Trends in marine dissolved oxygen: implications for ocean circulation changes and the carbon budget

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Recent measurements and model studies have consistently identified a decreasing trend in the concentration of dissolved O_2 in the ocean over the last several decades. This trend has important implications for our understanding of anthropogenic climate change. First, the observed oceanic oxygen changes may be a signal of an incipient reorganization of large-scale ocean circulation in response to anthropogenic radiative forcing. Second, the repartitioning of oxygen between the ocean and the atmosphere requires a revision of the current atmospheric carbon budget and the estimates of the terrestrial and oceanic carbon sinks as calculated by the Intergovernmental Panel on Climate Change (IPCC) from measurements of atmospheric O_2/N_2.

Trends in Dissolved Oxygen: Observations and Models Identify Ocean Circulation Changes as the Main Mechanism

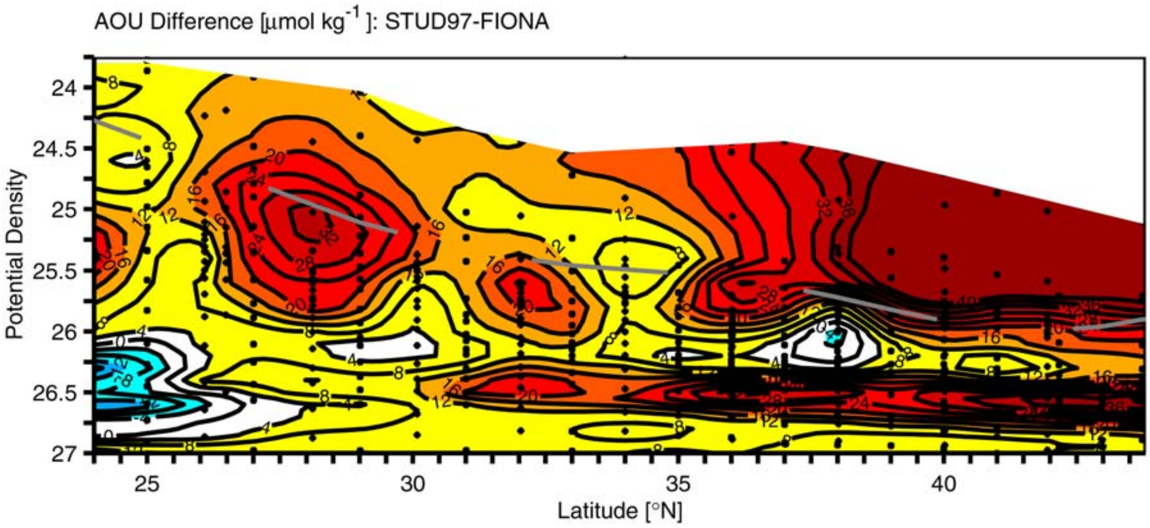

Figure 1: *Observed decrease in dissolved oxygen concentration in the thermocline of the North Pacific (Emerson et al., 2001). Plotted are differences in apparent oxygen utilization (AOU) as measured on two cruises on the same transect between 24°N and 44°N in 1981 and 1997. The contour interval is 4 µmol kg^{-1}. An increase in AOU, shown by yellow and red, corresponds to a decrease in dissolved oxygen.*

Detectable reductions in dissolved O_2 have been observed in all major ocean basins. Local changes as large as 30 µmol kg^{-1} are found (Figure 1), whereas basin-average changes in the North Pacific amount to a few µmol kg^{-1} only (Keller et al., 2002). For example, Kim et al. (2000) report a large long-term decrease in the oceanic O_2 concentration of more than 20 µmol kg^{-1} in the Japan Sea since the mid-1950s. Keller et al. (2002) analyzed GEOSECS and WOCE data to calculate basin-wide changes for the North Pacific. They find a decrease in dissolved O_2 in the upper ocean and an increase in the deep. Decreasing O_2 concentrations are also found by Ono et al. (2001) and Watanabe et al. (2001) in subsurface water in the western subarctic Pacific between 1968 and 1998 and by Emerson et al. (2001) analyzing data of four different cruises in the North Pacific during the 1980s and 1990s. Substantial reductions in dissolved O_2 are also reported for the eastern South Pacific above 3000 m (Shaffer et al., 2000), the Indian Ocean (Bindoff and McDougall, 2000), the North Atlantic (Garcia et al., 1988; Pahlow and Riebesell, 2000), and the Southern Ocean (Matear et al., 2000). Taken together, these observations suggest a general decrease in the oceanic O_2 inventory, although increases have been observed in the deep North Pacific (Keller et al., 2002), and the deep South Indian Ocean (Bindoff and McDougall, 2000). The former are also found in model simulations (Plattner et al., 2002).

Dissolved Oxygen is controlled by a range of processes. Oxygen is produced in the oceanic surface layer by biological production whereas it is removed in sub-surface waters by the respiration of sinking organic matter. Air-sea gas-exchange rapidly equilibrates near-surface waters and the atmosphere, whereas sub-surface oxygen removal is balanced by the transport of oxygen-rich surface waters into the interior ocean. The consequence is that sub-surface oxygen concentrations, and the overall partitioning of oxygen between atmosphere and ocean, are sensitive to the rate of surface-to-deep ocean circulation and mixing, biological production, as well as temperature and salinity (the latter determine oxygen solubility).

The observationally-based analyses identify ocean circulation changes as the main cause of the observed decrease in dissolved O_2 (Emerson et al., 2001; Keller et al., 2002; Kim et al., 2000; Watanabe et al., 2001; Ono et al., 2001; Shaffer et al., 2000; Bindoff and Mc Dougall, 2000). Changes in O_2 solubility and changes in biological export production and, hence, O_2 consumption at depth may have also contributed.

Most models simulate a slow-down of the ocean's meridional overturning circulation (Cubasch et al., 2001) in response to anthropogenic forcing. Models also show that a consequence is a net loss of oxygen to the atmosphere and estimate that on average between 0.2 to 0.7 10^{14} mol O_2 yr^{-1} have been released from the ocean to the atmosphere during the past decade (Sarmiento et al., 1998; Matear et al., 2000; Bopp et al., 2002; Plattner et al., 2001; Plattner et al., 2002). The modeled concentration changes, ranging from a few µmol kg^{-1} on global average up to 40 µmol kg^{-1} locally, are comparable with the observations (Matear et al., 2000; Plattner et al., 2002). A reduction in the rate of transport of O_2 to depth due to changes in ocean circulation and convection are identified as the primary reason for the simulated reduction in sub-surface dissolved O_2 and the increase in the net sea-to-air O_2 flux. Solubility changes, mainly driven by sea surface warming, are responsible for only about 20 % of the modeled O_2 decrease (Plattner et al., 2002; Bopp et al., 2002; Matear et al., 2000), and modeled changes in biological production have minor effects on the O_2 inventory (Plattner et al., 2002). In conclusion, both the observation-based and ocean model studies identify circulation changes as the dominant mechanism underlying O_2 inventory changes.

Further Ocean Circulation Changes Ahead?

Further ocean circulation changes may lie ahead. Since the detection of rapid abrupt climate change in Greenland ice cores, European lake sediments, and sediments in the deep Atlantic (Oeschger et al., 1984; Broecker et al., 1985; Clark et al., 2002), concerns have been expressed that the formation of North Atlantic Deepwater may cease in response to global warming (Broecker, 1987; Stocker et al., 2001). This would imply a reduced ocean heat transport to the North Atlantic region with large consequences for the climate in Europe and the Northern Hemisphere.

The same models that simulate a decrease in dissolved O_2, also project a continued decrease in the meridional overturning circulation and North Atlantic Deep Water formation rate over the century as greenhouse gas emission and global anthropogenic climate change continues. Model results suggest that the meridional overturning circulation is vulnerable to changes in the hydrological cycle and in sea surface temperature (Cubasch et al., 2001). North Atlantic Deep Water formation may even eventually cease in response to anthropogenic forcing (Stocker and Schmittner, 1997), similar to what happened frequently during the last glacial period. However, since such ocean circulation changes, and in particular large scale reorganizations, are highly non-linear processes involving thresholds, there are inherent limitations to the predictability of such phenomena (Knutti and Stocker, 2001). We conclude that monitoring of the ocean for the circulation changes projected by models is required (Hirschi et al., 2003) and that oxygen may be a particularly sensitive indicator for this purpose.

Revised Estimates of Oceanic and Terrestrial Carbon Sinks

The observed and modeled decrease in dissolved oxygen and the implied net sea-to-air O_2 fluxes also affect estimates of CO_2 sinks (Table 1). CO_2 is the most important anthropogenic greenhouse gas, and understanding the processes and the magnitude of the terrestrial and oceanic carbon sink is a prerequisite to project its future atmospheric concentration. The IPCC has estimated carbon uptake by the land biosphere and the ocean using decadal trends in atmospheric oxygen and carbon dioxide (Prentice et al., 2001). The assumption has been that net ocean-to-atmosphere O_2 fluxes are negligible on decadal time scales. Recent observations and model results imply that this assumption is flawed (Bopp et al., 2002; Keeling and Garcia, 2002; Plattner et al., 2002).

Adjusting the carbon budget for marine oxygen outgassing is, however, not straightforward. The ocean data remain too sparse to estimate global net outgassing. Models do not realistically resolve decadal variability, e.g., in observed ocean heat uptake. Volcanic eruptions interrupt the long-term outgassing (Plattner et al., 2002). An indirect approach needs to be applied until improved models or a better observational database become available. A model-derived empirical relationship between ocean heat uptake and oxygen outgassing has therefore been combined with available ocean heat data to estimate net O_2 outgassing. With this approach, the net terrestrial carbon sink estimated for the 1990s is a factor of two lower than the central estimate by the IPCC (Plattner et al., 2002; Table 1).

	1980 to 1989	1990 to 1999
Atmospheric increase	3.3 ±0.1	3.2 ±0.1
Fossil emissions	5.4 ±0.3	6.3 ±0.4
Ocean atmosphere flux	-1.7 ±0.6 (-1.9±0.6)	-2.4 ±0.7 (-1.7 ±0.5)
Land-atmosphere flux	-0.4 ±0.7 (-0.2±0.7)	-0.7 ±0.8 (-1.4 ±0.7
Land use change	2.0 ±0.8	2.2 ±0.8
Residual terrestrial sink	-2.4 ±1.1	-2.9 ±1.1

Table 1: Revised global CO_2 budgets (in GtC yr^{-1}) based on measurements of atmospheric CO_2 and O_2 and estimated ocean outgassing of O_2. The atmospheric increase and fossil emissions are from Prentice et al., 2001, the oceanic and terrestrial carbon uptake fluxes are from Plattner et al., 2002, and the land use change fluxes are from Houghton, 2002. The residual terrestrial sink is inferred by difference using independent analyses of the land use change term. Recent studies (e.g. Archard et al., 2002) suggest that the land use change term and the residual terrestrial sink may be substantially smaller. The numbers in parentheses are the sinks estimated by IPCC (Prentice et al., 2001), on the assumption of no net O_2 outgassing due to circulation changes.

Important caveats prevent us from firmly quantifying O_2 outgassing and from concluding that ocean circulation is indeed undergoing a global reorganization. It is difficult to extrapolate relatively sparse observations in restricted locations to the global ocean. A possible role of decadal variability for the observed O_2 changes is also not well understood. Nevertheless, dissolved O_2 is a sensitive integrating property reflecting physical and biogeochemical changes in the marine environment (Bindoff and McDougall, 2000). The O_2 signal is influenced not only by physical transport, but also by the remineralization of organic matter and biological production, which are themselves strongly controlled by nutrient transport into the surface ocean.

A Strategy for Future Research

Given current model results, and the potentially major climate and societal impact of large-scale changes in ocean heat transport, an observation-based strategy for detecting large-scale ocean circulation change is urgently required. We suggest that the ocean's oxygen distribution can be a sensitive indicator of such changes in meridional overturning, and that an observation-based strategy should be developed hand-in-hand with model development. Time-series and models of dissolved oxygen inventories have the added benefit of correcting bias and narrowing uncertainties in the contemporary carbon budget.

Such an observational strategy will require a vastly expanded data set for dissolved oxygen compared to that which has been collected in the past. Up to now, accurate oxygen measurements were dependent on infrequent and geographically-limited research vessel-based-hydrographic surveys. The need for higher spatial and temporal resolution of ocean temperature and salinity data has led the climate community to develop and deploy an array of new autonomous measurement platforms (profiling floats, gliders, moorings). An excellent example is the international ARGO program (http://www-argo.ucsd.edu).
Use of these platforms for oxygen measurements was limited by a lack of O_2 sensors with the required sensitivity and calibration stability, and possibly, by a lack of awareness of the utility of oxygen as an indicator of circulation change. However, the recent introduction of a

fundamentally new optode-based oxygen sensor for marine applications holds promise for overcoming the limitations of previous O_2 measurement technologies (Figure 2). Initial field tests have shown exceptional sensitivity and excellent stability (AK and DW, unpublished data). The new technology seems well-suited to deployment on long-term in-situ moorings, profiling floats, and other autonomous platforms.

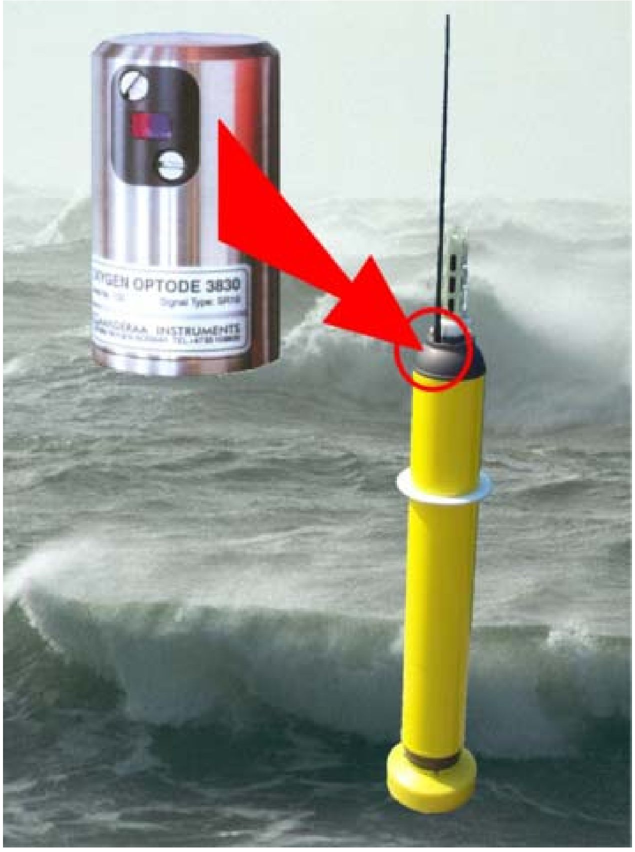

Figure 2: *Dissolved oxygen has a century-long history of use as a tool for deducing the details of ocean circulation. A global, long-term, measurement-based, view of changing oceanic oxygen inventories can now potentially be obtained through incorporation of accurate oxygen sensors into the next generation of profiling floats. Such a measurement program would benefit both the climate and carbon-cycle communities.*

Given the utility of oceanic oxygen for addressing uncertainties in two major global change concerns (ocean circulation/climate and global carbon sinks) we recommend that serious attention be given to oceanic oxygen inventories by the modeling and ocean measurement communities, including consideration of integrating oxygen measurements into future physical oceanography and climate autonomous measurement programs.

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References

Archard, F., H.D. Eva, H. Stibig, P. Mayaux, J. Gallego, R. Richards, and J. Malingreau, Determination of deforestation rates of the world's humid tropical forest, *Science, 297*, 999-1002, 2002.

Bindoff, N.L., and T.J. McDougall, Decadal changes along an Indian Ocean section at 32 S and their interpretation, *J. Phys. Oceanogr., 30*, 1207-1222, 2000.

Bopp, L., C. LeQuéré, M. Heimann, A.C. Manning, and P. Monfray, Climate-induced oceanic oxygen fluxes: Implications for the contemporary carbon budget, *Global Biogeochem. Cyc., 16*, 10.10292001GB001445, 2002.

Broecker, W.S., D.M. Peteet, and D. Rind, Does the ocean-atmosphere system have more than one stable mode of operation?, *Nature, 315*, 21-25, 1985.

Broecker, W.S. Unpleasant surprises in the greenhouse. *Nature, 328*, 123-126, 1987.

Clark, P.U., N.G. Pisias, T.F. Stocker, and A.J. Weaver, The role of the thermohaline circulation in abrupt climate change, *Nature, 415*, 863-869, 2002.

Cubasch, U., G.A. Meehl, G.J. Boer, R.J. Stouffer, M. Dix, A. Noda, C.A. Senior, S. Raper, and K.S. Yap, Projections of future climate change, in Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, Cambridge Univ. Press, New York, 525-582, 2001.

Emerson, S., S. Mecking, and J. Abell, The biological pump in the subtropical North Pacific Ocean: Nutrient sources, Redfield ratios, and recent changes, *Global Biogeochem. Cyc., 15*, 535-554, 2001.

Garcia, H., A. Cruzado, L. Gordon, and J. Escanez, Decadal-scale chemical variability in the subtropical North Atlantic deduced from nutrient and oxygen data, *J. Geophys. Res., 103*, 2817-2830, 1998.

Hirschi, J., J. Baehr, J. Marotzke, J. Stark, S. Cunningham, and J.-O. Beismann, A monitoring design for the Atlantic meridional overturning circulation, *Geophys. Res. Let.,* submitted, 2003.

Houghton, R. A., Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000, *Tellus*, in press, 2003.

Keeling, R.F., and H. Garcia, The change in oceanic O_2 inventory associated with recent global warming, *Proc. US Natl. Acad. Sci., 99*, 7848-7853, 2002.

Keller, K., R.D. Slater, M. Bender, and R.M. Key, Possible biological or physical explanations for decadal scale trends in North Pacific nutrient concentrations and oxygen utilization, *Deep Sea Res. II, 49*, 345-362, 2002.

Kim, K.-R., K. Kim, D.-J. Kang, S.Y. Park, M.-K. Park, Y.-G. Kim, H.S. Min, and D. Min, The East Sea (Japan Sea) in change: A story of dissolved oxygen, *MTS Journal, 33*, 15-22, 2000.

Knutti, R., and T.F. Stocker, Limited predictability of the future thermohaline circulation close to an instability threshold, *J. Clim., 15*, 179-186, 2002.

Matear, R.J., A.C. Hirst, and B.I. McNeil, Changes in dissolved oxygen in the Southern Ocean with climate change, *Geochem. Geophys. Geosyst.,1*, 2000GC000086, 2000.

Oeschger, H., J. Beer, U. Siegenthaler, B. Stauffer, W. Dansgaard, and C.C. Langway, Late glacial climate history from ice cores, in Climate Processes and Climate Sensitivity, edited by J.E. Hansen and T.Takahashi, Volume 29 of Geophysical Monograph, pp. 299-306, Am. Geophys. Union, 1984.

Ono, T., T. Midorikawa, Y.W. Watanabe, K. Tadokoro, and T. Saino, Temporal increases of phosphate and apparent oxygen utilization in the subsurface waters of western subarctic Pacific from 1968 to 1998, *Geophys. Res. Let., 28*, 3285-3288, 2001.

Pahlow, M., and Riebesell U. Temporal trends in deep ocean Redfield ratios. *Science, 287*, 831-833, 2000.

Plattner, G.-K., F. Joos, and T.F. Stocker, Revision of the global carbon budget due to changing air-sea oxygen fluxes, *Global Biogeochem. Cyc., 16*, 1096, doi: 10.10292001GB001746, 2002.

Plattner, G.-K., F. Joos, T.F. Stocker, and O. Marchal, Feedback mechanisms and sensitivities of ocean carbon uptake under global warming, *Tellus, 53B*, 564-592, 2001.

Prentice, I.C., G.D. Farquhar, M.J.R. Fasham, M.L. Goulden, M. Heimann, V.J. Jaramillo, H.S. Kheshgi, C. LeQuéré, R.J. Scholes, and D.W.R. Wallace, The carbon cycle and atmospheric carbon dioxide, in Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, Cambridge Univ. Press, New York, 183-237., 2001.

Sarmiento, J.L., T.M.C. Hughes, R.J. Stouffer, and S. Manabe, Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature, 393*, 245-249, 1998.

Shaffer, G., O. Leth, O. Ulloa, J. Bendtsen, G. Daneri, V. Dellarossa, S. Hormazabal, and P.-I. Sehlstedt, Warming and circulation change in the eastern South Pacific Ocean, *Geophys. Res. Let., 27*, 1247-1250, 2000.

Stocker, T.F., G.K.C. Clarke, H. LeTreut, R.S. Lindzen, V.P. Meleshko, R.K. Mugara, T.N. Palmer, R.T. Pierrehumbert, P.J. Sellers, K.E. Trenberth, and J. Willebrand, Physical climate processes and feedbacks, in Climate Change 2001, The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, 417-470. Cambridge University Press, 2001.

Stocker, T.F., and A. Schmittner, Influence of CO_2 emission rates on the stability of the thermohaline circulation, *Nature, 388*, 862-865, 1997.

Watanabe, Y.W., T. Ono, A. Shimamoto, T. Sugimoto, M. Wakita, and S. Watanabe, Probability of a reduction in the formation rate of the subsurface water in the North Pacific during the 1980s and 1990s, *Geophys. Res. Let., 28*, 3289-3292, 2001.