AI-Driven Climate Solutions: Leveraging LEO Satellites for Sustainability

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Abstract

Space science is entering a transformative phase, with thousands of satellites launched into space to serve various functions, from exploration to improving life on Earth. This paper studies the high density of satellites in the Low-Earth Orbit (LEO) and their critical role in climate change monitoring through remote sensing technology. The aspects of climate change focused on in this paper are air pollution, atmospheric humidity, and wildfires. These three areas are emphasized due to their high impact on climate change, public health, and economic costs. Remote sensing works to monitor air quality, track atmospheric humidity, and capture real-time thermal imagery of fires, aiding early warning systems to prevent drastic impacts on land. This paper further delves into the benefits of integrating Artificial Intelligence (AI) in enhancing data collection and interpretation through on-board computing, space cloud framework, and machine learning models. These reduce the latency of responses making climate monitoring more efficient and advanced.

Introduction

Space science is moving into a new era with thousands of satellites being launched serving various purposes, some exploratory and some with the aim to make our planet better for humans to live in.

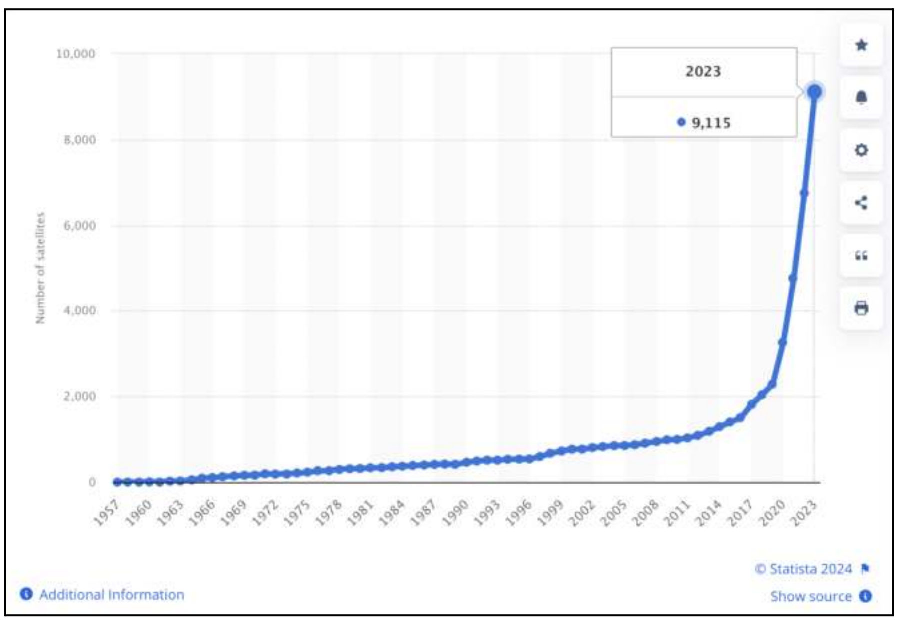

Figure 1: Number of active satellites from 1957 to 2023 (Statista Research Department)

Figure 1 shows the rapid transformation of the purpose and functioning of satellites launched into space in enormous numbers every year, especially in the last 7 years. Crossing 9000 satellites in 2023, the exponential growth of satellites also indicates the scope of development and innovations in this sector for contributing to societal well-being.

The proliferation of satellites in orbit has revolutionized various sectors, from telecommunications to earth observation. As seen in Table 1, the distribution of satellites across different orbits and their intended purposes acts as the primary assessment of the current state of space utilization and planning for future missions (Sebastian).

Purpose Orbit Type	Elliptical	GEO	LEO	MEO	Grand Total
Communications	13	480	5100	20	5514
Earth Observations	16	48	1169	2	1235
Technology Developments	8	17	346	1	372
Navigation/Global Positioning	2	20	0	120	142
Space Science	20	1	78	0	99
Technology Demonstration	0	1	63	0	64
Earth Science	0	0	28	0	28
Surveillance	0	0	20	0	20

Table 1: Summary of the number of satellites in various orbits: Elliptical, GEO, LEO, and MEO classified by their purpose. Note that this is not an exhaustive list, there are few other satellites with a small number and not relevant to this paper. (Sebastian)

As depicted by Figure 1 and Table 1, the highest density of satellites is located within the LEO belt. This research paper will go further into what LEO satellites are, how their technology of remote sensing monitors climate change, and the integration of AI to make data collection and onboard processing to assist climate change monitoring more efficiently and advanced.

LEO Satellites

Defining LEO Satellites

LEO satellites range from altitudes of 200–300 km to 1,600 km. Other orbits include Medium Earth Orbit (MEO) at 1,200–20,000 km and Geostationary orbits (GEO) at around 36,000 km. MEO and GEO orbits are biased toward the containment of satellites for navigation and global positioning while the purposes of LEO satellites are more vast in areas. LEO satellites offer a high level of accessibility, cost, and accuracy. This orbit is widely used for positioning, communication, earth observation, scientific development, and surveillance. In light of the expanding role of LEO satellites, this paper aims to provide a comprehensive and in-depth analysis of the satellites' role in monitoring climate change and the scope of AI integration.

Leading space agencies such as the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA) are key players in the development and utilization of satellite technology, including the areas of climate change monitoring.

Remote Sensing

Remote sensing by satellites is a crucial tool for understanding our planet and addressing global challenges such as climate change, resource management, and disaster response. Remote sensing is heavily reliant on the data collected by LEO satellites for measurements of various Earth observations. It is the process of collecting information about the Earth's surface and atmosphere from space using various types of sensors on satellites. The process includes satellites that use imaging, light radars, and microwave technology.

LEO Constellations

In the recent past, LEO constellations have been very effective, offering global coverage with the ability for its network to be rapidly deployed in emergencies, providing internet access in disaster-stricken areas. This has proven particularly beneficial in regions with unreliable connectivity, supporting education, communication, and emergency services. These technologies are designed to provide high-speed internet to hard-to-reach locations, making them crucial to remote communities.

For example, Starlink is a LEO network developed by the private spaceflight company SpaceX to provide low-cost internet to remote locations. As of September 2024, there are 6,426 Starlink satellites in orbit, of which 6,371 are working. Starlink has provided high-speed, low-latency internet on tens of thousands of flights and counting, keeping passengers connected from the moment they step onboard their aircraft and throughout their travels around the world (Pultarova and Howell).

Another significant player is Amazon’s Project Kuiper, which is an initiative to increase global broadband access through a constellation of more than 3,000 satellites in low Earth orbit. Its mission is to bring fast, affordable broadband to unserved and underserved communities around the world (Amazon).

Data Set Collection

LEO satellites collect and process a variety of data sets for Earth observation, specifically climate change monitoring. Optical imagery captures visible light and is used for observing land use and surface changes. Multispectral imagery, spanning different wavelengths including visible and near-infrared, is key to analyzing vegetation health, water quality, and environmental conditions. Radar data, specifically Synthetic Aperture Radar (SAR), provides detailed information on Earth's surface features by bouncing radar waves off the ground. SAR can operate through clouds and darkness, making it effective for tracking surface changes, deforestation, and urban development. Thermal imagery captures heat emissions from the Earth's surface, aiding in monitoring sea surface temperatures, wildfires, urban heat islands, and energy efficiency (Klimenko).

Data collected by LEO satellites include elevation and terrain mapping through LIDAR, which uses laser light to create detailed 3D models of landscapes, forests, and urban areas (eoPortal). Atmospheric data on temperature, pressure, and humidity are crucial for weather forecasting and climate studies. Gravity field mapping measures changes in Earth's gravity, offering insights into phenomena like ice mass loss and sea level rise. Satellites also gather GPS data for accurate positioning, navigation, and timing services, along with magnetic field data for studying Earth's interior and navigation systems. Together, these datasets provide comprehensive information for scientific research, environmental monitoring, and disaster management.

Artificial Intelligence

AI refers to the simulation of human intelligence in machines that are designed to think, learn, and problem-solve like humans. It enables systems to perform tasks such as decision-making, pattern recognition, and language understanding without human intervention (Laskowski et al.).

This paper will focus on how AI can have a significant impact on the way LEO monitors climate change. AI integrated with LEO satellites is transforming climate change monitoring by enabling real-time data analysis and prediction. LEO satellites provide detailed environmental data on air quality, wildfires, and humidity, while AI accelerates pattern recognition, increases accuracy, and enhances predictive capabilities. Together, they offer innovative solutions for timely responses to climate-related disasters, helping mitigate their impacts and inform better policy decisions.

LEO Satellites and Climate Change

This research specifically focuses on air pollution, atmospheric humidity, and wildfires due to their critical impact on climate change, public health, and economic costs. These areas were chosen because they are highly responsive to satellite monitoring and AI-driven analysis, offering actionable insights for early intervention and mitigation. By targeting these aspects, the study aims to demonstrate how AI and LEO satellites can provide timely, accurate data to address some of the most pressing climate challenges. Key areas of study include atmospheric conditions like carbon levels, landforms such as surface elevation and soil moisture, and vegetation canopy height, which helps estimate forest biomass and aboveground carbon. Satellites also track greenhouse gas emissions, cloud and radiant energy systems, and gravity field anomalies. According to the World Health Organization (WHO), in 2019, outdoor air pollution contributed to over 4.2 million deaths, with particulate matter being a major contributor (World Health Organization (WHO)). In 2020 alone, nearly 9,900 wildfires in California burned over 4 million acres of land (Kerlin). Climate-exacerbated wildfires cost the U.S. between $394 to $893 billion each year in economic costs and damages (Joint Economic Committee).

Air Pollution

Monitoring air pollution through LEO satellites, specifically with remote sensing, is crucial and effective in ensuring the mitigation of the effects of global warming and climate change, especially by collecting aerosol data.

Aerosol data is information about suspended particles in the air, such as dust and smoke, that can be used to monitor air quality and global warming. Aerosols are a part of air pollution and are dangerous to human health. When we breathe in these tiny particles, they can damage lung tissue and lead to lung diseases (UCAR). By measuring aerosol concentration, scientists can assess the levels of harmful particulate matter in the atmosphere. Understanding aerosol data also improves climate models and forecasts, thereby enabling better policy-making and public health responses.

NASA’s GEO-LEO Dark Target Aerosol Data Products initiative shows the significance of aerosol measurements and their various sources to study and collect aerosol data in the atmosphere (Earthdata).

Target aerosol data products provide detailed information about the concentration, distribution, and types of aerosols in specific regions. These data products are often derived from satellite-based sensors, such as NASA’s MODIS (Moderate Resolution Imaging Spectroradiometer), and are used to monitor and analyze air quality, pollution levels, and the effects of aerosols on climate and weather patterns (Earthdata).

Moreover, the California Air Resources Board (CARB) has been researching how to use satellite data, specifically NASA’s MODIS Aerosol Optical Depth (AOD), to estimate particulate matter (PM2.5) levels in California from 2006 to 2012. This research has helped identify areas with high pollution levels and understand how PM2.5 spreads across different regions. CARB has also funded various projects utilizing remote sensing for tracking other pollutants and greenhouse gases (Garcia).

Monitoring air pollution is helping in identifying and tracking pollution hotspots in urban areas. This capability is proving to be particularly valuable in rapidly urbanizing cities where industrial emissions, vehicle exhaust, and construction activities contribute to high levels of air pollution (Garcia).

Atmospheric Humidity

Remote sensing with LEO satellites plays a vital role in the monitoring of the hydrologic cycle and water quality parameters. It can measure precipitation, snow cover, soil moisture, runoff, evapotranspiration, cloud and atmospheric humidity, and water quality (Jiang and Wang). By tracking changes in humidity levels over time, scientists can observe shifts in regional climates, monitor drought conditions, and study the impact of rising global temperatures on water vapor, which is a potent greenhouse gas. This data helps improve climate models, predict extreme weather events, and assess the overall health of the Earth's climate system.

Aqua is a satellite launched by NASA in 2002 as part of the Earth Observing System (EOS), specifically designed to monitor the Earth's water cycle. Aqua carries the Atmospheric Infrared Sounder (AIRS), which measures humidity levels in the atmosphere at different altitudes. By analyzing this data, scientists can better understand water vapor distribution and its role in weather and climate processes (A. NASA).

AIRS data is crucial in studying El Niño and La Niña events, which are driven by changes in sea surface temperatures and atmospheric moisture levels. By monitoring humidity patterns during these events, researchers have been able to predict shifts in global weather patterns, such as increased rainfall or droughts in different regions. This satellite-based humidity data also contributes to improving long-term climate models and forecasting the frequency and intensity of extreme weather events, such as hurricanes or monsoons, linked to climate change (A. NASA).

Wildfires

Wildfire monitoring through remote sensing technology, particularly with small LEO satellites, has become a critical tool for detecting, tracking, and managing fire events. Satellites provide real-time data on fire locations, intensity, and spread, which are crucial for early warning systems and disaster management. LEO satellites can capture thermal infrared imagery that identifies heat signatures from active fires and smoke plumes, providing a detailed overview of the fire's impact on land and atmospheric conditions (Chen et al.).

In addition to tracking active fires, satellites also offer insights into the post-fire landscape, such as vegetation loss, soil degradation, and carbon emissions. NASA’s Fire Information for Resource Management System (FIRMS) is an example of how satellite-based remote sensing is used to monitor wildfire events globally. Their system capturing data on burned areas, aerosol emissions, and particulate matter released from fires contributes to a better understanding of wildfire behavior and its broader environmental effects, such as air quality degradation and ecosystem disruption (NASA).

Wildfire monitoring through remote sensing is particularly valuable in remote or hard-to-reach areas where ground-based observation is limited. This technology aids in identifying high-risk zones, such as drought-affected regions prone to wildfires, and assessing how factors like wind, terrain, and fuel type influence fire spread. As wildfires become more frequent due to climate change, satellite data is becoming indispensable for predicting, mitigating, and responding to these destructive events (Chen et al.).

AI Integration with LEO Satellites

AI in Data Processing - Satellite Frameworks, On-board Computing, and Cloud Architecture

In traditional satellite data processing, raw data is collected by the satellite and transmitted to a ground station. It can introduce significant latency due to the time it takes to transmit data to

Earth and then process it. Space cloud framework with AI integration addresses this latency issue by performing data processing directly on the satellites themselves (Bernstein).

On-orbit processing enables the transmission of only processed results, which are much smaller in size than raw data, significantly reducing the amount of data sent over satellite communication links. By processing data closer to its source, the time to deliver results to users is dramatically shortened, which is crucial for applications requiring real-time or near-real-time information, such as disaster monitoring and environmental surveillance. This approach enhances efficiency and responsiveness, particularly in scenarios where timely data is critical (Razmi et al.).

As seen in Figure 2, the cloud computing framework approach significantly enhances processing time and efficiency compared to traditional ground-based systems, enabling more responsive and scalable operations for various satellite-based applications.

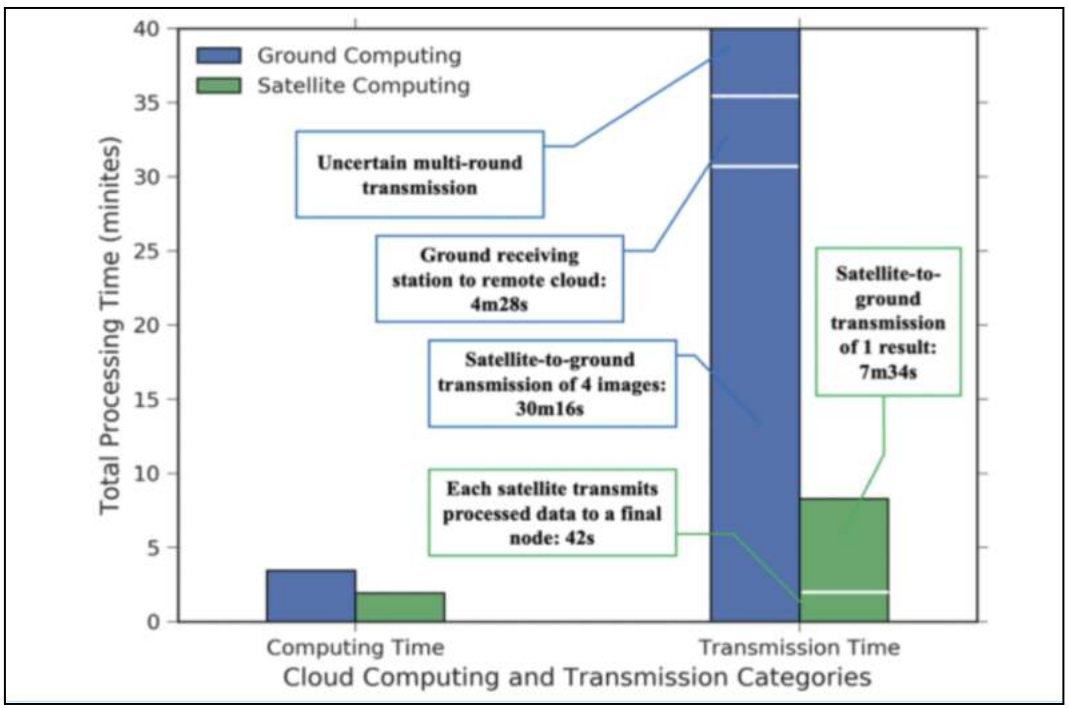

Figure 2: Comparison between Satellite and Ground-based Computing and Transmission time

By leveraging AI algorithms, these LEO satellites can achieve real-time data processing and immediate response to various environmental challenges. These tasks aid in monitoring climate change impacts on air pollution, humidity, and wildfires, enabling real-time detection of pollution hotspots, moisture levels, and active fire zones, providing rapid and accurate data for timely interventions and mitigation efforts.

Space missions have started evaluating how to process and analyze imagery onboard, placing greater demands on flight computing. An innovative approach is by a Finnish company ICEYE, which utilizes synthetic aperture radar (SAR) technology to provide immediate responses to natural disasters. By analyzing SAR imagery, ICEYE can send real-time information to responders in affected areas, aiding in disaster relief efforts (ICEYE).

Machine learning models can process and interpret vast datasets in real time, detecting patterns and anomalies such as pollution spikes or wildfire outbreaks. This AI-driven approach reduces the need for constant human intervention and increases efficiency (Razmi et al.).

As seen in Figure 3, the on-orbit computing and cloud architecture envisions LEO satellites functioning as distributed computing nodes, while a master node, typically a GEO satellite, coordinates tasks sent by users. Users send their requests to the satellite control center through a ground network. The control center uploads the missions to satellite clouds through ground-satellite radio links. This collaborative computing model enhances efficiency in processing large datasets for time-sensitive critical applications such as disaster relief, smart city management, and environmental monitoring. By distributing computational tasks across LEO satellites, this system significantly improves processing speed and data handling for real-time, large-scale operations (Razmi et al.).

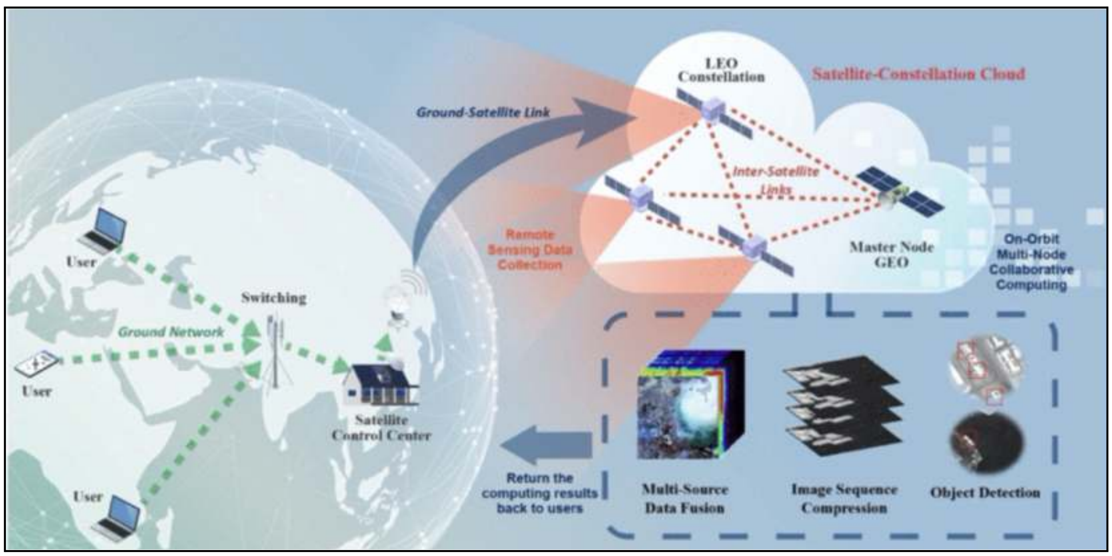

Figure 3: A Satellite Framework with distributed storage and computing resources on multiple on-orbit LEO satellites.

Applications and Future Implications

This satellite-based architecture is particularly valuable for climate change efforts, as it enables real-time monitoring of key environmental factors like air pollution, wildfires, and atmospheric humidity. By leveraging on-orbit AI and cloud computing, LEO satellites can rapidly detect pollution hotspots, active fire zones, and shifts in moisture levels, providing crucial data for early intervention and more informed climate strategies.

The LEO constellation-based cloud framework is poised to revolutionize applications such as smart cities, disaster management, and global healthcare by enhancing data processing and connectivity. The integration of LEO satellite constellations with other communication systems could create a comprehensive spatial information network, facilitating real-time global monitoring and decision-making. For example, LEO satellites can provide coverage in remote and underserved areas where traditional cell towers cannot reach. This integration enhances connectivity between regions, enabling real-time monitoring and management of resources like traffic, utilities, and public safety, or even disaster management. (Razmi et al.).

AI Integration with Climate Change

AI and Air Pollution/Quality

Artificial Intelligence (AI) is playing a transformative role in enhancing the capabilities of LEO satellites for air quality monitoring, enhancing the accuracy, efficiency, and real-time capabilities of data collection and analysis.

AI-driven systems process the vast amounts of data collected by these satellites, including measurements of pollutants like nitrogen dioxide (NO2), sulfur dioxide (SO2), and particulate matter (PM2.5), enabling real-time analysis of air quality across the globe (Heydari et al.). By using machine learning algorithms, LEO satellites can detect patterns in pollution levels, identify sources of emissions, and track the spread of pollutants over time. For example, NASA's TEMPO (Tropospheric Emissions: Monitoring of Pollution) mission, which is set to monitor air quality from space, leverages AI to refine data processing and provide hourly measurements of air quality over North America (Platnick). AI also enables predictive modeling in air quality monitoring, helping to quickly forecast pollution trends and the impact of policy interventions. By analyzing historical data alongside real-time satellite inputs, AI models can predict future pollution spikes or trends related to urbanization, industrial activities, or natural events like wildfires (Guo et al.).

The integration of AI with satellite data also helps governments and environmental agencies to make more informed decisions for pollution control and public health. For instance, ESA uses AI to process data from its Sentinel satellites to assess the impact of traffic emissions and industrial activities on air quality across Europe (ESA).

AI and Atmospheric Humidity

AI plays a transformative role in enhancing the capabilities of LEO satellites for atmospheric humidity monitoring. These satellites collect vast amounts of data on humidity levels using sensors and instruments like microwave radiometers and infrared detectors. AI algorithms process this data in real-time, enabling efficient extraction of relevant information, such as variations in humidity levels across different regions (NOAA). Machine learning models, particularly those designed for predictive analysis, help create accurate humidity forecasts and track trends over time. By integrating AI with data from other sources like ground-based sensors, the accuracy of the humidity data improves, enabling better weather forecasting and climate modeling. Moreover, AI facilitates automated calibration of sensors on satellites, reducing the risk of errors due to instrument drift and enhancing the reliability of collected data.

ESA Earth Explorer missions utilize AI to interpret satellite data, including humidity levels, for monitoring atmospheric processes (ESA). AI-driven insights help these agencies provide more timely and accurate predictions of extreme weather events, improving disaster preparedness and responses globally. By integrating AI with satellite data, global organizations can gain deeper insights into how atmospheric moisture impacts local climates and ecosystems (European Space Agency).

LEO satellites assisted with AI integration have revolutionized atmospheric humidity monitoring by making the process faster, more accurate, and predictive. The integration of AI into these satellites that monitor atmospheric humidity offers enhanced environmental and climate data, improving the understanding and forecasting of weather patterns, particularly as the world faces increasing climate challenges.

AI and Wildfires

AI integration with LEO satellites is revolutionizing wildfire monitoring by providing real-time detection, predictive modeling, and damage assessment.

Various AI technologies are employed in wildfire management, such as object detection algorithms that are used to identify smoke from potential fires, allowing rapid notifications to first responders. LEO satellites equipped with AI algorithms can quickly process data from various sensors, including optical, infrared, and thermal imaging, to detect the early signs of wildfires. For instance, AI can analyze heat signatures and smoke plumes in satellite imagery, identifying potential fire outbreaks even in remote or cloud-covered areas. Such AI applications help improve detection, prediction, and response strategies in addressing wildfires as a result of climate change (Ahmed et al.).

Technology and artificial intelligence are crucial in combating wildfires, driven by the increasing frequency of such events due to climate change. Startups like Pano AI and OroraTech utilize advanced camera systems and satellites for real-time detection and hotspot identification, enhancing rapid response efforts. AI initiatives, such as the FireAid project in Turkey, have demonstrated significant accuracy in predicting wildfires, achieving around 80% prediction accuracy. The economic impact of wildfires is substantial, costing the U.S. economy approximately $893 billion annually (Hillsdon). Collaborative efforts are essential for improving resource efficiency and ensuring that innovative solutions are accessible globally.

AI also aids in the tracking of wildfire spread, a critical factor in mitigating their destructive impact. By integrating historical fire data, weather patterns, and current satellite observations, AI models can forecast the path and intensity of wildfires. For example, ESA has used AI-driven satellite monitoring to predict the behavior of wildfires in areas like the Mediterranean, where fires are frequent (ESA). AI systems also enable automated analysis of terrain features, vegetation dryness, and wind speeds to anticipate where a wildfire is most likely to spread. This predictive capability, combined with real-time monitoring, allows for more effective coordination of firefighting efforts, ensuring that high-risk areas receive attention faster, potentially reducing the overall devastation caused by wildfires.

Risks

As discussed in this paper, LEO provides numerous advantages to harness the power of AI to aid in areas of climate change.LEO satellites also come with risks, which can be carefully managed. LEO satellites have collision risk in orbit, frequently involved in close encounters with other spacecraft. While companies plan to deorbit aging satellites to prevent space debris accumulation, the process of burning these satellites during reentry could potentially alter atmospheric chemistry. However, companies are working to collaborate with organizations to minimize the impact of LEO satellites on the environment. By combining better space traffic management, improved design practices, and innovative solutions like active debris removal, the risks associated with LEO satellite collisions and atmospheric impact from satellite reentry can be significantly mitigated. One crucial method is international coordination for regulations and policies.

Conclusion

The integration of LEO satellites, AI, and cloud architecture is playing a transformative role in climate change monitoring, particularly for air pollution, wildfire detection, and air humidity tracking. LEO satellites equipped with advanced sensors can provide high-resolution, real-time data on pollutants like carbon dioxide, methane, and particulate matter, offering valuable insights into air quality. AI plays a crucial role in processing vast datasets from these satellites, enabling accurate analysis and predictive modeling. This real-time data is essential for understanding how pollution spreads across different regions and formulating effective policies to mitigate its impact on climate and public health.

Moreover, the integration of AI with LEO satellites has shown immense potential for wildfire detection and air humidity monitoring. Satellite-based AI systems can quickly identify early signs of wildfires, track their spread, and provide critical information to emergency responders, reducing response time and limiting damage. Similarly, AI-driven analysis of air humidity data aids in forecasting weather patterns, enhancing climate models, and providing vital information for agricultural planning and water resource management. These advancements in LEO satellite technology, combined with AI and cloud computing, offer significant benefits in understanding and combating climate change, making these technologies indispensable for building a more sustainable future.

AI can greatly enhance climate change efforts by accelerating data analysis, improving prediction accuracy, saving lives, and driving environmental well-being in areas like air pollution, wildfires, and air humidity. By rapidly processing vast environmental datasets, AI facilitates timely decision-making and effective disaster response. Machine-learning techniques refine forecasting models, allowing for reliable predictions that help communities prepare for health impacts from pollution and wildfires. Additionally, AI-integrated early warning systems enable proactive measures to protect lives, while accurate predictions can minimize property damage and reduce costs for industries. Ultimately, AI not only aids in addressing climate challenges but also fosters public safety and economic sustainability.

The insights gained from studying these areas are invaluable for various stakeholders. Scientists use the data to refine climate models and predict future trends, helping manufacturers design cleaner technologies and reduce environmental footprints. The data also guides emergency responders in preparing for and reacting to natural disasters, such as wildfires and droughts. Policymakers rely on this research to develop informed regulations that curb pollution, reduce carbon emissions, and manage natural resources more sustainably. For example, the Deforestation Regulation Impact in a new European Union regulation mandating companies to ensure commodities are sourced from deforestation-free areas, facilitating compliance through spatial analysis (CARTO). Overall, these studies empower governments, industries, and international organizations to collaborate effectively and address climate challenges proactively.

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