

# Advancing Satellite Technology to Monitor Ocean Phytoplankton

Professor Michael Behrenfeld

# ADVANCING SATELLITE TECHNOLOGY TO MONITOR OCEAN PHYTOPLANKTON

Tiny marine plants known as ‘phytoplankton’ play a disproportionately large role in maintaining the health of our planet, and they provide a rapid signal of changing climate conditions.

**Professor Michael Behrenfeld** at Oregon State University and his many collaborators are developing new satellite approaches, including space-based lasers, to monitor ocean ecosystems. With these technologies, a 3D map of global phytoplankton communities is on the horizon, which will revolutionise our understanding of how these microscopic organisms make Earth a healthy place to live.

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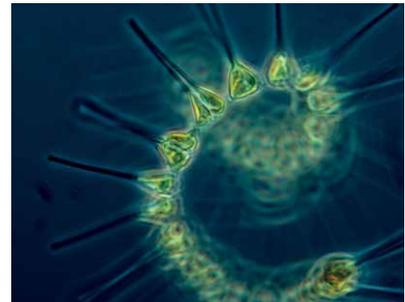
## Phytoplankton

Phytoplankton are the life force of our oceans. Every day, these countless little engines absorb the Sun’s energy and convert it into sugars, which feed nearly all marine food webs – including the fisheries we rely on for sustenance and a blue economy. Phytoplankton live fast and die young. Over periods of just a few days, the entire global population is either eaten, killed by viruses, or lost through sinking from the sunlit surface into the dark depths of the ocean. Fortunately, these losses are continually replaced by new individuals, so the stock of phytoplankton remains in balance.

Just like land-based plants, photosynthesis fuels the growth of phytoplankton. However, instead of taking carbon dioxide directly from the atmosphere, phytoplankton use the carbon dissolved in seawater. This dissolved carbon is then replaced by atmospheric carbon dioxide, creating a direct line between phytoplankton and climate change. ‘An amazing fact about phytoplankton is that in

total they perform around half of the photosynthetic production on Earth, yet they represent only about 2% of the total mass of plants,’ says Professor Michael Behrenfeld of Oregon State University. ‘This is possible because phytoplankton populations turn over quickly, so nearly as fast as they create new cells their carbon is passed on to animals higher up in the food web.’

An important consequence of this rapid turnover is that any change in surface ocean conditions, such as that resulting from a change in climate, quickly results in a change in phytoplankton populations. ‘The distribution of phytoplankton thus provides a sensitive signature of environmental change,’ explains Professor Behrenfeld, ‘and we can globally observe these signatures using satellites.’ By monitoring these changes today, satellite measurements are telling us a lot about how future ocean ecosystems may look, and their overall health, as the climate continues to warm.



To study phytoplankton, satellites currently enable the monitoring of one key property: the colour of the ocean’s surface. In the absence of phytoplankton, an ocean of pure seawater would be a uniform shade of deep blue. However, as the phytoplankton population grows, the chlorophyll pigments they use for photosynthesis cause the water to become greener. ‘With very sensitive instruments, we detect these shifts in colour from space and we have been doing this now for more than three decades,’ says Professor Behrenfeld. ‘The record we’ve collected clearly shows that ocean warming results in lower levels of phytoplankton chlorophyll, implying reduced production, but it is also becoming



PACE. CREDIT: NASA-GSFC

clear that a full understanding of climate change implications requires advances in satellite technology.'

### **Ocean Ecosystems in Technicolor**

Phytoplankton have been evolving in the oceans for over three billion years and today thousands of different species share the sunlit surface layer. Some of these species are excellent food for crustaceans, such as shrimp, making phytoplankton the cornerstone of the marine food webs that fuel a global fishing industry worth over \$200 billion in 2017. Other phytoplankton species are less valuable food sources and their production largely ends up being converted back to carbon dioxide. 'One of the big unknowns regarding climate change is how it will change the species that populate our future oceans,' emphasises Professor Behrenfeld. 'This question cannot be answered with the satellites we've launched so far.'

To address the problem, NASA is developing a new satellite, call PACE, that will be launched in late 2022. Rather than just measuring six or seven

specific colours of visible light like past satellites, the PACE instrument will measure the full spectrum from ultraviolet to near-infrared light at an astonishing resolution of every five nanometres. 'This is the key, because different species have evolved with different pigments and this gives them different colours. By measuring the full colour spectrum, PACE will be able to distinguish different types of phytoplankton and give us a first glimpse into how these species uniquely respond to environmental changes,' explains Professor Behrenfeld. 'Borrowing a term from the 1970s, the PACE mission will allow us to study ocean ecosystems in Technicolor!'

### **Difficulties with Ocean Colour Measurements**

With the PACE satellite now in development, Professor Behrenfeld is refocussing his energy on shortcomings in the satellite record that not even PACE can address. 'Since the first satellite was launched into space to observe ocean ecosystems, we have recognised some unavoidable

limitations of the measurements,' he emphasises. 'The exciting thing is that we now have a way to solve these problems.'

One of the big problems he is referring to is that the ocean's surface colour reveals nothing about the phytoplankton below the first 10 meters or so, making scientists effectively blind to how deeper populations are changing. Light penetrates the ocean much deeper than ten meters in many places, and so a lot of productivity can occur below what traditional ocean colour satellites can sense. What is known from ship measurements is that the subsurface populations can be more abundant, more productive, and even composed of different species than phytoplankton near the surface.

Another limitation is that the ocean only displays colour when the sun is shining, and measuring this colour from space requires the Sun to be shining at just the right angle. This means that observations close to the poles, where phytoplankton populations are showing the most extreme responses to climate



CREDIT: NASA

change, are unavailable for many months during the year. The requirement for sunlight also means that ocean ecosystems cannot be observed at night, which is the only time when huge numbers of ocean animals migrate to the surface to feed on the day's production. 'The solution to these problems is to use a new technology that does not rely on sunlight, but rather carries its own source of light,' concludes Professor Behrenfeld, 'and that technology is now available.'

### Ocean Exploration with Lidar

Professor Behrenfeld's current research focuses on a technology called 'lidar', which stands for 'light detection and ranging'. Lidar combines a laser-based light source with a large telescope receiver. 'The laser sends out a short pulse of light at a very specific wavelength,' describes Professor Behrenfeld. 'As this laser light travels toward Earth it intercepts particles in the atmosphere and phytoplankton in the ocean. When this happens, some of the laser light is scattered backward and into the telescope. Detectors in the telescope measure this return signal at close to the speed of light, allowing the precise location of the scattering events in the atmosphere and ocean to be calculated.'

The outcome of this is that a lidar allows phytoplankton concentrations and distributions to be mapped out at meter-scale resolution through the water column. This solves one of the major shortfalls of traditional ocean colour measurements. But that's not all. By using an artificial light source instead of sunlight, a lidar can monitor changes in polar phytoplankton populations when clouds or the angle of the Sun prevent any ocean colour measurements. Likewise, the artificial light allows lidar to operate at night and globally study deep sea animals that migrate to the surface after sunset – a very important part of the ocean ecosystem puzzle.

### Graveyard of Great Ideas

It is very common practice to build prototype aircraft instruments as a stepping stone toward flight in space. These prototypes allow scientists to 'work out the bugs' of new

technology and demonstrate its feasibility for space. Aircraft instruments are also relatively cheap. However, with far greater costs and far greater risks, the final step from airplane to space has proven the graveyard of most instrument concepts. 'We got lucky this time,' Professor Behrenfeld recalls, 'because a satellite lidar already existed that we could potentially use to transition our concept to space with essentially no cost and no risk.'

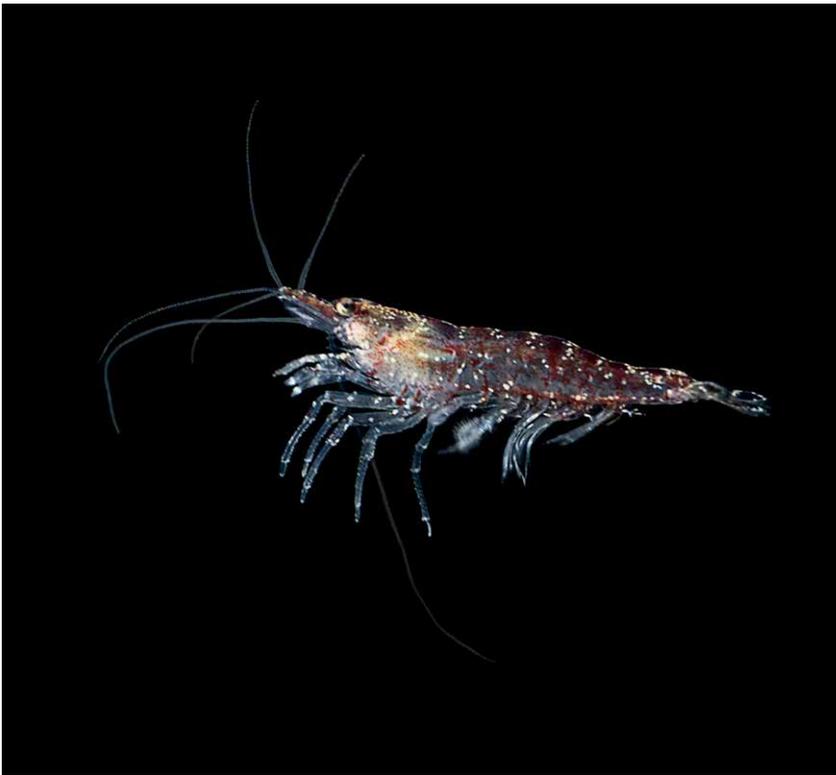
The lidar he is referring to is called CALIOP and it was launched in 2006 on the CALIPSO satellite as a joint mission between NASA and CNES in France. CALIOP was built to study clouds and aerosols in the atmosphere, not phytoplankton in the ocean. Undeterred, Professor Behrenfeld and his colleagues at NASA's Langley Research Centre began looking for an ocean signal in the CALIOP data as soon as the instrument was on orbit and operating. And they found it: CALIOP was registering a distinct signal of backscattered laser light that was coming from up to 20 meters below the ocean's surface.

The critical next step was to verify the apparent ocean signal. To do this, the researchers coordinated a large experiment near the Azores Islands in the Atlantic Ocean, where ship and airplane data were simultaneously collected with CALIOP measurements. All three sources of data gave the same results, meaning that the CALIOP ocean signal was real. With this success, the team boldly gathered all CALIOP ocean data into a single global map of phytoplankton biomass – the first to be created by a spaceborne lidar. It was the dawn of a new lidar era in satellite oceanography.

### Breaking Science

'Creating the global map of phytoplankton with a lidar was important as a technological proof-of-concept,' says Professor Behrenfeld, 'but the fact was that similar maps had been made with ocean colour data. What we really needed was to show how lidar enables new science, so we turned our attention on polar ecosystems.' With 10 years of CALIOP data now in hand, Professor Behrenfeld's team published a paper in the journal *Nature Geoscience* demonstrating how a lidar can continuously monitor polar phytoplankton populations right up to the ice edge throughout the months when traditional ocean colour data are absent. It was the first unbroken satellite record of these critical and threatened ecosystems. What the study also showed is that changes in polar phytoplankton over the past decade were caused by ice cover changes in the south and ecological disturbances in predator-prey relationships in the north. These discoveries could never have been made without a satellite lidar.

'After the polar study, the next target I wanted to investigate was a signal from the migrating animals,' Professor Behrenfeld says. 'The basic idea is that a night-time invasion of the surface ocean by these animals should cause an intense increase in the laser light scattered back to the telescope.'



Professor Behrenfeld and his colleagues are now working to publish their findings, which will represent a landmark in oceanography, because it will be the first time that marine animals have been detected from space at a global scale. It will also be important because this daily animal migration is crucial for fisheries and the ocean's ability to rapidly move the carbon taken up by phytoplankton in the sunlit ocean layer to the deep ocean, where it can be stored for decades to centuries.

### Doing it Right

As mentioned, the CALIOP instrument was built to study the atmosphere, not the ocean. Its receiver detectors are far too insensitive to retrieve ocean signals from deep in the water, its electronics are too slow to see phytoplankton layers, and the types of measurements it makes can't separate different components of ocean ecosystems. Having celebrated its 13th birthday, it is also unlikely to last much longer. 'CALIOP has been a ground breaking instrument and given us the proof we needed that ocean plankton can be measured with a satellite lidar,' Professor Behrenfeld concludes, 'but it is now time to get serious about putting

a lidar in space that is actually built for studying the oceans.' In preparation for this, Professor Behrenfeld's colleagues at the NASA Langley Research Centre have successfully developed a more sophisticated lidar technique called high-spectral resolution lidar (HSRL).

HSRL adds an additional detector system to independently separate scattering and absorbing components in the water. More importantly, it can retrieve these signals at meter-scale resolution deep into the surface ocean to map distributions of phytoplankton in the water column. Airplane-mounted HSRL instruments have already been extensively deployed over the ocean and demonstrate superior skill in observing phytoplankton compared to earlier lidar. Professor Behrenfeld is hoping that an opportunity will soon arise to launch an ocean-optimised HSRL lidar into space. 'It looks like we might get lucky again,' he says. 'The Europeans are planning to soon launch an HSRL lidar to conduct advanced atmospheric measurements. The instrument will not have the right laser wavelength or depth resolution for ocean studies, but it will provide the needed proof-of-concept for HSRL measurements from space.'

### An Oceanographic Revolution

No single satellite technology can provide all the measurements needed to understand our global ocean ecosystems and how they are being influenced by environmental change. Lidar can address the limitations of traditional ocean colour monitoring that have been recognised for decades, but lidar does not replace the need for ocean colour data. Ocean colour instruments can observe the entire Earth every two days, whereas a lidar globally samples the Earth approximately every 16 days. Passive ocean colour sensors also provide measurements at more wavelengths of light than lidar, which provides details on phytoplankton communities. It has therefore been Professor Behrenfeld's long term vision to create a constellation of satellites providing important and complementary measurements.

'We are at a very special time in the history of satellite ocean observations,' he says. 'When the PACE mission is launched, we'll begin an ocean colour record with unprecedented science potential. If we could get a lidar in space at the same time that was actually designed for ocean studies, the complement of the two instruments would yield a value for society far greater than the sum of its parts. CALIOP has demonstrated that ocean retrievals are feasible from space. An advanced HSRL technique has been shown to greatly improve the lidar retrievals. The time is now to realise this PACE-lidar vision. With it, we could reconstruct 3D representations of ocean ecosystems, and tie their structures to the physics driving them. It would present an amazing opportunity to understand more about what controls the distribution and function of these fragile and Earth-sustaining ecosystems.'



# Meet the researcher

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Professor Michael Behrenfeld received his PhD in Oceanography in 1993 from Oregon State University. Since then, he has worked in many universities and research institutes, including Brookhaven National Laboratory, Long Island University, Rutgers University, and the NASA Goddard Space Flight Center. He currently works as a Professor in the Department of Botany and Plant Pathology at Oregon State University. Beginning in 2001, he was deeply involved in a grass-roots community effort promoting an advanced ocean colour sensor, an effort that ultimately led to the PACE mission. In 2015, he was awarded an Earth Venture Suborbital grant to conduct the North Atlantic Aerosol and Marine Ecosystem Study (NAAMES), which has combined ship and aircraft measurements to improve understanding of ocean plankton blooms and their impact on atmospheric aerosols and clouds. Professor Behrenfeld is recognised as a world leader in the physiological ecology of marine phytoplankton; his research interests include remote sensing of the biosphere, photosynthesis, physiological adaptation to environmental stress, climate change, and carbon cycling.

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## FUNDING

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## FURTHER READING

CA Hostetler, MJ Behrenfeld, Y Hu, J W Hair, JA Schullien, Spaceborne lidar in the study of marine systems, Annual review of marine science, 2018, 10, 121–147.

MJ Behrenfeld, RH Moore, CA Hostetler, J Graff, P Gaube, LM Russell, G Chen, SC Doney, S Giovannoni, H Liu, C Proctor, The North Atlantic Aerosol and Marine Ecosystem Study (NAAMES): Science Motive and Mission Overview, Frontiers in Marine Science, 2019, DOI: 10.3389/fmars.2019.00122.

MJ Behrenfeld, Y Hu, RT O'Malley, ES Boss, CA Hostetler, DA Siegel, J Sarmiento, J Schullien, JW Hair, X Lu, S Rodier, A.-J. Scarino, Annual boom-bust cycles of polar phytoplankton biomass revealed by space-based lidar, Nature Geoscience, 2017, 10, 118–122.

M Babin, Marine biology: Polar merry-go-round, Nature Geoscience, 2017, 10, 74.

JA Schullien, MJ Behrenfeld, JW Hair, CA Hostetler, MS Twardowski, Vertically-resolved phytoplankton carbon and net primary production from a high spectral resolution lidar, Optics Express, 2017, 25, 13577–13587.

MJ Behrenfeld, Y Hu, CA Hostetler, G Dall'Olmo, SD Rodier, JW Hair, CR Trepte, Space-based lidar measurements of global ocean carbon stocks, Geophysical Research Letters, 2013, 40, 4355–4360.

