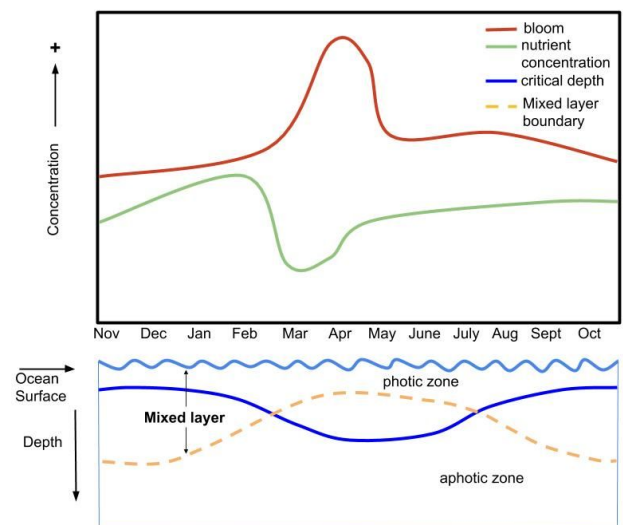
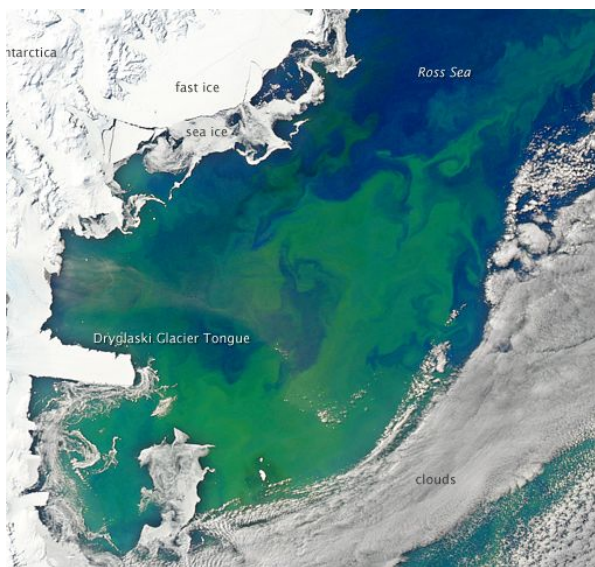


Blooming diatoms: Ocean gardens a nutrient balancing act

Update by Barbara Steffens, from the science lab of Monica Orellana, PhD (2017)

GROUP A: The Bloom

Phytoplankton **bloom** each year in the ocean, not unlike flowers forming big expansions covering hundreds of square miles visible in satellite images. And, just as terrestrial plants, they are the base of a complex food web for the globe. Single-celled photosynthetic organisms, such as diatoms, coccolithophorids, dinoflagellates and green algae, supply all of us with nearly 50 percent of the available **oxygen** on earth, with plants producing the other 50 percent. In the process phytoplankton consume an enormous amount of **carbon** --the amount of carbon that makes its way from the atmosphere to the ocean varies depending on many variables in the ocean. The diatoms are part of a giant carbon processing plant for the planet, they account for 1/5 of the photosynthesis on earth. The timing of the bloom varies, but in general diatoms bloom in the early spring and summer in high latitudes. The marine ecosystem that feeds phytoplankton and specifically diatoms is dynamic, supplying all the needed **nutrients** and **carbon** as well as the right temperature, and salinity, just like the terrestrial system that feeds plants. Ongoing investigations are asking: How do the increase in carbon dioxide and decrease in ocean acidity over the last 50 years impact the flow of carbon in the global marine ecosystem?



Caption image: NASA image courtesy Norman Kuring, [Ocean Color Team](#) at NASA Goddard Space Flight Center. Caption by Mike Carlowicz, with information from Hugh Powell, COSEE-NOW. Instrument(s): Aqua - MODIS [1]. **Figure 1:** Representation of the combination of variables that bring about phytoplankton bloom. Fig. 1 [2] interpretative illustration by B. Steffens (ISB). Red bloom line on chart (right) represents the highest bloom time period which appears bright green in the satellite image (left). Lower chart shows the changes in ocean layers triggering bloom. Nice photo of bloom

The fate of the bloom is determined by the nutrients available. One team of scientists recently looked at how bloom and death rates of **phytoplankton** vary and just how much carbon may be rerouted due to changes in the marine ecosystem. What do these changes mean? "There can be a benefit to the cycle, for example there is recycling of nutrients, that are then uptaken by photosynthesizers to benefit their growth," said Monica Orellana, TRACERS Co-Chief Scientist based out of Seattle's Institute for Systems Biology. On the other

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extreme, after a massive bloom, decomposition at a high rate can create an oxygen depleted zone or death zone in some geographic areas. **Bacteria** helping recycle the **phytoplankton** use up a lot of oxygen in the process. When oxygen is used up quickly, surrounding life suffocates. [3] The phytoplankton blooms also affect how much carbon is taken up from atmospheric carbon dioxide by the ocean, and is negatively affected by high temperatures. [3] Total carbon available in the atmosphere and in the ocean affects many parts of the marine ecosystem.

Timing is important. If the increase in CO₂, and lower pH as well as higher temperatures in the oceans cause changes in the diatom bloom schedule or phytoplankton diversity, the effect on the oceanic carbon cycle could be significant. We know phytoplankton responses to a carbon dioxide increase in the seawater varies. On land unseasonal wet winters or over-dry warm days can throw a fruit tree bloom timing off schedule. Blooms could appear too early, before bees have arrived, disrupting creation of fruit. A 2016 research study shows coccolithophores and diatoms have complex intertwined bloom schedules -- the interdependence is linked not only in the **nutrients (P, N)** but also the available **(Si), (Fe) and (Ca)** in the water column. And in turn, the bloom growth changes the rate of carbon production as it flows through the phytoplankton processing plant providing food for the marine food web. So what does this mean for the amount of carbon that sinks to the depths, and what is returned to the system? [4]

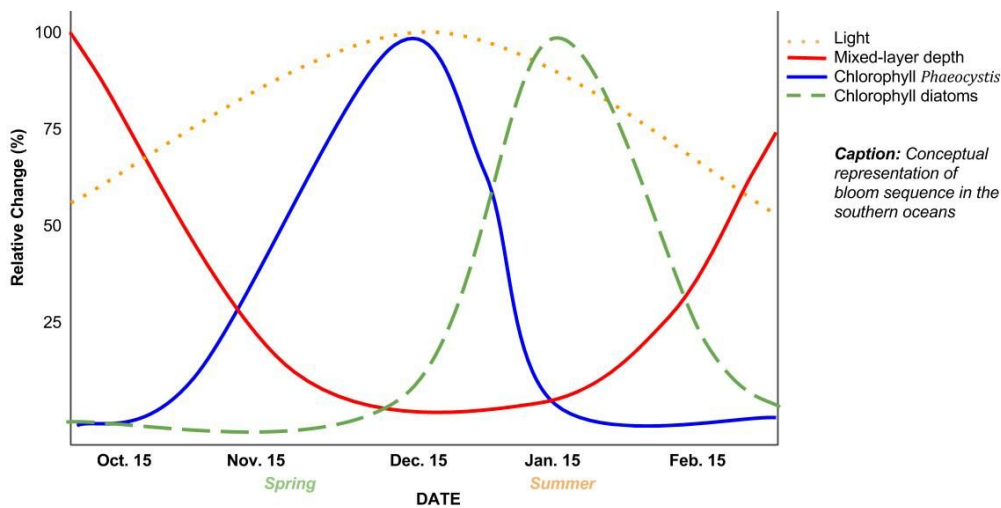


Fig. 2 Caption: Simplified representation of variables that influence the seasonal bloom timing of diatoms and their successional counterparts (*Phaeocystis antarctica* and the coccolithophorids). This pattern describes what is found in the southern oceans. Spring increases are due to the rise of the mixed layer carrying nutrients closer to the light at the surface. Available nutrients change as the season moves into summer. The earlier spring bloom of *Phaeocystis* (*Prymnesiophyte*) diatoms starts to die off when they become limited by (Fe). That, and a secondary bloom of diatoms grows during summer along with the continued mixing of the oceans, which brings on the subsequent recycling of nutrients. [5] **Fig. 2 credit:** Interpretation of variables (10), ISB_B Steffens

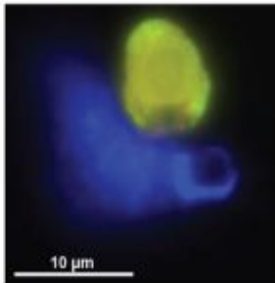
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GROUP B: Changes in nutrient supply or who eats who?

As populations of phytoplankton rise and fall at different rates it leads to the changing supply of **carbon** and other micro-**nutrients**. As laboratory experiments show, changes in pH can cause the coccoliths (shells) of the tiny coccolithophores (type of phytoplankton) to dissolve bringing an early death, before stores of carbon and nutrients are built up in their cells. Thus, reducing the nutrients and carbon passed on in the marine food web. **Diatoms** die off as the nutrients **(Si)** and **(Fe)** are **depleted**. Their death in turn, when remineralized by bacteria, releases a mix of supplemental nutrients. But unlike the coccolithophore a drop in pH does not cause diatom shells to dissolve and lead to early death (diatom frustules (shell) are made of silica); in some areas the diatom populations are on the increase. If not consumed first, the cells are remineralized by bacteria, releasing more dissolved organic carbon. All of which influence other blooms of phytoplankton.[6] Decomposed, consumed or buried at the bottom of the ocean each has a very different effect that leads to different **concentrations** of **carbon** and the available **nutrients**.

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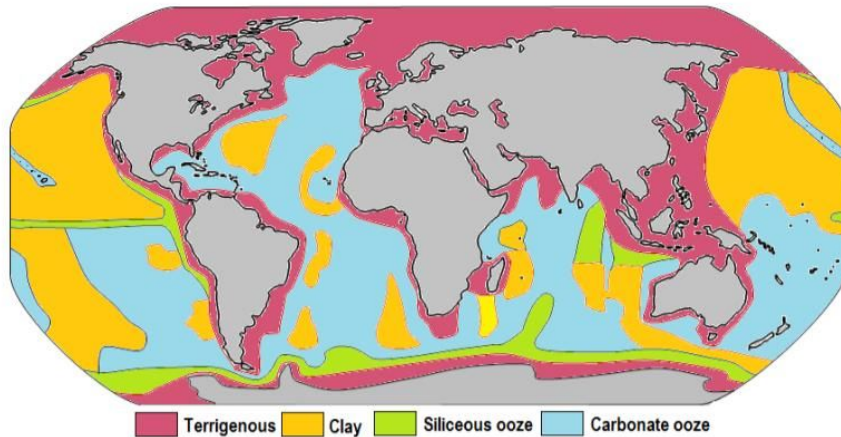
Caption: Reduced light, carbon, and other nutrients signal death for the green chlorophyte (*D. salina*), releasing glycerol and other organic nutrients (in blue) complementing nutrient requirements of the Archaea (*H. salinarum*) in saline environments[6]

Diatoms and **coccolithophores** both have the power to tip the balance of who is the more dominant population, according to the **availability of nutrients** present in the ocean. Succession of one species followed by another occurs during each bloom season, just as in terrestrial ecosystems. Think about the predatory **Lynx** and the **Hare**, its prey, two species in an **interdependent** pattern of **population growth** and **decline**. As Lynx populations rise, they eat more hares increasing their own population. The Lynx population will crash when the nutrient source, the Hare, is depleted. Likewise with diatoms, as (Fe) and (Si) are depleted from the water column, cell death increases, and population growth decreases ending the bloom cycle. Recycling of (Fe) and (Si) then slows, which in turn reduces the available nutrients. Coccolithophores in contrast can reproduce using fewer of the same nutrients at warmer temperatures found later in the season. Some coccolithophores, require the nutrient (Si) in calcification of (Ca) to make their shell (4), which leads to a change in that community. The bloom and decline among different types of phytoplankton, much the same as the Lynx and Hare links directly to their need for these nutrients. (4).

With the rise of the **mixed layer** of nutrient rich ocean water, toward the light the diatom population soars slightly earlier, when (Si) is abundant. Coccolithophore blooms occur when calcium (Ca) is available to absorb. The dying diatoms supply (Si) from breakdown and dissolution by bacteria of their outer shell, which becomes part of the diet for coccolithophores. The timing will vary depending on location and on global nutrient, light and carbon availability. (6)

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Caption: Recent data for silica deposits in ocean sediment (shown in pale green) indicate the highest concentrations are in the Southern Ocean. (Source: [Physical Geology](#) by Steven Earle used under a [CC-BY 4.0](#) international license; Download this book for free at <http://open.bccampus.ca>)

Location Location -- nutrient and light patterns vary globally. Sampling from regions around the globe show that silica deposits--left by diatoms-- tend to happen more in the polar areas. In coastal areas, the cells are being consumed, dissolved and recycled, and the silica deposits are small or nonexistent. The ratio of diatom cells undergoing dissolution and recycled compared to the exported cells that sink into the carbon dump is higher in polar areas. (7) Will this pattern change as more CO₂ is pumped into the system?

Water sampling shows the nutrient mix is not the same in all areas of the ocean at all times. Iron (Fe) affects phytoplankton blooms, and mostly is carried by the wind from Fe rich deserts and fertilizes the oceans. Pelouin & Smith (2007) also observed diatom blooms that occurred after the decline of a non-diatom algae called *Phaeocystis antarctica*. Increased (Fe) occurred as the *P. antarctica* declined, signaling growth for the diatoms. (Fe) and other nutrients absorbed by the cells help signal cell protein processes to begin or end (8). The mechanism by which this may occur remains unknown. (9) Nitrate (N) and phosphorus (P) levels, essential for building DNA, also measured relatively high during one sampling mission. All of these factors lead to changes in the bloom growth rate, and therefore to how much carbon is being recycled back into the carbon system through phytoplankton. (9)

Carbon is being recycled as the different phytoplankton and algae die and sink into the deep ocean, or are consumed. Global scale changes in dissolved carbon may have a positive effect on the diatoms, though negative in other phytoplankton groups. And in turn the oxygen production rate changes too. Where is the tipping point in the ecosystem balance over the long term? Scientists have to keep an eye on the flows and ebbs in the system, investigate over time and predict tangible outcomes.

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GROUP C: Tracing carbon or tracking Marine Snow

Scientists trying to model the amount of carbon uptake and export to the burial ground in the deep ocean headed to the Ross Sea Antarctica. A research expedition called TRACERS: Tracing the Fate of Algal Carbon Export -- including Orellana's team, spent 1.5 months taking 1500 samples, at multiple sample sites. The Southern Ocean is a big area, and carbon is being exported in greater amounts which can tell scientists much about global climate effects. The area used for research is relatively pristine, less subject to human interference than other oceans around the globe. [\[10\]](#)



Caption: The ship RVIB NATHANIEL B. PALMER during TRACERS expedition at a polynya in the Ross Sea. [\[11\]](#)

Tracing the diatoms as they descend, scientists can track what is happening to the dying [diatoms] and where their carbon is going. As blooms form near the surface, where there is enough light, they can be seen from space by satellite (Fig.1). To bloom and grow successfully, diatoms need **nutrients** and **light**. Nutrients move upward in currents formed when the strong winds of winter churn the waters to create **mixed layers**. Similarly, gardeners add mulch in the fall that will **decompose** into the soil providing nutrients for growing plants the following spring. The TRACER scientific team took their samples at *polynyas*, places in the Arctic and Antarctic where the ice melts seasonally and allows sunlight to warm the surface water. Phytoplankton bloom here from November to January/February—the highest sunlit period in the Southern Ocean. [\[11\]](#)

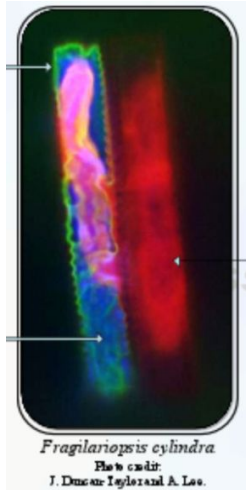
In 2016, during the TRACERS expedition, they used satellite images to locate and sample diatom blooms in the Ross Sea (Antarctica). The images measured the chlorophyll across the swath of the Ross Sea. (Blooms look pale green-blue against the dark ocean because of the absorptive qualities of their internal chlorophyll and the outer shells of these microscopic creatures). The diatoms' glassy, silica shells refract and absorb light, creating the colors in the image. Coccolithophores absorb light differently, appearing pale blue, because of their calcium carbonate shell. [\[12\]](#) Water column samples confirm what was seen in the satellite data.

The science team can follow the path of the phytoplankton and thus the carbon by tracing cells as they die. In death phytoplankton release mucous and other molecules stimulating the cells to attach to each other forming bigger size particles that sink fast. Bacteria colonize these cell rich-particles remineralizing the nutrients as part of the fuel they need to live. As these particles known as "**marine snow**" fall into the deep ocean, cameras can capture images of the cells from the scatter of light they reflect. By staining the cells scientists can

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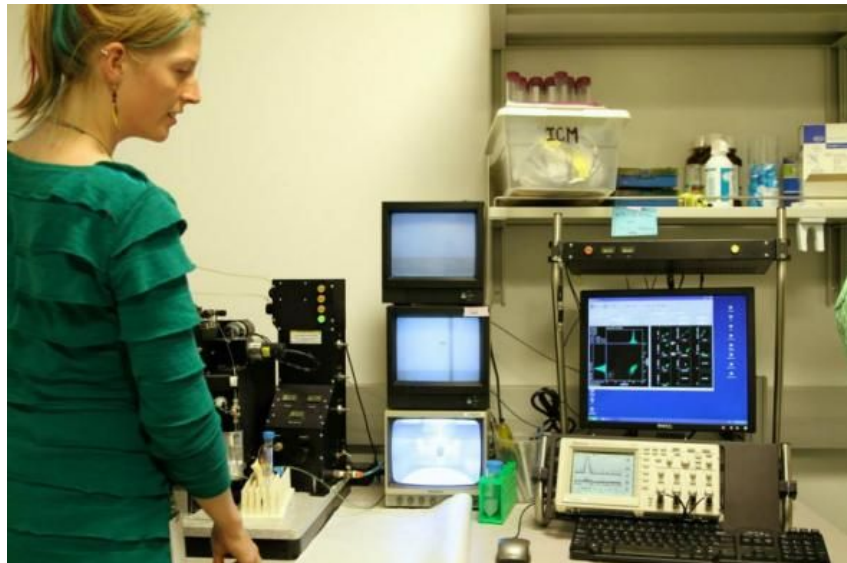
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trace the dead cells as they are going down to the depths out of the **euphotic zone** and the **carbon cycle**. As (Fe) is depleted, death is triggered for the phytoplankton, and the particles formed from dying cells sink to the deep ocean.



Caption: Image of tagged phytoplankton (diatom) from TRACER scientists. They tagged the cells using Annexin labelled protein + a DNA stain Sytox Blue. The stains are visible only when the cells are dying, because as they die the cell membrane becomes permeable to the stain. Once the cells are tagged it is possible to count the dead cells using a flow cytometer. Cells with both tags (Fluorescent Annexin and Sytox) combined show that the cells are dying. (Fig X, The diatom *F. cylindrus* stained with FITC labelled Annexin showing a green undulating membrane, a second live cell shows the cell is auto-fluorescing red due to chlorophyll). **Photo Credit:** Allison Lee and J. Duncan Taylor, Institute for Systems Biology (2013) [13]

Caption: Image of Allison Lee using flow cytometer.
Photo Credit: Institute for Systems Biology.



To find out the number and types of cells that were dying the scientists used **flow cytometry** and **gene sequencing**. They counted the phytoplankton cells that were showing signs of genetically programmed cell death. This comes about when the cells are stressed, for example lacking micronutrients such as Fe. In addition, the TRACER science team took gene arrays of the specimens to show what type of organisms are present; e.g., a census of all of the diatoms, dinoflagellates, eukaryotes, and others within the community. Scientists determined that the most abundant type of organism, at the time, was a diatom group named *Chaetoceros*.

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GROUP D: What is dying is more important than how it is dying.

Due to carbon increases pH levels in the ocean were expected to go down (increase acidity). The diatom, *Chaetoceros*, which supplies **carbohydrates** to herbivores in the food web is the most abundant diatom in the world oceans (14)(Tara Oceans). At the end of the productive bloom when the cells are stressed by the lack of important micronutrients such as Fe they undergo cell death dragging **carbon** out of circulation to be buried in sediments. In the Ross Sea diatoms contribute between 38-61% to the annual **productivity** of that important area(10). Diatoms and other phytoplankton are responsible for **taking up** ~ 50% of the global atmospheric **carbon** each season, similar to the carbon uptake by all the land plants together.

Current conditions measure ocean water at pH 7.9-8.08. Twenty years ago the pH was around 8.27. Essentially the dissolved CO₂ in the oceans has increased, due to increased atmospheric carbon. The carbon that remains in the ocean, leads to increasing acidity. This may seem like a small change, but a change in pH of 0.1 is a 10-fold change since its a logarithmic scale. Think about the difference between tap water(pH 7.0) and urine (pH 6.0)-- the acid is 0.1 x 10 stronger. What will this mean to the global system?

Coccolithophores help reduce the potential greenhouse gases that contribute to global warming, as well. They remove carbon, one atom at a time, from circulation in order to form their shells from CaCO₃. “Three hundred twenty pounds of carbon go into every ton of coccoliths produced. Much of this material later sinks to the bottom of the ocean to form sediment.” [15] Data show that increases in CO₂ and warmer temperatures cause increases in their populations. Scientists have also discovered that certain **diatoms** change during photosynthesis and will stop taking in carbon at the same rate. If the rate of **carbon uptake** decreases because of this, the acidity of the ocean will continue to increase. Because of CO₂ remaining, global warming can lead to rising temperatures [16].

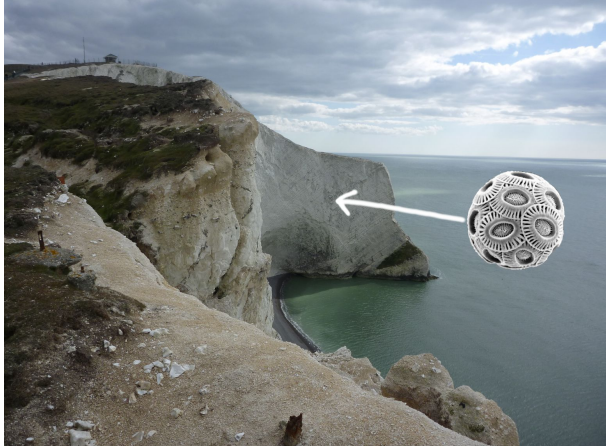
Scientists found a mechanism in **diatoms** that could be contributing to their reduced rate of **carbon uptake**. Ocean water pH, at the current levels, causes diatoms to turn off their internal carbon processing plants (CCM). When CO₂ is elevated the diatoms shut off carbon intake via cAMP signals. The cAMP is a protein-signalling process that turns on CCM genes, which then shut off the need to take in as much carbon, and conserve vital energy. So, less carbon is taken out of the atmosphere, because less is taken up in the ocean.[16] If carbon levels continue to rise, it makes sense that diatom populations rise too. And diatoms are indeed, increasing magnificently, but the uptake of carbon is not.

On the other hand, as ocean acidity increases (pH decrease), seawater contains fewer carbonate ions, robbing **Coccolithophores** of the building materials for shells or skeletons made of CaCO₃. Production of their structures can slow and the breakdown of existing CaCO₃ parts can speed up. Reduced supplies of nutrients such as (Si), can affect the ability to uptake the needed calcium (Ca).[17] Laboratory studies have shown the rate of calcification could slow 30 to 50% in some marine organisms.[18] In that case, carbon, along with the nutrients like silica and calcium, would sink to the bottom removing it from circulation at a faster rate. This leaves less building material in the global carbon processing plant.

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Evidence shows shift in phytoplankton populations over geological time. Blooms of the tiny phytoplanktonic have been measured for decades. This helped scientists observe how the populations have been responding to environmental changes. A 2015 *Science* journal



report shows that since the 1930s, there has been an explosion in the population of **coccolithophorids** that scientists attribute to the combined effect of carbon dioxide and temperature increases. Data collected with an instrument called “Continuous Plankton Recorder” in the Atlantic Ocean and North Sea, shows corresponding spikes in this population. [20]

Caption: Cliffs on Isle of Wight show deposits of coccolithophores alternating with glassy-shelled organisms. **Photo Credit:** Saher, M.H. Yorkshire University; coccolithophore image: Saskia Kars, Vrije Universiteit Amsterdam [19]

Carbon and nutrients move through the ocean cycle bringing on the repeating seasonal blooms every year. Over geological time CO₂ has fluctuated in the atmosphere directly affecting the marine carbon system--including photosynthetic phytoplankton. But, changes are occurring at a rate faster than observed over millions of years. Scientists are trying to foresee the future, and predict where the trends are heading.

In geological history the white cliffs of Dover are evidence of the changes in environmental conditions that cause changes in population. [21] “[The cliffs] are white because of massive deposits of [chalk coated] **coccolithophores**. ...The white deposits [are] interrupted by slender, dark bands of flint, a product of [**diatoms**] that have glassy shells made of silicon...,” [21] The darker silica-based bands, show time intervals where the coccolithophores were less abundant, and diatoms more. The coccolithophores abundant periods match the pattern of the warmer temperature, high CO₂ levels of the interglacial periods. [21]

What does this mean as carbon levels grow ever higher? Examining the bloom and death rates of different types of phytoplankton in the ocean garden helps scientists map the tipping points of the whole ocean system. The availability of **nutrients, (Si, Fe, Ca, P and N)** and **carbon** for making new cells, limits the ability of phytoplankton to carry out the blooming process. Populations shifts when the balance of available ocean carbon, and nutrients tip the balance in different ways. Growth that is rapid in one phytoplankton population may overwhelm the system leading to collapse and further repercussions in the food web. Coccolithophores and diatoms help uptake the excess carbon and produce 1 out of every 5 breaths of the globes’ oxygen through photosynthesis. Introduce more CO₂ to the system, the balance tips in one direction; reduce the CO₂ and the balance tips in the other. Scientists need to keep monitoring the ocean, to be able to predict when and where the tipping points will occur.

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Further useful links:

Ocean Acidification Curriculum Collection:

<http://www.oacurriculumcollection.org/wp-content/uploads/2015/06/Ocean-Acidification-Literacy-Framework-Draft-1.pdf>https://www.st.nmfs.noaa.gov/Assets/Nemo/documents/lessons/Lesson_7/Lesson_7-Teacher%27s_Guide.pdf (Reference lesson: effects on mixed layer (pycnocline, thermocline)

http://serc.carleton.edu/eet/phytoplankton/part_3.html (Reference for creating figures from buoy data)

https://microbewiki.kenyon.edu/index.php/Pelagibacter_ubique

<http://www.marinespecies.org/aphia.php?p=taxdetails&id=149241>

<http://hahana.soest.hawaii.edu/agouroninstitute/course/Kirchman%20NATO%202004.pdf>

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