

AI Applications and Innovations for Climate Change Mitigation and Adaptation: A Survey

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Abstract— Climate change poses one of the most significant challenges of our time, impacting ecosystems, economies, and human health worldwide. The integration of artificial intelligence (AI) presents promising opportunities for both mitigating and adapting to these climate-related challenges. This survey explores the diverse applications of AI across various sectors, including climate modeling, energy management, wildlife conservation, disaster response, and sustainable agriculture. We review the current state of AI technologies, such as machine learning, deep learning, and natural language processing, highlighting their contributions to enhancing predictive capabilities and decision-making processes. Additionally, we examine case studies that demonstrate successful implementations of AI in real-world scenarios, as well as the challenges and limitations faced in deploying these technologies effectively. Finally, we discuss future directions and the potential for interdisciplinary collaboration to maximize AI's impact on climate change solutions. This survey aims to provide a comprehensive overview of how AI can serve as a powerful tool in the fight against climate change, fostering innovation and inspiring action across multiple domains.

Index Terms— Machine Learning, Climate Change, AI.

I. INTRODUCTION

Urgency of Climate Change and Its Global Impact

Climate change represents an urgent and unprecedented challenge that affects the planet on multiple levels. Here are key points outlining its urgency and global impact:

1. Rising Global Temperatures:

- Average global temperatures have increased significantly over the past century, primarily due to human activities, particularly the burning of fossil fuels and deforestation.[1]
- This warming leads to extreme weather events, such as heatwaves, droughts, and heavy rainfall, disrupting ecosystems and human life.

2. Melting Ice Caps and Rising Sea Levels:

- Polar ice sheets and glaciers are melting at alarming rates, contributing to rising sea levels.
- Coastal communities face increased flooding and erosion, threatening livelihoods, infrastructure, and biodiversity.

3. Impact on Biodiversity:

- Climate change alters habitats, leading to species extinction and loss of biodiversity. Many ecosystems, such as coral reefs and forests, are particularly vulnerable.
- The loss of biodiversity undermines ecosystem services essential for human survival, including clean water, food security, and disease regulation.

4. Food and Water Security:

- Changing climate patterns disrupt agricultural productivity, affecting crop yields and food supply. Regions reliant on specific crops face heightened risks of food shortages.
- Water scarcity is exacerbated by altered precipitation patterns and increased evaporation rates, impacting drinking water availability and sanitation.

5. Human Health Risks:

- Climate change is linked to increased respiratory and cardiovascular diseases, heat-related illnesses, and the spread of vector-borne diseases like malaria and dengue.
- Vulnerable populations, including the elderly and low-income communities, are disproportionately affected due to limited resources and adaptive capacity.

6. Economic Consequences:

- The financial costs of climate change are staggering, with estimates projecting trillions of dollars in damages from extreme weather, infrastructure loss, and health impacts.
- Industries such as agriculture, tourism, and fisheries face significant disruptions, leading to job losses and economic instability.

7. Global Displacement and Migration:

- As climate-related disasters become more frequent and severe, populations may be forced to migrate, creating climate refugees and increasing geopolitical tensions.
- Urban areas, especially in developing countries, may struggle to accommodate the influx of displaced

individuals.

8. **Feedback Loops:**

- Climate change triggers feedback loops, such as the release of greenhouse gases from melting permafrost, further exacerbating warming.
- These self-reinforcing cycles make it critical to take immediate action to mitigate emissions.

9. **International Urgency:**

- Global agreements, such as the Paris Agreement, emphasize the need for immediate and collective action to limit global warming to well below 2°C above pre-industrial levels.
- The Intergovernmental Panel on Climate Change (IPCC) stresses that time is running out to implement effective solutions.

Artificial Intelligence (AI) encompasses a range of technologies and methodologies that enable machines to perform tasks typically requiring human intelligence, such as learning, reasoning, and problem-solving. In recent years, AI has emerged as a transformative force across various domains, including climate science and sustainability. Its relevance in these fields stems from several key capabilities:

1. **Data Processing and Analysis:**

- Climate science generates vast amounts of data from sources like satellite imagery, climate models, and sensor networks. AI techniques, particularly machine learning, excel at processing and analyzing this data, uncovering patterns and insights that may not be evident through traditional analytical methods.

2. **Enhanced Predictive Modeling:**

- AI can improve the accuracy of climate models by integrating diverse datasets and identifying complex interactions within the climate system. This capability enhances our understanding of climate dynamics, enabling better predictions of future climate scenarios and their potential impacts.[2]

3. **Resource Optimization:**

- In the realm of sustainability, AI can optimize the use of resources across various sectors. For instance, AI algorithms can enhance energy efficiency in buildings, optimize irrigation in agriculture, and improve waste management practices, all contributing to reduced carbon footprints.

4. **Real-time Monitoring and Response:**

- AI technologies facilitate real-time monitoring of environmental conditions, such as air quality, deforestation rates, and water availability. By providing timely data, AI enables more effective responses to climate-related events and helps in disaster management.

5. **Decision Support Systems:**

- AI can support policymakers and stakeholders in making informed decisions by analyzing potential outcomes of various climate action strategies. Decision support systems powered by AI can simulate the impacts of policies, guiding more effective climate interventions.

6. **Interdisciplinary Collaboration:**

- AI fosters collaboration among scientists, engineers, and policy makers by providing tools that bridge gaps between disciplines. This interdisciplinary approach is crucial for tackling the multifaceted challenges posed by climate change.

7. **Public Engagement and Awareness:**

- AI-driven applications, such as chatbots and educational tools, can raise public awareness about climate issues and promote sustainable practices. Engaging communities in climate action is vital for driving behavioral changes and fostering a culture of sustainability.

The primary objectives of the survey titled "AI Applications and Innovations for Climate Change Mitigation and Adaptation" are as follows:

1. **Comprehensive Overview:**

- To provide a detailed overview of the current landscape of AI applications specifically aimed at addressing climate change challenges, including both mitigation and adaptation strategies.

2. **Highlight Key Innovations:**

- To identify and discuss innovative AI technologies and methodologies that are being developed and deployed in various sectors relevant to climate action, including energy, agriculture, and disaster management.

3. **Assess Effectiveness:**

- To evaluate the effectiveness and impact of existing AI applications in improving climate predictions, optimizing resource use, and enhancing resilience against climate-related impacts.

4. **Examine Case Studies:**

- To present real-world case studies that illustrate successful implementations of AI in climate change contexts, showcasing lessons learned and best practices.

5. **Identify Challenges and Limitations:**

- To analyze the challenges and limitations associated with the deployment of AI technologies in climate science, including issues related to data quality, ethical considerations, and scalability.[3]

6. **Future Directions:**

- To explore potential future directions for AI research and applications in climate change, including emerging technologies, interdisciplinary collaboration, and policy

implications.

7. *Encourage Interdisciplinary Collaboration:*

- To emphasize the importance of collaboration among scientists, policymakers, industry stakeholders, and communities in leveraging AI for effective climate action.

By achieving these objectives, the survey aims to contribute to the growing body of knowledge on the intersection of AI and climate science, guiding future research and practical applications in the field.

II. OVERVIEW OF CLIMATE CHANGE CHALLENGES

Climate change poses a multitude of interrelated challenges that affect ecosystems, economies, and societies world wide. Understanding these challenges is crucial for developing effective mitigation and adaptation strategies. Here are some of the major challenges:

a. Emissions Reduction

- **Greenhouse Gas Emissions:** The rise in global temperatures is primarily driven by increasing concentrations of greenhouse gases (GHGs) in the atmosphere, particularly carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O).
- **Statistics:** According to the Intergovernmental Panel on Climate Change (IPCC), global CO₂ emissions reached approximately 36.4 billion metric tons in 2019. To limit warming to 1.5°C, global emissions must be halved by 2030 and reach net-zero by 2050.
- **Challenges:** Transitioning from fossil fuels to renewable energy sources, enhancing energy efficiency, and changing consumption patterns are significant hurdles.[4]

b. Climate Modeling

- **Complexity of Climate Systems:** Accurately modeling climate change is complicated due to the intricate interactions among atmospheric, oceanic, and terrestrial systems.
- **Projections:** Current models predict that without significant mitigation efforts, global temperatures could rise by 2°C to 4°C by the end of the century, leading to severe environmental and socio-economic impacts.
- **Challenges:** Improving the accuracy and resolution of climate models is essential for better forecasting and informing policy decisions.

c. Resource Management

- **Water Scarcity:** Changing precipitation patterns and increased evaporation due to rising temperatures threaten freshwater supplies. By 2025, it is estimated that 1.8 billion people will live in areas with absolute water scarcity.
- **Agricultural Impact:** Climate change adversely affects crop yields, with projections suggesting that staple crops

could see declines of 10-25% by 2050, exacerbating food insecurity.

- **Challenges:** Sustainable management of natural resources is needed to balance human needs with environmental conservation.

d. Extreme Weather Events

- **Increased Frequency and Intensity:** Climate change is linked to the rise in frequency and intensity of extreme weather events such as hurricanes, floods, and wildfires.
- **Statistics:** The National Oceanic and Atmospheric Administration (NOAA) reports that the U.S. experienced 22 separate billion-dollar weather and climate disasters in 2020 alone.
- **Challenges:** Developing robust infrastructure and emergency response systems to withstand these events is critical.

e. Biodiversity Loss

- **Ecosystem Disruption:** Climate change threatens biodiversity by altering habitats and forcing species migration or extinction. The World Wildlife Fund (WWF) estimates that a 2°C rise in temperature could lead to the extinction of up to 30% of species.
- **Challenges:** Effective conservation strategies and habitat restoration efforts are necessary to protect vulnerable species.

f. Health Risks

- **Public Health Threats:** Climate change exacerbates health risks through increased air pollution, heat stress, and the spread of vector-borne diseases.
- **Statistics:** The World Health Organization (WHO) estimates that climate change will cause an additional 250,000 deaths per year between 2030 and 2050 due to malnutrition, malaria, diarrhea, and heat stress.
- **Challenges:** Strengthening healthcare systems and public health initiatives to address these emerging challenges is essential.

III. AI TECHNOLOGIES AND METHODS

AI technologies and methodologies are increasingly being utilized to address the challenges posed by climate change. Here, we explore key AI techniques, including machine learning, deep learning, and natural language processing, and their applications in climate science and sustainability.

a. Machine Learning

Supervised Learning:

- **Description:** This technique involves training a model on labeled data, where input-output pairs are provided. The model learns to map inputs to outputs, enabling it to make predictions on new, unseen data.[5]

• **Applications:**

- **Emissions Prediction:** Models can predict greenhouse gas emissions from various sectors, helping policymakers design targeted reduction strategies.
- **Climate Modeling:** Supervised learning can improve the accuracy of climate forecasts by correlating historical climate data with outcomes.

Unsupervised Learning:

- **Description:** In unsupervised learning, models are trained on data without explicit labels, allowing them to identify patterns and structures.
- **Applications:**
 - **Clustering Climate Zones:** Unsupervised techniques can classify regions based on climate characteristics, aiding in regional climate adaptation strategies.
 - **Anomaly Detection:** Identifying unusual weather patterns or environmental changes that may signal emerging climate threats.

Reinforcement Learning:

- **Description:** This technique involves training agents to make decisions by interacting with an environment and receiving feedback in the form of rewards or penalties.[6]
- **Applications:**
 - **Energy Management:** Reinforcement learning can optimize energy consumption in smart grids by dynamically adjusting resource allocation based on real-time demand.
 - **Adaptive Environmental Policies:** Agents can simulate and evaluate the impacts of various policy decisions, providing insights into the most effective strategies for climate mitigation.

b. Deep Learning

Description: Deep learning, a subset of machine learning, uses neural networks with multiple layers to model complex patterns in large datasets. It excels in tasks involving unstructured data, such as images and text.[7]

Applications:

- **Image Recognition for Environmental Monitoring:**
 - **Remote Sensing:** Deep learning models analyze satellite images to monitor deforestation, urbanization, and changes in land use, providing critical data for conservation efforts.
 - **Biodiversity Assessment:** Image recognition techniques are used to identify and count species in camera trap images, supporting wildlife conservation initiatives.
 - **Disaster Response:** Deep learning can assess damage from natural disasters by analyzing aerial imagery, facilitating quicker response efforts and resource allocation.

c. Natural Language Processing (NLP)

Description: NLP involves the interaction between computers and human language, enabling machines to understand, interpret, and generate text.[8]

Applications:

- **Analyzing Climate-Related Texts:**
 - **Literature Review and Research Analysis:** NLP techniques can automate the extraction of insights from scientific papers, helping researchers identify trends and gaps in climate science literature.
 - **Policy Analysis:** NLP can evaluate the language and content of climate policies, assessing their effectiveness and public reception.
- **Public Sentiment Analysis:**
 - **Social Media Monitoring:** NLP tools can analyze public sentiment towards climate change initiatives and policies by processing social media posts, enabling better engagement strategies.
 - **Survey Analysis:** NLP techniques can assess open-ended survey responses, providing insights into public perceptions and attitudes toward climate action.

IV. APPLICATIONS OF AI IN CLIMATE CHANGE

AI technologies are being leveraged across various sectors to combat climate change effectively. Here are some significant applications:

a. Climate Modeling and Prediction

- **Description:** AI enhances climate models by simulating complex interactions within the climate system, leading to more accurate predictions of future climate scenarios.[9]
- **Applications:**
 - **Data Integration:** AI algorithms can process vast datasets from satellites, sensors, and historical records to improve the fidelity of climate simulations.
 - **Scenario Analysis:** Machine learning models can explore different climate scenarios, helping scientists understand potential outcomes based on varying emissions trajectories and mitigation efforts.
 - **Improved Forecasts:** AI-driven models can increase the accuracy of long-term climate forecasts, aiding in planning and policy development.

b. Energy Management

- **Description:** AI optimizes energy systems to enhance efficiency, reduce waste, and promote the use of renewable energy sources.
- **Applications:**
 - **Smart Grids:** AI systems enable real-time monitoring and management of energy distribution, balancing supply and demand efficiently.

- **Energy Consumption Prediction:** Machine learning models can predict energy usage patterns, helping utilities manage resources and reduce peak loads.
- **Renewable Energy Optimization:** AI can enhance the integration of solar and wind energy by forecasting production based on weather patterns and optimizing storage and distribution. Wildlife Conservation
- **Description:** AI technologies are employed to monitor and protect endangered species and their habitats, providing crucial data for conservation efforts.
- **Applications:**
 - **Tracking and Monitoring:** AI-powered camera traps and drones use image recognition to monitor wildlife populations and track movements, enabling conservationists to respond to threats in real-time.
 - **Habitat Analysis:** Machine learning algorithms analyze environmental data to assess habitat conditions and identify areas requiring protection or restoration.
 - **Anti-Poaching Efforts:** AI systems can analyze patterns of poaching activity, helping authorities deploy resources more effectively to combat wildlife crime.
- c. **Disaster Management**
 - **Description:** AI enhances preparedness and response to natural disasters by analyzing data to predict events and assess impacts.
 - **Applications:**
 - **Predictive Analytics:** Machine learning models can forecast the likelihood of hurricanes, floods, and wildfires by analyzing historical weather patterns and real-time data.
 - **Risk Assessment:** AI can evaluate vulnerabilities in infrastructure and communities, aiding in the development of effective disaster response strategies.
 - **Emergency Response:** AI tools can assist in resource allocation and logistics during disasters, ensuring timely aid delivery and efficient management of relief efforts.
- d. **Agriculture**
 - **Description:** AI applications in agriculture focus on optimizing crop yields, resource management, and sustainability practices.[10]
 - **Applications:**
 - **Precision Farming:** AI systems analyze soil health, weather conditions, and crop growth patterns to provide tailored recommendations for planting, irrigation, and fertilization.
 - **Yield Prediction:** Machine learning models predict crop yields based on historical data and real-time observations, helping farmers make informed decisions.

- **Pest and Disease Management:** AI-powered image recognition tools can identify pests and diseases in crops early, allowing for targeted interventions and minimizing chemical use.

V. CASE STUDIES

Here are several noteworthy case studies that highlight successful applications of AI in addressing climate change challenges:

a. Google's AI for Flood Prediction[12]

- **Overview:** Google partnered with the Indian government to develop a flood prediction system using AI and machine learning algorithms.
- **Implementation:** By analyzing historical rainfall data, satellite imagery, and topographical information, the system can predict flooding events with greater accuracy.
- **Impact:** The AI-driven tool has significantly improved the timeliness of flood alerts, allowing for better preparedness and response strategies, ultimately saving lives and reducing economic losses.

b. IBM's Green Horizon Project[13]

- **Overview:** IBM launched the Green Horizon project to leverage AI for environmental monitoring and energy optimization in urban settings.
- **Implementation:** The project uses machine learning models to analyze weather data, pollution levels, and energy usage patterns to forecast air quality and optimize energy consumption.
- **Impact:** Cities using this system have seen improved air quality management and energy efficiency, leading to reduced greenhouse gas emissions and enhanced public health.

c. The Nature Conservancy's AI for Wildlife Conservation[14]

- **Overview:** The Nature Conservancy utilized AI to monitor wildlife populations in various ecosystems, including forests and marine environments.
- **Implementation:** Using AI-powered camera traps and drones, they track animal movements and behaviors, employing image recognition to identify species and assess population health.
- **Impact:** This approach has improved the ability to respond to conservation needs, helped combat poaching, and informed habitat protection efforts.

d. Microsoft's AI for Earth[15]

- **Overview:** Microsoft's AI for Earth program supports projects that use AI to address environmental challenges, focusing on climate, agriculture, biodiversity, and water.
- **Implementation:** One example includes a partnership with the organization Land O'Lakes to develop AI models that optimize crop management and sustainability

practices.

- **Impact:** This initiative helps farmers increase yields while reducing environmental impacts, fostering sustainable agricultural practices.
- e. **Climate.ai's Climate Risk Assessment[16]**
- **Overview:** Climate.ai offers AI-driven solutions to help businesses and governments assess climate-related risks and develop resilience strategies.
 - **Implementation:** Their platform utilizes machine learning to analyze a variety of climate data and generate localized forecasts, assessing potential impacts on infrastructure and operations.
 - **Impact:** Organizations using Climate.ai's tools can make data-informed decisions to enhance resilience and adapt their strategies in response to changing climate conditions.
- f. **AgroAI's Precision Agriculture Solutions[17]**
- **Overview:** AgroAI provides AI solutions for precision farming, helping farmers optimize their practices and reduce resource consumption.
 - **Implementation:** Using satellite imagery and AI analytics, AgroAI offers insights on soil health, crop conditions, and pest threats, allowing farmers to make targeted interventions.
 - **Impact:** Farmers utilizing AgroAI's technology report increased crop yields and reduced use of water and fertilizers, promoting sustainability and economic viability.

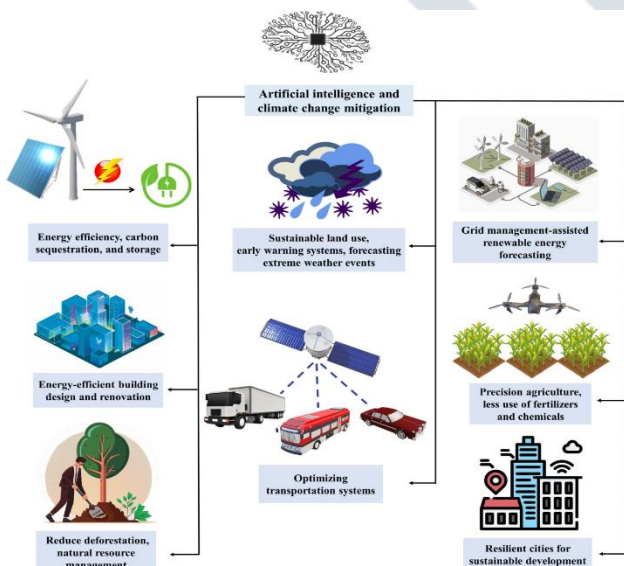


Fig. [Artificial intelligence-based solutions for climate change][11]

VI. CHALLENGES AND LIMITATIONS

While AI holds significant promise for addressing climate change, several challenges and limitations must be considered:

- Data Quality and Availability**
 - **Challenge:** AI models rely heavily on high-quality data. In many regions, especially in developing countries, data may be sparse, inconsistent, or of poor quality.
 - **Impact:** Inaccurate or incomplete data can lead to flawed predictions and ineffective interventions, undermining the credibility of AI applications.
- Model Complexity and Interpretability**
 - **Challenge:** Many AI models, particularly deep learning algorithms, are complex and operate as "black boxes," making it difficult to interpret their decision-making processes.
 - **Impact:** Lack of transparency can hinder trust among stakeholders, including policymakers and the public, who may be hesitant to rely on AI-driven recommendations.
- Scalability and Implementation**
 - **Challenge:** Developing AI solutions that are scalable and can be implemented in diverse geographic and socio-economic contexts poses a significant hurdle.
 - **Impact:** Solutions that work well in one context may not be directly transferable to another, limiting the broader applicability of AI innovations.
- Ethical and Social Considerations**
 - **Challenge:** The deployment of AI technologies raises ethical concerns, including potential biases in algorithms and unequal access to AI tools.
 - **Impact:** Marginalized communities may face disproportionate impacts from climate change, and AI applications that do not account for these disparities can exacerbate existing inequalities.
- Resource Constraints**
 - **Challenge:** Implementing AI solutions often requires substantial financial and technological resources, which may be beyond the reach of some organizations or governments.
 - **Impact:** Limited resources can hinder the development, deployment, and maintenance of AI systems, particularly in low-income regions.
- Integration with Existing Systems**
 - **Challenge:** AI applications must be integrated with existing environmental management and policy frameworks, which can be complex and bureaucratic.
 - **Impact:** Resistance to change and lack of collaboration between different sectors can impede the effective adoption of AI technologies.
- Rapidly Evolving Nature of Climate Science**
 - **Challenge:** The science of climate change is constantly evolving, with new findings and technologies emerging regularly.

- **Impact:** AI models may quickly become outdated, requiring continuous updates and adaptations to remain relevant and effective.

h. Regulatory and Policy Frameworks

- **Challenge:** There is often a lack of clear regulatory frameworks governing the use of AI in climate applications, which can create uncertainty for developers and users.
- **Impact:** Unclear regulations can slow down innovation and implementation, as stakeholders may be hesitant to invest in technologies without established guidelines.

VII. FUTURE DIRECTIONS

The future of AI in climate change mitigation and adaptation is set for significant advancements through several key areas. Enhanced data integration and accessibility will enable better collaboration among stakeholders, improving model accuracy and decision-making. Explainable AI (XAI) will foster trust and facilitate policy integration. Tailoring solutions to local contexts will make AI applications more relevant, while interdisciplinary collaborations will address both environmental and socio-economic factors. AI will aid in proactive climate resilience planning and necessitate clear ethical guidelines. Additionally, integrating emerging technologies like blockchain and edge computing will enhance data management and real-time decision-making. Public engagement through AI tools will promote sustainable practices, and adaptive AI systems will ensure ongoing effectiveness. Together, these strategies aim to maximize AI's potential in combating climate change.

VIII. CONCLUSION

In conclusion, AI applications and innovations represent a pivotal advancement in the fight against climate change, offering transformative solutions for both mitigation and adaptation. By harnessing the power of machine learning, deep learning, and natural language processing, AI can significantly enhance our understanding of climate dynamics, optimize resource management, and improve predictive capabilities. The diverse case studies illustrate successful implementations across various sectors, from energy management and disaster response to wildlife conservation and precision agriculture. However, the journey forward must address challenges such as data quality, model interpretability, and ethical considerations to ensure that AI technologies are both effective and equitable. As we look ahead, a collaborative approach that integrates interdisciplinary expertise and prioritizes local contexts will be essential in maximizing the impact of AI. By fostering innovation and adaptability, we can create resilient systems that not only respond to the pressing challenges of climate change but also contribute to a sustainable and equitable future for all.

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