Response of Marine Plants to Changes in Temperature

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RESPONSE OF MARINE PLANTS TO CHANGES IN TEMPERATURE

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According to the IPCC, CO_2-induced global warming will be net harmful to the world's marine species. One consequence of such harm, is a projected decline in ocean productivity. And in light of what the IPCC frequently refers to as the unprecedented modern rise in global temperature, it might reasonably be expected there should already be signs of a major negative impact on oceanic productivity. Yet the studies highlighted in this summary yield little evidence in support of the IPCC point of view.

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Sarmiento *et al*. (2004)[1] conducted a massive computational study that employed six coupled climate model simulations to determine the biological response of the global ocean to the climate warming they simulated from the beginning of the Industrial Revolution to the year 2050. Based on vertical velocity, maximum winter mixed-layer depth and sea-ice cover, they defined six biomes and calculated how their surface geographies would change in response to their calculated changes in global climate. Next, they used satellite ocean color and climatological observations to develop an empirical model for predicting surface chlorophyll concentrations from the final physical properties of the world's oceans as derived from their global warming simulations, after which they used three primary production algorithms to estimate the response of oceanic primary production to climate warming based on their calculated chlorophyll concentrations. When all was said and done, the thirteen scientists from Australia, France, Germany, Russia, the United Kingdom and the United States arrived at a global warming-induced increase in global ocean primary production that ranged from 0.7 to 8.1%.

In addition to Sarmiento *et al*.'s model-based study, a number of real-world *observations* also suggest the IPCC's concern of future declines in ocean productivity in response to rising temperatures are unfounded.

[1] http://www.co2science.org/articles/V7/N42/B2.php.

Drinkwater (2006)[2] examined marine ecosystems of the North Atlantic, determining "in the 1920s and 1930s, there was a dramatic warming of the air and ocean temperatures in the northern North Atlantic and the high Arctic, with the largest changes occurring north of 60°N," which warming "led to reduced ice cover in the Arctic and subarctic regions and higher sea temperatures," as well as northward shifts of multiple marine ecosystems. Accordingly, this early twentieth century warming "contributed to higher primary and secondary production," in the words of the author, and "with the reduced extent of ice-covered waters, more open water allow[ed] for higher production than in the colder periods."

Goes *et al*. (2005)[3] analyzed seven years (1997-2004) of satellite-derived ocean surface phytoplanktpon productivity data, as well as associated sea surface temperatures (SSTs) and winds in the Arabian Sea. They report for the region located between 52 to 57°E and 5 to 10°N, "the most conspicuous observation was the consistent year-by-year increase in phytoplankton biomass over the 7-year period." This change was so significant that by the summer of 2003, in their words, "chlorophyll *a* concentrations were >350% higher than those observed in the summer of 1997." They also report the increase in chlorophyll *a* was "accompanied by an intensification of sea surface winds, in particular of the zonal (east-to-west) component," noting these "summer monsoon winds are a coupled atmosphere-land-ocean phenomenon, whose strength is significantly correlated with tropical SSTs and Eurasian snow cover anomalies on a year-to-year basis." More specifically, they say "reduced snow cover over Eurasia strengthens the spring and summer land-sea thermal contrast and is considered to be responsible for the stronger southwest monsoon winds." In addition, they state "the influence of southwest monsoon winds on phytoplankton in the Arabian Sea is not through their impact on coastal upwelling alone but also via the ability of zonal winds to laterally advect newly upwelled nutrient-rich waters to regions away from the upwelling zone." Their final conclusion about the matter is "escalation in the intensity of summer monsoon winds, accompanied by enhanced upwelling and an increase of more than 350% in average summertime phytoplankton biomass along the coast and over 300% offshore, raises the possibility that the current warming trend of the Eurasian landmass is making the Arabian Sea more productive."

In setting the stage for a study conducted off the other side of the African continent, McGregor *et al*. (2007)[4] say "coastal upwelling occurs along the eastern margins of major ocean basins and develops when predominantly along-shore winds force offshore Ekman transport of surface waters, which leads to the ascending (or upwelling) of cooler, nutrient-rich water." In addition, they note these regions of coastal upwelling account for about 20% of the global fish catch while constituting less than 1% of the area covered by the world's oceans. Thus, in an attempt to better understand the nature of this productivity-enhancing phenomenon of great practical and economic significance, they studied it's long-term history along the northwest coast of Africa-in the heart of the Cape Ghir upwelling system off the coast of Morocco-by analyzing two sediment cores having decadal-or-better resolution that extend from the late Holocene to the end of the twentieth century, i.e., from 520 BC to AD 1998.

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2 http://www.co2science.org/articles/V9/N14/C2.php.

3 http://www.co2science.org/articles/V8/N33/B2.php.

4 http://www.co2science.org/articles/V10/N19/EDIT.php.

An anomalous cooling of sea surface temperatures during the twentieth century was found, which the four researchers say "is consistent with increased upwelling." In addition, they note the "upwelling-driven sea surface temperatures also vary out of phase with millennial-scale changes in Northern Hemisphere temperature anomalies and show relatively warm conditions during the Little Ice Age and relatively cool conditions during the Medieval Warm Period." In discussing how this happens, one potential scenario posed by McGregor *et al*. starts with an impetus for warming that leads to near-surface air temperatures over land becoming warmer than those over the ocean. The greater warming over the land then "deepens the thermal low-pressure cell over land while a higher-pressure center develops over the slower-warming ocean waters." As this occurs, "winds blow clockwise around the high and anticlockwise around the continental low." With the coast representing the boundary between the two centers, the resulting wind is "oriented alongshore and southward (equator-ward), which thus drives the upwelling and negative sea surface temperature anomalies."

In addition to *their* observations of this phenomenon, McGregor *et al*. state similar anti-phased thermal behavior-i.e., the *cooling* of coastal waters that leads to enhanced coastal upwelling during periods of hemispheric or global *warming*-has been observed in the Arabian Sea and along the Iberian margin, as well as in parts of the California Current and the Peru-Chile Current. Consequently, it would appear that by enhancing the upwelling of cooler nutrient-rich waters along the eastern margins of major ocean basins, global warming helps to significantly enhance global-ocean primary productivity, which leads in turn to an increase in global-ocean secondary productivity, as represented by the global fish catch.

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Boyd *et al*. (2007)[5] reported somewhat analogous findings in their major review of iron enrichment experiments conducted between 1993 and 2005, which experiments conclusively demonstrate, in their words, "phytoplankton grow faster in warmer open-ocean waters, as predicted by algal physiological relationships." This conglomerate of results indicates total ocean productivity should have benefited immensely from twentieth century global warming, and that it will likely continue to benefit from continued global warming.

[5] http://www.co2science.org/articles/V10/N19/EDIT.php.

Marasovic *et al*. (2005)[6] analyzed monthly observations of basic hydrographic, chemical and biological parameters, including primary production, that had been made since the 1960s at two oceanographic stations, one near the coast (Kastela Bay) and one in the middle Adriatic Sea. They found mean annual primary production in Kastela Bay averaged about 430 mg C m^{-2} d^{-1} over the period 1962-72, exceeded 600 mg C m^{-2} d^{-1} over the period 1972-82, and rose to over 700 mg C m^{-2} d^{-1} over the period 1982-96, accompanied by a similar upward trend in percent oxygen saturation of the surface water. The initial value of primary production in the open sea was much less (approximately 150 mg C m^{-2} d^{-1}), but it began to follow the upward trend of the Kastela Bay data after about one decade. Marasovic *et al*. thus conclude "even though all the relevant data indicate that the changes in Kastela Bay are closely related to an increase of anthropogenic nutrient loading, similar changes in the open sea suggest that primary production in the Bay might, at least partly, be due to global climatic changes," which, in their words, are "occurring in the Mediterranean and Adriatic Sea open waters" and may be directly related to "global warming of air and ocean," since "higher temperature positively affects photosynthetic processes."

Raitsos *et al*. (2005)[7] investigated the relationship between Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll-*a* measurements in the Central Northeast Atlantic and North Sea (1997-2002) and simultaneous measurements of the Phytoplankton Color Index (PCI) collected by the Continuous Plankton Recorder survey, which is an upper-layer plankton monitoring program that has operated in the North Sea and North Atlantic Ocean since 1931. By developing a relationship between the two data bases over their five years of overlap, they were able to produce a Chl-*a* history for the Central Northeast Atlantic and North Sea for the period 1948-2002. Of this record they say "an increasing trend is apparent in mean Chl-*a* for the area of study over the period 1948-2002." They also say "there is clear evidence for a stepwise increase after the mid-1980s, with a minimum of 1.3mg m^{-3} in 1950 and a peak annual mean of 2.1 mg m^{-3} in 1989 (62% increase)." Alternatively, it is possible the data represent a more steady long-term upward trend upon which is superimposed a decadal-scale oscillation. In a final comment on their findings, they note "changes through time in the PCI are significantly correlated with both sea surface temperature and Northern Hemisphere temperature," citing Beaugrand and Reid (2003).

Antoine *et al*. (2005)[8] applied revised data-processing algorithms to two ocean-sensing satellites, the Coastal Zone Color Scanner (CZCS) and SeaWiFS, over the periods 1979-1986 and 1998-2002, respectively, to provide an analysis of the decadal changes in global oceanic phytoplankton biomass. Results of the analysis showed "an overall increase of the world ocean average chlorophyll concentration by about 22%" over the two decades under study, which results are truly impressive considering (a) the significant increase in the air's CO_2 content over the period of study-the continuation of which the IPCC claims will decimate all types of aquatic life-and (b) the supposedly unprecedented (over the past two millennia) rate of rise of the mean temperature of the globe-which the IPCC claims will do the same.

6 http://www.co2science.org/articles/V8/N30/B1.php.
7 http://www.co2science.org/articles/V8/N22/B3.php.
8 http://www.co2science.org/articles/V8/N46/B1.php.

Focusing on the Southern Ocean, Hirawake *et al*. (2005)[9] analyzed chlorophyll *a* data obtained from Japanese Antarctic Research Expedition cruises made by the Fuji and Shirase ice-breakers between Tokyo and Antarctica from 15 November to 28 December of nearly every year between 1965 and 2002 in a study of interannual variations of phytoplankton biomass, calculating results for the equatorial region between 10°N and 10°S, the Subtropical Front (STF) region between 35°S and 45°S, and the Polar Front (PF) region between 45°S and 55°S. They report an increase in chl *a* was "recognized in the waters around the STF and the PF, especially after 1980 around the PF in particular," and "in the period between 1994 and 1998, the chl *a* in the three regions exhibited rapid gain simultaneously." They also say "there were significant correlations between chl *a* and year through all of the period of observation around the STF and PF, and the rates of increase are 0.005 and 0.012 mg chl *a* m^{-3} y^{-1}, respectively." In addition, they report the satellite data of Gregg and Conkright (2002) "almost coincide with our results." In commenting on these findings, the Japanese scientists say "simply considering the significant increase in the chl *a* in the Southern Ocean, a rise in the primary production as a result of the phytoplankton increase in this area is also expected."

Also working in the Southern Hemisphere, Sepulveda *et al*. (2005)[10] presented "the first reconstruction of changes in surface primary production during the last century from the Puyuhuapi fjord in southern Chile, using a variety of parameters (diatoms, biogenic silica, total organic carbon, chlorins, and proteins) as productivity proxies." Noting the fjord is located in "a still-pristine area," they say it is "suitable to study changes in past export production originating from changes in both the paleo-Patagonian ice caps and the globally important Southern Ocean."

The analysis revealed the productivity of the Puyuhuapi fjord "was characterized by a constant increase from the late 19th century to the early 1980s, then decreased until the late 1990s, and then rose again to present-day values." For the first of these periods (1890-11980), they additionally report "all proxies were highly correlated ($r > 0.8$, $p < 0.05$)" and "all proxies reveal an increase in accumulation rates." From 1980 to the present, however, the pattern differed among the various proxies; and the researchers say "considering that the top 5 cm of the sediment column (~10 years) are diagenetically active, and that bioturbation by benthic organisms may have modified and mixed the sedimentary signal, paleo-interpretation of the period 1980-2001 must be taken with caution." Consequently, there is substantial solid evidence that, for the first 90 years of the 111-year record, surface primary production in the Puyuhuapi fjord rose dramatically, while with lesser confidence it appears to have leveled out over the past two decades.

Thus, in spite of contentions that the "unprecedented" increases in mean global air temperature and CO_2 concentration experienced since the inception of the Industrial Revolution have been bad for the biosphere, Sepulveda *et al*. presented yet another case of an ecosystem apparently thriving in such conditions. Nevertheless, claims of impending ocean productivity declines have not ceased, and the study of Behrenfeld *et al*. (2006)[11] is often cited

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9 http://www.co2science.org/articles/V8/N17/B2.php.
10 http://www.co2science.org/articles/V9/N4/B1.php.
11 http://www.co2science.org/articles/V9/N50/EDIT.php.

as support of such claims, for which the supporting data looked almost halfway decent ... initially, at least.

Working with NASA's Sea-viewing Wide Field-of-view Sensor (Sea WiFS), the team of ten U.S. scientists calculated monthly changes in net primary production (NPP) from similar changes in upper-ocean chlorophyll concentrations detected from space over the past decade. They report this period was dominated by an initial NPP increase of 1,930 teragrams of carbon per year (Tg C yr^{-1}), which they attributed to the significant cooling of "the 1997 to 1999 El Niño to La Niña transition," and they note this increase was "followed by a prolonged decrease averaging 190 Tg C yr^{-1}," which they attributed to subsequent warming.

The means by which changing temperatures were claimed by the researchers to have driven the two sequential linear-fit trends in NPP is based on their presumption that a warming climate increases the density contrast between warmer surface waters and cooler underlying *nutrient-rich* waters, so that the enhanced stratification that occurs with warming "suppresses nutrient exchange through vertical mixing," which decreases NPP by reducing the supply of nutrients to the surface waters where photosynthesizing phytoplankton predominantly live. In contrast, the ten scientists suggest "surface cooling favors elevated vertical exchange," which increases NPP by enhancing the supply of nutrients to the ocean's surface waters, which are more frequented by phytoplankton than are under-lying waters, due to light requirements for photosynthesis.

This is all well and good; but it is informative to note from approximately the middle of 2001 to the end of the data series in early 2006 (which interval accounts for more than half of the entire data record), there has been, if anything, a slight increase in global NPP. Does this observation mean there has been little to no net global warming since mid-2001? Or does it mean that the global ocean's mean surface temperature actually *declined* over the last five years? Either way, *neither* alternative is what would be expected if the model-based projections of CO_2-induced climate warming were correct.

On the other hand, the relationship between global warming and oceanic productivity may not be nearly as strong as what Behrenfeld *et al*. suggest; and they actually leave themselves some significant "wiggle room" in this regard, saying "modeling studies suggest that shifts in ecosystem structure from climate variations may be as [important as] or more [italics added] important than the alterations in bulk integrated properties reported here," noting that some "susceptible ecosystem characteristics" that might be so shifted include "taxonomic composition, physiological status, and light absorption by colored dissolved organic material." It is therefore possible that given enough time, the types of phenomena Behrenfeld *et al*. describe as possibly resulting in important "shifts in ecosystem structure" could well compensate, or even *over*-compensate, for what might initially appear to be negative warming-induced consequences.

Another reason for not concluding too much from the oceanic NPP data set derived by Behrenfeld *et al*. is that it may be of too short a duration to reveal what might be occurring on a much longer timescale throughout the world's oceans, or that its position in time may be such that it does not allow the detection of far greater short-term changes of the opposite sign that may have occurred a few years earlier or that might occur in the near future.

Consider, for example, the fact that the central regions of the world's major oceans were long thought to be essentially vast biological deserts (Ryther, 1969), but that several studies of primary photosynthetic production conducted in those regions over the 1980s (Shulenberger and Reid, 1981; Jenkins, 1982; Jenkins and Goldman, 1985; Reid and Shulenberger, 1986; Marra and Heinemann, 1987; Laws *et al*., 1987; Venrick *et al*., 1987; Packard *et al*., 1988) yielded results that suggest marine productivity at that time was twice or more as great as it likely was for a long time prior to 1969, causing many of that day to speculate "the ocean's deserts are blooming" (Kerr, 1986).

Of even greater interest, perhaps, is the fact that over this particular and more extended period of time (1970-1988), the data repository of Jones *et al*. (1999) indicates the Earth experienced a (linear-regression-derived) global warming of 0.333°C, while the data base of the Global Historical Climatology Network indicates the planet experienced a similarly-calculated global warming of 0.397°C. The mean of these two values (0.365°C) is nearly twice as great as the warming that occurred over the post-1999 period studied by Behrenfeld *et al*.; yet this earlier much larger warming (which according to the ten researchers' way of thinking should have produced a major decline in ocean productivity) was concomitant with a huge increase in ocean productivity. Consequently, it would appear that just the opposite of what Behrenfeld *et al*. suggest about global warming and ocean productivity is likely to be the more correct of the two opposing cause-and-effect relationships.

In the years that followed the Behrenfeld *et al*. study, a number of other researchers have published findings that run counter to concerns of ocean productivity decline in response to rising global temperatures.

Arrigo *et al*. (2008)[12] introduce their work by writing "between the late 1970s and the early part of the 21st century, the extent of Arctic Ocean sea ice cover has declined during all months of the year, with the largest declines reported in the boreal summer months, particularly in September (8.6 ± 2.9% per decade)," citing the work of Serreze *et al*. (2007). In an effort to "quantify the change in marine primary productivity in Arctic waters resulting from recent losses of sea ice cover," the authors "implemented a primary productivity algorithm that accounts for variability in sea ice extent, sea surface temperature, sea level winds, downwelling spectral irradiance, and surface chlorophyll *a* concentrations," and "was parameterized and validated specifically for use in the Arctic (Pabi *et al*., 2008) and utilizes forcing variables derived either from satellite data or NCEP reanalysis fields."

By means of the protocol they pursued, Arrigo *et al*. were able to determine "annual primary production in the Arctic increased yearly by an average of 27.5 Tg C per year since 2003 and by 35 Tg C per year between 2006 and 2007," 30% of which total increase was attributable to decreased minimum summer ice extent and 70% of which was due to a longer phytoplankton growing season. Arrigo *et al*. thus conclude if the trends they discovered continue, "additional

[12] http://www.co2science.org/articles/V11/N47/B1.php.

loss of ice during Arctic spring could boost productivity >3-fold above 1998-2002 levels." Hence, they additionally state if the 26% increase in annual net CO_2 fixation in the Arctic Ocean between 2003 and 2007 is maintained, "this would represent a weak negative feedback on climate change."

Working in the Southern Ocean, Smith and Comiso (2008)[13] employed phytoplankton pigment assessments, surface temperature estimates, modeled irradiance, and observed sea ice concentrations-all of which parameters were derived from satellite data-and incorporated them into a vertically-integrated production model to estimate primary productivity trends according to the technique of Behrenfeld *et al*. (2002). Of this effort, the two authors say "the resultant assessment of Southern Ocean productivity is the most exhaustive ever compiled and provides an improvement in the quantitative role of carbon fixation in Antarctic waters."

Results indicated that over the nine years (1997-2006) analyzed in the study, "productivity in the entire Southern Ocean showed a substantial and significant increase," which increase can be calculated from the graphical representation of their results as ~17% per decade. In commenting on their findings, the two researchers note "the highly significant increase in the productivity of the entire Southern Ocean over the past decade implies that long-term changes in Antarctic food webs and biogeochemical cycles are presently occurring," which changes are positive.

Focusing in on the Antarctic Peninsula, Peck *et al*. (2010)[14] begin their analysis by noting that the loss of glaciers and ice shelves is often thought of as something "will predominantly increase warming of the Earth because of changes in albedo and heat uptake by newly uncovered ground and ocean." However, they state an important opposing effect of this phenomenon "is the opening up of new areas for biological productivity."

Working with the database of Cook *et al*. (2005) that contains a detailed centennial history of changes in all coastal ice fronts associated with the Antarctic Peninsula-compiled from historical accounts, aerial photographs, and satellite imagery-Peck *et al*. developed a time series of changes in the surface ice/water boundary surrounding the Antarctic Peninsula since the early twentieth century. Complementing this information with a ten-year time series of chlorophyll depth profiles (1997-2007) obtained from a near-shore site in northern Marguerite Bay developed by Clarke *et al*. (2008), they reconstructed the magnitude of new oceanic production that developed around the Antarctic Peninsula as sea ice progressively gave way to ever-more open water.

In describing their findings, the five researchers with the British Antarctic Survey report as the ice cover along the Antarctic Peninsula has retreated over the past 50 years, "more than 0.5 Mtonnes of carbon has been incorporated into biological standing stock that was not there previously, 3.5 Mtonnes is fixed by phytoplankton blooms and 0.7 Mtonnes deposited to the seabed." Regarding likely future trends, they state if only 15 percent of the remaining ice-covered areas act in the same way, "over 50 Mtonnes of new carbon would be fixed annually

13 http://www.co2science.org/articles/V11/N34/B1.php.
14 http://www.co2science.org/articles/V13/N49/B3.php.

and around 10 Mtonnes of this deposited to the seabed in coastal or adjacent areas," while "over 9 Mtonnes of carbon would be locked up in biological communities in the water column or on the sea bed." And they suggest that over a period of tens, hundreds, or thousands of years, "this process may act as a climate control mechanism."

Brown *et al*. (2011)[15] investigated the widespread assumption that the Bering Sea is "rapidly warming and losing sea ice" by employing "satellite-derived sea ice concentration, sea surface temperature, and ocean color data as input to a primary productivity algorithm to take stock of environmental change and primary production" in this oceanic region. As the three U.S. researchers report, "rather than declining," they found mean annual sea ice extent in the Bering Sea "has exhibited no significant change over the satellite sea ice record (1979-2009)," because, as they discovered, significant warming during the satellite sea surface temperature record (1982-2009) "is mainly limited to the summer months." In addition, and despite certain hot spots of primary production and a strong pulse in the spring, they also determined "the rate of annual area-normalized primary production in the Bering Sea (124 g C per m^2 per year) is below the global mean (140 g C per m^2 per year)." And as a result of "comparing warm, low-ice years (2001-2005) with cold, high-ice years (1998-2000 and 2006-2007)," they were driven to conclude "Bering Sea primary productivity is likely to rise under conditions of future warming and sea ice loss." And that rise could be quite substantial, as they report "basin-wide annual primary production ranged from 233 to 331 Tg C per year under the influence of highly variable sea ice and temperature conditions."

Chavez *et al*. (2011)[16] reviewed the concepts and methods used to estimate ocean primary production (PP), after which they used the modern global instrumental record of sea surface temperature (SST) to analyze the principal modes of inter-annual to multi-decadal climate and ocean variability. Spatiotemporal patterns derived from *in situ* and satellite time-series of PP were then compared with the known time-series of climate and ocean variability in a search for the processes responsible for the observed patterns in PP, after which paleoclimate studies were introduced in an attempt to broaden the temporal context and "lead into speculation regarding century-scale variability."

Based on the first part of their analysis, the three researchers-all from the Monterey Bay Aquarium Research Institute of Moss Landing, California (USA)-write "general conclusions from the satellite and *in situ* time-series presented here are that PP is increasing globally," and they note global marine PP appears to have risen over the past several decades in association with multi-decadal variations in climate. In addition, they report data from Continuous Plankton Recorder surveys conducted in the north Atlantic depict "increases in chlorophyll from the 1950s to the present," citing McQuartters-Gollop *et al*. (2007).

In the second part of their analysis, Chavez *et al*. report ocean sediment cores containing an "undisturbed history of the past" have been analyzed for variations in PP over timescales that include the Little Ice Age (LIA, ~1400-1800; Gutierrez *et al*., 2009)." And based on reconstructed flux rates of total organic carbon (Sifeddine *et al*., 2008), diatoms, silica, and fish scales, bones

15 http://www.co2science.org/articles/V14/N43/B2.php.
16 http://www.co2science.org/articles/V14/N30/B3.php.

and vertebrae, they determined during the LIA the ocean off Peru had "low PP, diatoms and fish," but "at the end of the LIA, this condition changed abruptly to the low subsurface oxygen, eutrophic upwelling ecosystem that today produces more fish than any region of the world's oceans (Chavez *et al*., 2008)." Concluding their analysis, the researchers write "in coastal environments, PP, diatoms and fish and their associated predators are predicted to decrease and the microbial food web to increase under global warming scenarios," citing Ito *et al*. (2010). However, they say, "present-day trends and the sedimentary record seem to indicate that the opposite might occur."

Tremblay *et al*. (2011)[17] set the stage for their study by noting that the Canadian Beaufort Shelf and adjacent bays make up a small part of the Arctic Ocean, but that they are of "prime social, economical and cultural importance" for coastal communities, in that they are "hotspots of marine productivity and staging," as well as "feeding areas for large aggregations of resident and migrant marine birds and mammals," citing the work of Carmack and MacDonald (2002). Wondering what would happen to the productivity of this important coastal region if it were to warm any further than it already has, Tremblay *et al*. set out to compare time series of ice cover, wind forcing and satellite-based assessments of photosynthetic carbon production for the years 2002-2008 with corresponding *in situ* measurements of salinity, nutrients, new production, biological stocks and biogenic fluxes obtained during overwintering surveys in 2003-2004 and 2007-2008.

What the fifteen researchers discovered was truly amazing. They report, first of all, that in 2007-2008-in areas where ice was no longer present, due to enhanced seasonal warming-there was significant wind-induced upwelling of growth-promoting nitrates, which were brought up from deep and dark waters into the euphotic zone, where photosynthesis occurs. And as a result of this fertilization effect, the herbivorous copepod *Calanus glacialis*-which they say is "the key link between diatom production and apex consumers on Arctic shelves," citing Soreide *et al*. (2010)-experienced a total abundance that was "3 to 33 times higher than in 2003 during mid-fall and 1.6 to 13 fold higher than in 2004 during early summer." Also, on the region's central shelf, they observed "sedimentary chlorophyll *a* was over 20-fold higher than at any station not influenced by upwelling," and they likewise found "benthic carbon demand was among the highest ever observed in the Arctic ocean," citing Clough *et al*. (2005). Therefore, it was not surprising that the end result of these related phenomena was that the "repeated

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[17] http://www.co2science.org/articles/V14/N49/B1.php.

instances of ice ablation and upwelling during fall 2007 and summer 2008 multiplied the production of ice algae, phytoplankton, zooplankton and benthos by 2 to 6 fold."

Tremblay *et al*. conclude the phenomena they observed are "likely to prevail with the increasingly deep and frequent seaward retreat of the central ice pack and the greater incidence of upwelling-favorable winds," as described in detail by Yang (2009); and they state "new production is also bound to rise as winds gain in intensity and upwelling draws deeper into the nutrient-rich, upper Pacific halocline."

In a different type of study, McMinn and Martin (2013)[18] write "most algae regularly experience periods of darkness ranging from a few hours to a few days," during which time they say "they are unable to photosynthesize, and so must consume stored energy products." However, they note "some organisms such as polar algae and some microalgal cysts and spores are exposed to darkness for months to years, and these must use alternative strategies to survive." In an effort to learn more about this subject, while focusing in particular on microalgae, McMinn and Martin reviewed the scientific literature pertaining to this intriguing subject.

Based on their review, the two Australian researchers-who work at the University of Tasmania's Institute for Marine and Antarctic Studies-report "some taxa, such as dinoflagellates, form cysts and become dormant," while "others use physiological methods or adopt mixotrophy," noting "the longest documented survival of more than a century was for dinoflagellates buried in sediments in a Norwegian fjord." In the future, however, they opine that polar microalgae will have to survive "the same period of seasonal darkness but at higher temperatures, and this will require a greater drawdown of stored energy." Fortunately, McMinn and Martin report "recent experimental work has shown that both Arctic [Martin *et al*., 2012] and Antarctic [Reeves *et al*., 2011] phytoplankton are able to survive increases of up to 6°C in the dark." Because such a temperature increase is "unlikely to be experienced in a few centuries as a result of climate change," polar microalgae are pretty much assured to survive for a long, long time to come.

Exploring the topic from yet a different angle, according to Aberle *et al*. (2012)[19], in places such as the Baltic Sea a "temporal match of zooplankton peaks with the spring phytoplankton bloom is required to provide an efficient energy transfer up the food web at the start of the growing season," but they note some have predicted "warming will affect the different trophic levels unequally," resulting in a counterproductive "temporal mismatch between predators and their prey." Investigating such claims, Aberle *et al*. conducted a set of indoor mesocosm experiments "to analyze time-lags between phytoplankton and micro-zooplankton during the spring succession of Baltic Sea plankton in relation to changing temperature [0 and 6°C above the decadal mean] and light conditions," along with "model simulations using a modified Rosenzweig and MacArthur (1963) predator-prey model incorporating temperature-dependent growth, grazing and mortality rates of autotrophic and heterotrophic components."

In discussing their findings, the five German scientists say "during the experiments, we observed reduced time-lags between the peaks of phytoplankton and protozoan biomass in

[18] http://www.co2science.org/articles/V16/N27/B3.php.
[19] http://www.co2science.org/articles/V16/N15/B1.php.

response to warming," adding "warming induced a shift in micro-zooplankton phenology leading to a faster species turnover." In addition, they say the models they employed also "predicted reduced time-lags between the biomass peaks of phytoplankton and its predators (both micro-zooplankton and copepods) with warming." Given such findings, in the concluding sentence of their paper's abstract, Aberle *et al*. write that their study shows "instead of a mismatch, warming might lead to a stronger match between protist grazers and their prey," which represents a huge benefit for the Baltic Sea's marine life.

In a study going way back in time, Renaudie *et al*. (2010)[20] conducted a quantitative micropalaeontological analysis of siliceous phytoplankton remains found in a sediment core extracted from the seabed at an ocean depth of 2,549 meters at ODP Site 1260 (~9.2°N, 54.65°W) on the Demerara Rise, which is a continental shelf located off the coast of Surinam, focusing on a 200,000-year period of warmth during the Eocene between approximately 40.0 and 40.2 million years ago. According to the five French scientists, their results indicated "the pre-warming flora, dominated by cosmopolitan species of the diatom genus *Triceratium*, was replaced during the warming interval by a new and more diverse assemblage, dominated by *Paralia sulcata* (an indicator of high productivity) and two endemic tropical species of the genus *Hemiaulus*." In addition, they state "the critical warming interval was characterized by a steady increase in tropical species of the genus *Hemiaulus*." They also state "the microflora preserved above the critical interval was once again of low diversity and dominated by various species of the diatom genus *Hemiaulus*." Renaudie *et al*.'s findings thus establish that warmer is better, a maxim exemplified in the current case by the greater productivity of the tropical ocean during the warmer period and the ocean's continuous upward trend in the diversity of phytoplanktonic species throughout the period of warming.

Going yet even further back in time, Cermeño (2011)[21] begins his paper on marine planktonic microbes by stating "micro-organisms dominate terrestrial, aquatic and aerial ecosystems and largely rule our planet's life by playing pivotal roles in global biogeochemical cycles," citing the writings of Staley and Fuhrman (2002) and Falkowski *et al*. (2008), while declaring that as a result of these facts, "life on Earth is microbe dependent." Thereafter, Cermeño used records of climatic variability and microfossil data covering the past 65 million years, which were obtained from the world's oceans, to "explore the linkage between the rate of climate change and the probability of extinction, origination and net diversification of marine planktonic diatoms and calcareous nannoplankton," analyzing the evolutionary dynamics of the two phytoplankton groups throughout the 65-million-year period of study and comparing the results with the climate change record.

According to the Spanish researcher, his findings demonstrate "the probability of extinction of microbial plankton species did not increase during periods of enhanced climatic instability over the past 65 million years." In fact, he says his results show "exceptional climatic contingencies, such as those occurring across the Late Palaeocene-Eocene and the Eocene-Oligocene boundary transitions, caused substantial morphological diversification."

[20] http://www.co2science.org/articles/V13/N27/B3.php.
[21] http://www.co2science.org/articles/V15/N21/B1.php.

In summing up his findings and their significance to the concerns of our day, Cermeño concludes his analysis by stating "to the extent that contemporaneous trends in climate change have analogies with the climates of the geological period analyzed here, my results suggest that these microbial plankton groups will persist in the future ocean, perhaps even expanding their ranges of morphological diversity." Such findings are obviously extremely good news, particularly in light of the fact, as Cermeño states, "life on Earth is microbe dependent."

Although a number of rapid climatic switches were noted throughout the course of the record, representing periods of what they called "extreme environmental variability," the scientists report no extinctions were observed, and that the benthic ecosystems "appear to be both resilient and robust in response to rapid and often extreme environmental conditions."

Additional evidence that marine biota are well equipped to adapt to rising temperatures comes from the study of Cannariato *et al*. (1999)[22], who investigated the character, magnitude and speed of responses of benthic foraminifera to millennial-scale climate oscillations manifest in data obtained from an ocean sediment core in the Santa Barbara Basin of the Northeast Pacific that covered the most recent 60,000 years. Although a number of rapid climatic switches were noted throughout the course of the record, representing periods of what they called "extreme environmental variability," the scientists report no extinctions were observed, and that the benthic ecosystems "appear to be both resilient and robust in response to rapid and often extreme environmental conditions." Even though faunal turnovers occurred within *decades*, they determined they did so "without extinction or speciation."

Another stunning example of marine biota resiliency comes from a report examined the density and population structure of giant kelp "forests" located near Bahia Tortugas, Baja California, Mexico, both before and after, as well as during, the 1998 El Niño. At the height of the extreme warming event, sea surface temperatures (SSTs) were 3°C higher than the previous 10-year average for this region, and they led to the complete disappearance of the giant kelp that had historically inhabited the area. However, when the SST anomalies subsided, the giant kelp were once again found to be growing there; and from evidence derived from population structure data, plus the rapidity with which the plants had reestablished themselves, Ladah *et al*. (1999)[23] deduced "a microscopic stage that was not visible during dive surveys survived the stressful conditions of ENSO and caused the recruitment event, supporting the hypothesis that a bank of

[22] http://www.co2science.org/articles/V2/N6/C4.php.
[23] http://www.co2science.org/articles/V3/N21/B1.php.

microscopic forms can survive conditions stressful to macroscopic algae." In addition, they note there was independent evidence to suggest "microscopic stages may subsist in nature under low light intensities in a semi-dormant state until conditions become favorable."

In a follow-up study published several years later, Ladah and Zertuche-Gonzalez (2004)[24] reveal a second and more likely predominant means by which the return was made possible. Although all giant kelp growing at 15 m depth or shallower died during the peak warmth of the El Niño, the pair of researchers discovered there were numerous large fertile adults located between 25 and 40 m depth unaffected by the high surface water temperatures. Although the upper 15 meters of these plants died and sloughed off, regenerated fronds had reached the surface of the sea by the fall of 1998.

The two scientists say "survival in deep water during this extreme El Niño may have been due to local hydrography, such as internal waves bringing cool nitrate-rich water into the deeper regions of the shelf from below the thermocline, providing a refugium against the warm temperatures, low nutrients, and heavy wave action associated with warming events." They also note "the increased light that often occurs after canopy removal apparently resulted in ... recruitment events ... from newly produced spores from nearby fertile individuals surviving in deeper waters." Thus they conclude "deep-water populations may regularly survive El Niño warming in this region due to internal wave activity, and go undetected due to the depth at which they occur and the sloughing of the shallow (<15 m) biomass." And if they can regularly survive El Niño warming, they are all the more likely to be able to survive modest warming of any type, be it natural or anthropogenic.

Zheng *et al*. (2012)[25] write that dinoflagellates "are generally believed to prefer warm temperatures and presumably may do better in the face of temperature increases," noting that *Prorocentrum donghaiense* was able to grow at temperatures ranging from 10 to 27°C and that it achieved its maximum specific growth rate at the latter temperature (Xu *et al*., 2010). Likewise, they state for *P. minimum* "growth rates increased from 0.25/day at 4°C to 0.98/day at 20°C," citing Lomas and Gilbert (1999a,b). And they report the composition of phytoplankton exposed to a temperature rise in the vicinity of a nuclear power plant's thermal effluent "tipped toward dinoflagellates both in terms of species number and cell abundance (Li *et al*., 2011)," likely due to the fact "some dinoflagellates were found to produce heat-shock proteins to stabilize protein secondary structure in response to thermal stress (Alexandrov, 1994)," while further noting in this regard "heat shock protein 70 was induced in *Alexandrium tamarense* when subjected to a 10°C jump from its acclimated temperature of 20°C (Kobiyama *et al*., 2010)."

In an effort to gain further enlightenment about the subject, Zheng *et al*. studied the effects of temperature shock on the growth of the dinoflagellate *Polarella glacialis*. This they did "by monitoring its physiological and biochemical responses to temperature rises from 4°C to 10 and 15°C," while examining the growth rate and expression of two important genes for this alga. The three researchers say "it is noteworthy that in the present study the cultures were directly

[24] http://www.co2science.org/articles/V8/N11/B2.php.
[25] http://www.co2science.org/articles/V16/N19/B1.php.

transferred from 4°C to 10 and 15°C without progressive intermediate steps," and they state in response to these sudden temperature shifts, "the cultures first experienced a period of declination, then cell density tended to become stable, a sign that a part of the cell population survived."

In light of what they observed, Zheng *et al*. conclude "if the species can survive such heat shock in the long term, there is good opportunity that it can be transported from polar regions to temperate or even warmer waters," which perhaps explains, in their words, why "taxa closely related to this species occur in temperate aquatic environments (Lin *et al*., 2009, 2010)." And if *P. glacialis* and other related species can do *that*, coping with projected global warming should be a non-problem.

Lastly, Clark *et al*. (2013)[26] used "a quantitative genetic breeding design to establish whether there is a heritable variation in thermal sensitivity in two populations of a habitat-forming intertidal macroalga, *Hormosira banksii* (Turner) Descaisne," wherein "gametes from multiple parents were mixed and growth and photosynthetic performance were measured in the resulting embryos, which were incubated under control and elevated temperatures (20°C and 28°C)." The four researchers report "significant interactions between male genotype and temperature in one population indicated the presence of genetic variation in thermal sensitivity," such that "selection for more tolerant genotypes thus has the ability to result in the evolution of increased thermal tolerance." In addition, they found "genetic correlations between embryos grown in the two temperatures were positive, indicating that those genotypes that performed well in elevated temperature also performed well in control temperature." Clark *et al*. write, in the concluding paragraph of their paper, that their "finding of genetic variation in thermal tolerance of *H. banksii* embryos suggests resilience to thermal stresses."

In light of the many real-world observations cited above, not only does there appear to be no indications of any widespread decline in oceanic productivity over the twentieth century in response to increases in air temperature, evidence indicates that just the opposite is occurring, thanks to the very same environmental change, which is actually proving to be beneficial.

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