Methane mitigation: Learning from the natural marine environment

Jing-Chun Feng,[1,2,*] Jinyue Yan,[3] Yi Wang,[4,*] Zhifeng Yang,[1,2] Si Zhang,[1,2] Sai Liang,[1] and Xiao-Sen Li[4]

[1]School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou 510006, China
[2]Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China
[3]Future Energy Center, School of Business, Society and Engineering, Mälardalen University, SE-721 23 Västerås, Sweden
[4]Key Laboratory of Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, China
*Correspondence: fengjc@gdut.edu.cn (J.-C.F.); wangyi@ms.giec.ac.cn (Y.W.)

During the past decades, public attention regarding global warming has mainly focused on CO_2 reduction; however, CH_4, another important greenhouse gas, has a global warming potential that is 84 times higher than that of CO_2 on a 20-year basis. The annual atmospheric amount of CH_4 in 2020 reached its highest level since systematic monitoring began in 1983 (Figure 1A). To date, despite coronavirus 2019 shutdowns, methane has contributed approximately 30% to global warming. Recently, a series of timely appeals, such as "The Global Methane Pledge" signed at the United Nations Climate Change Conference (COP26) and the "Global Methane Assessment" from the United Nations Environment Program, have called on global methane reduction and mitigation.[1]

Identifying global emission sources and sinks and establishing an effective atmospheric CH_4 removal strategy are urgently needed to tackle the continuously increasing emission trend. It has been revealed that anthropologic sources, such as the oil and gas industry, agriculture and livestock activity, landfills, and waste disposal, rather than natural sources, comprise the major driving forces of methane emissions (Figure 1A).[1] Currently, chemical loss, including atomic oxygen radicals and chlorine radicals, is regarded as the main sink that can remove almost more than 90% of methane. Various methods, devices, and policies, such as the direct-air-capture method, in which CO_2 is directly captured from the air and converted into chemical product through facilities containing selective chemicals, have been proposed to enhance the methane sink capacity.[1] Currently, about 18 direct-air-capture devices are in operation globally. Owing to their absorption efficiency and the intricacies of required devices, such removal methods must still be considered speculative.

As the deep-sea sediments are the world's largest methane reservoirs, herein, we propose that control of methane emission from the marine environment should not be overlooked. Historically, massive amounts of methane-emission events from oceans have been evoked in the era of climatic shifts. Persistent methane seepage also occurs ubiquitously in the contemporary deep-sea sediments. However, marine methane sinks, such as the methane anaerobic activity mediated by methane-oxidizing organisms, have such high efficiencies that they can effectively filter and impede the entry of methane into the atmosphere. These examples demonstrate that we can learn and seek solutions from the natural ocean.

LEARNING FROM HISTORICAL METHANE RELEASE EVENTS

Marine methane reservoirs are sensitive to global warming, and the corresponding negative feedbacks are inestimable because oceans cover 71% of the earth's surface. A large-scale investigation verified that massive amounts of methane are discharged into the water column from underlying methane hydrate dissociation in the southern hemisphere.[2] Actually, methane release from hydrate dissociation has been linked to major environmental changes and biological extensions throughout Earth's history. Examples include the global surface temperature increase of 5°C−7°C in the Paleocene-Eocene thermal maximum (PETM), the obvious negative carbon excursion in the Jurassic period, and the deglaciation and warming in the Ediacaran period, all of which were speculated to have been triggered by the destabilization of methane hydrate according to the recording of isotope changes in deep-sea sediment[3] (Figures 1B and 1C).

On a millennial scale, greenhouse gas emission rates at the boundary of the PETM are approximately comparable to the current industrial extent. Hence, lessons from historical methane events can provide unique guidance regarding mitigation of increasing methane releases in an environmentally uncertain future. Improving our understanding of historical methane events, therefore, is crucial to revealing the spatio-temporal changes of methane ebullition and seepage. Based on richer signals and evidence from the geological, biogeochemical, paleo-

climatic, and ecological perspectives, we can obtain more information and awareness of short- (decadal) and long-term (millennial) interactions between the environment and oceanic methane release (Figure 1D). Multi-dimensional isotope detections are required based on the fact that isotope changes of carbon and oxygen in deep-sea sediment may be affected by mineralizing processes in the sediment. Other stable detection methods, e.g., investigating the historical changes in biomarkers, require synergistic detection techniques.

SOLUTIONS OF METHANE EMISSION RELIEF DERIVED FROM OCEAN

There is a huge environmentally impactful imbalance caused by the significant amount of methane trapped in the sea floor, methane released from the deep sea, and atmospheric methane derived from the ocean. Currently, it is difficult to definitively allocate methane in the atmosphere to a direct source of marine hydrate. One important reason for this is the deficiency of extensive marine observation and sampling due to the difficulty of access to the deep-sea environment. How to avoid or retard the triggering of massive methane-release events like the historical PETM is an urgent question. We need to know the fragile areas with methane-releasing potential that are sensitive to climate change and human disturbance. Identifying the dynamic inventory of oceanic emission areas is indispensable to establishing a global, effective methane emission mitigating strategy and heavily relies on robust marine monitoring and investigative ability.

Despite knowing the sources, we must survey all possible methane sinks in the ocean and uncover the environmental process of methane transformation. It is important to gain in-depth knowledge of the threshold value of methane flux, which can be filtered by the methane oxidation and hydrate formation, before release to the deep-sea floor. There is a threshold of a critical bubble volume fraction of methane that can migrate from the sediment to the water. We should acquire holistic knowledge of phase change, oxidation mechanisms, and the driving forces of methane dissolution during its migration in marine sediment and water columns, thereby clearly identifying all the hypersensitive sites of marine methane emission.

Applying a massive methane-reduction ability will lead to a relatively small proportion of ocean-derived methane in the current atmosphere. Employing the natural marine methane filtering capturing and transforming mechanism and developing a scalable reduction technology in engineered systems could lead to methane reduction from anthropologic methane sources, because unlike CO_2 separation from the atmosphere, which requires additional energy of at least 18 kJ/mol, the phase change of methane hydrate formation and methane oxidation are exothermic processes that require no extra energy once the activation energy is overcome.

Strong geological and biogenic evidence has revealed that methane oxidation in the deep-sea floor performs like a high-efficiency filter that could digest methane. Such a phenomenon plays an important role in sweeping alkane away in major environmentally destructive events like the massive Deepwater Horizon oil spill. Enriching the anaerobic oxidation of methane mediated by archaea or bacteria in bioreactors has been verified as an effective mitigation method;[4] thus, applying such mechanisms and enhancing the process of methane utilization efficiency in bioreactors to absorb methane in an engineered system could be a promising methane-reduction method (Figure 1E). In the future, innovative methods for pure culturing of functional microorganisms under pressurized conditions, along with single-cell sorting, may brighten the future development of purifying methane-oxidizing microorganisms. Furthermore, forming methane hydrate with additives in custom reactors not only has the advantage of capturing methane but also contributes to cold storage, which has huge commercial and industrial potential in the growing demand for energy storage in the
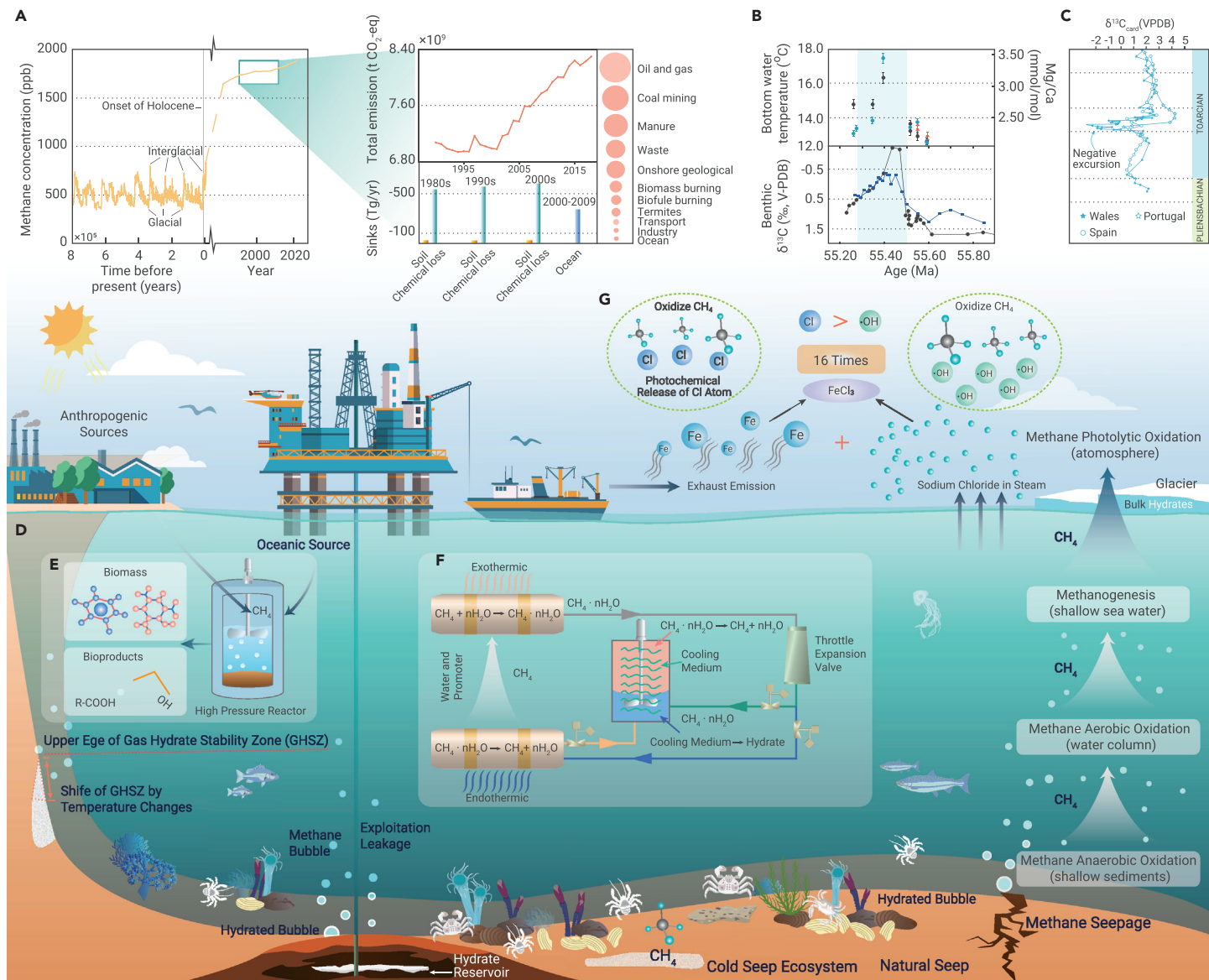
Figure 1. Records of methane emissions and mitigation solutions (A) Records of atmospheric methane concentration. The dashed line is the global emission trends. The pink circle and bar graph indicate source and sink contributors, respectively. (B) Temperature rise and carbon excursion in the PETM period. (C) Carbon excursion in a Jurassic oceanic anoxic event. (D) Mechanisms of methane releases and sinks in marine environment. (E–G) Methane reduction by biotransformation, hydrate formation, and photochemical oxidation, respectively.

upcoming nearly-zero-carbon society (Figure 1F).[5] The cold-seep ecosystem and the carbonates also have the potential to promote methane absorption and methane storage, which can be considered to be applied in the engineered system. In addition, once methane crosses the water-air interface and enters the atmosphere, methane-depletion technology facilitated by a Cl atom sink can be brought to bear. With a maximum methane-reduction efficiency of 11%, such a process is attractive because the Cl atoms can be generated via the Fe^{3+}/Fe^{2+} sunlight photo-catalyzed reaction (Figure 1G).[1]

Consequently, learning from natural methane sinks in the marine environment and applying an industrial version of such a mechanism could be considered an effective solution to the global problem of increasing methane.

REFERENCES

1. Ming, T., Li, W., Yuan, Q., et al. (2022). Perspectives on removal of atmospheric methane. Advances in Applied Energy **5**, 100085–100089.
2. Ketzer, M., Praeg, D., Rodrigues, L.F., et al. (2020). Gas hydrate dissociation linked to contemporary ocean warming in the southern hemisphere. Nat. Commun. **11**, 3788–3789.
3. Hesselbo, S.P., Gröcke, D.R., Jenkyns, H.C., et al. (2000). Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event. Nature **406**, 392–395.
4. Aoki, M., Ehara, M., Saito, Y., et al. (2014). A long-term cultivation of an anaerobic methane-oxidizing microbial community from deep-sea methane-seep sediment using a continuous-flow bioreactor. PLoS One **9**, e105356-14.
5. Cheng, C., Wang, F., Tian, Y., et al. (2020). Review and prospects of hydrate cold storage technology. Renew. Sustain. Energy Rev. **117**, 109492.

DECLARATION OF INTERESTS

The authors declare no competing interests.