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Warming of the World Ocean, 1955-2003

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[1] We present updated estimates of the temporal variability of ocean heat content based on: a) additional data that extends the record to more recent years and; b) additional historical data that improves the estimates for earlier years. Between 1955 and 1998 the world ocean heat content (0-3000 m) increased by 14.5×10^{22}J corresponding to a mean temperature increase of 0.037 ºC at a rate of $0.20 Wm^{-2}$ (per unit area of the earth's surface).

INDEX TERMS: 1625 Global Change:Oceans; 4215 Oceans:Climate and Interannual Variability

1. Introduction

[2] Based on the physical properties and mass of the world ocean as compared to other components of earth's climate system, Rossby (1959) suggested that world ocean heat content may be the dominant component of the temporal variability of earth's heat balance. Recent observational work (Levitus *et al*., 2000, 2001) has confirmed Rossby's suggestion. Warming of the world ocean due to increasing atmospheric greenhouse gases was first identified in a committee report published by the White House (1965). The delay of atmospheric warming by increasing atmospheric greenhouse gases due to initial heating of the world ocean was first suggested in a National Research Council report (NRC, 1979). Previously (Levitus *et al*., 2000) we published estimates of yearly ocean heat content for the period 1948-1998 for the upper 300 m of the world ocean and pentadal estimates of the 0-3000 m layer for 1948-1952 through 1992-1996. Here we present yearly estimates for the 1955-2003 period for the upper 300 m and 700 m layers and pentadal (5-year) estimates for the 1955-1959 through 1994-1998 period for the

upper 3000 m of the world ocean.

[3] The heat content estimates presented here are based on an additional 1.7 million historical (Levitus *et al.*, 2004) and modern temperature profiles that have become available as part of the *World Ocean Database 2001* (Boyer *et al.*, 2002; Conkright *et al.*, 2002; Locarnini *et al.*, 2002; Stephens *et al.*, 2002). Additionally, we have processed approximately 310,000 additional temperature profiles since the release of WOD01 and have also incorporated these data into our analyses. Much of the recent data we use represent real-time and delayed-mode data reported via the IOC Global Temperature Salinity Profile Project (IOC, 1998). We use 1957-1990 as the base period for our climatology. All heat content computations are the same as described by Levitus and Antonov (1997).

2. Global and Basin Time Series

[4] Figure 1 shows yearly (1955-2003) estimates of world ocean heat content for the upper 300 and 700 m layers and pentadal (1955-1959 through 1994-1998) estimates for the upper 3000 m of the world ocean. Figure 1 documents that a large part of the total change in ocean heat content during the past 50 years has occurred in the upper 700 m of the world ocean.

[5] All three series show similar variability. For the world ocean the linear trend of heat content (for the 0-3000 m layer for 1955-1998) is 0.33×10^{22}J year^{-1} (corresponding to a rate of 0.20 Wm^{-2} [per unit area of the earth's surface]) representing an increase in heat content for the world ocean of 14.5×10^{22}J. For the Atlantic, Pacific, and Indian Oceans the increases of heat content (based on the linear trend) are respectively 7.7, 3.3, and 3.5×10^{22}J. As with our previous results, it is the Atlantic Ocean that contributes the

most to the observed global increase in heat content. Ocean heat content time series for individual ocean basins as well as the world ocean but with confidence intervals added can be found in the online supplementary materials[1]. Table T1 in the online supplement to this paper presents the change in heat content (based on the linear trend for each basin) and the basin average change in temperature. The linear trends used to compute these changes in heat content are presented in Table T2 (also in supplementary material) along with the corresponding heat storage estimates (heat storage is the time derivative of heat content per unit area. In this table the values are per unit area of the corresponding ocean basin as opposed to the values given above which are given per unit area of the earth's surface.

[6] One of the dominant features of the curves in Figure 1 is the large decrease in ocean heat content beginning around 1980. The 0-700 m layer exhibits a decrease of approximately 6 $\times 10^{22}$J between 1980 and 1983. This corresponds to a cooling rate of 1.2 Wm^{-2} (per unit area of the earth's total surface). Most of this decrease occurs in the Pacific Ocean. Supplementary Figure S4 shows the interpentadal difference in zonally averaged heat content by 100-m thick layers for the Pacific for (1986-1990) minus (1977-81). Most of the net decrease has occurred at 5ºS, 20ºN, and 40ºN latitude. Gregory *et al.* (2004) have cast doubt on the reality of this decrease but we disagree with their assessment. Examination of the pentadal data distributions at 400 m depth (not shown here) indicate excellent data coverage for these two pentads.

[1]Auxiliary material is available at ftp://ftp.agu.org/append/gl/2004GL021592

[7] As we have documented previously (Levitus, 1989; Levitus *et al.,* 2000), large temperature anomalies are observed for the North Atlantic even at 1750 m depth, however, the net contribution to the global heat content integral by these anomalies is relatively small but not negligible. Figure S5 shows the heat content integrals for the North Atlantic alone and documents that the contribution of the 1000-3000 m layer is approximately 1.3×10^{22}J, this is about 9 percent of the global increase (for the 0-3000 m layer) during this period. We emphasize that this does not mean this region is unimportant for climate change, only that its net contribution is relatively small to the global integral of ocean heat content.

3. Liner Trend of Zonally Integrated Heat Content as a Function of Depth

[8] In Figure 2 we show the linear trend of zonally integrated ocean heat content (by one-degree latitude belts) for the world ocean computed for 100-m thick layers. Figures S6-S8 are similar figures for individual ocean basins and Figures S9-S12 shows the percent variance accounted for by the linear trend for each basin as a function of depth. The linear trend of the world ocean (Figure 2) is positive at most latitudes with the largest increase in the upper layer of the world ocean with one notable exception. There is a large negative trend centered at about 150 m depth in the equatorial and southern hemispheric tropics. Examination of Figures S6-S8 shows that much of this cooling occurs in the Pacific Ocean. This may be associated with the reversal of polarity of the Pacific Decadal Oscillation (Stephens *et al.*, 2001) that occurred during the late-1970s. The equatorial Indian Ocean also exhibits subsurface cooling centered along 10°S. Two other regions of cooling include the North Pacific Ocean centered at around 40°N and the North Atlantic Ocean centered at 60°N. It is well known that the subarctic gyre of the

North Atlantic has been cooling (and freshening) during recent decades. For example, Levitus *et al.* (1994, 1995) documented a linear cooling trend of about 0.13°C at 125 m depth based on Ocean Weather Station "C" data during 1948-85 with quasi-decadal oscillations of about 2.0°C range. Dickson *et al.* (2002) documented the cooling and freshening of the deep waters of the Labrador Sea since the early 1970s which via advection has resulted in the cooling of the deep waters of the entire subarctic gyre of the North Atlantic (Levitus and Antonov, 1995). The Pacific cooling trend at 40°N may represent movements of the large-scale front in this region (*e.g.*, Minobe (2002) suggests this possibility using altimeter data) or it may simply represent changes in the temperature in this frontal region. In the southern hemisphere there is a positive linear trend extending to 1100 m depth centered at 40°S. In addition to the earlier work by Levitus *et al*. (2000), Southern Ocean warming between the 1950s and 1980s has been documented by Gille (2002) based on a combination of *in situ* observations including PALACE float data. Based on *in situ* data Willis *et al.* (2004) have documented a positive linear temperature trend centered along 40°S for the 1993-2003 period and Cabanes *et al.* (2001) have inferred a linear trend in this region based on a comparison of altimeter data and *in situ* data for the 1993-98 period. Overall, Figures 2 and S6-S8 document that the linear trend of zonally integrated ocean heat content is most intense in the upper part of all ocean basins.

4. Earth's Heat Balance

[9] To understand the variability of the earth's climate system it is important to estimate the relative roles of different terms in the earth's heat balance. In Figure 3 we update some of our previous estimates (Levitus *et al*., 2001) of the different components

of the earth's heat balance. In addition to our updated ocean heat content estimate an additional term in the earth's heat balance now available is the variability of the heat content of the earth's lithosphere. This is based on the work of Beltrami *et al*. (2002) who used temperature profile data from boreholes to make their estimate. They estimate that the earth's continents warmed by approximately 0.9×10^{22} J during the past 50 years. This estimate is of the same order as the warming of the earth's atmosphere during this period and the heat of fusion associated with possible melting of the Antarctic continental glacier assuming an estimated maximum melting rate (IPCC, 2001). Inspection of Figure 3 indicates that the world ocean is responsible for approximately 84% of the estimated possible total increase of heat content of the earth system during 1955-1998.

[10] Variability of heat content changes associated with the heat of fusion of the melting (or possible melting) of sea-ice and land ice are relatively small as noted in our earlier work although they may ultimately have larger effects due to feedback mechanisms associated with changes in albedo. Of interest though is the estimate of the decrease in Antarctic sea-ice extent by de le Mare (1997) based on observations of sea-**ice** by whaling vessels, a result which has been questioned by Vaughn (2000) although more recent work (Curran *et al*., 2003) provides support for the work of de la Mare.

5. Discussion and Perspective

[11] In terms of the causes of the observed increase in ocean heat content we believe that the long-term trend as seen in these records is due to the increase of greenhouse gases in the earth's atmosphere as stated in earlier work (Levitus *et al*., 2001). In fact, estimates of the net radiative forcing of the earth system (Hansen *et al*., 1997) suggest the possibility that we may be underestimating the warming of the world ocean. This is quite

possible since we do not have complete data coverage for the world ocean. However, the occurrence of the large decrease in ocean heat content starting around 1980 suggests that internal variability of the earth system may very significantly affect the earth's heat balance on decadal time-scales.

[12] After publication of our previous work (Levitus *et al*., 2000), one question put to us that we address here is that since atmospheric greenhouse gases such as carbon dioxide, methane, nitrous oxide, and freons are well-mixed in the atmosphere, why isn't the ocean responding uniformly? There are three reasons one does not expect uniform heating of the ocean from the observed increase in atmospheric greenhouse gases. The first is that internal variability of the earth system (*e.g.,* El Nino) may affect regional ocean heating rates in a non-uniform manner. The second is that the natural and anthropogenic aerosols are not well-mixed geographically and can have a substantial effect on regional warming rates. This has been documented for the northern Indian Ocean by Ramanathan *et al*. (2001a,b) who estimate a decrease of absorbed surface solar radiation exceeding $10 Wm^{-2}$ over much of the Indian Ocean due to the presence of aerosols. The IPCC (2001) report also documents the geographical variability of various aerosols, ozone, black carbon, *etc*. that affect the amount of radiation available to enter the world ocean. The third reason is that any change in the earth's radiative balance may induce global and regional changes in the circulation of the atmosphere and ocean which could in turn affect the net flux of heat across the air-sea interface on a regional basis.

[13] We now quantify a relation between heat and temperature anomalies of the ocean and atmosphere for the purpose of documenting how the climate system works. The heat content (H_o) associated with some mean temperature anomaly of the world ocean, ΔT_o

(ºC), can be written:

$H_o = m_o c_{po} \Delta T_o$

in which the m_o is the total mass of the ocean (1.4×10^{21} kg), c_{po} is the specific heat of sea water at constant pressure at the sea surface (4×10^3 J(ºC-kg)$^{-1}$). Similarly, the heat content (H_a) associated with some mean temperature anomaly of the global atmosphere, ΔT_a (ºC), can be written:

$H_a = m_a c_{pa} \Delta T_a$

in which the m_o is the total mass of the atmosphere (5.3×10^{18} kg) and c_{pa} is the specific heat of dry air at constant pressure (1×10^3 J(ºC-kg)$^{-1}$). The values used in these two equations have been taken from the works of Gill (1982) and Curry and Webster (1999). By equating these two and solving for ΔT_a we find that $\Delta T_a = 1056\,(\Delta T_o)$. Thus, a mean temperature change of 0.1ºC of the world ocean would correspond roughly to a mean temperature change of 100ºC of the global atmosphere if all the heat from the ocean was transferred from the ocean to the atmosphere. This of course will not happen but this computation illustrates the enormous heat capacity of the ocean as compared to the atmosphere.

[14] The question that climate-system modelers are working to answer is just how much of the observed and/or forecast increase in ocean heat content due to increasing greenhouse gases will be radiated to space, how much heat will remain in the ocean, and how much of this heat will end up heating the atmosphere and the response times of each component of the climate system. Our discussion here has not been to minimize the impacts of warming of the lower atmosphere due to increasing greenhouse gases, we are simply trying to place earth's heat (radiation) balance in perspective. The response of the

earth's climate system to changes in radiative forcing is often cast as the response of the earth's surface temperature to these forcings. This is understandable because humans live at the earth's surface and there has been a lack of subsurface ocean data with which to conduct earth system heat balance studies.

[15] Improved scientific understanding requires that we study the response of all components of the earth's heat balance, of which the world ocean is the dominant term. The global deployment of profiling floats that will provide upper ocean profiles of temperature (Roemmich and Owens, 2000) every 10 days will result in improved estimates of the internal variability of ocean heat content and the response of the earth's climate system to changes in radiative forcing. Substantial amounts of historical ocean profile data still exist in manuscript form, or are simply not yet available yet for international distribution. Incorporation of these data into internationally accessible archives will allow for improved estimates of the historical variability of ocean heat content.

[16] Electronic versions of the yearly and pentadal heat content fields used in this study and data distribution maps by yearly and pentadal compositing periods for selected depths are available at www.nodc.noaa.gov.

[17] **Acknowledgments.** This work was supported by the NOAA Climate Change Data and Detection Program with support from DOE. We thank the many scientists, technicians, data center staff, and data managers for their contributions of data to the World Data Center system which has allowed us to compile the database used in this work. We also thank our colleagues at the Ocean Climate Laboratory for their work in constructing the *World Ocean Database* which made this work possible. The views, opinions, and findings contained in this report are those of the authors, and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

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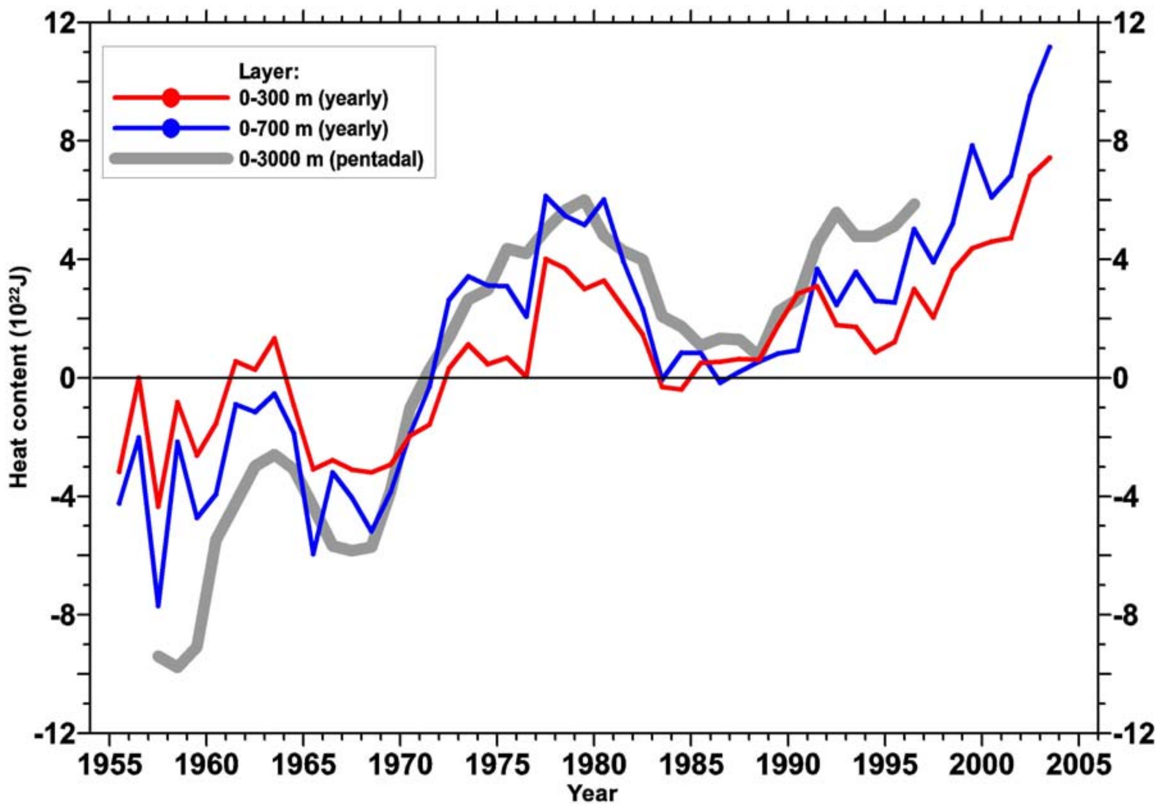
FIGURE CAPTIONS:

Figure 1. Time series of yearly ocean heat content (10^{22} J) for the 0-300 and 0-700 m layers and pentadal (5-year running composites for 1955-59 through 1994-98) ocean heat content (10^{22} J) for the 0-3000 m layer. Each yearly estimate is plotted at the midpoint of the year, each pentadal estimate is plotted at the midpoint of the 5-year period.

Figure 2. Linear trend (1955-2003) of the zonally integrated heat content of the world ocean by one-degree latitude belts for 100-m thick layers. Heat content values are plotted at the midpoint of each 100-m layer. Contour interval is $2x10^{18}$J year^{-1}.

Figure 3. Estimates of earth's heat balance components for the 1955-1998 period.



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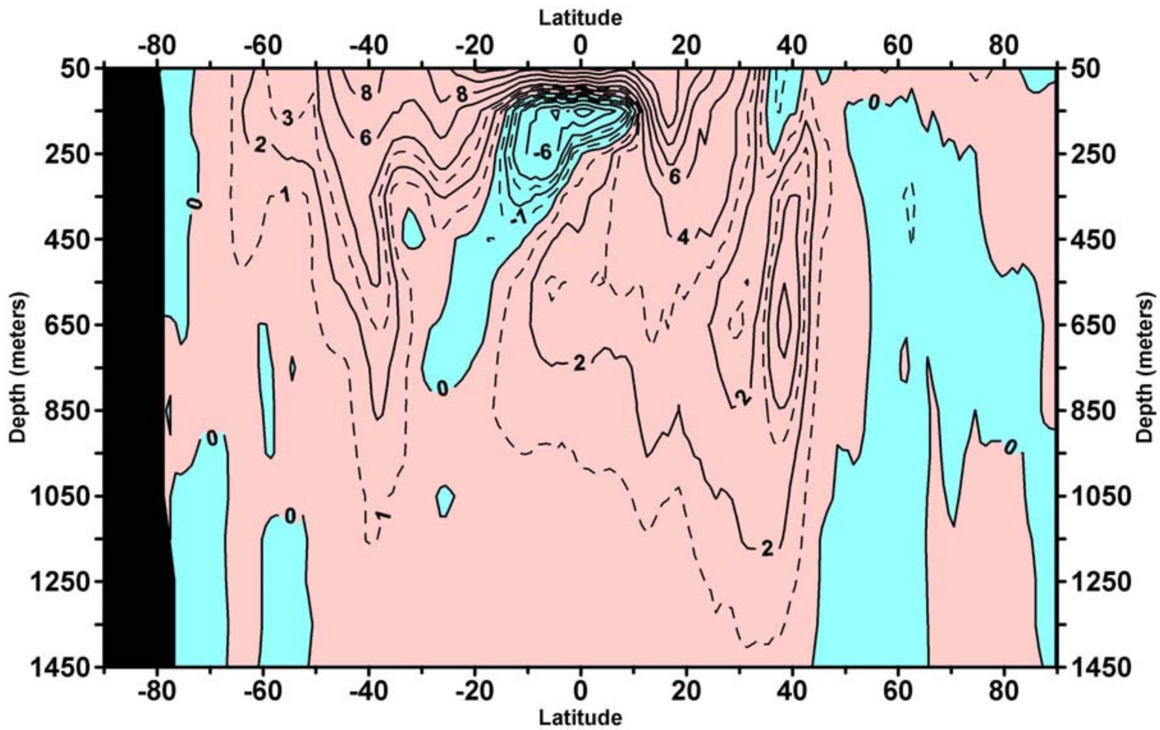

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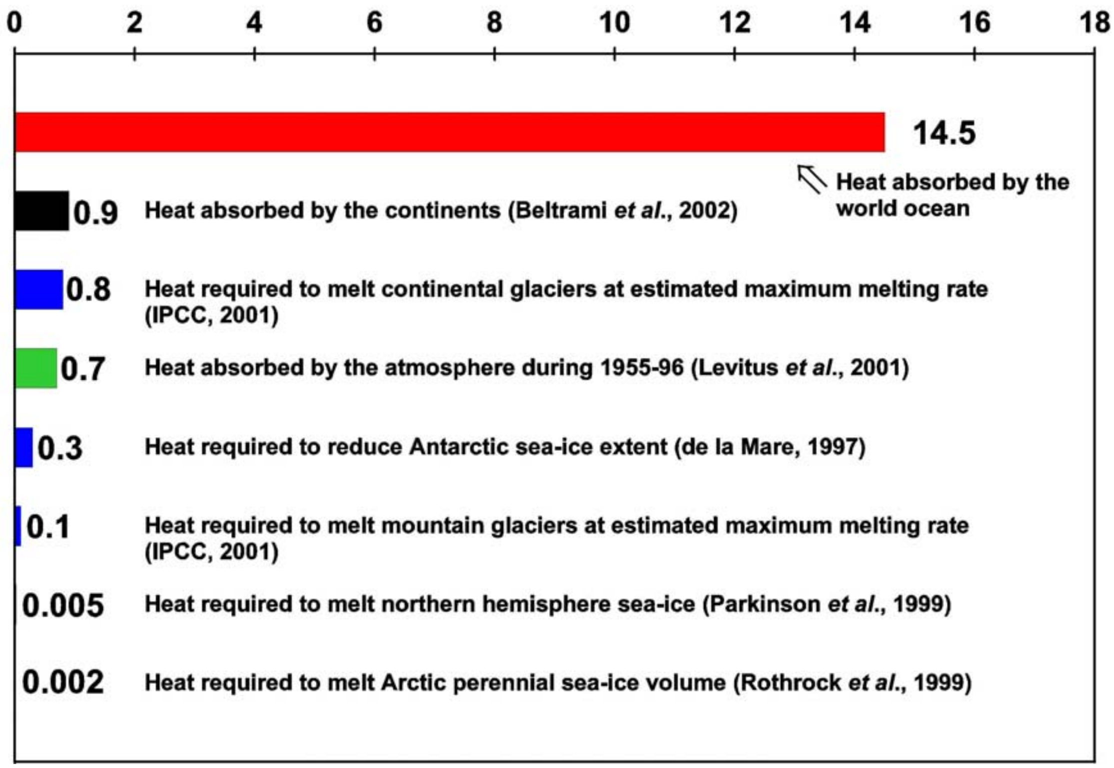

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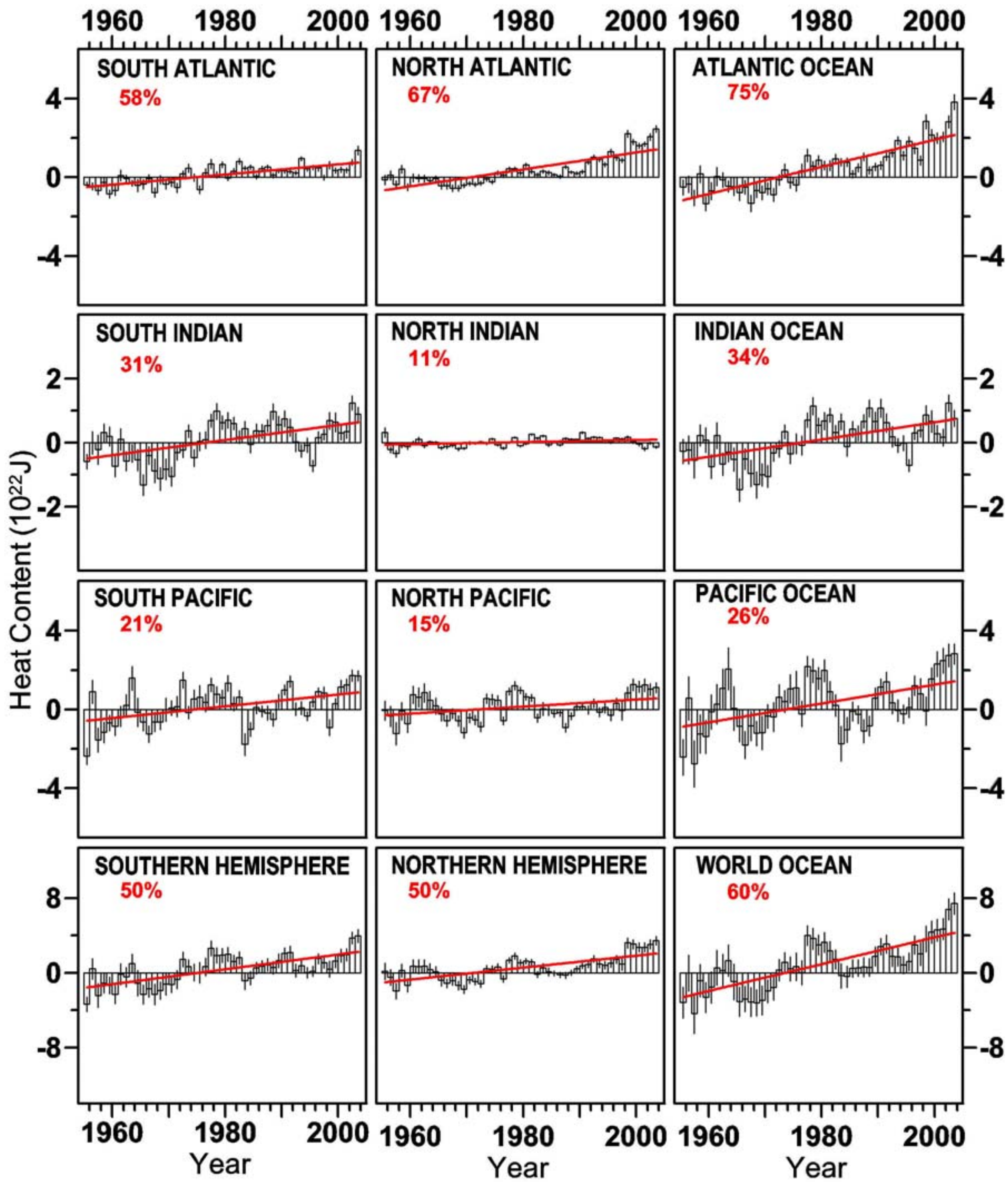

Figure S1.

Time series (1955-2003) of yearly ocean heat content (10E+22 J) for the upper 300 m of the world ocean and individual ocean basins. Vertical lines through each yearly estimate represent plus and minus one standard error of the estimate of heat content. The linear trend is plotted as a red line. The percent variance accounted for by this trend is given in the upper left corner of each panel.

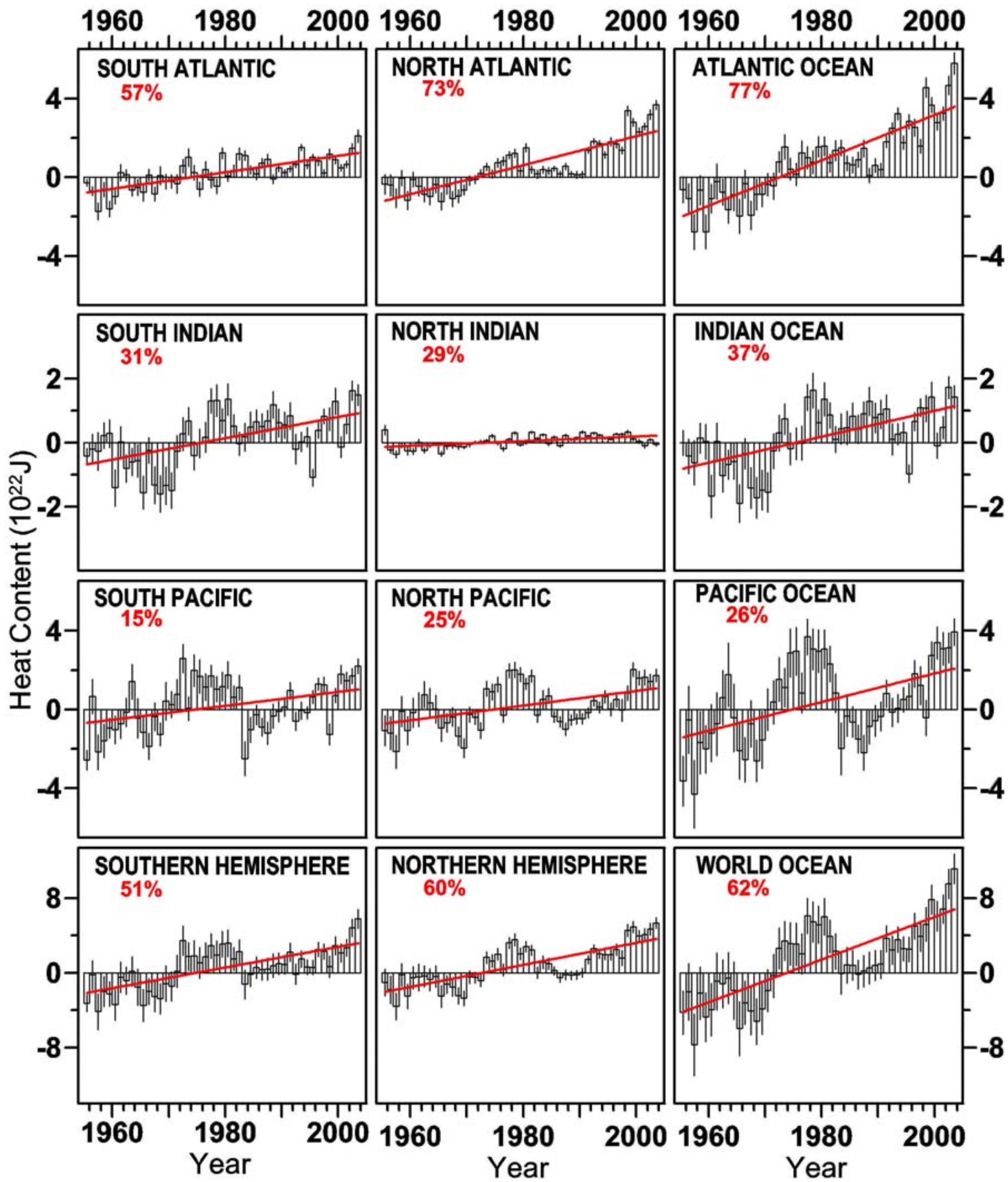

Figure S2.

Time series (1955-2003) of yearly ocean heat content (10E+22 J) for the upper 700 m of the world ocean and individual ocean basins. Vertical lines through each yearly estimate represent plus and minus one standard error of the estimate of heat content. The linear trend is plotted as a red line. The percent variance accounted for by this trend is given in the upper left corner of each panel.

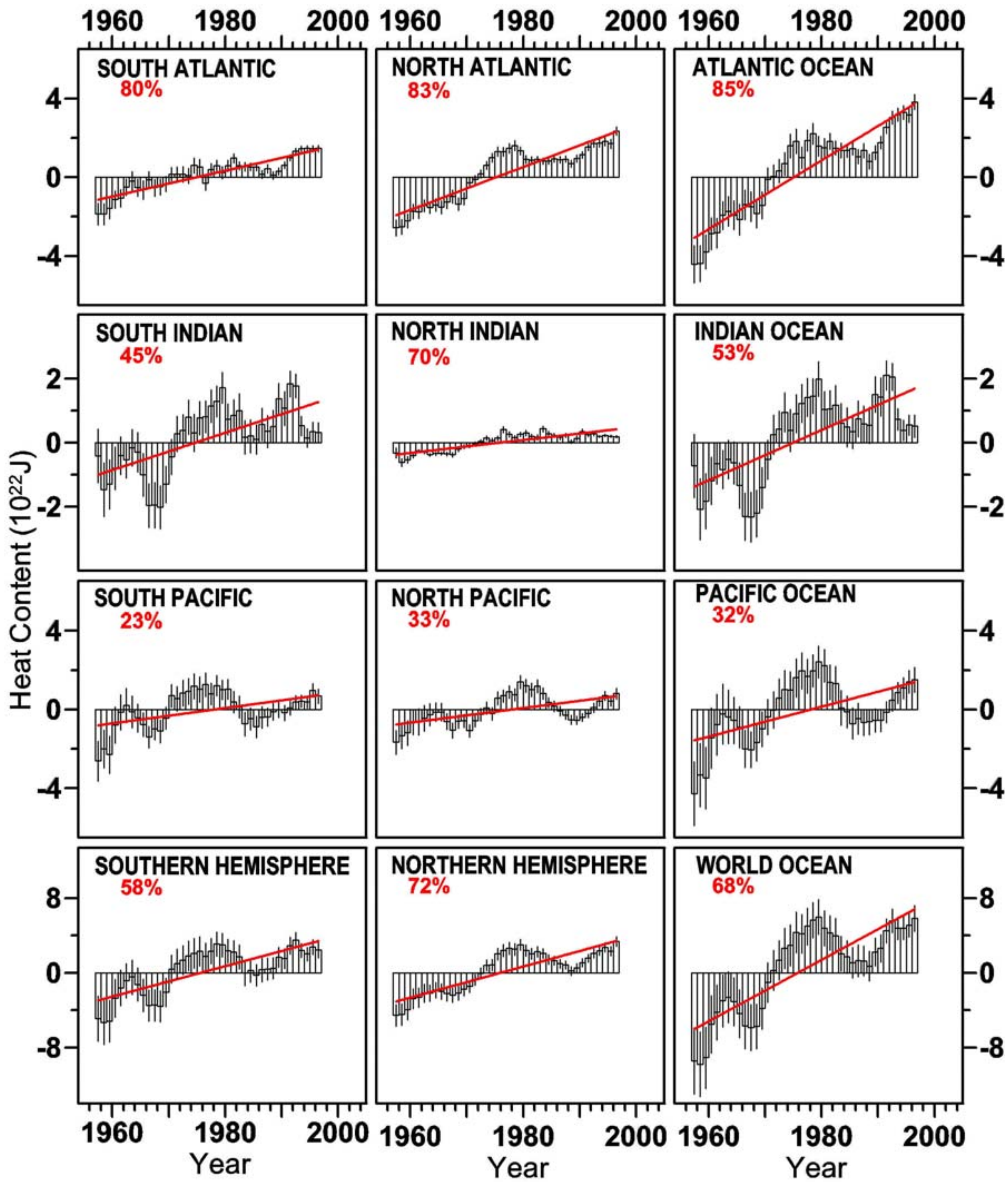

Figure S3

Time series of pentadal (5-year running composites for 1955-59 through 1994-98) ocean heat content (10E+22 J) for the upper 3000 m for each major ocean basin. Vertical lines represent plus and minus one standard error of the five-year mean estimate of heat content. The linear trend is plotted as a red line. The percent variance accounted for by this trend is given in the upper left corner of each panel.

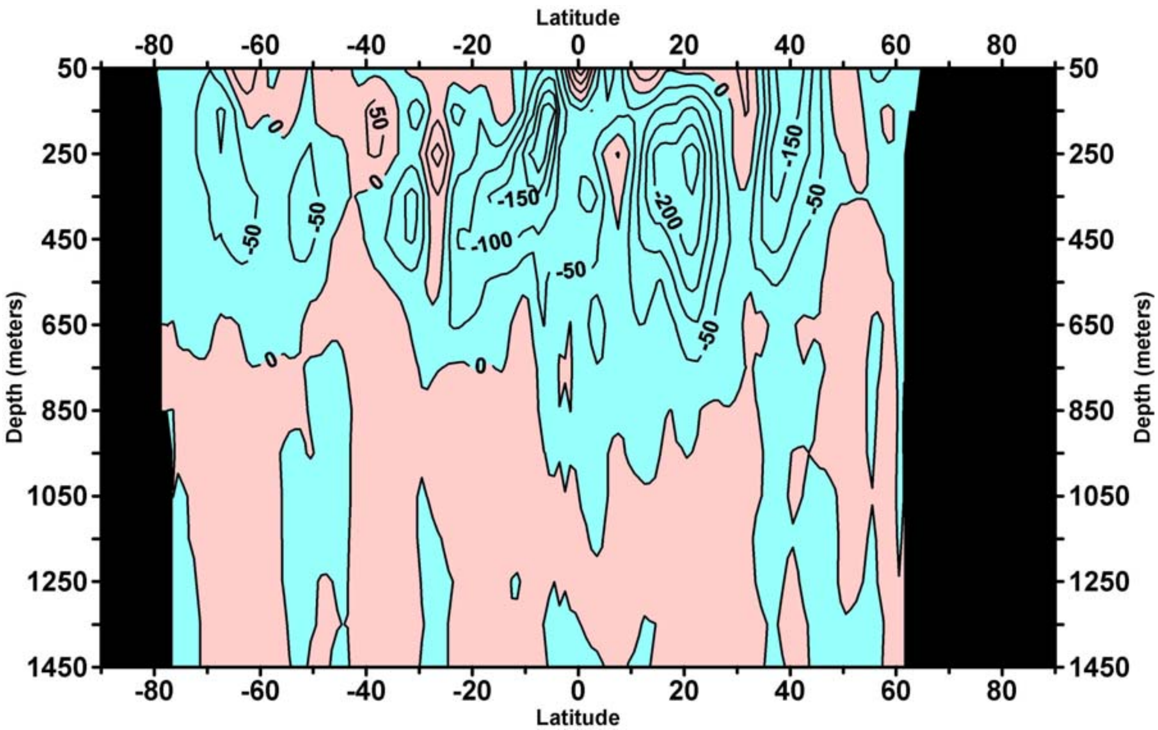

Figure S4

Interpentadal difference (1986-90) minus (1977-81) of zonally integrated heat content (10E+18 J) by 100-m thick layers for the Pacific Ocean. Heat content values are plotted at the midpoint of each 100-m layer.

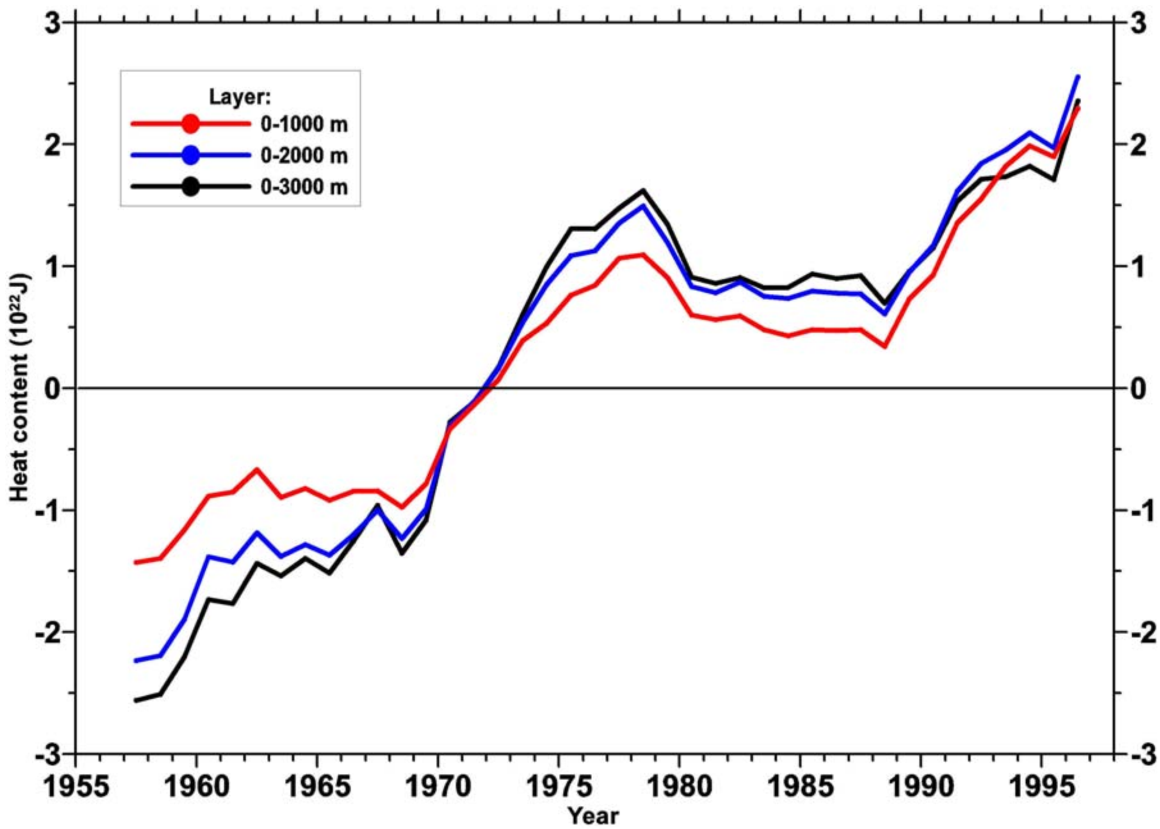

Figure S5

North Atlantic Ocean pentadal heat content (10E+22 J) time series as a function of depth integrated through 1000, 2000, and 3000 m depth.

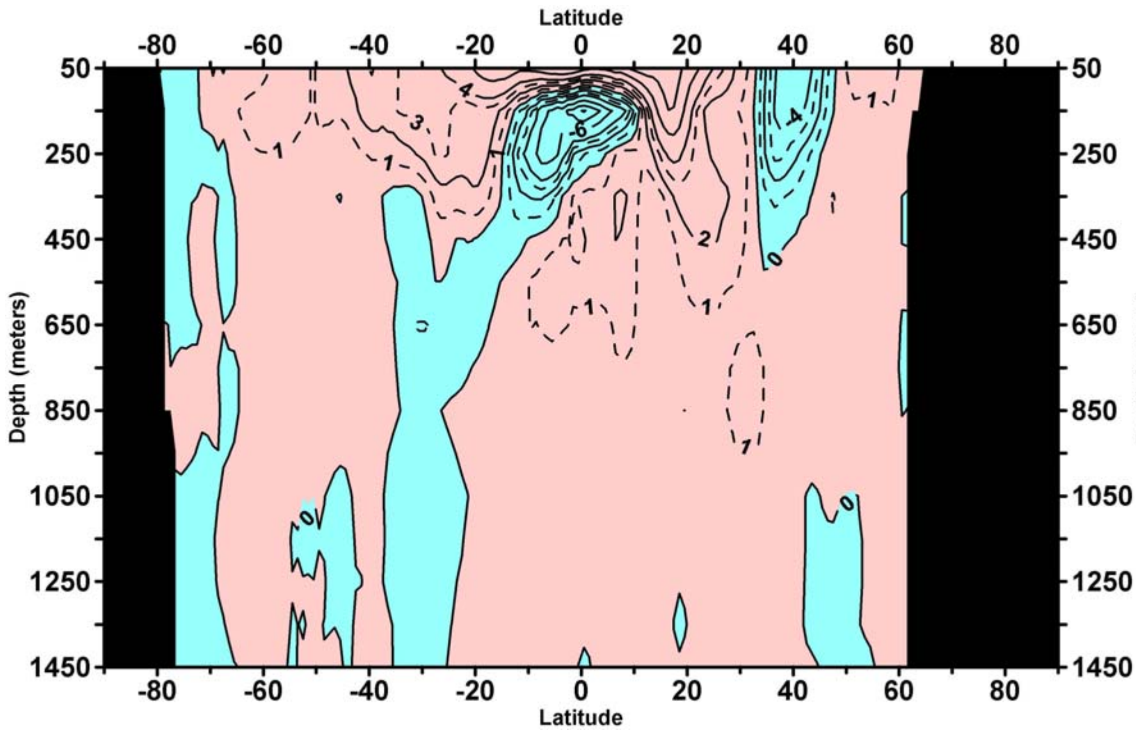

Figure S6

Linear trend of the zonally integrated heat content of the Pacific Ocean for 100-m thick layers. Trend values are plotted at the midpoint of each 100-m layer. Contour interval is 2x10E+18 J/year.

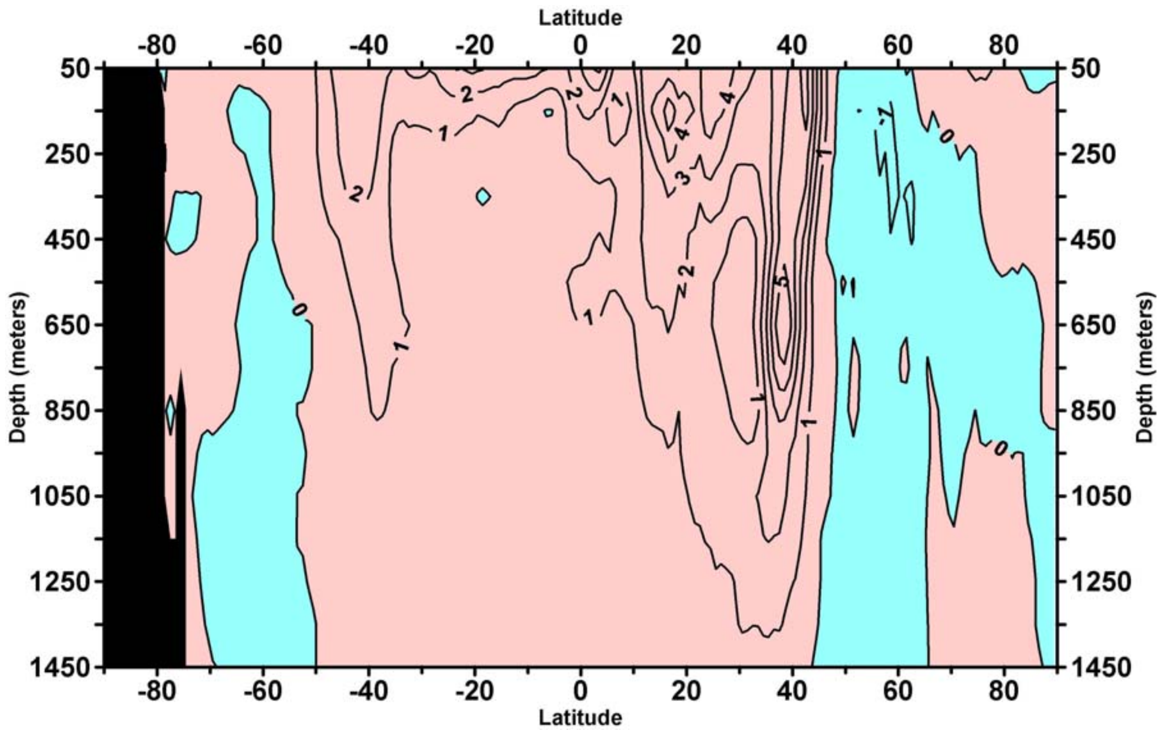

Figure S7

Linear trend of the zonally integrated heat content of the Atlantic Ocean for 100-m thick layers. Trend values are plotted at the midpoint of each 100-m layer. Contour interval is 1x10E+18 J/year.

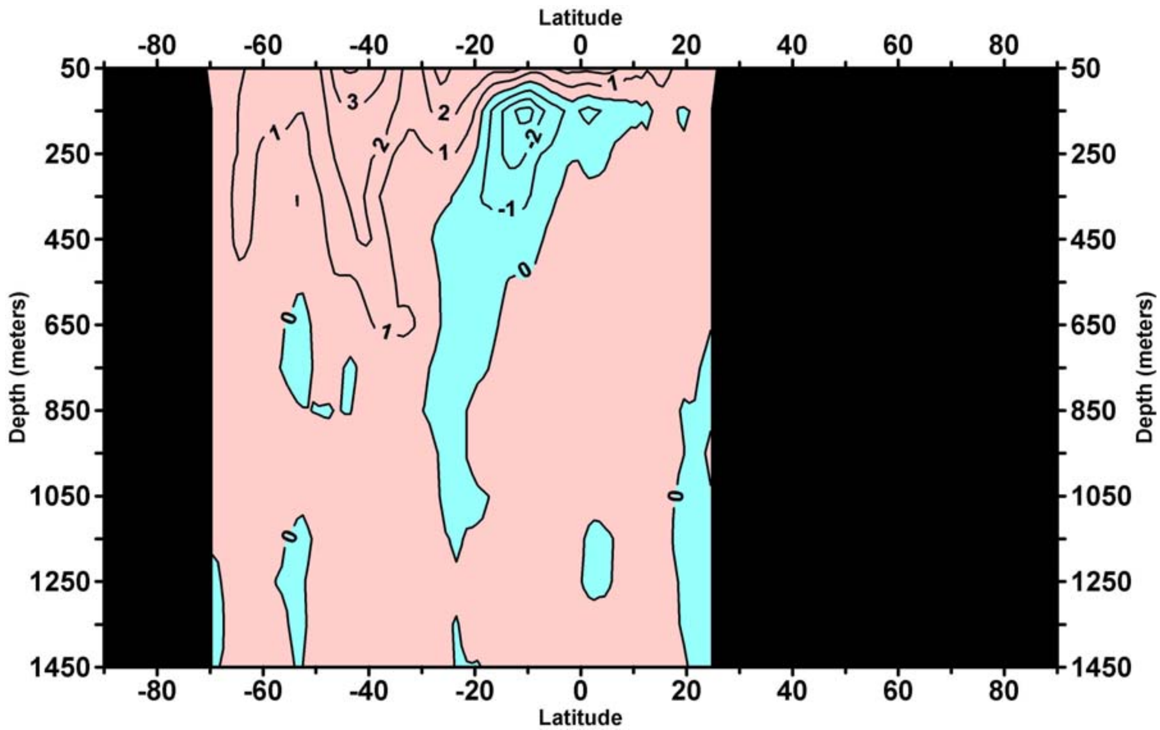

Figure S8

Linear trend of the zonally integrated heat content of the Indian Ocean for 100-m thick layers. Trend values are plotted at the midpoint of each 100-m layer. Contour interval is 1x10E+18 J/year.

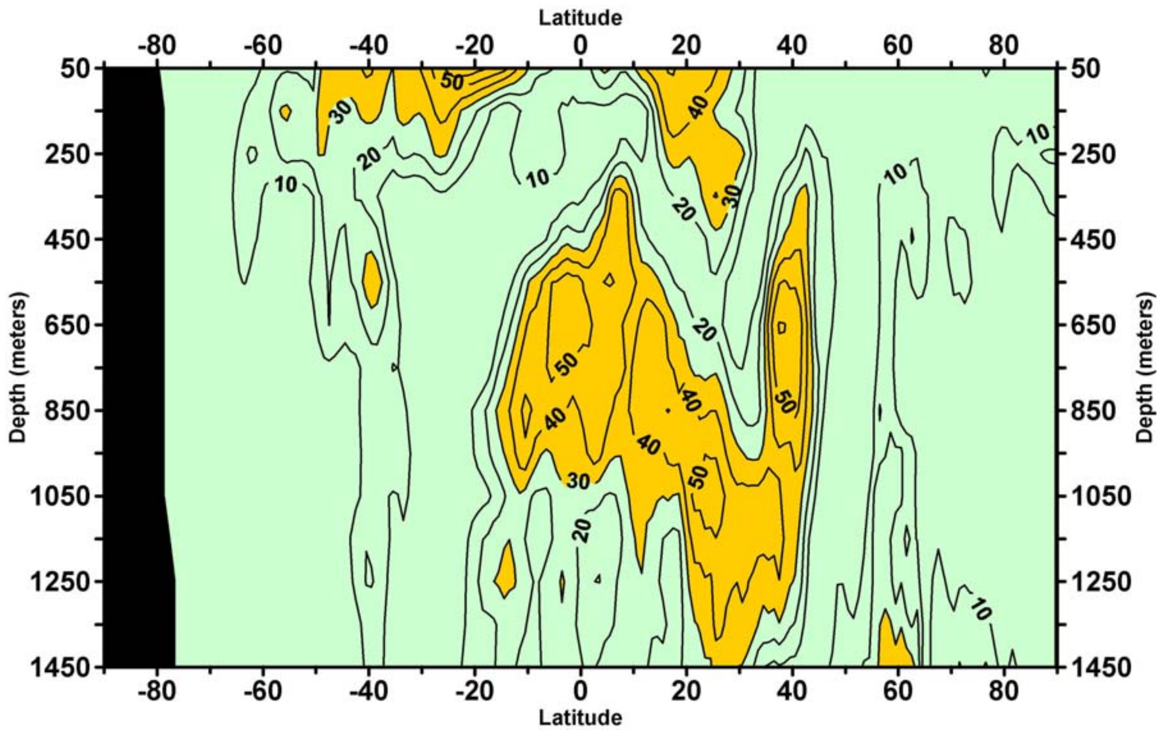

Figure S9

Percent variance accounted for by the linear trend of ocean heat content for the World Ocean shown in Figure 2.

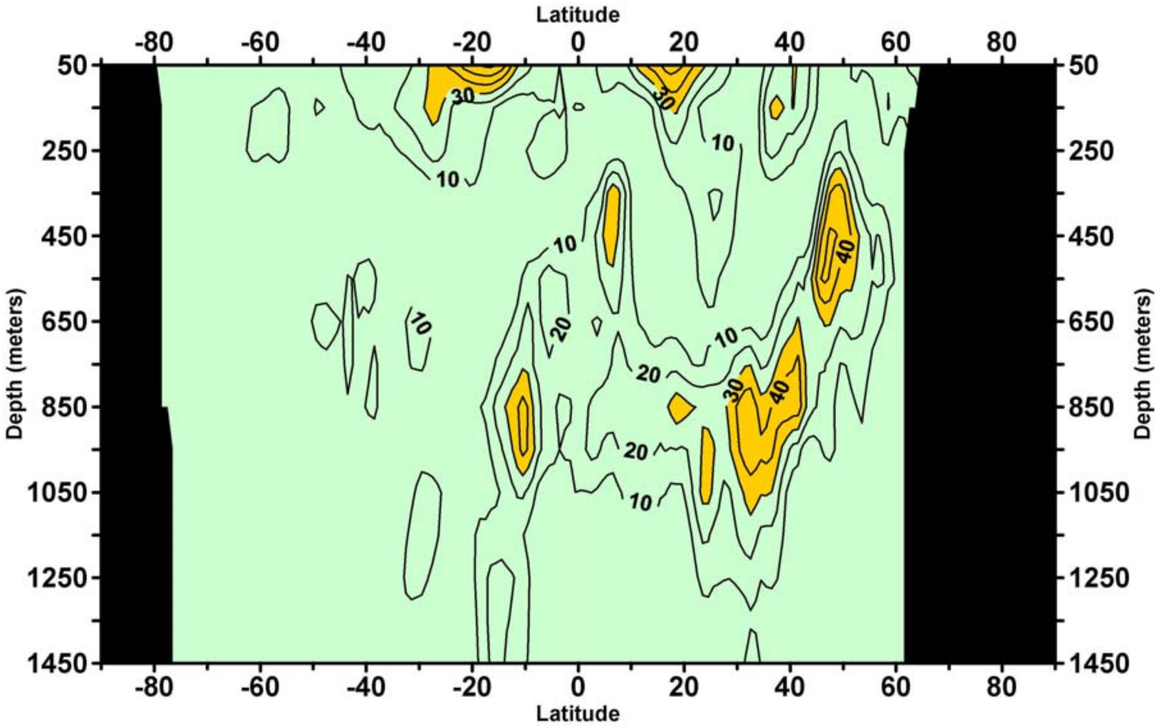

Figure S10

Percent variance accounted for by the linear trend of ocean heat content for the Pacific Ocean shown in Figure S6.

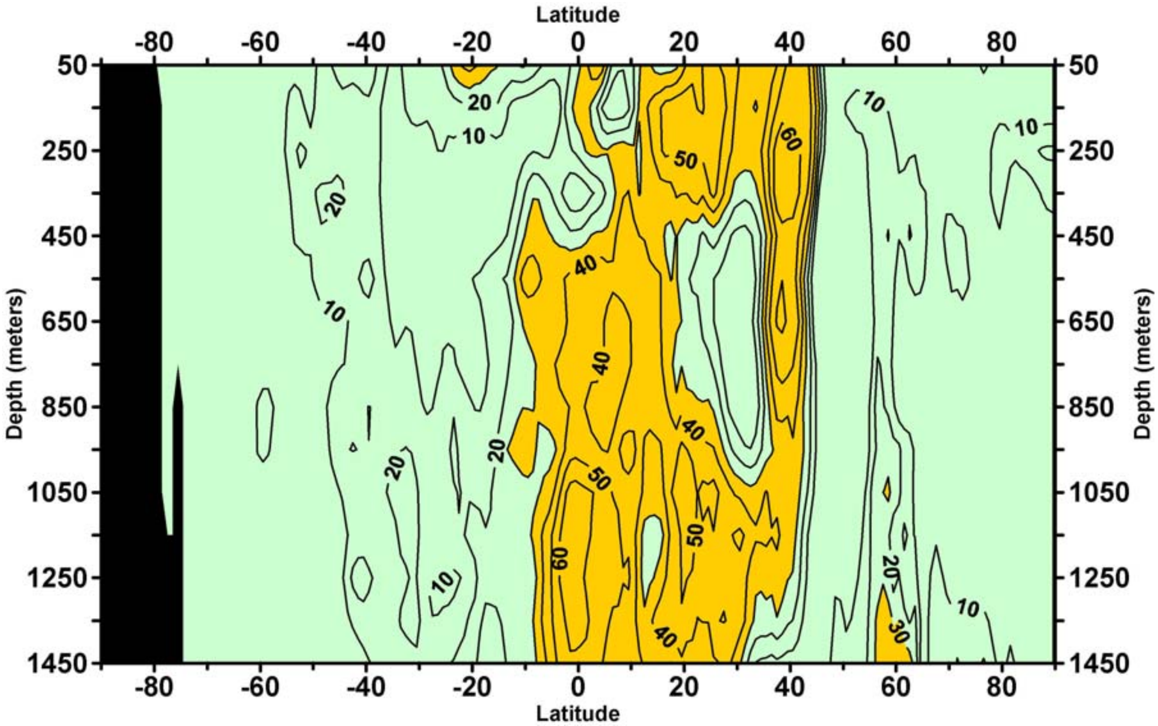

Figure S11

Percent variance accounted for by the linear trend of ocean heat content for the Atlantic Ocean shown in Figure S7.

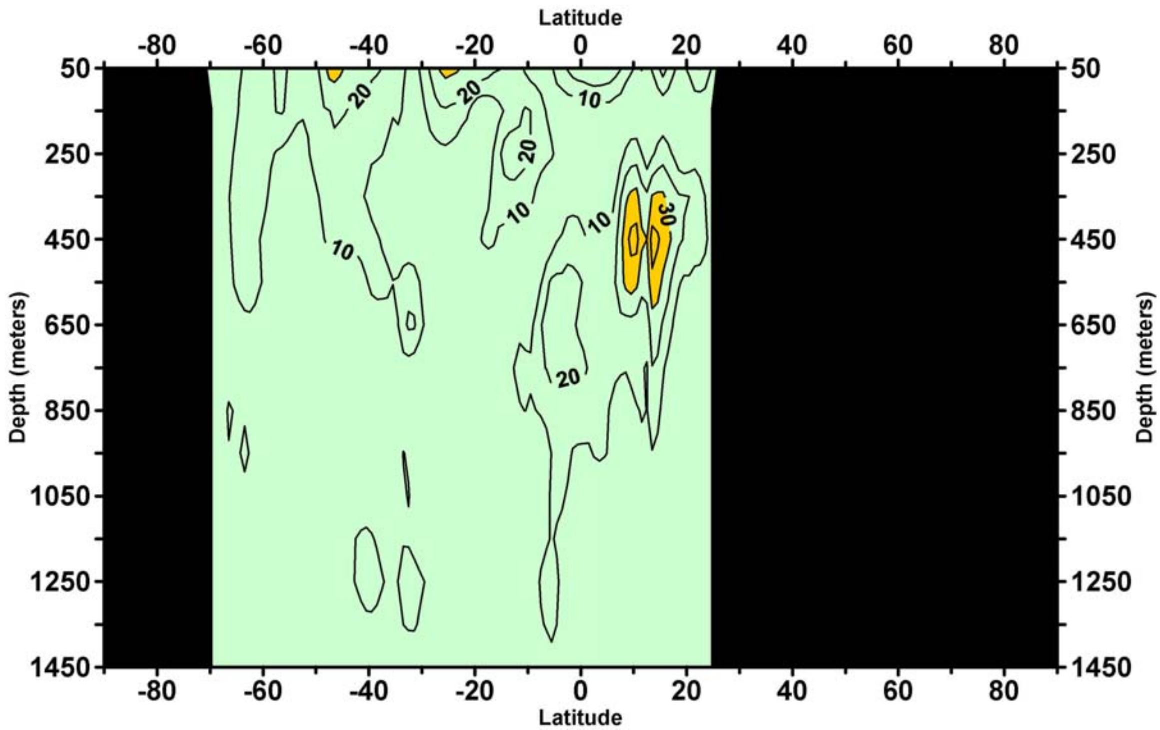

Figure S12

Percent variance accounted for by the linear trend of ocean heat content for the Indian Ocean shown in Figure S8.

Table T1. Change in ocean heat content (10^{22}J) and mean temperature (ºC) as determined by the linear trend for the world ocean and individual basins.

Ocean basin	Change in heat content and mean temperature as determined by linear trend					
	0-300 m (1955-2003)		0-700 m (1955-2003)		0-3000 m (1955-59) to (1994-98)	
	Δ heat content (10^{22}J)	Δ mean temperature (ºC)	Δ heat content (10^{22}J)	Δ mean temperature (ºC)	Δ heat content (10^{22}J)	Δ mean temperature (ºC)
World Ocean	7.029	0.171	11.192	0.118	14.473	0.037
N. Hem.	3.137	0.188	5.781	0.153	7.317	0.048
S. Hem.	3.891	0.159	5.411	0.095	7.156	0.031
Atlantic	3.373	0.297	5.656	0.221	7.683	0.075
N. Atl.	2.109	0.354	3.606	0.274	4.808	0.095
S. Atl.	1.264	0.233	2.050	0.165	2.875	0.056
Pacific	2.343	0.112	3.558	0.073	3.344	0.017
N. Pac.	0.875	0.093	1.826	0.084	1.624	0.018
S. Pac.	1.468	0.127	1.732	0.064	1.721	0.016
Indian	1.319	0.150	1.987	0.098	3.457	0.041
N. Ind.	0.159	0.125	0.358	0.122	0.896	0.076
S. Ind.	1.159	0.154	1.629	0.093	2.561	0.035

Table T2. Linear trend of ocean heat content (10^{22}Jyr^{-1}) and heat storage (Wm^{-2})(per unit area of ocean surface) for the world ocean and individual basins.

Ocean basin	0-300 m (1955-2003)		0-700 m (1955-2003)		0-3000 m (1955-59) to (1994-1998)	
	Heat content trend (10^{22}Jyr^{-1})	Heat storage (Wm^{-2})	Heat content trend (10^{22}Jyr^{-1})	Heat storage (Wm^{-2})	Heat content trend (10^{22}Jyr^{-1})	Heat storage (Wm^{-2})
World Ocean	0.143	0.131	0.228	0.209	0.329	0.301
N. Hem.	0.064	0.142	0.118	0.262	0.166	0.369
S. Hem.	0.079	0.124	0.110	0.172	0.163	0.253
Atlantic	0.069	0.223	0.115	0.374	0.175	0.566
N. Atl.	0.043	0.260	0.074	0.444	0.109	0.659
S. Atl.	0.026	0.181	0.042	0.294	0.065	0.458
Pacific	0.048	0.086	0.073	0.131	0.076	0.137
N. Pac.	0.018	0.072	0.037	0.149	0.037	0.148
S. Pac.	0.030	0.098	0.035	0.116	0.039	0.128
Indian	0.027	0.117	0.041	0.177	0.079	0.342
N. Ind.	0.003	0.096	0.007	0.215	0.020	0.598
S. Ind.	0.024	0.121	0.033	0.170	0.058	0.298