Does petroleum resource extraction and oceanic heat transfer increase geothermal heat flux? A global multi-sensor study of oil basins

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WHAT, WHERE, AND WHEN

Geothermal heat flux reflects the upward transfer of heat from Earth's interior and is expressed as deviations from the global average of 60–80 mW m^{-2}. High values occur in magmatic and hydrothermal regions, while low values characterize stable cratons; however, long-term petroleum extraction can modify subsurface thermal regimes by altering pressures and fluid insulation. Additionally, heat transfer from oceanic crust to the oceans and atmosphere represents an important pathway linking Earth's internal heat to climate processes. The motivation for this commentary is to critically evaluate how petroleum resource extraction and oceanic geothermal inputs intersect to influence localized and regional heat-flux patterns. It builds based on the recent multi-sensor data to highlight the dual role of anthropogenic extraction and natural ocean-atmosphere coupling in modifying Earth's heat budget. Recent multi-sensor data refer to a combination of thermal infrared, microwave, and gravity-based remote-sensing datasets. These datasets follow established acquisition and calibration standards as documented in previous studies, including NASA's MODIS and ECOSTRESS thermal products and ESA's GRACE/GRACE-FO gravity missions. Geothermal gradients for Figures 1A–1C were compiled from published borehole temperature and heat-flow datasets for major sedimentary basins, while oil-field locations and productivity status were derived from publicly available petroleum statistics and industry reports. The integration of these validated multi-sensor observations enhances the reliability of the thermal analysis and supports the robustness of the results. Specifically, it examines variations in geothermal gradients across oil-producing basins, with a focus on the Middle East, and situates these findings within a broader context of climate and energy geoscience.

In this study, the geothermal gradient values were compiled from published borehole temperature logs and global heat-flow databases, while satellite-based thermal and gravity observations were obtained from NASA's MODIS and ECOSTRESS sensors and ESA's GRACE/GRACE-FO missions. Oil-field boundaries and productivity attributes were sourced from publicly available petroleum datasets. These multi-sensor datasets form the basis for the global thermal interpretation presented in Figure 1.

Some of the giant oil and gas fields are concentrated in the Middle East, such as the Ghawar, Zubair, Rumaila and South Zagros fields, making the region an ideal natural environment for studying thermal disturbances associated with extraction.

By addressing both terrestrial and oceanic contributions, this commentary aims to provide a framework for integrated monitoring and modeling of extraction-induced thermal signals. Recent studies emphasize the growing importance of subsurface anthropogenic influences on heat flux[1] and the role of ocean heat uptake in amplifying climate trends,[2] while there is also serious emphasis on the development of advanced geothermal monitoring systems. These insights underscore the relevance of linking petroleum geoscience with global energy balance research.

WHY AND HOW

Hydrocarbon extraction alters subsurface thermal regimes by removing oil and gas that naturally act as thermal insulators within reservoir rocks. Large-scale petroleum extraction perturbs subsurface thermal regimes by inducing pressure depletion and changes in fluid saturation within reservoirs. The removal of hydrocarbons, which act as effective thermal insulators, reduces bulk thermal resistance and enhances vertical conductive heat transfer from deeper crustal levels. In addition, production- and injection-induced fluid redistribution can locally modify convective heat transport, leading to measurable deviations from the natural geothermal gradient.[3] As saturation declines, thermal resistance decreases, promoting vertical heat conduction from deeper crustal levels. This mechanism explains the elevated geothermal gradients observed near major oil fields. Although atmospheric greenhouse gases primarily drive global warming, emerging evidence suggests that large-scale subsurface extraction may contribute modestly to Earth's surface heat budget. Simple scaling arguments indicate that any globally averaged perturbation associated with such extraction is unlikely to exceed 10^{-2} W m^{-2}, compared with 3 W m^{-2} for present-day greenhouse-gas radiative forcing, underscoring that this contribution is small and localized. The disruption of geothermal equilibrium through deep resource removal, especially in tectonically active basins, may enhance local or regional heat flux. Detecting such anthropogenic thermal signals requires integrated monitoring systems, including microseismic sensors, temperature loggers, and real-time production data, all linked through machine learning (ML), which can identify extraction-induced anomalies with high precision. In the Middle East (Figure 1A), productive fields such as Zubair, Ghawar, and the Southern Zagros exhibit high geothermal gradients (31°C–40°C km^{-1}), which are closely tied to complex geological structures.

The geothermal gradient map in Figure 1A was produced using inverse distance weighting (IDW) interpolation of compiled data, preserving local thermal variations and generating a continuous surface for regional comparison of productive and non-productive basins. Such extraction-induced thermal effects have been documented in several thermo-hydro-mechanical studies and oil-field case analyses, which show that long-term production can enhance vertical heat conduction and lead to locally elevated geothermal gradients.[4] In contrast, cratonic and non-productive regions show lower gradients (17°C–25°C km^{-1}), reflecting thermal stability. This spatial distribution of higher geothermal gradients in productive sedimentary basins compared with surrounding cratonic or non-productive regions is consistent with recent global analyses of geothermal gradients in sedimentary basins.

The global gradient map further supports the spatial correlation between elevated heat flux and long-term oil and gas production (Figure 1B). Globally, productive fields cluster in zones exceeding 30°C km^{-1}, while undeveloped basins fall below 25°C km^{-1}. These findings highlight the feedback loop: extraction not only modifies resource availability but also alters the thermal structure of sedimentary basins, an effect that warrants closer attention in future geoscientific and climate assessments. The productive oil fields are associated with higher geothermal gradients, often exceeding 30°C km^{-1}. In comparison, non-productive fields tend to fall below 25°C km^{-1} (Figure 1C). Productivity categories in Figure 1C were assigned based on documented commercial oil production over the multi-decadal interval 1990–2020. Fields exhibiting sustained production throughout this period were classified as active, whereas those lacking significant recorded production were categorized as inactive or non-productive. This pattern highlights a clear relationship between field productivity and subsurface thermal conditions, supporting the hypothesis that long-term hydrocarbon extraction may contribute to localized increases in geothermal gradients. Compared with non-producing regions, high-yield oil basins are characterized by thick, deeply buried sediments, active fault-fracture systems, and prolonged hydrocarbon production that removes thermally insulating fluids. These geological and

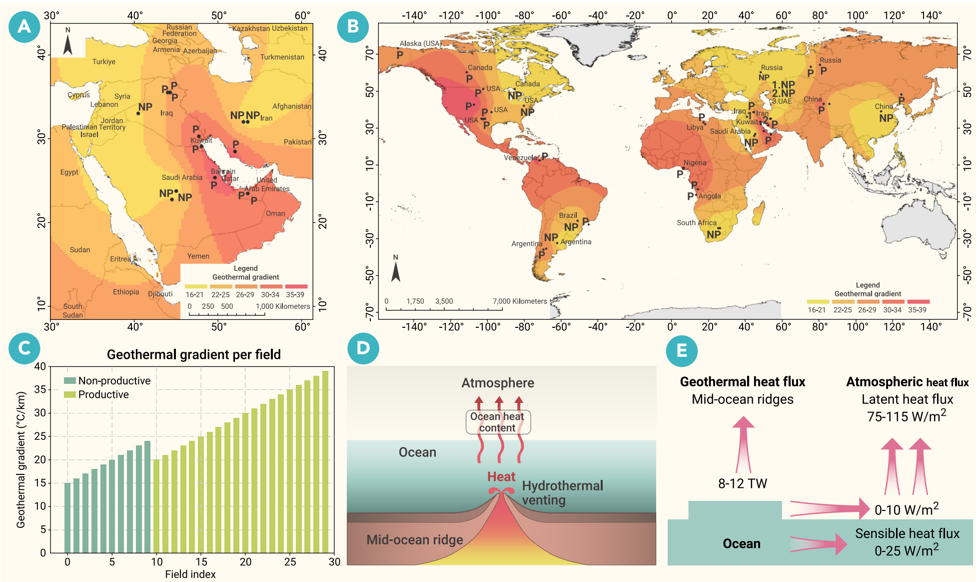

Figure 1. Geothermal gradients and heat flux patterns in relation with oil-field productivity in the Middle East and worldwide (A) Interpolated contour map of geothermal gradients (°C km^{-1}) across selected oil-producing and non-producing areas in the Middle East, highlighting higher values in productive basins. (B) Global contour map of geothermal gradients, showing elevated values in major oil fields compared with non-productive regions. (C) Distribution of geothermal gradients across global oil fields classified by productivity status. (D) Schematic of heat transfer from mid-ocean ridge vents to the atmosphere via ocean heat content. (E) Conceptual model of geothermal flux from mid-ocean ridges and its transfer to the atmosphere through latent and sensible heat fluxes.

human-induced factors reduce subsurface thermal resistance and enhance upward heat transfer, explaining the higher geothermal gradients in productive fields compared to non-oil areas. Figures 1D and 1E illustrate the pathways of geothermal heat generated in the lithosphere ascending to ocean waters, which is subsequently released into the atmosphere as heat.

OCEAN-TO-ATMOSPHERE HEAT FLUX

The oceans play a key role in transferring geothermal energy to the atmosphere, with heat released by hydrothermal circulation at mid-ocean ridges contributing to the global geothermal budget. This heat accumulates in the deep ocean, is redistributed by ocean circulation, and is ultimately exchanged with the atmosphere mainly through latent heat flux from evaporation, with minor sensible heat transfer. Although small compared to radiative forcing, geothermal heat provides a persistent background contribution to the ocean-atmosphere system. Geothermal heat flux is on the order of 0.09 W m^{-2}, whereas recent assessments place net anthropogenic radiative forcing above 2.7 W m^{-2}, indicating that geothermal inputs account for less than about 5% of the present planetary energy imbalance.[5]

In recent decades, ocean heat content has exhibited a clear increasing trend, reflecting not only the cumulative influence of greenhouse-gas forcing but also the contribution of internal geothermal inputs. Global ocean heat content estimates show that the upper 2,000 m have accumulated more than 400 ZJ of heat since the mid-20th century, with the past decade recording the highest values on record.[2] This dual process enhances the role of the ocean as both a reservoir and a regulator of planetary heat. The acceleration of ocean heat gain documented in global datasets highlights the importance of integrating geothermal processes into climate assessments. As shown by Cheng et al.,[2] the sustained rise in oceanic heat storage underscores a critical linkage between deep Earth processes, ocean dynamics, and the regulation of atmospheric energy balance. It should be noted that mid-ocean ridge geothermal flux is a natural, long-term background process that operates independently of human activities. The localized thermal perturbations associated with petroleum extraction represent only small, basin-scale anomalies that are superimposed on this broader natural flux. Their relevance here lies in illustrating an additional, though modest, component in the lithosphere-ocean heat-transfer pathway.

WHAT IS NEEDED NOW

To advance the understanding of extraction-induced thermal effects on subsurface systems and their contribution to global warming, three key actions are recommended. First, expanding microseismic and temperature-logging networks across major oil fields will enhance the spatial and temporal resolution of heat-flux anomalies associated with prolonged hydrocarbon withdrawal. Second, the real-time integration of production data (pressure, flow, and volume) with thermal monitoring will enable the dynamic tracking of changes in subsurface gradients. Third, developing ML models to distinguish natural geothermal fluxes from signals induced by extraction is essential for predictive thermal modeling. Complementarily, accelerating the adoption of alternative energy sources, particularly geothermal and solar, can reduce reliance on fossil fuels and help stabilize subsurface thermal regimes over time.

CONCLUSION AND RECOMMENDATIONS

The study shows that high geothermal gradients coincide with tectonically active and hydrocarbon-rich basins, while low gradients characterize stable interiors, underscoring the importance of heat flux in petroleum system evolution and exploration risk. It also reveals a measurable thermal impact of long-term hydrocarbon extraction on basin-scale heat distribution. To address extraction-induced thermal impacts and their broader implications, we suggest the following.

(1) Implement real-time thermal monitoring in active petroleum basins.
(2) Integrate heat-flux data into exploration and maturity models to enhance understanding of reservoir properties.
(3) Develop ML-based tools to separate natural from anthropogenic thermal signals.
(4) Accelerate the shift to renewable energy sources, particularly geothermal, solar, and wind energy, to reduce fossil fuel dependence and stabilize subsurface thermal regimes.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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