Microbial control of the carbon cycle in the ocean

By Ling Wang

The oceans cover 71% of the area of our planet and serve as a major repository for anthropogenic CO₂. The amount of dissolved organic carbon (DOC) in the ocean is comparable to the amount of CO₂ in the atmosphere. If all this DOC were to be respired, it would double the CO₂ level in the atmosphere and result in catastrophic consequences. Over the past few decades, scientists have increasingly begun to understand the vital role that microbes play in the cycling of carbon in the ocean. Concepts such as the Microbial Loop (ML) and the Microbial Carbon Pump (MCP) have been proposed to describe the mechanisms by which microbes contribute to carbon flux and storage in the ocean, and the impact that this has on climate change.

Recently, National Science Review held a forum focusing on microbially-mediated carbon cycling in the ocean and gathered renowned scientists to discuss the key questions and challenges in this field. Professor Nianzhi Jiao of Xiamen University hosted the panel discussion.

THE NOVEL MICROBIAL CARBON PUMP CONCEPT

Jiao: As we know, the oceans absorb a huge amount of anthropogenic CO₂, but the mechanisms behind their formation are not really well understood. Hypotheses and concepts are thus suggested by scientists to address this matter, and MCP is one of them. What do you think of the MCP concept?

Azam: The MCP concept was proposed by Nianzhi Jiao, and we matured the writing under Nianzhi’s leadership. It is significant because prior to that, the biological mechanism for long-term carbon storage was thought to be the biological pump (BP), which is based on the process of downward flux of particulate organic matter and its burial on the ocean floor. The MCP proposed the potential for the sequestration of carbon in the form of long-lived dissolved organic matter, which is resistant to biological decomposition and assimilation. While trees store carbon for decades, the age of refractory DOC is about 6000 years. So
the recognition that microbes play a dominant role in ‘pumping’ bioavailable carbon into refractory DOC throughout the water column is an exciting idea.

Legendre: All these concepts come from observations. If we measure the concentration of CO$_2$ in the ocean’s water column, strangely enough, there is more CO$_2$ in the deep waters thousands of meters below the surface than in the upper waters. It was initially a mystery because the source of the CO$_2$ is atmosphere, and the only way to explain the observed increase in CO$_2$ concentration with depth is the existence of mechanisms called ‘ocean carbon pumps’, which have been proposed over the last few decades; these move the CO$_2$ from the surface into deep waters. Another observation is the accumulation of DOC in the ocean under the form of apparently useless refractory DOC. There was no easy or logical explanation why this occurred until the recent development of the MCP concept. This large pool of carbon is relative inert, like CO$_2$ in the atmosphere, and contrary to dissolved CO$_2$, it does not contribute to ocean acidification.

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—Farooq Azam

We are now at the stage where none of the hypotheses concerning carbon pumps has been fully tested experimentally because of a lack of appropriate facilities, and this is why we use models. The modelers pick up information from existing field observations and laboratory experiments, and put them together to reproduce the observations. Once this is done, the models can be used to predict future conditions. If all of the necessary observations and experiments have been made, then the models should be able to reproduce the field observations. This is seldom the case in oceanography: not because modelers are not good, but because some elusive processes are missing. The value of models is then to point out what the main unknowns are and where the main gaps are in either the observations or the experiments. Even if present models are not perfect, we still use them to catch a glimpse of the future based on existing observations.

Polimene: I think Louis introduced the role of models very well. Very often people think that models may only be used for predictions, while the first role of models is to provide a mechanistic understanding of observed phenomena. This is a prerequisite to the ability to make accurate predictions. This is why, even at this preliminary stage of understanding (where the origin of refractory DOC is still under debate), the modelling approach is extremely useful to the study of the MCP, as it is a means to build a mechanistic understanding of the process. What we need to do is exploit the current knowledge to highlight (and write in mathematical form) all the mechanisms that are likely to underpin the MCP. Crucially, by developing a numerical tool, we can account for biological, chemical and physical aspects, providing a multidisciplinary synthesis rarely achievable in field and experimental studies. Such a model needs to be revised constantly following new empirical knowledge and subsequent new hypotheses. Model simulations, in turn, may inform future experiments and field studies, highlighting knowledge gaps and missing processes. By iteratively refining our formulations we can eventually develop a robust model that is able to deliver reliable predictions. A key methodological aspect that is essential for the success of this approach is a close collaboration between modelers and experimental scientists. This needs to be considered in future projects and proposals.

Suttle: Although the MCP was proposed in 2010, it has actually existed for a very long time. When we go back in Earth’s history, the microbes were recycling carbon and were probably the only cellular living organisms on Earth. That was actually the MCP. There was a transition from the MCP to the BP when larger organisms evolved. So it is interesting that the MCP is the original process, even though it has only recently been recognized.

Zhang: I think that Curtis explained the question well. As for the importance of the MCP, I can think of two things. The first one is that, we will find a new way to look into the carbon cycle in the ocean. If we only focus on the BP, we are looking at 0.1% of carbon being stored at the bottom of ocean. The MCP suggests that there is another large pool, the organic matter in the water column, that does not sink. The second one is that it brings different disciplines together under the new umbrella, which better aligns our efforts. I was trained as a geologist, and dragged by Nianzhi into the MCP world; however, I am so excited about it now because it allows me to address new questions. I think that the MCP is just beginning, and it will gradually show its importance in ocean carbon sequestration.

HUGE IMPACT OF MCP ON CLIMATE CHANGE

Robinson: In order to progress in MCP research, we need to emphasize the potentially huge impact of the MCP on climate change. One important fact to remember is that the amount of carbon contained in dissolved organic matter in the ocean is as much as the amount of CO$_2$ in the atmosphere, and if it were to be broken down and respired by microbes, the resultant production of CO$_2$ would have a significant impact on the CO$_2$ level in the atmosphere and therefore global climate. There is a vast array of different bacteria, viruses and archaea in the ocean, so why can they not use the DOC? If we do not understand the reason, we cannot predict how this might change in a warmer world.

Azam: If we oxidize all of the organic matter in the sea, it would double the current level of CO$_2$ from 238 ppm to over 400 ppm, and we would be in a scorchingly hot environment. It is indeed an intriguing and scary fact.

Suttle: Correct. Whether the carbon is released via respiration or stored as DOC will have a huge impact on climate change.

Zhang: Especially, we are concerned that a 2°C increase in temperature will occur, above which our lives on Earth would be severely threatened.
Robinson: So the MCP concept is really a collection of hypotheses as to why there exists such a large pool of DOC in the ocean, and what we are discussing at this meeting is how to motivate the international community to work together to test these hypotheses.

Zhang: Right. It is a refractory DOM pool that the MCP creates. But what is the nature of refractory DOC? How do we quantify that pool? It is more difficult than playing the virus gene games. With sequencing you can get all the genes, but we are way behind in quantifying the specific composition of the organic matter. With the focus on the MCP, we bring all the efforts towards solving this colossal problem.

Wallace: I think that the DOC pool of the ocean is large and old, but that it is also extremely complex in terms of its molecular structure. At the same time, the key way in which the organic carbon pool can be mobilized by microbes in the ocean relies on the diversity and complexity of microbial life in the ocean. Much of this diversity is still being characterized. If we put these two things together, it raises a lot of questions, including how microbes can produce and also remove this long-lived organic carbon. The way that can happen relies on many different processes, because of the complexity of the carbon and the complexity of the microbial community. Then, if you change the environment in which the microbes are living, their ability to produce or degrade this carbon will change accordingly. This presents a real challenge for chemists to predict what will happen in this changing biophysical setting. The MCP concept creates a framework of hypotheses that can be tested through experimentation involving chemists, biologists and geologists working together.

Azam: We need a research agenda that enables the scientific community to unite to focus on the MCP.

Suttle: The average age of the carbon in the refractory DOC pool is about 6000 years, and it apparently accumulates quite slowly. So what could be the mechanism that causes this accumulation? We need to know both what is producing the DOC and what is breaking it down. If we could change the kinetics of the process, the carbon could be broken down more slowly or accumulated more rapidly. Either way would have a significant impact on the rate of CO₂ accumulation in the atmosphere. When the CO₂ is going into the ocean, carbon accumulation occurs through the biological processes within the ML and the MCP is the way in which this carbon can be sequestered. This accumulation of DOC is not the same as the dissolution of dissolved inorganic carbon that causes ocean acidification, which is why we need to differentiate this microbially mediated carbon pump from the solubility pump.

Azam: I want to mention the fact that the organic carbon contains a mixture of molecules, some of which are young and some of which are relatively old, turning over on timescales of days to months. If global temperature increases by 2°C, the kinetics of the turning over of the short-lived and long-lived carbon pools would not be affected to the same degree. The most likely scenario is that the turnover rates of the younger pool will increase more than the turnover rates of the older pool. If that happens, then the overall total pool of organic matter will shrink. Then the MCP could compensate for this by converting the short-lived organic matter to the particulate phase.

Suttle: It is because of the microbes that the organic carbon cannot go back into the atmosphere. Overcompensation would happen.

Azam: With that scenario, the planet would cool down. Because of the activity of the MCP.

MCP AND ML: TWO SIDES OF A COIN

Jiao: The ML was first proposed in 1983 and, as far as I know, that single paper has been cited over 5000 times. I was a young student when I first read this paper and was surprised, because I learnt that microbes could do something else in addition to respiring, such as removing DOC from the water and returning it back to the food web as particulate organic carbon (POC).

Azam: The ML is a mechanism that brings DOC back into the grazing food chain. The DOC enters the food web by bacteria assimilating the dissolved organic matter and changing the phase from dissolved to particulate. The MCP achieves the opposite; it produces long-lived DOC.

Jiao: The MCP is transforming the carbon into a distinct pool that could stay for a long time.

Azam: Regular microbiologists in the 1980s recognized that microbes move the carbon into the food web in the ocean. First, studies quantified the natural bacterial community, but when genomics approaches became available, we were able to undertake culture-independent analysis of the composition of the bacterial communities. Now we have a long list of microbes, all of which are involved in two processes: mediating carbon molecules moving into the food web or leaving them behind as refractory DOC to be accumulated over time.

Suttle: I think it is important to recognize that the bacteria are using carbon all the time, but not all of the carbon is removed, some is left behind.

Azam: The ML allows carbon to be transformed into more microbial cells, creating ‘food’ for larger organisms. Although scientists were not sure about the number of bacteria that occurred in a defined water column at first, with advances in technology, they now know that there are far more bacteria than was ever imagined, and that these bacteria play a vital role in the metabolism of the marine biota. Bacteria are the dominant bio-force.
Suttle: Something that we need to emphasize is that the ocean is microbial and produces half of the oxygen in the planet. Microbes in the ocean that you cannot see keep the planet in balance. That is why the ML has had so much attention. It represented a total paradigm shift; although scientists knew that bacteria existed in the sea, they did not realize their crucial importance.

Azam: In the early days, microbiologists were discussing a similar question: what fraction of carbon is fixed through photosynthesis by plankton in the ocean? The answer was about 1%, but it turns out that the microbes are the major force distributing organic matter and carbon in the ocean, fixing as much as 60 gigatons of carbon per year of CO₂ to organic carbon, roughly the same amount as fixed on land.

Jiao: While the ML removes DOC from the water and transfers it as POC to higher tropic levels including fisheries, the MCP removes DOC from the short-term carbon flow into another pool, the refractory DOC, which keeps the carbon in the water column for a long time.

“Microbes in the ocean that you cannot see keep the planet in balance.”
—Curtis Suttle

INNOVATION REQUIRES INTERNATIONAL COLLABORATION

Jiao: In order to explore the mechanisms of carbon storage in the oceans, we not only need direct observations of the oceans but also representative manipulation experiments. What should we do to maximize the advantages of the two methods?

Legendre: Observations and experiments have shown that there are large amounts of refractory DOC in the oceans, and we have to figure out why it is like that. When we work in a given discipline, we become very passionate about it, and we often favor explanations of natural phenomena related to that discipline. The role of scientists is to try to understand the present and figure out the future. In order to do that, we formulate hypotheses and test them. To test hypotheses about the refractory DOC in the ocean, we could build large incubation chambers whose conditions and size would be comparable to those of the natural environment. In other words, we need to work at spatio-temporal scales that are pertinent to those of the ocean. For example, in the incubation chambers we would need to reproduce the fact that, in the ocean, waters are denser at depth than at the surface. We would also need to use consistent experiment approaches, meaning that we should have both control and experimental chambers, each of them being replicated. We have to understand that using such a large experimental facility would be a challenge, because planning the facility and the experiments would take years and operating the facility would not be technically easy. This would require international collaboration, because it would probably be too costly for a single country to operate such a facility and run the experiments. Mathematicians, modelers, chemists and geologists should all come and work together to use the facilities to test key hypotheses.

If we look at CERN (the European Organization for Nuclear Research) as an example, the planning of some experiments in fundamental physics implemented there started 20 years before being done, and involved hundreds of people. If we were clever and lucky, there would be one such major facility for marine research in the world. It would not be like a radio telescope, of which there are many as these are observation instruments, but more like the Large Hadron Collider (LHC) at CERN, which is a unique experimental machine.

Wallace: The large-scale facility motivated by the MCP will provide the opportunity for innovation. What we need in innovation is nucleating points: different brains come together, partly because the facility is there, and partly because a unifying hypothesis is there to be tested. That is where real scientific leadership comes, by creating a venue for people to come together and exchange and test ideas.

Jiao: Future collaboration and international organization is the key to testing and developing the MCP protocols.

Robinson: Definitely. As we always knew, the overarching question requires a number of different nations, and a number of different disciplines to work together to achieve the answer. We also need international standards and protocols for how we measure refractory DOC, including an intercalibration exercise to compare the measurements from all of the laboratories taking part in the project. For example, around the world, there are observation stations collecting data at a particular geographic position, creating decadal time series of data on plankton abundance and diversity. If we could collect water from such a time series station with which to do our hypothesis testing experiments, we could take advantage of this context of data showing how the ocean changes on a decadal scale. We also need make sure that the data and facility are easily accessible to scientists throughout the world. This is a global cutting-edge question, and we have to be very innovative and let our imaginations bloom.

Wallace: Another issue is that large-scale land-based facilities are also very important, because you cannot easily manipulate the environmental conditions of the ocean.

Jiao: That is correct. We need collaborative efforts all over the world from different disciplines and different pathways to address the overarching hypotheses.

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—Louis Legendre
Azam: Absolutely, maybe 10 or 100 times as much money has been allocated to research on human health as compared to the health of the ocean, but the two are actually intertwined. It is time to address the importance of marine research.

Robinson: The benefit of a large international research initiative is to mobilize scientists around science funding and large research facilities. Such facilities crystalize the international community into working together to address large-scale questions that cannot be addressed by small groups or even single nations.

Wallace: In Canada, we have the longest coastline in the world, and there is a real problem of understanding of what is going on along the coast. For us Canadians, we can see the real need to go together with international colleagues to solve large-scale problems.