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Review

Leveraging artificial intelligence for research and action on climate change: opportunities, challenges, and future directions

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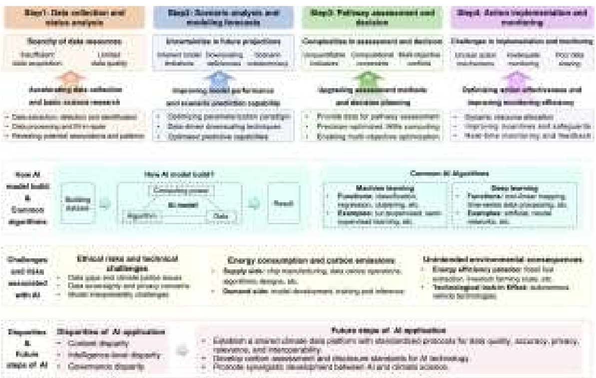
Abstract

Research and action on climate change (RACC) represent a complex global challenge that requires a systematic and multi-dimensional approach. Although progress has been made, persistent limitations in data processing, modeling, and scenario evaluation continue to hinder further advances. Artificial Intelligence (AI) is emerging as a powerful tool to address these challenges by integrating diverse data sources, enhancing predictive modeling, and supporting evidence-based decision-making. Its capacity to manage large datasets and facilitate knowledge sharing has already made meaningful contributions to climate research and action. This paper introduces the RACC theoretical framework, developed through a systematic integration of the research paradigms of the three IPCC Working Groups (WGI, WGII, and WGIII). The RACC framework provides a comprehensive structure encompassing four key stages: data collection, scenario simulation, pathway planning, and action implementation. It also proposes a standardized approach for embedding AI across the climate governance cycle, including areas such as climate modeling, scenario development, policy design, and action execution. Additionally, the paper identifies major challenges in applying AI to climate issues, including ethical concerns, environmental costs, and uncertainties in complex systems. By analyzing AI-supported pathways for mitigation and adaptation, the study reveals significant gaps between current practices and long-term objectives—especially regarding content, intelligence levels, and governance structures. Finally, it proposes strategic priorities to help realize AI's full potential in advancing global climate action.

Graphical abstract



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Introduction

Climate change is one of the most critical global challenges, posing serious threats to natural ecosystems and sustainable socio-economic development. The effects of global warming are becoming increasingly evident, with the Earth's average surface temperature having risen by approximately 1.1 °C since the pre-industrial era. This warming has been accompanied by rising sea levels, shrinking glaciers and ice caps, and more frequent and intense extreme weather events [1]. These changes have profound and far-reaching impacts on biodiversity, food security, water resources, and human health, highlighting the urgency of addressing climate change [2].

The global community recognizes the need for immediate and coordinated efforts to mitigate and adapt to climate change. However, effectively tackling this crisis requires more than high-level agreements—it demands advanced tools and methods to uncover the underlying mechanisms of climate change, project future scenarios, design effective response strategies, and turn planning into concrete actions. This comprehensive and systematic process—including scientific research, policymaking, and implementation—is hindered by key challenges such as limited data availability, forecast uncertainty, and the complexity of decision-making.

Artificial Intelligence (AI) refers to the ability of computer systems to perform tasks that typically require human intelligence, enabled by technologies such as Machine Learning (ML), which extracts patterns from data; Deep Learning (DL), which identifies complex and hidden relationships; Natural Language Processing (NLP), which interprets and generates text; and Computer Vision (CV), which analyzes images and videos [3]. These capabilities position AI as an emerging and powerful tool in climate change research.

A notable example is Google's "Flood Hub" early warning system, which uses CV for accurate flood mapping and ML with LSTM-based dynamic models to deliver reliable flood forecasts up to five days in advance [4]. In carbon monitoring, AI is driving significant advances: DL applied to drone and satellite data enables tree-level carbon stock estimation [5], while the integration of GONGGA's atmospheric inversion with two AI-enhanced dynamic global vegetation models greatly improves the accuracy of carbon sink predictions, allowing for near real-time global carbon budget tracking [6]. These developments mark a shift from static assessments to dynamic, intelligent monitoring—offering new technical support for climate governance and advancing global climate action [7].

This paper reviews current applications of AI across the research and action process on climate change (RACC) and identifies key challenges facing the field. It examines how AI technologies are being integrated into climate science, assessing both their potential benefits and possible drawbacks, including ethical concerns and the environmental footprint of large-scale AI deployments. Looking ahead, the paper outlines emerging AI applications in areas such as scientific discovery, climate impact assessments, and the development of adaptation and mitigation strategies. By analyzing trends at the intersection of AI and climate science, this study aims to contribute to innovative approaches that support more effective and timely responses to the climate crisis.

Section snippets

General process

The Intergovernmental Panel on Climate Change (IPCC) plays a central role in synthesizing and presenting the latest scientific knowledge on climate change at the global level [8]. Fig. 1 illustrates the structure and content of IPCC reports and the underlying logic that connects them. Working Group I (WGI) focuses on the physical science basis of climate change, providing the scientific foundation for Working Group II (WGII), which addresses impacts, adaptation, and vulnerability, and for …

Application of AI in RACC

AI, first introduced in 1956, is a field of science and technology focused on enabling computers to simulate and perform tasks typically associated with human intelligence [19]. By the mid-1980s, AI technologies were already being applied in basic climate research, helping to analyze complex systems and predict environmental patterns. In the current era—characterized by rapid advances in parallel computing, big data, and ML—the potential for AI in climate research and governance has expanded …

Challenges and risks associated with AI

While AI has proven to be a powerful tool for improving data collection, scenario analysis, modeling, and pathway assessment in climate change research, it also introduces several significant challenges and risks (Fig. 4) that could limit or offset its benefits for climate action. These challenges include technical and ethical concerns, the high energy use and carbon footprint of AI systems, and uncertainties surrounding their real-world application.

(1) Technical and ethical risks. …

AI applications …

Summary and outlook

Climate change remains a critical global challenge, threatening economic development and social progress. The rapid growth and adoption of AI technologies provide powerful tools to improve climate research and enhance responses to these threats. This paper highlights how AI is being used in key areas of climate research, examining its applications, challenges, and inequalities, and offering insights for guiding its future role (Fig. 4). …

Conflict of interest

The authors declare that they have no conflict of interest. …

Acknowledgments

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Author contributions

Xianchun Tan, Hongshuo Yan, and Deliang Chen designed the study. Zhe Peng and Yonglong Cheng performed the collection and analysis of the literature. All the authors conducted the results discussion. Xianchun Tan, Zhe Peng, and Hongshuo Yan wrote the first draft. Deliang Chen edited the final paper. All authors contributed to the …

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