



A conceptual model for the temporal spectrum of oceanic oxygen variability

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[1] Changes in dissolved O₂ observed across the world oceans in recent decades have been interpreted as a response of marine biogeochemistry to climate change. Little is known however about the spectrum of oceanic O₂ variability. Using an idealized model, we illustrate how fluctuations in ocean circulation and biological respiration lead to low-frequency variability of thermocline oxygen. Because the ventilation of the thermocline naturally integrates the effects of anomalous respiration and advection over decadal timescales, short-lived O₂ perturbations are strongly damped, producing a red spectrum, even in a randomly varying oceanic environment. This background red spectrum of O₂ suggests a new interpretation of the ubiquitous strength of decadal oxygen variability and provides a null hypothesis for the detection of climate change influence on oceanic oxygen. We find a statistically significant spectral peak at a 15–20 year timescale in the subpolar North Pacific, but the mechanisms connecting to climate variability remain uncertain. **Citation:** Ito, T., and C. Deutsch (2010), A conceptual model for the temporal spectrum of oceanic oxygen variability, *Geophys. Res. Lett.*, 37, L03601, doi:10.1029/2009GL041595.

1. Introduction

[2] Dissolved oxygen in the ocean plays a central role in fundamental biogeochemical processes. The distribution of O₂ reveals the circulation of O₂-rich surface waters into the ocean interior, as well as the respiratory consumption of O₂ along those pathways [Jenkins, 1982]. In-situ concentration of oxygen also exerts a direct influence on important biological and chemical processes, including the physiology of marine organisms [Portner and Knust, 2007] and numerous oxidation reactions governing the abundance of trace metals [Morel and Price, 2003] and nitrogen [Codispoti, 1995]. The ocean's oxygen content may respond very sensitively to global ocean warming [Bopp et al., 2002; Keeling and Garcia, 2002; Plattner et al., 2002] because as the ocean is heated from above, O₂ becomes less soluble in surface waters and is also less readily transported to depth in areas of increased thermal stratification.

[3] Analyses of historical O₂ measurements have detected declining O₂ in the upper ocean in most ocean basins [Garcia et al., 1998; Bindoff and McDougall, 2000; Matear et al., 2000; Schaffer et al., 2000; Emerson et al., 2001; Ono et al., 2001; Watanabe et al., 2001; Keller et al.,

2001; Stramma et al., 2008], providing considerable evidence for this sensitivity. However, the observed character of O₂ variability is far more complex than a steady uniform decrease, making long-term trends at a basin scale difficult to detect [Garcia et al., 2005]. Time series stations provide the most comprehensive temporal picture, and these indicate that O₂ changes are dominated by interannual and decadal variability superimposed on a much smaller, long-term trend [Ono et al., 2001; Whitney et al., 2007]. These observations suggest that internal climate variability may also be an important cause of O₂ changes, or that the sensitivity of O₂ to factors besides long-term warming and stratification, such as biological productivity and ocean circulation variability, are also important.

[4] The presence of decadal and shorter-term variability of O₂, complicates the detection of long-term responses to global warming, but also provides the opportunity to understand basic sensitivities of ocean processes to perturbations at a wide range of time scales including long-term climate change. Here we offer a new interpretation of oceanic oxygen variability based on multi-decadal time series data and a conceptual model.

2. Conceptual Model

[5] To illustrate the underlying mechanisms of thermocline O₂ variability, we employ a simple box model of the upper ocean O₂ cycle (schematically illustrated in Figure 1), in which O₂-rich surface water is transported from the mixed layer to the interior ocean, where O₂ is consumed by the respiration of sinking organic material. The governing equation for the oxygen concentration in the thermocline can be written as

$$\frac{d[O_2]}{dt} = \lambda([O_{2,sfc}] - [O_2]) - OUR$$

where [O₂] and [O_{2,sfc}] are oxygen concentration in the thermocline and in the surface mixed layer. Oxygen Utilization Rate (OUR) is the rate of oxygen loss due to respiration and λ is a gross measure of the inverse timescale of thermocline ventilation by advection and eddy stirring processes. The mean state (denoted by overline) is determined by the balance between the supply of oxygen due to ventilation and consumption due to respiration:

$$\overline{[O_2]} = \overline{[O_{2,sfc}]} - \frac{\overline{OUR}}{\lambda} \quad (1)$$

This simple mean state illustrates the primary influences on long-term O₂ trends, provided the changes are slow relative to the ventilation time scale. Since [O_{2,sfc}] is very close to

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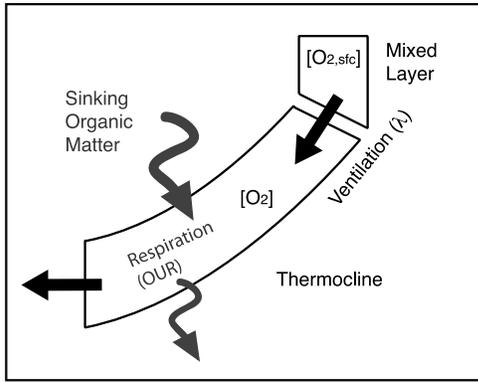


Figure 1. A schematic diagram of the oxygen cycle associated with thermocline ventilation. The thick solid arrows represent physical transport, and the wiggly grey arrows represent the flux of sinking organic matter. The convergence of physical transport balances the sink due to the respiration of the organic matter.

saturation with the overlying atmosphere, an increase in SST will reduce thermocline O_2 through the reduction of surface O_2 . The associated increase in thermal stratification may also weaken the thermocline ventilation, leading to a decrease in λ and thus O_2 . These two processes in combination can deplete thermocline oxygen. However, since the overall nutrient supply to the surface also scales with the rate of thermocline ventilation, OUR may also decrease and counteract the decline of thermocline O_2 .

[6] In order to examine the response to forcings that fluctuate quickly relative to the thermocline ventilation timescale, the non-steady state response of O_2 must also be considered. Model variables in (1) are separated into a mean state and a time-dependent perturbation denoted by primes, e.g. $[O_2] = [\bar{O}_2] + [O_2]'$. The linearized evolution equation can be written as follows

$$\left(\frac{d}{dt} + \bar{\lambda}\right) [O_2]' = \bar{\lambda} [O_{2,sfc}]' - OUR' + \lambda' ([\bar{O}_{2,sfc}] - [\bar{O}_2]) \quad (2)$$

Four major processes are represented in the above equation including the mean ocean ventilation and eddy stirring (2nd term of LHS), variability at the isopycnal outcrop (1st term of RHS), variability of respiration rates (2nd term of RHS) and circulation variability (3rd term of RHS). Oxygen anomalies are generated by processes on the RHS of equation (2), but are continuously damped out by the flushing effect of the mean thermocline ventilation and turbulent eddies, represented by the LHS of equation (2). While it is possible to diagnose the magnitudes of individual terms on the RHS of equation (2) from a marine biogeochemistry model coupled to an ocean GCM [Deutsch *et al.*, 2006], the temporal or frequency characteristics of the individual processes are difficult to establish empirically, and even less is known about their interactions. It is therefore useful to consider the simplest case in which all the processes that generate O_2 anomalies (i.e., the entire RHS) are combined into a single forcing term, $\eta(t)$, and seek a statistical relationship between $[O_2]$ and $\eta(t)$. By taking the Fourier transform of equation (2), the power spectrum of

oxygen anomalies can be related to that of its forcing, $\eta(t)$ without assigning specific structure to the forcing.

$$|\hat{O}_2|^2 = \frac{|\hat{\eta}|^2}{\bar{\lambda}^2 + \omega^2} \quad (3)$$

where the hat (^) properties are the Fourier transform. This equation is identical to that of classical stochastic climate model [Hasselmann, 1976].

[7] The forcing of O_2 anomalies, $\eta(t)$, represents the combined effects of variability in the ocean circulation (from mesoscale eddies to basin scale flows) as well as the episodic and patchy export fluxes of organic matter. As a first step, we consider a simplest possible case where $\eta(t)$ is characterized by a white noise which contains power in all frequencies equally. In this special case, the variability of dissolved oxygen has a constant magnitude at timescales much longer than the ventilation time scale, but declines rapidly for frequencies higher than the ventilation rate of the thermocline waters ($\omega \gg \lambda$) where the magnitude of oxygen fluctuations will be proportional to ω^{-2} .

[8] In reality, the forcing itself, $\eta(t)$, may be represented by a red noise spectrum since physical properties such as sea surface height, temperature and salinity often show declining variance with frequency [Wunsch, 1972; Hasselmann, 1976; Wunsch, 1996]. This implies that oxygen spectra may exhibit even stronger low-frequency variability than physical properties as illustrated by equation (3), and the oxygen variance may be proportional to ω^{-n} where $n > 2$ for timescales shorter than the mean ventilation time. Biological respiration (OUR') may be indirectly related to physical circulation variability as nutrient supply depends on entrainment and upwelling of thermocline waters into the sun-lit surface layer. While our understanding of physical-biological coupling is far from complete, the spatial and temporal structure of the forcing is likely complex. Regardless of the detailed structure of $\eta(t)$, we predict the oceanic oxygen cycle will exhibit stronger low-frequency variability than the physical and biological forcing themselves.

3. Observed Oxygen Variability in the North Pacific

[9] The subarctic North Pacific contains two of the longest time series of oxygen measurements anywhere in the open ocean [Ono *et al.*, 2001; Whitney *et al.*, 2007]. In both the eastern and western basins, relatively weak long-term trends in O_2 have been estimated in the presence of strong variability from intra-annual to decadal timescales. Here we further analyze the frequency content of oxygen data (Figure 2) from the time-series station P (50°N 145°W) [Whitney *et al.*, 2007]. The changes we analyze in the eastern basin are similar to those observed in the western subpolar gyre [Ono *et al.*, 2001].

[10] We focus on waters with a potential density of $\sigma_0 = 27.0$ which is within the main thermocline of the eastern North Pacific basin. This water mass is below the base of the euphotic zone and the winter mixed layer, and thus reflects basin-scale physical transport and biological activity, rather than local surface processes. A linear, decreasing O_2 trend on the isopycnal surface $\sigma_0 = 27.0$ in this dataset is approximately $-0.5 \text{ mmol/m}^3/\text{yr}$, which explains about

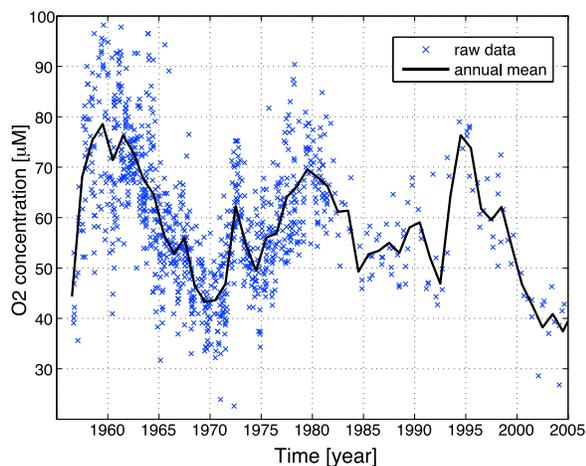


Figure 2. Time series of dissolved O_2 at Station Papa [Whitney *et al.*, 2007] in the subarctic North Pacific (50N, 145W). O_2 concentrations have been interpolated to the density surface $\sigma_0 = 27.0$. The black solid line is the annually averaged O_2 , and the blue crosses are the individual measurements.

18% of variance. The data also contains strong variability at shorter timescales from months to decades. To investigate the temporal O_2 fluctuations over longer timescales, we computed the periodogram of annually averaged oxygen anomalies after removing the long-term linear trend (blue solid line in Figure 3). The periodogram of annual O_2 anomalies shows an overall trend from relatively low variance in the inter-annual time scale, increasing toward a maximum variance in decadal timescales. The slope of the O_2 spectrum based on historical measurements thus resembles the simple model with white noise forcing (black solid line in Figure 3), indicating that the pronounced low-frequency O_2 variability could be explained by the integration of random physical and biogeochemical variability by the slow, oceanic ventilation.

[11] The power spectra of physical ocean properties such as temperature and salinity often show declining variance as frequency increases [Wunsch, 1972; Hasselmann, 1976; Wunsch, 1996; Huybers and Curry, 2006]. However, salinity at this location is not strongly correlated with oxygen, especially in inter-annual and longer timescales (correlation coefficient of -0.3), as would be expected from a simple physical shift in water mass boundaries. The processes driving the low-frequency variability of O_2 therefore must include additional mechanisms, such as biological respiration and its impact on the background O_2 gradients.

[12] We take the stochastic solution as a null hypothesis for the power spectrum of O_2 , and test for frequency bands that deviate significantly from the relationship defined by equation (3). Here we consider a white noise induced variability since the detailed structure of $\eta(t)$ is not well known, and because it is consistent with the overall slope of the observed O_2 spectrum at sub-decadal frequencies. It has been hypothesized that the thermocline of the subarctic North Pacific undergoes a quasi-periodic oscillation with an 18-year periodicity, potentially associated with tidal forcing and/or large-scale climate variability [Ono *et al.*, 2001; Andreev and Baturina, 2006; Watanabe *et al.*, 2008].

A spectral peak at approximately 17^{-1} [cycles/year] is indeed observed (Figure 3) and its frequency range of $1/20.6 < \omega < 1/14.6$ [cycle year $^{-1}$] contains approximately 60% of the O_2 variance. A standard statistical test (a one-tailed test using the F-distribution) must be performed to evaluate whether this apparent spectral peak rises significantly above the predicted background red noise spectrum given the finite time series length. A spectral peak in the specified frequency band with the magnitude observed at $\sim 17^{-1}$ [cycles/year] would occur fewer than 1 out of 20 times by chance ($P < 0.05$), and is thus a statistically significant deviation from the simple red noise spectrum.

[13] The exceptional variance in this timescale suggests a mode of oceanic O_2 variability potentially associated with tidal forcing or large-scale climate variability as hypothesized by previous studies. However, this result must be interpreted with caution. The existing O_2 time series is relatively short, covering only 3 putative cycles, and our understanding of this apparent spectral peak is limited by the lack of a clear mechanism. Statistical correlations have been identified between the oxygen data from the subpolar North Pacific and climate indices such as North Pacific Index [Ono *et al.*, 2001]. The time series from Station P is also correlated with the North Pacific Gyre Oscillation index [Di Lorenzo *et al.*, 2008] between 1980 and 2007 (-0.64 , 95% confidence interval) and shows a similar oscillatory pattern to the time series from the western basin. Further modeling and analyses of observational data will be required to elucidate the mechanisms underlying these statistical relationships.

4. Discussion

[14] The concentrations of O_2 in the ocean interior respond to climate change through both physical and biological mechanisms. Observations reveal a complex spatial and temporal pattern of O_2 variability that has proved difficult to relate directly to specific climate trends

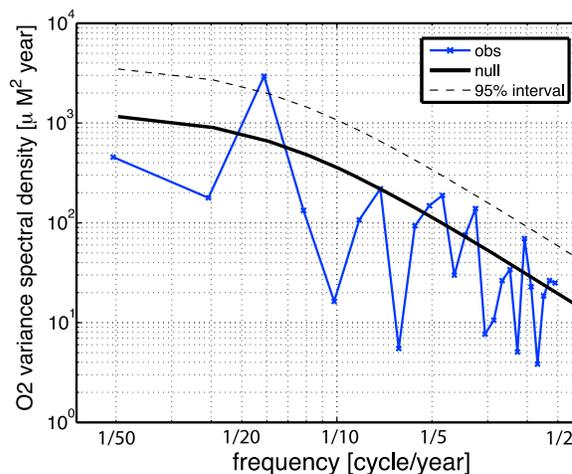


Figure 3. Periodogram of dissolved oxygen is plotted on the logarithmic scale (blue line), which is computed from detrended, annually averaged observations. The black solid line represents the null hypothesis predicted by the randomly forced simple model, and the thin, black dash line is the 95% confidence interval.

or modes of variability [Mecking *et al.*, 2008]. The spectral power of oxygen variability increases from inter-annual to decadal frequencies, which can be explained using a simple conceptual model of an ocean thermocline exposed to random climate fluctuations. The theory predicts that the bias toward low-frequency variability is expected to level off as the forcing timescales become comparable to that of ocean ventilation. On time scales exceeding that of thermocline renewal, O₂ variance may actually decrease due to the coupling between physical O₂ supply and biological respiration [Deutsch *et al.*, 2006], since the latter is typically limited by the physical nutrient supply.

[15] Elevated O₂ variability in the decadal frequency band reflects the imprints of climate and biogeochemical variability that are reddened by the flushing effect of the thermocline ventilation. Even without any special forcing at decadal time scales, O₂ variance should accordingly exhibit larger amplitudes at decadal timescales. The stochastic model offers a quantitative method to distinguish a specific mode of O₂ variability from the reddened random noise, which can be applied to in-situ observation or numerically simulated O₂ time-series data. For timescales shorter than that of ventilation, the detection of a particular mode requires a significant deviation from the background spectrum, which is a necessary step in detecting climate change signals in ocean biogeochemistry. In the eastern subpolar North Pacific, a spectral peak at a period of ~17 years is statistically significant, but further modeling and analyses of observational data will be required to elucidate the underlying mechanism. The spatial patterns of O₂ variability from ongoing repeat hydrography and emerging observations on profiling floats [Riser and Johnson, 2008] provide complementary constraints on the links between modes of large-scale climate and biogeochemical variability.

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