (1979), A global ocean-atmosphere climate model with seasonal variation for future studies of climate sensitivity, *Dyn. Atmos. Oceans*, *3*, 393–426.
Merle, J. (1980), Seasonal heat budget in the equatorial Atlantic Ocean, *J. Phys. Oceanogr.*, *10*, 464–469.
Stephens, C., J. I. Antonov, T. P. Boyer, M. E. Conkright, R. Locarnini, and T. D. O'Brien (2002), *World Ocean Atlas 2001 Volume 1: Temperature* [CD-ROM], edited by S. Levitus, NOAA Atlas NESDIS 49, U.S. Govt. Printing Office, Washington, D. C.

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