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Comment on "Could the Late Permian deep ocean have been anoxic?" by R. Zhang et al.

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[1] *Zhang et al.* [2001] present results of a three-dimensional (3-D) biogeochemical ocean model for the Permian and suggest that a low-meridional temperature gradient is insufficient to cause deep water anoxia unless the hydrologic cycle was strongly perturbed to cause a "haline" mode of ocean circulation.

[2] These results stand in stark contrast to the results of *Hotinski et al.* [2001], in which a low equator-to-pole gradient was found to substantially lower deep water oxygen levels without a haline circulation. Zhang et al. comment that the difference between our results "probably lies in the details of their biogeochemical model in which negative oxygen concentrations are allowed when oxidation of organic matter occurs in the absence of dissolved oxygen" and that these negative oxygen concentrations diffuse downward and cause artificial anoxic conditions in the abyss. We respectfully disagree and hold that the differences between our model results are in large part the result of dissimilar definitions of "weak" or "reduced" meridional temperature gradients, and that negative oxygen values provide oxygen balance in any biogeochemical model that includes anaerobic remineralization of organic matter with unspecified oxidants.

[3] The most obvious difference between the two Late Permian "low-gradient" simulations is the selection of sea-surface temperatures with which the models are forced. For their "weak-gradient," Zhang et al. use zonally averaged surface temperatures derived from a climate model for the Permian using 5 × $p\mathrm{CO}_2$ and a 1% reduction in solar luminosity [*Kutzbach and Gallimore*, 1989; *Kutzbach et al.*, 1990]. Surface temperatures average less than 0°C at 70° south and are not consistent with the "equable" climates previously invoked as causes of sluggish ocean circulation and anoxia [e.g., *Wignall and Twitchett*, 1996; *Knoll et al.*, 1996].

[4] In fact, the Zhang et al. "weak" gradient temperatures are akin to the Hotinski et al. "high-gradient" surface temperature forcing derived from a Late Permian climate simulation by *Rees et al.* [1999] with 8 × $p\mathrm{CO}_2$ and a 2.1% reduction in solar luminosity (note that a doubling of $p\mathrm{CO}_2$ is roughly equivalent to a 2% change in solar luminosity [*Wetherald and Manabe*, 1975]). This high-gradient scenario was so named because of its rough similarity to the modern gradient and, like the Zhang et al. forcing, it produced a vigorous ocean circulation and well-oxygenated deep waters [*Hotinski et al.*, 2001, Figures 2a and 3b].

[5] In contrast, the Hotinski et al. "reduced-gradient" ocean simulation was forced with a zonally symmetric meridional sea-surface temperature profile with polar temperatures of 12°C, a forcing derived from estimates of the SST's during the analogous Late Paleocene Thermal Maximum [*Bice and Marotzke*, 2001]. In addition to producing lower oxygen saturation concentrations in newly formed deep waters, this temperature forcing difference results in substantially reduced meridional overturning and increased drawdown of high-latitude phosphate concentrations. *Hotinski et al.* [2001] argued that this combination of lowered O_2 in surface waters and increased export of phosphate and organic carbon to deep waters created anoxia in the simulated deep Permian ocean.

[6] Finally, we suggest the negative oxygen values that Zhang et al. cite as a deficiency in our model are in fact necessary for balancing the oxygen budget of the ocean if oxidants other than oxygen are not explicitly modeled.

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Both models specify that, regardless of the oxygen concentration, organic matter is remineralized according to a fixed, depth-dependent profile below the photic zone with O_2 depleted in fixed proportion to phosphate released. In the Hotinski et al. model, negative oxygen values represent the reduced species created when other oxidants are used to remineralize organic matter after oxygen is completely used up in a particular grid cell. These reduced species (primarily H_2S) can be transported and deplete dissolved oxygen elsewhere, a process that is represented by the advection and diffusion of negative O_2. (Note that denitrification may not be realistically modeled in this fashion due to spatial separation of remineralization and oxygen utilization as O_2 is depleted in the photic zone where nitrogen is fixed, rather than in deep waters where remineralization occurs. However, nitrate is a small reservoir compared to sulfate and contributes only ~60 of the 350 micromolar oxygen deficit in intermediate waters that could influence deep ocean oxygen).

[7] Because Zhang et al. do not let oxygen concentrations fall below zero, yet continue to remineralize organic matter once oxygen is depleted, they imply use of other oxidants but do not keep track of the oxygen-reducing potential of the reduced products. Neglect of this potential artificially elevates deep ocean oxygen levels and probably contributes to differences in our results.

[8] In summary, it seems that the differences between the Hotinski et al. and Zhang et al. results are a product of very different "weak-gradient" surface forcings as well as of treatment of reductants produced by anaerobic remineralization of organic matter. Rather than being unrealistic, however, we feel that inclusion of negative oxygen values provides balance in the oxygen cycle that prevents overestimates of deep water oxygen levels.

References

Bice, K. L., and J. Marotzke, Numerical evidence against reversed thermohaline circulation in the warm Paleocene/Eocene ocean, *J. Geophys. Res.*, *106*(C6), 11,529–11,542, 2001.

Hotinski, R. M., K. L. Bice, L. R. Kump, R. G. Najjar, and M. A. Arthur, Ocean stagnation and end-Permian anoxia, *Geology*, *29*(1), 7–10, 2001.

Knoll, A. H., R. K. Bambach, D. E. Canfield, and J. P. Grotzinger, Comparative Earth history and Late Permian mass extinction, *Science*, *276*, 235–238, 1996.

Kutzbach, J. E., and R. G. Gallimore, Pangean climates: Megamonsoons of the megacontinent, *J. Geophys. Res*, *94*(D3), 334–3357, 1989.

Kutzbach, J. E., P. J. Guetter, and W. M. Washington, Simulated ocean circulation for Pangean time, *Paleoceanography*, *5*, 267–279, 1990.

Rees, P. M., M. T. Gibbs, A. M. Ziegler, J. E. Kutzbach, and P. J. Behling, Permian climates; evaluating model predictions using global paleobotanical data, *Geology*, *27*(10), 891–894, 1999.

Wetherald, R. T., and S. Manabe, The effect of changing the solar constant on the climate of a general circulation model, *J. Atmos. Sci.*, *32*, 2044–2059, 1975.

Wignall, P. B., and R. J. Twitchett, Oceanic anoxia and the end Permian mass extinction, *Science*, *272*, 1155–1158, 1996.

Zhang, R., M. J. Follows, J. P. Grotzinger, and J. Marshall, Could the Late Permian ocean have been anoxic?, *Paleoceanography*, *16*(3), 317–329, 2001.

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