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Effects of increased isopycnal diffusivity mimicking the unresolved equatorial intermediate current system in an earth system climate model

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[1] Earth system climate models generally underestimate dissolved oxygen concentrations in the deep eastern equatorial Pacific. This problem is associated with the "nutrient trapping" problem, described by *Najjar et al.* [1992], and is, at least partially, caused by a deficient representation of the Equatorial Intermediate Current System (EICS). Here we emulate the unresolved EICS in the UVic earth system climate model by locally increasing the zonal isopycnal diffusivity. An anisotropic diffusivity of $\sim 50{,}000\,\mathrm{m}^2\,\mathrm{s}^{-1}$ yields an improved global representation of temperature, salinity and oxygen. In addition, it (1) resolves most of the local "nutrient trapping" and associated oxygen deficit in the eastern equatorial Pacific and (2) reduces spurious zonal temperature gradients on isopycnals without affecting other physical metrics such as meridional overturning or air-sea heat fluxes. Finally, climate projections of low-oxygenated waters and associated denitrification change sign and apparently become more plausible. **Citation:** Getzlaff, J., and H. Dietze (2013), Effects of increased isopycnal diffusivity mimicking the unresolved equatorial intermediate current system in an earth system climate model, *Geophys. Res. Lett.*, *40*, 2166–2170, doi:10.1002/grl.50419.

1. Introduction

[2] A significant fraction of global climate variabilities have been traced back to processes in the eastern equatorial Pacific (EEP). This region features an especially strong ocean-atmosphere exchange of heat, freshwater, and climate relevant species such as carbon dioxide. Naturally, the region has been the focus of many modeling studies exploring past and future climate variability. Even so, a range of problems associated with coupled ocean-atmosphere models persist. Primary among these problems are poor representations of sea surface temperatures in the equatorial upwelling zone and a spurious "double split" of the intertropical convergence zone.

[3] "Nutrient trapping" [*Najjar et al.*, 1992] (hereafter NT) is another, maybe less prominent but equally persistent, problem in the pelagic biogeochemical model component of earth system models. NT refers to spuriously enhanced nutrient concentrations at depth in the EEP [*Najjar et al.*, 1992]. The problem has an oxygen counterpart, i.e., it is related to spurious suboxia in the EEP, because the remineralization of this spurious surplus of nutrients is generally accompanied by uptake of dissolved oxygen. This related oxygen problem degrades simulations of oceanic suboxia which, by itself, adds considerable uncertainty to the future evolution of pelagic denitrification and the associated release of climate-relevant N_2O [*Dietze and Loeptien*, 2013].

[4] This view, that the current generation of models may not be up to the task of simulating the evolution of oxygen dissolved in the ocean is backed by *Stramma et al.* [2012], who compared simulations with observations. Their set of observations from the tropical Pacific imply a decrease of dissolved oxygen in a warming world (1960 to 2010). This is consistent with increased air-sea buoyancy fluxes sustaining an increased stability of the water column which, in turn, inhibits convection and associated ventilation of the deep ocean. Instead, *Stramma et al.* [2012] find an opposing behavior in models, i.e., an increase of oxygen in a warming climate. There is some evidence that NT and poor model representations of oxygen dynamics are associated with a deficient representation of zonal equatorial currents below the Equatorial Undercurrent (EUC) [*Dietze and Loeptien*, 2013].

[5] In the tropics, below the EUC and above, about 2500 m, the circulation is dominated by a set of deep zonal currents of amplitude 10 to 15 cm/s. These currents are divided into two groups: a group of currents trapped on the equator that change sign with depth with a wavelength of about 500 m (the Equatorial Deep Jets) and a group of currents of large vertical scale that alternate with latitude every 1–2° between 10°S and 10°N (the Equatorial Intermediate Currents). Here we define this set of deep zonal currents as EICS (note, this definition is different from the one used in *Ascani et al.* [2010]).

[6] Surprisingly, these currents rank among the strongest currents at depth, alongside with the barotropic Antarctic Circumpolar Current and the western boundary currents (Figure 1a). Because these important currents are not well resolved neither in coarse resolution Earth System Models (Figure 1b) nor in eddy-resolving ocean circulation models [*Ascani et al.*, 2010], questions remain about the impact of this missing circulation on simulated nutrients and oxygen in the EEP.

[7] Here we explore the significance of an unresolved EICS by parameterizing its effects using an increased isopycnal diffusivity in the zonal direction in a numerical earth system model. Note that this is a pragmatic approach. The success of the parameterization on the simulation is judged by focusing on the spatial distribution of dissolved oxygen (and its trend in a warming climate) in the tropical Pacific.

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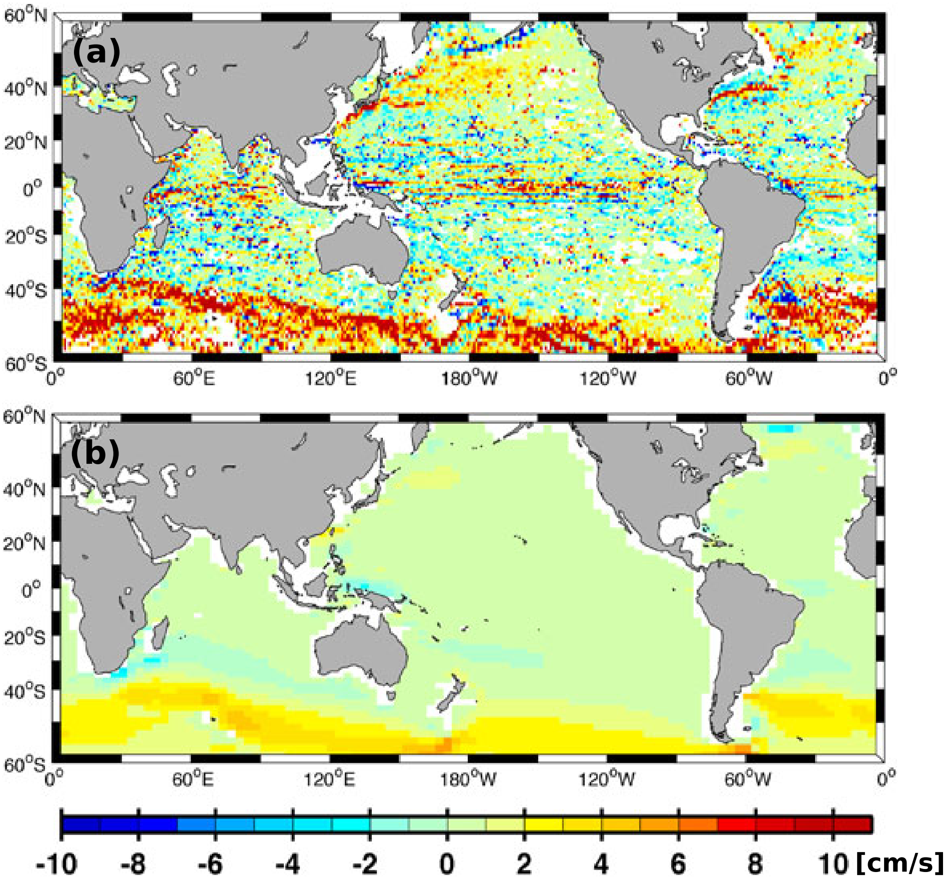

Figure 1. Zonal velocities at 1000 m depth. (a) This is based on trajectories of Argo floats at parking level [*Lebedev et al.*, 2007]. Note that this is a reproduction of *Ascani et al.* [2010, their Figure 2] and that *Cravatte et al.* [2012] published a more detailed view. (b) This refers to annual mean velocities of the reference simulation.

2. Model

[8] We use the University of Victoria (UVic) Earth System Climate model [*Weaver et al.*, 2001] version 2.9. The model features a full three-dimensional primitive-equation global ocean model [*Pacanowski*, 1995] coupled to the following: (1) a single-level atmospheric energy-moisture balance model, (2) a dynamic-thermodynamic sea ice model, (3) a simple marine pelagic ecosystem model comprising (among other, prognostic variables) dissolved oxygen, and (4) an active terrestrial vegetation model. All model components use a horizontal resolution of 1.8° latitude × 3.6° longitude. The vertical grid of the oceanic component has 19 levels with a thickness of 50 m near the surface, increasing gradually to 500 m in the abyss. The model is of intermediate complexity, i.e., the winds are prescribed. A comprehensive description of the model configuration is given by *Keller et al.* [2012]. The only change we apply to their configuration is the addition of a zonal, anisotropic, isopycnal diffusivity. This diffusivity is added between 5°S and 5°N below the EUC (~ 250 m). Its purpose is to mimic the effect of the unresolved EICS (compare the two panels in Figure 1).

[9] In total, seven simulations with differing diffusivities are run to quasi-equilibrium in a 3000 year spin-up starting from the already spun-up state described in *Keller et al.* [2012]. The reference simulation (REF) is identical to the one described in *Keller et al.* [2012] (except for the prolonged spin-up). REF features an anisotropic isopycnal diffusion coefficient of 1200 $\mathrm{m}^2\,\mathrm{s}^{-1}$. Six additional simulations, dubbed D1, D2, D4, D5, D6 and D10, feature an added zonal, anisotropic, isopycnal diffusivity of 1×10^4, 2×10^4, 4×10^4, 5×10^4, 6×10^4 and 10^5 $\mathrm{m}^2\,\mathrm{s}^{-1}$, respectively.

[10] In addition, we compare the transient behavior of the reference configuration with that of D5. These transient simulations are forced by atmospheric carbon dioxide emissions corresponding to the IPCC A2 SRES scenario [*Nakicenovic et al.*, 2000].

3. Results

[11] Figure 1 shows that the EICS is not well resolved at depth by our model. We suspect that zonal mixing in the tropics is greatly underestimated in the model, because it lacks the strong zonal jets that alternate their direction with latitude. Here we strive to parameterize this unresolved part of the circulation by a zonal, anisotropic isopycnal diffusivity. Per se, it is not clear if such an approach would yield realistic results— and if so, what the value of such a diffusivity should be. Hence, we tested, as described above, a range of diffusivities. Figure 2 shows, for each of the simulations, the volume-weighted root mean square deviations of temperature, salinity, and oxygen from respective observations [*Locarnini et al.*, 2006; *Antonov et al.*, 2006; *Bianchi et al.*, 2012]. All of these global metrics suggest that a

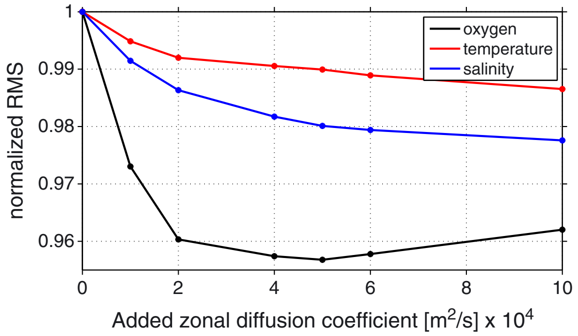

Figure 2. Normalized volume weighted root mean squared (RMS) deviations between observations [*Locarnini et al.*, 2006; *Antonov et al.*, 2006; *Bianchi et al.*, 2012] and simulations. Each symbol refers to a quasi-equilibrated simulation featuring differing levels of added isopycnal, anisoptropic, zonal diffusivity applied below the EUC between 5°S and 5°N. The colors refer to oxygen (black), temperature (red), and salinity (blue).

drastic increase of the zonal isopycnal diffusivity does result in a more realistic simulation. Oxygen appears to be most sensitive to diffusivity. Its misfit to observations features a minimum at a diffusivity of around 50,000 $m^2\,s^{-1}$ (simulation D5). In the following, we describe the D5 simulation in more detail.

[12] While in the global fields of temperature, salinity and oxygen improve, changes of the maximum of the meridional overturning circulation are insignificant with 17.7 and 18.05 Sv in REF and D5, respectively. In comparison, *Kanzow et al.* [2010] derive 18.7 ± 2.1 Sv from observations. We conclude that an increased zonal diffusivity improves the model, but expressed as global metrics, does little to change the physics. This does also apply to local changes of air-sea heat fluxes and precipitation which, averaged over 1 year, change less than 5% and 2%, respectively (not shown).

[13] Regionally, in the tropical Pacific, however, we find a drastic improvement of the zonal distribution of dissolved oxygen: Figures 3a–3c show a comparison between observed and simulated oxygen concentrations (meridionally averaged between 5°N and 5°S). The reference simulation is biased towards lower oxygen values down to 55 mmol $O_2\,m^{-3}$ in the EEP which is a problem related to NT, as explained in *Dietze and Loeptien* [2013]. As also suggested by *Dietze and Loeptien* [2013], the reference simulation features a related problem in the western equatorial Pacific, where simulated oxygen concentrations are biased towards higher values by similar amounts (up to 40 mmol $O_2\,m^{-3}$). This problem is most pronounced between 500 and 900 m depth. Figure 3c shows the oxygen concentrations in the D5 simulation which are much closer to the observations: the strong overestimation in the western equatorial Pacific is replaced by slight underestimation. Further, in the EEP, the effect of NT is strongly reduced, corresponding now to an oxygen underestimation of less than 20 mmol $O_2\,m^{-3}$.

[14] Associated with the improved representation of oxygen in the eastern tropical Pacific, we find a change in pelagic denitrification rates. The simulation REF features a global total of 151 TgN y^{-1} while the simulation D5 features 105 TgN y^{-1} only. This change is effected by a reduced volume of suboxic water in D5, which catches comparably less export that is then denitrified.

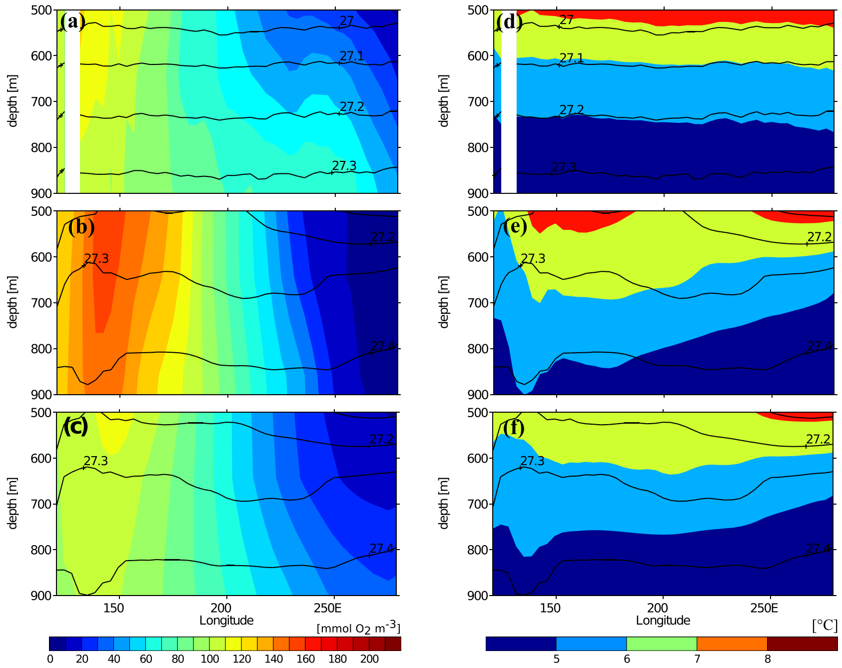

Figure 3. (a–c) Zonal section of oxygen (colored contours) and σ_0 (black lines) averaged between 5°S and 5°N. Figure 3a refers to observations [*Bianchi et al.*, 2012; *Locarnini et al.*, 2006; *Antonov et al.*, 2006], Figure 3b to the reference simulation (REF) and Figure 3c to the simulation with the added isopycnal anisoptropic zonal diffusivity of 50,000 $m^2 s^{-1}$ (D5). (d–f) Zonal section of temperature (colored contours) and σ_0 (black lines) averaged between 5°S and 5°N. Figure 3d refers to observations [*Locarnini et al.*, 2006; *Antonov et al.*, 2006], Figure 3e to REF and Figure 3f, D5.

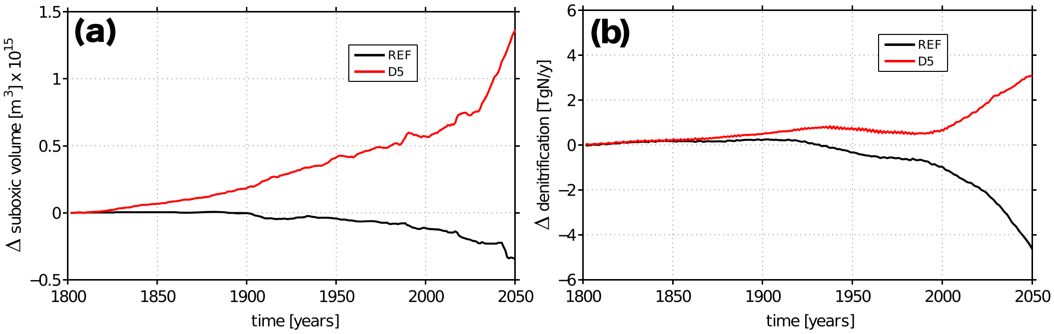

Figure 4. Anomaly of Pacific (a) suboxic volume (defined as water hosting less than 10 mmol O_2 m^{-3}) and (b) denitrification rate. In Figures 4a and 4b, the reference simulation (black) and the simulation with the added isopycnal anisotropic zonal diffusivity of 50,000 m^2s^{-1} (red) are referenced to the quasi-equilibrated state prior to 1800.

[15] In addition to the simulated biogeochemistry, as expressed by oxygen misfits to observations, the model physics does also improve. Figures 3d and 3e show that the reference simulation features spurious zonal temperature gradients on both isopycnals and surfaces of constant depth. In the D5 simulation, these gradients are reduced and appear more realistic (Figure 3f).

[16] All these improvements of the quasi-equilibrated state of the earth system climate model discussed here, raise the question if the model's response to anthropogenic carbon emissions has changed as well. To this end, we compare two simulations branched off the quasi-equilibrated state of the reference and the D5 configuration, respectively. Both are forced by carbon emissions corresponding to the IPCC A2 SRES scenario (see section 2).

[17] Surprisingly, most measures exhibited only minor changes between the two projections (e.g., the cumulative air-sea flux of carbon differs by less than 1% in the period 1801 to 2100 among the two projections). In contrast, the evolution of the suboxic volume, defined here as water hosting less than 10 mmol m^{-3} O_2, does differ dramatically. The reference configuration predicts a decrease of the suboxic volume while the prediction based on D5 shows an increase of similar magnitude (Figure 4a). Consequently, the predictions of total global pelagic denitrification also differ (Figure 4b). In the reference simulation, the increase of the suboxic volume is associated with a reduced area hosting denitrification and, hence, the denitrification rates decline. The opposite holds in the D5 configuration where an increase of the suboxic volume causes a shift from oxic remineralization to denitrification. Note that the simple relationship between a larger suboxic volume hosting increased rates of denitrification breaks down after 2050 (not shown) when global export production patterns change and modulate the export of organic matter to the suboxic zones.

4. Summary and Conclusion

[18] A general problem of earth system climate models is a notorious overestimation of phosphate in the eastern equatorial Pacific dubbed "nutrient trapping" (NT). In our reference model configuration, coupled by a Redfield ratio, this problem has an oxygen counterpart, i.e., a spurious oxygen deficit which host a significant fraction of the 151 TgN y^{-1} simulated global pelagic denitrification rates. Stimulated by *Dietze and Loeptien* [2013], who suggest that the NT problem is associated with a deficient representation of the Equatorial Intermediate Current System (EICS), we mimic the unresolved effect of the EICS with a crude parameterization. We find that the addition of a zonal, anisotropic, isopycnal diffusivity of 50, 000 m^2 s^{-1} (our D5 simulation) below the Equatorial Undercurrent between 5°S and 5°N latitude improves the simulation of oxygen, temperature, and salinity globally. Further, it reduces (1) spurious zonal temperature gradients on both isopycnals and surfaces of constant depth, and (2) spurious zonal oxygen gradients. The latter improvement is associated with a more realistic distribution of suboxia in the ocean and, in turn, effects a 46 TgN y^{-1} lower global pelagic denitrification rate of 105 TgN y^{-1}, a value that is closer to the recent estimates (52 ± 14 TgN y^{-1} by *Eugster and Gruber* [2012]; 70 ± 50 TgN y^{-1} by *Bianchi et al.* [2012]).

[19] As with respect to climate projections, the UVic earth system model appears rather insensitive towards even massive increases of the zonal isopycnal diffusivity. In this prospective, the simulation of pelagic suboxia, which hosts denitrification, is an exception. The reference configuration projects a decrease of the suboxic volume in a warming climate. This result, while common in state-of-the art models, is difficult to reconcile with observations [*Stramma et al.*, 2012]. Contrary to the reference simulation, the addition of diffusivity mimicking the effect of the unresolved EICS induces an increase in the modeled suboxic volume and associated denitrification. This appears more plausible since the oceanic stratification increases and oxygen solubility decreases in a warming world. Because the combined effect of a decreased solubility and an increased oceanic stratification hinders the ventilation of the ocean, it is straightforward to assume that the oxygen concentrations decrease and suboxia, which hosts denitrification, increases. In conclusion, for the time being, we advocate the use of an increased zonal diffusivity in the deep equatorial band of the Pacific Ocean in earth system models that aim to simulate dissolved oxygen. However, it remains to be seen if such an approach is also dynamically consistent with the transport associated with the EICS.

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References

Antonov, J. I., R. A. Locarnini, T. P. Boyer, A. V. Mishonov, H. E. Garcia (2006), World Ocean Atlas 2005, Volume 2: Salinity, in *NOAA Atlas NESDIS*, vol. 62, edited by S. Levitus, 182 pp., U.S. Government Printing Office, Washington, D.C.

Ascani, F., E. Firing, P. Dutrieux, J. P. McCreary, and A. Ishida (2010), Deep equatorial ocean circulation induced by a forced-dissipated Yanai beam, *J. Phys. Oceanogr.*, *40*(5), 1118–1142.

Bianchi, D., J. P. Dunne, J. L. Sarmiento, and E. D. Galbraith (2012), Data-based estimates of suboxia, denitrification, and N_2O production in the ocean and their sensitivities to dissolved O_2, *Global Biogeochem. Cycles*, *26*, GB2009, 13 pp., doi:10.1029/2011GB004209.

Cravatte, S., W. Kessler, and F. Marin (2012), Intermediate zonal jets in the tropical pacific ocean observed by argo floats, *J. Phys. Oceanogr.*, *42*(9), 1475–1485.

Dietze, H., and U. Loeptien (2013), Revisiting “nutrient trapping” in global biogeochemical ocean circulation models, *Global Biogeochem. Cy.*, 1–20, doi:10.1002/gbc.20029.

Eugster, O., and N. Gruber (2012), A probabilistic estimate of global marine N-fixation and denitrification, *Global Biogeochem. Cycles*, *26*, GB4013, doi:10.1029/2012GB004300.

Lebedev, K. V., H. Yoshinari, N. A. Maximenko, and P. W. Hacker, (2007), Yomaha’07: Velocity data assessed from trajectories of argo floats at parking level and at the sea surface, *IPRC Technical Note 4(2)*.

Kanzow, T., et al. (2010), Seasonal variability of the atlantic meridional overturning circulation at 26.5° N, *J. Climate*, *23*, 5678–5698, http://dx.doi.org/10.1175/2010JCLI3389.1.

Keller, D., A. Oschlies, and M. Eby (2012), A new marine ecosystem model for the University of Victoria Earth System Climate Model, *Geosci. Model Dev.*, *5*, 1195–1220, doi:10.5194/gmd-5-1195-2012.

Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, H. E. Garcia (2006), World Ocean Atlas 2005, Volume 1: Temperature, in *NOAA Atlas NESDIS*, vol. 61, edited by S. Levitus, 182 pp., U.S. Government Printing Office, Washington, D.C.

Najjar, R., J. Sarmiento, and J. Toggweiler (1992), Downward transport and fate of organic matter in the ocean: Simulations with a general circulation model, *Global Biogeochem. Cycles*, *6*(1), 45–76.

Nakicenovic, N., et al. (2000), Special report on emissions scenarios: A special report of working group III of the intergovernmental panel on climate change. Other information: Pbd: 3 Oct 2000.

Pacanowski, R. C., (1995), MOM 2 documentation, user’s guide and reference manual, *Tech. Rep. 3*, GFDL Ocean Group.

Stramma, L., A. Oschlies, and S. Schmidtko (2012), Mismatch between observed and modeled trends in dissolved upper-ocean oxygen over the last 50 yr, *Biogeosciences*, *9*, 4045–4057, doi:10.5194/bg-9-4045-2012.

Weaver, A. J., et al. (2001), The UVic earth system climate model: Model description, climatology, and applications to past, present and future climates, *Atmos. Ocean*, *39*, 361–428.