Machine Learning for Weather Research and Forecasting: A Survey

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1. Introduction

Large language models (LLMs) have demonstrated versatile problem-solving capabilities, extending beyond natural language processing to tasks related to tabular data [3]. Tabular data, also known as structured data, is a common and essential data format in machine learning, with applications in diverse fields like finance, medicine, business, agriculture, and education [6]. In this format, data is organized into rows and columns, where each column represents a specific feature or variable. This structure is particularly well-suited for capturing the kinds of information used in weather forecasting [1].

In weather forecasting, these features can include temperature, pressure, wind speed, humidity, precipitation, and other meteorological measurements [9]. The ability to organize and analyze these diverse data points is essential for creating accurate and timely predictions. Machine learning models are trained on historical and real-time tabular weather data to learn patterns and relationships that can be used to make predictions [5].

The review of AI/ML activity within the National Weather Service (NWS) notes the increasing use of these technologies in the atmospheric sciences [10]. Machine learning is being applied to various aspects of weather forecasting, including:

- Quality control of weather observations [11]
- Improving physical parameterization for weather, ocean, and ice modeling, as well as enhancing the computational performance of numerical models [4]
- Aiding weather warning generation [8]
- Supporting partners in wildfire detection and movement [11]
- Processing, interpretation, and utilization of earth observations [10]

These applications demonstrate the potential of AI/ML to assist operations by processing large data volumes and extracting explicit information quickly [2]. Traditional weather forecasting primarily relies on Numerical Weather Prediction (NWP) models, which use mathematical equations based on atmospheric physics to simulate and predict weather patterns [9]. However, NWP models face several challenges, including limited understanding of physical mechanisms, difficulties in extracting valuable insights from vast amounts of observational data, and the need for substantial computational resources [7]. Machine learning techniques have gained significant popularity across a wide range of domains due to their ability to handle large and complex datasets, identify intricate patterns, and make accurate predictions [5].

AI/ML can complement and enrich these traditional numerical weather prediction systems [10]. By leveraging the strengths of ML weather forecasting methods to process vast datasets and identify intricate patterns, the field is expected to achieve more robust and efficient forecasting capabilities. *Machine Learning Methods for Weather Forecasting: A Survey* reviews machine learning applications in weather forecasting, covering methods from traditional machine learning to advanced deep learning techniques [5]. It also introduces commonly used datasets and evaluation metrics, offering guidance for future research. Bias correction, ensemble forecasting interpretation, better data assimilation, and the emulation of computationally costly parameterizations can help achieve accurate, high-resolution NWP model forecasts [1].

Despite the promising applications, the sources also highlight obstacles to the successful operational implementation of AI/ML in weather forecasting [11]. These include a lack of workforce training, curated datasets, and a centralized clearinghouse for technical expertise, as well as limited operational compute resources and a clear project pathway from exploration to operational use [10]. There is also a need for coordination and thoughtful inclusion of the expertise and operational requirements of specific entities within the NWS [4].

To fully utilize the potential of machine learning in weather forecasting, it is important to address challenges related to data, infrastructure, and expertise [11]. The creation of standardized datasets, organized according to agreed-upon frameworks, would be a major step forward in facilitating AI/ML development efforts [1]. Additionally, team-based approaches, where individuals have sufficient training to bridge the gap between the meteorological/operational domain and the AI/ML domain, are essential [10].

1.1. Taxonomy

Machine learning (ML) techniques have transformed weather forecasting, enabling more accurate and efficient predictions. As meteorological data grows, driven by advancements in satellite technology and ground-based observation systems, sophisticated analytical methods become increasingly critical. This survey categorizes ML methodologies applied in weather forecasting, providing a structured overview of the field.

We present a taxonomy of ML methods for weather forecasting, as illustrated in Figure 1. This taxonomy is organized into three primary categories: Data Sources, Prediction Models, and Forecasting Objectives.

1) **Data Sources**:
   - **Satellite Data**: Provides global coverage, capturing key atmospheric variables such as temperature, humidity, and cloud cover for large-scale weather monitoring [8].
   - **Radar Data**: Crucial for monitoring precipitation and storm systems in real-time, enhancing short-term forecasting capabilities [10].
   - **Ground-Based Observations**: Includes weather stations providing local measurements of temperature, pressure, and wind speed.
   - **Reanalysis Datasets**: Combines historical observations with modern models to reconstruct past weather patterns, useful for training AI models and long-term predictions [9] [10].
2) **Prediction Models**:
   - **Regression Models**: Traditional statistical methods, such as linear regression, establish baseline predictions.
   - **Neural Networks**: Deep learning approaches model complex patterns in large datasets, learning intricate relationships between input features and target variables [3].
3) **Forecasting Objectives**:
   - **Now-casting (0-6 hours)**: Real-time predictions, often relying on radar and satellite data for immediate weather conditions [10].
   - **Short-Term Forecasting (6 hours to 7 days)**: Predictions made within hours to days, effective in adapting to changing atmospheric conditions [11].
   - **Medium-Range Forecasting (1-4 weeks)** Multi-week projections, that incorporate ensemble prediction systems (EPS) to account for uncertainty [5].
   - **Long-Term Forecasting (1 month - 1 year)**: Year long projections that analyze seasonal patterns and climate anomalies, relying on historical data and climate models [5].
   - **Subseasonal-to-Seasonal (S2S) Forecasting**: Bridges the gap between weather and climate, using coupled models for 2-week and 3-month forecasts.

This taxonomy provides a foundational framework for understanding ML methodologies in weather forecasting, offering a clearer perspective on the current landscape of research and applications.

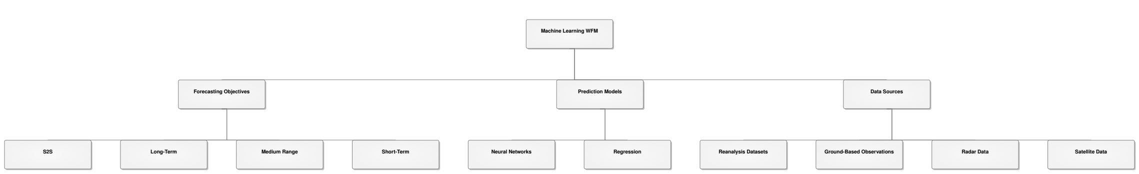

Figure 1. A Taxonomy of Machine Learning Methods for Weather Forecast Prediction

2. Research Gap

Despite the significant advancements in weather forecasting through machine learning techniques, several gaps remain in the current literature that warrant further investigation. Mishra and Joshi [1] provide a comprehensive overview of machine learning applications in weather forecasting, yet they do not delve deeply into the integration of large language models (LLMs) with tabular data, which has shown promise in other domains [3]. This presents an opportunity to explore how LLMs can enhance predictive accuracy and interpretability in meteorological contexts.

Furthermore, while Bochenek and Ustrnul [2] discuss various applications of machine learning in weather prediction, they highlight the need for more robust models that can handle the complexities of climate data. Zhang et al. [5] echo this sentiment, emphasizing the necessity for a unified framework that can accommodate diverse machine learning methodologies. However, there is a lack of consensus on the best practices for model selection and evaluation in this field.

Additionally, the survey by Ruan. [6] on language modeling techniques for tabular data suggests that there is untapped potential in leveraging these methods for weather-related datasets. This indicates a research gap in applying advanced language modeling techniques to improve the understanding and prediction of weather phenomena.

Moreover, while the Weather Research and Forecasting (WRF) model has been extensively reviewed [9], there is limited exploration of how artificial intelligence (AI) and machine learning can be systematically integrated into existing forecasting frameworks. Roebber [10] highlights the activity of AI within the National Weather Service, yet there remains a need for empirical studies that assess the impact of these technologies on operational forecasting.

Lastly, the recent report by the U.S. Government Accountability Office [11] on AI in natural hazard modeling underscores the importance of addressing severe weather events, yet it does not provide a detailed analysis of the challenges and limitations faced by current machine learning approaches in this domain. This gap presents an opportunity for future research to focus on developing more resilient models that can effectively predict and mitigate the impacts of extreme weather events.

In summary, the intersection of machine learning, language modeling, and traditional meteorological methods presents a rich area for future research, particularly in enhancing predictive capabilities and operational applications in weather forecasting.

3. Chronological Overview

Year	Title	Description
2004	Occurrence and Quantity of Precipitation Can Be Modeled Simultaneously	Explores the simultaneous modeling of precipitation occurrence and quantity, providing insights into meteorological modeling techniques.
2017	The Weather Research and Forecasting Model: Overview, System Efforts, and Future Directions	Provides an overview of the WRF model, discussing system efforts and future directions in weather forecasting research.
2021	A Comprehensive Study on Weather Forecasting using Machine Learning	Examines various machine learning techniques, including linear regression and artificial neural networks, for improving weather prediction accuracy.
2022	Machine Learning in Weather Prediction and Climate Analyses—Applications and Perspectives	Discusses the applications of machine learning in weather forecasting and climate analysis, highlighting challenges such as data reliability and computational complexity.
2022	Understanding of Cyclone Vayu with WRF-ARW Model: A Case Study	Presents a case study on Cyclone Vayu using the WRF-ARW model, analyzing the model's performance in simulating cyclone behavior.
2022	A Review of Artificial Intelligence and Machine Learning Activity Across the United States National Weather Service	Reviews the integration of AI and machine learning within the National Weather Service, highlighting ongoing projects and future opportunities.
2022	SCADA Systems With Focus on Continuous Manufacturing and Steel Industry: A Survey on Architectures, Standards, Challenges and Industry 5.0	Covers SCADA systems in industrial automation, focusing on architectures, standards, and challenges in the steel industry.
2023	Large Language Models on Tabular Data: Prediction, Generation, and Understanding - A Survey	Reviews the application of large language models to tabular data for predictive modeling, data synthesis, and interpretability.
2023	Artificial Intelligence in Natural Hazard Modeling: Severe Storms, Hurricanes, Floods, and Wildfires	Assesses the role of AI in modeling natural hazards, focusing on severe storms, hurricanes, floods, and wildfires.
2024	Language Modeling on Tabular Data: A Survey of Foundations, Techniques and Evolution	Discusses the latest advancements in language modeling techniques for tabular data, focusing on foundations and applications.
2024	Machine Learning Methods for Weather Forecasting: A Survey	Reviews machine learning applications in weather forecasting, covering methods from traditional machine learning to advanced deep learning techniques.
2024	PreMevE-MEO: Predicting Ultra-Relativistic Electrons Using Observations from GPS Satellites	Describes a method for predicting ultra-relativistic electrons using GPS satellite observations, contributing to space weather forecasting.

TABLE 1. CHRONOLOGICAL OVERVIEW OF REFERENCES

4. Conclusion

In conclusion, the integration of machine learning (ML) and artificial intelligence (AI) into weather forecasting represents a transformative shift in the field of meteorology. As demonstrated by various studies, including those by Mishra and Joshi [1] and Bochenek and Ustrnul [2], ML techniques have shown significant promise in enhancing the accuracy and efficiency of weather predictions. The ability to analyze vast amounts of historical and real-time data allows for the identification of complex patterns that traditional numerical weather prediction models may overlook.

Moreover, the exploration of large language models [3] and their application to tabular data further underscores the potential for innovative approaches in meteorological analysis. As the field continues to evolve, it is crucial to address the challenges associated with data quality, computational resources, and the need for specialized training within the workforce [10]; [11].

Future research should focus on developing standardized datasets and fostering collaboration between meteorologists and data scientists to bridge the gap between operational needs and advanced analytical techniques. By leveraging the strengths of AI and ML, the meteorological community can enhance forecasting capabilities, ultimately leading to better preparedness for severe weather events and improved public safety.

References

[1] D. Mishra and P. Joshi, "A Comprehensive Study on Weather Forecasting using Machine Learning," in *2021 9th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO)*, Noida, India, 2021, pp. 1-5, doi: 10.1109/ICRITO51393.2021.9596117. Available: https://ieeexplore.ieee.org/abstract/document/9596117

[2] B. Bochenek and Z. Ustrnul, "Machine Learning in Weather Prediction and Climate Analyses—Applications and Perspectives," *Atmosphere*, vol. 13, no. 2, p. 180, 2022. doi: 10.3390/atmos13020180. Available: https://www.mdpi.com/2073-4433/13/2/180

[3] X. Fang, W. Xu, F. A. Tan, J. Zhang, Z. Hu, Y. Qi, S. Nickleach, D. Socolinsky, S. Sengamedu, and C. Faloutsos, "Large Language Models on Tabular Data: Prediction, Generation, and Understanding - A Survey," Amazon, 2023. Available: https://assets.amazon.science/f1/0c/5f8a587c452d9b1c687f70b731ab/large-language-models-llms-on-tabular-data-prediction-generation-and-understanding-pdf

[4] M. Sverko, T. Galinac Grbac, and M. Mikuc, "SCADA Systems With Focus on Continuous Manufacturing and Steel Industry: A Survey on Architectures, Standards, Challenges and Industry 5.0," *IEEE Access*, vol. 10, pp. 12345-12367, 2022. doi: 10.1109/ACCESS.2022.3211288. Available: https://ieeexplore.ieee.org/document/3211288

[5] H. Zhang, Y. Liu, C. Zhang, and N. Li, "Machine Learning Methods for Weather Forecasting: A Survey," *Atmosphere*, vol. 16, no. 1, p. 82, 2025. doi: 10.3390/atmos16010082. Available: https://www.mdpi.com/2073-4433/16/1/82

[6] Y. Ruan, X. Lan, J. Ma, Y. Dong, K. He, and M. Feng, "Language Modeling on Tabular Data: A Survey of Foundations, Techniques and Evolution," 2024. Available: https://arxiv.org/abs/2408.10548

[7] P. K. Dunn, "Occurrence and Quantity of Precipitation Can Be Modeled Simultaneously," 2004. Available: https://research.usq.edu.au/download/bb3fe60cce6c5cb7ef993e6cdae3f3a55a2ad2167f0dd745ea0fbe6c44717d2e/214983/paper.pdf

[8] P. Mukherjee and B. Ramakrishnan, ”Understanding of Cyclone Vayu with WRF-ARW Model: A Case Study,” in *2022 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Kuala Lumpur, Malaysia, 2022, pp. 6514-6517. doi: 10.1109/IGARSS46834.2022.9883923. Available: https://ieeexplore.ieee.org/document/9883923

[9] J. G. Powers and Coauthors, ”The Weather Research and Forecasting Model: Overview, System Efforts, and Future Directions,” *Bull. Amer. Meteor. Soc.*, vol. 98, pp. 1717–1737, 2017. doi: 10.1175/BAMS-D-15-00308.1. Available: https://journals.ametsoc.org/view/journals/bams/98/8/bams-d-15-00308.1.xml

[10] P. J. Roebber, ”A Review of Artificial Intelligence and Machine Learning Activity Across the United States National Weather Service,” Meteorological Development Laboratory, Silver Spring, MD, October 2022. Available: https://vlab.noaa.gov/documents/6609493/8249989/TechMemo86.pdf

[11] U.S. Government Accountability Office, ”Artificial Intelligence in Natural Hazard Modeling: Severe Storms, Hurricanes, Floods, and Wildfires,” Technology Assessment, December 2023. Available: https://www.gao.gov/assets/d24106213.pdf

[12] Y. Feng, Y. Chen, and Y. Lin, ”PreMevE-MEO: Predicting Ultra-Relativistic Electrons Using Observations from GPS Satellites,” *Space Weather*, vol. 22, e2024SW003975, 2024. doi: 10.1029/2024SW003975. Available: https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2024SW003975