On the variability of dissolved oxygen and apparent oxygen utilization content for the upper world ocean: 1955 to 1998

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[1] We document variability in O_2, AOU, and heat content in the top 100 m of the world ocean (70°S–70°N) between 1955 and 1998 using observational data. The lowest O_2 (highest AOU) content in the late-1950s are followed by high content in the mid-1980s and by low content in the late-1990s. The O_2 and AOU content variability is characterized by relatively small linear trends superimposed on large decadal-scale fluctuations. The largest O_2 content changes occur in the Northern Hemisphere (NH). The NH exhibits a negative linear trend in O_2 content of ~ -30 Tmol per decade between 1983 and 1998 and a positive linear trend of ~ 6 Tmol per decade between 1955 and 1998 (1 Tmol = 10^{12} mol). The trends in O_2, AOU, and heat content are sensitive to the time frame of the measurements. The results indicate that a constant upper-ocean O_2 content inventory should not be assumed on decadal time-scales. **Citation:** Garcia, H. E., T. P. Boyer, S. Levitus, R. A. Locarnini, and J. Antonov (2005), On the variability of dissolved oxygen and apparent oxygen utilization content for the upper world ocean: 1955 to 1998, *Geophys. Res. Lett.*, *32*, L09604, doi:10.1029/2004GL022286.

1. Introduction

[2] A constant oceanic O_2 inventory implies a gross long-term balance between changes in O_2 production and respiration, the O_2 solubility pump, and the air-sea O_2 flux. However, evaluation of oceanographic data collected in the past few decades in different geographic locations of the world ocean have documented inter-annual to decadal time-scale decreases or increases in O_2 or Apparent Oxygen Utilization (AOU) of intermediate waters [e.g., *Joos et al.*, 2003; *Keeling and Garcia*, 2002]. Model simulation studies predict sea-to-air O_2 outgassing due to the effect of increase vertical stratification in recent decades due to ocean warming [*Sarmiento et al.*, 1998; *Matear et al.*, 2000; *Plattner et al.*, 2002; *Bopp et al.*, 2002]. Documenting changes in the global O_2 inventory on inter-annual to decadal-scale time-scales has important implications for understanding climate change. However, it has been difficult to quantify decadal-time scale variability in the global ocean O_2 content because there have been no available data compilations on these spatial scales.

[3] We present a description of the observation-based decadal-scale variability in O_2, AOU, and heat content anomaly in the top 100 m of the world ocean between 70°S–70°N for the 1955 through 1998 period. This layer was chosen because it is most directly affected by the direct exchange between the atmosphere and the ocean. We show that the basin-scale content variability in O_2, AOU, and heat in this layer is characterized by relatively small linear trends superimposed on large decadal fluctuations. The magnitudes of the O_2 and AOU trends are dependent on the starting and ending time periods chosen as reference end-points indicating that the trends for one time period should not be extrapolated to other time periods. The observations indicate also that there is no obvious O_2-to-heat content relation which unambiguously relates the trends in O_2 content to the trends in heat content for all time periods. We hypothesize that both physical and biochemical processes which affect the upper-ocean O_2 content vary in time and space.

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2. Methods

[4] Objectively analyzed monthly climatologies of O_2 and AOU were prepared using quality-controlled oceanographic data from the *World Ocean Database 2001* (*WOD01*) [*Locarnini et al.*, 2002a, 2002b] at standard depths between 0–100 m and on a 1° latitude/longitude grid (70°S–70°N). AOU is defined as the O_2 solubility (O_S) in seawater minus the measured O_2 concentration. We carried out quality control on the O_2 fields to identify questionable values resulting in a data set of about 0.53 million profiles. Five-year (pentadal) running mean anomaly fields were then calculated between 1955–59 and 1994–98. To remove the annual cycle, the O_2 and AOU anomaly fields correspond to each observed value minus the climatological monthly value. This process was carried out at 7 standard depths (0, 10, 20, 30, 50, 75 and 100 m). The O_2 and AOU anomalies in each grid box and in each pentad were then averaged at each standard depth and then objectively analyzed. Grid boxes with no data were assigned a value of zero as the first-guess field in the objective analysis. The analysis was repeated 3 times, each time with a diminishing radius of influence (R_i) around each grid point of 888, 666, and 444 km, respectively. The number (±1 SD) of grid boxes with ≥ 3 mean O_2 anomaly values within 444 km of each grid box is 70 ± 9% (79 ± 9% in the Northern Hemisphere (NH) and 65 ± 11% in the Southern Hemisphere (SH)). The South Pacific and the North Atlantic have respectively, the smallest (61 ± 14%) and largest (88 ± 9%) number of grid boxes with ≥ 3 mean anomalies within the smallest R_i. The largest source of uncertainty is O_2 data coverage. To quantify the quality of the O_2 data, we calculated the standard error (SE) of the mean of all data collected in each grid box for the 1958–62, 1973–77, and 1993–97 periods between the surface and 100 m depth (Figure 1). These periods represent

typical O_2 samples collected during the late-1950s International Geophysical Year, the mid-1970s Geochemical Ocean Sections Study, and the early-1990s World Ocean Circulation Experiment. The SE range for all data ($\geq$30 observations) in these time periods is $\sim\pm1-3$ μmol kg^{-1}. The mean SE for all O_2 data (±2 μmol kg^{-1}) is at the high-end of the precision for individual observations ($\pm1-2$ μmol kg^{-1}) [*Saunders*, 1986; *Garcia et al.*, 1998].

3. Results and Discussion

[5] To quantify O_2 and AOU variability, we calculated linear least-squares trends to 1° latitude band zonal averages (70°S–70°N) of the 1955–59 through 1994–98 pentads as a function of depth (0–100 m). The spatial patterns of the trends show a significant increase (positive trend) in O_2 from the surface to ~50 m depth except between ~50°–60°N (Figure 2a). Below ~50 m depth, the zonal mean trends exhibit regions of O_2 decrease (60°–70°S, 20°S–10°N, 50–60°N) and increase (60°–20°S, 10°–50°N, >60°N). A striking feature is the large-scale spatial uniformity of the O_2 trends as a function of depth. The variance accounted for by the trends is >20% at most latitudes in the upper 50 m depth suggesting that O_2 variability is essentially surface forced. The trends are larger in the NH than in the SH. We note that the O_2 trends could only be measurable on pentadal time-scales given the precision of the data (±2 μmol kg^{-1}). The distribution of trends for AOU is roughly reversed from that of O_2 (Figures 2b). By definition, AOU removes the effect of O_S which is primarily driven by temperature. The distribution of the temperature trends indicate warming throughout most of the water column at most latitudes except poleward of ~35°N, between 10°S and 10°N, and poleward of ~65°S (Figure 2c). The largest positive temperature trends (>0.01°C yr^{-1}) are found in the tropics (20°S–20°N) at depths <60 m.

[6] To quantify the oceanic O_2 and AOU evolution, we computed volume integrals of the objectively analyzed anomalies of the 0–100 m layer in each hemisphere for the 1955–59 through 1994–98 pentads (Figure 3). We refer to these values as O_2 and AOU content. The O_2 and AOU content variability is characterized by small trends superimposed on large decadal-scale variability. The lowest O_2 (highest AOU) contents in the late-1950s are followed by high contents in the mid-1980s and by low contents in the late-1990s. The variance accounted for by the O_2 and AOU trends in both hemispheres is small (<23%). While the content changes in both hemispheres each exhibit similar phasing (positive O_2 trend and negative AOU trend), the magnitudes of the trends and the percent variance accounted for by the trends are larger in the NH than in the SH (Figures 3a–3b). This inter-hemispheric North-to-South gradient could in part be due to the uneven data coverage between hemispheres. Our results miss O_2 source or sink processes in data sparse regions >70° latitude. The O_2 content anomaly decadal variability is large, particularly in the NH. For comparison, the NH peak-to-peak O_2 content anomaly (~0.5×10^{20} μmol) is about one quarter of the climatological NH peak-to-peak monthly O_2 content anomaly (~2×10^{20} μmol) [*Garcia et al.*, 2005] and corresponds to an O_2 concentration of ~4 μmol kg^{-1} if spread evenly over the top 100 m of the NH ocean area (~1.4×10^{14} m^2). The AOU content variability follows an approximately inverse relation to that of the O_2 content. Figure 3c shows heat content changes for the upper 100 m layer based on the analysis of *Levitus et al.* [2005]. The major basins exhibit similar O_2 and AOU content patterns suggesting common processes (Figures S1–S2[1]).

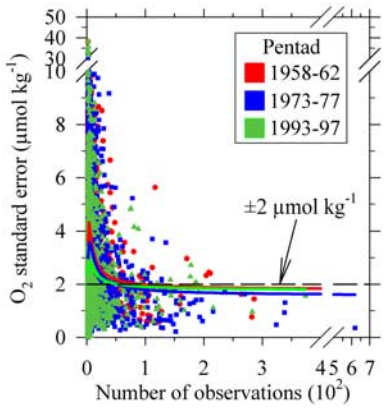

Figure 1. Comparison of the standard error (SE) of the mean of all WOD01 measurements collected in each 1° grid box for the 1958–62, 1973–77, and 1993–97 periods between the surface and 100 m depth. The solid lines represent fits to the SE for each period.

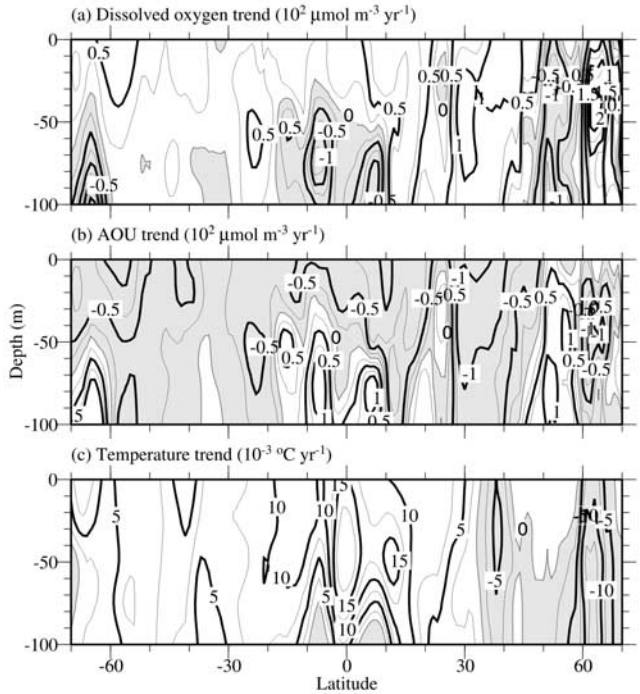

Figure 2. Linear trends (1955–59 through 1994–98) of the zonally averaged pentadal (a) oxygen, (b) apparent oxygen utilization (aou), and (c) temperature anomalies. Shading denotes negative trends. The contour intervals are 0.25×10^2 μmol m^{-3} yr^{-1} for O_2 and AOU, and 0.2×10^{-3} °C yr^{-1} for temperature.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL022286.

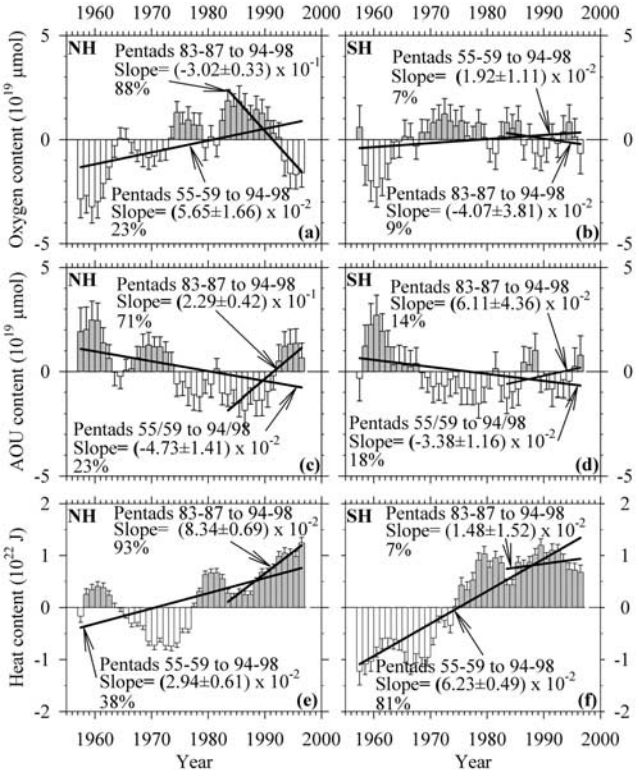

Figure 3. Variability in oxygen (top panel), apparent oxygen utilization (middle panel), and heat (bottom panel) content of the 0–100 m layer in the Northern (NH) and Southern (SH) Hemispheres (1955–59 to 1994–98). The 1957–61 to 1986–90 grand mean content has been removed. The vertical lines about each pentad value represent ±1 standard errors. Shading denotes positive contents. The black lines are linear least-squares fits for the 1955–59 to 1994–98 and for the 1983–87 to 1994–98 periods.

[7] Next we describe variability of the relation between heat and O_2 contents to gain insight into the relative role of physical and biological forcing. It is difficult to separate variability in terms of biological and physical processes considering the tight coupling of the mechanisms that affect O_2. Upper-ocean warming, for example, is expected to result in (1) decreases in O_2 content by sea-to-air outgassing (solubility pump) and (2) increases in vertical stratification which could reduce the input of relatively nutrient-rich deep waters to the euphotic layer and thus lowering biologically-mediated O_2 production [*Sarmiento et al.*, 1998]. In the absence of biological variability, a relation between O_2 decreases and heat increases in the thermocline layer should reflect the release of O_2 and uptake of heat at the air-sea boundary in a more or less constant O_2-to-heat ratio (OH_r) of ~ -6 nmol of O_2 per Joule of heat (1 mol = 10^9 nmol); or ~ -22 µmol kg^{-1} °C^{-1} [*Sarmiento et al.*, 1998; *Bopp et al.*, 2002]. OH_r's have been used to estimate ocean O_2 outgassing based on ocean warming rate estimates [*Plattner et al.*, 2002; *Keeling and Garcia*, 2002]. How different ocean warming rates can affect OH_r in surface and thermocline waters is unclear. *Levitus et al.* [2005] indicate that the largest linear increases in world ocean heat content (0–3000 m) between 1955 and 1998 occur within the thermocline in the upper 700 m depth layer.

[8] As shown in Figure 3, no overall positive or negative correlation between O_2 and heat content anomaly for all time periods is apparent from the estimates. For example, the NH exhibits a decrease in O_2 (-3.0×10^{18} µmol yr^{-1}) and an increase in heat (8.3×10^{20} J yr^{-1}; $\sim$0.015 °C yr^{-1}) content between 1983–87 and 1994–98 indicating a negative OH_r of ~ -3.6 nmol J^{-1} (-14 µmol kg^{-1} °C^{-1}). Our -3.6 nmol J^{-1} ratio is smaller by about half than model predicted values (-6.1 to -6.6 nmol J^{-1}) [*Sarmiento et al.*, 1998; *Bopp et al.*, 2002] but in agreement with global surface O_2 flux/heat flux ratios (-1 to -5 nmol J^{-1}) [*Garcia and Keeling*, 2001]. This raises the possibility that OH_r in the thermocline are larger than those near the surface. Nevertheless, the observed decrease in O_2 content between 1983–87 and 1994–98 is consistent with thermally-mediated sea-to-air O_2 outgassing due to ocean warming [*Matear et al.*, 2000; *Plattner et al.*, 2002; *Keeling and Garcia*, 2002]. The O_2 content trends as a function of depth for this period exhibit consistent spatial patterns with the largest negative trends in the NH (Figure S3). However, for the 1955–59 to 1994–98 period the NH shows increases in both O_2 ($\sim 0.6 \times 10^{18}$ µmol yr^{-1}) and heat ($\sim 2.9 \times 10^{20}$ J yr^{-1}; $\sim$0.005 °C yr^{-1}) content indicating a positive OH_r of $\sim$1.9 nmol J^{-1} (8 µmol kg^{-1} °C^{-1}). This suggests that the O_2 content trend between 1955–59 and 1994–98 is not primarily thermally-mediated. For comparison, the SH shows OH_r smaller than but of the same sign to those of the NH: -2.8 nmol J^{-1} (-11 µmol kg^{-1} °C^{-1}) and 0.3 nmol J^{-1} (1.2 µmol kg^{-1} °C^{-1}) for the 1983–87 to 1994–98 and the 1955–59 to 1994–98 periods. The results show that projections of variability in O_2 content based on heat content rates alone for one period should not be extrapolated to all time periods.

[9] Assuming that the O_2 content variability is all biologically mediated, the change in carbon production can be estimated by multiplying the O_2 (or AOU) trends by a constant oxidative molar ratio between carbon and oxygen of 106C:$-$138O_2 [*Redfield et al.*, 1963] and by the timeframe of observations. For example, the NH O_2 trend for the 1983–87 to 1994–98 is equivalent to $\sim$0.5 Pg C (1 Pg = 10^{15} g). This carbon change is equivalent to $\sim$1% of primary production ($\sim$48 Pg C yr^{-1}) [*Behrenfeld and Falkowski*, 1997] and 3–7% of new production (7–16 Pg C yr^{-1}) [*Falkowski et al.*, 1998; *Chavez and Toggweiler*, 1995] global ocean rate estimates. This suggests the possibility that small changes in net annual biological O_2 production could account for some of the variability in O_2 (or AOU). However, increases in biological O_2 production do not necessarily lead to a net increase of the O_2 content of the euphotic layer. This is because excess biologically O_2 produced could be outgassed into the atmosphere, respired, or exported to deeper waters without necessarily changing the O_2 content of the euphotic layer on time-scales shorter than examined in this study. Global oceanic biological production has been shown to be spatially and temporally variable [*Field et al.*, 1998]. For example, *Gregg et al.* [2003] reported that global ocean annual primary production (PP) has declined by $\sim$6% from the early-1980s to 2002 based on satellite chlorophyll data. Such a decrease in

PP is qualitatively consistent with our estimated decrease in O_2 content between 1983 and 1998. Variability in coastal upwelling systems also could be an important source or sink for O_2 content. Quantitative evidence is required to examine the long-term net effect of variability in biological production on O_2 and AOU content in the water column.

4. Summary

[10] By means of independent analysis of historical oceanographic data, we have quantified decadal-scale variability in O_2, AOU, and heat content in the top 100 m of the world ocean between 70°S and 70°N for the 1955 through 1998 period. The observations illustrate that globally and temporally the upper ocean exhibits strong sinks and sources of O_2 during the observational time domain. Significant increases in O_2 (decreases in AOU) are observed from the surface to about 50 m depth for the 44-year data record. The O_2 and AOU content variability is characterized by relatively small linear trends superimposed on large decadal-scale fluctuations. The lowest O_2 (highest AOU) contents in the late-1950s are followed by high contents in the mid-1980s and by low contents in the late-1990s. We show that O_2 trends for one time period should not be extrapolated to other time periods because the trends depend on the time frame of the measurements. Similarly, the comparison of repeat hydrographic sections collected several years apart could lead to erroneous conclusions regarding basin-scale O_2 content trends. Globally distributed in-situ measurements are required. Our results show that there is no consistent O_2-to-heat relation which satisfactorily explains the O_2 (or AOU) content changes for all time periods. The results also indicate that a constant oceanic O_2 content inventory should not be assumed on inter-annual to decadal time-scales. We believe that the variability in O_2 content results from coupling of physical and biological process acting on different time and spatial scales. Additional historical O_2 data and the acquisition of future data including ARGO floats equipped with O_2 sensors [*Emerson et al.*, 2002; *Körtzinger et al.*, 2004] will help provide observational constraints on the nature of and the co-variability between O_2, AOU, and heat content changes.

[11] Data distribution maps and objectively analyzed anomaly fields by pentadal periods for O_2, AOU, and heat are available at http://www.nodc.noaa.gov/ocl/indprod.html.

[12] **Acknowledgments.** We thank the scientists and data centers for their contributions to the World Data Center system which has allowed us to compile the database used in this work. We thank our colleagues at the Ocean Climate Laboratory for their work in constructing the *World Ocean Database* which made this work possible. We are grateful to two anonymous reviewers for constructive comments. The views, opinions, and findings contained in this work 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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On the variability of dissolved oxygen and apparent oxygen utilization content for the upper world ocean: 1955 to 1998
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Geophysical Research Letters

Introduction: This supplementary material contains three figures (2004GL022286-FigureS1.eps, 2004GL022286-FigureS2.eps, and 2004GL022286-FigureS3.eps). These figures provide information on variability in the spatially integrated oxygen and Apparent Oxygen Utilization content anomalies based on the World Ocean Atlas 2001 (WOA01). For more information about the WOA01, see http://www.nodc.noaa.gov/OCL/indprod.html.

2004GL022286-FigureS1 figure caption:
Figure S1. Variability in oxygen content of the 0-100 m layer for major ocean basins (1957-61 to 1994-98). The 1957-61 to 1986-90 grand mean content has been removed. The vertical lines about each pentad value represent ±1 standard errors. The red lines are linear least-squares fits for the 1957-61 to 1994-98 period.

2004GL022286-FigureS2 figure caption:
Figure S2. Variability in Apparent Oxygen Utilization content of the 0-100 m layer for major ocean basins (1957-61 to 1994-98). The 1957-61 to 1986-90 grand mean content has been removed. The vertical lines about each pentad value represent ±1 standard errors. The red lines are linear least-squares fits for the 1957-61 to 1994-98 period.

2004GL022286-FigureS3 figure caption:
Figure S3. Linear trends (1983-87 through 1994-98) of the zonally averaged pentadal (a) O2, (b) apparent oxygen utilization (AOU), and (c) temperature anomalies. Shading denotes negative trends. The contour intervals are 2 x 10^2 micromol per cubic meter per year for O2 and AOU, and 10 x 10^-3 °C per year for temperature.

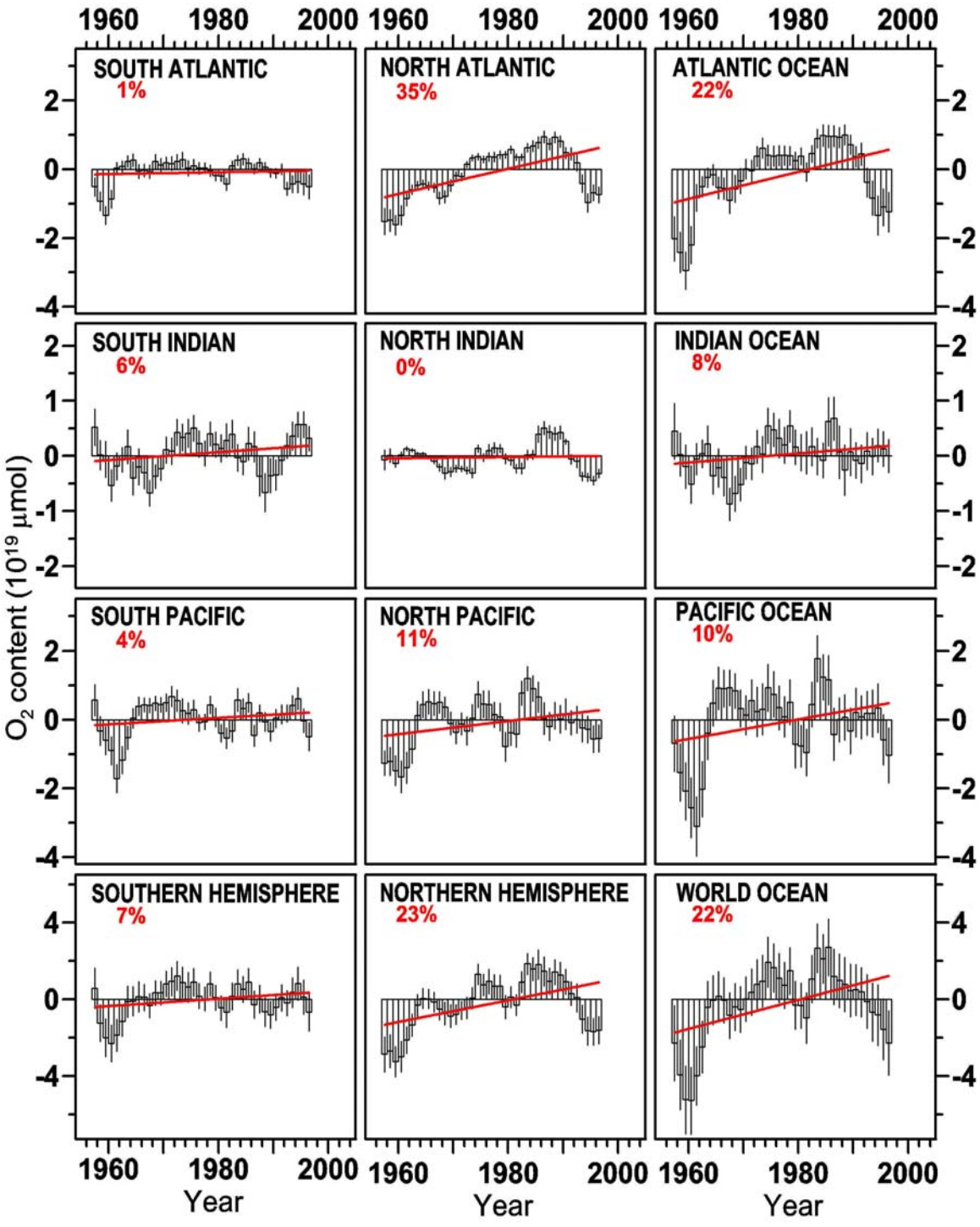

Figure S1. Variability in oxygen content of the 0-100 m depth layer for major ocean basins (1957-61 to 1994-98). The 1957-61 to 1986-90 grand mean content has been removed. The vertical lines about each pentad value represent ±1 standard errors. The red lines are linear least-squares fits for the 1957-61 to 1994-98 period.

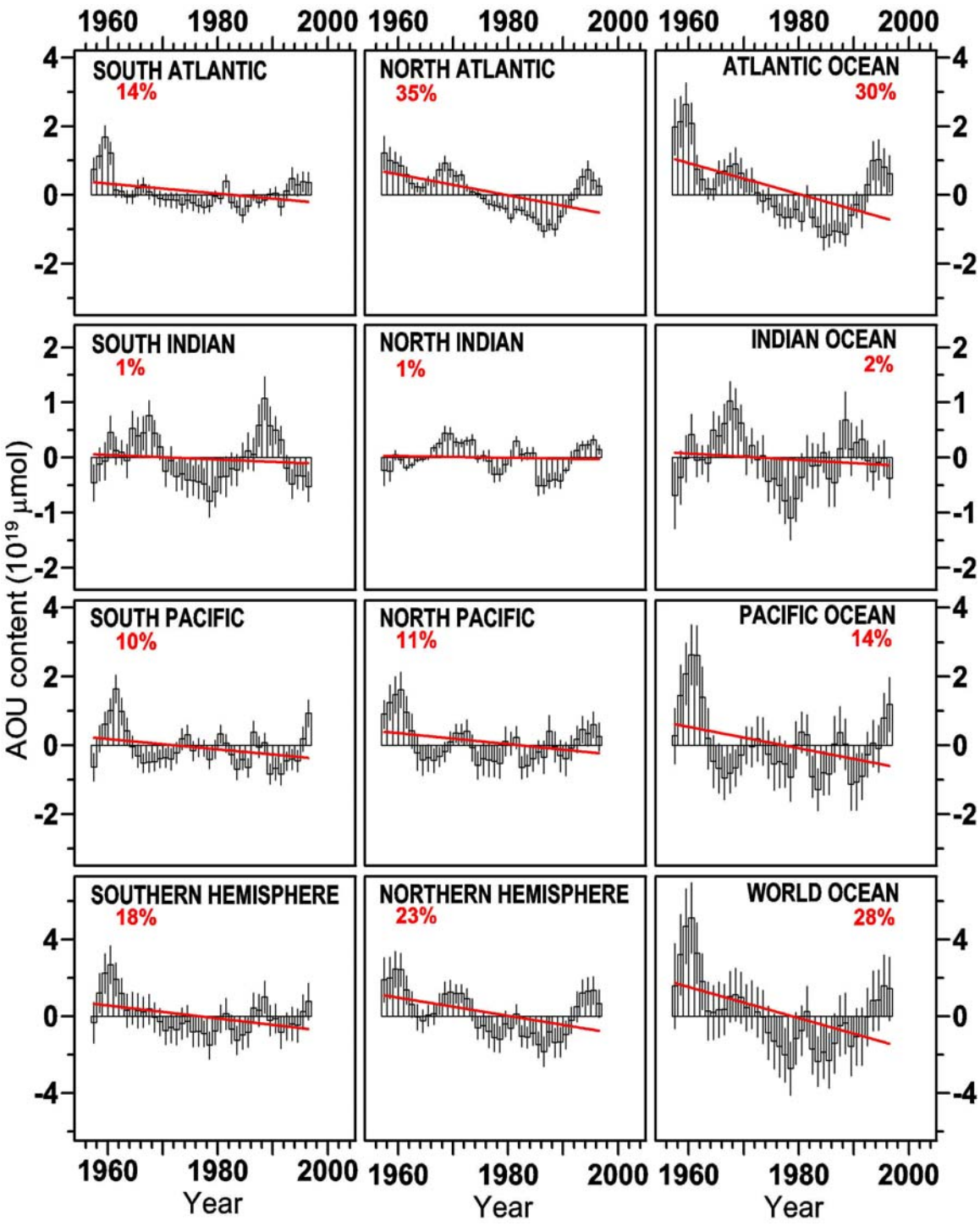

Figure S2. Variability in Apparent Oxygen Utilization content of the 0-100 m layer for major ocean basins (1957-61 to 1994-98). The 1957-61 to 1986-90 grand mean content has been removed. The vertical lines about each pentad value represent ±1 standard errors. The red lines are linear least-squares fits for the 1957-61 to 1994-98 period.

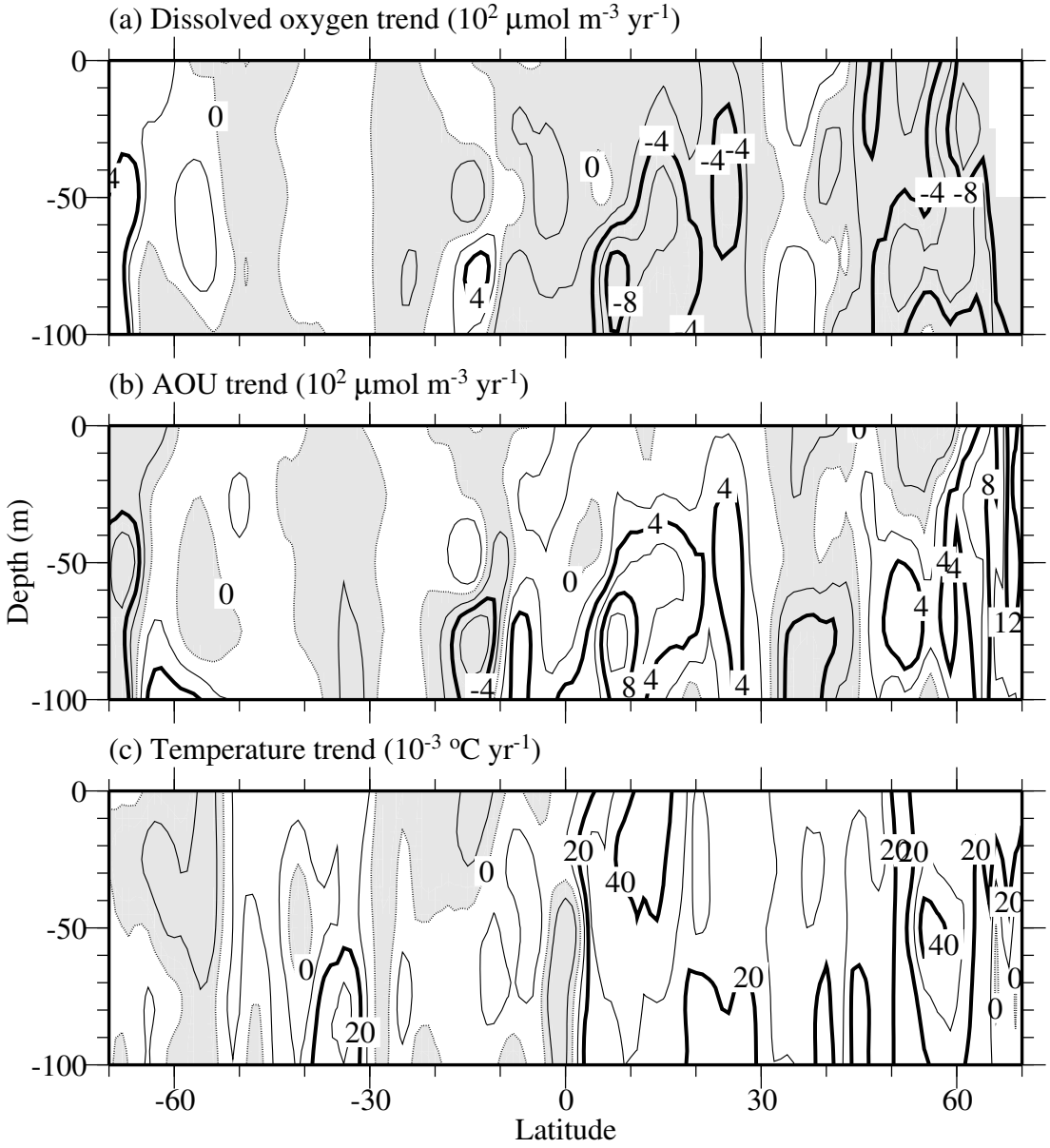

Figure S3. Linear trends (1983-87 through 1994-98) of the zonally averaged pentadal (a) O_2, (b) Apparent Oxygen Utilization (AOU), and (c) temperature anomalies. Shading denotes negative trends. The contour intervals are 2 x 10^2 μmol m^{-3} $year^{-1}$ for O_2 and AOU, and 10 x 10^{-3} ^0C $year^{-1}$ for temperature.