2014, *Oceanography* 27(1):108–119, http://dx.doi.org/10.5670/oceanog.2014.14

Historical and Future Trends in Ocean Climate and Biogeochemistry

Authors | Abstract | Full Article | Citation | References

Authors

Scott C. Doney | Marine Chemistry & Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Laurent Bopp | Centre National de la Recherche Scientifique, Le Laboratoire des Sciences du Climat et l'Environnement, Gif-sur-Yvette, France

Matthew C. Long | Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO, USA

Top

Abstract

Changing atmospheric composition due to human activities, primarily carbon dioxide (CO_2) emissions from fossil fuel burning, is already impacting ocean circulation, biogeochemistry, and ecology, and model projections indicate that observed trends will continue or even accelerate over this century. Elevated atmospheric CO_2 alters Earth's radiative balance, leading to global-scale warming and climate change. The ocean stores the majority of resulting anomalous heat, which in turn drives other physical, chemical, and biological impacts. Sea surface warming and increased ocean vertical stratification are projected to reduce global-integrated primary production and export flux as well as to lower subsurface dissolved oxygen concentrations. Upper trophic levels will be affected both directly by warming and indirectly from changes in productivity and expanding low oxygen zones. The ocean also absorbs roughly one-quarter of present-day anthropogenic CO_2 emissions. The resulting changes in seawater chemistry, termed ocean acidification, include declining pH and saturation state for calcium carbon minerals that may have widespread impacts on many marine organisms. Climate warming will likely slow ocean CO_2 uptake but is not expected to significantly reduce upper ocean acidification. Improving the accuracy of future model projections requires better observational constraints on current rates of ocean change and a better understanding of the mechanisms controlling key physical and biogeochemical processes.

Top

Full Article

1.41 MB pdf

Top

Citation

Doney, S.C., L. Bopp, and M.C. Long. 2014. Historical and future trends in ocean climate and biogeochemistry. *Oceanography* 27(1):108–119, http://dx.doi.org/10.5670/oceanog.2014.14.

Top

References

Arora, V., G. Boer, P. Friedlingstein, M. Eby, C. Jones, J. Christian, G. Bonan, L. Bopp, V. Brovkin, P. Cadule, and others. 2013. Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models. *Journal of Climate* 26:5,289–5,314, http://dx.doi.org/10.1175/JCLI-D-12-00494.1.

Balmaseda, M.A., K.E. Trenberth, and E. Källén. 2013. Distinctive climate signals in reanalysis of global ocean heat content. *Geophysical Research Letters* 40:1,754–1,759, http://dx.doi.org/10.1002/grl.50382.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. *Nature* 444:752–755, http://dx.doi.org/10.1038/nature05317.

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 oxygen. *Global Biogeochemical Cycles* 26, GB2009, http://dx.doi.org/10.1029/2011GB004209.

Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, and others. 2007. Observations: Oceanic climate change and sea level. Pp. 385–432 in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on*

Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Bopp, L., C. Le Quéré, M. Heimann, A.C. Manning, and P. Monfray. 2002. Climate induced oceanic oxygen fluxes: Implications for the contemporary carbon budget. *Global Biogeochemical Cycles* 16(2), 1022, http://dx.doi.org/10.1029/2001GB001445.

Bopp, L., P. Monfray, O. Aumont, J.L. Dufresne, H. Le Treut, G. Madec, L. Terray, and J.C. Orr. 2001. Potential impact of climate change on marine export production. *Global Biogeochemical Cycles* 15:81–99, http://dx.doi.org/10.1029/1999GB001256.

Bopp, L., L. Resplandy, J.C. Orr, S.C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, and others. 2013. Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences* 10:6,225–6,245, http://dx.doi.org/10.5194/bgd-10-3627-2013.

Brewer, P.G., and E.T. Peltzer. 2009. Limits to marine life. *Science* 324:347–348, http://dx.doi.org/10.1126/science.1170756.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, and D. Pauly. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries* 4:235–251, http://dx.doi.org/10.1111/j.1467-2979.2008.00315.x.

Comiso, J.C., 2011. Large decadal decline of the Arctic multiyear ice cover. *Journal of Climate* 25:1,176-1,193, http://dx.doi.org/10.1175/JCLI-D-11-00113.1.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, and others. 2007. Couplings between changes in the climate system and biogeochemistry. Pp. 499–587 in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Diaz, R.J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321:926–929, http://dx.doi.org/10.1126/science.1156401.

Doney, S.C. 2010. The growing human footprint on coastal and open-ocean biogeochemistry. *Science* 328:1,512–1,516, http://dx.doi.org/10.1126/science.1185198.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas. 2009. Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science* 1:169–192, http://dx.doi.org/10.1146/annurev.marine.010908.163834.

Doney, S.C., M. Ruckelshaus, J.E. Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, and others. 2012. Climate change impacts on marine ecosystems. *Annual Review of Marine Science* 4:11–37, http://dx.doi.org/10.1146/annurev-marine-041911-111611.

Dore, J.E., R. Lukas, D.W. Sadler, M.J. Church, and D.M. Karl. 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proceedings of the National Academy of Sciences of the United States of America* 106:12,235–12,240, http://dx.doi.org/10.1073/pnas.0906044106.

Dlugokencky, E., and P. Tans. 2013. NOAA/ESRL Global CO_2 Data. http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html.

Feely, R.A., S.R. Alin, J. Newton, C.L. Sabine, M. Warner, A. Devol, C. Krembs, and C. Maloy. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science* 88:442–449, http://dx.doi.org/10.1016/j.ecss.2010.05.004.

Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* 320:1,490–1,492, http://dx.doi.org/10.1126/science.1155676.

Foster, G., and S. Rahmstorf. 2011. Global temperature evolution 1979–2010. *Environmental Research Letters* 6, 044022, http://dx.doi.org/10.1088/1748-9326/6/4/044022.

Frölicher, T.L., F. Joos, G.-K. Plattner, M. Steinacher, and S.C. Doney. 2009. Natural variability and anthropogenic trends in oceanic oxygen in a coupled carbon cycle-climate model ensemble. *Global Biogeochemical Cycles* 23, GB1003, http://dx.doi.org/10.1029/2008GB003316.

Gattuso, J.P., and L. Hansson, eds. 2011. *Ocean Acidification*. Oxford University Press, Oxford UK, 326 pp.

Gehlen, M., N. Gruber, R. Gangstø, L. Bopp, and A. Oschlies. 2011. Biogeochemical consequences of ocean acidification and feedbacks to the Earth system. Pp. 230–248 in *Ocean Acidification*. J.P. Gattuso and L. Hansson, eds, Oxford University Press, Oxford, UK.

Gruber, N. 2011. Warming up, turning sour, losing breath: Ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society A* 369:1,980–1,996, http://dx.doi.org/10.1098/rsta.2011.0003.

Gruber, N., H. Frenzel, S.C. Doney, P. Marchesiello, J.C. McWilliams, J.R. Moisan, J.J. Oram, G.-K. Plattner, and K.D. Stolzenbach. 2006. Eddy-resolving simulation of plankton ecosystem dynamics in the California Current System. *Deep-Sea Research Part I* 53:1,483–1,516, http://dx.doi.org/10.1016/j.dsr.2006.06.005.

Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T.L. Frölicher, and G.-K. Plattner. 2012. Rapid progression of ocean acidification in the California current system. *Science* 337:220–223, http://dx.doi.org/10.1126/science.1216773.

Harvell, C.D., C.E. Mitchell, J.R. Ward, S. Altizer, A.P. Dobson, R.S. Ostfeld, and M.D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* 296:2,158–2,162, http://dx.doi.org/10.1126/science.1063699.

Helm, K.P., N.L. Bindoff, and J.A. Church. 2011. Observed decreases in oxygen content of the global ocean. *Geophysical Research Letters* 38, L23602, http://dx.doi.org/10.1029/2011GL049513.

Henson, S.A., J.L. Sarmiento, J.P. Dunne, L. Bopp, I. Lima, S.C. Doney, J. John, and C. Beaulieu. 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences* 7:621–640, http://dx.doi.org/10.5194/bg-7-621-2010.

Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R. Zeebe, L. Kump, R.C. Martindale, S.E. Greene, and others. 2012. The geological record of ocean acidification. *Science* 335:1,058–1,063, http://dx.doi.org/10.1126/science.1208277.

Keeling, R.F., A. Körtzinger, and N. Gruber. 2010. Ocean deoxygenation in a warming world. *Annual Review of Marine Science* 2:199–229, http://dx.doi.org/10.1146/annurev.marine.010908.163855.

Kennedy, J., P. Thorne, T. Peterson, R. Reudy, P. Stott, D. Parker, S. Good, H. Titchner, and K. Willett. 2010. How do we know the world has warmed? Pp. S26–S27 in State of the Climate in 2009. D.S. Arndt, M.O. Baringer, and M.R. Johnson, eds, Special supplement to the *Bulletin of the American Meteorological Society*, vol. 91.

Kosaka, Y., and S.-P. Xie. 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature* 501:403–407, http://dx.doi.org/10.1038/nature12534.

Kwok, R., and D.A. Rothrock. 2009. Decline in Arctic sea ice thickness from submarine and ICESat records:1958–2008. *Geophysical Research Letters* 36, L15501, http://dx.doi.org/10.1029/2009GL039035.

Le Quéré, C., R.J. Andres, T. Boden, T. Conway, R.A. Houghton, J.I. House, G. Marland, G.P. Peters, G.R. van der Werf, A. Ahlström, and others. 2013. The global carbon budget 1959–2011. *Earth System Science Data* 5:165–185, http://dx.doi.org/10.5194/essd-5-165-2013.

Le Quéré, C., T. Takahashi, E.T. Buitenhuis, C. Rödenbeck, and S.C. Sutherland. 2010. Impact of climate change and variability on the global oceanic sink of CO_2. *Global Biogeochemical Cycles* 24:GB4007, http://dx.doi.org/10.1029/2009GB003599.

Levin, L.A., W. Ekau, A.J. Gooday, F. Jorissen, J.J. Middelburg, S.W.A. Naqvi, C. Neira, N.N. Rabalais, and J. Zhang. 2009. Effects of natural and human-induced hypoxia on coastal benthos. *Biogeosciences 6*:2,063–2,098, http://dx.doi.org/10.5194/bg-6-2063-2009.

Levitus, S., J.I. Antonov, T.P. Boyer, O.K. Baranova, H.E. Garcia, R.A. Locarnini, A.V. Mishonov, J.R. Reagan, D. Seidov, E.S. Yarosh, and M.M. Zweng. 2012. World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters* 39, L10603, http://dx.doi.org/10.1029/2012GL051106.

MacFarling Meure, C., D. Etheridge, C. Trudinger, P. Steele, R. Langenfelds, T. van Ommen, A. Smith, and J. Elkins. 2006. Law Dome CO_2, CH_4 and N_2O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33, L14810, http://dx.doi.org/10.1029/2006GL026152.

Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix. 2013. A reconstruction of regional and global temperature for the past 11,300 years. *Science* 339:1,198–1,201, http://dx.doi.org/10.1126/science.1228026.

Marinov, I., S.C. Doney, and I.D. Lima. 2010. Response of ocean phytoplankton community structure to climate change over the 21st century: Partitioning the effects of nutrients, temperature and light. *Biogeosciences* 7:3,941–3,959, http://dx.doi.org/10.5194/bg-7-3941-2010.

Meehl, G.A., J. Arblaster, J. Fasullo, A. Hu, and K. Trenberth. 2011. Model based evidence of deep ocean heat uptake during surface temperature hiatus periods. *Nature Climate Change* 1:360–364, http://dx.doi.org/10.1038/nclimate1229.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, and others. 2007. Global climate projections. Pp. 747–845 in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Nye, J.A., J.S. Link, J.A. Hare, and W.J. Overholtz. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series* 393:111–129, http://dx.doi.org/10.3354/meps08220.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, and others. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on marine calcifying organisms. *Nature* 437:681–686, http://dx.doi.org/10.1038/nature04095.

Paulmier, A., and D. Ruiz-Pino. 2009. Oxygen minimum zones (OMZs) in the modern ocean. *Progress in Oceanography* 80:113–128, http://dx.doi.org/10.1016/j.pocean.2008.08.001.

Polovina, J.J., E.A. Howell, and M. Abecassis. 2008. Ocean's least productive waters are expanding. *Geophysical Research Letters*, 35, L03618, http://dx.doi.org/10.1029/2007GL031745.

Pörtner, H.O., and A.P. Farrell. 2008. Physiology and climate change. *Science* 322:690–692, http://dx.doi.org/10.1126/science.1163156.

Purkey, S.G., and G.C. Johnson. 2010. Warming of global abyssal and deep southern ocean between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *Journal of Climate* 23:6,336–6,351, http://dx.doi.org/10.1175/2010JCLI3682.1.

Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang. 2010. Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences* 7:585–619, http://dx.doi.org/10.5194/bg-7-585-2010.

Sabine, C.L., and T. Tanhua. 2010. Estimation of anthropogenic CO_2 inventories in the ocean. *Annual Review of Marine Science* 2:175–198, http://dx.doi.org/10.1146/annurev-marine-120308-080947.

Sarmiento, J., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, and others. 2004. Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles* 18, GB3003, http://dx.doi.org/10.1029/2003GB002134.

Siegel, D.A., M.J. Behrenfeld, S. Maritorena, C.R. McClain, D. Antoine, S.W. Bailey, P.S. Bontempi, E.S. Boss, H.M. Dierssen, S.C. Doney, and others. 2013. Regional to global assessments of phytoplankton dynamics from the SeaWiFS mission. *Remote Sensing of Environment* 135:77–91, http://dx.doi.org/10.1016/j.rse.2013.03.025.

Smith, T.M., R.W. Reynolds, T.C. Peterson, and J. Lawrimore. 2008. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). *Journal of Climate* 21:2,283–2,296, http://dx.doi.org/10.1175/2007JCLI2100.1.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, and others. 2007. Technical summary. Pp. 19–91 in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Somero, G.N. 2012. The physiology of global change: Linking patterns to mechanisms. *Annual Review of Marine Science* 4:39–61, http://dx.doi.org/10.1146/annurev-marine-120710-100935.

Steinacher, M., F. Joos, T.L. Frölicher, L. Bopp, P. Cadule, V. Cocco, S.C. Doney, M. Gehlen, K. Lindsay, J.K. Moore, and others. 2010. Projected 21st century decrease in marine productivity: A multi-model analysis. *Biogeosciences* 7:979–1,005, http://dx.doi.org/10.5194/bg-7-979-2010.

Steinacher, M., F. Joos, T.L. Frölicher, G.-K. Plattner, and S.C. Doney. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences* 6:515–533, http://dx.doi.org/10.5194/bg-6-515-2009.

Stramma, L., G.C. Johnson, J. Sprintall, and V. Mohrholz. 2008. Expanding oxygen-minimum zones in the tropical oceans. *Science* 320:655–658, http://dx.doi.org/10.1126/science.1153847.

Stramma, L., E.D. Prince, S. Schmidtko, J. Luo, J.P. Hoolihan, M. Visbeck, D.W.R. Wallace, P. Brandt, and A. Körtzinger. 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic fishes. *Nature Climate Change* 2:33–37, http://dx.doi.org/10.1038/nclimate1304.

Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier. 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters* 39, L16502, http://dx.doi.org/10.1029/2012GL052676.

Tans, P., and R. Keeling. 2012. Trends in atmospheric carbon dioxide, full Mauna Loa CO_2 record. http://www.esrl.noaa.gov/gmd/ccgg/trends.

van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, and others. 2011. The representative concentration pathways: An overview. *Climatic Change* 109:5–31, http://dx.doi.org/10.1007/s10584-011-0148-z.

Walsh, J.E., and W.L. Chapman. 2001. 20th-century sea ice variations from observational data. *Annals of Glaciology* 33:444–448, http://dx.doi.org/10.3189/172756401781818671.

Wang, M., and J.E. Overland. 2012. A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters* 39, L18501, http://dx.doi.org/10.1029/2012GL052868.

Ward, J.R., and K.D. Lafferty. 2004. The elusive baseline of marine disease: Are diseases in ocean ecosystems increasing? *PLoS Biology* 2:e120, http://dx.doi.org/10.1371/journal.pbio.0020120.

Whitney, F.A., H.J. Freeland, and M. Robert, 2007. Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. *Progress in Oceanography* 75:179–199, http://dx.doi.org/10.1016/j.pocean.2007.08.007.

Top

Oceanography Magazine, The Oceanography Society, P.O. Box 1931, Rockville, MD 20849-1931, USA
Tel: (1) 301-251-7708, Fax: (1) 301-251-7709, E-mail: **magazine@tos.org**
Send comments about this site to **webmaster@tos.org**