HIGHLIGHT

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Climate warming amplified by aerobic methane oxidation during the Palaeocene-Eocene Thermal Maximum

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Submarine methane, over 500 Gt stored in marine sediments, represents a critical component of the global carbon cycle (Milkov, 2004). With climate warming and sea-level fall, submarine methane hydrates are prone to dissociation, releasing methane into the ocean and atmosphere (Ruppel and Kessler, 2017). In modern high-sulfate oceans, most methane is transformed through anaerobic methane oxidation (AOM) in sediments, where ~90% of seeping methane is consumed (Reeburgh, 2007; Regnier et al., 2011; Yang et al., 2020). The modern ocean thus constitutes a minor source (<2%) of atmospheric methane (Weber et al., 2019), with limited climatic impact. However, it is unclear how the methane oxidation process and climatic effect occurred in the past ocean with different chemical conditions (e.g., redox conditions, sulfate concentrations).

The Palaeocene-Eocene Thermal Maximum (PETM, ~56 million years ago) is a period of global warming, with temperatures rising by 5–11 °C (Stokke et al., 2020; Tierney et al., 2022; Újvári et al., 2025), which is marked by the negative carbon and oxygen isotope excursion (Kennett and Stott, 1991; Gutjahr et al., 2017; Westerhold et al., 2020). These geochemical symbols are mainly attributed to the massive release of ^{13}C-depleted carbon, predominantly methane, into the ocean–atmosphere system (i.e., methane hydrate hypothesis; Dickens et al., 1995; Sluijs et al., 2007; Ruppel and Kessler, 2017). However, this hypothesis largely overlooks the effect of methane oxidation on carbon cycle and environmental feedback in the ocean, and fails to account for the prolonged warming during the PETM (~170–200 kyr, Röhl et al., 2007), implying sustained carbon forcing and associated environmental perturbations beyond a single catastrophic release event (Frieling et al., 2016; Lyons et al., 2019; Kim et al., 2025).

Kim et al. (2025) present geological biomarker evidence for the aerobic methane oxidation (AeOM) in the Arctic Ocean during the PETM, offering new insights into the sustained warming of the PETM. The Arctic Ocean was a low-sulfate system (~5–10 mmol/L) during the early PETM, compared to the modern ocean (~28 mmol/L, Algeo et al., 2015; Kim et al., 2025). This sulfate depletion suppressed sulfate-dependent AOM, allowing methane to escape from the sediments into the water column, where it was oxidized into carbon dioxide (CO_2) through AeOM (Fig. 1). AeOM was identified through the ^{13}C-depleted hopanoid compound hop-17(21)-ene, indicating bacterial methanotrophy populations (Kim et al., 2025). In contrast to AOM, which generates alkalinity (HCO_3^-) in sediments, AeOM directly produces CO_2 in the water column, promoting the Arctic toward a net CO_2 source and driving prolonged warmth. Kim et al. (2025) reveal that AeOM amplified warming under a low-sulfate ocean during the PETM.

Beyond marine methane oxidation, terrestrial methane oxidation in lakes and wetlands may sustain PETM warmth (Pancost et al., 2007; Chen et al., 2025b). During the PETM, warming-driven water-column stratification and bottom-water deoxygenation in East Asian lakes enhanced methanogenesis and methane emissions and oxidation, thereby reinforcing climate warming (Chen et al., 2025b). Concurrently, bacteria-derived biomarker evidence (e.g., ^{13}C-depleted hopanoids) in the wetland from southeast England and northeast China indicates methanotrophy populations during the PETM, suggesting enhanced AeOM activity that transformed methane into CO_2 and thereby contributed to sustained warmth (Pancost et al., 2007; Chen et al., 2025a).

AeOM potentially contribute to ocean acidification through CO_2 production (Penman et al., 2014). The episodic productivity flourishing likely enhanced organic carbon (OC) burial during the PETM (Bains et al., 2000; Wei et al., 2025), however, acidification could have suppressed calcification, reorganized eukaryotic phytoplankton communities, and reduced OC export efficiency, thereby weakening marine carbon sequestration (Dai et al., 2025). Thus, in addition to the CO_2 directly generated from AeOM, the acidification-driven ecological and biogeochemical feedbacks may weaken the ocean's long-term buffering capacity against atmospheric CO_2, helping to maintain elevated CO_2 concentration and prolong climate warming during the PETM, even after the initial methane-release pulse declined. This mechanism, however, remains hypothetical and requires further testing.

AeOM-driven ocean acidification should be captured by the

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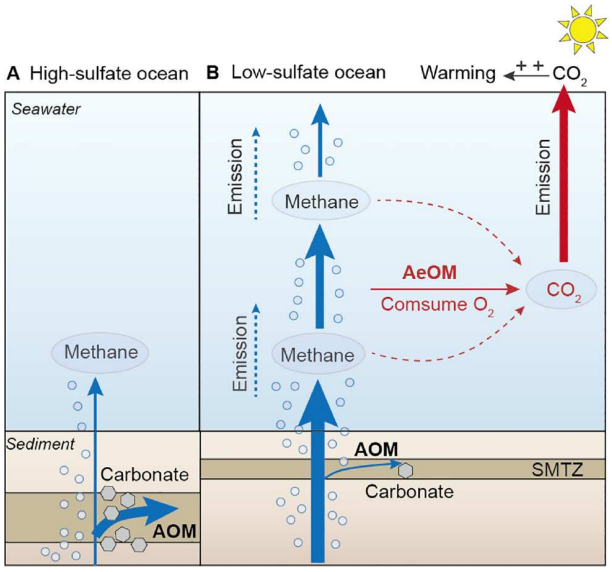


Fig. 1 Conceptual schematics of methane cycling and potential climatic impacts in the high- and low-sulfate oceans. (A) In high-sulfate oceans, methane released from destabilized hydrates is largely consumed by sulfate-driven AOM near the sulfate-methane transition zone (SMTZ) in sediments, increasing alkalinity and potentially contributing to carbonate formation. (B) In low-sulfate oceans, the AOM may be weakened, allowing a larger fraction of methane to escape into the water column, where it is oxidized into carbon dioxide (CO_2) through aerobic methane oxidation (AeOM), potentially maintaining climate warming on longer timescales (e.g., the PETM). The figure is modified from Kim et al. (2025).

boron isotopic composition ($\delta^{11}B$) of carbonates (Gutjahr et al., 2017), a well-established proxy for seawater pH (Foster and Rae, 2016). Penman et al. (2014) documented a ~0.8‰ decline of planktonic foraminiferal $\delta^{11}B$ during the PETM in the North Pacific, corresponding to a surface seawater pH decrease of ~0.3 units. However, Kim et al. (2025) provide no $\delta^{11}B$ evidence, leaving a critical gap in support for AeOM-driven acidification in the Arctic Ocean. This absence may result from poor carbonate preservation, caused by enhanced dissolution and reduced biogenic carbonate production under acidified conditions during the PETM (Gibbs et al., 2006), rather than the absence of acidification itself.

In addition to seawater acidification, intensive methane release and associated AeOM may enhance local oxygen consumption, thereby promoting localized low-oxygen conditions in bottom waters (Li et al., 2021). Where intense and persistent, such oxygen depletion likely leaves corresponding signals in redox-sensitive trace elements (e.g., Mo, U, Re, and V; Bennett and Canfield, 2020). The co-occurrence of biomarkers, carbonate dissolution records, pH proxies, and redox-sensitive element anomalies would strengthen the case for AeOM and its environmental impacts, whereas their absence may indicate that AeOM was short-lived, spatially restricted, or too weak to leave a detectable geochemical imprint.

Beyond uncertainties of geochemical signals' preservation, the spatial representativeness of existing records is a key limitation to evaluate the climatic effects of AeOM. The evidence reported by Kim et al. (2025) derives from a single deep-basin site (ACEX, 1,299 m water depth), limiting the broader applicability of conclusions about AeOM and its climatic impacts. During the PETM, the Arctic was characterized by bathymetric gradients and hydrographic heterogeneity (Gaina et al., 2025), exerting controls on the methane release, transport, and oxidation across the Arctic. Extensive continental shelves, such as the Siberian and Barents shelves, are generally shallower than 200 m, where methane may be directly released to the sea-air interface as bubbles (Shakhova et al., 2010), partly bypassing water-column oxidation and reducing the likelihood of AeOM signals (e.g., lipid biomarkers). Conversely, the absence of biomarker evidence in PETM records does not necessarily preclude AeOM. In shallow shelf settings, stronger oxic conditions and early diagenesis may modify the abundance, distribution, and isotopic composition of biomarkers (Sinninghe Damsté et al., 2002), thereby obscuring the AeOM signal. Therefore, future work should expand spatial sampling across Arctic basins, slopes, and shelves, and combine multiple proxies to identify AeOM and its environmental effects, allowing an assessment of the regional expression and global climatic significance of AeOM during the PETM.

Despite these uncertainties, Kim et al. (2025) provide valuable insights into the non-negligible coupling between methane cycling and climate feedbacks in the Arctic. Current anthropogenic carbon emissions likely exceed the sustained carbon release rate during the PETM by roughly tenfold (Zeebe et al., 2016), and ongoing warming renders methane hydrate increasingly vulnerable to destabilization. These parallels raise the possibility that Arctic AeOM could be enhanced under future warming scenarios, shifting methane's climatic role from direct radiative forcing toward sustained CO_2 production. However, such an analogy must be drawn with considerable caution. The modern Arctic differs from its PETM in several critical respects, with higher seawater sulfate concentrations, a fresher and stratified seawater, and different circulation and ventilation regimes (Algeo et al., 2015; Timmermans and Marshall, 2020), all of which modulate methane release, transport, and oxidation. Therefore, whether AeOM could generate a significant climatic effect under modern oceanic conditions remains an open and important question.

Addressing this question will require sustained and spatially integrated observations in the Arctic Ocean to track methane release and oxidation dynamics across heterogeneous environments, from deep basins to continental slopes and shallow shelves. These observations should be complemented by in-depth geochemical and microbiological investigations into the fate of released methane, and by improved Earth system models to parameterize methane oxidation processes under varying temperature–pressure and chemical regimes. Together, these approaches will be essential to constrain methane's role in future climate feedbacks and to assess the extent to which past analogues can inform Arctic climate change.

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Compliance and ethics

The authors declare no conflict of interest.

References

Algeo T J, Luo G M, Song H Y, et al. 2015. Reconstruction of secular variation in seawater sulfate concentrations. Biogeosciences, 12: 2131–2151

Bains S, Norris R D, Corfield R M, et al. 2000. Termination of global warmth at the Palaeocene/Eocene boundary through productivity feedback. Nature, 407: 171–174

Bennett W W, Canfield D E. 2020. Redox-sensitive trace metals as paleoredox

proxies: A review and analysis of data from modern sediments. Earth-Sci Rev, 204: 103175
Chen Z, Lü P, Tang Z, et al. 2025a. Wetland methane feedback during the early Eocene hyperthermals. Geology, 53: 404–408
Chen Z, Lü P, Yang S, et al. 2025b. Extreme warming intensified lacustrine deoxygenation and methane cycling during the Paleocene-Eocene Thermal Maximum. Commun Earth Environ, 6: 592
Dai R, Wen Z, Hong H, et al. 2025. Eukaryotic phytoplankton drive a decrease in primary production in response to elevated CO_2 in the tropical and subtropical oceans. Proc Natl Acad Sci USA, 122: e2423680122
Dickens G R, O'Neil J R, Rea D K, et al. 1995. Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. Paleoceanography, 10: 965–971
Foster G L, Rae J W B. 2016. Reconstructing ocean pH with Boron isotopes in foraminifera. Annu Rev Earth Planet Sci, 44: 207–237
Frieling J, Svensen H H, Planke S, et al. 2016. Thermogenic methane release as a cause for the long duration of the PETM. Proc Natl Acad Sci USA, 113: 12059–12064
Gaina C, Jakobsson M, Straume E O, et al. 2025. Arctic Ocean bathymetry and its connections to tectonics, oceanography and climate. Nat Rev Earth Environ, 6: 211–227
Gibbs S J, Bown P R, Sessa J A, et al. 2006. Nannoplankton extinction and origination across the Paleocene-Eocene Thermal Maximum. Science, 314: 1770–1773
Gutjahr M, Ridgwell A, Sexton P F, et al. 2017. Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum. Nature, 548: 573–577
Kennett J P, Stott L D. 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. Nature, 353: 225–229
Kim B, Zhang Y G, Zeebe R E, et al. 2025. Arctic CO_2 emissions amplified by aerobic methane oxidation during the Palaeocene-Eocene Thermal Maximum. Nat Geosci, 18: 975–982
Li N, Yang X, Peckmann J, et al. 2021. Persistent oxygen depletion of bottom waters caused by methane seepage: Evidence from the South China Sea. Ore Geol Rev, 129: 103949
Lyons S L, Baczynski A A, Babila T L, et al. 2019. Palaeocene-Eocene Thermal Maximum prolonged by fossil carbon oxidation. Nat Geosci, 12: 54–60
Milkov A V. 2004. Global estimates of hydrate-bound gas in marine sediments: How much is really out there? Earth-Sci Rev, 66: 183–197
Pancost R D, Steart D S, Handley L, et al. 2007. Increased terrestrial methane cycling at the Palaeocene-Eocene Thermal Maximum. Nature, 449: 332–335
Penman D E, Hönisch B, Zeebe R E, et al. 2014. Rapid and sustained surface ocean acidification during the Paleocene-Eocene Thermal Maximum. Paleoceanography, 29: 357–369
Reeburgh W S. 2007. Oceanic methane biogeochemistry. Chem Rev, 107: 486–513
Regnier P, Dale A W, Arndt S, et al. 2011. Quantitative analysis of anaerobic oxidation of methane (AOM) in marine sediments: A modeling perspective. Earth-Sci Rev, 106: 105–130
Röhl U, Westerhold T, Bralower T J, et al. 2007. On the duration of the Paleocene-Eocene Thermal Maximum (PETM). Geochem Geophys Geosyst, 8: 2007GC001784
Ruppel C D, Kessler J D. 2017. The interaction of climate change and methane hydrates. Rev Geophys, 55: 126–168
Shakhova N, Semiletov I, Salyuk A, et al. 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. Science, 327: 1246–1250
Sinninghe Damsté J S, Rijpstra W I C, Reichart G. 2002. The influence of oxic degradation on the sedimentary biomarker record II. Evidence from Arabian Sea sediments. Geochim Cosmochim Acta, 66: 2737–2754
Sluijs A, Brinkhuis H, Schouten S, et al. 2007. Environmental precursors to rapid light carbon injection at the Palaeocene/Eocene boundary. Nature, 450: 1218–1221
Stokke E W, Jones M T, Tierney J E, et al. 2020. Temperature changes across the Paleocene-Eocene Thermal Maximum—A new high-resolution TEX86 temperature record from the eastern North Sea Basin. Earth Planet Sci Lett, 544: 116388
Tierney J E, Zhu J, Li M, et al. 2022. Spatial patterns of climate change across the Paleocene-Eocene Thermal Maximum. Proc Natl Acad Sci USA, 119: e2205326119
Timmermans M-L, Marshall J. 2020. Understanding Arctic Ocean circulation: A review of ocean dynamics in a changing climate. JGR Oceans, 125: e2018JC014378
Újvári G, Kele S, Rinyu L, et al. 2025. Substantial continental temperature rise over the Paleocene-Eocene Thermal Maximum in the Pyrenees. Commun Earth Environ, 6: 499
Weber T, Wiseman N A, Kock A. 2019. Global ocean methane emissions dominated by shallow coastal waters. Nat Commun, 10: 4584
Wei G Y, Pohl A, Jiang S, et al. 2025. Changes in continental weathering regimes inhibited global marine deoxygenation during the Paleocene-Eocene Thermal Maximum. Nat Commun, 16: 9163
Westerhold T, Marwan N, Drury A J, et al. 2020. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science, 369: 1383–1387
Yang S, Lv Y, Liu X, et al. 2020. Genomic and enzymatic evidence of acetogenesis by anaerobic methanotrophic archaea. Nat Commun, 11: 3941
Zeebe R E, Ridgwell A, Zachos J C. 2016. Anthropogenic carbon release rate unprecedented during the past 66 million years. Nat Geosci, 9: 325–329

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