Proceedings of the 4th International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/83/2025.19953

The Role of Climate Models in Predicting Extreme Weather Events in a Warming World

Yixiao Li[1,a,*]

[1]*Wuhan Britain-China School, Wuhan, China*
a. yknminato4@gmail.com
**corresponding author*

Abstract: Global warming and climate change are major challenges facing humankind in the twenty-first century. With the increase in greenhouse gas (GHG) emissions, global temperatures are rising, leading to a significant increase in the frequency and intensity of extreme weather events. This paper explores the correlation between climate change and extreme weather events, focusing on examining the application of Global Climate Models (GCMs) and Regional Climate Models (RCMs) in predicting extreme weather. By simulating atmospheric, oceanic, and terrestrial systems, climate models provide an important scientific basis for forecasting extreme weather events and help mitigate the social and economic impacts of these events. This paper also discusses the current status of climate model development, the application of data assimilation techniques, and possible ways to improve prediction accuracy in the future. With the continuous progress of science and technology, the predictive accuracy and resolution of climate models will gradually improve, providing more accurate early warning of extreme weather events. Through the in-depth application of these models, mankind will be able to formulate precautionary measures in a more timely manner to mitigate the economic and social losses caused by climate change. At the same time, these models will provide a scientific basis for national policymaking and help address the global climate crisis.

Keywords: Climate Models, Extreme Weather Prediction, Climate Change.

1. Introduction

Global warming and climate change are among the greatest challenges facing humankind in the twenty-first century. The rapid increase in greenhouse gas emissions since the industrial revolution has led to a steady rise in global temperatures and significant changes in the climate system. Extreme weather events usually refer to weather phenomena that occur with a frequency and intensity well above average climatic conditions, such as hurricanes, droughts, floods and heat waves. Because of their extreme nature, these events pose a serious threat to the natural environment and human society. More critically, this climate change has led to a significant increase in the frequency and intensity of extreme weather events, with far-reaching impacts on global ecosystems and human societies [1]. Extreme weather events, such as droughts and floods, directly threaten the safety of human lives and property, damage infrastructure, affect food production, and cause huge losses to the global economy [2]. For, instance, during 2019, the U.S. experienced several active extreme weather events, suffering from millions of cumulative cost [3].

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Against this background, accurate prediction of extreme weather events has become particularly important. Through effective forecasting, human beings can take early response measures to reduce the social and economic impacts of extreme weather. For example, hurricane forecasts can help coastal residents evacuate in advance, drought predictions can provide guidance for agricultural production, and heat wave warnings can provide a basis for decision-making by public health authorities [4]. Therefore, improving the prediction capability of extreme weather events has become a common goal for scientists and policy makers around the world. Climate modelling, as a powerful tool, is becoming an important means of predicting extreme weather events.

In recent years, the prediction accuracy of extreme weather events has been significantly improved with the improvement of climate model resolution, the development of data assimilation techniques, and the enhancement of computational power. This paper, aiming at evaluating the models, will first introduce the connection between climate change and extreme weather events, then review the fundamentals of numerical climate modelling methods and their progress in application, and finally discuss the future direction of climate modelling and its potential in extreme weather prediction.In response to this growing concern, scientists are continuously improving climate models to more accurately predict trends in the occurrence of extreme weather events. Climate models simulate the interactions of the atmosphere, ocean and land systems and help to identify the causes and pathways of extreme weather events. Advances in computational technology, particularly in data assimilation methods, have enabled the integration of a large amount of observational data into models, significantly improving their accuracy. For example, data assimilation techniques such as Kalman filtering can dynamically adjust forecasts to be closer to real-time observations, thus reducing uncertainty. The application of these technologies not only helps governments and related organisations to make early warning preparations in advance, but also provides decision makers with more scientific coping strategies.

Looking ahead, with the further improvement of climate models and the addition of artificial intelligence and big data technologies, the accuracy and timeliness of extreme weather forecasts will be significantly improved. This will not only help to enhance the ability of human beings to cope with the risks posed by climate change, but will also provide a solid scientific basis for countries around the world to formulate relevant policies and mitigate the socio-economic impacts of climate change, thereby more effectively protecting the sustainable development of human society and the Earth's ecosystem.

2. Linkages between Climate Change and Extreme Weather Events

As global temperatures rise, the energy of the atmospheric and oceanic systems increases, which provides additional impetus for the occurrence of extreme weather events. In addition, warming has altered atmospheric circulation and ocean circulation patterns, which in turn affects the stability of weather systems and the characteristics of regional climates. As a result, global warming has not only led to an increase in global average temperatures, but has also triggered significant changes in the frequency, intensity and distribution of extreme weather events.

The frequency of extreme weather events has risen significantly in recent years due to increasing global temperatures. A notable example is the increase in heat wave events. According to several studies, climate warming has led to a significant increase in extreme heat events worldwide, especially during the summer months, when record-breaking temperatures are frequently experienced in the mid-latitudes of the northern hemisphere. For example, according to the World Meteorological Organization (WMO), the frequency of extreme heat events triples for every 1-degree Celsius increase in global average temperature. In addition, many mid-latitude regions have experienced frequent record high temperatures in recent years, especially during the summer months Heat waves would lead to significant crop yield losses, and they will also cause serious public health problems.

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For example, the 2003 heatwave in Europe resulted in the deaths of about 70,000 people, which is considered to be part of a long-term trend driven by global warming [5].

In addition to increased frequency, warming has significantly increased the intensity of extreme weather events. A classic example is the intensification of hurricanes. By increasing the surface temperature of the oceans, climate change allows tropical cyclones, such as hurricanes, to absorb more energy during their formation and development, thereby increasing their strength. Hurricane Harvey, for example, was an extremely intense storm that rapidly intensified before making landfall in Texas and subsequently bringing record-breaking rainfall. Scientists analyzed climate models and found that the increase in ocean surface temperatures and the increase in water vapor content in the atmosphere were important factors in the increased strength of Hurricane Harvey [6]. This not only led to the extended duration of Hurricane Harvey, but also significantly increased its destructive power.

Warming has also altered the geographical distribution patterns of extreme weather events. For example, global warming has led to a significant increase in the frequency of drought events in some regions, while other regions are likely to experience more frequent floods and heavy rains. Climate change affects the spatial and temporal distribution of precipitation by altering atmospheric circulation and water cycle patterns. For example, many parts of sub-Saharan Africa are facing more severe droughts as a result of reduced precipitation, while the monsoon regions of South-East and South Asia are experiencing more extreme rainfall events [7].

The impact of climate change on extreme weather events has been demonstrated in a number of cases, with global warming not only increasing the frequency of extreme weather events, but also significantly increasing their intensity and changing their distribution patterns. Events such as Hurricane Harvey clearly demonstrates the contribution of climate change to extreme weather events. Through these cases, the impact of climate warming on natural disasters can be better understood, thus providing a scientific basis for future climate prediction and disaster defense.

3. Application of Numerical Climate Modeling

Two models have become a common choice for climate prediction, Global Climate Models (GCMs) and Regional Climate Models (RCMs). Global Climate Models are sophisticated mathematical models that simulate Earth's climate system on a global scale, incorporating interactions between the atmosphere, oceans, land surface, and ice. They work by dividing Earth into a three-dimensional grid, with each grid cell representing a specific region’s climate characteristics, such as temperature, humidity, and pressure. Through solving complex equations based on physical laws, GCMs predict how these variables evolve over time. Regional Climate Models, in contrast, operate at a finer spatial resolution, focusing on specific geographic areas. RCMs are often nested within GCMs, taking their larger-scale outputs as boundary conditions to refine the simulation in a particular region. This downscaling process allows RCMs to better capture local climate dynamics, such as precipitation patterns, mountainous terrain effects, or coastal processes that GCMs may overlook due to their coarser resolution. By offering high-resolution insights into regional climate variations, RCMs are particularly useful for studying climate impacts on a local scale, like urban heat islands or regional flooding risks [8].

In both GCMs and RCMs, accurate input data is crucial to simulate climate conditions effectively. Wide range of factors such as temperature, humidity, pressure and wind speed are important when constructing the models. These variables influence climate and weather patterns at both the global and regional levels, affecting phenomena like precipitation, cloud formation, and heat distribution. One of the most critical variables in climate models is temperature because it drives many of the Earth’s physical and chemical processes. In GCMs, temperature data help simulate large-scale climate patterns and long-term trends. For example, GCMs use global surface temperature data to

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project potential warming scenarios over decades, which is essential for understanding changes in global circulation patterns, sea level rise, and other major climate feedback loops. Studies show that accurately capturing temperature variations on a global scale is critical to simulating large-scale atmospheric dynamics [9]. In RCMs, temperature plays an equally critical role. Since RCMs operate at a finer spatial resolution, they can capture temperature variations within specific geographic areas, such as urban heat islands or coastal zones. These regional temperature changes affect local weather events, such as heatwaves or cold spells. For instance, a study using RCMs demonstrated that regional temperature variations significantly influenced the frequency and intensity of heatwaves in Southern Europe [10].

There is hence the necessity of obtaining accurate data when modelling. In both GCMs and RCMs, data assimilation, a technique that integrates observational data with model simulations to refine climate predictions and enhance the accuracy, is critical for managing the uncertainties. Techniques like Kalman filtering and variational methods allow models to adjust their output in near real-time by incorporating observations from satellites, weather stations, and ocean buoys [11]. This continuous updating process helps align model simulations with actual climate conditions, thereby improving predictive skill.

4. Conclusion

Global warming has exacerbated the frequency and intensity of extreme weather events, with widespread and far-reaching impacts on the natural environment and human society. This paper provides an in-depth analysis of how climate change drives extreme weather events such as heat waves, hurricanes, droughts and floods, and summarises the important role of climate models in extreme weather prediction. Global Climate Models (GCMs) and Regional Climate Models (RCMs) can effectively provide global and regional climate trends through 3D grid simulations and high-resolution local analyses. In addition, the application of data assimilation techniques, such as Kalman filtering and variational methods, has significantly improved the accuracy of the models. In the future, with the improvement of computing power and data sets, climate models will play a more critical role in extreme weather prediction and provide scientific support for mitigating the impacts of climate change and formulating countermeasures.

Global warming has exacerbated the frequency and intensity of extreme weather events, with wide-ranging and far-reaching impacts on the natural environment and human society. This paper provides an in-depth analysis of how climate change drives the occurrence of extreme weather events, including heat waves, hurricanes, droughts and floods, and summarises the important role of climate models in extreme weather prediction. Global Climate Models (GCMs) and Regional Climate Models (RCMs) are effective in providing global and regional projections of climate trends through 3D grid simulations and high-resolution local analyses. These models not only describe large-scale climate change, but also simulate more accurate extreme weather conditions by combining local meteorological features, thus providing a scientific basis and early warning information for governments and research institutions. In addition, the application of data assimilation techniques, such as Kalman filtering and variational methods, has significantly improved the accuracy of the models. By combining observational data and model simulations to optimise climate prediction results, these techniques greatly reduce uncertainty and provide more reliable scientific support for extreme weather prediction. Looking ahead, the role of climate modelling in extreme weather prediction will become more prominent as computing power improves and datasets are refined. The development of artificial intelligence and big data technologies will bring new enhancements to climate models, allowing climate predictions to reach a new level of accuracy and resolution. This will not only help improve the understanding of climate change, but also provide scientific support for the development of disaster prevention and mitigation measures.

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