

# Climate-informed engineering for subsurface management: Concept, framework, and applications



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## ABSTRACT

Subsurface resource management underpins a wide range of energy, storage, water, and extraction systems that operate over long timescales and interact with complex geological environments. The performance and integrity of these systems are sensitive to variability in surface climate conditions that control thermal loading, fluid recharge, pressure evolution, and mechanical response in the subsurface. As precipitation patterns, temperature regimes, and extreme events evolve, traditional engineering approaches based on stationary or spatially coarse climate assumptions introduce increasing uncertainty into long-term design, operation, and risk assessment. This paper advances the emerging concept of Climate-Informed Engineering by developing a forward-looking framework tailored to resilient subsurface management and earth energy systems. The framework emphasizes the use of high-resolution, time-dependent climate information to define site-specific boundary conditions that are directly relevant to subsurface processes. By discussing advances in climate modeling, subsurface process understanding, and engineering decision-making, we identify key climate drivers and coupled hydro-thermal-mechanical-chemical processes that govern system performance, integrity, and risk. The applicability of Climate-informed Engineering for Subsurface Management (CIE-SM) is examined across major subsurface domains, including geothermal energy systems, underground energy storage, carbon storage, managed aquifer recharge, and subsurface mining and excavation. By treating climate as a time-evolving, site-specific boundary condition, this work positions CIE-SM as a practical foundation for robust, adaptive, and physically grounded subsurface engineering under environmental uncertainty.

## 1. Introduction

Subsurface resource management supports a wide range of energy production, storage, and extraction activities that are essential to energy transition efforts and critical infrastructure development (Blunt et al., 2024). Earth energy systems and subsurface applications—including geothermal systems, underground energy storage, carbon storage, managed aquifer recharge, and subsurface mining—involve complex interactions between engineered infrastructure and heterogeneous geological environments at different scales (Berre et al., 2025; Spurin et al., 2025). Once deployed, these systems are difficult to

access, governed by strongly coupled physical processes, and offer limited options for corrective intervention (Pandey and Vishal, 2017; Lackey et al., 2023; Shu et al., 2025). Consequently, their performance, safety, and operational reliability depend critically on the evolution of environmental boundary conditions over decades to centuries.

Historically, subsurface engineering practice has relied on historical climate observations and the assumption that environmental drivers such as temperature, precipitation, groundwater levels, and surface loading remain relatively stationary over the lifetime of a project. Design parameters, safety margins, and operational protocols have therefore been calibrated to past conditions. Increasing evidence,

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however, indicates that climate variability and long-term environmental change are altering these boundary conditions (Kandalai et al., 2023). Shifts in temperature regimes, precipitation patterns, groundwater recharge, and the frequency of extreme events introduce non-stationarity into Earth systems, directly affecting subsurface thermal, hydraulic, mechanical, and chemical processes. Under such conditions, engineering approaches based solely on historical statistics introduce growing uncertainty into long-term system performance and risk assessments.

At the same time, advances in Earth system modelling (Hohenegger et al., 2023), climate projections, and environmental monitoring now make it possible to explicitly incorporate evolving climate information into engineering analysis (Shokri et al., 2023). These developments have motivated the emerging field of Climate-Informed Engineering (CIE) (Shokri et al., 2023), which seeks to systematically integrate climate variability, projected trends, and associated uncertainties into the planning, design, operation, and management of engineered systems. Rather than assuming fixed boundary conditions, CIE treats climate as an evolving input that can be evaluated through scenario-based and uncertainty-aware frameworks to support more robust engineering decisions.

While climate-informed approaches have been increasingly applied in surface infrastructure, water resources, and coastal engineering (Aminzadeh et al., 2024; Valente and Pinho, 2025; Nevermann et al., 2024; Huynh et al., 2024; Fereshtehpour et al., 2025), the application to subsurface management and earth energy systems remains limited and fragmented. This gap is particularly significant because subsurface systems evolve slowly, are governed by strongly coupled hydro-thermal-mechanical-chemical processes (Habibi et al., 2023; Vaezi et al., 2025), and retain long memory of past conditions. As a result, climate-driven perturbations may accumulate over time or manifest abruptly once critical thresholds are exceeded. Changes in climate conditions can influence subsurface temperature gradients, pore pressure evolution, geomechanical stability, fluid flow pathways, and geochemical reactions, with direct implications for system integrity, storage performance, and leakage risk (Rotta Loria, 2023; Pan et al., 2024).

Integrating Climate-Informed Engineering into subsurface resource management therefore represents both a scientific and practical necessity. It provides a structured pathway for linking climate science, subsurface process understanding, and engineering decision-making within a unified conceptual framework. By embedding climate information directly into engineering workflows, CIE enables more transparent risk assessment and enhanced robustness under environmental uncertainty. The objective of this paper is to articulate a conceptual foundation for Climate-Informed Engineering applied to resilient subsurface resource management. Specifically, the paper aims to (i) synthesize existing knowledge on Climate-Informed Engineering and subsurface engineering, (ii) identify key climate drivers and subsurface processes that govern system sensitivity, and (iii) establish a framework for integrating climate information into engineering design, operation, and decision-making. Rather than presenting new experimental or numerical results, the paper adopts a forward-looking perspective, outlining scientific challenges, research directions, and practical pathways for operationalizing Climate-Informed Engineering in subsurface contexts.

The remainder of the paper is organized as follows. Section 2 introduces the principles of Climate-Informed Engineering and reviews its current applications across engineering disciplines, emphasizing the unique characteristics of subsurface systems. Section 3 examines the climate sensitivity of subsurface and earth energy systems by discussing relevant climate drivers and their influence on subsurface processes. The subsequent sections develop a conceptual framework for climate-informed subsurface engineering, discuss key application domains, and outline decision-support tools, challenges, and future research needs.

## 2. Climate-informed engineering: concepts, principles, and state of the art

### 2.1. Definition and core principles of climate-informed engineering

Climate-Informed Engineering (Shokri et al., 2023) is an emerging field that seeks to explicitly incorporate climate variability, high-resolution climate change projections (Hohenegger et al., 2023), and associated uncertainties into engineering analysis and decision-making. At its core, CIE moves beyond the assumption of stationary environmental conditions and recognizes climate as a dynamic boundary condition that evolves over the lifetime of engineered systems. This shift requires not only new data and models but also a rethinking of how engineering problems are formulated and solved.

Several core principles define Climate-Informed Engineering (Shokri et al., 2023). First, CIE is enabled by the availability of high-resolution climate information, in which kilometer-scale Earth system models provide spatially and temporally resolved projections that are directly relevant to engineering design and operation (Hohenegger et al., 2023). Unlike earlier climate-informed approaches based on coarse-resolution data, this new generation of models allows climate information to be mapped meaningfully onto engineered systems and local environmental conditions. Second, CIE accounts for uncertainties in climate projections and coupled Earth system responses, while making use of ensemble simulations and scenario-based analyses (Hassani et al., 2021). Third, CIE promotes resilient design strategies that allow systems to maintain performance (Brunow et al., 2023) or recover efficiently under evolving environmental conditions. Finally, CIE integrates climate information across the full system lifecycle, from planning and design to operation, monitoring, and, where applicable, decommissioning. Together, these principles define a practical engineering framework that translates recent advances in climate modeling, computational capacity, and digital infrastructure into climate-informed engineering design and operation.

### 2.2. Current applications of CIE in engineering disciplines

Climate information has been widely utilized in surface-based engineering disciplines, particularly as advances in climate modeling have enabled increasingly high-resolution, decision-relevant datasets. In civil infrastructure, climate information has been incorporated into the design and assessment of transportation networks, buildings, and urban systems exposed to temperature extremes, flooding, and other weather-driven loads (IPCC, 2023; Yan et al., 2024; Dharmarathne et al., 2024). In water resources engineering, climate-informed approaches have been applied to evaluate reservoir performance (Nevermann et al., 2024; 2025), flood control capacity, and drought risk under non-stationary hydrological conditions (Brunner and Gilleland, 2024). Coastal and offshore engineering have similarly integrated projections of sea-level rise into design criteria and risk assessments (Sobhi Gollo et al., 2024; Nevermann et al., 2023). In energy systems, climate-informed methods are used to investigate surface and atmospheric interactions, including the influence of climate variability on wind and solar power generation (Liu et al., 2024), and the availability of cooling water for thermal power plants. Collectively, these studies demonstrate that access to spatially and temporally resolved climate information has enabled improved system-level planning, reliability assessment, and operational decision-making.

By contrast, the application of Climate-Informed Engineering to subsurface systems remains limited. Existing studies often consider climate influences only indirectly, for example through simplified or static boundary conditions, or focus on short-term operational effects rather than long-term system evolution. This limitation has been driven in part by the historical reliance on coarse-resolution climate data, which provided limited information at spatial and temporal scales relevant to subsurface processes. Recent advances in kilometer-scale

climate and Earth system models now offer high-resolution climate information that can be directly mapped onto local surface and near-surface boundary conditions. However, these capabilities have not yet been systematically translated into subsurface engineering workflows. As a result, subsurface energy systems have not fully benefited from the conceptual frameworks, and uncertainty-aware methodologies, which can be developed within the broader CIE concept.

### 2.3. Why subsurface systems are a special case

Subsurface and earth energy systems present distinctive challenges that require tailored climate-informed approaches. First, these systems operate on long timescales—often decades to centuries—over which climate conditions may evolve substantially, rendering stationary boundary-condition assumptions increasingly invalid. Second, subsurface behavior is governed by tightly coupled hydro-thermal-mechanical-chemical (HTMC) processes (Cui and Tang, 2013; Viswanathan et al., 2022), such that modest, climate-driven perturbations in temperature, recharge, or stress can produce nonlinear and path-dependent system responses. For example, climate-driven reductions in groundwater recharge combined with sustained fluid extraction can lead to progressive compaction and land subsidence (Davydenko et al., 2024), which may accumulate slowly and result in damage to surface and subsurface infrastructure once critical thresholds are exceeded. Third, limited accessibility and sparse monitoring constrain direct intervention, increasing reliance on predictive models for design and risk management.

Collectively, these features position subsurface processes and earth energy systems as a technically demanding yet underdeveloped application domain for Climate-Informed Engineering. Progress requires explicit coupling of high-resolution climate information with subsurface process models and engineering decision frameworks, rather than treating climate variability as a secondary consideration.

## 3. Climate sensitivity of earth energy systems and subsurface processes

### 3.1. Relevant climate drivers affecting subsurface systems

Climate influences subsurface energy systems through a range of interrelated drivers that operate across spatial and temporal scales. Temperature trends and extremes directly affect surface energy balances (Aminzadeh et al., 2023) and propagate into the subsurface. Over long timescales, warming trends can alter geothermal gradients, thermal stresses, and temperature-dependent material properties. Precipitation patterns and variability play a central role in governing groundwater recharge, pore pressure evolution, and fluid availability in subsurface reservoirs. Changes in precipitation intensity, seasonality, and spatial distribution can lead to shifts in recharge regimes, influencing both the quantity and timing of subsurface fluid flow. Extended droughts and extreme precipitation events can impose episodic loading conditions on subsurface systems, undermining assumptions of steady-state behavior often utilized in engineering design. Additional climate drivers include evapotranspiration, snowmelt dynamics, and land surface processes that modulate surface-subsurface coupling. Wind and atmospheric circulation indirectly influence subsurface conditions through their effects on surface temperature, moisture fluxes, and land-atmosphere interactions. Together, these drivers define the evolving boundary conditions under which subsurface energy systems operate.

### 3.2. Climate impacts on subsurface processes

The sensitivity of subsurface processes and earth energy systems to climate variability arises from the fundamental physical processes governing subsurface behavior. Heat transport in porous and fractured

media depends on both conductive and advective mechanisms, which are influenced by surface temperature trends and fluid flow pathways (Heinze, 2024; Heinze and Pastore, 2023). Climate-driven changes in recharge and fluid circulation can modify thermal regimes, affecting geothermal system efficiency and long-term sustainability (Tsybin et al., 2024). Fluid flow and pressure evolution are particularly sensitive to climate variability. Altered recharge patterns can change hydraulic gradients, influence reservoir pressurization, and modify connectivity between geological units. In underground storage, such changes may affect storage capacity, contaminant transport, and leakage risk.

Geomechanical responses represent another critical pathway through which climate affects subsurface systems. Variations in pore pressure and temperature can induce stress changes, potentially leading to deformation, subsidence (Davydenko et al., 2024; Shirzaei et al., 2021), or fault reactivation. These processes are of particular concern in regions where subsurface energy activities intersect with active or mechanically sensitive formations. Geochemical and reactive transport processes further complicate the climate sensitivity of subsurface systems. Temperature- and moisture-dependent reactions can alter porosity, permeability, cracking dynamics, and mineral stability, feeding back into fluid flow and mechanical behavior. Over long timescales, such coupled processes may significantly reshape subsurface system properties.

A central challenge in climate-informed subsurface engineering is the mismatch between the timescales of climate variability and those of engineering design and operation. Climate forcing may change slowly or appear intermittently, while subsurface systems often respond with significant delay, allowing stresses to accumulate over long periods. This disconnect complicates risk assessment and makes system behavior harder to anticipate. Nonlinear responses further increase this risk. For example, sustained groundwater extraction during prolonged dry periods can progressively increase effective stress, leading to land subsidence that may remain unnoticed for years before manifesting itself and causing damage to surface infrastructure (Ohnenhen et al., 2025). Such delayed and nonlinear system responses highlight the limitations of static design approaches and emphasizes the need for climate-informed frameworks that explicitly account for evolving environmental conditions. Understanding and managing these complexities is essential for the sustainable development of subsurface projects and earth energy systems. Climate-Informed Engineering provides a structured approach to address these challenges by linking climate drivers, subsurface processes, and engineering decisions.

## 4. Climate-informed subsurface management: a conceptual framework

### 4.1. Framework overview

To operationalize Climate-Informed Engineering for subsurface resource management, a unifying conceptual framework is required that explicitly links high-resolution climate information to subsurface processes and engineering decision-making (Figs. 1 and 2). Here, we propose a Climate-Informed Engineering for Subsurface Management (CIE-SM) framework that integrates climate drivers, subsurface process understanding, and engineering workflows. The framework is not prescriptive but rather a flexible structure that can be adapted to diverse subsurface energy applications and varying levels of data availability.

At its core, the framework consists of four interconnected components: (i) high-resolution climate information and projections from kilometer-scale Earth system models (Bauer et al., 2021; Hohenegger et al., 2023), (ii) subsurface process models capturing coupled hydro-thermal-mechanical-chemical dynamics (Viswanathan et al., 2022), (iii) engineering design and operational decisions, and (iv) monitoring, feedback, and adaptive management.

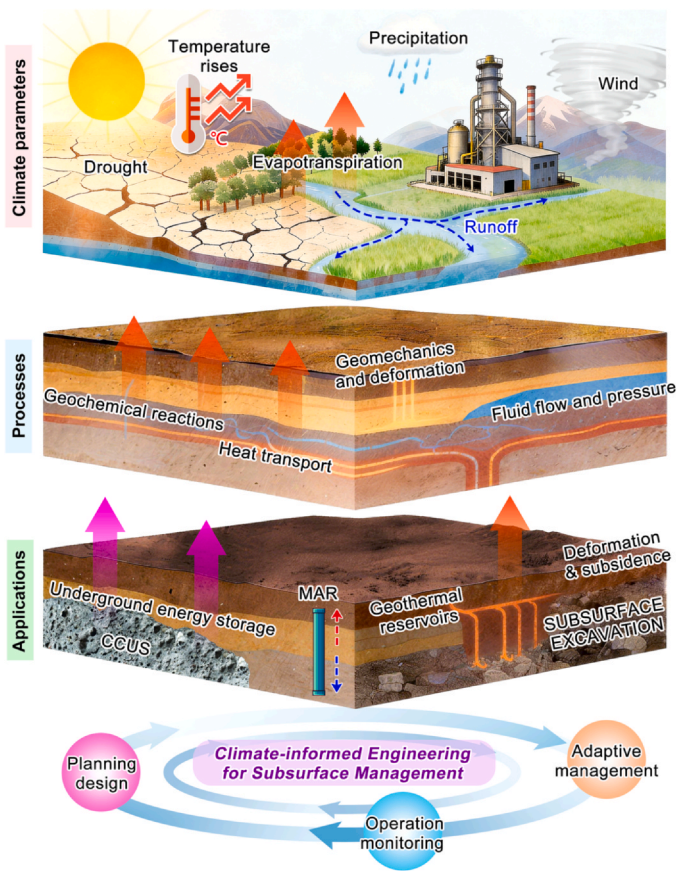


Fig. 1. Conceptual diagram of Climate-Informed Engineering for Subsurface Management (CIE-SM). Climatic parameters influence subsurface processes and states including heat transport, fluid flow and pressure, geomechanics and deformation, and geochemical reactions. This in turn affects various subsurface applications including but not limited to geothermal reservoirs, underground energy storage, mining and subsurface excavation, carbon capture, utilization, and storage (CCUS) and managed aquifer recharge (MAR). Climate-informed engineering for subsurface management (CIE-SM) utilizes high resolution climate information for planning & design, operation & monitoring and adaptive management.

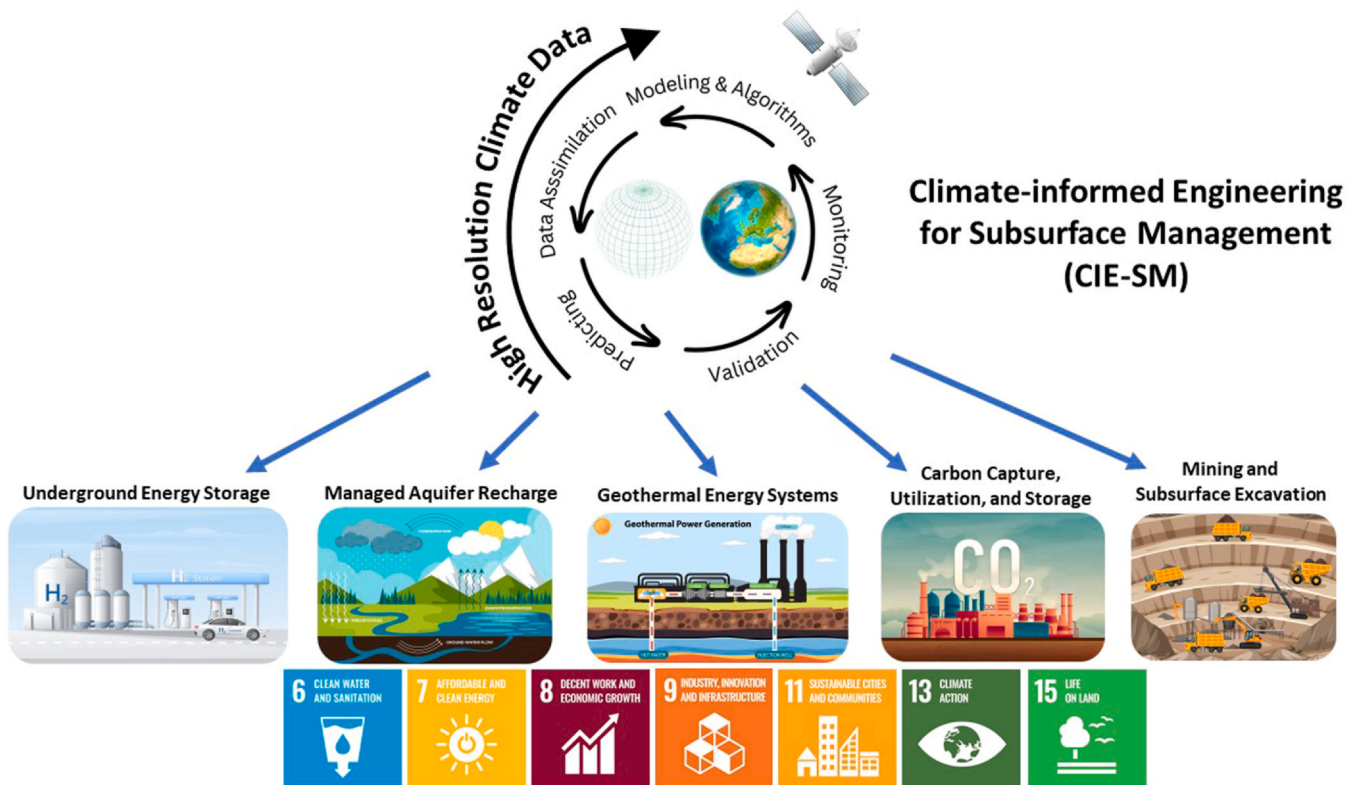


Fig. 2. Workflow for climate-informed decision-making in subsurface projects. High-resolution climate data drives iterative Earth system modeling to enable sustainable management of subsurface technologies including but not limited to underground energy storage, managed aquifer recharge, geothermal energy systems, carbon capture, utilization and storage, and mining and subsurface excavation. The decision-support framework contributes to several UN SDGs including, particularly UN SDGs 6, 7, 8, 9, 11, 13, and 15 (Photo credit for icons representing applications: Freepik.com, macrovector/Freepik.com and brgfx/Freepik.com).

The components are linked through iterative feedback loops that allow learning and adjustment as new data and knowledge emerge, as demonstrated in previous work (Dragos and Smarsly, 2024). Climate information defines evolving environmental boundary conditions that directly affect subsurface behavior, including groundwater pressures, thermal regimes, and land subsidence, which can gradually accumulate and damage infrastructure if thresholds are exceeded. Subsurface process models translate these evolving conditions into insights on system performance and vulnerabilities, guiding engineering decisions that are then refined through monitoring and adaptive management.

A defining feature of the CIE-SM framework is its explicit treatment of uncertainty. Rather than relying on single deterministic forecasts, the framework emphasizes scenario-based analyses and probabilistic reasoning to explore a range of plausible futures (Hassani et al., 2021). By linking high-resolution climate projections with subsurface dynamics and engineering workflows, the framework enables more robust, resilient, and adaptive strategies for subsurface processes and earth energy systems under environmental uncertainty.

#### 4.2. Integrating climate information into engineering workflows

Integrating climate information into subsurface engineering requires moving beyond traditional workflows in which planning, design, and operation are treated as largely independent stages under fixed environmental assumptions. Within the proposed framework, high-resolution climate information is incorporated explicitly across the system lifecycle, enabling climate forcing to enter engineering analysis as physically meaningful, time-dependent boundary conditions.

During planning and site selection, climate-informed analyses constrain baseline assumptions about groundwater recharge, surface temperature, and hydrological variability that control long-term subsurface conditions. The availability of kilometer-scale climate data allows these drivers to be evaluated at spatial and temporal scales relevant to subsurface systems. For example, projections of declining or increasingly variable recharge can directly affect the suitability of sites for geothermal development or underground energy storage, while climate-driven changes in stress and pore pressure evolution may influence the selection and ranking of storage formations. In the design phase, climate information is translated into time-dependent boundary conditions for subsurface models, informing parameters such as thermal loading, pressure evolution, and material performance over the project lifetime. Rather than relying on static safety factors calibrated to historical conditions, climate-informed design enables explicit evaluation of system behavior under evolving climate forcing, including conditions that may promote reservoir compaction or land subsidence.

In practical terms, the translation of climate information into subsurface boundary conditions follows a sequence of physically based mappings. Precipitation and evapotranspiration are combined through surface and vadose-zone hydrological models to estimate groundwater recharge, which defines time-dependent flux or head boundary conditions for subsurface flow. Surface temperature projections are translated into thermal boundary conditions by prescribing time-varying temperature or heat flux at the ground surface, which propagates into the subsurface through conductive and advective processes. Extreme events, such as intense rainfall or prolonged droughts, are represented as boundary conditions that introduce episodic recharge pulses or sustained deficits. These hydrological and thermal inputs, when coupled within subsurface models, drive pore-pressure evolution and stress changes through hydro-thermal-mechanical feedbacks. While the specific implementation depends on site conditions and data availability, this workflow illustrates how high-resolution climate variables can be systematically mapped onto physical boundary conditions for subsurface analysis.

During operation and monitoring, subsurface observations—such as pressure evolution, ground deformation, temperature changes, or shifts in fluid chemistry—are interpreted in the context of climate conditions

rather than in isolation. The proposed approach supports timely operational adjustments, such as moderating injection or extraction rates, altering storage cycling strategies, or temporarily suspending operations, to reduce the likelihood of crossing critical limits associated with subsidence or mechanical instability. Adaptive management closes the loop by integrating monitoring data and updated high-resolution climate information into revised models and decisions. The iterative process reduces dependence on early design assumptions and supports sustained system performance under evolving environmental conditions.

#### 4.3. Managing uncertainty and risk in climate-informed subsurface engineering

The emergence of kilometer-scale Earth system models—enabled by advances in computation, data infrastructure, AI algorithms, and sensing technologies (Hohenegger et al., 2023)—now provides climate information at spatial and temporal scales relevant to subsurface boundary conditions. Within the proposed framework, uncertainty is addressed only after climate information has been translated into time-dependent boundary conditions for subsurface models at the site scale. High-resolution climate data enable explicit representation of boundary conditions such as the timing and magnitude of extreme precipitation, seasonal soil moisture evolution, and surface temperature variability, which directly control recharge pulses, thermal loading, and pressure evolution in the subsurface—processes that are commonly smoothed out in coarse-resolution or ensemble-mean climate products. The representation allows engineers to trace how specific climate sequences—such as prolonged droughts followed by intense recharge events or sustained surface warming—translate into cumulative subsurface loading over time. As a result, design and operation shift away from fixed assumptions toward explicit management of time-dependent boundary conditions that govern long-term system behavior.

It is important to note that increasing the resolution of climate forcing does not eliminate uncertainties associated with subsurface heterogeneity, which often spans multiple spatial scales. In practice, the benefits of high-resolution climate inputs must therefore be considered alongside uncertainties in geological structure and material properties. This highlights the need for integrated approaches in which both climate variability and subsurface heterogeneity are treated jointly in uncertainty analysis and decision-making.

### 5. Application domains: climate-informed approaches across subsurface processes

While the proposed framework is broadly applicable, not all subsurface systems require the same level of climate-informed analysis. Systems that are strongly coupled to surface boundary conditions—such as those dependent on groundwater recharge or shallow thermal regimes—are particularly sensitive to climate variability and therefore benefit most from a CIE-SM approach. In contrast, systems that are weakly connected to surface processes or operate over shorter time-scales may be less sensitive, although climate-informed analysis can still improve robustness. In the following, several representative application domains are discussed.

#### 5.1. Geothermal energy systems

Geothermal energy systems are particularly sensitive to climate variability because their performance depends directly on subsurface temperatures, fluid recharge, and the long-term sustainability of the reservoir (Ciapala et al., 2021). While geothermal resources are often perceived as thermally stable, their performance is coupled to surface and near-surface climatic conditions that control groundwater recharge, fluid circulation pathways, and thermal boundary conditions.

Therefore, changes in surface temperature and precipitation patterns can influence geothermal productivity (Ratouis et al., 2017).

Rising surface temperatures may alter shallow thermal gradients and, over long timescales, influence near-surface conductive heat fluxes, while changes in recharge regimes can affect advective heat transport and reservoir pressure. Reduced recharge under prolonged drought conditions can limit fluid availability, increase thermal drawdown rates, and shorten reservoir lifetimes. Conversely, intensified precipitation or episodic recharge events may introduce thermal and hydraulic transients that affect reservoir stability and well performance. These effects are rarely considered in conventional geothermal design, which typically assumes stationary recharge and thermal conditions.

Climate-Informed Engineering enables systematic assessment of long-term geothermal reservoir sensitivity by integrating high-resolution climate data directly into reservoir modeling and operational planning. Kilometer-scale climate projections (Hohenegger et al., 2023) allow site-specific representation of recharge dynamics, surface temperature evolution, and extreme events, which can be translated into time-dependent boundary conditions for geothermal reservoirs, enabling evaluation of how climate-driven forcing influences pressure evolution, thermal drawdown, and reinjection performance over operational timescales. Within this framework, decisions such as well placement, extraction rates, and reinjection strategies are informed by resolved climate forcing rather than stationary assumptions or ensemble-mean trends. Climate-informed operational strategies can then be adjusted as reservoir conditions evolve, supporting sustained energy production while reducing the risk of long-term performance degradation. In this sense, CIE shifts geothermal development from short-term optimization toward explicit management of climate-driven boundary conditions that govern long-term resource behavior.

### 5.2. Underground energy storage (hydrogen, gas)

Underground energy storage systems—including natural gas, hydrogen, compressed air, and thermal energy storage—play an increasingly important role in balancing variable renewable generation and maintaining grid reliability (Krevor et al., 2023; Wang et al., 2026). These systems depend on the ability of subsurface formations to accommodate repeated pressure and temperature cycling. Climate variability introduces additional forcing on these systems by modifying groundwater recharge, near-surface stress conditions, and thermal regimes that influence subsurface pressure and deformation.

High-resolution climate data are particularly relevant for underground storage because storage performance is sensitive to baseline conditions and their temporal evolution. Kilometer-scale projections allow climate-driven recharge variability, drought persistence, and extreme precipitation events to be translated into time-dependent pressure and hydraulic boundary conditions at storage sites. These effects can influence working gas capacity, pressure dissipation rates, and the mechanical response of reservoir and caprock units.

Within a Climate-Informed Engineering framework, underground storage systems are evaluated under resolved climate-driven loading histories rather than a single assumed baseline. The capability enables design and operational decisions—such as allowable pressure ranges, injection-withdrawal cycling strategies, and monitoring placement—to be defined to account explicitly for evolving climate forcing. In this way, high-resolution climate information supports storage designs that remain functional and controllable under realistic future conditions.

### 5.3. Carbon capture, utilization, and storage (CCUS)

Carbon Capture, Utilization, and Storage operates on timescales comparable to climate change itself, making it particularly sensitive to long-term evolution of subsurface boundary conditions (Szulczewski et al., 2012). Although CCUS is intended as a climate mitigation strategy, many storage assessments implicitly assume stationary

hydrological, thermal, and mechanical conditions over decades to centuries. This assumption may underestimate risks associated with climate-driven changes in pressure dissipation, fluid migration, and geomechanical stability. High-resolution climate data enable CCUS assessments to move beyond simplified representations of future forcing. Kilometer-scale projections can be used to resolve spatial and temporal variability in recharge, surface temperature, and extreme events that influence groundwater flow patterns, pressure gradients, and thermal conditions at storage sites. These climate-driven changes can affect CO<sub>2</sub> plume migration, trapping efficiency, geochemical reactions, and stress evolution in reservoir–caprock systems.

Climate-Informed Engineering provides a framework for integrating these resolved climate forcing into CCUS site selection, design, and monitoring strategies. Rather than relying on ensemble-mean trends, storage performance can be evaluated under physically consistent climate trajectories that drive time-dependent boundary conditions. The evaluation allows engineers to identify climate conditions that warrant more conservative pressure management, enhanced monitoring, or alternative site selection. Embedding high-resolution climate information into CCUS design strengthens confidence that storage systems will remain secure under the evolving climate conditions they are intended to mitigate.

### 5.4. Mining and subsurface excavation

Subsurface mining and excavation activities are increasingly influenced by climate-driven changes (Odell et al., 2018) in groundwater inflow, thermal conditions, and rock mass behavior. Shifts in precipitation patterns and recharge can alter groundwater pressures and inflow rates, affecting stability, and operational safety, potentially triggering deformation, or functionality loss in built underground infrastructure (Hartmann et al., 2025). Surface warming can further modify subsurface thermal environments, with implications for ventilation design and worker conditions (Li et al., 2025; Liu et al., 2025).

From a geomechanical perspective, climate parameters could influence fracture development, rock mass degradation, and subsidence over the lifetime of a mine. These effects are particularly relevant for deep or long-lived operations, where small but persistent climate signals may accumulate over decades. Traditional mine planning and support design typically rely on historical or short-term hydrological conditions and rarely consider such long-term environmental evolution. Climate-Informed Engineering introduces a more realistic basis for subsurface excavation planning by incorporating high-resolution climate data into hydrogeological and geomechanical analyses. Kilometer-scale climate projections allow mine designers to represent future groundwater recharge and thermal forcing at scales relevant to excavation stability and inflow control. This information can inform mine layout, dewatering system design, and support strategies that remain effective under evolving conditions.

### 5.5. Managed aquifer recharge and climate-resilient groundwater systems

Managed Aquifer Recharge (MAR) is increasingly used to enhance groundwater availability, mitigate overdraft, and reduce land subsidence (Meles et al., 2024). Unlike many subsurface energy systems, MAR performance is controlled almost entirely by surface-driven hydrological processes, particularly the timing, intensity, and spatial distribution of precipitation and runoff (Qiu et al., 2025; Ren et al., 2025). As a result, MAR systems are highly sensitive to climate variability and cannot be reliably designed using long-term average recharge rates or stationary hydrological assumptions. Changes in precipitation and temperature increasingly control recharge through discrete events—such as intense storms or prolonged droughts—rather than through stable mean conditions. In many regions, total annual precipitation may change only modestly, while the frequency of intense rainfall events and multi-year droughts increases. These dynamics

directly control whether water is available for recharge, how quickly it infiltrates, and how pressure and deformation evolve in aquifer systems.

Climate-Informed Engineering offers a clear advantage for MAR by enabling the use of high-resolution, time-resolved climate data to explicitly represent recharge-relevant boundary conditions. Kilometer-scale climate models can resolve storm intensity, seasonal soil moisture dynamics, and surface temperature variability that govern infiltration capacity, runoff generation, and evaporation losses (Hohenegger et al., 2023). When translated into subsurface models, this information allows engineers to simulate discrete recharge pulses, leading to more realistic predictions of subsurface system response over time. This capability is particularly important in regions affected by land subsidence due to groundwater extraction (Davydzenka et al., 2024). High-resolution climate data make it possible to identify when recharge events are large and persistent enough to influence pore pressure recovery. The information enables MAR systems to be operated in a way that directly counteracts stress accumulation in compacting formations, while avoiding recharge strategies that are poorly timed or hydraulically ineffective.

Operationally, climate-informed MAR enables dynamic recharge strategies that respond to evolving climate conditions rather than fixed schedules. For example, infiltration and injection operations can be intensified during short-lived wet periods identified by high-resolution forecasts, while prolonged drought conditions may trigger conservative extraction limits to prevent irreversible compaction. By explicitly linking high-resolution climate forcing with subsurface hydraulic and mechanical response, Climate-Informed Engineering provides a physically-based framework for designing and managing MAR systems under different climate conditions. This approach improves groundwater reliability, reduces subsidence risk, and strengthens the role of MAR as a core component of climate-resilient water systems (He et al., 2021).

## 6. Decision-support tools and operationalization of CIE

### 6.1. Decision-support frameworks for subsurface energy systems

Operationalizing Climate-Informed Engineering requires decision-support frameworks that can directly connect climate forcing, subsurface process models, and engineering constraints. In subsurface energy projects, decisions about site selection, design margins, and operational limits are tightly coupled to assumptions about boundary conditions that evolve over decades. Treating climate as a fixed background condition obscures these dependencies and limits the ability to evaluate long-term system behavior. Within a CIE context, decision-support frameworks are structured around the translation of high-resolution climate data into time-dependent boundary conditions that drive subsurface response. Rather than relying on single deterministic assumptions or ensemble-averaged trends, these frameworks allow engineers to compare alternative designs and operational strategies using high-resolution climate data. Equally important, such frameworks provide a transparent basis for documenting uncertainties, and decision rationales. For subsurface systems—where direct observation is limited and public and regulatory scrutiny is high—this transparency is essential for building confidence in long-term safety and performance.

### 6.2. Role of earth system models and digital infrastructure

Advances in Earth system modeling and digital infrastructure are central to making Climate-Informed Engineering operational. The emergence of kilometer-scale climate models allows climate forcing to be resolved at spatial and temporal scales relevant to subsurface boundary conditions, enabling direct coupling between surface climate dynamics and subsurface simulations. The coupling represents a qualitative shift from earlier approaches that relied on coarse or statistically downscaled climate inputs. Digital infrastructure, such as

integrated modeling platforms and digital twins (Smarsly et al., 2024), provide a practical mechanism for propagating climate signals into engineering workflows. When combined with monitoring data, the tools allow subsurface models to be updated as climate conditions and system behavior evolve, supporting operational decision-making based on observed trends (Peralta et al., 2026).

### 6.3. Institutional and policy interfaces

The adoption of CIE–SM is constrained not only by technical challenges but also by institutional and regulatory frameworks. Engineering standards and risk assessment guidelines for subsurface projects typically reference historical conditions or fixed design envelopes, which may limit the formal use of climate projections in decision-making. Enabling CIE–SM in practice requires regulatory frameworks that recognize time-dependent boundary conditions and adaptive management as legitimate engineering approaches. Clear guidance on how high-resolution climate information can be incorporated into design, monitoring, and contingency planning would reduce uncertainty for project developers and promote consistency across jurisdictions.

Education and professional training are equally important. As high-resolution climate data become more widely available, engineers must be equipped to interpret and apply the information within subsurface models and operational workflows. For CIE–SM to transition from research into practice, technical innovations must be matched by institutional frameworks and regulatory practices.

## 7. Research challenges, knowledge gaps, and future directions

Despite recent advances, significant challenges remain in integrating Climate-Informed Engineering into subsurface processes and earth energy systems. A central scientific challenge is translating high-resolution climate information into site-specific boundary conditions for subsurface models. While kilometer-scale climate projections represent a major step forward, linking these outputs to subsurface processes governed by strong heterogeneity, nonlinear feedbacks, and long memory effects remains an active area of research.

A related challenge concerns the adaptability of existing coupled hydro–thermal–mechanical–chemical (HTMC) models. Many current modeling frameworks were developed under assumptions of quasi-stationary forcing and may not be well suited to representing evolving climate-driven boundary conditions over long timescales. Key bottlenecks in HTMC frameworks to long-term climate-informed simulations include several interrelated factors. These include limitations in constitutive relationships under evolving thermal and hydrological conditions, computational cost associated with high-resolution and long-duration simulations, and challenges in fully coupled multiphysics integration.

Monitoring and data availability present additional limitations. Long-term subsurface datasets that capture climate-driven trends are rare, and observations are often spatially sparse. Advances in sensing technologies, geophysical monitoring, and data assimilation offer opportunities to improve model calibration and validation, but integrating the data streams into climate-informed workflows, for example in the form of novel types of digital twins, remains challenging.

Addressing these challenges will require coordinated efforts across climate science, subsurface engineering, and decision science. Continued advances in Earth system modeling, high-performance computing, and integrated digital platforms provide a strong foundation for this work.

## 8. Conclusions: toward climate-informed subsurface energy engineering

Subsurface energy systems are central to energy transition strategies but are increasingly exposed to climate-driven changes that unfold over

the same timescales as system operation and storage. Engineering approaches that assume stationary environmental conditions are therefore becoming less defensible.

This paper has developed a Climate-Informed Engineering perspective tailored to subsurface processes and earth energy systems, emphasizing the role of high-resolution climate data in enabling physically consistent, time-dependent boundary conditions for subsurface analysis. By linking climate forcing directly to subsurface processes and engineering decisions, CIE provides a practical framework for evaluating long-term system behavior under evolving environmental conditions.

Across applications—including geothermal energy, underground energy storage, CCUS, subsurface excavation and managed aquifer recharge—the analysis demonstrates that the value of CIE lies in the ability to resolve climate forcing at scales relevant to subsurface processes. This capability allows engineers to move beyond static design assumptions and explicitly manage climate-driven stresses over system lifetimes.

Looking forward, the successful adoption of Climate-Informed Engineering will depend on continued advances in climate modeling, subsurface simulation, monitoring technologies, digital twinning, and institutional frameworks. By embedding high-resolution climate information into the core of subsurface engineering practice, Earth Energy Science can better anticipate long-term risks, improve system reliability, resilience, and support energy infrastructure that remains functional under a changing climate.

#### CRedit authorship contribution statement

**Nima Shokri:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Marcus Rutner:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Bo Kang:** Writing – review & editing, Visualization, Investigation. **Maryam Rutner:** Writing – review & editing, Investigation. **Kay Smarsly:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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