Journal of Applied Science and Education, 2025,
Vol. 05, Iss. 02, S. No. 104, pp. 1-10
ISSN (Online): 2583-1372

AI-Based Weather Prediction

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How to cite this paper: S. Dubey, "AI-Based Weather Prediction," *Journal of Applied Science and Education (JASE)*, Vol. 05, Iss. 02, S. No. 104, pp 1-10, 2025.

https://doi.org/10.54060/a2zjournals.jase.104

Received: 12/02/2025
Accepted: 18/06/2025
Online First: 14/07/2025
Published: 14/07/2025

Abstract

Weather prediction has always been challenging because the atmosphere is complex and constantly changing. Traditional methods use physics-based models that rely on mathematical equations to predict how the weather will evolve. However, these models take a long time to run and have uncertainties, the results are not very efficient and accurate.
Now, Artificial Intelligence (AI) is helping improve weather forecasting (AI-driven forecasting). AI can quickly analyse huge amounts of weather data from satellites, weather stations, and radars. It learns patterns from past weather events and makes predictions faster and more accurately than 7traditional models.

- *Artificial Intelligence (AI)*
- *Machine learning (ML) (particularly)*
- *Deep learning (DL)*

These are helpful in revolutionizing weather forecasting by improving accuracy, reducing computational costs, and enabling real-time predictions.
Accurate weather prediction is essential for disaster preparedness, agriculture, and climate research. AI-based weather prediction offers a promising solution by integrating deep learning techniques with physics-based models to enhance forecast accuracy and efficiency. This paper explores hybrid approaches that combine machine learning with fundamental atmospheric equations to improve weather predictions. We discuss advancements in AI-driven parameterization, and uncertainty reduction, highlighting their potential to revolutionize meteorology.
The findings indicate that AI-augmented climate models can significantly improve forecasting capabilities, paving the way for more accurate and efficient weather prediction systems.

Keywords

- *AI-driven forecasting*
- *Climate physics models*
- *Numerical weather prediction*
- *Deep learning*
- *Hybrid modelling.*

1. Introduction

Weather prediction has always been a challenge for the whole human race, whether it's just the agriculture industry or whole sports world. In a country like India, we see a lot of people suffering especially the farmers in rural areas with weather, many of them end up getting bankrupt or end up taking their own lives due to unexpected rains. Or if we look at the sports industry, we see a lot of matches getting delayed because of Rain or storms. Hence weather sometimes led to loads of loss to companies, farmers, and the media industry.

Well here comes the importance of weather prediction. If we have a accurate weather prediction model we can deal with all of it by preparing ourselves, it's not as if we don't have weather prediction models right now, it's just that they are not that accurate and enhanced if we compare them with today's technology.

Weather prediction is useful for preparing for weather conditions like Hurricanes, heatwaves, and storms. Traditional forecasting has relied on numerical weather prediction (NWP) models, which use fundamental physical equations. Although there have been upgrades in NWP as well, it is still not up to the mark and that is accurate. A significant advancement in AI-based forecasting in weather and climate is the integration of AI methods with physics-based models. Hybrid models, which include AI-based pattern recognition along with a numerical weather simulation, may help to mitigate some of the constraints of traditional models. Hybrid models utilize AI methods to improve the output of the model, improve biases, and enhance parameterization schemes so that the predictions are more accurate. For instance, models that incorporate Physics-Informed Neural Networks (PINNs) and AI-assisted data assimilation tools implement fundamental principles of the atmosphere into model formulations so that model predictions and simulations are self-consistent and grounded in established physics.

In AI based weather prediction model there are several methodologies of AI used

1. Machine Learning
2. Deep Learning
3. Generative Adversarial Networks (GANs).

2. What is AI?

AI stands for artificial intelligence. It is one of the many branches of computer science. It is basically an ideology which focuses on reducing human work and enhancing the quality of work. It basically copies a particular pattern and gets the work done without any human intervention or minimal human intervention.

AI is basically of two types:

1. Narrow AI
2. General AI.

Narrow AI is basically the weak one, for example- Siri and Alexa, these are basically used for voice recognition or voice, typing or image classification, etc. The other one, General AI is a strong one, which can perform tasks which a normal human can like an intellect, but it hasn't been developed yet.

3. AI in weather prediction Model

Now, if we talk about AI's contribution in weather prediction than first two names, which come up or Machine Learning and Deep Learning.

These are basically like the two subsets of AI, which are used with the prediction models. AI driven weather forecasting, take large amounts of data set from satellites, radars, weather stations and climate models. These data sets contain information about the humidity, wind, speed, atmospheric pressure, and other variables required for predicting the weather.

Hence, use of AI with the prediction models may help us in many ways such as it will provide us with fast forecasting, improved, accuracy, improved weather prediction.

Figure 1.

4. Why AI weather prediction models over traditional methods?

AI-based weather prediction is revolutionizing and becoming the new future, by making forecasts faster, more accurate, and more efficient compared to traditional methods. With AI technology evolving, it is becoming a preferred method over traditional forecasting techniques.

Traditional weather forecasting relies mostly on Numerical Weather Prediction (NWP) models, which uses a set of complex equations to simulate atmospheric behaviour. These models require many powerful supercomputers and vast computational resources which often take hours to generate accurate forecasts. While effective, they can be slow and sometimes less accurate, especially for rapidly changing weather conditions.

Whereas AI-driven models of weather prediction use Machine Learning (ML) and Deep Learning algorithms to analyse the massive amounts of past and real-time weather data. By recognizing patterns and trends that traditional models mainly overlook, AI helps in enabling quicker and more reliable forecasting. This not only enhances the prediction but also the accuracy and improves the anticipation of extreme weather events.

An important advantage of AI-based forecasting is its ability to learn and improve over time without any human intervention. Unlike traditional models that require manual adjustments, AI algorithms are continuously being refined by themselves by processing and analysing new data. This makes AI-driven weather models more adaptive and efficient over traditional methods

AI also excels at integrating data from multiple sources, including satellites, radar, sensors, and IoT devices and combining information from these diverse sources. AI generates highly detailed and localized weather forecasts and offers greater precision.

AI-based forecasting is extremely valuable in disaster management. It can generate early warnings for extreme weather events like hurricanes, floods, and heatwaves, allowing authorities and communities to prepare in advance. By improving early warning systems, it can help in reducing casualties and damage caused by natural calamities. AI even plays a crucial role in climate change research. By analysing long-term weather patterns and historical climate data, AI can predict future environmental changes and thus aid scientists and policymakers in developing sustainable solutions. This is vital for addressing global challenges like rising temperatures and shifting weather patterns in certain areas

Another advantage of AI is that it can reduce computational costs and time. Traditional forecasting methods are highly dependent upon expensive supercomputers, whereas AI can process vast amounts of data efficiently using cloud and edge computing technologies. Hence making AI-based weather prediction more scalable and accessible.

As AI continues to evolve, its role in meteorology will grow. Improved machine learning algorithms, real-time sensor networks and big data integration will help in enhancing the forecast precision. It can anticipate weather patterns and can benefit the farmers, businesses, travellers, and disaster preparedness efforts.

AI is reshaping weather prediction by making forecasts faster, accurate, and cost-effective. It can process vast data and recognize intricate weather patterns. It is improving over time making it a powerful tool for meteorologists, emergency responders, and climate researchers. As AI technology is progressing it will become an essential asset for meteorology, climate science, and disaster management, ensuring a more prepared future.

5. ML in AI based Weather Prediction Model

ML stands for machine learning. It is a subset of AI. The use of ML is very crucial in weather prediction models. The traditional methods have uncertainty somewhere since they weren't completely based on statistics, for example, a few years back or even at present in many rural areas, many people predict the weather by alignment of stars or behaviour of clouds, but these predictions are not always accurate, but this is where ML steps in, ML basically learns patterns from historical events or historical data and makes an algorithm for itself to give us accurate faster and efficient forecast based on the historical patterns. It basically teaches the pattern of weather being followed in that particular area since the last couple of seasons and provides you with numbers of predictions based on that.

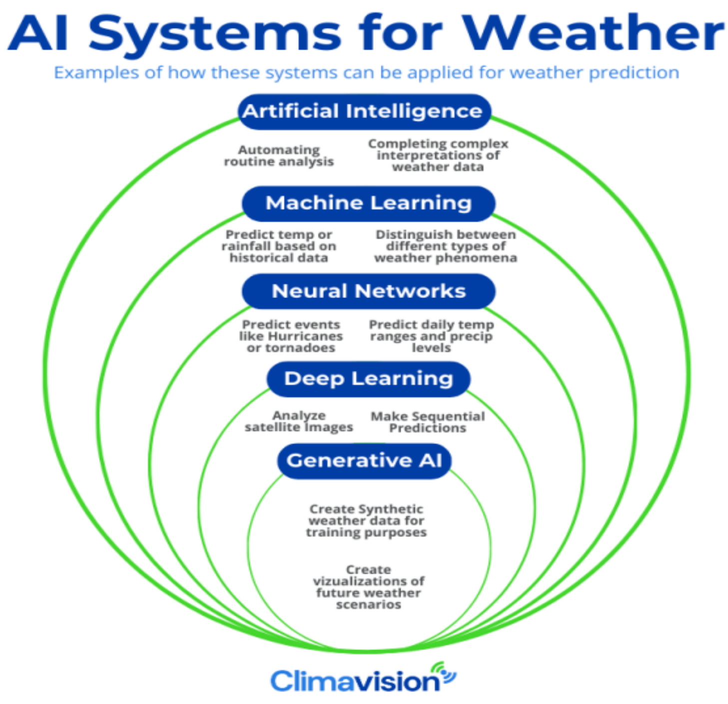

Figure 2.

6. What is ML exactly?

6.1. A Meteorological Analyst Learning to Predict Avalanches

Consider a human meteorological analyst stationed in a mountainous region tasked with predicting snow avalanches.
At first, the analyst lacks experience. However, they are given years of historical records: atmospheric pressure changes, temperature fluctuations, snowpack characteristics, wind speed, and crucially, infrasonic signal patterns recorded prior to past avalanche events.

The analyst studies these records, gradually recognizing that certain patterns in the data such as a specific low-frequency vibration combined with a rapid drop in temperature often precede an avalanche. With enough cases studied, the analyst becomes proficient at forecasting avalanche occurrences, even in unfamiliar scenarios, based on subtle, previously unseen combinations of environmental factors.

This mirrors how a supervised machine learning model operates. During training, the model is exposed to labelled examples (data + known outcome). It "learns" by identifying patterns and associations that differentiate avalanche events from non-events. Once trained, the model can generalize this knowledge and make predictions on new, unlabelled data.
In this analogy:

- The analyst = the ML model
- Historical avalanche data = the training dataset
- Recognized patterns = learned decision boundaries
- Forecasting new events = generalization/inference

ML models take data sets from various sources such as:

1. Satellites- Satellite provide us with data of temperature, cloud cover, and atmospheric pressure data.
2. Radar system- It provides us with data or information about the precipitation and storm tracking.
3. Weather stations- It provides us with data related to wind, speed, humidity, and local temperature readings

The main task of ML is to identify the hidden patterns in the provided data by the above sources.

Hence, ML is helping in revolutionising the whole concept of AI based weather prediction by enhancing the model and its accuracy and enabling real time forecasting. By creating a hybrid model or integrating ML with traditional physics-based approaches, we can develop more reliable and efficient forecasting systems in the future.

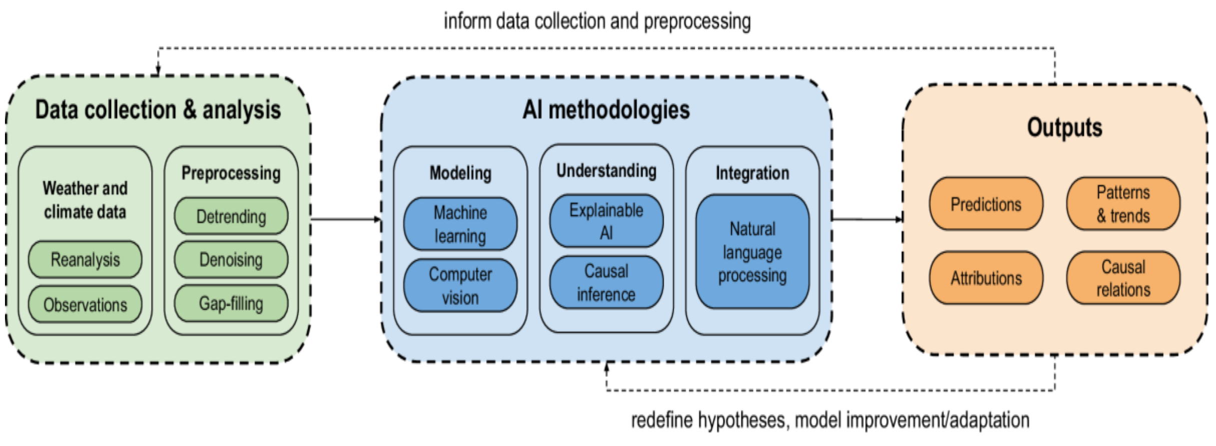

Figure 3.

7. DL in weather prediction model

DL stands for Deep Learning. It is also a subset of AI. Deep Learning is basically used to identify or recognise more complex patterns in meteorological data and improve the prediction capability of the weather production model.
This is how DL contributes to AI driven weather prediction:

DL uses recurrent neural networks (RNNs) and long short-term memory (LSTM) networks, these are specifically designed to handle the obtained data and provide with accurate output. LSTM and RNNs help us in reducing error and noise in meteorological data. It also helps us in storing long-term dependencies in Weather patterns.

DL also helps in reading large scale image data from satellites and climate models.

DL also improves data assimilation, which is basically the observation of real time data. For example, satellite readings, weather stations. Physics informed neural networks (PINNs) make sure that DL model stick to physical constraints while making weather predictions. This leads to faster updates to weather forecasts and enhanced extreme Weather event detection such as storms and heatwaves.

Hence, deep learning (DL) too is helping us in revolutionising AI base with the prediction, by improving the accuracy in result of forecast and by reducing computational needs. By combining DL architectures like CNNs, RNNs, LSTMs, GANs an integrated hybrid AI model can be developed, which will be more reliable and efficient.

Each of the ML architectures mentioned RNNs, LSTMs, PINNs, and GANs serves a distinct role in improving the accuracy and interpretability of the prediction system.

7.1. Recurrent Neural Networks (RNNs)

RNNs are a class of neural networks designed to capture temporal dependencies in sequential data. In the context of avalanche prediction, environmental parameters such as infrasound intensity, pressure, and temperature evolve over time. RNNs help the model learn temporal patterns and correlations between past and present values, making them suitable for time-series forecasting of weather-induced events.

7.2. Long Short-Term Memory Networks (LSTMs)

LSTMs are an advanced form of RNNs designed to handle long-range dependencies in time-series while mitigating issues like vanishing gradients. LSTMs are particularly well-suited for this application, as avalanche-triggering events often result from gradual environmental changes over hours or even days. The use of LSTMs allows the model to retain critical historical context and improve predictive performance over standard RNNs.

7.3. Physics-Informed Neural Networks (PINNs)

PINNs integrate physical laws—represented by partial differential equations (PDEs)directly into the training of the neural network. In this research, PINNs are used to ensure that predictions adhere to known physical constraints, such as snowpack dynamics or thermodynamic relationships in the atmosphere. This hybrid approach combines the strengths of data-driven learning with domain-specific knowledge, resulting in more physically consistent predictions.

7.4. Generative Adversarial Networks (GANs)

GANs are utilized for data augmentation and enhancement, especially in scenarios where labeled data is scarce. Avalanche events are rare and unpredictable, making it difficult to gather a sufficiently large training dataset. GANs help simulate realistic infrasonic and meteorological patterns, thereby expanding the dataset and improving the robustness of the primary predictive model.

8. Importance of Accurate Forecasting

Accurate forecasting plays a vital and a crucial role in various sectors by helping individuals, businesses, and governments make informed decisions.

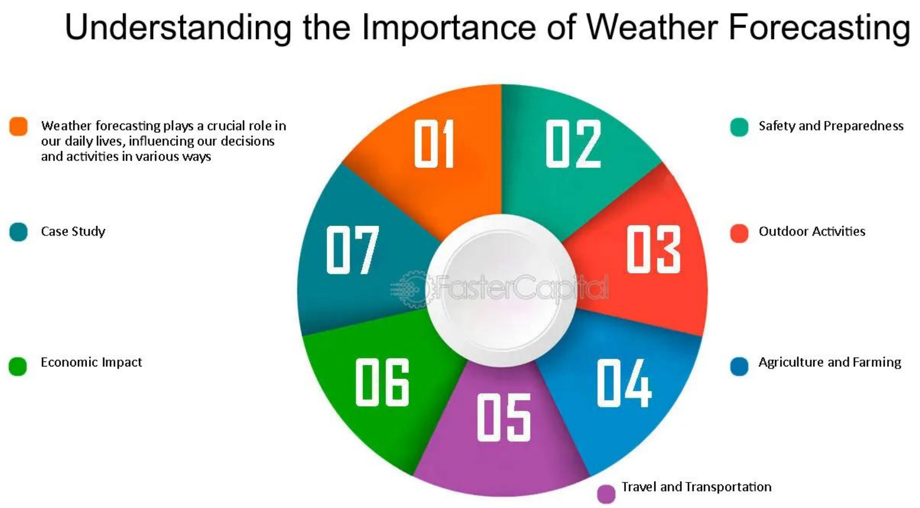

Figure 4.

8.1. Better Decision-Making

Forecasting enables individuals and businesses to make well-informed decisions by predicting the future conditions and trends. Be it market trends, financial investments, or resource planning, accurate predictions help in planning effectively and in a strategic manner. For example, businesses can adjust their production based on the expected demand, and individuals can make a better financial and career choices.

8.2. Cost Saving

By anticipating the future needs and potential risks before time, organizations can allocate their resources more efficiently. Accurate forecasting helps in reducing the unnecessary expenditure by ensuring that money and resources are used more efficiently and in a judicious manner.

8.3. Risk Prevention

Forecasting helps in identifying the potential threats and uncertainties, thus allowing organizations to take proactive measures to mitigate the risks before a natural calamity hits.

8.4. Environmental and Disaster Preparedness

Accurate weather and climate predictions are essential for preparing for natural disasters like hurricanes, floods, and heat-waves. Thus forecasting allows authorities to issue an early warning and thus minimise the damage and improve response strategies. This ensures that the emergency services, infrastructure, and communities are better prepared to handle extreme weather conditions.

8.5. Economic and Policy Planning

Governments and businesses rely on forecasting to develop the economic policies and manage the financial risks. By analysing trends in employment and market stability so that the policymakers can make an informed decision to support sustainable economic growth. Hence for businesses, forecasting helps in long-term planning, investment decisions, and market expansion strategies.

Accurate forecasting is a powerful tool that enhances decision making and reduces costs, it also helps in preventing risks and in improving disaster preparedness and thus supporting economic stability. As forecasting techniques continue to improve, industries and governments can make better and data-driven decisions for a more sustainable and secure future.

9. Case Study

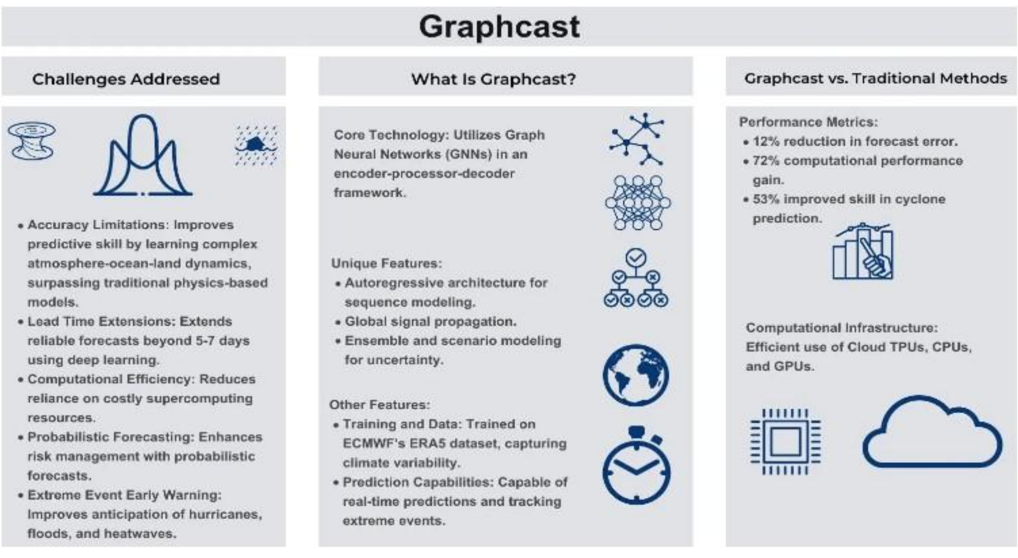

Figure 4. "GRAPH-CAST- By Google's DeepMind"

Graph-cast is an AI model which is present in today's world for weather prediction. It is developed by Google. It uses machine learning to predict weather. A team of Google which is called 'Google DeepMind' is behind the development of this model. It is one of the finest and most accurate models for weather forecasting now.

It uses both ML and DL to provide faster forecasts than traditional methods, It can give us a 10-day weather forecast within a minute.

Graph-cast is basically dependent on graphs; it has a graph-like structure which has nodes. It uses Graph Neural Networks (GNNs) to study complex weather patterns and provide us with accurate predictions.

Graph-casts have been designed by integrating historical data while they were being programmed. It learns from decades of weather data and patterns to provide weather forecasting.

9.1. Working at Graph-Cast

1. **Capturing Data**: Graph-Cast captures historical data and current environmental conditions so that the data can be further analysed and our prediction can be provided.
2. **Graph Neural Network (GNNs):** The Graph-Cast model uses GNNs, which is a powerful tool for machine learning on

graphs. It reads the data and finds the link between the data and presents it in the form of graph.

3. **Prediction output:** The Graph-Cast model then provides us with a prediction or output by learning the patterns across the graph which have been constructed by the above data.

9.2. Limitations of Graph-Cast

- Graph-Cast doesn't work in every region since it requires high-quality training data, which may not be available in certain regions.
- Some of the predictions made by the graph cast are not explainable since AI model operate as black boxes
- Climate changes are unpredictable at times and AI models may struggle to adapt to certain changes in weather conditions.
- The main problem of Graph-cast is it provides data by global analysis, which means the weather prediction basically will be applicable globally, not locally

10. The Solution

Since I come from a computer science background, my idea is to develop an app which gives you the protection around a particular area or a village since by main motive by developing AI based prediction model is to help farmers in dealing with unpredictable with the changes. An app should be developed which can be used easily and which is easily accessible to anyone who wants to use it and which provides accurate and efficient data prediction for a particular area.

11. Conclusion

AI in weather prediction is revolutionizing meteorology to provide faster, accurate, and cost-effective forecasts. Unlike the traditional methods that rely on numerical models and require extensive computational power. AI uses machine learning to analyze the vast amounts of real-time and historical weather data. This allows and helps AI to recognize complex patterns and improve forecasting accuracy and provide localized predictions with greater precision.

One of AI's biggest advantages in weather prediction is its role in disaster preparedness. By generating early warnings for extreme weather events such as hurricanes, floods, heatwaves, AI helps authorities and communities take proactive measures and it will not only help in reducing morbidity but also mortality, without any need of human intervention.

Beyond the short-term forecasting, AI also plays a crucial role in climate change research. By analysing long-term climate data, AI helps in predicting the future environmental shifts, in assisting the scientists and policymakers in sustainable development.

AI-based weather prediction is transforming how we understand and prepare for weather-related challenges and with global warming becoming a threat to all the sectors. By using AI, we can make forecasts more reliable. AI improves both short-term predictions and long-term climate planning. With technology evolving, AI will become an essential tool in meteorology, disaster management, and climate science, ensuring a safer future.

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