

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 the beginning of a re-organization 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 .

Observations, Models Identify Ocean Circulation Changes as Main Mechanism

Detectable reductions in dissolved O_2 have been observed in all major ocean basins (for references, see Plattner *et al.* [2002]; or Keeling and Garcia [2002]). Local changes as large as $30 \mu\text{mol kg}^{-1}$ are found (Figure 1), whereas basin-average changes in the North Pacific amount to a few $\mu\text{mol kg}^{-1}$ only.

For example, Kim and colleagues report a large, long-term decrease in the oceanic O_2 concentration of more than $20 \mu\text{mol kg}^{-1}$ in the Japan Sea since the mid-1950s. Keller and colleagues analyzed GEOSECS and WOCE data to calculate basin-wide changes for the North Pacific. They found a decrease in dissolved O_2 in the upper ocean and an increase in the deep. Decreasing O_2 concentrations were also found by Ono and co-workers, and by Watanabe and co-workers, 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 by Shaffer and colleagues; for the Indian Ocean by Bindoff and McDougall; for the North Atlantic by Garcia and co-workers, and by Pahlow and Riebesell; and for the Southern Ocean by Matear and colleagues.

Taken together, these observations suggest a general decrease in the oceanic O_2 inventory, although increases have been observed in the deep North Pacific and the deep south Indian Ocean. 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 equilibrates near-surface waters and the atmosphere on the time scale of weeks, whereas sub-sur-

face oxygen removal is balanced on longer time scales 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, and biological production, as well as temperature and salinity (the latter two determine oxygen solubility).

The observation-based analyses identify ocean circulation changes as the main cause of the observed decrease in dissolved O_2 . 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 slowdown 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 $0.7 \cdot 10^{14}$ 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; Plattner *et al.*, 2001; Bopp *et al.*, 2002; Plattner *et al.*, 2002]. The modeled concentration changes, ranging from a few $\mu\text{mol kg}^{-1}$ on global average up to $40 \mu\text{mol kg}^{-1}$ 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

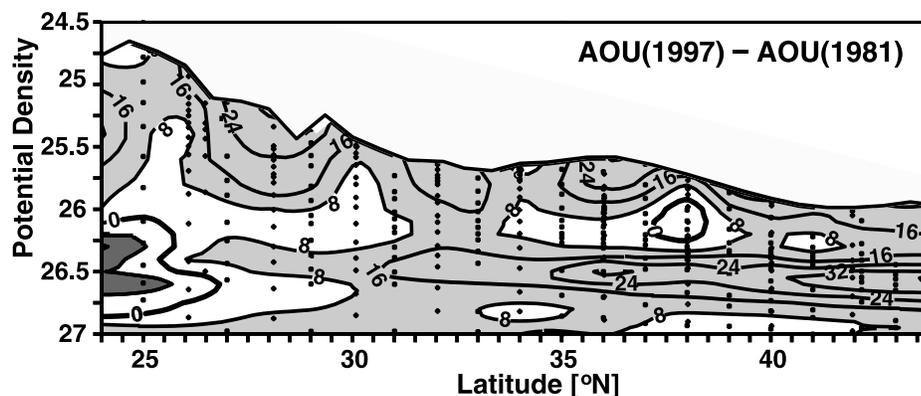


Fig. 1. Observed decrease in dissolved oxygen concentration in the thermocline of the North Pacific [Emerson *et al.*, 2001]. Plotted are differences in apparent oxygen utilization (AOU) as measured on two cruises on the same transect between 24°N and 44°N in 1981 and 1997. The contour interval is $4 \mu\text{mol kg}^{-1}$. AOU is the difference between the O_2 equilibrium concentration, calculated from the observed in-situ temperature and salinity and atmospheric O_2 pressure at sea level, and the measured in-situ concentration of O_2 . An increase in AOU corresponds to a decrease in dissolved oxygen. (Figure courtesy of Steve Emerson).

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 [Matear *et al.*, 2000; Bopp *et al.*, 2002; Plattner *et al.*, 2002], 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 (see Clark *et al.* [2002]), concerns have been expressed that the formation of North Atlantic Deep Water may cease in response to global warming [Broecker, 1987]. 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, similar to what happened frequently during the last glacial period. However, since such ocean circulation changes, and in particular, large-scale re-organizations, 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, 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 an understanding of 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 [Keeling and Shertz, 1992; Prentice *et al.*, 2001]. The assumption has been that net ocean-to-atmosphere O_2 fluxes are negligible on decadal time scales. (A small correction to account for changes in solubility has been included in the IPCC budget for the

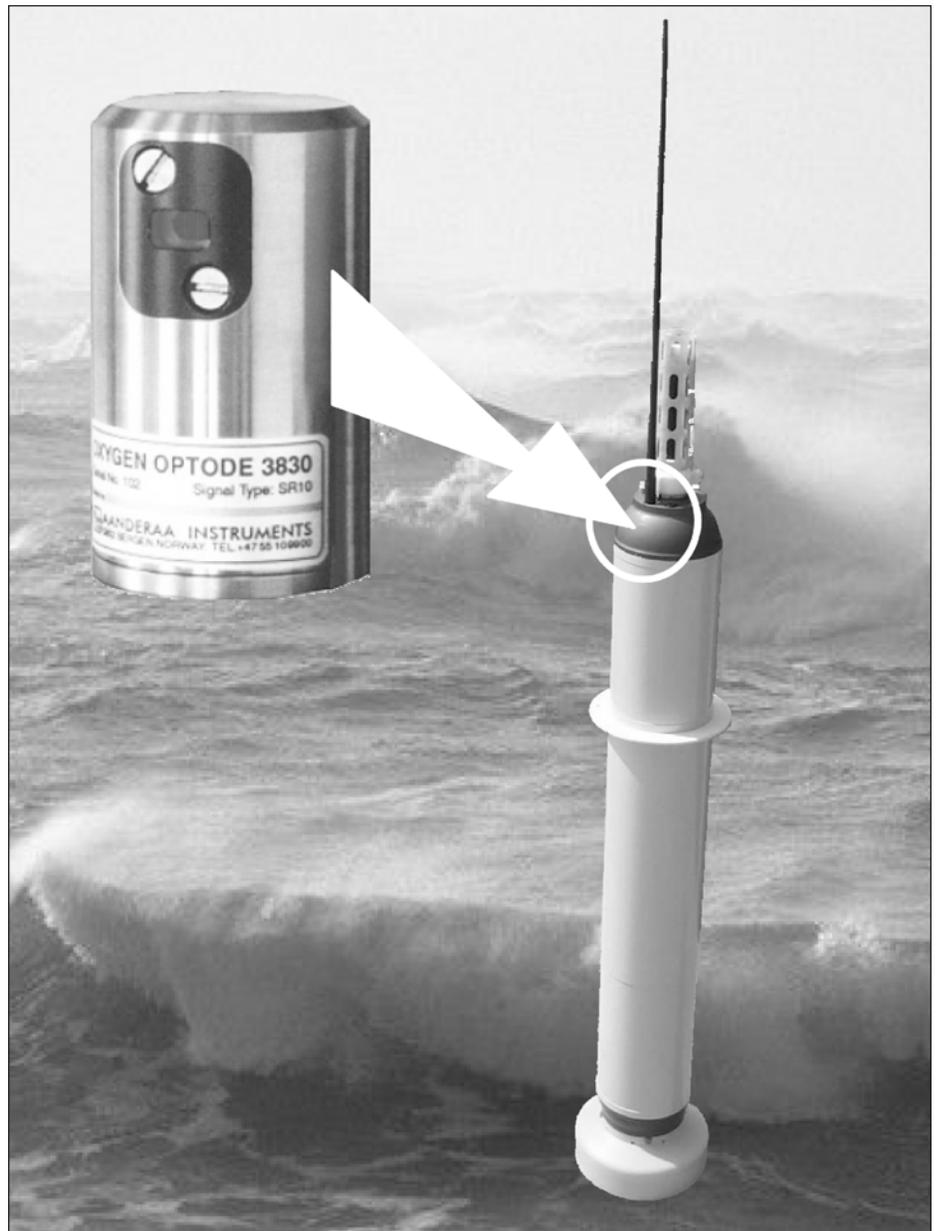


Fig. 2. Dissolved oxygen has a century-long history of use as a tool for deducing the details of ocean circulation. A global, long-term, measurement-based view of changing oceanic oxygen inventories can now potentially be obtained through incorporation of accurate oxygen sensors into the next generation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

1990s.) Recent observations and model results imply that this assumption is flawed [Plattner *et al.*, 2001; 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 data base become available [Bopp *et al.*, 2002; Keeling and Garcia, 2002; Plattner *et al.*, 2002]. A model-derived empirical relationship between ocean heat uptake and oxygen outgassing has therefore been combined with available

ocean heat data [Levitus *et al.*, 2000] to estimate net O_2 outgassing. With this indirect 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).

Important caveats prevent us from firmly quantifying O_2 outgassing, and from concluding that ocean circulation is indeed undergoing a global re-organization. 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 cannot be currently quantified. Nevertheless, dissolved O_2 is a sensitive integrating property reflecting physical and biogeochemical changes in the marine environment. 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 (A. Körtzinger and D.W. R. Wallace, University of Kiel, unpublished data, 2002). The new technology seems well-suited to deployment on long-term in-situ moorings, profiling floats, and other autonomous platforms.

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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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 .

	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

Note: 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 [2003]. 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. The corrections in the sink fluxes suggested by Plattner et al. [2002], based on an ocean heat uptake rate of $-0.39 \cdot 10^{22} J\ yr^{-1}$ for the 1980s, and $+1.24 \cdot 10^{22} J\ yr^{-1}$ for the 1990s, and a model-derived relationship between heat uptake and changes in atmospheric O_2/N_2 due to outgassing of 1.56 per meg ($10^{22} J$)⁻¹, are similar to those found by Bopp et al. [2002], but considerably larger than those proposed by Keeling and Garcia [2002] and LeQuéré et al. [2003]. The residual terrestrial sink is inferred by difference, using independent analyses of the land use change term. Recent studies suggest that the land use change term and the residual terrestrial sink may be substantially smaller.

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