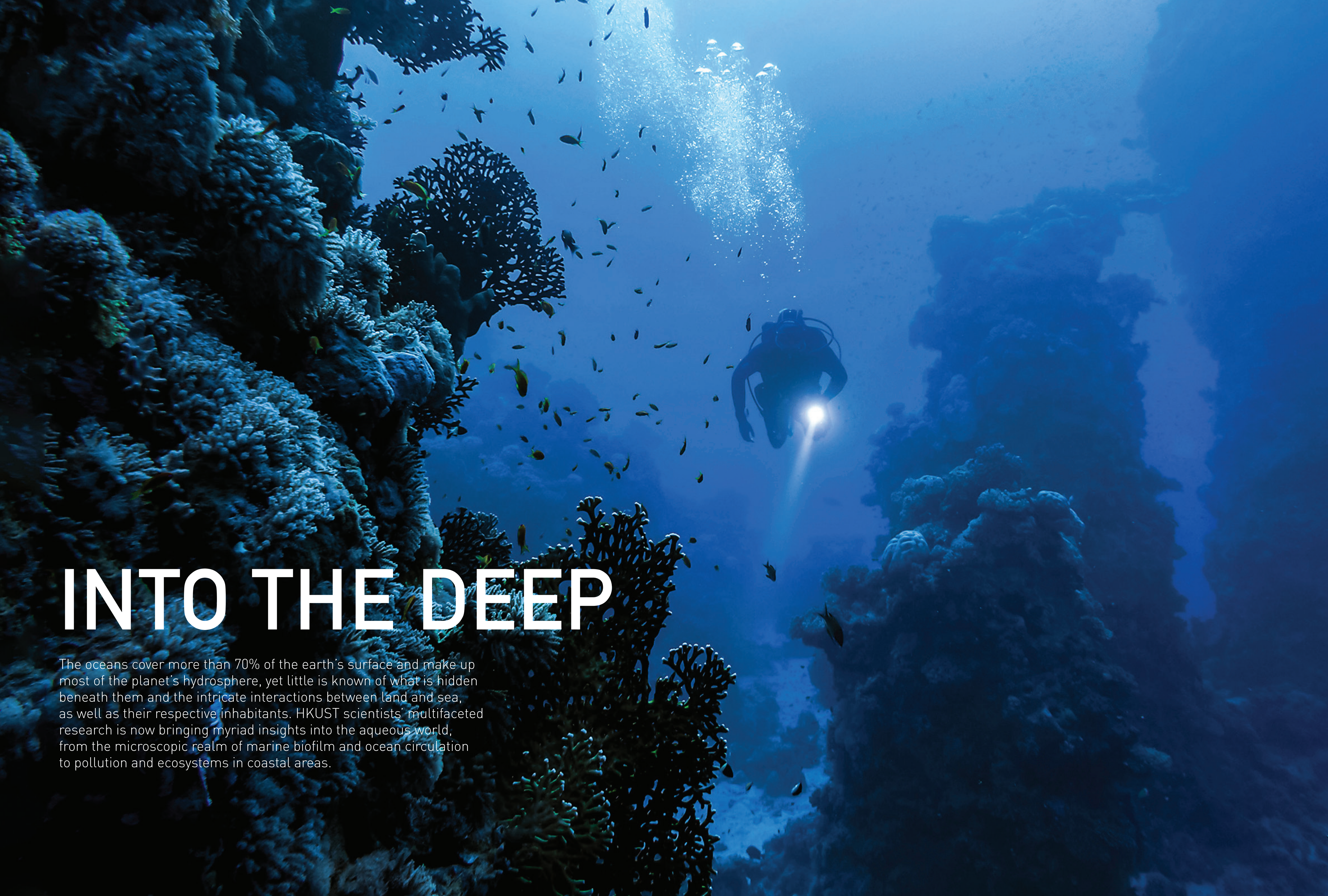
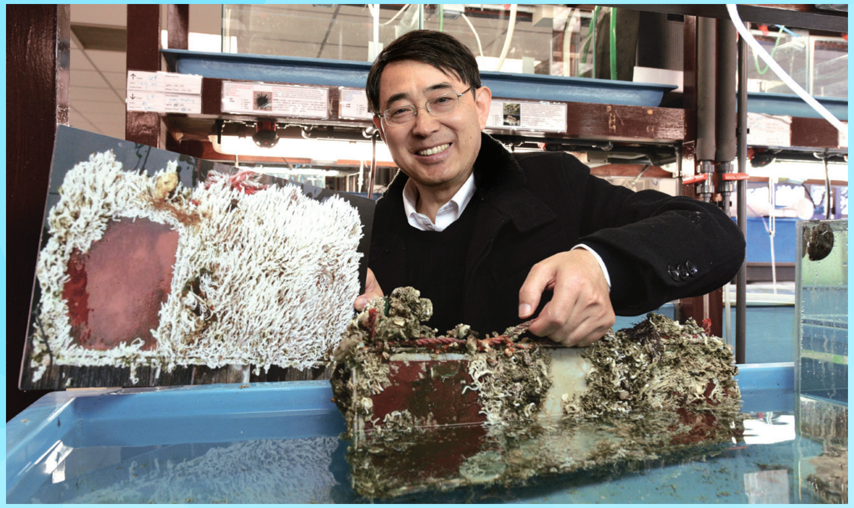


INTO THE DEEP

The oceans cover more than 70% of the earth's surface and make up most of the planet's hydrosphere, yet little is known of what is hidden beneath them and the intricate interactions between land and sea, as well as their respective inhabitants. HKUST scientists' multifaceted research is now bringing myriad insights into the aqueous world, from the microscopic realm of marine biofilm and ocean circulation to pollution and ecosystems in coastal areas.

SIGNALING BREAKTHROUGHS



> The intricate relationships between microbes, animals, and the environment, whether in the ocean or on land, are treasure troves of secrets waiting to be discovered

PROF PEIYUAN QIAN
David von Hansemann Professor of Science, Head, Department of Ocean Science

The equilibrium of any ecosystem is established by three components that exert influence on each other – the environment, microbes, and animals. Chemical signals provide communication between the three, playing a crucial role in the composition and overall functioning of the ecosystem.

Marine biologist Prof Peiyuan Qian uses modern bioinformatics and unique sequencing methodologies in his quest to understand the delicate interactions between microbe populations, animals, the environment, and the chemical cues that tie them together. It is a research journey that has taken him from coastal marine environments to the deepest depths of the ocean, and finally, to life on land.

Biofilm Discoveries

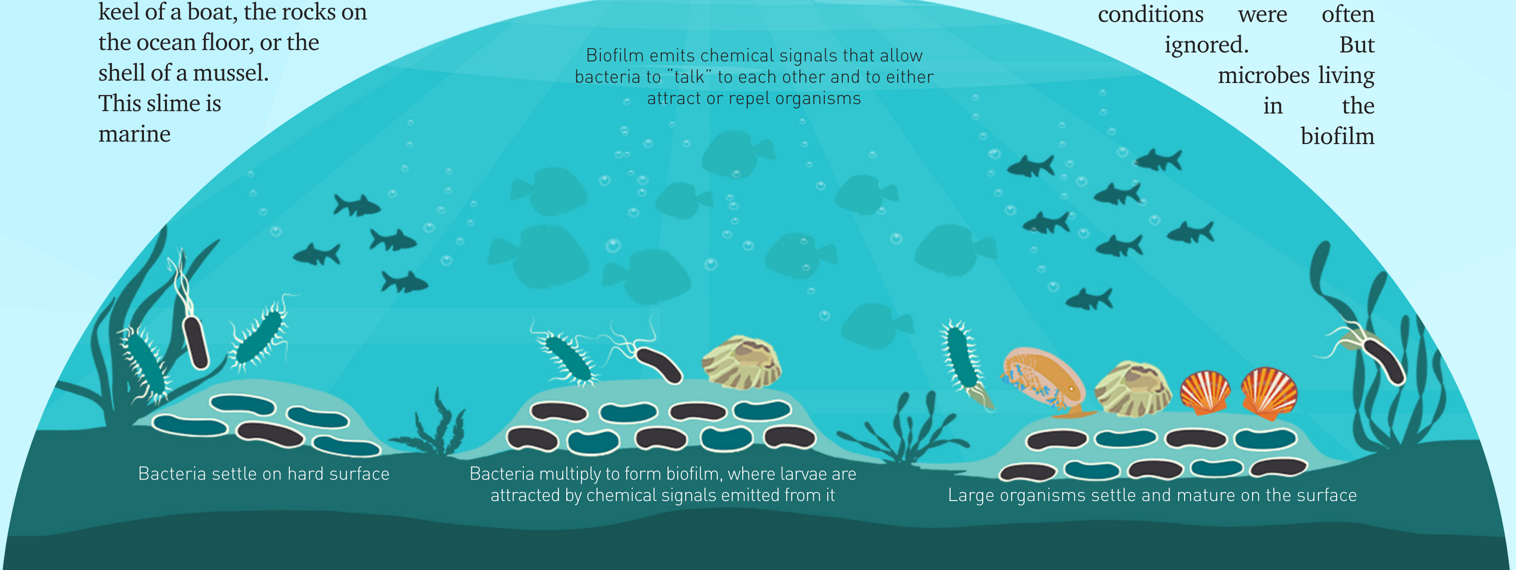
One of Prof Qian's scientific passions is for slimy surfaces, whether on the keel of a boat, the rocks on the ocean floor, or the shell of a mussel. This slime is marine biofilm, housing thousands of types of bacteria, algae and other micro-organisms that emit chemical signals which affect the behavior of larger macro-benthic organisms.

These benthic invertebrates are aquatic organisms that settle in or on the seafloor, such as shellfish, molluscs, crustaceans, and barnacles. Although their movement is limited, they are still mobile in their larval stages and respond to chemical signals emitted from biofilm. Through this exchange of signals, these benthic organisms determine where they will eventually settle and live.

Prof Qian, David von Hansemann Professor of Science and Head of HKUST's newly established Department of Ocean Science, has been the first globally to study the dynamics of marine biofilm and the chemical interactions within it. His lab is unique in its focus on larvae, biofilms, and chemical cues that affect the behavior of marine animals, and how the biofilm structure is affected by environmental changes. Among their findings is the discovery that certain non-toxic organic compounds, synthesized by bacteria themselves, can either attract or repel benthos to encourage or discourage settlement.

Such new knowledge is based on advances in big data mining and high-throughput sequencing technology that Prof Qian applied to single genes, genomes, and metagenomes. "Without sequencing technology, you are not going to be able to recognize the high biodiversity and various functions of microbes living in the biofilm," he said.

"In the past, people took a snapshot approach. In taking samples and analyzing them, rapid changes of both microbial community structures and functions in biofilm in response to changes in environmental conditions were often ignored. But microbes living in the biofilm are very sensitive to environmental changes, such as water temperature and nutrients. What you see today is different from what you see tomorrow."



Heavy fouling on boat surfaces

Antifouling solution applied on ship surfaces to repel marine benthos

Prof Qian uses a novel and comprehensive methodology, where sample analysis incorporates analysis of environmental variables.

By applying this understanding, Prof Qian's lab has been able to identify butenolides, simple non-toxic organic compounds produced by bacteria that can repel benthos and can be synthesized. He then extended his findings further to develop environmentally friendly antifouling coatings using butenolides as repellants to prevent marine foulers from attaching to the hulls of boats, solving a major problem in the shipping industry where settlement of unwanted organisms or seaweed on boat surfaces costs billions of dollars annually.

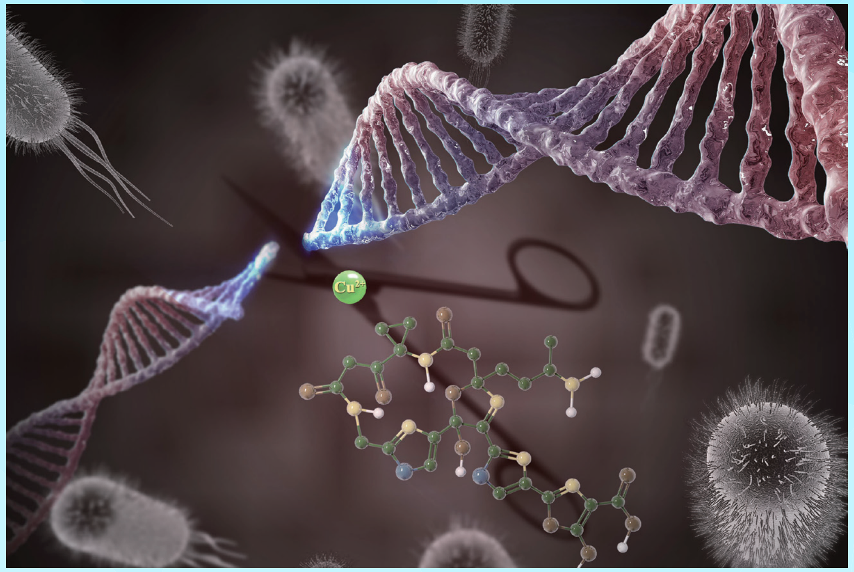
"We need to find broad-spectrum compounds that work in a wide range of conditions," he said. Conventional chemical coatings aimed at discouraging the fouling process are typically toxic or damaging to the surrounding environment and, as a result, have been banned.

Following tests on marine and fresh-water fish, 13 of Prof Qian's antifouling compounds have been patented and several are now being trialed on specialized vessels in Chinese waters. Meanwhile, aquaculture farmers want to know the type of biofilm that can attract the larvae of benthic species, such as abalone and oysters. Such use of compounds derived from biofilm is just one of many potential gifts from marine slime.

Racing to Beat Antibiotic Resistance

The basic principle of microbes in the biofilm emitting signals that attract or repel other organisms has huge implications beyond the sea, including biomedical research into new cancer treatments, antibiotics, and understanding of antibiotic resistance.

To assist with this, Prof Qian has used genome mining and synthetic biology to screen compounds found in biofilm. He has sped up such work substantially by conducting systematic analysis of gene clusters in microbial genomes rather than the conventional method of screening for bioactives, which is slow and less effective. Novel biosynthesis pathways can then be identified, and potential bioactive compounds predicted, based on the analysis of gene arrangements of biosynthesis pathway gene clusters.



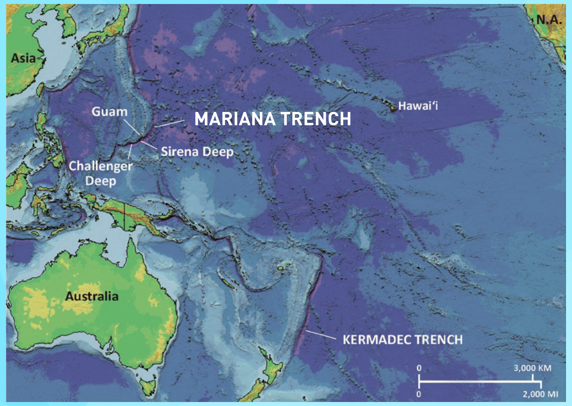
E. coli produces colibactin, activated by copper, and can cause double-stranded DNA breakage, which leads to cancer

It takes a computer cluster about a month to identify some of the novel pathways from over 12,000 microbial genomes, based on the algorithms and matrix created by his team. "After we discovered a new biosynthesis pathway, we used our cloning platform to clone the entire biosynthesis pathway gene cluster in one go into yeast or *E. coli*, or another microbial host, and then used them as "factories" to produce the novel compound. Furthermore, we conduct gene editing to knock out or knock in genes to improve the production of such compounds," Prof Qian explained. "It is now possible to produce the compound biologically by understanding the genome."

A recent and much-publicized Qian discovery is how bacteria can mutate to develop enzymes that can break down antibiotics, leading to antibiotic resistance (*Nature Chemical Biology*, 2018).

Peptide antibiotics, such as polymyxin, vancomycin, and teixobactin, are among the last-line-of-defense antibiotics for broad-spectrum bacteria. By analyzing nearly 6,000 bacterial genomes through a network-associated global genome-mining approach, and chemical and enzyme validation, a family of D-stereospecific resistance peptidases (DRPs) was found to be responsible for peptide antibiotic resistance. Prof Qian and his team also discovered that many strains of bacteria have developed these resistant enzymes.

The researchers are now contributing to the global search for novel classes of antibiotics. In a paper published in *Nature Communications* in 2018, they analyzed over 7,000 bacterial genomes, and identified two new compounds, brevicidine and laterocidine, that demonstrated efficacy against pathogens such as *E. coli* in a



Studying how deep-sea crustaceans and mussels have adapted to living and thriving in the Mariana Trench's extreme conditions

mouse model with low risk of resistance. Prof Qian believes many more peptide antibiotics with low risk of resistance are still to be identified.

Using the same research strategy (microbiome analysis, genome mining, gene cluster cloning, and gene editing, bioactive compound screening and structure identification of novel compounds), his collaborative team successfully isolated and identified the chemical structure of colibactin from human gut bacteria *E. coli*, and decoded the mystery of how colibactin causes DNA damage, leading to human colon cancer (*Nature Chemical Biology*, 2016; *Nature Chemistry*, 2019).

Prof Qian received a State Natural Science Award from China's State Council in 2016.

Deep Ocean Survival Tactics

Prof Peiyuan Qian's interest in biofilm has extended to a depth of 11,000 meters in the Mariana Trench. In this work, he examined how crustaceans have adapted to such an inhospitable environment and its huge hydrostatic pressures and sometimes toxic conditions, involving high concentrations of hydrogen sulfate and methane gas. He found the answer lies in the chemical compounds these creatures produced to make their surfaces more fluid and tolerant of such conditions (*Molecular Ecology*, 2017). Prof Qian used bioinformatics to sequence the genome of deep-sea vent mussels and compared the results to their shallow-water counterparts to try to ascertain how they have adapted. He found that the symbiotic relationship between microbes in the gills of deep-sea mussels was responsible for transporting toxic chemicals outside their gill epithelial cells. Changes in their genetic makeup were also found, involving enzymes and enhanced immune systems (*Nature Ecology and Evolution*, 2017).

Amphipod from Challenger Deep, Mariana Trench - about 7.5cm long, 7 times longer than shallow-water amphipods

Shallow-water amphipod - about 1cm long

PROVINCIAL MARINE LAB HOSTED AT HKUST

HKUST now hosts the Hong Kong Branch of the Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) to support the development of marine science and technology in the Greater Bay Area. Headed by Prof Peiyuan Qian, the Lab's 15-year vision includes research on Greater Bay Area marine ecosystems that are under stress from climate change and pollution. It will also develop key interdisciplinary research and technologies for strategic resource utilization in the South China Sea, expand areas for marine industry advancement, and help promote a high-quality marine economy in Guangdong.

DIAGNOSIS AND PROGNOSIS OF OCEANS

> Through our mathematical modeling, we can extrapolate limited spatiotemporal field data and predict the future of the oceans

PROF JIANPING GAN
Chair Professor of Ocean Science and Mathematics

Rivers, deltas, sea shelves, and the deep ocean basin to which they are connected form an amazing interlinked ecosystem, influenced by human activity but shaped by the underlying physical and biogeochemical processes of nature – wind, tides, currents, temperature, biogeochemical substances, climate change, and the cycle and web of life itself.

This watery world is the domain of physical oceanographer Prof Jianping Gan, who brought the study and mathematical modeling of complex ocean dynamics to Hong Kong when he arrived at HKUST 16 years ago. Since then, research based on numerous seagoing adventures and related modeling studies has provided new understanding of the patterns of ocean circulation and ecosystems in coastal waters and in the broad South China Sea basin, with important global significance for water management, pollution mitigation, and climate change.

Ocean Circulation

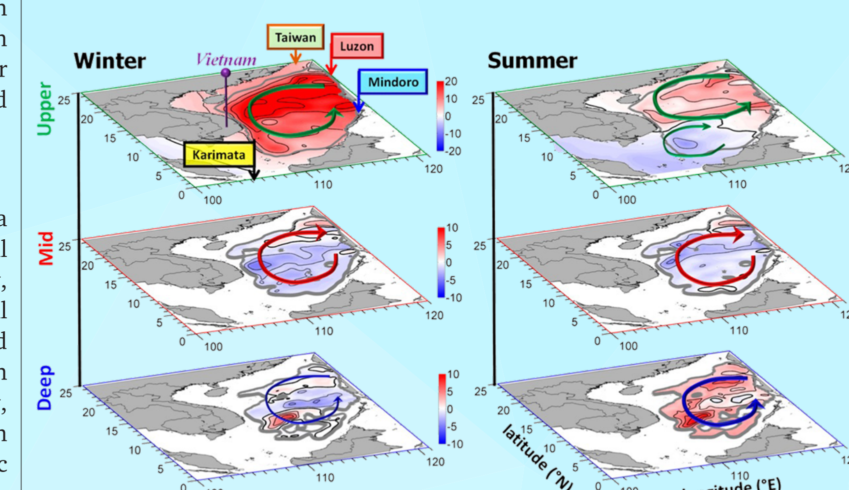
In his research, Prof Gan uses a unique combination of geophysical fluid dynamics, numerical modeling, coupled physical-biogeochemical dynamics capabilities, and field measurements. From data collected on survey expeditions around Hong Kong, the Pearl River Delta estuary, South China Sea, and adjacent western Pacific Ocean, Prof Gan identified the three-layer alternating spinning circulation of the South China Sea, which provided an important hydrodynamic framework for understanding heat and energy transport, the carbon cycle, ecosystems, and climate variability in the region. His research elucidated physically for the first time that waters in the region circulated anti-clockwise at the upper layer, clockwise at the mid-layer, and anti-clockwise in the deep layer. The resulting article, published by the *Journal of Physical Oceanography* in 2016, attracted global attention, becoming one of the most downloaded papers during the year.

The dynamics that Prof Gan observed is crucial for determining the transport of water masses, energy, and biogeochemical substances in the region and adjacent western Pacific. Such implications have contributed to an understanding of the generation of tropical cyclones and storm surges, sustainability of fisheries, and the progress of climate change. They can also lead to more accurate forecasting and mitigating action.

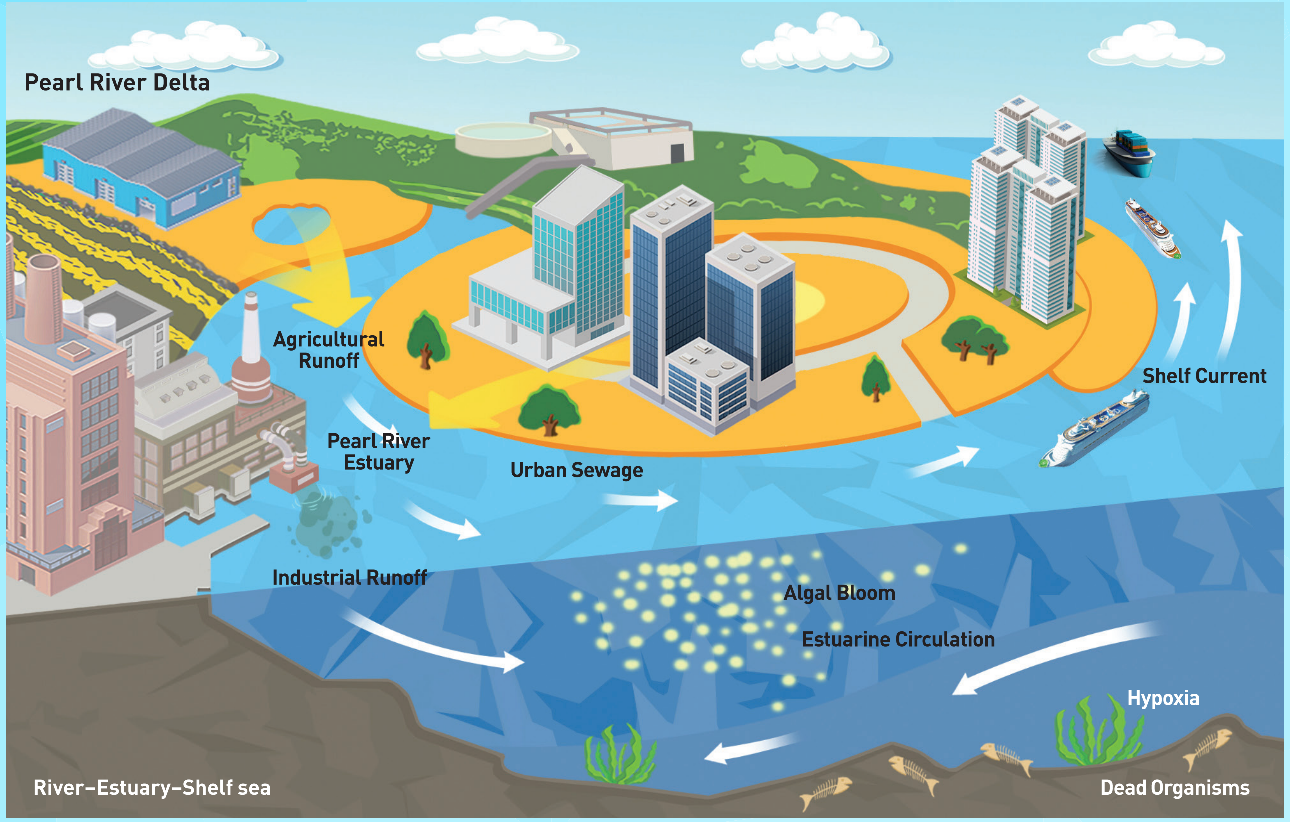
Tracing Hypoxia and Eutrophication

Building on such understanding, Prof Gan is now setting out to add insights toward two major local problems of international interest: hypoxia and eutrophication. Hypoxia is manifested in what are known as "dead zones" in oceans, seas, rivers, and lakes – when oxygen saturation falls below 2mg per liter and life can no longer be sustained. After dead organisms sink to the bottom

THREE-LAYER CIRCULATION



A vertically alternating anti-clockwise, clockwise and anti-clockwise three-layer circulation was identified in the South China Sea by a large-scale mathematical model. The three-layer circulation shapes the three-dimensional pattern of water motion from season to season in the South China Sea, and plays a critical role in transporting heat and energy that affect regional climate variability and biogeochemical substances in sustaining biological productivity (*J. Phys. Oceanogr.*, 46, 2309, 2016).



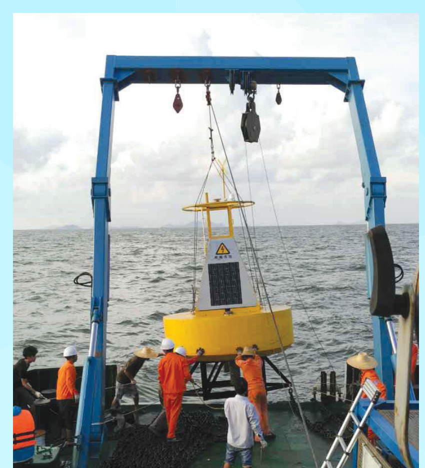
Agricultural and industrial runoff as well as urban sewage contain nutrients such as phosphates and nitrates that are carried from rivers by ocean currents, which then pass through the Pearl River Delta estuary. These nutrients form eutrophication and algal blooms on the surface and hypoxia (low oxygen) at the bottom over the continental shelf off Hong Kong.

of the ocean, their decomposition consumes more oxygen and contributes to hypoxia. It is closely linked to eutrophication, caused by excessive nutrients discharged into the ocean by river and sewage effluent, that results in algal blooms.

"Hong Kong is surrounded by ocean and its oceanic area (3,000 km²) is twice as big as its terrestrial area and facing great challenges," Prof Gan said. "It has a problem with eutrophication – which we see in red tides – and it is getting worse. Hypoxia will likely spread across Hong Kong waters, according to current trends, if we do nothing."

Pinpointing the precise sources of eutrophication and hypoxia through evidence-based strategies is the way forward to assist future water management schemes and rectify the problem. Prof Gan and his collaborators are now participating in the large-scale theme-based research project Ocean Circulation, Ecosystem and Hypoxia around Hong Kong Waters, known as OCEAN-HK and funded by Hong Kong's Research Grants Council. Comprising leading marine researchers from Hong Kong and Mainland China, the five-year project launched in 2017 straddles disciplines such as physical, chemical and biological oceanography, and marine ecology. The investigation of the waters in and near Hong Kong, the Pearl River Delta, and the Greater Bay Area of the South China Sea is based on extensive multidisciplinary field surveys, real-time monitoring, and the novel coupled physical-biogeochemical pollution modeling system. Prof Gan, the OCEAN-HK coordinator and co-principal investigator, explained that this holistic approach combines field observations of hydrographic properties, ocean currents, nutrients, oxygen, plankton, and pollution, with atmospheric and physical modeling of circulation and tides, and biochemical modeling of the ecosystem.

The HKUST team includes biological oceanographer Prof Hongbin Liu, who is investigating food web dynamics; and marine ecologist Prof Stanley Lau, for his expertise in identifying and tracing strains of bacteria. The three researchers are among the key members of the University's new Department of Ocean Science, which will spearhead research and teaching in the field, inspire future generations of oceanographers, and is the first of its kind in Hong Kong.

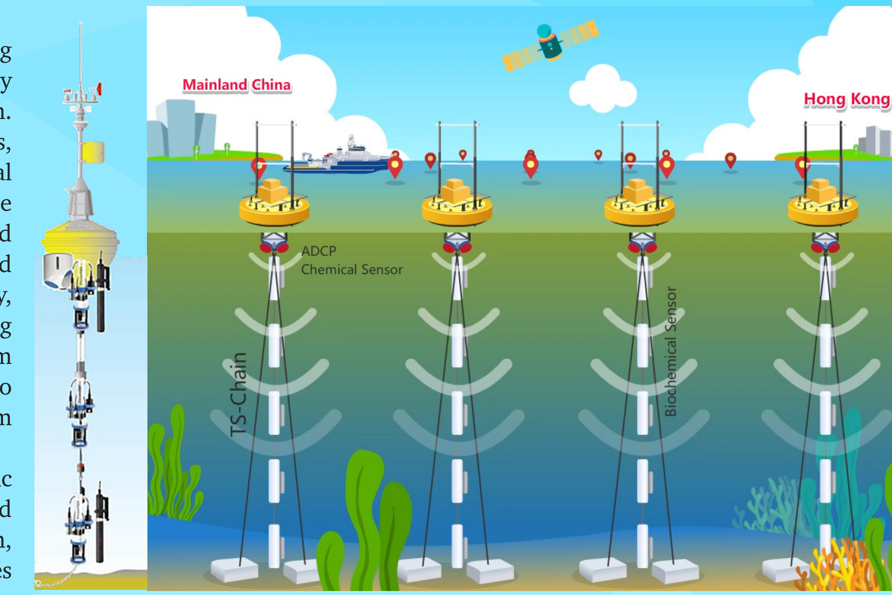


Deployment of buoy for an ocean survey conducted by joint shipboard mapping

Data is being gathered continuously, and in real time, using a network of mapping by research vessels, and time-series monitoring by buoys and unmanned autonomous research vessels. A particular area of concern is the city's iconic Victoria Harbor that is currently experiencing a trend of decreasing dissolved oxygen at the bottom depths of the water, despite major government clean-up efforts.

Real-time Data Collection

The research will inform the Hong Kong government's future strategy for water treatment and protection. Key government departments, including the Environmental Protection Department, the Agriculture, Fisheries and Conservation Department, and the Hong Kong Observatory, are involved through a steering committee, and benefiting from training that will enable them to run their own monitoring system developed by the project.



Moored buoys in the waters off Hong Kong. Real-time physical and biogeochemical data are transmitted to a land-based station and integrated into a mathematical model for forecasting. The buoys sense salinity, temperature, pressure, dissolved oxygen, chlorophyll, nitrate, and atmospheric variables.

Although the team's dynamic model for the diagnosis and prognosis of eutrophication, hypoxia, and their consequences for the ecosystem will be unique to the Pearl River Delta area, it will also be relevant to the studies of hundreds of other coastal water systems. "It provides many innovative methodologies and approaches that are new and applicable to other hypoxic zones in the world," Prof Gan said. "It is creating holistic understanding of eutrophication and hypoxia in river-estuary-ocean shelf systems both locally and globally."

Among the project's different aspects is the monitoring of water temperature. Prof Gan predicts that, if current human activity is not modified, within 100 years, temperatures may rise by 3 to 4 °C, which will increase the partial pressure of carbon dioxide (pCO_2) in the ocean and change the mitigating effect the ocean has on atmospheric carbon dioxide (CO_2). "I don't know if the problems facing our oceans can really be addressed by ocean science alone, given the complexity involving science, social, economic, and political issues. But I am sure that without ocean science, we can't resolve them," he said.

Prof Gan, who conducted his early research at the Ocean University of China and Third Institute of Oceanography, followed by postgraduate work in Canada and the US, has been one of the most active sea-going researchers in the region, venturing as far as the Antarctic in the 1990s. He still actively takes to the ocean for fieldwork surveys.

CENTRE FOR OCEAN RESEARCH IN HONG KONG AND MACAU

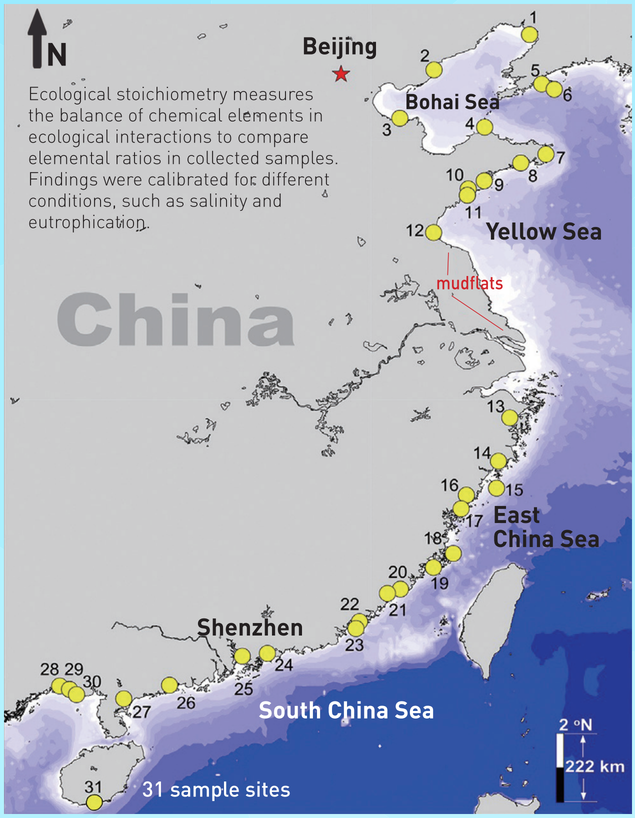
The recently established Centre for Ocean Research (CORE) in Hong Kong and Macau at HKUST serves as a platform for integrated and interdisciplinary ocean science research. It focuses on four key areas: air-sea-land interactions, ocean physics and biogeochemistry, environmental simulations and forecasting, and ocean big data. Exploration of these areas will provide strategies to address regional challenges in marine sustainability, with potential global implications. CORE is headed by Prof Jianping Gan, participated by members from universities in Hong Kong and Macau, and supported by the Qingdao National Laboratory for Marine Science and Technology. CORE is expected to make significant contributions toward the development of ocean science and technology in the region.

WHY DELTA OYSTERS ARE BLUE

Metal contaminants flowing into rivers and seas from ever-increasing industry along the 14,500-kilometer China coast is not good news for oysters and other marine creatures – or for lovers of seafood. Now, after mapping the entire coast for metal pollution for the first time, HKUST researchers have identified the most toxic sites.

Prior to this, the northern coast was regarded as the most polluted, due to heavy industry in the area. But marine scientist Prof Wenxiong Wang and his team found that the Pearl River Delta estuary suffers a problem more severe.

The discovery was made when the researchers analyzed over 3,000 individual oysters, mussels, and clam samples, gathered within a short time frame from more than 30 stations along China's coastline.



Environmental Pollution, 224, 658 (2017)

Building on earlier monitoring in the delta, the full coastal mapping revealed oysters in the South and East China Seas accumulated higher concentrations of cadmium, zinc, and copper, compared with those in the Bohai Sea and Yellow Sea; and significantly higher concentrations of nickel and chromium at levels several times higher than food safety limits. Prof Wang's long-term research in the delta also found while the levels of metals such as nickel and chromium have declined, others, such as copper and zinc, have increased.

“We now have a better understanding of the metal pollution distribution along the China coastal area”

PROF WENXIONG WANG
Chair Professor of Ocean Science

There are government regulations for emissions of the most toxic metals, for example, lead and mercury. This is not the case for minerals essential for humans, such as copper and zinc, which are also toxic in excessive quantities.

Prof Wang and his team use radioisotopes to trace metal behavior in organisms. The radioisotope quantifies the rates of metal contamination and where it goes in the cellular structure and organs, while the kinetics governs the rate of metal accumulation and removal. It is the excessive copper that gives contaminated oysters their alarming blue hue.

His latest work demonstrated that oysters can act as a sentinel organism for tracking the source of zinc contaminants in marine environments. Such scientific monitoring provides vital information for industry planning, control, and clean-up operations. In the June 2019 edition of the prestigious journal *Environmental Science & Technology*, Prof Wang's publication was selected as the cover feature.

While metal pollution levels in our waters appear to have improved due to changes in industry, that does not mean the problem is solved. “There is a lesson from Hong Kong. In the 1970s, it was very polluted, but now the environment is better because the industry has moved. But we are paying a big price for the past, because of the contaminated sediment. Even though pollution in the water is reduced, at the bottom it is still there, and needs to be cleaned up,” he said.

Oysters severely contaminated with copper have a blue hue